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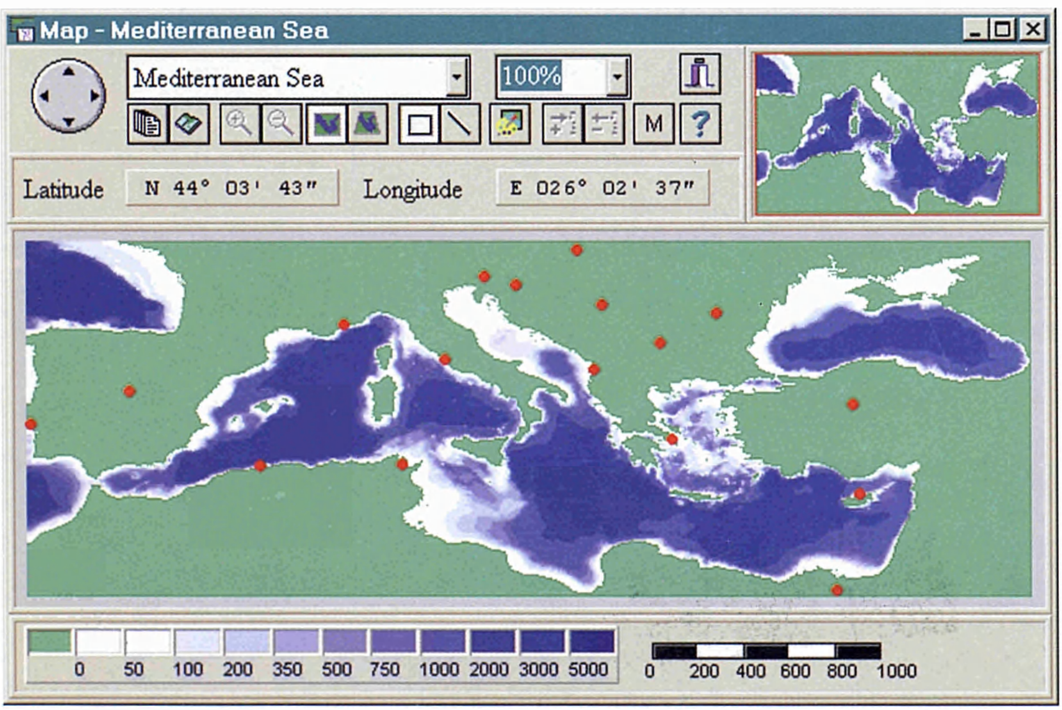
Interdisciplinary research in the Mediterranean Sea

A synthesis of scientific results from the Mediterranean targeted project (MTP) phase I 1993-96



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European Commission

Interdisciplinary research in the Mediterranean Sea

A synthesis of scientific results from the Mediterranean targeted project (MTP) phase I 1993-96

Edited by
Elisabeth Lipiatou

Directorate-General
Science, Research and Development
Directorate for Environment

Marine science and technology programme

1997

A great deal of additional information on the European Union is available on the Internet. It can be accessed through the Europa server (http://europa.eu.int).

Cataloguing data can be found at the end of this publication.

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INTRODUCTION

In 1993 the European Commission established the pilot phase of the Mediterranean Targeted Project (MTP) under the Marine Science and Technology Programme (MAST). The aim of the MTP was and still is to examine the functioning of the Mediterranean Sea in all its aspects, and that is with a strong multidisciplinary approach considering physical, geochemical and biological processes at the same time and with the same priority.

The MTP combined 10 different projects (see Figure) into one overall project involving 200 scientists from 70 institutions and 14 European countries. Each of these projects was multidisciplinary and each had from 5 to 14 partners from different European institutions and countries. All focused on different aspects of ecosystem functioning and contributed to the same overall objectives of the MTP. Project objectives included to (1) reduce the uncertainties in understanding the variability of the general circulation of the Mediterranean Sea; (2) investigate the biogeochemical exchanges between the continental margin and the open sea; (3) improve the knowledge of the biology of the region and its long-term changes. The overall project was co-ordinated by a Steering Committee, led by MAST, and its pilot phase had a duration of three years (1993-1996). It had a budget of ECU 11 million from the European Commission and matching funds from the Member States.

At the conclusion of the MTP pilot phase the project had generated an unprecedented level of scientific co-operation in the area and a large volume of results. In order to better disseminate these multidisciplinary results to the scientific community and also the policy makers, the science had to be synthesized. The Steering Committee of the project then decided that each of the ten projects would present its final results as a "synthesis" article, which would accompany the extended final reports to the Commission. In this volume you will find these ten articles of the MTP projects.

At the end of this volume there are also two articles on Biogeochemical Budgets by Heussner and Price, and on Coupled physical-biogeochemical models by Pinardi et al.. These have been written following two Workshops held in Bologna (May 30, 1996) and in Brussels (June 27-28, 1996) with the objective to synthesise the work of the Mediterranean Targeted Project.

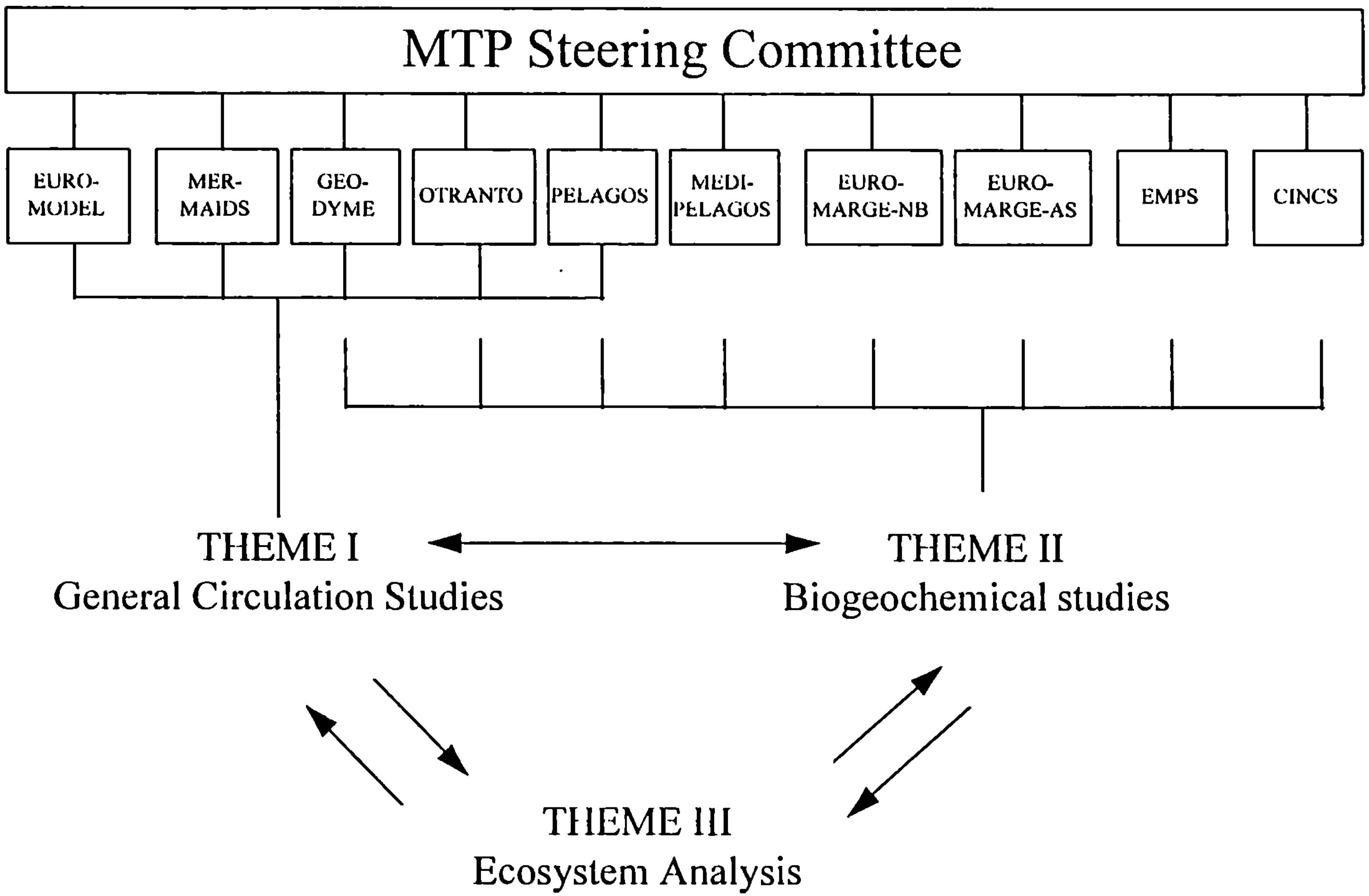
The Mediterranean Targeted Project is now in its second phase (1996-1999). The new MAST project has the name Mediterranean Targeted Project Phase II-Mass Transfer and Ecosystem Response (MTP II-MATER, contract MAS3-CT96-0051) and it involves 53 partners from 13 countries in Europe as well as Morocco and Tunisia.

The MTP was and continues to be an important instrument for the scientific co-operation which the EU promotes in the Mediterranean Sea.

Ms Christine VAINES is greatly acknowledged for her contribution to the editing of these proceedings.

Elisabeth LIPIATOU
MAST Programme

FIGURE


MTP Steering Committee
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EMPS
CINCS
THEME I
General Circulation Studies
THEME II
Biogeochemical studies
THEME III
Ecosystem Analysis

NOTE

All contributions contained in this volume have been reviewed by an independent scientific expert panel

Mediterranean Targeted Project (MTP)-EUROMARGE - AS Project
Contract MAS2-CT93-0052

Synthesis of Final Results

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Starting date : 1 August 1993
Duration : 33 months
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Transfer pathways and fluxes of organic matter and related elements in water and sediments of the northern Adriatic sea and their importance on the eastern Mediterranean Sea.

ABSTRACT

Work on the Adriatic shelf and basins has been directed to understanding seasonal biogeochemical exchanges of carbon and related elements between the river outfall, the western continental shelf and mid- and southern basins. River Po elemental discharges have been calculated from measurements taken from 1993-5. The river's annual fluctuation in nutrient discharge to the shelf is an important control on primary productivity and biomass measurements. Plankton on the shelf is dominated, sometimes exclusively, by diatoms. Given a southward pattern of shelf flow, suspended particulate matter (SPM) studies have shown that elemental transport is the result of direct riverine injections, but more importantly sediment resuspension. Budgets of transport have been calculated for two transects on the shelf and through the Strait of Otranto.

Geochemical characteristics and abundance of POC, PON, $\delta^{13}C$, I/C_{org} ratios and mineralogy of sediments collected in time series traps and seabed sediments indicate little across-shelf transport, and the export of riverine outfalls and shelf sediment occurs through the Otranto Strait. Anthropogenic metals' (Pb, Zn, Cu) accumulation histories and spatial ranges show that they are limited to the northern shelf and originally were sorbed onto Fe/Mn oxyhydroxides which are relatively unreactive in river and shelf waters. Dissolved heavy metals can show either a high degree of conservatism (Ni, Cu) as introduced from the river or show in the case of Zn, Pb, Cd and Mn extra contributions through benthic release caused by redox cycling in the sediments. Evidence from SPM and sediment from pore water studies shows that the amplitude of redox cycling is seasonal, fed by variation in primary productivity and fallout from overlying waters. Primary productivity shows both temporal and spatial variations and is much higher in summer in waters close to the Po delta. However, substantial production can occur in winter at times of high river discharge.

There is a very strong N-S decreasing gradient in macro- and meio-fauna and microbiology populations. These findings and pore water fluxes show that there is an intense benthic-pelagic coupling between these and the flux of organic matter supplied to the seabed, such that there is an insignificant export of marine carbon from the shelf. Much of the carbon on it is identified as terrestrial, which is higher (~75%) on the northern shelf and equates with its delivery from the river. Ammonifying species dominate the bacterial population. A study of the pelagic-benthic coupling of Corg and Si_{bio} indicates that there has been no appreciable extra loading of nutrients to the shelf over the past two decades.

Key Words: Adriatic, biogeochemistry, sediment, benthic-pelagic coupling

INTRODUCTION

Study of the Adriatic Sea is of vital importance to our understanding of the Mediterranean ecosystem. It represents one of the major shelf areas of the Mediterranean, especially on its northern side, that contributes dissolved and particulate materials to the Mediterranean basins. Furthermore, major rivers, especially the River Po, contribute a high load of nutrients, so promoting a north-south gradient from eutrophic to oligotrophic conditions along its western side. Additionally, the River Po releases much sediment, a number of natural radioisotopes and anthropogenic metals to the shelf, and the study of these in respect of pathways and sedimentation can be used to assess biogeochemical budgets and fluxes. From these features, the main scientific objectives of EUROMARGE - AS were :

1. To study and quantify seasonal and interannual variability of biogeochemical exchanges between river outfalls, the western continental margin and the mid and southern basins of the Adriatic Sea.
2. To improve knowledge of key biological elements (pelagic and benthic) and the processes of their respiration. To understand their biogeochemistries and to understand the influence these have on related metals and radioisotopes.
3. To describe the biogeochemical compositions of shelf and basin waters and sediments and relate them to terrestrial inputs, especially from the River Po.
4. To assess longterm (10^1-10^4 yrs.) environmental changes that have occurred and to predict future trends from the chemical composition of sediments.
5. To understand the environmental causes of temporal changes of the ecosystem on the continental margin, especially over a seasonal cycle.
6. To attempt to quantify a biogeochemical budget for this system and to relate this with other areas that are to be studied in the MTP.

The principal research outlined below involves study of the River Po discharge and its effect on the biology and biogeochemistry of the shelf waters and sediments with a view to understanding the geochemical balances of the Adriatic ecosystem. The major tasks undertaken have been interdisciplinary, and have focused on spatial and temporal change in the system. However, much of the research is process driven, in order to establish interrelationships of biology and biogeochemicals between water and sediments and within sediments, in a domain that can be considered unique with respect to the Mediterranean. Emphasis is given to the estimation of material fluxes (horizontal and downward) and budgets within the Adriatic system as well as through the Otranto Strait to the Eastern Mediterranean Basin. This research emphasises the importance of River Po discharge both in terms of particles and its nutrient output on primary production rates, biopigments, phytoplankton taxonomy and biomass of shelf waters. It has also investigated the influence of river discharge and the temporal variability of hydrographic parameters on the spatial distribution and downward fluxes of particulate major and minor elements, including radioisotopes on the shelf and in basins. An attempt has also been made to study the relationship these have to the concentrations of dissolved elements in the waters.

The N-S gradient of eutrophism to oligotrophism has been exploited for a study of the accumulation of organic matter and related, including redox sensitive, elements in sediments. It attempts to understand the interaction of biology and microbiology on these. An important consideration of the research is the understanding of the temporal and spatial changes of benthic-pelagic coupling on the shelf and the importance this has on the budgets and fate of carbon within the benthic system as well as its export to the eastern Mediterranean.

Environmental Setting And Field Sampling

The circulation of the Adriatic is cyclonic, hence much of the material transport on its western limb is southwards along the western Adriatic shelf. With the realisation that the River Po is a major control on this circulation, we need to know what its importance is in the composition of its waters and sediments. Numerous studies on the biology, water and particularly sediments of the wstern shelf have been made over the past two decades. Historically, the Adriatic was regarded as a closed basin dominated by the cyclonic gyre and only recently has attention been paid to its exchange with the Ionian Sea. With regard to water discharge, its northern rivers contribute some 28% of the fresh water discharge to the Mediterranean; approximately 65% of it is contributed by the River Po(~1570 m^3sec^{-1}) (Cranzini and Cescon, 1973). Sediment discharge estimations by Dal Cin (1983) suggest a decrease from 16.9 to 10.5 x 10^6 years in recent times, but even such vast quantities constitute less than 50% of the sediment discharge to the western shelf. Previous estimates of annual inputs for Cu, Pb and Zn of 970, 1080, 2500 tons (Provini and Paschetti, 1982; IRSA, 1977) are unspecified with respect to dissolved vs particulate transport, and one is not sure whether these represent total or anthropogenic deliveries. Interaction and fate of these on the shelf are largely unknown although they are known to accumulate in some sediments (Guerzoni *et al* 1984). They appear to be mostly transported by particulate matter (Price *et al*, 1994). Nutrient P, N, Si inputs of 11 x 10^3, 90 x 10^3 and 180 x 10^3 (Marchetti 1984) induce local eutrophism in the area of the Po outfall.

The patterns of water circulation between winter and summer are in marked contrast, and may have some influence on the dispersal of sediment and dissolved substances. Winter circulation is essentially thermohaline and circulation of the northwestern Adriatic is governed by strong salinity variations and heat exchange processes to the atmosphere, which can produce an essentially vertically homogeneous and potentially unstable water column (Franco *et al*, 1982), Frascari *et al*, 1988). Under these conditions the cold water discharge of the Po forms as a southward directed current along the shelf, separated from more saline central Adriatic waters. Hence the transport pathway of biogeochemicals and riverine detritus is narrow and extends southwards to the Otranto Strait.

Waters and sediments from the shelf, the middle (Jabuka Pit) and Southern Adriatic Basin stations (Fig. 1) were sampled at different seasons during several major cruises including EC organised STEP(S) and MTP (EMAS / PALMAS)(E) cruises on N/O Urania between 1993-5. Additionally, water sampling occurred across the Otranto Strait during the MERIDIONALE (POEM) 1993 and MTP OTRANTO-4 1994 cruises on N/O Urania and R/V Aegaio. Local seasonal cruises on N/O Daphne (Cesenatico) and

N/O Salvatore lo Bianco (CNR Ancona) reoccupied the E stations and collected cores from E and M (MAST-I) stations along the shelf from Cesenatico to the Po outfall.

Sediments as cores and pore water samples were analysed for their macro-, meio and microbiology and geochemistry and radiochemistry. *In situ* and deck incubation experiments (O_2, nutrients) were also performed on them. Water samples, collected by 101 Niskin and Goflo bottles, were used to determine primary productivity, plankton biomass, chlorophyll-a, nutrients, dissolved heavy metals, particulate major and minor elements and radioisotopes (^{210}Pb, ^{210}Po). Large volume pumps were also used for the collection of radioisotopes (^{234}Th).

SYNTHESIS OF RESULTS

River Po discharge

Sampling of particulate matter on 27 occasions between 1993-5 provided material to assess particulate discharge against river flow and to assess carrier phases of heavy elements. Annual delivery of major and minor and excess (or anthropogenic) elements of the SPM (Table 1) can be compared with previous (Dal Cin 1993, Provini and Paschetti 1982 and IRSA 1977) and more recent (Pettine *et al* 1994) estimates of discharge. On the basis that riverine particulates contain ~5%Al the total SPM delivery (10-15 x 10^6 tons yr^{-1}) is close to estimates by Dal Cin (1983). Contributions of total excess metals are much closer to the data of Provini and Paschetti (1982) and IRSA (1977) than the data of Pettine *et al* (1994). The delivery of C_{org} is ~1% of the riverine load and implies a substantial delivery of terrestrial C_{org} to the shelf. Detailed assessments and interrelationships between SPM elements and data on dissolved metal concentrations (e.g. Pettine *et al*, 1994) showed that iron oxyhydroxides rather than organic matter and other constituents is the major carrier phase of anthropogenic metals. Moreover there is little interaction between dissolved and major phases in the estimation zone largely because of the high alkalinity of the river (pH~8.2). During periods of low flow, especially in summer, additional Mn is discharged, as the element can be mobilised from river sediment due to increased biological production.

Metal	This study		Pettine et al. (1994)	
	Total	Excess	Total	Excess
Aluminium	7.88 x 10^5	--	8.29 x 10^4	--
Calcium	7.38 x 10^5	--	1.54 x 10^5	--
Organic carbon	1.52 x 10^5	--	--	--
Iron	4.47 x 10^5	9.29 x 10^4	7.32 x 10^4	--
Manganese	1.17 x 10^4	3026	3650	--
Copper	697	269	210	--
Nickel	1530	664	348	--
Zinc	2860	1880	756	--
Lead	915	726	162	--
Cadmium	29.3	--	3.25	--

Table 1 : Supply rates of particulate metals from the River Po to the Adriatic (tonnes y^{-1}).

Shelf response to riverine input :

- Plankton, productivity and nutrients

River output and other seasonal parameters produce temporal changes in water structure on the shelf such that, except for the winter, two vertically structured water masses exist and are separated by an intense thermocline in summer. Salinity and nutrient concentrations of the upper water are highly influenced by riverine discharge and the latter are, for all periods of sampling, higher at station E1 nearer the Po than at stations further south. Consequently chlorophyll-a concentrations and phytoplankton abundance are highly correlated to this discharge. Other than light, the riverine nutrient discharge is the major control on primary productivity which appears to be phosphorus limited. Productivity decreases southwards from the Po outfall as does phytoplankton biomass, which is predominantly of diatoms (~90%). The effect of nutrient input is shown from productivity measurements and biomass at station E2. Highest biomass peaks in surface waters occurred in February 1995 and 1996, times of high runoff; 360mgC m^{-3} and 297mg C m^{-3} respectively; for other periods of high input, daily primary production ranged between 197mg $Cm^{-2}d^{-1}$ (Nov) and 2023mg C $m^{-2}d^{-1}$ (June).

Nutrient balance above and below the thermocline differ in that dissolved inorganic nitrogen (DIN) ratios to P and Si are very different e.g. at Station E1, DIN / P and DIN / Si ratios are 206 and 3.2 respectively, while below the thermocline they are 28 nd 0.5 respectively. Within the upper layers, P concentrations are often >0.1 µmol implying periodic phosphorus limitation on the system. The subthermocline environment appears as an important site for remineralisation processes with a remineralisation AOU : N : Si : P ratio of 426 : 16 : 41 : 1. This is different from an "oceanic ratio" of 276 : 16 : 15 : 1 and the Adriatic may have different phytoplankton compositions (with lower phosphorus content) and different processes, such as Si regeneration at the benthic boundary.

- Suspended particulate matter

Seasonal changes in productivity and biomass in the proximity of the Po outfall are reflected in POC concentrations. Little POC, 100 µg/l, occurs in winter, but in midsummer increases to 600 µg/l at station E1. Southwards, POC concentrations decrease to 90-150 µg/l at Station E2 and E3 commensurate with the falloff in primary production. Basin POC concentrations are much lower (20-50 µg/l) as exemplified in the upper and mid waters of the Southern Basin (Station E5) in August. These changes do not exclusively reflect biomass changes on the shelf as POC/PON ratios can, in certain waters, be elevated over normal marine values. Ratios of >7 and reaching ~10 occur, especially in some shelf bottom waters and basin midwaters, reflecting either the presence of significant terrestrial or highly degraded marine organic matter.

The distribution of biogenic elements examined as midshelf longitudinal (NW-SE) transects and sections across the shelf normal to the coast, illustrate the pathway and extent of riverine influence on the shelf. In summer (1994) a high concentration lobe of biogenic silica occurs in surficial water and extends from the Po outfall to Ancona, which is the most southerly position for recognising riverine discharge. The southward extending lobe of particulate organic P is more limited. Even so, Si_{bio}, organic phosphorus (POP) and chlorophyll-a are closely linked in the northern shelf waters and offshore are all seen deepening to ~50m. These trends are also seen at the Strait of Otranto.

Dispersal of detritus directly discharged is exemplified by Al, Fe and Ca, and is seen in surface water extending southwards. Gypsum ($CaSO_4.2H_2O$), unstable in seawater, can be identified at times of very low water discharge and can also be seen as a surface water lobe extending ~120km south of the Po. However, most material transfer on the shelf occurs from sediment resuspension which is normally confined, at least on the shelf, to the deepest 20m of water and always underlies the thermocline. Only under intense bora winds (NE) at times of poorly density structured water (winter) is this pattern disturbed, and resuspension can pervade the whole water column. In deeper waters and over the sides of basins some pluming of detritus occurs and is seen in the south and especially in the Otranto Strait, where resuspended sediment from the shelf and upper slope is recognised in outgoing modified LIW between 50-300m.

Much of the concentration of redox sensitive elements (Fe, Mn) comes either from river output or sediment resuspension. However, the distribution of particulate Mn and Mn/Al ratios, especially in the north, also indicates a benthic source from the inner shelf. Study of Mn in surficial sediments shows its redoxcline to deepen southwards from 1-2mm near the Po outfall to >1cm south of Ancona, while in the basins, as exemplified in the Jacuba Pit (S/E10), it is less well defined and is >10cm. An associated study of Mn in their porewaters and expressed as diffusional release to bottom waters shows that the amplitude of this release is seasonal, being higher in summer at times of higher productivity, fallout and benthic organic matter respiration. This seasonal pattern of release is confirmed by seasonal variations in particulate Mn concentrations and Mn/Al ratios in shelf bottom waters.

Particulate heavy metals, particularly Zn, Pb, Cu and Cd on the shelf have in most waters interelement ratios similar to that in the river (e.g.Zn/Pb - 2.6); however, some midwaters, especially where chlorophyll-a and Si_{bio} concentrations are high, show Zn/Pb ratios of 3.5 suggesting some preferential Zn uptake, associated with a standing stock high in diatoms. The same feature can also be seen at 50m in the Jabuka Pit. However, excess metal/Al ratios tend to be lower than those delivered by the river, implying some dilution from other sources.

^{210}Pb / ^{210}Po distributions

An understanding of the discharge of dissolved and particulate ^{210}Pb and ^{210}Po from the river is essential for any understanding of the behaviour of these radioisotopes on the northern shelf and in the basins. In oceanic environments these two radioisotopes have been observed to be involved, more so with ^{210}Po, in biological uptake and respiration and may be acting as proxies for the pattern of behaviour of trace metals in this system. On the shelf, ^{210}Po and ^{210}Pb activities show seasonal differences and relate to riverine input and sediment resuspension. Here the riverine contribution to the shelf is much higher than Bacon *et al* (1994) have assumed for the eastern seaboard of the United States and this masks any role that these radioisotopes play in production / respiration processes on the shelf.

In the southern basin (Station E5) partitioning between the dissolved and particulate phases is reversed with respect to the shelf stations and is compatible with a lower biological productivity and lower suspended sediment load. Dissolved phases always have higher activities than particulate phases. Surface waters show small increases in dissolved ^{210}Pb which may be from atmospheric input; also the station shows everywhere that the particulate phase is more enriched in ^{210}Po than ^{210}Pb. At no depth for either the dissolved or particulate phase is ^{210}Po depleted relative to ^{210}Pb. This contrasts with what was observed on the shelf. It also differs from the patterns observed in the N. Atlantic and Southern Ocean (Shimmield *et al*, 1995), and indicates that in the southern Adriatic removal from the dissolved phase by biological scavenging is very limited and confirms oligotrophism in these southern waters. Allied to this work is a study of ^{238}U / ^{234}Th disequilibrium which indicates scavenging rates and residence times in the Adriatic. In most cases, activities of ^{234}Th of particles are lower than dissolved, and in general this is best seen in upper waters which may be a reflection of lower SPM concentrations, as there is for all waters an inverse relationship between particle concentration (turbidity) and dissolved ^{234}Th activity. However, this relationship is complex due to the variability of particle composition (organic vs inorganic) which cannot be easily discerned from turbidity measurements alone. This variation may be the cause of residence time discrepancies in some waters. Where the concentration of particles is high, as in water containing resuspended sediment, ^{234}Th reacts rapidly and its residence time in solution is in the order of 4-11 days. In other waters (e.g.upper water) its residence time increases to 21-72 days. Residence times of particles in the water column are also in the order of a few days with the exception of some basin waters (Station E5, E10).

- Dissolved trace metals

Like the metals in the SPM, a study of the distribution of dissolved heavy metals (Co, Ni, Zn, Pb and Cd) has been made and has been used to understand this transport pathway on the shelf and in basins, and metal reactivity in water. The distribution of dissolved Ni and Cu tends to show highest concentrations in surface waters and can be related to riverine (and possibly atmospheric) discharge. At depth, their vertical distribution on the shelf and in basins reflects mixing of different water masses. Overall, Ni and Cu are highest (30nM and 25nM) near to the Po outfall and decrease southwards such that metal/salinity diagrams indicate only conservative mixing and imply little or no reactivity in the waters. These trends contrast with Cd and Zn, which often show surface concentrations lower than those in bottom waters. There is abundant evidence, as seen in metal/salinity and other associations, of a major benthic input for Zn, although this is more difficult to establish for Cd. In the basins (e.g.Station E10) concentrations are lower in the top 100m than in the deeper water column and may be caused by biological uptake. This trend is supported by high particulate Zn at this station, which has been ascribed to diatom production. Benthic release of certain heavy metals may be coupled to Mn and Fe cycling described above. The effect of this is to influence the pattern of Co and Zn especially, and possibly other elements (Westerlund *et al*, 1986).

The concentration of dissolved Pb in the coastal environment is typically 0.1nM. There appear to be no significant benthic inputs, since increasing concentrations towards the bottom are not systematically observed. The metal/salinity diagram is scattered, and consequently it is difficult to show that mixing between Adriatic water and the River Po is conservative or not. Atmospheric sources of Pb may be an important factor for its distribution, and this has been ascribed to explain lead distribution in sediment traps.

A study of the partition coefficients between solution and particle phases (K_ds) for all metals allows some inference to be made on their distribution. K_ds correlate with log SPM in different ways. Much scatter occurs for Fe and Mn which can be ascribed to changing redox conditions at the sediment interface, and greatly influences their dissolved and particulate concentrations. K_ds of Ni and Pb do not vary much with SPM and in this does not appear to depend on SPM concentration, in contrast to those of Zn, Cu and Cd, which decrease with increasing SPM, as has been noted by Morel and Gschwend (1983). This association may be related to the presence of colloids (Santschi and Honeyman, 1991) which play an important role in the uptake of trace metals.

Environment	Depth range	Cu (nM)	Ni (nM)	Zn (nM)	Cd (nM)	Data Source
Mediterranean Sea	surface (1-100 m) Deep (150-2700m)	1.7 1.5	2.4 3.1	2.7 4.7	0.062 0.066	Tankere et al, 1995
Indian Ocean	surface (0-150m) intermediate (210-1500m) deep (1750-4885 m)	0.8 2.8 1.3	2.6 7.2 5.6	0.8 2.7 7.3	0.010-0.101 0.670 0.510	Morley et al.. (1993)
North Atlantic Ocean	Upper water column (0-500 m) Deep water (500-4300 m)	0.7-1.7 1.7-3.5	1.7-3.0 3.0-5.0		0.100-0.125 0.200-0.350	Saagher (1994)
North Pacific Ocean	Upper water column (0-375 m) Deep water (595-4875 m)	0.5-1.3 1.9-5.3	2.5-5.3 7.5-11	0.08-1.89 4.97-9.07	0.002-0.490 0.81-1.00	Bruland (1980)
North Sea	Central southern North sea	2.8±2.0	4.3±2.5	3.7±2.0	0.17±0.07	Burton et al.(1993)
Northern Adriatic Sea		7.14	9.06	3.69	0.083	This study
Southern Adriatic Sea	surface (0-50 m) deep (200-600 m)	2.95 1.51	5.27 4.72	2.71 3.93	0.076 0.067	This study

Table 2 : Typical concentrations of dissolved Cd, Cu, Ni, and Zn in the Adriatic and other seas, and in the open ocean.

Given that the River Po is considered to be a major input of contaminating metals to the eastern Mediterranean, we have attempted to compare the dissolved trace metal concentrations in the Adriatic with other areas. Table 2 compares typical concentrations of dissolved Cu, Ni, Zn and Cd between the Adriatic and data from the Mediterranean, North Sea and other areas. Each of these metals has to a varying degree a nutrient-like distribution in the oceanic water column and thus there are significant differences in concentration between surface and deep waters. Cu and Ni show highest elevations relative to open Mediterranean waters, a factor of about four times. As concentrations decrease markedly away from the Po outfall, most Adriatic values are similar to the open Mediterranean. Adriatic concentrations and distributions are similar to the North Sea (Tappin *et al*, 1993) in that highest concentrations are found in near shore waters influenced by riverine inputs. Zn also shows only a modest increase over Mediterranean concentrations and are lower than in the corresponding zones of the North Sea.

It is clear that Cd, Cu, Ni and Zn are not greatly elevated in the central and northern Adriatic and this implies that the Sea cannot be considered as contaminated with dissolved metals to any significant extent. Only waters near the Po input show a modest increase from pollution. It is possible that the non-elevation of dissolved metals in the Adriatic may be a result of dominant particulate metal discharge owing to the high pH of the river. Moreover, interaction between dissolved and particulate matter seems to be rather limited, possibly due to limited biological productivity, especially in the central and southern parts of the Sea. The only significant dissolved/particulate metal interaction occurs at the sediment interface, which contributes Zn, Co and possibly other elements to bottom waters and almost certainly relates to organic fallout rates and Mn and Fe recycling.

- Downward fluxes of particulate biochemicals

Although horizontal fluxes of transported material in the upper waters (0-300m) at the Strait of Otranto are quantitatively much greater, by at least two orders of magnitude over their downward fluxes, research during the EUROMARGE - AS project has attempted to evaluate the biogeochemical fluxes and particulate exchange between the continental margin and southern basin. Temporal changes in downward flux have also been used to understand the nature of material settling out of the water column and the relationships these have to one another; these are major biogeochemical constituents, trace organic substances, trace metals and stable radioisotopes. This study can be used to understand the coupling between the water column and sediment and allows for an assessment of the carbon and biogenic Si budget.

A trap array has been employed at one mooring in the centre of the Southern Basin (E5) for 18 months (1April 1994 - 31Oct. 1995) and 12 months (15Nov. 1994 - 31Oct 1995) at 35m (mab) and 500m (mab) above seabed at this 1020m station.

Total mass fluxes were characterised by high temporal variability, from 7.7-1577 mg m^2 d^{-1} at 35mab and 0.9-435 mg m^{-2} d^{-1} at 500mab. They do not present clear seasonal trends except for a very strong biogeochemical signal in July 1994, and there is good correspondence since November 1994 of the temporal patterns of the two traps with the 500mab flux being lower, often by a factor of 2-3, and implies some lateral input. On the basis of flux weighted concentration of major constituents, fallout material has been assessed over four time periods : Phases I and III representing spring and early summer and Phases II and IV late summer-winter. Temporal patterns of opal and carbonate showed opposite trends. Organic matter showed a maximum value (34%) during late November 1994 when there was exceptional riverine nutrient discharge (>8000m^3sec^{-1}) from the Po. Under more normal circumstances its mean contents for the four phases ranged between 6.86 and 10.3%. The lithogenic component of the traps is high (58-61%) and is assumed to come from the shelf edge or northern sources. Characteristics of the settling organic matter have been examined by assessment of their $\delta^{13}C$ signatures and minor constituents. At all times $\delta^{13}C$ shows values between -21 and -24.7 $^{o}/_{oo}$ and reflects change in the admixture of autochthonous marine (-21$^{o}/_{oo}$) and terrestrial carbon (-28$^{o}/_{oo}$); end members that have been identified in the Gulf of Trieste (Faganeli *et al*, 1988). The origin of the POM reaching the 35mab trap, derived from linearly proportioning the $\delta^{13}C$ signatures of trap material between the two end members, suggests that in the centre of the Southern Basin at 35mab, between 50 and 100% (during blooms) of the organic matter is marine, and these closely correlate with the percentage of opal. The 500mab trap shows an even higher content of marine POC (75-100%). Carbohydrate analysis of trap samples tends to confirm the $\delta^{13}C$ variations. They occasionally show high glucosamines (>10%) never found at Mediterranean sites, and possibly relate to fresh marine material associated with a mucilage of phytoplankton origin, but of unknown source, which may sink as large polysaccharide-rich macroaggregates and constitute an excellent biotope for bacteria. Serratore *et al* (1995) and Fogg (1995) consider that bacteria play an important role in the production of mucilage aggregates in the NW Adriatic. High marine inputs are also identified by high hexose (62%). Comparison of carbohydrates between the traps indicates a higher and fresher proportion of organic material in the lower trap, which presents an apparent paradox. Such a distribution has been addressed by Monaco *et al* (1990) who believe that this could be accounted for by differential settling patterns of particles dominated by lateral advection.

^{210}Pb activities and fluxes of the two traps show average fluxes at 500mab and 35mab of 0.34 and 0.55 dpm $cm^{-2}yr^{-1}$ with maxima occurring in March 1995 (500mab) and July 1995 (35mab). This investigation has shown that the ^{210}Pb flux is very dependent on the flux of sedimentary material. Correlation of ^{210}Pb activities with the principal constituents implies that ^{210}Pb at 500mab is directly correlated with organic matter rather than Si_{bio}, while the 35mab trap shows a strong relationship between ^{210}Pb and lithogenic debris. Here the negative correlation between ^{210}Pb and organic matter is thought to be a covariation between two parameters, rather than a causal relationship. The ^{210}Pb flux to the seabed (0.98 dpm cm^{-2} yr^{-1}) is reliable as it is calculated from the ^{210}Pb inventory in the sediment. It shows that extra inputs of sediment mass and ^{210}Pb fluxes to the sediment are needed over that measured in the 35mab trap, and suggest much sediment focusing which seems to occur as a lateral input from sediment resuspension near to the seabed (<35m) which probably occurs as an impulse process.

The pattern of trace metals (Zn, Pb, Ni, Cu, Mn (Fe and Al)) shows no immediate and obvious relationship to the major biogeochemical constituents including marine and terrestrial carbon. As seen in the geochemistry of the SPM, Mn, Fe and Al closely correlate with each other, indicating that aluminosilicates are the main carrier phases of oxyhydroxides. During Phase II, when lateral inputs are high, excess Cu, Pb and Zn are associated with excess Fe, and excess Ni and Zn are related to excess Mn. No correlation was observed with any of the organic components, which is probably due to organic associations being swamped by resuspended inorganic materials. During Phase III the vertical flux is more dominant, and excess Pb was shown to be associated with both total and marine organic matter. These data can be compared with those of the Cretan / Ionian Seas (PELAGOS project) where lateral input is small, and the dominant source of trace metals is atmospheric, rather than riverine, and is sorbed by and recognised in the biota. Here, the relationship between trace metals and major biogeochemical constituents is more easily identified and Pb and Cu are associated with organic matter, while Zn is related to the biogenic silica fallout.

Tentative budgets of organic carbon and biogenic silica in the Adriatic can be compared with estimates of their production in surface waters; 206g C m^{-2} yr^{-1} and 1942 mM Si m^{-2} y^{-1} respectively. The estimates of their downward fluxes at 500 and 35mab, benthic respiration and burial fluxes (see below) are given in Table 3 and imply a strong near bottom input of material between the deeper trap and the bottom sediment.

	Biogenic silica (mmol m^{-2} y^{-1})	Organic carbon (g m^{-2} y^{-1})
Primary production	1942	206
Flux at 500 mab	88	3.1
Flux at 35 mab	136	2.3
Benthic remineralisation	365	· 31 ± 22
Burial	37	2.6

Table 3 : Silica and carbon budget at trap site (South Adriatic Pit depth 1020m).

- Dissolved and particulate elemental budgets

An attempt has been made to assess dissolved and particulate budgets (Tables 4a & b) crossing two across-shelf transects (Fig. 1) in May 1995 and July 1994, using dissolved and particulate element concentrations and water transports crossing these, determined by the MERMAIDS project using a simplified version of POM (Princeton Ocean Model). Budgets through the Strait of Otranto were made with current meter information provided by the OTRANTO project on the modified outflowing LIW water. The budgets were equated with those delivered by the River Po. Annual discharges were calculated using flow estimates for the months given below. Particulate budgets through the Straits are similar to those from the river, especially in November 1994 when there was a high concentration of plumed resuspended sediment over the Strait. The lower particulate budgets on the shelf indicate that most material transport probably occurs during periods of storms. A much higher proportion of Mn relative to Al compared with river inputs leaves the Adriatic and is attributed to redox fluxing from the sediment. A high proportion of the anthropogenic Zn input to the Adriatic also is lost through the straits. Input budgets of dissolved metals from the river are very small compared with particulate metals. Those within the Adriatic are introduced mostly from the eastern Mediterranean and are linked to water circulating within the cyclonic gyre. River inputs are very small compared with outside sources of dissolved metals (Table 4a).

Time	Total Fe	Total Mn	Total Zn	Total Cu	Total Pb
RIVER PO (annual input budget)					
1994 - 1995	79	76	160	120	4
Transect 2					
July 1994	312	4.07×10^3	436	1.07×10^3	36
Transect 3					
July 1994	222	5.65×10^3	608	1.15×10^3	50
STRAIT OF OTRANTO (annual horizontal transport)					
Nov 1994	--	--	4.52×10^3	3.66×10^3	--

Table 4a : Provisional estimates of dissolved element budgets (tonnes yr^{-1}).

Time	Total Al	Total Ca	Excess Fe	Excess Mn	Excess Zn	Excess Cu	Excess Pb
RIVER PO input budget (annual)							
1993-1995	0.788×10^{5}	0.738×10^{6}	9.29×10^{4}	3.03×10^{5}	1.88×10^{5}	269	726
1956-1973(1)	1.096×10^{6}	--	--	--	--	--	--
SHELF calculated annual horizontal transport							
1. Transect 2							
July 1994	3.43×10^{4}	4.49×10^{4}	4.37×10^{5}	1.19×10^{5}	--	--	--
May 1995	5.39×10^{4}	5.99×10^{4}	4.55×10^{4}	401	--	--	
2. Transect 3							
July 1994	8.12×10^{4}	1.30×10^{5}	1.25×10^{4}	1.85×10^{5}	--	--	--
May 1995	2.99×10^{5}	2.93×10^{5}	1.85×10^{4}	1.40×10^{5}	--	--	
STRAIT OF OTRANTO calculated annual horizontal transport							
Aug 1993	0.13×10^{6}	0.139×10^{6}	2.05×10^{4}	2.12×10^{5}	--	--	--
Nov 1994	0.60×10^{6}	0.537×10^{6}	4.80×10^{4}	7.82×10^{5}	1.02×10^{5}	--	--

(1) Dal Cin (1983)

Table 4b : Provisional estimates of particulate element budgets (tonnes yr^{-1})

Sediment investigations :

- Sediment accumulation rates and spatial compositional variations

^{210}Pb and ^{137}Cs methods have been used to estimate sediment accumulation rates. Using activity-depth profiles of ^{210}Pb and the depth of the 1963 ^{137}Cs peak, estimates of sediment accumulation at the northern (E) stations show variation between 0.57 and 0.31g $cm^{-2}yr^{-1}$using ^{210}Pb. Correspondence between ^{210}Pb and ^{137}Cs dating is good, but ^{137}Cs shows severe downward diffusion and methods using the 1954 onset of ^{137}Cs for dating are unreliable. Towards the south (station E4) sediment accumulation rates vary between 0.31 and 0.12g cm^{-2} yr^{-1} over the last half century. Much lower accumulation rates occur in the basins e.g. Station E5; 0.09g m^{-2} yr^{-1}.

Combining these data with those published by Frignani and Langone (1991), it seems that near the Po outfall accumulation rates can be very variable, but are usually substantially higher than are found to the south. Away from the immediate vicinity of direct Po outfall the shelf shows more uniform accumulation rates implying blanket deposition. The much lower accumulation rates in the basins implies little across shelf transport of detritus and that southward sediment transport prevails. The southward increase of ^{137}Cs and ^{210}Pb inventories in northern cores between stations E1-3 is not continued at station E4. Radioisotope inventories do not vary with sediment accumulation rates. This mismatch is probably caused by two factors; a substantial riverine delivery of ^{210}Pb (and ^{137}Cs) as noted above, and a proportionately higher level of erosion relative to gross accumulation with substantial loss of ^{210}Pb in the central areas (E2 and E3) on the shelf. Palaeomagnetic measurements, especially saturation isothermal remanent magnetism (SIRM) of 5m cores sited at M1 and M5 and dated at ~3,500yr BP show that sediment sited near the Po outfall has been subjected to some 26 episodes of major erosion during this period of time.

- Spatial and temporal composition variations

Studies on the spatial and temporal trends in sediment composition have been directed towards three important systems :

a) the patterning of Mn in surficial sediment which has already been addressed with respect to redox cycling and seasonal trends in pore water and SPM compositions.
b) sources of organic matter and its diagenesis during burial
c) the accumulation of anthropogenic metals in shelf sediments.

- Organic matter source and diagenesis

The spatial distribution of C_{org} in surface sediments shows only a limited association with the biological productivity of overlying waters, and spatial change of carbon by itself is a rather unprofitable indicator of overlying productivity. Some cores, especially those collected in summer, show well defined exponential depth decreases in C_{org} and N_{tot} contents within the 5cm of sediment. Over this interval C/N (wt) ratios increase from 7-8.5 to >11. These trends imply either secular changes in organic matter provenance or intense benthic respiration, with preferential loss of N_{tot} at the benthic boundary layer, leading to very degraded organic matter of high C/N ratio. Faganeli *et al* (1994) have demonstrated that a high content of riverine carbon occurs in all shelf sediments. In order to confirm this and to investigate patterns of diagenetic change of the organic matter during burial at the different sites, we have investigated the relationship between I (and Br) with carbon in various surficial sediments. It is known that I is almost exclusively associated with marine organic carbon and tends to have a fixed I/C_{org} ratio of 250 x 10^{-4} in the surface organic matter of the open shelf and hemipelagic environments. During burial diagenesis I is removed from the sediment preferentially to $C_{org,}$ and I/C_{org} ratios as a depth profile usually show a smooth exponential decrease which can occur over a few centimetres to >1 metre. Such a pattern can be interrupted by environmental and sedimentological changes during the accumulation of the sediment. Surface sediments on the Adriatic shelf have I/C_{org} ratios of >>250 x 10^{-4}, indicating high terrigenous carbon. In the north between E1 and E3 estimates of marine carbon range from 24% to 56%. There is a general southward increase such that sediment carbon at station S8 north of Pescara is 72% marine. I/C ratios for surface sediment in the basins, as evidenced at station S/E10, shows 84% marine carbon and demonstrates little transfer of organic matter from the western shelf occurs. This supports the evidence of $\delta^{13}C$ and trace organic substances in the traps at station E5 that a predominant marine fallout occurs over the basins.

The patterns and rates of I/C_{org} change with time (i.e. $\delta(I/C_{org})/\delta t$ in the sediments differs considerably and have been interpreted as illustrating the patterning and extent of benthic respiration. In the northernmost stations i.e. station M5, iodine removal from the sediment is very rapid (~5years) implying very high rates of respiration; southwards (station M4, M1) the rate of change in I/C_{org} ratio with time is more protracted, but more difficult to evaluate, although at station M1 iodine exhaustion occurs over a period of ~70 years. However, the pattern of diagenetic loss of I with depth or age is fluctuating and often is interrupted by changes in the input to and erosion from each station. The profiles imply non-steady state accumulation rates, especially on the northern shelf, and this obviously has implications for interpreting the ^{210}Pb activity trends and inventories of these cores.

- Anthropogenic metal accumulation

Three anthropogenic metals (Zn, Pb and Cu) have been studied on the shelf. The contents of these have been computed by calculating excess metals by comparing the metal/V ratios against those in preanthropogenic sections of cores. Excess, or anthropogenic, metal contents in cores usually show decreases with depth, but the complicated pattern of sedimentation at some sites often results in a staggered profile or sometimes an overall increase in metals at depth. The latter trend conflicts with the findings of Guerzoni *et al* (1984) and Price *et al* (1994) of a temporal increase in anthropogenic loading towards the sediment interface. These trends can be caused by episodic erosion and storm inputs, but a major factor here relates to the provenance of the sediment. The sediments on the northern shelf represent a mixture of riverine sediment, containing anthropogenic metals diluted by sediment derived from north of the Po and lacking metals. On the basis that the Po is essentially free of dolomite (Mg/Al = 0.36) and sediment from the north is dolomite enriched (Mg/Al = 0.63) we have apportioned the content of riverine sediment in each core and attempted to show temporal and spatial trends of metals in them. Surface metal contents in cores nearest the Po (200-300ppm) are similar to the mean content of Zn (~200ppm) in the river. Southwards, between station S11 and E2, its content falls dramatically to ~40ppm. The general upward increases towards the core tops imply that metal contamination from the river has not abated in recent years. The interrupted and staggered temporal change in riverine accumulation is caused by either storm surges of sediment of low metal content from the river or periods of shelf sediment erosion that preferentially removes the metals in fine detritus relative to the coarser sediment component. This contention is substantiated by higher Zr/Al ratios, representing coarser grained sediments occurring at most inflexions on the metal profiles.

Benthic biology and microbiology

Temporal changes in the biological and microbiological activity at stations E1, E2 and E3 have been made from 1993-1995, with the intention of coupling these findings to the overlying biological activity in water, as well as to certain sediment parameters such as texture and composition. In this study, several aspects of benthic activity including zoobenthos (macro and meiofauna), bacteria and benthic metabolic activity (sediment oxygen consumption -SOC) have been made. The chlorophyll-a concentration of the sediments shows strong spatial and temporal variations, but without any distinct gradient. For instance, highest chlorophyll-a was found in September 1994 at station E1, but at this time lowest values were found at station E2. This could imply either that the location of highest primary production varies with season and/or the presence of microphytobenthos. This entails that food supply to the benthos does not have a clear spatial gradient, but varies with season and that chlorophyll-a alone or in combination with organic carbon cannot be used to predict or explain benthic activity and long term food supply to the benthos at stations E1, E2 and E3. Therefore a more appropriate indicator of food availability may be derived from estimates of C-flux at each site.

- Macrofauna, meiofauna, carbon fluxes and respiration

Table 5 summarises the carbon flux and benthic densities and activities expressed as gm C $m^{-2}yr^{-1}$. The benthic metabolic activity (SOC) was measured during three seasons. SOC was converted to carbon equivalents using a RQ of 0.85 and presented as carbon mineralisation. The burial rate was estimated by multipying the sediment accumulation rate with the background POC. Here it is assumed that all organic matter is of marine origin. Annual carbon fluxes of 115, 133 and 60gm C m^{-2} yr^{-1} respectively were calculated for stations E1, E2 and E3, which correspond to macrofaunal trends. The above data provide evidence of an intense benthic-pelagic coupling. The station with the highest carbon flux supports the largest macrofaunal production (Station E2). However, station E3 with a relatively low carbon flux supports a relatively high macrobenthos production. The benthic metabolic activity (SOC) show everywhere an increase in spring and summer culminating in a maximum during September. Its minimum was found in February.

	Station E1	Station E2	Station E3
Annual Carbon Flux ($gC.m^{-2}.yr^{-1}$)	115.29	132.92	59.71
Carbon Mineralization ($gC.m^{-2}.yr^{-1}$)	86.85	89.25	53.93
Macrofauna Annual mean densities ($\#.m^{-2}$)			
0-5 cm	4045	12509	6072
0-20 cm	6384	15812	9081
filter feeders	1705	7625	2152
Meiofauna Annual mean densities 0-5 cm (ind.* 10^6. m^{-2})	4.97	3.4	6.07
Macrofauna Annual Mean Biomass ($gC.m^{-2}$)			
0- 5 cm	7.01	10.57	5.46
0-20 cm	9.87	12.74	10.82
filter feeders	4.18	6.25	3.24
Macrofauna Annual Production ($gC.m^{-2}.yr^{-1}$)			
0-5 cm	10.08	17.06	9.20
0-20 cm	16.46	22.95	15.46
filter feeders	5.02	9.17	4.31

Table 5 : Annual carbon flux and benthic activity data at stations E1, E2, E3.

Respiration usually correlated with temperature at each station. Contrary to expectation, highest benthic metabolic activity was found at station E2 and not station E1. SOC ranged from 79-752 µm O_2 m^{-2} hr^{-1} in February; 596-1005 µm O_2 m^{-2} yr^{-1} in April 1995 and 938-2387 µm O_2 m^{-2} yr^{-1} in September 1994. Some correlation of these findings are seen with macrofaunal densities which were studied in February and June 1994; the latter period showing much higher densities i.e. 4,400-10,200 (February) and 8,400-21,400 individuals m^{-2} (June). In February, molluscs and polychaetes were dominant, but in June, crustaceans increased mainly due to *Ampelisca* which reached extremely high densities. *Corbula gibba* was also abundant and varied between 800-900 ind m^{-2}. The mean annual biomass of macrofauna for different sediment depths at stations E1, E2 and E3 are given in Table 5. Production (P) was calculated for each phyllum separately using formulae given by Brey (1990). In February (1994) *Corbula gibba* accounted for 6-33% of the SOC whilst forming 32-80% of the total macrofaunal biomass. However, in April (1994) it accounted for only 1-7% of the SOC whilst forming 10-89% of the total biomass and there is seasonal variation in the contribution of *Corbula gibba* to total SOC. Overall, it may be responsible for 22%, 26% and 24% of the annual respiration at stations E1, E2 and E3. Macrofauna densities and biomass in the basins i.e. Station E5 are very low and clearly reflect, as expected, lower flux of degradable organic matter with increased water depth. Macrofaunal annual production (0-20cm) is estimated as 16, 23 and 15gm C m^{-2} yr^{-1} at the same stations, and between 60% and 74% of the production occurs in the upper 5cm of sediment, of which 50% is attributed to filter feeders. Where *Ampelisca* is an active filter feeder, estimates suggest that it can account for at least 50% of the annual sediment oxygen uptake. These two examples show that metazoan components can contribute substantially to benthic community metabolism.

The permanent meiofauna and foraminifera in the upper 5cm of sediment was studied on three occasions. Annual mean densities are 5.0, 3.4 and 6.1 x 10^6 ind m^{-2} respectively at stations E1, E2 and E3. Nematodes and forams together form 80-90% of the meiofaunal community at all sampling dates. In general, meiofauna are affected by both food supply and interactions with benthic macrofauna: the positive effect of an increased food supply in more productive areas may be counteracted by biological interactions, except in hypoxic regions, where the meiofauna have a high negative importance (Moodley *et al*, 1992). This could explain the reduced meiofauna densities at station E2 where maximal macrofaunal activity is encountered.

- Spatial variations

Spatial variations in benthic activity and their relationship to the influence of the Po were assessed in April 1995 using a further three stations; E11 in the north and 12 and 9 in the south, in addition to stations E1, E2 and E3. At these, long term (to 70 days) sediment decomposition experiments were used to complement mineralisation rates based on short term (3-4 hours) on deck incubations. The average respiration rates varied between 722-1058 μm O_2 $m^{-2}hr^{-1}$ with no significant differences between stations. Similarly macrofauna biomass showed no significant differences between the stations. Net ΣCO_2 production from these cores measured by gas chromatography indicated the organic decomposition rate. These varied from 1.5-10.4 mmol $Cm^{-2}d^{-1}$ but indicated no difference in mineralisation rates in surface (0-2cm) sediment except perhaps for station E2 which was 2.7mmol C $m^{-2}d^{-1}$. However, there was a noticeable threefold decrease in mineralisation in the 2-4cm subsurface layer which indicates that lability of organic matter decreases with depth. I/C_{org} ratios support these measurements.

- Carbon budgets

Individual contributions by EUROMARGE - AS scientists allows for a synthesis to be made of processes occurring at the sediment -water interface, and may provide an overview of integrated signals, that are not only considered more informative, but can be compared with other systems in order to gain an insight into the key factors or forces structuring or maintaining this marine system. Comparison of primary production with the carbon fluxes reaching the sediment allows a compilation of the carbon budget. Carbon flux, the sum of burial and respiration rates, expressed as carbon equivalents divided by primary production, allows sedimentation coefficients to be made. These suggest that overall ~52% of primary production reaches the sediment interface. These are much higher than measured by Justic *et al* (1993) for the northern Adriatic but are similar to another river dominated coastal sediment, the northern Gulf of Mexico

(Rabalais *et al*, 1991). There is a strong seasonal variation in sedimentation coefficients and at station E1 and E2 the carbon fluxes can exceed primary production in April, in this implicating lateral transport. In contrast, at station E3 the coefficient remains seasonally constant (0.64) and implies a very strong benthic-pelagic coupling. It also indicates little or no supply of active organic substances from the north. It implies little or no export of carbon from the shelf.

Detailed subsurface distributions of macrofauna in February show not just a simple decline in densities and biomass with depth (Table 5) but also a shift in trophic groups. Bioturbation, based on the occurrence of macrofauna, extends to at least 25cm. However, the mixed layer as estimated from ^{210}Pb profiles is ~10cm and this represents the layer of maximum activity.

- Bacterial populations and activity

Bacterial populations in northern Adriatic sediments vary both seasonally and spatially with respect to the proximity to the Po discharge. Hydrodynamic factors in this region also play an important role in regulating the quantity and quality of organic matter reaching the sediment, and therefore the response of the benthos including bacteria involved in the nitrogen cycle. An objective of EUROMARGE - AS was to investigate the role of the various groups of bacteria involved in the nitrogen cycle both in the water column and sediments. Bacteria have a fundamental role in determining the conservation or removal of nitrogen from the marine environment, thus influencing the degree of local eutrophication. Organic-N bound within the plankton or other organic material can be remineralised to ammonia-N by the proteolytic action of heterotrophic ammonifying bacteria. In the presence of oxygen, chemolithotrophic nitrifying bacteria oxidise ammonia -N to nitrite and ultimately nitrate. In the absence of oxygen, nitrate can be respired by fermentative bacteria in a dissimilatory reduction reaction with the concomitant production of nitrite and ammonia. Oxidative denitrifying bacteria, however, reduce nitrate to nitrite and subsequently to nitrous oxide and eventually dinitrogen gas. Denitrification therefore represents a net loss of nitrogen from the aquatic environment. These are considered below.

The heterotrophic ammonifiers emerged as the dominant group at each sampling site and populations showed marked temporal variation. Maximum viable cell numbers in surface sediments (4.7×10^9 ml sed^{-1}) were recorded in June 1994 at sites E1 and E2 and were much higher than at other times. This is mostly the result of increased temperatures and organic supply .Their presence in such abundance represents a significant potential for the remineralisation of organic nitrogen and subsequent reassimilation by phytoplankton. Populations in the water column immediately above the sediment were more dynamic, both spatially and seasonally, ranging from $<10^2$cells ml^{-1} in winter (station E3) to 4.6×10^9 in summer (Station E1). These results of population gradient are in good agreement with the primary production data of the overlying water column. Ammonifying populations in the winter were both low in the sediments and bottom water. However in the autumn (September 1994) little variation occurred even though there was a strong primary productivity gradient in the water. Excepting this aberrant trend, there is in general a good benthic-pelagic coupling with remineralisation occurring as the result of episodic pulses of organic matter from the overlying water column. Even so, high populations of active ammonifying bacteria in the sediments did not correlate with increased fluxes of ammonia across the sediment water interface, because these bacteria have the capacity to incorporate ammonium into their bacterial biomass. The depth distribution of ammonifying bacteria exhibits considerable variability, and no clear trends are observed at a given station, although significant differences occur from station to station.

Data attempting to show spatial distributions and seasonality of populations of autotrophic nitrifying bacteria at the three stations show that their populations are extremely low (usually 10^2-10^3 cells ml sed^{-1}) and show no consistent temporal and spatial pattern. Likewise, nitrate respiring bacteria in sediments and bottom water were consistently low at all stations (max. 6.5 x 10^2ml sed^{-1}) and showed little change with season. It is therefore unlikly that significant amounts of nitrogen are removed from this habitat through the process of denitrification.

- Incubation experiment

Results from the EUROMARGE AS field programme, studying biogenic fluxes in the north west Adriatic Sea, indicated that benthic-pelagic coupling in the system required more detailed investigation. A laboratory experiment was therefore undertaken to investigate the role of remineralisation of organic matter and nutrient exchange across the sediment-water interface. Specifically, the experiment was designed to increase understanding of the interrelationships between a) the chemistry of solid phase, bottom and pore waters, b) benthic fluxes, and c) population dynamics of bacteria involved in nitrogen cycling. Ten sediment cores, five from each site, were collected from stations E1 and E2 by SCUBA divers. Two cores were extruded immediately and sectioned into 0-1, 1-2, 2-3, 3-5 cm depth horizons. Each section was then analysed for pore water and solid phase chemistry and enumeration of populations of nitrogen cycling bacteria. The remaining cores were then incubated in a recirculating sea water tank at 12°C. Three cores were enriched with pelleted diatoms. Cores to be enriched with organic matter were removed from the tank, the upper 1cm of each core was removed and the diatoms added. The resultant enriched sediment slurry was then placed back on top of the original sediment. After 3, 7 and 10 days each core was fitted with a perspex lid to allow the measurement of nutrient fluxes and oxygen consumption over a 12 hour period. Samples were also regularly removed from the overlying water and analysed for nutrients and alkalinity, in order to estimate benthic respiration and associated fluxes of dissolved nutrient species across the sediment-water interface.

At the end of the incubation period, the populations of bacteria involved in N-cycling, porewater and solid phase chemistry were determined and compared with data obtained at zero time for the unenriched controls. These included measurement of changes in concentrations of NH_4-N, NO_3-N, PO_4-P, $Si(OH)_4$-Si, TCO_2, optical properties (absorption and fluorescence), DOC, CHN and populations of ammonifying, nitrifying, denitrifying and nitrate ammonifying bacteria and ammonification rates (azocasein assay).

Pore water nutrient chemistry showed clear increases in concentrations of NH_4-N, NO_3-N, PO_4-P, $Si(OH)_4$-Si in incubated cores compared to the controls. The concentration gradients observed can be interpreted as showing the presence of sources of organic matter, other than the artificially added diatom organic matter which degrade at different rates. Interpretation of solid phase chemistry and benthic flux data are difficult due to artefacts introduced by the experimental design. The quantity of the algal debris used to enrich the cores was greatly in excess of the calculated carbon rain settling on the sediment surface under natural conditions. This was intended to stimulate bacterial growth. However, this amount of organic material may also have affected the mineralization rates and hence the solid phase chemistry. The action of mixing the added cells with sediment, rather than settlement on the sediment surface (difficult under simulated current conditions), may also have affected the results due to breakdown of the spatial structure of the surface sediment. The DOC concentrations vs depth profiles, however, showed interesting features. Two significant peaks appear in the profiles from both stations. At Station E1 the peak appears in the zero time unenriched core, whilst at Station E2 a similar peak was present after the incubation of the enriched cores. The optical properties of these DOC peaks suggest the presence of low molecular weight aromatic compounds indicating the decomposition of fresh organic matter.

The bacteriological data show that an increased input of organic matter to the sediments stimulated growth of ammonifying bacteria. These increases in bacterial activity were spatially correlated with the observed increases in pore water nutrient concentrations. However, ammonia-N budgets calculated on the basis of ammonification rates inferred that the ammonifying bacterial populations may act as a sink for ammonia, i.e. *in situ* simultaneous hydrolysis and uptake of ammonia can occur. A further observation was that within two days of the transfer from seabed to the incubation tank cores showed evidence of a sediment colour change (from uniform grey to black flecked), probably due to the action of sulphate reducing bacteria. It had previously been noted that *in situ* there was little or no evidence of sulphate reduction, both from visual appearance and sulphide profiles, at any of the Adriatic sampling sites. Observations on the incubated cores suggests that the sediment at both sites 1 and 2 has the capacity for sulphate reduction, which was not expressed *in situ* under normal environmental conditions of oxygen concentration and available carbon. The dense populations of meio- and macro-fauna have a profound effect in determining not only the spatial distribution of the bacterial populations within the sediments but also their metabolic activity. Moribund fauna can provide a substantial source of organic carbon to the heterotrophic bacterial community and in the experimental system may have overridden any effects of the algal additions.

This experiment helped to outline some important features which must be taken into consideration when combining laboratory studies with field observations. Valuable information was gained, but perhaps at the expense of realistic environmental conditions. Future similar studies will employ limited variables and use a more mechanistic approach.

Benthic mineralisation - coupling to water column production

A study has been made on sediment water interaction with specific objectives for understanding early diagenesis and to couple the findings of pore water chemistry to the biological activity of the overlying waters. It provides a measure of the benthic-pelagic coupling and assesses its spatial variation.

Biogeochemical parameters measured in the water column and used for this purpose involve primary productivity, T°C, S psu, nutrients, alkalinity, chlorophyll-a and plankton taxonomy and biomass. The seabed work involved collection of duplicate cores from Stations E1, 2, 3, 4 5, 10, 11 and 12 (Fig 1) which encompasses the whole western shelf, the Jabuka Pit and Southern Basin, and preliminary measurements of C_{org}, N_{tot} and Si_{bio} were made on them. Sediment accumulation rates were determined (as above) or extracted from the literature (Frignani and Langone, 1991). Oxygen penetration depths were made using a micro electrode. Some of the cores were sectioned under nitrogen and pore waters extracted by centrifugation at *in situ* temperatures. These were analysed for alkalinity, nutrients (DIN, NO_3-N, NH_4-N, P-PO_4, $SiOH_4$-Si), dissolved Fe and Mn, DOC and certain optical properties (absorption and fluorescence). Benthic fluxes of O_2 and nutrients were calculated a) as diffusive fluxes for concentration gradients across the sediment-water interface, and b) by using a duplicate core and conducting deck incubations at ambient temperatures.

A study of the DOC concentrations in pore waters was made in order to help distinguish the relative abundance of degradable and refractory organic matter in the sediments and to understand the reaction pathways on different diagenetic time scales. According to the anoxic reaction model of Krom and Westrich (1981) the labile fraction of DOC is degraded to soluble, non-fluorescent LMWO (low molecular weight organics) which either degrade producing ammonia and alkalinity, or polymerise to yield fluorescent HMWO (high molecular weight organics) of which humics would dominate.

Concentrations vs depth profiles of DOC at 5 E stations (April 1995) range between 0.187 and ~2 mM, very close to those measured in Chesapeake bay sediments (Burdige, 1994). Cores from E11 and 5 represent the two end members, from the proximity of the Po and the Southern Basin respectively, i.e. terrigenous vs marine, the other cores being an admixture of these. A graph of absorbance vs fluorescence for λ = 355nm is typical for humic components with data for E11 lying on a different gradient from other cores. Moreover, a large fraction (13 mg/l) of the DOC does not absorb, indicating a large contribution of aliphatic compunds. Only at core E11 is there any linear relationship between DOC and ammonia and alkalinity, indicating that organic matter degradation pathway at this station is more effective than in other cores.

Benthic fluxes have been made by applying Fick's first law to pore water concentration gradients across the sediment water interface. These calculations are affected by higher uncertainty because of a lack of data immediately below and above the sediment water interface. At station E5 the concentrations of nutrients in the bottom waters were always high, resulting sometimes in reversed diffusive fluxes (from water to sediments). Diffusive fluxes were similar to those measured by Giordani and Hammond (1985) and Barbanti *et al*, (1995) showing much higher values of phosphate (0.01-0.025mmol m^{-2} d^{-1}) compared to shelf stations south of E3 and in the basins (~0.003mmol $m^{-2}d^{-1}$). Diffusive fluxes of NH_4-N and $SiOH_4$-Si are higher by two orders of magnitude but show no obvious spatial trends. However, they do show a slight seasonal trend at northern stations.

Results of on deck incubations with benthic chambers were overall rather unreliable, as they did not always show linear changes in concentration with time, and estimates of nutrient gradients are prone to considerable error, and tend to be much higher than that calculated from pore/bottom water measurements. Incubation fluxes measured during July 1994 and April 1995 tend to show much higher fluxes by an order of magnitude for NH_3 , and a factor of two for Si in summer when primary productivity is much higher.

Burial fluxes of carbon and Si_{bio} calculated from their content and sediment accumulation rates have been added to the benthic flux of these elements to obtain rain rates (benthic flux to the sediment from bottom water), in mmol m^{-2} d^{-1}. These have been plotted for the various cores, together with calculations of the oxygen flux into the sediment. At stations near to the Po outfall, where accumulation exceeds 5mm yr^{-1} , the burial flux may be 50-70% of the rain rate, but to the south at stations of slower accumulation most of the rain of C_{org} and Si_{bio} is remineralised. Given that some of the C_{org} is terrestrial, especially in the north, the respiration of marine carbon will be considerably higher and hence closer to the calculated O_2 flux, determined by O_2 microelectrodes.

These observations allow one to consider quantitatively the benthic-pelagic coupling of the system. The fraction of the primary production that rains to the seabed providing a benthic flux to the sediment is strongly depth dependent, and is regenerated in the water column. It is difficult to use the rain rate of carbon to estimate the level of regeneration, because of the effect of terrestrial input on its calculation. However, if the biogenic silica is not affected by substantial dissolution or horizontal transport, a plot of the biogenic silica rain vs primary production, should reflect the C:Si ratio in phytoplankton growth. This yields an estimate of 21±3 for the C:Si ratio, for stations north of Ancona. If net carbon production is ~50% of the measured primary production this would indicate that the ratio of C:Si used in plankton growth is 11. This is in good agreement with Brzezinski (1985) for diatom compositions, and indicates a very close pelagic coupling for the northern stations. Stations in deeper waters may not be so closely linked.

It is important to know if the ecosystem of the northern Adriatic is changing in response to changes in nutrient inputs from the Po and other rivers. The benthic-pelagic coupling in the shallow regions of the Po outfall needs to be examined to test the behaviour of the system. Furthermore, because time constraints for remineralisation of biogenic rain exceeds the time scales of phytoplankton blooms and variability introduced by currents, benthic fluxes may provide an average measure of the net productivity. A time series of O_2 flux and Si flux calculations show that primary productivity and the contribution of diatoms to the system has changed by less than a factor of two since 1982.

DISCUSSION

Much of the research involved in the EUROMARGE - AS project has been focused on work in the coastal environment of the northwestern Adriatic shelf, as we considered that the River Po exerts important influences on water circulation and the budgets and behaviour of a number of chemical and biogeochemical parameters.
Modelling of horizontal transport has shown that the river discharge appears to be a major buoyancy input, and has a fundamental influence on the general circulation of waters on the shelf and the promotion of cyclonic circulation in the Sea. Estimates of southward flowing water budgets crossing selected transects normal to the shelf extending seawards of the 20m contour show temporal change which directly relates to river discharge. The variability of river discharge thus has a direct impact on chemical deliveries to the Adriatic as well as their southward transport along the western shelf including that of resuspended sediment. Attempts have been made to equate riverine discharges of anthropogenic metals with those exiting the Adriatic via the Strait of Otranto.

Investigations on the River Po elemental discharge and the distribution of dissolved and particulate metals in coastal waters and sediments show a very strong biogeochemical linkage which either governs or is governed by the pelagic and benthic biology. River discharge of anthropogenic metals, i.e. Pb, Zn, Cu mostly occurs as particulate matter carried on oxide coatings. The budgets of these and the relatively constant ratios between metals, imply that little interaction between particulate and dissolved phases occurs during estuarine mixing and during shelf transport, and the major control on their accumulation in sediments is the balance between input supply and erosion. The major transport of these and most other elements in the particulate matter is through sediment resuspension rather than direct transport in surface waters. This is seen along the entire western shelf to the Strait of Otranto.

Nutrient, chlorophyll-a concentrations and primary productivity estimates in coastal waters of the northwest shelf appear to be directly influenced by River Po discharge identified from salinity variations in surface/subsurface waters. Additional factors together with a nutrient loading from the river produce a good seasonal signal of production and standing crop, especially near the Po outfall, but also show a marked southward falloff in these and associated parameters. For instance, concentrations of specific biogenic elements, e.g. Si_{bio} as well as POC and PON, follow these spatial and temporal patterns of change. A sixfold seasonal variation in POC concentrations can occur in northern stations and a similar spatial change can occur between the northern and southern stations, where concentrations in basins as opposed to coastal waters are lowest. High biogenic Si concentrations in coastal surface/subsurface waters show elevated signals from the Po to offshore Ancona, and are directly associated with Si discharge from rivers. Its concentration, on various transects normal to the shelf, show as does POC that most biological production in the water is confined to the coastal zone.

The biology and biogeochemistry of the underlying sediments seems to be directly associated with temporal and spatial changes of biogeochemicals associated with the standing crop in the overlying waters. Fallout rates of phytodetritus have been measured only in the Southern Basin, because severe sediment resupension on the shelf precludes sensible estimates using sediment traps. Even the midwaters of the Southern Basin show ≥ 30% of the organic carbon flux is from reworked sediment, and traps positioned 35m above the seabed show much higher contributions of shelf reworked or terrestrial carbon.

Studies of sediment C_{org} contents are a poor reflection of the patterns of biological productivity in overlying waters or respiration rates at the sediment interface. However, the spatial and temporal patterns of metal behaviour in surficial sediments attest to the distribution of POC and associated elements in the water column, and reactivity of carbon at the sediment interface. For instance, the depth of the Mn redoxcline deepens southwards from ~0.1-0.2cm in the north to >1cm in the south, and in the basins shows a progressive loss to >25cm, implying that benthic respiration is most intense in the north and is very limited in the basins. Temporal changes in pore water Mn concentrations reflect the extent of benthic respiration and show highest concentrations during the summer at times of high biological productivity and fallout. Sediment reactivity, caused by organic respiration, is also seen in elevated dissolved Zn and Cd, implying benthic releases. However, the patterns of Cu, Ni, Co and probably Pb in all waters are probably associated with river discharge. River budgets of these elements are very small compared with the values calculated for across-shelf and Strait of Otranto transects, and indicate that most of the dissolved metals in the Adriatic Sea are introduced from the eastern Mediterranean.

Detailed examination of the biology, microbiology and biogeochemical reactivity, especially in terms of benthic respiration rates of carbon in surficial sediments collected seasonally from stations close to the River Po outfall, and offshore of Cesenatico and Ancona, have been qualitatively and quantitatively expressed in terms of pelagic-benthic coupling of this system. Population changes in macro- and to a lesser extent meiofauna, expressed in terms of annual production, can be directly related to the overlying biological productivity. A similar trend is seen in sediment oxygen consumption which generally is associated with the sediment biology and microbiology as well as pore water nutrient regeneration rates. The overall trend of these parameters is one of increase in summer to reach maximum values in September, while during the winter very low benthic activity prevails. Higher biological activity and respiration usually prevails at the northern stations. The metabolic contribution of macrofauna to the sediment oxygen consumption seems to be of minor importance compared to the bacterial metabolism of food supply, mainly caused by ammonifiers, which accounts for much of the annual carbon mineralisation rate of ~85 g C $m^{-2} y^{-1}$.

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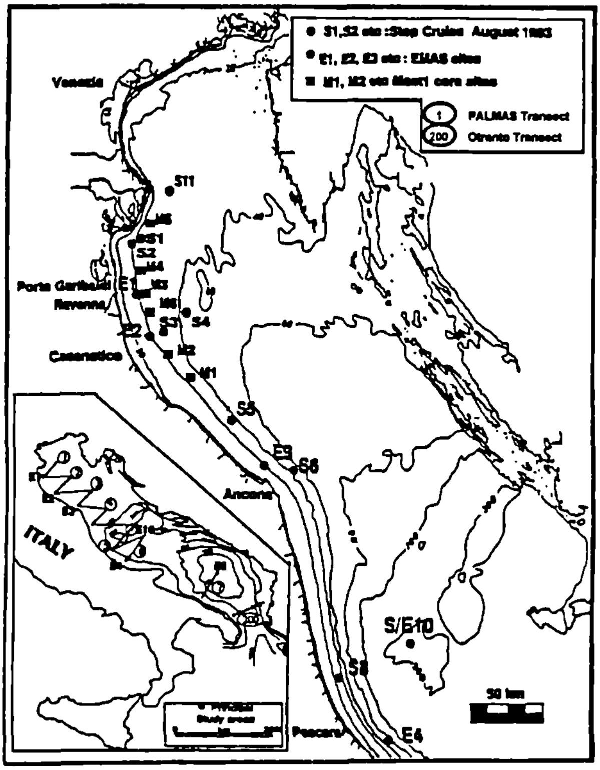

Fig. 1 : Sample locations in the Northern Adriatic with insert indicating transects studied

Mediterranean Targeted Project (MTP) - EUROMARGE-NB Project
Contract MAS2-CT93-0053

Synthesis of Final Results

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Transfer of matter and energy on European continental margins

ABSTRACT

The EUROMARGE-NB Project is a contribution to the Mediterranean Targeted Project first phase, from 1993 to 1996. EUROMARGE-NB has developed a mesoscale strategy (over several hundreds of km) covering the whole Northwestern Mediterranean margins and deep basin. This is, to the best of our knowledge, the first experiment at such a scale. The strategy includes simultaneous long-term monitoring of physical and biogeochemical parameters on four key sites (Marseilles, Perpignan, Barcelona, North Baleares) by means of instrumented arrays, as well as quasi-synoptic cruises carried out regularly and covering the whole study area. Amongst the more outstanding results it is worth mentioning the unique data set gathered about deep circulation, suspended particulate matter (SPM) characteristics and dynamics (including the living and non-living components), particle fluxes and their relations to other environmental parameters, and the benthic response to such fluxes.

The circulation results confirm the role of the cyclonic regional circulation as a major dynamical factor along the Northwestern Mediterranean slopes, with two segment margins (Perpignan and Barcelona) exporting large quantities of particulate matter with a dominant lithogenic character, and relatively high primary production (Perpignan), and two other segment margins (Marseilles and Baleares) with weak exportation and particularly oligotrophic (Baleares). Particle flux patterns show an offshore decrease and a depth increase at a given location, with an along-slope increase downstream the general circulation. Consequently, total mass fluxes and fluxes of any constituents are progressively increasing from Marseilles down to Barcelona. The Baleares site shows the lowest fluxes of the entire system. Significant changes of total mass fluxes with time occur both on a short scale of a few weeks (flux peaks) and on a seasonal time scale (winter fluxes higher than summer fluxes), and are quite concomitant at the scale of the entire region. Due to the limited range of contents in various constituents (by comparison with the large range of total mass fluxes), fluxes of any constituents are almost totally controlled by the factors controlling total mass flux. This feature also applies to constituents which are derived from biological activity (e.g., organic carbon and opal) and budgets for such constituents cannot be constructed solely on a one-dimensional (vertical) basis.

Biogenic inputs to depth rely upon advective processes which transfer material from shallow sources (e.g., shelf waters) of either primary particles (e.g., newly formed) or resuspended material. The horizontal component dominates the transfer. Driving forces on fluxes are either external (e.g., river discharge of suspended sediments, storms) or

internal ones (e.g., circulation patterns of water masses, interactions with topography). The first group controls the amount of material which is injected into the water column, whereas the second one provides the routes along which transfer takes place. The exact importance of biological processes in this system remains relatively unknown. Meiobenthos quantitative patterns point out the peculiarities of the Balearic margin as well as the enrichment of canyon axis as compared to interfluves and therefore attests of the organic matter transfers at the continental margins. Being closely correlated with the POM collected in near-bottom particle traps, meiofauna abundance provides an interesting biological tool to assess organic matter fluxes at the sea-bed. However, macrofauna would also respond to other factors, like specific habitat requirements and mass-physical properties of the sediments.

The integration of various of the results obtained allows to the establishment of the Carbon budget in the key study sites, which could be extended to the overall study area.

Key words: Biogeochemistry, transfer, continental margin, suspended particulate matter, water circulation, particle fluxes, benthic response, Northwestern Mediterranean Sea.

INTRODUCTION

Organization Of The Project And Scientific Objectives

This contribution aims to provide the reader with a general background about the EUROMARGE-NB Project and its scientific results, which are hereby presented in a synthethic form.

The EUROMARGE-North Baleares (NB) Project, a component of the Mediterranean Targeted Project (MTP), has been conducted from the 1rst of July, 1993 to the 31 of March, 1996 for a total of 33 months, by a multidisciplinary team formed by 12 partners and various subcontractors (see last page). The Project has been coordinated by the University of Barcelona (Spain) through the intermediation of the Foundation «Bosch i Gimpera. Main partners were, apart from the University of Barcelona, the «Laboratoire de Sédimentologie et Géochimie Marines» of the University of Perpignan (France), the «Observatoire Océanologique de Banyuls» (France) and the «Instituto de Ciencias del Mar» of Barcelona (Spain).

The aim of the EUROMARGE-NB Project is to understand, through a multidisciplinary study, the functioning of the Northwestern Mediterranean continental margin ecosystems. Special attention is given to the study of fundamental processes, in and between water column and sediment, which affect biogeochemical fluxes and material budgets.

The main objectives of the EUROMARGE-NB Project are:

A) To study and quantify the exchange biological, sedimentary and chemical processes occurring between the coastal domain and the open sea at the water column, sediment-water interface and surface sediment levels.

B) To study material (suspended particles and sediments) and element (C, N, Si, P, metals and artificial radionuclides) cycling.

C) To study pelagic and benthic processes and their role in element cycling, which is specially important in view of the strong enrichment of the NW Mediterranean zone.

D) To verify the working hypothesis of a mid-slope depositional centre which mediates particle transfer to the deep sea.

E) To study the resulting sedimentation, integrated over time, as it bears witness to recent natural or induced changes. The continental margins which may subject to a terrigenous (Gulf of Lions and Catalonia margins) or carbonate sedimentation (Balearic Islands margin) lend themselves particularly well to the recording and interpretation of these changes.

The study area

The study area covers the northernmost part of the Western Mediterranean Sea, north of the Balearic Islands, and includes the otherwise named Gulf of Lions, the Catalan Sea and part of the Algero-Provençal Basin (Fig. 1). This means that the Project operates at a mesoscale level. Most of the work has been carried out off the shelfbreak, on the continental slope and rise, from 200 to 2.400 m of water depth, with special attention to the mid-slope fringe, broadly from 500 to 1.200 m.

In the study area various types of continental margins exist. Very large shelves (60 to 120 km wide) appear on the Gulf of Lions and off the Ebro river mouth, while narrow shelves (less than 20 km wide) characterize the Balearic Islands. Shelves with intermediate widths characterize most of the Catalan margin, from the Ebro to the Gulf of Lions. The continental slope and rise environments are particularly developed in the Gulf of Lions, where a dendritic system of submarine canyons exists. In none of the other margin segments of the study area, submarine canyons are so developed. The Ebro slope is only incised by short gully-type canyons; the Catalan margin is cut by a few, tectonically controlled canyons, like La Fonera, Blanes and Foix, from north to south (Fig. 1). Finally, no canyons in strictu senso have been observed in the margin north of Mallorca and Minorca.

The entry of continent-derived sediment inputs determines the sedimentary type of the various margin segments, which have been classified as terrigenous (or siliciclastic), receiving heavy riverine contributions, carbonated, which lack of significant river inputs and hence most of the particle production is autochtonous, both pelagic and benthic, and mixed (Fig. 1). The Gulf of Lions and most of the Catalan margin, including the Ebro segment, are terrigenous, while the Balearic margin is carbonated. Mixed types appear only locally, as in the segment limited by La Fonera and Blanes canyons.

Other aspects which have been considered in the sectorisation and, as a consequence, in the definition of the field strategy (see below) of the various margin segments are primary productivity and anthropogenical influence. The Gulf of Lions and Catalan margins are much more productive and anthropogenically influenced than the oligotrophic margin north of the Baleares.

All the margins of the study area are swept by the Northern Current (or Algero-Provençal Current) which enters the study area from the eastern Gulf of Lions, contours the western Gulf of Lions and Catalan segments and goes back, towards the northeast, along the slope north of the Baleares (Fig. 1). This main circulation path is locally affected by the morphological irregularities, like canyons, of the various margin segments and, occasionally, by entries of surficial Atlantic waters through the west Balearic passages.

Methodological approach, field strategy and instrumentation

The methodological approach followed into EUROMARGE-NB basically includes:

1) The quantitative, simultaneous assessment of water masses, suspended particle standing stocks, and particulate fluxes over the entire margin system by means of a multidisciplinary approach (hydrology, nephelometry, biology, sedimentology).

2) The calculation of mass balances and budgets within the water column of significant biogenic constituents (POC, PON,..), trace elements and radionuclides.

3) The identification and understanding of the relation between energy supply and biological response of benthic communities.

In accordance to the features of the study area, which was selected because of the biogeochemically contrasted character of their various margin segments (see above), and to the scientific objectives to be addressed, an specific field strategy was adopted. This included the identification of four key sites to permanently monitor biogeochemical parameters, in combination with various synoptical regional and local oceanographic cruises.

- Continuous monitoring of major biogeochemical and physical parameters by in situ moored instrumentation at selected stations

Moored instrumented arrays were deployed in four key study sites, from the entry to the issue of the system defined by the Northern Current (see above): I) the Planier Canyon, off Marseilles ("Marseilles site"), II) the Lacaze-Duthiers Canyon, off Perpignan ("Perpignan site", III) the Foix Canyon, south of Barcelona ("Barcelona site", and IV) northwest of Minorca, in the Balearic Islands ("Baleares site"). At each site, the instrumented arrays which included PPS3 Technicap particle traps and Aanderaa rotor current meters were deployed both in canyons and in the vicine interfluves, at 550 to 770 m («shallow» stations) and 990 to 1350 m («deep» stations) depth (Fig. 1 and Table 1). Moored transmissometers were also deployed in the Barcelona site. In the Gulf of Lions, an additional intermediate array (Sête Canyon), situated between the Marseilles and Perpignan sites, was also deployed. In all, 12 permanent mooring stations were in operation for at least one continuous year each, with sampling intervals of 15 days or 1 month depending on the particle trap model (Heussner at al., 1990 and 1996a). Recovery and redeployment of moored arrays were made every six months. The deep, canyon axis arrays of the four preferential sites included one particle trap/currentmeter pair about 30-35 m above the bottom, and a second pair, about 500 m above the bottom. The other arrays consisted of a single trap/currentmeter pair deployed at 30-35 m above the bottom (Table 1).

Approximately 6700 days of recording were performed at a sampling rate of a set of currentmeter measurements (velocity, direction, temperature, conductivity / pressure / transmission, leading to about 80400 two dimensional vectors) every two hours and a particle sampling every fortnight or month. Trap preparation before deployment as well as laboratory preliminary treatment of trap samples were performed according to state-of-the-art procedures (Heussner et al., 1990). The following parameters were currently analysed for all traps: total mass flux, organic and inorganic carbon, biogenic silica and refractory (lithogenic) constituents. They represent the major constituents of trapped particles. Determination of biogenic constituents (e.g., fecal pellets, coccoliths, diatoms) and analyses of biogeochemical compounds (e.g., sugars, amino acids, phenols), trace metals (e.g., Cu, Cd, Zn, Ni and Ba) and isotopic tracers (e.g., ^{210}Po, ^{210}Pb, C and Th isotopes) were also performed on selected samples (Sánchez-Cabeza and Canals, 1996). They were used to qualify the nature of collected samples, with the aim of tracing the sources and fate of settling particles within the water column.

- Regional and local oceanographic cruises

Twenty-three cruises, four regional or mesoscale, and nineteen local, have been performed during the 33 months span of the EUROMARGE-NB Project (Table 2). At all, they represent 253 days of work at sea. The specific objectives and summary reports of each of these cruises have been delivered to the MAST Programme as ROSCOP forms (Canals et al., 1994 and 1995).

These cruises have concentrated on water column, water-sediment interface and sediment investigations, together with the recovery, maintenance and redeployment operations of the moored arrays. Intensive field samplings and measurements have been carried out till 2400 m to provide information about the circulation, biogeochemical transfers and biological processes in the water column, geological processes at the sediment water interface, biogeochemical fluxes at the sediment water interface and sediment records.

Approximately 900 CTD casts have been recorded, some of them with transmissometer, fluorimeter and oxygen probes. ADCP underway measurements have been performed during two cruises. An approximate amount of 1100 water samples has been obtained from rosettes during CTD casts. Analyses included total suspended matter, size spectrum of seston, POC, trace metals and radionuclides. A number of other parameters have been also analysed (phenol compounds and carbohydrates, nutrients, chlorophyll,...) in a sub-set of stations (Sánchez-Cabeza and Canals, 1996).

Sediment samples have been collected using mostly a multicorer, but also box corers and gravity corers. Over 100 cores have been collected and analysed for a variety of parameters such as biochemical parameters, paleoceanographic indicators, trace metals, radionuclides, etc. Also, 24 cores have been dated for ^{210}Pb. Approximately 110 zooplankton net hauls have been performed (Sánchez-Cabeza and Canals, 1996).

Benthic samples have been taken using a multicorer and a box corer for meio- and macrofauna analysis, respectively. Benthic macrofauna has been also investigated by means of Sediment Profile Imagery, SPI (Rhoads and Germano, 1982). Parallel sampling was made for the study of granulometry and sedimentary particulate organic matter. Benthic metabolism in terms of oxygen consumption and CO_2 production was measured in situ with a free-vehicle automated lander (4 deployments) equipped with oxygen sensors and sequential water samplers.

A large amount of «non conventional» data were also collected during the project, such as high resolution seismic profiles, multibeam bathymetric profiles, deep-towed side scan images, vertical video profiles, acoustic reflection on marine organisms. Large volumes of surface water and atmospheric particles were sampled for radionuclide analysis.

RESULTS

Circulation

- Surface circulation at basin scale

The four key sites are under the influence of a common regional surface circulation that skirts the slopes of the Northwestern Mediterranean Basin: the Northern Current. The density-related flow (Fig. 2) and the current (ADCP) measurements (Fig. 3) reveal the position and structure of the regional slope current and the presence of frontal structures near the shelf-break.

- Deep slope currents

Deep currents along the continental slope, albeit much weaker than the surface flow, are likely to control the exportation of shelf material at depth. For that reason, currentmeter measurements, coupled to sediment trap measurements, were collected at the four experimental sites. With twelve moorings deployed in submarine canyons and on their adjacent open-slope, this currentmeter monitoring represents the first intensive follow-up of near-bottom and mid-depth slope currents in the Northwestern Mediterranean Basin. These observations complement deeper current measurements made within the same area during the SOFARGOS project.

Near-bottom currents appear to be strongly constraint by the local topography (Fig. 4). This is particularly obvious inside the canyons and to some extent in interfluve locations. This seems to validate some numerical experiments about the Neptune effect on the circulation in the Western Mediterranean (EUROMODEL Project). At intermediate depths the ellipses of variance are rather isotropic and do not indicate any marked topographic control. However, the mean currents follow the continental slope direction as the slope frontal currents of the zone do (Fig. 3).

The spectral analysis emphasize different dynamics for the across and along isobath components. The across-isobath component is dominated by inertial frequency motions and the along-isobath component presents a very intense peak at lower frequencies (2-10 days band). This spectra is seasonally variable and differs slightly from site to site. In general, it is observed that the low frequency band is stronger in winter. In summer, the energy increases towards the inertial band almost everywhere.

Eddy activity of currents is higher at deep levels than at mid-depth. The winter EKE increase, reported for surface currents by other studies made in the Ligurian Sea (EUROMODEL Project), is confirmed for the Marseilles, Barcelona and Baleares sites, where the Northern Current skirts the slope. The Perpignan site appears to be less affected by the fluctuations of the Northern Current, as this latter left the slope.

Suspended particulate matter: Distribution and composition

- <u>Distribution of the suspended particulate matter</u>

The simultaneous measurement of several optical parameters (transmission, scattering, fluorescence) offers an efficient tool to distinguish the organic and inorganic suspended matter. The profiles gathered during the various cruises (Fig. 5) show: i) a surface layer about 100 m thick linked to the thermocline, the high fluorescence values being due to phytoplankton biomass, ii) intermediate nepheloid layers, developing at shelf break or at mid-slope depths, concomitant with density gradients and probably due to resuspension, iii) the presence of a turbid bottom layer.

These observations confirm the following typology:

- The two extreme sites, Marseilles and Baleares, are characterized by an strong development of a surface nepheloid layer and a minor extension and concentration of intermediate nepheloid layers.

- The large development of surface nepheloid layers in the slope between Perpignan and Barcelona, particularly in the canyon axis.

- The central part of the Northwestern Mediterranean Basin is marked by the lack of a bottom nepheloid layer.

- Surficial and near-bottom spatial distribution of SPM concentrations are displayed at Fig. 6. Surficial SPM concentrates a) along a strip close to the Catalan continental margin, specially on canyon heads, and b) in an offshore zone between Marseilles and Minorca, caused by the NW wind forcing of the Northern Current (Thunus, 1995). Near-bottom SPM concentrations show a general decrease with respect to surface values and only the shelves with fluvial inputs (Barcelona and Ebro) present significant concentrations.

- <u>Comparison of light transmission and the distribution of large particles</u>

For the first time, the concentration of large particles has been measured in the Northwestern Mediterranean Basin with a marine snow camera during the EUROMARGE 95 cruise. The aim was to characterize the distribution and concentration of large particles (aggregates), that are sought to be a major contributor to the downward particulate fluxes measured by sediment traps. Combined vertical profiles of these parameters were made at few hours intervals. They clearly reveal some common features (Fig. 7): i) peaks at the shelf break and mid-depth nepheloid layers, ii) seaward decrease of concentrations, and iii) variations between experimental sites. Unlike the Marseilles and Baleares transects, that show reduced large particle concentrations below the shelf edge plume. the Perpignan transect shows large concentrations of aggregates in the canyon head and within mid-depth layers in the lower canyon.

- <u>Particulate organic carbon and nitrogen</u>

Figs. 8 and 9 show the surficial and near-bottom distribution of POC (% wt) and C/N relation. In the surface layer the high values of POC appear as spots along the continental margin. These maximums are inversely correlated with both SPM concentration and C/N relation. In the near-bottom layer, the maximum values of POC and C/N are situated in deep-basin locations, associated either to pelagic/degraded and/or bottom resuspension sources.

- <u>Major elements and trace metals</u>

Suspended particulate material was analysed for major elemental composition: Cl, Si, Al, Fe, Mg, Ca, K, Ti, Mn, P, S and Ba, as well as for trace elements for a selected number of water stations: Cr, Co, Ni, Zn, Cu, As, Cd, Sn and Pb. In addition, complementary analyses were performed for the particulate organic carbon and nitrogen.

The major element chemistry of the SPM in the Marseilles transect shows very clearly the plume of material derived from the shelf edge to be dominated by, excluding carbon, alumino-silicates and calcium. The phosphorous concentration, total and excess, appears not to correlate with the fluorescence; the greatest concentrations appear around the shallow depths.

The Perpignan transect shows an area of sediment resuspension on the shelf and a plume of material derived from the shelf edge. Excess particulate silica is shown focused in two areas of surface waters. Organic phosphorous shows greatest concentrations on the shelf.

The Baleares transect shows lower values of major elements than the other two transects and appears not to exhibit a shelf edge derived plume of material. Instead, a plume of material exhibiting higher aluminium and calcium figures was seen on the shelf-slope region. Total particulate silica concentrations are dominated by excess values and occupy the surface waters.

Biological production and processes in the water column

- Phytoplankton communities

Phytoplankton was analysed qualitatively by taxonomic identifications and quantitatively by estimation of cell biomasses from counts and biovolume calculations. The relative importance of three size classes: e.g. ultra-plankton (< 10 mm), nanoplankton (cell size between 10 and 20 mm) and microplankton (> 20 mm) was also determined.

Biomass profiles (Table 3) clearly show low values in surface waters (between 15 and 60 mg.m^{-3} or 1 to 5 mgC.m^{-3}), a maximum around 40 m depth (228 mg.m^{-3} or 18 mgC.m^{-3} in Perpignan at 40m) and very low values at 100 m (below 1 mgC.m^{-3}). Cell numbers decrease from surface to the bottom of the euphotic layer as surface waters are colonised by smaller cells living on regenerated nutrients. They take part to the microbial loop, while maximum biomasses correspond to microplanktonic forms growing in nutrient enriched waters. Because of the sampling season (summer), dinoflagellates were well represented and often dominant in the three sites. At the opposite, diatoms were abundant only in coastal samples. The relative importance of the different size fractions differs in detail from site to site, but ultra- and nanoplankton are usually the dominant fractions, except at the biomass maximum around 40 m. Coccolithophorids are better represented in Marseilles and Perpignan, and are localised in the lower part of the photic zone (maximum at 65m) at the Baleares site, but never are the main component of the Phytoplankton. The Perpignan site appears to be the richest, both in species number and in biomass values.

- Primary production

Primary production, estimated from «in situ» incubations with the Let-go apparatus at the three sites (Marseilles, Perpignan and Baleares) presents different structures and functioning systems, and displays a wide variability from coastal areas to open sea.

The Perpignan site (coastal area) is the richest with the highest production. Temperature stratification is less pronounced than in other sites. Chlorophyll and production maximal occur around 40 m and surface and subsurface layers are devoid of nutrients. The nitracline depth appears at 30m near the coast and sinks to 50 m in open sea waters. The Baleares site is most characteristic of oligotrophic conditions found in early summer. Nutrients are lacking in the first 50 m and a low chlorophyll maximum is found between 60 and 70m. This situation is not improved in its coastal part. The Marseilles situation is somewhat intermediate, with a weak chlorophyll maximum at 50m in the coastal area, found deeper in the open sea part. Primary production is high near the coast in surface waters, but low elsewhere. Finally, from results collected during the last three years on the Marseilles site, the new production of this area is estimated to approximately 50 to 60 gC.m^{-2}.y^{-1}.

