Thermohaline properties and circulation in the Otranto Strait

by

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ABSTRACT

Thermohaline water characteristics and sub-inertial flow properties in the Strait of Otranto are summarized, analyzing the recent long-term current measurements and seasonal hydrographic surveys carried out in the framework of the OTRANTO project (February 1994-May 1995). The most energetic variability in current field occurs on the synoptic time scales of the order of ten days. The surface current flow along both eastern and western boundaries is associated mainly with the wind, as inferred from the correlation calculations. The central portion of the strait surface is dominated by mesoscale features. Less energetic, but more important for the water mass exchange between the two adjacent basins, Adriatic and Ionian, is a seasonal variability. In winter, the large scale flow, as a part of the dominant cyclonic general circulation, prevails with the inflow into the Adriatic in the eastern portion of the strait and the outflow from the Adriatic in the western part. In summer the flow is dominated by eddies, since the basin-wide forcing mechanisms in driving the water exchange through the Otranto strait (identified mainly as freshwater buoyancy input, air pressure gradient and wind pattern) are weakened. Besides, the outflow of the Adriatic Deep Water (ADW) reaches its maximum in spring, as a consequence of the contribution of a newly formed deep water. The secondary maximum of the ADW outflow, evidenced in autumn, is explained in terms of the contribution of the North Adriatic Dense Water to the bottom layer of the South Adriatic Pit. An overall salinity increase over the study period in the eastern

portion of the strait is attributed to the stronger influence of Ionian waters inflowing into the Adriatic Sea. The mechanism responsible to a certain extent for this phenomenon is a freshwater buoyancy input, originating mostly in the North Adriatic. This forcing function, besides having a seasonal signal, is subject to the prominent interannual modulation, contributing to the intensification of the cyclonic circulation in the Adriatic, and thus strengthening the inflow of Ionian Surface Waters (ISW) and Levantine Intermediate Water (LIW) along the eastern boundary. For February 1995, both inflow and outflow total rates through the strait are of the order of 1 Sv, inflow being more stable than the outflow.

RÉSUMÉ

Les propriétés thermohalines et les caractéristiques des courants sub-inertiaux dans le détroit d'Otrante sont ici synthétisés sur la base de mesures récentes de courants sur le long terme, ainsi que sur celle des résultats des expéditions océanographiques saisonnières menées dans le cadre du projet OTRANTO (février 1994-mai 1995). La variation la plus importante dans le champ des courants se manifeste sur des échelles de temps synoptiques de l'ordre de dix jours. Le courant de surface le long des côtes orientale et occidentale est principalement associé au vent ainsi que nous pouvons le déduire de nos calculs. Les courants de la partie centrale du détroit sont dominés par des structures à l'échelle moyenne. La variation saisonnière est moins active mais plus importante pour les échanges de masse d'eau entre les deux bassins adjacents, ionien et adriatique. En hiver, le flux à large échelle, comme composant de la circulation générale à dominante cyclonique, prévaut avec un afflux vers l'Adriatique dans la partie orientale du détroit et un écoulement hors de l'Adriatique dans sa partie occidentale. En été, le flux est dominé par des tourbillons puisque les contraintes forçant à l'échelle de tout le bassin les échanges de masses d'eau au travers du détroit d'Otranto – principalement les apports d'eau douce, les gradients de pression atmosphérique et le vent – sont affaiblis. En outre l'écoulement des eaux profondes adriatiques (ADW) atteint son maximum au printemps, conséquence de la formation récente d'eaux profondes. Un pic secondaire en automne s'explique par l'apport d'eaux denses nord-adriatiques à la couche inférieure de la fosse sud-adriatique. L'augmentation générale de la salinité pendant la période étudiée est attribuée à la plus forte influence des eaux ioniennes pénétrant en Adriatique. Le mécanisme responsable en partie de ce phénomène est l'apport d'eau douce originaire essentiellement du nord de l'Adriatique. Cette force contraignante possède non seulement un signal saisonnier mais en outre elle est sujette à une importante modulation interannuelle, contribuant à l'intensification de la circulation cyclonique en Adriatique et renforçant par là l'afflux des eaux de surface ioniennes (ISW) et des eaux levantines intermédiaires (LIW) le long de la côte orientale. Les mesures des flux dans les deux sens sont de l'ordre de 1 Sv pour février 1995, l'afflux étant plus stable que l'écoulement.

