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European Commission

Air–sea and sea–ice interactions

Scientific report of an EC marine science and technology workshop held in Brussels, 7 and 8 January 1999

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PREFACE

In Europe, Air-Sea and Sea-Ice interactions have been the subject of increased activity and awareness in the scientific community. Several projects of the European Community's Programmes on the Environment dealt with these subjects which will continue to be important in the Fifth Framework Programme (1998 – 2002), under the key actions Sustainable Marine Ecosystems and Global Change, Climate and Biodiversity.

Under the MAST Programme several projects deal with processes, modelling or instrumentation of air-sea-ice interactions. A part of these projects are finishing at the beginning of 1999 and a part started in 1998. Some projects of the Environment and Climate Programme also addressed air-sea-ice interactions indicating that a sizeable community of European scientists is active in the subject.

The objective of the meeting held in Brussels 7 – 8 January 1999 which gathered coordinators and principal investigators of eight projects, was to present the main results of the above projects. This was an opportunity for better coordination of research on those subjects. The meeting also permitted "old" and "new" project participants to establish links for future initiatives.
And we recognise how important it is to provide information to policy makers who negotiate or support conventions relating to impacts of air-sea-ice interactions.

Christian Patermann
Director, DG XII/DI

Publications to date in the *Research in Enclosed Seas Series* :

- EUROHAB : Harmful Algal Blooms in European Marine Waters (E. Granéli et al., Ed.) EUR 18592 EN, (in press, 1999).

- Marine Research and Policy Interface – Links, Interdisciplinary Co-Operation, Availability of Results, Case Studies (M. Cornaert and E. Lipiatou, Eds), (1999)

- Catalogue of publications from Marine Science and Technology projects – Mediterranean Sea, Volume 2 (E. Lipiatou, Ed.) EUR 18226 EN, 1999

- Scientific Report of the First European Conference on Progress in Oceanography of the Mediterranean Sea (E.Lipiatou, R. Mosetti, S. Heussner, A. Tselepides, J. Tintoré, R. Santoleri & A. Monaco, Eds.) EUR 18312 EN, 1998.

- Catalogue of publications from MAST projects in the Mediterranean Sea – results from EU research, Volume 1 (E. Lipiatou, Ed.) EUR 18021 EN, 1997

- Interdisciplinary research in the Mediterranean Sea : A synthesis of scientific results from the Mediterranean Targeted Project (MTP) phase I, 1993-96 (E. Lipiatou, Ed.) EUR 17786 EN, 1997

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1. Introduction

On January 7 and 8, 1999 a workshop was held on the subject of Air-Sea-Ice Studies: Processes, Modelling and Instrumentation. The Workshop took place at the European Commission premises in Brussels, Belgium. The Workshop was attended by 34 scientists from 12 countries, who were participating in, or affiliated with, the MAST projects ASGAMAGE, AUTOFLUX, BALTEX-BASIS, ESOP-2, IMCORP, MASTOC, MERLIM and SINOPS (in alphabetical order, see Annex I). The workshop was intended to improve the interaction between the participants of these MAST projects and to make an inventory of research priorities for the 5th framework as felt by the participants.

1.1. Course of the Workshop

The first day of the Workshop was devoted to presentations by representatives of the various projects and a review by Dr.Jozef Pacyna of the Norwegian Institute for Air Research (NILU) of the conclusions of an earlier MAST workshop on Sea-Air Exchange, held at his institute. After the presentations the meeting defined four research areas on which further discussions were going to be focussed and recommendations would be formulated. These areas were

- Global Carbon Balance
- Microscale Processes
- Air-Sea-Ice Interactions
- Instrumentation

The second day of the meeting was used for the discussion of these topics. To optimize the discussions in connection with the specific interests and expertise of the participants, the meeting was divided into two successive periods of two parallel sessions, the first one about the Global Carbon Balance and Microscale Processes, the second about Air-Sea-Ice Interactions and Instrumentation. The conclusions of the sessions were summarized during the workshop and afterwards expanded upon by participants who volunteered to do this for specific subjects. After these contributions had been received and edited, the text was submitted to the participants for their comment and re-edited, taking into account their observations. In the following pages you'll find the final result of these activities.

2.Global Carbon Balance

Rapporteur: C.Heinze
Contributions by E.Jansen, O.Ragueneau, C.M.G. van den Berg and A.J.Watson

The most important greenhouse gas in the atmosphere, after water vapour, is CO_2 . From ice core measurements we know that the atmospheric partial pressure of CO_2 has increased by about 32 percent from the beginning of the industrial revolution up to now (Neftel et al., 1985; pre-industrial CO_2 level 270-280 ppmv).
From emission estimates (Marland et al., 1999; about 6.5 GtC/yr in 1996 from fossil burning; additional source of about 1 GtC/yr from deforestation) and tropospheric pCO_2 measurements (Keeling and Whorf, 1998; about 364 ppm in 1997) it can be deduced, that about 50 percent of anthropogenic emissions are taken up by the oceans and the terrestrial biosphere together.
The quantification of the splitting over these sinks is under debate (CSIRO, 1997). The ocean alone presumably takes up about 35 percent of the anthropogenic emissions. The sink in the terrestrial biosphere is the most difficult to quantify and will remain so in the foreseeable future, due to the heterogeneity of the system.

The anthropogenic CO_2 change (compared to preindustrial levels) in the atmosphere is presently of the same order as the glacial interglacial pCO_2 shift (about 190 to 275 ppmv) which was accompanied by a complex change of the marine carbon cycle as documented in the climate signal of marine sediment cores (Barnola et al., 1987; Broecker and Peng, 1986).
While for the fossil fuel uptake capacity the inorganic marine carbon cycle is still considered as the most important factor, the biological carbon pumps may change also as a consequence of anthropogenic climate change and large scale changes of marine ecosystems such as coral reefs can result.

Advances in marine carbon cycle research are urgently needed for both the inorganic as well as the biological CO_2 pumps in order:

(A)To make the best quantitative forecast of atmospheric CO_2 concentrations for given scenarios of future climate evolution.

(B)To quantify optimally the role of the terrestrial biosphere through a deconvolution based on CO_2 emission rates, values of the CO_2 airborne fraction, and correct estimates of the marine CO_2 budget (organic, inorganic).

(C)To estimate the impact of climate change on marine ecosystems and marine biodiversity and additionally the corresponding feedback on the carbon cycle.

