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Adriatic Sea hydrography*

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SUMMARY: This paper is intended as a short summary of 20 years of research on the Adriatic Sea carried out by the Oceanography Department of IRPeM-CNR. The objective is to give a general overview of the sea and describe the environment in which anchovies live. The Adriatic Sea is a narrow basin elongated from north-west to south-east for about 800 km with a maximum width of 200 km at Bari and a minimum width of 100 km in front of Rimini. It communicates with the Ionian Sea through the Otranto Straits (74 km wide and 800 m sill depth). It is the most continental sub-basin of the Mediterranean, defined between two mountain chains: the Apennins to the west side and the Dinaric Alps and Balkans to the east. The Adriatic can be divided into three distinct sub-basins: Northern, Middle and Southern. Due to the geographical position, its orography and bathymetry, the Adriatic Sea hydrography is strongly influenced by meteorological conditions, particularly in the north. Climatologically, temperature variations greater than 20°C are observed between winter and summer, and about 8 °C from north to south in winter, as well as a salinity gradient of about 3 psu (practical salinity unit) between the western coastal water and the offshore water. Interannual variability has been evident from the first systematic oceanographic observations of this sea and is remarkable. There are three principal water masses in the Adriatic Sea: the Adriatic Surface Water (AdSW), the Levantine Intermediate Water (LIW) and the Adriatic Deep Water (AdDW) (every sub-basin has its own characteristic deep water). The general circulation is cyclonic with a flow towards the northwest along the eastern side and a return flow towards the southeast along the western side. The circulation in the three sub-basins is often dominated by their own cyclonic gyres that vary in intensity according to the season. The sub-gyre of the southern Adriatic tends to persist throughout the year. The sub-gyre of the middle Adriatic is more pronounced in summer and autumn, while in the north, a cyclonic gyre is evident, in front of the Po river mouth, only in autumn.

Key words: Physical oceanography, water masses, general circulation, climatology, Adriatic Sea.

RESUMEN: HIDROGRAFÍA DEL MAR ADRIÁTICO. – En este trabajo se presenta un breve resumen de 20 años de investigación en el mar Adriático llevada a cabo por el departamento de Oceanografía del IRPeM-CNR. El principal objetivo es dar una visión general del ambiente en que habita la anchoa. El mar Adriático forma una cuenca estrecha que se alarga unos 800 km de noroeste a sureste, con una anchura máxima de 200 km frente a Bari, y una anchura mínima de 100 km a la altura de Rimini. El Adriático comunica con el mar Jónico a través del estrecho de Otranto (74 km de ancho y 800 m de profundidad). Es la sub-cuenca más continental del Mediterráneo, situada entre dos cadenas montañosas: los Apeninos al oeste y los Alpes Dináricos y Balcanes en el este. El Adriático puede dividirse en tres sub-cuencas: Norte, Media y Sur. Debido a su situación geográfica, su orografía y batimetría, la hidrografía del mar Adriático está fuertemente influenciada por las condiciones meteorológicas, particularmente en el norte. Climatológicamente, se observan variaciones de temperatura de más de 20 °C entre invierno y verano, y de unos 8 °C de norte a sur en invierno, así como un gradiente de salinidad de cerca de 3 psu entre las aguas de la costa oeste y las de mar afuera. La variabilidad interanual desde las primeras observaciones sistemáticas es evidente y remarcable. En el mar Adriático hay tres masas de agua principales: La adriática superficial (AdSW), la intermedia levantina (LIW) y la adriática profunda (AdDW) (cada sub-cuenca tiene su propia agua profunda característica). La circulación general es ciclónica, con un flujo hacia el noroeste a lo largo de la costa este y un flujo de retorno hacia el sudeste a lo largo de la costa oeste. La circulación en las tres sub-cuencas está dominada a menudo por giros ciclónicos, que varían en intensidad según las estaciones. El sub-giro del Adriático sur tiende a permanecer durante todo el año. El sub-giro del Adriático medio es más pronunciado en verano y otoño, mientras que en el norte, el giro ciclónico es solo eviente en otoño (Traducido por los editores).

Palabras clave: Oceanografía física, masas de agua, circulación general, climatología, Adriático.

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INTRODUCTION

The Adriatic (Fig. 1) is the most continental basin in the Mediterranean Sea (excluding the Black Sea), is enclosed between two mountain chains (Appennini and Balkans) and elongated latitudinally. It has a major axis (oriented from SE to NW) with a length of 800 km and a mean width of 180 km, and is connected to the Ionian Sea by a strait (Otranto) only 74 km wide.

The basin shows clear morphological differences, along its longitudinal axis and the transversal one as well, and it is divided into three sub-basins (Artegiani *et al.*, 1996 a). The northern sub-basin spans from the northernmost part to the 100 m bathymetric line (in front of Giulianova, Italy) and is characterised by an extremely shallow mean depth (about 30 m) with a very weak bathymetric gradient along the major axis, and by a strong river runoff (~ 3000 $m^3 s^{-1}$) relative to the receiving basin; in fact, Po and the other northern Italian rivers are believed to be the source of about 20% of the total Mediterranean river runoff (Hopkins, 1992).

The middle Adriatic is a transition zone between the northern part and the southern sub-basin which shows some open sea conditions. This central zone spans from the 100 m contour to the Pelagosa sill (about 170 m depth), located around the line connecting Vieste and Split. It is characterised by two depressions, the Pomo (or Jabuka) Pits, having a maximum depth of about 270 m.

The southern sub-basin extends from Pelagosa sill to Otranto sill which divides it from the Ionian Sea. Each of the western and eastern coasts have a narrow continental shelf (20-30 km wide to the shelf break at 200 m depth), a steep continental slope reaching 1000 m and a fairly flat abyssal plain, with a maximum depth of 1270 m (often referred to as the south Adriatic Pit).