- Zooplankton and micronecton

Zooplankton communities were studied through different biological parameters such as species identifications, direct counts, biomass estimations, food uptake and energetic budget. Zooplankton was collected in the surface layer (0-50 cm) with a neuston net (330 mm mesh size) and in the water column, with a WP2 net (200 mm mesh size) between 0 and 200m.

Zooplankton abundances in the water column are strongly influenced by vertical migrations on a site, but also depend on the distance from the coast and on morphological depth profiles. In coastal areas, most of the zooplanktonic biomass is found in the first 100 m. Surface layers are heterogeneous as vertical migrations occur during the night and high concentrations of copepods are found in the neuston layer, specially in Perpignan and Marseilles where maximum biomasses are registered. Nocturnal biomass of neustonic organisms is frequently 4 to 10 times higher than the diurnal one. A marked feeding rhythm with a nocturnal maximum appears in copepods collected in neurotic as in oceanic waters of the Perpignan area, characterized by the highest concentrations of Chla. Taxonomic composition is different at the Baleares site where chaetognaths, cladocerans and gelatinous organisms as well as fish eggs are much more abundant than in Perpignan and Marseilles where copepods are largely dominant.

The size of the preys ingested by zooplanktonic organisms varies from 8 to 30 mm. It seems that particles below 8 mm are not ingested, which would indicate that ultraplankton is not included in the trophic chain but is restricted to the microbial loop system. Analyses on metabolism show an omnivorous feeding activity of the zooplanktonic compartment, influenced by the availability of Phytoplankton preys and particle density. The grazing pressure varies between 9 and 100% in Marseilles where particle density is particularly low.

Micronecton is mostly represented by crustaceans but includes also some fishes. Euphausiid species as well as peracarides have also a nychtemeral activity and are good indicators of water masses with typical neritic and oceanic species. Crustaceans are more abundant in the Baleares site but Boreomysis artica (a pseudo-oceanic mysid) is found only in canyon axis, along the Marseilles and Perpignan transects. This species is well-known to accumulate at the upper slope and in canyon heads. Two species of cyclothone fishes have an identical distribution on the three transects and are limited to open sea areas.

The coastal part of the Marseilles site is characterized by the concentration of pelagic zooplankton. The Baleares site receives superficial waters of oceanic origin and advection is only visible for neritic species in the Perpignan and Baleares transects.

- Acoustic detection of living particles in the water column

Three size categories were detected by acoustic reverberation, according to emission frequency:

- 120 kHz allowed the detection between 0 and 150m of organisms which size is over 0,5 cm

- 38 kHz was used in the 0-250m water column for organisms larger than 1.2 cm

- 12 kHz selected organisms larger than 3 cm between 0 and 400m.

Smaller organisms are present in the first 50 m, during day or night, but maximum densities occur during the night. Middle size organisms are found during day time in the water column in shallow waters and migrate near surface waters during the night. Large organisms are never found in coastal waters below 100 m. They stay in deep waters during day time and migrate in the 0-200m layer at night. A general trend is the migration of organisms towards surface layers between 18 and 22 h. The Perpignan site is characterized by a vertical stratification, absent in the Baleares site. The situation is opposite at these two sites for the spatial distribution of organisms: in the Perpignan area, organisms are concentrated during day time in open sea waters and at night in coastal waters, while in the Baleares site maximum biomasses are observed in coastal areas during day time and in open sea areas at night.

Very small particles (ultraplankton, below 10 mm) remain in the water column, except probably for some coccolithophorids, and are included in the microbial loop in a system based on regeneration. Larger particles (nanoplankton and microplankton) are at the basis of the food chain and are used as food preys for zooplankton. Their production, which depends on nutrient supply and water fluxes, is limited to the first 100m of the water column. Secondary producers are characterized by their mobility and migrations are generally associated with feeding activities. Size of organisms increases with depth, and larger animals, including adult fishes, are rather found in open sea areas.

Particle dynamics

- Stationarity of the particulate system

Repeated casts on the continental slope during different cruises highlightens the local variability of the particulate structures. While the hydrological structure is usually stable over short intervals of time (Fig. 10), significant changes in the vertical distribution of particle may occur over the same lapse of time, especially in the head of the canyons. However, turbid structures observed at close intervals at one shelf station off Perpignan show a clear recurrence of the bottom nepheloid layer (Fig. 10). Moreover, a two year follow-up for one shelf and one slope station along the Perpignan transect also shows a seasonal recurrence of the turbid structures (Fig. 11). The main features are winter mixing, a frequent and coherent presence of a shelf bottom nepheloid layer and a shelfbreak-depth intermediate nepheloid layer. The permanence of these structures suggests that suspended particulate matter transport on theshelf occurs mostly near the bottom and is exported seaward as a shelf edge plume.

Particle residence times, inferred from the dissolved and particulate ^{234}Th distributions, are fairly constant on the shelf (about 15 days) and variable at slope stations (between 2 and 125 days). Although the conditions were not stationary, these results suggest rather different exchange kinetics on the shelf and the slope environments. The residence time of dissolved thorium is lower in the organic layer and inorganic particles seem to settle more rapidly. A rough estimate of particle settling velocity gives results from 0.83 to 2.93 m. d^{-1}.

- Shelf-slope exchanges

Preliminary results of the 1993-1995 follow-up in the Gulf of Lions indicate a good link between the hydrological and nephelometric vertical structures and gradients on the shelf and slope. This relation highlightens the influence of two major advective processes (cyclonic general circulation and winter dense water cascading) involved in the exportation of suspended matter from the shelf (Durrieu de Madron and Panouse, 1996).

- Influence of the general circulation in summer

The general circulation was studied during two cruises made in summer 1994. The calm meteorological conditions during these cruises allowed us to evaluate the geostrophic circulation. The summer conditions are characterized by a strong density stratification. The nepheloid structures along the sections and on the entire shelf generally show either a mixed or a stratified turbid bottom layer associated with the density bottom mixed layer (BML). Most of the density profiles indicate that the BML is lighter than if the BML had been formed locally. This density anomaly suggests a downslope advection in the bottom layer and implies a seaward transfer of suspended matter. The bottom transport on the northern part of the shelf of the Gulf of Lions is likely to be driven by the cyclonic baroclinic circulation. Eventual detachment of this bottom layer occurs at the shelf edge, together with its isopycnal intrusion and dilution into the slope waters. On the south-eastern part of the shelf, the currents are mostly oriented across the shelf and have less effect on the cross-isobath bottom transport. Besides, the presence of a cold pool of bottom water, trapped in the depression located in the centre of the shelf and around which the cyclonic circulation flows, indicates that bathymetric features can hamper such bottom transport. However, exportation of suspended matter probably takes place where the currents leave the shelf, between the Marseilles and Perpignan sections.

- Influence of cascading of winter dense shelf waters

Winter dense water formation under the influence of evaporation and surface cooling is known to occur in the Gulf of Lions shelf. This water mass cascades from the shelf down to the slope until it reaches its buoyancy equilibrium at a few hundred meters deep. The influence of this winter downwelling on suspended matter exportation was studied during one cruise made in February 1995. Thermal and nephelometric profiles indicate the presence of mixed and cold water on the shelf. The spreading of this cold water layer is well traced over the slope environment between 100 and 200 m deep. The corresponding mid-depth maximums of turbidity and fluorescence reveal a rapid transfer of biogenic suspended matter from the shelf. This exportation is more intense on the Perpignan section, where the coldest bottom waters are observed, than on the Marseilles section. This enhanced southwestern exportation probably results from an increased dense water formation and spreading on the western shelf, linked to higher north-westerly winds frequency, the presence of wind-induced downwellings along the North-South Roussillon coast and, also, the westward transport of the cyclonic shelf circulation.

Numerical simulation of the particle transport

The knowledge acquired from the field observations in the Gulf of Lions area has been used to initiate the development of a particle-tracer model aimed at simulating the behaviour of the suspended matter on the continental margin and on the shelf area (Thunus, 1995). This approach takes advantage of the experience gained through the various applications of the PGCM (Prosper General Circulation Model), previously developed by the Oceane Group (Zuur, 1991).

The final objectives of the simulations are to locate the potential zone of accumulation/deposition of the suspended matter, and to identify the major processes and forcings to be considered in the analysis of its dispersion. A pragmatic approach is adopted, in order to avoid duplication and overlapping with the variety of nested and embedded hydrodynamic models which are presently under development in the area of the Gulf of Lions for other purposes. The long term goal here is to develop a rather user friendly, modular product, which do not requires prohibiting computer resources while correctly reproducing the major features observed or known to exist. Thus, the model is used as a tool to conduct general dispersion experiments, by injection of virtual particles at key locations, selected according to the field observations. Observed or modelled forcing (wind, flux of the Northern Current) are applied as drivers of the dynamics. The size and resolution of the domain, the settling velocities, the order of magnitude of the horizontal velocities as well as the available data determine the time scales which are relevant for such regional simulations. Special attention is paid to maintain a coherent ratio between the scales of the processes and the duration of the simulations. For instance, for particles having a residence time magnitude about 1 month in the water column and horizontal velocities of the order of 10 cm s^{-1}, the appropriate spatial scale is about 260 km. Reciprocally, the size of the domain and the order of magnitude of the velocities determines the classes of particles which need to be included in the simulations. Fast settling particles deposite in the immediate surrounding of the sources, while very small, slow settling particle escape from the domain without settling significantly. The broad size distributions and the variety of particle's types (organic, mineral) makes it hopeless to calculate a precise spectrum of the settling velocities. To keep the model tractable, the particle population is actually characterized as a distribution of Stokes settling velocities. As the model is modular, such an standard distribution can be substituted at any time by any other settling velocities distribution either calculated or experimentally determined. By comparing the order of magnitude of the vertical velocities of the water with the Stokes' settling velocities, a rigorous resolution of the vertical velocities field appears to be of paramount importance in such simulations (Zuur, 1995). Indeed, the strong vertical gradients of the horizontal velocities may significantly modify the trajectories of particles according their settling velocities, and thus significantly promote their dispersion. Special attention is also paid to the critical problem of the open boundaries, in view of a future coupling with large scale hydrodynamical models.

The first series of simulations carried out to date address the effect of events of wind forcing and their influence on the transport of particle at time scale of weeks to months. The initial and boundary conditions are inferred from the GHER seasonal climatological maps obtained by the inverse method. Virtual sources of particle are considered near the Rhone river outlet, on the continental shelf and along the continental margin in order to estimate their dispersion (Fig. 12). The comparison between the seasonal situations confirms an enhanced exportation of the suspended material at the southwestern limit of the Gulf of Lions, a fact which is in agreement with the cascading effect of the SPM observed during the Suivilion experiment (Durrieu de Madron and Panouse, 1996). In the next future, the model shall be improved by adding resuspension and particle transformation modules while preserving its modular structure.

Particle fluxes: Temporal and spatial variability of total mass fluxes

Among the various studies necessary to improve our knowledge on the role of the oceans in the global cycling of CO_2, those dedicated to the mechanisms controlling particulate transfer in marine systems occupy a central position. On continental margins, biological, physical and geochemical processes distribute and inject large quantities of land-derived and/or surface-produced particulate matter to depth and ultimately to sediments (Monaco et al., 1990a; Biscaye and Anderson, 1994). The study of such processes passes through the ability to quantify and chemically assess downward fluxes of settling particles. Sediment traps are currently the only existing tool which allow such measurements and they are, for that reason, of paramount importance into the EUROMARGE-NB project.

The Northern Current, flowing along-slope from the northeast to the southwest, represents the major dynamical feature of this region (cf. Chap. 4.1) and is believed to be the main driving force controlling, over the entire NW Mediterranean margin, the water column distribution of suspended particles, the «source-term» of particle fluxes (Durrieu De Madron et al., 1990; Monaco et al., 1990a, b).

The range of observed fluxes of settling particles in the different sites of the Northwestern Mediterranean slopes is large, both in time and space. Total mass fluxes cover a broad range of values (almost 2 orders of magnitude) from approximately 1 mg m^{-2} d^{-1} to almost 50 g m^{-2} d^{-1} (Fig. 13). Nevertheless, fluxes exhibit similar temporal trends between the different experimental sites. Flux peaks are observed on several occasions, approximately during the same periods of the year and for all traps (e.g., canyon heads, canyon axes and open slopes): in October-November 93, February-March and May-July 94.

On a seasonal scale, total mass fluxes are higher during winter, a feature summarized by the seasonally weighted means of Fig. 14. Winter mean fluxes are generally 2-3 times higher than summer means for most traps. The only noteworthy differences concern: (i) the canyon axis and open slope traps off Marseilles and the Baleares where the seasonal differences are more pronounced, the winter means being up to 10 times higher than the summer means; and (ii) the near-bottom axis traps off Perpignan and Barcelona for which the seasonal means are reduced or equal.

Annual mean mass fluxes are closer to each other and cover a range of only 3 orders of magnitude from a minimum of 86 mg m^{-2} d^{-1} (Baleares) to a maximum of 17165 mg m^{-2} d^{-1} (Barcelona), the latter value being a biased annual estimate since it represents only summer values.

These general features strongly suggest that temporal patterns of particle transfer on the Northwestern Mediterranean margin are largely controlled by factors (dynamical and/or climatic) that concern the mesoscale (several hundreds of km).

In terms of spatial variability, the experimental strategy allows to address flux variations at different scales. At the local scale (x * 1 - 10 Km), total mass fluxes decrease in the across-slope direction, from the canyon head down to the 1000 m mooring sites. Fig. 15 summarizes this general trend for the 4 mean sites. Mean annual fluxes are normalized to the mean flux of the 500 m.a.b trap in the canyon axis at mid-slope. In the near-bottom traps, fluxes markedly decrease downcanyon. Furthermore, fluxes at 35 m.a.b within the canyon axis are higher than on the open slope, except for the Marseilles site where the opposite is found. This situation confirms previous findings in the same region where fluxes measured within the canyon axis were 2 times higher than on the adjacent open slope (Radakovitch, 1995; Monaco et al., in preparation) and underlines the channelling effect of canyons which act as conduits for the transfer of particles to deeper parts of the slope. The fact that the Marseilles site reacts differently could be related to the shallower depth of deployment of the interfluve set with respect to the one in the canyon axis (750 vs. 1100 m). The interfluve set will receive therefore slightly more settling material from the shelf and upper slope. Finally, mean fluxes increase with depth at all canyon axis sites by a proportion of 1.6 to 3.2 (Fig. 14). This further confirms previous results obtained in various parts of the world ocean, where at any given location on the slope flux increases with increasing depth (Biscaye et al., 1988; Monaco et al., 1990b; Biscaye and Anderson, 1994; Heussner et al., 1996b).

At the mesoscale (x * 10 -100 Km), mean mass fluxes normalized to the mean flux of the 500 m.a.b canyon axis trap off Marseilles globally increase from the Marseilles site down to the Barcelona site to 34 times. They subsequently strongly decrease at the Baleares site. Downstream flux increase is approximately proportional for the various canyon traps at a given site, as shown by mean fluxes of traps in identical position, normalized to the mean fluxes of their counterpart traps in the Marseilles site: 3 to 4-fold increase at the Sête and Perpignan sites, 4 to 5 off Barcelona. This situation is not observed for the open slope traps, for which the flux increase is less important (1.9-fold increase for the Perpignan open slope trap) or even no flux increase as for the Barcelona open slope. For equivalent traps, the Baleares exhibit mean annual values which represent only 20-30 % those off Marseilles.

Annual fluxes of the major constituents of settling particles

Fig. 16 summarizes the overall compositional variability of settling particles from the various traps. Variability is expressed by the coefficient of variation (CV = standard deviation as % of the mean) of total mass flux and major constituents for each trap. On a general scale, variability is highest for the total mass fluxes and lowest for lithogenic contents. For all trap positions except canyon heads, contents in major biogenic constituents (organic and inorganic carbon, opal) become less variable in the direction of the general circulation, that is from Marseilles down to Barcelona and then strongly increase for the Baleares samples. For the variability in lithogenic content, on the contrary, a steady increase between Marseilles and the Baleares is found. The explanation of these general trends can be found in the covariation of composition with total mass flux (Heussner et al., 1996a).

The overall distribution of the weightened annual mean contents for each constituent and for all traps directly reflects that of total mass fluxes: the higher the mass fluxes, the lower the biogenic contents. Organic carbon means vary between 1.25 % (Sête) and 7.91 % (Baleares). The general trend is a decrease southward from Marseilles to Barcelona. Baleares samples present the highest mean at each trap position. Organic carbon content decreases in the following way: mid-water canyon axis trap, open slope, near-bottom canyon axis, canyon head. This reflects the progressive dilution of the marine biogenic signal by lithogenic particles (either resuspended or freshly introduced to the region by rivers).

The trends for mean inorganic carbon contents are less obvious since the range of values is very narrow. For equivalent trap positions, the Baleares present the highest means for the near-bottom canyon and open slope traps. Inorganic carbon has two origins, detrital (through resuspension) and authigenic (primary flux signal from surficial waters), and the latter becomes more important, relatively, when the mass fluxes are low.

The highest opal means are generally observed for the mid-water and open slope traps, reinforcing the idea that this constituent originates from marine production.

The lithogenic fraction is calculated by substracting organic matter (C org. x 2), carbonate (taken as calcium carbonate; C inorg. x 8.33) and opal from total mass flux. Mean values are quite similar from Marseilles to Perpignan (around 60 %), increasing slightly at the Barcelona site. The Baleares present the lowest lithogenic mean contents, around 50 %. The terrigenous contribution is therefore dominant at all sites, even at the Baleares, a result which is typical of continental margins.

From the combination of weighted mean mass fluxes and annual mean contents, mean annual fluxes of the major constituents are calculated for the different sites (Fig. 17). These values integrate the various sources of variations described above and represent therefore a basis of comparison with other parts of the Mediterranean. They are important to define the amount of particulate material exported to depth in sites of different trophic regimes.

The most striking feature of Fig. 17 is the strong contrast of fluxes along the continental margin from Marseilles down to Barcelona and those registered at the Baleares site, which appear almost negligible. Fluxes in the southwestern part of the Gulf of Lions and off Barcelona largely dominate the system. The main characteristics of particle transfer are therefore a strong alongslope increase in the amount of material exported, an increase with depth at any site of the margin and an across-slope decrease. Particulate transfer on any of these constituents is essentially driven by the factors controlling the overall mass transfer.

These annual mean fluxes represent also the best available estimates of carbon inputs to the benthic system as well as the importance of carbon (e.g., energy) export from the surficial waters. Organic carbon is delivered either by primary production in overlying waters or by resuspension of deposited organic matter. Based on the present, but also on former results (Heussner et al., 1993), we therefore consider that 15-20 mg m^{-2} d^{-1} could be a good estimate of the amount of primary flux reaching the mid-slope depth of about 1000 m in this part of the Mediterranean. As a corollary, fluxes above this value should represent advective transport of organic carbon from other parts of the margin, most probably the shelf and upper slope regions. This mechanism would therefore deliver from 40 (Perpignan open slope) to 70 % (Barcelona canyon axis) of the organic carbon to mid-slope sediments, and almost the totality at canyon heads. These first order calculations are approximately correct only if one assumes that primary production and/or the amount of exported production (e.g., new production) is more or less constant over the entire system. Conan et al. (1996) estimate new production off Marseilles at 140-160 mg C m^{-2} d^{-1}. Despite all the approximations made in this kind of calculation, this estimate would indicate that almost 90 % of the exported production would be remineralized (or exported laterally) during particle settling through the first hundreds meters of the water column. Further integration of this kind of results will be necessary in the future to better assess carbon export from surficial waters.

Factors controlling particle transfer vs. flux variations

Daily river discharges (Rh™ne and Llobregat) and meteorological conditions (wind speed and direction) at 2 sites (near Marseilles and near Perpignan) are so far available, and allow to investigate the connections between flux variations and variations of some internal (dynamical and hydrological) and external (climatological) factors (cf. Chap. 3 and 4.1, and Fig. 18).

As we have seen from the previous chapters, strong seasonal variations in total mass fluxes are recorded for the Marseilles and Baleares sites, with mean mass fluxes 5 to 10 times higher in winter than in summer (Fig. 14). On the Perpignan and Barcelona sites, winter fluxes differ from the summer fluxes by a factor of two at the most. Also, large fluctuations of mass fluxes appear at the same periods on the northern sites. Those observed in winter are generally concomitant with more intense winds and river discharges (Fig. 18). The rivers supply the shelf with particulate matter, while the wind enhances its resuspension and dispersion. The winter period is also characterized by an homogenization of the water column, dense shelf water cascading (Durrieu de Madron and Panouse, 1996) and an intensification of the mean flow and current variability at depth. Thunus (1996) shows from numerical simulations that the seasonal changes of the shelf circulation in the Gulf of Lions yield significant different dispersion patterns of particulate matter with an enhanced winter exportation of the suspended material at the southwestern limit of the Gulf of Lions (Durrieu de Madron et al., 1996). The role of these latter exchange processes is confirmed, but with strong spatial variations due mainly to the bathymorphologic constraints.

The mesoscale variability of the deep slope current has been characterized by monthly kinetic energy (mean and eddy kinetic energies) by Heussner et al. (1996a). A winter increase of monthly KE values is observed at the Marseilles, Barcelona and Baleares sites, where the Northern Current skirts the slope. These periods of intensified flow and shelf-slope exchanges are coherent with some major winter peaks of mass fluxes. The Perpignan site, which is located outside the main path of the Northern Current, is little affected by its winter mesoscale variability. However, even under different dynamical conditions, large mass flux peaks also occur during winter. The latter probably results from other exportation processes, as for example the intensification of shelf circulation and cascading of dense water formed on the shelf, which is particularly strong on the southwestern part of the Gulf of Lions. These results emphasize the simultaneous influence of various climatological and dynamical processes, which converge to produce conditions extremely favourable to off-shelf export of particulate matter.

The benthic response

Meiofauna, which represents the more reactive component of the benthic faunal compartment, has been investigated during three cruises: Flubal 93, Euroswap 94 and Euromarge 95 (cf. Chap. 3). Benthic macrofauna has been analysed during the last two cruises.

As a result, two faunal patterns can be pointed out:

a) The first is related to the continental margin and shows unexpectedly, at comparable depths, a relative enhancement of meiofaunal densities in the canyon axes as compared to the adjacent interfluves (Fig. 19); this is particularly well illustrated by the Flubal '93 and Euroswap '94 Figs.

b) The second, more classical pattern, is observed at the Balearic margin where meiobenthos abundances regularly decrease with increasing depths.

The average level of meiofaunal abundance recorded during each cruise is roughly comprised in the 250-750 ind.5 cm^{-2} range and does not reflect a significant year-to-year variation among the entire ecosystem. While referring to the same period (e.g., June to August), Table 4 data set however support the hypothesis of the enhancement of communities in 1995. Patchiness of populations strongly affects mean values of densities which should therefore be considered under circumspection. By comparison with previous records (see, for example, the review by Soyer, 1985), the relative high level of standing stocks recorded during the Euromarge-NB experiment is explained by the better efficiency of the multi-corer as compared to other samplers such as the Reineck and/or the USNEL box-corers (Bett et al., 1994).

Macrofauna is particularly scarce in the whole investigated area and should therefore be considered as undersampled. No significant feature is therefore detectable with regard to an interfluve vs. axis comparison. The species composition however shows a dominance of Bivalves at the northern sites (e.g. Marseilles and Perpignan) and the replacement of these by Polychaetes at the Balearic margin. Faunal abundance and composition which are presumably linked to energy supply to the seabed thus reveal differences in the functioning of the four selected sites of the benthic survey.

Analysis of SPI and surface photographs have revealed evidence of a zone of intense crustacean bioturbation on the mid continental slope between 400 and 1000 m, which follows closely that of the zone of upper slope sediment accumulation described by Courp and Monaco (1990). The presence of large burrow fields whether active or relict are the integrated response of the benthos to sediment accumulation and organic carbon flux over time.

The presence of a zone of intense burrowing activity has important implications for sediment geochemistry. Burrows may increase the area of the sediment/water interface by a factor of > 2 which affects solute chemistry and microbial activity due to increased sub-surface sediment oxygenation. Excavated mounds change surface Benthic Boundary

Layer (BBL) flow characteristics and alter sediment shear characteristics. The mounds may act as baffles promoting retention of fine material in the troughs. Relict burrows identifiable in profile images due to infill by pellet fluff must promote rapid sub-surface transfer of 'fresh' organic material.

Given the lack of autochtonous primary production, the benthic biota is entirely supported by organic matter supply at the sediment-water interface. Faunal abundance is therefore expected to be linked to biochemical parameters which classically refers to the bulk of POM (TOC, POC, TON) or to its utililizable fractions (hydrolyzable organic carbon «HOC», total amino acids «Aa», total sugars). All these descriptors were taken into account in the three synoptic surveys while a special attention was paid to chlorophyllous pigments as indicators of phytodetritus deposition.

From the rather large data set ($17<n<66$) collected over the 1993-1995 period, several statistically significant positive correlations have been found (Buscail et al., 1996). It is confirmed that the widely used POC descriptor has poor meaning with respect to the trophic conditions on the bottom. The observed covariation of meiofauna and nitrogen underlines the general relationship with the pool of organic matter while, surprisingly, negative trends are found with descriptors of the POM labile fractions (HOC, aminoacids, sugars). It should be mentioned that meiobenthos density is also independent from the geochemical nature of the substrate (characterized by the carbonate content) of the Northwestern Mediterranean system (Buscail et al., 1996). Apart from nitrogen, the best explanation of the community standing stock is finally found in the abundance of phytodetritic matter at the sediment-water interface, particularly through Chl.a content which is related to freshly sedimented material. This suggest the prominent role of phytoplanktonic blooms in sustaining the benthic biomass.

By targeting all core samples near the sites of sediment trap moorings, the sampling strategy of Euromarge-NB intended to find new evidence of the benthic-pelagic coupling. A few pairwise comparisons between fluxes and faunal biomasses are so far available, all of them drawn from the Lacaze-Duthiers (Perpignan site) experiment of June 1994. An acute concordance is found between meiofauna densities and mass fluxes measured at 35-40 m.a.b. during the 15-days period preceding the benthic sampling. More detailed analysis of the sediment trap organic matter reveals that POC, nitrogen, aminoacids and sugar fluxes are equally linked with the meiobenthos standing stocks. Reversely, no covariation between chlorophyllous pigments and meiofauna is observed. Additional data from similar experiments previously conducted in the tropical Atlantic and Bay of Biscay finally lead to a linear model for the meiofauna-POC flux relationship (Fig. 20).

Carbon budgets

The integration of primary productivity data, measured carbon fluxes through the water column, carbon fluxes reaching the sediment/water interface (derived from sedimentation rates measured by ^{210}Pb, organic carbon content in the sediment, and sediment bulk density) and the organic carbon content in the subsurface sediment allows to establish the carbon budget for a given site. The calculation procedure follows the guidelines by Buscail et al. (1990), who calculated the carbon budget in the Perpignan mesotrophic site. During EUROMARGE-NB this budget has been established for the first time in the Marseilles, Barcelona and Baleares sites, and recalculated for the Perpignan site.

The Baleares carbon budget represents the first obtained in Western Mediterranean oligotrophic conditions (Fig. 21). The primary productivity amounts 110.5 gr C m^{-2} y^{-1} (Estrada and Margalef, 1988). Only 2.22% of the primary productivity reaches the 700 m depth sediment trap, while 4.5% of the primary productivity is measured at the near-bottom, 1200 m depth, sediment trap. This situation indicates an advective input which represents about the 50% of the carbon near-bottom flux. Again, in surface sediment, a decrease is observed, down to 3.9% of the primary productivity. This decrease represents a loss of 12.2% with respect to the near-bottom sediment trap flux. The reasons for that decrease are not known strictly. Finally, the subsurface sediment contains a mean of organic carbon of only 0.3%, it is 1.8% of the measured primary productivity, or about half the carbon content of the surface sediment. So, only about 2% of the surficial waters primary productivity becomes stocked into the sediment.

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Due to its nature, a synthetic article cannot include all the relevant and detailed information produced during the project's life, and the decision about what has to be included, being subjective by nature, is the responsibility only of the Project Coordinator. For those colleagues whose contributions are not included in this synthesis, it is necessary to state that their inputs are equally appreciated and have at least the same scientific merit than the ones finally chosen and as such they have been incorporated in the Extended Contribution volumes which complement and complete this synthesis, and which were released to the EC in due time.

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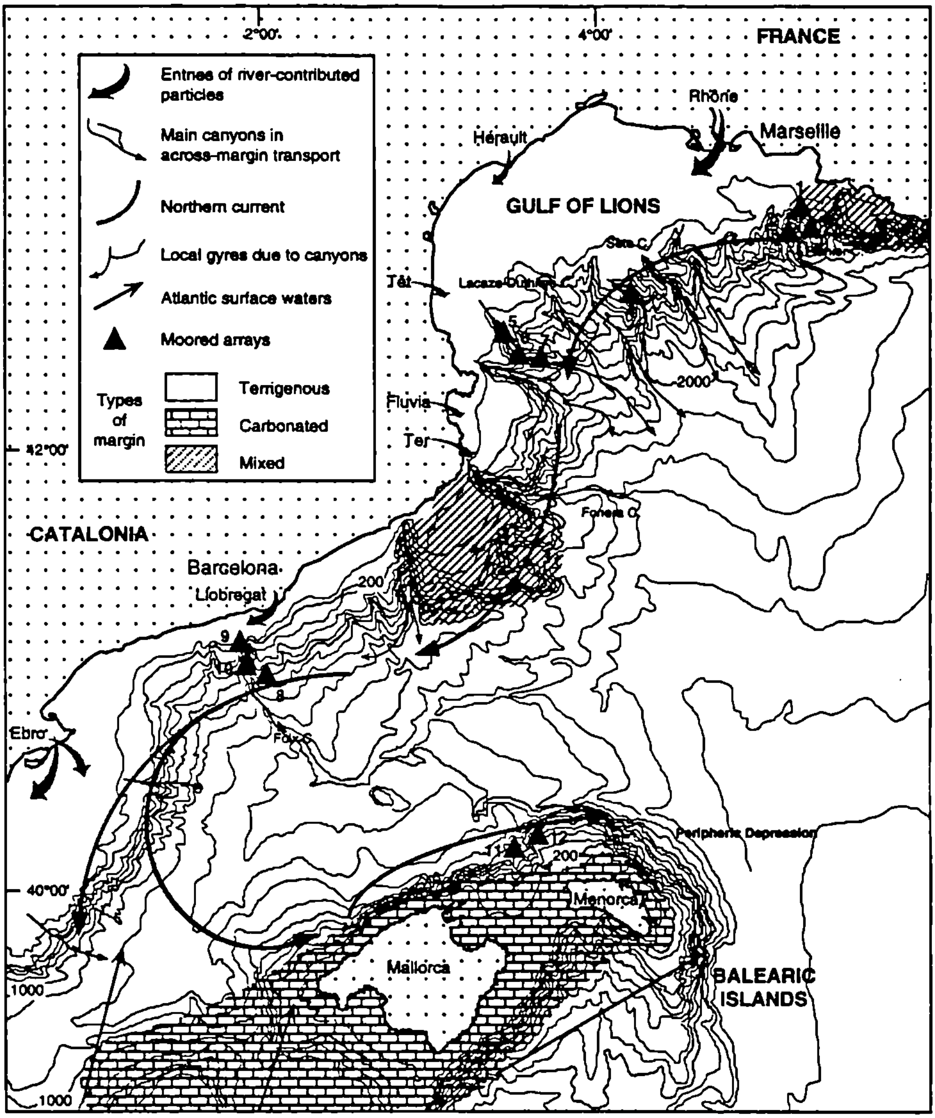


Fig. 1.- Study area and mooring sites of the EUROMARGE-NB Project. Information about significant sedimentary, morphological and hydrodynamical features is overimposed.

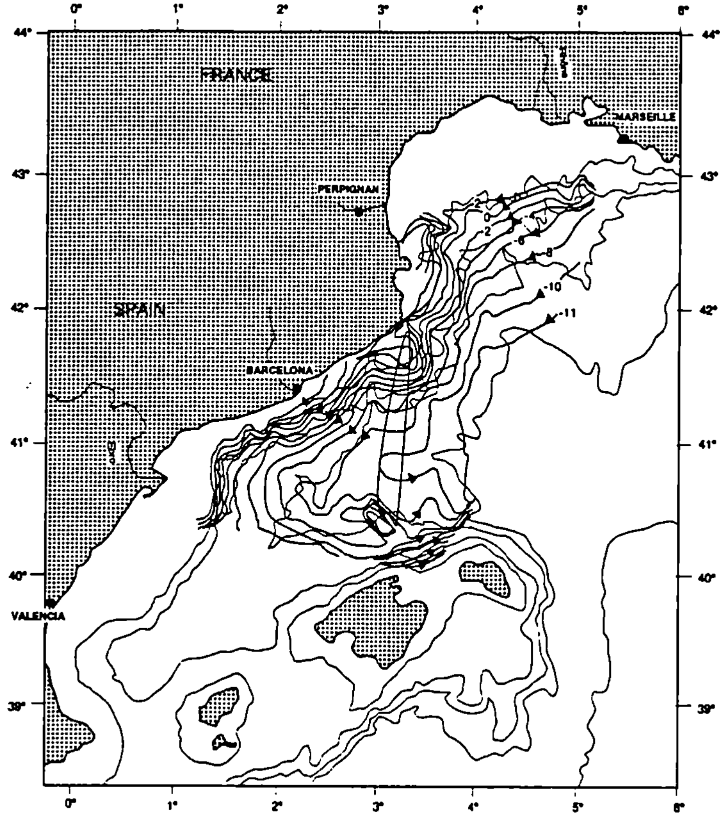


Fig. 2.- Surface dynamic topography ($m^2 s^{-2}$) during the FLUBAL cruise (August 1993). Reference level was taken at 2500 dbar. Stream lines clearly outline the cyclonic path of the Northern Current along the Gulf of Lions, Catalan and north Balearic continental margins.

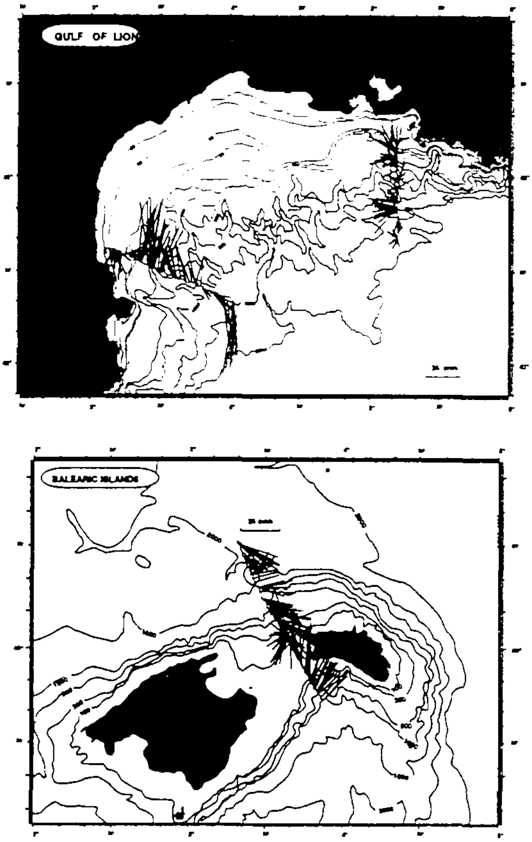


Fig. 3.- Alongtrack ADCP relative velocities at 14 m on June 18, 1995 (Marseilles section), June 21, 1995 (Perpignan section) and June 24, 1995 (Balearic section). Reference levels at 230 m or last levels above bottom when it is shallower.

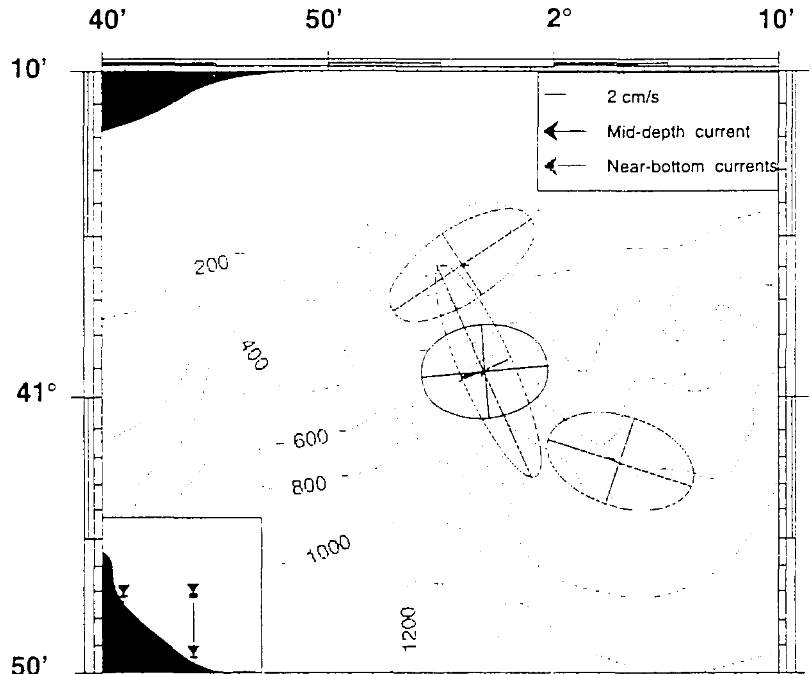


Fig. 4.- Example of mean currents and variance ellipse in the Foix canyon (Barcelona site).

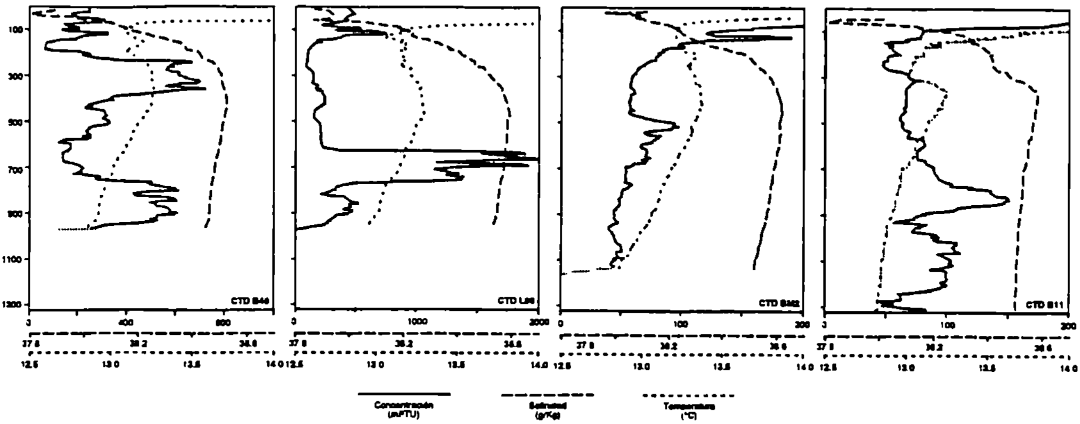


Fig. 5.- Mean situation of hydrological and nepheloid profiles for four selected stations from Marseilles to Baleares sites.

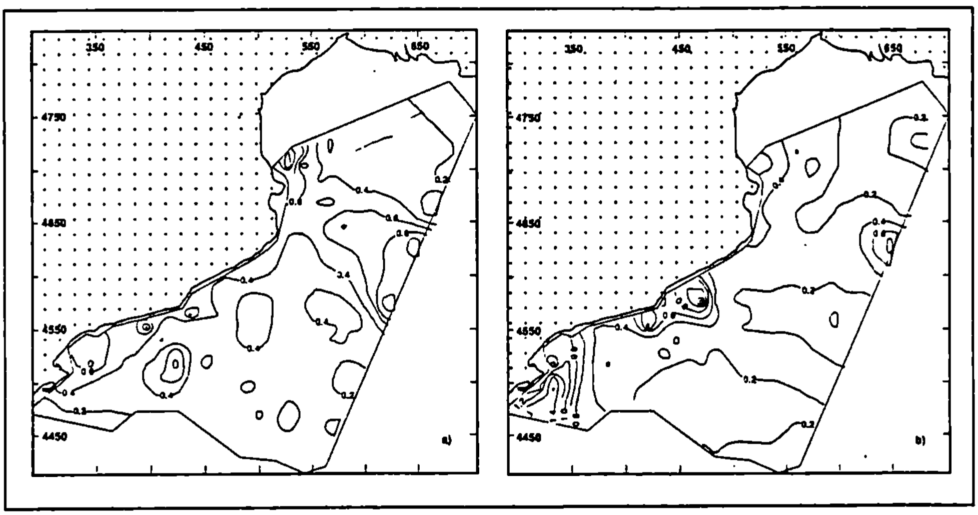


Fig. 6.- Distribution of surface (a) and bottom (b) suspended particulate matter in mg.l^{-1}.

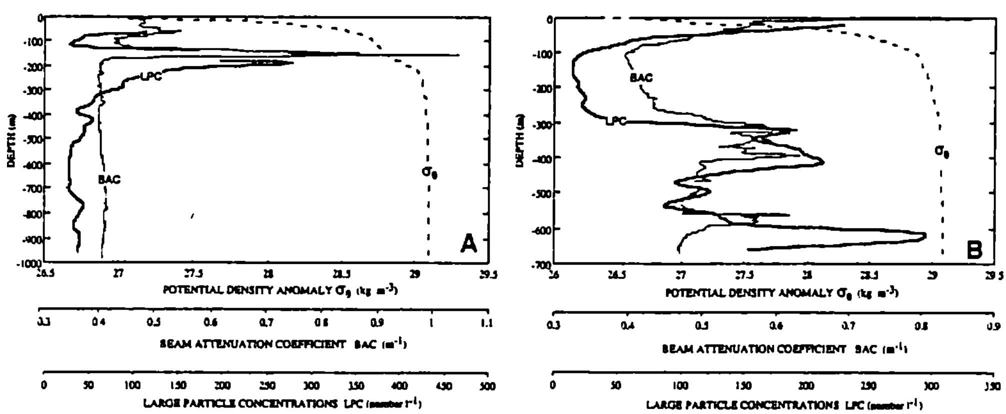


Fig. 7.- Comparison of vertical distribution of large particle concentrations vs. turbid structures seen by transmissometer (beam attenuation coefficient). A) Marseilles site (M3 station); B) Perpignan site (B4 station).

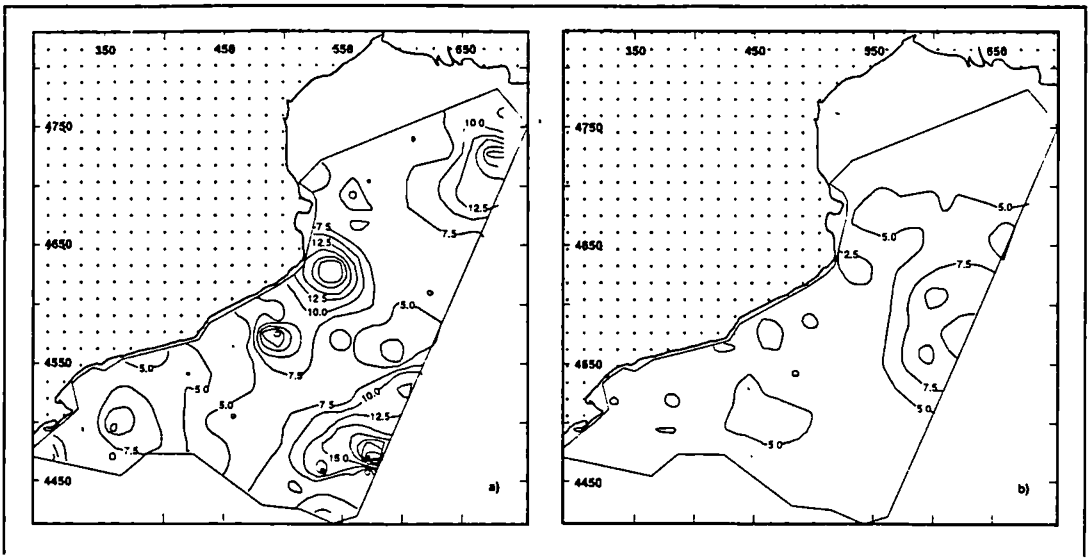


Fig. 8.- Distribution in percentages of the particulate organic carbon on surface (a) and bottom (b) waters.

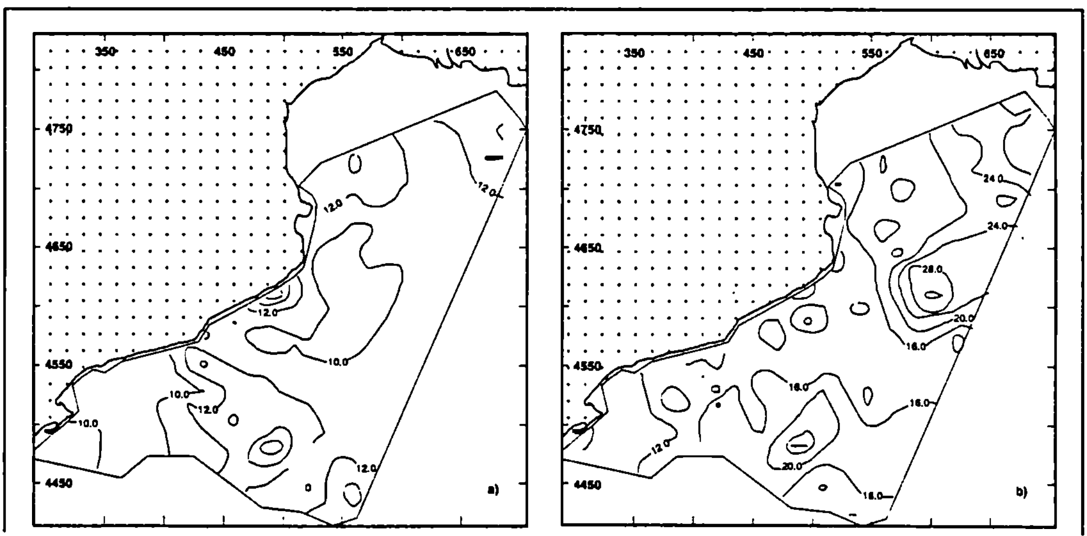


Fig. 9.- Distribution of the C/N index of the suspended particulate matter on surface (a) and bottom (b) waters.

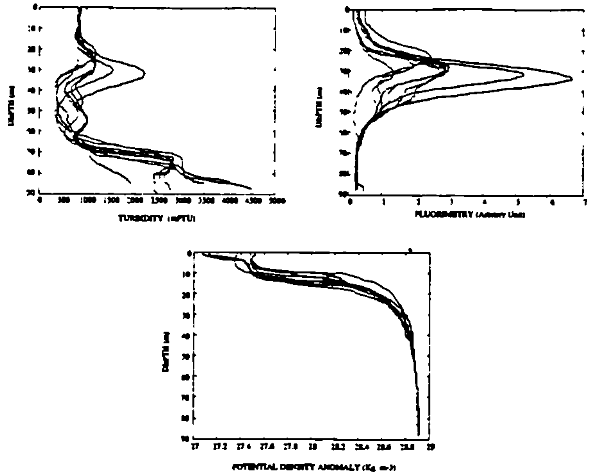


Fig. 10.- Time series of 9 repeated turbidity, fluorescence and density profiles taken during 11 hours at a shelf station off Perpignan (B2) during the EUROMARGE Ò95 cruise. Turbidity was measured by light scattering and is expressed in Formazine Turbidity Units (mFTU).

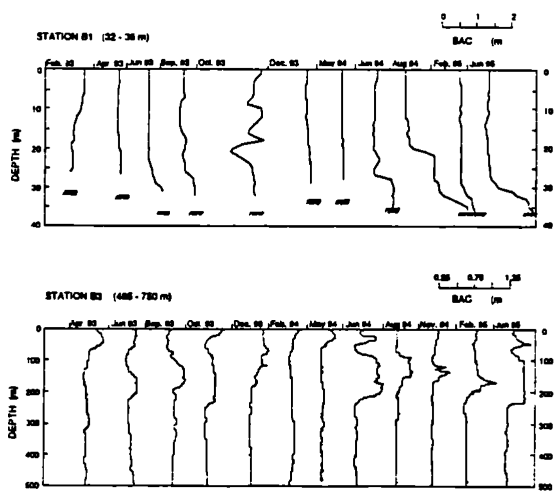


Fig. 11.- Time series of turbidity profiles (light transmission expressed as beam attenuation coefficient) at a shelf and a slope station off Perpignan taken between January 1993 and June 1995.

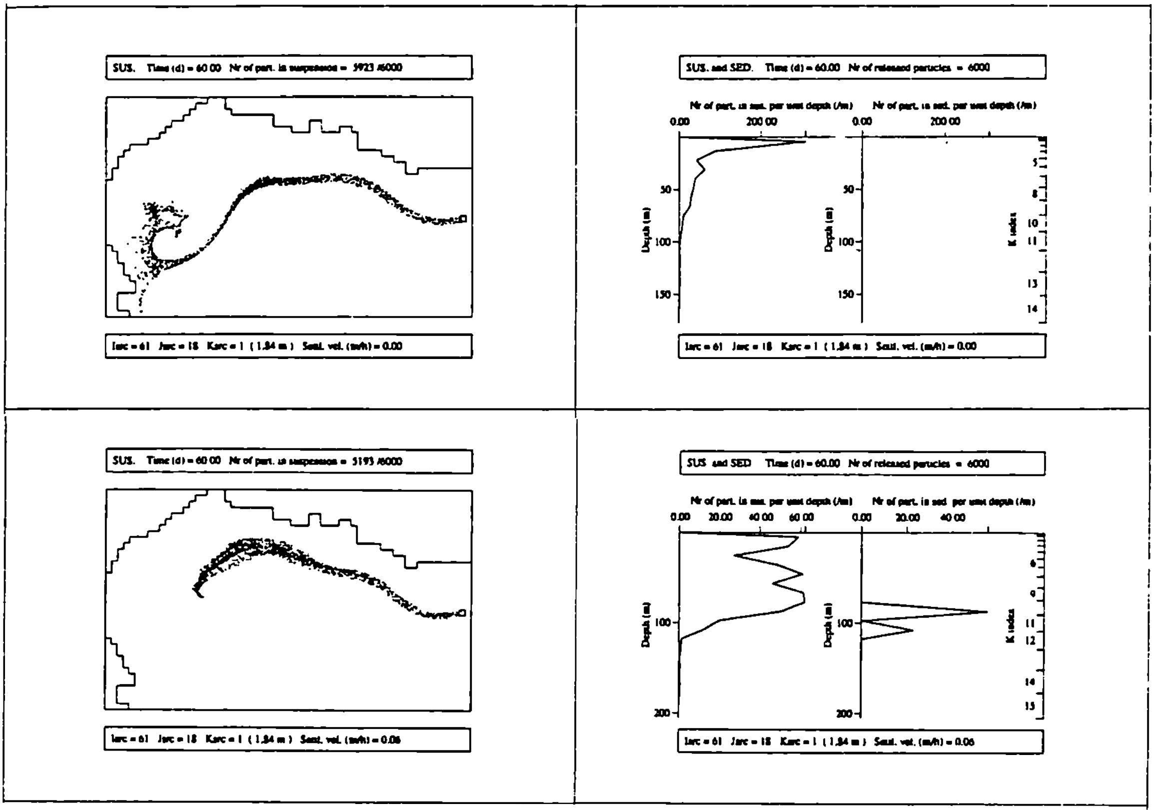


Fig. 12.- Example of trajectories of virtual particles released in the Eastern part of the Gulf of Lions over 60 days. In the first situation particles are neutraly buoyant. They are trapped, vertically transported and dispersed in the gyre observed in the western part of the domain. In the second case, the particles are released in the same conditions but have a vertical velocity of 0.06m h^{-1} which influences their trajectories and promotes their earlier settling.

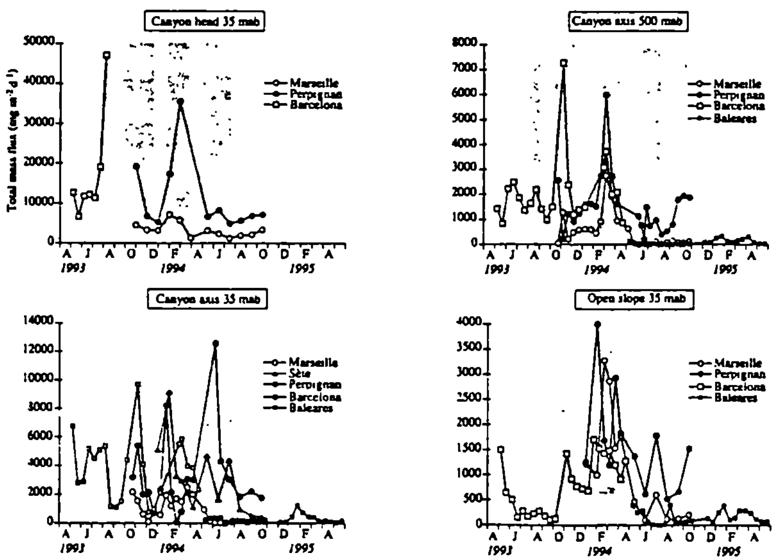


Fig. 13.- Time-series plots of total mass fluxes (mg m^{-2} d^{-1}). Dotted areas represent periods during which flux peaks were observed for several or all traps.

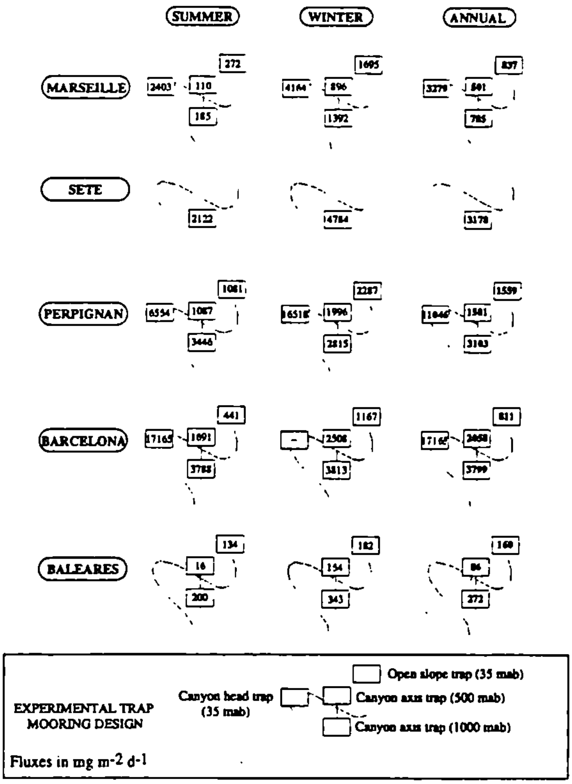
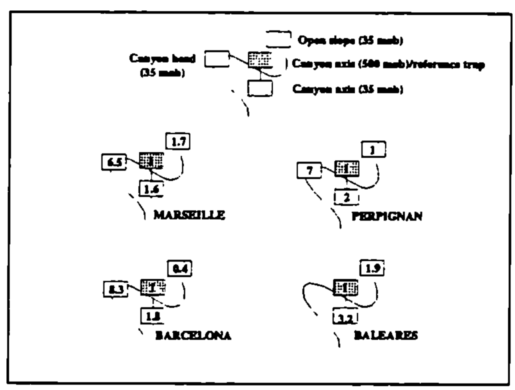


Fig. 14.- Seasonal and annual weighted mean mass fluxes (mg m^{-2} d^{-1}).

Fig. 15.- Variability of mean mass fluxes within each experimental site. Each annual mean was normalised to the flux calculated for the 500 m.a.b canyon axis trap (reference trap).



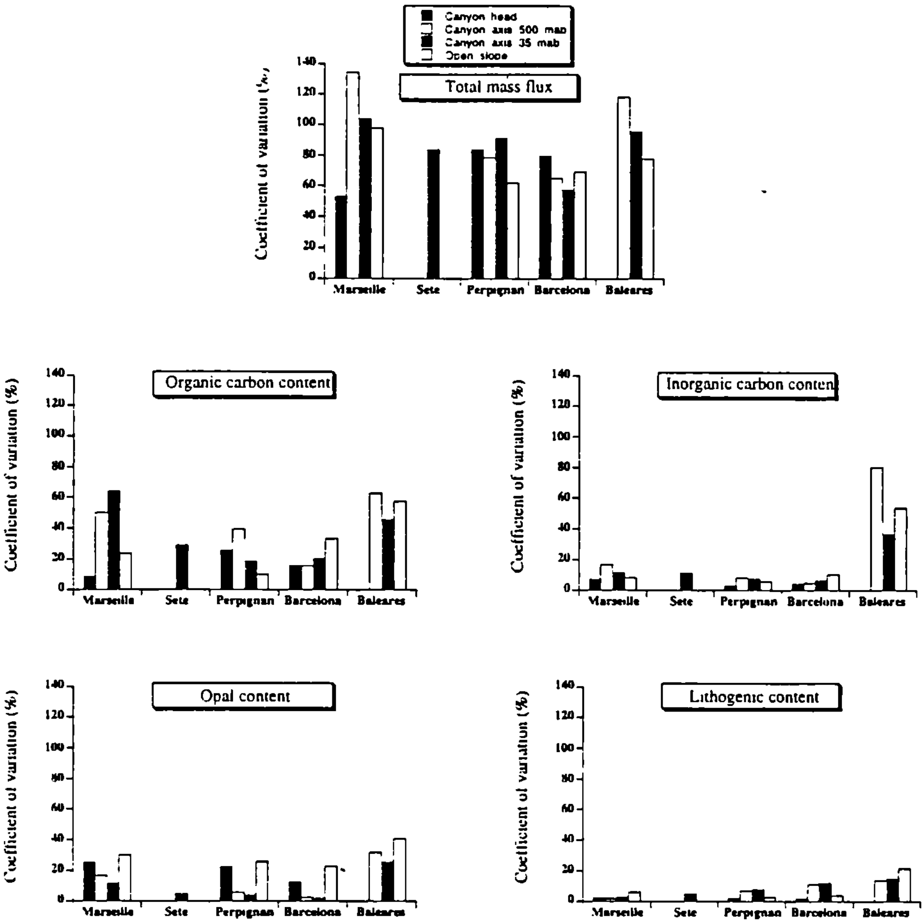


Fig. 16.- Variability of the contents of the major constituents of settling particles (coefficient of variation = s/m*100) at the different experimental sites.

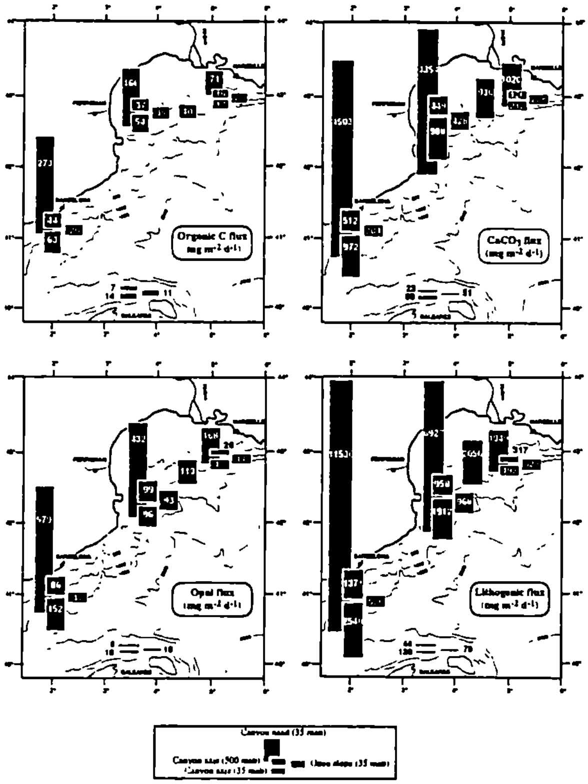


Fig. 17.- Annual mean fluxes of major constituents of settling particles

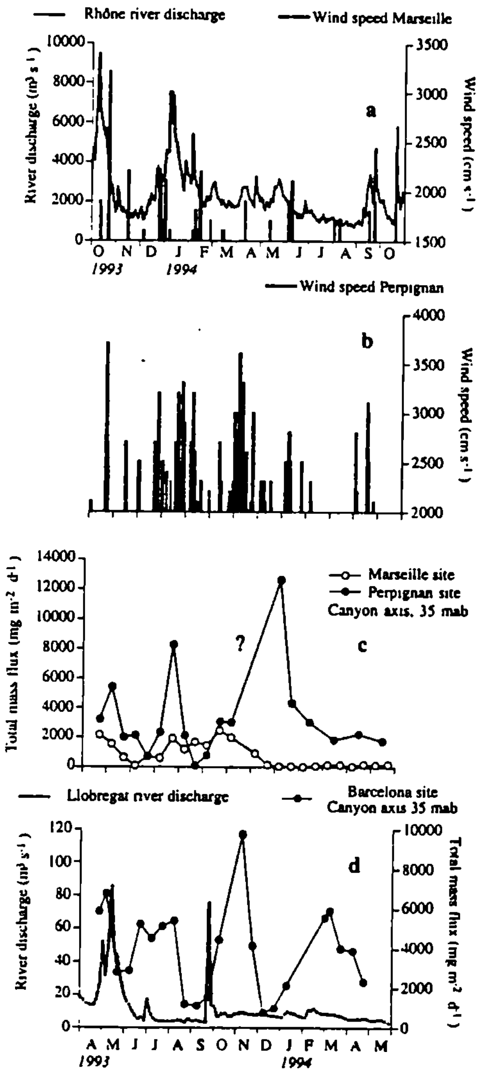


Fig. 18.- Temporal evolution of wind speed (threshold speed at 15 m s^{-1}) at Marseilles and Rhône river discharge (a), wind speed at Perpignan (threshold speed at 20 m s^{-1}), (b) and selected mass fluxes from the Marseilles and Perpignan sites (c); mass fluxes at the Barcelona site are presented together with the discharge of Llobregat, the nearby local river from that site (d). Dotted areas represent periods of concomitance between high values of these external factors and high flux values.

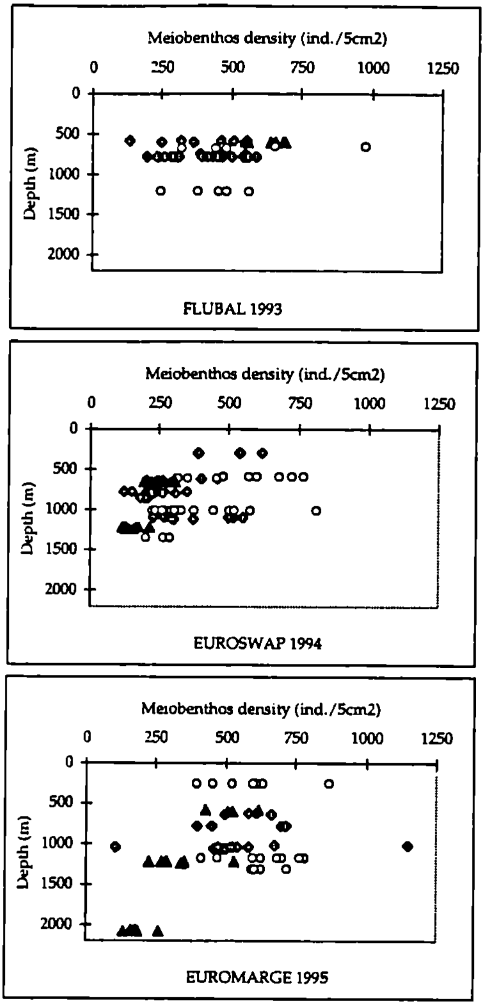


Fig. 19.- Meiobenthos abundance vs. depth distributions observed during the EUROMARGE-NB experiment 1993-1995 (circles = axis cayon; diamonds = interfluves; triangles = Baleares slope).

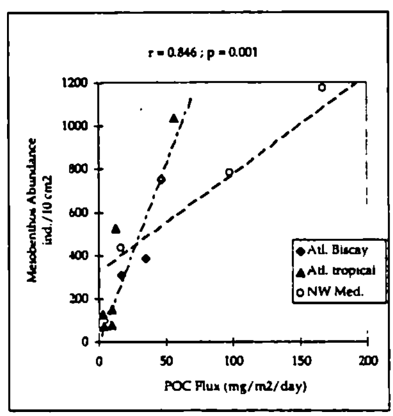


Fig. 20.- Relationship between meiobenthos abundance and POC fluxes measured by sediment traps (35-40 m.a.b.) in various Atlantic and Mediterranean areas.

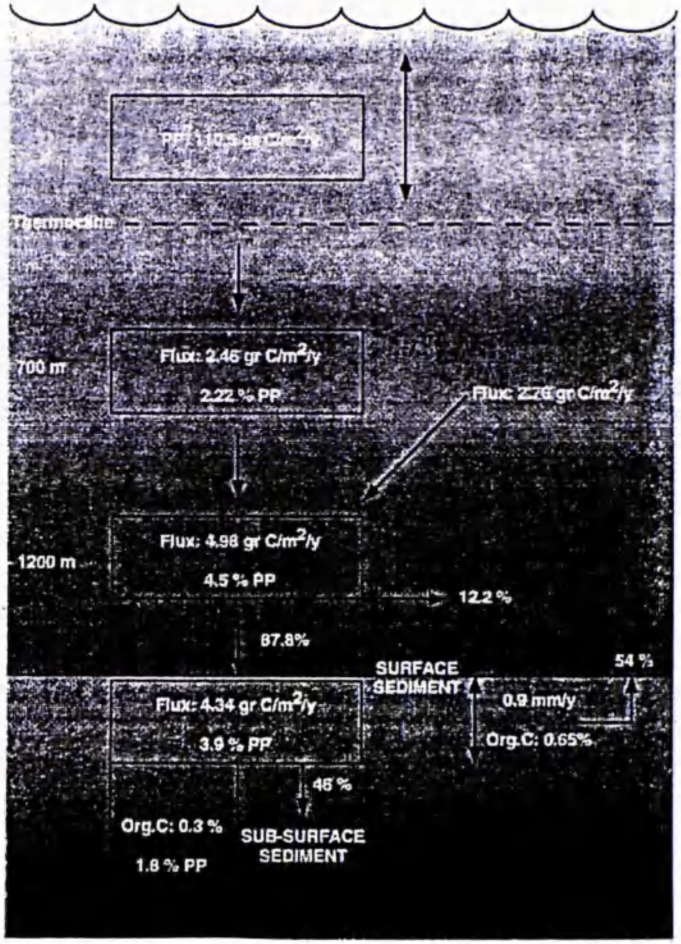


Fig. 21.- Carbon budget in the Baleares site.

Table 1.- Identification data of the moored arrays of the EUROMARGE-NB project. On the Depth (m)-Location column, In indicates the Interfluve moorings, and Ca the canyon axis moorings.

Site	Array	Coordenates	Depth (m)-Location	Sed. traps-C.meter pairs (m above bottom)	Sampling periods
			Planier Canyon		
I	1	43.06°N-05.13°E	560-Ca	30	10.93-05.95
I	2	43.02°N-05.11°E	1070-Ca	30-500	10.93-05.95
I	3	43.02°N-05.16°E	750-In	30	10.93-05.95
			Aude Canyon		
I-II	4	42.42°N-04.14°E	1120-Ca	30	10.93-05.95
			Lacaze-Duthiers Canyon		
II	5	42.32°N-03.27°E	550-Ca	30	10.93-05.95
II	6	42.26°N-03.33°E	1020-Ca	30-500	10.93-05.95
II	7	42.28°N-03.41°E	770-In	30	10.93-05.95
			Foix Canyon		
III	8	40.59°N-02.02°E	1195-In	30	04.93-11.94
III	9	41.06°N-01.55°E	635-Ca	30	04.93-11.94
III	10	41.02°N-01.56°E	990-Ca	30-500	04.93-11.94
			Northwest of Minorca		
IV	11	40.13°N-03.29°E	1350-Ca	30-500	05.94-06.95
IV	12	40.15°N-03.39°E	650-In	30	05.94-06.95

Table 2.- Research cruises carried out into the EUROMARGE-NB project.

Dates	Cruise name	Research ship	Study sites
	Mesoscale cruises		
30.07-18.08.93	Flubal '93	Minerva	I to IV
17.06-02.07.94	Euroswap '94	Tethys II	II, III and IV
15.05-01.06.95	Big '95	Hesperides	IV and S of III
04.06-08.07.95	Euromarge '95	Le Suroit	I to IV
	Local cruises		
20.04-29.04.93	Concentra I	Garcia del Cid	III
01.06-22.06.93	Varimed	Hesperides	III and IV
03.09-05.09.93	Suivilion 04	P. Georges Petit	I and II
18.10-20.10.93	Suivilion 05	Tethys II	I and II
22.10-25.10.93	Concentra II	Garcia del Cid	III
22.11-01.12.93	Technilion 2	P. Georges Petit	II
04.12.93	Suivilion 06	P. Georges Petit	II
12.02-13.02.94	Suivilion 07	L'Europe	I and II
24.04-02.05.94	Suivilion 08	L'Europe	I and II
02.05-08.05.94	Concentra III	Garcia del Cid	III and IV
26.06-07.07.94	Suivilion 09	L'Europe	I and II
18.08-01.09.94	Ecocot 1	L'Europe	I and II
26.08-03.09.94	Suivilion 10	P. Georges Petit	I and II
17.09-27.09.94	Euroflux	P. Georges Petit	II
08.11-16.11.94	Suivilion 11	P. Georges Petit	I and II
12.11-15.11.94	Concentra IV	Garcia del Cid	III
28.11-05.12.94	Balear Traps II	Salvamar C.B.	IV
16.02-18.02.95	Technilion 3	Tethys II	II
17.05-27.05.95	Suivilion 12	P. Georges Petit	I and II

Table 3.- Total phytoplanktonic biomass in the Baleares, Perpignan and Marseilles sites. Figures in mg m^{-3}

TOTAL BIOMASS

Depth	Baleares	Perpignan	Marseilles
100m	9	6	12
65m	49	71	29
40m	79	228	32
20m	23	66	45
5m	59	58	15

Table 4.- Mean densities of meiobenthos at the four main depth levels (A= 250-300m, B = 500-800m, C = 1000-1400 m, D = 2000-2200 m) of the Euromarge-NB experiment (1993-1995).

		1993			*1994*			*1995*		
		Inter-fluve	Axis	Balear. margin	Inter-fluve	Axis	Balear. margin	Inter-fluve	Axis	Balear. margin
A	Mean					545,25			576,38	
	S.E.					98,19			134,43	
	n					4			8	
B	Mean	409,03	560,83	629,67	556,27	247,04	246,40	575,75		519,00
	S.E.	125,01	232,08	62,06	149,82	76,21	42,22	118,30		77,72
	n	36	6	6	11	24	10	8		4
C	Mean		376,99		347,10	304,94	141,62	479,14	632,67	289,41
	S.E.		107,63		155,19	119,88	29,41	233,69	109,72	106,01
	n		6		18	9	11	12	12	6
D	Mean									174,60
	S.E.									43,68
	n									6

Mediterranean Targeted Project (MTP)- Mermaids-II Project
Contract MAS2-CT93-0055

Synthesis of Final Results

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Contract No.: MAS2-CT93-0055
Starting date: 1 September 1993
Duration: 33 months
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Mediterranean Eddy Resolving Modelling And Interdisciplinary Studies-II

ABSTRACT

The project studied the seasonal and interannual variability of the Mediterranean Sea general circulation through the combination of numerical model simulations and observations. Furthermore, it developed numerical models of the marine ecosystem capable in principle to simulate the primary productivity levels of the basin considered. The results showed that the interannual variability of the upper ocean flow field is connected to changes in atmospheric forcing conditions, as well as the rates of intermediate and deep waters occurring in the basin. Intermediate water mass spreading and deep water outflows have been studied and successfully simulated. A new state of the Eastern Mediterranean waters was observed with Aegean waters in addition to traditional Adriatic deep water sources. Regional hydrodynamical models of different complexity have been successfully implemented in the Adriatic and Aegean Sea and the resulting flow field compares well with climatological observations of the areas. Several ecosystem models of different complexity have been implemented and calibrated for the Mediterranean area: The simulations of primary productivity compare reasonably well with climatological observations.

Key Words: general circulation modeling, water mass formation and spreading, thermohaline circulation, seasonal and interannual variability of circulation, climatological studies of historical data, satellite altimetry data analysis, Adriatic Sea modeling, Aegean Sea modeling, ecosystem modeling at basin and regional scales, altimetric data assimilation.

INTRODUCTION

The general aim of the project can be stated as follows: to study the general circulation of the Mediterranean Sea through the combination of observations and models in order to understand the seasonal and interannual variability of the basin currents, the water mass formation and spreading processes, the thermohaline circulation and to produce the hydrodynamical forcing for the development of ecosystem models capable to simulate the primary productivity of the basin. In other words, Mermaids-II considers the observations (mostly already available but with some important exceptions, as for the Topex/Poseidon data and the Meteor 1995 cruise) and the numerical models which could be used to make a synthetic picture of the basin hydrodynamics, and in particular it want to understand the recently discovered seasonal and interannual time variability of the flow field. In addition, it develops the numerical tools which could be capable of simulating the observational distribution of nutrients and primary production, studying the effect of physical forcing components on the biogeochemical cycles. In order to achieve these scientific aims the project develops novel data analysis techniques for in situ and satellite data sets, develops and implements numerical models and data assimilation techniques and compares data and models at different time and space scales.

The emerging view of the basin circulation driving mechanisms is schematically represented in Fig. 1. The basin currents are composed of subbasin scale gyres, boundary and mid-ocean jets which are driven by wind stress curl structures and reinforced by deep water formation processes, which in turn are driven by surface heat fluxes and occur in limited regions of the basin. In a second instance the Gibraltar in and outflow system reinforces these effects. On a regional point of view, the Po river run-off and the Black Sea waters inflow can control the local dynamics of currents. The antiestuarine vertical circulation of the basin is connected to the atmospheric forcing and to the basin geometry. Together with this climatological view of the circulation the project aims to the understanding of the variability with a special effort on the interannual time scales. The most recent observational data sets seem to indicate dramatic changes in the circulation structure from year to year and this project will try to understand the reasons for that. In the following we explain the methodological approach and we overview the major scientific results.

The knowledge and the availability of successful simulations of the seasonal cycle of the basin currents has allowed the development of ecosystem models of the primary production. A basin wide ecosystem model has been develop using an aggregated formalism for biochemical variables (only one nutrient, one phytoplankton group and detritus) but complete physical processes as described within the General Circulation model developed in Mermaids. The findings indicate that the large scale latitudinal and longitudinal gradients are associated to horizontal and vertical nutrient transport mechanisms due to slow upwelling in basin gyres and coastal regions. The second ecosystem modelling set-up is more complex, coupling full hydrodynamics and mixing processes to complex biochemical interactions between several nutrients and various functional groups of primary and secondary producers. This modelling effort has shown that detailed chlorophyll gradients in the Adriatic can be reproduced together with a reasonable succession of phytoplankton blooms in the various areas of the basin.

MATERIALS AND METHODS

The study area is the overall Mediterranean basin together with its two major regional Seas, the Adriatic and the Aegean. The methodology and the tools used in this study can be grouped into four categories:

- Objective Analysis techniques of in situ and satellite altimetry data. The project initiated the development of new objective analysis techniques to regularly grid the observations for model validation, initialization and assimilation. A new objective analysis method, based upon variational theory (Brasseur et al., 1996, Brankart and Brasseur, 1996a,b) has been developed, implemented and calibrated for the Mediterranean Oceanic Data Base (MODB) hydrographic data set. Different objective analysis techniques have been applied to the mapping of satellite altimetry data (Larnicol et al., 1996, Ayoub et al., 1996).

• Ocean General Circulation Models (OGCM). The project continued from Mast-I the development and implementation of a hierarchy of ocean general circulation models in order to simulate the seasonal and interannual variability of the flow field, from the surface to the deep ocean, from the eddy scale to the large scale circulation. These models are used at different levels of complexity but they are all based upon the Modular Ocean Model (MOM) and the Princeton Ocean Model (POM). The major developments for OGCM-MOM considered: air-sea interaction physics (Roussenov et al., 1995, Castellari et al., 1996), vertical mixing parameterizations (Castellari, 1996), convective adjustment schemes (Roussenov et al., 1996), eddy advection parametrizations (Wu and Haines, 1996a and b), horizontal and vertical resolution and horizontal viscosity. The methodology is based upon the comparison of hydrography with models solutions, transient tracer data with equivalent model tracers and advanced model diagnostics to check on the model solutions.

• Data Assimilation Techniques. This project developed novel techniques of satellite altimetry data assimilation, first applied to the Mediterranean but clearly exportable to other parts of the world ocean. The techniques are based upon theoretical models of the information content of sea surface height (Cooper and Haines, 1996, Pinardi et al., 1995) and simplified Kalman filters (Hoang et al., 1994, 1996, De Mey, 1995, 1996).

• Ecosystem models of different complexity. The project developed: 1) an aggregated model of the nutrient cycles of the Mediterranean basin coupled to the advanced OGCM-MOM (Civitarese et al., 1996, Crise et al., 1996) and 2) the coupling of the European Regional Seas Ecosystem Model (ERSEM, Baretta et al., 1995) to POM one dimensional (Allen et al., 1996a,b) and three dimensional. Both these ecosystem models are coupled on-line with the hydrodynamics and use the most advanced physical parametrizations developed for the OGCM's.

Objective analysis is a statistical method based on error minimisation and the technique provides an estimation of this minimum. One can easily show that the error field is a function of the spatial data distribution and the statistical properties of the observed quantities. In regions void of data, it will tend to the background error variance; in well covered regions it may decrease to very small values (depending on data density and data error variance). The variational formulation, developed in this project, has been demonstrated to be identical to standard objective analysis, and an hybrid of the statistical and variational methods allows to compute error fields associated to the climatology. The free parameters of the scheme are determined using a cross-validation algorithm to extract the best seasonal statistics from the observed data sets.

Many versions of the OGCM-MOM exists and are used by the different groups within the project but contacts have been maintained between partners to check on model improvements and exchange information. The OGCM-MOM version developed during Mast-I as at 1/4 X 1/4 degrees resolution and 19 levels in vertical. In Mast-II two new versions of the OGCM-MOM have been tested and released to the Mermaids-II community: the first is the most advanced 1/4 X 1/4 X 31 levels version (PE4L31) with Mellor-Yamada turbulence closure schemes and new air-sea interaction physics. The second is the high resolution 1/8 X 1/8 X 31 levels version (PE8L31). The models have been implemented with different heat flux forcing parameterizations, from surface relaxation to climatological values of surface salinity and temperatures to advanced interactive air-sea physics to compute heat fluxes from daily values of surface atmospheric parameters. For momentum, either perpetual year conditions are considered (monthly mean climatological wind stresses are persisted each year at the top of the model, simulating perpetual seasonal conditions) or daily wind stress values. Model physics (meaning subgrid scale processes parametrizations inside the water column) has been tested for a range of vertical mixing schemes (Mellor- Yamada, standard and non standard convective adjustment schemes, non uniform ad hoc vertical diffusion, etc.) and horizontal viscosity (laplacian versus biharmonic, Gent-McWilliams scheme). Some of the partners customized the advanced air-sea physics developed for the OGCM-MOM for the POM implementation.

The data assimilation techniques developed during the project are novel and show a potential for being generalized to different world ocean areas. The basic knowledge acquired during this study is the connection between sea surface height changes and subsurface isopycnal displacement, temperature and/or barotropic components changes. A method of Optimal Interpolation has been developed for the assimilation of satellite altimetry considering this advancement in understanding. Different methods of state-reduction in the vertical (decreasing the degrees of freedom in the representation of the vertical current profiles) were intercompared for the first time.

The aggregated biogeochemical model developed during the project is coupled to the OGCM-MOM. The aggregated trophodynamics nitrogen model is described by N,P, and D (N represents the dissolved inorganic nitrogen, P is the phytoplankton biomass nitrogen equivalent and D the organic forms from DON to the detritus plus epibacteria aggregates). Within this NPD framework, an attempt to develop a better and more general parametrization of vertical biology- controlled nitrogen transport processes is made. A new estimation of detritus sinking velocity for the particulate organic form is made according with weighted averages of reported vertical settling velocities for different fraction of D operationally grouped in fecal pellets, aggregates and the labile part of DOM. Using literature data for all those D forms, a regeneration time scale of ten days was obtained; an averaged sinking velocity of 5 meters/day was estimated on theoretical and experimental considerations.

The coupled ERSEM/POM model relies on "standard" POM characteristics and the "standard" ERSEM (Baretta et al., 1995). The latter is a biomass based ecosystem model (originally developed to model the North Sea ecosystem dynamics), describing the biogeochemical processes occurring in the water column and in the sediments, as well as their mutual relationships, in terms of flow of Carbon Nitrogen, Phosphorus and Silicon within the marine ecosystem. Biota are defined as functional groups (e.g.: phytoplankton, subdivided in the two "diatoms" and "flagellates" functional groups) according to their trophic level. The fully 3D version of POM has been coupled "on line" to this ERSEM. The circulation model is forced by wind stress,,water and heat flux. The solar radiation is provided also to the primary production submodel of ERSEM as photosynthetically available radiation (PAR: 40% of the solar radiation reaching the sea surface). Every model time step POM provides ERSEM with information about the physical environment. In particular ERSEM receives from POM information about the temperature (T), velocity (u,v,w), horizontal (A) and vertical (k) diffusion coefficients fields, that is used by ERSEM to calculate the metabolic response of the different biota to variations in temperature and the advective/diffusive rate of change of the biogeochemical state variables (through a transport submodel constituting the interface between the two models) which is added to the rate of change of the pelagic variables depending on the different biogeochemical processes The transport submodel operates to reconcile the different integration methods used in POM (leapfrogging) and ERSEM (Euler integration) as well as the possible differences in the time step adopted by the two parts of the coupled system . In fact the model runs at the internal time step required by POM but ERSEM maintains the possibility of a dynamical time step cutting. When ERSEM requires such cutting (as in the case of a phytoplankton bloom or bloom decay), the physics fields remains "frozen" and the ecological variables are integrated for a number of time steps that matches the time step of POM and the average of the result of all these simulations is finally calculated and adopted as value correspondent in time to the physical variables calculated by POM.

RESULTS

Part of the project results were already described in the previous section since the analysis techniques and the numerical models developed were part of the aims of the Mermaids-II project. However, on the more specific scientific results, we can synthesize the findings into twelve major categories:

1. An up-to-date climatological analysis of the MODB (Mediterranean Oceanic Data Base) historical in situ hydrographic data sets has been produced for model validation and initialization. This analysis showed the definitive presence of subbasin scale gyres, boundary and mid-ocean jets with important fluctuations in strength and location at the seasonal time scales (see Fig. 2).

2. An advanced analysis of the sea level variability has been produced from Topex/Poseidon and ERS-1 satellites data which showed for the first time the basin mean sea level seasonal cycle amplitude and the synoptic variability of the basin currents. The data have been mapped in the model regular grid (1/4 degrees) and the seasonal variability of the basin currents has been described for the whole basin for the first time. The large scale cyclonic circulation is intense during winter while anticyclonic mesoscale and sub-basin scale gyres amplify during summer. The Alboran gyre and Iera-Petra gyre have the largest seasonal cycle in amplitude with respect to the other basin structures (see Fig. 3).

3. The interannual variability of the general circulation has been studied by means of the OGCM developed during the project. Process studies on the wind driven ocean response were carried out to clarify the importance of this forcing on the general circulation (Simioli and Pierini, 1995, Pierini, 1996, Pierini and Simioli, 1996) The important discovery is that the wind and heat fluxes variability is partially responsible for the interannual variability of the observed circulation (see Fig. 4 and Korres, 1996, Pinardi et al, 1997, Pinardi and Korres, 1996).This is novel because traditional ideas on gyre scale variability had pointed out only the effects of mesoscale and eddy-mean flow interactions. Furthermore, it has been shown that interannual variability in the basin can consist even of current reversals which is not a common behaviour in mid-latitude basins. An explanation for the Sicily channel transport estimates from hydrography and current meters has been given which considers the wind stress forcing anomalies as major causes of the observed variability.

4. The OGCM and other models have been used to study the Levantine Intermediate Water (LIW) formation and dispersal in the basin. The major discoveries of this study are that: the process of new LIW formation occurs mainly in the Rhodes gyre area and that the rate of water formation is connected to the eddies which are allowed to develop on the rim of the well-mixed water column (Nittis et al., 1996). Another important discovery is that the

LIW contributes to the formation of Deep Western Mediterranean Waters, indicating that the intermediate and deep thermohaline cells of the Mediterranean are linked (Haines and Wu, 1996a and b). For the first time the interannual variability in water mass formation has been simulated for realistic forcing of the general circulation (see Fig. 5).

5. Numerical models of different complexity were used to understand the deep water formation processes in the Eastern and Western Mediterranean sub-basins (Marshall et al., 1994 and 1996, Vested et al., 1996). Theoretical and non- hydrostatic numerical models were used to understand how water masses formed at the surface sink in the deep ocean (convection events) through large mixing plumes producing chimneys and then developing baroclinic instabilities of the rim currents.

6. The thermohaline circulation induced by the deep water outflow from the Otranto Strait has been studied with the help of transient tracer data. The work developed the methodology of using transient tracers observations for the OGCM verification (Roether et al., 1996b and c). After a new convection schemes was developed and enhanced surface forcing imposed, the models CFC-12 tracer distribution compared well with observations (see Fig. 6). Thus we conclude that the thermohaline circulation which has created such tracer distribution in the model is approximately correct and we studied it. It was found that the overall thermohaline circulation of the Eastern Mediterranean is induced by water outflow from Otranto which slowly upwells in the rest of the abyssal basins. The renewal time for intermediate and deep waters in the Eastern Mediterranean is longer than in the Western basin (70 years for Eastern and 50 years for Western) confirming a traditional picture of the thermohaline circulation of the basin (Stratford and Williams, 1996, Stratford et al., 1995).

7. A new state of the abyssal circulation of the Eastern Mediterranean has been observed which consists of Aegean waters contributing to the pool of deep waters of the entire Eastern Mediterranean (Roether et al., 1996). These waters have higher salinity and temperatures than the traditional Adriatic deep water source for the deep Mediterranean basins. The implications of such event on the overall thermohaline circulation need to be studied in the future programs.

8. The Adriatic Sea general circulation has been described for the first time from historical observations (Artegiani et al., 1996 a and b, Russo and Artegiani, 1996, Raicich, 1996). The numerical simulations have shown an important mechanism of river run-off control on the general circulation. The Western Adriatic Coastal Current, normally southward along the Italian coasts, is found to be capable of reversing in direction if low river run-off conditions are achieved. For climatological conditions, fresh waters from Po river run-off compensate for the low temperatures found along the coasts, thus producing a weak density gradient and by consequence a weak density driven current system. If an unbalance is created in such compensation, stronger southward or northward current components could be obtained.

9. The general circulation of the Aegean Sea has been simulated for the first time at seasonal and interannual time scales (Krestenitis and Valioulis, 1996). The model simulations compare reasonable well with observations. The fate of Black Sea waters has been traced in the model solutions and found to be dominating the Northern Aegean circulation structures. In the Southern Aegean the seasonal reversal of Cretan Sea currents is observed due to the climatological forcing and the seasonal strength of the Asia Minor Current inflow.

10. Data assimilation models and techniques have been developed for the Mediterranean Sea in order to assimilate satellite altimetry data. The sea surface height signal is found to be correlated with isopycnal displacements and barotropic currents (Drakopoulos et al., 1996). The first assimilation runs, done with the techniques developed during this study, showed the improvement in model currents due to the assimilation of satellite sea surface height with respect to the pure simulation.

11. An aggregated ecosystem model of the Mediterranean Sea basin has been developed and studied (Crise et al., 1996). The model is capable of simulating the spatial and temporal gradients in surface chlorophyll at the basin level (see Fig. 7). From the model simulations it is possible to elucidate the role played by the physical forcing on the distribution of nutrients and the importance of the food web structure in determining the primary productivity levels of several Mediterranean subregions. The longitudinal and latitudinal oligotrophic gradients in the basin can be explained with different rates of nutrient supply in the euphotic zone determined by the structure of downwelling/upwelling regions of the Mediterranean Sea.

12. A vertical column coupled ERSEM/POM model has succesfully simulated the nutrient cycling and primary production in three different locations (North, Middle, South) of the Adriatic Sea. Interesting anoxic conditions can be achieved in the North due to nutrient diffusion from sediments and oxygen consumption due to remineralization processes.

13. The coupled ERSEM/POM model was used to simulate the coastal-shelf-open ocean primary productivity gradients in the Adriatic Sea. Preliminary analysis of biochemical data (Zavatarelli et al., 1996) gave the phenomenological background for the model set-up. It is the first time that such complex biochemical model is fully coupled to a primitive equation hydrodynamic model which could exploit in the future high horizontal and vertical resolution. The results show well defined primary production peaks ranging from spring to summer in the different subregions of the Adriatic Sea (shelf, shelf slope and deep basin). The results show also the influence of horizontal transport on the distribution of primary producers (Fig.8). The different food web structure and functioning simulated in the three regions of the Adriatic (northern, middle and southern) provide a first evidence for a decreasing red field ratio in the axial direction of the Adriatic, meaning that different levels of phosphorous limitation are active in the Adriatic.

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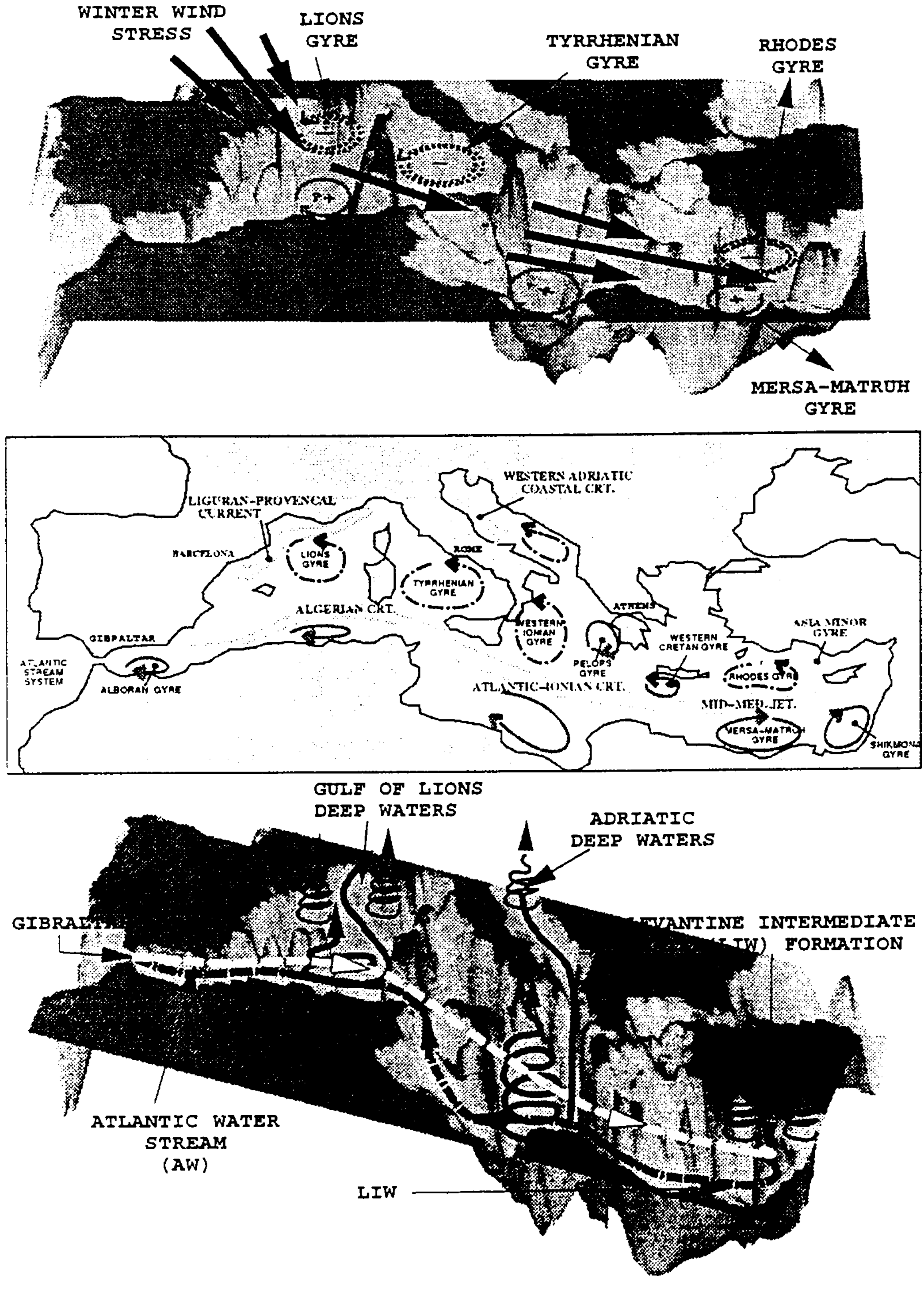

Figure 1. Schematics of vertical and horizontal circulation patterns in the Mediterranean area. The top panel illustrates the relationship between the structure of the wind stress forcing and the subbasin scale gyres. The middle panel shows the gyres and currents nomenclature (redrawn from Roussenov et at., 1995). The bottom panel represents the longitudinal and meridional large scale convective cells induced by water mass transformation processes occurring in the Mediterranean, emanating from the locations indicated by arrows.

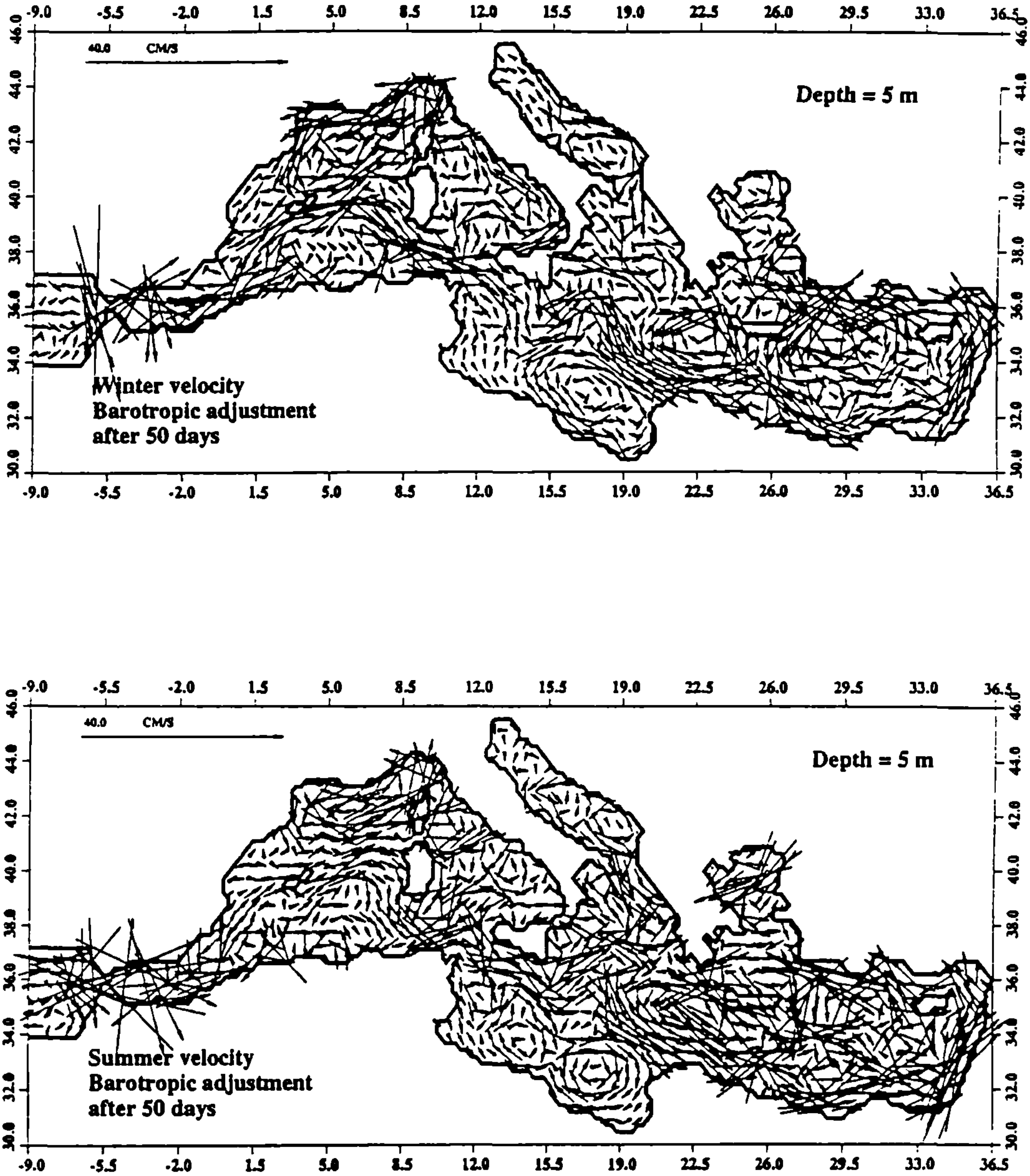

Figure 2

Figure 2. The surface winter and summer circulation calculated from the MODB hydrographic data using the GHER primitive equation model in a diagnostic mode. Wind forcing is imposed to produce the correct barotropic mode (from Brankart and Brasseur, 1996).

