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Descriptive model of the Northern Adriatic

Hydrodynamics
Modeling
Adriatic
Sea level
Circulation

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Adriatique
Niveau de la mer
Circulation

P. Franco [a], L. Jeftić [b], P. Malanotte Rizzoli [c], A. Michelato [d], M. Orlić [e]
[a] Istituto Biologia del Mare, CNR, Venice, Italy.
[b] Department of Planning and Environmental Protection, Zagreb, Yugoslavia.
[c] Istituto per lo Studio della Dinamica delle Grandi Masse, CNR, Venice, Italy.
[d] Osservatorio Geofisico Sperimentale, Trieste, Italy.
[e] "Rudjer Bošković" Institute, Centre for Marine Research, Zagreb, Yugoslavia (*).

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ABSTRACT

One of the tasks undertaken by the Yugoslav-Italian Modeling Group, defined in the 5-year program, was: collection, classification and descriptive analysis of existing data of the Northern Adriatic relevant to physical oceanography. Work along these lines started at the beginning of 1980, and the final outcome of the joint Yugoslav-Italian effort is presented in this text.

It was felt that the following topics: sea level changes – tides and storm surges and seiches –; currents and circulation will represent the most important processes for physical oceanography, and therefore the following text is structured accordingly.

More than a hundred papers and data sources were consulted in order to prepare this text and the most important ones, namely, those directly cited in the text, are given at the end of it as references.

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RÉSUMÉ

Un modèle descriptif de la mer Adriatique septentrionale.

Un des projets entrepris par le groupe de modélisation yougoslavo-italien dans le cadre du programme de 5 ans a trait à la compilation, la classification et l'analyse descriptive de données d'océanographie physique obtenues dans l'Adriatique Nord. La réalisation de ce projet a commencé au début de 1980; le résultat final de cette coopération yougoslavo-italienne est présenté ici.

Il apparaît que les aspects les plus importants pour l'océanographie physique sont les suivants : les variations du niveau de la mer (marées, tempêtes et seiches), les courants et la circulation. C'est sur ce plan qu'a été conçu le présent article de synthèse, qui repose sur la consultation d'une centaine de références diverses, dont les plus importantes sont mentionnées dans la bibliographie.

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SEA LEVEL CHANGES

The two main factors causing sea level changes in the Northern Adriatic are tidal forces and atmospheric forces (air pressure and wind). According to the opinion of the majority of authors in the field, the dynamics of the Northern Adriatic can be taken as linear for all practical purposes; this allows for an independent study of tidal and atmospherically induced phenomena.

Tides

Although not exceptional, the tides in the Adriatic 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 tide amplitudes increase from South to North and reach 18 cm for the main diurnal constituent (K_1) at the head of the basin.

(*) Authors listed in alphabetical order.

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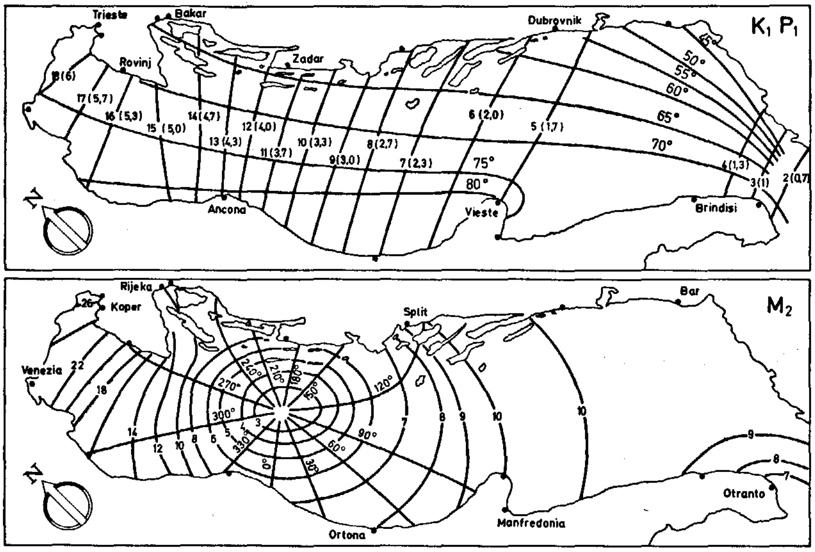

Figure 1

Cotidal and corange maps for the diurnal constituents K_1 and P_1 (upper) and semidiurnal constituent M_2 (lower). From Polli (1960 b).

The semidiurnal tide exhibits a well-developed amphidromic point at the latitude of Ancona. The existence of the amphidromic point is not accepted by Zorè-Armanda *et al.* (1975) who, on the basis of a two-month series of current measurements made just near the theoretically established amphidromic point, conclude that the semidiurnal constituent could be described as a standing wave. The phase of the semidiurnal tide varies with each different position in the Adriatic, whereas that of the diurnal tide changes only slightly. Cotidal and corange maps for the seven main constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1) were constructed by Polli (1960 *b*) taking as a basis harmonic tide constants for 30 ports of the Adriatic. The maps for the diurnal constituents K_1 and P_1 and for semidiurnal constituent M_2 are reproduced in Figure 1.

Further computations of harmonic constants for Adriatic ports were carried out by Trotti (1969), Mosetti and Manca (1972), and Godin and Trotti (1975) for Trieste harbour. A complete list of harmonic constants for some Adriatic harbours is given in Purga *et al.* (1979). The majority of authors (e. g., Defant, 1961) assumes Adriatic tides to be dependent, i. e., not generated by the direct action of the gravitational tidal forcing but the result of co-oscillation with the Ionian tides. Sterneck (1919) and Mosetti (1959) calculated the contribution of independent tides to the total tide to be about 6-15% for the diurnal components and 3-10% for semidiurnal components. On the contrary, Filloux (1974) believes that, for the main semidiurnal component M_2, direct gravitational forcing is the main factor of tidal dynamics in the Adriatic Sea. His conclusion is based on calculations of energy budgets for the whole Adriatic and a qualitative extension of results, obtained by Hendershott and Speranza (1971), about the position dependence of amphidromic points upon tidal energy dissipated within a bay. According to his estimation, the direct gravity flux of energy from the moon (1.2-2.45 × 10^7 J/sec.) balance both the frictional dissipation within the Adriatic (0-2.05 × 10^7 J/sec.) and the energy transfer by radiation from the Adriatic (0.4-1.4 × 10^7 J/sec.). This estimation is, however, notably altered if one changes the position of the amphidromic point.

