Adriatic Sea
Water masses
General circulation
Wind and thermohaline forcing
Inertial and tidal currents

Mer Adriatique
Masses d'eau
Circulation générale
Vent et forçage thermohalin
Courants inertiaux et courants de marée

The currents and circulation of the Adriatic Sea

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ABSTRACT

This paper reviews the present state of knowledge of the Adriatic general circulation and its higher-frequency current variability. All studies show that the surface circulation consists of a large-scale cyclonic meander with several smaller cells embedded in it, and that the circulation system is modulated seasonally. Water mass analyses and direct current measurements indicate that the cyclonic meander also occurs in the intermediate layer, dominated by the current that inflows along the eastern coast. In the bottom layer, an outflowing current pressed against the western coast prevails.

The circulation patterns are constantly perturbed by the higher-frequency current variations. Tidal currents modify the mean, residual flow rather weakly. On the other hand, winds have recently emerged as an important driving force, causing transient currents which may surpass in order of magnitude all the other contributions to the Adriatic current field. It has been found that the wind-driven currents are controlled by vorticity of the wind field, and that under the summer, stratified conditions, wind pulses may trigger oscillations of the inertia period.

The physical processes occurring along the two opposing coasts of the Adriatic Sea differ markedly in their characteristics. Water exchange between the semi-enclosed basins of the eastern coast and the open sea is mainly forced by the local wind. Conversely, the shelf area along the western coast is dominated by the Po River outflow, which in winter mostly remains confined to a coastal boundary layer, whereas in summer it spreads to the open sea as well.

Critical gaps in the present knowledge are identified, and ways of approaching them are suggested. Future work must specifically address the question of the relative importance of different forcing mechanisms in driving the Adriatic general circulation. Special attention must be paid to the exchange of water through the Otranto Strait and its relation to the rate of dense water formation in the Adriatic. The relative contribution of different water masses to the formation of the outflowing Adriatic water should be assessed. Combined modelling efforts, satellite data analysis and *in situ* measurements are suggested to study the rather poorly known mesoscale features and processes.

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RÉSUMÉ

Courants et la circulation dans la Mer Adriatique

Cet article résume les connaissances actuelles sur la circulation résiduelle et sur la variabilité à haute fréquence des courants en Adriatique. Toutes les études indiquent que la circulation résiduelle de surface consiste en un méandre cyclonique de grande échelle comprenant plusieurs cellules plus petites, et que le système de circulation varie avec les saisons. L'analyse des masses d'eau et les mesures directes des courants indiquent que le méandre cyclonique se trouve aussi dans la couche intermédiaire, dominée par un courant arrivant le long de la côte orientale. Dans la couche de fond, le courant prédominant est le flux d'eau profonde adriatique vers la Méditerranée.

La circulation est constamment perturbée par les fréquences élevées des variations des courants. Les courants de marée modifient plutôt faiblement le flux moyen. D'autre part, on observe que le vent est une force importante, qui engendre des courants dépassant d'un ordre de grandeur toutes les autres contributions au champ des courants adriatiques. On a trouvé que les courants créés par le vent sont contrôlés par la vorticité du champ du vent. En été, quand la stratification verticale est présente, les coups de vent peuvent déclencher des oscillations fortes de la période d'inertie.

Les processus déterminant la circulation le long des deux côtes opposées de l'Adriatique, diffèrent notablement dans leurs caractéristiques. L'échange d'eau entre les bassins semi-fermés de la côte orientale et le large est en général créé par le vent local. D'autre part, la région le long de la côte occidentale est dominée par les apports fluviaux du Pô, qui, en hiver, restent dans une couche-limite cotière, alors qu'en été, il se dispersent vers la large.

Des propositions sont faites pour combler les lacunes relevées dans les connaissances actuelles. La recherche future devra concerner l'importance relative des mécanismes du forçage influençant la circulation générale adriatique. Une attention particulière devra être portée à l'échange des eaux par le détroit d'Otrante et à ses rapports avec la formation des eaux profondes issues de l'Adriatique. Ainsi devra-t-on déterminer la contribution relative des différentes masses d'eaux à la formation de l'eau profonde adriatique qui s'écoule en Méditerranée au voisinage du fond. Il est suggéré d'étudier aux échelles moyennes les phénomènes assez peu connus, en utilisant l'analyse des données satellitaires, les données *in situ*, ainsi que la modélisation numérique.

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INTRODUCTION

The Adriatic Sea has a long history of oceanographic studies. Investigations into the physical processes taking place there began in the 19th century with studies by Lorenz (1863), Wolf and Luksch (1887) and others. Since then, there have been many regional studies as well as several reviews, the most recent ones being those by Buljan and Zore-Armanda (1976) and Franco *et al.* (1982). In the years since these reviews, extensive *in situ* measurements have been made and remote sensing techniques utilizing satellite data have been applied to the Adriatic Sea. In addition, several analytical and numerical models have been used to interpret various aspects of the Adriatic dynamics.

Ocean scientists in the countries bordering the Adriatic and Northern Ionian Seas are currently preparing a cooperative investigation of the physical processes in the region. Thus, it appears appropriate to reexamine old and new results in order to reappraise the present thinking on the processes involved in the general circulation and the higher-frequency current variability. On this basis, the present paper will review previous studies and present a comprehensive picture of the dynamics of the sea. It will also identify critical gaps in knowledge and suggest means and approaches to overcome these gaps.

Our text is organized as follows: Section 2 describes the regional characteristics. Sections 3 and 4 discuss the open Adriatic variability, the former focusing on the water masses and general circulation and the latter on high-frequency oscillations. Section 5 is devoted to the near-shore processes occurring along the eastern and western coasts. The text ends with Section 6 discussing the previous sections and presenting the comprehensive picture of the general dynamics. This section also contains remarks on the present gaps in our knowledge of the Adriatic Sea dynamics and possible approaches to filling these gaps.

REGIONAL CHARACTERISTICS

Topography

The Adriatic Sea's elongated shape (some 800 by 200 km) and almost land locked position play an important role in controlling the dynamics of its waters (Fig. 1). The long basin may be considered as having three parts, increasing in depth to the Otranto Strait at its southern entrance. The first part, containing the Gulf of Venice, is shallow and has a fairly even slope gradually deepening to 100 m and then dropping quickly to 200 m at the start of the second part just south of Ancona. This second part has an important feature at its northern end called the Jabuka Pit (about 280 m deep). The rise south of this deep, called the Palagruža Sill, continues to the end of the second part. The third part also has a deep at its centre, the South Adriatic Pit (*ca.* 1 200 m deep). The bottom rises again in the Otranto Strait where the Adriatic opens on the Ionian Sea. The maximum sill depth of the strait is 780 m, while the mean depth is 325 m over the 75 km width. The volume of the Adriatic is close to 3.6×10^4 km^3. The western coast of the Adriatic Sea is regular, with isobaths running parallel to the shoreline, the depth increasing uniformly seaward. The more rugged eastern coast is composed of many islands and headlands rising abruptly from the deep coastal water.

Meteorology

The Adriatic Sea is situated between the subtropical high-pressure zone and the mid-latitude or westerlies belt, in which atmospheric disturbances generally move from west to east. These zones shift throughout the year "cum sole", causing sharp seasonal differences. Through most of the year, the effects of the westerlies belt dominate the region, with frequent cyclones and anticyclones appearing in the lower troposphere. In summer, the subtropical high-pressure zone dominates and the cyclonic and anticyclonic disturbances of the westerlies belt all but disappear from the Adriatic. Meteorological conditions are also influenced by the secondary atmospheric centres: the Iceland low and the Eurasian high in winter, the Azores high and the Karachi low in summer. Besides the synoptic disturbances, planetary atmospheric waves also occur over the Adriatic area, while mesoscale atmospheric phenomena (land and sea breezes, gravity waves etc.) may locally modify the global weather conditions.

In winter, the dominant winds are the Bora (blowing from the Northeast) and the Sirocco (Southeast), with the former gusting up to 50 m/s. In summer, Etesian winds (blowing from the northwest) occur, particularly in the southern Adriatic where 53 % of all winds come from this direction (Makjanić, 1976). Along the coast, land and sea breezes develop during the warmer part of the year (Orlić *et al.*, 1988).

Global radiation received by the Adriatic Sea varies between 400-500 J/cm^2/day in December and 2200-2600 J/cm^2/day in July (Penzar and Penzar, 1960). Air temperatures are highest in July, lowest in January (Furlan, 1977). The summer temperature field is rather uniform, ranging from 22 to 26°C. The winter temperatures range from about 10°C in the south to about 2°C in the north, the eastern coast being warmer (by about 2°C) than the western coast.