(D)To quantify the importance of the biological pump in the removal of CO_2 from the atmosphere and to evaluate the importance of biogeochemical parameters (such as bioavailability of iron) which may affect the biological pump.

(E)To decipher the climate signal as stored in ice cores and marine sediment cores to provide a correct reconstruction of past ocean states for a validation and calibration of existing climate models.

The importance of the biological pump (see item (D) above) for removal of anthropogenic pCO2 is controversial, as discussed by e.g. de Baar (1989), Broecker (1991), Sarmiento, J. L. (1996), Maier-Reimer et al. (1996), and Sarmiento et al. (1998).

However, the importance of the biological pump for natural pCO2 variations, of a correct estimate of the terrestrial carbon sink and of a well quantified interpretation of intra-annual and interannual pCO2 variations, as well as the understanding of the sediment core record of climate change are not under debate.

Further research on all oceanographic disciplines and a strengthening of an interdisciplinary carbon cycle research network are necessary to improve our knowledge on the marine branch of the global carbon balance. In this connection the following subjects within the various branches of Oceanography are considered to be essential:

1. *Physical Oceanography.*

As deep water production is the "bottle neck" for the storage of CO2 in the deep ocean, a better understanding of the associated physical processes is needed. Our knowledge of the actual deep water production mechanisms is still marginal and bulk estimates of deep water production for the Northern Seas and the Southern Ocean are very crude (e.g. Broecker et al., 1998). Better direct observations are needed in convective areas during winter. The improved understanding has to result in better parameterizations of ocean climate models.

A further analysis of gas exchange processes will be essential to estimate correctly the vertical transport of excess CO2. Especially the kinetics of gas exchange during deep convective processes are here of interest. Remote sensing techniques have to be developed further in order to deliver global distributions of appropriate boundary conditions such as time dependent wind speed distributions.

2. *Geochemistry/Chemical Oceanography.*

Improved techniques must be developed in order to measure reliably directly the invasion of anthropogenic CO2 into the ocean. The key parameters total inorganic CO2, alkalinity, and surface ocean CO2 partial pressure (plus atmospheric pCO2 at the sea surface) have to be monitored world wide. Analogue tracer techniques for estimating the anthropogenic CO2 invasion into the ocean including the use of chlorofluorocarbon measurements have to be refined. Links between the carbon cycle and other chemical substances have to be identified and quantified. Among these chemical species are iron (from aeolian input), silicon (the major component of marine shell material besides CaCO3, e.g. de Baar, 1995; Heinze et al., 1999) and all other nutrients such as nitrate and phosphate.

Investigations of the cycling of these substances should include the effect of anthropogenic disturbances (such as retention of material through construction of fresh water reservoirs).

Especially the interfaces of the ocean with other geochemical compartments such as continental boundaries (river load) and the sea floor (burial of matter, redissolution) must be understood better to enable a closed local and global balance.
Special emphasis has to be placed on experimental determination of the deposition and burial rate of carbon species in shelf seas and pelagic areas.

3. *Biological Oceanography.*
The limiting factors for marine biological productivity and the partitioning into carbon-containing substances and non-carbon-containing substances are still not well quantified and the underlying mechanisms are only vaguely known, if at all (Codispoti, 1989; Geider, R. J., and J. LaRoche, 1994; Dugdale and Wilkerson, 1998).
Possible interdependencies between climate change, including carbon cycle perturbations and biological processes, have to be investigated further. Some progress has been made here (cell doubling rate, fractionation of isotopes, e.g. Riebesell et al., 1993) but further investigations are needed. The results in these fields will be of importance also for the interpretation of the sediment record of climate change.
Bulk figures of global biological primary production rates of particulate matter can be estimated only roughly.
A further combination of laboratory and in situ measurements on one side and modelling efforts on the other side are necessary to correctly estimate these quantities. Measurements of oxygen isotopes in tropospheric air can help elucidate the magnitude and timing of large scale biological production rates (Keeling, 1996).

4. *Geological Oceanography.*
An improved quantitative interpretation of the marine sediment signal of carbon cycle and climate change is needed. In order to link global climate models appropriately to the paleo observations, corresponding models have to be developed which allow a direct comparison between the paleo tracers as measured by geologists.
For a proper reconstruction of the strength of the biological carbon pump in the past, a multi proxy approach has to be used in order to narrow the uncertainties in determinations of paleoproductivity with the various methods at hand (e.g. Ragueneau et al., 1996).
A broadening of the scale of available proxies for further parameters and variables is needed (such as for dissolved oxygen in the water column, age of deep water, nutrients, turbulence etc.).
As the input of trace metals into the ocean through river runoff and aeolian transport (e.g. Broecker and Henderson, 1998) can influence the carbon cycle significantly, corresponding source distributions must be reconstructed for the most relevant time slices in the geological past.

3.Microscale Processes

Rapporteur W.A.Oost

Contributions by A.Graham, B.Jähne, S.Larsen, P.Liss, P.D.Nightingale, W.A.Oost and D.K.Woolf.

1.Boundary layers.

The importance of the oceans for exchange processes between the atmosphere and the underlying surface needs little discussion, if only for the fact that they cover some 70% of the global surface. In this connection the actual water surface is often regarded as the main resistance. There, in a layer with a thickness less than 0.1cm, the turbulent motions responsible for the transport of momentum, heat and material substances in the main bodies of both atmosphere and ocean, are suppressed and transports have to proceed in a slow, quasi-laminar fashion. The effect of the surface on those transports is, however, not limited to this quasi-viscous layer. The turbulent eddies responsible for the transport in the bulk of the water or air mass are generated by shear of the flow or its thermodynamic (in)stability. Their sizes are limited by the surface, an inversion layer or, in the case of shallow water, the bottom. Box models implicitly attribute the effect of these eddies on the transport properties fully to the water surface. Their parametrizations take the eddies into account only in an averaged way, so their size distribution, the parameters affecting that distribution and the fluctuations in it remain unheaded. As far as the water is concerned the structure of these layers is further complicated by the presence of waves, which through their orbital velocities introduce additional movement down to depths of half their wavelength - which can be hundreds of meters. In the atmosphere too the signature of the waves can be detected in the turbulence up to some limited height. At the surface, waves have their strongest effects when they break, disrupting the structure of the near-surface water layer and affecting all exchange processes both in the air and in the water.