Also for the diurnal constituents, preliminary results (Tomasin, 1976) seem to suggest that the direct gravitational forcing is comparable to the radiative forcing through the Adriatic-Ionian boundary. Adequate current measurements in the Strait of Otranto would provide a definitive answer to the problem. Numerical reproduction of tidal motion by means of a hydrodynamical model has been performed by Accerboni and Manca (1973). The distribution of amplitudes and phases given by the model are similar to those obtained by Polli (1960 *b*), but the corange lines are slightly different and more reliable in the open sea, due to the fact that Accerboni and Manca's results were obtained through numerical interpolation of the actual coastal data. Polli's results, on the other hand were qualitatively interpolated. A similar investigation for M_2 and K_1 tides in the northern part of the Adriatic has been carried out by McHugh (1974).

Seiches and storm surges

As far as the influence of atmospheric factors on sea level is concerned, we shall distinguish between free oscillations (mainly seiches) and the forced oscillations – usually called storm surges, but incorporating, in fact, a much wider spectrum of sea level changes than the term "storm surge" implies – although both are in fact wind driven.

Free oscillations

The Adriatic Sea is perturbed by free oscillations or seiches. These are mainly associated with the blowing of intensive SE winds and with the passage of frontal systems or a cyclonic area over the Adriatic Sea. The main seiches of the Adriatic have periods of about 22 and 11 hours. The 22 hours seiche represents the fundamental longitudinal free oscillation of the basin, with a nodal line at the southern opening. The amplitude of this uninodal seiche decreases from the north to the south (see Fig. 2) and the phase is fundamentally similar along the whole Adriatic. Still obscure is the spatial variation of the second seiche of 11 hours. Defant (1961) considers it as the uninodal seiche (with the nodal line at the centre of the basin), assuming the

Adriatic to be closed at Otranto (on account of the great narrowing). Nevertheless, considering the Adriatic to be open, the 11 hours oscillation might be interpreted as the binodal seiche. Besides these fundamental oscillations, other seiches of shorter period have been observed. In general, seiches are higher in winter and in the North Adriatic, lower in summer and in the South Adriatic (Mosetti, 1973). The average amplitude of the seiches is about 20-30 cm in the North Adriatic and only 5 cm in the extreme South Adriatic. Seiches of higher amplitude (60-80 cm) can appear during storm surge period. The decay time of seiche amplitude is generally very long (10-15 days).

Analyses of the Adriatic seiches, performed in the period before World War II, have been well summarized by Goldberg and Kempni (1938). Later studies include those carried out by Vercelli (1941), Kasumović (1959; 1963), Polli (1961; 1962), Manca *et al.* (1974). The specific seiches of the Gulf of Trieste were studied by Dovier *et al.* (1974), and by Godin and Trotti (1975). The reader is referred to the original papers for the details of the analyses.

Various authors have performed studies on the Adriatic seiches by means of hydrodynamical analytical and numerical models. The computations have been carried out using the real topography of the basin and considering—in the most sophisticated models—both Coriolis force and bottom friction.

Treating the Adriatic Sea as a one-dimensional nonrotating barotropic basin and using Crystal's method, Bajc (1972) calculated the period of 21.5, 12.5 and 8.5 hours for the first three seiches. The first and the third of these were obtained by considering the Adriatic as an open basin and prescribing a node at Otranto. The second value (more uncertain) was determined by assuming the basin to be closed: this result seems to support Defant's hypothesis of the "closed Adriatic". Sguazzero *et al.* (1972) applied a variational method for the evaluation of the Adriatic seiches. Accerboni and Manca (1973) and Michelato (1975), using a two-dimensional model, found respectively a period of 20.6 and 20.8 hours for the principal longitudinal seiche of the Adriatic. A further study was carried out by Stravisi (1973), who also identified the periods of 8.5, 5, 3.5 and 3 hours in sea level oscillations at Trieste and Venice. The 3-3.5 hours seiche is probably due to an oscillation between Trieste and Venice. Poretti (1974) studied the Adriatic seiches by analyzing with spectral techniques the sea level oscillations computed by a model with a grid of 10 km mesh size. He found good agreement between the computed seiches and those obtained through the power spectrum analysis of tide gauge records.

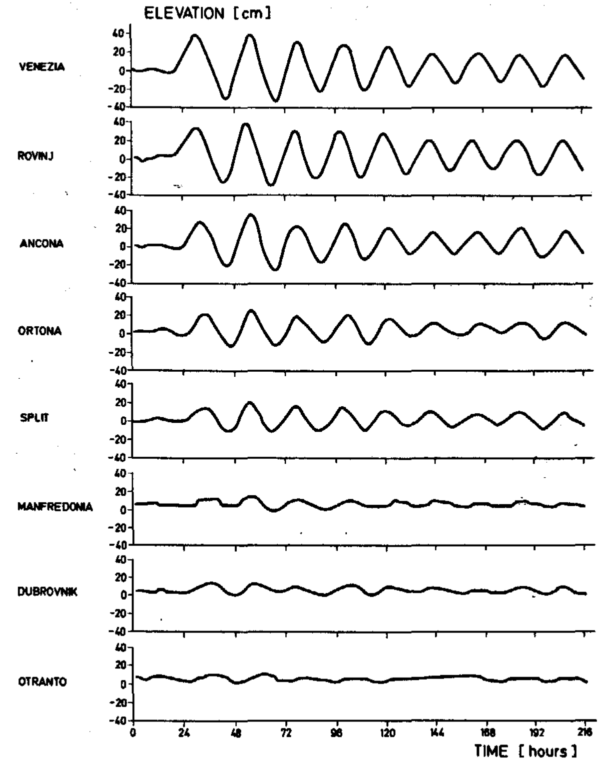

Figure 2

Simultaneous plots of the seiche in different harbours of the Adriatic. Progressive hours from 16 *February* 1967, 1 *a.m. From Mosetti* (1973).