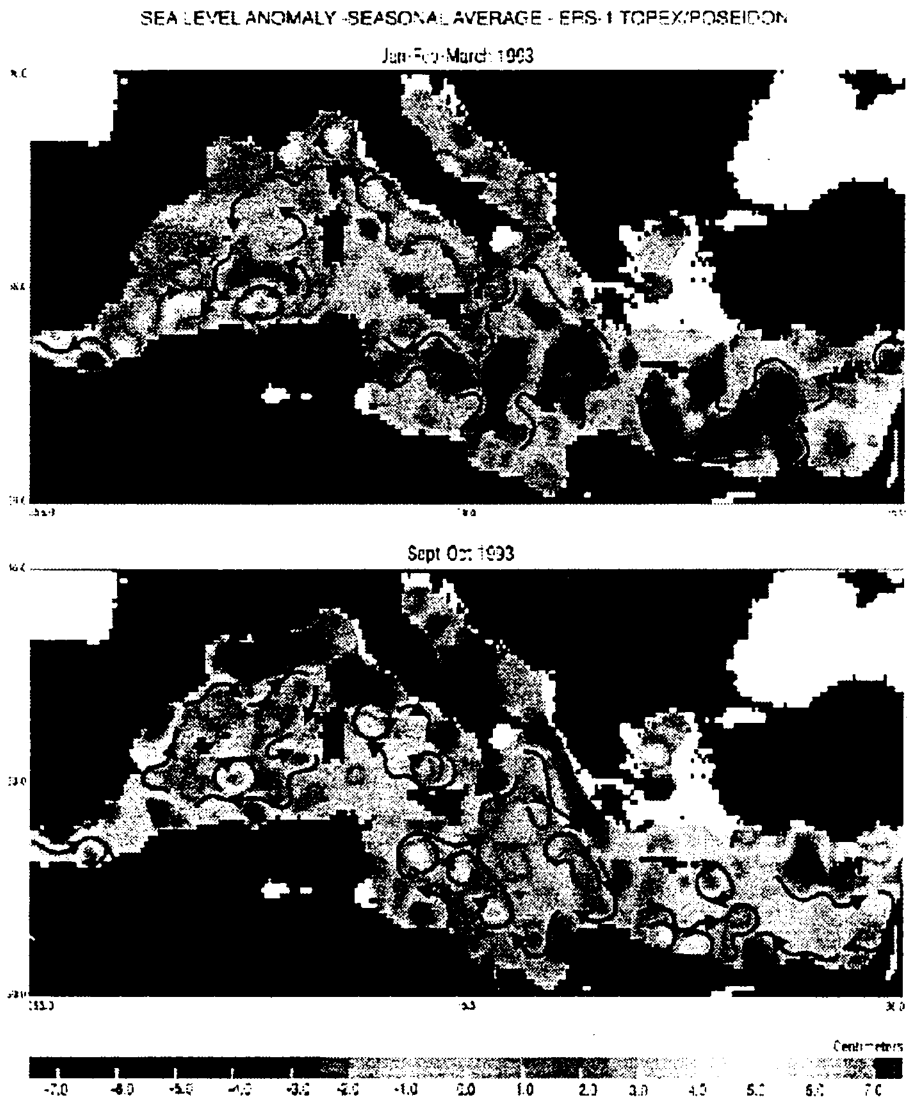

Figure 3. The sea surface height anomaly from Topex/Poseidon and ERS-1 combined analysis. The upper panel shows the anomaly of the January-FebruaryMarch 1993 winter average and the lower the anomaly for the 1993 simmer average of August-September. A two year 1992-1994 mean has been subtracted (from Ayoub et al., 1996).

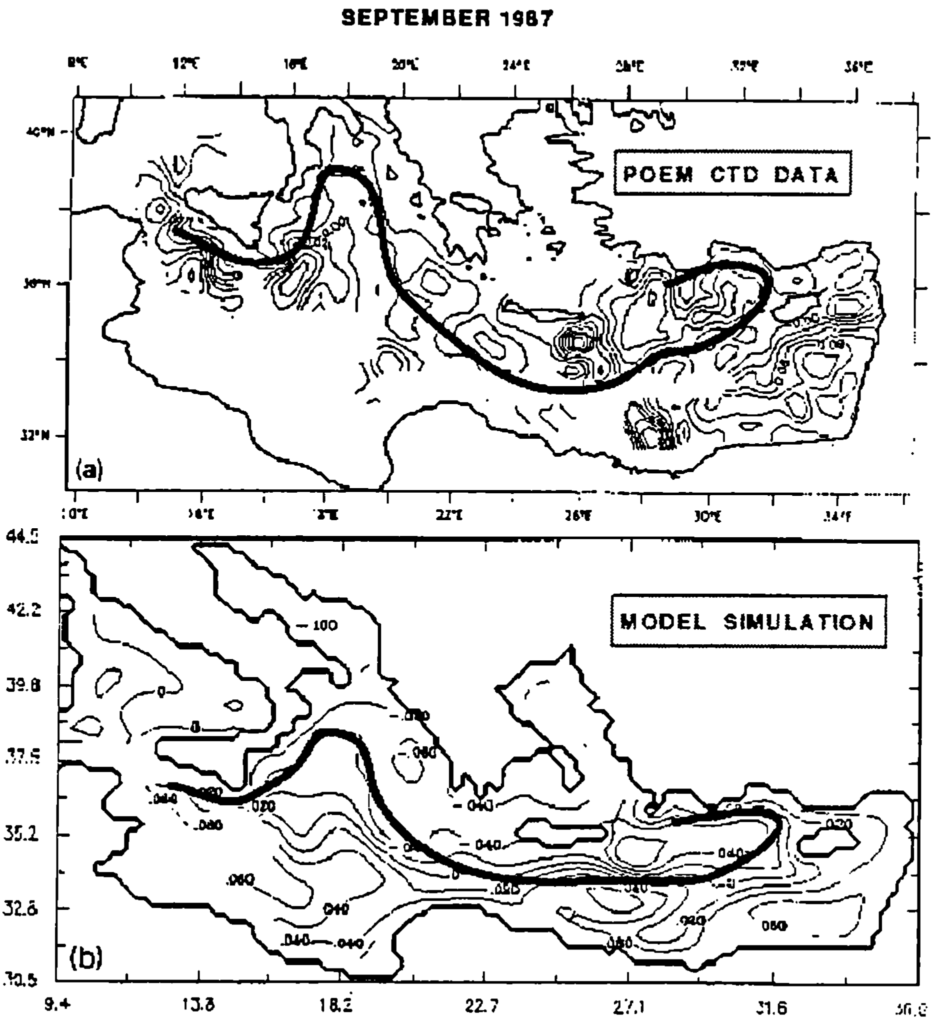

Figure 4. Comparison of model simulation with POEM general circulation survey for September 1987. The pictures represent dynamic height at 5 meters with respect to 450 meters reference level depth. The top picture is taken from Robinson et al. (1991) and the bottom is the monthly average of the model simulation done with monthly mean atmospheric forcing (from Pinardi et al., 1996). Notice that the model has been run "free" from observations for seven years, only atmospheric has been used to identify the seasons.

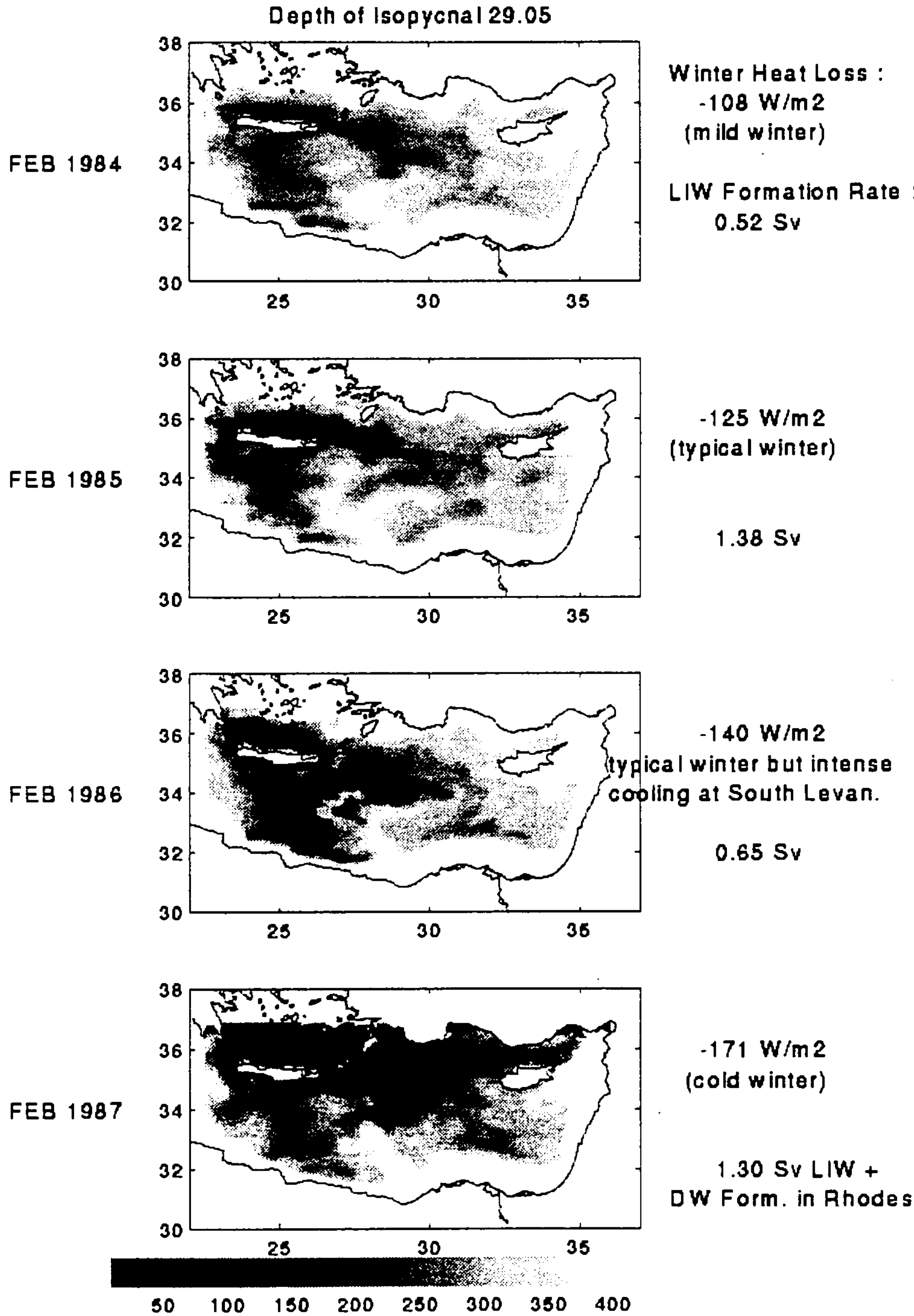

Figure 5. LIW formation simulation experiment. The depth of the 29.05 isopycnal is used to show the area of ventilation of the newly formed LIW waters. The time is always February but for the years 1984-1987.

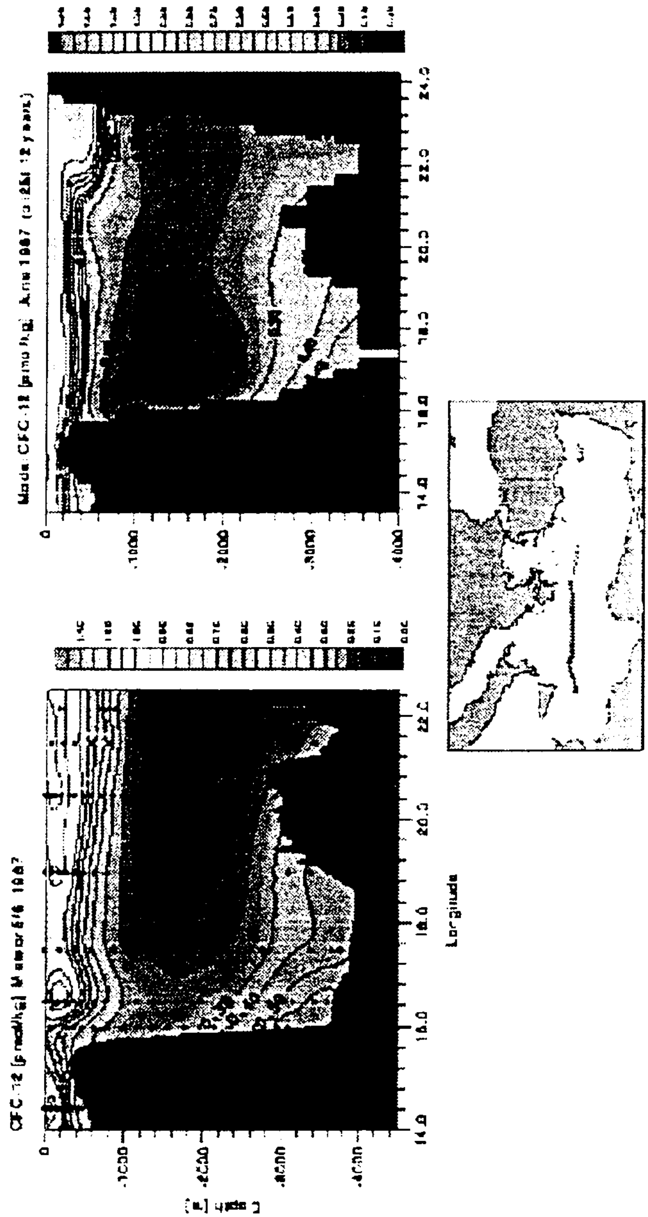

Figure 6. Model data intercomparison experiment for the thermohaline cell of the Mediterranean Sea. The results shown are distributions of observed and simulated CFC-12 concentrations along a section in the middle of the Ionian basin. The color code is the same for observations and model.

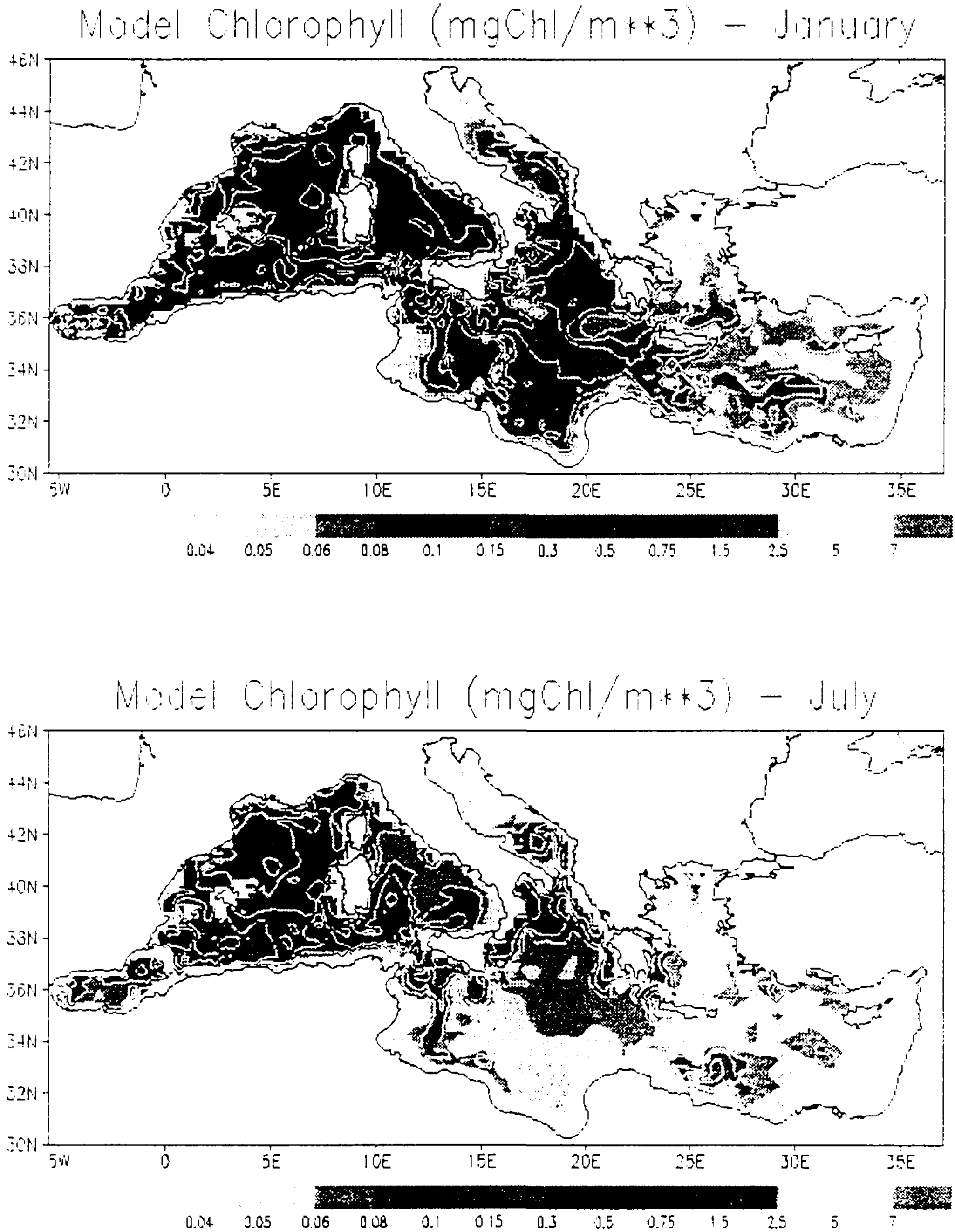

Figure 7. a) Aggregated model chlorophyll concentrations in January and July integrated over the first 20m (mg Chl/m3)

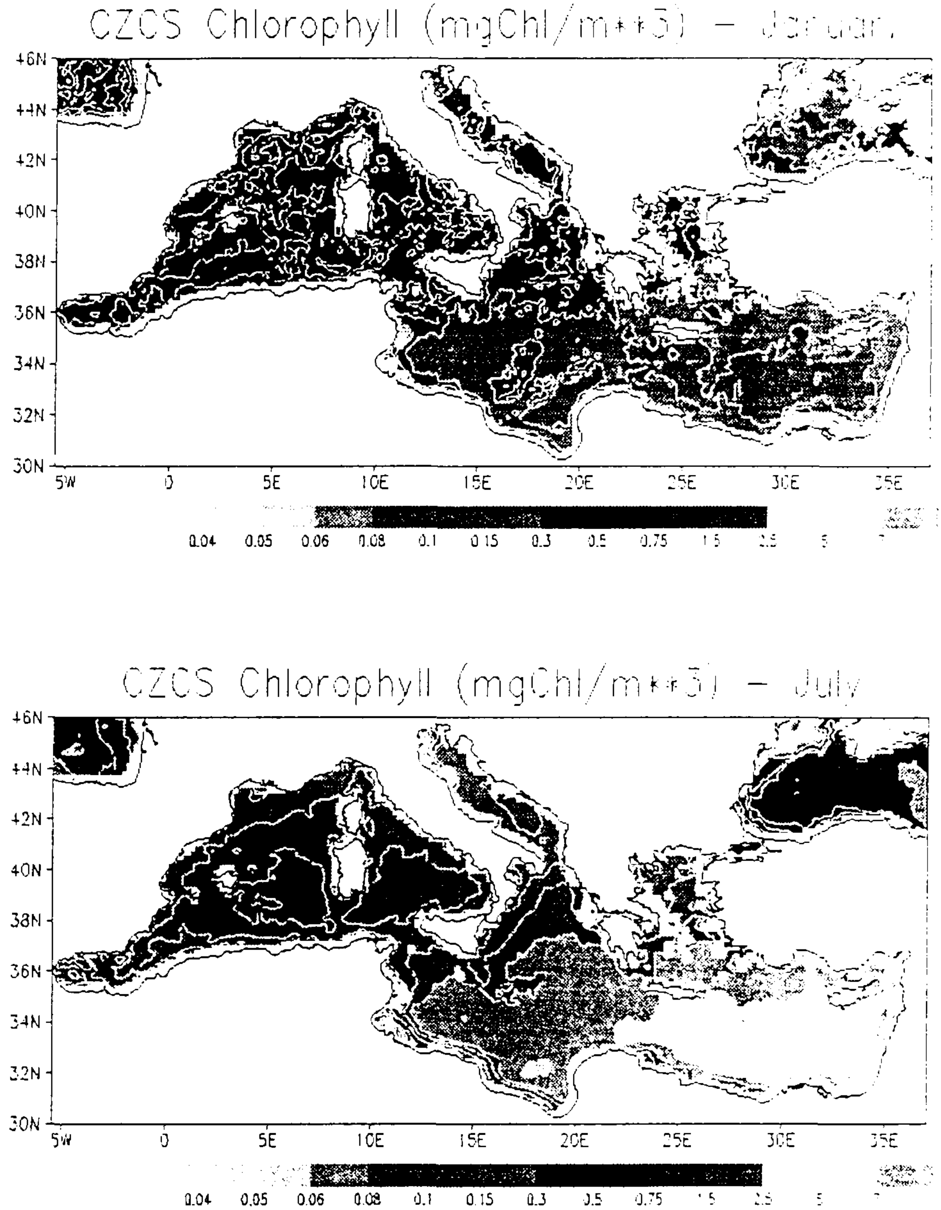

Figure 7. b) Chlorophyll surface concentrations in January and in July obtained from the monthly mean CZCS data(mg Chl/m3)

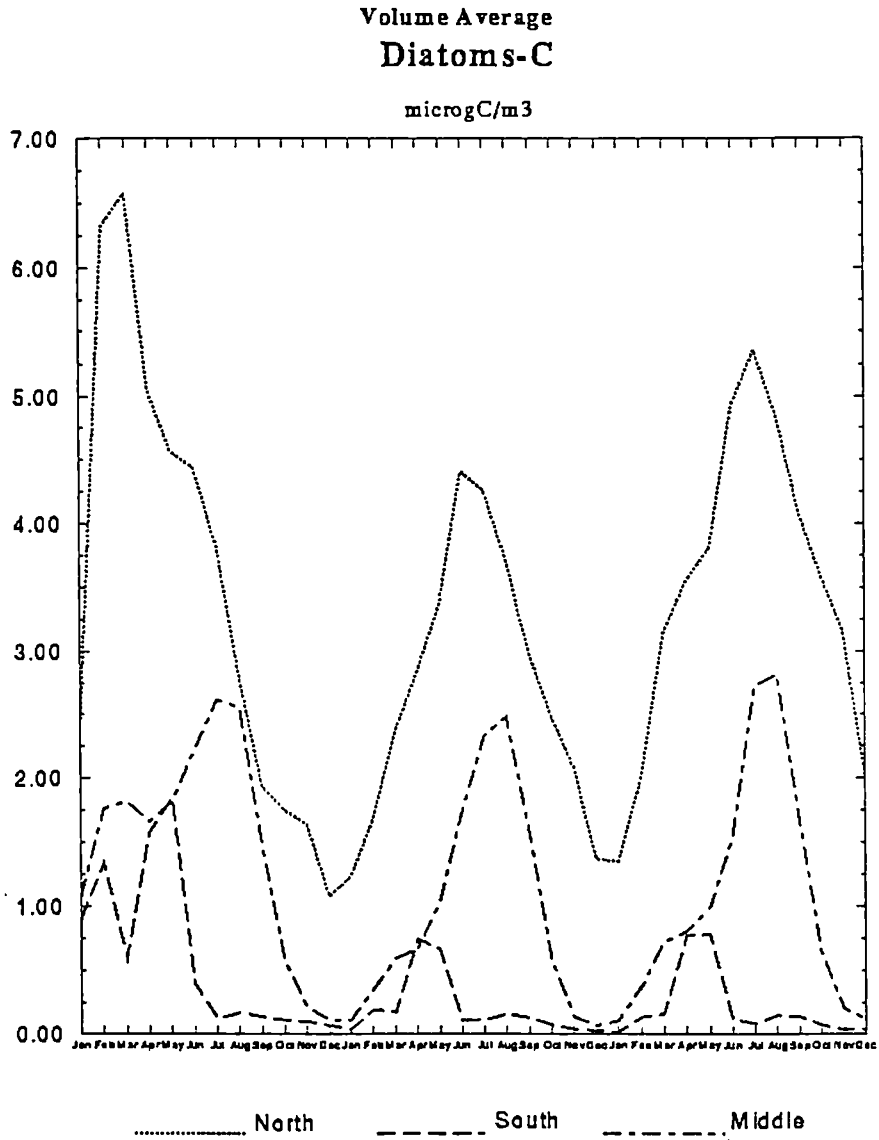

Figure 8 a) Results from the coupled three-dimensional ERSEM/POM model. Volume averaged simulated diatoms concentrations (in mg-C/m3) for the Northern, Central and Southern part of the Adriatic Sea.

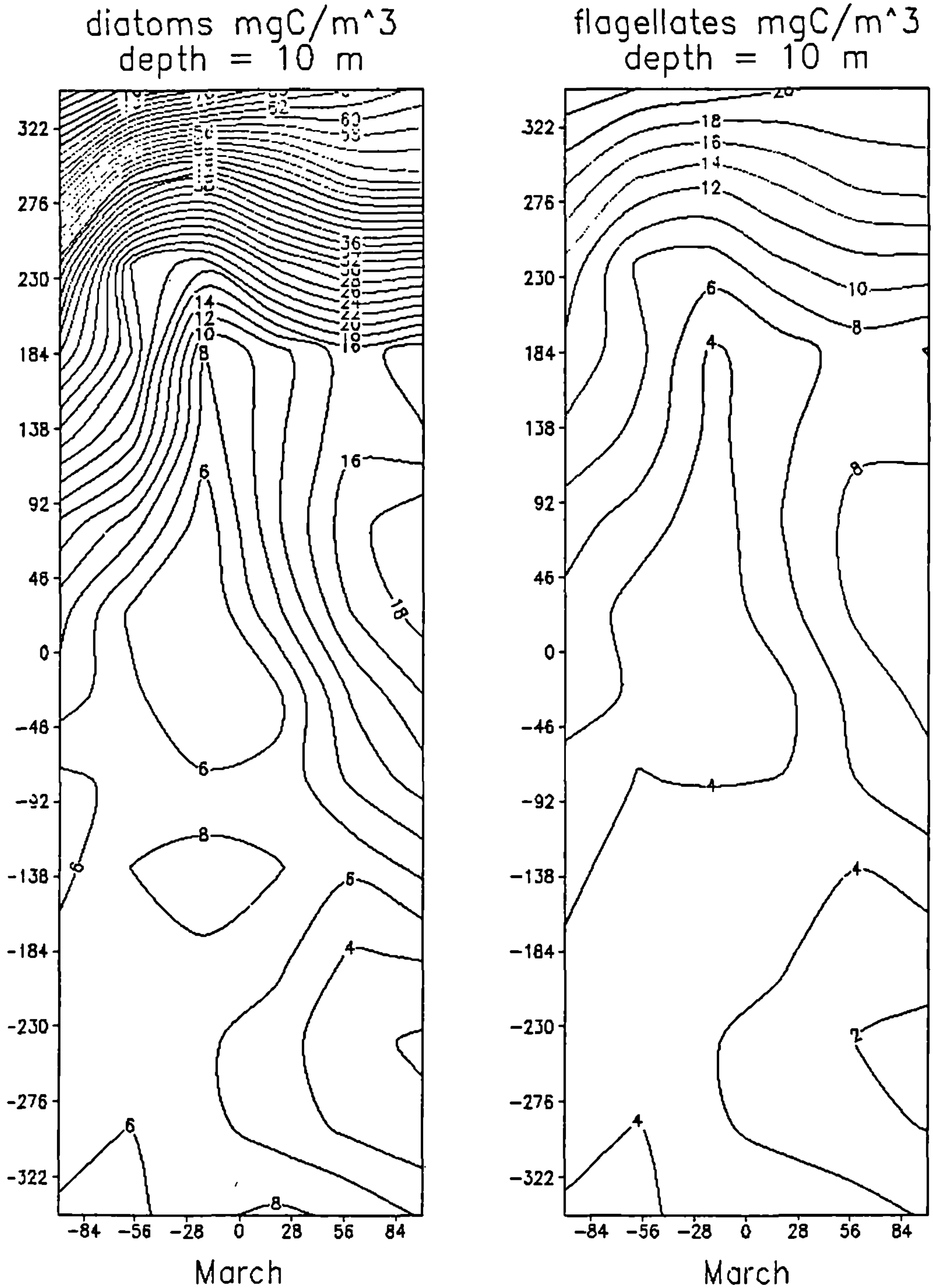

Figure 8 b) Results from the coupled three-dimensional ERSEM/POM model. Simulated horizontal distribution of diatoms and flagellates at the surface and in March.

Mediterranean Targeted Project (MTP) - PELAGOS Project
Contract MAS2-CT93-0059

Synthesis of Final Results

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Contract No.: MAS2-CT93-0059
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Hydrodynamics And Biogeochemical Fluxes In The Straits Of The Cretan Arc (Aegean Sea, Eastern Mediterranean Basin)

ABSTRACT

Seasonal multidisciplinary oceanographic data were collected in the Eastern Mediterranean Sea (South Aegean, northwestern Levantine and southeastern Ionian Seas) within the framework of the CEC/MAST-MTP PELAGOS Project, during 1994-1995. Analysis of the data provide a strong evidence of a new dynamical and hydrological regime over the region and confirm that a multiscaled circulation pattern and complex hydrographic structures prevail in the South Aegean Sea. The general circulation does not show any significant seasonal signal, indicating circulation patterns different than those observed in the past (1986-87), and thus suggesting an interannual variability. A significant and persistent outflow of the Cretan Deep Water (CDW), considerably contributes to the formation of the new, warmer, saltier and denser Deep Water of the Eastern Mediterranean, that displaces the Eastern Mediterranean Deep Water (EMDW) of Adriatic origin, not only in the adjacent open sea regions outside the Aegean Sea, but also in long distances in the Ionian and Levantine Seas, thus making the Cretan Sea the unique source of the new type of EMDW. The CDW outflow takes place through the Kassos and Antikithira Straits, at an approximate mean annual rate of 0.6 Sv, meaning that the volume of the annualy transported deep water from the Cretan Sea to the open sea region of the Eastern Mediterranean Basin represents almost the 1/3 of the total volume of water of the Cretan Sea. Transition Mediterranean Water (TMW) of low salinity, temperature and oxygen and rich in nutrients inflows, from the open sea regions of the Eastern Mediterranean into the South Aegean Sea, predominantly through the Kassos Strait, and fills the intermediate layers (200-600 m) of the entire Cretan Sea, thus drastically changing the chemical conditions of the region. Biomass concentrations, primary production rates, constituent concentrations in suspended particulate matter and total mass fluxes of settling particles support the view that the South Aegean Sea is one of the most oligotrophic regions of the world. Total mass fluxes of settling particles, during summer are the lowest (1-2 $mg.m^{-2}.d^{-1}$) ever registered in the world ocean. The nutrient enrichment of the intermediate layers of the Cretan Sea, mentioned above, is expected that will influence the extremely oligotrophic character of the South Aegean and will have a direct effect on the biology of the region. Dissolved element concentrations are comparable with those reported for other straits of the Mediterranean. Particulate Fe and Mn show unusual concentrations, which is likely to be caused by hydrothermal sources, existing in the South Aegean Sea.

Key Words: Eastern Mediterranean, Aegean Sea, water masses, circulation, fluxes, nutrients, primary production, zooplankton, phytoplankton, dissolved and particulate elements, major and trace elements, settling particles.

INTRODUCTION

The South Aegean Sea, the eastern Ionian and the northwest Levantine Basin consist the central part of the eastern Mediterranean (Figure 1). This dynamically active area presents unique physiographic and hydrodynamical characteristics and plays important role in the regime of the Mediterranean. The physiographic complexity of the Aegean Sea as well as the prevailing typical meteorological conditions have been described elsewhere (see inter alia, Theocharis, 1992). Even though, it is worth to mention that the Cretan Sea constitutes the larger and deepest basin of the south Aegean characterised by an average depth of 1000 dbar and two deeper troughs in the eastern part reaching 2500 dbar. To the northwest the Mirtoan basin reaches 1000 dbar. The Cretan Sea is bounded to the North by the Kiklades Plateau at a depth of 400 dbar and to the South by the Cretan Arc islands. It communicates with the Ionian and the Levantine Seas through a series of six Straits, namely the Cretan Arc Straits, characterised by high relief. The sill depths range for the various straits from 150 to 1000 dbar, as follows: Rhodos Strait (sill depth: 350m, width: 17km), Karpathos Strait (sill depth: 850m, width: 43km), Kassos Strait (sill depth: 1000m, width: 67km), Antikithira Strait (sill depth: 700m, width: 32km), Kithira Strait (sill depth: 160m, width: 33km) and Elafonissos Strait, (sill depth: 180m, width: 11km) (Theocharis *et al.*, 1993). Outside the Straits the sea bed plunges towards the deep basins of the Hellenic Trench (d~3000-4000 dbar).

Exchanges of water and associated material (either diluted or in suspension) between the Aegean Sea and the adjacent open sea regions of the Mediterranean Basin is a scientific research area of major importance, from both the theoretical and pragmatic considerations. Due to their physiographic characteristics the Cretan Sea and the Straits of the Cretan Arc form an important part of the control of the aforementioned exchanges. In particular, the Straits of the Cretan Arc play a key role for fluxes through them and therefore the regions on either side of the straits are dominated by powerful physical and biogeochemical processes. In some respects, the South Aegean Sea along with the northwestern Levantine Sea and the southeastern Ionian Sea have received important research, especially with regard to their water masses and circulation (Malanotte-Rizzoli and Hecht, 1988; Ozsoy *et al.*, 1989; Ozturgut, 1976; Robinson *et al.*, 1991; Theocharis *et al.*, 1992; Theocharis *et al.*, 1993; Theocharis *et. al.*, 1988; Unluata, 1986). Considerable attention has also been given to the chemical and biological oceanography of the above mentioned areas (Souvermezoglou, 1989). These sporadic investigations provided comprehensive data sets, which advanced our knowledge about the region, but in a temporal sense, they provide insufficient temporal resolution to determine the system's response to its long term trends. Since 1986 a number of national and international projects have intensified the research activity in the region. However, all these projects were mainly devoted to the physical oceanographic study of the area, paying less, if not at all, attention to other important scientific disciplines, such as biology and biogeochemistry. Therefore, there have not been enough basin-wide, interdisciplinary oceanographic campaigns, from which integrated assessments of the South Aegean Sea and the Straits of the Cretan Arc, as a marine system, could be made.

The PELAGOS Project was launched in 1993 within the framework of the Mediterranean Targeted Project (MTP) of the Marine Science and Technology Programme (MAST) of the European Union; it associated Greek, British and French Institutions. The MAST contract supporting PELAGOS, started in September 1993, and ended in March 1996. Main objective of the Project was to promote further knowledge, on processes and phenomena of the South Aegean Sea and the Straits of the Cretan Arc, through an interdisciplinary approach, by combining complementary strategic measurements. Detail objectives of the research were: (i) To establish an improved understanding of the hydrodynamics of the South Aegean Sea and in particular across and on either side of the Straits of the Cretan Arc together with its seasonal and interannual variability (ii) To estimate the exchange of water and dissolved and particulate matter between the South Aegean Sea and the adjacent open sea regions of the eastern Mediterranean Basin (Ionian and Levantine Seas), through the Straits of the Cretan Arc (iii) To understand and predict water circulation and transport processes in the South Aegean Sea and particularly in the Straits of the Cretan Arc through the application of numerical models, on different space and time scales, and (iv) To calibrate, test and validate the above numerical models, with laboratory experiments in a small scale physical model of the South Aegean Sea and the results of an intensive field measurement programme.

MATERIALS AND METHODS

The "PELAGOS" Project study area covered the Straits of the Cretan Arc (Eastern Mediterranean Basin) and it was further extended to the overall South Aegean Sea and in addition to the southeastern Ionian Sea and the northwestern Levantine Sea (Figure 1). This means that the Project operated from basin-scale to mesoscale. However, most of the work was concentrated in the Straits of the Cretan Arc. A combination of field observations, numerical modelling and laboratory experiments were used. Data collection was carried out during four seasonal basin-wide oceanographic cruises, supplemented by a number of specialised surveys, which were implemented in the South Aegean Sea (with particular emphasis to the Straits of the Cretan Arc), the northwestern Levantine Sea and the southeastern Ionian Sea (Figure 1), during 1994-1995 (total ship time 109 days). The highly interdisciplinary character of the Project made necessary the collection of a great diversity of oceanographic data. Thus, the PELAGOS field measuring programme involved: (i) CTD measurements and currents by self recording current meters and a ship mounted acoustic Doppler current profiler (ii) analyses of water samples for dissolved oxygen, salinity, nutrients (phosphates, nitrites, nitrates, silicates), trace elements (Fe, Mn, Co, Ni, Cr, Cu, Pb, Cd) and dissolved phases of radioisotopes (^{210}Pb); (iii) analyses of suspended particulate matter for major and trace elements (Al, Ti, Ca, Sr, Li, Mg, K, Si, Fe, Mn, Cu, Ni, Pb, P, S, Ba), POC and PON, supplemented by morphological, textural and mineralogical description; (iv) biological measurements and analyses for primary production, photosynthetic pigments, phytoplankton cell counts and size fractionated estimates and also zooplankton qualitative and quantitative determinations, and (v) analyses of settling material (collected by time-series sediment traps) for total mass major constituents (carbon, silica, carbonates, refractory material), selected trace elements (Al, Fe, Mn, Pb. Zn, Ni, etc.) and radioisotopes (^{210}Pb, ^{210}Po), in conjunction with microscopic characterisation by Scanning Electron Microscope. It is stressed that most of the above mentioned data types were collected for the first time in the study area. A three dimensional diagnostic and a two dimensional two-layered numerical models were developed to investigate water circulation and mass transport features (Matsoukis, 1995, 1996; Skarvelis *et al.*, 1996; Koutitas *et al.*, 1994). In addition, laboratory experiments were conducted in a 5.2m rotating tank, built for the PELAGOS Project (Kotsovinos, 1996a; 1996b). It is obvious that flow exchanges, in the Straits of the Cretan Arc, cannot be seen in a isolated way and separately from the flow phenomena taking place in the remaining portion of the Eastern Mediterranean and therefore the numerical and laboratory models limits were forced in the far field to include either the entire of a large portion or the Eastern Mediterranean Basin (Matsoukis *et al.*, 1996)

RESULTS

Analysis of the data obtained within "PELAGOS", advanced scientific knowledge about the upper thermocline and deeper circulation, and also the hydrological structure and water mass exchanges between the basins, through the Straits of the Cretan Arc (Theocharis *et al.*, 1996a, 1996b, 1996c, 1997; Theodorou *et al.*, 1994, 1996a, 1996b; Balopoulos 1995; Balopoulos *et al.*, 1995; 1996a; 1996b). Furthermore, provided evidence of drastic chemical changes in the waters of the Eastern Mediterranean Sea (Souvermezoglou *et al.*, 1996a, 1996b, 1996c, 1996d) and enabled an assessment of the oligotrophic character of the region (Ignatiades *et al.*, 1995, 1996a, 1996b, 1996c; Gotsis-Skretas *et al.*, 1996; Moraitou-Apostolopoulou *et al.*, 1996). Finally, afforded a deep insight into the biogeochemical variability, processes and fluxes (Price *et al.*, 1995; Varnavas and Balopoulos, 1994; Varnavas, 1996; Varnavas *et al.*, 1996a, 1996b; Voutsinou *et al.*, 1996). This is timely when considering the Cretan Sea as the unique source of the dramatic change recently occurred in the deep thermohaline circulation of the region (Roether *et al.*, 1996; Theocharis *et al.*, 1992; Theocharis *et al.*, 1996a).

Hydrodynamics: Water Masses, Circulation and Fluxes

The water circulation and hydrography of the South Aegean Sea, the Straits of the Cretan Arc and the adjacent open sea regions of the northwestern Levantine Basin and southeastern Ionian Sea have been generally known for some time (see inter alia, Hopkins, 1978, Malanotte-Rizzoli and Hecht, 1988). Three main water masses exist in the eastern Mediterranean Basin, that is, the Modified Atlantic Water (MAW), the Levantine Intermediate Water (LIW) and the Eastern Mediterranean Deep Water (EMDW) (Wust, 1961; Hopkins, 1978; Theocharis *et al.*, 1993; The POEM group, 1992). Apart from the water masses mentioned above, the Aegean receives at its northeastern part a considerable amount of less saline waters (24.0-35.0 psu) of Black Sea (BSW) origin through the Straits of Dardanelles (Theocharis and Georgopoulos, 1992). During the warm period of the year, the warm and saline Levantine Surface Waters (LSW) are also detected, in most of the regions of the eastern Mediterranean (Lacombe and Tchernia, 1960) and are considered to be the product of intense evaporation (Unluata, 1986), of their salinity, at the end of summer, being particularly high (~39.5 psu), especially in the Rhodos area. They enter the Aegean through the eastern Straits of the Cretan Arc. The core properties of the water masses are transformed while they spread to the different regions. Studies on the circulation and water mass exchanges between the various basins have been suggested different patterns (Lacombe *et al.*, 1958; Ozturgut, 1976; Ovchinnikov *et al.* 1976; Hopkins 1978). Recent studies in the frame of the international collaborative POEM programme in 1986-1987 revealed the new concepts of the eastern Mediterranean circulation that focus upon the existence of three scales of motions, that is the basin, sub-basin and mesoscale (Theocharis *et al.*, 1993).

Analysis of the PELAGOS field data combined with outputs from numerical and laboratory modelling experiments, confirmed that a multiple scale circulation pattern prevails in the region and revealed new phenomenology. Confinement of the motions within the basins' boundaries leads to basin scale, sub-basin scale and mesoscale dynamical structures with dimensions ranging from 100-250 km to some 15-20 km. Specifically, two cyclonic gyres, two anticyclonic eddies and other smaller scale structures, interconnected by currents and jets, variable in space and time populate the south Aegean Sea (Figure 2). Some of the features in the entire area under study are permanent, others seem transitional or recurrent. These observations are partially in agreement with earlier ones, since these circulations show significant changes and different scales of variability compared to the 1986-87 patterns. The present situation is characterised by mesoscale spatial and temporal variability, not necessarily seasonal, that modifies the flows through the Straits of the Cretan Arc (Papageorgiou and Theocharis, 1996). This complex circulation pattern determines the water mass distribution and transport, that also considerably differ from earlier regimes (Theocharis *et al.*, 1996a). The present hydrological structure is complex and variable (Theodorou *et al.*, 1996a). The dynamical and hydrological state at the Straits of the Cretan Arc are highly variable and do not present qualitatively any significant seasonality. Topographic control is evident on the flows through the straits.

More specifically, the general situation concerning the water mass pathways and the dynamics in the area under study is the following: Modified Atlantic Water (MAW) coming from the western Ionian and carried within the surface and/or sub-surface layers by Mid Mediterranean Jet (MMJ) and/or MMJ branches, reaches and enters the Cretan Sea through mainly Antikithira and occasionally Kassos Strait. The former inflow is confirmed by long-term current meter data collected in the surface layer of the Antikithira Strait, which indicate a maximum annual current speed of the order of 40 $cm.sec^{-1}$ and a mean annual speed of around 10 $cm.sec^{-1}$. The surface Black Sea Water (BSW) flows from the north and west Aegean and reaches the Mirtoan Sea. Its influence can be sometimes traced up to the Kitherian straits (Theocharis, 1995). This transport is also reflected in numerical modelling predictions (Figure 3). During summer, the surface Black Sea waters flow to the south following a route along the main axis of the Aegean Sea (Skarvelis *et al.*, 1996).

The Asia Minor Current (AMC) carries, by two branches, towards the south Aegean the surface saline waters of Levantine origin that extend over large areas of the Cretan Sea (Figure 2). The branch through the Rhodos Strait is more intense of its maximum speed reaching 80 $cm.sec^{-1}$ and the mean around 35 $cm.sec^{-1}$. Maximum current speeds of the second branch, through the Karpathos Strait, where the circulation appears to be more variable, are also high, of the maximum annual reaching 64 $cm.sec^{-1}$ and the mean annual 22 $cm.sec^{-1}$. This input promotes formation of high saline intermediate waters within the Cretan Sea. The seasonal variability concerning the salinity of Cretan Intermediate Water (CIW) can be attributed to the participation of MAW to the formation processes. However, it is also detected less saline intermediate water formation within the Basin, as well as intermediate waters of deeper characteristics having their origin in the Mirtoan Basin. Thus, the intermediate water masses are represented at different areas in the Θ-S diagram (Theocharis, et al., 1996c). Consequently, it is clearly distinguished the typical Levantine Intermediate Water (LIW) that enters the Aegean through the straits both from the Levantine and the Ionian Seas, as well as, the more saline CIW and the colder and denser Mirtoan Intermediate Water (MIW). Interestingly, the latter flows southwards and, being enough dense, sinks in the deep troughs of the western Cretan Sea, thus probably contributing to the formation of the new very dense deep water in the Cretan Sea. The existence of a well-defined intermediate "minimum temperature and salinity" Transition Mediterranean Water (TMW) layer in the south Aegean Sea consists the new important structural feature. It enters the south Aegean through mainly the Kassos and Antikithira Straits, with very low speeds (mean annual speed around 5 $cm.sec^{-1}$), and then following two opposite paths, fills the intermediate layers of the entire Basin.

Recently, the Cretan Deep Water (CDW) considerably contributes to the formation of the new, warmer, saltier and denser Deep Water of the Eastern Mediterranean, that displaces the Eastern Mediterranean Deep Water (EMDW) of Adriatic origin, not only in the adjacent open sea regions outside the Aegean Sea, but also in long distances in the Ionian and Levantine Seas. This makes the Cretan Sea the unique source of the new type of EMDW. Analysis of self recording current meter data, for a full year, suggested that a deep persistent outflow of Cretan Deep Water (CDW) (sigma-theta > 29.2), with a total yearly mean of ~0.6 Sv, occurs, through the Antikithira and Kassos Straits, at depths below 400 m and 500 m, respectively (Figure 4). Maximum current speeds at both straits are of the same order of magnitude (~ 45$cm.sec^{-1}$) but mean current speeds at the Kassos Strait are much higher than at the Antikithira Strait. Based on the data collected near bottom of these stations and also on the water property distributions along these straits, the CDW fluxes were calculated (Table I). In both straits it is observed that CDW outflow has a seasonal signal with a total maximum outflow (~0.8 Sv) in mid to late spring (April-June) right after the water formation processes have passed and therefore the outflow is very active. The lower (~0.3 Sv) values occur in mid to late fall (October-December) before the onset of the preconditioning phase and the restart of the new water formation cycle. The yearly mean transport of the CDW is estimated 0.6 Sv (Kontoyiannis et al., 1996). This means, that the volume of the annualy transported deep water, through the Kassos and Antikithira Straits, represents almost the 2/3 of the total deep water mass of the Cretan Sea. The increased activity of the Straits is attributed to the new hydrological regime in the area (increase of density in deep layers by 0.15).

Further analysis of the current data suggest that the upper 400-500 meters of the Cretan Arc Straits flow regime can be divided into three dynamically different regions: (i) The Rhodes and Karpathos Straits, affected by the Asia Minor Current which exhibits a weakly varying inflow transport of ~2.1 Sv in fall (September 1994) and 1.7 Sv in summer (June 1995), (ii) The Antikithira and Kithira Straits, influenced by the Mirtoan/West Cretan Cyclone which in the upper 400 m drives a net outflow but with seasonally varying values, stronger (~2.5 Sv) in early winter (December 1994) and weaker (~0.8 Sv) in summer/early fall. (June 1995, September

Table I. Cretan Deep Water ($\sigma_\theta > 29.2$) Outflow Transports (Sv)

STRAIT	PERIODS			
	APRIL-JUNE	JULY-SEPTEMBER	OCTOBER-DECEMBER	JANUARY-MARCH
ANTIKITHIRA	0.38	0.34	0.19	0.26
KASSOS	0.45	0.40	0.16	0.24
TOTAL	0.83	0.74	0.35	0.50
YEARLY MEAN TRANSPORT: 0.6 Sv				

1994), (iii) The Kassos Strait with complex and highly varying flow structure and transportgoverned by the interaction between the East Cretan Cyclone, the Ierapetra anticyclone and the westward extension of the Rhodes Gyre. In the latter strait a net inflow of ~0.7 Sv was observed in fall and early winter (September 1994 and December 1994) and a net outflow of 0.5 Sv in early spring and summer (March 1994, June 1994 and June 1995). The analysis of the variability of the currents relative to the mean, revealed that 44% of the standardised variance can be explained by the first three significant EOFs (Tsimplis *et al.*, 1996). This coherent part of the variability is related to the events longer than 20 days as well as to events with periods around 5 days. The spatial characteristics of the EOFs are obscured by the effect of topography on the flows. The strong correlation between the surface currents at the Antikithira Strait and the surface current at the eastern Straits suggests that probably some of the coherent part of the variability could be due to atmospheric forcing.

Analysis of ERS-1 SAR images obtained in the late summer of 1994 over the Rhodos and Karpathos Straits revealed the presence of both internal wave groups (linear and solitary) and isolated waveforms (Velegrakis *et al.*, 1996). Both categories of waves showed different types of modulation (slick and dynamical); this diversity is indicative of the complexity of the processes responsible for the generation of these internal waveforms. The internal waves identified did not show a common area of generation and/or a preference for a direction of propagation, as it is mostly the case in other areas (e.g., the western European shelf). Moreover, there has been no evidence to suggest the presence of packets of wave groups (or isolated waveforms) in the study area. This may be explained by the fact that Rhodes and Eastern Karpathos Straits are characterised by very small tidal currents (if compared with the overall flow), and there is very little evidence for internal tidal oscillation of significant amplitude. The extremely irregular topography of the area (characterised by bottom topography of high relief and the presence of numerous islands) combined with strong flows and the complex stratification in the upper part of the water column provide a multitude of internal wave generation points. These oscillations may play an important role in the primary productivity of the area as they may cause significant mixing close to the seasonal pycnocline, thus allowing the supply of nutrients from the deeper layers to reach the surface.

Finally, it is identified the densest water mass of the south Aegean, namely Mirtoan Deep Water (MDW), almost isolated in the deep and bottom layers of the Mirtoan Basin. The new hydrological vertical structure of the Cretan Sea, that is characterised by the superposition of three and/or four basic water masses, presents significant thermohaline gradients developed between them. This structure has limited the depth of the convective mixing down to about 250 dbar, while in the past it was stated that homogenisation of the entire water column was possible (Theocharis *et al.*, 1996a; Theocharis *et al.*, 1997). This also indicates that the "new" CDW has its origin in the surrounding areas, as the Mirtoan Basin and/or the Kiklades Plateau. The persistence of the basic circulation elements and the vertical hydrological structure throughout the observation period indicate that a rather stable regime is reached. However, in the context of the drastic changes occurred during the last seven years in the deep thermohaline cell of the eastern Mediterranean, it would be considered this regime transitional.

The two-dimensional two-layered numerical model produces, under real time surface wind and atmospheric pressure forcing, the basic hydrological features observed in the area of Cretan straits during PELAGOS expeditions and most of the transient or persistent gyres in the Cretan Sea. In addition, it produces current magnitudes statistically comparable to the measured ones. The observed drastic differences of the current magnitude between surface and deep water are well reproduced. The model further produces mass exchange rates both in terms of magnitude and direction across the various sections of the straits which seem realistic and comparable to those deduced by the integration of local current measurements across the cross sections of the straits. The temporal variability of the currents produced by this numerical model deduced from the current spectral analysis, contain basic periodicities justified by the Coriolis effects and the searching modes of the Aegean and East Mediterranean basins (Skarvelis *et al.*, 1996). The laboratory (stratified, rotating) model shows a stable bottom outflow from Kassos and from Antikithira strait, and very weak and unstable middle and bottom outflows from Karpathos. This important observation is in agreement with the PELAGOS field measurements. The above essential difference of these two straits regarding their outflow characteristics, is, according to the laboratory observations, due to the geometry of straits and the Coriolis effect (tendency of the outflow to turn right).

Biogeochemistry: Variability and fluxes

The hydrological structure observed in the Cretan Sea has a strong chemical signature. Since the TMW is considered "old" water, and therefore is "nutrients rich and oxygen poor", drastically changes the chemical conditions of the intermediate layers of the entire South Aegean Sea. Thus, nutrient concentrations measured in the intermediate layers of the Cretan Sea, during the PELAGOS Project, are the highest measured in the same region (increase of nitrates by ~2.5 μM, of phosphates by ~0.05 μM and of silicates by ~2.5 μM), on various occasions, over the last ten years (Souvermezoglou *et al.*, 1996a; 1996b, 1996c). Conversely, decrease of oxygen concentrations, in this layer, is remarkable, reaching 0.8ml/l (35 μM). Figure 5 indicates the vertical distribution of silicates along a west-east section in the Cretan Sea, clearly showing the nutrient rich intermediate layer water mass entering the South Aegean Sea, mainly through the Kassos Strait. Similar patterns are seen for all the other nutrient and dissolved oxygen distributions during all the PELAGOS Cruises.

Oxygen and nutrients concentrations and their exchanges through the Straits of the Cretan Arc are affected by the mesoscale circulation patterns prevailing in the region. Low oxygen and high nutrients concentrations which lead to more intense biological activity are found in the centre of cyclonic gyres (Souvermezoglou, 1996). Nutrient concentrations in the intermediate and deep waters of the Cretan Sea are lower than nutrient concentrations in the intermediate and deep waters of the adjacent open sea regions of the Eastern Mediterranean Sea. In contrast, oxygen concentrations in the aforementioned water layers are higher in the Cretan Sea than in the adjacent basins, confirming earlier investigations (Souvermezoglou, 1989; Salihoglu *et al.*, 1990). One of the principal reasons for this, is the limited exchange of water masses between the Cretan Sea and the adjoining basins (Souvermezoglou, 1996). As the newly formed CDW is "nutrient poor - oxygen rich", results to an important increase of oxygen and decrease of nutrients, in the deep and bottom layers, of the waters outside the Cretan Sea. In general it is not observed any significant seasonal signal on the distribution of chemical parameters in question, except some variability of the surface and intermediate layer. These layers are found richer in nutrients and poorer in oxygen in late winter - early spring (March 1994) than in late summer - early autumn (September 1994).

Assessment of the budgets of dissolved oxygen and nutrients (nitrates, phosphates, silicates) through major Straits of the Cretan Arc (Antikithira, Kassos and Karpathos Straits), suggests that generally, in the Antikithira and Kassos Straits a net export of oxygen and nutrients (nitrates, phosphates, silicates) from the Cretan Sea to the open sea waters of the Mediterranean Sea (southeastern Ionian, northwestern Levantine) is observed throughout the year (Table II). In the Antikithira Strait, maximum net exports of the above mentioned dissolved elements are seen in winter (January 1995) and minimum during summer (June 1994). In the Kassos Strait, maximum oxygen net exports take place in summer (June 1994) and maximum net exports of nutrients in autumn (September) and winter (January). During all seasons, net exports of all the above mentioned dissolved elements, through the Kassos Strait are much higher than those seen for the Antikithira Strait. Finally, in the Karpathos Strait, a net import of oxygen and nutrients is observed in March and September, of the maximum values seen during the former period.

TABLE II. Horizontal Fluxes of Dissolved Oxygen (10^{10}xtons/year), Nitrates (10^{5}xtons/year), Phosphates (10^{4}xtons/year) and Silicates (10^{5}xtons/year) through major Straits of the Cretan Arc (Antikithira, Kassos and Karpathos Straits), during March 1994 to January 1995.

PARAMETER	MARCH 1994			JUNE 1994			SEPTEMBER 1994			JANUARY 1995		
	IN (+)	OUT (-)	NET	IN (+)	OUT (-)	NET	IN (+)	OUT (-)	NET	IN (+)	OUT (-)	NET
ANTIKITHIRA Strait												
Dis. Oxygen	1.32	4.68	3.36 (-)	4.26	6.32	2.06 (-)	1.39	7.76	6.37 (-)	1.36	11.93	10.57 (-)
Nitrates	0.70	4.76	4.06 (-)	2.64	4.30	1.66 (-)	0.67	4.79	4.12 (-)	1.13	8.56	7.43 (-)
Phosphates	0.65	3.86	3.21 (-)	2.23	3.96	1.73 (-)	0.61	4.56	3.95 (-)	0.88	4.89	4.01 (-)
Silicates	1.24	7.21	5.97 (-)	6.15	10.76	4.61 (-)	1.69	11.58	9.89 (-)	2.98	22.64	19.66 (-)
KASSOS Strait												
Diss. Oxygen	7.13	16.7	9.57 (-)	3.48	17.56	14.08 (-)	11.76	20.63	8.87 (-)	-	-	-
Nitrates	6.76	13.00	6.24 (-)	3.57	6.86	3.29 (-)	8.00	15.40	7.40 (-)	3.17	12.52	9.35 (-)
Phosphates	3.58	7.50	3.92 (-)	3.29	7.37	4.08 (-)	6.81	18.28	11.47 (-)	2.38	8.90	6.52 (-)
Silicates	11.80	22.16	10.36 (-)	8.65	21.03	12.38 (-)	20.51	39.65	19.14 (-)	10.01	38.35	28.34 (-)
KARPATHOS Strait												
Diss. Oxygen	29.1	0	29.10 (+)				14.92	5.51	9.41 (+)			
Nitrates	24.5	0	24.50 (+)				9.72	3.71	6.01 (+)			
Phosphates	20.5	0	20.50 (+)				12.10	3.15	8.95 (+)			
Silicates	48.05	0	48.05 (+)				25.04	8.12	16.92 (+)			

Due to the low nutrient concentrations in the Cretan Sea, mentioned above, all the examined biological parameters, throughout the study area and sampling depths, indicate very low values. Thus, the measured mean annual concentrations of chlorophyll-á, (19.15 mg.m^{-2}), phytoplankton (1.54x10^7cells.m^{-3}), primary production rates (5.74 mgC.$h^{-1}m^{-2}$), zooplankton (4x10^2 m^{-3}), dry weight (29.4 mg.m^{-3}) and the underwater penetration of the blue light (480 nm) from 140 to 250 m depth confirm that the study area is one of the most oligotrophic regions in the world (Ignatiades et al., 1996c). Estimates for the fractionated pigments clearly show the quantitative importance of picoplankton in the oligotrophic waters of South Aegean Sea. Mean relative contributions of pico-fractions (total of 0.4 and 0.2 ìm) were 46% for chl-*á*, 75% for chl-*b* and for 55% for chl-*c*.

The aforementioned values of total chlorophyll biomass and phytoplankton abundance are generally in agreement with corresponding values reported by Mihailov (1964) for the Sea of Crete; Mihailov and Denisenko (1963), Denisenko (1964), Blasco (1974), Ignatiades (1976), Gotsis-Skretas and Satsmadjis (1984), for the Aegean Sea; Rabitti *et al.* (1994) for the Ionian Sea, Kimor *et al.* (1987) for the offshore Israeli waters, Gotsis-Skretas *et al.* (1993) and Pagou and Gotsis-Skretas (1990) for the S. Aegean and Ionian Sea. The very low values of primary production found in the study area are comparable to those reported by Becacos-Kontos (1968) for the outer Saronikos Gulf (Central Aegean Sea), and to the photosynthetic rates (range: 0.69-9.79 mgC.m^{-2}.h^{-1}) obtained by Berman *et al.* (1984) for the Eastern Mediterranean. The vertical gradient of the three wave lengths measured (red, green, blue) show the greater attenuation of red and green in relation to blue light, and these data may characterise the sea water of the study area as "blue" oceanic water (Owens et al., 1993). The estimated levels of zooplankton are similar to those (83 to 3.8x10^2 ind.m^{-3}) given by Pancucci - Papadopoulou *et al.* (1992) from samples collected from the eastern Mediterranean (east to Crete) at the 0-150m layer and also by Moraitou-Apostolopoulou, (1972, 1985). Mazzocchi *et al.* (in press) found the density of zooplankton (for the 0 - 300 m layer) to reach maximum values in the Sicily Channel (200 ind.m^{-3}) and lowest in the Cretan Sea (45 ind.m^{-3}). As far as, the overall composition of the zooplankton is concerned, it shows a dominance of copepods throughout the year (annual range: 50.8-95.16%; annual mean: 72.69%), which is in agreement with the results reported by Kimor and Berdugo (1967), Moraitou-Apostolopoulou (1972, 1985) and Pancucci-Papadopoulou *et al.* (1992) for the Eastern Mediterranean.

Total Chl-a and fractionated pigments fluxes though major Straits of the Cretan Arc (Table III), suggest that in the Antikithira Strait there is a net biomass export towards the southeast Ionian Sea throughout the year, which, for total chl-a, ranges between 554-2.800 tons/year for the upper 100m and 204-1.200 tons/year for the upper 50m. In the Kassos Strait it is observed a net biomass export towards the northwestern Levantine Sea, during summer and winter, and a net biomass import towards the South Aegean Sea, during early spring and autumn. The net biomass export is much higher in summer than in winter and, for total chl-a reaches 1.662 tons/year for the upper 100m and 289 tons/year for the upper 50m. All the above mentioned values represent minimum fluxes, since biological sampling took place in the central parts of the straits and it can be expected that biomass concentrations closer to the coasts are higher.

Table III. Seasonal chlorophyll biomass budgets (tons/year) through major Straits of the Cretan Arc, during 1994

ANTIKITHIRA Strait													
BIOMASS	DEPTH	MARCH			JUNE			SEPTEMBER			DECEMBER		
(μg/l)	m	IN (+)	OUT (-)	NET (-)	IN (+)	OUT (-)	NET (-)	IN (+)	OUT (-)	NET (-)	IN (+)	OUT (-)	NET (-)
Total Chl-a	0-100	707	3.452	2.745	311	865	554	407	1.469	1.062	806	3.609	2.803
Total Chl-a	0-50	240	1.440	1.200	75	279	204	82	366	284	279	1.233	954
Chl-a (0.8 μm)	0-50	149	895	746	35	130	95	32	144	112	131	581	450
Chl-a (0.4 μm)	0-50	49	293	244	29	109	80	23	104	81	64	284	220
Chl-a (0.2 μm)	0-50	42	253	211	21	79	58	27	121	94	99	438	339
Chl-b (0.8 μm)	0-50	17	100	83	3	12	9	18	81	63	18	82	63
Chl-b (0.4 μm)	0-50	29	175	146	5	18	13	9	39	30	34	150	116
Chl-b (0.2 μm)	0-50	35	210	175	7	26	19	10	46	36	36	158	122
KASSOS Strait													
BIOMASS	DEPTH	MARCH			JUNE			SEPTEMBER			DECEMBER		
(μg/l)	m	IN (+)	OUT (-)	NET (+)	IN (+)	OUT (-)	NET (-)	IN (+)	OUT (-)	NET (+)	IN (+)	OUT (-)	NET (-)
Total Chl-a	0-100	2.706	346	1.730	50	1.712	1.662	3.463	369	3.094	556	560	4
Total Chl-a	0-50	924	543	381	0	289	289	156	52	102	302	421	119
Chl-a (0.8 μm)	0-50	619	364	255	0	155	155	112	38	74	199	278	79
Chl-a (0.4 μm)	0-50	159	94	65	0	87	87	22	7	14	66	91	25
Chl-a (0.2 μm)	0-50	144	85	59	0	44	44	21	7	14	104	145	41
Chl-b (0.8 μm)	0-50	6	4	3	0	42	42	427	144	283	24	33	9
Chl-b (0.4 μm)	0-50	26	16	11	0	35	35	270	91	179	27	37	11
Chl-b (0.2 μm)	0-50	27	17	12	0	29	29	341	115	226	23	32	9

Furthermore, examination of the various biological parameters indicate the existence of significant seasonal fluctuations, with phytoplankton, chlorophyll-a and primary production maxima occurring in spring and winter and minima in summer and autumn. Zooplankton also shows a clear seasonal pattern, with highest abundance in autumn and winter, declining to minimal population in spring and summer. A seasonal succession of phytoplankton and zooplankton taxa was also recorded. Diatoms and "other groups", mainly cryptophytes, prevailed in spring, dinoflagellates predominated in summer, coccolithophores was the first dominant group in autumn, whereas the algal biomass in winter was dominated by diatoms and "other groups". Copepoda dominated absolutely the mesozooplankton assemblages at all zooplankton samples (with an annual mean contribution of 72.69%), with the chaetognaths to follow (annual mean: 7.62%). The variations in phytoplankton and zooplankton both quantitatively and qualitatively, are considered usual and present similarities with other oligotrophic open sea waters. Therefore, it seems that since the waters with increased nutrients concentrations remain below the euphotic zone throughout the year, they do not apparently affect the biology of the area. However, the distribution of biogenous elements Ca, Si, P, and S show a pattern in surface waters, of the eastern and western parts of the Cretan Sea, that correlates well with chlorophyll-a concentrations and also relate to the presence of cyclonic eddies in the upper waters of these areas, which presumably induce nutrient upwelling and increased productivity (Figure 6).

Concentrations, distribution, behaviour and chemical speciation of dissolved and particulate trace metals concerning the Western Mediterranean Sea from the Straits of Gibraltar, the adjacent Atlantic Ocean, the Alboran Sea and the Straits of Sicily have been reported by Morley *et al.*, (1990); Zhang and Wollast, (1990); Achterberg *et al.*, (1993); Chou and Wollast, (1993); Martin *et al.*, (1993); Morley and Burton, (1992), etc. Morley and Burton (1993) estimated fluxes of Cd, Co, Cu, Mn, Ni, Pb and Zn expressed as inputs to the W. Mediterranean. Much less attention has been given to the eastern part of the Mediterranean Sea. Before the PELAGOS Project the information about trace metal concentration in Eastern Mediterranean seawater remained sparce. Reviewing the existing literature it can be found few data concerning the Aegean Sea: Rozhanskaya (1973) reported Mn, Cu and Zn concentrations for eight surface seawater samples collected from the Aegean Sea. Distributions of Cd, Cu, Zn, As, Hg, Ni, Cr, Fe, Pb in Aegean Sea seawater samples have been reported by Fukai and Huynh-Ngoc, (1976); Romanov *et al.*, (1977); Huynh-Ngoc and Fukai, (1978); Aubert *et al.*, (1980); Scoullos and Dassenakis, (1981); (1983); Ferrara *et al.*, (1990). Some results concerning coastal environments characterised by the presence of pollution of anthropogenic origin (Fytianos and Vassilikiotis, 1983) are also available. Generally, in the Mediterranean Sea trace metal surface concentrations are relatively high compared to surface concentrations in the Atlantic or Pacific Oceans and at depths > 300 m the concentrations appear quite homogenous (Bethoux *et al.*, 1990).

Dissolved trace elements measured within PELAGOS (Table IV) are in good agreement with those reported by Martin *et al.* (1993) for the Sicily Channel and by Tankere et al. (1994) for the Straits of Gibraltar and Sicily. The mean values reported by Yoon *et al.* (1994) for the west Mediterranean are lower. On the contrary, dissolved metal values reported for the Aegean Sea 10-20 years ago (Rozhanskaya, 1973; Fukai and Huynh-Ngoc, 1976; Romanov *et al.*, 1977; Huynh-Ngoc and Fukai, 1978; Scoullos and Dassenakis, 1981; 1983; Aubert *et al.*, 1980) are much higher. In the instance of Fe, values measured in the study area are generally high and comparable with those recorded for the coastal area of the northwest Aegean Sea, which receives the discharge from large river systems (Thermaikos Gulf; Fytianos *et al.*, 1986). Some metals (Co, Cd) show generally very small fluctuations in their spatial variability. On the contrary, other elements such as Mn have a large range of values, even within a short distance between water levels of the same station. Dissolved Cd shows a clear nutrient-like behaviour at the Antikithira Strait and the open waters of the Cretan Sea, similar to that described for major oceans, having a positive correlation with PO_4. It is concluded that biological activity plays an important role in the recycling of Cd. Likewise, Pb being transported to the South Aegean Sea from the Black Sea, its behaviour at the Antikithira Strait shows similarities with that of Cd, showing a strong positive correlation with PO_4, despite the fact that lead has an anthropogenic and aeolian origin.

Generally, the distribution pattern of the trace element concentrations show for the whole study area maxima values during summer and lowest ones during winter. This is true for Cd and Pb and to a lesser degree for Co. Copper and Ni show in the Western Straits their highest concentrations during the winter period, while the remaining study area follows the above mentioned tendency, with higher values observed in summer. Iron present maximum values in autumn for the whole study area. Overall, for all sampling periods, all elements exhibit their lowest average values in the Cretan Sea. The Eastern Straits depict maximum mean values for most trace elements analysed, while maximum mean values are observed for Cu and Cr in the Western Straits. Most of the dissolved trace elements analysed have almost a similar vertical distribution pattern characterised by three distinguished maxima, that is one at the subsurface, mainly of biogenic origin, a second one at the depth of 500-600m and a third one in deeper waters (around 1100m), related to the CDW (Varnavas *et al.*, 1996a, 1996b).

Table IV: Ranges and mean values of dissolved trace element concentrations (nM)

Period	Values	Cu	Cd	Pb	Ni	Co	Mn	Cr	Fe
		nM							
WESTERN STRAITS									
June 1994	maximum	7.03	1.601	9.218	10.39	1.069	11.38	3.27	39.57
	minimum	1.31	0.089	1.641	3.46	0.204	0.33	0.38	3.94
	mean	3.51	0.719	3.582	4.82	0.632	2.51	1.78	17.50
September 1994	maximum	9.24	0.560	5.840	12.37	0.831	29.12	3.25	225.50
	minimum	0.60	0.044	0.555	0.70	0.068	0.86	0.15	4.83
	mean	3.06	0.196	2.364	5.58	0.323	7.69	1.22	40.71
December 1994	maximum	15.21	0.605	4.778	15.33	1.018	22.75	3.85	81.83
	minimum	0.35	0.071	0.227	0.55	0.102	1.18	0.19	10.39
	mean	4.81	0.206	1.969	4.56	0.274	7.75	0.87	31.04
CRETAN SEA									
June 1994	maximum	9.52	1.477	7.239	15.98	1.103	6.10	3.85	55.87
	minimum	0.80	0.534	0.140	3.87	0.102	0.56	0.38	13.25
	mean	4.32	0.818	3.294	8.10	0.390	3.45	1.67	25.86
September 1994	maximum	5.60	0.356	4.194	8.52	0.764	11.38	5.94	71.62
	minimum	0.63	0.036	0.338	1.86	0.068	0.18	0.15	6.45
	mean	2.69	0.162	2.006	4.92	0.207	5.67	1.14	30.34
December 1994	maximum	5.02	0.463	3.528	5.28	0.492	13.09	3.27	50.14
	minimum	1.62	0.071	0.386	2.79	0.068	0.31	0.19	9.49
	mean	2.77	0.172	1.213	3.84	0.168	3.73	0.65	21.45
EASTERN STRAITS									
September 1994	maximum	6.66	1.334	8.456	12.77	1.917	16.44	2.77	90.60
	minimum	1.67	0.071	0.999	4.02	0.102	1.66	0.19	16.29
	mean	4.24	0.374	3.854	6.99	0.550	7.78	1.18	54.82
December 1994	maximum	5.00	1.103	4.440	6.13	1.137	16.75	4.23	58.73
	minimum	0.16	0.018	0.236	0.68	0.068	0.17	0.15	11.10
	mean	2.30	0.184	1.795	3.28	0.217	4.05	0.77	28.41

Spatial variability in the composition of the particulate matter is strongly influenced by the water circulation. The BSW flowing from north to south transports particulate matter to the southern Aegean Sea rich in Fe, Pb and Cu. This particulate matter is identified at the Mirtoan Basin and the Western Cretan Sea. Extraordinary metal enrichments in particulate form at this area are considered to result from the cyclonic water movements reported both in autumn and winter in this area. Particulate Mn, Cu and Pb maxima observed in the upper part of the water column are related to inflow of high salinity Levantine waters having high velocity at the upper waters. Despite the oligotrophic character of the Southern Aegean Sea biological processes play an important role in the spatial and temporal element variability in the water column. Significant particulate metal enrichments at 50m and 100m depth coincide with maxima in chlorophyll and therefore have a strong biogenic affiliation (Varnavas *et al.*, 1996a, 1996b).

Overall biogenic Si is depleted in the bottom waters particularly in the deepest basin, implying that biogenic debris do not reach the seafloor in the deeper zones. This is in consistence with the dissolution of Si at the sediment-water interface and its behaviour in the oceanic water column. Exceptionally, in the Western Cretan Margin biogenic Si is enriched as a result of resuspension of seafloor sediments. This process is confirmed both by the particulate Al increase observed in the bottom waters and the direction of Si gradient which is parallel to the direction of the steep seafloor slope. In winter the spatial distribution pattern of biogenic Si suggests input to the Cretan Sea through the Kassos Strait. Overall biogenic Si is associated with the less saline TMW, suggesting that its inflow in the South Aegean Sea contributes significantly in the production transport of biogenic Si. Using biogenic Sr as tracer the carbonate variability in the Southern Aegean Sea is deduced. It is demonstrated that in autumn biogenic carbonate is distinctly enriched in the intermediate zone of the central part of the study area, where biogenic Si is depleted. Significant enrichments in dissolved Mn, Fe, Ni, Cu and Pb and depletions in their particulate form are encountered both in autumn and in winter at 200m and 500m and they coincide with an oxygen minimum. The above variations are associated with the TMW inflowing the Southern Aegean Sea through the Antikithira Strait being characterised by low salinity low oxygen and high concentrations of nutrients. Reduction of Mn in sediments and its diffusion in the bottom waters along with the associated metals (i.e., Ni, Pb, Cu) is considered as a main process responsible for the enrichment of their dissolved form and the depletion of their particulate form in the oxygen minimum layers. A greater degree of dissolution of Mn, Fe and associated metals is encountered in the Western Cretan Straits than in the remaining areas as the oxygen minimum layers (Varnavas *et al.*, 1996a, 1996b).

Virtually all the elements in the SPM are to varying degrees partitioned between two or more constituent phases. The only exception to this is Al, which is assumed to be held almost exclusively (>>90%) in terrigenous aluminosilicates. Aluminium concentrations were found to be extremely low, much lower than in other areas examined within the MTP Project, especially the northwestern Mediterranean and the Adriatic Sea. Concentrations often of less than 1 μgAl/l seawater are generally found in oceanic waters. For instance they can be compared to concentrations recorded (Price and Doff, 1984) for the eastern and central parts of the Atlantic, but are much lower than those reported in the Sargasso Sea (Sholkovitz *et al*, 1994) which can reach concentrations of ~10 μg/l. The depth distributions of particulate Al examined as a west-east transect for March and September show exceptionally low concentrations in the uppermost 50-150m of water where concentrations are <1 μg/l and in many instances <0.2 μg/l (Price et al., 1995). Such low concentrations imply little direct terrigenous input from rivers and the atmosphere. Perhaps the only exception to this is seen in the extreme western and eastern stations where there may be influence from either the atmosphere or Black Sea waters or both. Concentrations of Al in intermediate waters show a marked increase at most stations and often show isolated peaks between 100-200m. The underlying waters show even higher concentrations (1-2 μg/l) with a well defined high between 500-700m (Figure 7). The deepest waters are generally of lower Al concentration and do not show evidence of sediment resuspension from the bottom of the basin, except at station (~200m depth) in the Antikithira strait. The overall increase of Al concentrations, at least to 500-700m, implies sediment shedding from the sides of the basin, and this is most evident at the bottom of certain water masses, especially in water immediately above the CDW and water of upper slope depths (200m).

POC, PON show extremely small surface water POC concentrations of 30-70 μg/l and conform to the very low primary production. At depth POC concentrations are reduced by respiration toPOC, PON show extremely small surface water POC concentrations of 30-70 μg/l and conform to the very low primary production. At depth POC concentrations are reduced by respiration to10-15 μl. PON shows an overall similar trend to POC, but POC/PON ratios show a general decrease at depth from ratios of ~7 as observed in surface waters. The pattern of total particulate Fe for most of the water column tends to follow Al, because most of its concentration is intimately bound within the structure of aluminosilicates The distribution of particulate Fe and Mn show unusual concentration of Fe relacting to Al and is likely to be caused by an additional supply over that of terrigenous input, such as the atmosphere or hydrothermal sources (Price 1996). The existence of such hydrothermal sources in the Cretan Sea have been reported by other investigators (Varnavas, 1989; Varnavas et al., 1993).

Surface levels of dissolved ^{210}Pb show activities of 6-7 dpm/100l (10-11.7 mBq/10l). This activity is dictated by atmospheric input to the upper water column. In late summer (September 1994), surface water dissolved ^{210}Pb is appreciably lower, 4dpm/100l (Price 1996). Ritchie and Shimmield (1991) have shown a latitudinal dependency of the atmospheric input of ^{210}Pb. The results here also imply a seasonal change (atmospheric input) in the Cretan Sea. The lower activity in September compared with late winter (March 1994) is consistent with a lower washout during the dry season of late summer. The activity of dissolved ^{210}Pb in subsurface waters decrease which may be caused by a lower influence of atmospheric lead or by increased extraction onto particles. Surface water particulate ^{210}Pb activities of 0.2-0.35 dpm/100l (0.33-0.58 mBq/10l) occur in late winter (March 1994), at most regions of the study area, and below increase to maximum values of ~5dpm/100l at 150m. A similar surface and depth pattern was observed in late summer (September 1994), although the increase between 0-150m was less marked and at Kassos Strit there is an actual decrease in ^{210}Pb at 150m compared with the surface. Surface particulate ^{210}Pb activities in the Atlantic Ocean tend to be higher than the Cretan Sea (Ritchie and Shimmield, 1991), and some areas show higher activities in the upper waters (0-150) than below (400-500m). Much of this patterning is probably related to water structure and a high biological/biogeochemical activity. The subsurface ^{210}Pb activity (150m) in the Cretan Sea could imply a greater scavenging in March than September, which is consistent with what is known of the standing crop. Further higher particulate ^{210}Pb activity at 150m compared with that in surface waters could be connected with MnO_x precipitation below the photic zone. However, unless ^{226}Ra profiles are known it is not possible to equate the profiles of dissolved and particulate ^{210}Pb during the above mentioned periods, with respect to ^{210}Pb production and atmospheric inputs and deficits due to scavenging. ^{226}Ra in most oceanographic studies is usually determined by Ra/Si measurements of a specified ocean water (Bacon *et al*, 1976). Unfortunately the Ra/Si relationship is not established for the Mediterranean Sea.

Table V: Particulate elemental budgets, in Major Cretan Arc Straits (10^3 tons y^{-1})

ANTIKITHIRA STRAIT								
	March				September			
Element	CDW Outflux (-)	Total Influx (+)	Total Outflux (-)	Net	CDW Outflux (-)	Total Influx (+)	Total Outflux (-)	Net
Al	8.26	11.40	8.49	2.92 (+)	10.70	15.80	15.40	0.49 (+)
Fe	6.15	11.50	6.32	0.52 (+)	7.95	13.80	16.60	2.84 (-)
Ca	29.00	111.00	30.20	79.80 (+)	38.20	66.40	67.40	0.65 (-)
Mn	0.33	0.38	0.33	0.05 (+)	0.55	0.58	0.74	0.17 (-)
KASSOS STRAIT								
	March				September			
Al	56.60	0	118.00	118.00 (-)	12.30	14.30	14.20	0.10 (+)
Fe	28.10	0	115.00	115.00 (-)	12.95	15.50	14.70	0.80 (-)
Ca	198.00	0	537.00	537.00 (-)	43.30	85.80	53.70	32.10 (-)_
Mn	1.72	0	3.38	3.38 (-)	0.36	0.50	0.96	0.46 (-)

Major elemental budgets (tonnes y^{-1}) for outgoing and ingoing waters and also the net budget and the CDW budgets, are shown in Table V. Elemental budgets through the Antikithira Strait for March and September 1994 are very small, except for Ca in March 1994. Ca is the dominant element present in the waters and the increased productivity in March may be the cause of the large net inflow budget. In September 1994 the net budget for all elements is well balanced and this may be caused by the use of current measurements rather than computing flow from geostrophic balances. Discharge of elements into the Ionian Sea are minute compared with the discharge through the Strait of Otranto. For instance 0.6 x 10^5 tonnes y^{-1} enters the Ionian Sea via LIW waters emanating from the Adriatic sea (B. Price, CEC/MAST-MTP EUROMARGE-AS Project; Final Report, 1996). Transport of Al, Fe, Ca and Mn through the Kassos Strait is much higher, especially in March 1994, whereas in September 1994 there appears to be well balanced influxes and outfluxes of elements with Mn showing a modest net outflow. Transport of elements in the deep waters (CDW) is much higher in March, particularly Ca which may relate to higher Ca productivity at this time.

Sediment trap experiments were implemented on either side of the Antikithira Strait for a full year. Total mass fluxes registered, span over several orders of magnitude. Total mass fluxes of 1-2 $mg.m^{-2}.d^{-1}$ recorded during the summer 1994 at the internal (Aegean) and external (Ionian) sides of the Antikithira Strait are the lowest mass fluxes ever registered in the world ocean, a feature that directly relates to the strong oligotrophy of this part of the Mediterranean (Heussner *et al.*, 1996a). Chemical and microscopic composition of the settling material collected on either sides of the strait indicate a common and mixed origin of particles (terrigenous and biogenic); despite the strong oligotrophic character and the depths investigated (880 - 1345 m), particles exhibited a significant biogenic signature marked by the high content in carbonate and sometimes in opal due to coccolitophorids and diatom production respectively. This character is confirmed by SEM observations and biomarkers analyses, especially carbohydrates. The more sophisticated isotopic analyses of lead further revealed an anthropogenic atmospheric contribution which "polluted" the South Aegean waters. Organic carbon fluxes were quite low. The lithogenic fraction (including clays and minerals) predominated in the near-bottom traps (on either side), closely followed by carbonate (Figure 8).

The one year survey allowed to demonstrate a clear seasonal quantitative and qualitative evolution relating particle flux variations with the general climatic conditions in the Mediterranean Sea (Heussner *et al.*, 1996b). Two sequences were distinguished: a summer "biogenic" low flux period and a winter/spring high flux period. This latter was also marked by a strong phytoplanktonic bloom in February (cf. the important increase of the glucidic fraction). During this specific flux event, the Cretan Arc system behaved, unexpectedly, similarly to the Mid-Adriatic eutrophic environment in terms of energetic transfer to depth. This feature should lead to define the concept of trophic level not only on the nutrient availability and phytoplankton composition, but also on the quantity of energetic particulate fluxes. In terms of quality, an oligotrophic environment can produce pulses of energetic matter which, under favourable hydrodynamical conditions, can be transferred to depth and feed the benthic ecosystem.

Table VI: Annual downward fluxes (mmol $m^{-2}.y^{-1}$) for each element studied and trap location.

Element	Aegean 500 m	Aegean 965 m	Ionian 800 m	Ionian 1265 m
Al	35.982	19.949	14.339	23.982
Fe	10.398	59.493	45.763	72.093
Mn	838	3.900	1.880	3.990
Cu	44	89	53	121
Ni	53	194	81	167
Pb	16	39	17	35
Zn	159	251	198	238

Using the mass fluxes for each collection period and the sediment composition data, the mean annual downward flux of each trace metals studied was calculated (Table VI), which range between 36000 mmol $m^{-2}.y^{-1}$ for Al to 16 mmol $m^{-2}.y^{-1}$ for Pb. These values are an order of magnitude higher than those reported by Kremling and Streu (1993) for the North Atlantic and by Jickells *et al.* (1984) for the Sargasso Sea, despite the current study area being extremely oligotrophic in nature. The large fluxes experienced by these traps is an indication that the material entering them does not come in entirety from downward fallout (Price 1996).

CONCLUSIONS

(i) A multiscaled circulation pattern and complex hydrographic structures prevail in the South Aegean Sea, where a succession of cyclones and anticyclones dominate throughout the year.

(ii) The general circulation does not show any significant seasonal signal. However, it is different from the circulations observed in the past (1986-1990), suggesting an interannual variability.

(iii) Major surface and intermediate water inflow (~2.0-2.5 Sv) occurs through the Rhodes and Karpathos Straits, as a result of which, Levantine origin waters have an important influence on the surface and subsurface layers of the southeastern Aegean Sea.

(iv) The Cretan Sea has a significant and continuous contribution to the deep (and bottom) layers of the Eastern Mediterranean. The newly formed Cretan Deep Water outflows at an approximate mean annual rate of ~0.6 Sv, through the Kassos and Antikithira Straits. The volume of the annualy transported deep water represents almost to 1/3 of the total volume of water of the Cretan Sea. The increased activity of the Straits is attributed to the new hydrological structure in the area (increase of density in deep layers by 0.15).

(v) Biomass concentrations, primary production rates, constituent concentrations in suspended particulate matter and fluxes of settling particles confirm that the South Aegean Sea is one of the most oligotrophic areas in the world.

(vi) A new intermediate "minimum salinity, temperature and oxygen, rich in nutrients", layer, which is defined as the TMW (Transition Water between LIW-EMDW), is extended in the entire Cretan Sea and it is expected to influence the extremely oligotrophic character of the South Aegean Sea.

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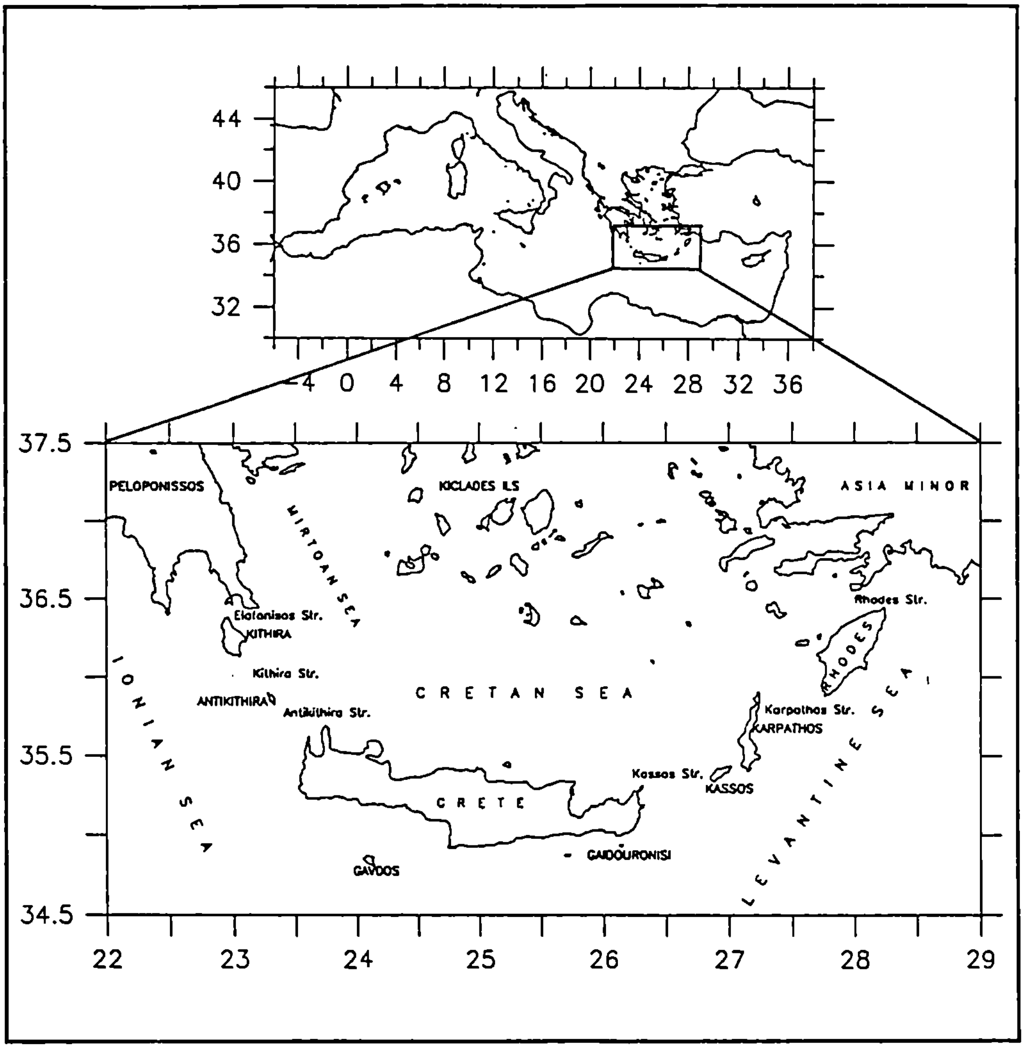

Figure 1 - The study area

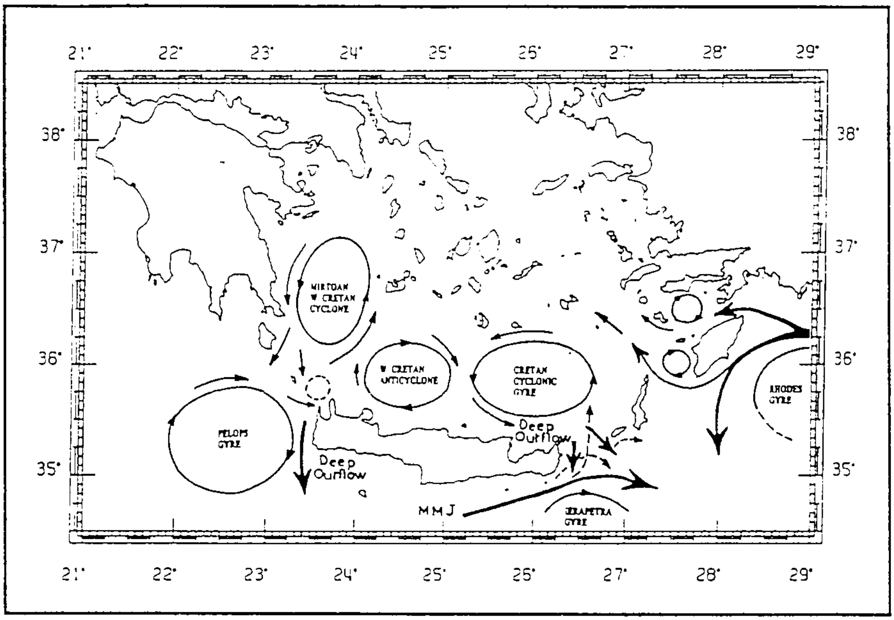

Figure 2 - Main circulation features of the Cretan Sea (Synthesis from the PELAGOS Cruises).

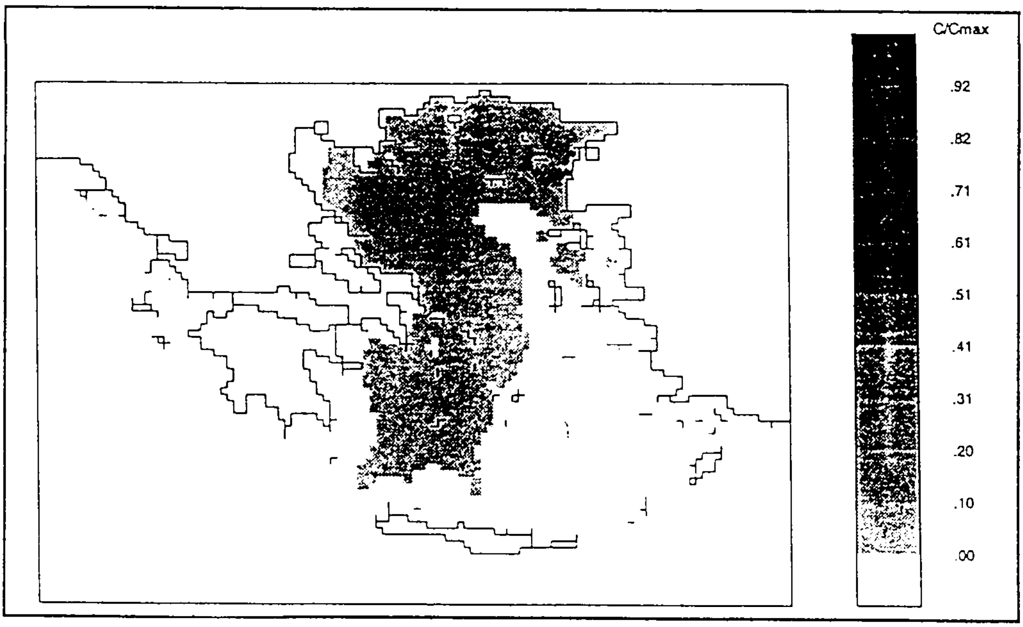

Figure 3 - Transport of material originating from the Black Sea, during winter (14 January 1995), as predicted by a two-dimensional two-layered model, forced with real wind and pressure data.

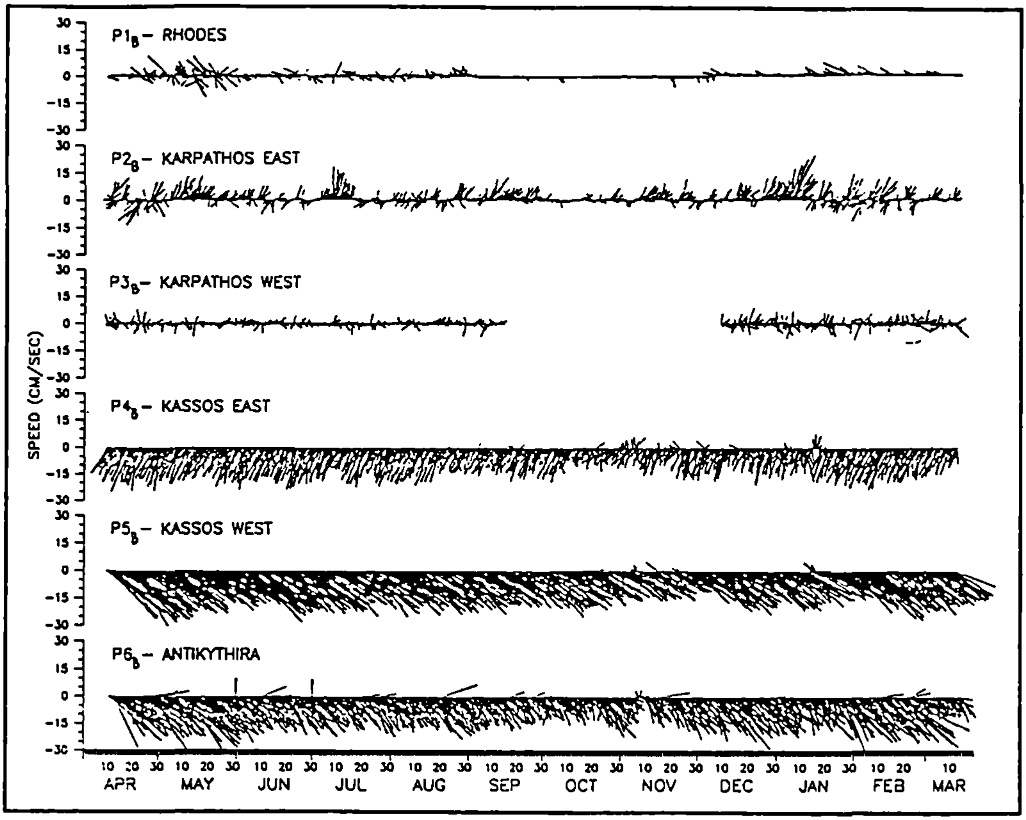

Figure 4 - Half-hourly stick diagrams of bottom currents (50 m off the sea bottom) at six mooring sites within the Cretan Arc Straits.