Relative humidity is at a minimum in summer, a maximum in autumn (Škreb *et al.*, 1942). However, more pronounced are its "synoptic" variations: a pulse of the Bora can lower humidity by 60-70 %. Cloud amount depends on the passage of synoptic atmospheric disturbances, being greatest in late autumn (*ca.* 6/10) and least in summer (1/10-4/10). Correspondingly, maximum precipitation occurs in late autumn, with minimum precipitation characterizing summer. Precipitation amounts are greater at inland (about 1 000 mm/year) than at coastal stations (approximately 400 mm/year).

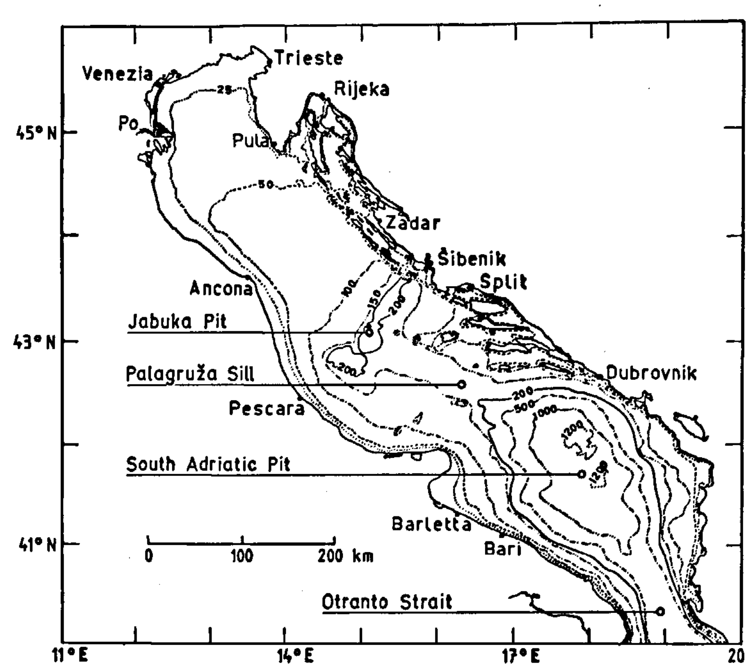


Figure 1

Position and topography of the Adriatic Sea.

Hydrology

The major fresh water source is the Po river, with an annual mean runoff of about 1 700 m^3/s. Its maxima are much higher and are associated with snow melt in spring and strong precipitation in autumn (Marchetti, 1984). The annual mean runoff of the north- and west-coast rivers other than the Po is 350 m^3/s; the rivers inflowing along the greater part of the eastern coast contribute about 700 m^3/s, whereas the annual mean runoff concentrated along the 150 km of the eastern coast converging on the Otranto Strait amounts to about 1150 m^3/s (Zore-Armanda, 1969 *a*). Along the eastern coast there are numerous submarine springs (known as "vrulje") which discharge fresh water originating in the littoral karst area (Alfirević, 1969) but are probably not of major importance in the overall water budget.

WATER MASSES AND TRANSPORT

Water mass properties and dense water formation

The Adriatic Sea is the major source of the densest water in the Eastern Mediterranean: the Eastern Mediterranean Deep Water, or EMDW (Pollak, 1951; Zore-Armanda, 1963 *a*; Ovchinnikov *et al.*, 1985; El-Gindy and El-Din, 1986). Meteorological conditions favourable to dense water formation occur during winter when cold, dry air outbreaks during Bora events take place over the sea (Hendershott and Rizzoli, 1976; Malanotte-Rizzoli, 1977). Zore-Armanda (1963 *a*) describes the generation of three types of dense water during this period: North Adriatic Water or NAW (11°C, 38.5, 29.52 sigma-t), Middle Adriatic Water or MAW (12°C, 38.2, 29.09 sigma-*t*) and South Adriatic Water or SAW (13°C, 38.6, 29.20 sigma-*t*). The water types and their spatial extent are illustrated in Figures 2, 3, and 4.

The highly dense NAW forms during winter in the shallow North Adriatic and pours into and fills the bottom of the Jabuka Pit (Zore-Armanda, 1963 *a*). Recent STD measurements (Franco and Bregant, 1980; Artegiani and Salusti, 1987) have shown the core of this water type to be pressed against the slope of the western coastal shelf, forming a vein of water which flows along the isobaths near the coast. The vein appears to split in two branches, one descending into the Jabuka Pit and the other pouring over the Palagruza Sill (Zoccolotti and Salusti, 1987). The water content of the vein is highly variable, its sigma-*t* values ranging from 29.4 to 29.8, depending on the meteorological conditions of the particular winter.

MAW is not as distinct a water mass as the others and, in fact, has not been reported by investigators other than Zore-Armanda (1963 *a*), who states that MAW is formed in the area of the Jabuka Pit during winter periods of weak inflow of Mediterranean water through the Otranto Strait. According to Artegiani *et al.* (1989), who analyzed hydrographic data collected over a 70-year period, the bottom layer of the pit is filled with NAW modified through mixing with the Mediterranean water that inflows along the eastern coast. The mixture is somewhat warmer and saltier than the original water type, and its oxygen content is low in summer (< 80 % ; Artegiani and Salusti, 1987), showing long residence time. It is not clear whether this water mixes upwards or is occasionally pushed out of the Jabuka Pit over the Palagruža Sill.

SAW originates in the South Adriatic Pit in the centre of the South Adriatic gyre during the period of the strongest winter cooling: *i. e.* the second half of February - first half of March (Zore-Armanda, 1963 *a*, and Ovchinnikov *et al.*, 1985). The latter authors also present evidence that this dense water formation process has time scales of several days and length scales of a few tens of kilometres. However, it is not clear how they estimate these time and length scales from cruise data collected in different years with coarse station spacing. The dissolved oxygen content is very high during winter over the entire water column including the bottom layer of the South Adriatic Pit, showing that the water is well ventilated, probably by these dense water formation processes.

As already mentioned, NAW inflows into the South Adriatic Pit concentrated in a vein which may be observed close to the western coast. Bignami *et al.* (1990 *a*; 1990 *b*) showed that the current approximately follows the isobaths until it encounters an offshore-oriented canyon near Bari. The vein then sinks and flattens, and at the same time its waters are vigorously mixed. The process resembles that observed by Sugimoto and Whitehead (1983) in a laboratory experiment.

The question of the relationship between NAW and SAW is highly controversial. Ovchinnikov *et al.* (1985) found SAW overlaying NAW in the South Adriatic Pit. Zore-Armanda (1963 *a*) remarks that the two water types occasionally mix in the pit. However, Zoccolotti and Salusti (1987) suggest that mixing occurs between the relatively smaller volume of NAW and the inflowing Mediterranean water and that SAW is a result of this process. We believe this to be an important point and will consider it further in the concluding section.

Despite this controversy, all the authors agree that it is SAW which flows south through the Otranto Strait to mix and eventually become the bottom layer of the Eastern

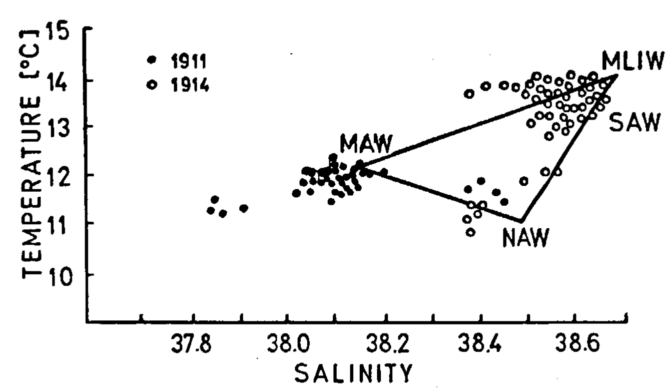


Figure 2

T-S diagram for the Middle Adriatic area for winters 1911 and 1914: triangle corners represent the water types (Zore-Armanda, 1963 b*).*