The entire western coast is generally regular, sandy and with a gentle slope, while the eastern coast is irregular, with many islands, and a rocky steeply sloping bathymetry.

The Adriatic Sea circulation is strongly influenced by winds, with significant differences between winter and summer wind regimes. During winter season, meteorological depressions pass over the Adriatic Sea, the first sector of the cyclone exposes the sea to warm Saharan air, which along its path on the Mediterranean Sea increases its humidity. This wind is called Scirocco, and blowing from the southeast it establishes the sea level of the north

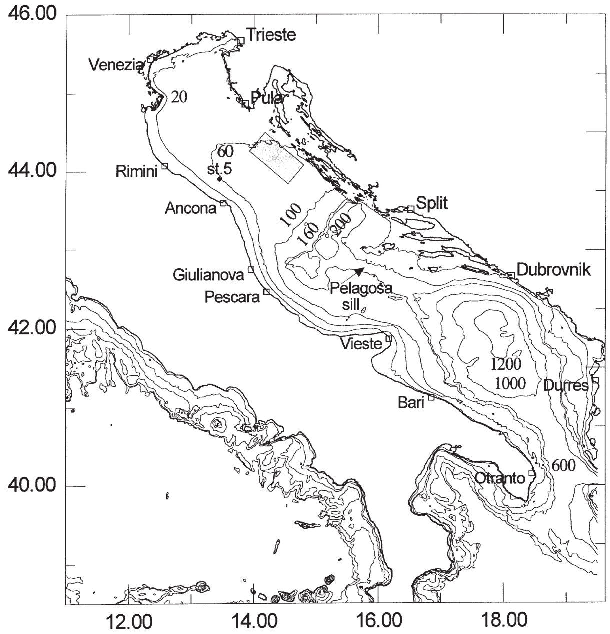

FIG. 1 – Adriatic Sea coastline and bathymetry.

Adriatic Sea (mostly responsible for the “high water” phenomena in Venice). As the cyclone passes, the winds reverse and expose the Adriatic Sea to a polar continental air mass coming from the north over central Europe. This is the so called Bora wind, which is very dry, cold and strong, and blows over the Adriatic Sea from the north and north-east. Bora wind may also occur when a anticyclone develops over Central Europe while there is a low pressure area over the Mediterranean Sea. In summertime, besides local breezes, the dominant wind - the Maestrale - comes from the northwest.

Climatological studies about the heat content of the water column (Artegiani *et al.*, 1996 a) have resulted in the following definition of the Adriatic marine seasons: winter spans from January to April, spring occurs in May and June, summer goes from July to October, and autumn occurs in November and December. Moreover, these studies confirm that the Adriatic Sea is a dilution basin (precipitation plus river runoff is greater than evaporation, with a fresh water gain of 1.14 ± 0.20 m per year). At the same time the Adriatic Sea imports heat (it has been computed that there is a surface heat loss of 19-22 W m^{-2} per year); hence salt and heat balances are maintained through the water exchanges across the Otranto Straits, where relatively fresh and cold waters leave the Adriatic basin and warmer, saltier waters enter from the Ionian Sea in the Adriatic Sea.

WATER MASSES

We have classified the various water mases of the Adriatic Sea (Table 1) on the basis of ATOS.1 (Adriatic Temperature Oxygen Salinity data set, Artegiani *et al.*, 1996 a), formed by 5483 historical casts in "open sea". Deep waters, in particular, are defined in terms of mean values and standard deviations from this data set.

Some of the Adriatic water masses originated inside the basin and some other come from outside the basin. The Levantine Intermediate Water (LIW) enters the Adriatic Sea through the Otranto Straits. They originate in the Levantine basin and are distinguishable by the intermediate salinity maximum in the water column. Also arriving through the Otranto Straits are the Ionian surface waters, which enter in the Adriatic Sea. The Atlantic Surface Water (ASW) enters the Mediterranean Sea, through the Gibraltar Straits, and then follows the African coast. Of the ASW passing through the Sicily Straits into the Ionian Sea, there is a sub-branch that flows northward toward Otranto (Artegiani *et al.*, 1988). The ASW along its path is distinguishable by a subsurface salinity minimum.

The most important water masses originating in the Adriatic Sea are the bottom waters, which are the main source of the Eastern Mediterranean bottom waters (Pollack, 1951; Hopkins, 1978; Roether and Schlitzer, 1991).

A certain amount of the Adriatic bottom waters is formed in the northern sub-basin, the NAdDW (Northern Adriatic Deep Water), characterised by a very low temperature, relatively low salinity and high density ($\sigma_t > 29.2$). The processes generating NAdDW start in December with the preconditioning phase; this consists in the homogenisation of the whole water column, the last one being about 30 m on average. During January and February the water column continues to loose heat, and when the Bora wind blows from the eastern coast over the Northern Adriatic it causes strong evaporation and cooling in a few days, forming a certain quantity of NAdDW. NAdDW are usually observable on the bottom of the Northern Adriatic in winter and spring; the characteristics of new formed NAdDW vary significantly from year to year according to the meteorological and oceanographic conditions during the winter.

MAdDW (Middle Adriatic Deep Water) are observed all the year at the bottom of the Pomo Pits, below the depth of the Pelagosa Sill, and are characterised by $\sigma_t > 29.1$. NAdDW formed in the Northern Adriatic flow along the western side of the basin and, if their density is high enough, they can invade the Pomo Pits in spring, renewing the MAdDW. During this event, a not well quantified amount of NAdDW and MAdDW enters in the southern sub-basin.