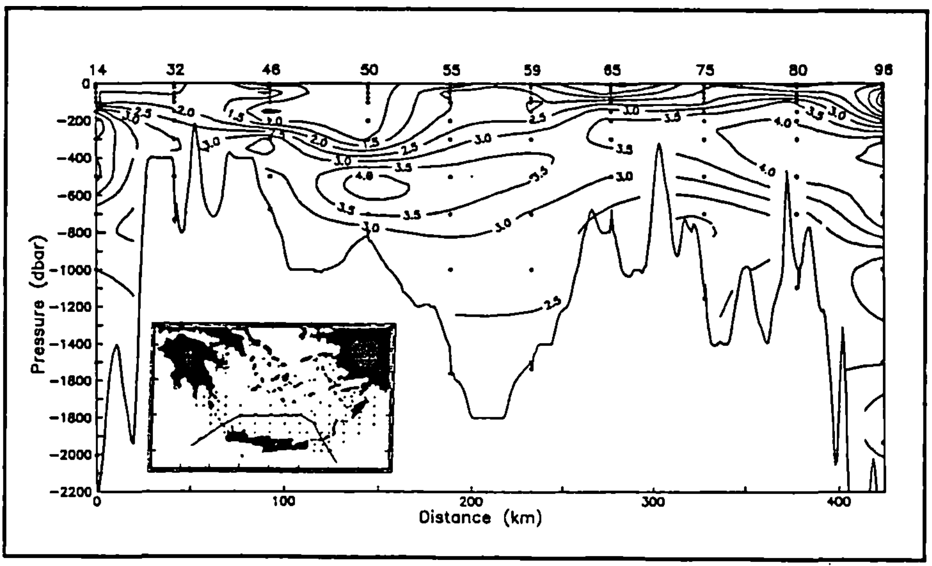

Figure 5 - Vertical distribution of silicates(μM) along a West-east section (36° N longitude) in the Cretan Sea, during the PELAGOS-IV Cruise (January 1995).

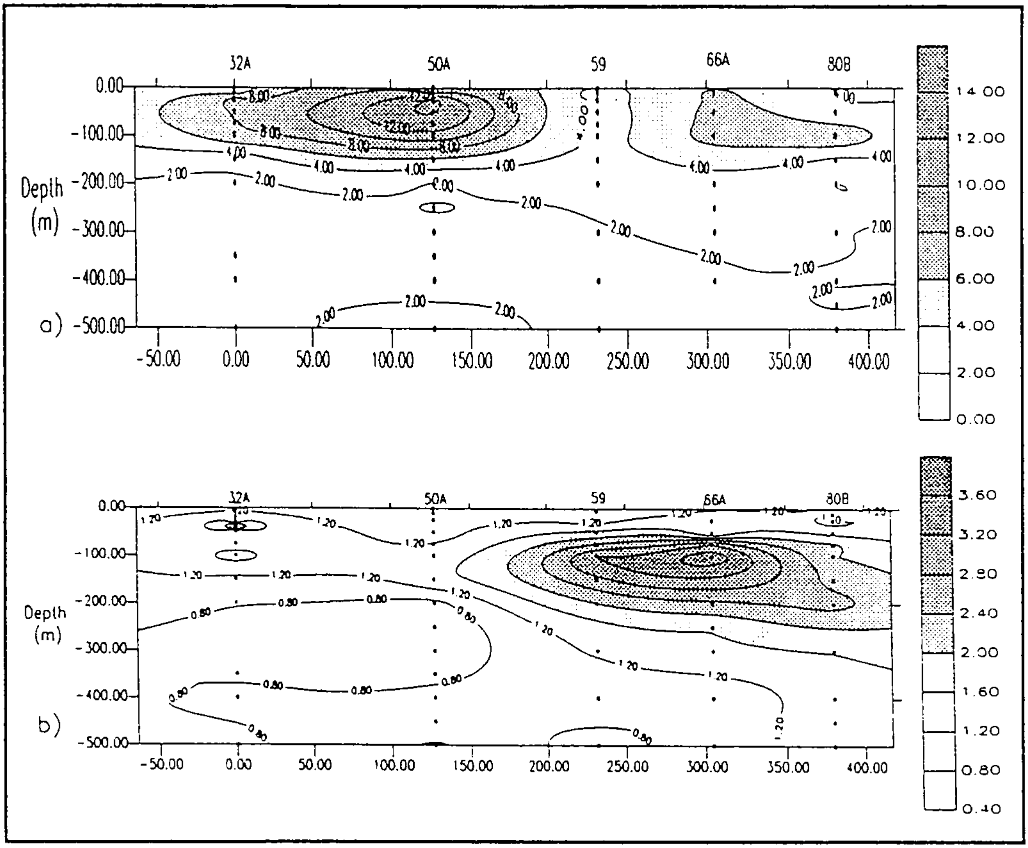

Figure 6 - Particulate silica distribution (ug/l), of a west to east section of the Cretan Sea, in: (a) March 1994, and (b) September 1994

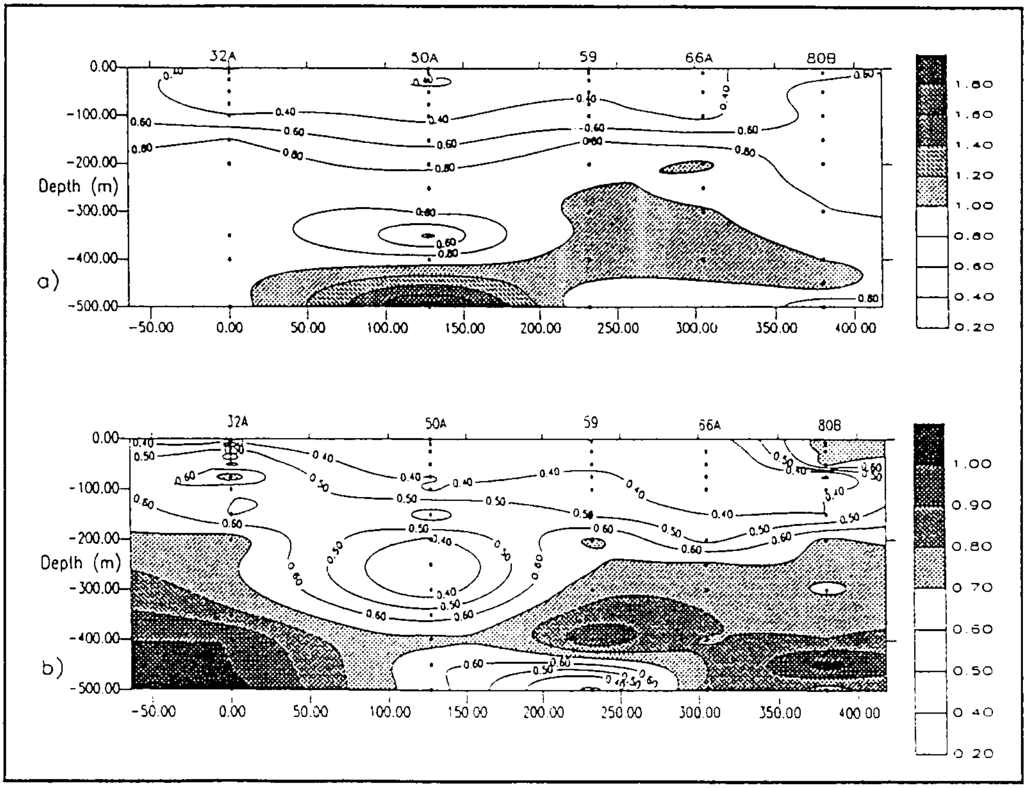

Figure 7 - Particulate aluminium distribution (ug/l), of a west to east section in the Cretan Sea: (a) March 1994, and (b) September 1994.

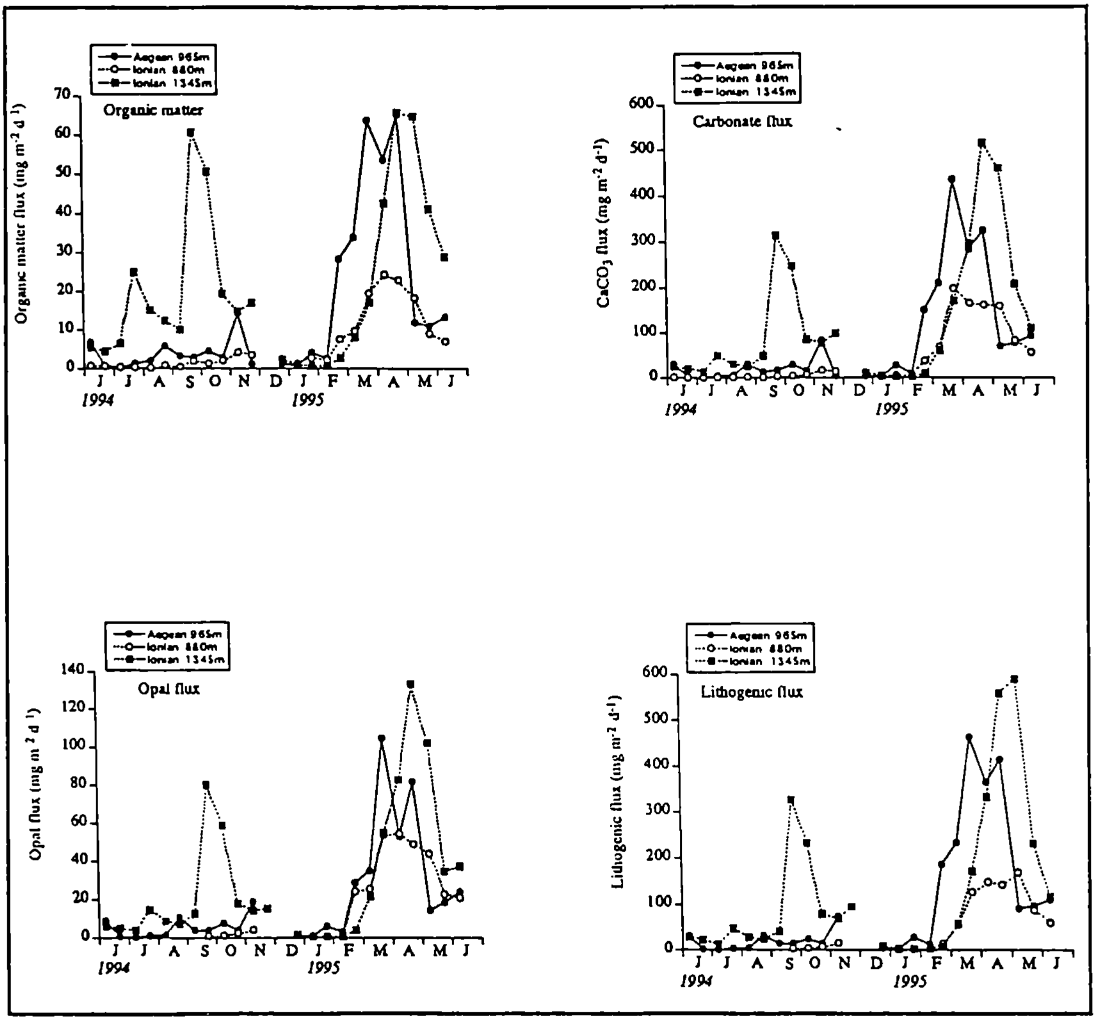

Figure 8 - Time-series plots of major constituents fluxes (mg.m^{-2}.d^{-1}).

Mediterranean Targeted Project (MTP) - GEODYME Project
Contract MAS2-CT93-0061

Synthesis of Final Results

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Mediterranean Targeted Project (MTP) - GEODYME project
Synthesis of Results

Geochemistry and Dynamics of the Mediterranean Sea

ABSTRACT

The aim of the GEODYME proposal was to acquire physical and chemical data to monitor changes occurring in deep-water characteristics (temperature, salinity, nutrient and trace-metal content) and to improve modelling of fluxes together with climatic and environmental evolutions. The project was justified by previous research showing changes in the deep-water of the Algero-provençal Basin (Western Mediterranean). During GEODYME, results were acquired concerning monitoring of changes, knowledge of intermediate and deep water behaviours, evaluation of surface changes in driving forces (climate and environment) and first representations of phytoplankton at basin scale by chemical taxonomy and by flow cytometry. These new representations of the biological ecosystem, together with results from nutrient budgets, allow the study of interactions between ecosystem, marine and terrestrial environments and their different evolutions.

Key Words: Mediterranean Sea, past and present evolutions, hydrology, nutrients, trace metal, biological ecosystem (chemical taxonomy, flow cytometry)

INTRODUCTION

There are several evidences of past and present changes in the Mediterranean Sea and in its environment. Apart from geodynamical evolutions which are at very long time scales (millions of years), in the sediment there are signatures of past changes in climate, hydrology, fauna, oxygen, and biological production (e.g. the peculiar example of the sapropel layers over the last half million years). In the upper sediment, there are also traces of recent lead pollution by anthropogenic activities. Since the last three decades, changes are occurring in the temperature and salinity characteristics of the Western Mediterranean deep-waters. They are signatures of evolutions of climate and/or environment which are not truly perceptible at the local scale of terrestrial or coastal measurements. Trace metals together with nutrients also give examples of non-steady state concentrations in sea-water, according to the environmental evolution, with probable interactions with the biological ecosystem. These marine changes prove that the Mediterranean Sea offers the opportunity of an unique challenge to describe, understand and monitor in real time the evolution of a deep-sea enduring climatic and environmental changes. Evolution scenarios are necessary in order to model and forecast the environmental consequences. But anthropogenic changes are difficult to define and quantify at the Mediterranean basin scale, insofar as differences are great between bordering countries (demography, standard of living, mean gross national product, industrial and agricultural activities..). According to the strong spatial and temporal variability of the local climate, detection of a climatic trend (heat and/or water budget) over the whole sea is also difficult to investigate from ground observatories alone. Nevertheless, quite isolated from the oceanic advection, the Mediterranean Sea may be an opportunity to detect probable consequences from the increasing green-house effect over the northern hemisphere. The proposal concerned: 1) the monitoring of western deep-water characteristics and the marine signatures of change; 2) the use of marine records to monitor surface evolutions and the improvement of the models previously focused on the data from the Algero-Provencal basin by the integration of boundary conditions from the Tyrrhenian and Ionian Seas; and 3) the quantification of biological transfers and new production, as well as of their expected evolutions.

MATERIALS AND METHODS

From preliminary analysis of historical data, it appeared that temperature, salinity and phosphate content of the western Mediterranean deep-waters were increasing during the last three decades (Bethoux et al., 1990; 1992). Hydrological changes in deep water characteristics involve changes in heat and water budgets across the sea surface. Changes in nutrient content of deep water involve evolutions of the Mediterranean environment, together with induced changes in the biological ecosystem.The use of deep-sea records to detect and monitor surface changes needs to take into account marine dynamics and to be able to compare results at basin scale with atmospheric or watershed data, i.e. with data acquired at different temporal and spacial scales. Together with the monitoring of changes in the Algero-Provençal basin, the priority was to define the exact role of the Tyrrhenian Sea in the western Mediterranean circulation and to analyse the possible changes in the eastern Mediterranean, namely in the Ionian Sea, in spite of the few historical data. Analyses of historical data were completed by direct measurement according to cruise opportunities across the different parts of the Mediterranean Sea (Fig.1). In the western basin, the SEMAPHORE cruise in 1994 was devoted to nutrient and chlorofluorocarbon studies. In the eastern basin, during the METEOR 31/1 cruise in early 1995, a strong effort was made in acquiring bio-geochemical data, mainly elements of the carbon budget, the organic pigments analysed by HPLC and the concomitant analysis of planktonic population and size distribution by flow cytometry. In the Ligurian Sea (western Mediterranean), several opportunities aboard coastal ships allowed the monitoring of hydrology and trace metal concentration together with some experiments on biological processes. Results were acquired by the use of rather new techniques (e.g.flow cytometry and HPLC), the improvement of routine measurements (chlorofluorocarbons, alkalinity partial pressure of CO_2) and the measurement of some specific trace elements: Iodine, Rare Earth Elements, Barium, Strontium, isotopic composition of Neodymium. Consequently, the specific data bank of the project concerns hydrology, nutrients, trace elements, carbon cycle, organic pigments and specifics of size distribution and fluorescence signature of phytoplankton.

RESULTS

Temperature and salinity changes in deep and intermediate waters

In the Algero-Provencal basin (western Mediterranean), analysis of measurements made since the early sixties has shown that temperature and salinity in the deep water (from about 1000m depth to the bottom at 2700m) were increasing with time (Bethoux et al., 1990). Temperature and salinity changes occurring in the deep waters of the western basin are indications of changes in heat and/or water budgets occurring at the surface of the western and/or eastern basin. With the data acquired during the project, the deep water warming is 0.13°C and the salinity increase is about 0.04 psu, between 1959 and 1995, in the western deep-water. The yearly mean trends are equal to 3.6 10^{-3} °C (R^2=0.97) and 1.1 10^{-3} psu for salinity (R^2=0.93). These data were used as a first control of the CTD probe calibration (Bethoux and Gentili, 1996). In the intermediate water (at 300 and 400m depth) of the Ligurian Sea, at about 30 miles off Nice, temperature and salinity increasing trends are about twice the deep water trends (i.e. 6.8 x 10^{-3} °C and 1.8 10^{-3} psu, respectively, for potential temperature and salinity). From analysis of historical data together with newly acquired data, Zodiatis and Gasparini (1996) proposed quite stronger temperature and salinity increasing trends in the intermediate layer of Tyrrhenian Sea (i.e. 9.3 x 10^{-3} °C and 2.4 10^{-3} psu, respectively, for potential temperature and salinity in the 600-1500m layer), proving an imported effect from the eastern basin.

Studies of the interannual variability of hydrographic characteristics in the eastern Mediterranean are another effort of the GEODYME project. Presently, an impressive increase of temperature and salinity is apparent in the deep and intermediate layers of the Ionian Sea (Roether et al, 1996). From a first analysis of historical data, there appear strong signs of interannual variability, but, in contrast with the western Mediterranean, there is no unique trend but rather "oscillations". This may be related either to a complex dynamic response of the basin to external forcing or to internal variability of the basin which oscillates from one state to another.

The warming trend in western deep-water was assumed to be early evidence of the green-house effect, concomitant with a change of the water budget linked to an increase in evaporation as well as to a decrease of rainfall, as evidenced from meteorological data around the north-western Mediterranean sea. In other studies (Rholing and Bryden, 1992; Leeman and Schott, 1991), the warming trend was also anticipated as a response to a salinity increase, imported from the eastern basin and linked to changes in the freshwater budget (e.g. damming of the Nile river in 1964 and of rivers of the Black Sea since the early fifties). The use of marine records towards a monitoring of climatic or environmental evolutions requires not only a quantitative knowledge of marine circulation but also the changes of surface driving forces: precipitation, river runoff, air-sea exchanges.., at a basin or whole sea scale. At present, calculated surface evolutions (e.g. temperature) do not agree with surface mean trends from meteorological data, probably according to differences in time and space scales (Bethoux and Gentili, 1994). Nevertheless, according to different climatic and environmental hypotheses, calculations (Bethoux and Gentili, 1996) of salinity changes constitute a first explanation of the strong change of hydrological characteristics found in the eastern basin in January 1995 during the Meteor 31/1 cruise (Roether et al, 1996). Presently, a better use of marine records needs an improvement in the knowledge of water budget change at the basin scale (precipitation and river discharge changes).

Tyrrhenian Sea hydrology

One of the objectives of the GEODYME project was to study and quantify the exchanges of intermediate and deep water between the Tyrrhenian Sea and the other Mediterranean basins in order to improve simple box-models previously used to detect surface changes from deep water signatures. Monitoring and analysis of Tyrrhenian circulation were ensured by continuous measurements across the Sicily-Sardinia and Corsica straits and several hydrographic cruises which improved our knowledge of the role of Tyrrhenian basin in modifying the Levantine intermediate water and the western deep-water and the flux across the straits (Astraldi and Gasparini, 1994; Gasparini et al., 1994; Gasparini et al., 1996; Zodiatis and Gasparini, 1996).

The water crossing the strait of Sicily and entering into the Tyrrhenian Basin is not entirely homogeneous. Below the classical Levantine intermediate water (LIW), we can distinguish a water type, having about the same salt content, but a lower temperature, which seems to be a mixing between LIW and the Ionian deep water. This water is heavier than the LIW and, when it enters the Tyrrhenian Sea, it sinks reaching its buoyancy equilibrium at depths greater than 1000m. This induces important effects in the heat and salt transfer from the intermediate to the deep layer of the basin, with an increase of the salt content of the deep water. Furthermore this process seems to be an important heat and salt source for the step structures present in the interior of the basin. In the deepest part of the Tyrrhenian Basin, between the LIW and the deep water, a well developed step structure is present both in temperature and in salinity (Zodiatis et al., 1996). The comparison of these steps with the historical data reveals the "quasi-permanent" presence of the step-structure in this area, but, starting from 1973, a progressive decrease of the step number associated with an increase of the step size, can be observed. In the same period, a progressive increase of temperature and salinity was observed in the 600-1500m layer, reaching about 9.1 x 10^{-3}°C/year and 2.4 10^{-3} psu/year, trends greater than those observed in the intermediate layer (300-500m) in the Ligurian Sea.

The water sinking along the Tyrrhenian southern boundary and the step structure in the basin interior are the most important processes connecting the intermediate and the deep water. Even though the circulation of the Tyrrhenian deep water is still largely unknown, an important result obtained during the GEODYME project is the identification of remarkable inflow/outflow processes at the bottom of the southern opening of the basin. The deep water, coming from the western Mediterranean, enters the Tyrrhenian Sea in a narrow vein flowing very close to the southern wall of the deep trench in the Sicily-Sardinia section, between 800m and 2500m. A modified flow of deep water (warmer and saltier) exits through the same section, at the opposite side of the trench and at about the same depth range.

All the previous results underline the central role played by the Tyrrhenian basin in the Mediterranean circulation for what concerns the modifications of the intermediate and deep waters. Furthermore, the long-term changes of the Tyrrhenian hydrographic structure provides relevant information on long-term variability of the water characteristics and their dynamics, thus evidencing that this basin seems to be a privileged area for observing the climate evolution of the Mediterranean Sea.

Dense water behaviour (formation, spreading, change)

Dense water formation is a climatic peculiarity that the Mediterranean Sea shares with a few world locations: the Arctic and Antarctic areas and the Red Sea. On the one hand, the use of marine signatures of change observed in the western deep water needs a better knowledge of the origin and behaviour of dense water in this basin. This was the contribution of the paper by Bethoux and Tailliez (1994) who raised questions concerning the spreading of the newly formed deep water. On the other hand, in the sediment of the eastern basin are different signatures of past episodes of anoxia of the deep water, proving changes in dense water formation. Studies of these sapropel episodes are useful for the knowledge of climatic functioning of the Sea, in the past as for the present (Bethoux, 1993; Bethoux and Gentili, 1994).

The deep water of the western Mediterranean Sea originates in the wintertime dense water formation processes occurring off the Gulf of Lions and the Ligurian Sea and feeds the deep Mediterranean outflow towards the Atlantic via the Gibraltar Strait. Dense water formation, deep inner basins and shallow sills allow the storage of thick homogeneous deep layers. In the western basin, residence time of deep water is rather short. Temperature and salinity characteristics reflect the surface water and heat budgets integrated over 15 to 20 years. Results from the analysis of historical data show that the newly-formed deep water propagates quickly over the whole Algero-Provencal basin, at its equilibrium buoyancy depth. Its year-to-year variations of temperature and salinity may be linked to the effects of climate integrated over fall and winter. In the deep layer, these variabilities are progressively shaded by the climatic warming trend (Bethoux et al., 1990) and by the Earth heat flow through the sea floor, which facilitates the vertical homogeneity. In the Tyrrhenian Sea, heat flow may be mainly responsible for homogeneities in temperature and salinity and for oxygen ventilation of deep waters down to 3600m depth, these waters being perhaps poorly connected to those of the Algero-Provencal basin (Bethoux and Tailliez, 1994; Zodiatis et al., 1996). The effect of Earth heat flow in vertical structure of deep waters was revisited concerning the Ionian and Cretan Seas (Lascaratos, personal com.). The result is an effective homogenization till 1000m over the bottom and the progressive vanishing, over two or three years, of the yearly peculiar climatic signatures, i.e. new constraints for modelling of the Mediterranean dynamics and circulation.

Deep sediments of the eastern basin conserve the signatures of 11 sapropel events, denoting concomitant anoxia of deep water, over the last half million years. Sapropel formation indicates simultaneous changes in deep-water formation in the Adriatic and Cretean Seas. These events may be explained by changes in water budget, mainly affecting dense water formation in the Adriatic and Aegean Seas (Bethoux, 1993; Bethoux and Gentili, 1994). They may result from increasing freshwater input (via tropical climatic oscillations) and changes in sea-level (via global climatic change). Changes in hydrographic characteristics of the eastern deep water observed in January 1995 during the Meteor 31/1 cruise (Roether et al., 1996), constitutes a confirmation that dense water formation in Adriatic Sea may decrease and, in this present case, be replaced by dense water formation in other places, Levantine basin or Aegean Sea.

Nutrient signature

During the project, in autumn 1994, new and accurate distributions of phosphate, nitrate and silicate across the western basin were aquired during the cruise "Semaphore. Estimates of mean concentrations and standard deviations prove the homogeneity at basin scale of nutrient concentrations from about 400m depth down to the bottom at 2700m. Analysis of historical data together with these new data proved again increasing concentrations of phosphate in the deep water, at a rate of about 0.5% a year since the early sixties, as previously shown (Bethoux et al., 1992) and evidenced a similar increase of nitrate. These increasing trends constitute constraints for the Mediterranean nutrient budgets and behaviours.They are consequences of increasing population and industrial and agricultural activities around the sea, mostly since the early sixties. Via marine circulation, this marine increase was calculated to correspond to a 3% yearly increase of atmospheric and/or terrestrial discharges around the whole Sea. From ground enquiries, there is no corresponding estimate available, but this result is in agreement with a global scenario where total dissolved phosphorus in land surface water globally increases proportionally to the watershed population and to its energy consumption (Meybeck, 1982). Effectively, in the Mediterranean countries, socio-economic data show inhabitant increase of 1.6% a year, standard of living of +4.5% a year and energy consumption +6% a year, over the 1960-1985 period (UNEP, 1988). But since the end of the eighties, the slack times for socio-economic activities, the change in agricultural methods and the beginning of implementation of waste-water treatment, we have no more evaluations of the real anthropogenic pressure at a basin scale.

Terrestrial inputs of phosphorus occur in the coastal area, increasing inputs are evidenced by frequent eutrophication in some hot spots. But, more diffusely, they mean increasing biological production in the surface layer, increasing consumption of oxygen in deep water for the remineralization of organic matter settling from the surface, and a probable partial anoxia in a few decades. Simulation and prediction of oxygen trends need to evaluate biological new production at basin scale, which may be made from nutrient budgets across the Gibraltar and Sicily straits. In the Mediterranean, nitrate budget at basin scale requires a high fixation of molecular nitrogen by plankton species. In order to verify this assumption, an attempt of determination of cyanobacteria population (capable of atmospheric nitrogen uptake) was made by flow cytometry technics across the eastern basin during the Meteor 31/1 cruise in January 1995. First results confirmed important population of cyanobacteria in wintertime, as previously found by Li et al.(1993) in summer.

Trace metal signatures

Trace metal profiles in the Mediterranean sea are quite different from those in the open oceans, i.e. rather high concentration in the surface layer and more or less constant vertical profile (Ruiz-Pino et al., 1990; 1991). These differences were explained by the non-steady-state of the Mediterranean concentrations and allowed the calculation of dissolved atmospheric and terrestrial inputs and their probable evolutions between 1960-1985: +6% a year for zinc and lead and +2% a year for copper and cadmium (Bethoux et al., 1990). These data gave a new evaluation, at a basin scale, of the changing environment of the Mediterranean Sea and these changes are monitored by continuous measurements since the year 1983. Another example of the fast evolution of the Mediterranean environment was given during the project by determining the decreasing lead concentration in the surface layer since 1988 in the North-Western Basin (Nicolas et al., 1994). Halving of the surface concentration followed the application of the European policy concerning the decrease of lead additives in gasoline and the increasing use of unleaded fuel. Moreover, using economical scenario for the evolution of population, energy consumption and vehicle numbers over the 1950-2025 period, a pre-vision of the marine lead concentration evolution was proposed (Tian and Ruiz-Pino, 1995). In this study, it was shown that without regulation of lead emission in the eastern basin, in a few decades, lead concentration in water column would become dangerous for the ecosystem. As a result of marine circulation, lead pollution of the eastern basin may again increase concentration in the western basin.

Other results of the project concern:
- determination of iodine profiles in the Mediterranean (Tian and Nicolas, 1995) by polarography technics and the use of iodine components to evaluate new versus regenerated production (Tian et al., 1996),
- estimate of heavy metals in rainwater and atmospheric deposition (Migon and Caccia, 1993),
- measurement of arsenic and antimony in Corsica estuary (Migon et al., 1995),
- measurement of Rare Earth Elements, Neodymium isotopic composition, Barium and Strontium in the eastern Mediterranean during Meteor 31/1 cruise.

Chlorofluorocarbons in the Western Mediterranean

As other chemical tracers such as nutrients, CFC's are used to characterize the different water masses and their main interest resides in their transient tracer behaviour which provide estimates in the ventilation time of newly formed deep-waters. During the SEMAPHORE 1994 cruise, a section of 11 hydrological stations has been occupied between the entrance of the Mediterranean Sea (Alboran Sea) and Toulon (South of France). In addition to classical hydrological CTD measurements of temperature and salinity, water samples have been collected for analysis of different geochemical tracers including nutrients, CFC's and trace metals (Connan et al., 1996).

Vertical profiles of F11 and F12 exhibit a well-marked subsurface maximum (from 100 to 200m depth) corresponding approximately to the temperature minimum. The F11 and F12 concentrations observed at the subsurface maximum correspond to values at equilibrium with the atmosphere during the preceding winter when the water mass was at the surface. The minimum values observed in the above surface waters reflects the exchanges with the atmosphere during the spring and summer heating. Below the surface waters, a minimum in F11 and F12 concentrations is observed between 600 and 800m depth in the lower part of the intermediate waters, as the depth of this minimum is well under the salinity maximum. This shift is evident in the chlorofluorocarbon/salinity diagrams. It may be the result of differences in vertical mixing between intermediate waters and the overlying surface waters and underlying deep waters. An alternate origin may be the existence of different values in the vertical diffusion coefficient for salinity and chlorofluorocarbons. Below 800m depth, concentrations increase linearly towards the bottom. These higher values in deep waters correspond to a more recent input of chlorofluorocarbons during deep water convection in the northern part of the basin while minimum values in the Intermediate Waters reflect an horizontal advection of "older" Levantine Intermediate Waters from the eastern basin. These features: subsurface maximum, intermediate waters minimum and linear increase in the deep waters are found in all the profiles of the section. The linear increase in the deep waters is observed at the basin scale and confirms the hypothesis of the spatial homogeneity previously mentioned in the hydrological and nutrients data.

Phytoplankton ecosystem

During the GEODYME project, efforts were made for determination and quantification of phytoplankton populations at basin scale, a rather unknown field, in order to specify links with geochemistry and to allow modelling of probable evolutions. Apart from the determination of new production from nutrient budget at basin scale, new techniques were used: chemical taxonomy by pigment determination (HPLC), ETS and flux cytometry techniques. Organic pigments and flow cytometry techniques may give new images of the basic biological ecosystem, at a basin scale (Daugeron et al., 1994; Bustillos et al., 1995; 1996). The relationship between phytoplankton cell size distribution and rate of metabolic $C0_2$ production in the aphotic layer was first investigated in the Ligurian sea (Lefevre et al., 1996).Then, a strong effort was made in the exploitation of bio-geochemical data acquired during the METEOR 31/1 cruise in the eastern basin in the early 1995. Concerning flow cytometry, a presentation of preliminary results was made by Martin and Denis (1996). Biparametric cytograms provided the resolution of 8 populations characterized by their fluorescence and light-scattering properties, and their depth location. For each resolved population, the depth profile of its cell concentration has been determined. These populations have been labeled as distinct cell groups with some specificities as following.The population labeled cell group 7 is the dominant one when present and has been identified with Cyanobacteria, considering its size (less than 1 μm) and fluorescence. Cyanobacteria make up more than 20% of the overall phytoplanktonic population above 100 m depth for the reported stations. This is of particular interest due to their possible role in the nitrogen cycle by direct molecular nitrogen uptake. Cell group 6 corresponds to cells of about 10 μm in diameter which are tentatively identified with Cryptophytes. This population is present almost evenly over the upper 200 m at all stations. Cell group 5 exhibits the typical features of Prochlorophytes. When present, Prochlorophytes represent 1 to 11 % of the overall phytoplanktonic population, and are mainly in the 0-90 m layer in the western basin, and in the 90-150 m layer in the eastern basin. Cell group 4 is made of larger cells, about 6 μm in diameter and exhibits rather low red and green fluorescence like cell group 5. This population is found almost exclusively between 35 and 100 m depth in the western basin and is absent in the stations of the eastern Basin reported above except station 74 (Figure 3) where it is observed at 150 m depth. Cell groups 1 and 2 represent populations exhibiting more red fluorescence than green and differing by their size (10 and 2 μm respectively). As expected, large cells are less abundant (less than 1.5 % of the overall phytoplanktonic population). Their concentration is higher in the western than in the eastern basin. Cell group 3 is characterized by green fluorescence more intense than red and by sizes larger than 10 μm. This group could consistof Diatoms. It is evenly distributed over the entire basin within the 0-200 m layer, with similar concentrations.

Diagnostic pigment concentrations (chlorophylls and carotenoids), as analyzed by HPLC, were used as biomarkers of the specific phytoplankton biomasses. The complete data set acquired during the METEOR 31/1 cruise, which corresponds to about 700 discrete samples, was analyzed (Vidussi et al., 1996). As an example, the phytoplankton pigment signature of one station (Station 74) near the Cyprus eddy, an anticyclonic eddy south of Cyprus in the Levantin basin is summarized. The integrated concentration (0 to 200 m) in total chlorophyll *a* (chlorophyll *a* plus divinyl-chlorophyll *a*) is very low (11.4 mg m^{-2}). Nanoflagellates (prymnesiophytes and chrysophytes) are the dominant phytoplankton and autotrophic prokaryotes (cyanobacteria and prochlorophytes) are the second most abundant. This characteristic attests the very oligotrophic nature of this area, which is confirmed by the low value (0.08) of the Fp ratio, a proxy of the f-ratio (new production / total production). The total chlorophyll *a* concentration ranged between 0.074 and 0.118 μg l^{-1} in the upper 100 m and drastically decreased to undetectable values at 200 m. Vertical profiles of zeaxanthin (cyanobacteria and prochlorophytes) and divinyl-chlorophyll *a* (prochlorophytes) show typical vertical segregation in phytoplankton distribution : while cyanobacteria were present in the surface lightened layers, prochlorophytes dominated at the level of the chlorophyll maximum.

Carbon cycle in the Mediterranean Sea

During the METEOR 31/1 cruise, the carbon cycle was studied by acquiring measurements of:

- partial pressure of carbon dioxide (pCO_2) in the surface waters,
- pH and alkalinity,
- total organic carbon (TOC)

pCO_2 measurements were the first one in the eastern basin and allowed estimates of carbon dioxide fluxes between the atmosphere and the sea. At the time of the cruise (January), mean value in the surface layer for the whole basin is estimated to 313.5 μatm, while in the atmosphere mean value was higher by 43.5 μatm. Consequently surface waters were undersaturated and the Mediterranean was a sink for CO_2. According to wind speed varying up to 40 m/s, calculated fluxes of CO_2 were strongly variable in time and space. Moreover, different available formulas for transfers between air and sea may give very different results with high wind speed. pH and alkalinity measurements allow estimates of mineral carbon budget when measurements are accurate and water flow across the straits definitively known. The linear relationship between alkalinity and salinity previously found in the Alboran sea (Copin-Montegut, 1993) is now verified for the whole eastern basin. It permits calculation of the net flux of alkalinity between the different basins in relation with the water budget across the sea surface. Consequently, if the river inputs of alkalinity are well known, alkalinity budget may constrain water budget and flow evaluations across the straits.

Total organic carbon data, TOC, together with previous measurements give estimate of global carbon budget and recycling rate of organic matter. The TOC concentrations in the eastern basin are comparable to those in the western basin: 900 to 1300 µg/l in the surface water and 600 to 900 µg/l below the euphotic zone. Higher values in the surface layer result from photosynthesis of organic mater and its recycling into dissolved organic mater.

CONCLUSION

Geodyme project was focused on the study of the Mediterranean ecosystem evolution. When climatic and geochemical studies in the open ocean are complicated with advection processes, the relative isolation of the Mediterranean Sea from the Atlantic ocean showsevidence of local driving forces: climate and environment. Mediterranean deep-water trends constitute boundary conditions and constraints for transfer processes and evolutions occurring at the sea surface. The succession of deep inner basins separated by straits and/or sills favours studies on e.g. nutrient, trace metal, carbon and oxygen budgets and new production. They allow the monitoring of the environmental evolution at a basin scale. It seems rather impossible to realize this task from sporadic measurements in a few places scattered in different nations with different cultural environments. Recent changes in physical and chemical characteristics of deep water were monitored during the Geodyme project, and evolutions of surface driving forces were estimated.They concern changes in the heat and water budgets across the sea surface and the trace metal and nutrient inputs. These latter, linked to socio-economic evolutions (increase in inhabitants and in gross national product), probably result in increases of new production and oxygen consumption. But the complete use of the deep-water signatures indicating environmental or climatic evolution at the sea surface needs continuous improvement in the dynamic knowledge of the Mediterranean Sea (horizontal and vertical fluxes in the different basins). Geochemical tracers such as chlorofluorocarbons acquired during the project in the western basin may be useful in addition to results acquired in the Tyrrhenian Sea. Moreover, the new image of phytoplankton ecosystem given by chemical taxonomy and flow cytometry allows the quantification of the interactions between sea water chemistry (nutrient concentration, N/P ratio) and ecosystem functionning (new production, nitrogen uptake and evolutions). From the results acquired during the project, one may consider that the monitoring of physical and bio-geochemical evolutions is on the right track. But, instead of a study for the unique benefit of the Sea knowledge, this monitoring may also be useful in charting the progress for the whole Mediterranean environment (sea, watershed population and activities, climate) as far as marine changes determined at the basin scale may be compared to climatic and socio-economic studies and may be used in evolution scenario.

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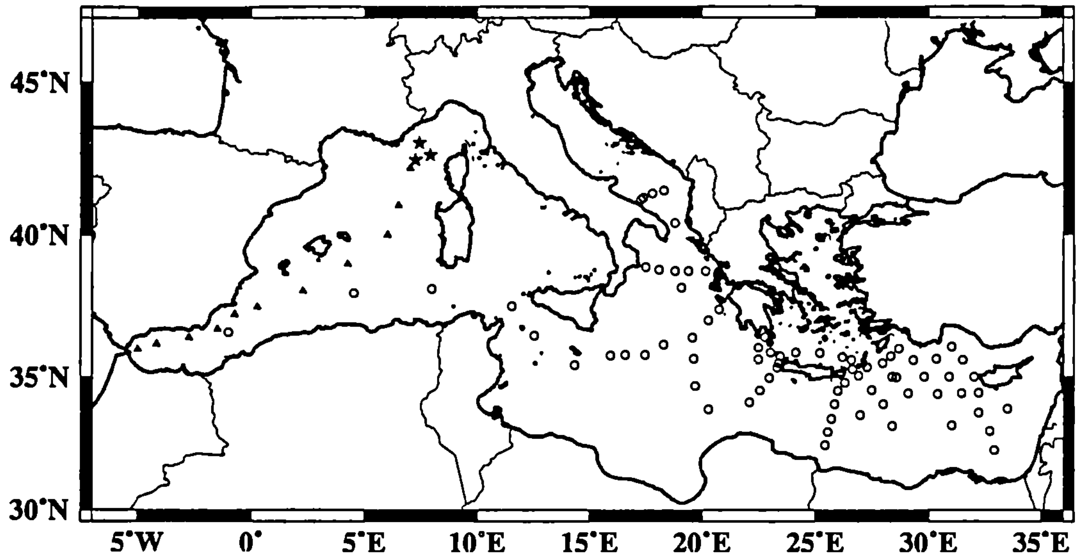

Fig.1 Locations of marine observations made during GEODYME contract in the Algero-Provençal basin (western Mediterranean) and in the eastern Mediterranean. Black triangles correspond to SEMAPHORE cruise, in September 1994 aboard French navy ship"D'Entrecasteaux", with special attention to nutrient, freon and trace metal concentration. Black stars in the Ligurian Sea (north-western basin) mark the GEOTETHYS stations visited in 1994 and 1995, with special attention to hydrology (temperature, salinity and oxygen), trace metal and alkalinity. Other cruises were made in the Gulf of Lions and Ligurian Sea in 1994 and 1995 for biological process studies and the sampling for flow cytometry. White circles correspond to METEOR 31/1 cruise in January 1995, managed by MERMAIDS project. During this cruise, GEODYME team was in charge of CO_2 and alcalinity measurements, chemical taxonomy and flow cytometry techniques for determination of picophytoplankton at basin scale. Moreover, different hydrographic radials were made in the Tyrrhenian Sea and in the Sicily straits by the Italian team, a cooperation between GEODYME and EUROMODEL projects.

Mediterranean Targeted Project (MTP) - MEDIPELAGOS Project
Contract MAS2-CT93-0063

Synthesis of Final Results

Coordinator:

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Station Zoologique	Starting Date: 1 July 1993
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Mediterranean Pelagic Ecosystem Study: Plankton Dynamics

ABSTRACT

Key results of the Medipelagos project, a 30 month collaborative effort involving 7 institutions representing 4 European countries, are presented. Research efforts were focused on nutrient dynamics in the N. W. Mediterranean, an issue of importance not only in terms of the goal of MTP (a system model) but also of immediate relevance to management. The main issues addressed were: determining which of the macro-nutrients likely limits production in the N. W. Mediterranean in the spring and summer months, identifying the major pathways of nutrients within the pelagic food web, and examining the effects of rapid changes in nutrient concentrations. Results obtained, using different lines of evidence, strongly support the hypothesis of phosphorus limitation in the N. W. Mediterranean during summer months. In addition to phytoplankton, bacterial uptake is likely a major nutrient uptake pathway in this system. Excretion by grazers on bacteria and small phytoplankton and viral lysis of bacteria are probably responsible for most of the regeneration of phosphorus in the water column. Rapid changes in nutrient concentrations can lead to rapid changes in the structure of the pelagic food web. However, the food webs appear to be capable of quickly reverting back to their previous structure.

Key Words: Nutrients, Phosphorus, Nitrogen, Bacteria, Virus, Phytoplankton, Microzooplankton

INTRODUCTION

The long term goal of the Mediterranean Targeted Project (MTP) is the construction of a model of the system capable of predicting both short and long term changes. The pilot phase of MTP, 1993 - 1996, was specifically focused on four objectives as preliminary steps. The role of MEDIPELAGOS (Mediterranean Pelagic Ecosystem Study) was within the objective "to improve knowledge of key biological (pelagic and benthic) processes in the biogeochemical cycles and their controlling factors" (MTP General Technical Annex 1A).

The key biological process in aquatic escosystems is primary production. In most marine systems, primary production is limited by a nutrient in short supply, which is generally nitrogen (N), in contrast to freshwater systems, in which phosphorus (P) supply usually limits primary production (Hecky & Kilham 1988). However, in recent years evidence has accumulated suggesting that, similar to freshwater systems, the Mediterranean Sea could be P-limited, especially the eastern basins (e.g., Krom et al. 1991; Bethoux et al. 1992) and perhaps the western basin as well (Berland et al. 1988; Raimbault & Coste 1990). Investigating this question was the major motivation behind Medipelagos, a collaborative study of nutrient limitation and pathways in the North-western Mediterranean Sea. The project was designed to provide authoritative answers to questions of nutrient dynamics because correct characterisation of the key biological process in the ecosystem was clearly a prerequisite to MTP modelling efforts.

Medipelagos joined researchers from France, Norway, Spain and Sweden, representing 7 institutions: CNRS-URA 716, Villefranche-Sur-Mer, France, Institut de Ciències del Mar, Barcelona, Spain, Centre d'Estudis Avancats de Blanes, Spain, Department of Microbiology, University of Bergen, Norway, Laboratory of Biotechnology, University of Trondheim, Norway, CNRS-UPR-4601, Roscoff, France, Department of Microbiology, Umea University, Sweden. Over a 30 month period, through collaborative efforts in the form of co-ordinated research programs, workshops, group experiments, and oceanographic cruises, three main questions were addressed:

Which macro-nutrient N or P likely limits primary production?

What are the major pathways of nutrients within the pelagic food web?

What are the effects of rapid changes in nutrient concentrations (pulses)?

In addition to serving the long-term goals of the MTP, the aim of Medipelagos- understanding nutrient limitation in the Mediterranean, has an immediate utility in management decisions. Determining the nature and extent of nutrient limitation is fundamental to understanding the factors controlling the trophic state of an aquatic ecosystem. The clear blue waters of the Mediterranean are evidence, and a product of, its largely oligotrophic condition. Preservation of the trophic state of the Mediterranean, a preoccupation in management decisions in the areas of sewage treatment-disposal, tourism and fishing, requires knowledge of the identity of the limiting nutrient as well as nutrient dynamics in the system.

RESULTS

Which macro-nutrient N or P likely limits primary production?

Preliminary investigations demonstrated that the turnover time of P (as orthophosphate) in coastal surface waters was very short (a few hours) during summer stratification (Dolan et al. 1995). These observations suggested that P could be limiting the growth of phytoplankton and/or bacteria, the producers of particulate organic matter. We critically tested our initial assumption of P-limitation in the Mediterranean using a variety of independent techniques. Experiments were conducted with natural populations from surface layers during seasons when the water column is thermally stratified. The experimental site was on the French Mediterranean Coast, "Point B" the entry of the Bay of Villefranche, a standard oceanographic sampling site in an oligotrophic area, considered typical of the N.W. Mediterranean (Ferrier-Pages & Rassoulzadegan 1994b). We found:

1) Stimulation of DNA synthesis in the primary producer *Synechococcus* with P but not N additions (Vaulot et al. 1996).
2) Stimulation of bacterial growth and the degradation of dissolved organic carbon compounds with P but not N additions (Thingstad et al., submitted).
3) Rapid uptake of added orthophosphate in excess of growth requirements "luxury consumption") in both phytoplankton and bacterial size-fractions (Thingstad et al. submitted).
4) High alkaline phosphatase activity (Thingstad et al. submitted).
5) High short-term variability of bacterial exoenzyme activities (Karner & Rassoulzadegan 1995)

In our opinion, our findings unequivocally demonstrated that both phytoplankton and bacteria in our North-western Mediterranean test site, Villefranche Bay, experience a starvation for P.

What are the major pathways of nutrients?

Determining the relative importance of pathways involves estimating standing stocks as well as fluxes. Stock distributions of P in Villefranche Bay, determined using standard methods, mirrored those of other P-limited systems (such as lakes):

1) Most P is present in the form of dissolved organic phosphorus (Dolan et al. 1995; Thingstad et al. 1996).
2) The largest pool of particulate P is found in the size fraction corresponding to bacteria and small phytoplankton, 0.2 - 5 µm in size (Thingstad et al. 1996).

Fluxes of P into the particulate stocks via absorption of orthophosphate, which represents uptake by the producers of particulate organic matter, was examined using ^{32}P-labelled orthophosphate. Results showed:

1) During the summer, concentrations of dissolved inorganic P are undetectable. During this period, we found rapid P-turnover times, occasionally under 1 hour and P uptake to be dominated (>50 %) by bacteria (Thingstad et al. 1996, submitted).
2) Larger size-fractions (> 5 µm), increase their share in nutrient uptake at higher P concentrations (Dolan et al. 1995).

Such results support the hypothesis that temporarily high concentrations of nutrients, "nutrient pulses", as preferentially profiting larger phytoplankton cells.

As the dominant consumers of P were found to be bacterioplankton and small phytoplankton, a major flux of P from the particulate phase back into the dissolved phase (nutrient regeneration or recycling) should be the excretion of P by consumers of bacterioplankton and phytoplankton. Laboratory data was used to estimate excretion of phosphorus and ammonia by microflagellates and ciliates, organisms that ingest bacterioplankton and small phytoplankton. Other experiments examined the role of viruses in nutrient regeneration, as viral attacks also represent "consumption" of bacteria. The results showed:

1) Microflagellates and ciliates have high weight-specific excretion rates, higher than those of larger organisms, conforming to expectations based on theoretical size-metabolic rate relationships (Allali et al. 1994; Ferrier-Pages & Rassoulzadegan 1994; Dolan 1997)
2) When microflagellates and ciliates are growing rapidly, excretion of phosphorus compared to ammonia is high, suggesting that consumers of bacteria and small phytoplankton may be more efficient recyclers of orthophosphate (P) than ammonia (N) (Dolan 1997).
3) Viral attacks may be a significant mortality source for bacteria and be disproportionately important in the regeneration of P relative to N because bacteria are P-rich (Blackburn et al. 1996, Zweifel et al. 1996).

Consideration of the patterns established in P uptake and excretion, combined with recent observations on the role of dissolved organic carbon in carbon flux to Mediterranean deep waters, led to the development of a new conceptual model. The model postulates that dissolved organic phosphorus acts as a short-term phosphorus sink and the form of phosphorus exported from the surface layer with water column mixing (Thingstad & Rassoulzadegan 1995).

The Thingstad & Rassoulzadegan model has provided a conceptual basis for linking the observed P-limitation of bacteria to a lowered degradation of dissolved organic carbon in the Mediterranean (Thingstad et al. 1997). This adds a new element to our understanding of how carbon is sequestered, and it what form, from the atmosphere in the Mediterranean Sea (Figure 1).

The model, which links surface layer increases in dissolved organic carbon to those of dissolved organic phosphorus, illustrates the considerable importance of a previously ignored pathway- formation and consumption of dissolved organic phosphorus

What are the effects of rapid changes in nutrient concentrations (pulses)?

There is a general agreement that hydrographically stratified, nutrient-poor pelagic systems (such as most of the Mediterranean) develop rather complex "microbial food webs" with small algae at the base of the food web (picoplankton -> flagellates -> ciliates -> copepods -> fish larvae). In contrast, turbulent, nutrient-rich environments are characterised by simpler "classical food chains" based on primary production by large algae (diatoms -> copepods -> fish larvae). While the Mediterranean Sea is generally nutrient poor, it is far from homogeneous spatially or temporally. Marked increases in nutrient concentrations are often found in frontal areas and following water column mixing events associated with sustained periods of strong winds. Such temporally nutrient-rich systems often show changes in food web structure (Legendre & Rassoulzadegan 1995).

We examined the hypothesis that food web structures could be variable in the Mediterranean on relatively small scales of time and space. More specifically, the oceanographic cruises, "Fronts 93 & 95", were conducted to study differences in food web structures across a frontal zone in the Catalan Sea. Temporal variability was examined in the Ligurian Sea through "Dynaproc" cruises which investigated short-term effects of wind-driven water column mixing events. Laboratory studies with mesocosms were employed to examine experimentally the effects of sudden increases in nutrients on surface layer microbial communities. The mesocosm studies were carried out in Barcelona, Spain. Studies with clonal cultures were conducted in Roscoff, France.

For the oceanographic cruises, data analysis is far from complete. The three cruise programs represented over 60 total ship days and are expected to produce a very large amount of data. However, the last cruises were completed only as of June 1995 so that only a limited amount of data is available to date.

From the Oceanographic Cruise Programs FRONTS 93 & 95:

The Catalan front separates communities with different food web structures. In late spring, differences in the abundance of microbes were relatively small between frontal and non-frontal zone stations. For example, stocks of ciliate micro-zooplankton were quite similar among stations (Dolan & Marrasé 1995). However, differences in their activities were significant. Dimethylsulfoxide (DMSO) concentrations are tightly linked to bacterial activity and a marked gradient across the frontal zone was detected (Simo et al. 1995). In the frontal zone, a relatively high percentage of phytoplankton carbon circulated through the microbial food web. The reverse was true for the carbon processed by zooplankton (Calbet et al. submitted). These spatial changes can be related to the availability of nutrients in the lower part of the euphotic zone.

From the Oceanographic Cruise Program DYNAPROC :

Wind-mixing events which inject nutrients from deep layers into surface waters can yield changes in the phytoplankton communities. In particular, such events may profit diatoms but the algal community can revert to its previous composition within a few days.

From the Laboratory Studies:

The mesocosm studies, which were used to experimentally examine the responses of native microbial communities to nutrient additions, indicated that N and P-deficiencies markedly affect both the biochemical and microbial compositions of planktonic communities.

1) P levels affect mainly DNA concentration which indicates total community biomass (Berdalet et al. 1996).
2) Protein or chlorophyll concentrations are related to the availability of N (Berdalet et al. 1996).

Culture studies were employed to examine short-term changes in cell cycles in the prokaryotic alga *Prochlorococcus*.

1) In the Mediterranean strain, cell cycle arrest induced by phosphorus starvation could be reversed by the addition of phosphorus (Parpais et al. 1996).

Our results suggest that nutrient pulses can produce temporary increases in phytoplankton stocks. Nevertheless, microbial food web components appeared to vary only within narrow limits.

Additional MEDIPELAGOS benefits

In addition to providing answers to the three major questions posed, several technical advances, in the form of the refinements or developments of new techniques also resulted from MEDIPELAGOS. A new method was developed to measure pico and nano detritus (particles ranging in size from 0.2 - 20 µm) in the water column (Mostajir et al. 1995a); such small particles likely represent a food and nutrient resource for microbial communities and (Mostajir et al. 1995b). Analysis of nutrient-limitation effects on cell cycles was based on techniques of DNA analysis using flow cytometry and new techniques for flow cytometry were developed and refined for the analysis of picoalgae (Marie et al. 1996). A novel method for investigating selective predation on picoplankton, adding in target populations to natural samples, was investigated (Perez et al. 1996). An automatic phytoplankton culturing device which allows continuously fluctuating nutrient supplies was developed (Bernard et al. 1996). A procedure to microscopically distinguish living from dead bacteria in seawater was introduced (Zweifel & Hagström 1995). Improvements were made in fluorometric methods for estimating concentrations of DNA and RNA in seawater (Fara et al. 1996). Also, the innovative use of existing techniques was developed. For example, the proposal of the ratio of chlorophyll *a* to *in vivo* fluorescence as an ecological indicator (Estrada et al. 1995).

CONCLUSION

The overall results of Medipelagos strongly support the hypothesis that phosphorus most likely limits primary production in the North-western Mediterranean, from late spring through late autumn. We also found that planktonic microorganisms other than algae are important components of nutrient pathways. For example, bacteria compete with algae for nutrients while protists, who feed on bacteria and small phytoplankton, and viruses who lyse bacteria are probably the most important "recyclers" of nutrients. We hypothesise that the dynamics of P in the Mediterranean are intimately tied to those of carbon much like nitrogen and carbon dynamics in the Atlantic and Pacific Oceans.

In terms of scientific output, over 40 research reports, formally acknowledging the financial support of the European Community contract, have been produced. Over 30 papers have been published or are in press, as of November 1996, in standard peer-reviewed scientific journals. Medipelagos was also quite successful in terms of building international relationships. This can be seen in the significant number of MEDIPELAGOS publications and manuscripts in which authorship was shared by researchers representing partners of different countries.

A collaborative, European effort, Medipelagos provided important information needed to accurately characterise the Mediterranean ecosystem, vital to the long-term MTP goal of constructing a model capable of predicting change. It also produced findings of immediate significance for the management of the Mediterranean Sea by providing evidence of phosphorus rather than nitrogen limitation.

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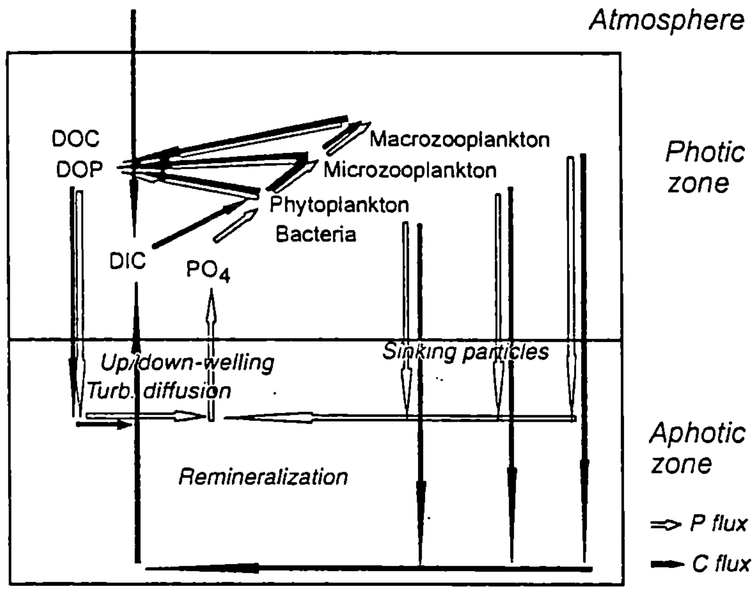

Illustration of a conceptual model suggesting an alternative functioning of the photic zone food web in phosphorus cycling: in addition to transforming imported 'new' phosphorus into sinking particles, it is also transformed into DOP re-exported by the processes of turbulent diffusion and downwelling. Spatial separation of C and P in deep waters is suggested to occur primarily for particle transport

Mediterranean Targeted Project (MTP) EUROMODEL II Project
Contract MAS2 - CT93 - 0066

Synthesis of Final Results

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The hydrodynamics of the Western Mediterranean Sea

ABSTRACT

The Mediterranean Sea is an ideal test basin to the "Observe, Understand and forecast" challenge in ocean research. The main objective of the EUROMODEL group is to describe, understand and simulate the circulation in the Western Mediterranean Sea with particular emphasis on the seasonal and mesoscale variabilities at basin and subbasin scale. Observations, theoretical, physical and numerical models are systematically employed using a process studies approach by which we have identified the major physical processes that drive and control the circulation in this basin.

The exchanges between the different subbasins and with the Atlantic ocean and the Eastern Mediterranean Sea are monitored in conjunction with PRIMO through extensive measurements in the major straits and passages. The Intermediate Water outflow is simulated in a physical experiment on a rotating platform. The role and relative importance of the topography constraint and the external forcings on the circulation are modelled and quantified while a robust dignostic simulation provides a description of the basin scale flow. In different subbasins, *in situ* experiments and numerical studies have shown the importance of the mesoscale circulation and its significant effects on the large, basin scale circulation. The high resolution numerical model simulations of the Western Mediterranean basin provide an accurate description of the basin scale and regional circulation and its variability.

Key Words : Western Mediterranean - Straits - Thermohaline fluxes - Wind stress - Topography constraint - General circulation - Sub basin circulation - Modelling - Data assimilation.

INTRODUCTION

The Western Mediterranean Sea is a thermodynamical system working under three external forcings (the density gradients through the Straits of Gibraltar and Sicily, the thermohaline atmospheric - buoyancy - fluxes and the wind stress), the flow itself being constrained by the topography. The atmospheric forcing presents a significant seasonal variability all over the Western basin, as does the circulation in the north, in particular with deep water formation that transforms Atlantic Water into Mediterranean Water, whereas no clear seasonal cycle is observed in the south. Simple budget considerations from the atmospheric thermohaline fluxes in the different subbasins and layers show that heat and salt must be transported from one place to the other. The present knowledge of the circulation is summarized in §2.1.

To achieve an overall description and a comprehensive understanding of the circulation, fundamental questions arising from the simple observations set out above are addressed concerning the quantification of the exchanges between the subbasins and the relation with the regional circulation (§2.2). The new scientific elements obtained by the EG within MAST 2 are presented thereafter (§3 and §4).

What is the circulation in the Western Mediterranean Sea ?

- What is known ?

In situ observations of the water masses characteristics, the currentmeters measurements and satellite IR images evidence the basin scale circulation in the Western basin as presented through the scheme in Millot (1987). Within the frame of MAST 1, the EG has been working in improving the scheme on several aspects and understanding the reasons for such a scheme through process studies in relation to seasonal and mesoscale variabilities of the circulation. The following paragraph summarizes the knowledge at the beginning of the EUROMODEL Mast 2 programme ; more details can be found in the papers referred at the end of the EUROMODEL MAST 1 report and in the EUROMODEL MAST 2 proposal.

Atlantic Water enters the Western Mediterranean Sea through the Strait of Gibraltar. In the western Alboran Sea, it forms an anticyclonic gyre whose dynamics is mainly controlled by the density gradient at the strait. The mesoscale circulation is observed to be highly variable with the presence of cyclonic eddies observed around the edge of the anticyclone and that could significantly affect the wavelike pattern of the flow. The AW could form a second anticyclone as it progresses eastward across the Alboran Sea. The flow further forms the Algerian Current whose baroclinic instability can generate eddies that could propagate northward in the basin, as both observed and modelled. No seasonal variation of the Algerian Current has been clearly evidenced from the observations. The surface cyclonic flow of Modified Atlantic Water reaches the Sardinia Channel. Part of it penetrates into the Eastern basin through the Strait of Sicily, the rest of the flow continues cyclonically around the Tyrrhenian Sea, exits at the Corsica Channel, joins the Western Corsica Current to form the Mediterranean Northern Current. Wintertime deep water formation (DWF) in the Gulf of Lions transforms the MAW in Mediterranean Water that occupies the western basin below 800 m. Numerical simulations show that DWF drives a significant part of the Mediterranean Northern Current. The observed seasonal variability in the Northern basin corresponds to a wintertime increase of the Mediterranean Northern Current transport as it becomes narrower and thicker. In the Balearic Sea, *in situ* and satellite observations showed that the Mediterranean Northern Current presents seasonal variations and strongly depends on the presence of two slope fronts. Intense mesoscale activity is characterized by very energetic eddies and filaments.

The subsurface circulation pattern is characterized by the Levantine Intermediate Water inflow through the Strait of Sicily and that flows into the Tyrrhenian Sea following the Italian coast, around Sardinia and northward along Corsica towards the french coast.

Water with LIW origin is also observed to flow eastward along Algeria. The thermohaline circulation cell closes with Mediterranean Water outflowing into the Atlantic Ocean through the Strait of Gibraltar.

- What is unknown ?

Fundamental questions arise from the simple considerations that the atmospheric conditions above the Western Mediterranean Sea present a significant seasonal cycle associated with a net annual heat loss in the northern part of the basin and a net annual heat gain in the southern part of the basin through the surface, which requires heat to be transported from the south to the north, and that in the northern part of the basin, DWF occurs in wintertime. The thermohaline cell thus described needs to be further understood and quantified. What are the associated exchanges between the different subbasins and vertically within each subbasin ? What are the connections between the exchanges ? What are the mechanisms that control or constrain them ? Are the different atmospheric conditions above the Ligurian Sea and the Tyrrhenian sea linked to the Corsica Current intensification in winter as observed in currentmeter measurements ? What is the effect of the wind and of atmospheric pressure ? What processes are involved ? Where are the crucial zones ? Where and when does the transformation of MAW into WMDW happen ? How much MAW is transformed into WMDW ? How and where does the newly formed water spread into the interior of the Western basin ? If no seasonal signal clearly appears at the Strait of Gibraltar in the MW outflow, it isn't directly fed by the DWF areas. Then where does the water come from ? How does the circulation in the subbasins affect the exchanges and vice versa ? What is the influence of the mesoscale circulation, particularly in the Alboran Sea where AW is modified as it enters the Western basin and in the Balearic Sea where recent MAW meets older MAW from the Mediterranean Northern Current ? Because of the similarity between the LIW flow at the Strait of Sicily and the MW outflow at the Strait of Gibraltar, is it possible that "Leddies" are generated in the Western basin as Meddies are generated in the Atlantic Ocean ?

To address these questions, the EG strategy is a multi-means approach with laboratory and numerical models, observation and monitoring experiments at sea.

Basin scale circulation

Describing and understanding the basin scale circulation is addressed both through observations and models. In the EUROMODEL MAST 2 proposal, the EG suggested that an accurate estimate of the seasonal variability of the transports in specific key places is able to significantly improve our understanding of the functioning of the whole Mediterranean Sea. Monitoring the straits thus appears as crucial in the observation programme. Observations in the Corsica Channel, in the Strait of Sicily and in the Mediterranean Northern Current are here presented while a model of the Strait of Gibraltar exchanges aims at understanding the interaction between the density flow and the tides. In parallel, several process studies related to the basin scale circulation clarify the role of the external forcings and of the topography constraint while a diagnostic simulation of the circulation in the Western basin brings a large scale description of the flow on a monthly basis.

- Key points monitoring

- The Strait of Gibraltar

The understanding of the exchanges between the Mediterranean Sea and the Atlantic ocean through the interaction of the tidal propagation and the density flow is addressed in a numerical model of the flow at the Strait of Gibraltar. A primitive equation model using an implicit algorithm and vertical s-coordinates is applied to an area spanning the Gulf of Cadiz to the Alboran Sea with a realistic topography. The horizontal resolution reaches 1/20° in latitude and varies in longitude from 1/10° at the boundaries to 1/20° in the strait. In a barotropic tidal flow simulation, the four most significant tidal harmonics (M2, S2, K1 and O1) are imposed at the western boundary from the Global Oceanic Tidal Model of Schwiderski while radiation conditions are prescribed at the eastern open boundary (Santos and Neves 1991). Simulated time series of surface elevation agree both in phase and amplitude with measurements by Garcia Lafuente (1986) on the western side of the strait. On the eastern side, the surface elevation decreases more than expected, which could be due to an inaccurate bathymetry. The 90° phase difference between the sea level and the velocity shows that bottom drag doesn't play an important role in the tidal flow across the strait and that the tidal wave is stationary. A southward / northward gradient of sea level during the flood / ebb tide at the strait can be related to a Kelvin wave. Attempts to simulate the density-driven flow emphasize the importance of the eddy viscosity in the model on the entrainement of Atlantic Water by Mediterranean Water and the necessity to implement double s-coordinates.

- The Tunisia - Sardinia - Sicily area

The PRIMO 1 experiment was organized to monitor the seasonal variability of the fluxes in the Western / Eeastern Mediterranean connection region, and the evolution of anticyclonic eddies in the Algerian basin near the Sardinia Channel. The EG, who has been involved in the PRIMO programme for many years, prepared and initiated the moorings experiment in the Sicily-Sardinia-Tunisia region. In November 1993, 4 moorings (21 currentmeters) were deployed along the Sardinia -Tunisia section and 13 CTD casts were performed (figure 1). At the same time, two moorings were set close the two sills of the Strait of Sicily, each of them supporting 4 instruments, two in the surface layer of MAW and two in the LIW below (the management of the eastern mooring was made in collaboration with IUN of Naples). The goal was to keep the two moorings in place for at least one year in order to check the existence of a seasonal variability in the transport through the channel.

A maintenance operation in May 1994 on the Sardinia - Tunisia moorings evidenced the existence of defective material in the mooring lines (inox parafil terminals) that resulted in strong corrosion and severe loss of instruments. Even if preliminary results account for a general cyclonic circulation at the intermediate and deep levels along the slope, and for the occurrence of intense inertial oscillations at depth, the definitive results will be relatively poor. As shown thereafter, this last conclusion was rather pessimist. The definitive recovery of the moorings occurred in October 1994 with the italian R.V. Urania. As supported by the current meters deployed in the vicinity on the THETIS 2 moorings, the whole data set clearly indicates that all intermediate and deep waters flow along the continental slope, eastward on the Tunisian-Algerian side and westward on the Sardinian one. As detailled in the EUROMODEL-3 proposal, new hypotheses have emerged, mainly from this data set analysis. Consistently with our schematic circulation diagrams, we are now thinking that WMDW formed in the Gulf of Lions first fills the Algero-Provençal basin (max depth ~ 2900 m) before flowing through the Channel of Sardinia (depth of ~ 2000 m) and thinking into the Tyrrhenian Sea (max depth of ~ 3900 m) where it mixes with the waters issuing from the Channel of Sicily to form TDW. TDW will be the sole Mediterranean deep water issuing through the Strait of Gibraltar together with LIW.

A hydrographic survey with CTD casts and water sampling was made across the Strait of Sicily (with the exception of the Tunisian waters). A preliminary analysis of the data shows that the vein of LIW outflowing from the eastern Mediterranean directly enters the Tyrrhenian Sea close to the western and northern sides of Sicily. The central ridge encountered in the Channel of Sicily causes this outflow to bifurcate. A satisfactory estimation of the dynamic conditions governing the water fluxes through the Channel of Sicily is far from being reached as past values spanned from 0.65 to more than 3 Sv. Together with two mooring lines set in both sides of the channel, CTD casts have been collected in Nov. 93, May and Oct. 94. A quite energetic current is found at all depths on the tunisian side, markedly affected by an intense mesoscale activity in the surface layer, and appearing impulsive in the bottom layer. Another vein of MAW was seen to flow over the Sicilian shelf, thus defining a wide central region. LIW fills the two deep channels with cores well defined in S (38.75) at ~ 250 m. A bottom vein of colder (13.60°C) and denser water has been observed for the first time flowing northward, which is expected to play a major role in the mixing processes occurring in the Tyrrhenian Sea to form TDW.

The LIW flow at the Strait of Sicily and the Mediterranean outflow at the Strait of Gibraltar present some similar characteristics that raise the question of whether "Leddies" can be generated in the Western basin as Meddies are generated in the Atlantic Ocean. The EG addresses this question through laboratory modelling of an intermediate current and its instability. Experiments were conducted on the 14 m diameter rotating platform. The intermediate water flow was modelled by introducing intermediate density water in a two-layer system of salted and fresh water ($Dr/r=10^{-3}$). The current is observed to flow along the tank and is evacuated far away (40 m) from the injection location. The experimental facility allows to access to a large range of dimensionless numbers. The relevant parameters appear to be the Ekman (Ek_0) and the Bürger (Bu_0) numbers. There is a significant evolution of the current as the Bürger number increases while the Ekman number is constant. In particular, when both numbers are both small (Ek_0= 2.10^{-4} and Bu_0=0.25), eddies are generated along the vein. A meander forms and grows while getting thinner near the wall, and separates from the vein to form a lens of intermediate water. Another meander then appears at the same location, and the process repeats itself. In sensitivity experiments, the flow pattern is observed to be strongly dependent from the Ekman and Bürger numbers (Baey *et al.* 1995). Conditions in nature correspond to Bürger numbers smaller than 1. The parametrical study is in progress.

It is the opinion of some of us that, although presenting some similarities, the Sicily and Gibraltar outflows present some differences, the former spreading over a much wider depth interval than the latter. This could be essential to better understand the mixing processes occurring in the Tyrrhenian Sea and will be discussed during the next MAST days.

- The Corsisa Channel

A currentmeter chain is continuously working since 1985 (with the exception of 1989-1990. The time series indicates that the seasonal oscillation of the current represents the most important feature of the regional circulation. Nevertheless, it shows a relevant interannual variability and its energy has been seen to strongly decrease in the most recent years. This is interpreted by Astraldi and Gasparini (1992, 1994), Astraldi *et al.* (1994 a and b) and Artale *et al.* (1994) as a significant change sustained by the atmospheric-climatic conditions over the basin. As these conditions have significantly evolved (increase of the winter air temperature over the basin and regression of the Alps ice cover), the annual variability of the transport in the Corsica Channel could be indicative of the response of the whole Mediterranean circulation to the atmospheric forcing.

- Density gradients at the Straits of Gibraltar and Sicily

The first specific study is devoted to the response of the Western Mediterranean Sea to density gradients through the Straits of Gibraltar and Sicily and preliminary results were obtained during EUROMODEL MAST 1. Attention is focused on surface and intermediate water circulations and on the effect of topography upon them in sensitivity experiments using a three-dimensional primitive equation numerical model.

A lock exchange experiment with a realistic transport at Gibraltar shows an initialization of a coastal current by a Kelvin wave modified by topography which generates the Algerian current. The coastal current is baroclinically unstable along the Algerian coast.

A cyclonic circulation sets up in the North due to the separation of the current at the Strait of Sicily (Herbaut *et al.*, 1995). A process study on the influence of a sill on a coastal current gave a first insight in the separation dynamics of the upper layer circulation (figure 9, Herbaut et al., 1995). The responsible mechanism can be analysed as follows. Let us consider a baroclinic coastal current initiated by a coastal Kelvin wave front. When the current arrives near the strait, the bottom current is constrained by the sill topography to cross the strait entraining part of the upper current by vorticity conservation. Another part of the upper current follows the cost and penetrates into the strait. The detail mechanism involves the generation of double Kelvin waves at the sill and a barotropisation of the current by the bottom torque. Sensitivity experiments show that the shallower the sill the larger the cross strait transport.

The Mediterranean Northern Current is 40 % of the transport of 1.8 Sv as estimated by Béthoux et al. (1982). The uncertainty of the observed transports at the Strait of Sicily does not allow to validate the results, but they are of a reasonable order of magnitude. This experiment shows that there is a link between the Strait of Gibraltar and the Strait of Sicily. The transport in the Strait of Sicily depends as much on the density gradient at the strait as on the MAW transport coming from the Strait of Gibraltar. The experiment hasn't been run for more than a year since there is no mechanism to transform the incoming AW into Mediterranean Water : the Western Mediterranean sea is thus continuously filled up with AW, which would lead to an irrealistic hydrological state after some years of integration (Herbaut *et al.* 1995).

- Transports through the straits and thermohaline fluxes

The second set of experiments addresses the role of the forcing of the thermohaline fluxes and its seasonal cycle. The daily thermohaline fluxes are provided by the analysed fields of the Péridot model. To compensate for the low heat loss in winter (compare to the FNOC data set) - crucial during the preconditioning phase of deep water formation -, for the homogeneous initial T and S fields and for the lack of wind, the fluxes are artificially increased in January and February above the DWF area.

The basin scale cyclonic circulation sets up as described in §2.1. At the end of February of the first year, DWF occurs in the Gulf of Lions. The water characteristics (T=12°80 C and S=38.42 psu) are comparable to observations (Gascard 1978, Schott and Leaman 1991, Schott *et al.* 1994). In the convection area, a cyclonic circulation at the surface over an anticyclonic circulation at depth is in agreement with the studies of Crépon *et al.* (1989) and Madec *et al.* (1991 a and b).

Deep water formation modifies the regional circulation in several areas. During the first year, the southward transport across the Channel of Ibiza in the surface layers (first 100 m) decreases from December to May. Meanwhile, the southward transport in the deep layers (between 200 m and the sill) increases. These transport variations can be interpreted through the propagation of an internal Kelvin wave along the Spanish coast generated by DWF. In fact, Madec and Crépon (1991) explain the propagation of such a Kelvin wave along the Spanish coast when the DWF zone is located near the coast. In the present experiment, the density gradient associated to the DWF zone (located near the coast during the first year) generates a baroclinic Kelvin wave propagating southward along the Spanish coast. These fronts tend to decrease the southward surface current and to increase the current at intermediate depths. A direct consequence of DWF is the generation in the simulation of a surface current flowing to the North-East between Minorca and Sardinia. This current starts at the beginning of the first winter. The thermohaline flux generates a North-South density gradient between the Northern and the Algerian basins, driving this surface current. Advection of less salty MAW directly from the Algerian basin modifies the characteristics of the deep water formed. After 5 years of integration, its temperature and salinity decrease to 12°4 C and 38.37 psu only.

The simulation allows to investigate the transports in the straits and their relationships. Variations of the eastward surface transport (0 - 100 m) in the Sardinia Channel are correlated to the surface transport in the Strait of Sicily. The processes involved in the Strait of Sicily seem to be different from these at Gibraltar. Indeed, the variations of the density gradient between the Gulf of Cadiz and the Western Mediterranean Sea drive the transport variations in the Strait of Gibraltar. On the opposite, the transport variations in the Strait of Sicily seem to be forced by the transport variations of MAW in the Sardinia channel. Variations of the westward surface transport (0 - 100 m) along the northern coast of Sicily are correlated to these of the Corsica Current with about ten days lag. This correlation is due to the fact that a part of the MAW enters into the Tyrrhenian sea and forces the transport into the Strait of Corsica. In this simulation, there is a decrease of the Corsica Current transport in winter. It is associated with the decrease of the surface current through the Sardinia Channel due to the northward flow between Minorca to Sardinia. This is different from the correlation between heat fluxes over the Tyrrhenian and Ligurian Seas and the Corsica Current transport as suggested by Astraldi and Gasparini (1992) and detailed in 3.1.2.

- Wind stress

In order to investigate the sole role of the wind stress from the two Péridot data sets, experiments are run where the Strait of Gibraltar is closed (in order to avoid the thermohaline effect of the absence of DWF). At the initial time, the density profiles are horizontally homogeneous. The model is forced during a ten month period (from June to March) with the Péridot daily wind only. No definite surface circulation pattern emerges except in the Liguro-Provençal basin and in the northern part of the Tyrrhenian Sea. With the P89 wind forcing, an anticyclonic eddy develops within a month to the West of the Gulf of Lions and intensifies (above 0.4 m/s at 80 m in March 1989). This structure is related to the high negative wind stress curl centered near Cap Creus. A similar anticyclonic eddy is simulated with the P92 wind forcing, but it moves to the southwest after 7 months. In the surface layer, a large cyclonic circulation occupies the Ligurian Sea and the eastern part of the Gulf of Lions, trapping a cyclonic eddy off Toulon that extends down to 400 m. With the P89 wind forcing, the cyclonic circulation pattern splits in winter into two cyclonic structures (one corresponding to the cyclonic eddy off Toulon, the other one in the Ligurian Sea), shutting off the coastal current. With the P92 forcing, the large cyclonic circulation remains in the Northern basin until the end of the experiment. In the Northern Tyrrhenian Sea, a dipole structure with the cyclonic eddy to the North sets up in front of the Strait of Bonifacio. With the P89 wind forcing, the northward transport in the Corsica Channel exhibits two maxima of about of 0.7 Sv in December and March, which is of the same order of magnitude as observed by Astraldi *et al.* (1994 a). However, the P92 wind forcing induces a significant transport across the Corsica Channel to the South (0.5 Sv) that reverses at the beginning of the winter (around 0.6 Sv). The detailed analysis of the results is still in progress.

- Topography constraint

The basin scale circulation of the Western Mediterranean Sea is well observed to follow a definite cyclonic path as successfully modelled in numerical simulations. However, systematic deficiencies at a subbasin scale are observed, in particular with the determination of the Algerian current as a narrow current along the African coast or the cyclonic circulation observed in the Balearic Sea. Holloway (1992) suggests that subgridscale eddy-topography interaction ('topostress') may be responsible for such systematic defects. Using a statistical mechanics approach, it is possible to obtain a parametrization of this effect, the so-called "Neptune" effect, for modelling the ocean circulation on basin scales and over time scales from years to centuries in relation to climatic problems. The importance of the Neptune effect on the circulation in the Western Mediterranean Sea is tested in a primitive equation model. Different numerical experiments of the Western Mediterranean were done with and without eddy-topography interaction. In an ideal Western Mediterranean configuration with closed straits, the influence of the Neptune effect parametrization is tested. It is shown that the interaction between eddies and topography could be responsible for the cyclonic pattern of the general circulation in the Western Mediterranean (Alvarez *et al.* 1994 a and b). In the more realistic case of open straits and without the Neptune effect parametrization, the modelled circulation, mainly driven by the influence of the straits, shows clear deficiencies with a wide AW inflow that mainly penetrates into the Eastern basin. When the Neptune effect parametrization is included, a clear cyclonic pattern emerges, with several characteristic features of the general circulation of the Western Mediterranean : a thin Algerian Current following the African coast, the Mediterranean Northern Current, the Western Corsica Current and the Balearic front (figure 2). The Neptune effect may thus be a significant factor in the basin and subbasin scale circulation in the Western Mediterranean Sea. Its parametrization was then included in the diagnostic basin scale circulation model where it intensifies the cyclonic circulation.

- A perpetual year robust diagnostic simulation

A description of the basin scale circulation is obtained with a diagnostic computation in a three-dimensional primitive equation model (Beckers 1991, 1992 a and b, Deleersnijder and Beckers 1992, Beckers and Deleersnijder 1993, Beckers 1994 b). A perpetual year simulation is conducted with a relaxation technique towards climatological monthly mean fields of temperature and salinity kindly provided by P. Brasseur (MODB data base) and with a time scale of the order of the month in the main water body (and decreasing near the bottom and the coasts) (Haney 1971, Brasseur 1991, Stanev and Friedrich 1991, Verron *et al.* 1992, Brasseur and Brankart 1993, Malanotte-Rizzoli 1994, Brasseur *et al.* 1994). The atmospheric forcing is provided by the 1988 - 1989 Péridot data, modified to comply with climatological indirect estimates of the air-sea fluxes. The Péridot wind speed has a mean value of about 4 m/s, which is much smaller than the 5.5 to 7.5 m/s estimated in Garrett *et al.* (1992). A correction of the wind speed by increasing it by 25% is suggested, the latent heat flux is then changed in a coherent way to comply with climatological values. By doing so, the latent heat flux value can indeed be corrected from the low value of 80.5 W/m^2 to a more plausible 98 W/m^2, consistent with salinity budgets (Garrett *et al.* 1992). Uncertainties in parameters in the infrared computation allow to reduce the upward flux by 1.5%, which gives a net radiation flux of 81 W/m^2, rather than the initial 88 W/m^2. The atmospheric data set is thus compatible with the generally accepted climatology, but includes synoptic atmospheric perturbations necessary for deep water formation and mixing in the surface layer (Beckers 1993).

The seasonal variability of the basin scale cyclonic circulation appears for example in the Algerian Current as the latter flows closely to the African coast in February whereas intrusions of Atlantic Water directly into the Balearic Sea occur in December. The salinity concentrations in the Northern basin show a seasonal signal linked to deep water formation. The preconditionning phase is evident end of December with a doming of the isopycnals in the Gulf of Lions. Mixing reaches the deeper layers a month later. Several diagnostic tools have been used to characterize the response of the basin (Beckers *et al.* 1993, 1994). In particular, it is shown that the sea surface elevation is mainly related to the dynamic height computed from the density field referenced at the bottom. The Mediterranean Northern Current transports shows a wintertime intensification as observed during the Primo-0 experiment. The modelled transport through the Corsica Channel can be related to the atmospheric forcing. The correlation between the transport and the pressure difference seems to be the predominant one, which means that a high pressure over the Gulf of Lions would decrease the flux through the Corsica Channel. This effect is fast whereas heat flux effects would be delayed in time (Astraldi and Gasparini 1992).

- <u>A twenty year adjustment simulation</u>

A specific experiment is designed to understand how the water masses characteristics and the basin and subbasin scale circulation set up in the Western Mediterranean Sea under the external forcings. The Western Mediterranean basin model is initialized with horizontally homogeneous profiles of temperature and salinity and at rest (as in §3.2.1) and forced for twenty years by the Péridot original heat fluxes and winds. The basin scale cyclonic surface circulation presents a high mesoscale variability in the Algerian basin. DWF occurs in the first three years. This emphasizes the importance of the wind in the process since DWF didn't happen in the experiment described in §3.2.2 without an artificial intensification of the fluxes. No DWF occurs anymore after the fourth year : one reason may be that no more LIW is locally available since it has been consumed by DWF during the first three years and is not yet advected from the Strait of Sicily. Another explanation can be due to the advection of light AW from the Southern basin that reaches the Northern basin. Cold and fresh water is formed in winter in the south of the Gulf of Lions down to around 400 m and spreads to the southwest towards the Balearic Sea. LIW fills up the whole Tyrrhenian Sea around 400 m and slowly flows northward along the west coast of Sardinia : it takes about 15 years to reach the Northern basin (figure 3). Some LIW is entrained by mesoscale eddies in the interior of the Algerian basin. The LIW transport through the Corsica Channel is weak, around 0.05 Sv compare to 0.1 - 0.2 Sv as observed by Astraldi and Gasparini (1992). The inflow through the Strait of Gibraltar stabilizes around a mean value of 0.85 Sv and presents a 10 % variability. In the Strait of Sicily; the transport varies from a minimum of 0.3 Sv in winter to 1.2 Sv.

- Control of the basin scale circulation by the thermohaline fluxes

- Design of a control experiment

The basin scale experiments point out the importance of an accurate description of the thermohaline fluxes involved in the DWF process. The present atmospheric data sets present some inconsistency if they are to be used for climatic simulations. Correcting the fluxes by an offset or a factor is arbitrary and might not reflect a possible regional or seasonal inaccuracy. The EG suggests an indirect estimate of the correction to the thermohaline fluxes through a control experiment. Control theory with a variational approach offers the adequate framework to the problem formulated as : what are the thermohaline fluxes compatible with an annual cycle of the basin scale circulation? How sensitive is the flow pattern to modifications of the atmospheric forcing?

- The circulation in subbasins

As shown in EUROMODEL MAST 1, mesoscale activity in regional basins can strongly modify the basin scale circulation pattern. Regional investigations and process studies are conducted through *in situ* observations and numerical modelling to apprehend the physical mechanisms involved in the mesoscale circulation. Such an approach is crucial to understand the related specific behaviour of the circulation in the basin scale models.

- The Alboran Sea

The Alboran Sea is the first Mediterranean basin encountered by inflowing Atlantic Water. The large scale circulation is fairly well known with a meandering current associated with one or two anticyclonic gyres (the Western and Eastern Alboran Gyres). The spatial and temporal variability of the circulation is however not yet fully understood, with a significant mesoscale activity and the occasional collapses of the Eastern Alboran Gyre and the Almeria-Oran front.

An intensive field experiment was carried out by the EG between September 22 and October 7, 1992. Data include 134 CTD casts, ADCP and satellite imagery. A well defined wavelike front is observed with two significant anticyclonic gyres in the Western and Eastern Alboran Sea. Smaller scale cyclonic eddies were also observed. The front separates the more saline, older MAW (S > 36.8) in the northern region from the fresher, more recent MAW (S<36.8) to the south. The associated baroclinic jet has a mean transport of 1 Sv and maximum geostrophic velocities of 1 m/s. The three-dimensional structure and spatial scales of both gyres are similar, 90 km long and 220 m deep. In the Eastern Alboran, northeast of Oran, the origin of the Algerian Current was also detected with an eastward transport of 1.8 Sv. The general picture can be presented as a structure formed by a wavelike front coupled with two large anticyclonic gyres - small cyclonic eddy systems (Alonso *et al.* 1991, Viudez and Tintoré 1993, Viudez *et al.* 1995 b, Gil and Gomis 1994, Tintoré *et al.* 1994 b).

The relative importance of stratification, relative vorticity, and Froude number in the distribution of potential vorticity has been examined. Potential vorticity conservation was used to infer vertical motion. It was found that the strong meridional shears due to mesoscale phenomena in the western Alboran play a main role in this forcing. The vertical velocities associated with these mesoscale structures reach maximum absolute values of 15 m/day (Viudez and Tintoré 1993). The three-dimensional velocity field was diagnosed through density dynamical assimilation in a primitive equation model with mesoscale resolution. The ageostrophic motion was computed from fields produced by short-term backward and forward integrations of the primitive equation model initialized with quasi-synoptic CTD data from the Alboran Sea. A weight function was applied to the resulting time series of model variables to obtain the final, dynamically balanced, density and three-dimensional velocity fields. The weight function is based on the Digital Filter Initialization (DFI) method of Lynch and Huang (1992), modified here to account for the non-stationary spin-up effects in the time series. The diagnosed ageostrophic motion was checked by comparison of the vertical velocity field with that obtained from the classical quasi-geostrophic (QG) Omega equation. The two methods produce generally similar results, with typical vertical motions in the range of 10-20 m/day associated with jet meanders (figure 4). Local differences are attributed to known limitations of the QG theory, but could also be partly due to computational errors associated with the high order derivatives required by the QG method. The general success of this approach could provide an alternative to QG diagnosis in mesoscale dynamics (Viudez *et al.* 1995 a).

With the aim to study the temporal evolution of mesoscale dynamics, the imaging Synthetic Aperture Radar of the ERS-1 satellite was used. ERS-1 SAR has evidenced to be useful in tracking sea surface mesoscale structures related to current shear in the western Mediterranean (Martinez *et al.* 1992, Font *et al.* 1993, Font and Shirasago 1993). A set of 36 SAR images corresponding to the 1992 Alboran sea campaign (mid September to mid October) were corrected and georeferentiated, following the methodology previously developed by the EG (Font and Martinez 1993). A first general sea surface roughness map for September has been constructed with six ERS-1 night-time ascending passes and three day-time descending passes. The presence of shear lines allows the identification of the western and eastern gyres, as well as smaller cyclonic eddies along their northern boundaries. The structure is similar to what has been identified by the EG with *in situ* data, which confirms that SAR can be a valuable tool to monitor sea surface mesoscale variability in this region. A comparison with upper layer ADCP measurements indicates a good correspondance, especially in the area of the formation of the Algerian current.

The ERS-1 radar altimeter has also been used in investigating a longer time scale variability of the Alboran sea surface, in collaboration with Dr. J. Vazquez (JPL, Pasadena, USA). Alongtrack data were corrected (including tidal effects) and interpolated onto a regular grid in space-time for the period February 1992 - February 1994. Sea surface height maps at 10 day interval were created, and the total time variability at each point was computed. The Complex Empirical Orthogonal Functions analysis, that resulted to be very efficient with Geosat altimeter data in the Gulf Stream (Vazquez, 1993), was applied to our data set and evidenced the temporal variability to be mainly associated to the major Alboran Sea dynamic features (Gibraltar inflow, anticyclonic gyres, Almeria-Oran front, mesoscale eddies, Algerian current formation). In a further analysis, a more precise orbit determination has been used to compare altimetric and sea surface temperature maps (Vazquez *et al.* 1995). The results appear to be significantly better than previous altimeter-infrared comparisons made with Geosat in the Algerian basin (see 4.2.2). ERS-1 will be used together with Topex-Poseidon altimetry (whose preliminary analysis shows a very good performance) in a high resolution study of eddy variability in the Algerian current region.

Experiments carried on the rotating platform underline the coupling between the regime of the Strait of Gibraltar flow and the general circulation pattern of the Atlantic Water in the Alboran Sea (Gleizon *et al.* 1994). Moreover, they enabled to diagnose some observed phenomena. As expected on the basis of previous experiments, the flow pattern shows one or two anticyclones which can be related to the Alboran gyres. The response of the surface flow in the basin to the strait hydrodynamics is reproducible in a deterministic sense. In particular, the two gyres develop for a Rossby radius of deformation, at the outlet of the strait, approximately equal to 1.2 time the width of the strait. The discharge of Atlantic Water defines the time of evolution of the Western Gyre (a higher flow rate related to a shorter time evolution). For instance, when the flow rate of the Atlantic current is close to 2 Sv (which is rather high compared with the measured value of 1 Sv), after two months, the Western Gyre occupies the whole area of the Western part of the Alboran Sea. The general flow pattern shows a good analogy with the numerical model of Speich *et al.* (1994). Some additional characteristics of the flow are underlined in the physical model. In the periphery of the Gyre, the flow exhibits mesoscale turbulent activity. Cyclonic eddies form in the northern part of the jet (front) and are advected by it. The mechanism involved can be related to this described by Wang (1993). These features appear only when the Gyre has grown to the stage where the jet 'hit' the northern limit of the basin (the Spanish Coast) and split into two branches, one coming back to destabilize the front of the Atlantic inflow near the outlet of the strait. It can be assumed from the experiments that the eddies are produced by baroclinic instabilities. These cyclonic structures can be compared to those observed by Tintoré *et al.* (1991 b). Their characteristic sizes (in "nature scale") are in the order of 15 km as observed. The circulation of dense water (corresponding to Mediterranean Water) reveals a weak anticyclone under the Western Gyre, as modelled by Speich (1992). It is probably due to stress induction at the interface and by increasing curvature and depth of the interface undan increasing curvature and depth of the interface under the Western Gyre, thus involving a change of relative vorticity by conservation of potential vorticity in the layer. This appears to be a typical feature of the dense water in the experiments.

- <u>The Algerian basin</u>

- Instability of a coastal current

Observations (Benzohra and Millot 1995 a and b) and model simulations (Herbaut *et al* 1995) show that the mesoscale activity associated with the Algerian Current is definitely related to the northward spreading of Atlantic Water and the flow through the Sardinia Channel, as well as to the water characteristics changes. The mesoscale wavelengths and the evolution of the eddies have thus to be accurately described and understood. Following the investigation of the dynamics of the Algerian Current during EUROMODEL MAST 1 (Beckers 1992 a, 1994 a, Beckers and Nihoul 1992, Mortier 1992), the instability of a coastal current in relation with its interaction with the topography is addressed in a numerical experiment. More specifically, the influence of the shelf break topography on the unstable behaviour of a gravity coastal current and on the deep mean flow generated by the mesoscale circulation is addressed in a primitive equation model with a two-layer fluid schematizing the stratification in the Algerian Basin.

In a simulation in a periodic domain with a schematic shelf break, the effect of the topography is to shorten the length of the most unstables waves and to disminish the growth rate with respect to the flat bottom case. The process can be described as follow : the second class wave that propagates in the deep layer is accelerated by the topography gradient and then interacts with the surface layer wave at shorter wavelengths. The role of topographic gravity waves still has to be deepened since these are able to exchange energy with other componants of the flow.

The behaviour at large amplitude waves is similar to the flat bottom case. The surface current forms meanders that generate anticyclonic coastal eddies. These eddies migrate offshore and become baroclinically unstable. They split into two eddies with an enhanced barotropic componant as the vertical stratification weekens. This is associated in the deep layer with the generation of an eastward mean deep flow trapped at the coast. This alongshore flow is much stronger and the offshore eddy more barotropic than in the flat bottom case. It is noticed that in presence of topography the current flows eastward near the coast whatever the depth as found in observations. The steeper the slope, the more intense the barotropisation. Effect of canyons and bumps was also investigated.

This mechanism has now to be interpreted in the context of the deep alongshore and eastward mediterranean flow observed in the Algerian Basin. The bottom torque - which is an efficient mechanism to generate barotropicity and then enhanced deep circulation -, could provide the adequate framework for this interpretation. In fact, this barotropisation due to the topography could explain the Algerian eastwards flows whatever the depth, as observed on currentmeter records of Médiprod-5.

This kind of numerical experiments are particularly severe for testing the parametrizations and approximations of a 3D model. Indeed, unacceptable problems arise from the z vertical coordinates system that was used for the earlier experiments. The discretization of the bottom topography is too coarse, generating strong step shaped discontinuities that completely modified the topographic waves. When energetic barotropic eddies are generated and interact with these steps, a non realistic diffusion must be added for the model to hold. A generalized s-coordinate system is thus used for the unstratified deep layers, allowing for a good description of the bottom without altering the pressure gradient or the horizontal diffusion (Madec *et al.* 1994). For the surface stratified layers, z-coordinates are conserved. Satisfying results are obtained allowing an exact comparison with analytical wave solutions. This mixed vertical coordinate system seems adequate for a Mediterranean GCM since the deep mediterranean layers are only weekly stratified and tests will be performed in that sense with the realistic basin and stratification.

- The Algerian Basin circulation revisited

Revisited analysis of the Médiprod-5 experiment (Benzohra and Millot, 1995 a, b, Millot *et al.*, 1995) and results of numerical and physical models enlighten the understanding of the dynamics of the Algerian basin (Beckers 1994 a, Obaton *et al.* 1995 a and b). The Algerian Current - which is formed of MAW - is relatively narrow (about 30 km) and deep (about 400 m at the coast) at about 0° and becomes wider and thinner while progressing eastwards. It can strongly interact with mesoscale eddies (diameter of 100-150 km) which are in a quasi-stationary state in the open sea and it can entirely spread seawards, thus leading MAW to be directly advected into the Catalan Sea between the Balearic Islands. In the Algerian coastal zone, all water masses, and especially WIW and LIW, are found to flow eastwards; at about 0°, a 1.7 Sv transport (0-700 dbar) has been estimated from one hydrological transect. According to the previous schematic circulation diagrammes (Millot 1987, 1991) which are supported and complemented by the available data sets, the EG now clearly suspects that the surroundings of Cape Gata (or more generally the northeastern Alboran Sea) constitute a very crucial zone where the inflowing MAW encounters the various waters flowing southwards along the spanish continental slope, i.e. the whole resident MAW (thinner than the inflowing MAW), part or the totality of WIW and the upper part of LIW (depending on the relative thicknesses).