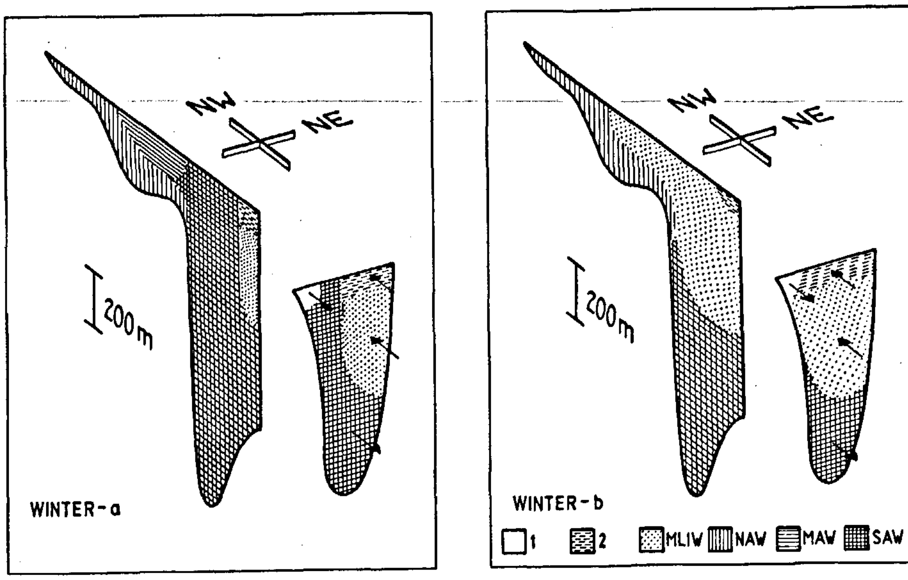


Figure 3

Schematic representation of surface waters and water types of the Adriatic during winter, with: a) lower; and b) higher inflow of high-salinity waters. Numbers 1 and 2 denote surface waters, whereas letters denote the water types. Central longitudinal sections redrawn after Zore-Armanda (1963 a), the Otranto Strait transverse sections constructed from data of Burkov (1976), Gržetić (1982), Lavenia et al. *(1983) and Vučak and Škrivanić (1986).*

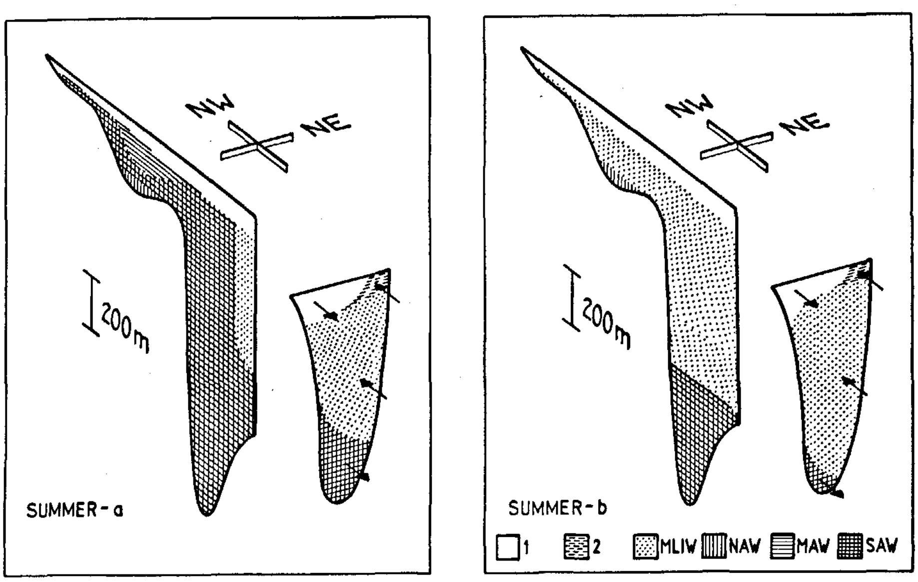


Figure 4

As in Figure 3, except for summer.

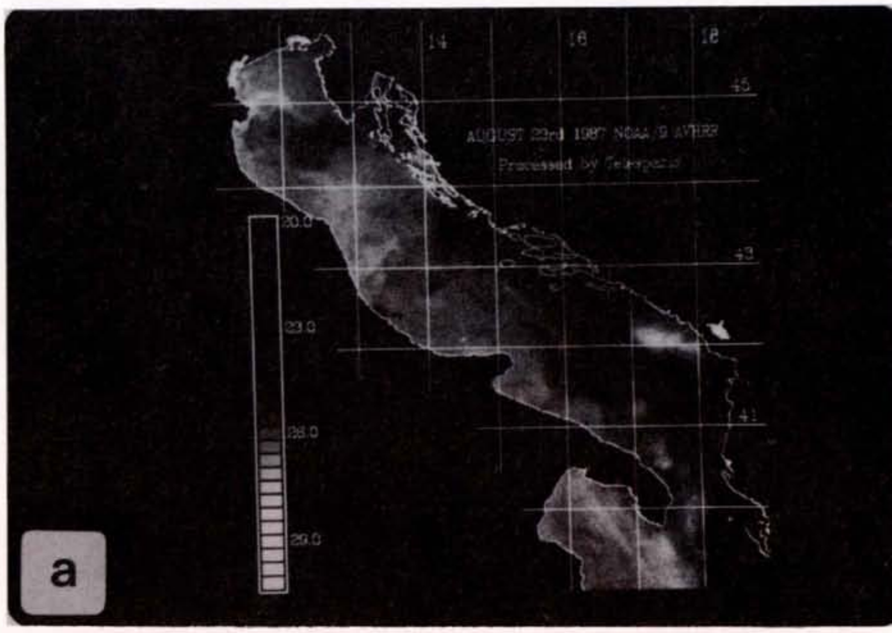
Mediterranean: EMDW. Hopkins (1978) indicates that it is in the Ionian Sea that SAW joins the Levantine Intermediate Water (LIW) to form EMDW. Bignami *et al.* (1990 *a*; 1991) document the transformation of SAW into EMDW, following it from the South Adriatic all the way to the Sicilian coast. They show that the cross-section of the vein containing SAW increases downstream, whereas its proportionate density surplus decreases, due to the entrainment of surrounding waters. These results agree with predictions obtained by Smith (1975) and Killworth (1977) for a steady density-driven current over a sloping, rotating shelf.

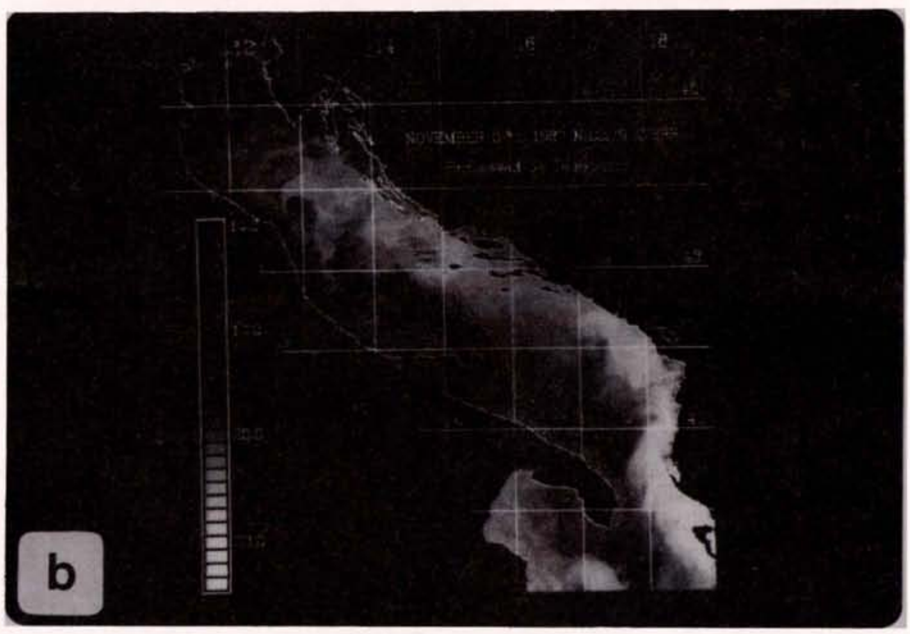
In addition to the water masses of Adriatic origin described above, there is an intermediate water mass (core at about 200 m) - called Modified Levantine Intermediate Water (MLIW, winter temperature 14°C, salinity 38.7, sigma-t 29.06, Fig. 2). This water originates in the Levantine basin, and is characterized by high salinity (Wüst, 1959; 1961; Lacombe and Tchernia, 1960; *see* also review by Malanotte-Rizzoli and Hecht, 1988). On its way from the Levantine basin to the Ionian Sea it descends to the intermediate layer and is transformed into LIW (Theodorou, 1990). In the Ionian Sea and the Otranto Strait, LIW mixes with denser Adriatic water (Zore-Armanda, 1974). Part of the mixture flows into the Adriatic (Fig. 3, 4), where it is discernible as MLIW of relatively high salinity.