Most of the Adriatic bottom waters are formed in the southern Adriatic sub-basin (Roether and Schlitzer, 1991; Artegiani *et al.*, 1996 a). They are named South Adriatic Deep Water, SAdDW, and are warmer and saltier than NAdDW and MAdDW. The formation processes of SAdDW are quite different in respect of NAdDW, probably being formed in winter via convective cells and subsequent mixing with LIW. The Adriatic bottom waters are the main source of the eastern Mediterranean bottom waters (Pollack, 1951; Ovchinnikov *et al.*, 1985).

The amount and the sites of formation of the named deep water masses are not well studied; to date no experimental project was dedicated to this issue.

TABLE 1. – Characteristics of the Adriatic Sea water masses.

Water mass	Temperature (°C)	Salinity (psu)
NAdSW Northern Adriatic Surface Water	<11.5 (in winter)	<38.0
MAdSW Middle Adriatic Surface Water	>11.5 <13.5 (in winter)	>38.0 <38.5
SAdSW Southern Adriatic Surface Water	>13.5 (in winter)	>38.3 <38.6
NAdDW Northern Adriatic Deep Water	11.35 ± 1.4	38.3 ± 0.28
MAdDW Middle Adriatic Deep Water	11.62 ± 0.75	38.47 ± 0.15
SAdDW Southern Adriatic Deep Water	13.16 ± 0.3	38.61 ± 0.09
LIW (Middle Adriatic) Levantine Intermediate Water		>38.5
LIW (Southern Adriatic)	>13.5	>38.6

CIRCULATION AND VARIABILITY

From the historical data analysis performed by Zore-Armanda (1956) and more recently by Orlic *et al.* (1992) and Artegiani *et al.* (1996 b), a surface general circulation composed (Fig. 2) of two branches, one flowing northward along the Albanian-Croatian coast and the other flowing southward along the Italian coast, is described. The flow along the western (Italian) coast results from these three sub-basin currents, one for each sub-

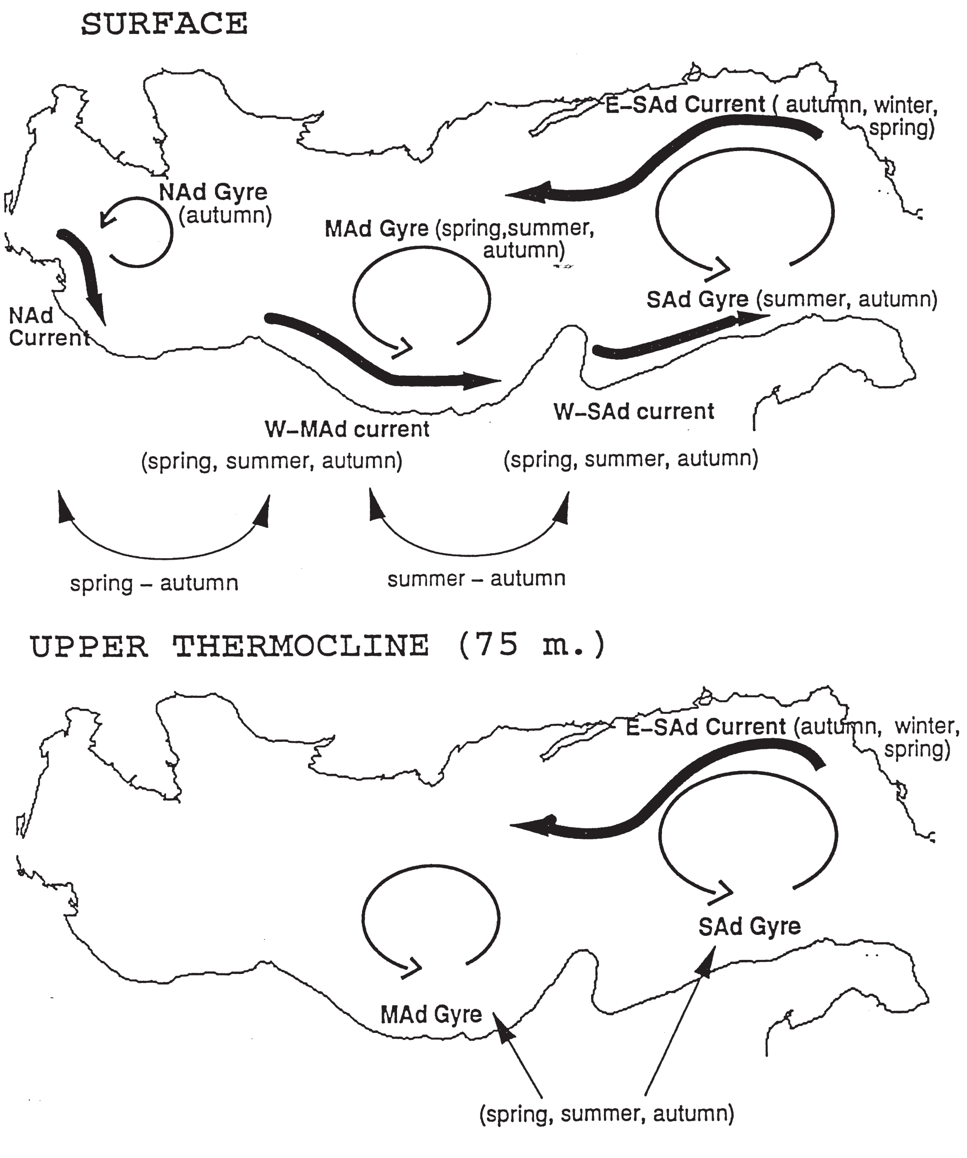

FIG. 2 – Schematic of the Adriatic Sea general circulation (from Artegiani et al., 1996 b).

basin, that only in autumn are connected with each other. The three sub-basins exhibit, with a certain seasonal variability, a cyclonic circulation. In summer and autumn it was possible to identify a cyclonic gyre in the Southern Adriatic Sea, despite a relative scarcity of data. This gyre partially traps the waters coming from the Ionian Sea in the sub-basin. In the middle Adriatic Sea, during summer and autumn seasons, there is a cyclonic gyre that partially decouple the northern Adriatic system from the remaining part of the basin. In the northern Adriatic a defined cyclonic gyre is present during the autumn season only.