As an illustration of the possible importance of these effects a recent modelling exercise can be mentioned in which the effect of the water boundary layer was studied. This showed that data from one of the more sophisticated methods for air-sea gas exchange measurements may be off by some 15%, due to near-surface concentration gradients related to the boundary layer structure.

2.Coordination of field, laboratory, and modelling studies.

For the successful study of exchange processes at the (water) surface, it is crucial to achieve a high degree of coordination between field, laboratory, and modelling work. The EC initiative of clustering research projects provides an excellent framework for such a coordinated effort. The benefits will be substantial. Laboratory measurements can be performed to address specific questions that arose from field experiments and vice versa. New physically-based models can be tested in both field and laboratory experiments. Any improvement in the understanding of the processes can immediately enter into the modelling and help to provide the best possible predictions for application studies. (Traditionally, the knowledge entering modelling

efforts considerably lagged behind because of the lack of communication between modellers and experimentalists).
Laboratory measurements of small-scale air-sea interaction processes has been a dominant research area in Europe since the 1970's. Important facilities that can be mentioned in this respect are the "Grande Soufflerie" (now: IRPHE and recently the scene of the experimental part of the MAST-III LUMINY project) at Marseille/Luminy, France, the wave flumes of Delft Hydraulics in the Netherlands and the circular wave flume at Heidelberg University, Germany.
With the opening of the new large Air-Sea Interaction Facility ("Aeolotron") at Heidelberg University in the summer of 1999 a new unique European research facility will become available which will further strengthen the European position in this research area and open up new possibilities for collaborative European and international research projects. Coordination of the research to be performed at this facility with field measurements, e.g. at "Meetpost Noordwijk", one of the very few stable research platforms available worldwide, puts Europe in a unique position for the study of processes at the boundary of air and water. The Noordwijk platform and the IRPHE facility already figured in earlier successful collaborative projects of this type.

3.Understanding the underlying processes.
The intense research in air-water gas transfer in the past years significantly enhanced our knowledge of the processes that control the exchange of climate-relevant gases between the atmosphere and the sea. Several processes have been identified besides the wind speed that influence the gas exchange rate. However, most of them (such as bubble-mediated air-gas transfer and the role of surface films) can only be described qualitatively. Thus an important focus of future research lies in the actual understanding of the underlying processes in a quantitative way.

4.More fundamental understanding.
Integration of recent modelling, laboratory and field studies indicates that a more fundamental understanding of the mechanisms controlling air-sea gas exchange is within reach. Modelling work suggests that long-held assumptions concerning complete mixing in the bulk layer immediately below the microlayer may be incorrect and for the first time allow us to start answering questions about the importance of stationarity and homogeneity. An important consequence is that the possible existence of, and effects due to, horizontal and vertical gradients should not be neglected. We have a better understanding now of the implications of the so-called Webb correction (describing the effect of density fluxes) and can start making statements about its accuracy for different weather situations. Laboratory studies (e.g. the LUMINY project) are providing a clearer picture of the role of bubbles in gas exchange and are allowing an assessment of the relevant importance of different mechanisms involved in flux enhancements induced by bubbles/breaking waves. Laboratory studies have also highlighted the potential of naturally occurring surface films to inhibit exchange rates at sea. Although laboratory-based experiments are clearly more suited to detailed investigation of exchange mechanisms, multi-

disciplinary co-ordinated field campaigns should be a priority in order to test these observations in the oceans. An in-situ gas exchange study in an algal bloom induced by addition of iron (IronEx 2) has shown that mechanistic studies ought to be possible in the oceans.

Of particular importance are results from recent field experiments (e.g. ASGAMAGE, GasEx 98). The previously large differences between the radiocarbon budgeting technique and air-based measurements techniques have been greatly reduced. The considerable progress that has been made with the micrometeorological techniques, especially eddy correlation, suggests that direct flux measurements may in future become the norm. More data is now available from the dual tracer technique. Experiments for different regions of the globe now give reasonable agreement and act as constraints for parameterisations of gas exchange rates. The technique has been improved by the use of non-volatile tracers that allow assessment of the power dependence of gas transfer on molecular diffusivity.

The various techniques now give so much better agreement compared with the situation a few years ago, that we can start using the different methods to provide a new perspective on the processes governing air-sea gas exchange, allowing us to put better constraints on their effects and relative importance.

5. Measurement technology for the marine boundary layer.

A major reason that parametrizations of air-sea gas transfer have so far been limited largely to empirical relationships to, for example, wind speed, is the paucity of methods for investigating the processes that are directly responsible for transfer across the marine boundary layers (which is usually the "rate-limiting" process in air-sea exchange of poorly soluble gases). Apart from performing measurements in a wave-following frame, as mentioned in the chapter on instrumentation, there are two main methodologies for studying experimentally the critical processes at the surface and in the adjacent marine boundary layers:

a) (Largely) acoustical methods for measuring turbulent processes and bubbles from close to the surface down to several metres below the sea surface.
b) Infra-red methods for investigating spatial and temporal patterns of sea-surface temperature resulting from "surface renewal processes" and a net air-sea heat flux.

While significant progress has been made in developing both technologies, further development is necessary to bridge major gaps in our understanding. A full understanding of both the forcing and the general characteristics of surface renewal processes is especially critical to air-sea gas exchange studies. Thermal imagery has revolutionised the study of these processes taking "surface renewal" from being solely a conceptual model to an observable, physical reality. However, it remains to establish a complete description of the nature (for example, what eddies, if any, totally renew the surface directly from the bulk?) and scales of these motions, and to understand the forcing of these motions). In order to understand the relationship of the surface-renewing eddies to the wave field, wave breaking, sub-surface turbulence and bubbles, infra-red measurements need to be integrated into an instrument package with other measurements.

8. The shallow water environment.

The present uncertainty in gas-transfer rates, and their dependence on environmental conditions, probably exceeds any systematic difference between their values in open ocean and shelf sea. Recent gas-transfer measurements made at the Meetpost Noordwijk platform, situated near the Dutch coast in 18m deep water, may therefore be ascribed a global validity, and the platform remains a site of first choice for experimental investigation of air-sea exchange processes. At the same time, it is essential to identify any coastal influences on the measured transfer rates. The high biological activity in shallow seas turns them into a disproportionately large sink for gases like CO2, when we compare their total surface to that of the oceans.