Topping these water types is the surface layer, formed by the Ionian waters (entering on the eastern side of the Otranto Strait) and diluted waters outflowing from the Adriatic along the western coast. During winter, low salinity waters hug the western coast (Fig. 3). In summer, the riverine influence is felt over the greater part of the Adriatic surface layer, whereas Ionian waters are located closer to the eastern coast (Fig. 4). Sea surface temperature distribution shows that: a) during summer, diluted waters along the western coast are warmer than the open sea waters; b) in winter, the temperature gradient reverses with inflowing Ionian waters on the eastern side being warmer than the outflowing fresh waters along the western coast (Fig. 5). The transition between the summer and winter pattern occurs in October and April. Böhm *et al.* (1986) used the winter IR satellite images to determine position of the front which separates cold waters observed close to the western coast from warm offshore waters. Utilizing satellite imagery and a simple model, they found that the

Figure 5

Representative NOAA Advanced Very High Resolution Radiometer (AVHRR) thermal satellite imagery for: a) summer; and b) winter. In the imagery, light tones represent warm features, dark tones represent cool features. Note the seasonal variations indicated by the thermal gradients, occurring in the coastal flows.





coastal current speeds range from 10 to 40 cm/s. Bracalari *et al.* (1989) observed instabilities at the summer coastal front, and interpreted them with the aid of densimetric Froude number.

Different waters and water types of the Adriatic Sea undergo not only seasonal, but also year-to-year variability. Severe winters cause vigorous mixing and intensive dense water formation processes (Fig. 3 *a*); mild winters, combined with a strong inflow of MLIW, may bring about significant increase in both the salinity and temperature of the Adriatic Sea (Fig. 3 *b*). During the summer, heat input stabilizes the water column, enabling surface waters to spread over the Adriatic. In the deeper parts of the basin four water types are variously distributed, depending on the strength of the Mediterranean water inflow (Fig. 4 *a*, *b*). Stronger inflows of MLIW are named "ingressions" - after Buljan (1953) who studied them in some detail.

General circulation

The general surface circulation of the Adriatic Sea may be described as a large-scale cyclonic meander, with a northerly flow along the eastern coast and a southerly return flow along the western coast. The meander appears in both subjective (Zore, 1956; Mosetti and Lavenia, 1969) and objective (Limić and Orlić, 1986) analyses of relative geostrophic currents. Surface currents computed relative to 50-dbar level show that in winter, the wide eastern current is more pronounced; in summer, the western current predominates (Fig. 6). Typical speeds are below 10 cm/s, but may locally reach higher values, particularly close to the western coast in winter.

The cyclonic surface circulation and its seasonal variations were qualitatively explained by Zore (1956) in terms of density gradients that develop in the Adriatic Sea. She

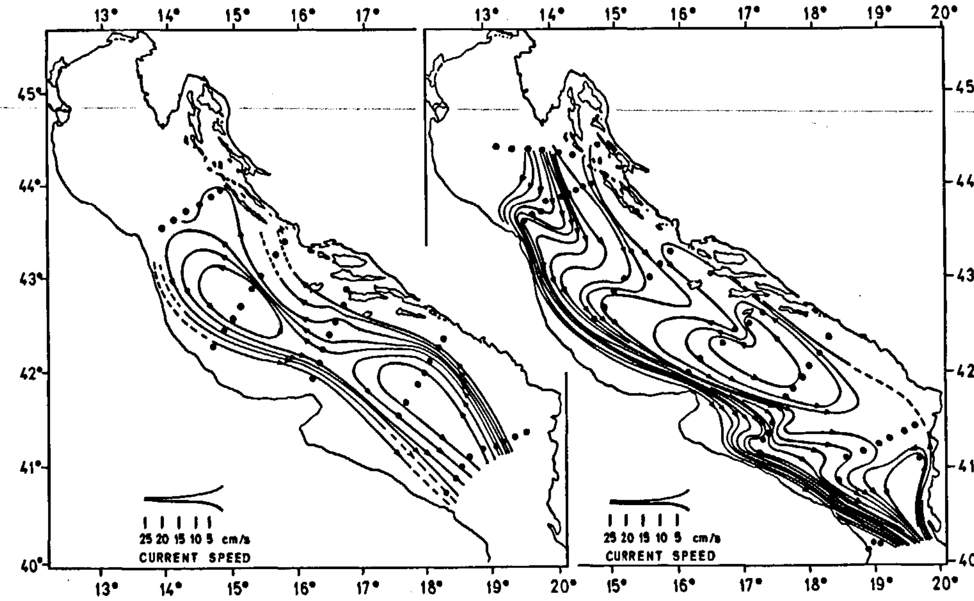


Figure 6

Geostrophic surface currents in the Adriatic Sea, calculated relative to the 50-dbar surface (left: winter 1913/1914, right: summer 1911), after Zore (1956). The strengthening of the outflowing current during the summer is evident.

states that during winter, water in the South Adriatic is warmer and saltier than the waters in the Middle and North Adriatic. However, since differences in temperature are more important than differences in salinity, the steric height slope generates northward flow along the eastern shoreline. During summer, the North Adriatic water is warmer and less saline than the water mass in the Middle Adriatic. This is the cause, she believes, of the stronger summer southerly flow along the western coast. The Etesian winds have also been invoked in the explanation of the increase in the summer western flow (Zore-Armanda, 1969 *b*), whereas recurrent episodes of the Sirocco wind may be thought of as reinforcing the winter eastern flow. Rivers and other coastal fresh water inputs cause the cyclonic surface circulation.

The winter North/Middle Adriatic circulation, according to numerical simulation by Hendershott and Rizzoli (1976), is driven by lateral thermohaline variations of: a) the fresher/colder water on the western side; b) the warmer/saltier water on the eastern side; and c) the dense water pool in the centre of the basin. The dense water pool (Fig. 7) results from rapid evaporation and strong heat fluxes during outbreaks of cold, dry Eurasian air. Horizontal density gradients, induced by these buoyancy fluxes and coastal fresh water input, are capable of driving a horizontal cyclonic flow in the Adriatic, with a net transport of about 0.1 Sv.

The summer circulation of the North and Middle Adriatic may be modified by the appearance of smaller circulation cells (Fig. 8). According to modelling results of Malanotte-Rizzoli and Bergamasco (1983), such a current system is undoubtedly of thermohaline origin, the Po river outflow being of primary importance for its development. Cerovečki *et al.* (1991) showed that the summer circulation is subject to a variability at a time scale of about ten days, due to changes in stability of the water column.

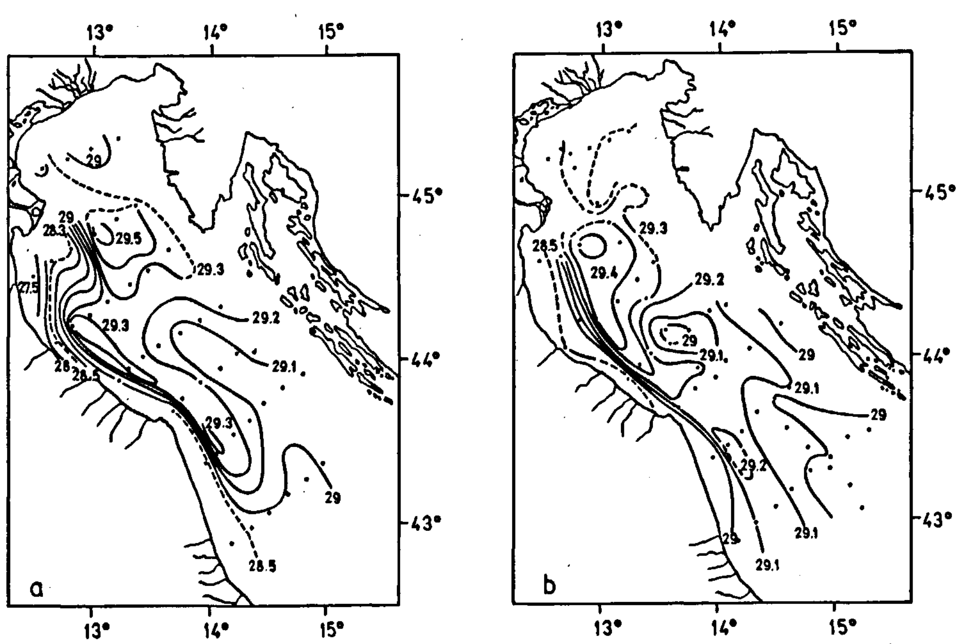


Figure 7

Contours of surface sigma-t values measured in: a) January 1972; and b) February 1972 (Malanotte-Rizzoli, 1977). The dense water pool is present in the center of the basin in both situations.