It must be pointed out that the results obtained with the different models are strongly influenced by the position in which the nodal line at the opening has been placed. However, various selections of open boundaries can correspond to different situations that occur in reality and can therefore explain the dispersion of the periods measured. While there is the tendency for energy to be trapped in the Adriatic, the changes in the depth and the width of the sea and in the Otranto Strait make uncertain the position of the line of "inverse" reflection of long waves, i. e., of the nodal line.

Forced oscillations

The atmospherically forced oscillations of the Adriatic Sea have been studied from two points of view: in the majority of papers the attention is focused on the atmospheric factors (air pressure, wind) that act on the sea surface; a few works have been concerned with the corresponding atmospheric formations.

The influence of atmospheric pressure on sea level has aroused the interest of a number of researchers in the field. From the early works by Vucić (1861; 1866) and Lorenz (1863), via the nice papers by Mazelle (1895; 1896) and Sterneck (1904) up to the newer investigations of Kasumović (1958) and Polli (1960 *a*), the acting of air pressure on the sea surface has always been explained in terms of the so-called equilibrium theory—either explicitly or implicitly. One finds surprising the fact that the simple equilibrium between atmospheric-pressure gradient and sea elevation gradient is so well realized in the Adriatic. However, it seems that the contributions of other terms in the equations of motion balance each other (Coriolis force and friction). This leads to the relation 1 cm-1 mb as a good first approximation for the sea level/atmospheric pressure relationship. The following values of the (non-dimensional) barometric factors were obtained for various ports in the Adriatic: Venice: −16.6; Trieste: −19.6; Bakar: −10.7, 11.9, 13.3. Here the barometric factor is defined as the average ratio over a year between atmospheric pressure fluctuations and sea level variations, computed on a daily basis. The recent application of spectral analysis and systems analysis to Northern Adriatic time series

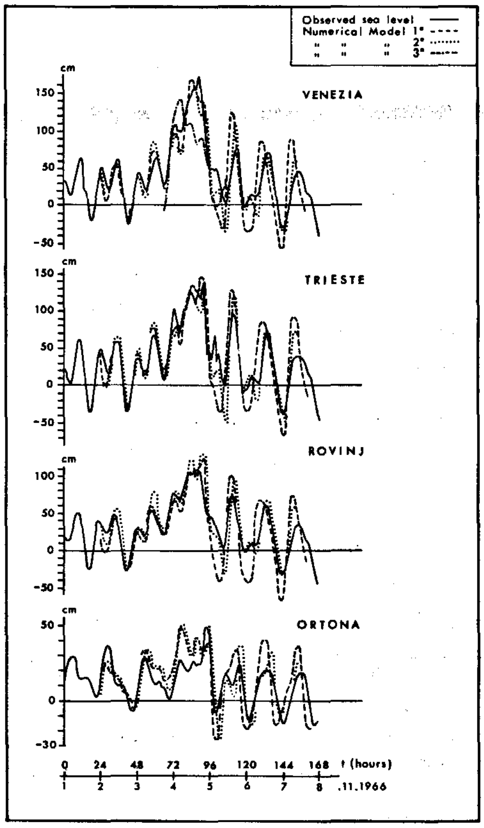

Figure 3

Adriatic Sea level distribution due to the total effect of wind, atmospheric pressure and tide, for November 1966, *at various coastal stations in the Adriatic. From Accerboni and Manca* (1973).

(Karabeg, Orlić, 1981) has shown that the influence of air pressure on the sea level is of far greater significance in the long period range (periods of 22 days and more) than in the short period range. Furthermore, a linear relationship was shown to exist with proportionality factor negative and near to the theoretical value.

The earliest investigations of sea level changes in the Adriatic due to wind have been limited to simple descriptions (Lorenz, 1863; Mazelle, 1895; 1896; Sterneck, 1904; Kesslitz, 1911). For the first time Polli (1968) and Mosetti and Bartole (1974) tried to connect elevations of the sea with the various parameters describing wind field. They were primarily concerned with the southern winds, which cause piling up of the water in the Northern Adriatic and occasionally bring about flooding in Venice. For wind speeds between 10 and 60 km/hr., the range of elevations at the northern end of the Adriatic Sea is 20-100 cm.

The influences of wind and air pressure on sea level have been formulated in various empirical relationships, giving sea levels at a certain point as a function of selected meteorological parameters over the wider area. Mosetti and Bajc (1972) express the maximal elevation in Venice with the aid of zonal atmospheric pressure gradient over the Adriatic. Sguazzero *et al.* (1972) give residual sea levels in Venice as a function of earlier sea level heights in the same place, and of various powers of air pressure gradients above the Adriatic. A modification of this latter approach is mentioned by Tomasin and Frassetto (1979). Probably the highest level of sophistication, as far as the acting of atmospheric factors on the sea is concerned, has been reached in hydrodynamical numerical models. These models are commonly based upon the shallow water barotropic equations of motion (hydrostatic approximation) in the small amplitude limit (nonlinear advection terms are neglected) and not considering lateral friction. In one-dimensional models transverse currents are also neglected, and the integration of the equations of motion and continuity is performed over the cross-sections of the Adriatic Sea. On the open boundary, a nodal point is defined (Accerboni *et al.*, 1971; Finizio *et al.*, 1972; Tomasin, 1973) and linear law is introduced for bottom friction. Reasonably good correspondence between the measured and computed sea level heights has been obtained. The two-dimensional models are based on the integration of relevant equations over the vertical profiles only. Bottom friction is expressed either by linear (Stravisi, 1972; 1973) or quadratic law (Accerboni, Manca, 1973; Michelato, 1975). The open boundary is defined as nodal line. Again, calculated values agree well with the measured curves (Fig. 3).