Strong tides, often present in coastal regions, make it difficult to distinguish between advection of fixed horizontal gradients in water-mass properties and their Lagrangian evolution. It is therefore necessary in these areas to obtain water-mass measurements at several longstream locations simultaneously. Freshwater outflows in coastal waters can act so as to suppress near-surface turbulence, as well as conveying a partly estuarine biogeochemistry, with attendant surface-active films.

Turbulence is, however, also generated by the tidal flow over the seabed, marked upward ejections occurring in bursts. The turbulence acts so as to mix away overlying fresh water, and to destabilise and to some extent break up Langmuir circulation, the ejections also forcing divergence at the surface, causing the destabilisation and breaking of short wind-waves as they propagate into the region of marked surface shear. The bottom also modulates the waves directly, limiting the swell and inducing peaky waves. It constrains convective processes such as Langmuir circulation that would otherwise cascade to larger cellular sizes, and force separation from the surface at greater convective velocities.

9. Research priorities for various gases.

At a recent EC sponsored scientific workshop at the Norwegian Institute for Air Research (NILU) a table was drafted of gases that were being exchanged between the oceans and the atmosphere and that were important in connection with their effects on climate change, on stratospheric ozone destruction or for their toxicity for the (marine) environment. This table is still valid and may be considered as rather complete, but for the omission of water vapour, which is important as an important greenhouse gas in itself and for its effects on the transport of other gases as well.

The table is reproduced below; copies of the NILU workshop report (Pacyna,J.M., D.Broman and E.Lipiatou (eds.): Sea-Air Exchange: Processes and Modelling, EUR 17660) can be obtained from the European Commission.

Gas	Air to sea	Sea to air	Seawater production/ destruction	Air/sea exchange processes	Atmospheric role
CO_2	√	√	√	√	√*(4)
CO	-	√	√	-	√
CH_4	-	√	(√)	-	(√)
$NO_{x/y}$	√	-	√(2)	√(1)	-
N_2O	-	√	√*(5)	-	-
NH_3	√	√	√(2)	√(3)	√*(6)
COS	-	√	√	-	(√)
Organo-halogens	-	√	√	-	√*(6)
LMWHCs	-	√	√		√
POPs	√	-	-	√*(8)	-
Hg	-	√	√	-	-

√ = Primary Research Topic
(√) = Secondary Research Topic
* = Special Research Topic

(1) Interaction with sea spray
(2) Sources of N-nutrient
(3) Is liquid resistance important?
(4) Role of oceans in atm.CO_2 seasonality
(5) Importance of oceans in global budget
(6) Role in atmospheric particle formation
(7) Role in atmospheric oxidant chemistry
(8) Exchange processes untested
(9) Role of wind, waves, bubbles, spray and films in exchange processes not well established

4.Air-Sea-Ice Interactions

Rapporteur J.Launiainen
Contributions by: B. Brummer, S.Larsen, J.Launiainen, J. Pacyna and A.J.Watson.

1. Fluxes over ice and water

The flux of momentum characterises the dynamic interaction between air and ice or air and sea. Fluxes of sensible and latent heat, i.e. water vapour, and radiation fluxes define the thermal interaction and water vapour exchange. Qualitatively, fluxes of non-reactive gases can be treated by analogy with the other turbulent fluxes. However, the difference in Schmidt (Prandtl) numbers leads to quantitative differences in the fluxes.

Local turbulent fluxes depend on aerodynamic and scalar roughness of the surface and on meteorological conditions and stratification. The latter ones include wind speed, air and surface temperature and net radiation. For gases, the air-surface gas concentration difference (the partial gas pressure difference) provides the driving force to the fluxes. The sea ice fields tend to be broken with cracks and leads and cause ice ridges etc.. These features yield heterogeneities in form drag and skin roughness and in this way produce internal boundaries. To be able to determine the spatial and temporal fluxes accurately and to parameterize them for modelling, experiments are still necessary. This is relevant e.g. if we want to relate the ice and snow surface geometric roughness to resistances of the turbulent transfer.

Over ice and snow, the determination of radiation fluxes may cause additional problematics. Incoming short wave radiation may lead to multireflection between the low-level clouds and the surface. The surface based bulk parameterization of the outgoing long-wave radiation for freezing surfaces and water is still rather inaccurate.

2. Effects of inhomogeneities and parameterizations of area representative fluxes over broken ice

Sub-grid scale surface fluxes of heat, moisture (and other gases), and momentum over broken ice cannot simply be parameterized in terms of the well-known bulk formulae using the area averaged values of the respective quantities at the surface and in the air. For example in the Arctic, the area averaged temperature difference between the air and the surface, covered by broken ice, tends to be positive in the winter, but the area averaged sensible heat flux is upward. This is due to the fluxes from regions of open water (leads etc.). The areal fraction of those regions does not cover more than a few percent of the total area, but here high upward fluxes prevail and dominate the area-averaged flux. On the other hand, stable stratification over the sea ice decreases the turbulent flux downward. It is known that coupled air-ice-sea climate models are especially sensitive and uncertain in the Arctic regions.

In an air mass flowing over a surface discontinuity, as e.g. the ice-sea-discontinuity, the atmospheric boundary layer is modified due to the change in surface roughness, albedo, surface temperature, moisture, heat capacity etc. The largest portion of the modification takes place within the first tens of kilometres from the surface discontinuity. Sea fog and clouds may develop and clouds may be organised in regular patterns. Often vertical motions are induced by thermal (heating from the surface) and dynamical (wind shear) instabilities, which contribute substantially to the vertical fluxes of heat, momentum and material in the atmospheric boundary layer. These processes occur on the micro- and meso-scale and are not resolved in coupled air-ice-sea climate models. Experimental studies and high-resolution numerical modelling are needed to understand and quantify effects of inhomogeneities. Existing theories and parameterisations to deal with inhomogeneities in large-scale models need to be tested and improved, or new parameterisations need to be developed. Experimental studies in this research field may just as well be conducted over marginal seas (e.g. Baltic Sea), because many of the physical processes going on there can be generalised to describe the physics of polar regions as well.

3. Heat fluxes in ice and snow.
For climate studies, the heat flux through the ice from the ocean to the atmosphere can be calculated from budget studies or as a rough mean bulk estimation. For process studies and short and medium range air-ice-ocean modelling, the heat flux (conduction & radiation) *in* the ice should be estimated. That is a precondition for estimation e.g. of the surface temperature of ice or snow and it is a critical quantity for coupled models. Integrated studies for air-ice-modelling should include appropriate measurements to be able to calculate and verify the temperature and flux profiles in ice and snow. A horizontally inhomogeneous structure of sea ice, i.e. a mixture containing level ice, ridged ice and cracks and leads, involves a special downscaling approach, in analogy with air-ice fluxes, to obtain area-representative flux values.