INTRODUCTION

The Strait of Otranto is a 75 km wide and up to 800 m deep connection between the Adriatic and Ionian seas, with an average depth of 325 m. The flow through the strait and its variability not only affect the local oceanographic conditions, but also influence the hydrodynamic, biological and chemical properties of the adjacent water bodies, including the entire Eastern Mediterranean basin. Two peculiarities of the Adriatic Sea are of note here: on the one hand, it is a dilution basin with an average annual freshwater gain of about 1.14 m; on the other hand, the heat loss reaches, according to some recent estimates (ARTEGIANI *et al.*, in press), about 20 W/m^2 per year. As a result the Adriatic Sea is a deep-water formation site for the entire Eastern Mediterranean. These two competing mechanisms determine the water exchanges through the Strait of Otranto. They consist of outflows of low salinity Adriatic Surface Water (ASW), Adriatic Deep Water (ADW) near the bottom and inflows of more saline Ionian Surface Water (ISW) and Levantine Intermediate Water (LIW).

Until the last decade, knowledge of the water circulation through the strait was mainly based on data obtained from surface drift bottles and classical hydrographic measurements with subsequent geostrophic calculations (WÜST, 1961; OVCHINNIKOV, 1966; ZORE-ARMANDA, 1969; LAVENIA *et al.*, 1983; ORLIC *et al.*, 1992). The water exchange pattern through the Strait of Otranto based on these indirect current estimates may be summarized as follows: in the surface layer, the flow through the strait appears subject to seasonal fluctuations due to both meteorological forcing and differences in thermohaline properties between Adriatic and Ionian surface waters.

In winter, when Adriatic waters are denser than Ionian waters and south-easterly winds together with an average northward air pressure gradient prevail over the region, an inflow (into the Adriatic) occurs along the Albanian coast and in the central portion of the strait. Thus, the intensity of the ISW inflow is related to the frequency of prevailing southerly or south-easterly winds (POLLAK, 1951). The outflow of the low-salinity ASW is documented along the western shoreline and represents a density-driven current. Additionally, a signal associated with the Atlantic Water – which enters the Mediterranean Sea and flows eastward along the North African coast – has been evidenced occasionally in the Strait of Otranto (HOPKINS, 1978) under strong southerly winds (OVCHINNIKOV, 1966).

In summer, when the meteorological and oceanographic conditions reverse – lighter water in the Adriatic than in the Ionian Sea, prevailing north-westerly winds associated with a zonal air-pressure gradient – an outflow predominates along the Italian coast and in the central portion of the strait. The inflow, on the other hand, is concentrated in a relatively narrow coastal band on the eastern side (ZORE-ARMANDA, 1969).

In the intermediate layer, an outflow of Adriatic water along the western shelf-break occurs, while an inflow of highly saline LIW takes place in the remaining part of the strait, the main core of the latter being centered at a depth of about 150 m. No evidence on seasonal variations in the LIW inflow has been reported in published papers so far; however, the existence of long-term changes in the inflow of the LIW and their influence on thermohaline conditions in the entire Adriatic Sea area have been documented (BULJAN, 1953; ZORE-ARMANDA, 1974).

Finally, in the bottom layer, the dense water formed in the southern Adriatic (ADW) outflows into the northern Ionian basin. This water mass subsequently spreads towards and throughout the bottom layer of the Levantine basin (BULJAN and ZORE-ARMANDA, 1976). As early as 1951, POLLAK found the ADW to be the main component of the Eastern Mediterranean Deep Water (EMDW) with no substantial contribution from the Aegean Sea. This was corroborated in 1987 by the results of Freon-12 and oxygen measurements (see SCHLITZER *et al.*, 1991) but it is still disputed. Thus, understanding the water exchange regime in the Strait of Otranto offers the possibility to estimate both the volume of the EMDW and its residence time. The ADW outflow undergoes strong interannual variations, the estimates by OVCHINNIKOV (1978) and OVCHINNIKOV *et al.* (1985) ranging in from 0.2 to 1.24 x 10^6 m^3/s. The ADW outflow probably depends on the volume of the water formed, itself a function of winter climatic conditions. Recent observations aboard F/S *Meteor* (ROETHER *et al.*, in press) have shown for the first time that the EMDW can also be influenced by transient intrusions from a second potential deep-water formation area, the Aegean Sea. Whether the Aegean does not produce any bottom water in certain years or whether its contribution becomes evident in the case of reduced ADW formation and outflow rates, it is not yet clear.