75 m (lower part of Fig. 2), circulation is quite similar to that at the surface, with two exceptions:

1. there is no current along the Italian coast; this current interests only the shallow area close to the coast, this means that the outflow from the northern Adriatic is confined to a narrow area along the Italian coast;

2. the southern Adriatic Gyre is present in spring, too.

This is the climatological seasonal behaviour of the circulation on the basis of the baroclinic component; however, we have to consider that the barotropic component overlaps (and, in wintertime, often dominates) the baroclinic one.

The Adriatic Sea is a continental basin and therefore it shows strong variability both in space and time, which has a great consequence on biological aspects.

SPATIAL VARIABILITY

Seasonal objective analyses of ATOS.1 data are showed in Figs. 3, 4, 5 and 6. Data were pre-averaged with a 12 km search radius and interpolated on a 8 by 8 km grid, using a correlation scale of 100 km and a decay scale of 60 km (chosen according to the basin scales, because climatologically we have to consider basin-wide scales, not sinoptic or mesoscales). More details are reported in Artegiani *et al.* (1996 b).

Climatological maps of sea temperature at 5 m depth (Fig. 3) show a pronounced thermal gradient along the longitudinal basin axis in winter, while in

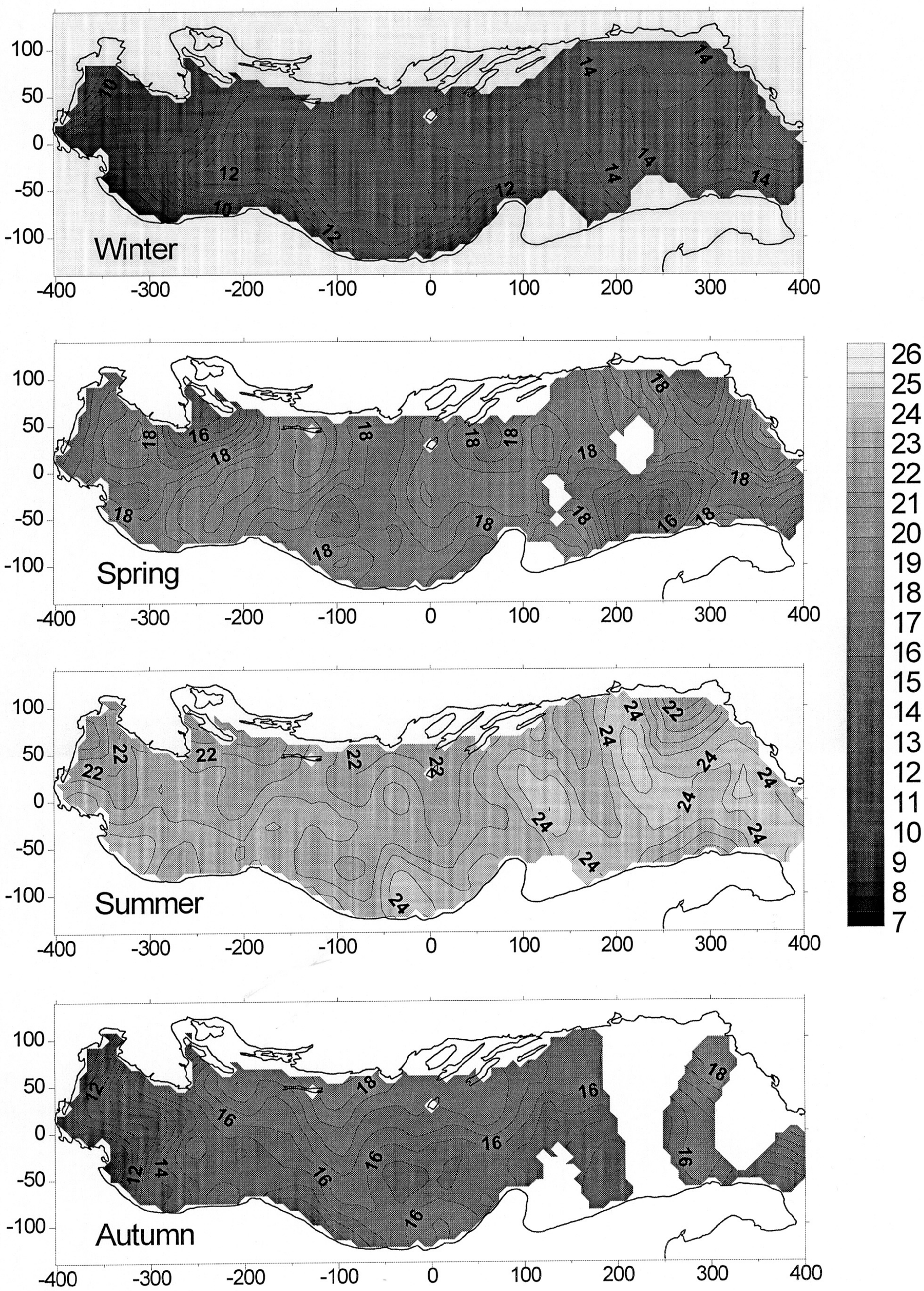

FIG. 3 – Seasonal temperature (°C) maps at 5 m depth. The contour interval is 0.5 °C, the field is plotted for expected error less than 30%.