4. Fluxes from the ocean at the ice-ocean interface
For coupled air-ice-ocean modelling the heat flux from the sea into the ice is to be estimated. An approach using "a bulk aerodynamic method" for the ocean/ice interface is a proper tool to parameterize ocean-ice fluxes. However, the problems of bulk parameterization lead to questions analogous to those of air-sea and air-ice fluxes. Even the proper definition of structure and roughness of an ocean-ice boundary is far not trivial. Accordingly, specific studies should investigate how to relate the ice-ocean interface roughness, current velocity and stratification to the eddy fluxes in a quantitative manner.

5. Remote sensing of sea ice properties and dynamics,
For the determination of air-ice interaction and air-ice-ocean exchange, the structure and variability of the sea ice fields are to be known. Ice concentration and thickness, ice and snow surface structure (form drag, roughness) and basic information of the ice dynamics (ice drift, compression, opening of cracks and leads, ridging) need to be studied and modelled. Sea ice and its movements can be studied on the meso- and synoptic scales using remote sensing. For the detection of general movements and coarse estimation of ice concentration, SSM-I and larger scale radar satellite images may be used. For more detailed studies of the ice field and its properties high

resolution data (SAR/ERS1-2, ENVISAT) are needed, in combination with exhaustive ground truth studies and the development of new analysis methods.

6. Mesoscale effects of ice-sea baroclinicity

In wintertime the temperature difference between the ice surface and the ocean surface may be up to 30 K in the polar regions. This strong temperature contrast, resulting in strong baroclinicity, may cause several types of meso-scale circulations. Like the sea breeze in the tropics or in the summertime in mid-latitudes, an ice-sea breeze is generated by the strong temperature difference across the ice edge zone. Generation of meso-scale lows or modification of existing lows is promoted, if the relations between the temperature gradient and mean background air flow are favourable. The ice-sea breeze interacts with the ice distribution in the marginal ice zone, loosening the ice cover and promoting ice melting. Such interaction processes at the ice edge have not been studied so far. They should be investigated by experimental methods as well as by coupled meso-scale ice-atmosphere models.
Movement of a meso-scale low across an ice area has substantial consequences (dynamical and thermodynamical) on the ice pack, due to the variable wind field during the passage of the depression. Such meso-scale lows, which develop e.g. in the Fram Strait area of the Greenland Sea, may be supposed to have not only local but also non-local consequences, because the ice export from the Arctic ocean into the Atlantic ocean is affected. Therefore, a study of meso-scale effects of air-ice-sea interaction in key regions of the climate system is of particular importance. That requires comprehensive experimental and modelling efforts on a wide range of scales.

7. Chemical and biogenic processes in the air-ice-ocean system

An important new air-ice-ocean field of research is the development of interdisciplinary methods and models to study and simulate the transfer of various chemicals in the air-ice-ocean system. The ice is a central compartment in this acting both as a sink of chemicals from the atmosphere and as a source of chemicals to the atmosphere and ocean as well. The atmosphere is the major source for the deposition of various chemicals on the ice surface. Finally, the ocean is a sink of chemicals during periods of ice melting.
Various scavenging processes of chemicals from the atmosphere over the ice need to be identified and quantified, including those that are involved in the interception of chemicals by snow and their deposition on the ice surface. In addition to the wet deposition, other ways of atmospheric deposition should be investigated, including dry deposition in particulate and gaseous form. The accumulation potential and the quantities affecting the accumulation of chemicals in ice should be defined and studied in various polar regions.
Research is needed to assess the environmental impact of chemicals released into the ocean from the ice during melting periods. Occasional releases of large quantities of chemicals, which have accumulated for several months in the ice, may have a dramatic effect on the biology of the ocean, affecting the food web in polar regions.

There is growing evidence that the zone in which the ice melts in the spring is an area of intense biological activity in the water. Such biological activity produces a whole suite of trace gases, many of which are potentially important for the atmospheric chemistry; obvious examples are dimethyl sulphide and a variety of organo-halogen gases. Once released to the atmosphere the trace gases undergo transformations via photochemistry/radical attack to produce sulphate particles, in the case of dimethyl sulphite, or changes in redox chemistry from breakdown of organo-halogens. Dimethyl sulfide can e.g. act as a source of cloud condensation nuclei. This very new area of investigations requires a well planned and coordinated research effort. The concepts of chemical and biogenic system in air-ice-ocean models, described above, need verification through measurements of processes and concentrations in the various compartments of the environment. Sampling and analysis procedures currently available should be modified and adjusted to the polar regions and to low concentrations.
A number of case study locations are to be identified for validation of chemical and biogenic air-ice-ocean models. Those validation studies should be used to model both the chemical pathways and the physics of the air-ice-ocean system on regional and larger scales.

8. Coupled air-ice-sea models
A suite of dynamically coupled air-ice and air-ice-ocean models is necessary if we want to understand the coupling of oceans and ice covered seas with the atmosphere. For climate studies and scenarios and for studies of the sea ice effects on the circulation of the oceans, large scale models need simplification and areal averaging, due to the limitations of even the largest computer systems. The proper way to do this is by performing local and high resolution studies and averaging the results. Therefore models are needed for all time and space scales: from local ones, via regional short and medium range weather and marine forecasting, to climate and general circulation models. A number of suitable coupled models for various scales have been developed in recent years, but for their verification and optimization high quality experimental and process study data are chronically needed.

5.Instrumentation

Rapporteur W.A.Oost

Contributions by C.M.G.van den Berg, A.Graham, Chr.Heinze, B.Jähne, G.de Leeuw, W.A.Oost, P.K.Taylor, A.J.Watson and D.K.Woolf.

1.Improved CO2 sensors.

Part of our uncertainty about the amount of the most prominent greenhouse gas, CO_2, that is absorbed by the oceans, relates to the fact that the values for this process were obtained with indirect techniques that rely heavily on the assumption that the diffusivities of gaseous substances can be related by their Schmidt number (the ratio of the molecular diffusivity and the kinematic viscosity). Another basic characteristic of these methods is the need for measurement times of 24 hours or more. It is therefore not possible to study changes in the CO_2 fluxes (flows) in the course of a day due to e.g. wind speed fluctuations .