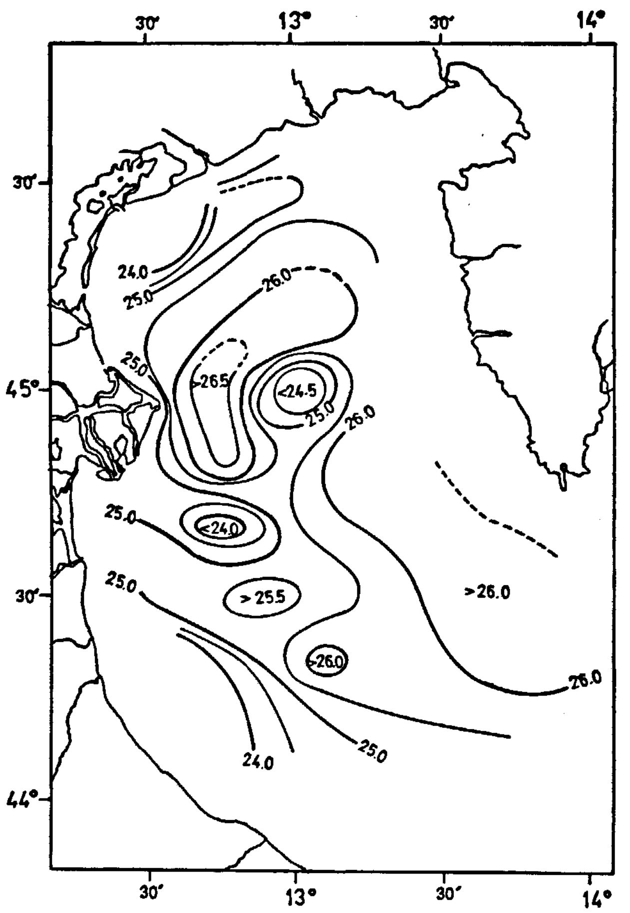


Figure 8

Contours of sigma-t values at the 10 m depth, measured in July-August 1965 (Franco, 1970). Several light and dense water pools are present in the area.

In the South Adriatic a separate cyclonic gyre is usually embedded in the Adriatic circulation (Fig. 6). It appears to be topographically controlled by the South Adriatic Pit and the Palagruža Sill (Zore-Armanda, 1968; Zore-Armanda and Bone, 1987). The gyre was well documented from hydrographic and some biological data by Faganeli *et al.* (1989).

Compared with the surface circulation, the deeper circulation is not well known. It appears from what little data is available that the pattern of the deeper circulation is similar to the surface circulation. The South Adriatic cyclonic gyre is also evident in the intermediate layer, its western part being dominated by the outflowing vein along the shelf break, its eastern part by the broad inflow. In the bottom layer, the outflowing current predominates.

Water exchange with the Ionian Sea

Our present knowledge of the water exchange processes through the Otranto Strait is mostly based on hydrographic measurements and is summarized in Figures 3 and 4. In the surface layer, inflow occurs close to the eastern coast, outflow prevails along the western coast; the currents are seasonally modulated. In the bottom layer of the Otranto Strait there is an outflow of SAW throughout the year. In the intermediate layer, inflow of more saline Mediterranean water occurs along the eastern coast, and outflow of the Adriatic water is found along the western coast.

Zore-Armanda and Pucher-Petković (1976) estimated the transports into and out of the Adriatic on the basis of some direct current measurements. Their estimates agree in order of magnitude with transports computed for a summer situation by Mosetti (1983) and for a winter situation by Theodorou (1990). The results, summarized in the Table, indicate that winter transports are higher than summer transports. This seems acceptable, since thermohaline forcing is more energetic during the colder part of the year. Interpretation of distribution and transport of the Adriatic water masses in terms of buoyancy forcing was proposed by Zore-Armanda (1963 *a*). However, a model that would quantify these ideas is still lacking.

Recently, long-term direct current measurements were carried out in the Otranto Strait. Frassetto and Tomasin (1979) described data collected close to the western coast, Michelato (1986) as well as Michelato and Kovačević (1991) discussed data for the western half of the strait, whereas Ferentinos and Kastanos (1988) analyzed measurements performed at an array of five stations distributed evenly across the strait. All the authors have found outflow along the western coast throughout the water column. In the central strait and close to the eastern coast, inflowing currents have been recorded in the surface layer, outflowing currents in the bottom layer. These findings agree with earlier hydrographic analyses. All the authors have also detected variability on the several-day time scale, and have attributed it mostly to the wind forcing. This interpretation is supported by Lascaratos and Gačić (1990), who analyzed variations of sea-level slope between the Adriatic and Ionian Seas, and have found them related to the passage of mid-latitude cyclones over the area. Ferentinos and Kastanos have also detected inertial oscillations in the Otranto Strait, as well as variability that could be attributed to eddies propagating from the Ionian to the Adriatic Sea (with spatial scales of approximately 10 km, and temporal scales of about ten days).

Table

Transports through the Otranto Strait (in Sv, recalculated after Zore-Armanda and Pucher-Petković, 1976).

Season	Layer	Inflow	Outflow
Winter	Surface	0.153	0.057
	Intermediate	0.252	0.141
	Bottom	-	0.154
	TOTAL	0.405	0.352
Summer	Surface	0.026	0.116
	Intermediate	0.226	0.096
	Bottom	-	0.064
	TOTAL	0.252	0.276

CURRENT FIELD VARIABILITY

Wind-driven currents

Air-pressure disturbances may bring about significant sea-level changes in the Adriatic. Mesoscale atmospheric processes (Caloi, 1938), synoptic atmospheric disturbances [reviewed by Buljan and Zore-Armanda (1976), and Franco *et al.* (1982)], and planetary atmospheric waves (Orlić, 1983; Lascaratos and Gačić, 1990) have all been proven to be important. However, there has not been any evidence that air-pressure variations are effective in generating currents in the sea.

On the other hand, there has been growing empirical evidence on wind-induced currents in the Adriatic. Recent analyses of simultaneous wind and current time series (Kuzmić *et al.*, 1985; Orlić *et al.*, 1986; Zore-Armanda and Gačić, 1987) have shown that the Bora wind induces pronounced, although transient contributions to the North Adriatic current field. A striking example of wind/current correlation is shown in Figure 9, with data indicating speeds of currents increasing up to 50 cm/s in the presence of 10 m/s winds. Such speeds are significantly higher than the current speeds due to free oscillations triggered by wind pulses. In the shallow North Adriatic, the flow lags only slightly behind the wind.

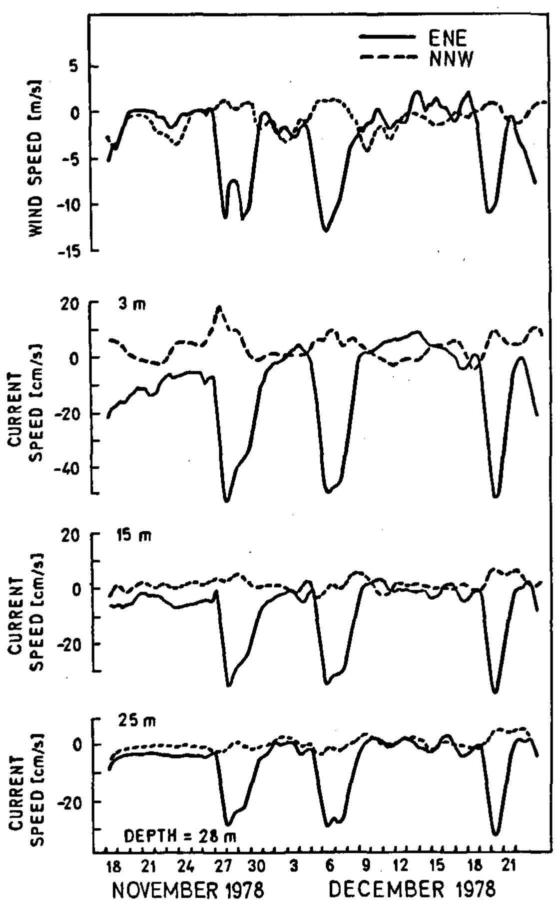


Figure 9

Low-pass filtered time series of wind and currents measured at the Panon station (φ = 45° 24.8' N, λ = 13° 01.6' E), close to the northern Adriatic coast (Orlić et al., *1986). The strong wind events impart momentum almost instantaneously throughout the water column.*

Stravisi (1977) formulated a two-dimensional model of Bora-forced circulation in the northernmost part of the Adriatic Sea. His results show a semicircular anticlockwise flow developed under the influence of wind-stress curl. Malanotte-Rizzoli and Bergamasco (1983) simulated currents driven by spatially constant wind, using a two-layer fluid model. They concluded that the wind-driven circulation is secondary in average, standard meteorological conditions. However, it can become dominant during intense transient episodes, when for example the Bora wind can increase current speeds by one order of magnitude with respect to seasonal thermohaline values. Kuzmić *et al.* (1985) and Orlić *et al.* (1986), applying a three-dimensional model to the North Adriatic, demonstrated the control topography and wind-stress curl have on the currents. Their numerical experiments showed that the Bora wind can induce separated cyclonic gyre in the North Adriatic.