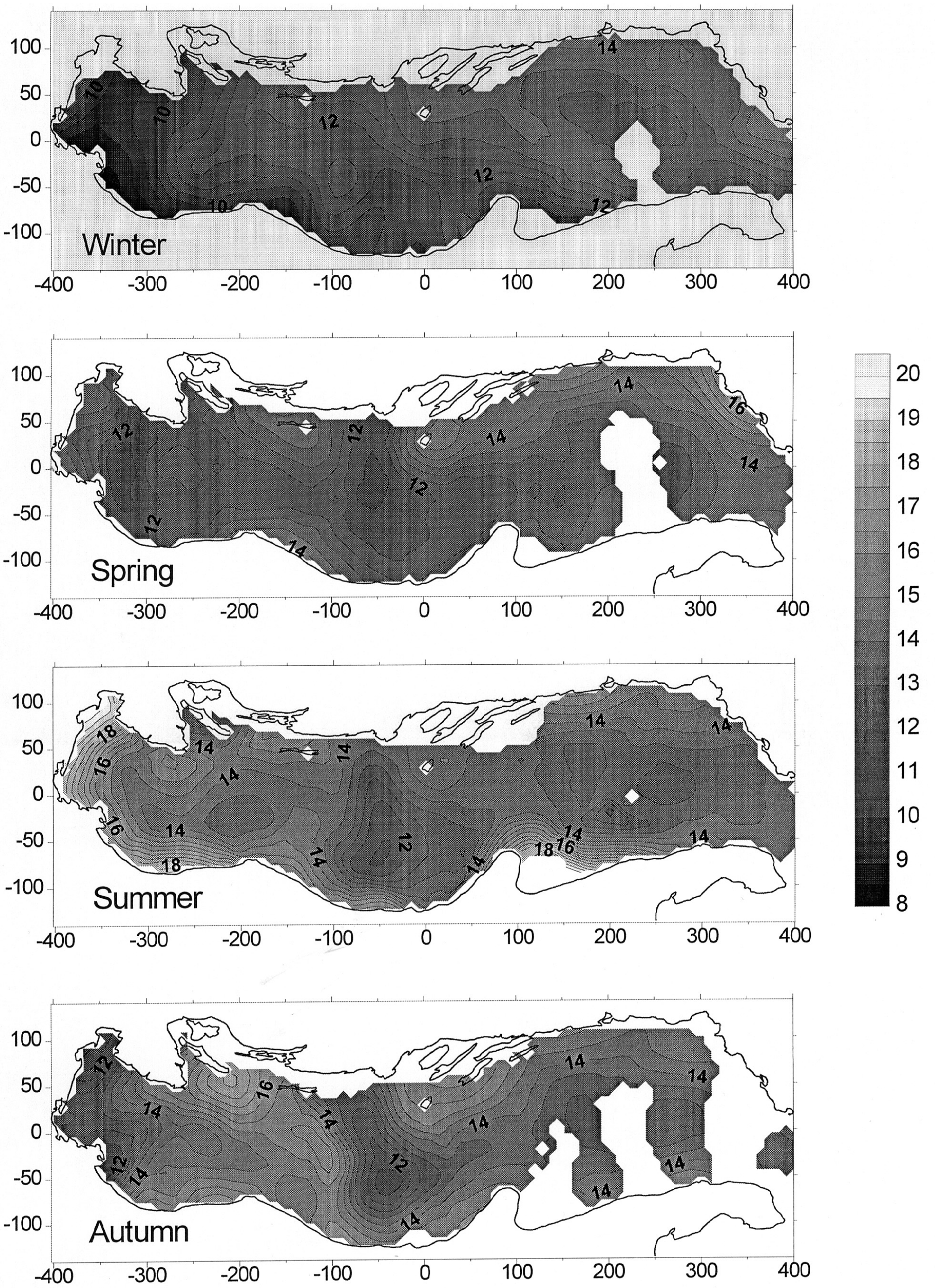

FIG. 4 – Seasonal temperature (°C) maps at bottom. The contour interval is 0.5 °C, the field is plotted for expected error less than 30%.

summer the gradient is almost flat. This is a consequence of the combined action exercised by heat fluxes and shallowness of the northern Adriatic Sea. From Artegiani *et al*. (1996 a), the northern Adriatic undergoes a greater heat loss than southern Adriatic in autumn-winter, while in summer, the southern sub-basin receives more heat than the northern one. This is a latitudinal effect, with some contribution of different wind regimes. The extreme shallowness of the northern Adriatic modifies the effects of the heat fluxes on the water column temperature. In winter, it becomes extremely cold because the vertical convection is limited by the shallow sea bottom, and in summer, despite the scarce heat fluxes, the temperature reaches values comparable to the southern sub-basin. That is because the mixed layer