A potentially powerful method to improve on this situation is to use the so-called eddy-correlation (EC) technique, a micrometeorological method that provides a direct measurement of the CO_2 flux and requires only 20 minutes. However, results from this technique in the late seventies and eighties provided fluxes that were an order of magnitude or more larger than those obtained with the more conventional methods. Meanwhile large improvements have been made in the EC technique and recently EC measurements were obtained that agreed with simultaneously performed differential tracer data (a sophisticated indirect method) as good as could be expected in view of the uncertainties related to the basic assumptions of the techniques. The sensitivity of the CO_2 sensors used is still marginal, however, for use at sea, resulting in a low signal-to-noise ratio.

If we want to have a detailed picture of the oceanic sinks and sources for CO_2 it is necessary to know the precise relationship between the wind speed and the transfer velocity, a measure for the resistance CO_2 experiences in the air-sea exchange process. This information cannot be derived from measurements lasting 24 hours. The use of the EC method (or related techniques, see below) is then inevitable, which stresses the importance of the development of more sensitive, fast responding CO_2 sensors then presently available. (The transfer velocity alone is not sufficient to characterize the sinks and sources, but must be supplemented by information concerning the CO_2 content of those spots).

Other techniques that can provide information about the relationship between the wind speed and the transfer velocity are the eddy accumulation (EA) and inertial dissipation (ID) methods. Like the EC method, EA is a direct method, requiring only short measurement times. However, one of its main advantages over the EC method is that it can be applied to various types of gases without the extreme requirements the EC method poses on the gas sensor. Although it lacks some of the difficulties of the EC method the EA method has its own problems and has so far yielded useful results over land only, not at sea. Combined experiments in which the EA and EC methods are used side by side should be promoted. The ID method is less direct since it depends on assumptions concerning the structure of turbulence. It provides values for the magnitude but not the direction of the flux, a particular disadvantage with regard to gas fluxes. However it requires short measurement times and is less sensitive to airflow distortion by the sensor and instrument platform than the EC and EA methods. An advantage for use at sea is that it does not require high frequency measurements of the platform motion. Methods which combine EC and ID techniques are being developed for ship board use. In experiments where EC data are obtained, the ID technique may be used to confirm that flow distortion problems have been eliminated.

2.Autonomous sensitive instruments for chemical parameters.
There is a need for instrumentation which can produce data on the chemical composition of the surface ocean

- autonomously
- accurately and reliably
- cheaply

The ideal would be instrument packages which could be deployed by semi-skilled personnel and which could collect data on parameters such as CO2 parameters, salinity, temperature, nutrients and other parameters as available. Obviously this is a long-term aim; initially such instrumentation is likely to be expensive. Substantial advances in these fields have been made, including work done under various MAST projects (i.e. IMCORP, MASTOC). More needs to be done, particularly with the aim of reducing the size and cost and increasing the reliability of such instrumentation.
Possible routes for such instrumentation include the miniaturization of wet chemistry techniques, the development of reliable micro-electrode techniques, the automation of flow injection and electrochemical procedures. It is only because so much progress has been made during the decade of the nineties that we can even contemplate such sophisticated techniques. The advantages to a Global Observing System of such techniques are clear.
We can see two stages in the development of this kind of instrumentation:

1. In the short term, instruments will be developed which can be deployed in limited numbers on remote platforms, such as instrumented buoys and voluntary observing vessels. This will enable the characterization of the surface oceans in much greater detail than we presently are able. Present projects are already making progress in these developments and we should encourage further such developments.
2. In the longer term smaller, cheaper (but no less accurate) systems need to be produced which can be deployed in larger quantity and on a very routine basis. Such systems would be analogous to the present-day use of XBT's in the ocean or radiosondes in the atmosphere. By mass production, they could be made sufficiently cheaply to enable a truly global monitoring of the chemistry of the surface oceans to be attained. This objective is at least a decade away, but careful thought needs to be given to the possibilities now if we are to achieve this.

4.Porewater profiler.
Sediments are both a sink and a source for various components in natural waters. For instance they are a sink for organic carbon, carbon in coccoliths, and various metals if these become locked up underneath an increasing thickness of sediments. However, the sediments can act as a source when reducing conditions develop. Previously adsorbed metals may for instance become released in the frontal zone of the reducing layer and diffuse into the overlaying waters. Major elements which control the redox processes in the porewaters are oxygen, iron, manganese and sulfide. It is difficult to detect the distribution of oxygen, sulfide, iron and manganese in porewaters without disturbing the original situation. Existing methods include sample collection using "peepers" or syringes, and the use of equilibrating gel-slides. There is a clear need for the development and use of in-situ probes for porewater profiling. Such a probe could be electrochemical (utilising voltammetry or potentiometry, and advances in microelectrodes), or possibly based on fluorescence or other spectrophotometric detection. The probe should be sufficiently small that the measurement does not appreciably disturb the original porewater composition. Concentration ranges are expected to be on the order of micromolar levels.

3.High-sensitivity trace metal sensors.
Several metals (including iron, zinc, copper, and cobalt) are either essential, or toxic at slightly enhanced concentrations, to microorganisms including phytoplankton in natural waters. For instance low concentrations of iron are known to control primary productivity in large parts of the world oceans. These metals are known to occur strongly complexed by organic matter and the concentrations of their free, inorganic, species are therefore very low and difficult to determine. Therefore we need sensors for the detection of metal (e.g. iron, copper, zinc and cobalt) concentrations, or individual metal species, of biological importance in natural waters (including sea and fresh water). The sensors may be based on voltammetry, potentiometry, fluorescence, or possibly other novel methods, and may utilise ligand competition. The expected concentration range is on the order of picomolar for the inorganic fraction of all these metals, and low nanomolar for the total metal concentrations.