Variability at smaller spatial and temporal scales (mesoscale and sub-inertial variability) is poorly known, mainly because very few direct current measurements – none longer than a month – have been carried out so far in the strait. Only recently have direct current measurements revealed a prominent mesoscale variability superimposed on the mean water exchange pattern. This variability is mostly associated with mesoscale eddies (FERENTINOS and KASTANOS, 1986). Also wind-induced current reversals, as part of the sub-inertial variability, have been documented in the shallower coastal area of the strait (FERENTINOS and KASTANOS, 1986; MICHELATO and KOVACEVIC, 1991).

The aim of this paper is:

– to summarize the characteristics of the water exchange pattern, the thermohaline properties of water masses and their distribution in the Strait of Otranto,

– to further develop a phenomenological model of water exchange through the strait by analyzing data collected within the EU-MAST project OTRANTO,

– to give a detailed description of the sub-inertial variability of the current field on temporal scales of the order of a day up to a season.

THERMOHALINE PROPERTIES

This section primarily deals with the spatial distribution of the water masses found in the Strait of Otranto and with the seasonal and the sub-basin scale variabilities of their thermohaline properties. The presence of the water masses as well as their spatial extension will be discussed analyzing T-S diagrams and maps of horizontal and vertical distribution of temperature, salinity and density. The data were obtained from six seasonal cruises in the area, covering a period from February 1994 until May 1995. The cruises are referred to as OTRANTOn where "n" is the chronological number of the cruise ranging from 1 to 6. The grid of stations occupied over the six campaigns is presented in Figure 1. The measurement methods and data quality control have been presented extensively elsewhere and need not be discussed here.

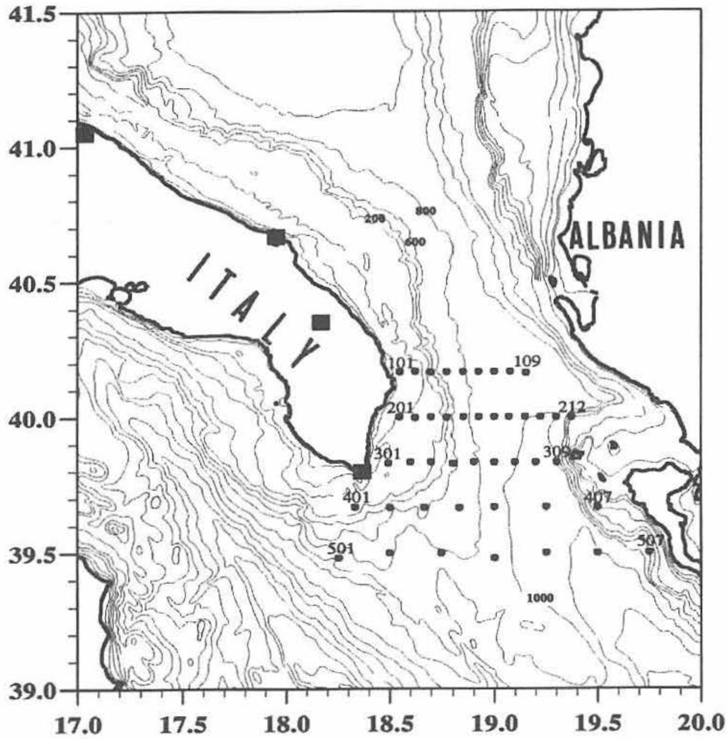

Figure 1 – Hydrographic station locations occupied during surveys conducted in the Strait of Otranto. Location of wind measurement sites is indicated by squares. Depth is given in meters. At each transect the first and last station numbers are denoted. The first digit in the station number denotes the transect number.

T-S diagrams (Figure 2) of all data recorded during the summer and winter surveys show clearly the presence of the distinct water masses and their modification during the annual cycle:
a) the densest ADW with a temperature of about 13°C and a salinity of about 38.65 psu occurring in the form of a tail in the T-S diagrams,
b) the slightly lighter LIW which is the saltiest water in the area with a salinity reaching 38.85 psu, but warmer than the ADW with a temperature of about 14°C,
c) the least saline ASW outflowing from the Adriatic along the western strait boundary and the more saline ISW entering the Adriatic along the eastern shoreline. The two surface waters show, however, highly variable thermohaline properties so that it is sometimes hard to distinguish them.