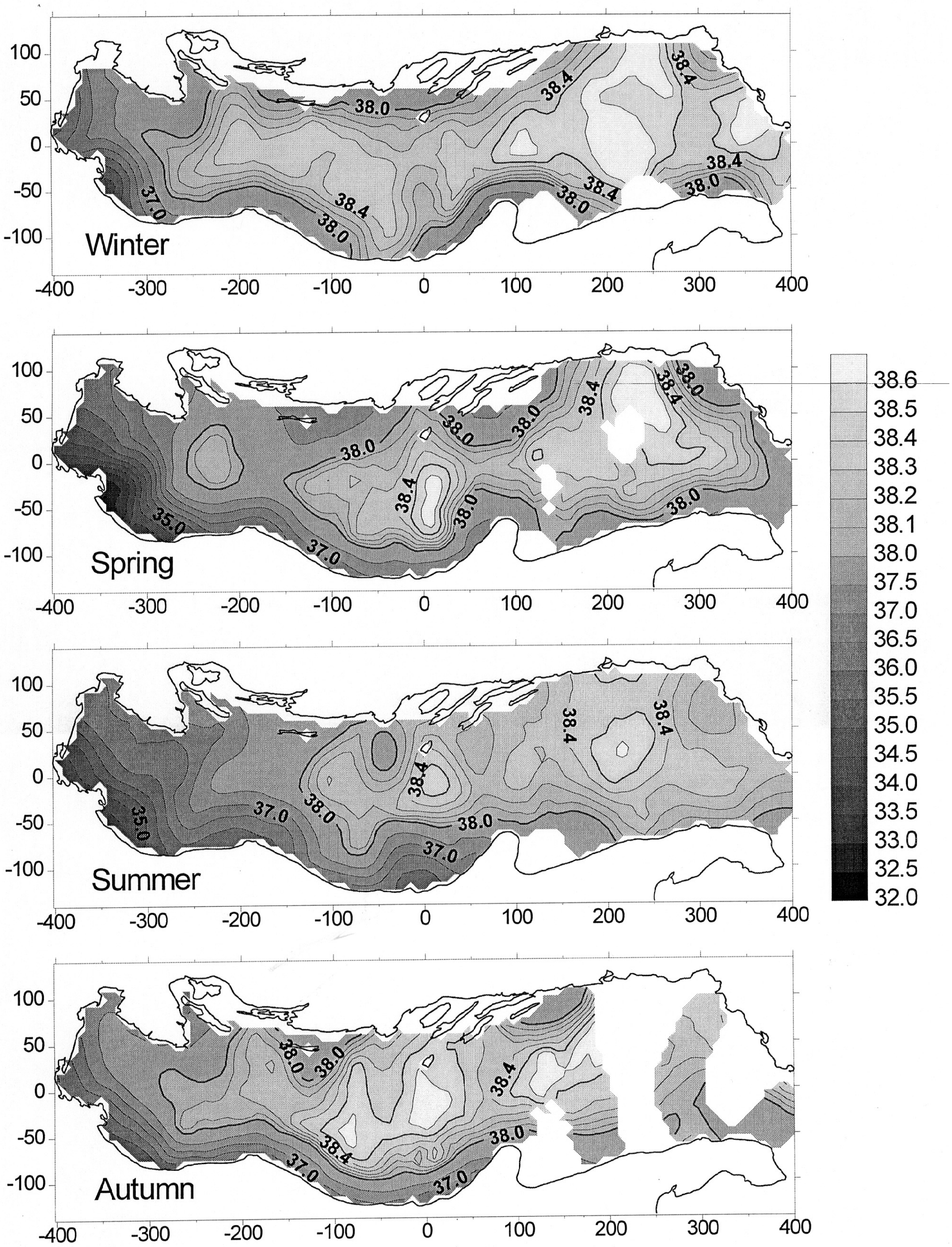

FIG. 5 – Seasonal salinity (psu) maps at 5 m depth. The contour interval is variable (as indicated by gray scale), the field is plotted for expected error less than 30%.

is thinner than the Southern one, due to the sub-basin shallowness and the thermal stratification enhanced by the haline one.

During winter and autumn, the waters near the western coast are cooler than those of the Eastern coast. This transversal gradient is more evident in the northern and middle sub-basins, while during the summer period there is a quasi-homogeneity, with temperature values along the eastern border slightly lower than those ones along western shores.

During winter, the bottom layer (Fig. 4) exhibits a longitudinal thermal gradient with about the same magnitude as the one of the surface layer, while the transversal gradient is steeper in the middle part of the basin, again with lower temperature along the western coast. In summer, the bathymetric effect