A considerably smaller amount of literature has been devoted to the question of atmospheric formations acting on the sea. As pointed out by Kasumović (1958), cyclones bring about the occurrence of extremely high sea levels in the Adriatic, while anticyclones act in the opposite sense. Mosetti (1971) and Sguazzero *et al.* (1972) analyzed synoptic situations concurrent with the occurrence of exceptionally high sea levels in the Adriatic Sea. They concluded that the most common situation is connected with the cyclonic disturbance, which can be formed in the lee of the Alps (Fig. 4) and which eventually migrates eastwards. Both low air pressure and strong SE winds, associated with such disturbances, contribute to the piling up of water in the Northern Adriatic. However, the described disturbances are only those belonging to the synoptic meteorological scale (spatial dimension $\sim 10^3$ km, temporal dimensions $\sim$ a few days). During the last decade attention has been turned to the planetary scale disturbances as well ($\sim 10^4$ km, ~ 10 days). At first, Mosetti (1969) and Mosetti and Purga (1978; 1979) had shown that here exists very good correspondence between air pressure and sea level oscillations, at periods greater than about 10 days. Full physical explanation was given by Penzar *et al.* (1980), who carried out the comparison between

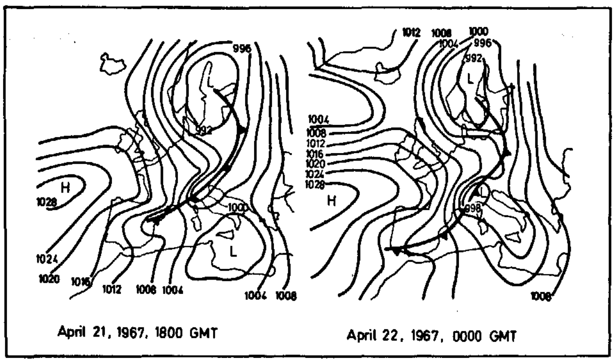

Figure 4

A typical case of cyclogenesis; depression is formed at the western end of the Alps. From Tomasin and Frassetto (1979).

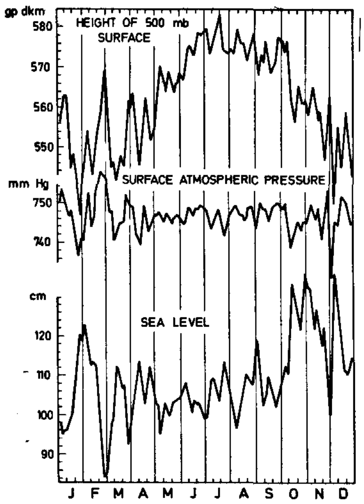

Figure 5
Long-term oscillations of the geopotential height of 500 mb surface of 15°E (upper curve), surface atmospheric pressure (middle curve) and sea level (lower curve) in the Adriatic in 1976. From Penzar et al. (1980).

geopotential heights of 500 mb surface, air pressure and sea level (Fig. 5). These authors concluded that long-term oscillations of sea level should be primarily attributed to the influence of planetary atmospheric waves on the sea. On the basis of the last paper, Orlić and Karabeg (1981) were able to explain the seasonal variations that occur on sea level spectra in the Adriatic by seasonal changes in the general atmospheric circulation.

All these investigations make it possible to distinguish between planetary- and synoptic-scale forcing of the Adriatic Sea. Models of the Mediterranean should be developed for the planetary-scale forcing, and they would provide open boundary conditions for the existing models of the Adriatic Sea itself.

CURRENTS AND CIRCULATION

For its water masses, baroclinic circulation, thermohaline forcing, etc., the Adriatic must be looked at in the more general context of the Mediterranean. In particular, the eastern Mediterranean is probably fundamental in determining the long-term scales in the water masses and circulation properties of the Adriatic Sea through exchange occurring at the mouth of Otranto.

The hydrography of the Mediterranean (Lacombe, Tchernia, 1960; Wüst, 1961) is dominated by the evaporation from the sea surface. The total evaporation and heat budgets on a yearly or seasonal basis are still known only on the basis of old and rough estimates (Sverdrup *et al.*, 1942). Carter (1956) estimates the loss by evaporation to be about twice the gain from precipitation and river flows with a resulting net loss of water over the whole Mediterranean equivalent of about 400 mm drop in level per year ($\sim 1\,200$ km^3/year). This loss must be made up by a net inflow through the Strait of Gibraltar.

The light water inflow in the surface layer at Gibraltar and the salty water formation in the eastern Levantine basin determine the distribution of the four different water masses which have been identified in the Mediterranean (Sverdrup *et al.*, 1942; Lacombe, Tchernia, 1960; Wüst, 1961). Most important is the so-called Levantine intermediate water, characterized by a maximum of salinity, which, except for the source region in the Levantine basin, is found in the whole Mediterranean at various intermediate depths between 200 and 600 m. This water is formed in February and March between Rhodes and Cyprus, where at the surface there is a combination of low temperatures (about 15°C) and high salinities (39.1‰) favorable for vertical thermohaline convection reaching to a depth of 100-200 m. From this winter source of high salinity, the Levantine intermediate water spreads out within the core layer to all western basins.

The movement of this salty water mass in the intermediate layer affects the average circulation of all the Mediterranean subportions, in particular, therefore, of the Adriatic Sea. In fact, from the 1911-1914 data collected in the Adriatic by the Austrian-Italian Commission (cruises Ciclope-Najade; Buljan, 1953; Buljan, Zoré-Armanda, 1976), salt intrusions can be recognized. These salt intrusions seem to be related to synoptic meteorological conditions dominating over the whole of Europe. The annual pressure differences between Trieste and Athens (representative stations for Northern Adriatic and Northeastern Mediterranean) have been compared with the maximum annual values of the salinity in the central Adriatic (Zoré-Armanda, 1974). Recently, Hendershott and Zicarelli (private communication) have correlated precipitation at an inland station (Milan) with salinity at a typical station in the Northern Adriatic, always for 1911-1914 data; there exists the possibility of a correlation with river outflows (in particular of the Po) in the Northwestern Adriatic. Moreover, the salt intrusion phenomena may be connected with the periods of dense water formation (see the following) in the Northern and Southern Adriatic, under successive winters of extreme meteorological conditions.

This dense, deep water formation process is one of the most studied oceanographic problems in the whole Mediterranean. The Mediterranean basin has two principal sites of dense, deep water formation: the Ligurian-Provençal (Gulf of Lions) basin and the Adriatic Sea itself.