Although a model-to-data comparison (Kuzmić and Orlić, 1987) has been encouraging, it pointed to weak points of the present models. It appears that the efficiency of these models in describing the current field response to the wind forcing primarily depends on the open-boundary conditions and the parameterization of eddy viscosity.

Oscillations of the inertia period

There is increasing evidence of a broad spectrum of free oscillations in the Adriatic Sea. Among these, seiches have been extensively investigated (*e. g.* Defant, 1961; and also Buljan and Zore-Armanda, 1976, and Franco *et al.*, 1982) but only as far as sea-level changes are concerned. Among other free oscillations, which are expected to manifest themselves through the current variations, those of inertia period have attracted some interest.

Investigations of inertia-period motions have been performed in the open Adriatic, where this signal is more pronounced than in coastal waters. Accerboni *et al.* (1981) as well as Gačić and Vučak (1982) have shown that during summer, significant energy maxima appear in the current spectra at the 17-hour period (Fig. 10). Moreover, they concluded that the inertia episodes coincide with transients in the wind field over the Adriatic Sea. Gacic and Vucak also showed that the phase difference of the clockwise current oscillations is about 180° across the thermocline.

Orlić (1987) analysed wind, current and hydrographic data, taken during three summer seasons at four stations on the Adriatic shelf. He has found that the inertia-period oscillations occurred in episodes lasting several days. Vertically, the oscillations displayed a simple structure: the clockwise current-vector rotations were opposed in phase across the thermocline with the energy partition between two layers depending on the thermocline depth. Horizontally, the inertia-period currents accounted for about 10 % of the total current variance at stations close to the longitudinal boundary, and for 20-30 % at stations farther offshore. The oscillations in the current field were accompanied by temperature variations. Orlić interpreted the phenomenon in terms of the internal mode and a few horizontal modes of the two-layer sea contained in a rotating rectangular chan-

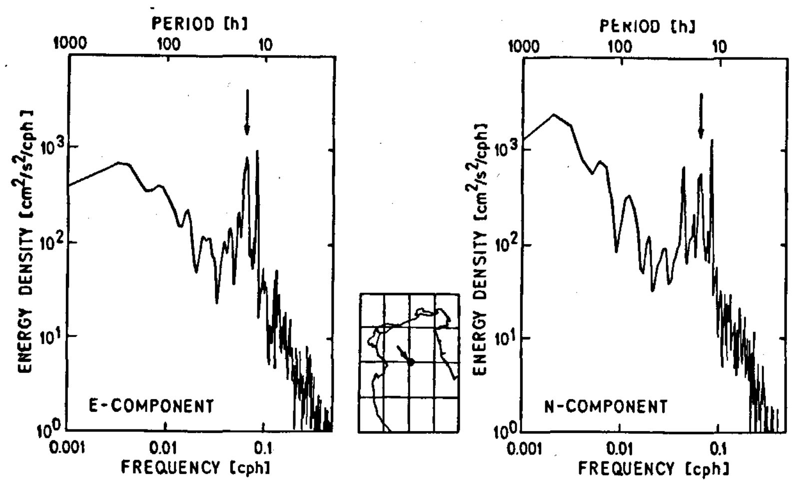
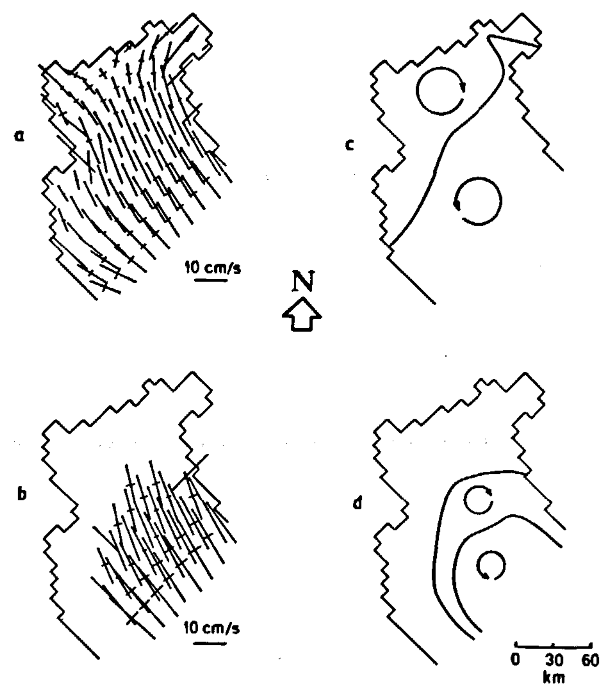


Figure 10

Spectra of current components, measured in summer 1979 at the open sea station shown in the inserted figure, at the 10 m depth. Arrows mark the inertia peaks interpolated between the tidal maxima (after Accerboni et al.*, 1981).*

Figure 11

Current ellipses of the M2 tidal constituent, computed by the North Adriatic model: a) semiaxes at the sea surface; b) semiaxes at the 35 m depth; c) sense of rotation at the sea surface; d) sense of rotation at the 35 m depth (after Cavallini, 1985).



nel. For a typical Adriatic wind stress (0.25 N/m^2) the model gave inertia-period currents of 5-10 cm/s, in fair agreement with the observations. The linearized bottom friction damped the oscillations with the realistic decay time (1-2 days).

Tidal currents

Although not exceptional, tides in the Adriatic Sea are remarkable in view of the modest tidal amplitudes of the adjacent Ionian Sea. They are of a mixed type and can be described reasonably well by use of seven harmonic constituents. The diurnal tidal amplitudes increase from the southeast to northwest, reaching 18 cm for the main diurnal constituent (K1) at the head of the basin. The semidiurnal tidal constituents exhibit an amphidromic point at the latitude of Ancona; maximum amplitude of the M2 constituent equals 26 cm. The majority of authors assume the Adriatic tides to be dependent, *i. e.* not caused by the direct action of tide-generating forces but the result of co-oscillation with the Ionian tides. Models supporting this view, as well as some results that oppose it, have been reviewed by Defant (1961), and more recently by Buljan and Zore-Armanda (1976) and Franco *et al.* (1982).

Zore-Armanda *et al.* (1975) analyzed a two-month series of current measurements made on an offshore platform in the North Adriatic, close to the amphidromic point. By applying a simple filter, they came to the conclusion that the tidal currents they examined are almost linearly polarized. Therefore, the authors questioned the existence of the amphidromic point.

Cavallini (1985) performed harmonic analysis of the current time series, measured at a number of stations in the North Adriatic. Moreover, he computed the parameters of the M2 tidal ellipses and found that the current-vector tips follow elliptical paths, with major axes being an order of magnitude greater than minor axes (about 5-10 *versus* 0.5-1 cm/s). The major axes of tidal ellipses were aligned with the shoreline, and the current vectors generally turned anticlockwise. Cavallini compared his empirical results with the simulations obtained by a three-dimensional barotropic model of the North Adriatic. The model results showed that clockwise movements of current vectors dominate the shallow parts of the North Adriatic, whereas anticlockwise movements characterize the deeper, southeast part of the basin (Fig. 11).

NEAR-SHORE DYNAMICS

The two opposing coasts of the Adriatic Sea markedly differ in their geometry (Fig. 1). The eastern coast is rugged, flanked by many islands, while the western coast is regular so that major part of it can be approximated by a straight shore. Consequently, physical processes governing current field variations are different at the two coasts. Water exchange between the semi-enclosed basins along the eastern coast and the open sea should be mainly locally forced. On the other hand, the shelf area along the western coast should be dominated by motions that originate through coupling between coastal and open-sea waters.

Eastern coast

Current spectra (Fig. 12) from the eastern coastal waters show the prevalence of low-frequency oscillations at

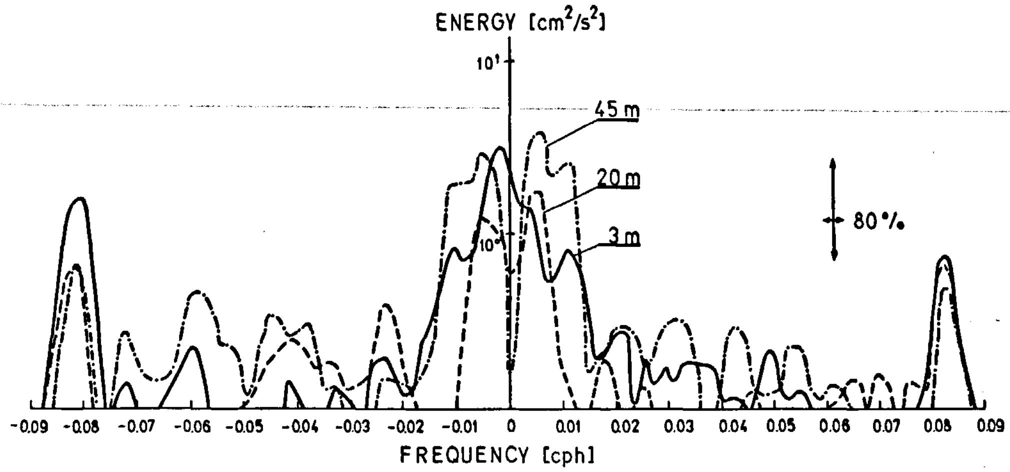


Figure 12

Rotary current spectra for a coastal station in the Adriatic Sea (φ = 44° 19.2' N, λ = 15° 00.4' E, depth about 60 m). The data were collected in summer 1975. Confidence limits and frequency resolution of spectral estimates are denoted by the vertical and horizontal arrows, respectively (Gačić, 1980 a).

time scales of seven to ten days (Gačić, 1980 *a*; Gačić *et al.*, 1982). These oscillations appear to be forced by local winds, and are controlled by coastal topography and by stratification.