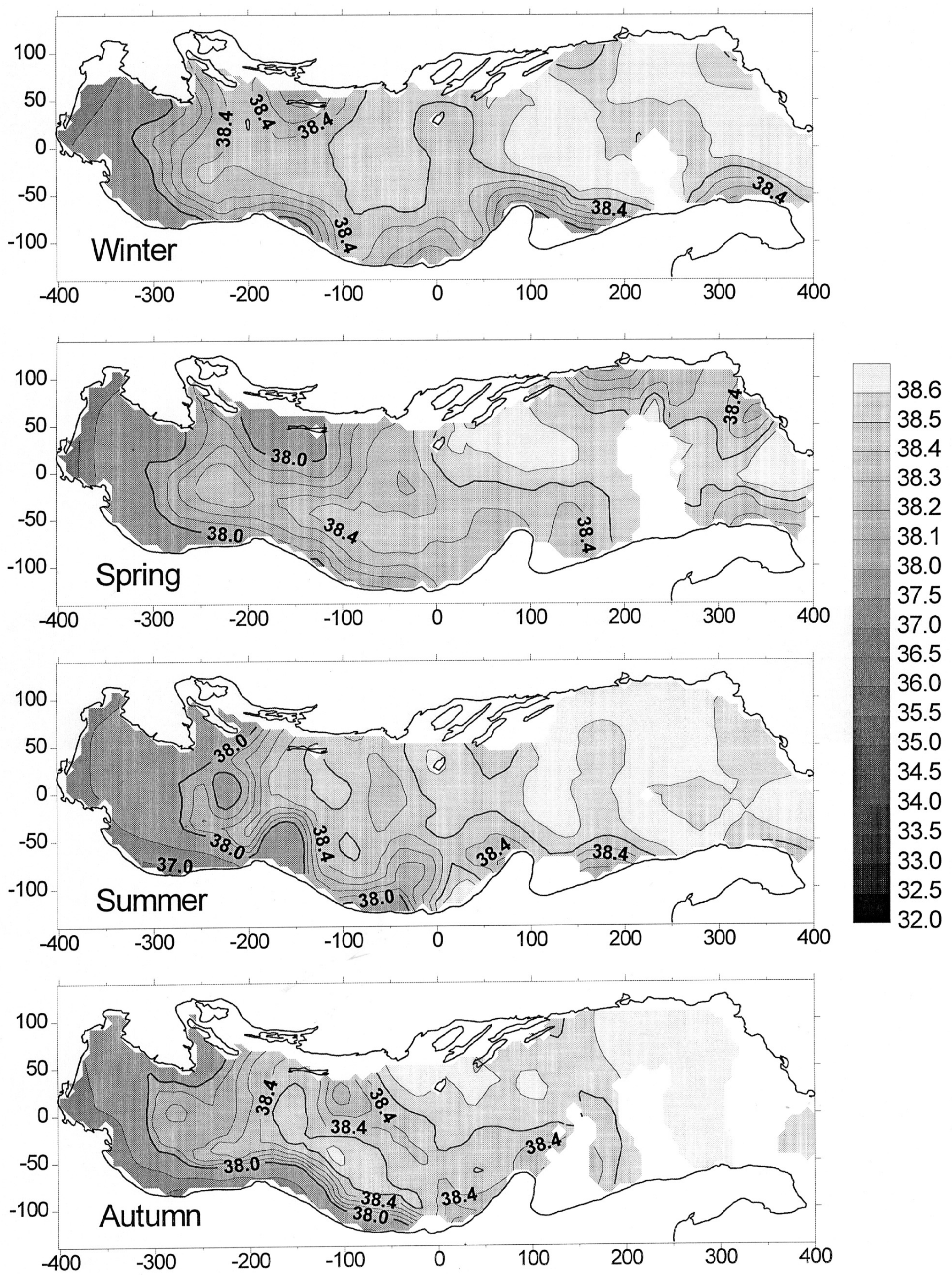

FIG. 6 – Seasonal salinity (psu) maps at bottom. The contour interval is variable (as indicated by gray scale), the field is plotted for expected error less than 30%.

(intending that the temperature gradients are at the same locations of topographic gradients) is evident: we observe higher temperatures in the northern part and along the western coast and lower temperature in the southern part and along the eastern coast. For what concerns transition seasons, spring conditions are more similar to the summer ones, and autumn conditions are nearer to the winter ones.

The distribution of salinity in the surface layer (Fig. 5) is strongly influenced (especially in the northern part and along the western coast) by river outflow, above all Po and other northern rivers. Albanian rivers (Raicich,1994) have a certain influence along the Albanian shore and along the coast northwards. During winter, river waters are confined near the coast, forced by vertical homogeneity of the water column due to wind forcing on the shallow water column, whereas during summer, thermal stratification allows a wide horizontal distribution of these river waters inside the basin (vertically they are confined within the mixed layer, 10-30 m thick). The 38.0 psu isohaline is located near the coast during winter, while during spring and summer, it spreads southward and offshore. We consider 38.0 psu isohaline because this is the mean salinity value (computed from ATOS.1 data) of the surface layer in the rectangular area reported in figure 1; we can consider that area as not directly affected by the freshwater discharged by Italian rivers.

Salinity at the bottom (Fig. 6) shows a different behaviour in respect of the surface layer. Salinity values are generally higher, almost never below 37 psu. In the Northern Adriatic the area with salinity < 38.0 psu remains almost the same in every season, generally confined within the 40 m isobath.

TIME VARIABILITY

Seasonal

The Adriatic Sea has the greatest observed seasonal thermal gradient in the Mediterranean Sea, especially in the northern Adriatic, where near the coast the surface temperature ranges from about 5°C in winter until 27°C in summer (from Fig. 3 and from minimum and maximum values of ATOS.1 data). Variations are more limited offshore, with a range of 10-12°C. Salinity variations are obviously much greater near the coast than offshore, and are related to variations in Po runoff, which show a two maxima in spring (May) and autumn (November) and a minima during summer (August) and winter (January), as shown in figure 7. At the bottom, seasonal variation of salinity are rare, and mostly due to the NAdDW cycle. Salty waters (S > 38.4 psu) have their maximum extension both at the surface and bottom layer of the middle-northern sub-basins during autumn and winter.

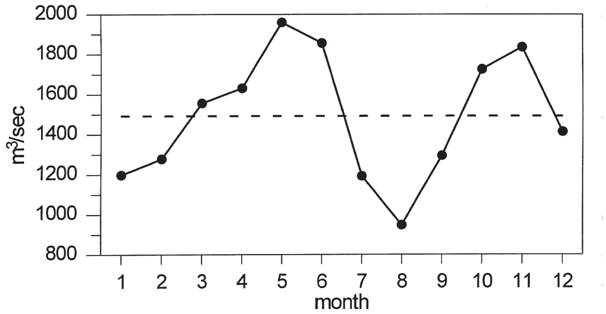

FIG. 7 – Monthly average (from 1918 to 1992) of Po river flow rate (m^3/s).

Interannual

A strong interannual variability, particular for salinity, has been observed in the Adriatic Sea start-