5. Remote measurement of marine microlayer properties.
Beside other physical, chemical and biochemical parameters the viscoelastic properties of the marine microlayer are critical to the air-sea exchange of gases. Both for the practical purpose of enabling routine measurement, and the scientific aim of a totally non-intrusive measurement, remote measurement of surface properties is highly desirable. The simplest and most practical remote-sensing methods for the viscoelasticity of the surface do not directly measure physico-chemical properties, but rather measure the high frequency wave field. Surfactants of all kinds generally damp waves, and the specific modulation of the high frequency waves can yield quite specific information on the viscoelastic properties of active surfactants. A crude (i.e., non-spectral) measurement of "sea surface roughness" will often suffice to establish the presence of slicks. For example in SAR imagery slicks may be evident as areas of very low scatter, or in less extreme cases may be evident

through, for example, the characterisics of imaging of internal waves. Multi-frequency radar can provide spectral information on the modulation of short waves by surface-active material. Modulation of acoustic scattering from the surface, at the frequency of the surface waves can yield similar information. More direct interrogation of physicochemical properties or the chemical composition of the surface is more difficult to achieve, but some methods are emerging from the laboratory into the field. Measurements of optical refractive properties yield information on the upper micrometres of the microlayer. Second Harmonic Generation (SHG) methods are a laser-based technology that directly interrogate the surface molecules, revealing their polar properties.

6. Remote measurement of gas exchange at the water surface.
In the past few years the controlled flux technique (CFT), which uses heat as a proxy tracer, has been developed to determine the transfer velocity of air-water gas exchange, as an alternative to the eddy-correlation method. This technique was first successfully demonstrated in the laboratory (Jähne et al., 1989) and later in the field (Haussecker and Jähne, 1995, Jähne and Haussecker 1998). Now it is developed to the point that it can be used for systematic studies of air-water gas transfer. The combined usage of eddy-correlation and CFT will give an unprecedented insight into the processes controlling air-water gas transfer. In contrast to any tracer technique based on mass balancing, the CFT has a temporal resolution comparable to the eddy correlation technique.
By directly imaging the interplay of diffusion and the microturbulence at the ocean interface it gives a direct insight into the mechanisms. In addition, the CFT is insensitive to bubble-mediated transfer (heat is a tracer with very high solubility). Thus it will help to single out the influence of bubbles on air-water gas exchange.

7.Measurement of Marine Turbulence
In any experimental campaign to improve knowledge of air-sea gas fluxes, monitoring the agents of surface renewal is a prerequisite. A key aim in the development and refinement of instrumentation is thus to obtain measurements more closely related to the mass transports immediately below the surface. The leading challenge faced by all prospective techniques is to obtain usefully accurate turbulence measurements in the intense two-phase flow that occurs within a wave period after a wind-wave begins entraining air as it breaks, when much if not most of the gas exchange may take place.
Doppler techniques may be used remotely and thus safely below the zone of wave breaking, but each beam profiles only one component of the flow, and producing three coincident beams to yield particles' vector velocities may be difficult. Laser Doppler techniques give high spatial resolution but poor penetration, even of bubble-free water, making a deployment near to the wave-breaking zone necessary. Distinguishing between returns from particulates and microbubbles may also be problematic. Acoustic techniques have low resolution, and so might usefully be employed well below the waves, under minimal in-situ motion, to measure the large-scale vertical turbulent transport of bubbles, Doppler returns providing a means of

discriminating between the advection of bubbles through the beam and wave-breaking in it. Particle-imaging techniques show considerable promise in the laboratory for capturing the characteristic flows of low-energy breaking waves, but face great challenges at sea, in the seeding of particles, and from the in-situ motion, which aside from the dangers to the instrument, makes it difficult to measure turbulent intensities and stresses with respect to a fixed frame. Finally, a turbulence probe may be used to measure the actual (rates of dissipation of) turbulent kinetic energy, but does not reveal the instantaneous flow field.

8. Measurements in a wave-following mode.
In most models for the exchange of gaseous materials as well as of heat across the sea surface that surface is treated as a more or less homogeneous entity with certain specific properties, that may or may not be dependent on certain parameters, such as the wind. Immediately above the actual water surface, however, is an atmospheric layer the properties of which are strongly affected by the presence of surface waves. The strongest effects of waves on transport properties are due to the breaking of gravity waves and the related corruption of the water surface. But so-called microscale breaking of gravity-capillary waves will also introduce non-linear complexities that affect the surface flow - and with it the resistance - of the water surface. These processes manifest themselves in the properties of the air flow adjacent to the water surface. Study of this flow provides one of the rare pathways to study the surface properties which we need to know if we want to have a better understanding of the impact measurable parameters like wind speed and wave height and length have on transport processes. The development and application of instrumentation to measure the small scale structure of the water surface and to make wave following (flux) measurements in the atmosphere as close to the water surface as possible, indeed well below the level of the waves, should therefore be promoted.

9.Buoy systems as reference stations
Time series measurements of surface exchange variables will be valuable for verifying and improving regional and global ocean-atmosphere models which include detailed parametrisation of the bio-geophysical air-sea exchanges. Such measurements would also be used for verifying remote sensing estimates of air-sea exchanges. The significant progress in recent years in both sensor technology and data processing and telecommunications mean that it is now feasible to deploy autonomous instrumentation packages, both on ships of opportunity, drifting buoys and fixed, moored buoy platforms. For example autonomous buoy-mounted systems have been demonstrated for the air-sea fluxes of heat and wind stress and for components of the ocean CO2 budget. It is believed that autonomous measurements of water vapour and atmospheric CO2 fluxes will soon become possible (e.g. the AUTOFLUX project). On a longer time scale autonomous measurements of other gas and particle exchanges will become possible.
It is therefore recommended that reference sites be established, consisting of one or more moored buoys with both atmospheric and subsurface instrumentation, data

logging, processing and telecommunication facilities, and power supplies such that maintenance periods are at least a month and preferably more. Such sites should be maintained for periods of at least a year and be established in regions representing different climatic and bio-geophysical regimes. A complimentary approach should be the deployment of autonomous instrumentation on ships of opportunity (e.g. Voluntary Observing Ships of the World Weather Watch system).
This proposal could contribute to monitoring and detection of global change processes and be a contribution to the Global Ocean Observing System.