Build-up of water against the straight coast under homogeneous conditions is mostly due to the alongshore wind (Gačić, 1983). The Bora, an offshore and the most frequent wind, induces offshore surface transport under stratified conditions. Consequently, upward motions take place in the eastern coastal areas. Gačić (1980 *b*) reported that, as a consequence of the upward slope of isopycnal surfaces, alongshore geostrophically balanced flow is generated. Some evidences of upwelling along the eastern coast were presented in the IR satellite images by Barale *et al.* (1984). In the class of barotropic motions, the existence of a weak signal, explained in terms of continental shelf waves, was documented from cross-spectral analysis of sea levels recorded at Split and Dubrovnik (Gačić, 1983).

The water exchange between the semi-enclosed basins along the eastern coast and the adjacent sea also seems forced by the local wind (since, generally, the freshwater inflow is rather small; Zore-Armanda, 1980). Gačić *et al.* (1987) noted that up to 70 % of the total current field variance in the inlet of a small bay (the Kaštela Bay near Split) could be explained in terms of the local wind forcing. Wind induces in the inlet a vertical current pattern similar to the first baroclinic mode. Kovačević (1989) showed that the major part of salinity and temperature variance (more than 90 %) in the same bay can be explained in terms of seasonal heating/cooling and wind-induced basin-wide mixing and advection.

The influence of stratification on the wind-forced circulation pattern was investigated in some other semi-enclosed basins along the eastern coast. Zore-Armanda and Dadić (1984) showed that when the Vir Sea (near Zadar) is stratified, alongshore wind induces horizontal circulation

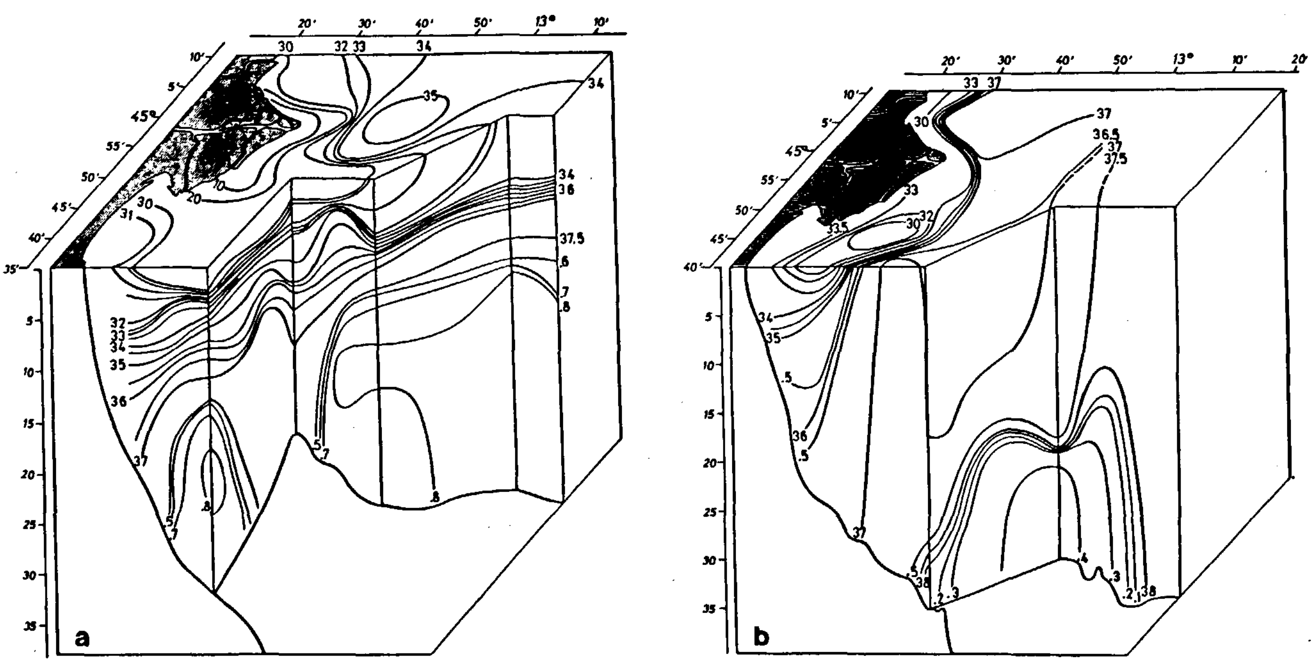


Figure 13

Distribution of salinity close to the Po river mouth: a) 8 July 1978; b) 10/11 December 1978 (Franco, 1983). In summer the Po river water spreads in the surface layer over the entire basin interior; during winter, however, the fresh water is confined to the western coast.

without a bottom compensatory current; in homogeneous conditions, well developed vertical circulation cell forms. On the other hand, the Bora under stratified conditions induces vertical recirculation (*i. e.* offshore flow in the surface layer with the coastal upwelling) whereas in homogeneous conditions it induces a horizontal gyre.

The vertical structure of the water exchange between bays and the greater Adriatic Sea is also influenced by density stratification. Studies of wind-driven currents in a bay which has two inlets (the Rijeka Bay, North Adriatic) showed that: a) in stratified conditions, the vertical current structure is similar to the first baroclinic mode; and b) under homogeneous conditions, the water exchange is barotropic, current oscillations in one inlet being 180° out of phase with respect to the oscillations in the other (Gačić *et al.*, 1982). Calculations of geostrophic velocities showed that the horizontal circulation pattern has a strong seasonal variability. In summer, the typical spatial scales are small and the anticyclonic residual flow between the two inlets develops, with separate circulation cells appearing close to the coast (Limić and Orlić, 1987). During winter, the residual circulation is cyclonic, the Bora probably enhancing this circulation pattern (Orlić and Kuzmić, 1980; 1985).

The drift current /wind speed ratio, studied in the Gulf of Trieste (North Adriatic), ranges from 0.02 to 0.03 (Mosetti, 1972; 1985), which compares well with the values obtained elsewhere. Mosetti and Purga (1990; *see* also Mosetti and Mosetti, 1990) demonstrated that the Bora induces cyclonic gyre in the Gulf. The gyre was reproduced in the numerical simulations carried out by Longo *et al.* (1990). A successful data-to-model comparison has also been performed, for a summer situation when currents were very weak, being driven by tides and small-speed winds (Rajar, 1989). Detailed experimental study of tidal currents in the Gulf has been carried out by Mosetti (1990), who also compared his data with the results of a hydrodynamical numerical model.

Western coast

The western coastal waters are strongly influenced by the fresh water outflow of the Po river. The fresh water spreads in the surface layer, forming a plume which is separated from the Adriatic waters by frontal surfaces (Grancini and Cescon, 1973). As shown in Figure 13, the river-forced plume is confined to the western coast in winter, and is well developed in the cross-basin direction in summer (Franco, 1970; 1972; Orlić, 1989). Barale *et al.* (1986), studying Coastal Zone Color Scanner (CZCS) images, found that the plume spreading is positively correlated with the Po river discharge.

In winter, the Po outflow forms along the western coast a coastal boundary layer of light water, some 10-20 km wide and 10 m deep. The strong horizontal density gradient between this layer and the open sea is considered the most important driving force for the coastal flow (Malanotte-Rizzoli and Dell'Orto, 1981). Residual southeasterly currents reaching 10-20 cm/s were recorded close to the coast (Michelato, 1983). Such currents are capable of advecting the density field (Shaw and Csanady, 1983). Both offshore, dense waters (Hendershott and Rizzoli, 1976) and inshore, light waters (Artegiani and Azzolini, 1981) may be followed on their way down the western coast.