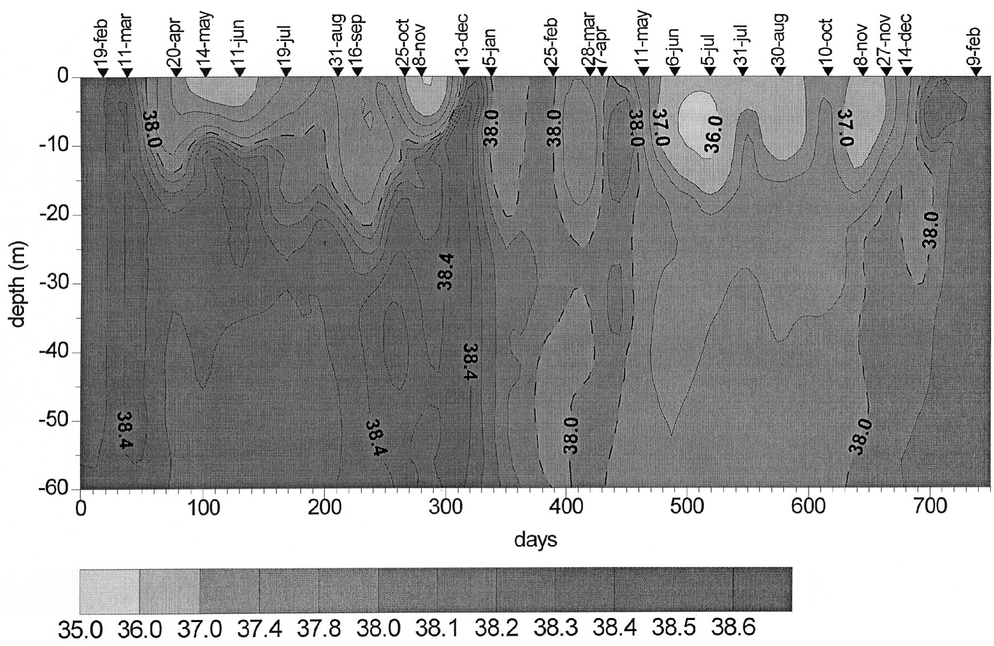

FIG. 8 – Time evolution of salinity (psu) during two years, from February 1, 1993 (left) to February 15, 1995 (right) at the station n° 5, 15 nm offshore Senigallia (North of Ancona). Sampling dates are reported on the top axis; the location of the station is reported on Fig. 1.

ing from the beginning of oceanographic observations (Buljan and Zore-Armanda, 1976 and Zore-Armanda *et al*. 1991). During some severe winters, marine ice was formed near the coast of the north-eastern part of the Adriatic Sea (Buljan and Zore-Armanda, 1976). At Pelagosa area, over a period of 36 years from 1947 to 1983 (Artegiani *et al*., 1996 a), range of variation of about ±0.5 psu around the mean salinity value has been observed at the surface. At 100 m, variations are still considerable (about ±0.4 psu). A station located 15 nautical miles offshore Senigallia (st. 5 in Fig. 1) was sampled monthly during two years by IRPEM. The time evolution of salinity along the water column measured with a CTD Sea Bird 9/11plus is reported (Fig. 8). It is evident that during 1994 salinity was not more than 38.0 psu, about 0.5 psu less than that observed during 1993. An hypothesis (Artegiani *et al*., 1996 c) to explain this fact could be found in the meteorological conditions. Bora wind during the winter of 1993-94 blew less than during winter 1992-93, while the behaviour of the Scirocco wind was opposite (Archivi dell'Istituto Talalassografico di Trieste del CNR, unpublished). This implies a minor deep water formation during 1993-94 (in fact along the Senigallia transect we observed a very little amount of NAdDW during this period) and a longer residence time of northern Adriatic waters (Hopkins *et al*., 1996). Longer residence time implies that northern Adriatic waters become fresher and fresher due to Italian river runoff (Po river mean runoff was almost the same, only slightly greater during 1994 than during 1993).

MESOSCALE AND UPWELLING

Inputs from the Po and other Italian rivers are mostly confined near the western coast, but a certain quantity is transferred offshore by means of Ekman transport and mesoscale circulation.

The Adriatic Sea circulation has a mesoscale component that should be relatively intense. IRPeM accomplished the first Adriatic mesoscale experiments (AMEX-I e II, 1988 and 1993) and showed that water mass exchange between the coastal area and the offshore area happens by means of mesoscale eddies. In the Middle Adriatic, eddies are characterised by a spatial scale of 10-30 km and a time scale of one month (Paschini *et al*., 1993; Masina and Pinardi, 1994). These scales are remarkably smaller than those of other basins located at the same latitude.

The other major mechanism of water transfer between coastal and offshore areas is Ekman transport. In the Adriatic area, the Scirocco winds blow parallel to the Italian coast, dragging offshore the western coastal waters, allowing upwelling of deeper waters. On the other side of the basin, Croatian researchers have recorded several upwelling events along the eastern coast and islands as a result of Bora and Maestrale winds (Buljan and Zore-Armanda, 1979). Such phenomena have an influence on the fishery in the Adriatic area.

CONCLUSIONS

The peculiar water masses and circulation scheme of the Adriatic Sea have an obvious influence on biology and, in particular, on small pelagic fishes such as anchovy. We tried in this paper to give a general description of the physical environment in which anchovy live. The main remarks regard the seasonality of the circulation and the great seasonal and interannual variability of temperature and salinity. The general circulation is cyclonic; a northward current flows along the eastern coast, while a southward, not well connected current flows along the western coast. Each sub-basin has a cyclonic gyre (the northern one is climatologically evident in autumn only).

The northern sub-basin has peculiar characteristics, due to its shallowness and to the great river runoff (about 20% of total Mediterranean river runoff). Ther is high dilution in this area, but it is also (in winter), a densification area with important (depending on interannual variability) formation of dense waters (NAdDW).

The middle Adriatic sub-basin is characterised by a cyclonic gyre located on the Pomo Pits. This is another quite peculiar area, with a dense water mass (MAdDW) always observed in the Pits. MAdDW from spring to autumn are the coldest and densest waters of the Adriatic and eastern Mediterranean.

The southern sub-basin has been the object of few observational programs. Its water mass characteristics are more similar to the eastern Mediterranean, having a relatively large mass exchange with the Ionian Sea (Zore-Armanda, 1963, evaluated about $0.2\text{-}0.5 \cdot 10^6 m^3 \cdot s^{-1}$ of water exchange at Otranto). It is the site of dense water formation, and it is the main source of the eastern Mediterranean bottom waters.

The importance of spatial and time variability of the physical parameters is evident, as well as the importance of fresh water and meteorological conditions.

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