Only one campaign (Médiprod-5) was specifically devoted to understand the physics of the Algerian Current and some major questions remain about the characteristics of the so-called "coastal eddies" (50-100 km in diameter) and about their links with the Algerian Current. When considering drifting buoys and ship trajectories, it appears that the mesoscale IR features are closely related to coherent currents in a few 10 m surface layer. During the 9-month experiment of Médiprod 5, several "coastal eddies" have been detected, from infrared images as well as from *in situ* temperature measurements, progressing eastwards at a few km/day. The problem is that the increase of these mesoscale features has not been observed (on the contrary to what was hypothesized before the experiment), some of them even disappearing within a few days. Only one of these "coastal eddies" has been associated with very intense and deep mesoscale currents and the sole possibility the EG has found to make coherent the whole data set is imagining the following structure (figure 3 in Millot, 1994). The basic feature is a solitary meander of the Algerian Current which generates, between its inner edge and the coast, an anticyclonic circulation (figured out by what we have called a "coastal eddy") in a 100-200 m surface layer. This feature is completely coherent with data analysis from physical experiments conducted on the rotating platform at IMG (in 1992 during EUROMODEL MAST 1). These experiments clearly show very similar instabilities developing when the Burger numbers range between 0.2 and 0.7. As these instabilities grow, meanders are formed, each of them "enclosing" a coastal eddy (Chabert d'Hières *et al.* 1991, Obaton and Chabert d'Hières 1995, Obaton and Tritton 1994). In addition, *in situ* data strongly suggest that this meander occurring in the surface layer could be rapidly associated in the whole deeper layer with a "quasi-barotropic" and relatively intense anticyclonic eddy of about 150 km in diameter. Such a structure can be compared with those depicted in the atmosphere as a result of the interactions between the meandering jet streams and the high and low surface pressure systems, and it can be explained in terms of potential vorticity conservation. But our data set and theoretical considerations are not sufficient to validate our analysis and both laboratory and numerical experiments more specifically dedicated are strongly needed.

The sea surface elevation associated with such mesoscale events needs to be monitored as the accuracy of actual altimeters probably allows to evidence their signatures. An analysis of the GEOSAT data simultaneously collected with the Médiprod-5 experiment (in 1986-1987) showed a relatively large variability of the altimetric signal in both time and space which does not seem to correspond to actual marine phenomena. We have not been able to establish clear relationships with the thermal features from infrared imagery, but this cannot be considered as a definitive conclusion. Indeed, we are actually performing the same kind of analysis with Topex-Poseidon-ERS data sets and the preliminary results are much more encouraging. The Médiprod-5 current time series have also allowed a very interesting analysis of the tidal (mainly M2, S2, N2) currents (Albérola *et al.* 1995 a). These currents are clearly barotropic and their amplitudes decrease from a few cm/s in the west to a few mm/s in the east, while the phase significantly increases eastwards, which is consistent with numerical models.

- Instability of an intermediate water flow

The path of LIW in the Western Mediterranean Sea is still puzzelling. Is the LIW vein stable? Is it trapped by topography? In order to answer to these questions a study of the instability of an intermediate water flow was conducted on the large rotating plateforme of IMG at Grenoble. One investigated the stability of a constant volume flow of intermediate water into a rotating two-layer system initially at rest. Five flow regimes were explored with different Ekman and Burger numbers. The smaller the Ekman and Burger numbers, the more instable the fluid. At small Ekman and Burger numbers there is formation of dipoles or even anticyclonic lenses of intermediate water similar to meddies. Previous observations favored topographical singularity, i.e. as triggering the formation of such lenses. An important conclusion from the present study is that topographical effects are not necessarily required for the generation of long-lived lenses of intermediate.

- <u>The Mediterranean Northern basin</u>

The Mediterranean Northern Current is actually a unique entity which flows along the continental slope from the Ligurian Sea as far as the Channel of Ibiza. Its observed transport is maximum (1.6-1.7 Sv between 0 and 700 dbar) during a relatively long winter season, but its structure markedly changes with time. This might explain some of the discrepancies found in the literature (Béthoux *et al.* 1982, Astraldi *et al.* 1990) about its seasonal variability, since using current or hydrological measurements can provide very different (although complementary) information. The Mediterranean Northern Current has been recently investigated during two experiments, the first one conducted from May to December 1985 during the Prolig-2 experiment (Sammari *et al.* 1995) when 12 currentmeters were moored, the second one conducted from December 1990 to May 1991 during the PRIMO-0 experiment (Albérola *et al.* 1995-b, Conan and Millot 1995) when 60 currentmeters were moored. These experiments permit a clear understanding of the behaviour of this current (Albérola 1994). In summer, the Mediterranean Northern Current is relatively wide and shallow, and it displays a relatively reduced mesoscale variability. In the Catalan Sea, it flows below a very warm superficial layer (due to a sheltering effect of the Pyrénées), a part of which possibly directly issued from the Algerian Basin, thus being perpendicular to a very intense thermal front in the vicinity of Cap de Creus (Lopez-Garcia *et al.* 1993, 1994). In winter, the northwesterly winds swept away these surface waters, leading to a frontal system (the so-called North Balearic Front) which now occupies its most extreme position along the Balearic Islands. The Mediterranean Northern Current becomes thicker and narrower while it tends to flow closer to the slope. At this time, it develops relatively intense mesoscale meanders (with amplitude and wavelength of a few tens of km), as evidenced by very characteristic features during PRIMO-0 : the semimajor axes of the dispersion ellipses are perpendicular to the coast in the core of the current and display a clockwise (resp. anticlockwise) rotation of the current on its inner (resp. outer) side. As previously observed (Taupier-Letage and Millot 1986), this mesoscale variability is associated with a turbulence which clearly spreads seawards over large distances. Some aspects of the winter distribution of the intermediate waters have been clearly evidenced. WIW appears to result from an overlaying of cooled and mixed MAW by less cooled one (a process which can occur everywhere in the sea) while LIW no more flows like a vein along the continental slope, but spreads seawards where, as well known, it participates to the formation of WMDW. In a several-km coastal zone (between the inner edge of the current and the coast), it seems that most of the time, except maybe in the deep winter, a relatively small scale turbulence precludes from clearly evidencing any significant mean circulation (Albérola *et al.* 1995-b). In such a case, it would be extremely difficult to make a significant forecast of the circulation there.

The seasonality of the mesoscale motion in the Mediterranean Northern Current in the Balearic Sea has been investigated with a long time series (1987-1992) of current meter data in the shelf break off the Ebro river (Font *et al.* 1995). In that location, the general flow is alongslope with occasional disruptions for periods of several days (mesoscale events) and a marked barotropic character. Clockwise rotations in a near-inertial frequency are repeatedly present, even at the deepest level recorded (100 m). The main observed feature in a low-passed time series below the thermocline is a rapid and strong autumn increase in mesoscale activity, that results to be always present and with very small interannual variability on its temporal location. The maximum of mesoscale activity is followed by a rapid decrease in winter and then by a continuous lowering until the end of the summer. This seasonal characteristics are coherent with the observations made in the Ligurian Sea Albérola *et al.* 1995 b, Sammari *et al.* 1995). A complete characterisation of the mesoscale motion in the Mediterranean Northern Current, including its origin and interaction with the main flow, requires more extensive experimental and numerical work. Our results have demonstrated this motion displays a clear seasonal cycle and presented several evidences that the recorded mesoscale activity is much more linked to the shelf / slope front evolution than to local wind variability.

Even if the major characteristics of the Mediterranean Northern Current itself as well as those of its associated mesoscale meanders can now be considered as pretty well described, we are not yet able to clearly account for an accurate seasonal variation of the transport of this current which might be indicative of its relationships with the WMDW formation. Nevertheless, data analysis is still in progress, especially the comparison of the Primo-0 data in the Ligurian Sea and the Channel of Corsica.

- <u>The Balearic Sea</u>

The Balearic Sea is located between the Balearic Islands and the Northeast Spanish coast. The studies carried out in the '80 clearly define a circulation pattern with two thermohaline fronts located over the continental and the Balearic Islands shelf-slopes. Intensive field experiments revealed a high regional mesocale activity of the surface layer. The mesoscale structures are related to frontal instabilities and to the high irregular topography of the basin (mainly submarine canyons, islands and the variable shelf-slope bathymetry) (Maso and Tintoré 1991, Salat *et al.* 1992, Tintoré *et al.* 1991, 1994 a and c). Essentially because of the limited nature of the experiments, these structures could be local and transient, but new interrogations arise in relation to the influence of the observed mesoscale variability. Is it appropriate to speak about a "large scale" circulation or in other words, does the mesoscale activity systematically modify the "large scale" circulation ? What are the mechanisms responsible for the observed high mesoscale activity and what is the relation with the variability of the subbasin exchanges with the other subbasins ?

With the aim to investigate all these aspects, several interdisciplinary oceanographic surveys were carried out in the Balearic Sea in the last few years. They mainly addressed the exchanges with the adjacent basins (the Northern and the Algerian basins), the structure, variability and dynamics of the surface and intermediate layers, and the role of those dynamics in controling the biomass distribution (Font *et al.* 1993). During FE89 (June 1989), FE91 (June 1991) and HE93 (June 1993) cruises, extensive CTD, ADCP and AXBT measurements were performed (figure 1). In addition, oxygen and fluorescence data were collected. A summary of the most recent observations made in the frame of EUROMODEL is presented here, as well as a brief overview of the main findings to date.

- Recent observations and dynamics analysis

One of the important questions to be addressed about the circulation in the Balearic Sea is the origin and dynamics of the recent Modified Atlantic Water (MAW) that generates the Balearic front. The analysis of the data obtained during the 3 surveys all assess the presence of recent MAW within the Channel of Ibiza and over the slope of the Balearic Islands (Buzzi *et al.* 1991, Garcia Ladona *et al.* 1994 a and b, Gomis and Pedder 1994, Pinot *et al.* 1994, Salat 1994). The low density recent MAW is found in the top 150 m layer forming the Balearic front at its offshore boundary. Although generally confined over the islands slope, the MAW extends towards the center of the basin at some particular locations forming narrow mesoscale filaments or wider plumes that overspread higher density waters. These results agree with infrared satellite observations that showed high mesoscale activity at the surface associated with intrusions of MAW (Lopez *et al.* 1993, 1994) extending far off the Balearic Islands, as also indicated in Millot' scheme (Millot 1987). Over the continental shelf and slope, old MAW is also systematically been reported although a substantial discharge of fresh continental waters at the Delta of Ebro strongly modifies the hydrographic structure over the wide shelf in the Gulf of Valencia, enhancing the density gradients over the shelf-break. A major outcome of those studies is that part of the flow of old MAW leaves the continental slope in the southern Balearic Sea and veers to the open sea interacting with the recent MAW northward inflow.

A detailed study of the Balearic front was performed (Pinot *et al.* 1994). The meandering structure of the front appears to be strongly correlated with bottom topography. Small cold eddies and warm filaments are found to be embedded within the meanders and a clear relationship between those eddies and Winter Intermediate Waters (WIW) pools has been established. The structure of the intermediate layer (100-500 m) is related to the high spatial variability observed in the surface layer. Hydrographic transects exhibit an eddy-rich intermediate layer occupied by patchy LIW and WIW pools. Those eddies extend deep in the intermediate layer and interact with the bottom topography in the slope regions. They are likely to steer the surface layer and may explain some intrusions of the recent MAW. Most of the hydrographic analysis leads to the interpretation that the WIW tends to accumulate to the north of the sills of Ibiza and Mallorca in the southern Balearic Sea. Within the intermediate layer, no clear vein of LIW neither WIW is observed around the islands. This layer at this time of the year is made of adjacent LIW and WIW eddies with respectively cyclonic and anticyclonic circulations. Although the flow at those depths seems to be largely controlled by the topographic constrain and tends to follow the isobaths, the mean circulation is rather the result of several eddy contributions than a continuous and homogeneous flow. This suggests that the Balearic Sea may be a place where there exists a strong mixing between water masses within both the intermediate and the surface layers. To diagnose the three-dimensional circulation associated with the Balearic front and the inflow/outflow through the Channel of Ibiza, hydrographic data collected by the Instituto Espanol de Oceanografia in Palma were also used. The study focuses on an eddy/front system observed in the Channel of Ibiza during November 1990. The ageostrophic motion is derived from the horizontal geostrophic circulation by the mean of the Omega equation (Pinot *et al.* 1995 b). Substantial upward velocities (5 m/day) are found at the cold side of the front and within the adjacent cyclonic eddy. The associated ageostrophic cross-frontal horizontal motion is also quantified. The relevance of the full 3-D motion in accounting for the high nutrients chlorophyll / zooplankton concentrations observed synoptically within the eddy located at the cold edge of the front is further examined (Varela *et al.* 1992, Pinot *et al.* 1995 a). These results confirm the importance of the frontal mesoscale events for the regional ecology of the Balearic Sea. In order to validate the scheme for computing the vertical motions at an oceanic front using the quasi-geostrophic Omega equation, a developing front was simulated in a primitive equation model and analyzed through the Omega equation procedure. Both quasi-geostrophic (QG) and semi-geostrophic (SG) formulations were tested and compared. The results show that the QG Omega equation has to be used carefully at oceanic fronts because the QG approximations. In such frontal situations, the more general and complex SG theory is more accurate for diagnosing the ageostrophic motions. The SG formalism suggests a new approach for diagnosing vertical motions. The QG Omega equation can be forced with the model horizontal velocities instead of the geostrophic velocities. The result obtained provides a promising methodology for computing vertical motions in real ocean from ADCP horizontal velocities measurements.

Finally, to establish a more accurate circulation in the Balearic Sea, objective analyses of both the dynamic height fields and ADCP velocities were carried out. With the exception of some regions near the coast and over the shelf where the geostrophic assumption is violated, results are in good agreement and depict the interaction between the current along the spanish coast and the Balearic Current in the southern part of the Balearic Sea (Salat 1995). An anticyclonic gyre occupies most part of the shelf in the Gulf of Valencia where fresh continental waters mainly coming from the Ebro river runoff recirculate.

- Coastal flow modification by submarine canyons

Small scale topography has a strong influence over local circulation, like submarine canyons that strongly modify the downstream circulation and the shelf-slope exchanges. This problem has been particularly analysed in the case of the canyon of Palamos, which is one of the canyons that indent the shelf and slope of the northeastern coast of Spain. Three specific brief cruises were carried out approximately two weeks apart in May and June 1993. Data evidence the existence of strong intrusions onto the shelf just over the canyon. Modifications induced by the canyon over the vertical structure of the Continental Current have been analyzed. Simultaneously to the cruises, ERS-1 SAR synoptic images were obtained. The highly locally variable wind conditions were unfortunately not always adequate for the radar backscatter to be modulated by the wave-current interaction. However, shear lines are identified in the vicinity of the canyon in the direction of the topographically deflected flow.

- Exchanges with the other subbasins

The computation of the transports from observational data in the Balearic Sea is essential for the knowledge of the circulation in the interior of the basin and for the quantification of the exchanges with the adjacent basins. Furthermore, it provides key information to validate the numerical results of the basin scale circulation models. The exchanges are quantified for the different surveys (Garcia Ladona *et al.* 1995 a and b) through geostrophic transports computation. The transport involved in the northward inflow through the Channel of Ibiza (mainly recent MAW) is generally about 0.6-0.7 Sv but sometimes is lower (0.2 Sv at the time of the FE89 cruise). Despite the observed variability, these values are surprinsingly high and the existence of such an energetic inflow through this channel was not expected. A major interrogation that these results raise is how should be the circulation of the recent MAW between the Eastern Alboran Sea and the Channel of Ibiza to account for such a substantial transport in early summer. A permanent flow of MAW towards the Balearic Sea at this time of the year appears to be a likely hypothesis although the link with the results of Millot (1992) about large anticyclonic eddies generated by the Algerian Current that further propagate northward remains to be clarified.The transport associated with the southward flow along the continental slope is about 1.0 Sv at the latitude of Barcelona. The exact relationship between this transport, the last results about the Mediterranean Northern Current transport (Albérola *et al.* 1995 a) and the Northern Catalan Sea still needs to be investigated to establish the actual circulation in the northwestern Mediterranean and its variablity. Furthermore, this transport is not constant along the continental slope in the Balearic Sea. As commented before, submarine canyons and other irregularities of the slope are often found to trigger branching and recirculation of the flow at specific locations. As a result, old MAW is directly advected to the open sea before reaching the southern Balearic Sea. Another new and really astonishing conclusion is the weak southward outflow (0.23 Sv in 1989 and 0.45 Sv in 1991) that is observed through the Channel of Ibiza. This result strongly refutes the historic belief that the major part of the continental slope waters could exit the Balearic basin at its southern boundary. In fact, the southward flow of old MAW shifts offshore in the southern part of the Balearic basin and further merges with the recent MAW that flows northward. Both contributions lead to an enhanced northeastward transport of 1.0 Sv at the latitude of Mallorca and Menorca. The link of this northeastward flow with the northern Balearic front still has to be clarified. The reason for the shift of the Continental Current back to the North may be given by the existence of the energetic inflow of recent MAW in the Channels of Ibiza and Mallorca. However, the role of a strong WIW anticyclonic recirculation just north of the sill also has to be considered. It is likely to partly block the exchanges within the channel since it occupies a wide area. The whole mechanism should of course be considered from the seasonal variability perspective since WIW would probably not be found in the Balearic Sea during summer and fall.

- Conclusions

The new view that emerges from the analysis of the *in situ* data collected during the recent experiments in the Balearic Sea is that of a basin characterized by a strong ubiquitous mesoscale turbulence. Several physical processes can be involved in generating the field of eddies and filaments that populate the center of the basin. The first that comes in mind is the unstable nature of the surface baroclinic jets that flow over both slopes. The bottom or coastal irregularities such as canyons or islands should play an important role in triggering those instabilities and generating onshore / offshore intrusions.

A second aspect that must now be kept in mind is the structure of the underlying intermediate layer characterized by a strong spatial variability. This layer may steer the thin surface layer so that part of the variability observed at the surface may be explained in terms of the dynamics of the intermediate layer.

CONCLUSION

The main outcomes of the EUROMODEL project are :

an understanding of the different processes driving the basin scale circulation

- the density forcing through the straits driving the cyclonic basin scale circulation
- the thermohaline atmospheric forcing driving the deep water formation in the Northern Mediterranean basin and reinforcing the cyclonic basin scale circulation and then the prominence of the seasonal signal in the basin circulation.
- the wind forcing driving a barotropic circulation via the Sverdrup balance
- the emphasis of the role of instabilities in the rectification of the coastal currents (like the Algerian current)
- the role of the bottom topography on the basin scale circulation through the Neptune effect
- the role of the local bottom topography of the Rhône river fan in the preconditioning phase of the deep water formation process

an understanding of the regional circulation in

- the interactions, in the Alboran Sea, between the flow of "recent" MAW coming in from Gibraltar and the flow of "old" MAW, WIW and LIW flowing south along the Spanish slope, and their consequences on the circulation of the intermediate waters ; the significant mesoscale variability of the circulation in the Alboran Sea with the vacillation of the western and eastern gyres and the disappearing of the Ameria-Oran front ; the theoretical understanding and role played by small cyclonic vortices around the western anticyclonic gyre. The role of vorticity in the flow pattern of the Alboran Sea gyres
- the role of the Balearic Sea as a connection subbasin between the Liguro-Provençal Basin and the Algerian Basin with the Modified Atlantic Water inflow through the Ibiza and Mallorca channels and the presence of the Balearic Current outflowing the subbasin north of Menorca
- the characteristics of the Mediterranean Northern Current and its mesoscale variability, that has been observed to present a clear seasonal evolution ; the behaviour of the Algerian Current as a function of upstream conditions, and the very nature of its instabilities
- the circulation of LIW and DW in the eastern Algerian Basin the interaction between the Continental and Balearic Currents in the Balearic Sea
- the role of density fronts in slope circulation
- the role of mesoscale structures in modifying the subbasin scale circulation
- an understanding of the role of straits and passages in the regional and large scale circulation of the Mediterranean Sea.

First evidences of a significant interannual variability on the regional and basin scale circulations have also been established. But the relative importance of the atmospheric forcing variability compare to the internal variability of the system is still far from being understood.

A major outcome of the studies is to point out the crucial role of the regional circulation flow patterns in the "general circulation", and even to question the concept of a "general circulation" in a Mediterranean context. The well known example of deep water formation is not unique : typical regional phenomena (the Alboran gyre, the Almeria-Oran front, the Sardinia Channel circulation...) appear to strongly constrain the basin scale circulation in the Western Mediterranean Sea.

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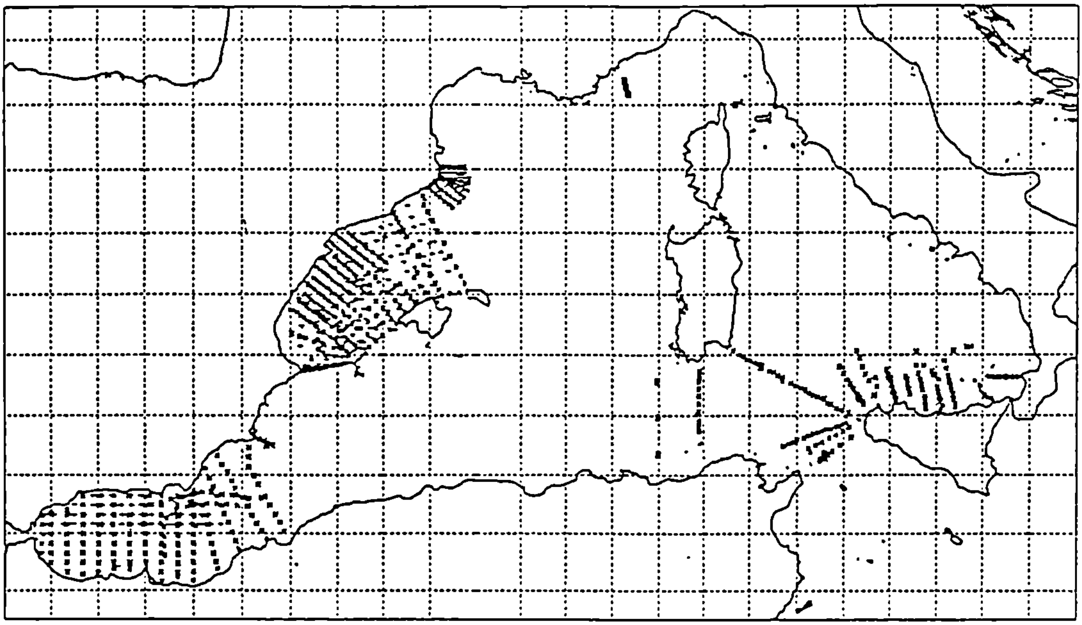

Figure 1 : The observational network during the PRIMO and EUROMODEL experiments, with the participation of the EG :
CTD stations (*), AXBT / XBT (+) and moorings locations (x)
Alboran Sea : Alboran 92 (September 22 to October 7), Alboran 90 (March)
Balearic Sea : FE 89 (June), FE 91 (June), HE 93 (June)
Canyon of Palamos : PRIM 92 (3 campaigns, 7 days each in May and June)
Mediterranean Northern Current - Toulon : PRIMO-0
Sardinia - Sicily : PRIMO-1

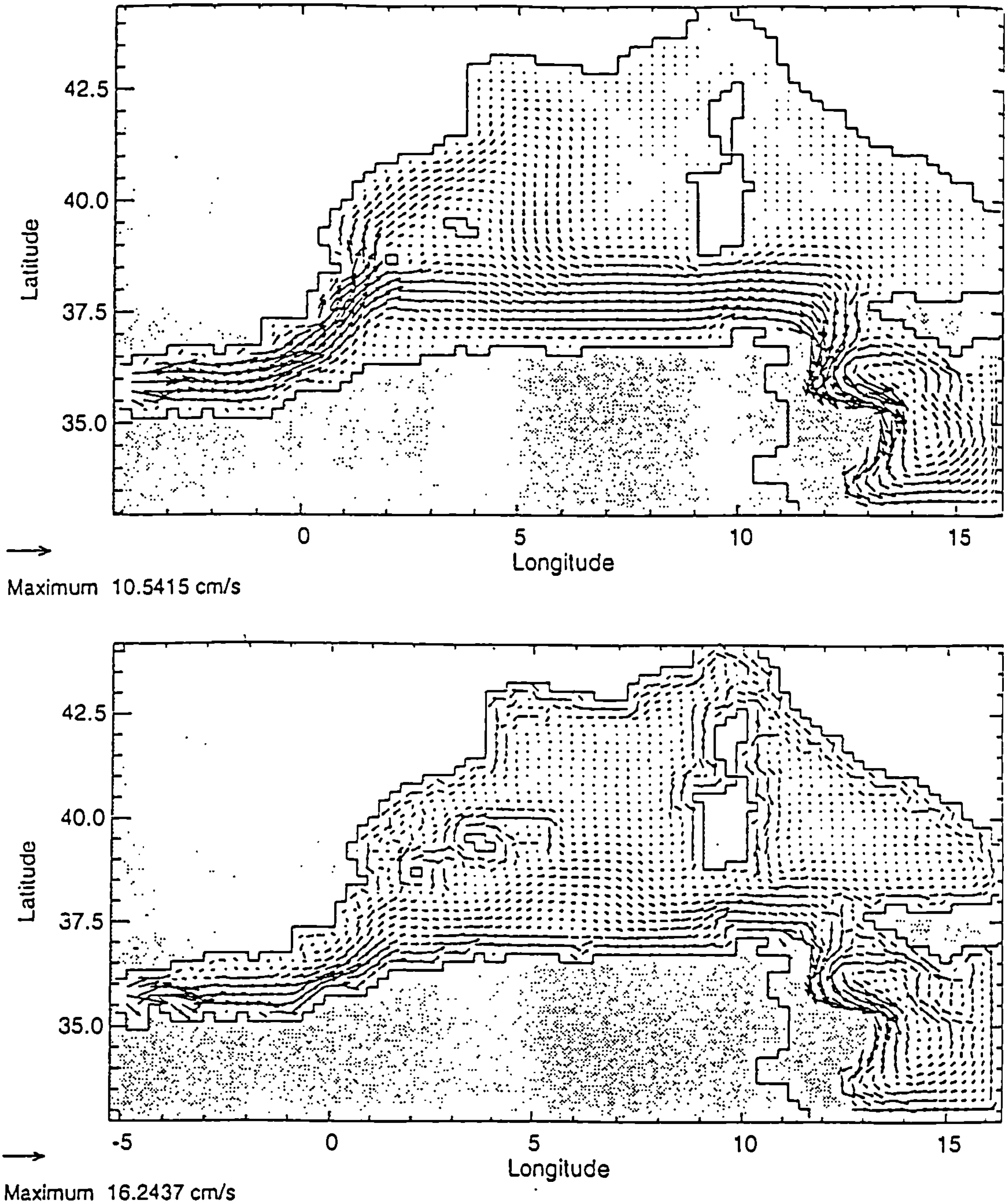

Figure 2 : Circulation at 80 m obtained after 20 years of integration with open straits, without (top) and with (bottom) Neptune effect.

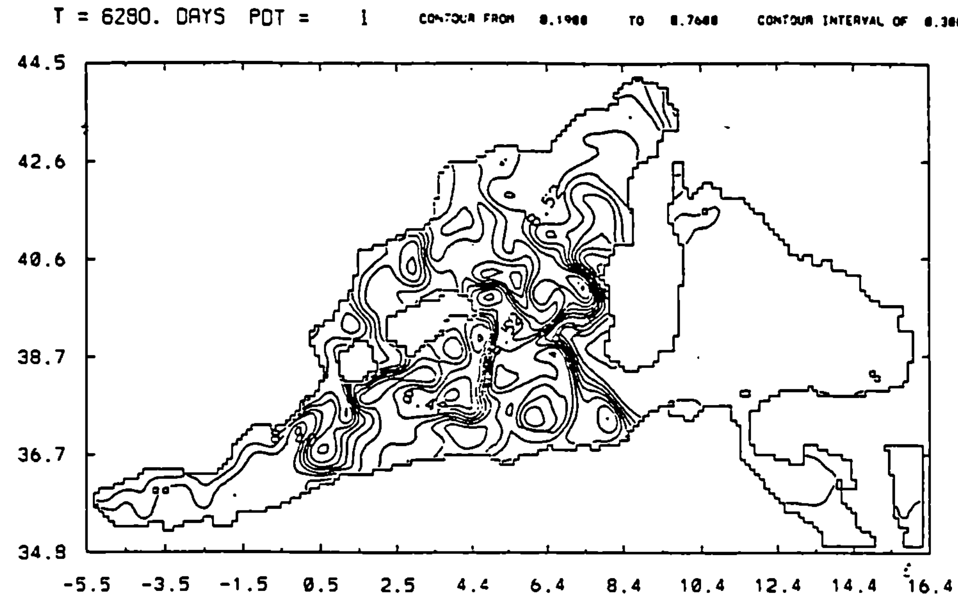

Figure 3 : Salinity field at 400 m at the end of the 20 year experiment.

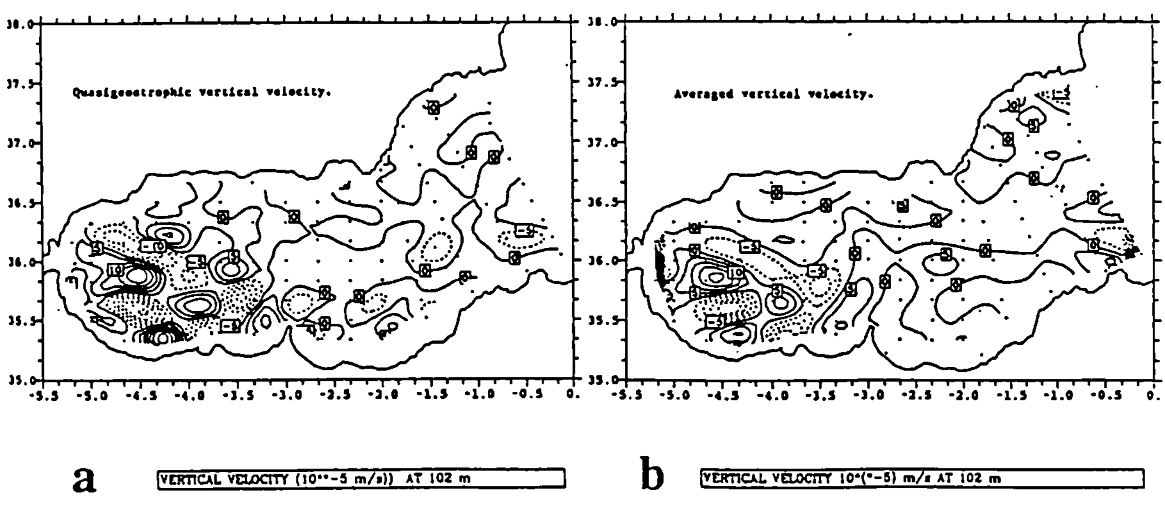

Figure 4 : a) Quasigeostrophic (Omega equation) vertical velocity distribution at 100 m (c.i. = 5 x 10^{-5} m/s).

b) Vertical velocity distribution computed from short-term backward and forward integrations of the primitive equation model initialized with the CTD data (c.i. = 5 x 10^{-5} m/s).

Mediterranean Targeted Project (MTP) - OTRANTO project
Contract MAS2-CT93-0068

Synthesis of Final Results

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Hydrodynamics and Geochemical Fluxes in the Strait of Otranto

ABSTRACT

A multidisciplinary experiment in the Strait of Otranto was carried out with the principal aim to determine water and biogeochemical fluxes and their temporal variability on the sub-inertial time scales. Long-term current measurements were combined with the seasonal hydrographic surveys and biogeochemical sampling. The annual average water exchange pattern revealed by this experiment is rather similar to the well known flux structure obtained by previous research mainly based on thermohaline properties and geostrophic calculations. However, very energetic sub-inertial variations have been discovered, which often cause the complete current reversals in various layers including the bottom one. Circulation in boundary areas (western shelf and in the vicinity of the eastern boundary) is mainly under the influence of the local wind and strongly polarized in alongshore direction. Adriatic Deep Water outflow displays also a highly transient nature presumably associated to the entire water column pulsations trapped at the western continental slope. High coherence between these barotropic-like fluctuations and the longitudinal sea-level slope was documented. Estimates of the water volume flux were obtained from the Eulerian current measurements. The total outflow/inflow rates are of about one Sverdrup, which is several times higher than the ones obtained elsewhere. Possible errors associated to these estimates are discussed. The contribution of the ADW to the total outflow is about 25% while the LIW contributes up to 50% to the total inflow. Spatial distribution of biogeochemichal parameters demonstrate a strong east-west asymmetry with the western shelf area being mainly under the terrestrial influence. The eastern portion of the strait is influenced by oligotrophic Mediterranean waters. Dissolved and suspended matter flux estimates suggest that the Adriatic is an important nutrient source for the Ionian Sea and possibly also for the entire Eastern Mediterranean. Suspended matter net flux is approximately zero. The hypothesis that the well known N/P ratio anomaly in the Eastern Mediterranean originates mainly from Adriatic Sea because of the selective enrichment in nitrate associated to the freshwater inputs and North Adriatic shelf processes, is put forward.

Key words: current field, Eulerian measurements, sub-inertial variability, water masses, nutrients, suspended matter, volume flux, material transport, Otranto Strait

INTRODUCTION

The Strait of Otranto is an inlet connecting the Adriatic and Ionian Seas. It is a relatively wide and deep opening (with an average depth of about 300 m and a minimum width of 75 km). The strait plays an important role on one hand, in determining the deep, closed Eastern Mediterranean conveyor belt, and on the other hand, in driving the Adriatic Sea horizontal circulation cell. For studies of the balance of water masses, suspended and dissolved material in the Adriatic Sea it is essential to have good and reliable estimates of fluxes through the Otranto Strait as well as their temporal variability. All previous flux estimates were based on geostrophic currents calculated from hydrographic data (Orlic et al., 1992) and thus it was possible to resolve only a seasonal signal. The continuous Eulerian current measurements offer an opportunity to study wide range of temporal scales of current field and water volume flux variability, from the order of hours up to scales the record lenghts. One is then able to carry out a detailed analysis of the possible forcing mechanisms to the sub-inertial current field and volume flux variability. The long-term Eulerian current measurements give also the possibility to estimate variance associated with the average monthly, seasonal and annual volume fluxes.

Taking into account the lack of understanding of the water exchange processes and of the importance of the strait for the overall Adriatic and Eastern Mediterranean dynamics, the main objectives of the OTRANTO project were:

- to improve the knowledge of the hydrodynamics of the Strait of Otranto at synoptic, seasonal and seasonal scales;
- to estimate the exchanges of water and associated material between the Adriatic and Ionian Seas, and to evaluate their variability;
- to increase understanding of the influence of the strait upon the adjacent water bodies and
- to provide a consistent data set both for validation of the models and assessment of complementary programs.

In this paper we will synthesize the knowledge on the phenomenology and forcing mechanisms for the exchange processes acquired from the OTRANTO project data. Also, we will give new estimates of the water volume fluxes and describe their temporal variability. Furthermore, net exchange rate of the suspended and dissolved material will be estimated and discussed in terms of the known historical results.

MATERIAL AND METHODS

The Eulerian current measurement experiment within the OTRANTO project was aimed at getting long-term current time-series to be subsequently used for better estimates of the water volume fluxes through the strait and their sub-inertial variability. Four moorings between the western and eastern border in the southernmost area of the Otranto Channel were planned (at locations of stations 301, 304, 306 and 308, Fig. 1). Only three were deployed initially, in February 1994, lacking the clearence from the military authorities for the central mooring 306. As from Fig. 2a, the successful recovery of the currentmeter data was very poor in the period from February through November 1994, due to the malfunctioning of the current recorders, and due to the loss of the complete mooring at station 308. In November 1994 an additional mooring was deployed (3025), and in the following December two other moorings were deployed at stations 306 and 309. The current measurements at stations 306 and 309 were carried by Saclant Undersea Research Centre of La Spezia, Italy (SACLANTCEN). In May 1995, after the official end of the experimental phase of the project, the current recorders were redeployed at six moorings (M1=301, M2=3025, M3=304, M4=306, M5=308, M6=309) in the Strait of Otranto by SACLANTCEN in the framework of the project Otranto Gap (Poulain et al., 1996) and the measurements continued. All the instruments were finally recovered in mid November 1995. The distribution of the autonomous current recorders along the mooring line in the Strait of Otranto is depicted in Fig. 2b. The instruments employed were NBA, SMART, Aanderaa RCM7, and RDI 75 kHz Acoustic Doppler Current Profiler (ADCP). The latter was deployed at about 440 m depth at station 306, looking upwards and measuring the water currents in the range 59-447 m in 8 m bins and averaging over an hour the acoustic signals received every four minutes. For NBA and SMART acoustic current meters the sampling interval was set to 20 and 10 minutes, respectively. Subsequently mean hourly values were calculated. The Aanderaa current meters averaged the data recorded over 50 samples taken every 72 seconds, giving thus a mean hourly value. They were equipped also with temperature, conductivity and pressure sensors. Thus, temperature and salinity at each current meter position were obtained as well. The sensors were calibrated against a CTD data profile performed just before the deployment of the instruments.

With all instruments employed and operating the horizontal resolution of the data points was 14-15 km, while the vertical one varied between 70 m in the shallow shelf waters (stations. 301 and 3025) and 300 or 600 m in the rest of the strait. The vertical resolution at station 306 with the ADCP was 8 m; however, after examining the correlation between time-series at different levels, it turned out that the currents over the entire water column from the ADCP depth up to the surface of the shallowest bin are quite well correlated, excerting mostly barotropic fluctuations. Thus only data at about 60 and 300 m depth at that station were chosen for the subsequent analysis.

Hourly mean current data were decomposed into the east and north current components. Since the longitudinal strait axis orientation is in the North-South direction, the inflowing or outflowing current coincides approximately with the north current components. Subsequently, the current components, as well as temperature and salinity data when available, were treated by 24m214 digital filter (Thompson, 1983) with a cut-off period of 24 hours, to remove tidal and inertial signal from the hourly data. Thus obtained low-passed time series, denoted as sub-inertial current flow, were used for further analysis.

Although the currents were monitored for almost 22 months, the time-series of approximately 12 months spanning the period from December 1994 to November 1995 will be examined more in details. The reason is that from February to November 1994 spatial coverage across the strait was very poor, missing the complete eastern side of the strait and with large data gaps in the rest of it.

In parallel to Eulerian current measurements, seasonal hydrographic surveys of the area were carried out six times during the project duration from February 1994 to May 1995. The hydrographic station network together with the currentmeter moorings is presented in Fig. 1. The cruises are referred to as Otranto*n* where 'n' is the chronological number ranging from 1 to 6 and their periods are marked by the arrows of Fig.2.

The temperature and salinity measurements were carried out with a CTD SeaBird 911 *plus* coupled with a 24-bottles General Oceanics Rosette sampler. Readings from SIS digital thermometers and pressure sensors, reversed prevailingly at lower depths, as well as salinity determinations by Autosal Guildline salinometer were used to check during the cruise the stability of the laboratory calibration of CTD sensors which were regularly made before and/or after the each cruise. Corrections in temperature of -0.015°C for Otranto1 (winter 1994) and for +0.011°C for Otranto3 (summer 1994) were applied. The salinity check performed by meand of post-cruise quality control procedures showed that corrections of +0.039, +0.008, +0.007, -0.006 and +0.001 units were necessary as far as Otranto 1 to 5 cruises are concerned. During the Otranto6 survey, performed with two ships, R/V *Alliance* and ITS *Magnaghi*, two N. Brown MkIIIC CTDs were employed. Their intercalibration was carried out in the deepest portion of common stations, occupied daily one for each transect within a time-lag of one hour. Post cruise intercomparison procedures showed that corrections of +0.009oC and +0.008 units for temperature and salinity respectively were necessary to the data set collected on ITS *Magnaghi*.

The CTD data used for the analyses were those collected during the down-cast only at a sampling frequency of 24 Hz while the CTD/Rosette system was lowered at a rate of about 1 m/s. The system was stopped at presumed depths during the up-cast and one or more bottles were triggered at each level to collect samples for salinity, chemical and biological determinations. The first processing of CTD data was carried out on board by visual inspection of temperature, salinity and density profiles vs. pressure. Subsequently the data were checked to eliminate spikes caused by electronic failures and/or differences of time constant of temperature and conductivity sensors. As final step the high resolution CTD profiles were averaged over 1 dbar pressure intervals; salinity and all relevant oceanic parameters were computed from pressure, temperature and conductivity averaged values according to the standard algorithms (UNESCO, 1983).

Apart from the CTD measurements, water sampling was carried out for determination of dissolved oxygen, nitrates, nitrites, ammonia and phosphates. Also, particulate matter analyses from discrete water samples were carried out determining the following parameters: total suspended matter (TSM), particulate organic carbon (POC), particulate nitrogen (PN), particle concentrations and size distributions. In addition, two current meter moorings at the Italian shelf and slope area were coupled with the sediment traps having a 15-day integration interval.

Dissolved oxygen concentrations were determined by means of a Metrohm automatic burette according to the procedure by Winkler (Carpenter, 1965). In some cruises the final point was determinated automatically by means of a redox electrode. During Otranto1 and Otranto3 cruises all nutrient determinations were carried out on board by means of a hybrid autoanalyzer equipped with a Chemlab flow-colorimeter, following the procedure described by Grasshoff et al. (1983) with some modifications. For the remaining cruises, samples were collected in 100 mL polyethylene bottles and kept continuosly in a deep freezer at -20° C until their analysis in the laboratory by means of a Technicon CSM6 autoanalyzer. Phosphate was measured by means of a Perkin-Elmer Lambda 2S UV/VIS Spectrometer following the procedure described by Murphy and Riley (1962).

The particulate matter studies were carried out during the six seasonal surveys with a CTD probe (SeaBird SBE 16) coupled with SeaTech transmissometer and fluorometer.

For TSM, POC and PN determinations prewashed and precombusted (at 500 °C for 4 hours) glass fiber filters Whatmann GF/F (25 mm diameter) were used. Samples were immediately stored at -20°C. Dry weight filters were subsequently measured by gravimetric method (Strickland and Parsons, 1972); the organic fraction was estimated as weight loss after incineration at 480°C for 4 hours. POC and PN were determined by means of a Perkin-Elmer 2400 CHN elemental analyzer. The inorganic carbon was removed through vapour phase acidification (Hedges and Stern, 1984). After sampling, particle concentration and size distribution were immediately determined by means of a Coulter Counter Model TA II in the range from 2 to 40 µm. Phytoplankton abundances and species composition were determined on selected samples utilizing a Zeiss ICM 405 inverted microscope (Utermöhl, 1958).

RESULTS

Water masses analysis

The results obtained from the analysis of temperature and salinity data collected during the six seasonal cruises are presented, examining in succession the θ-S diagrams constructed for each cruise (Fig. 3). All the diagrams exhibit clearly the presence of the distinct water masses and their modification during the annual cycle. The first cluster of points is the densest Adriatic Deep Water (ADW) with a temperature of about 13 °C and a salinity of about 38.65 reaching a density maximum of γ_θ= 29.24 kg/m^3. The core of ADW is quite evident in all six diagrams indicating that the deep layer in the Otranto Strait is occupied in all the cruises with the outflow of this water mass of Adriatic origin. Equally evident is the second cluster of points located in the θ-S space slightly above the ADW, marking the lighter Levantine Intermediate Water (LIW) which is the saltiest water in the strait area. It occurs with a core property values of S $\cong$ 38.82 and temperature of about 14°C during the annual cycle from winter 1994 until winter 1995 cruise included (Fig. 3 a-e). The situation met during the spring 1995 cruise shows a significant change in the LIW properties (Fig. 3 f). They appear to be warmer of about 0.8 °C and for about 0.15 saltier than in the previous cruises, while the ADW characteristic values do not show any significant change.

The dense cluster around the LIW core spreads towards less saline waters, showing the transitional mixtures between the intermediate LIW water type and surface layer water. Here the flow through the strait appears subject to seasonal fluctuations due to both meteorological forcing and difference in thermohaline properties between Adriatic and Ionian surface waters. During winter (Fig. 3 a and e) two different surface water masses are clearly visible, i.e. the Adriatic Surface Water (ASW) which is also the coldest one in the area with a temperature minimum of about 11 °C and the saltier and much warmer Ionian Surface Water (ISW) with a temperature of more than 15 °C and salinity above 38.25. During spring (Fig. 3 b and f) the salinity gap between ASW and ISW is much reduced, while the vertical stratification increases owing to the increase of solar radiation. However comparing the two spring cruises, May 1994 in Fig. 3 b and May 1995 in Fig. 3 f, a noticeable difference between the two patterns appears. The 1994 pattern showed a rather evident mixture across the strait, while the 1995 cruise exhibits two branches at different salinity indicating a strong horizontal shear with a net separation between the outflowing ASW and the inflowing ISW. Moreover, the water of Ionian origin revealed an unusual increasing of ISW salinities. During summer, (Fig. 3 c), the uniform temperature stratification extends at all stations in the upper 50-100 m. The two surface water masses are not so easily distinguished from their thermohaline properties, in fact the entire area above the seasonal thermocline displays rather uniform horizontal temperature distribution and the distinction between various surface water masses is due mainly to salinity. The autumn situation is represented in Fig. 3 d. The presence of both ASW, marked by a cluster of points of lower salinities, and ISW is again evident owing to the increased river runoff. A very thick branch departs from LIW cluster towards the less saline water, indicating a continuum of mixture of LIW with Adriatic waters at the sub-surface layer. At the surface we find the cluster of points in the range $17 \leq \theta \leq 22$ °C with salinity progressively increasing from 37.6 to 38.8. This surface layer shows the maximum in salinity of the ISW during the annual cycle.

All these water masses are evident in the vertical distribution of temperature, salinity and density along the latitudinal band at 40° N, indicated as transect 2. Fig. 4 compares the winter and summer situations. During winter in the deepest part of the transect the ADW is confined mostly against the deepest western continental slope limited by the isotherm of 13.3°C, the isohaline of 38.70 and the isopycnal of 29.20 kg/m^3. The signal associated with the LIW, which is defined as the water contained in the layer with salinity higher than 38.75, is evident only as a maximum in the salinity field that lies between 150 and 400 m depth prevailingly against the eastern part of the section. A tongue of ASW enclosed by the isotherm 13.8 °C and by the isohaline of 38.15 protrudes off-shelf between the warmer and more saline Ionian surface and intermediate waters. The summer situation (Fig. 4 b) shows a reduced horizontal variability in the surface layer which is partly associated to the minimum river run-off. At the same time the presence of the seasonal thermocline is clearly visible. In the deep layer the pattern qualitatively remains unchanged; however, the signal associated to the ADW is weaker, while differences between summer and winter in the LIW signal are much evident, due to an increase of both thickness and salinity of the LIW tongue.

In order to follow more closely the temporal variability of thermohaline properties of the more identifiable water masses, average θ and S values were calculated for the ADW where γ_θ is larger than 29.18 kg/m^3 and for LIW where S is higher than 38.75. The average values of temperature and salinity for LIW and ADW are presented graphically in Fig. 5 for all six Otranto cruises, together with some historical data mainly obtained in the framework of Physical Oceanography of Eastern Mediterranean (POEM) programme. The standard deviations within each cruise (not shown here) are smaller than the instrumental errors. One can observe the similarity in the temporal variability of temperature and salinity in both LIW and ADW. This means that the thermohaline properties compensate each other in the equation of state maintaining rather constant density values and as a consequence the scheme already described of the water exchange regime in the Otranto Strait is a permanent feature. The overall range of variability for temperature and salinity are the same for LIW and ADW, being of 0.4 °C and 0.08 units respectively. In general the interannual variability in both ADW and LIW is substantially higher than the seasonal one as obtained during the six Otranto cruises (1994-1995), with the exception for the spring '95 cruise when the average salinity of LIW increased considerably. This increase was confirmed also during the next winter 1996 survey, when the Otranto Strait was visited again, showing a continuity of the trend observed since 1992 both for LIW and ADW. This suggests that an increase of the Ionian water influence in the Southern Adriatic Sea has been taking place. The ADW trend is complementary with LIW one: this may suggest that the LIW intrusion into the Adriatic affects the ADW formation in the Southern Adriatic on longer time scale.

Currents

Statistical characteristics of the current data for all the available time-series are presented in Table 1. The data span interval from about 50 days to almost 600 days at some locations. In most cases the north current component is several times larger than the east component due to the topographic constraint. The topographic influence is also evident in the standard deviations which are larger along the north-south axis than along the east-west one at all stations except at station 306 which is situated in the central part of the strait. This means that both the residual steady current and oscillatory motions are polarized along the longitudinal strait axis.

Standard deviations are larger than the corresponding mean current components, suggesting that the amplitude of the time varying water flow throughout the strait is larger than the residual steady flow (Fig. 6). Only at the bottom of the central mooring (306) where the outflow of the Adriatic Deep Water occurs, the average southward (outflowing) current component is larger than its standard deviation. The stable average currents occur in the surface layer of the eastern portion of the strait (stations 308 and 309) where persistent Ionian Surface Water inflow takes place.

Spatial distribution of the average north current component (Fig. 6) shows that the western portion of the strait is characterized by the steady outflowing (southward) flow which occupies the entire water column including the western continental shelf and slope areas. Station 306 displays a vertical shear with the inflowing current at the surface and the outflow in the intermediate and bottom layers. In the eastern portion of the strait (stations 308 and 309) the inflow takes place over the major portion of the water column. Thus, it can be concluded that the residual water exchange pattern shows a two-layer structure only in the central part of the strait. In addition, the residual water flow through the strait is characterized by the cyclonic shear which is present over the entire water column.

Sub-inertial variability of the flow across the strait was investigated also by applying the Empirical Orthogonal Function Analysis (more details are given in the Final Report). Here the principal results only are reported. The flow patterns for the three seasons were determined from the low-pass north-south current component. The greatest portion of the total variability across the strait in winter and autumn is localized in the upper layers along the boundaries. To a great extent it is driven by the wind (through the Ekman dynamics) that may reverse the prevalent outflow along the western shore as well as the prevalent inflow along the eastern. In summer, when the wind forcing is less pronounced, the variability over the western shore is reduced, while that along the eastern one remains prominent.

The current fluctuations throughout the water column over the western slope in the form of pulsations of the order of ten days, with the bottom intensification, is another feature of the summer pattern, as illustrated in Fig. 7. They seem to be coherent with the ADW pulses occurring over the Otranto sill some 100 km North of the strait.

No clear indications of the forcing mechanisms for such a sub-inertial variability of the ADW outflow over the sill have been found so far, and they certainly deserve a more profound experimental study combined with numerical exercises.

Biogeochemistry

Spatial distribution of biogeochemicals is a result of the combined influence of physical processes (advection, mixing, etc.) and biological activity (production and consumption). Dissolved oxygen, nutrients and particulate matter distributions (Fig. 10) show generally a four layers structure in the vertical section through the strait: the *surface layer* (from 0 to 50 meters), the *vertical gradient layer* (from 50 to about 200 meters), the *intermediate layer* (from 200 to about 600 meters), and the *bottom layer*. On the other hand, from the hydrographic point of view, the strait is characterized by the presence of the four main water masses described previously in paragraph 3.1: ASW, ISW, LIW and ADW.

The first 50 meters of the water column are characterized by a significant seasonal variability both in dissolved nutrients and particulate matter distributions, due to the seasonal modulation of physical forcing mechanisms and of biological processes.

In winter the surface layer shows a strong east-west gradient for nitrate, oxygen, particles and particulate carbon and nitrogen concentrations. The western side is richer (>260 μM for oxygen, up to 3 μM for nitrate, about 17,000 particle/cm^3, 0.5 mg/dm^3 of TSM, 30 % of organic matter, 3.5 μM POC, 0.5 μM PN, C/N molar ratio of 6.9) than the eastern one (NO_3 depletion, 5000 particle/cm^3, 0.1 mg/dm^3 TSM, 60 % of organic matter, 2.4 μM POC, 0.3 μM PN, C/N molar ratio 7.6). The same does not occur for phosphate and silicate; the first is present at very low levels (about 0.05 μM), near the detection limits, in the whole surface layer; the latter one shows concentrations below 2 μM without any evident east-west gradient.

In spring the surface layer evolves towards the typical post-bloom nutrient depletion stage that will be completed only in summer, when the whole surface layer becomes homogeneous horizontally and appears nutrient-depleted exhibiting the oxygen maxima due to the biological activity. The sub-surface oxygen maximum, found sometimes in spring, is well correlated with the presence of a series of patches of the sub-surface chlorophyll maximum, coincident with phytoplankton biomass maxima (about 4 μg C/dm^3) and spots of biogenic Calcium (B. Price, pers. comm.), possibly related to the development of Coccolithophorids populations. The surface layer appears homogeneous horizontally in the particulate matter content as well (values of 4000 particle/cm^3, TSM 0.1 mg/dm^3, POC 3.4 μM, PN 0.5 μM, C/N molar ratio 7.4), without any evident differences between western and eastern sides.

The vertical gradient zone extends from 50 to 200 meters (400 meters for silicate distribution) and it is only weakly seasonally modulated. In this layer the concentrations increase from 0.5 to 5.4 μM for nitrate, from 0.05 to about 0.24 μM for phosphate and from 1.5 to about 8 μM for silicate. Dissolved oxygen levels decrease from their maximum values of about 250 μM to less than 195 μM at the base of the layer. For what concerns the particulate matter, from 100 to 200 m the concentrations remain unchanged, with particle concentration between 2000 and 3000 particle/cm^3 and 0.8 μM of POC.

The large body of water extending from 200 to about 600-800 meters is characterized by the presence of the LIW (Levantine Intermediate Water) that occupies the eastern half of the section with a maximum salinity core of more than 38.75 at about 200 m depth. The dissolved oxygen level decreases to its minimum value (185-190 μM) at a depth of about 400 meters; below that it increases due to the influence of the oxygen-rich Adriatic Deep Water. Nutrient concentrations increase up to 5.5-6.0 μM for nitrate, 0.24-0.26 μM for phosphate and 8.5-9.0 μM for silicate, whose maximum values lie deeper (about 600 meters) than of the other nutrients. The decrease of nutrient concentration towards the bottom is not always evident except for silicate. The LIW is characterized by almost constant concentrations both for particle (less than 2000 particle/cm^3) and POC (0.3 -0.7μM) and PN (0.03 - 0.1 μM), with C/N molar ratio from 8 to 12 along the year. These values are the absolute minima for the area.

The bottom layer is occupied by the Adriatic Deep Water, a water mass characterized by a relatively high concentration of dissolved oxygen (maximum value of 218 μM in winter) and lower values of nutrients (4.5-5.0, less than 0.22, and less than 8.5 μM for nitrate, phosphate and silicate, respectively). The layer of the prominent vertical gradients separating intermediate from the bottom layer, is particularly evident in the oxygen and silicate distributions and it coincides well with the upper boundary of the ADW layer as defined from the hydrographic data. Particle concentrations, POC and PN show more or less constant properties in time (about 2000 particle/cm^3, 0.6 - 1.6 μM for POC and 0.05 - 0.15 μM for PN, with a C/N molar ratio from 8 to 16). The observed gradient for oxygen and silicate is also present in particle concentration, POC and PN, that slightly increase in ADW. This relative enrichment occurs also at the bottom of the Ionian basin (Boldrin et al., 1990), confirming the presence of the signal associated to the southward advection of the dense waters of Adriatic origin.

In the bottom layer over the Italian continental shelf and in the continental slope area a nepheloid layer presenting relatively high particulate matter concentrations occurs. Horizontally this layer is confined on the shelf and its extension varies with seasons, being particularly pronounced during summer, with a particle concentration of 8000 particle/cm^3 (twice the surface layer), POC 1.3 µM , PN 0.2 µM and a C/N molar ratio of 13.4. This layer, not being evident from its hydrographic properties, is considered important for the exchanges in the area, being relatively rich in suspended matter.

As previously stated, only in the surface layer biological and chemical parameters exhibit a significant seasonal variability connected either with the hydrographic and circulation regimes or with the time evolution of biological activity. During winter the shelf along the Italian coast is occupied by a relatively fresh and cold water (Adriatic Surface Water - ASW) flowing southward. ASW is selectively enriched in NO_3, as also shown from the vertical distribution of NO_3:PO_4 ratio (Fig. 11), in which the relative excess of nitrate is clearly evident on the western side and in small lenses in the center of the section due to the cyclonic sub-basin scale recirculation cells. Also the area occupied by the ADW outflow shows a slight but significant increase of the N:P ratios. This behaviour is confirmed by previous studies carried out in the Southern Adriatic (G. Civitarese, pers. comm.) and it is always associated with strong outflows of ASW and ADW. The selective enrichment in NO_3 is particularly significant because it suggests a possible role of the Adriatic Sea in supporting the well known N:P ratio anomaly in the Eastern Mediterranean. Recently, some theories have been developed to explain the deviation of the N:P ratio in the Mediterranean with respect to the oceans: we can mention, among the others, nitrogen fixation (Bethoux and Copin-Montegut, 1986) and phosphate removal from the water column due to adsorption onto Saharian dust particles blown across the Mediterranean (Kromm at al., 1991). Our results suggest that the anomaly in the N:P ratio could originate directly from the formation site of the Eastern Mediterranean Deep Water, i.e. the Adriatic Sea, because of a selective enrichment in nitrate due to freshwater inputs and the active role of Northern Adriatic shelf in the efficient removal of phosphorus from the water column via burial in the bottom sediments. Our hypothesis is thus, that the coastal and shelf areas influence is felt in the entire Eastern Mediterranean through the closed deep conveyor belt.

The particulate matter observed along the western side of the strait (Fig. 11) shows clearly the influence of various processes taking place in the Adriatic basin (especially in the coastal belt) and determining the particulate matter composition. More specifically these are: transport of material of riverine origin connected to the coastal currents and the seasonally modulated biological activity. These different mechanisms determining the particulate matter composition are evidenced in the time-series of samples collected by sediment traps, in the Italian shelf area and along the continental slope. In fact, in the western shelf area (station 301), directly interested by the ASW southward flowing current carrying a terigenic material, the inorganic fraction prevails, whereas in the continental slope area (st. 304) the contribution of the organic part increases from 10 to 13% (Boldrin et al., 1996). This suggests that moving from the coastal boundary layer towards the open sea the importance of biological processes in determining the suspended matter composition increases.

Phytoplankton abundance and biomass estimates clearly show the east-west asimmetry. Compared with the eastern side, the western portion of the Strait is characterized by larger phytoplankton biomass (8 μgC/dm^3), in February, with a decreasing eastward gradient (3 μgC/dm^3), to be related to the corresponding nutrient availability. The taxonomic group composition reflects in the western part the Adriatic origin, diatoms being more represented (>15%), if compared with the summer composition (<4%) when the flow is reduced and the phytoplankton population shows characteristics typical of the northern Ionian basin (Rabitti et al., 1994).

Sediment traps were moored for the entire project duration, and recovered successfully at station 301 (western shelf station) and at station 304, i.e. in the western continental slope area. The results of the data analysis show that in the "open" sea fluxes are 10% lower than those occurring on the shelf.

During winter the main fraction of the total mass flux is represented by inorganic constituents which are the result of active dynamic processes in the shelf area. At the slope the inorganic fraction is still predeominant because the biological activity is reduced. In both areas, however, the contribution of the organic fraction increases in spring-summer period when biological processes become relevant as a source of particulate matter. Suspended matter fluxes recorded on the shelf area seem to be associated to the combined influence of the vertical transfer due to biological activity within the water column and to advective transport. This latter mechanism gains an increasing importance during high riverine discharge episodes. In the continental slope area, the observed fluxes appear mainly related to the vertical transfer of biogenic particulate material. The variability of the phytoplankton cell flux coincides with the total mass flux variations, suggesting a coupling between the water column production processes and the vertical transfer of suspended matter.

The comparison between phytoplankton concentrations in the water column and cell countings on sediment-trap samples suggests rather clearly the existence of a seasonal phytoplankton cycling, with early spring maxima and late summer minima.

Fluxes estimate

As said in the introduction, one of the main objectives of the OTRANTO Project was to estimate the water, dissolved and particulate matter fluxes and their seasonal and possibly interannual variability through the Strait. To achieve this, the first step was to measure the current velocity field in a section of the strait, at least throughout one entire year. The current field exhibited high variability on the synoptic time scales, and it was heavily influenced by transient mesoscale features (Gacic et al., 1996). The spatial resolution of the experiment design was not fine enough to resolve these mesoscale eddies, passing through the area of the shear zone between inflow and outflow. The volume transport rates were calculated from the low-pass current meter data centered at noon of the each day for the period 4 December 1994 — 17

November 1995 when the spatial coverage of the transect was the most complete. North velocity components were interpolated on the regular grid with horizontal and vertical distance of 2400 m and 40 m respectively. Two ways of the average transport calculations were carried out; the first one was based on the integration of the average inflowing current speed over the transect area for the entire study period specified above. The second method consisted of the calculation of the water volume transports obtained by integrating once a day instantaneous current velocities and thus obtaining the volume transport values once a day. The estimate of the average transport was then obtained by averaging daily transports over the entire studied period. The two approaches in the water volume transport estimates do not necessarily have to give the same result. The second method gives the water volume exchange rates which essentially consist of the two parts; the first part represents contribution of the mean current to the exchange rate, while the second part gives the contribution of the current temporal variability to it (Bryden et al., 1994). It can be shown that the second term is practically the covariance of the transect area and the velocity. The higher is the correlation between the transect area and velocity fluctuations the larger is the contribution of that term.

In the Strait of Otranto for the average inflowing water volume rate for the entire studied period the following value was obtained:
1.1517 ± 0.5295 Sv, while the outflowing water volume exchange rate is:
1.1581 ± 0.5300 Sv. The standard deviations are rather high showing that the sub-inertial variability of the tranport is relatively high. Since the studied period is approximately one year the net water exchange rate should equal the estimated difference between the evaporation and precipitation rates. According to Artegiani et al., 1996 this difference is -0.006 Sv. i.e. the precipitation is stronger than evaporation which then results in the net outflow through the Strait of Otranto. Computing the difference between the total outflow and inflow rates we obtained a the net water exchange rate of *-0.0059 ± 0.5878* Sv which is unexpectedly close to the estimated E-P value and of the correct sign. Of course one has to take into consideration a large standard deviation associated to the obtained values of the net transport. Calculations also showed that the low-frequency variability contributed only about 10% to the total volume exchange rate, i.e. that the transport calculated from the averaged velocity field is rather good approximation of the average transport. The comparison of our results with the estimates previously obtained from geostrophic calculations (see Orlic et al., 1992), shows that our transport values are about three times larger. They may represent some overestimates due to the fact that the current measurement transect is located to the south of the sill and thus large values of the total volume transport may be to some extent a result of the topographic recirculation on the sill. Indeed, it seems that some recirculation does occur, as it follows from surface drifters' data launched in December 1994 along the eastern strait boundary (Gacic et al., 1996), when one out of six drifters turned toward the west coast and moved southward without crossing the Sill and entering the Adriatic. It is difficult to estimate the contribution of the recirculation but our guess is that it influences to a small amount our volume flux calculations. The recirculation probably influences more the transient part of the volume flux estimates than the average one.

Now the temporal variability of the volume fluxes will be analyzed in more details. The time series of the daily transport rates for the entire studied period (Fig. 8) show large variability at time scales of about ten days of both in- and outflowing transports. These variations often lead to large net exchange rates (up to 2 Sv) which is physically impossible. An explanation for the unbalanced exchange rates may be in the low horizontal resolution of our currentmeter station network which in the best case is about 15 km. From previous studies (Ferentinos and Kastanos, 1988) it was shown that mesoscale eddies, formed in the horizontal shear zone, pass rather often through the Strait of Otranto. With their passages changes at time scales of about ten days in current field are associated. Since the length scales of these eddies are about ten kilometers our mooring array does not resolve them, so that probably transient occurrences of unbalanced water exchange rates are simply due to their presence in the study area. By doing an average over the period of time long enough to filter them out we are, however, able to obtain rather reliable and balanced estimates of the water exchange rates. Certainly part of the large standard deviation around the mean water transport is associated to these mesoscale eddies.

In addition to the yearly average transport rates, the monthly mean transport rates were calculated. The time series of monthly values (Fig. 9) shows a clear seasonal signal with a minimum in spring/early summer. Of course again the standard deviations around mean are very large, partly due to the mesoscale eddies' activity as discussed in a previous paragraph.

To calculate dissolved and particulate matter fluxes the following procedure was employed: as biogeochemical data are discrete in time, sampled in different seasons, they need to be associated with a corresponding representative flow pattern, with balanced input (northward) and output (southward) fluxes. Therefore, to smooth the current structure and to filter out the influence of mesoscale eddies, as well as to obtain a representative current transects for the time in which the biogeochemical sampling was carried out, the currents at each measuring site were averaged over an interval of time centered or close to the sampling time. The averaging period was determined by doing averages over a varying time intervals so that the net transport becomes zero or minimum.

The averaged current field was then interpolated on the same regular grid mentioned before (Fig. 10) and the fluxes of water across the Strait were calculated. The same interpolating procedure was applied to biogeochemical concentrations, then the interpolated values were used to obtain the fluxes of matter.

Fluxes computation shows (Tab.2) a net loss through the strait for nitrate (30,300 x 10^6 moles y^{-1}), phosphate (1,100 x 10^6 moles y^{-1}) and silicate (67,700 x 10^6 moles y^{-1}), while a slight gain occurs for POC and PN (not shown in the table). The net fluxes are larger than those previously estimated by Zore-Armanda and Pucher-Petkovic (1976) and, for nitrogen, by Civitarese et al. (1996). Also, they are not balanced by the major freshwater inputs in the Northern Adriatic. We think that any budget calculation for the Adriatic Sea must take into account the biogeochemicals that are actually available to the advective transport. Since the Northern Adriatic receives the highest discharge from rivers but also it is the largest shelf area in the Eastern Mediterranean with a real turn for biogeochemicals removal, only a part of the terrestrial inputs, both natural and anthropogenic, is lost by water mass transport southward. The remaining part is buried into sediment. As estimated by Degobbis and Gilmartin (1990), only about 30% of the total nitrogen and total phosphorus inputs is lost from the Northern Adriatic. This increases further the discrepancy between the export from the North and the negative balance in the Strait. The contribution of the remaining Adriatic rivers (from Croatia, Albania and Italy) is very difficult to assess because of the scarcity of the available data. Although the total nutrient input from these regions is presumably lower than the input from the Northern Adriatic, the lack of a wide shallow shelf area could make horizontal advection more important than burial in sediment. Also, the nitrogen input coming from the rainfall, that in the Northern Adriatic was estimated to be 14% of the total nitrogen input (Degobbis and Gilmartin, 1990), could significantly contribute to balance the budget. Further, we must take ito account that the error in water transport estimates due to mesoscale eddies and sub-basin scale recirculation, that do not actually contribute to the water exchange rate, probably introduces errors in the fluxes calculations.

CONCLUSIONS

Results of the multidisciplinary experiment in the Strait of Otranto have revealed new features of the spatial distributions across the strait and have enabled us to give robust estimates of the water, suspended and dissolved matter exchange rates. Vertical distributions of thermohaline properties as well as suspended and dissolved matter suggest an east-west asymmetry, where the western shelf area is under the influence of the Adriatic freshwater sources. Eastern portion of the strait area is under an influence of the Eastern Mediterranean oligotrophic waters of relatively high salinity, low nutrient and particle content. In addition, low saline well ventilated and rich in particles, bottom water of the Adriatic origin exits near the western continental slope. Our results suggest that the well known anomaly in the N/P ratio could originate directly from the formation site of the Eastern Mediterranean Deep Water, i.e. from the Adriatic Sea because of the selective enrichment in nitrate due to freshwater inputs and an active role of the North Adriatic shelf in the preferential removal of phosphorus from the water column via burial in the bottom sediments.

Current regime shows highly variable time-dependent component which is, in the coastal area and surface layer along both boundaries forced by the local wind. The quasi-steady current component prevails along both boundaries, entering along the eastern flank and outflowing along the western shelf area. Both transient and steady current components are highly polarized along the longitudinal strait axis especially along the boundaries and in the bottom layer near the western continental margin. The Adriatic Deep Water outflow shows strong temporal variability at the time scale of ten days which is associated to the barotropic-like pulsations of the entire water column trapped at the western continental slope. It was shown that these pulsations are coherent with the longitudinal Adriatic-Ionian sea level slope.

Water volume transport estimates show that the total volume exchange rates are about one Sverdrup which are appreciably higher than the old estimates. Consequently the new estimates of the Adriatic water renewal time are about one year. Obtained suspended and nutrient exchange rates suggest that the Adriatic Sea represents a significant source region for the Eastern Mediterranean of all nutrient salts, with a slight gain of particulate carbon and nitrogen.

Future studies should address in a more detailed manner a problem of the a problem of the Southern Adriatic as an ecological system and its relation to the highly eutrophic Northern Adriatic. In such a context the hypothesis of the Adriatic Sea as a source of the anomalous N/P ratio in the Mediterranean should be tested. Repeating the Eulerian current measurements in the Strait of Otranto for another year and with better resolution in some parts of it, would give an opportunity to understand wether obtained exchange rates are anomalously high or they are "typical" values. The importance of mesoscale variability should be assessed in future studies using satellite data.

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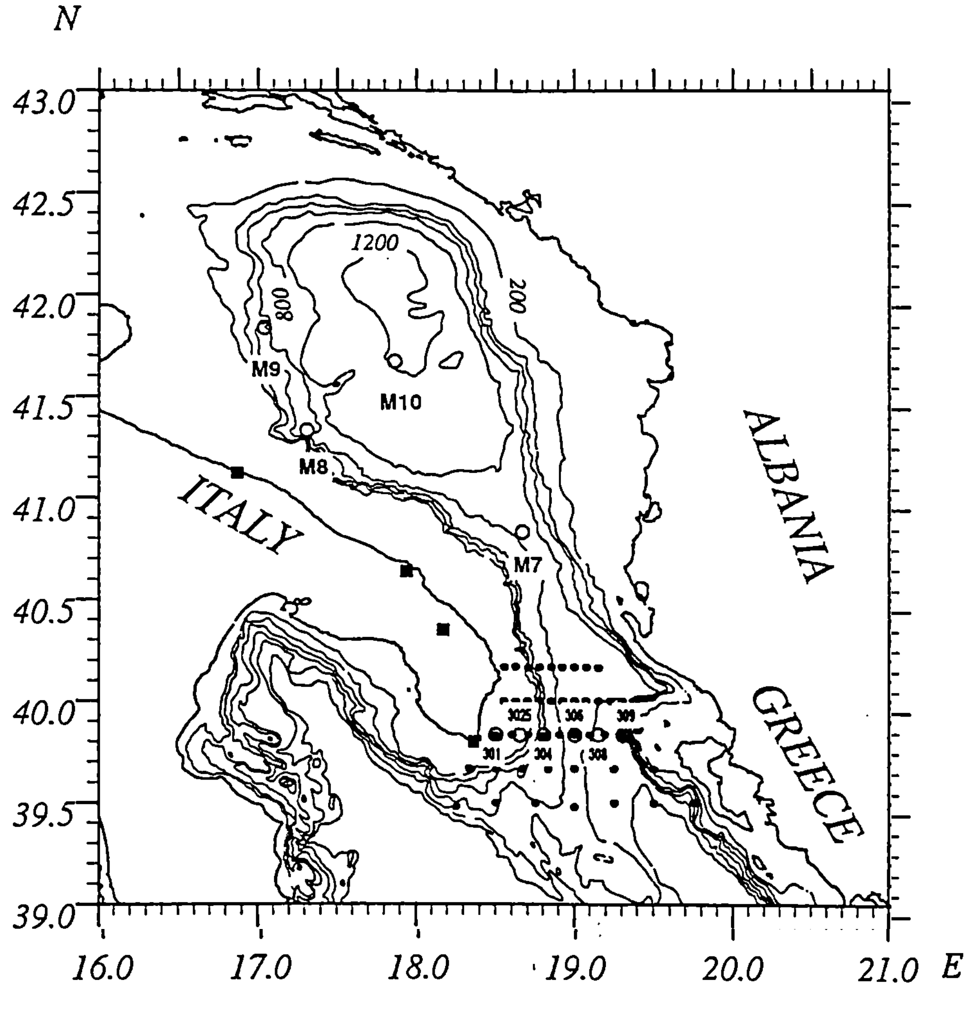

Fig. 1: Hydrographic and biogeochemical sampling stations (dots) and mooring sites (circles).

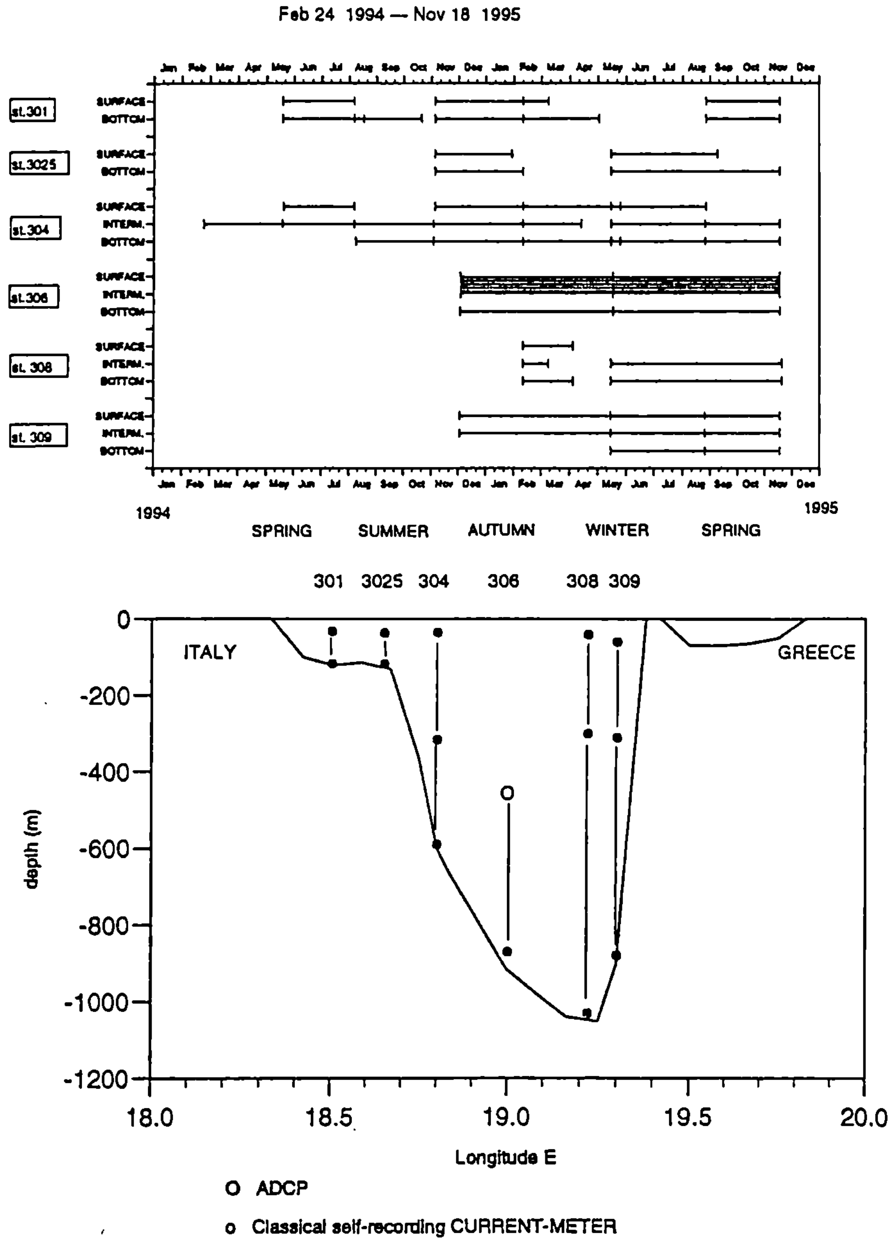

Fig. 2: Available Eulerian time-series for the Otranto transect (upper panel) and mooring array structure (lower panel).

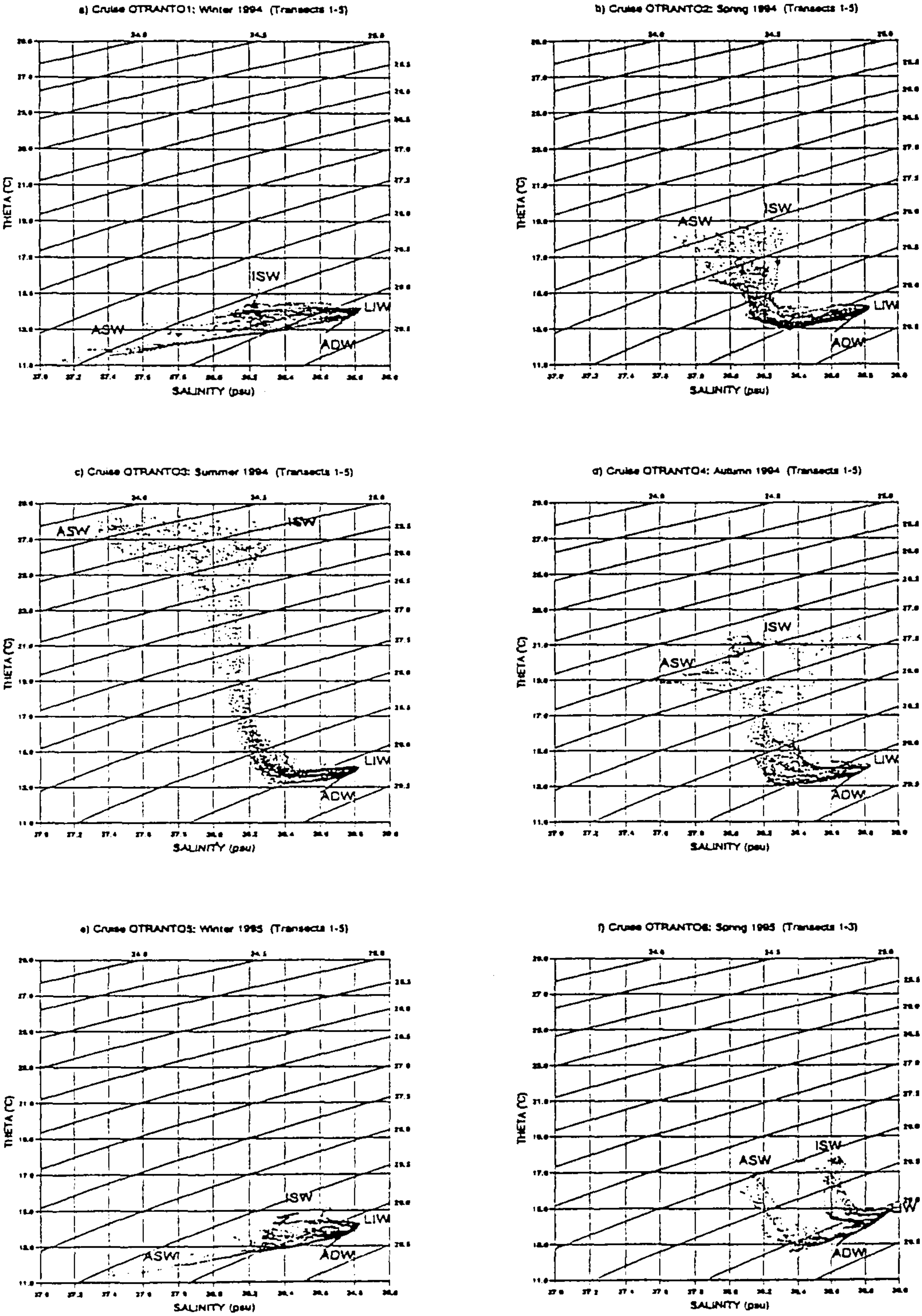

Fig. 3: θ - S diagrams of the six seasonal cruises.

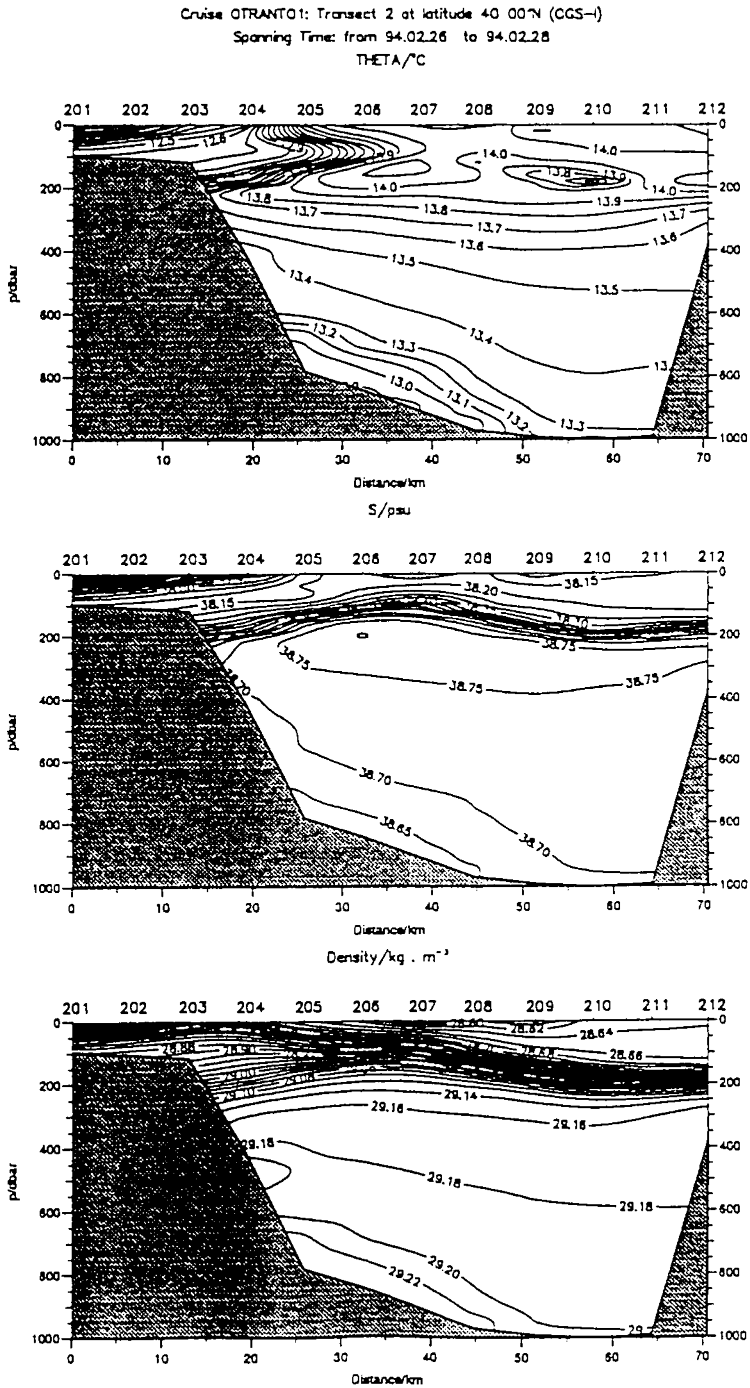

Fig. 4a: Vertical sections of potential temperature (upper panel), salinity (middle panel) an densityexcess(lower panel) for winter 1994 survey at transect 2. The hydrographic sampling station are indicated by numbers on the top of the layout.

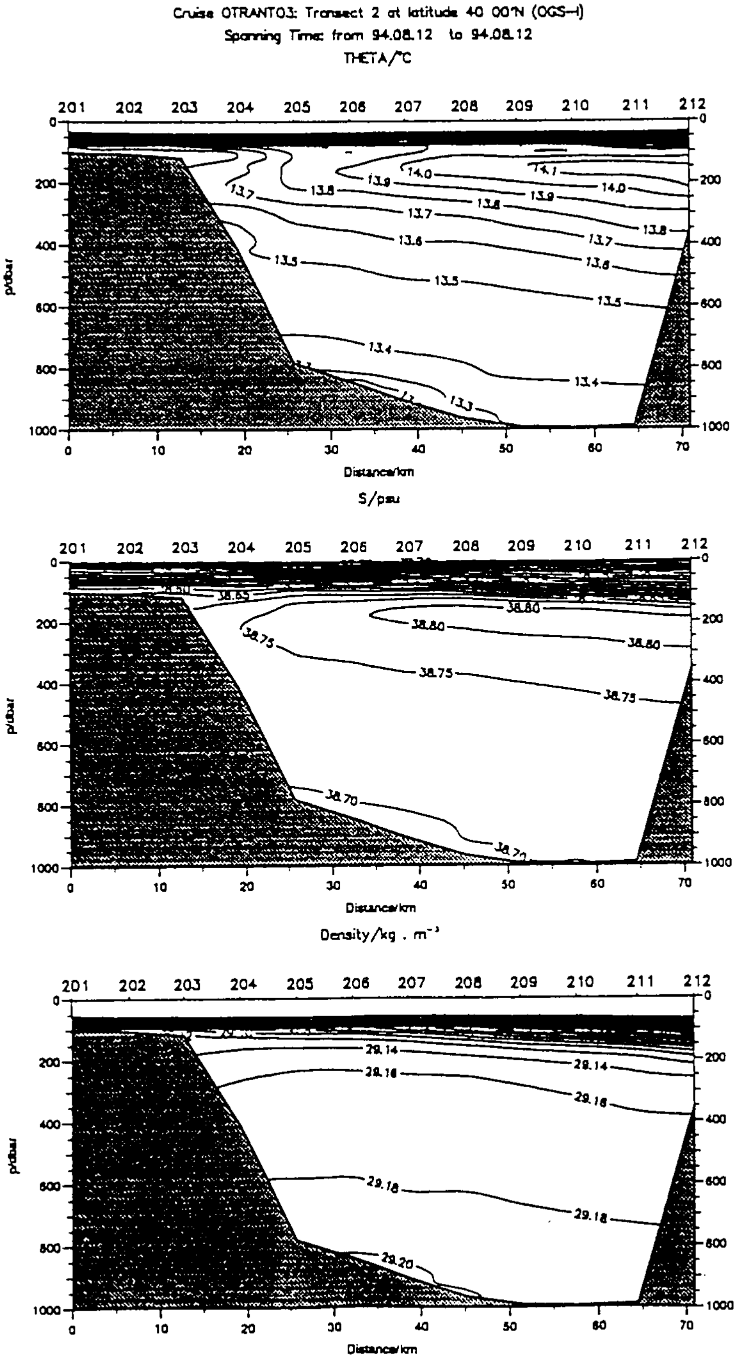

Fig. 4b: Vertical sections of potential temperature (upper panel), salinity (middle panel) and densityexcess(lower panel) for summer 1994 survey at transect 2. The hydrographic sampling stations are indicated by numbers on the top of the layout.

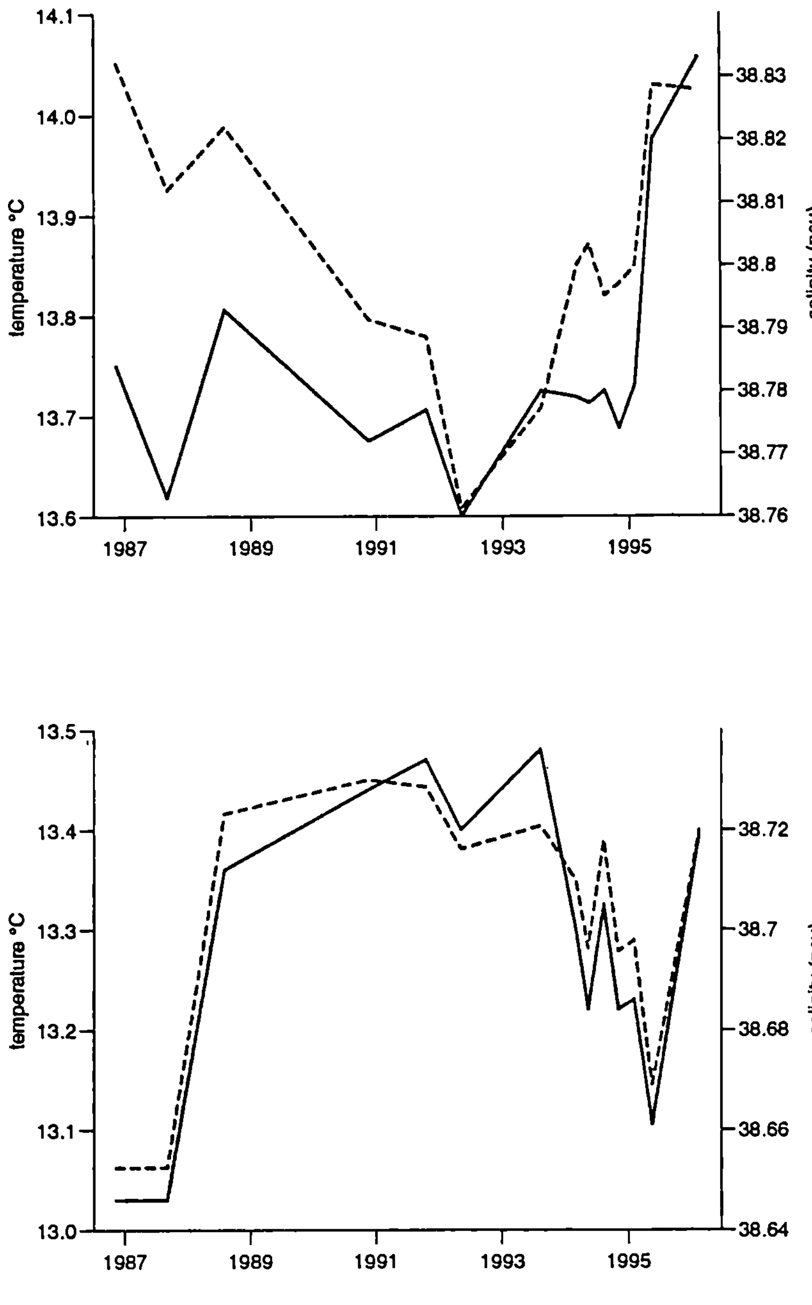

Fig. 5: Temporal variability of LIW properties (upper panel) and ADW (lower panel) from the data collected during the seasonal surveys within the OTRANTO project and from some historical data in the same area. Temperature time-series are denoted by dashed lines, while salinity ones by continuous lines.

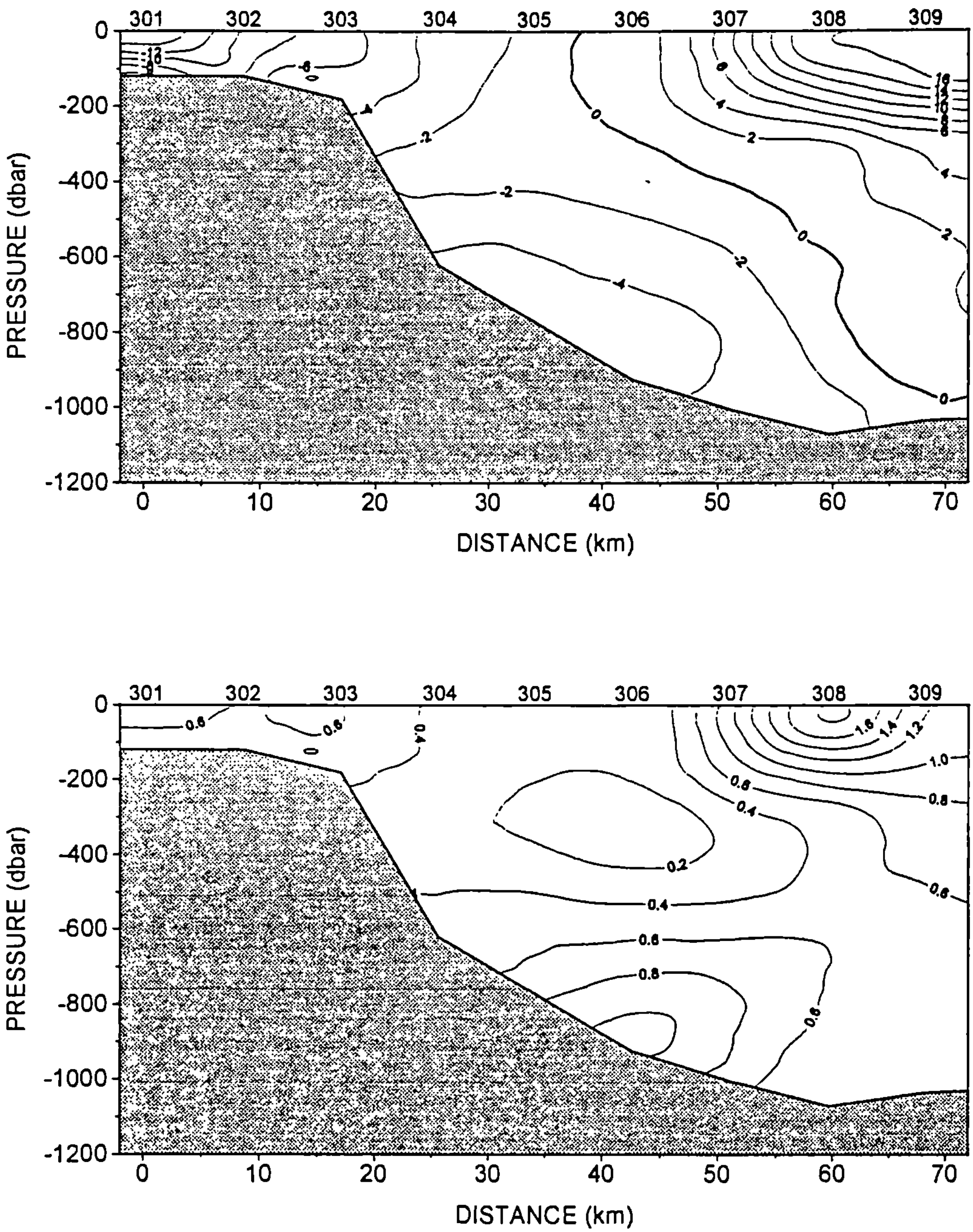

Fig. 6: Average inflowing (north) current component (upper) and the ration of the mean versus its standard deviation (lower panel).

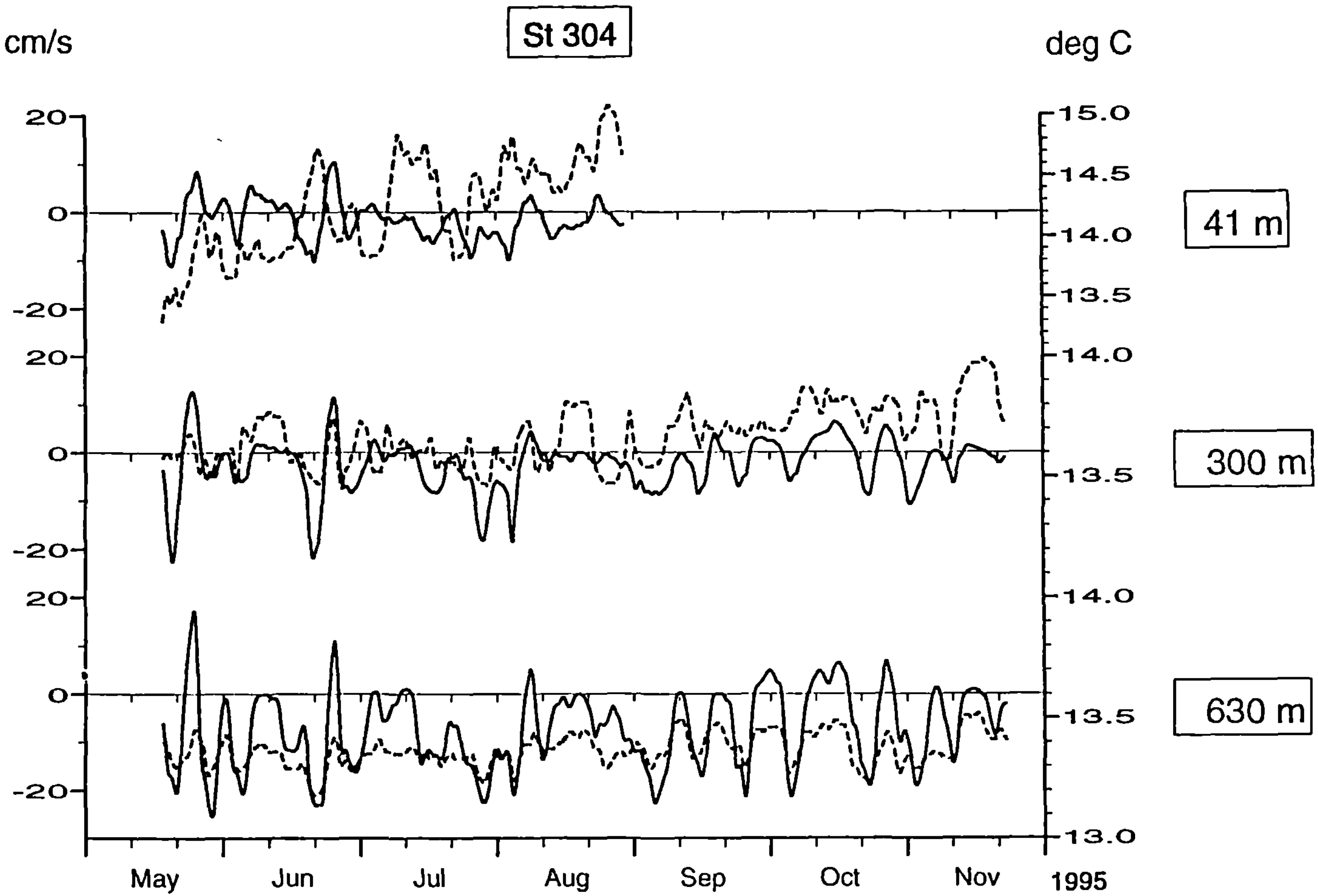

Fig. 7: Time-series of the north current component (continuous lines) and temperature (dashed lines) at three depths of the station 304 (western continental margin).