The Adriatic Sea in its northern half is entirely constituted by the continental shelf. As such, it is the shallowest part of the whole Mediterranean. The first studies in the Adriatic go back to 1887, when Wolf and Luksch produced the first general map of the Adriatic circulation. Later, De Marchi (1911) and Feruglio and De Marchi (1920) studied the data collected during the cruises Najade and Ciclope (1911-1914) of the Italian-Austrian Commission. Mazelle (1915) also studied the surface circulation on the basis of drift bottle experiments. Similar experiments were analyzed by Vucak (1964) for different seasons. A bibliographical synopsis of all studies until 1970 and a phenomenological description are given in Rizzoli (1970). See also Mosetti and Lavenia (1969), Zoré-Armanda (1956; 1963; 1968), Buljan and Zoré-Armanda (1976).

In the Adriatic, one can distinguish three layers for the vertical circulation:

Surface layer

Constituted of water of northern (river outflow) origin. The surface layer flows southward, more intensely along the western Italian side, where the light river water is usually concentrated producing an intense boundary current.

Intermediate layer of Ionian origin

This layer ultimately originates in the Levantine Sea and flows northward towards the extremity of the basin.

Bottom layer

Constituted of the dense water formed in wintertime, which migrates along the bottom outflowing from the Adriatic.

Horizontally, the Adriatic circulation in all seasons is a cyclonic gyre, with a northward flow from Otranto along the Yugoslavian side as a rather broad current occupying the eastern and interior parts of the basin, and a narrow and intense return current flowing southward along the Italian side to Otranto. The dynamic topographies illustrating primary geostrophic balances for winter and summer situations are shown in Figure 6*a*, *b* (from Zoré-Armanda, 1956). Zoré-Armanda (1963) gives a detailed analysis of the water masses of the Adriatic on the basis of the data collected during the Ciclope-Najade cruises (1911-1914). The three-layer configuration is typical for late spring-summer, when all the northern, shallow region is filled with a water mass of high temperature and low salinity, as compared with the water of the middle and South Adriatic. According to Zoré-Armanda (1968), the winter season has a typical 2-layer configuration, when dense-deep water is formed in the northern part (water S) and the southern deep basin (water J). Then cooling and evaporation mix the surface and intermediate layers into a single one, filling the northern shallow continental shelf with a unique, vertically homogeneous stratum. On the basis of dynamic computations, Zoré-Armanda (1967) concludes that in winter the current is strong (and northflowing) along the eastern coast; while in summer it is stronger (and southflowing) along the western one.

The Northern Adriatic Sea is, as mentioned, a basin for winter dense water formation in two of its parts. The first site of dense water formation occurs in the northern shallowest region, during episodes of cold, dry air blowing from Eurasia, typically occurring in January-February. Then, the densest water of the whole Mediterranean is formed with characteristic density anomaly $\sigma_t \leq 29.4$ to 29.9 (Hendershott, Rizzoli, 1976; Franco, 1972; Malanotte Rizzoli, 1977). This water flows southward along isobath contours, and replenishes the depths of the mid-Adriatic (Jabuka or Pomo) pit. Recently Franco and Bregant (1980) have shown that this dense water intrudes into the western part of the pit and mixes with the water already present in the pit itself in a way which depends upon the relative density of the two water masses. The mixing mechanism varies strongly, from the extreme of superposition of dense layers because of a stable stratification situation (March 1972) to the opposite extreme of a violent intrusion into the pit with the removal of its bottom waters and quick mixing with them (March 1971). The Pelagosa sill (120 m) separates the Jabuka pit from the southernmost, deep Adriatic (1 200 m). The shallow and deep regions may therefore sometimes have an independent dynamic behavior. Dynamic topographies and geostrophic computations relative to spring and autumn seem to show an almost negligible axial

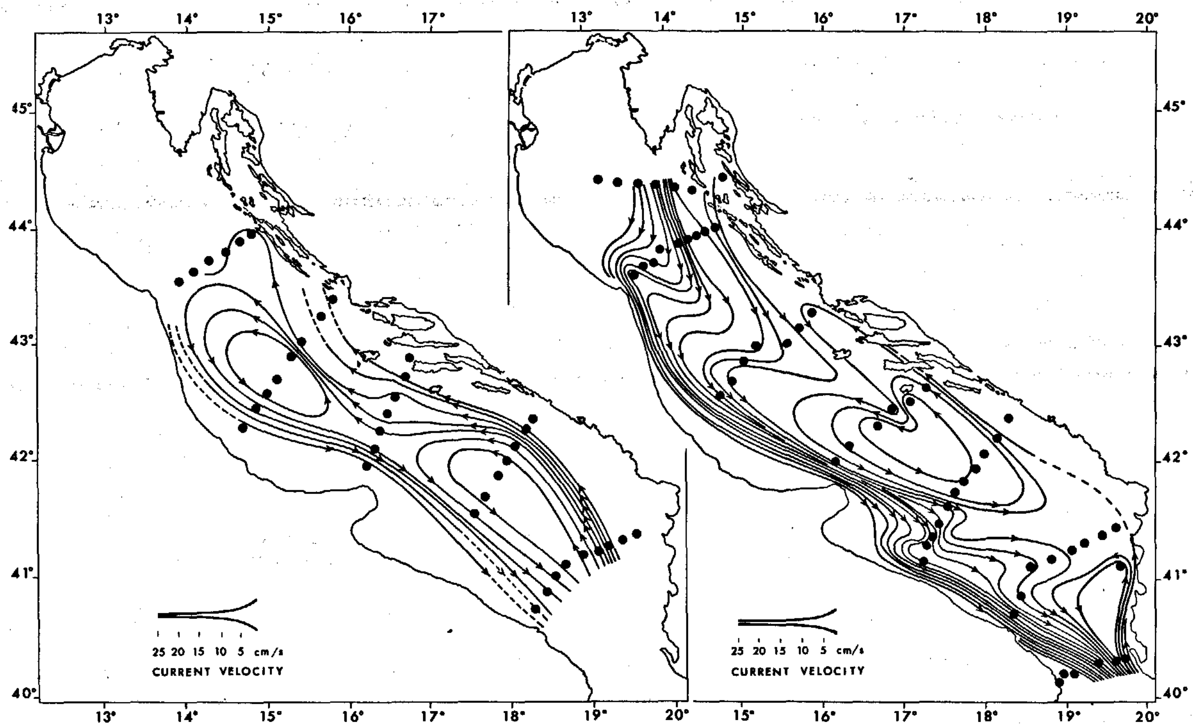

Figure 6

Geopotential topography of the sea surface in dynamic decimetres relative to the 50 dbar surface, for the period between 16 *and* 24 *November* 1913 (*left*) *and the period between* 16 *August and* 6 *September* 1911 (*right*).