Numerical studies by Malanotte-Rizzoli and Bergamasco (1983) have shown for summer that the signal of the Po river fresh water input is lost in the vicinity of the coast. Spring/summer satellite imagery show a small anticyclonic gyre just south of the Po river mouth, fed by the fresh water outflow (Barale *et al.*, 1984; 1986). The same feature was found in Eulerian measurements of residual current field (Dazzi *et al.*, 1983; Zore-Armanda and Vučak, 1984). The near-coastal summer transport is often directed northward, contrary to the winter pattern (Michelato, 1983; Artegiani *et al.*, 1983; Accerboni *et al.*, 1989). These findings may be explained by interesting numerical and laboratory experiments of Woods and Beardsley (1988), which showed that for a weak Po river discharge the plume turns to the right, and that for a strong discharge it moves farther offshore. On the other hand, numerical simulations by Djenidi *et al.* (1987) suggested that during summer the Po waters outflow from the Adriatic in the surface layer both along the western and eastern coasts, which disagrees with most empirical studies and modelling results obtained by Malanotte-Rizzoli and Bergamasco.

The buoyancy-driven Po river plume may be modulated by tides and winds. During the winter, a transient two-gyre system is formed in the North Adriatic in response to the Bora-wind forcing, with cyclonic gyre occurring in the north, anticyclonic gyre in the south (Zore-Armanda and Gačić, 1987; Kuzmić and Orlić, 1987). If combined with an increase of the Po outflow, such a current system may force the Po waters into the open Adriatic even in winter. Zore-Armanda and Gačić (1987) pointed out that the thermal front orientation in the North Adriatic depends on the Bora-wind forcing and the occurrence of the two-gyre circulation pattern, *i. e.* its position reveals variability on the same time scale as the wind field. During Bora events, when the two-gyre system is formed, the Po waters spread over the entire interior of the North Adriatic and the front extends zonally across the Adriatic. On the other hand, the front is parallel to the western shoreline when the wind blows from other directions and the major part of the Po waters spreads southward along the coastline. Kuzmić (1991; *see* also Sturm *et al.*, 1992) found a winter CZCS scene registered after a Bora episode that occurred simultaneously with an increase of the Po outflow. The scene shows the plume extending from the Po River mouth towards the eastern coast, in fair agreement with numerical predictions.

DISCUSSION AND CONCLUSIONS

Our reassessment of the dynamics of the Adriatic provides a picture of a sea heavily influenced by its topography and climatic environment. Although the picture we have derived has a dynamic consistency, there are critical gaps in the available knowledge. It may well be that the filling of these gaps could alter the present concept of dynamic conditions, especially as related to forcing. In the following discussion, we first summarize what our study has revealed. We then list the unknowns, or at least what we believe is needed to provide a better dynamic understanding. We end by discussing the possible approaches to arrive at this better understanding.

In our summary we discuss circulation of the sea in its three topographic areas: North Adriatic, Middle Adriatic and South Adriatic.

North Adriatic

In the shallow northern portions of the sea, the highly variable surface layer predominates (sometimes in winter being the only layer). The Po river seasonal discharge controls not only the content of much of the sea, but is a major factor in the circulation as well. The winter Bora is equally effective in mechanically modifying conditions in the region as well as generating a cold, dense water mass. This water mass hugs the western coast and then splits into two branches, one sinking to the bottom of the Jabuka Pit, the other continuing south and eventually leaving the Adriatic.

Middle Adriatic

The deeper Middle Adriatic has three distinct layers. In the surface layer, the contributions of the coastal rivers and local winds are still important but much less than in the northern area. Now the Bora contributes less to the cooling and evaporation and the formation of dense water. The surface and intermediate layers differ from the bottom water coming mostly from the shallow North Adriatic. The Jabuka Pit is a storing place for this bottom water that will diffuse upwards and/or be pushed out and moved to the south.

South Adriatic

The surface circulation over the South Adriatic Pit consists of a topographically-controlled cyclonic gyre which appears partially to separate the Middle Adriatic from the Mediterranean influence. It is not known to what extent this feature is driven by the surface and intermediate Ionian water inflow or how important is the seasonal wind field. Also, the fresh water coming from the east-coast rivers appears to influence the circulation. Coastal upwelling along the straight east-coast areas is mostly related to offshore Bora-wind forcing. There is an intensive low-salinity jet along the western shoreline that transports water southward following the coastal contours, even outside the Adriatic. The intermediate layer also displays a cyclonic circulation pattern with the MLIW entering along the eastern coast while the exiting water, in the form of the cold vein (that originated in the North Adriatic), flows along the western shelf slope. It is not known to what degree the various water masses (*i. e.* surface water, NAW, MLIW) participate in the SAW formation through mixing and/or vertical convection. Certainly, SAW occupies the bottom of the South Adriatic Pit. Oxygen data indicate the residence time which is probably shorter than for NAW in the Jabuka Pit, although the actual time is not known and appears to vary. SAW rises out of the pit and forms a continuous outflow through the Otranto Strait below the inflowing MLIW and Ionian surface water. In principle, EMDW appears to be the final stage of several dense water formations that start in winter in the northern portion of the Adriatic and descend to the Otranto Strait, with each area imparting its own characteristics on the developing water mass.

The dynamic picture presented above indicates that the Adriatic long-term varability is driven by the winter formation of dense water masses and the exiting of these waters at depth. Similar circulation studies in the Western Mediterranean (*e. g.* Manzella and La Violette, 1990) and Gibraltar (Bormans *et al.*, 1986) suggest that the compensating mechanisms for a bottom outflow are the dominant forcing of much of the circulation. That is, the exiting water should create a loss that must be compensated by an equal transport of incoming surface and intermediate waters. It would also appear that there must be a constant adjusting movement at all levels for the seasonal increasing and slackening of such transport and that this would be one of the primary causes of the regional flow and its seasonal and long-term variability. The adjustment would explain slackening of the Ionian surface water inflow and the dominance of the riverine water across the sea in summer, and the renewed inflow and resulting dominance of the Ionian surface water in winter.

The circulation patterns are unceasingly influenced by higher-frequency current variability. Periodic tidal currents perturb the mean, residual flow rather weakly. However, winds recently emerged as an important driving force, causing transient currents which may surpass in order of magnitude all the other contributions to the Adriatic current field. The sea responds to wind both in forced and free modes: wind-curl currents are formed under the direct influence of wind, whereas a broad spectrum of free oscillations is triggered by wind pulses. A possibility exists that transients in the current field may contribute nonlinearly to the quasi-steady flow component.

As for the unknowns in the overall dynamic picture, it should be noted that there are no detailed experimental or numerical studies addressing the issue of variable outflow from and compensating inflow in the Adriatic Sea. This deficiency is the most critical gap in our understanding of the sea. As we stated at the start of this section, the filling of this gap could substantially alter our understanding of the Adriatic circulation.

We believe future work in the Adriatic should address the following topics:

a) the relative contribution of different forcings to the general circulation (*i. e.* thermohaline *vs* wind);

b) the temporal and spatial spectrum of the water flow through the Otranto Strait (relative importance of synoptic, seasonal and year-to-year variations);

c) the components and their relative importance in the formation of SAW as well as the processes involved;

d) the interconnection between the North/Middle and South Adriatic (*i. e.* better information on the flow across the Palagruža Sill);

e) the residence time of deep water in the Adriatic pits and the mechanism that allows the water to leave deepest parts;

f) the detailed temporal and spatial scales of mesoscale features (eddies, gyres, filaments, fronts); and

g) the generation, propagation and decay of topographic Rossby and internal Kelvin waves in the coastal boundary layer.

Different field experiments are needed to satisfy these topics. To start with, long-term current measurements in the Otranto Strait and above the Palagruža Sill would provide data on the typical time scales of variations and mechanisms that generate the water exchange between different parts of the Adriatic, as well as between the Adriatic and Ionian Seas. Year-to-year comparisons of monthly satellite (visible and thermal) data averages would reveal interannual changes in the sea. Fine-scale hydrographic investigations guided by real time satellite imagery and using this imagery as part of the post-survey analyses are necessary to assess mesoscale variability in the Adriatic. Finally, current and hydrographic measurements, close to the coasts (inside the internal Rossby radius of deformation, *ca.* 5 km) would help us to understand some hitherto unresolved aspects of wind-related variability.

On the theoretical side, a hierarchy of models is needed to simulate the Adriatic dynamics. A fully nonlinear, baroclinic model, driven by wind and buoyancy forcings, is necessary to investigate dense-water formation in various parts of the Adriatic and the Eastern Mediterranean, and to reproduce spreading and mixing of water masses. An eddy-resolving model, which would bring into focus processes of smaller temporal and spatial scales, seems a natural next choice. Shift of interest towards still higher frequencies would necessitate the development of a nonlinear model of wind-driven and tidal transients, in order to clarify the possible transfer of vorticity from the oscillating currents to the mean field.

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