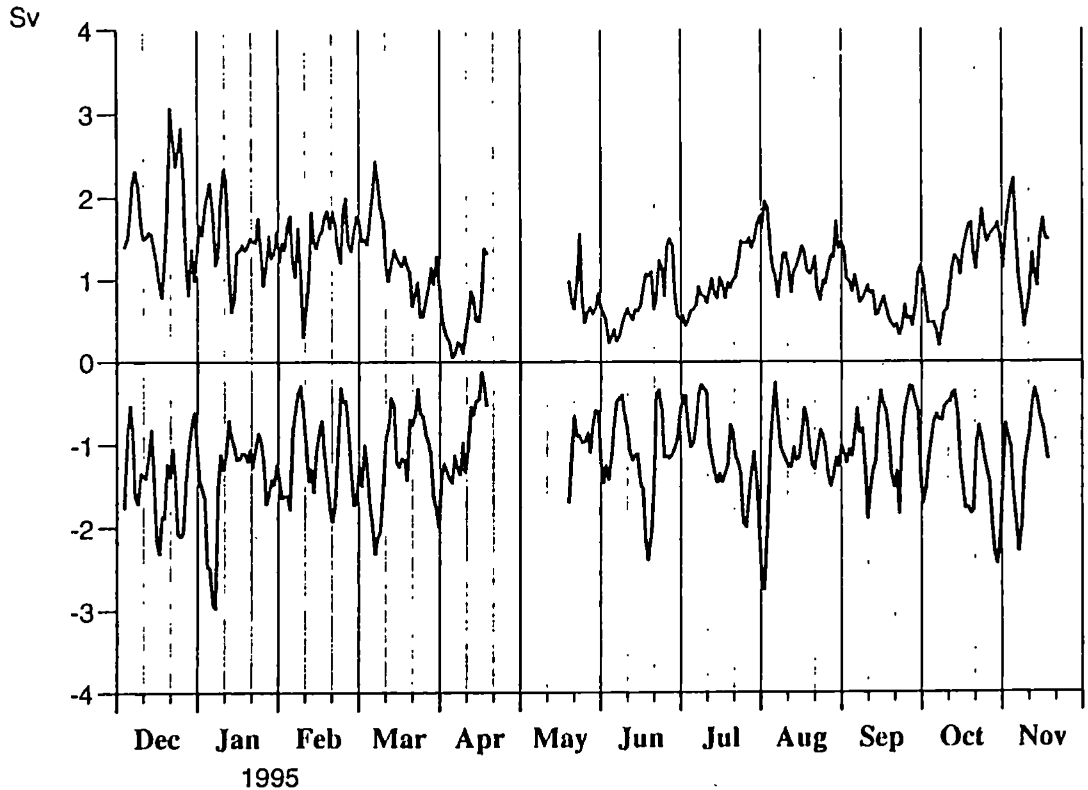

Fig. 8: Time-series of the daily volume transport rates in Sverdrups (positive inflow; negative outflow).

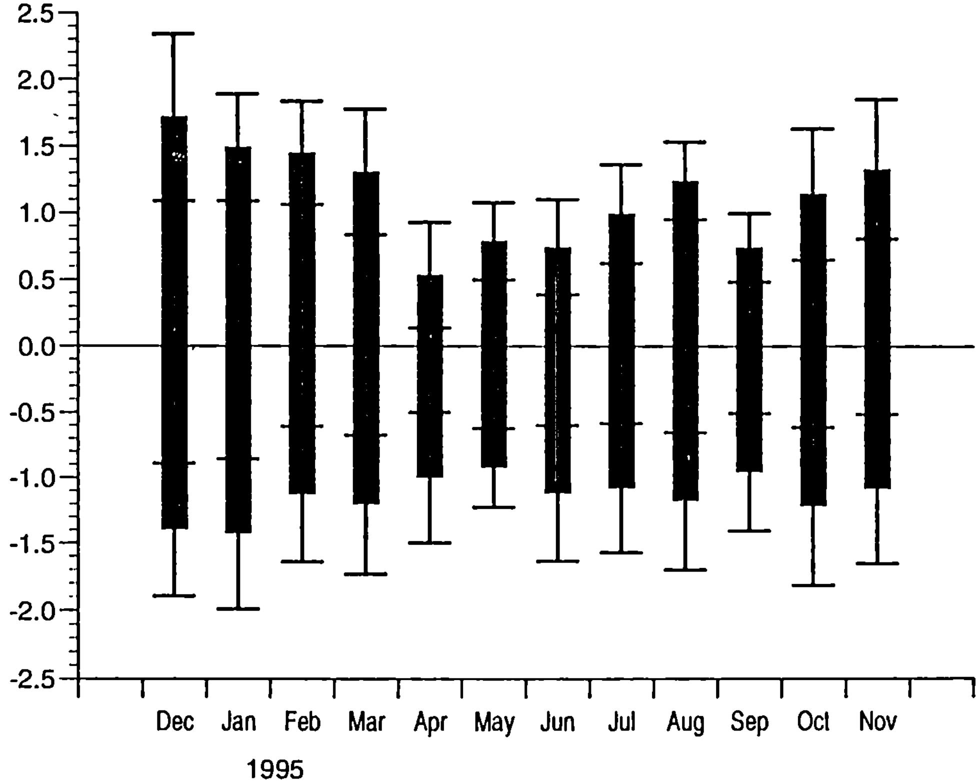

Fig. 9: Monthly values of the in- and outflow volume transport rates with respective standard deviations.

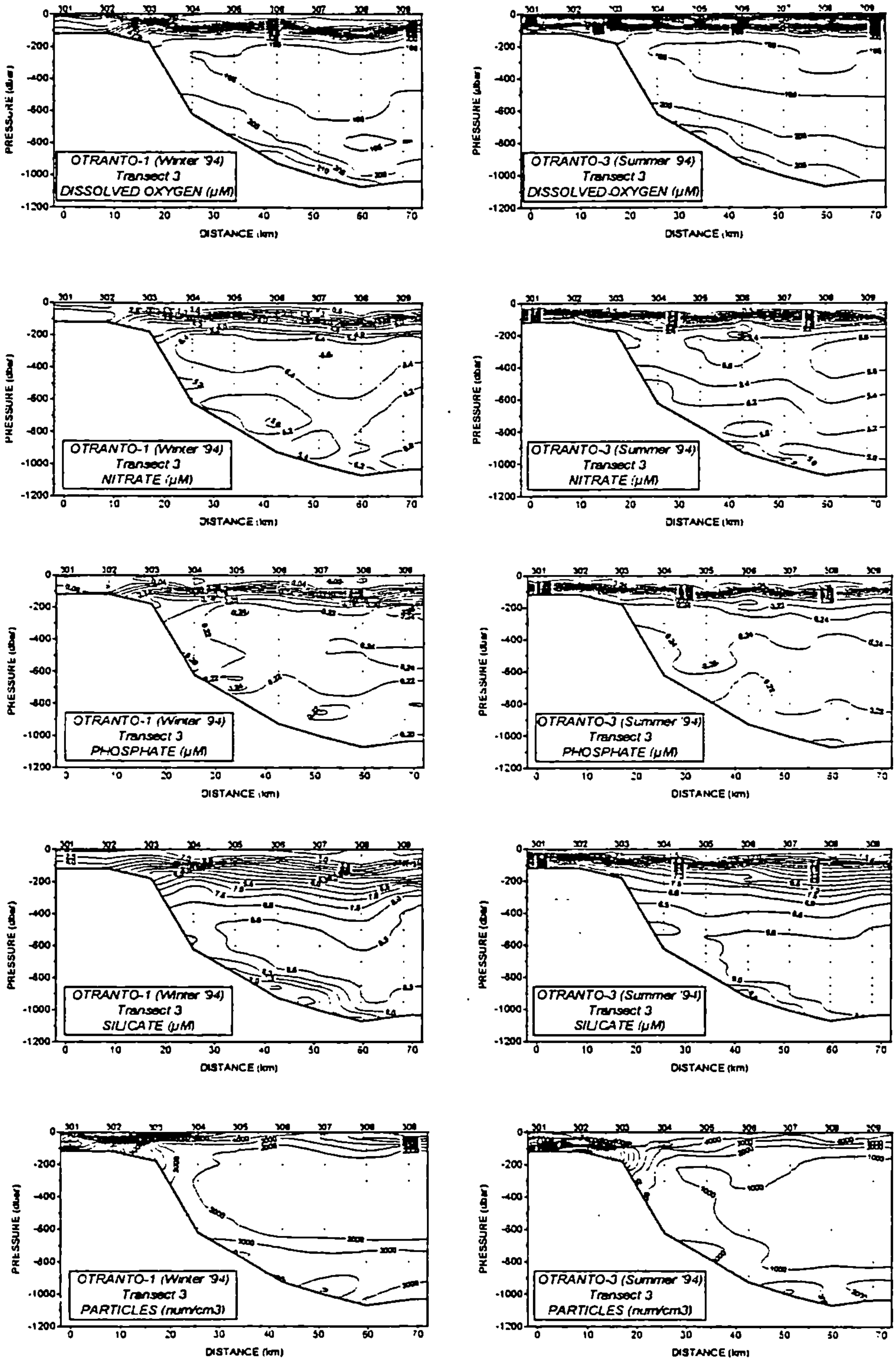

Fig. 10: Vertical distributions of biogeochemical water properties in winter and summer 1994.

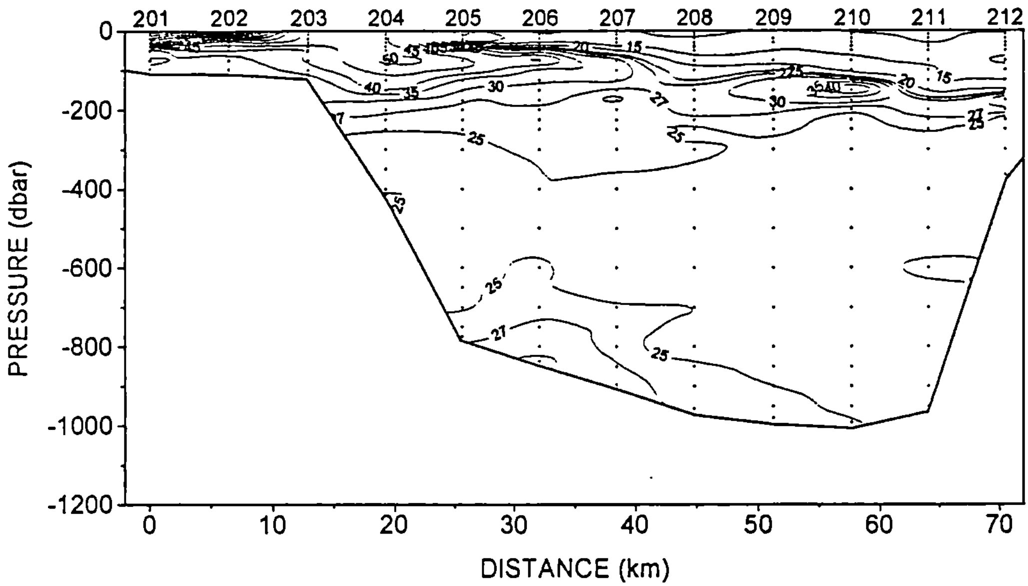

Fig. 11: The ratio NO_3/PO_4 in winter 1994.

Table 1. Statistics for current data collected in the Strait of Otranto (Feb '94 - Nov '95).

Location	water dep. (m)	period (days)	comp.	min (cm/s)	max (cm/s)	avg (cm/s)	std (cm/s)	mean vector speed (cm/s)	mean vector direction (° T)
301s	118	285	E	-85.2	40.6	-8.7	13.7	16.6	212
			N	-102.3	52.9	-14.1	21.0		
301b	118	348	E	-30.9	28.1	-1.7	6.5	5.3	199
			N	-54.6	45.9	-5.0	11.6		
3025s	132	210	E	-42.3	41.7	-3.8	9.6	8.3	207
			N	-49.8	23.4	-7.4	11.8		
3025b	132	284	E	-29.4	27.6	-1.0	8.3	3.7	196
			N	-35.6	23.3	-3.6	9.7		
304s	660	383	E	-29.3	27.8	-0.3	6.6	2.4	187
			N	-34.0	25.3	-2.4	7.7		
304i	660	597	E	-17.3	14.5	-0.2	3.1	1.3	189
			N	-27.6	17.2	-1.3	6.4		
304b	660	468	E	-13.1	14.2	0.1	2.3	4.3	179
			N	-30.2	23.3	-4.3	7.5		
306s	915	350	E	-23.2	22.1	-0.8	5.9	1.7	332
			N	-21.6	22.4	1.5	5.4		
306i	915	350	E	-24.0	20.2	-0.2	5.7	0.3	225
			N	-17.5	17.9	-0.2	4.8		
306b	915	350	E	-19.4	28.5	1.1	5.7	4.9	167
			N	-23.8	14.1	-4.8	4.6		
308s	1028	53	E	-32.8	22.4	-6.3	9.0	17.1	338
			N	-10.4	42.2	15.9	8.8		
308i	1028	213	E	-10.9	6.5	-0.4	1.7	1.3	342
			N	-9.5	16.3	1.2	2.8		
308b	1028	240	E	-16.2	15.8	-0.9	3.2	2.6	200
			N	-21.4	14.3	-2.4	5.1		
309s	900	350	E	-59.3	16.4	-7.5	8.3	18.7	336
			N	-29.5	76.7	17.1	16.4		
309i	900	350	E	-10.3	8.0	-0.8	2.3	4.4	349
			N	-13.3	24.5	4.3	5.7		
309b	900	186	E	-5.7	5.0	-0.3	0.9	1.7	350
			N	-13.7	19.0	1.7	4.0		

Tab. 2. Biogeochemical fluxes in the Strait

	from the Adriatic Sea	into the Adriatic Sea	NET FLUX
Autumn '94			
NO_3	27791	26609	-1182
PO_4	906	854	-52
SiO_4	42148	29211	-12937
POC	19735	20832	1097
Water	9.68	9.79	0.11
Winter '95			
NO_3	38683	22052	-16631
PO_4	1475	1086	-389
SiO_4	56496	31501	-24995
POC	12604	19857	7253
Water	10.1	11.3	1.2
Spring '95			
NO_3	12558	13614	1056
PO_4	564	597	33
SiO_4	18023	17666	-357
POC	11061	13806	2745
Water	3.51	3.08	-0.43
Summer '95 (*)			
NO_3	39460	25883	-13577
PO_4	1750	1071	-679
SiO_4	65393	35969	-29424
POC	21556	16575	-4981
Water	8.53	6.94	-1.59
Whole Year			
NO_3	118492	88158	-30334
PO_4	4695	3608	-1087
SiO_4	182060	114347	-67713
POC	64956	71070	6114
Water	31.82	31.11	-0.71

Biogeochemical unit in 10^6 moles; water unit in 10^{12} m^3.
(*) Biogeochemical data from OTRANTO-3 (summer 1994).

Mediterranean Targeted Project (MTP) - EMPS Project
Contract MAS2-CT94-0090

Synthesis of Final Results

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Contract No.: MAS2-CT94-0090
Starting Date: 1 September 1994
Duration: 24 months
EC Scientific Officer: E. Lipiatou

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European Microbiology of Particulate Systems

ABSTRACT

Microbial population dynamics was investigated in the water column of the north western basin of the Mediterranean Sea and in the Cretan sea. In the water column the concentration of particles > 100 µm, shown by Underwater Video Profiler, decreased from the coast to the open ocean and the distribution of these particles depended on the nature of the water masses. In the upper layer (70 m) the contribution of attached bacteria to total bacterial production ranged between 2-12 % . A dynamic simulation taking into account phytoplankton growth, nutrient depletion, carbohydrate exudation under nutrient limited conditions, aggregation, sinking and decomposition, nutrient regeneration and aggregate break-up, has indicated that the exudation of sticky carbohydrates and aggregation could confer a growth advantage on the phytoplankton that exude them. The ectoenzymatic activity per-cell is generally higher for free-living bacteria than for attached bacteria. Two bacterial communities (attached and free-living) showed different physiological behaviour. The effect of particulate material on heterotrophic bacterial activity was mainly visible in oligotrophic situations. The degradation of particulate material by microbial activity produced colloids and low molecular weight compounds. It could be demonstrated that the bacteria in the deep water column are adapted to the hydrostatic pressure conditions. The 16S rDNA sequence of particle associated and free-living ammonium oxidisers are different. Anaerobic bacteria processes (methanogenesis, denitrification) were demonstrated in particle collected in the globally oxygenated water column, the nature of the process being linked to the nature of the particulate material. Analysis of eubacteria 16S rDNA sequences of attached bacteria demonstrated a great diversity of the communities associated with particles.

Key Words

Bacterial community dynamics and vertical carbon fluxes

INTRODUCTION

The assessment of global cycling in marine ecosystems requires studies of processes controlling the fluxes of material from the productive layer to the sediment. Although microbial consortia are the major decomposers of the organic matter, the pelagic microenvironments in which such processes occur are not well known. The relationships between micro-organisms and particles are of reciprocal nature: microorganisms contribute to the physico-chemical constitution and alteration of particles, while particles provide conditions of life, allowing the coexistence of different, even unexpected bacterial species and metabolisms and interactions. On the other hand, because almost nothing is known about the taxonomical composition of bacterial communities in the oceanic waters, the exchange between the free-living and the particle-attached way of life for bacteria is still questionable.

The Mediterranean Sea is characterized by an oligotrophic trend increasing from west to east and more or less from north to south (McGill 1965). The benthic-pelagic coupling has been investigated in different projects of the MTP, through measurement of vertical geochemical fluxes by the use of sediment traps (Euromarge NB, Euromarge AS. Pelagos. Cincs). In such areas, particulate as well as dissolved export from the productive superficial layer in terms of organic material are obviously under the control of microbial mineralisation. However, until today the regulative processes of these microbial pathways are far from being identified

The overall objective of EMPS was to investigate the microbial population dynamics on particles and the role of microbial processes in the biogeochemistry of the water column. The relative biomasses. the specificity and physiological diversity of natural communities, and the autotrophic and heterotrophic bacterial activities in the particulate system were compared with those of free-living organisms. This was managed through cooperative studies of field and experimental microbiologists, molecular microbiologists, and modellers. Furthermore, a collaboration between EMPS project and two other MTP projects (EUROMARGE NB and CINCS) was performed through common cruises and exchanges of data.

The results obtained in EMPS project constitute a unique contribution in the knowledge of the particulate environment, its behaviour, and its implication in the functioning of the water column ecosystem of the Mediterranean Sea

MATERIALS AND METHODS

Strategy and cruises. The analysis of bacterial communities (biomass, processes, physiology, taxonomic composition) was performed on samples previously characterized by environmental parameters (Fig. 1).
Field studies were carried out during 6 cruises, i.e. 3 EMPS cruises (Pauline , Picnic , Mikel) and 3 joint cruises with the CINCS and Euromarge projects (Fig. 2).

Sampling procedure. Depending on the measured bacterial parameter, samples were collected by Niskin bottles, in situ pumps, Programmed Detritus Sampler (PDS) (Gorsky 1995) or High Pressure Sampler (Bianchi & Garcin 1993).

Environmental parameters. Hydrological parameters (temperature, salinity, oxygen, fluorescence, nephelometry) were measured using a CTD Sea Bird SBE. The distribution, size spectrum and equivalent carbon content of particles > 50 µm was determined by the Underwater Video Profiler (Gorsky *et al.* 1992). Dissolved and particulate compounds were determined as following: dissolved organic carbon (DOC) as Sugimura & Suzuki (1988) and Sharp *et al.* (1995), dissolved free amino acids (DFAA) as Lindroth & Mopper (1979), POC using a CHN analyser LECO, nitrogen salts (ammonium, nitrite, nitrate) as Tréguer & Le Corre (1975).

Laboratory experiments. Experimental determinations of rates and kinetic parameters of bacterial mineralisation of DOC and POC were carried out. Kinetic bacterial parameters of free-living and attached bacteria were measured using laboratory experiments with phytoplankton-derived particles. Additionally to the bacterial parameters, monomeric carbohydrate (Burney & Sieburth 1977, Johnson & Sieburth 1977) and DOC concentrations were measured.

Bacterial methodology. For SEM observations, aliquot fractions of the sampled particles from Niskin bottles or in situ pumps were collected on 0.22, 1.0, 3.0 and 10.0 µm mesh Isopore polycarbonate membranes and treated by the usual way for SEM and 45 to 120 pictures were recorded. For all the following parameters the method is described in the cited reference: bacterial biomass (Turley et al 1996), ATP determination (Poulicek & Danckers 1995), bacterial production (Furhman & Azam 1982, Kirchman 1993), hydrolytic potentialities (Hoppe 1983, Müller-Niklas *et al.* 1994), catabolic activities (Wright & Hobbie 1966; Hobbie & Crawford 1969), high pressure effect (Bianchi & Garcin 1993), nitrification (Feliatra & Bianchi 1994), denitrification (Omnes *et al.* 1996), methanogenesis (Marty 1993), sulfate reduction (Jørgensen 1978), diversity of attached communities (Ruimy *et al.* 1994), taxonomic composition of ammonium oxidizers (Stephen *et al.* 1996).

RESULTS AND DISCUSSION

Environmental Characterization

The sampling times (1994 - 1995) corresponded to the autumn situation (Pauline), i.e. mixing of the water column after the oligotrophic period of summer) and the spring (Picnic) and transient (Euromarge) periods, the later being the period between the late bloom and the oligotrophic summer situation.

Particle Distribution And Composition

For *in situ* abundance and size distribution estimations of fragile suspended aggregates, we have developed a non-destructive instrument, the Underwater Video Profiler (UVP). This approach based on underwater image recording and surface automated image analysis is more appropriate for the study of distribution patterns of suspended aggregates than collection by conventional techniques. At each station, water sampling was preceded by an UVP lowering and a rapid data treatment. The resulting abundance profile was printed out and used in the determination of subsequent sampling strategy. Sampling was carried out by a CTD/rosette system and by a new cable operated open-close sampler called Programmable Detritus Sampler (PDS) built by our team for non destructive sampling of macro-aggregates.

The sampling strategy described above was used during the four field cruises: Pauline, Picnic, Euromarge and Mikel.
The results, presented on Fig. 3, demonstrate that:

a) the vertical distribution of particles in the water column is not homogenous, but that different water masses carry different concentrations of particles;

b) this aspect is particularly distinct in the coastal zone;

c) the frontal circulation increases the heterogeneous vertical distribution of suspended particles by its hydrological discontinuity or downwelling effects;

d) the slope and the bottom re-suspension are found to be important sources of particles in the intermediate and deep layers;

e) the vertical winter mixing or the effect of a strong wind stress increases the heterogeneity in the vertical distribution of particulate matter.

Complimenting the above approach, Scanning Electron Microscopy (SEM) can give a direct insight into the number, nature and size spectrum of particles, and can even characterize the fine morphology of the surface of the particles (weathered or not, fresh or old fecal pellet, ...). In the case of EMPS, SEM observations of the sampled material during the four cruises: Pauline, Picnic, Euromarge and Mikel confirm bias in sampling with in situ pumps (depletion of fecal pellets and other macroaggregate densities, increase in the apparent biomass of some phytoplanktonic organisms, ...). SEM analysis of suspended material provides interesting observations about day to day and geographic variability of the nature and densities of the suspensions allowing some interpretation of results concerning metabolic aspects of the microbial community. Moreover, such an analysis can give clues towards the interpretation of results like anaerobic processes in open water associated with large intact faecal pellets embedded in peritrophic membranes or with terrigenous aggregates, distribution of some bacterial forms (spirilli, Fig.4a), free-living bacteria versus particle attached bacteria (Fig. 4b).

Bacterial Biomass And Production In The Photic And Aphotic Zones

Overall the integrated bacterial production comprises 9-46% (mean 22%) of the integrated primary production (calculated from Figs 5 a & c). Assuming a growth efficiency of 40% (Bjornsen & Kuparinen 1991) then 22-115% (mean 55%) of primary production may be routed through the DOC reservoir in order to support the bacterial carbon demand thus indicating that the microbial food web is important in the Mediterranean Sea.

There is a notable lack of a direct relationship between bacterial production and bacterial biomass in the upper 80 m (Fig. 5a) which is in contrast to the direct relationship occurring out of the photic zone (Fig. 5b). This indicates that while the deeper populations of bacteria may be in steady state this may not be true for the populations in the upper water column where the situation may be more dynamic with many factors influencing the population dynamics of the bacteria. This is also reflected in the discrepancies between results of ATP biomass measurements compared to bacterial biomass (Poulicek 1994, Poulicek & Danckers 1995). This is supported by the significant positive relationships between bacterial biomass and the rates of primary production (Fig. 5c) which is just one of the factors likely to influence bacterial biomass in the photic zone.

Estimation of the downward flux of labile carbon

In general, bacterial production shows a consistent exponential decline down to 600 m indicating that bacteria may have reached a steady-state. If this is the case, and if we assume production to be directly proportional to available labile organic carbon (ALOC), the observed decline reflects the balance between the downward flux of this carbon and its removal by respiration. Taking respiration to be proportional to production, this gives a direct estimate of the downward flux of labile carbon. Assuming 40% bacterial growth efficiency the estimated fluxes of ALOC at 200 and 1000m depth are 0.028 and 0.0001 g C m^{-2} d^{-1} in the spring, 0.073 and 0.022 g C m^{-2} d^{-1} in the summer and 0.023 and 0.007 g C m^{-2} d^{-1} in the autumn..As sediment trap estimates from the same area give a mean flux of 0.014 g C m^{-2} d^{-1} at 200 m and 0.0033 g C m^{-2} d^{-1} at 1000 m (Miquel *et al.* 1994) it is clear that the flux of particulate material could account for much of this. The difference could reflect the convective mixing of dissolved and colloidal organic carbon. In summer and autumn, the proportionate decline in the flux of labile carbon with depth is comparable to that for particulate carbon. In spring, prior to the development of a thermocline, it is much greater, presumably reflecting the transport of carbon which is less refractory, normally trapped above the thermocline, to greater depths. Our data and subsequent estimates contribute to the growing debate on the contribution of convective mixing of DOC to the vertical flux of carbon (Turley & Mackie 1994, Carlson *et al.* 1994).

Contribution of attached bacteria to total bacteria biomass and production

Although bacteria associated with particles only contributed 0.5-2.8% of total bacterial numbers they were consistently more metabolically active than the free-living bacteria with mean cell-specific leucine incorporation rates 2-10 times greater in the upper 70 m and 22-53 times greater below this depth for attached bacteria than for free-living bacteria (Table 1).

Table 1. Contribution of attached bacteria (PDS sampler) to total population biomass and production (Niskin sampler). Data from EUROMARGE cruise.

		Total bacteria		Attached bacteria			
Station	Depth (m)	Numbers (cells 10^6/l)	Production (mgC/l/d)	Numbers (cells 10^6/l)	Production (mgC/l/d)	Attached numbers (%)	Attached Production (%)
B5	40	687.0	0.851	14.9	0.051	2.2	6.0
B2	40	1295.0	2.427	36.4	0.122	2.8	5.0
S5	70	406.0	0.539	4.8	0.064	1.2	11.8
S5	380	133.0	0.058	1.2	0.028	0.9	47.8
S2	70	1004.0	1.282	9.7	0.036	1.0	2.8
M3	70	806.0	0.721	7.9	0.038	1.0	5.2
M3	160	317.0	0.197	1.7	0.024	0.6	12.5
M1	50	712.0	0.611	5.7	0.034	0.8	5.6

In the upper 70 m the contribution of attached bacteria to total bacterial production ranged between 2-12% (mean 6%) which is higher than the estimates of <0.5% in the subtropical Atlantic (Alldredge & Youngbluth 1985) and 1.8-3.4% in the temperate N Atlantic (Turley & Mackie 1994) but similar to estimates of 1-28% (mean 8%) in the Pacific off the Southern Californian coast (Alldredge *et al.* 1986, Alldredge & Gotschalk 1990). On particular occasions, such as the deeper water samples in this study, their contribution to total bacterial production is more significant, up to 48% (Table 1).

Coupled Nutrient and Phytoplankton Dynamics in the Surface Waters of the NW Mediterranean.

A dynamic simulation, based on the hypothesis presented in Fig. 6, in a which a cycle of phytoplankton growth, nutrient depletion, carbohydrate exudation under nutrient limited conditions, aggregation, sinking and decomposition, nutrient regeneration and aggregate break-up, has been run for range of carbohydrate 'stickinesses' and dispersion regimes in a hypothetical water column with prescribed hydrodynamics.

This has allowed the influence of aggregate formation and processes on the productivity of a hypothetical phytoplankton species in the water column over time to be investigated (Fig. 6) using intermediate dispersion rates (average over water column of 0.001 $m^2.s^{-1}$), growth rates from Cullen (1990), and initial conditions from the EMPS dataset. It is clear that fairly low degrees of stickiness, producing low degrees of aggregation, allow the phytoplankton to maximise nutrient regeneration, while minimising settling away from the light source (Fig.6). This maximises the phytoplankton concentration over the growth period. The NH_4 /NO_3 ratio seems to confer the largest advantage on growth rates (Fig.6). This is because growth on NH_4 is more rapid than growth on NO_3.

Large degrees of stickiness result in large aggregates and settling that rapidly strips biomass from the water column, while low levels of stickiness and/or removal of settling velocity (shown as open squares in Fig. 7) cause less efficient nutrient regeneration, less efficient tracking of the changing nutrient isopycnal and also the development of oxygen sags in the water column.

These modelling studies indicate that the exudation of sticky carbohydrates and aggregation could confer a growth advantage on the phytoplankton that exudes them. This advantage results largely from more efficient nutrient regeneration. Other runs of the model show that the mechanism confers these advantages in all but the highest water column mixing rates.

Ectoenzymatic Activity In The Water Column And On Particles

For all cruises there were some general trends discernable regardless of the enzyme tested. Ectoenzymatic activity declined with depth. While the use of in situ pump yielded high ectoenzymatic activity on the filter, on a volume basis ectoenzymatic activity was greatly reduced as compared to the bulk seawater indicating a significant loss of ectoenzymatic activity in the in situ pump. No clear trends in the enzyme kinetics are discernable although there is a tendency towards increasing Km with depth. Kinetics of the ectoenzymatic activity were performed for ambient waters and for marine snow. The Km was usually 1-2 orders of magnitude higher in marine snow as compared to ambient waters indicating low affinity of the ectoenzyme to the substrate. This is typical for environments with high substrate concentrations. The question remains, however, whether or not the per cell activity is higher in marine snow-associated bacteria than in their free-living counterparts.

In order to solve this question laboratory experiments were performed. The bacterial colonization and the development of the ectoenzymatic glucosidase activity and glucose uptake were followed together with bacterial growth (measured as thymidine incorporation) in laboratory experiments using phytoplankton-derived particles incubated in rolling tanks. Bacterial colonization of the particles was rapid. In the particles, bacterial growth rates (production / biomass) were lowest (0.02 to 0.14 d^{-1}) while in the ambient water growth rates increased from 0.1 d^{-1} to 23.3 d^{-1} until the end of the experiment. In the control, lacking any particles, turnover of bacteria ranged from 0.3 to 7.6 d^{-1}. Similarly, glucose uptake rates per bacterium were 1 to 2 orders of magnitude lower for particle attached bacteria than for their free-living counterparts. Generally, Km values for glucosidase activity declined over the incubation period in particles and free-living bacteria until 168 h, and slightly increased thereafter to values of approximately 0.1 µM (Fig. 8). While particle-attached bacteria exhibited significantly lower uptake rates of both thymidine and glucose per bacterium throughout the incubation, the per-cell ectoenzymatic activity was similar in particle-associated and free-living bacteria during the initial phase of the experiment but was significantly higher after ≈200 h.

Dissolved total (TCHO) as well as monomeric carbohydrates (MCHO) declined continuously in both particles and ambient water and remained constant in the control; TCHO comprised about 50 % of the dissolved organic carbon (DOC) in the particles, in ambient water TCHO contribution to DOC varied with only one exception between 25 and 45 % and in the control between 20 and 50 %.

The shift detectable in the relation between ectoenzymatic activity and uptake of substrate (thymidine and glucose) between free-living and attached bacteria over the incubation period might reflect changes in the physiologial conditions of the bacteria such as increased production of capsular material.

Potential Heterotrophic Activity Of Attached And Free-Living Bacteria

Glucose and amino acid potential uptake showed similar distribution with depth, amino acids uptake being always higher than glucose uptake. Maximum rates of potential uptake were generally detected in surface waters and there was a sharp decline along the first 100 m of the water column. Below 100 m the uptake rates of low molecular weight compounds were very low.

Bacteria associated with particulate material showed higher uptake rates per cell than bacteria living in the bulk seawater (Fig. 9). It is also remarkable that the potential activity of free-living bacteria on a cell basis was quite similar for all the samples analysed, while uptake rates of attached bacteria on a cell basis showed a great variability probably depending on the age and chemical composition of the particles. During the oligotrophic situation (Euromarge cruise) amino acids uptake rates per cell showed positive correlations with the volume of total particulate material and the size of particles (Spearman's rank correlation $P<0.05$).

The percentages of assimilation in the bulk seawater were similar for glucose and amino acids and they did not show significant variations with depth. The percentages of assimilation for the water samples ranged from 60% to 95% for most stations. However, the bacterial community attached to particulate material appeared to be good remineralizers since they showed lower percentages of assimilation than their free-living counterparts (range 20-70%).

Dealing with kinetic parameters, Vmax was generally higher for amino acids than for glucose both in bulk seawater and particles. Kt+Sn values in the particulate material were higher than in the bulk seawater (Fig. 9). Since Kt and Sn values are unknown, these results can be due to higher concentrations of natural substrates in particles than in the ambient water, higher values of the affinity constant for attached bacteria than for free-living bacteria or both. High Kt values for bacteria attached to particulate material would reflect the presence of low affinity uptake systems for amino acids and glucose, which characterizes a bacterial community adapted to high concentrations of substrates (Azam and Hodson 1981). Kinetic studies in seawater showed the existence of two uptake systems, a high affinity uptake system working at low concentrations of substrate (<20 μgC l^{-1}) and a low affinity uptake system working at high concentrations of substrate (>20 μgC l^{-1}), which might be related to the existence of two bacterial communities or ecological situations, attached and free-living bacteria.

In conclusion, these results point out the existence of two bacterial communities, bacteria attached to particulate material and free-living bacteria, which show different physiological behaviour, different Kt+Sn values for glucose and amino acid transport systems and different uptake rates on a cell basis, probably as a consequence of the nutritional status of their microenvironment, particles or ambient water. The total volume of particulate material and the size of particles were related to the potential heterotrophic activity on a cell basis only under oligotrophic conditions, which suggests that the effect of the particulate material on the heterotrophic bacterial activity is significant mainly in the oligotrophic situation of the system.

Particulate And Dissolved Carbon Mineralisation Rates

During the vertical transport of particulates a variety of processes such as microbial fragmentation as well as physico-chemical aggregation-disaggregation act to produce small particles, colloids or low molecular weight compounds. Because of the various turnover times of these components in the water column, the final step of degradation of organic matter, i.e. mineralization is difficult to determine. The objectives of our study are (1) to measure dissolved and particulate organic carbon (DOC and POC) through the water column, (2) to provide residence times for the labile fractions of the different components of the organic carbon pool and (3) to provide data set for the particle degradation models in the coastal Mediterranean Sea.

In DOC degradation experiments, rates of carbon consumption were examined by measuring changes of DOC. In the particle degradation experiment the particulate material was aseptically removed from the filter of the in situ pump by using 0.2 μm filtered seawater flow through a syringe and dispensed into precombusted glass bottles. Dissolved and particulate organic carbon were measured by LECO and high temperature catalytic oxidation (HTCO) analyzers, respectively. Bacterial abundances were determined as well as bacterial production. Turnover rates were calculated by applying first-order kinetics to incubation periods during which graphs of ln (DOC or TOC concentrations) against time were linear, the rate is then the slope of that line. Because variation of bacterial biomass reflected only net production, gross biomass production was directly obtained from cumulative bacterial carbon production (thymidine method). Conversion factors were 20 fg C per bacteria and 40 ng C produced per pmole thymidine incorporated into the DNA. Carbon growth efficiencies were defined as follows = (gross biomass production)/(DOC depletion) for liquid incubations whereas it was defined by (gross biomass production)/(TOC depletion) for particle incubations.

The results showed that simultaneously to the initial increase in bacterial abundance, 18-45 % (av. 29 %) of 0.02 μm > DOC, 23-45 % (av. 33 %) of 0.2 μm > DOC and 32-92 % (av. 54 %) of POC 10 μm were consumed during incubation periods. Moreover, the results indicated that the degradation of particles produced colloids and low molecular weight organic compounds. Although water leaching may generate particle fragmentation, alteration is mainly due to the microbial activity. During the time course and the laboratory conditions of the incubations the results indicated various residence times ranging from ca. 3 days (particles) to ca. 16 days (0.02 μm > DOC). Colloid residence was ca. 4 days indicating a particularly high bioreactivity and likely their particulate origin.

Catabolic Activity In Deep Water Column

The specificity of the Mediterranean in respect to temperature conditions in intermediate and deep-waters offers an exceptional opportunity to study the effects of increasing pressure conditions upon microbial activities independently of the effect of decreasing temperature. We used a high-pressure sampler (Bianchi & Garcin 1993) to estimate the effects of hydrostatic pressure conditions upon the metabolic activity of bacterial consortia throughout the whole water column.

When sea-surface samples are submitted to increased hydrostatic pressure conditions (50 bar) glucose uptake rates drastically decrease from 600 pmol C l^{-1} h^{-1} (under atmospheric pressure conditions) to 35 pmol C l^{-1} h^{-1}. This experiment shows clearly that surface living bacteria are not adapted to high-pressure conditions. Therefore surface-born bacteria carried down through the water column (i.e. deeper than 800 m) during particle sedimentation results only a minor contribution to the mineralisation of sinking particles.

Conversely, when metabolic activities of intermediate and deep water samples collected during stratification water period were measured under different pressure conditions, ^{14}C-glucose uptake rates appeared clearly lowered in decompressed samples. Briefly, an overall estimation (n =18 samples, average depth = 1330 m) shows that the V_{max} for glucose uptake in undecompressed samples is 2.3 fold the V_{max} measured on the corresponding decompressed samples. These results show that during the stratification period, bacteria living in intermediate and deep water masses are adapted to high-pressure conditions. We observed that the pressure effect increases with increasing depth and that even in deep watermasses, rates of microbial activity are subject to important annual variations possibly associated with fluctuations in the particle flow (peaks of activity in May and December) (Tholozan *et al.*, in preparation).

These data showed the necessity to maintain seawater samples in their natural hydrostatic pressure conditions during retrieval and incubation to get significant measurements of biologically processed biogeochemical rate. For this purpose we developed, and used during the last cruise, a new high-pressure serial sampler (HPSS) to get *in situ* microbial activity data from deep-sea waters (that is unbiased by decompression during retrieval) with the same frequency as used for measurement of other chemical and biological parameters (Bianchi *et al.*, submitted).

In conclusion, bacteria living in deep seawater are adapted to the hydrostatic pressure conditions exerted in their natural surrounding. This adaptation to high-pressure conditions can be considered as an hallmark of their deep-sea origin (Yayanos *et al.* 1982). On the other hand, due to the effects of increasing hydrostatic pressure, metabolic activities of bacteria associated with surface produced particles drastically decrease during their sinking through the water column. These data raise the question of the actual mineralization rates of particulate material during their sinking period through the water column. Are these particles slowly degraded by the initial (pressure sensitive) microflora, or are they newly colonised by deep-sea (pressure adapted) bacteria and therefore mineralised more rapidly than measured on decompressed samples? Finally these results suggest the interest for studying the microbial diversity in deep-sea samples to determine if the metabolically active deep-sea bacteria are high-pressure adapted strains of the unadapted species living in the superficial waters, or if they are an original community of species or genera taxonomically different.

Nitrification Processes And Structure Of Ammonia-Oxidizing Community

In the oligotrophic waters of the Mediterranean Sea, the nitracline corresponds to the depth where the light limits the primary production (Herbland & Voituriez 1977). At the same depth, at the base of the photic layer, the nitrification can contribute to the nitrate assimilation of phytoplankton (Ward *et al.* 1989). Examination of the vertical distribution of nitrification indicates that the highest rate of nitrification was measured, for the pelagic stations, under the peak of chlorophyll and corresponding to the peak of nitrite. During the Euromarge cruise, which was at the beginning of the oligotrophic summer situation of the Mediterranean ecosystem, the nitrate produced by nitrification was potentially able to contribute 2 to 11 % to the nitrate flux taken up by the primary producers. This contribution is of the same order as those already seen in the Alboran Sea (Bianchi *et al.* 1994) but lower than the 23 % measured in euphotic layer of the Algerian Basin by Gentilhomme and Raimbault (1994).

In the coastal stations, the allochtonous inputs provided some ammonium through particulate input (at Station 5.5 near Nice) or dissolved and particulate input near the Rhône river plume (Feliatra & Bianchi 1994). High rates were determined in the deep water column of the coastal station and in the vicinity of the Rhône area. The overall rates measured in the Western basin, were of the same range (3 to 6 nmol N l^{-1} h^{-1}).

Phylogenetic analysis demonstrated that sequences typical of the *Nitrosomonas* cluster of the ammonia oxidising bacteria were dominant in samples from particulate material (Fig. 10). Planktonic populations, however, contained very few ammonia oxidiser sequences and these belonged exclusively to the *Nitrosospira* cluster (Fig. 10). This result was further confirmed by hybridisation of the cloned library with probes specific to the relevant clusters of ammonia oxidising bacteria (Phillips *et al.* in preparation).

In other studies of the ammonia oxidising bacteria it has been shown that isolation of the bacteria using enrichment conditions *Nitrosomonas* like sequences are more common but in direct extraction of DNA from environmental samples *Nitrosospira* like sequences are more dominant (Belser *et al.* 1978; McCaig *et al.* 1994; Hiorns *et al.* 1995). In the Mediterranean Sea, domination of particle-associated populations by *Nitrosomonas*-like sequences may result from selection by localised high ammonium concentrations, similar to those found in laboratory media. The significance of dominance of planktonic samples by *Nitrosospira*-like sequences is more difficult to assess, due to the lack of cultured representatives of the marine *Nitrosospira* group, and consequent ignorance of their physiology. Observations however, during this EMPS project have suggested that planktonic ammonia-oxidisers may be responsible for the majority of the nitrification rates measured.

Denitrification And Nitrate Ammonification Processes

Denitrification can occur in highly turbid estuarine waters with a high nitrate concentration where particulate organic matter provides microniches permitting the anaerobic processes to occur in an oxygenated water column (Omnes *et al.* 1996). In addition to nitrate reduction by denitrifiers, bacteria in anaerobic ecosystems may compete for nitrate in a second pathway leading to ammonium and termed dissimilatory nitrate reduction to ammonium or nitrate ammonification (Koike & Hattori 1978). The aim of this section of the EMPS project is to test for both dissimilative nitrate reduction pathways associated with suspended particulate matter in the open sea.

Simultaneous determination of denitrification and dissimilatory nitrate reduction to ammonium in coastal water off Marseille and Nice were undertaken by using a combination of acetylene blockage and ^{15}N techniques (Omnes *et al.* 1996).

As an example, results of denitrification and nitrate ammonification measured in the particulate samples are given in the Fig. 11 (A: Pauline cruise, station M5; B: Picnic cruise, station 28 milles). Whatever the sampling period, the location and the depth, denitrification is the main process implicated in the dissimilatory nitrate reduction. The addition of substrate does not lead to an increase of this activity showing that the amount of enzyme associated with this process is the limiting factor for the *in situ* expression of denitification. In contrast, the addition of substrate results in an increase of nitrate ammonification that seems to occur in larger particles located in the upper layer in autumn (Pauline cruise) and spreads throughout the water column during the exportation period (Picnic and Mickel cruises). These results may indicate that denitrification and nitrate ammonification processes did not occur in the same kind of particles.

Methanogenic And Sulfate-Reducing Activities

The two processes of methanogenesis and sulfate reduction constitute the last steps of anaerobic mineralisation; they are carried out by strictly anaerobic methanogens and sulfate reducing. However, the constant supersaturation of methane observed in surface waters of the World's oceans indicates the presence of active methanogenic bacteria in the ocean water column (Oremland 1988). Methanogens, as well as sulfate reducers, cannot exist in a free state in the oxygenated water column, but could survive if associated with reducing microenvironments, such as suspended particles (Sieburth 1987, Bianchi *et al.* 1992).

In order to determine if these two anaerobic bacterial processes are involved in anaerobic mineralisation within anaerobic microenvironments provided by particles suspended in the water column, methane production (Marty 1993 1995) and sulfate-reduction (Jørgensen 1978) activities were investigated in particulate material collected with in situ pumps and Niskin bottles along the Marseille transect (Pauline-1, Euromarge, & Pauline-2 Cruises) and the Nice transect (Picnic, Dynaproc, & Mikel Cruises).

Marseille transect. With the exception of samples collected during the Euromarge cruise, which was conducted in June-July during oligotrophic regime, and in which no methane production was detected, methanogenic activity was observed in all samples collected with in situ pumps. The highest rates of methane production were measured in seawater layers containing numerous particles and corresponded either to the bottom nepheloid layer, or to the superficial layer located just below èuphotic zone. In contrast, sulfate-reducing activity was detected in only 78% of the samples collected with in situ pumps, but this activity was also detected in 17% of the samples collected with Niskin bottles, in which methanogenic activity was not evident.

Nice transect. Along this transect, sulfate-reducing bacteria exhibited a particularly limited activity, being present at only 2 depths for each station: 100 m and 700 m depth for Station 1 (5.5 milles), and 50 m and 260 m depth for Station 2 (28 milles); nonetheless, sulfate reducers were detected in samples collected with Niskin bottles at 100 and 300 m in Station 1, and 50 m in Station 2. Methanogenic activity, which is shown in the Fig. 12, was detected at all sampled depths in Station 1, and at 5 depths among the 7 depths sampled in Station 2. At these 2 stations, methanogenic activity appeared to be maximal around 100 m depth, and then decreased with depth to 400 m. It must be noted a layer harbouring many gelatinous animals occured at 420 m at Station 1 also had dramatically high methanogenic activity.

In conclusion, strict anaerobic processes, such as methanogenesis and sulfate reduction, can effectively occur in the globally oxygenated seawater column, each process developing in different kinds of particles. In contrast with sedimentary biotopes in which sulfate reducers play a key role in anaerobic mineralisation, in seawater column they have only a limited importance. However, the constant presence of methanogenic bacteria suggests that the potential for methane production is present in the water column; and it is likely that the activity of these particulate methanogens contribute to the methane supersaturation observed in oceanic surface waters.

Overall Community Structure By Low Molecular RNA Analysis

It is a well known dilemma of marine microbiology that marine bacteria are very difficult to grow in the laboratory, e.g. from open ocean seawater samples only about 1‰ of the cells detectable by microscopic methods can be cultured (Jannasch and Jones 1959, Austin 1989). We noticed a similar efficiency of cultivation in our mediterranean samples. On the other hand, most physiological and taxonomic analysis of bacteria require cultivated organisms. Using direct molecular analysis of taxonomic signature molecules like 16S rRNA as mentioned above in comparison with 16S rRNA sequences obtained from isolates of the same marine environments it is possible to identify the relevant marine bacteria.

The great problem with the genotyping of isolated bacteria is to reduce the number of redundant isolated strains, i. e. isolates of the same species. Therefore, Low-molecular-weight (LMW) RNA profiling was used as a rapid molecular screening techinques for isolated bacterial strains from the Mediterranean Sea that allows genotypic grouping at the species level (Höfle and Brettar 1996). About 160 Mediterranean isolates from station S1 and S2 were analysed by LMW RNA profiling and in the next analytical step the 16S rRNA sequences of the single genotypes were determined (Table 2). Within these isolates genotype B, identified as belonging to the genus *Pseudoalteromonas*, dominated by 44 %. Five other genotypes belonging to the a- and g - subdivision of the Proteobacteria accounted for a total 31% of the isolates. These genotypes were of an abundance of 3-14% of all isolates. The last quarter of the isolates were only present as single strains, i. e. these genotypes were isolated only once, but they showed a large diversity of different LMW RNA profiles. Since we also isolated free-living bacteria we could compare between the particle attached and the free-living forms. All major genotypes occurred in both fractions except for genotype E that was only observed with particles.

Table 2: Summary of all bacterial strains isolated from station S1 and S2 and their genotypic grouping by Low-molecular-weight (LMW) RNA profiles and identification of 16S rRNA sequencing. Taxonomic identification is based on a relationship to the 16S rRNA reference data base. 16S RNA similarities at 90% or below do not allow an identification at the genus level. n.d. = not determined,T. U. taxonomic unit, OTU : operational taxonomic unit

LMW-RNA profile T. U.	Phylum	Closest relative (16 S rRNA-sequencing	16 S rRNA Sequence similarity (closest relative)	Total number of isolated LMW-RNA OTUs	% of total isolates
A	a- Proteo-bacteria	*Erythrobacter longus*	93.4%	8	5
F	a- Proteo-bacteria	*Brucella canis*	90.4%	5	3
H	a- Proteo-bacteria	*Brevundimonas vesicularis*	99.4%	9	6
B	g- Proteo-bacteria	*Pseudoalteromonas atlantica*	94.6%	71	44
E	g- Proteo-bacteria	*Methylophaga marina*	85.4%	4	3
K	g- Proteo-bacteria	*Psychrobacter immobilis*	96.3%	23	14
G	n.d.	n.d.	n.d.	3	2
L	n.d.	n.d.	n.d.	3	2
others	n.d.	n.d.	n.d.	34	21

A comparison of the genotypes obtained from cultivation with the genotypes obtained directly from cloning the DNA from the marine environment indicates that the major isolate *Pseudoaltermonas* sp. genotyp B was also found in several clones obtained from DNA. For the other abundant isolated genotypes such corresponding clones could not be detected. It is evident from this comparison that the majority of the bacterial population in this marine environment has yet to be cultured and that the diversity of cultured bacteria is rather different from the diversity obtained directly from cloning.

Analysis Of Bacterial Diversity Associated With Particulate Matter

We have compared the community structures of bacteria associated with particles at different depths at the two stations during the Picnic cruise: at 5.5 milles (sampled at 100, 400 and 700 m) and at 28 milles (sampled at 100 and 400 m) using clone libraries of 16S rDNA sequences obtained after amplification (PCR) with universal eubacterial primers. A neighbour-joining phylogenetic analysis of the 202 isolated clones (Fig. 13) allowed a number of clusters as well as some deep branches to be distinguished. Phylogenetic identifications were carried out using a database of about 3800 previously aligned eubacterial nearly full-length 16S rDNA sequences.

These analyses demonstrated that not all of the clones were true eubacteria as 55 of the clones were clearly chloroplasts. This is not very surprising, since chloroplasts are symbiotic cyanobacteria, and a similar result had already been obtained during a study of particulate matter in the ocean (DeLong *et al.* 1993). The 147 true eubacterial sequences could be divided into at least 8 different phyla: 27 Cytophaga-Flavobacter & Bacteroides (CFB), 12 true *Cyanobacteria*, 1 *Fibrobacter*, 3 Firmicuta High G+C (FHGC), 6 Firmicuta Low G+C (FLGC), 18 Planctomycetales & Chlamydia, 77 Proteobacteria and 1 Spirocheta. Six clones had sequences that branched very deeply and could be new phyla. In order to take a conservative approach in estimating diversity, all of these clones but two were attributed to the most closely related phylum. The paucity of true Cyanobacteria is probably related to the specific ecological niche that was sampled, i.e., particulate matter well below the surface euphotic zone. The cyanobacteria detected were probably attached to particulate matter, and their presence at each location may suggest that this taxon was predominent in the top layer of the sea. By contrast, the many chloroplasts retrieved, in particular at 400 m at both sites, are likely to be of faecal origin. The 400 m layer is characterized by an abundant zooplanktonic community which may produce faecal pellets after their diurnal vertical migration to the surface to feed at night.

We found significantly more diversity than in similar studies carried out in the Atlantic or the Pacific oceans. Interestingly, all the phyla were retrieved at 700 m while fewer phyla were retrieved at 100 m, and most of the clones that could not be identified clearly to a phylum were found in the deeper water layers. Our sampling procedures differ from most previous studies in that we have sampled particulate matter rather than sea water and that we have also sampled deeper in the water column. However particulate matter had been sampled previously (DeLong *et al.* 1993) and a sample from 400 m had also been taken previously (Furhman *et al.* 1993). It is however striking that other studies, done in the upper marine layer (surface to 100 m) have mostly retrieved the same phyla as those found near the surface, a result that suggests that Cyanobacteria, CFB and Proteobacteria are well adapted to the ecological niche of the upper sea water layer. We therefore suggest that different bacterial OTUs may be present at different depths and that the estimation of bacterial diversity in the oceans should include many samplings at various depths and a simultaneous analysis of the same sample of free-living and particle-associated bacteria.

The increase in diversity with depth could be an artefact due to too few clones having been analyzed. This would in particular be the case if some phyla were represented by large cells numbers near the surface, while other phyla were restricted to only a few bacterial cells. This would account for not retrieving rare OTUs when only 30 true eubacterial clones are analyzed at each location.

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Environmental characterization

Hydrological parameters
Distribution, size and composition of particles

Bacterial studies
Field and *Laboratory*

Processes: aerobic, anaerobic, autotrophic, heterotrophic

Community: composition, diversity

Modelling

Figure 1 - Strategy of study applied in MTP-EMPS project

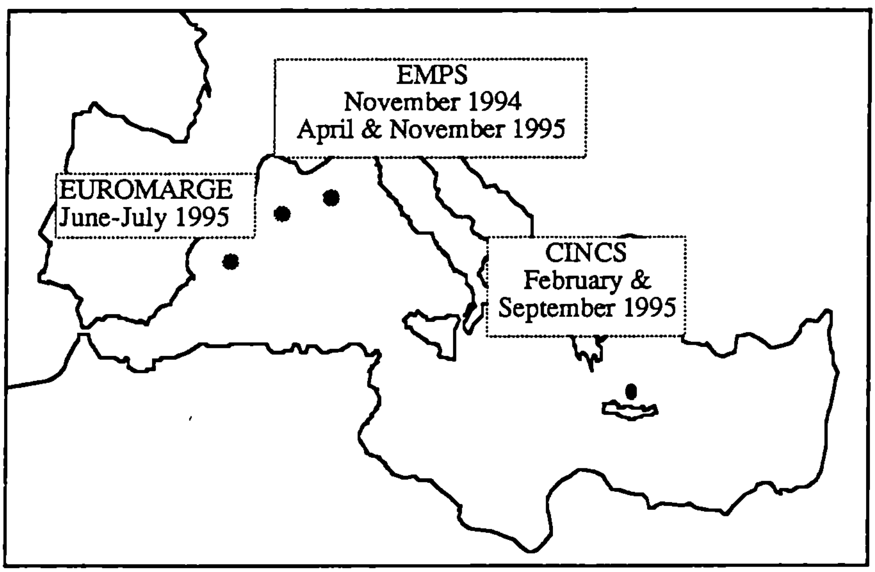

Figure 2 - Cruises of the MTP-EMPS project

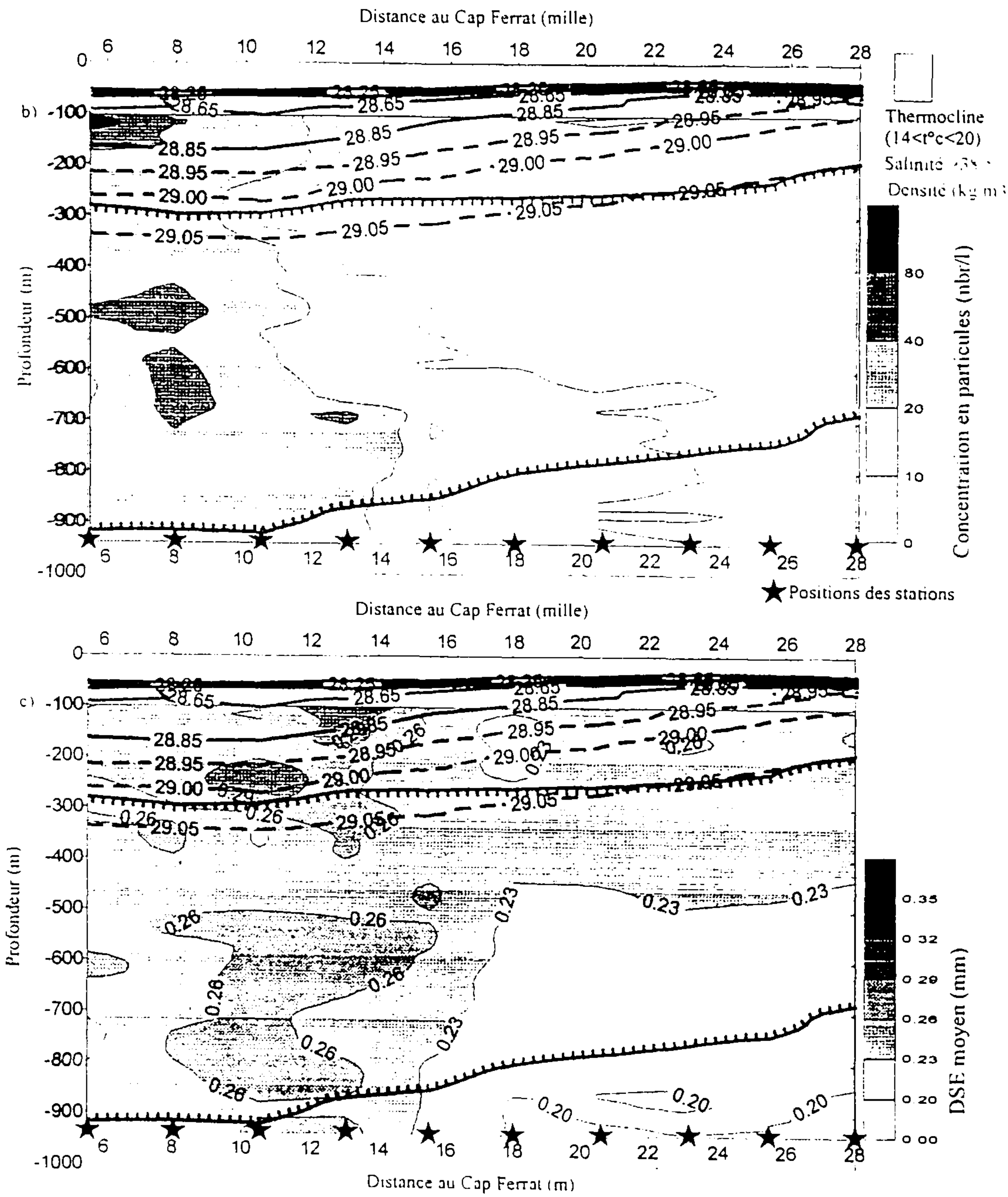

Figure 3 - 2 D representation of particles abundance (above) and size (as equivalent spherical diameter, bellow) of the Nice-Calvi section. In yellow: layer above the thermocline, in green: isopycnals, in red: levantine water layer, stars: UVP lowering

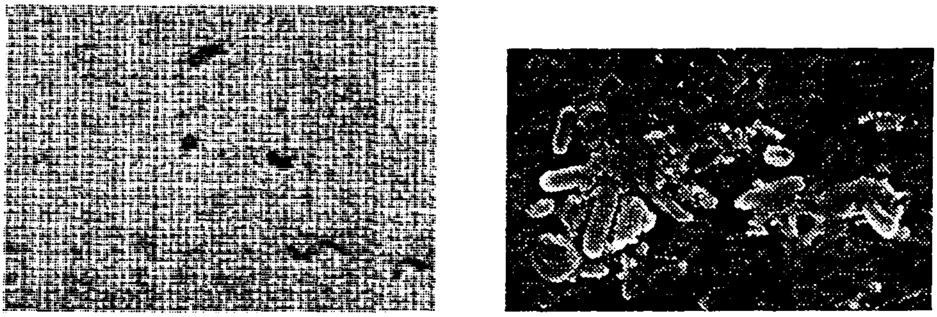

Figure 4 - SEM picture of free-living (a) and attached (b) bacteria collected during Pauline cruise

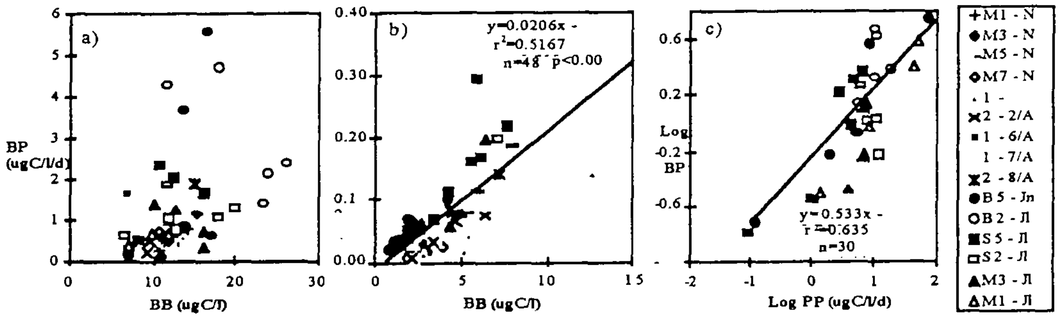

Figure 5 - Bacterial production plotted against a) bacterial biomass 0-80m (all cruises), b) bacterial biomass >80m and c) primary production. Data from PAULINE (stations - dates: M1-N, M3-N, M5-N, M7-N), PICNIC (stations - dates: 1-31/Mr, 2-2/A, 1-6/A,1-7/A, 2-8/A) and EUROMARGE cruises (stations - dates: B5-Jn, B2-Jl, S5-Jl, S2-Jl, M3-Jl, M1-Jl). Mr=March, A=April, Jn=June, Jl=July, N=November

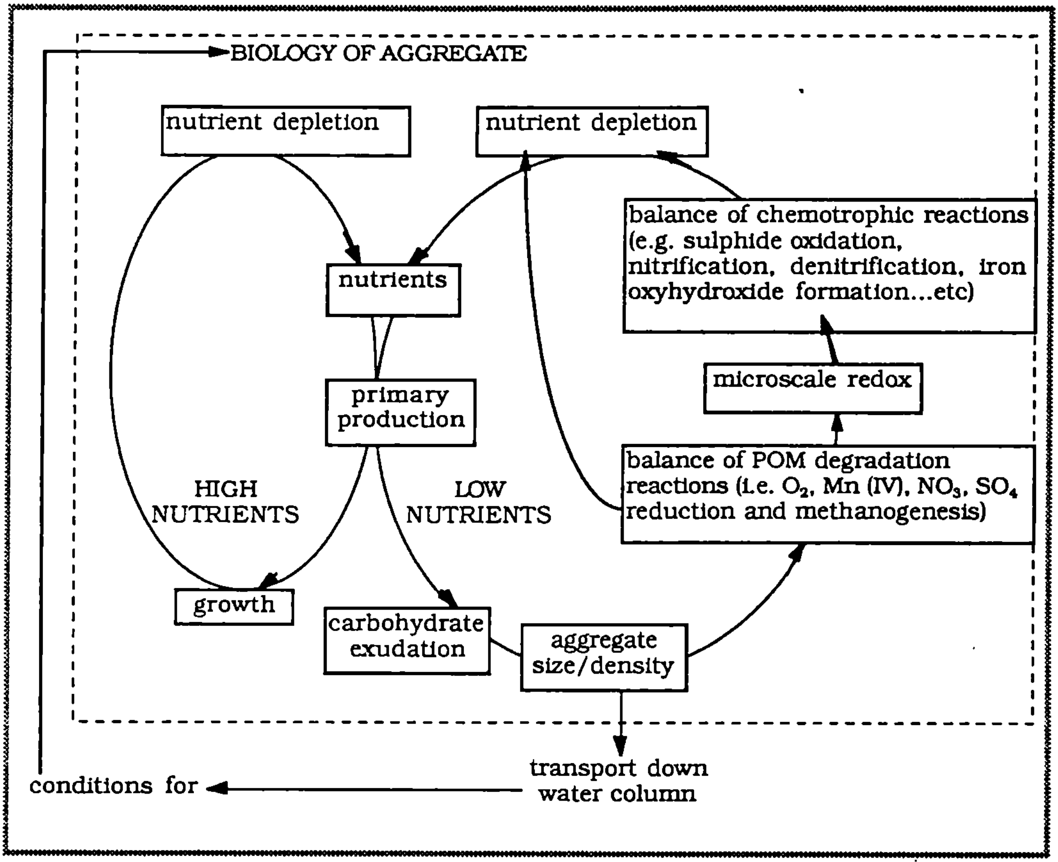

Figure 6 - Hypothesis for emergent organisation in marine water column

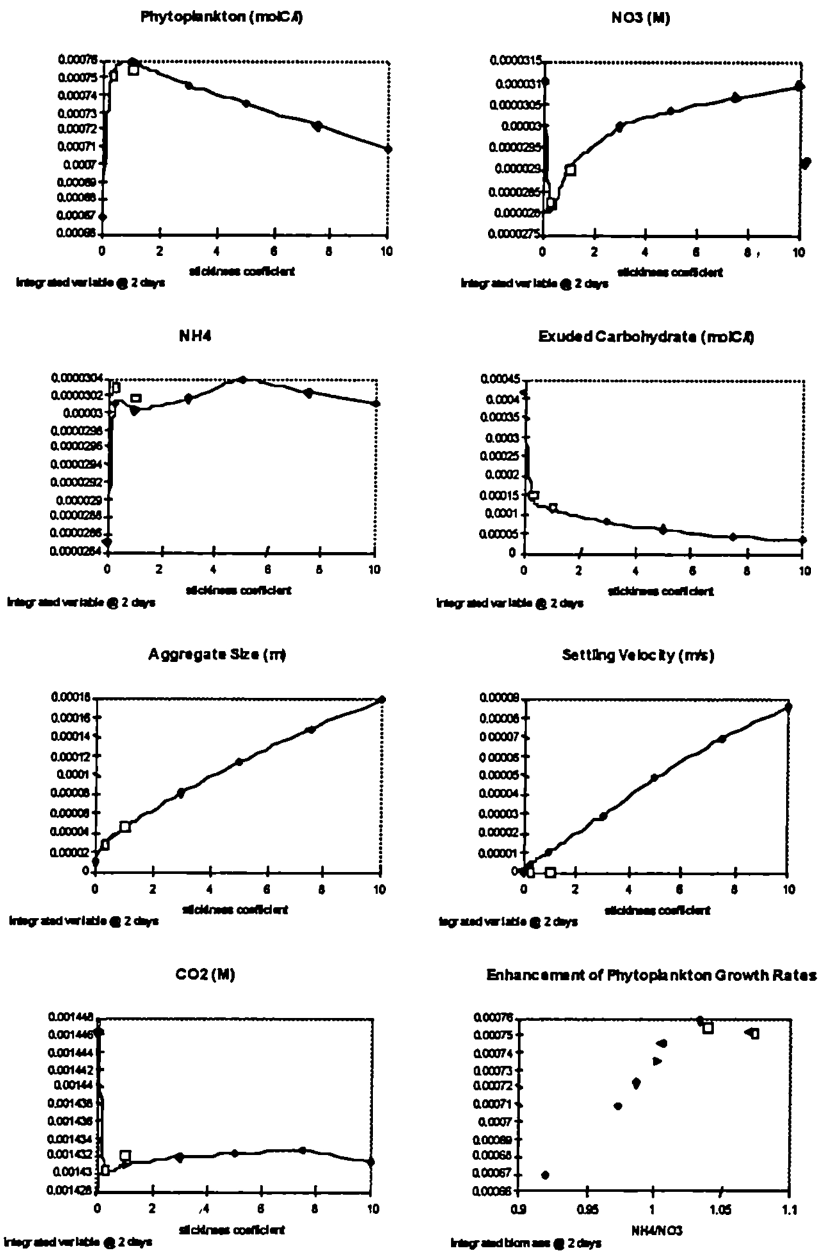

Figure 7 - Integrated variables of the model run after two days of growth under a range of carbohydrate "stickiness"

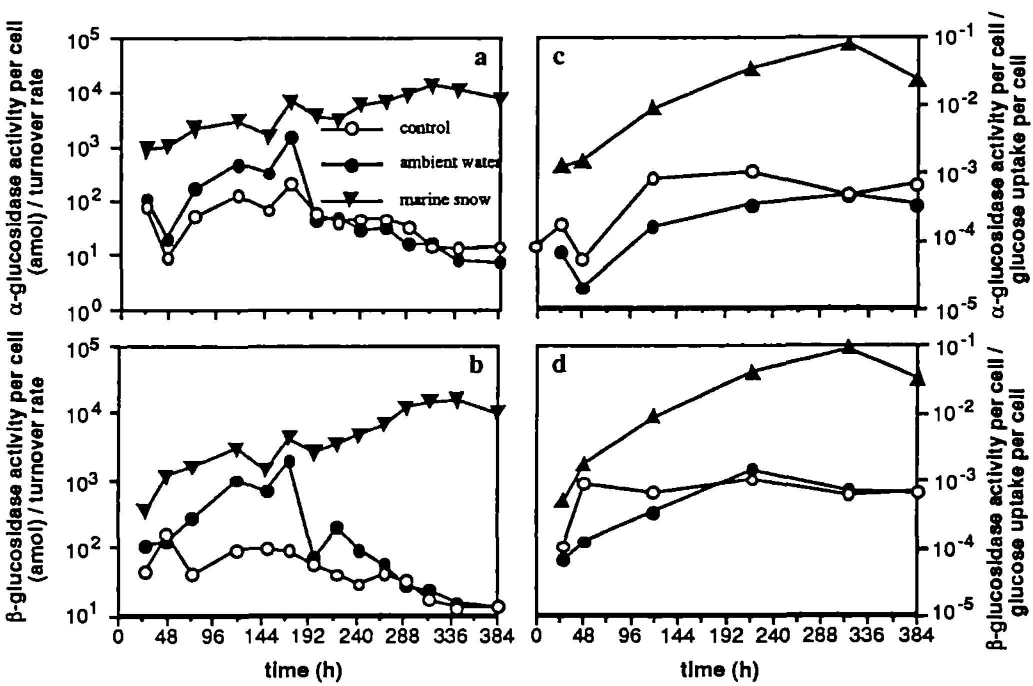

Figure 8 - Development of the ratio alpha-glucosidase activity to turn over rate (a) and glucose uptake per cell ©, respectively, and of beta-glucosidase activity to turn over rate (b) and glucose uptake per cell (d), respectively, for marine snow-attached bacteria and free-living bacteria of the ambient water and the control over the incubation period

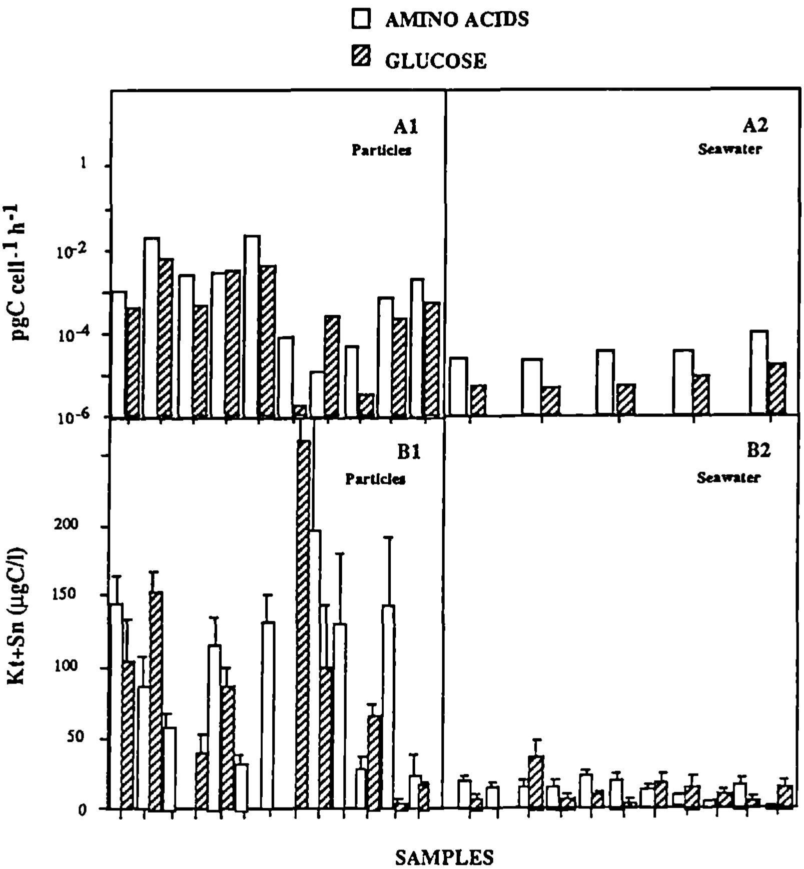

Figure 9 - Glucose and amino acids uptake per cell (A1 and A2) and Kt+Sn values (B1 and B2) in particles and bulk seawater. Bars represent standard errors

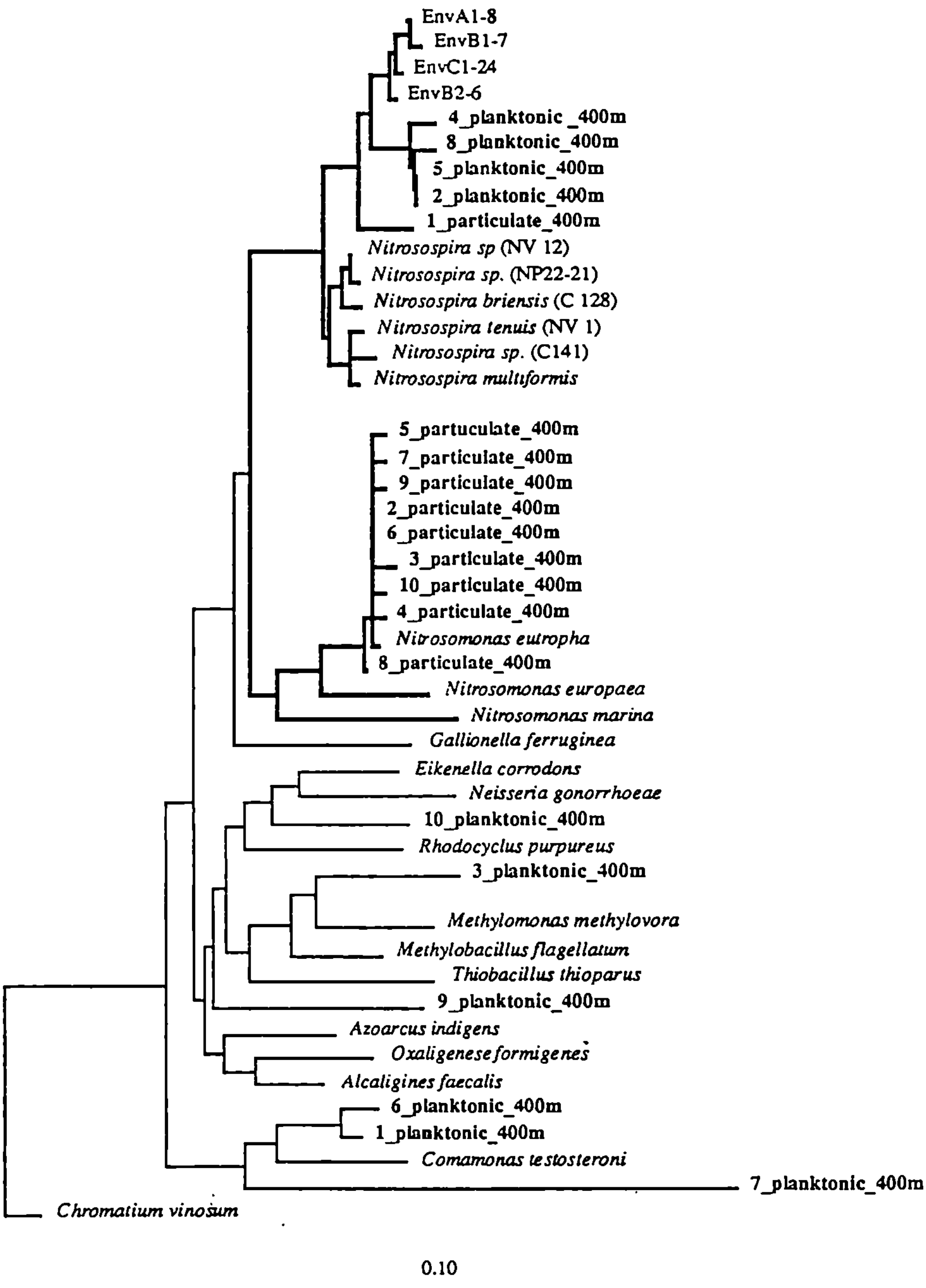

Figure 10 - Neighbour joining tree showing the position, within the b-proteobacteria, of partial 16S rRNA sequences obtained from DNA extracted from planktonic (plank) and particle associated (ass) samples from Station 2 (28 miles) 400 m. Escherichia coli (gamma) is used as the outgroup

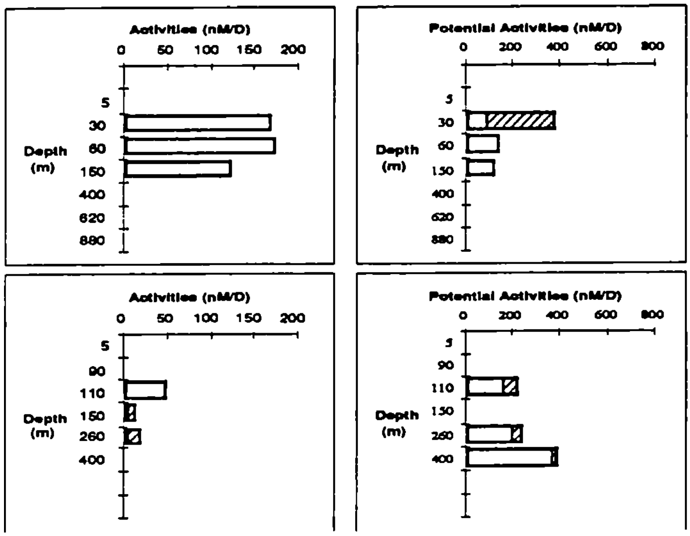

Figure 11 - Denitrification and Nitrate Ammonification determined in particulate samples collected during Pauline (A) or Picnic (B) cruises. The potential activities were estimated after glucose (1g/l) and nitrate (1mM) amendements

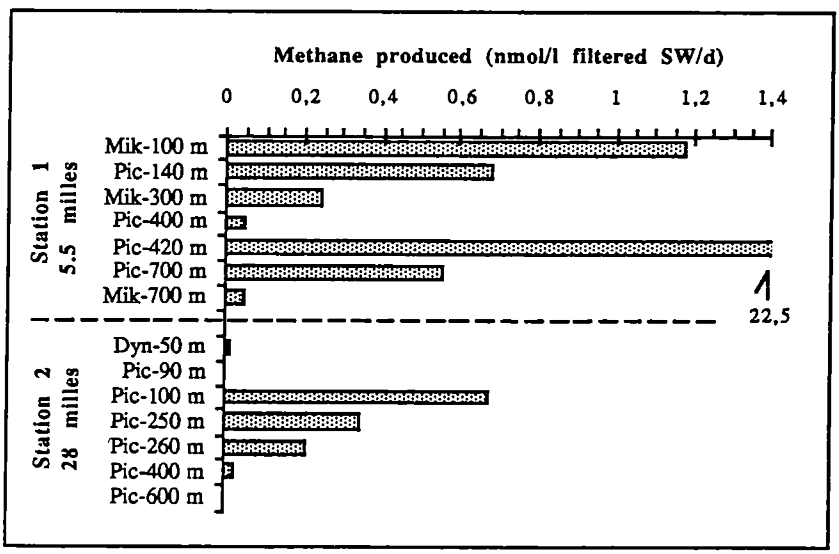

Fig. 12 - Methanogenic activity measured at different depths in Station 1 (5.5 milles) and Station 2 (28 milles) along Nice Transect. (Mik = Mikel Cruise; Pic = Picnic Cruise; Dyn = Dynaproc Cruise)

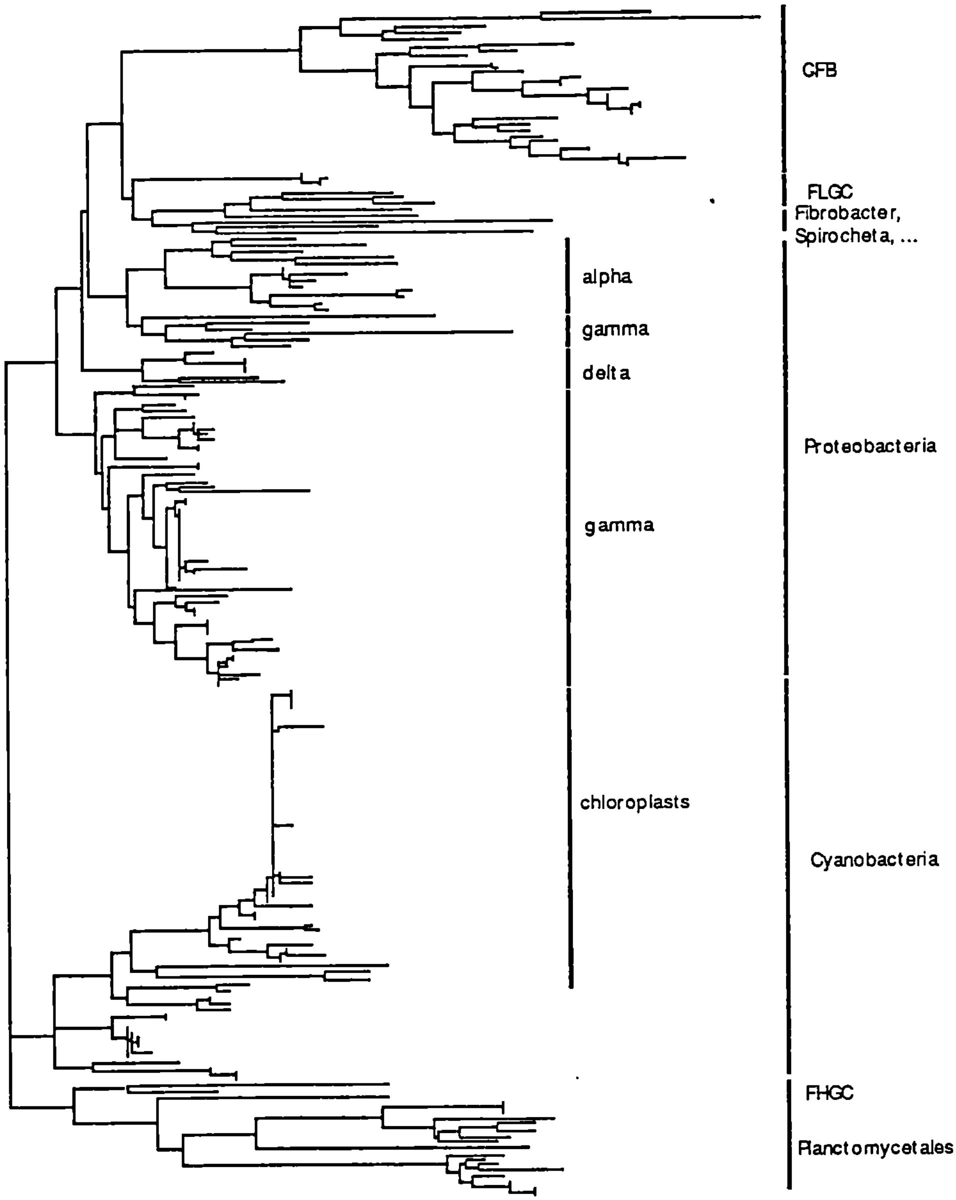

Figure 13 - Neighbor-joining analysis of the phylogenetic diversity of all 202 molecular clones. Partial 16S rDNA sequences of all of 202 molecular clones have been aligned and an unrooted phylogenetic tree was obtained using the neighbor-joining method. More detailled phylogenetic analyses were then effected to identify each branch to a eubacterial phylum and class (indicated on the right of the figure). A number of clones were readily identified as chloroplasts from unicellular algae.

Mediterranean Targeted Project (MTP) - CINCS
Contract number MAS2-CT94-0092

Synthesis of Final Results

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Contract No.: MAS2-CT94-0092
Starting date: 1 May 1994
Duration: 24 months
EC Scientific officer: Dr.E.Lipiatou

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Bacterial Production was undertaken in cooperation with the EMPS project - Micheline Bianchi,Microbiologie Marine, C.N.R.S.,

Pelagic-benthic Coupling in the Oligotrophic Cretan Sea

ABSTRACT

The overall picture emanating from the vertical distribution of the various hydrobiological parameters in the Cretan Sea does not leave any doubt, that we are dealing with a stratified, oligotrophic ecosystem that is characterised by a food chain composed of very small phytoplankton cells and a dominant microbial loop, both of which have a negative effect on energy transfer to the deeper water layers and the benthos. The effect is further magnified, if one also takes into account the prevailing high water column temperatures (>14°C) and high oxygen concentrations (> 4 ml/l) which enhance the decomposition rate of the small amounts of organic matter that succeed in leaking out of the euphotic zone.

Nutrient concentrations in the euphotic zone of the Cretan Sea were exceptionally low. The long-lasting and strong stratification of the water column inhibited the replenishment of the depleted surface layers. The euphotic zone was resupplied with nutrients transferred from deeper waters only during early spring (March), when intense vertical mixing episodes occured. These events were also responsible for the detection of phytoplankton at deeper water layers (down to at least 300 m). Even so, phytoplankton biomass remained at relatively low levels (as indicated by the weak maximum observed at 20 m) since the lack of phosphates acted as a strong limiting factor. Consequently, early spring was the only time of the year when "nutritious", surface derived, organic matter could reach the deeper water layers in a relatively short period of time and therefore fuel benthic life.

From the differences observed in the biogeochemical structure of the water column between 1994 and 1995 it became evident that the Cretan Sea is a very dynamic system, displaying pronounced interannual fluctuations. As a result, it undergoes periods of relatively high nutrient availability (due to the intrusion of the Transition Mediterranean Water mass from the east at intermediate depths, 200-500 m) which in turn may cause dramatic changes in the productivity of the area. When this does occur, the entire system responds by shifting its food web structure from a 'microbial type' to a 'classical type' which generates larger sedimenting particles and therefore increases energy transfer to the deeper water layers and the benthos.

Though the lack of seasonality was the rule as far as the macro- and mega-benthos were concerned, this was not the case for the sediment microbiota. The latter displayed a clear seasonal signal, with the maximum in abundance occurring during the late winter-early spring mixing period. This was directly related to the increase in the sedimentary chloroplastic pigment concentrations and the POM flux to the deep benthic environment

during the same time period. The response elicited by the system was further verified by the increase detected in its benthic metabolism or energetic demand (i.e. sediment community oxygen consumption - SCOC).

More specifically, during February 1995 the vertical carbon flux varied from 8.0 to 11.0 mg C m^{-2} d^{-1} and sediment carbon consumption was estimated (from SCOC) to be 9.0 mg C m^{-2} d^{-1}. In August 1995, however, these figures dropped to 3.5 and 2.0 mg C m^{-2} d^{-1}, respectively. It therefore became apparent that pelagic-benthic coupling is most efficient during the winter-early spring period.

Key Words: E. Mediterranean, Cretan Sea, primary production, nutrients, POM flux, sedimentary and water-column chemistry, Sediment Community Oxygen Consumption.

INTRODUCTION

Geological and Geographical setting

The Cretan Basin can be characterised as a back-arc basin, relative to the Hellenic Trench. It is an area where recent tectonism is dominated by the subduction of the African Plate below the Eurasia Plate. The study area, as shown in Figure 1, is located at the southern continental margin of the central part of the Cretan Basin, extending from the coastal zone of the island of Crete to the deeper parts (> 1500 m) of the Cretan Basin. Detailed description of the sea bed morphology is given in the 3-D diagram of Figure 1. The actual continental shelf of Crete is very narrow and quite steep (gradient 1.5°). The eastern part of the shelf is wider than the western part with the shelf break, more or less, coinciding with the 100-150 m depth contours. The slope is steep with gradients between 2° and 4°, while its configuration varies from west to east. Thus, the western side (transect B) is generally steeper (>3°) presenting a relatively flat plateau (gradient about 0.5°) at water depths between 900 and 1000 m. In contrast, the eastern side (transect D) is more uniform deepening constantly from the shelf break to a water depth of 950 m with an average angle of 2°. Between 950 m and 1700 m the slope gradient increases to 3° - 4°, while deeper parts of the Cretan basin (water depths >1700 m) display relatively low gradients (0.5°).

Hydrology and suspended particulate matter (SPM)

The hydrology and the dynamics of the water masses of the south Aegean Sea have been known from the historic works of Lacombe *et al.* (1958) and Ovchinnikov (1966). Malanotte-Rizzoli and Hecht (1988), in their review paper, summarized the state of knowledge for the E. Mediterranean. Recently, a more detailed picture of the central part of the Eastern Mediterranean and the Cretan Sea has emerged from data obtained and analysed within the POEM and PELAGOS programmes (Theocharis *et al.*, 1993; Balopoulos, 1995).

The observed water masses present seasonal and interannual variability, even at intermediate and deeper water layers. Modified Atlantic Water (MAW) is reccurently detectable in the surface or subsurface (~75 dbar) layer. Under the surface layer a very important water mass, the Cretan Intermediate Water (CIW), is permanently present. The hydrological characteristics of the CIW vary seasonally with very fast annual changes occuring. In deeper layers a "new" water mass is present: the Transitional Mediterranean Water (TMW). This enters the Cretan Sea from the eastern straits of the Cretan arc and occupies intermediate water depths. It is interesting to note that even in these depths the annual and interannual variability is not negligible. Below this water mass the Cretan Intermediate Water (CIW) can be detected either as a distinct layer of higher temperature, salinity and dissolved oxygen or as separate blobs. During the CINCS cruise of Nov. 94 it was very difficult to detect the CIW. These fast changes in the warmer saltier and more oxygenated CIW, located under the TMW, probably indicate the transport of energy, salt and dissolved oxygen from subsurface to deep and bottom layers.

The general SE flow at near surface (267 m) and near bed (1567 m) was recorded by *in situ* current meter measurements with velocities varying from 1.1 cm s^{-1} (rotor threshold value) up to 27 cm s^{-1}. In addition, during the summer period (May-Nov) currents were about 3-times faster than during winter (Nov.-Apr.) at both surface and near bed. Near bed currents capable of causing (induce shear stress >1 dyne/cm^2) resuspension of the sea bed sediments of the Cretan Basin were also observed during the summer period. In general, the area under investigation was found to be dominated by a water jet flowing constantly toward the SE and ESE direction. It is located between two major gyres, an anticyclonic in the West and a cyclonic in the East, and is affected by their combined action.

The SPM in the investigated area ranged from 0.2 to 1.5 mg l^{-1} (80 - 1.5 light transmission) with the higher values observed in November 1994. The very low concentrations of suspended particulate matter (SPM) recorded were indicative of the oligotrophic character of the Cretan Sea. The maximum SPM values in the bottom of the outer shelf, shelf break and upper slope could be attributed to the existence of a relatively weak bottom nepheloid layer (BNL) with increasing terrigenous inorganic constituents (i.e. quartz and clay minerals) toward greater water depths. The "biogenic" material consisted of calcite, Mg-calcite, coccoliths, diatoms, phytoplankton remains and organic aggregates. Surface and intermmediate nepheloid layers were absent. The SPM of the BNL of the shelf area may have originated from seasonal river inputs while in deeper waters (shelf break and upper slope) it may have been produced by resuspension processes induced by the near bed currents (>15 cm/s). In addition, local seismicity is expected to induce gravity driven mass movements feeding the BNL. Finally, the intense trawling activity, extending up to 500 m water depth, also contributed significantly to near bed resuspension processes.

Distribution of Nutrients and POM in the water-column

The Mediterranean Sea is considered (Thingstad & Rasssoulzadegan, 1995) to differ from the large ocean basins, in that phosphate is the main nutrient limiting the growth of phytoplankton. Moreover, the southeastern Mediterranean is strongly phosphorus limited (Krom et al. 1991, 1992) with its concentration decreasing eastwards. Consequently, the N/P (NO3 : PO4) ratio increases in the same direction (22.5 in the

Alboran Sea, 24.3 in the Cretan Sea and 27 - 29 in the eastern basin). More recently, Tselepides et al. 1993, reported an even higher (26.8) N/P ratio for the Cretan Sea.

Massive transport of nutrients, from the deep rich layers to the impoverished euphotic zone, occurs when intense vertical mixing processes are observed. Such short and cataclysmic events have a pronounced influence on the biogeochemical fluxes in the oceans, because they accelerate the completion of processes which under "ordinary" conditions would take much longer. In the Cretan Sea, the sporadic and episodic formation of intermediate water has been observed in a number of occasions (Georgopoulos et al. 1989, Tselepides 1992). Recently it has also been realized that the Cretan Sea is an area of deep water formation (Roether et al. 1996) of extreme importance in the general deep water circulation of the entire deep Eastern Mediterranean basin.

Particulate organic matter (POM) in marine ecosystems represents an important food source for consumers and plays an important role in pelagic-benthic coupling (Posedel & Faganeli, 1991). POM is composed of non-living (detrital) organic material and living organisms represented by sizable stocks of pico- (bacterioplankton, picophytoplankton), nano- (flagellates and other protozoans) and micro-plankton (phytoplankton, microzooplankton). In highly oligotrophic systems, bacterioplankton may represent the major fraction of particulate organic carbon (Cho & Azam, 1990). In these environments, the quantity, quality and cycling of the organic matter is largely controlled by the microbial loop (Fuhrman *et al.*, 1989).

The major goals of this study were: 1. to determine the biochemical composition of particulate organic matter, 2. to study the seasonal spatial distribution patterns of POM, and 3. to quantify the relative significance of the pico-, nano- and microparticulate fractions.

Primary and bacterial production. Microplankton community analysis. Bacterioplankton distribution

The Eastern Mediterranean Sea is considered as one of the most oligotrophic regions in the world, both in terms of primary productivity and chlorophyll *a* concentrations (Berman et al, 1984). In the Aegean Sea (N.E. Mediterranean), very few productivity studies have been conducted so far. The scanty information available indicates a typical oligotrophic biome (Becacos-Kontos, 1977) and productivity levels similar to those of pelagic waters of the Levantine Basin (Ignatiades, 1995), which is considered to be the most oligotrophic part of the Mediterranean Sea (Azov, 1991). In such ecosystems the bacterioplankton constitutes an important fraction of the living planktonic biomass. Their role in recycling photosynthetically produced dissolved and POM in the euphotic zone is very important. Therefore, the quantification of the various microbial processes is of major importance in order to assess the fate of phytoplankton-derived organic material sinking out of the euphotic zone.

It has also been hypothetized that the photic zone food web is separated, on a temporal basis, into two functional modes of operation (Thingstad & Rassoulzadegan 1995, Fowler *et al.* 1991) : a) A summer situation characterized by a DOC-Bacteria-Protozoa dominated food web, with minima in sedimentation, and b) a classical type of food web, during late winter-early spring, with diatom dominance and maxima in sedimentation.

The main goal of the work undertaken was to study the seasonal and vertical changes in primary and bacterial production rates and the associated phytoplanktonic and bacterial parameters, to identify differences between coastal and open waters of the Cretan Sea and to acquire gross daily and annual estimates. The contribution of bacterioplankton to the POM pool and their potential role in the turn-over of organic material was also estimated.

Downward fluxes

Over the last years, many scientists have been trying to understand the biogeochemical processes in the water column, and the factors controlling particle transfer. In order to accomplish this, one must study, both spatially and temporally, the quantitative and qualitative composition of settling particles collected by sediment traps.