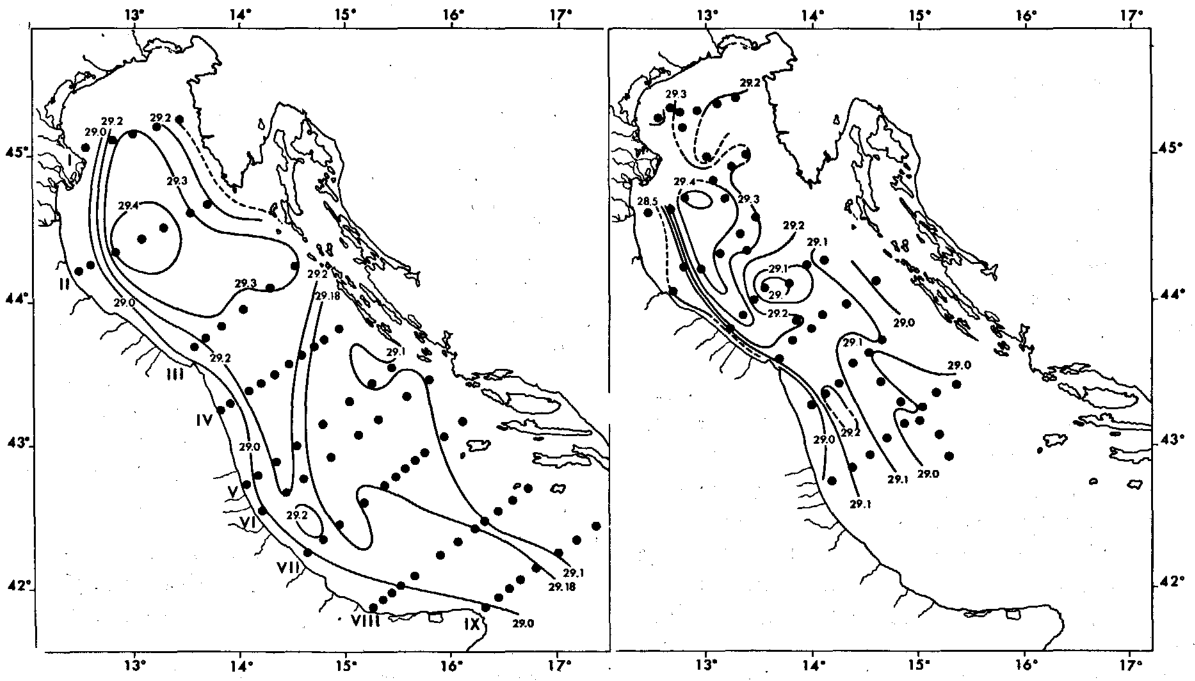

Figure 7

Surface distribution of density anomaly in the Northern Adriatic for winter 1966 (*left, from Hendershott and Rizzoli,* 1976), *and for winter* 1972 (*right, from Malanotte Rizzoli,* 1977).

transport across the Pelagosa Sill (Mosetti, Lavenia, 1969; Hendershott, Rizzoli, 1972) as do the model predictions for the winter circulation (Hendershott, Rizzoli, 1976).

This point is however controversial. The model predictions (Hendershott, Rizzoli, 1976) show the northern cyclonic gyre, thermally driven in wintertime, to be completely disconnected and independent from the forced flow at the southern open mouth. But this dense water formation and the resulting circulation pattern may be related to the invasion of the salty Levantine water spreading northward along the Yugoslavian side. Successive model computations which allow for the density boundary along the western, Italian side show in some instances the northern cyclonic gyre to be embodied in a more general cyclonic circulation pattern originated by the forcing at the southern mouth (Malanotte Rizzoli, Dell'Orto, 1980). The problem is still open.

Typical observational configurations of the dense water pool are given in Figure 7 *a*, *b* (from Malanotte Rizzoli, 1977 for winters 1966 and 1972). The winter Northern Adriatic circulation is thus of thermohaline origin, driven by the intense density gradients between the dense water of the interior and the light coastal water of river origin.

Also the Southern Adriatic in its deepest part is a site of dense water formation in wintertime, under the same northeast dry, cold wind meteorological conditions. Then a dense water is formed with overturning of the water columns down to variable depths. The phenomenon has less experimental evidence than the dense water formation in the northern part and must still be proved in its details. The existing evidence, however, suggests that this dense water sinks at depths and flows over the Otranto sill filling up the depths of the Ionian Sea. In an important study, Pollak (1951) shows that the depths of the Ionian Sea are filled with Adriatic bottom water, and that only small influences can come from the Aegean Sea by occasional overflow through the canals between Crete and Rhodes. The dense water formation in the second site has not yet been the object of any modeling efforts.

The summer situation is very different. The light Po River diluted water (down to ~10% in salinity) is colder in wintertime than the warmer interior water mass, which flows northward in the bottom layer; warmer in summer due to surface heating. It constitutes one of the basic driving forces of the northern basin. The summer situation, even though it has been explored much more extensively from the experimental point of view (Picotti, 1960; Trotti, 1969; Mosetti, Lavenia, 1969; Franco, 1970; 1972) has received less attention from the point of view of quantifying its phenomenological characteristics and modeling its dynamical behavior.

As far as the mechanically driven part of the circulation is concerned, the system of surface and bottom currents, as it appears in the vertical transect along the longitudinal axis of the Adriatic Sea, and its seasonal variations, was studied for evidence of the influence of mechanical factors (atmospheric pressure, wind) in various papers by Zoré-Armanda (1969-1972). Also Stravisi (1972; 1973) has constructed a two-dimensional linear model, essentially a storm surge model, to explore the transient dynamics. With this model, he has analyzed the effects of wind forcing and the wind-driven circulation in the Northern Adriatic, and in particular in the gulfs of Trieste and Venice. During the summer, a zonal atmospheric pressure gradient prevails over the eastern Mediterranean (directed from West to East), while during the winter a meridional atmospheric pressure gradient dominates (directed from South to

North). According to the authors, such a distribution of atmospheric pressure gives rise to surface flow from the Adriatic to the Ionian Sea in summer, and in winter it causes flow of just the opposite direction—with the compensatory currents in the deeper layers. The wind acts in the same sense, since its dominant direction is NW during the summer (Etesian winds) and SE during winter (Scirocco winds). All these meteorological elements can be connected with the seasonal movements of atmospheric formations. In particular, this is the case with the Iceland cyclone and the Siberian anticyclone; their influence on the winter situations in the eastern Mediterranean is visible in the formation of the water masses of different characteristics as well as in the exchange of water masses between various basins.