10. Remote sensing algorithms.
Remote sensing techniques, using instrumentation aboard satellites are of great importance for studies on air-sea interaction, providing regional to global coverage. Radiometers allow for spatial resolution starting at about 1x1 km^2, up to thousands of km^2. Some selected properties of and near the water surface, such as sea surface temperature (SST), wind speed and ocean colour are already routinely available.
To study the increased greenhouse effect we need to know the way in which anthropogenic CO2 is distributed over the three main reservoirs: atmosphere, solid earth and oceans. This requires an accurate knowledge of the air-sea gas fluxes of this gas, which so far has been lacking. As a contribution to the resolution of this problem new parameterizations for the transfer coefficients involved, based on the study of physical processes rather than on phenomenology, are being developed within the ASGAMAGE and LUMINY projects. To calculate the total amount of CO2 sequestered in the oceans in comparison with the terrestrial sink we additionally need to know the global distribution of the wind speed and of the partial pressure difference of the gas between water and air. The surface wind can be derived from radar backscatter measurements by, e.g., the synthetic aperture radar (SAR) on the ERS-2 satellite. The information on the partial pressure difference, however, is not a priori available from satellites, and need to be derived from ground measurements and relations of these with ambient parameters such as SST and chlorophyl concentrations, which can be derived from satellite observations. A problem requiring attention in this connection is to distinguish the reflection of the water surface from the reflection by aerosols, i.e. the atmospheric correction. Techniques are evolving to accurately determine the contribution of aerosols to the radiance received by satellite radiometers. The results can then be applied in the atmospheric correction for the derivation of other parameters. This requires a synergetic approach involving the use of several radiometers on the same satellite.
Technical features, offered by new sensors, offer great opportunities to improve the quality of the retrieved data. Synergy between several instruments on the same satellite is expected to contribute to a better data product. Further development of algorithms is necessary for use with the new instruments expected for the near future. They will extend the suite of data available as well as their quality and hopefully lead to the much needed improved understanding of air-sea-ice interaction processes on a global scale.

11.Deep sea particle flux sensors

Vertical fluxes of biogenic and non-biogenic particles through the water column are important for quantifying geochemical cycling of elements such as C, Si, and P, and in particular to quantify the interaction between the different earth subsytems. Measurements of marine particle fluxes by sediment traps in many cases do not show a monotonuous decrease of flux but spurious particle sources in the water column which are unrealistic.

Therefore a further refinement of sediment trap sampling systems is required, especially an independent method to check the results of existing trap methodology. Control or "double-check"-devices could potentially monitor the sediment traps through optical, acoustical or other methods. Furthermore more precise bottom flux sampling equipment is needed in order to quantify exactly the deposition of material onto the ocean floor. This would provide evidence for long term evolutions of a possible imbalance between matter fluxes which enter the ocean via river runoff as well as aeolian transport and the accumulation of matter in the sediments after having passed the chemically active bioturbated sediment pore waters.

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Annex I – Programme

Mast Projects Meeting : Objectives, Results & Links

Air-Sea-Ice Studies : Processes, Modelling and Instrumentation

Brussels, January 7-8, 1999
EC, Rue Montoyer 75, Room R5

Programme

Thursday, January 7

09:30	Welcome and Introduction *C. Patermann, Director DG XII-D* Organisation *E. Lipiatou, MAST Programme*

Project Presentations
Chair: E. Lipiatou

10.00 – 10.20	**BALTEX-BASIS** *MAS3-CT97-0117* Baltic Air-Sea-Ice Study Prof. Jouko Launiainen, Finnish Institute of Marine Research
10.20 – 10.40	**AUTOFLUX** *MAS3-CT97-0108* An Autonomous system for monitoring air-sea fluxes using the inertial dissipation method and ship mounted instrumentation Dr. Soeren E. Larsen, Risoe National Laboratory
10.40	Coffee Break
11.00 – 11.20	**MASTOC** *MAS3-CT97-0138* Micro analytical system for total organic carbon in sea Dr. Frank Zuther, Institut fuer Chemo- und Biosensorik, Muenster, e.V.
11.20 – 11.40	**SINOPS** *MAS3-CT97-0141* Silicon cycling in the world ocean: controls for opal preservation in the sediment as derived from observations and modelling Dr. Christof Heinze, Max-Planck-Institut fuer Meteorologie
11.40 – 12.00	Discussion
12:00	Lunch

13.30 – 14.15	Information on the Fifth Framework Programme *J. Boissonnas - MAST Programme*

Project Presentations / continued
Chair: W. Oost - KNMI - NL

14.15 – 14.45	**ESOP 2** *MAS3-CT95-0015* European subpolar ocean programe phase 2 : the thermohaline circulation in the Greenland Sea Prof. Eystein Jansen, University of Bergen, Norway
14.45 – 15.15	**IMCORP** *MAS3-CT95-0023* Instrumentation for marine CO2 from remote platforms Prof. Andrew J. Watson, University of East Anglia, United Kingdom
15.15	Coffee Break
15.45 – 16.25	**MERLIM** *MAS3-CT95-0005* Marine ecosystems regulation: trace metals and carbon dioxide limitations Dr. Hein J.W. de Baar, Netherlands Institute for Sea Research (NIOZ), the Netherlands Dr. C. Stan Van den Berg (University of Liverpool)
16.25 – 17.10	**ASGAMAGE** *MAS3-CT95-0044* The Asgasex Mage experiment/ Asgasex: air-sea gas exchange programme / Mage Dr. Wiebe A. Oost, Royal Netherlands Meteorological Institute (KNMI), the Netherlands
17.10 – 17.30	Presentation of the conclusions of the MAST workshop on Air-Sea Exchange : Processes and Modelling Dr. Jozef Pacyna, NILU, Norway
17.30 – 18.00	Discussion – organisation of the next day's working group

Friday, January 8

09.30	Working group discussions on research achievements and needs/Links amongst projects
10.15	Coffee Break
10.30	Working group discussions on research achievements and needs/Links amongst projects
12:00	Lunch
13.30	Continuation of working group discussions/Conclusions
17:00	End of meeting

Annex II – List of participants

Air-Sea-Ice Studies : Processes, Modelling and Instrumentation

Brussels, January 7-8, 1999 MO 75, R5

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EUR 18638 — Air–sea and sea–ice interactions

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In the marine science and technology programme, several projects deal with processes, modelling or instrumentation of air–sea–ice interactions. These subjects will continue to be important in the fifth framework programme of the EC.

In this context, the coordinators and principal investigators were invited to Brussels for a workshop on 7 and 8 January 1999. The objectives of the workshop were to present the main results of these projects, what questions had been answered, and what new questions had emerged. This meeting was a follow-up to the MAST workshop on air–sea exchange held in Norway in 1997 (EUR 17660).

This new publication presents the discussions and recommendations of the Brussels workshop participants. One of the recommendations described therein was that policy-makers, in order to negotiate or support conventions implying air–sea exchange, need better information on how to reduce uncertainties about processes and their impact.

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