The rate at which organic carbon is delivered to the seafloor is one of the most important questions posed by many benthic ecologists. For decades, sediment traps have been used to quantify this flux of organic matter and also inorganic components throughout the water column. Long-term time series sediment trap measurements have demonstrated that seasonal and episodic variations in surface productivity are manifested throughout the water column (Deuser & Ross, 1980; Honjo, 1982) resulting in highly variable amounts of organic matter arriving at the seafloor.

The main objectives of this part of the study were:
1. to obtain quantitative and qualitative information on settling particles
2. to examine the seasonal changes in the biogeochemical composition
3. to determine the flux of particulate matter to the benthos
4. to identify the origin (source) and the fate of the particles
5. to understand, on a spatial and temporal scale, the biogeochemical processes of the mass transfer over the continental margin.

Distribution of POM in the sediments

POM produced in the euphotic zone sinks through the water column and eventually reaches the ocean sea floor to fuel benthic communities. POM is thus an essential ecological link between the surface waters and the benthic ecosystem. It represents the main food source for the deep-sea benthos (Bruland et al. 1989) and consists of particles of a variable size spectrum. Seasonal pulses of larger particles, such as macroaggregates (marine snow) and detritus (phytodetritus), have been observed to settle on the sea floor in the temperate and boreal northeastern Atlantic (Billett *et al.*, 1983; Lampitt, 1985; Rice *et al.*, 1986; Pfannkuche *et al.*, 1988; Thiel *et al.*, 1988/89) and the Norwegian and Greenland Sea (Graf, 1989).

Particles arriving on the sea-floor are decomposed at various rates at or just below the sediment water interface (Emerson & Hedges, 1988). A portion of the incoming organic matter is ingested by large organisms and the remaining is oxidized and mineralized to

CO_2 and metabolites. Ultimately, organic matter is either preserved in the sedimentary record or mineralized and the elements returned to the marine environment.

The analysis of the biochemical composition of the organic matter (measured as lipids, proteins, soluble and total carbohydrates) has been used to determine the seasonal changes in quantity and nutritional quality of the sedimentary organic matter (Danovaro *et al.*, 1994; Danovaro & Fabiano, 1995). The above analyses are essential in understanding benthic processes as well (Rice & Roads, 1992).

This part of the study focussed on the spatial and seasonal changes in the distribution of POM (expressed as TOC, TON, chloroplastic pigments and ATP) as well as the composition of the bulk labile organic carbon in the sediments of the continental margin of North Crete. The main objective was to provide quali- and quantitative estimates of sediment organic matter composition and availability to higher trophic levels.

Sediment Community Oxygen Consumption (SCOC)

Since most heterotrophic benthic communities in subtidal habitats thrive on the organic matter produced in the photic zone there must evidently exist a coupling between the processes in the pelagic and benthic realm. Therefore, the annual mineralisation rates and biomass estimates of benthic communities in different open oceanic regions generally display a clear and predictable relation to the primary productivity and depth of the overlying water column (Rowe 1971, 1983; Smith & Hinga, 1983). Near continental margins, however, land (rivers) or shelf derived POM could potentially be added to the vertical rain of autochtonous POM reaching the benthic communities of the slope and the abyss (Jahnke *et al.*, 1990; Rowe *et al.*, 1994).

Whether pelagic-benthic coupling is discernable on a seasonal basis does not only depend on the annual cycle of primary production but also, on the quality of the deposited material (Graf *et al.* 1982). If the material is refractory due to intensive or extended degradation in the water column it does not elicit a rapid reaction neither in shallow (Graf *et al.* 1982) nor in deep waters (Graf 1989, Pfannkuche 1992 and Smith *et al.* 1994). Sayles *et al.* (1994) attribute the lack of a seasonal signal in the sediment metabolism in the oligotrophic Bermuda basin to the quality of the vertical POM flux.

Since the Eastern Mediterranean Sea is one of the world's most oligotrophic areas, oxic respiration is presumably the most important pathway for sediment carbon mineralisation Helder (1989) has shown this to be the case for the Gulf of Lions (W-Mediterranean) which is known to be less oligotrophic from its eastern counterpart.

During the course of this project, mineralisation (as SCOC) was measured, in sediments of the shelf, slope and deep basin of the Cretan Sea, for the first time in the E. Mediterranean. In conjunction to the SCOC measurements, phytopigment concentrations and biomass of both bacteria and heterotrophic nanoflagellates were also determined. The latter group was included because they belong to the principal predators of bacteria and their biomass has been found to covary with bacterial production in the sediment (Bak *et al.*, 1995).

MATERIALS AND METHODS

The study area (35°20'00 to 35°35'45 N and 024°40'00 to 025°10'00 E) (Fig.1) is located in the south part of the Cretan Sea (South Aegean-North Eastern Mediterranean) north of the Island of Crete. Seven stations were sampled on a seasonal basis (Aug 1994, Feb, May and Sept 1995) along a N-S transect (transect D, from 40 to 1570 m depth) using the R/V PHILIA. Sampling was also conducted over the established grid during May 1994 and Feb.-March and September 1995.

Biochemical composition of particulate organic matter in the water-column

Water - column samples were collected from selected standard depth layers (1, 20, 50, 75, 100, 120, 150, 200, 300, 400, 500, 700, 1000, 1200 and 1500 m) over the established grid of stations with the use of 5 l Niskin bottles, previously washed with a solution of 0.1 N HCl according to Burney *et al.* (1979). Samples were then filtered through Whatman GF/F and GS (4.7 and 2.5 cm diam.) glass fiber filters, which were in turn stored under -20 °C until further laboratory analysis of chlorophyll *a*, phaeopigments, ATP, POC and PON took place.

Subsamples of 200 ml were collected from each filtrate and stored immediately at -20 °C for nutrient concentration analyses (NO3, NO2, NH4, PO4 and SiO2). Nutrient content determination was carried out with the use of a Beckman DU 65 spectrophotometer according to Strickland & Parsons (1972), Grasshoff et al. (1983) and Parsons et al. (1984). Chlorophyll *a* and phaeopigments were determined according to Yentsch and Menzel (1963) using a TURNER 112 fluorometer. Mean integrated water - column values for both chlorophyll *a* and phaeopigments were determined according to Riley (1957). Organic carbon and nitrogen (POC and PON) measurements were undertaken according to Hedges and Stern (1984), with the use of a Perkin Elmer CHN 2400 analyzer. ATP analysis was conducted with some modification according to Parsons et al. (1984). Extraction was undertaken with the use of Tris buffer immediately after the samples were retrieved. The carbon equivalent of ATP (ATP-C) was calulated by multiplying the ATP concentrations with 250.

For the determination of size fractionated particulate proteins, carbohydrates, lipids and nucleic acids, subsamples (150-2000 ml) were prefiltered onto a 200 μm mesh to avoid larger zooplanktonic organisms, then filtered onto Nucleopore filters (12, 2.0, 0.2 μm pore size respectively). Samples were filtered on two filters (replicates) and stored at -20°C until further analysis took place. In order to extract organic particles for lipid, protein and carbohydrate analyses, filters were sonicated for two hours in 1 ml of distilled water. Particulate carbohydrates were determined according to Dubois *et al.* (1956) and D(+) Glucose was used as a standard. Particulate proteins were assessed according to Hartree (1972) and Bovine Serum Albumin (BSA) was used as a standard. Particulate lipids were extracted according to Bligh & Dyer (1959). The analyses were performed by carbonization according to Marsh & Wenstein (1966) and Tripalmitine was used as a standard.

Carbon equivalents of particulate lipids, carbohydrates and proteins were calculated using conversion factors of 0.75, 0.40 and 0.49 gC g^{-1} respectively. These were determined from the standard used. The biopolymeric carbon of particulate matter (C-BPF) was defined as the sum of carbohydrate, protein and lipid carbon equivalents (Fichez, 1991a, b).

Primary and bacterial production

Eleven (11) experiments were performed between July 1994 and October 1995 at two experimental stations, over the continental shelf (D2: 100 m) and slope (D4: 540 m) of. All sampling activity was performed aboard the R/V PHILIA. Underwater light penetration was estimated with a Secchi disk and the incident radiation was measured with a luxmeter. Water samples were collected from ten standard depths (1, 5, 10, 20, 30, 40, 50, 60, 75 and 100 m) using 5 l Niskin bottles. Photosynthetic carbon fixation rates were estimated by the C-14 technique (Steemann-Nielsen, 1952). Subsamples, in 250 ml polycarbonate bottles (2 light and 1 dark for each depth), were suspended in situ from 11:00 to 13:00 after adding 5 μCi of $NaH^{14}CO3$. After incubations, samples were filtered onto 0.2 μm pore-size polycarbonate filters which were soaked in 1 ml 0.1 N HCl prior to counting. Quantitative and qualitative determinations of micro- and nanophytoplankton (> 5 μm cell size) populations were performed by inverted microscopy (Utermohl, 1958).

Bacterial abundance was determined by epifluorescence microscopy according to Hobbie *et al.* (1977). Subsamples were stained with Acridine Orange and filtered on black Nuclepore 0.2 μm filters. Analyses were carried out on 3-5 replicates. 2 filters per replicate were processed. Free-living and attached bacteria were counted separately. At least 400 cells were counted from each filter. Bacteria were divided into different size classes. Bacterial biovolume was converted to carbon content assuming 310 fg C per μm^3 (Fry, 1990). The frequency of dividing cells was also determined. The hourly growth rate was calculated as: $\mu = e^{(0.299\,FDC - 4.916)}$. The doubling time (D) was calculate daily as follows: $D = 0.693/\mu$.

Bacterial production was studied only during two cruises, in March (Feb 28-March 2) and September (5-7) 1995, aboard the R/V PHILIA. Investigated stations were D2 (coastal station, 100 m max. depth) and D4 (continental slope station, 540 m max. depth), where primary production was simultaneously measured. Two open-sea stations, D6 (940 m max. depth) and D7 (1540 m max. depth), were also investigated. Samples were collected with Niskin water bottles around 12 a.m. and processed immediately. Bacterial production was estimated by the ^{3}H-Leucine approach (Kirchman *et al.*, 1986; Kirchman, 1993).

Sedimentary chemistry

Sediment samples were collected over the main transect D on a seasonal basis (May 94, Aug-Sept 94, Feb-March 95, May 95 and Aug-Sept 95) with the R/V PHILIA. Transect D consisted of three continental shelf stations: D1 (40 m), D2 (100 m) and D3 (200 m), three continental slope stations: D4 (540 m), D5 (700 m) and D6 (940 m), and one station in the deep Cretan Sea basin D7 (1570 m depth) (see **Fig.1**). Samples were also acquired over the established grid (transects A, B, C, D and E) of stations but only during May 94, Feb-March 95 and Sept. 95. In all cases, a Bowers and Connely multiple-corer was used.

Undisturbed sediment samples were collected with the use of the formentioned multicorer (8 cores, i.d. 9.0 cm; Barnett *et al.*, 1984). For the analysis of the biochemical composition of sedimentary organic matter, duplicate cores were collected at each station. Immediately after sampling, sediment cores were sectioned into 5 depth layers: 0-1, 1-2, 2-4, 4-6, 6-10 cm depth, sediments were homogenized, placed in sterile Petri dish, and frozen at -20°C. The sampling routine also included, Redox potential (Eh) measurements and subsamples for chloroplastic pigments, ATP and organic carbon. These samples were also sliced into four layers (0-1, 1-2, 2-4 and 4-6) labelled and stored frozen under -20°C for further laboratory analysis. Once in the lab, each analysis was conducted in three replicates.

Chlorophyll *a* and phaeopigment concentrations were determined according to the fluorometric method of Yentsch & Menzel (1963) and Lorenzen & Jeffrey (1980), using a TURNER 112 fluorometer. 90% acetone was used as an extractant, while phaeopigments were estimated by acidification with 0.1N HCL. The fluorometer was calibrated using an acetone extract of pure chlorophyll *a* from the algae *Anacystis nidulans* obtained from SIGMA. Chloroplastic pigment equivalents (CPE) were considered as the sum of chlorophyll *a* and phaeopigment content. Pigments were also analysed (by the NIOZ research team) by means of reverse phase HPLC with the detection phase consisting of a photodiode array plus fluorescence detector. The column, eluents and gradient were the same as used by Wright *et al.* (1991).

Redox potential (Eh) measurements were acquired at 1 cm intervals with the use of calibrated combined electrodes (Russell pH, Scotland, type no. CMPT 11/280/SA1.5), as described in Pearson & Stanley, 1979.

Total organic carbon (TOC) and nitrogen (TON) measurements were undertaken according to Hedges & Stern (1984), with the use of a Perkin Elmer CHN 2400 analyser.

The method applied for the ATP analysis was a slight modification of the method described in Parsons *et al.* (1984). Extraction was undertaken with the use of phosphate buffer immediately after the samples were retrieved.

Biochemical composition of sedimentary organic matter

Total carbohydrates (TCHO) were analysed according to Gerchacov & Hatcher (1972) and expressed as glucose equivalents. Acid soluble carbohydrates were extracted in 0.1 N HCl (2 h, 50°C). Another set of replicates was extracted in NaOH 0.1 M (4 h, ambient temperature).

Protein (PRT) analysis was carried out following an extraction with NaOH (0.5 M, 4 h) and concentration was determined according to Hartree (1972) modified by Rice (1982) to compensate for phenol interference. Concentrations are given as albumin equivalents.

Lipids (LIP) were extracted by direct elution with chloroform and methanol. Analyses were carried out using the methods of Bligh & Dyer (1959) and Marsh & Weinstein (1966).

All analyses were carried out on 3-4 replicates. For each biochemical analysis, blanks were used from sediments that were previously calcinated (550°C, 4 h). Carbohydrate, protein and lipid concentrations were converted to carbon equivalents assuming a conversion factor of 0.40, 0.49 and 0.75 respectively (Fabiano *et al.*, 1995).

Downward fluxes

Two mooring sites (1 and 2) were identified in the Cretan Sea along the CINCS main transect D at stations D7 (1550 m) and D4 (520 m) respectively. Unfortunately, the array at station D4 was lost, and never recovered, due to trawling activities.

Site 1 was located at 1550 m depth. Two traps, A and B (PPS3/3 Technicap with 0.125 m^2 collecting area and 12 receiving cups) each associated with two current meters (Aandera RCM7 with a sampling interval of 30 min), were deployed at 200 m [1350 m above bottom (mab)] and 1515 m depth (35 mab) respectively.

All traps were deployed from November 16, 1994 to November 30, 1995 during two mooring periods (referred hereafter as I, from 16/NOV/94 to 15/MAY/95 and II, from 16/MAY/95 to 30/NOV/95, deployments). The sampling interval was 15 to 16 days, the 1^{st} and 16^{th} of every month. Finally, 48 samples were collected throughout the experiment (24 from each trap).

The preparation of the sediment traps and the laboratory processing of the samples, including the preliminary treatment, of the removal of swimmers and subsampling are described in Heussner *et al.* (1990). The major constituents were determined according to Monaco *et al.* (1990).

Larger pellets and swimmers were counted from a volume split of 1/16 of the total trapped material. Ten selected pellets from each size-class were used to calculate an average biovolume and carbon flux. The conversion from biovolume to carbon was done according to Urrere & Knauer (1981). Microscopical analysis was made on a JEOL JSM 5300 scanning electron microscope.

The methodology applied for POC and PON was based on the procedures described in Hedges & Stern 1984, Smith *et al.* 1994 and Culmo*et al.* A Perkin-Elemer 2400 CHN analyser was used.

Carbohydrates, Lipids and Proteins were extracted according to the methodology described under the biochemical composition of organic matter. Carbohydrates (CHO), proteins (PRT) and lipids (LIP) were converted into carbon equivalents (C-BPF) using conversion factors of 0.40, 0.49 and 0.70 for CHO, PRT and LIP, respectively (Fichez, 1991a; Fabiano & Danovaro, 1994).

The food index (FI) was defined as the ratio of the sum of lipid, protein and carbohydrate concentration over the total mass flux, expressed in percentage.

Bacterial count and biomass were determined, by epifluorescence microscopy, as described by Hobbie *et al.* (1977). Bacteria were assigned to different size classes according to Palumbo *et al.* (1984). Bacterial biomass was then converted to carbon content assuming 310 fg carbon μm^3 (Fry, 1990).

Sediment Community Oxygen Consumption (SCOC)

Seven measurements were carried out along the main transect D, at depths of 40, 100, 200, 540, 700, 940 and 1570 m respectively. The deployments were carried out with the R/V AEGAEO during February/March and August/September 1995. These extreme periods were chosen with the assumption of being representative of the largest contrast in vertical POC flux and sediment mineralisation.

SCOC was measured *in-situ* with a free-falling bottom lander (BOLAS). The BOLAS tripod holds two independent benthic chambers (32 cm Ø) each containing a magnetic stirrer, O_2-sensors, a resistivity probe (cf. Andrews & Bennet 1981), and 3 pairs of syringes each of which draw 60 ml water samples from the chamber headspace at preset intervals. SCOC is calculated from the initial linear decrease of the O_2-content recorded by the electrodes. With each deployment the electrodes were calibrated against the O_2 in the syringes which were determined according to Pai *et al.* (1993). Depending on the expected flux rates, deployment times ranged between 12 and 40 hours.

RESULTS-DISCUSSION

Nutrients. POM composition and distribution in the water-column

The water column was well oxygenated, at all seasons, throughout the study area. Oxygen concentrations ranged from 4.05 - 6.00 ml/l. A relatively pronounced oxygen minimum (4.00 - 4.50 ml/l) was evident in the offshore stations, at 300 - 500 m depth, and was attributed to the inflow of the Transition Mediterranean Water (TMW) mass from the Eastern Mediterranean.

Phosphate (PO_4) levels were generally found to be low (0.00 - 0.76 μg-at/l). The exception were the relatively high values (0.15 - 0.43 μg-at/l) recorded at intermediate depths (200 - 500 m), during all seasons and especially during the 1994 sampling periods. Although relatively high values (0.60 - 1.60 μg-at/l) were observed just below the thermocline (70 - 100 m) at the deeper stations, nitrite (NO_2) concentrations were generally low (0.02 - 0.99 μg-at/l). Nitrate (NO_3) levels were low (0.20 - 0.90 μg-at/l) in the euphotic zone, increasing dramatically below 100 m depth to reach values as high as 4.00 - 5.00 μg-at/l in the deeper layers. NO_3 maxima (4.00 - 4.55 μg-at/l) were also observed at intermediate depths (300 - 400 m) in the offshore stations, especially during the 1994 sampling periods. In most cases, ammonia (NH_4) concentrations remained at low levels (0.10 - 1.10 μg-at/l), reaching maximum concentrations (0.40 -1.10 μg-at/l) at or near the primary production (10 - 20 m) and the chlorophyll *a* maximum (100 m), and slightly higher concentrations at intermediate water layers (0.40 - 0.80 μg-at/l, at 200 - 500 m depth). Silicate (SiO_4) concentrations occurred at relatively high levels (0.50 - 4.28 μg-at/l), following the distribution of ammonia in the surface layer and nitrate in the deeper layers, where maximum concentrations were reached (3.05 - 4.28 μg-at/l).

A distinct water mass was present at 200 - 500 m depth characterized by high PO_4, SiO_2 and NO_3 concentrations, low N/P ratios and low oxygen, POC and PON concentrations (Tselepides *et al.* 1996a). This was the signature of the TMW which entered the Cretan Sea from its eastern straits and whose presence was stronger in 1994 compared to 1995.

The N/P ratio calculated for the Cretan Sea was 20.1 for May 1994, and 25.7 and 25.5 for March and Sept. 1995, respectively. Phosphates were therefore the main limiting nutrient in 1995, while 1994 was not a phosphate limited period, due to the strong presence of the TMW which increased the PO_4, NO_3 and SiO_2 concentrations in the deeper layers of the Cretan Sea. The enrichment observed in the horizontal distribution of nutrients and POM from a NE direction was probably due to the upwelling caused by the eastern cyclonic gyre which brought TMW rich in nutrients waters to the euphotic zone.

The vertical distribution of chlorophyll *a* at the offshore stations of transect D, during the stratification period revealed the existence of a very characteristic Deep Chlorophyll Maximum (DCM) at a depth layer of 75 - 100 m. The observed DCM became more pronounced in an offshore direction (as the system became more oligotrophic), reaching maximum values at stations D6 and D7. Chlorophyll *a* ranged from nearly zero, at depths greater than 200 m, to 0.93 μg/l at the DCM layer (75 - 100 m depth) of the offshore stations D6 and D7.

The POC concentrations recorded during this study (16 - 250 μg/l) were within the same range of values reported from a number of locations around the world (Gordon et al., 1979; Radford-Knoery & Cutter, 1988). POC was generally proven to be a conservative parameter. It did not undergo dramatic spatial and seasonal changes and its vertical distribution was relatively constant below 200 m depth. The influence exerted by the combined action of the double gyre system and the TMW intrusion were evident in most cases. The C/N ratio was generally low in winter, with the exception of a mesopelagic maximum (at 700 m depth), in the deeper station D7. C/N values were higher in the summer, with maxima occurring over the slope and the deep basin at the 200 m and 400 m depth layers, respectively.

ATP concentrations were generally very low. In the surface layers (0 - 100 m depth) ATP values ranged from 30 - 70 ng/l, at intermediate depths (100 - 200 m) from 20 - 40 ng/l, while in the deeper layers all values were lower than 20 ng/l. Relatively high concentrations (40 - 100 ng/l) were observed in the euphotic zone over the continental shelf and upper slope in March and May 1995. Low values (< 30 ng/l) were observed during Sept. 94 and even lower (< 10 ng/l) during Sept. 95. In the winter, ATP-C ranged from 3 - 56% in the euphotic zone (0 - 100 m) and from 3 - 20% in the deeper layers. In the summer, the corresponding values were 3 - 25% and 2 - 20%.

- Labile organic compounds

POM concentrations were converted to carbon equivalents to allow for comparisons with bacterial carbon. The average concentration of C-BPF (as the sum of lipid, carbohydrate and protein carbon) was 56.1 μgC l^{-1}, ranging between 24.2 and 113.7 μgC l^{-1}. C-BPF concentrations exhibited a strong seasonal signal. C-BPF decreased from 53.9 μgC l^{-1} in August 1994 to 52.5 μgC l^{-1} in May 1995, followed by an increase in September 1995 (65.9 μgC l^{-1}).

Particulate carbohydrate concentrations (on average, 50.8 μg l^{-1}, ranging from 13.1 to 148.6 μg l^{-1}) displayed a clear seasonal pattern, decreasing from August 1994 (58.5 μg l^{-1}) to May 1995 (36.4 μg l^{-1}) and increasing again in September 1995 (62.1 μg l^{-1}). Particulate protein concentrations (on average, 35.8 μg l^{-1}, ranging between 6.9 and 92.2 μg l^{-1}) did not change considerably with time, while particulate lipid concentrations (on average, 24.2 μg l^{-1}, ranging between 4.3 and 63.2 μg l^{-1}) displayed little seasonal change, increasing from August 1994 (16.5 μg l^{-1}) to September 1995 (28.8 μg l^{-1}).

The relative significance of the three main biochemical classes did not change seasonally. Particulate carbohydrates were the major component (on average 45% of POM) followed by particulate proteins (33%) and lipids (22%).

One of the main characteristics of such an oligotrophic environment is the dominance of small particles. Picoparticulate matter was dominant in all biochemical classes of organic compounds accounting for more than 46% of the total particulate organic matter. The size spectrum of the biochemical particles was quite constant during the year. Picoparticles were dominant (43-45%) in all biochemical classes (lipids, proteins and carbohydrates).

The results reported in the present study clearly indicate the oligotrophy of the Cretan Sea. Lipid, protein and carbohydrate concentrations were very low and, indeed, about half the concentrations reported for the Western Mediterranean (Danovaro and Fabiano, in press; Fabiano *et al.*, 1984). Seasonal changes in the C-BPF concentration, were limited, with maximum values occuring in the summer. These changes are not related to higher primary production values (reported in late winter, Psarra *et al.* 1996) and only in September 1995 appeared to be related to the observed high bacterioplankton biomass. The extremely low concentrations of POM in conjuction to the low seston concentrations, indicate the autochtonous origin of the particulate matter in the Cretan Sea. However, in August 1994, May and September 1995 a pronounced increase in C-BPF concentration was found at depths between 200-500 m. Lipid and protein concentrations did not display considerable seasonal changes. Therefore, the higher amounts of C-BPF concentrations reported in August 1994 and September 1995 were mostly due to the increase of the carbohydrate concentration. The low lipid and protein contributions to the POM composition result in particulate matter of low caloric value.

The analysis of the spatial distribution of lipids and proteins revealed a decrease in their concentration from the coast to the open sea and a depletion of both components in the deeper water layers. By contrast, in February and September 1995 high carbohydrate concentrations were reported below 900 m depth. These data are in agreement with the results of Ittekot *et al.* (1982) and Liebezeit (1984) and indicate that carbohydrates (which may include some structural compounds) are more resistant to microbial degradation.

Primary production

During the entire experimental period the euphotic zone (defined by the 1% light level depth layer) extended down to 30 - 54 m and down to 54 - 74 m at the shelf station D2 (100 m) and at the slope station D4 (540 m) respectively. The coastal station had year-round higher chlorophyll *a* values (range: 0.05 - 1.1 mgm^{-3}, mean: 0.22 mgm^{-3}). At the pelagic station chlorophyll *a* concentration ranged from 0.03 to 0.54 mg m^{-3} (mean: 0.14 $mg.m^{-3}$). Primary production levels at station D2 ranged from 0.010 to 0.594 $mgCm^{-3}h^{-1}$ (mean: 0.239 $mgCm^{-3}h^{-1}$). At station D4 values were lower, ranging from 0.008 to 0.431 $mgCm^{-3}h^{-1}$ (mean: 0.169 $mgCm^{-3}h^{-1}$). Integrated water column productivity varied between 120 and 300 $mgCm^{-3}day^{-1}$. Concidering all primary production values an annual primary production input was estimated to be 80 and 59 $mgCm^{-3}yr^{-1}$ at the coastal and the pelagic station respectively.

The vertical distribution of primary production values exhibited maxima in the upper 10 m (D2:5 m, D4:10 m), were more or less stable down to 60 m and decreased sharply thereafter. Figure 2 illustrates the seasonal fluctuations of chlorophyll *a* and primary productivity at the two stations (integrals over depth). At the shelf station (D2), maximum chlorophyll *a* concentrations were recorded at late winter-early spring (March '95) and autumn (Nov. '94) with values declining in summer and early autumn (July-Oct. '95). Chlorophyll *a* at the slope station D4 had maxima in spring (April '95) and summer (July '94) and minima in autumn (Sept.-Oct. '95). Both stations exhibited similar seasonal patterns of primary production with maxima occurring in spring (D2: April '95, D4: March '95) and summer (July-Aug. '94) and minima in late summer (Sept.-Oct. '95).

This 16-month study demonstrated the existence of oligotrophic conditions in the pelagic waters of the Cretan Sea. The annual mean chlorophyll *a* content recorded at the slope station (0.14 mgm^{-3}) was identical to the values obtained by Azov (1986), which were in support of the contention that the Levant Basin is extremely oligotrophic. Chlorophyll *a* and primary production values for the late winter - early spring period, at this station, were twice as high than those reported by Ignatiades (1995) at a station in the adjacent deep basin of the South Aegean Sea (PELAGOS Project, First Annual Progress Report, 1995).

Ryther (1969) defined oligotrophic oceanic areas, coastal rich areas and upwelling areas, as having primary productivity of 50, 100 and 300 $mgCm^{-2}yr^{-1}$. Koblentz-Mishke *et al* (1970) defined oligotrophic oceans as those having primary productivity of 70$mgCm^{-2}day^{-1}$, with maximal values of 100 $mgCm^{-2}day^{-1}$. According to the above definitions and based on our results, the slope station D4 could evidently be characterized as oligotrophic (162 $mgCm^{-2}day^{-1}$, 59 $gCm^{-2}yr^{-1}$). The shelf station D2 appeared to have intermediate characteristics, which are certainly not oligotrophic but similar to those of coastal rich areas with productivity estimates comparable to those recorded in the W. Mediterranean (Estrada, 1985).

Dinoflagellates, with the exception of the late winter - early spring period, were the dominant group throughout the year followed by diatoms, at both stations. At the shelf station, the late winter - early spring maxima in primary productivity and chlorophyll *a* were coupled with maxima in phytoplankton abundances, mainly due to diatoms which represented 88% of total cell counts. More precisely, the genus Chaetoceros accounted for 61% of the population recorded, with the species Chaetoceros affinis alone representing the 54% of total cell counts. The maxima during summer at both stations were associated with dinoflagellates. Overall, for the period July'94 - Oct.'95, diatoms and dinoflagellates accounted for 30 and 62% of total cells counted at the shelf station and for 16 and 69% at the slope station, respectively.

The microscopical analysis of microplankton samples acquired on a seasonal basis along the entire transect D (i.e. from 40 to 1570 m depth) again revealed that the Diatom biomass was found to accumulate in coastal waters during March. This was interpreted as evidence in agreement with the concept of the dominance of the classical pelagic food web in coastal waters. During the summer a contrasting situation was observed, with the microplankton community being dominated by dinoflagellates and oligotrich ciliates, and therefore resembling a protozoan-microbial loop type of pelagic food chain. Thus, the observed temporal variations, in the planktonic food web, as manifested by the shifts in abundance of both the diatoms and protozoans, support the contention that the photic zone food web in the Mediterranean Sea displays pronounced temporal and spatial variations in its structure and function (Thingstad & Rassoulzadegan 1995). The accumulation of diatom biomass at the coastal stations during winter also seems to support the hypothesis that environmental changes in the oligotrophic ocean are primarily expressed by the diatoms (Venrick 1990). Our working hypothesis is that pelagic-benthic coupling on the north continental margin of Crete is largely dependent on primary production, downward flux of diatoms and diatom derived detritus, which are produced in coastal waters during winter and early spring, and therefore the coupling efficiency of the system could potentially be detected in the benthic fauna (Tselepides & Eleftheriou 1992).

In general, the microplankton of the oligotrophic Cretan Sea during the late summer period was characterized by diatoms which were associated to the DCM at about 100 m depth, and a dinoflagellate maximum which coincided with the ciliate maximum closer to the surface.

Bacterial production

The size structure of the suspended particulate matter and its rather constant biochemical composition are likely to be related to the bacterial dominance in this system. Previous studies have shown that, especially in oligotrophic areas, bacteria may account from 40 to more than 70% of the organic carbon (Cho & Azam, 1990; Fuhrrman *et al.*, 1989). However, such estimates were based on comparisons made using POC values, obtained from GF/F Whatman glass fiber filters (average retention of 0.7 μm pore size), that underestimate the bacterial contribution. In the present study the bacterial contribution to the particulate organic carbon was calculated from analyses carried out on the same Nucleopore filters (0.2 µm). This should improve the accuracy of these estimates, though not eliminate possible biases due to the conversion factor utilised for both the bacteria and the biochemical components. For instance, in the present study, the conversion factor used for bacteria (310 fgC μm^3) is lower than the one (350 fgC μm^3) reported by Lee & Fuhrman (1987). In the Cretan Sea bacteria accounted (on average) for more than 56% of the particulate biopolymeric carbon and were, by far, the most important component both in the photic and aphotic layer of the water column. As a result seasonal changes in the particulate organic matter concentrations were driven by seasonal changes in the bacterial biomass. This could have important implications as far as the food web structure, nutrient cycling and sinking flux of the system is concerned. In fact, the dominance of pico-size particles, that do not have high sinking velocities, would have as a result the reduction or inhibition of the downward flux of the organic material. These conclusions are confirmed by the extremely low values of the labile organic carbon flux at Station D7 (see Chronis *et al.* 1996), as well as the extremely low biomass values observed at the deep stations.

Bacterial density attained an annual average of $3.6 \cdot 10^8$ cells l^{-1}, ranging from $0.94 \cdot 10^8$ to $9.52 \cdot 10^8$ cells l^{-1} and displayed wide seasonal variations with higher values observed in February and September 95 (4.62 and 4.47 $\cdot 10^8$ cells l^{-1} respectively) and lower values in August 94 and May 95 (2.76 and 2.68 $\cdot 10^8$ cells l^{-1} respectively). The vertical distribution of bacterial abundance showed a clear pattern of decreasing values with depth at all seasons with highest values always found in the top 50 m (i.e. above the thermocline).

Bacterioplankton accounted (annual average) for 56% of the particulate biopolymeric carbon (C-BPF) with the bacterial contribution to the C-BPF ranging from 41% (August 1994) to 74% (February 1995) and decreasing with water depth.

The bacterioplankton in the Cretan Sea was characterized by relatively high growth rates and, consequently, short doubling times (on average 0.4, range 0.1-4 d). Considering that only a small fraction of the particulate biopolymeric carbon is available for heterotrophic metabolism (being mostly composed of bacterial carbon) and that bacterioplankton has a rapid turnover, it seems that bacteria must fulfill their food requirements from DOC (which usually accounts for more than 90% of the organic matter in the ocean, Sharp, 1973) and possibly supplement this source with inorganic nutrients (Zweifel *et al.*, 1993).

Important fluctuations in bacterial production were observed in the surface layers. Generally, peaks of bacterial production and bacterial abundance coincided with maxima in primary production (Psarra *et al.* 1996). Higher values of bacterial production in the upper layer were observed at the coastal station D2, where bacterial production reached 82 µg C m^{-3} h^{-1} at 50 m in March. At this coastal station, bacterial production remained high down to the bottom layer. In the open sea stations, maximum bacterial production was reached in the surface layers, although in some cases some high values were also obtained deeper in the water column. Some of the high values observed at station D7 corresponded to simultaneous high values of particulate organic carbon (Danovaro *et al.* 1996) suggesting that the peaks of bacterial production in deeper samples (500 m at D7 and 200 m at D4 during September) could be attributed to micro-niches rich in particles colonized by productive bacteria.

The relative importance of food supply or grazing, as factors controlling bacteria, were examined using the approach outlined by Billen *et al.* (1990), where bacterial production can be used as an index of the input flux of dissolved organic matter. Data were obtained only during March and yielded a significant correlation, suggesting, as already observed by Ducklow (1992), a seasonal progression from resource limitation of bacterial biomass in March (bloom situation) to predator limitation in September (post-bloom situation).

Integrated bacterial production at the open sea stations, was characteristic of highly oligotrophic environments. In the Cyprus eddy, very low bacterial production has already been described (Zohary and Robarts, 1992). In the euphotic zone of the Cretan Sea, integrated bacterial production was highest at the coastal station during the bloom observed in March, while it decreased in September, corresponding to a post-bloom situation (Table 1).

Table 1. Integrated bacterial production (mg C m^{-2} d^{-1}) over the upper layer (0-100 m) and the whole water column. M: March, S : September.

	Stations						
	D2		D4		D6	D7	
Date	M	S	M	S	S	M	S
0-100 m	131	51.1	36.5	7.4	19.5	40.1	32.1
Whole water column	131	51.1	64.5	61.9	70.5	70.9	465
Deeper level of integration	100m	100m	500m	500m	900m	1500m	1500m

Differences between the two seasons were mainly observed at the coastal station and, to a lesser extent, at the continental slope station D4. For this station, the peak of bacterial production during September, deepened concurrently with the chlorophyll a peak. Bacterial integrated production in the whole water-column is almost equal for stations D4, D6 and D7 during both seasons, except for the high value encountered in September in D7, due to high values measured in the deeper layers.

Another characteristic feature of the oligotrophy of the system is the dominance of bacterial biomass over phytoplankton biomass. In oligotrophic waters, food webs are often represented by an inverted pyramid with the heterotrophic biomass dominating the autotrophic biomass. With the exception of the coastal station during March, bacterial biomass was systematically higher than the autotrophic biomass.

The fraction of the carbon, photosynthetically produced, entering the microbial food web in the euphotic zone (0-100 m) can be estimated by the ratio BCD/PP, where BCD is the bacterial carbon demand calculated from integrated bacterial production, assuming 50 % bacterial growth efficiency, and PP is the integrated primary production (Psarra *et al.* 1996). At the coastal station, regardless of the season, bacterial carbon demand was equal to phytoplankton production (BCD/PP = 1.03 during March and 0.83 during September). In contrast, this ratio was only 0.35 and 0.37 at the continental slope station D4 during March and September, respectively. According to some recent studies on seawater cultures, bacterial growth efficiencies in an oligotrophic sea should be even lower than 0.5, reaching 0.1 - 0.3 (Kirchman *et al.*, 1991; Sempéré *et al.*, 1995, Carlson and Ducklow, 1996). According to these studies, much more than half of the primary production should be dissipated by mineralization in the upper layers of the open Cretan Sea during both periods.

Downward Fluxes

- SEM observations

In general, particles collected by the upper trap (at 200 m) displayed a composite character. Numerous fresh diatoms were present, validating the high opal and organic carbon content observed, mixed with detrital material (aluminosilicates, quartz and feldspar). The latter particles were attached to phytoplankton chains, while coccolithophorids were associated to faecal pellets.

The material collected by the near bottom trap (1500 m) exhibited a relatively high % of opal which was represented by the abundant diatoms (mainly *Chaetoceros* remains) and silicoflagellates. Detailed scans revealed that phytoplankton remains and Mg calcite were common in the Cretan Sea. The mixed nature of the particles included diatoms, detritus and terrigenous particles (aluminosilicates, quartz and feldspar), while composite particles such as aluminosilicates, which were associated to coccolithophorids, were also present and surrounded by a sticky matrix of amorphous material.

In conclusion, the surface samples were generally more biogenous compared to the near bottom ones. The terrigenous fraction, which was added to the samples of trap B, was probably advected from the southern margin of the Cretan Sea. The biological phase was diverse, associated to the significant presence of calcareous phytoplankton.

- Microscopical analysis of phytoplankton, microzooplankton and faecal pellets

Few intact phytoplankton cells were observed in the trap material, but diatom frustules of centric and pennate forms, coccolithophores, unidentified spinose and spherical cysts were observed. Coccoliths from *Emiliania huxleyi* were numerous in faecal pellets. Generally, most of the tintinnid flux (lorica) were found at 200 m depth. The trap material confirmed the abundance of coccolithophores and tintinnids normally not observed in the suspended samples (100 ml). Their presence in the trap material gives a hint of their importance in the pelagic food web. On the other hand, the particulate phytoplankton carbon flux (PPC) was of minor importance compared to the flux of faecal pellets and detritus.

Polycystine radiolarians (Nasellaria/Spumellaria) had their highest flux during November-February at 200 m depth, while relatively few were recorded at 1500 m depth. A clear seasonal maxima of foraminifera were not detected and most of the specimens recorded were of small size (30-80 µm), probably juveniles.

Microscopical analysis revealed that different types of faecal pellets and amorphous material made up the bulk of the material collected in the traps. Faecal pellets < 250 μm made up the majority of the total pellet flux to deeper waters, with no indications of seasonal differences evident. Among the larger size classes (> 250 μm) seasonal differences were observed in both traps. The trap-material from 200 m depth revealed a maxima of medium (80-200 μm) and large- sized (250-400 μm) elliptical pellets from January to June, and large cylindrical tapered pellets (> 800 μm) from August to October. At 1500 m depth a seasonal variation was recorded among the larger pellets. Noteworthy is also the presence of extra large elliptical pellets at this depth, not recorded in the trap-material from 200 m depth. These pellets are probably produced between 200-1500 m depth. The large elliptical pellets had a maxima during January-March, and large cylindrical pellets had a maxima in June. The faecal pellet flux was low compared to the POC-flux, and constituted 2.2-18.1% (average 6.5%) and 3.7-15.9% (average 8.6%) at 200 m and 1500 m depth respectively, with an increase of pellet flux with depth.

The carbon flux calculations indicated that only about 2.8-4.8 % of primary production accounted for the POC-flux, while only 0.2-0.4% of the primary production accounted for the carbon-flux in faecal pellets. These results seem to confirm the oligotrophic and regenerative nature of the Cretan Sea. The low levels of particulate organic matter are lower than expected based on the level of primary production (Psarra *et al.* 1996), indicating that the DOC component could be of greater importance than the POC/faecal pellet-component for the carbon export to deeper water.

- <u>Total mass flux</u>

Generally, total mass fluxes at 200m (trap A) depth were, almost always, lower than those at 1500 m (trap B), except during two periods: 16-30/Apr/95 and 16-30/Sep/95. The greatest variability was observed at the bottom trap B where two major peaks were recorded. Total mass fluxes at trap A were characterised by very low values, ranging from 3.3 (1-15/Nov/95) to 186.9 mg m^{-2} d^{-1} (16-30/Apr/95), with a mean annual flux 50 mg $m^{-2}d^{-1}$.

On an annual basis, the fluxes at the deeper trap (B) were higher by a factor of 4.2. The mean annual flux value reached 209 mg m^{-2} d^{-1}. A decline in the flux of the upper trap was observed between the two deployment periods (I and II). The mean flux value was 247 during the winter-spring period dropping down to 171 mg m^{-2} d^{-1} during the summer-autumn, with a dramatic decrease occurring during the last 60 days of the experiment (12.4, 47.9, 36.3, 119.9, and 13.9 mg m^{-2} d^{-1}, which were the lowest values for the deeper trap).

Two major peaks were recorded at the 1500m trap. The first one appeared at the I deployment (1-15/Mar/95) with a value of 459 mg m^{-2} d^{-1}, while the second was observed during the II period (1-15/Jul/95) with a value of 413.4 mg m^{-2} d^{-1}.

- <u>Organic matter flux</u>

The distribution of organic matter concentration (percentage by weight) decreased with water depth. The annual percentage mean at 200 m was 11.4% while at 1500 m the mean decreased to 4.8%. The fluxes at 200m depth were almost always lower than those at 1500m depth. It was obvious that during the winter-spring period, the fluxes were higher than during the summer-autumn period.

At trap A two major peaks were observed during the winter-spring period with values of 13.5 (1-15/Mar/95) and 16.1 mg m^{-2} d^{-1} (16-30/Apr/95). The first peak coincided to a secondary carbonate flux peak, while the second coincided to the maximum total mass flux at that depth. During the II deployment the organic matter flux displayed a similar decreasing trend as did the total mass flux, opal and carbonates.

At 1500m depth three major peaks were observed. The first (21.1-21.9 mg m^{-2} d^{-1}) covered a 45 day time period, which corresponded to the mass flux peak of March. The second (14.8-15.4 mg m^{-2} d^{-1}) appeared during the II deployment and within the same time-period of the mass flux peak. Finally, the third, a minor peak of 7.8 mg m^{-2} d^{-1}, appeared 15 days before the final sample.

- POC, PON and C/N ratio

The concentrations of POC and PON (percentage by weight) decreased with water depth (fig. 3). On the contrary the C/N ratio increased as a result of the degradation of the sedimenting organic matter. The mean annual percentage for POC, at 200 m was 5.55% while at 1500 m it dropped to 2.36%. For PON it was 0.82% at 200 m and 0.23% at 1500 m. The mean C/N ratio at 200 m was 8.2 and at 1500 m 11.7.

The time-series plot of trap A was characterised by three POC peaks (fig. 3). The first (7.2%) was recorded during the winter period (F1: 1-15/Feb/95), the second peak (8.7%) was noted during the last period of the first deployment (M1: 1-15/May/95) and the third (8.8%) from 16-30/Oct/95. The first peak occurred at the same time period as the opal peak. It was also characterised by three PON peaks. The first (1.18%) was recorded during the winter period (F1: 1-15/Feb/95), the second peak (1.55%) was noted during the last period of the first deployment (M1: 1-15/May/95) and the third (1.11%) from 1-15/Nov/95.

The time-series plot of trap B was characterised by three POC peaks (fig. 3) as well. The first peak occurred during the period from 16/Jan-28/Feb/95, and basically consisted of three peaks (with values of 3.57, 3.22 and 3.51%) which coincided with the February peak of the near surface trap A. This period (16/Jan-28/Feb/95) was of extreme importance because it was during this time of the year that pelagic-benthic coupling was most efficient (this finding supports and is supported by the sediment metabolism data). The second peak (2.85%) occurred from 1-15/Aug/95 and was not as pronounced as the first. The third peak (3.47%) occurred from 1-15/Oct/95 and in absolute values was as strong as the first but not of the same duration.

There are no strong PON peaks (fig.3) observed as far as trap B is concerned. Three weak peaks could be discerned from 16-31/Jan/95 (J2), from 1-15/Aug/95 (A1) and from the 1-15/Oct/95 (O1), with values of 0.31, 0.32 and 0.29%, respectively. It is again important to note that the first PON peak of trap B coincides with the first PON peak of trap A.

The C/N ratio displayed remarkable variability in both traps (fig. 3). As expected the material in trap A obtained lower values (i.e. it had a higher nutritional value) throughout most of the year. The only exception was the summer period, from 1/Jun-31/Aug/95, during which both traps display similar C/N ratio's. This is mainly due to the pronounced stratification of the water column which tended to prohibit the downward flux of "fresh" organic matter. In trap A, the lowest C/N ratio (5.2) was observed from 16-30/April/95 and the highest (11.9) from 16-31/Jul/95. In general, the C/N ratio in trap A displays a decreasing trend from November 94 to April 95, increasing thereafter.

The two (out of three) major POC and PON peaks observed at trap A (200 m) occurred during the winter-spring period. The first peak was found to coincide with the secondary carbonate flux peak, while the second coincided with the maximum total mass flux. During the II deployment period (1/Jun-30/Nov/95) the POC and PON flux fluctuated during the summer period and displayed a gradual increase towards Autumn and Winter.

- Labile organic matter flux

Overall, carbohydrates were the major component of the flux of organic matter accounting on average for 65.8 % and 67.5 % (at 200 and 1500 m depth respectively), followed by lipids, accounting for 20.0 and 21.1 % (at trap A and B, respectively) and proteins contributing for 14.2 % and 11.4 % (at trap A and B, respectively).

PRT/CHO ratios in the sediment traps were generally low. They ranged from about 0 to 0.89 at 200 m, with an annual average of 0.25, and from 0 to 0.48 at 1500 m depth with an average value of 0.18.

The biopolymeric (i.e. labile) carbon flux (C-BPF: the sum of lipid, protein and carbohydrate carbon) was on average 2.65 and 3.43 mgC m^{-2} d^{-1} at 200 and 1500 m, respectively. In the upper trap highest sedimentation rates were reported in April (5.01 mgC m^{-2} d^{-1}) and in July (5.45 mgC m^{-2} d^{-1}), while a minor peak was observed in September (4.19 mgC m^{-2} d^{-1}). By contrast, in trap B a main peak was reported during February 95 (6.3 mgC m^{-2} d^{-1}).

The sum of carbohydrates, proteins and lipids reported to total mass flux (utilised as a relative measure of the amount of food potentially available for benthic consumers, i.e. food index) trap A ranged between 5.2 % (March 24) and 60.6 % (July 8) with an annual average of 20.3%. Highest values were recorded during June and July (with monthly averages of 37.6 and 56.6 %, respectively) and during November 95 (47.1 %). In trap B, however, the food index was on average 5.57 % of the total material flux, with highest values during November 95 (34.3%) and low values of 1.8 % (July 95).

The biomass of bacteria attached to the settling particles in the traps varied seasonally. Bacterial biomass at 200 m was on an annual average 122.0 μgC m^{-2} d^{-1} and ranged from 54.16 μgC m^{-2} d^{-1} (during December 1994) to 866.9 μgC m^{-2} d^{-1} (during April 95). Bacterial biomass flux at 1500 m, was on annual average 228.8 μgC m^{-2} d^{-1} with maxima in February 23 (585.2 μgC m^{-2} d^{-1}) and March 8 (406.1 μgC m^{-2} d^{-1}). From March to November 95 the flux of bacterial carbon in both traps remained quite constant.

In trap A bacterial carbon accounted on annual average for 4.94 % of the C-BPF, ranging from 1.1 to 11.1 %. In the deeper trap, bacterial carbon accounted on average for 6.55 % with high values being recorded from November 94 to May 1995 (up to 10.8 % on April 1995) and low values reached by the end of the sampling period (lowest value was recorded on 23 June, 3.3%).

The first important conclusion derived from the sediment trap experiment was that the small amount of collected material highlighted the oligotrophic character of the Cretan Sea, since the mean annual mass fluxes were ~50 and 209 mg m^{-2} d^{-1} for the upper and deeper trap respectively. These values are equivalent to those recorded for the oceanic basins (Deuser and Ross 1980; Deuser 1987; Honjo 1980; Jickells *et al.*, 1984; Martin and Knauer 1985), the NW. Mediterranean basin (Buart-Menard *et al.*, 1989) and the Antikythira strait (Heussner and Monaco 1996). Fluxes from the Gulf of Lyon (Monaco *et al.* 1990), however, were much higher than the ones recorded in this study.

The relatively high values (mean 4.8%, ranging 3-7.1%) of organic matter in deep waters show a more or less significant organic input to the benthic community. The maximum flux observed at 200m depth has a delay of 15 days compared to that of carbonates. In spite of that delay, an organic input is confirmed in late April to early May. Organic matter flux at 1500 m depth displayed a different seasonal pattern, showing the different origin of the settling particles, compared to the one displayed by the other constituents.

POC generated during primary production undergoes significant remineralization in the surface mixed layer and the upper water column. These processes are even more significant when dealing with oligotrophic, stratified, two-layered systems (as is the Cretan Sea). Measurements of POC near the seafloor have shown that very little (maybe as little as 1%) of the carbon fixed in the surface waters reached the seafloor (Honjo, 1978; Rowe & Gardner, 1979; Berger *et al.*, 1989). The decrease observed in POC flux from the surface to the bottom waters of the Cretan Sea is in many cases more than two fold. If the PON flux is taken into consideration than the decrease is even more dramatic. In the latter case, the pronounced seasonal differences observed in the PON flux in the surface waters are almost completely lacking from the bottom waters. In fact the differences in the nutritional quality of the settling organic matter are minimal and therefore the larger benthic organisms do not display a detectable seasonal response. It is therefore not a surprise to find out that it is only the benthic microbiota (bacteria and protozoa) that undergo population changes in response to the reduced seasonal differences in the quality of the settling organic matter.

The labile organic carbon flux as C-BPF was on annual average 0.9 and 1.2 gC m^{-2} y^{-1} (at 200 and 1500m, respectively). Even though these values were based on different analytical procedures they could be compared to annual fluxes of organic carbon in other oceans, since it has been shown that C-BPF concentrations generally account for about 80% or more of the POC (Fabiano *et al.*, 1996). The labile carbon fluxes in the Cretan Sea are roughly equivalent to those reported in the Sargasso Sea (0.4-0.7 gC m^{-2} y^{-1}, Deuser *et al.*, 1983) or in the North Pacific (0.7-2.4 gC m^{-2} y^{-1}, Honjo, 1985), they are much lower, however, than those reported in the Black Sea, the Panama Basin and Bransfield Strait and Antarctica (Honjo *et al.*, 1982; Honjo *et al.*, 1987; Karl *et al.*, 1991; Wassmann, 1983, Wefer *et al.*, 1988 and literature therein). Similarly, carbohydrate and protein fluxes (compared as C equivalents and aminoacids respectively) were respectively 10 and 85 times lower than those reported by Buscail *et al.* (1990) in the northwestern Mediterranean margin (650 m depth).

The time series analysis of the labile carbon flux in the deeper trap confirmed the presence of high food input during January-February. The range of seasonal input from high to low by a factor 2x, confirms literature data on the sedimentation rate in the deep sea (Carney, 1989). Also, a range of detritus input on the order of 2.3x was reported by Deuser (1986). These data suggest that, in the Cretan Sea, during winter, higher amounts of organic carbon are available to the deep-sea benthic communities.

Some indications on the nature of the particles can be inferred by PRT/CHO ratio. This ratio was generally very low with higher values at 200 m in late spring, indicating a protein-depletion with depth, as well as an input of proteins during the phytoplankton bloom. Such depletion, in the Cretan Sea, is certainly enhanced by the high water temperatures (between 13-14°C during the entire year at 1500 m) and the strong water column stratification. However, settling rates are also expected to by reduced by the size of the particles, since it has been shown that about 65% of the suspended particulate protein, carbohydrate and lipid concentration is associated with particles ranging from 0.2 to 2.0 µm in size (Danovaro *et al.* 1996a).

The characteristics of the food supply to the benthos can probably be described better by the food index. The food index (% of labile organic compounds on the total mass flux) is much higher in the upper trap (20.3 % at 200 m and 5.6 % at 1500 m depth). Moreover, in the trap at 1500 m depth, no significant seasonal changes were observed, while at 200 m depth a sudden increase of the food index (up to 60 %) was observed during late spring-summer period. These data indicate that the quality of food reaching the floor at station D7 was very poor throughout the year. This could lead to the conclusion, supported by the lack of faunal response to the winter input (Tselepides *et al.* 1996; Danovaro *et al.* 1996c), that the higher amounts of C-BPF reported in January are partially balanced by the increase in sediment loads which devaluate (by dilution) the quality of food supplied to the benthos.

The flux of bacterial biomass was significantly correlated to the flux of labile organic carbon, and particularly to the fluxes of proteins and carbohydrates ($n=22$, $p<0.01$). In both traps, bacterial biomass presented a notable increase in responce to the inputs of labile compounds and was correlated to the seasonal fluctuations in primary production. Bacterial biomass accounted for 5-6.5% of the labile carbon flux (at 200 and 1500 m respectively). However, in late winter-spring (from late February to May) bacterial biomass accounted on average for about 10% of the labile carbon flux. Since bacteria are characterised by a low C:N ratio (C:N=4) their contribution to the protein-N flux can be estimated by converting protein content to nitrogen equivalents (as PRT-N=PRT/6.25). The average protein flux in both traps was 0.86 mg m^{-2} d^{-1}, which is equivalent to 0.14 mgN m^{-2} d^{-1}. Since bacterial nitrogen (obtained dividing bacterial biomass by 4) was, on annual average, 0.031 and 0.057 mgN m^{-2} d^{-1}, at 200 and 1500 m respectively, it can be concluded that 22% and 41%, respectively, of the labile protein-N was represented by bacteria. This result suggests that, even though bacteria accounted for a considerable fraction of the labile carbon flux, their potential role as a source of organic nitrogen is by far more important. Therefore, in the Cretan Sea, bacteria attached to the sediment particles can be considered as a major food source for deep-sea benthic organisms. This finding is consistent with the estimates reported by Karl *et al.* (1991) in the Bransfield Strait, which demonstrated that microbial biomass (measured as ATP content) may represent more than 50% of the carbon flux.

Sedimentary chemistry

- Redox potential

Sediment redox potential (Eh) measurements recorded relatively high values (74-528 mV) immediately above the sediment surface at all stations. The Eh sediment profiles that correspond to the continental shelf stations D1, D2 and D3 (at 40, 100 and 200 m depth) displayed a marked decline with sediment depth, indicative of the existence of a redox potential discontinuity layer (RPD) at 0-2, 2-4 and 4-6 cm depth respectively. The deeper stations (D3-D7) displayed no such trend, the Eh being constant throughout (>400 mV) throughout. Intense organic loading of the sediments was clearly evident during the summer (Sept. 94 and Sept. 95) at the 40 m station (D1).

- Seasonal and spatial changes in sediment organic matter

TOC concentrations gradually decreased from the shelf to the deep basin. Pronounced seasonal differences were not evident, with values ranging from 3-6 mg/g sed. DW. Relatively high concentrations of TOC were measured at 1570 m (sta. D7) during Sept. 94 and May 95 (mean values of 4.1 and 4.2 mg/g sed. DW, respectively). The highest TOC values at the deeper stations (i.e. beyond 540 m depth) were all recorded during May and Sept. 94. As was the case with the water-column parameters, 1994 seemed to be a different year, characterised by maxima which occurred over the sediments of the deeper stations.

The C/N ratio displayed little seasonal variability in the continental shelf sediments, with values ranging from 8 to 10. High variability was observed in the continental slope sediments, with values ranging from 5 to 12. Lowest values (5-6), indicative of the presence of organic material of high nutritional quality, were observed at mid-slope depths during May 1994.

A general feature in the distribution of CPE over the continental margin was its drastic (exponential) decrease in the sediments of the continental slope and deep basin. Beyond 500 m depth CPE concentrations dropped sharply (<3 μg/g sed. DW) forming a discrete cluster of values corresponding to the deeper stations. At this point, it should be pointed out that during May 94 chl *a* and CPE concentrations over the continental shelf and upper slope were 30-40% higher, in comparison to May 1995. High mean CPE concentrations were measured over the continental shelf with values ranging from 1.92 (at 200m in Sept. 95) to 12.95 (at 40 m in Sept. 94) μg/g sed DW. On the contrary, the continental slope and deep basin displayed low values with mean concentrations ranging from 0.22 (at 1570 m in Feb. 95) to 2.50 (at 700 m in Sept. 94) μg/g sed DW.

With the exception of station D6 (at 940 m), it was clearly evident that pronounced seasonal differences in chl *a* concentrations occurred only over the continental shelf stations. Mean chl *a* values (in the 0-1 cm depth layer) ranged from 0.25 to 4.22 μg/g sed DW over the continental shelf and from 0.01 to 0.10 μg/g sed DW over the continental slope and deep basin. The mean chl *a* (in the 0-1 cm depth layer) concentrations at each station per season are given in Table 2 below.

Table 2. Mean chl *a* concentration (in μg/g sed DW, 0-1 cm) at each station per season.

	Depth (m)						
Sampling period	40	100	200	540	700	940	1570
Sept. 94	4.22	0.83	0.40	0.03	0.10	0.03	0.07
Feb. 95	1.64	0.33	0.29	0.07	0.04	0.03	0.01
May 95	1.80	0.25	0.19	0.08	0.05	0.04	0.06
Sept. 95	2.39	0.60	0.10	0.05	0.07	0.04	0.04

It is worth noting the significant differences obtained between the values extracted from the 0-1 cm layer and those from the surface film (0-3 mm sediment layer). The latter gave values 2 to 3 and in some cases 4 times higher. Depending therefore, on whether the 0-10 (Table 2) or 0-3 mm (Table 3) sediment layer was taken into consideration the results obtained could have been drastically different. Pelagic-benthic coupling was clearly evident during the winter period when the latter methodology was followed.

Table 3. Mean chl *a* concentration (in μg/g sed DW, 0-3 mm) at each station, during winter and summer 1995, as calculated by the HPLC method applied by NIOZ.

	Depth (m)						
Sampling period	40	100	200	540	700	940	1570
0-3 mm sed.layer							
Feb. 95	4.31	0.66	0.57	0.28	0.14	0.13	0.07
Sept. 95	9.94	1.16	0.10	0.03	0.02	0.02	0.01

As was the case with chl *a* and CPE, ATP concentrations also displayed an exponential decrease with depth. Mean ATP values (at the 0-1 cm depth layer) were generally found to range from 116 to 575 ng/g sed. DW over the continental shelf and from 17 to 303 over the continental slope and deep basin (Table 4).

Table 4. Mean ATP concentration (in ng/g sed DW) at each station per season.

	Depth (m)						
Sampling period	40	100	200	540	700	940	1570
Sept. 94	325	391	304	220	138	232	215
Feb. 95	535	488	279	174	116	72	23
May 95	575	252	181	303	102	57	41
Sept. 95	399	424	116	158	73	22	17

Compared to their 1995 counterparts, the Sept. 1994 ATP samples displayed 3 to 10 times higher microbial activity at the deeper stations (D6 and D7).

There was no evidence of shelf to slope transfer of organic matter. On the contrary, a slight enrichment could be observed originating from the north-west (May 94 and Feb-March 95) and occasionally from the west (March 95).

In general, chloroplastic pigment concentrations were very low and decreased dramatically with depth at all sampling periods. Higher values were observed at the shallow shelf stations.

In contrast to what was stated above (which was based on the results obtained from the 0-1 cm sediment layer), when the 0-3 mm sediment layer was taken into consideration pronounced seasonal differences (with the maxima occurring in the winter) were evident even in the deeper stations (down to 1570 m depth). Pelagic-benthic coupling therefore does occur in the winter period as evidenced by the dramatic increase in the chl *a* content of the surficial sediments (0-3 mm). This very important conclusion is masked if the results are extracted only from the 0-1 cm layer, since chlorophyll *a* concentrations drop dramatically below 5 mm sediment depth. The shallow, 40 m continental-shelfstation, is a different case displaying an opposite trend possibly due to the increased influence of urban and industrial runoff during the summer.

Our study site is an area of moderate to very low productivity (80, 59 and 19 gC/m^2/y over the shelf, slope and deep basin respectively) and as such the sedimentation of POM is greatly influenced by the prevailing mesoscale hydrographic features (the cyclonic and anticyclonic Cretan Sea gyres) in the area. The latter in conjunction to the influence exerted by the intrusion of the TMW water mass during 1994, which changed the chemical structure of the water column, is capable of affecting the productivity of the surface layers and therefore the sedimentation rate of organic matter.

The distribution of ATP along transect D did not provide us with the insight that was initially expected. With the exception of the high concentrations observed during 1994 the differences recorded during the other sampling periods were not as pronounced. In any case, the microbial activity in the winter-sediments was found to be higher (by 20-200%, depending on the station) compared to the summer-sediments. ATP concentrations were therefore a relatively reliable index of the response of the benthic microbiota to the incoming organic matter.

- Labile organic compounds

Total carbohydrate (T-CHO) concentrations displayed strong seasonal variability. Highest concentrations were observed in August 1994 (on average 5.13 mg g^{-1}sed. DW). Values decreased in February and May 1995 (on average 2.57 and 0.66 mg g^{-1} sed. DW respectively) and increased to an average of 0.83 mg g^{-1} sed. DW in September 1995. Higher concentrations were observed in August 1994 and February 1995 at the deeper stations. Maximum values were recorded during August at stations D5 and D6 (7.86 and 7.48 mg g^{-1} sed. DW respectively), whereas on May and September 1995 no significant spatial changes were observed, with values ranging from 0.39 (May 1995, Stn. D1) to 1.54 mg g^{-1} (September 1995, Stn. D2).

Total carbohydrates represented the main component of the organic matter, accounting, on average, for 82.54 % in August 1994, 57.95 % in February 1995, 43.45 % and 61.44 % in May and September 1995, respectively. Soluble carbohydrates (as the sum of HCl and NaOH soluble carbohydrates) generally accounted for a small fraction of total carbohydrate concentrations. Sol-CHO concentrations showed a decrease with depth. In May 1995, Sol-CHO accounted on average for 8.21% of total carbohydrates, whereas in September 1995 was, on average, 6.21 %. From August 1994 to February 1995, Sol-CHO contribution decreased, accounting on average from 4.91 % to 0.79 %, respectively.

Protein (PRT) concentrations increased from August 1994 (on average 0.54 mg g^{-1}) to February 1995 (1.67 mg g^{-1}), decreasing thereafter (i.e. from 0.83 mg g^{-1} in May to 0.38 mg g^{-1} in September 1995). February 1995 was characterized by the highest protein concentrations at all stations with values ranging from 0.6 mg g^{-1} (Station D7) to 3.26 mg g^{-1} (Station D3).

The lipid contribution to the bulk of organic matter was always rather low, decreasing from August 1994 (7.23 %) to February and May (5.69% and 4.33 % respectively) and increasing in September 1995 (12.62 %). Carbohydrates in general, accounted for the majority of the bulk of the labile organic pool. Proteins accounted for a significant fraction, in February 1995, and became dominant in May 1995.

Highest biopolymeric carbon (C-BPF, as the sum of carbohydrate, protein, and lipid carbon equivalents) concentrations were observed in August 1994 (on average of 2.61 mg g^{-1}), decreasing continously from February (on average 2.04 mg g^{-1}) to May and September (0.73 and 0.65 mg g^{-1}, respectively) 1994. In August the highest values were found in the deeper stations, while, generally in all other seasons highest C-BPF concentrations were observed between 100 and 200 m depth decreasing with increasing depth.

Overall, the sediments of the Cretan Sea showed high biopolymeric carbon concentrations. The concentrations of the three main biochemical components (lipids, proteins and carbohydrates) were comparable or higher than those reported in other coastal, estuarine, or deep-sea areas (Danovaro *et al.* 1993, Fabiano & Danovaro 1994, Fabiano *et al.* 1995). In particular, total carbohydrate concentrations were higher (up to 4 times) than those observed in highly productive systems (Danovaro *et al.*, 1994). However, carbohydrate content does not always reflect the actual amounts of available food. In fact, it is well known that carbohydrate analysis may include some refractory (i.e. structural) compounds (positive to the phenol-sulphuric reaction). A better estimate of the amounts of readily available carbohydrate fraction may be obtained by the determination of the soluble carbohydrates, which, indeed, accounted for a small fraction. Protein concentrations were comparable to those reported for other more productive areas, such as the Gulf of Gascogne (Khripounoff *et al.*, 1985) whereas lipid concentration fell in the range of the literature values. The large amounts of biopolymeric compounds and the accumulation of refractory carbohydrates in the deeper stations are in contrast with the observed reduced labile organic flux (Chronis *et al.*, 1996). Two possible explanations may be identified: 1) low lability of the settling organic particles and 2) reduced utilization of the organic particles by consumers on the sediment floor.

The different biochemical classes of organic compounds exhibited different trends with time. Protein content, increased from about 20 to 250%, from August 1994 to February 1995 while both carbohydrate and lipid content of the sediments decreased. Such an increase in labile organic matter content could have been caused by the different composition of the settling particles. Data relative to labile carbon sedimentation rates were not available for August 1994, however the available data point out that a high protein flux occured in February, which decreased in May and September 1995. Seasonal changes in the relative contribution of labile organic matter indicate that significant changes in the quality of organic matter occured. In May, and partially in February 1995, proteins were the dominant fraction of the biopolymeric carbon. By contrast in August 1994 and September 1995, the sedimentary organic pool was dominated by carbohydrates which are characterized by a more refractory composition. The strong decrease of the soluble fraction in the deeper stations suggests a clear decline in food availability in the deeper sediments. These data indicate that, despite the very high T-CHO concentrations relatively small amounts of potentially oxidizable organic matter were present in the sediment.

Changes in the protein:carbohydrate ratio provide further evidence on the deterioration of the quality of organic matter with depth. The PRT:CHO ratio has previously been used as a measure of the bioavailability and "age" of the organic matter (Fabiano *et al.*, 1995). In the Cretan Sea, PRT:CHO ratios were extremely low. With the exception of station D1 (40 m depth), where organic matter was assumed to reach the sea floor without being significantly degraded, PRT:CHO ratios ranged from 0.02 to 1.2 decreasing with depth. Since proteins are more readily utilised than carbohydrates (Newell & Field, 1983) and are rapidly bound into refractory compounds, such low values confirm the role of proteins as a potential limiting source indicating the lower food quality found in the deeper sediments.

Overall, organic matter in the deep-sea sediments of the Cretan Sea was found to be composed primarily of detritus. Bacteria, which represent on average about 82% of the total benthic biomass (Danovaro *et al.*, 1996b) accounted only for a negligible fraction of the total protein-nitrogen pool. Similar results were obtained when assessing the bacterial contribution to the biopolymeric carbon. Thus, the main conclusion is that bacteria do not contribute significantly to the enhancement of the quality and/or nutritional value of the sedimentary organic matter.

The distribution of organic carbon, nitrogen, chloroplastic pigments, ATP, lipids, proteins, and carbohydrate concentrations were characterized by strong variability both in space and time. The quantity and composition of the sedimentary organic matter was found to vary significantly both seasonally and spatially, in response to the variations observed in the sedimentation rate. The influence of the TMW water mass was again clearly evident during 1994.

Sediment Community Oxygen Consumption

The *in-situ* SCOC measurements obtained with the BOLAS during two contrasting seasons (Feb. & Sept. 95), are given in Fig. 4. With the exception of the 40 m station, a pronounced and persistent difference between winter and summer was evident, with the summer values being lower than those in winter. In order to be able to compare the SCOC figures with the carbon supply measured with the sediment traps we converted them into carbon using an RQ of 0.85 (cf. Rowe *et al.* 1994). Consumption rates were, therefore, obtained ranging roughly from 120 to less than 10 mg C m^{-2} d^{-1}.

An important feature was the sharp decrease in SCOC with increasing water depth. This was more pronounced over the shelf and down to a depth of 500 m, beyond which values dropped gradually yielding a semi-log relationship between SCOC and depth. A similar, though less pronounced, SCOC-depth relationship was recorded by Tahey *et al.* (1994) in the western Mediterranean (Gulf of Lions). In the latter study, the SCOC rates at the upper slope (ca. 500 m), appear to be higher than in the Cretan Sea.

With the exception of the shallow 40m station, our measurements of SCOC yielded consistently lower values in summer when compared to winter. Though the differences are small in absolute terms the lower values are regarded as indicators of a diminished supply of labile POM to the benthos during the summer. This argument was supported by a variety of other measurements and parameters that showed the same trend. A reduced benthic food supply was evident during the summer when sediment microbial biomass and concentrations of chlorophyll *a* were taken into consideration. The biomass of bacteria and heterotrophic nanoflagellates (Danovaro *et al.* 1996b) closely followed the seasonal and bathymetric pattern of SCOC as well. Since the latter are bacterial predators, their biomass was coupled to bacterial production which in turn was controlled by organic sedimentation.

In the present study, SCOC and diffusive fluxes were found to compare quite well but in other habitats significant differences have been found due to macrofaunal irrigation (Rasmussen & Jørgensen, 1992). The absence of such discrepancies in the Cretan Sea indicate that the contribution of macrofauna to the sediment-water exchange of O_2 is quite small which is not surprising in view of the low macrofaunal biomass (Tselepides *et al.* 1996b).

A major conclusion that can be drawn from the SCOC data is that horizontal transport of metabolizable POC is lacking between the stations. In case of a substantial cross-slope transport one would expect a less steep profile of SCOC or zones with markedly enhanced SCOC values. An example of the latter situation has been found on the east-Atlantic continental slope where at 1000 m depth a depocenter of organic material was found with quite elevated SCOC rates (Rowe *et al.*, 1994). On the contrary, the almost proportional decrease of SCOC with increasing water depth strongly suggests that the quantity of labile POM arriving at the sea floor is governed by the vertical settling time, indicating that horizontal transport is not important.

In summary, with the exception of the 40 m station, substantial evidence exists to support a close coupling between phytoplankton biomass (production) and benthic metabolism (SCOC). This close coupling can be validated for the 1570 m station where a long-term sediment trap was deployed during 1995 (Chronis *et al.* 1996). During February the vertical carbon flux varied from 8-11 mg C m^{-2} d^{-1} and sediment carbon consumption was estimated (from SCOC) to be 9 mg C m^{-2} d^{-1}. In August these figures were 3.5 and 2 mg C m^{-2} d^{-1}, respectively.

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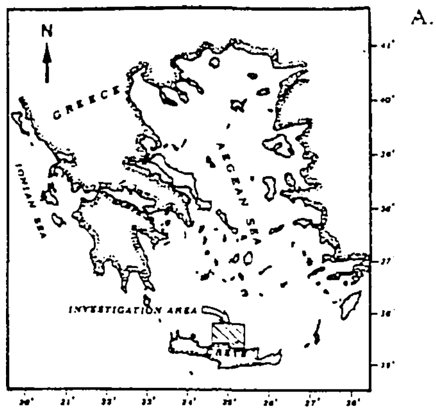
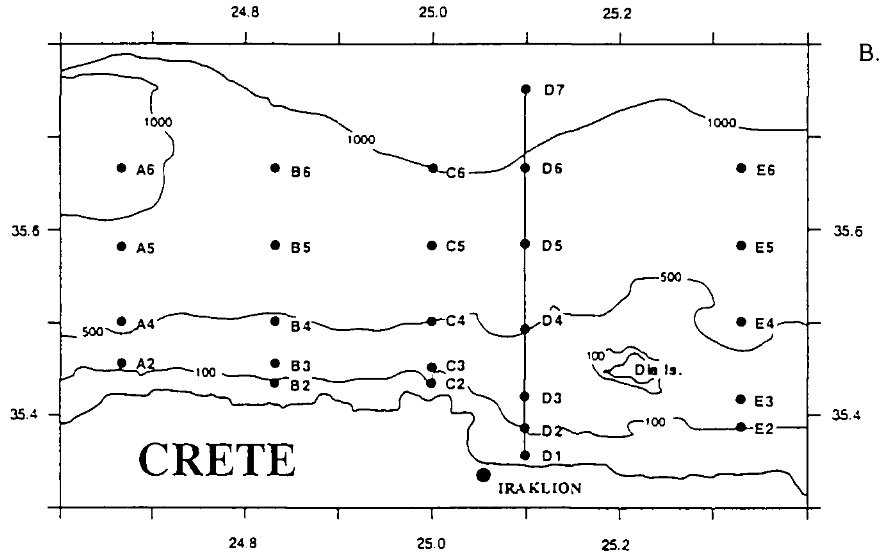


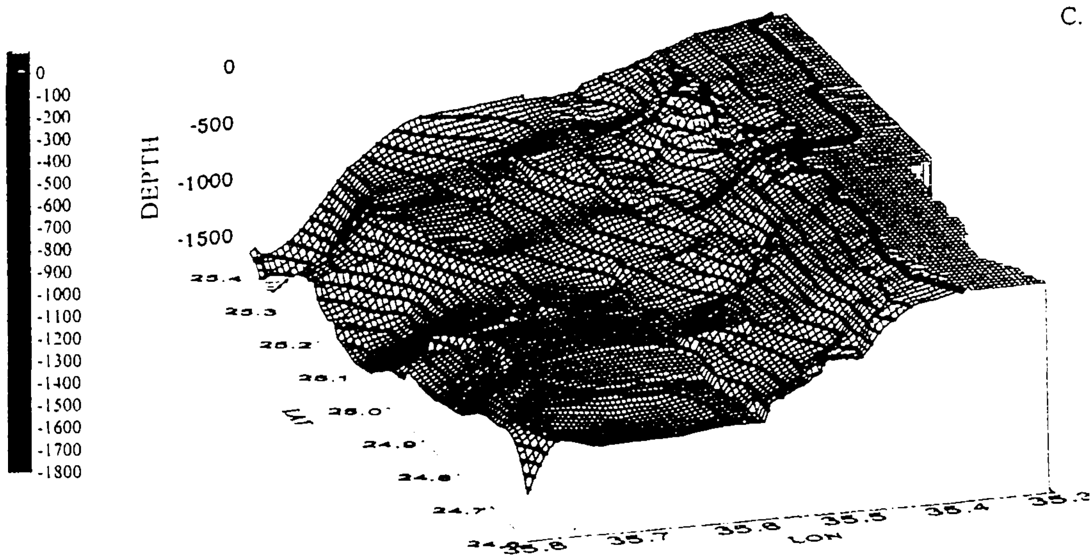
Figure 1

A. Location of the area under investigation

B. The established grid of stations with the main transect D indicated

C. Detailed bathymetry of the area





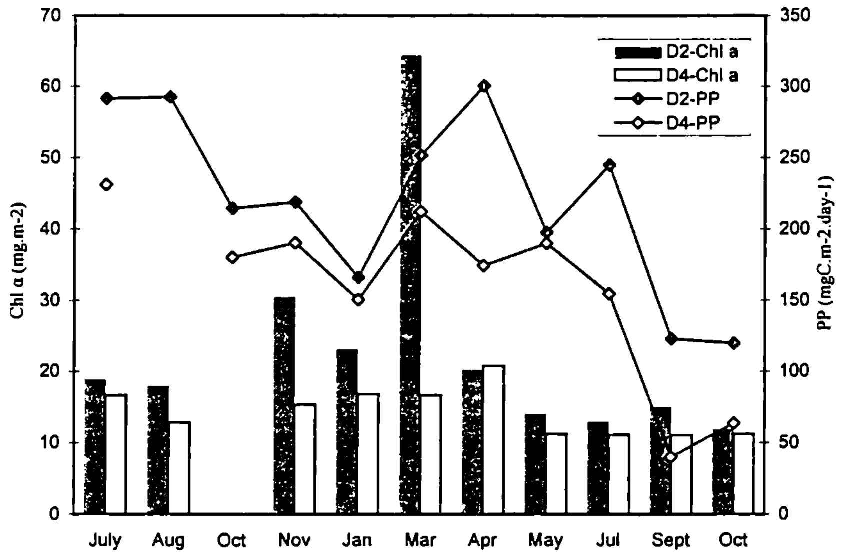


Figure 2. - Seasonal fluctuations in primary production and chlorophyll *a* at stations D2 (shelf, 100 m depth) and D4 (slope, 540 m depth) in the Cretan Sea.

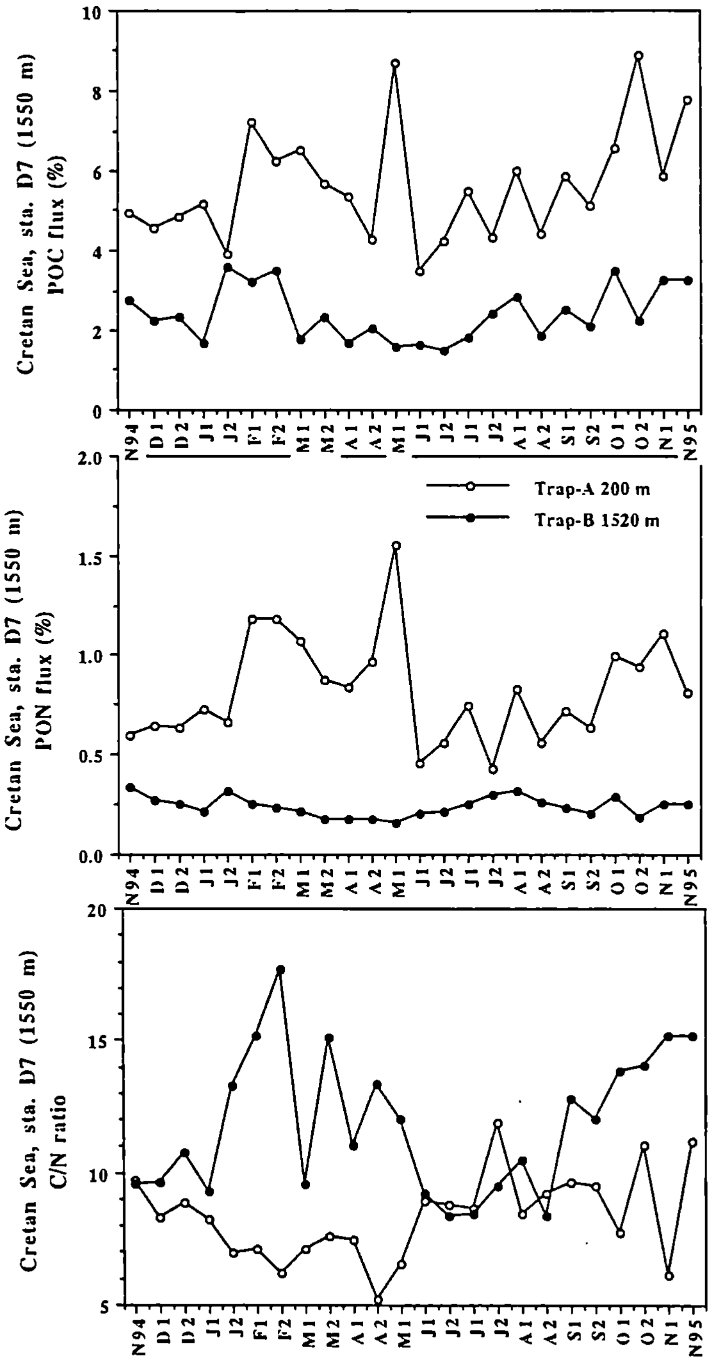


Figure 3 - POC, PON fluxes (from Nov. 94 to Nov.95) and corresponding C/N ratios at 200 and 1520 m depth at station D7 (1570 m) in the Cretan Sea.

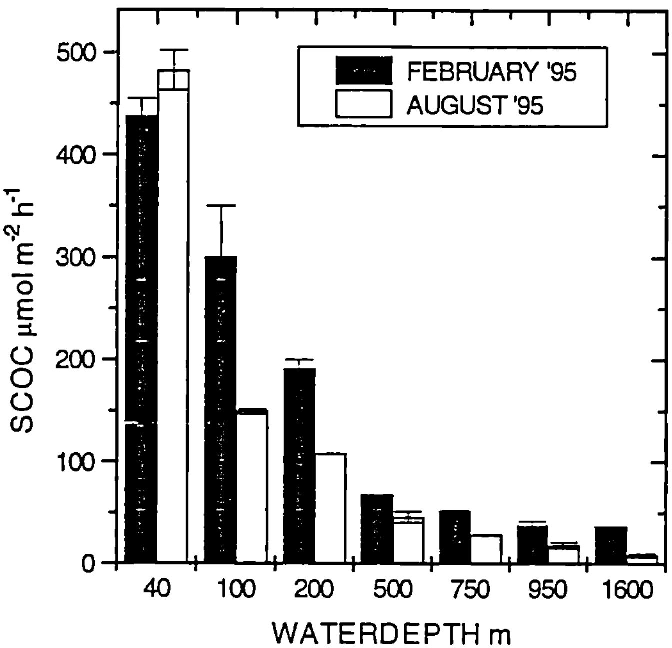


Figure 4 - Comparison of the in-situ SCOC rates (in µmol m-2h-1) measured with the use of the BOLAS in February and August 1995.

Mediterranean Targeted Project (MTP)
Research Theme on Biogeochemical Studies

Synthesis of Results

Mediterranean Targeted Project (MTP)
Research Theme on Biogeochemical Studies

Synthesis of Results from the CINCS, EMPS, EUROMARGE-AS, EUROMARGE-NB, MERMAIDS, OTRANTO & PELAGOS Projects

BIOGEOCHEMICAL BUDGETS

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1. Introduction

Transport of all types of materials has led to much research within the various subprojects of MTP 1. Data were produced that described the stocks and/or fluxes of water, solutes, and particles in different parts of the Mediterranean Sea characterised by various trophic regimes. A very first attempt to synthesize the major results of this research is presented here, principally with the aim of calculating biogeochemical budgets. The term 'budget' is taken in the broadest of contexts, that is an assessment of the quantity of water, solutes, or particles involved in, available for, or assignable to a particular location or situation. As such, budgets are important features which help in the characterisation of the different marine environments.

With the data sets available from MTP1 it is possible to calculate two major types of biogeochemical budgets, whether they address the horizontal or the vertical dimension. Quantitatively, horizontal transport is the most important contributor to particle transfer. The main driving force that controls this type of transfer is, of course, the general circulation of water masses. For that reason budgets of horizontal fluxes, either in the dissolved or the particulate form, generally concern meso- to large scale environments. Such calculations permit to assess the importance of material transported within a specific system (e.g., transfer within a basin or a subbasin, or transfer between subbasins). Due to the kind of data necessary for the calculations (horizontal water fluxes generally calculated from geostrophic approximations + representative estimates of the distribution of the parameter for which a budget is needed), horizontal budgets are restricted, at the present stage of existing data for the Mediterranean, to a limited number of locations (e.g., transect through a specific water mass or a current system; transport through a strait) and to discrete periods of time (generally a seasonal situation).

On the other hand, downward flux budgets are more restricted in terms of spatial scale but generally better solve the temporal resolution since fluxes are time-integrating measurements. The amount of material involved can be much lower than for horizontal transport but it represents a very important qualitative component since it provides the link between the surface "productive" layers and the deep environment.

The examples given below are intended to show how and what can be calculated, rather than to give an exhaustive, comparative data set. This is mainly due to the different levels of achievement in the respective data sets provided by the MTP 1 subprojects concerned by this aspect of budget calculation. Data will be further worked out in a near future to obtain comparable budget values for the main sites worked out during MTP 1.

2. Horizontal flux budgets

2.1. Horizontal fluxes in the North Balearic Basin.

Field data (CTD, light scattering, SPM, COP, NOP and nutrients) were assimilated to estimate geostrophic fluxes entering and exiting the North Balearic Basin. Geostrophic velocities were derived from the density field along sections with a reference level (level of no motion) at 1000 dbar.

Advective fluxes of water, suspended particulate matter (SPM) and particulate organic carbon (POC) were estimated along a cross-basin section at the eastern limit of the study area. Data were gathered during the EUROMARGE-NB FLUBAL cruise in August 1993 and therefore characterised the summer situation. SPM and POC concentrations, used to compute the fluxes, were derived from light scattering measurements by a linear relationship (Fig. 1). The transport of water and associated particulate matter showed similar features, with a westward transport on the northern side of the basin and an eastward transport on its southern side (Fig. 2). Water transport across the section was roughly balanced, and was about 1.0 Sv (1 Sv = 10^6 m^3 s^{-1}) on the northern and southern sides of the basin. The associated SPM and POC transports were about 0.250 T s^{-1} and 0.03 T s^{-1} respectively, which would represent a yearly transport of 7.8 10^6 T and 0.95 10^6 T respectively. The true value of yearly transport is probably higher than these estimates based on a summer situation, since the Northern Current flux generally increases by a factor of 2 during winter. The important consideration here is that these yearly estimates are on the same order as the solid discharge by the Rhône river.

2. 2. Horizontal fluxes in the Adriatic Sea

Computation of the flow regime with regard to horizontal transport of materials in the Adriatic relies on flow computations from the research of the MERMAIDS and OTRANTO projects. Modelling based on a simplified POM (Princeton Ocean Model) by MERMAIDS, which considers the functions of heat flux, wind stress and the River Po outfall on circulation, has been used to establish the flow regime across two transects (20-35m) normal to the shelf. Monthly variations across these show seasonality and budgets of 0.02 and 0.11 Sv. As most of the horizontal material transport on the western limb of the Adriatic is concerned with shelf/slope waters, the OTRANTO project has measured, using an array of current meters, seasonality in the flow regime of outgoing modified LIW waters (0-300m), which show variations from 0.2 - 0.7 Sv. Seasonal collections of SPM analysed for its major elements on these transects and at the Strait of Otranto show, similarly to EUROMARGE - NB, a complicated non-linear relationship between element concentration and turbidity. EUROMARGE - AS has used particulate element analysis to assess transports. Estimates of these across the shelf transects and the western parts of the Strait (Table 1 - page 314) show lower fluxes on the shallow shelf compared with the budget from the River Po. However, there is an increase in budget along the shelf, and this possibly relates to sediment inputs from small Appennine rivers. In the case of Mn, it shows seasonally related benthic inputs as well as input derived from the river. The inference of the calculated low budgets on the shelf compared with the river is that much of the material transfer on the shelf comes from major southward transfers during bora wind storms, particularly in winter.

Almost all the elemental budgets through the Straits relate to movements in shelf/slope waters, rather than in basin bottom waters. Temporal variations show change by a factor of 4 or 5, and budgets (Table 1 - page 314) are realistic with respect to riverine inputs. Chemically dynamic elements such as Fe, Mn and Zn, expressed as metal/Al ratios, and related to river inputs, show relatively greater exports compared with Al, and this implies that a considerable proportion of anthropogenic metals is exported to the eastern Mediterranean. Table 1 also shows the relative importance of particulate budgets over those of dissolved elements.

2.3. Horizontal fluxes through the Cretan Arc Sea Straits

Horizontal transport of particulate elements through the Cretan Sea Arc Straits is calculated from water measurements and geostrophic flows computed by the PELAGOS project. Transfers of particulate elements are minute compared with that in the north west Mediterranean and the Adriatic shelves and slope (Table 2). Further, most of the transport out of the Cretan Sea basin occurs as bottom water associated with Cretan Deep Water, and exits through the Antikithira and especially the Kassos Strait. An interesting observation is the unusual composition of SPM exported, and is associated with hydrothermal releases or extraneous inputs.

Table 2 . Provisional estimates of particulate element budgets through the Cretan Arc Straits (10^3 tonnes y^{-1}). (Data from PELAGOS).

	March 1994					September 1994			
Antikithira Strait									
	Al	**Fe**	**Ca**	**Mn**		**Al**	**Fe**	**Ca**	**Mn**
Cretan Deep Wat	8.26	6.15	29.0	0.33		10.7	7.95	38.2	0.55
Total Influx	11.4	11.5	111.0	0.38		15.8	13.8	66.4	0.58
Total Outflux	8.49	6.32	30.2	0.33		15.4	16.6	67.4	0.74
Net Budget	2.92 (i	0.52 (i	79.8 (i	0.05 (i)		0.49 (i)	2.84 (o)	0.65 (o)	0.17 (o)
Kassos Strait									
	Al	**Fe**	**Ca**	**Mn**		**Al**	**Fe**	**Ca**	**Mn**
Cretan Deep Wat	56.6	28.1	198	1.72		12.3	12.95	43.3	0.36
Total Influx	0	0	0	0		14.3	15.5	85.8	0.50
Total Outflux	118	115	537	3.38		14.2	14.7	53.7	0.96
Net Budget	118 (o)	115 (o)	537 (o)	3.38 (o)		0.1 (i)	0.8 (i)	32.1 (i)	0.46 (o)
(i) = in, (o) = out.									

2.4. Nutrient budgets

Annual horizontal fluxes of nitrate, phosphate, total chlorophylls and PN, transported by the Northern Current across the Marseille section were similarly calculated by EUROMARGE - NB from monthly surveys of the section between October 92 and June 94. They amounted to 75, 6, 0.7 and 12 10^3 T y^{-1} respectively. On the basis of these annual means, it was inferred that 10 to 40% of nitrate and phosphate and 50% of chlorophylls and particulate material circulated in the coastal area, whereas more than 50% were exported towards the open sea area.

There is a net export of all nutrients through the Strait of Otranto for the 4 seasons studied in 1994-5, and at all water depths. This contrasts with measurements of POC which statistically shows its transport budget to be in balance, and supports the hypothesis that little or no marine carbon is exported from the shelf.

3. Downward flux budgets and pelagos-benthos coupling

Collected data allow calculation of the annual biogeochemical budgets of downward fluxes for several locations in the Mediterranean Sea. An exhaustive comparison relating the carbon budget to that at the sediment / water interface and burial fluxes is not currently possible as sediment and biogeochemical accumulation rates are not available for all instrumented sites, although they are known for the northwest Mediterranean and for the shelf and basins in the Adriatic Sea. To calculate the pelagic/benthic budgets for each area, the following data / estimates are necessary :

• evaluation of primary production in the euphotic layer, and estimation of new production as a proxy for exported production;

• fluxes and composition (opal, organic and inorganic carbon, lithogenic fraction) of settling particles at different depths at the same location; data used for the calculations were provided by traps located at 500 m and 1000 m depth, that is at 500 and 35 meters above bottom (mab) respectively; it has to be noted that most of the trap experiments performed within the various MTP 1 sub-projects used the same experimental strategy and identical laboratory procedures, thus allowing a direct reliable comparison of values;

• sedimentation rates in the underlying sediments calculated from $xs^{210}Pb$ in sediments using two models (CRS and biodiffusive); sediments were collected by means of multitube coring.

• carbon cycling at the water-sediment interface can be compared with *in situ* measurements of benthic fluxes by benthic lander.

3.1. A yearly flux budget for the Northwestern Mediterranean continental margin

The downward flux budget presented in Fig. 3 was calculated for the experimental site located in the southwestern part of the Gulf of Lions (off Perpignan), considered as representative of the Northwestern Mediterranean margin. As on other margin systems, total mass fluxes recorded by the traps moored over a 1000 m water depth showed a marked increase between 500 m and 1000 m. This supplementary input of settling particles represents, at least, the same amount of material as the one that passes through the 500 m level.

The total mass flux recorded by the near-bottom trap is slightly lower than the amount of material deposited at the sediment interface. The latter value was calculated from mass accumulation rates calculated through $xs^{210}Pb$ in the sedimentary column and corrected for bioturbation. Within the various errors that affect such calculations, it can be assumed that the near-bottom flux, measured over a 1 year period by the trap balances quite well mass accumulation in the underlying sediments which are determined on a secular basis.

A first step towards 3-dimensional integrated mass budgets can be done at this stage, by comparing the relative importance of horizontal and downward transport. From Fig. 2 we can take an integrated SPM transport value of 200 kg s^{-1} for the first 50 km of the Marseille transect, a portion that encompasses the shelf and the slope down to approximately 2000 m depth. Assuming an homogenous distribution of SPM over this portion, this value yields a horizontal flux (from the surface down to the bottom) of roughly 350 kg d^{-1} per m of section. This amount is 5 orders of magnitude larger than the daily vertical flux settling over 1 m^2 in this part of the slope, showing that horizontal transport involves much more material than vertical transport. If one integrates now these values on a 3-dimensional scale, the situation is quite different. Horizontal transport does not change much through the entire Gulf of Lions, since it increases downstream, at the most, by 10 % at the height of Perpignan, and we can therefore keep the estimate of 7.8 10^6 T given in § 2.1. The value of 3.5 g m^{-2} d^{-1} can be taken as a first order approximation of the average mass flux for the entire slope of the Gulf of Lions from Marseille down to Perpignan (between 100 and 2000 m depth). This daily flux represents, integrated over a total slope area of 13 000 km^2 a yearly downward flux of 16 10^6 T. These estimates need, of course, to be refined; but they show that, when considered on a 3-D basis, horizontal transfer and downward transport of particulate material involve similar amounts of material (ca 10^7 T y^{-1}) in this part of the Mediterranean.

Organic carbon

The yearly estimate of primary production in the Gulf of Lions at the time of the EUROMARGE-NB experiment was 375 mg C m^{-2} d^{-1} (140 g C m^{-2} y^{-1}). Assuming an f ratio (new production/total production) of 0.3, this daily production leads to an exported production of ca 110 mg C m^{-2} d^{-1} out of the euphotic zone. On the basis of the variations of nitrite and dissolved organic N in the upper water column, an independant estimate of new production equivalent to 140 mg C m^{-2} d^{-1} was provided. The organic C flux to the mid-water trap (37 mg C m^{-2} d^{-1}) therefore represents roughly 25-35% of the exported production. If this flux at 500 mab is exclusively provided by the C export out of the euphotic zone (i.e., with no lateral input from the shelf for example), 65-75% of the organic matter leaving the euphotic zone is remineralized during settling through the first 500 m of the water column at this part of the Gulf of Lions.

The annual carbon flux increases from 37.4 to 53.6 mg $C.m^{-2}$ d^{-1} between the upper and the bottom trap, indicating that, at least (assuming no degradation between 500 and 1000 m), 31% of the organic carbon near-bottom flux is imported to the site. If we assume that the upper trap collection is representative of the material settling through the 500 m level in the entire study area, the minimum content Y (%) in organic carbon, opal and carbonate of the advected material B can be easily estimated using the following relation:

$$(A * \%) + (B * Y\%) = C * \%$$

with A = total mass flux at 500 m depth; B = total mass flux at 1000 m depth; and B = A-C, the supplementary input of particles in the deeper trap.

From the above relation, Y = 1 % for organic carbon, a value close to the organic carbon content of surficial sediments in this region. This feature suggests that at least a significant part of the supplementary input of particles in the near-bottom layer could be provided through resuspension processes.

At the water-sediment interface, the degradation of organic matter depends on sedimentary processes, redox conditions, sediment granulometry and biological activity. With respect to the organic carbon flux arriving at the bottom - for which the best estimate on hand is the flux given by the near-bottom trap - about 50 % of the organic carbon is buried and 50 % reminalized or transported futher seaward.

Concerning further the organic carbon budget at the sediment interface, a community oxygen consumption (SCOC) of 50 mgC m^{-2} d^{-1} has been evaluated. This value, calculated from O_2 consumption in a benthic chamber, represents total organic carbon mineralization (dissolved and particulate carbon). Consumption of total organic carbon by benthic communities is about twice the particulate organic carbon mineralization flux (27 mgC m^{-2} d^{-1}) which represent the difference between the near-bottom flux measured by the trap and the burial flux based on ^{210}Pb sediment accumulation rate. To balance the budget it is necessary to include mineralization of a dissolved organic fraction which is estimated at 23 mg DOC m^{-2} d^{-1}. With a minimum content of 1 mg l^{-1} of DOC, this mineralization would represent a daily consumption of the DOC standing stock contained in a 23 mm thick water layer at the maximum.

Carbonate fraction

On the Pyrenean margin, carbonate originates predominantly from pelagic (foraminifera, coccolithophorids, pteropods) and benthic production. The flux variation of carbonate between the two traps is similar to that of total flux. They increase by 100 % between 500 and 1000 m depth. The minimum content of the supplementary input between these two depths using the equation above is 32 %, a value slightly higher than the average content of surficial sediments. 96 % of the carbonate flux at 1000 m is accumulated in the sediment, and release seem neglectible (largely within the error of the different estimates).