From the above analysis it cannot be seen why the wind should cause the cyclonic surface circulation in the Adriatic, the circulation that is characterized by large scales and periods. That problem was analyzed by Emery and Csanady (1973), not only for the Adriatic Sea but for various marginal seas and lakes of the Northern Hemisphere as well. They attributed the occurrence of cyclonic circulation of mentioned characteristics to the drag of the wind blowing across the sea. Warmer surface water is displaced on the right-hand shore zone (facing downwind), where it produces greater surface turbulence and, thus, greater wind drag. This effect leads to cyclonic circulation regardless of the direction and, within limits, the duration of the wind.

Kaese and Tomczak (1974) prepared a homogeneous model with a quasi-continuous velocity distribution in all three spatial dimensions. In the model they incorporated the currents connected with great spatial and temporal scales, with the help of open boundary conditions. The authors analyzed the influence of mentioned currents and the acting of the wind on the current field of the Adriatic Sea, for the two winter and summer situations.

Finally, Zoré-Armanda and Mladinić (1976) explained the anticyclonic surface circulation system, that they found in the area south of the Po river-mouth in November 1974, by the influence of the discharge of that river. The authors stress that this system is probably developed only under special circumstances.

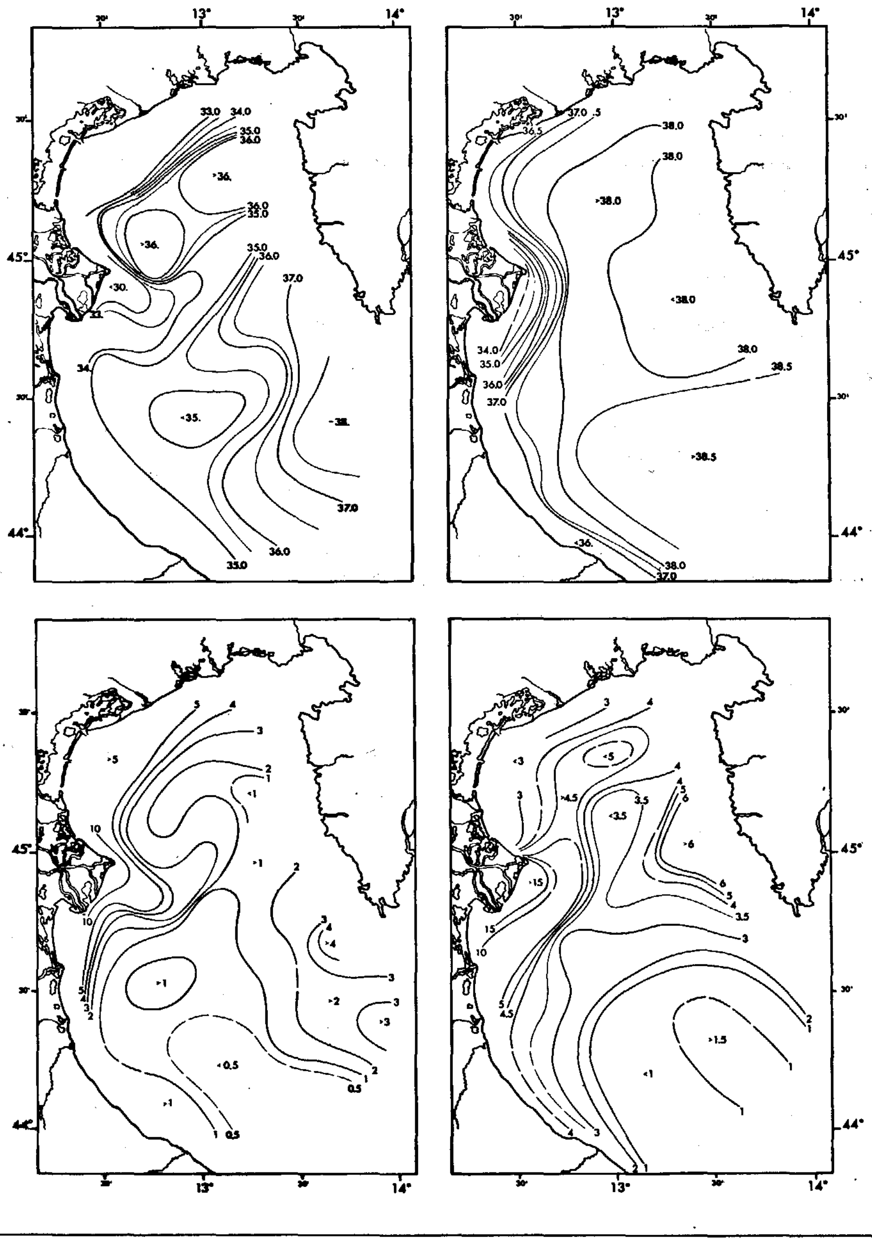

Figure 8 *a*

From the top: salinity (10^3), *and silica from ortosilicates* (μg-at.l^{-1} Si-SiO$_4^{4-}$) *in the surface layer* (0-5 m) *during summer* 1965 (*left*) *and winter* 1966 (*right*). *From Franco* (1970; 1972; 1973).

To summarize, two extreme average situations can be distinguished in the Northern Adriatic. The first one, typical of the seasonal conditions of the late autumn-winter, is characterized by essentially complete vertical homogeneity in the vertical distribution of properties (temperature, salinity hence density) in the interior of the basin. Here, the discussed phenomenon of dense water formation occurs under the episodes of cold dry air blowing into the sea from Eurasia. Vertical stratification, however, persists also in late autumn-winter in part of the narrow Italian coastal strip, due to the important river outflows concentrated along the Italian northwestern side, of which the Po is the most important one. This light river water remains concentrated in the narrow coastal region, a density boundary layer, forming an intense coastal current which flows southward and compensates the wider northward flow in the interior (see Malanotte Rizzoli, Dell'Orto, 1980, for a thorough discussion of the winter phenomenological situation).

In summer, on the other side due to surface heating the dense interior water disappears, and the light river water (mainly the Po) can spread in a jet-like form towards the interior of the basin. The Po water influence is sometimes found even near the opposite Istrian coast. The Po outflow, moreover, seems to give rise to a double-eddy circulation, consisting of two plumes, one spreading towards Istria and northward, the other spreading in a southward direction and closing upon itself to form a smaller, anticyclonic gyre which leaves almost stagnant the very nearcoastal water masses along the Emilia-Romagna littoral. The phenomenological evidence for this phenomena is however still little and controversial, even though current records both in the surface and in the bottom layer in the Emilia-Romagna coastal strip seem to indicate the presence of a smaller, recirculation gyre (Accerboni, unpublished data). Also the former plume, in its northeastern spreading, seems to close upon itself, giving rise to a northern gyre (Franco, 1970 and private communication; Malanotte Rizzoli, unpublished model results).

Stratification in late spring-summer is very noticeable. The thermal inversion at the surface in spring causes the formation of a surface layer, which progressively deepens in the summer, being layered by a system of pycnoclines. The surface ones are related to the plume

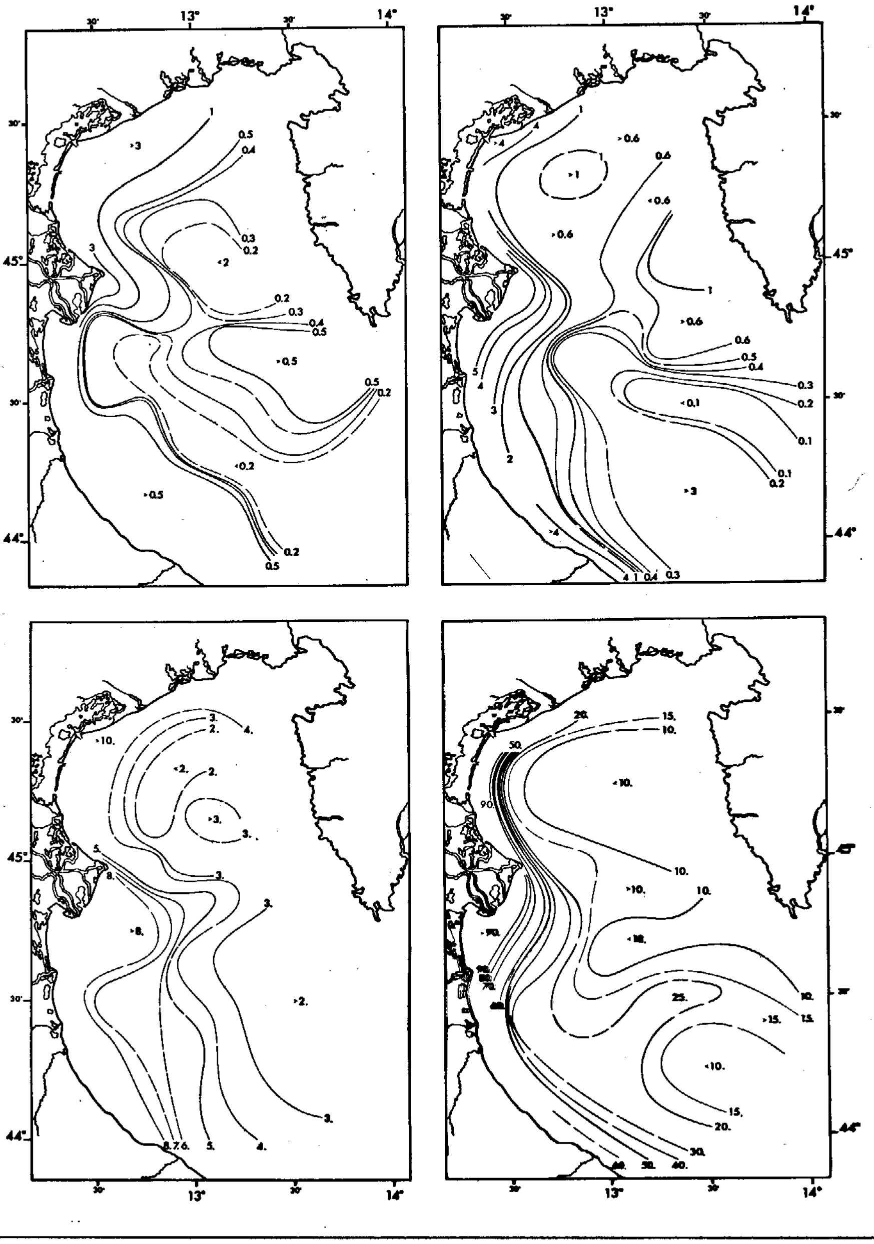

Figure 8*b*

From the top: nitrogen from nitrates (μg-$at.l^{-1}$ N-NO_3^-) *in the surface layer* (0-5 *m*) *and chlorophyll* a ($mg.m^{-2}$) *integrated over the water column* (0-20 *m*) *during summer* 1965 (*left*) *and winter* 1966 (*right*). *From Franco* (1970; 1972; 1973).

of the Po River, whose extension is controlled both by the inflow of surface and intermediate waters of southeastern origin. The deepest pycnocline separates the deep unmixed waters from the overlying ones, more or less diluted. While the circulation in the surface layers remains quite active, with a high exchange ratio with the southern basin, the deep water pool seems to be renewed only by slow lateral advection, losing progressively volume and reducing the covered bottom area.

The nearcoastal, lighter density boundary layer and related southward flowing current also persists in late spring-summer, even though it is not concentrated and intense as in wintertime. There seems to be phenomenological evidence of formation of eddies from the coastal current.

The two extreme seasonal patterns can also be found in horizontal as well as vertical distributions of nutrients and biomass. Figures 8 *a*, *b* (Franco, 1970; 1972; 1973) pictorially show these two behaviors in the horizontal patterns both for physical and biological parameters (salinities, silicates, nitrates and chlorophyll *a* as representative of biomass).

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