Biogenic silica (opal)

The fluxes oberved in the upper and lower traps are equivalent (respectively 99 and 96 mg m^{-2} d^{-1}), which should indicate that the particles injected between the two traps are opal-free (Y = 0 %). This is of course highly unrealistic and the constant opal flux therefore implies a dissolution of labile opal constituents. Assuming a minimum opal content of 3 % for the supplementary material advected at depth (this is the minimum value encountered in the Mediterranean) we calculate a minimum opal loss of around 40-50 % during settling between the 500 and 1000 m depth horizons.

From the burial flux of opal in sediments a loss of about 2/3 is calculated, due to remineralization/dissolution processes at the sediment interface. From this tentative budget, it appears that this major constituent is the less-preserved in sediments, a feature which could explain the overall very low (<3%) opal content in Mediterranean sediments.

3.2. Downward fluxes in the Southern Adriatic Basin

Downward flux measurements in the southern Adriatic basin differ from that in the north west Mediterranean and these probably relate to either intensity or gradient changes of barotropic control and geostrophic currents across these margins. Evidence of flux calculations between the 500 mab and 35 mab traps show increases in most biogeochemical fluxes, especially the lithogenic fraction, and provide evidence for some lateral input into the basin from the western shelf/slope and probably the eastern side too, although this has not been studied. For now, sediment accumulation rate in the Southern Adriatic Basin was not corrected for bioturbation. The value calculated from ^{210}Pb in the sediments indicates an upper limit of 1560 mg m^{-2} d^{-1}, that is about 5 times the flux given by the near-bottom trap. This overestimation can be probably largely explained by bioturbation, though supplementary near-bottom inputs cannot be ruled out. Absolute flux values are an order of magnitude lower for the two Adriatic traps, but they imply a lateral input that is proportionally quite similar to that determined in the Gulf of Lions (Fig. 4). Other differences relate to different evolution of constituent fluxes with depth which could indicate that the transfer mechanisms differ between the Adriatic and the north west Mediterranean sites.

Comparison of the Otranto Strait with that of the north west Mediterranean margin further suggests that there is proportionately less transport into the Adriatic basin; most material is directed southwards from the shelf and upper slope into the Ionian Sea. Fig. 5 shows a comparison of the total mass flux collected from September 1994 to April 1995, by the OTRANTO and EUROMARGE - AS project traps deployed at the edge of the shelf (108m) and over the slope (603m) (OTRANTO), and centred over the Southern basin at its deepest part (EUROMARGE - AS). The temporal trends on the shelf indirectly reflect discharge from the River Po, but there is no synchroneity between this and that observed in the slope and basin traps. Moreover, mass flux changes between the shelf and basin traps differ by up to 2 orders of magnitude, implying little transfer across the shelf/slope system. This contention is supported by the content of carbon in the three traps : those on the shelf contain 1-2% C_{org}, similar to contents of shelf sediments, much of which is terrestrial. In the basin, contents are higher (about 5%) and during periods of the 1994-5 deployment, could exceed 10% weight. Abundant evidence, including that of ^{13}C signatures and specific carbohydrate contents, show that terrestrial supply is limited to 0-20% in the basin traps. Evidence of sediment compositions in the middle and southern Adriatic basins indicates a dominance (86%) of marine carbon. This examination of trap materials and sediments suggests that the major provenance for basin sediment is the northern Adriatic rather than the western shelf.

The pelagic-benthic coupling on the western shelf and basins have obvious differences, which to a large extent relate to export production and respiration in waters of contrasting depth. It is not possible to directly establish the export flux of carbon on the shelf, as the thermocline occurs only metres above the sediment. However, here 50% of gross primary production respires in the water column. Studies using a variety of systems, including seasonal macro and meiofaunal activities, expressed as C_{org} consumption rates, microbiology and direct expressions of pore water diffusion studies (Si and C_{org}) (Fig. 6) show that the benthic/pelagic coupling is highly efficient on the shelf with 80-90% of the Corg flux (rain rate) to the sediment / water interface respiring in the uppermost 2cm or so of the sediment given that much of the carbon in sediments is terrestrial. Fig.6 shows the rain rates of C_{org} and Si to the sediment, and the oxygen fluxes required in the respiration of carbon at the sediment/water interface of shelf and basin cores. These change systematically from north to south. Seasonal changes in sediment respiration decrease southward and show no temporal change off Ancona. The results of this research indicate no export of carbon from the shelf.

3.3. Downward fluxes in the Cretan/Ionian Seas

Budgets of downward fluxes for these two areas are quite incomplete for now, essentially because integrated primary production data and sediment accumulation rates are still lacking. They are therefore reduced to flux changes between traps (Figs. 7 and 8). These very limited data sets show again the net influence of lateral inputs that increase the fluxes recorded at depth. The supplementary amount of settling particles represents a substantially higher contribution (up to 76% depending on the considered constituent) than those observed for the other sites.

Finally, studies of the trace elements collected in trap materials from the north west Mediterranean, the southern basin of the Adriatic and the Cretan/Ionian Sea reflect to a very high degree differences in the lateral input of sediments from the continental margin. In the case of the 2 former areas, the dominance of lithogenic material and in the case of the Adriatic in particular, high anthropogenic loads masks much of the biogeochemical associations between metals and biology, except possibly for lead, which has a significant atmospheric flux. However, in the Cretan/Ionian Seas the limited lithogenic flux and the absence of obvious anthropogenic elements allows one to consider the downward fluxes of trace metals that are related to specific biogeochemical constituents. Given the oligotrophism of this area, biogeochemical fluxes of metals are small. Here geochemical associations show that copper is associated with an organic carbon rain while zinc is closely related to siliceous fallout, probably as diatom frustules : lead, however, shows association with both C_{org} and oxyhydroxides.

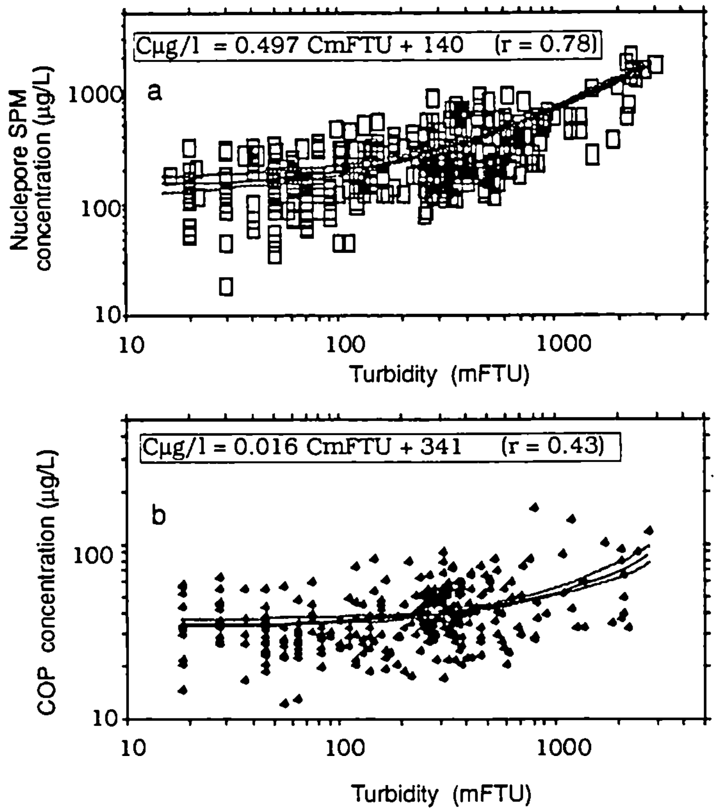

Fig. 1: Correlation and linear relationship between a) SPM concentration and turbidity, and b) POC concentration and turbidity. These relationship were inferred from 429 SPM and 471 POC concentration measurements made in summer condition. (Data from EUROMARGE - NB).

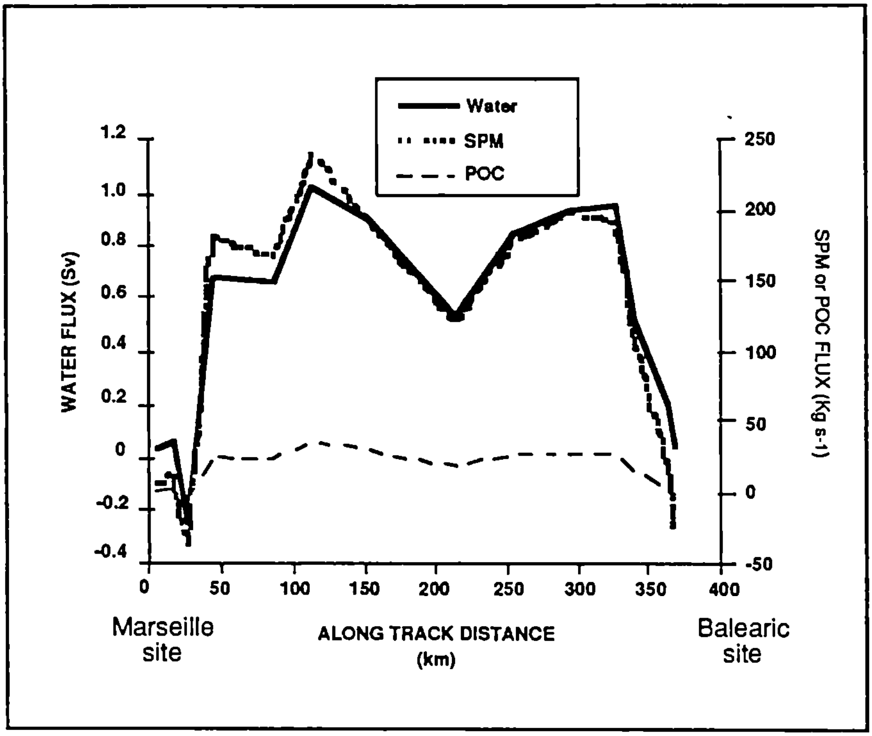

Fig. 2: Cumulative geostrophic transports of water, SPM and POC integrated along a cross-basin section extending from Marseille to Menorca. Positive values indicate westward integrated flow from the surface down to the bottom. (Data from EUROMARGE - NB).

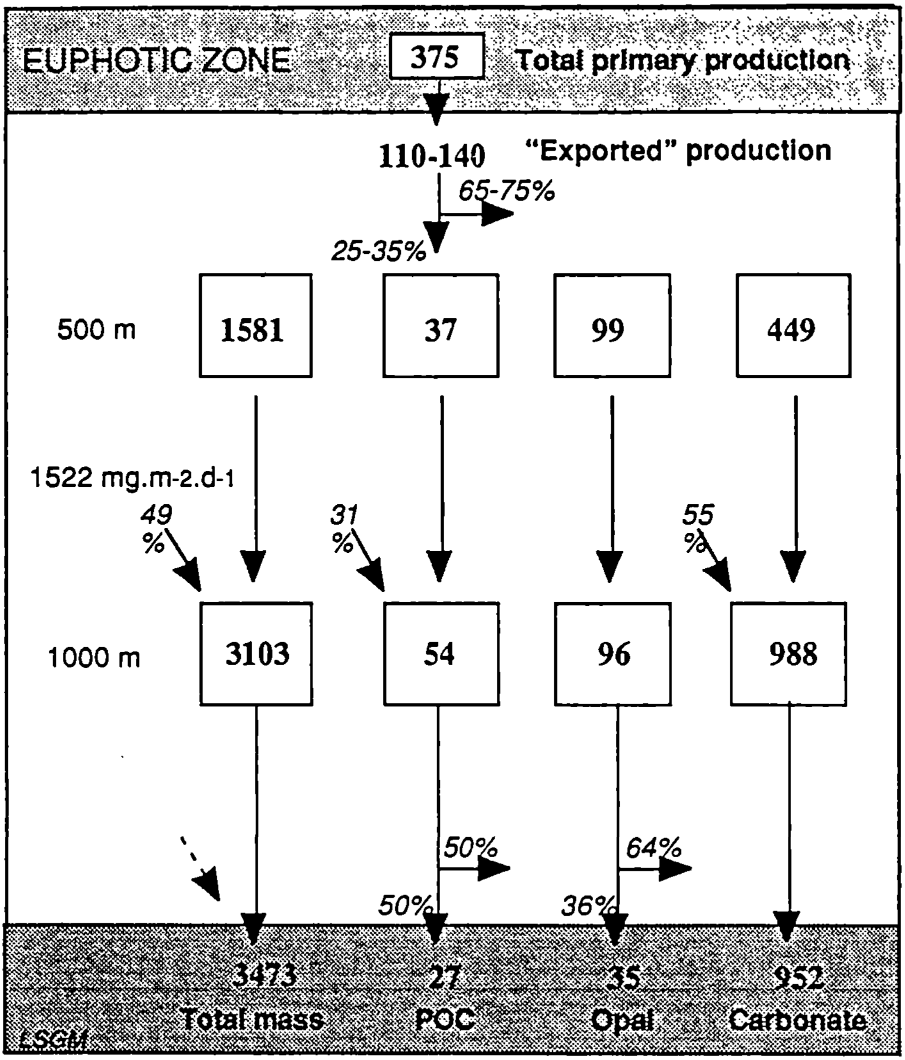

Fig. 3. Budget of total mass fluxes and fluxes of major contituents (POC, opal and carbonate) in the southwestern part of the Gulf of Lions calculated for the period October 93 to October 94. This site can be considered as representative of the Northwestern continental margin. Downward fluxes in the water column were measured by sediment traps at two depths (500 and 1000 m) and are given in mg m^{-2} d^{-1}. Burial fluxes within the sediment were determined from mass accumulation rates determined by $xs^{210}Pb$ and corrected for bioturbation. Arrows represent relative gain and loss between the two traps or between the near-bottom trap and the sediment. (Data from EUROMARGE - NB).

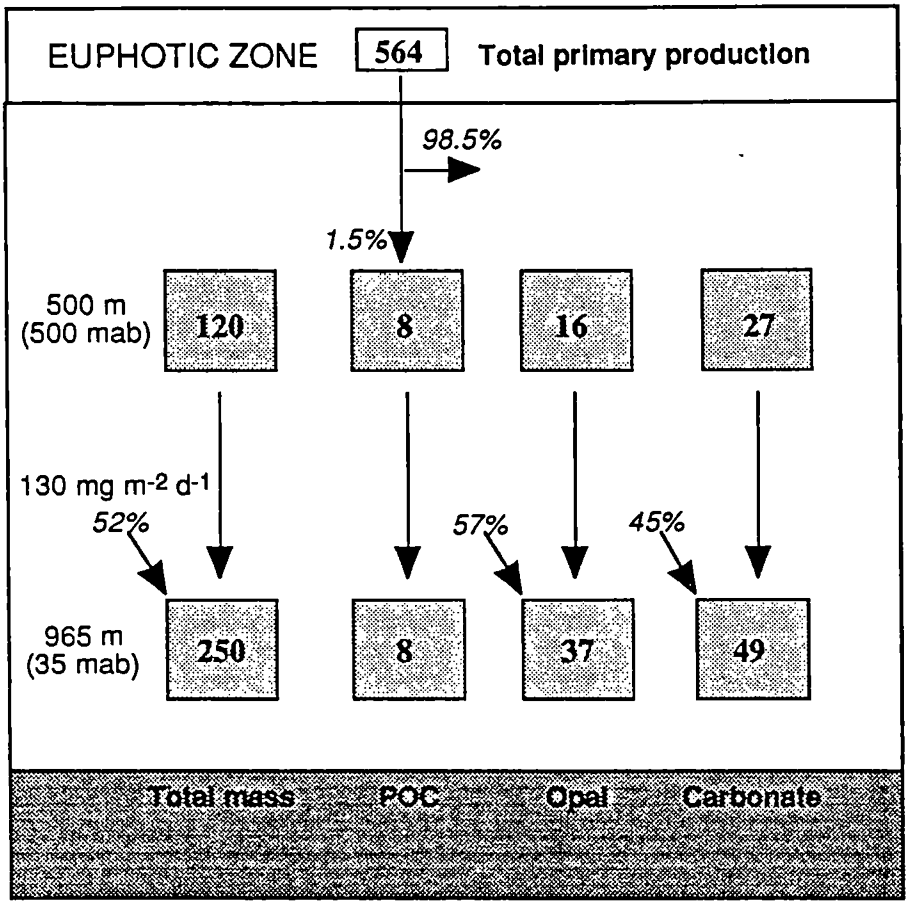

Fig 4. Partial budget of total mass fluxes and fluxes of major contituents (POC, opal and carbonate) in the southern Adriatic basin calculated for the period November 94 to June 95. Downward fluxes in the water column were measured by sediment traps at two depths (500 and 965 m) and are given in mg m^{-2} d^{-1}. Arrows represent relative flux gain between the two traps. Sediment accumulation rates corrected for bioturbation are not yet available and limit the buget calculation to the water column (Data from EUROMARGE - AS).

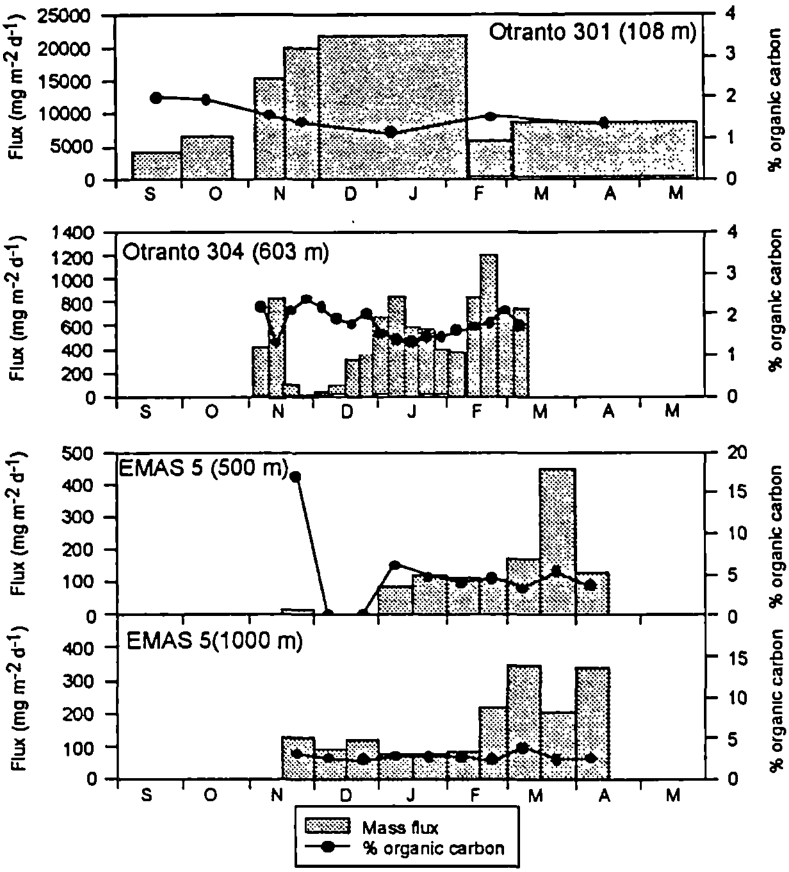

Fig. 5. Total mass fluxes and organic carbon content of settling particles collected by traps in various parts f the south Adriatic Sea. (Data from EUROMARGE - AS and OTRANTO).

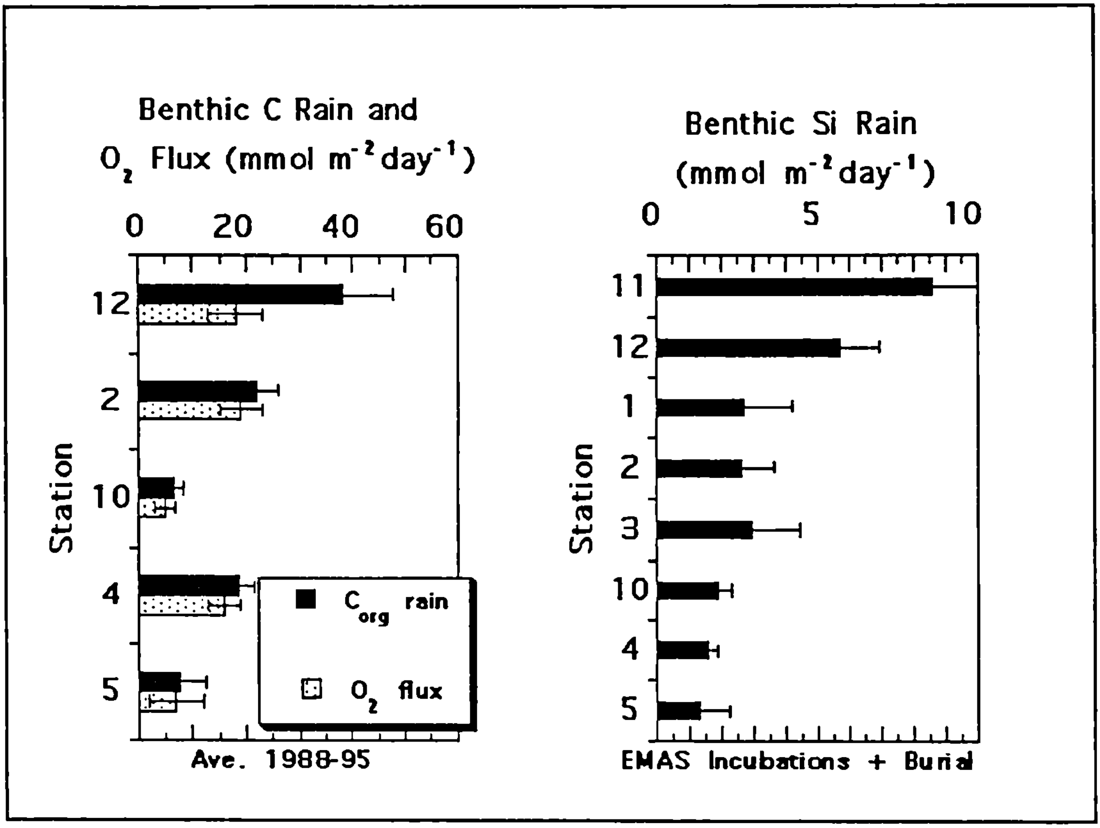

Fig. 6. Patterns of organic carbon rain, benthic oxygen consumption, and biogenic silica rain. Rain has been computed as the sum of benthic flux and burial. (Data from EUROMARGE - AS).

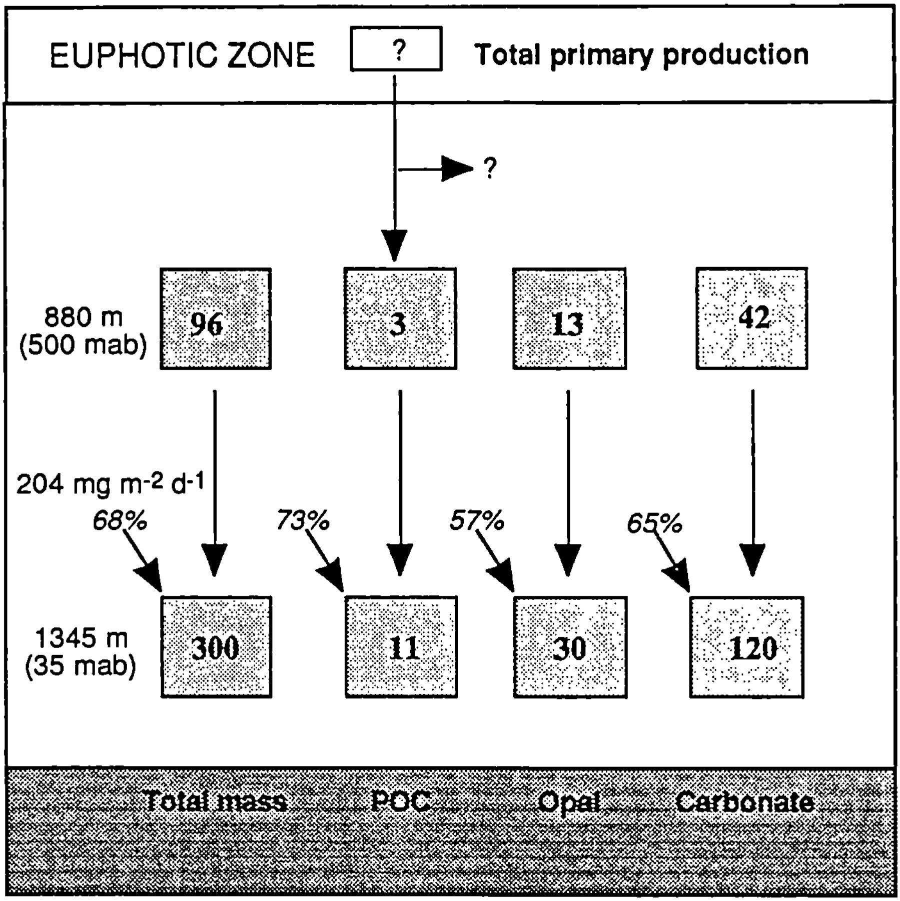

Fig. 7 Partial budget of total mass fluxes and fluxes of major contituents (POC, opal and carbonate) on the Aegean side of the Antikythira Strait, calculated for the period June 94 to June 95. Downward fluxes in the water column were measured by sediment traps at two depths (880 and 1345 m) and are given in mg m^{-2} d^{-1}. Arrows represent relative flux gain between the two traps. Integrated primary production estimates and sediment accumulation rates are not yet available (Data from PELAGOS).

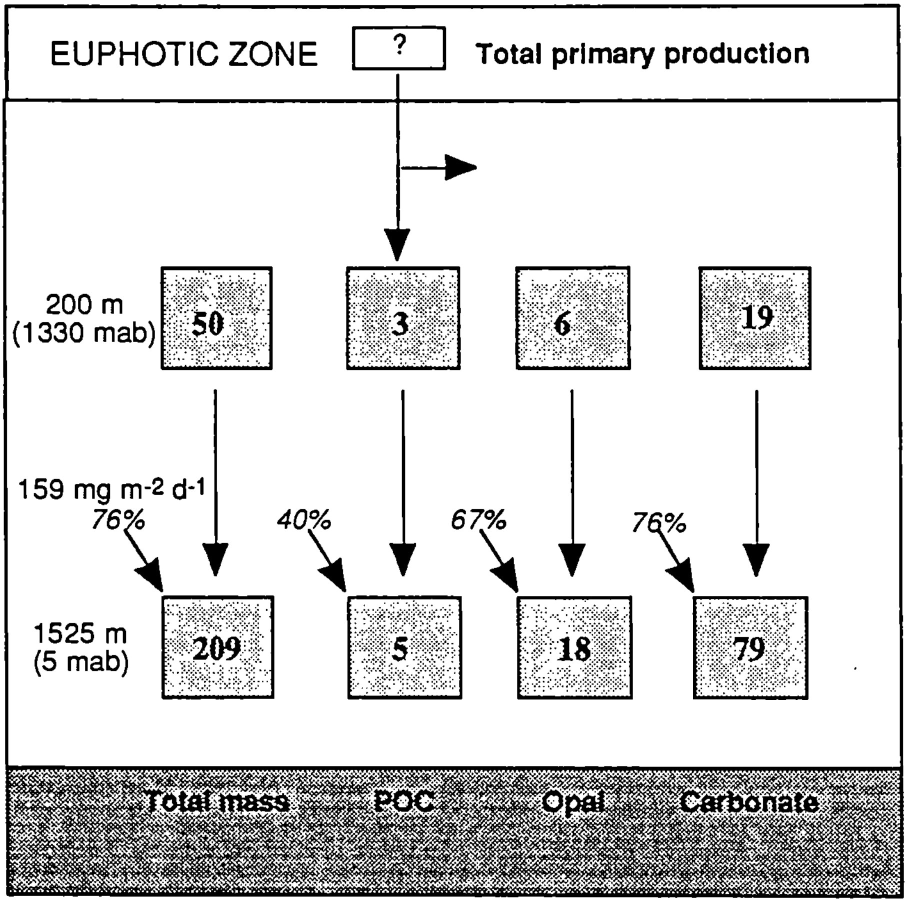

Fig. 8 Partial budget of total mass fluxes and fluxes of major contituents (POC, opal and carbonate) on the northern slope of Crete, calculated for the period November 94 to November 95. Downward fluxes in the water column were measured by sediment traps at two depths (200 and 1525 m) and are given in mg m^{-2} d^{-1}. Arrows represent relative flux gain between the two traps. Integrated primary production estimates and sediment accumulation rates are not yet available (Data from CINCS).

PROVISIONAL ESTIMATES OF DISSOLVED ELEMENT BUDGETS (tonnes yr^{-1})

Time	Total Fe	Total Mn	Total Zn	Total Cu	Total Pb
RIVER PO input budget (annual)					
1994 - 1995	79	76	160	120	4
SHELF					
Transect 2					
July 1994	312	4.07×10^3	436	1.07×10^3	36
Transect 3					
July 1994	222	5.65×10^3	608	1.15×10^3	50
STRAIT OF OTRANTO horizontal transport (annual)					
Nov 1994	--	--	4.52×10^3	3.66×10^3	--

PROVISIONAL ESTIMATE OF PARTICULATE ELEMENT BUDGETS (tonnes/yr)

Time	Total Al	Total Ca	Excess Fe	Excess Mn	Excess Zn	Excess Cu	Excess Pb
RIVER PO input budget (annual)							
1993 - 1995	0.788×10^6	0.738×10^6	9.29×10^4	3.03×10^3	1.88 x 103	269	726
1956 - 1973	1.096 x 106 (1)	--	--	--	--	--	--
SHELF							
1. Transect 2							
July 1994	3.43 x 104	4.49 x 104	4.37 x 103	1.19 x 103	--	--	--
May 1995	5.39 x 104	5.99 x 104	4.55 x 104	401	--	--	--
2. Transect 3							
July 1994	8.12 x 104	1.30 x 105	1.25 x 104	1.85 x 103	--	--	--
May 1995	2.99 x 105	2.93 x 105	1.85 x 104	1.40 x 103	--	--	--
STRAIT OF OTRANTO horizontal transport (annual)							
Aug 1993	0.13 x 106	0.139 x 106	2.05 x 104	2.12 x 103	--	--	--
Nov 1994	0.60 x 106	0.537 x 106	4.80 x 104	7.82 x 103	1.02 x 103	--	--

(1) Dal Cin (1983)

Table 1. Provisional estimates of dissolved and particulate element budgets calculated for the River Po, the Adriatic shelf and the Strait of Otranto. (Data from EUROMARGE - AS and OTRANTO).

Mediterranean Targeted Project (MTP)
Research Theme on Ecosystem Analysis

Synthesis of Results

Mediterranean Targeted Project (MTP)
Research Theme on Ecosystem Analysis

Synthesis of results from the EMPS, EUROMODEL, MEDIPELAGOS and MERMAIDS Projects

COUPLED PHYSICAL-BIOGEOCHEMICAL MODELS

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Summary

The present report summarizes the modeling activities carried out within the framework of the first Mediterranean Targeted Project (MTP) toward the development of coupled physical-ecological models of the marine ecosystem. Models considering separately the physical and biogeochemical components of the ecosystem are described in the first two parts of the report while, in the third part, the results arising from the fully coupled models are presented. In drawing the final conclusions an effort has been done to provide a first answer to some of the scientific questions that motivated the development of the pilot phase of MTP.

Foreword

This synthesis report has been written after two Workshops organized in order to synthetize the work done within the Mediterranean Targeted Project. The two workshops were held in Bologna (May 30 1996) and in Brussels (June 27-28 1996).

Introduction

This synthesis report tries to answer some outstanding scientific questions regarding the overall functioning of the Mediterranean Sea ecosystem and its subparts. They are:

1. What are the major driving mechanisms and what is the nature of the surface, intermediate and deep waters circulation in the overall basin and its major subregions?

2. What is the space-time variability of the flow field and the nature of the interaction between the different time and space scales which compose the basin general circulation?

3. What is the influence of hydrodynamic processes on the nutrient distribution and primary production processes?

4. What are the longitudinal and latitudinal oligotrophic gradients in the overall Mediterranean basin due to?

5. How does the Mediterranean differ from any other oligotrophic open ocean region? And if it does, is it because of a regional food web functioning or because of the net low input of nutrients or the physical forcing of the basin?

6. What are the major nutrient recycling pathways and time scales?

In order to answer these questions, the following methodological approach has been envisaged:

1) to establish coupled physical-biogeochemical models of different complexity levels in order to predict biogeochemical cycles on seasonal or longer, regional or overall basin scales;

2) compare model results with the results of the analysis of historical data and new data collected during MTP;

3) from this comparison, validate and calibrate the models and indicate future research issues.

From the analysis of the MTP projects concerned with physical and ecological models of the Mediterranean Sea it is evident that the last two tasks have only started and much more work is needed in order to calibrate and validate the models. The work during this pilot phase of MTP has concentrated on the identification and implementation of conceptual and numerical models of the major subportions of the ecosystem (physics, biology and chemistry). Models validation is a major task to be pursued in future programs especially if relevant data sets will be collected to accomplish model-data intercomparison.

In the following the results will be described first for the different components of the ecosystem, e.g.the physical, the biogeochemical and the fully coupled models.

Ecological Models

1 Physical Components

The Mediterranean basin seasonal and interannual circulation variability is studied by means of an hierarchy of theoretical, laboratory and numerical models which either try to study a process in isolation or try to simulate the variability of the complex flow field as accurately as possible. This work is in support of the coupled physical ecological models developed and discussed later.

1.1 Theoretical, laboratory and process-oriented models

These models try to study physical processes in isolation, physically restricting the domain of investigation and assuming that the interconnection with the remainder of the oceanic circulation is statistically unimportant or parameterized. In certain circumstances, they reproduce the flow field in a controllable laboratory experiment, simulate the processes in limited areas of the basin or construct a conceptual numerical experiment to prove that a certain process is at work. Normally these experiments are in support of the analysis of General Circulation Models (GCM) behavior. Comparison with observations is mainly qualitative but examples of a more quantitative comparison are shown below.

a. Algerian Current laboratory and numerical modeling (Euromodel)

Instabilities of the Algerian Current can be explained through hydrodynamic stability studies. Reduced gravity models have been shown to provide barotropic instability related to the peculiar horizontal shear of the velocity field. Two-layer shallow water simulations show that barotropic and baroclinic instability mechanisms both destabilize the current. However, the growth rate of the barotropic instability is one order of magnitude smaller than the growth rate of baroclinic instability.

Numerical modeling studies were used to investigate these instabilities. Numerical experiments were performed with both the LODYC[1] and the GHER[2] primitive equation models by using a channel with periodic boundary conditions and a fine grid resolution (2.5 km by 2.5 km). The initial state of the Algerian Current was schematized by a two-layer fluid with low density water at the coast, the interface crossing the sea surface. Both models gave similar results. During the spin-up phase, the classical baroclinic instability is the dominant process and the flow is in very good agreement with the linear model simulation. At larger amplitude, the surface current detaches from the coast and forms a large meander enclosing a coastal anticyclone of about 50 km diameter. The anticyclone moves offshore and splits : the flow appears as a system of two meandering jets, flowing westward near the coast and eastward offshore, both with an enhanced barotropic component. This system is barotropically unstable at wavelengths longer than the most baroclinically unstable wavelength of the initial instability. The barotropic instability generates an eastward mean flow along the coast affecting the whole water column. In most cases, during the reversing of the two-jet

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[1] Laboratoire de Oceanographie dynamique et Climatologie,Universitè de Paris.

[2] GeoHydrodynamics and Environment Research, Universitè de Liege.

system, the surface coastal anticyclones split, creating anticyclones offshore. Analytical stability analysis shows the main role of baroclinic instability of the Algerian Current in determining the characteristics of these eddies.

Laboratory experiments have been conducted on the rotating platform of IMG[3] The Algerian Current is modeled by intrusion of light water over dense water. A coastal current is formed along the wall of the tank. After a while the current may become unstable. The instability starts from small turbulent features that exist along the wall in the boundary layer and grows to form a large quasi-permanent anticyclonic eddy. The main current meanders around the eddy before reaching again the wall. The occurrence and number of instabilities along the wall depend on the Burger number, the ratio of the thickness of the current to its width and the Ekman number.

Comparisons between in situ measurements (CTD casts and current meters) and infrared satellite images taken during the Médiprod-5 experiment show that the above mesoscale features account for most of the observed characteristics of the circulation in the Algerian Basin.

b. Sicily Strait idealized modeling (Euromodel)

The Algerian current splits into two branches at the Sicily Strait: one is flowing into the Eastern Mediterranean through the strait, the other is crossing the Strait and enters the Tyrrhenian Sea

Analytical solutions show that the Strait topography plays a major role in the separation. When the depth of the sill of the strait is shallower than the ocean, double Kelvin waves propagate along the sill discontinuity line and are able to transport energy across the Strait. The shallower the sill, the smaller the transport of the surface current entering the strait at the western corner and the higher the current transmitted across the strait. Sensitivity experiments done with a high resolution primitive equation model confirm this behavior. These considerations explain the separation of the Algerian current into two branches at the Sicily strait level, one entering the Eastern Mediterranean Sea, the other flowing into the Tyrrhenian sea.

c. Alboran Sea Gyre modeling (Euromodel)

The Atlantic Water entering the Mediterranean Sea forms one or two anticyclonic gyres in the Alboran sea. As recently observed on thermal infrared satellite images, they can show vacillations of a period of weeks .The dynamics of the Alboran Sea has been investigated with the LODYC three dimensional primitive equation model. The strait circulation has been initiated by connecting two reservoirs filled with homogeneous waters of different density. The results are in agreement with observations. In the strait, a baroclinic circulation sets up : the light Atlantic Water flows into the Mediterranean Sea in the form of a surface layer while the dense Mediterranean water flows out to the Atlantic Ocean near the bottom. The surface water enters the Alboran Sea in the shape of a shallow and narrow buoyant jet with currents over 1 ms-1. After a three-day spin-up period, the flow transport in the strait reaches a steady realistic value of about 1 Sv. Hydraulic control does not seem to play a fundamental role as the Froude number is smaller than one in the strait. Systematic series of sensitivity experiments have then

[3] Institut de Mecanique, Grenoble

been performed to specify the conditions that control the gyre formation, its space scale and the major characteristics of the inflow and outflow in the strait. The results reveal that the gyre dimensions are very closely related to the density gradient between the two basins and, by a secondary effect, to the presence of the southern coastline in the Alboran Sea. The boundary conditions at the coast as well as a slight inclination towards the North of the strait, although sometimes argued, do not exhibit any relevant role in the gyre formation and in the overshooting of the inflowing jet. Physical experiments have been also performed on a large rotating tank at IMG. Two basins filled with different density waters are connected by a channel schematizing the Strait of Gibraltar. A large anticyclonic gyre develops, as simulated in the numerical model and observed by satellite infrared imagery. The structure of the Atlantic inflow is clearly related to the internal Rossby radius. Variations of climatic conditions modifying the density gradient, and thus changing the internal Rossby radius could explain the evolution of the gyres in the Alboran Sea. The number of gyres depends on the discharge.

d. Parameterization of bottom topography constraints onto the ocean circulation (Euromodel)

Topography constraints onto the ocean circulation is one of the most challenging task in ocean numerical modeling. Research has been conducted at UIB[4] to parameterize topography constraint into large grid scale ocean models by using a formulation derived from the Neptune effect introduced by G. Holloway. The results are very conclusive and lead to a significant improvement of the dynamics of large scale numerical models.

e. Intermediate water formation modeling (Mermaids)

This work, carried out at UAT[5] and UEDIN[6], is concerned with the understanding and simulation of Levantine Intermediate Water (LIW) formation processes which are so important for the overall Mediterranean ecosystem functioning. It is in fact well known that these waters are formed in the far Eastern Levantine basin regions and form the whole basin deep thermocline waters (300-500 meters average depth) which in turn show the minimum of nutrients concentrations. These waters enter the subsequent deep water formation processes occurring in the western Mediterranean areas, which then outflow at Gibraltar and contribute to the export of nutrients from the Mediterranean ecosystem.

The results of this work are synthesized as follows: 1) LIW is formed mainly in the Rhodes Gyre region, from where the newly formed waters spread both eastward and westward due to mean flow and eddy scale transports; 2) the process of LIW formation is triggered by the large heat losses at the surface during late February and march, and the weak stratification of the water column in the cyclonic Rhodes Gyre center; 3) the halting of the deepening of the connective chimney is due to heat inflow from the lateral borders of the formation area and strongly depends on the time scales of forcing with respect to the ocean internal time scale. The abundance of LIW in the Gulf of Lion area is found to be of crucial importance for deep convection to occur. Thus a correct

[4] Universitat des les Illes Balears, Departamento de Fisica.
[5] University of Athens, Department of Applied physics
[6] University of Edinburgh, Department of Meteorology.

modeling of the transport of these waters through the basin is required in order to model the latitudinal and longitudinal water mass structure of the Mediterranean and thus the global nutrient/primary production cycles of the region.

f. Transient tracers and Eastern Mediterranean thermohaline circulation modeling (Mermaids)

Transient tracers such as CFC-12 are useful to check the deep circulation in Ocean General Circulation Models. They give an integrated view of the circulation over a few decades. At the UBFETO[7], CFC-12 simulations were used to test the capability of the MERMAIDS GCM covering the entire Mediterranean to reproduce the thermohaline circulation of the Eastern Mediterranean. The model results have been validated against the data collected by the r/v *Meteor* in 1987 and 1995.

Model fields well corresponding to the observations were obtained and indicated that:

1) The ventilation of the Eastern Mediterranean is carried out mainly by the Adriatic Dense Water that can be identified as a core of water characterized by high CFC concentrations outcropping from the Otranto Channell and flowing into the Deep Ionian as a deep current moving along the western Boundary of the basin.

2)A clear CFC minimum is found at about 1500 m representing the "oldest" waters of the Eastern Mediterranean which ere ventilated only by upwelling of deep waters.

The model velocity field was also used to calculate the transport through selected sections.

The total outflow out of the Strait of Otranto amounts to 0.8 Sv, of which 0.6 Sv flow into the Ionian at depth greater than 1900 m. The deep current flows east and is accompanied by an upwelling of 0.4 Sv in the Ionian Basin and 0.2 Sv in the Levantine Basin. In the layers above 1900 m there is a net flow of 0.4 Sv from the Ionian into the Levantine Basin south of Crete, while 0.6 Sv return north of the island. The transport through the Strait of Sicily is close to 0.8 Sv, which is at the lower bound of values cited in literature

The model deep water formation rate of about 0.6 Sverdrup is about twofold too high. The higher transport rates arise from the fact that the model is not able to produce a boundary current which is confined to the bottom but much of the initially higher input is mixed into mid-depth level in the downflow region CFC concentrations in the Ionian further in the south agree well with the measurements. Despite of discrepancies in detail the basic features of the deep circulation in Eastern Mediterranean are represented reasonably well by the model.

g. Transport of water masses, renewal rates and spreading (Mermaids)

The MERMAIDS model of the Mediterranean Sea has been run at UEDIN for 100 years with monthly varying surface winds, and Haney salt and temperature relaxation at the surface repeated annually. Important circulation features maintained throughout the 100 year integration include:

(i) successful dispersal of LIW from the Levantine formation site via baroclinic eddies.

(ii) LIW entering the Adriatic increasing the density of Adriatic deep waters.

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[7] Universitat Bremen. Fachbereich 1, Trazer-Ozeanographie, Inst fur Umweltphysik

(iii) LIW crossing the Sicily Strait to the Western Basin
(iv) LIW reaching the Gulf of Lions triggering deep water formation each Winter.

Maintenance of the vertical water property structure and basin budget analyses have been carried out for the 100 year simulation. The most interesting results can be found from the role of the eddies in thermocline maintenance. From the model results it appears that:
1) the heat transport into the water formation is dominated by the mean flow, suggesting that the thermocline is maintained essentially by advection. In these water formation sites heat is removed at the surface and the mean flow supplies most of this heat near to the coastal regions while eddies supply most of the heat in open ocean regions.
2) away from the water formation sites the mean and eddy heat transports cancel out quite accurately showing that most locally measured temperature variations reflect adiabatic rearrangements of the water masses.

Ventilation is often found to produce mode waters, rather than produce a uniform distribution of water in density space. In the Mediterranean, characteristics mode waters are the Levantine Intermediate water (LIW) formed in the region of the Rhodes gyre. The characteristics of the LIW formation process have been already summarized; another relevant problem, related to the effect of a mode water on the circulation, is the maintenance of the mode water characteristics properties as it disperses. To face such problem a simple strategy has been developed at ULIV[8] to identify and monitor the formation and dispersal of mode waters within the MERMAIDS Model. By studying the behavior of a passive tracer injected into a specified region for a period of one year, the quantity of water subducted, has been estimated together with the path taken in its subsequent dispersal.

Monitoring the evolution of mode water properties shows that LIW maintains its q-S characteristics well on time scales of a few years, but is subject to strong mixing in the Adriatic. The low potential vorticity associated with the mode water appears to be an extremely robust characteristic, and shows little evolution on a time scale of 10 years.

Oxygen is an important tracer for biogeochemical studies and also for water mass analysis where it is often used as a proxy for the age of ventilated waters. The relationship between the age of water and its oxygen content has been examined using a number of numerical exercises, the results of which are used to convert climatological observations of oxygen into an age field. At 1000 metres and below, the recovered age typically reaches 60-70 years in the Eastern Basin and 30-50 years in the Western Basin.

h. Non hydrostatic modeling of the dense water formation events in the Northern Adriatic Sea (Mermaids)

The process of dense water formation has been studied at DHI[9] using a general non-hydrostatic model system and has formally addressed the following three tasks:
1. Application of a 3D non-hydrostatic baroclinic model to a limited area of the Northern Adriatic Sea. The initial fields have been taken from climatology.
2. Study heat exchange, evaporation and turbulent mixing with respect to estimating the dense water production and dispersal rates in the Northern Adriatic Sea.

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[8] University of Liverpool. Department
[9] Danish Hydraulic Institute, Hoersholm

3. Study the seasonal variability in terms of decay and generation of the mixed layer and the associated thermocline and the time and length scales of convection events

A model of the Northern part of the Adriatic Sea (NAS model) has been prepared during the first year of the project, with a rather coarse grid in the horizontal; but with a high vertical resolution.

Initially the NAS model was run with different cooling conditions for a 16 weeks long period, starting in December. Simulations with climatological forcing data and synthetic strong intense cooling of one week duration showed the generation of denser water in the northern part, which gradually starts to adjust to gravity and Coriolis confirming the existence of denser water below fresh water along the Italian coast. Next the model was forced with both water fluxes and cooling, on a monthly basis and spatially varying, using May's data. The simulation period was extended to cover the period from December to the end of June. These simulations clearly show a production of dense water in the Northern part, but also in the Middle Adriatic.

The rates of formation determined in the numerical simulations were found to range from one tenth to the same order of magnitude as reported in literature,

An attempt was also made to apply ECMWF forcing data for a specific period of Dec 92 - Jul 93. The results differed strongly from the ones obtained with climatological data,

One important observation, was that fluctuations in the meteorological forcing cause fluctuations in the dense water flow.

i.Wind driven adjustment processes in the Mediterranean (Mermaids)

The Tyrrhenian Sea area was chosen at IUN[10] as the main test site to carry out the model process studies with a shallow water model forced by realistic winds.

The main features of the wind-driven climatological Tyrrhenian circulation known from data and general circulation modeling are found to be reproduced by this process model. The Winter cyclonic circulation induced by the strong positive wind vorticity input evolves into a much weaker, partially reversed circulation in Summer months. A mainly northward flux through the strait of Corsica and a horizontally sheared current in the strait of Sicily are found.

The rapid fluctuations that the wind is able to induce in the ocean have been studied using a daily wind stress forcing The instantaneous currents are found to be up to 10 times larger than the corresponding climatological ones, with episodes of reversal over a period of few days.. The daily variability is found to be energetically an important part of the global wind-driven circulation with a distinctive seasonal statistics.

[10] Istituto Universitario navale, Università di Napoli.

1.2 General circulation models

In this section we describe the scientific results of investigations which used complex hydrodynamical simulation models to reproduce the current and density fields in order to compare with observations. These models are concerned with theair-sea interaction and its parameterization, external forcing through the Gibraltar Strait and other open boundaries of the regional domain. They differ from the previous models since they try to take into account all the physical processes occurring in the water column.

a. Global Mediterranean modeling (Mermaids)

The MERMAIDS General Circulation Model has been implemented and distributed by IMGA[11] with different horizontal and vertical resolutions and forced by different frequency atmospheric parameters. The model has been studied for its ability to reproduce known features of the general circulation and its seasonal characteristics. The results indicate an important variability of the circulation at the seasonal scales mainly induced by the changes in wind stress between winter and summer and the rate of deep water formation during the winter in the Levantine basin and the Gulf of Lion areas. The model physics (mainly the viscosity, diffusion and air-sea interaction parameterizations) have been studied in order to select a set of optimal parameters for the simulation experiments with realistic forcing.
The most important discovery is related to the demonstration of the interannual variability of the basin circulation as induced by interannual changes of the atmospheric momentum and heat fluxes (fig.1). Salt fluxes have not been considered yet due to the inaccuracy of precipitation data at interannual time scales. The results indicate that major parts of the structural changes of the basin circulation is due to the changes in wind stresses and heat fluxes over major portions of the Mediterranean Sea. Furthermore, it is found that wintertime atmospheric anomalies can induce changes which persists for over a season. This in turn implies that the predictability time scales of the system is locked to the seasonal cycle and that ocean predictability is largely connected to the atmospheric disturbances. Internal or mesoscale interannual variability is supposed also to be large but high resolution GCM experiments have not been yet carried out for extended periods of time.
The non-eddy resolving GCM results indicate that barotropic velocity components are important in the Sicily Strait region if volume transports could be connected to observations and that wind forcing is also important in boundary current regions such as the Algerian current.

b. Western Mediterranean modeling (Euromodel)

A series of sensitivity numerical experiments with a high resolution 3D primitive equation model was carried out at LODYC to understand the role of the different forcing in driving the circulation of the Mediterranean. A first experiment run with the density forcing at the Strait of Gibraltar and Sicily show that the strait forcing contribute in generating a realistic cyclonic surface and intermediate circulation in the

[11] Istituto per lo Studio delle Metodologie Geofisico Ambientali, Consiglio Nazionale delle Ricerche, Modena.

Western Mediterranean Sea basin. The transport of the Liguro-Provençal-Catalan Current reaches up to 50% of its actual value. We then investigated the influence of sea surface thermohaline fluxes and wind stress. A 25 year experiment was forced with the daily output of the fine grid mesh numerical weather prediction model PERIDOT. The major characteristics (fig.2) of the surface circulation are well reproduced. The main surface circulation is cyclonic all around the basin. The two anticyclonic Alboran gyres are present. The instabilities of the Algerian current generate large anticyclonic eddies which invade the whole Algerian basin. The Liguro-Provençal-Catalan current is well marked. However, deep water convection down to the bottom only occurs during the first 3 years, then Winter Intermediate Water is produced. The north-south gradient of the atmospheric thermohaline fluxes induces a northward surface transport of water from the Algerian basin into the LiguroProvençal basin. This pattern can be associated with the Balearic front. Furthermore by running dedicated experiments it was shown that the wind stress curl reinforces the cyclonic circulation of the Liguro-Provençal basin through a Sverdrup balance mechanism and contributes to the deep water formation. It is suggested that the variations of the transport in the Corsican channel are linked to the wind stress action rather than to heat flux gradient.

c. Adriatic Sea modeling (Mermaids)

A high resolution Adriatic Sea GCM has been implemented at IMGA in the Adriatic Sea in order to study the seasonal variability of the circulation and the dynamics of the western Adriatic Coastal Current system (WACC). The model is based upon the Princeton Ocean Model (POM) adapted to the Adriatic Sea with variable horizontal resolution (from 3 to 10 km) and a curvilinear grid. Open boundary conditions are imposed at the boundary of the domain located in the middle of the Northern Ionian Sea and the fields are taken from the integration of the MERMAIDS GCM in the overall Mediterranean area.
The most important results concern the study of the dynamics of the Adriatic Sea with respect to the three major driving forces: wind, heat and water fluxes. It is found that thermal and momentum fluxes are capable of producing the correct deep water masses at the end of winter and that the Italian river run-off (especially the Po river) is a major driving force for the formation of the WACC which in turn is part of the general circulation structures. The novel results are thus concerned with the understanding of processes which involve salinity-temperature compensation effects in the coastal areas of the western Adriatic during winter which allow the development of a southward Adriatic coastal current.

d. Aegean Sea modeling (Mermaids)

The Princeton Ocean Model has been implemented at UAT in the whole Aegean Sea The experiments carried out with a perpetual year surface forcing show that the North Aegean general circulation is dominated by an intense eddy-field.

From an energetic point of view, the volume integrated kinetic energy in the southern Aegean is almost twice that of the Northern Aegean. This probably reflects the fact that the Southern Aegean circulation is part of the general circulation of the Eastern Mediterranean, while the northern Aegean (mainly because of the Cyclades island barrier) is more isolated and 'local' circulation dominates.

The low salinity Black Sea waters flow along the Northern Greek coastline in a cyclonic way throughout the year, then move to the south towards the western straits of Crete.

According to the model results, no open sea deep convection seems to occur in the Northern Aegean. Instead, the deep waters that fill the North Aegean trough are formed in the shallow shelf area during February (when the highest values of surface densities are observed) and then sink to the deepest part of the trough.

The dense waters formed in the shelf flow towards the Southern Aegean over sills and depressions and mix with upper warmer and saltier water masses. In this way, their density decreases as they move southwards. In the Cyclades plateau their density is near 29.3 and seems to contribute to the deep Cretan waters.

The interannual variability of the Aegean Sea was addressed through a number of numerical experiments where the model is forced by the 12-hour NMC atmospheric data for the years 1980-1984. The main characteristics of the Aegean Sea general circulation that were described in the climatological experiment are also present in these five year of the interannual forcing. The most significant change compared to the climatic experiment is the intensification of the Asia Minor Current during Winter, especially in the cold Winters of 1980 and 1981 (fig. 37). The signal of this current is clearly present up to the North Aegean, where it contributes to a more well formed cyclonic circulation in comparison with the perpetual year forcing. The seasonal reversal of the flow in the Cretan Sea is observed in all the five years of integration.

e. Gulf of Lion high resolution nested modeling (Euromodel)

The dynamics of the Gulf of Lion was investigated with a high resolution (2.5 km*2.5 km, 25 levels) numerical model at LODYC. The model was forced by the wind and the thermohaline surface fluxes of the PERIDOT model and the basin circulation obtained from the fine resolution basin scale model of the Western Mediterranean Sea. The two models were coupled by using a nested technique which allows them to interact together. Attention was focused on coastal dynamics variability, the upwellings, the interactions between the shelf and the deep ocean.

2 Biogeochemical components

The work here is concerned with the understanding and the modeling of the trophic food chain and its relationship with the physical components of the ecosystem in order to explain the biogeochemical cycling of C, N, and P in the Mediterranean. Conceptual and numerical models have been developed and adapted to the Mediterranean Sea conditions and a dialogue has been established between ecosystem modellers and ecological process modellers in order to improve the mathematical description of the European Regional Seas Ecosystem Model (ERSEM) established previously in the North Sea. Furthermore, new aggregated models have been formulated for the overall basin and different subportions.

2.1 Theoretical, laboratory and process-oriented models

a. Conceptual process modeling of the nutrient cycling (Medipelagos)

The work has been concentrated at SZV[12] on the improvement of simple conceptual models for the description of the cycling of C, N and P in the photic zone. The major results can be summarized as follows (see fig.3): 1) the phytoplankton and heterotrophic bacteria in the Mediterranean are P-limited ; 2) high surface concentrations of DOC and DOP rapidly decay with depth; 3) bacterial degradation of DOC (dissolved organic carbon) is limited due to a combination of P-limitation and predatory control and 4) organisms in small size fractions dominate the regeneration of P in the water column. These observations all fit together in a scenario where the food web in the photic zone transforms imported PO_4 into DOP (dissolved organic compounds) which is not utilized by the biology. These aspects of the P-limited food web can be synthesized into a "microbial food web" as opposed to a "classical food web".

b. Microbial populations modeling (Emps)

EMPS is essentially concerned with the nature and role of the microbial populations involved in the degradative system of the marine water-column. Work has centered on the north-west Mediterranean and has been carried out at PML[13]. In line with the objectives of the project as a whole, the aim of the modeling component is to help elucidate the processes involved, rather than to produce a "complete ecosystem model" for a particular body of water. In this spirit, some steady-state analyses of a simple 1D (vertical) advection-dispersion model for microbial activity has been carried out.

Dynamic modeling is being undertaken within the modeling shell ECoS. This shell allows relatively rapid interactive modeling of discrete (biogeochemical) transfer systems within a 1 or 2D spatial framework which may be layered or branched. The dynamic modeling is again based on a 1D advection-dispersion representation (0-1000m) with a non-physical parameterization of vertical dispersion allowing simple

[12] Station Zoologique, Villefranche sur Mer.
[13] Plymouth Marine Laboratory, National Environment Research Council.

control of thermocline depth, thickness and strength. The model incorporates nutrient-limited (now N, in the future P), self-shading, primary production as a source of POC and a dynamic-heuristic representation of particle size determination (which it is hoped to relate to measured rates of POC-COC-DOC transfer). Currently degradation of organic carbon and organic nitrogen is parameterized, but the immediate objective is to incorporate direct representations of microbial populations in order to look at the extent to which these processes are dynamically limited (by patch colonization and population growth).

An exploratory model of the chemical and biological feedback involved in the formation of marine particulates, and their role in nutrient regeneration is also being developed. This complements the heuristic approach to particle dynamics indicated above with a more mechanistic representation of potential chemical, biological and physical mechanisms.

2.2 Simulation models of the marine ecosystem

a. ERSEM (Mermaids)

The European Regional Seas Ecosystem Model (ERSEM) has been developed in the past five years for the North Sea and it has now been exported to the Mediterranean Sea to study primary production in the Adriatic basin.

The model (fig. 4) consist of time dependent evolution equations for few functional groups ("phytoplankton", "zooplankton", "nutrients") pelagic and benthic submodels. The interaction with the physical environment is time dependent and depends on parameters such as light extinction in the water column, water temperature structure, vertical and horizontal mixing and diffusion and vertical/horizontal advection by water flows. The biochemical interactions between all the functional groups are described with numerous parameters chosen on the basis of empirical evidence or extrapolation to the region of interest.

The model has been applied in different approximations to the Adriatic Sea and results are discussed in the coupled models section. Adaptation of the food web parameters to the Mediterranean Sea has been minimal as of today but in the future we believe we should consider the modifications suggested by the observational and theoretical studies discussed in other parts of this report.

3 Coupled physical-biogeochemical components

Here we illustrate the coupled physical-biochemical models implemented and analyzed in the MTP. Progresses have been very rapid and results illustrate already the basic mechanism of forcing of the physical components of the pelagic biogeochemical cycles.

The work carried out has shown the possibility of coupling both aggregated and complex biogeochemical representations of the marine ecosystem with fully three dimensional hydrodynamical models.

One of the major unresolved problems at this stage is the validation/calibration of the ecosystem models against observational data.

3.1 Global Mediterranean Nitrogen cycles modeling (Mermaids)

The effect of the general circulation on the first trophic levels in the Mediterranean Sea has been studied trough the development of a three-dimensional hydrodynamical - ecosystem model developed at OGS[14]. The three-dimensional formulation is needed in order to appraise the influence on the nutrients dynamics of horizontal transport, of upwelling/downwelling processes and of vertical mixing on the nutrient distribution and cycling and possibly on phytoplankton dynamics at seasonal scales. The biogeochemical model is extremely aggregated , formed by three equations representing changes in dissolved inorganic nitrogen (DIN), phytoplankton and detritus.

The general oligotrophic regime of the Mediterranean Sea is induced by the inverse estuarine circulation and is typically modulated by subbasin permanent and recurrent features such as gyres and fronts that affect the spatial distribution and the seasonal variability of the primary production. Below the productive zone, the cyclonic areas increase the nutrient concentrations in the center of the gyres.

Furthermore the nutrient signal of coastal upwellings in the Ionian and Sicilian channel suggested a careful consideration of coastal margin - open ocean exchanges as, in a oligotrophic basin, even small but persistent nutrient advection can create significative patterns.

The model distribution of the nutrients exhibits a pronounced east-west gradient induced by the different physical and physically driven processes in the two basins. The longitudinal gradients are also evident in the phytoplankton distribution (Fig. 5) where the different light penetration depths are a major controlling mechanism.

More complex is the case of the north-south gradient which is clearly present in the Eastern Mediterranean where the dipole constituted by the Rhodes Gyre and the anticyclonic area traditionally connected with the Marsa Matruh anticyclone determines an evident unbalance of the nutrients distributions. In the Western Mediterranean the north-south trend is not present, possibly because the highly energetic upwellings along the Spanish coast mask the gradient present in the Algero-Provençal Basin. Surely the absence of the deep water formation in the Gulf of Lions (which cannot be obtained using perpetual year monthly forcing) prevents the energetic input of nutrients during the Winter period and this lack reduces the new primary production in the Gulf of Lions.

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[14] Osservatorio Geofisico Sperimentale, Trieste.

A numerical experiment was performed with a spatially constant light model, to analyze the response. The maxima in DIN concentration at 120-200m depth layer, where no primary production is present, are correlated with the cyclonic areas in the open sea, while coastal effects such as upwellings and boundary currents are the major system of import of nutrients into areas such as the Spanish coast of the Alboran Sea, the Sicily and Calabria coasts, and the Algerian current. On the contrary, the effect of the anticyclonic areas on the DIN distribution is less evident in the upper layer because the Ekman pumping in an anticyclonic vortex deepens the nutrient depleted layer, advecting water laterally in the upper layer.

In tab. 1 are reported the total nitrate budgets in the Gibraltar and Sicily straits after the first year of simulation. All the numerical experiments were obtained with the same physical submodel. These results are compared with some estimates obtained in terms of water fluxes and using the nitrate mean concentrations in the inflow and outflow water masses.

Nitrate concentrations	Water fluxes	Gibraltar	Sicily
Coste, 1988	Lacombe, 1971	-2.17	-
Coste, 1988; 1971	Bethoux, 1979	-3.11	-1.57
Coste 1988	Bryden et al., 1988	-1.57	-
Coste 1988; 1971	Sarmiento et al., 1988	-1.25	-0.91
Coste 1988; 1971	Harzallah et al., 1993	-1.41	-0.85
b8	PE4L31	-1.73	-0.51
b9	PE4L31	-1.78	-0.63
b10	PE4L31	-2.74	-1.85
b14	PE4L31	-2.50	-1.70

Table 1: Annual nitrate budget estimations in the Gibraltar and Sicily straits (tons/year). The model results are evaluated after the first year of simulation.

The model results are within the budget estimate ranges obtained by different authors. The lowest results were obtained using no sinking rate for detritus (run b8).This is due to the fact that in this run no organic matter vertical flux was introduced enriching deep waters.

An increased loss at the strait is obtained, considering a sinking rate of 1 m/day (run b9).

This result is magnified by a further increase in the sinking rate and regeneration time (run b10) suggesting that this could be a good choice for calibration of the overall model. Also the introduction of a variable penetration light coefficient diminishes the exchanges and this is due to lower biological activity in particular in the western part of the basin.

The striking difference between Eastern and Western Mediterranean can be explained in terms of several factors that can be summarized in table 2.

Process	Western Mediterranean	Eastern Mediterranean
Deep water formation Mesoscale activity Residence time	within the basin strong O[10y]	mostly outside the basin fair O[100y]
Phytoplankton composition First optical length Biochemical exchanges	micro + pico and nanoplankton 15m Atlantic	mostly pico and nanoplankton 30m marginal seas

Table 2: Western and Eastern Mediterranean Characteristics.

In this table all the hydrodynamical processes characterizing the eastern subbasin can induce directly or indirectly an oligotrophic situation: the absence of connective mixing due to deep water formation outside the basin, the reduced influence of the wind driven coastal upwellings and the exchanges with other basins are favorable conditions for a reduced import of nutrient in the euphotic zone.

In particular this is true during the Winter situation, which is known to be the period in which an accumulation of the 'biochemical currency" occur in the productive zone

The ecosystem response to the oligotrophy is typically modification of the food web, switching from a classical to a microbial loop trophic path. The smallest fractions phytoplankton are known to adapt better to these situation.

The nutricline erosion by primary producers grows with depth creating a deep nutrient-depleted layer where only regenerated production is present and turbulent entrainment is difficult not only during Summer, when stratification decouples the mixed layer from the biomass maximum, but also in Winter. For this reason, the early bloom in Winter in Western Mediterranean can be essentially connected to the shallower nutricline and more energetic wind forcing that allow a ubiquitous increase of the chlorophyll concentration even in the surface layer.

In contrast, the Eastern Mediterranean has still a deep nutricline in Januarythat can be affected only when dense water formation and convection processes take place, typically at the end of the Winter season.

3.2 1-D model of the Adriatic Sea ecosystem(Mermaids)

. In this study the European Regional Seas Ecosystem Model (ERSEM) has been coupled to a 1-D vertically resolved water column model at PML and applied to different parts of the Adriatic Sea in order to simulate the seasonal cycles of the lower trophic levels, nutrients and oxygen.

The study areas chosen for the model are selected sites representative of the Northern, Central and Southern Adriatic Sea.

The modeled seasonal cycles of chlorophyll, oxygen and nutrients show both some striking similarities and differences between the regions. At all three sites the seasonal cycles is marked by two distinct regimes: a well mixed period during the Winter when the water is relatively cold and strong vertical mixing takes place and the stratified Summer period when vertical mixing is weak. During the stratified period the stability of the water column is maintained by both heating and relatively low salinity water at the sea surface. The stratification breaks down in the Autumn due to the increase in wind strength at this time.

Modeled phytoplankton grows near the surface during the Autumn and Winter when the water column is well mixed. After the onset of stratification in the early Spring a sub surface chlorophyll maxima (SCM) forms which persists throughout the Summer and is broken down in the Autumn by seasonal mixing events. The depth of the SCM is primarily defined by the clarity of the water column and hence the depth of the euphotic zone rather than the thermocline depth.

A number of observed regional trends which illustrate the ecological gradients across the Adriatic Basin are reproduced by the model. In the north the ecosystem is potentially eutrophic and is characterized by periodic anoxic events in the late Summer and the total collapse of the benthic fauna population. The seasonal cycle of oxygen simulated at the northern site shows significant oxygen depletion in the near bed layers in the late Summer and Autumn. Benthic community collapse after extreme oxygen depletion has been successfully simulated by forcing the model with high nutrient inputs. The modeled middle and southern Basins are oligotrophic as is indicated by observations. As a consequence of this there is a significant change in the ecosystem behavior from north to south. The phytoplankton community of the modeled northern Basin with its high land derived nutrient inputs is dominated by diatoms. In the south they are flagellate/picoplankton dominated with relatively small diatom biomass.

The benthic pelagic coupling plays a significant role in the recycling of nutrients at the northern site. At this site the seabed is very close to the euphotic zone and so provides a major pathway for the recycling of nutrients providing 50% of the phosphate and 32% of the nitrogen required to meet phytoplankton demand. The remainder is recycled via pelagic heterotrophic organisms. As the water column deepens and the distance of the benthos from the euphotic zone increases the flux of nutrients into the water column decreases, as is illustrated in table 3. In the middle and southern Basin model phytoplankton nutrient demand is primarily met via heterotrophic recycling mechanisms.

Site	Depth	Nitrogen	Phosphate
North	30m	1203.85	92.50
Middle	150m	67.89	7.82
South	1000m	39.11	1.63

Table 3.:Flux of nutrients from the seabed mmol/m2/yr.

The regional variations in ecosystem behavior are a consequence of the decreasing influence of land derived nutrient inputs from north to south, the deepening of the nutricline as the water column deepens and water clarity increases, and the decreasing influence of the benthic system from north to south.

3.4 3-D model of the Adriatic Sea ecosystem (Mermaids)

Among the various Mediterranean regional seas the Adriatic Sea appears as a particular interesting area where to study the issues related to the role played by physical processes on the ecosystem dynamics. In fact, the morphology of the Adriatic Sea bathymetry, with its shallow northern shelf and its deep southern subbasin provides a coastal (shelf) ecosystem closely related with an open sea ecosystem; the general circulation is extremely interesting and shows features characterized by different temporal and spatial scales and by a strong seasonal (and probably interannual) variability. Finally the intense river discharge occurring in the basin and the pronounced anthropic impact make it a very interesting place for the study of the issues related to the land-ocean interactions in the coastal zone. Modellingwise, such characteristics make the Adriatic Sea a particularly interesting area where to test the skill of a coupled ecological model in reproducing correctly the relationships between the physical and the ecological processes.

The coupled model implemented for this modeling exercise by IMGA and EMC[15] is constituted by the Princeton Ocean Model, POM, and by the European Regional Seas Ecosystem Model, ERSEM.

In order to test the coupling procedure and to begin to investigate into the Adriatic Sea ecosystem dynamics an "idealized" Adriatic Basin has been set up. It is constituted by a rectangular basin (without open boundaries) having approximately the same size and the same geographical location of the "real" Adriatic. The bottom geometry is constituted by a sloping bottom with a minimum depth of 50 m in the north and a maximum depth of 500 m in the south. The model domain is covered by a coarse grid having an horizontal resolution of about 25 km. In the vertical the model has 10 sigma layers.

Such idealized model domain has-been forced with realistic data of wind stress, heat flux and river runoff pertinent to the Adriatic Sea, in order to focus on the role played by the physical environment in determining (from a qualitative point of view) some of the known biogeochemical characteristics of the Adriatic Sea. From this point of view the experiment carried out have been successful, as the model results have shown that the use of a "realistic" forcing in the framework of an idealized setup is able to reproduce an ecosystem dynamics which is in qualitative agreement with the characteristics of the Adriatic Sea.

For instance the model results give clear evidence of the formation and maintenance of a north-south trophic gradient with the northern (affected by riverborne nutrient inputs) part of the basin being the more productive while the southern part of the basin show more oligotrophic conditions.

The physical forcing on the ecosystem state variables is also able to reproduce some characteristics of the spatial distribution of phytoplankton typical of the Adriatic Sea, such as the southward transport of biomass along the western coast of the basin due to the development of a coastal current (fig.6).

Also the relation between the water column vertical structure and the distribution of biogeochemical properties is well represented by the model. During the Summer season, a subsurface phytoplankton maximum is developed, approximately located at the same depth of the thermocline, which characterize the water column until late Autumn when the vertical mixing processes homogenize again the water column.

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[15] Ecological Modelling Center Hoersholm.

Conclusions and future outlook

The work synthesized previously give us the possibility, at least partially, of answering at the scientific questions posed in the introduction:

Answer to question 1.

What are the major driving mechanisms and what is the nature of the surface, intermediate and deep waters circulation in the overall basin and its major subregions?

The modeling results show the importance of all the external driving forces on the structure of the general circulation (wind, heat fluxes Gibraltar Strait inflow). The character of the general circulation is imparted to the basin by both wind stress curl and Gibraltar Strait inflow, manifesting itself through the general cyclonic character of the circulation during winter. In the southern parts of the basin (Algerian current region, southern flank of the Atlantic-Ionian Stream in the Eastern basin) the tendency to develop anticyclonic motion can be reinforced by wind and heat fluxes anomalies.
The structure of the simulated surface, intermediate and deep water circulation has been found to be generally consistent with the observations even though model development is still required in order to reproduce processes such as water outflow from Straits, water mass formation and realistic dispersal characteristics. The deep circulation of the Eastern Mediterranean has changed dramatically in the past five to eight years due to the intrusion of deep Aegean waters in the abyssal circulation of the Eastern Mediterranean. Modeling is required to evaluate the importance of this climatic event in the overall structure of the basin water masses and currents.

Answer to question 2.

What is the space-time variability of the flow field and the nature of the interaction between the different time and space scales which compose the basin general circulation?

The variability of the Mediterranean Sea general circulation is connected with the structural changes in strength and shape and recurrence of subbasin scale gyres. This variability has maximum amplitude in the Western basin at seasonal time scales while in the Eastern basin is at interannual time scales. The atmospheric forcing winter anomalies seems to be a controlling factor in determining the largest structural changes in the circulation patterns. The interannual variability is then locked to the seasonal cycle and interaction between these two scales requires further studies. The space scales of the interannual fluctuations could be also partially composed of the mesoscale variability which is an energetic part of the flow field in the Aegean and Levantine regions.

Answer to question 3

What is the influence of hydrodynamic processes on nutrient distribution and primary production processes?

At the basin scale, the nutrient distributions are determined by gyres and coastal upwellings. The latter affects through horizontal advection and diffusion the nutrient distribution in the open ocean neighboring areas. The deep convective vertical mixing determines the vertical transport of substances in the upper layer during Winter and differences between the Eastern and Western Mediterranean oligotrophic conditions can be explained by invoking differences in the presence of such events in the two basins. These findings need to be confirmed in the future by comparisons with observations and with more refined aggregated biochemical models of the pelagic food web, and by developing new models incorporating the new concepts emerging from the experimental studies carried out within MTP-I.

Answer to question 4

What are the longitudinal and latitudinal oligotrophic gradients in the overall Mediterranean basin due to?

The "apparent" oligotrqphic character of the Mediterranean open sea regions seems to be connected to Phosphorus limitation for the phytoplankton and bacteria components of the food chain and to specific size distribution of phytoplankton.

The major oligotrophic gradients in the zonal and meridional directions are also related to the open ocean upwelling/downwelling structure of the wind driven general circulation of the basin. It is speculated that, due to the downwelling character of the circulation in the southern parts of the basin, river input changes could affect more the southern than the northern Mediterranean areas. In region of deep water formation, intense phytoplankton blooms can occur in Winter due to the strong upwelling areas along the borders of newly formed patches of deep water.

These model results are detailed enough to contribute to the design of new experimental approaches.

Answer to question 5

Does the Mediterranean differ from other oligotrophic open ocean region? And, if so, how?

In contrast to the open ocean recycling systems, where Nitrogen is a limiting nutrient for primary production, the Mediterranean seems to be Phosphorus limited. Since the N:P ratio is above the Redfield ratio value in the Mediterranean, neither peculiar redistribution processes within the water column (physical forcing) nor human induced changes in riverine inputs are thought to be responsible for such high ratio. The reason for this seems to be instead the development of a microbial food web during summer months and in the photic zone which transforms imported orthophosphate into DOP which is not biodegradable. The abundance of small phytoplankton organisms over large diatom populations could be responsible for the development of this particular food web.

Detailed representations of the microbial loop processes involved in nutrients recycling developed as theoretical models during MTP-I and from *in situ* experiments, should be implemented in coupled physical and ecological models in order to quantify the cycling of the micro nutrients on a basin scale and establish the contribution of the microbial loop processes to the total biogeochemical fluxes.

Answer to question 6

What are the major nutrient recycling pathways and time scales?

The Phosphorus limitation in the system is established by the following marine food web: 1) phytoplankton and bacteria growth is limited by Phosphorus availability; 2) high production of DOC and DOP in surface waters occur which is subducted during wintertime and it is degraded in the deep waters; 3) restricted bacterial degradation of DOC due to P-limitation itself and predation by microzooplankton (and viral?). This theory needs further experimental confirmation in wider and more open ocean Mediterranean areas. This system is an efficient transporter of C from the atmosphere to the deep ocean (through DOC/DOP instead of POC/POP) and its fundamental development time scale is the season.

The scientific questions emerging from this initial analysis are:

1) Why the Mediterranean Sea is Phosphorus limited?

2) How generic are the elements of the numerical ecosystem models set up and how can we calibrate them?

3) What is the predictability time scale of the Mediterranean Sea ecosystem?

In order to answer these questions there is a basic need of "new" data that should be collected on the basis of the evidences obtained by both experimental and numerical studies.

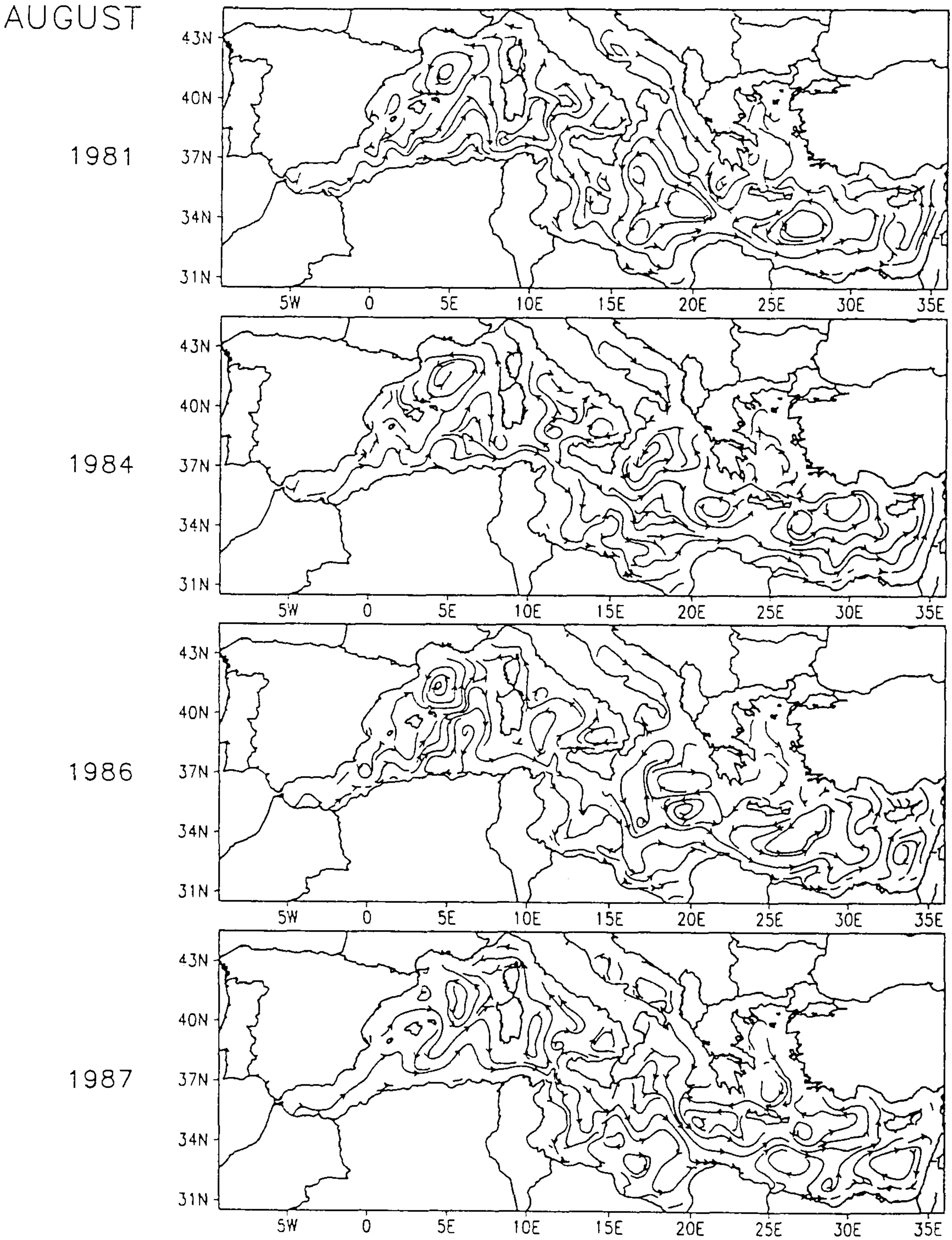


Fig.1: Mediterranean Sea model (Mermaids): Interannual variations of the circulation patterns. From: Pinardi N., Korres G., Lascaratos A., Roussenov V., Stanev E. (1996): Numerical simulations of the interannual variability of the Mediterranean Sea upper ocean circulation. *J. Geophys. Res.*, submitted

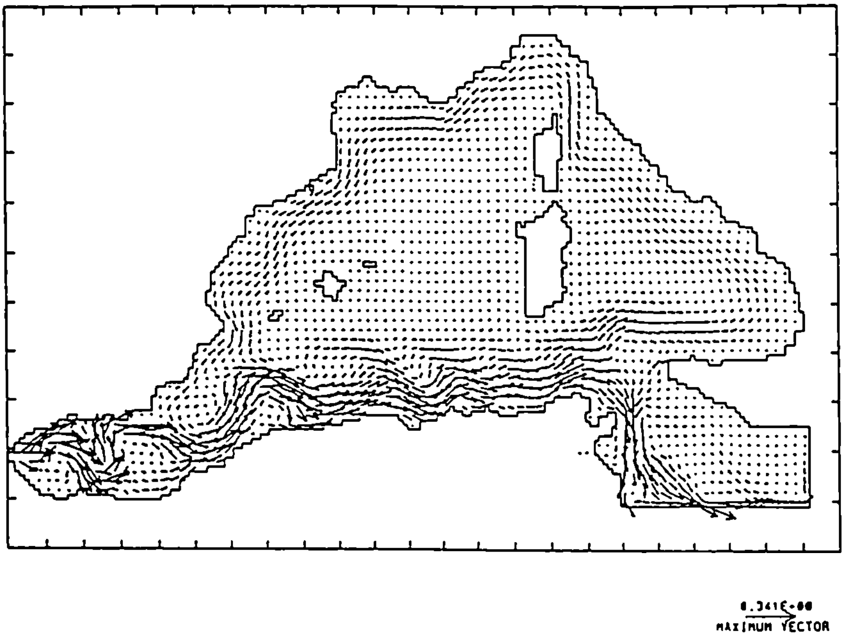


Fig.2: Western Mediterranean Model (Euromodel). From: Herbaut C., Mortier L., Crepon M. (1996): A sensitivity study of the general circulation of the Western Mediterranean Sea. Part I: The response to density forcing through the Straits. *J.Phys.Oceanogr.*,26(1), 65-84

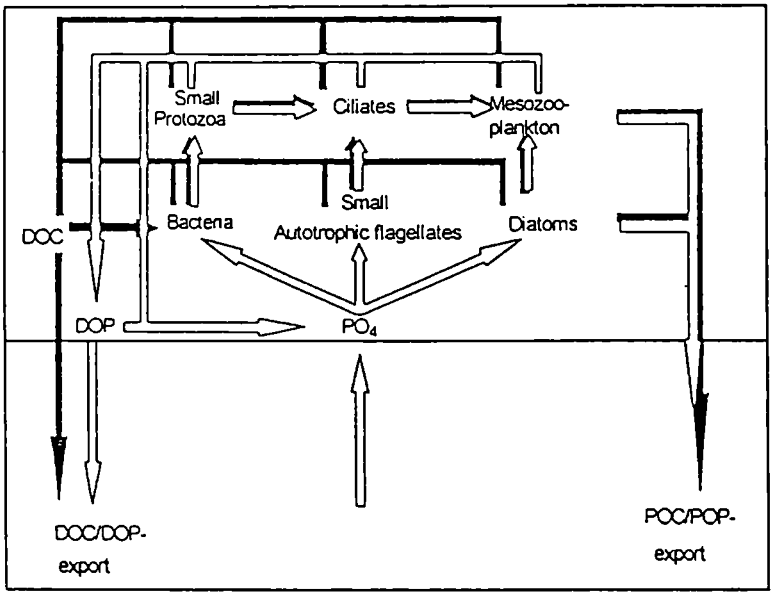


Fig.3: Conceptual model for the cycling of C, N and P in the Mediterranean Sea (Medipelagos). From: Thingstad T.F., Rassoulzadegan F. (1995): Nutrient limitations, microbial food webs and "biological C pumps": suggested interactions in a P-limited Mediterranean Sea. *Mar. Ecol. Progr.Ser.*, 117, 299-306.

ERSEM
(Baretta et al., 1995)

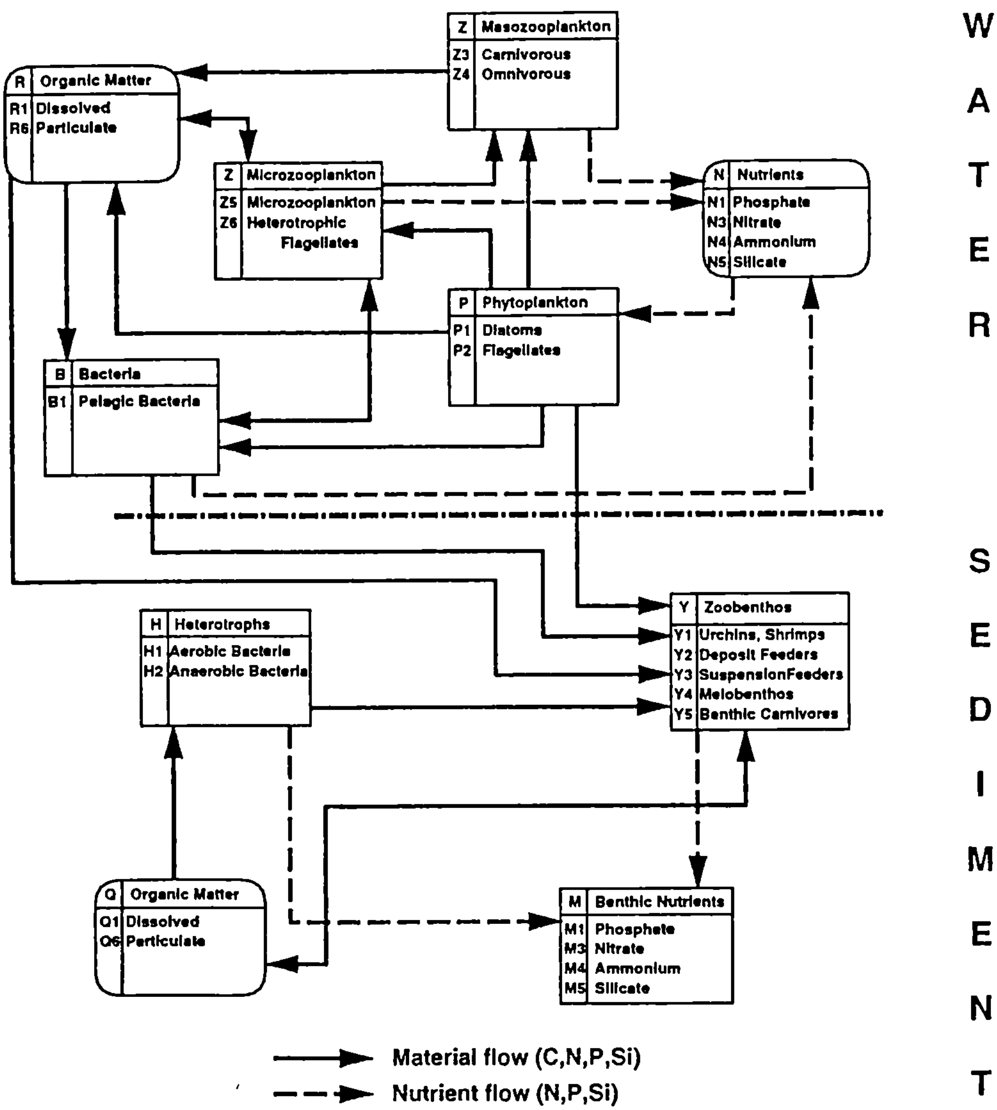
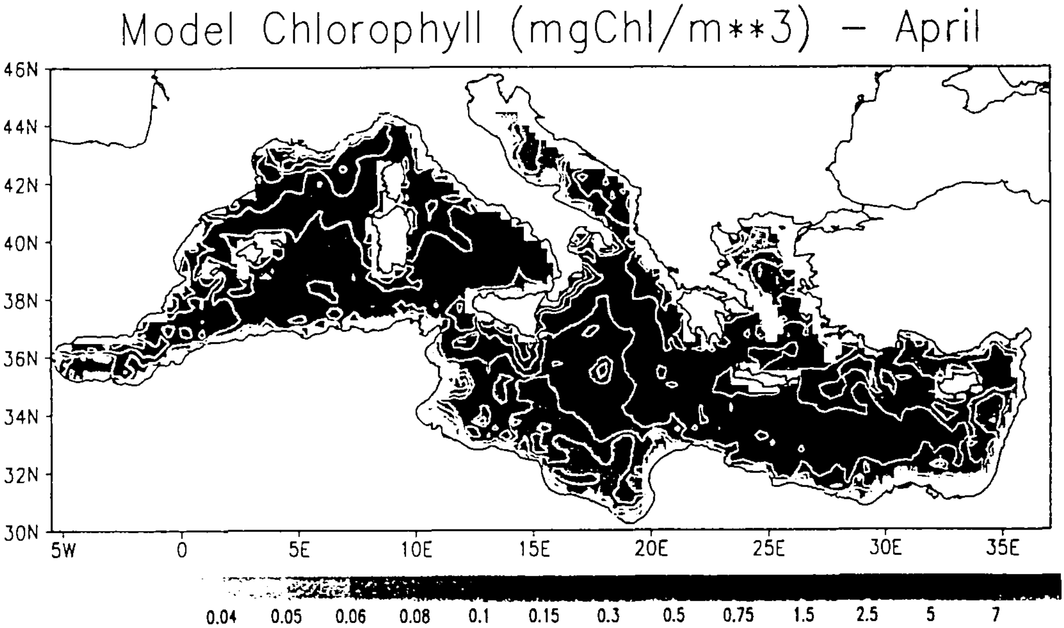


Figure 4

Fig. 4: Schematic of the ERSEM model structure used for the Mermaids Adriatic Sea ecological modeling studies. Modified from: Baretta J.W., Ebenhoh W., Ruardij P. (1995): The European Regional Seas Ecosystem Model, a complex marine ecosystem model. *Neth J. Sea Res.*, 33(3/3), 233-246.



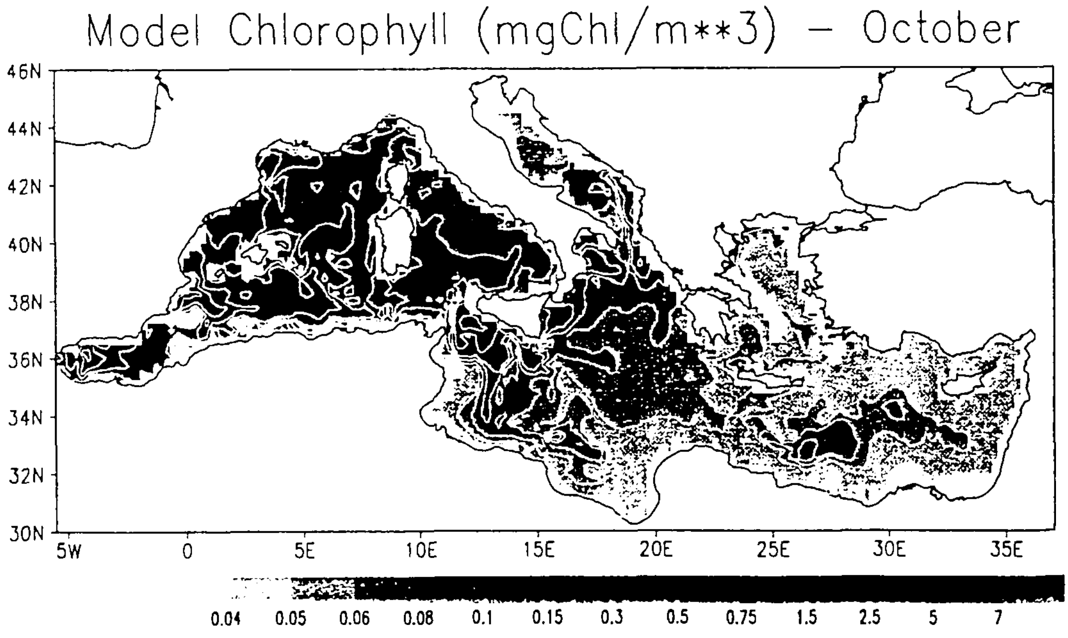


Fig. 5. Chlorophyll concentration in the surface layer (average from 0 to 20 meters) from model simulations. April and October monthly averaged conditions are shown in mg Chl/m^3. Courtesy of A.Crise, OGS, Trieste, Italy.

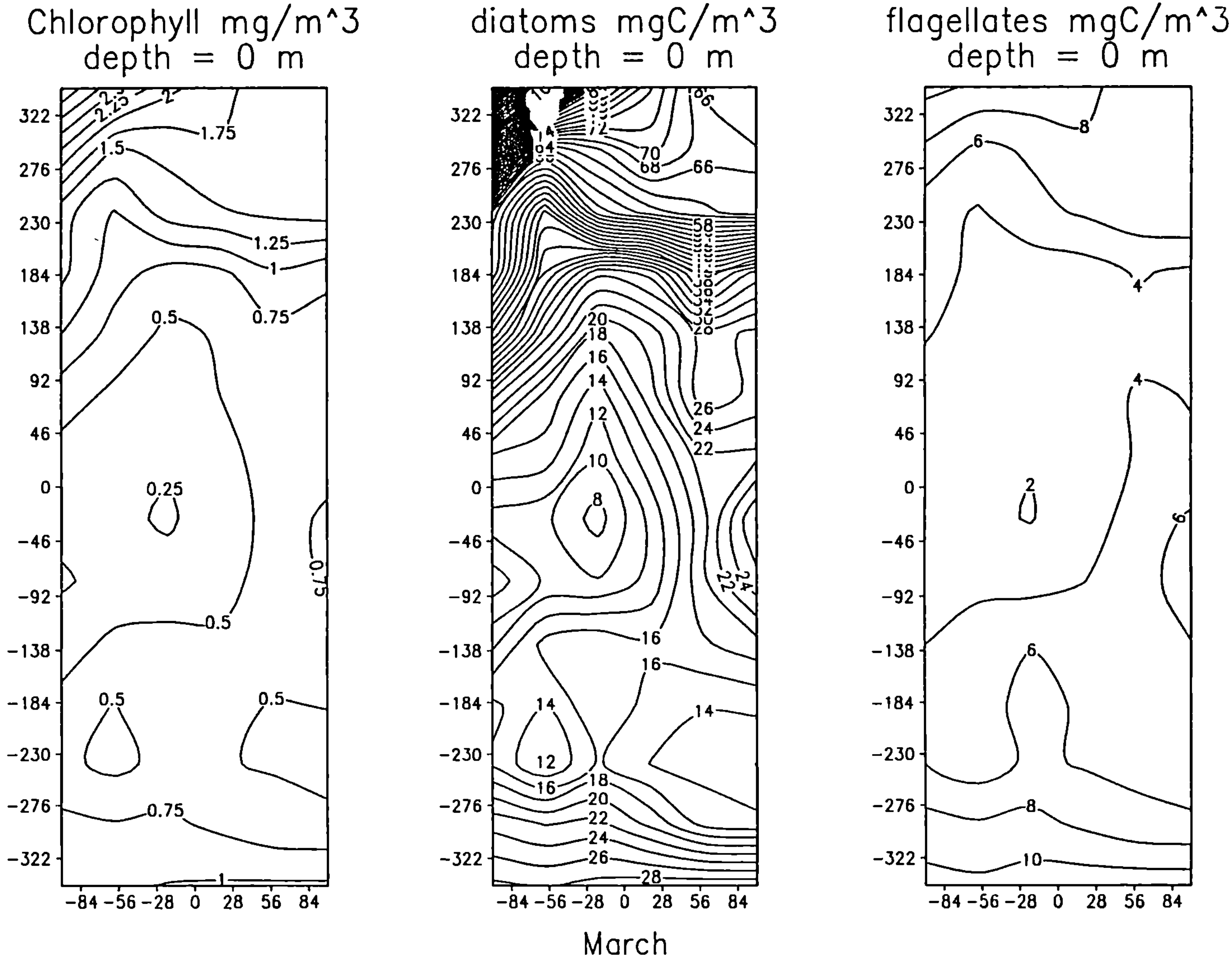


Fig. 6: Adriatic Sea idealized ecological model (Mermaids): Surface distribution of Chlorophyll (left), Diatoms (middle), Flagellates (right) in March. From: Zavatarelli M., Baretta J.W., Baretta-Bekker J.G., Pinardi N. (1996): The Adriatic Sea ecosystem dynamics. Part I: Idealized model study. *J. Mar. Sys.* submitted.

Documentation available on the Mediterranean Targeted Project (website: http://www.cetiis.fr/mtp/mater):

1) European Commission's Press Release : The Mediterranean Targeted Project: A new insight into the life of the Mediterranean Sea, November 19 1996.

2) European Commission's RTD Info Newsletter, Number 15: The lessons of the Mediterranean, p.10-11.

3 QA Quality Assurance Pilot Study, Selected Protocols, edited by C. Turley (PML, UK).

4) MTP News: a periodique Newsletter on the project, edited by M. Canals (Univ. Barcelona, ES)

5) Proceedings of the MTP Workshops held in Barcelona in 1994, edited by M.Canals (Univ. Barcelona, ES) and E.Lipiatou (European Commission) and in Crete in 1996, edited by P. Wassman (Univ. of Tromso, NO) and A. Tselepides (IMBC, GR).

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