During winter (Figure 2a) two different surface water masses are clearly visible, *i.e.* the ASW which is also the coldest one in the area with a temperature minimum of about 11°C, and the saltier and much warmer ISW with a temperature of more than 15°C and a salinity above 38.25 psu. The ASW over the western shelf area is characterized by a thermal inversion – temperature increase with depth throughout the entire water column –

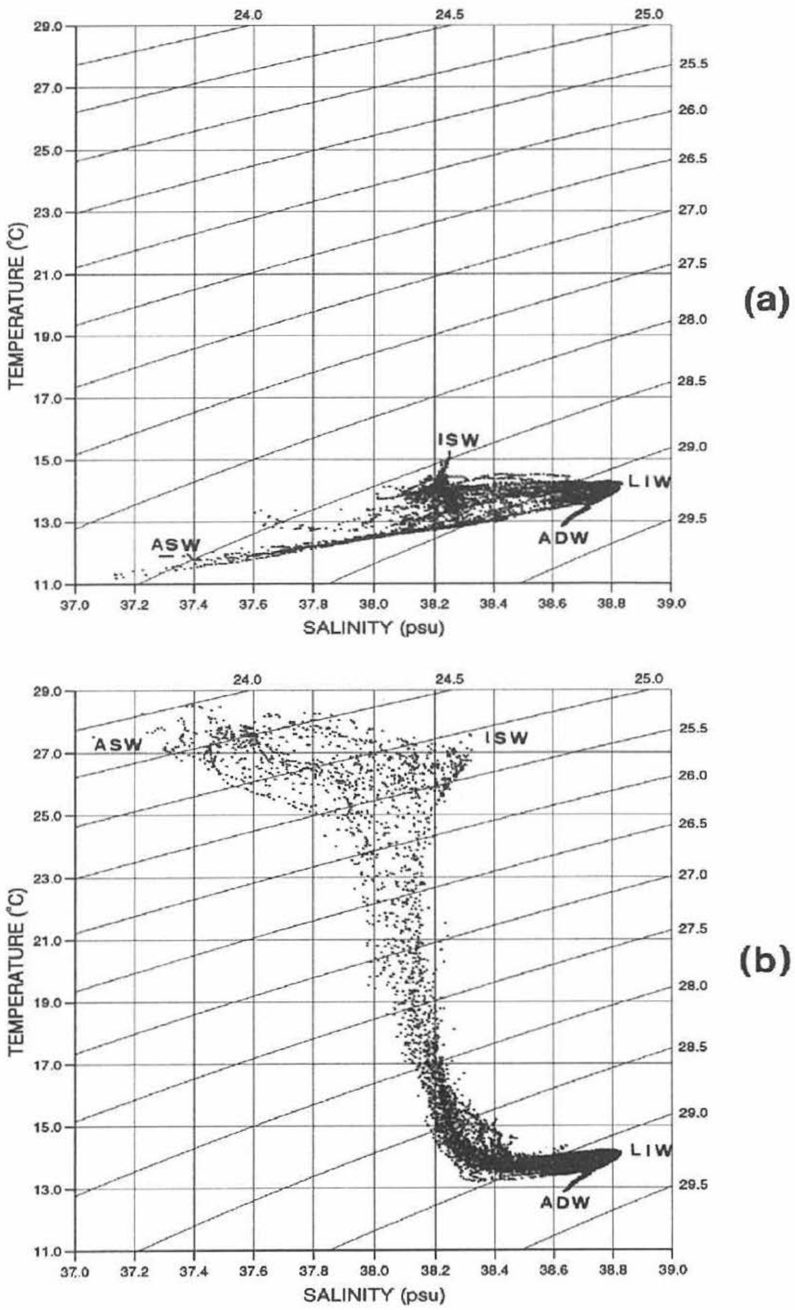

Figure 2 – Plots of potential temperature (°C) *versus* salinity (psu) of all stations occupied during (a) winter 1994 and (b) summer 1994 surveys. The different water types discussed in this paper are indicated by their acronyms.

where the vertical stability of the water column is due only to the salinity distribution. In the stratified season, the two surface water masses are not so easily distinguished from their thermohaline properties. Seasonal variability mainly occurs in the upper 100 m and is due to surface heat exchange and the freshwater inflow, while the T-S diagram in deeper layers displays small changes throughout the different seasons.

The vertical distributions of temperature, salinity and density along the transects show the spatial extension of the water masses. Figure 3 compares the winter and summer situations. The signal associated with ADW is evident in either temperature, salinity or density and it occurs as a bottom temperature and salinity minimum corresponding to a density increase. ADW is hereinafter defined as the water having potential density excess (σ_θ) larger than 29.20 kg/m^3. In contrast, the signal associated with the LIW – which is defined as the water contained in the layer with salinity higher than 38.75 – is only evident as a maximum in the salinity field. The winter situation (Figure 3a) is characterized by a coastal surface boundary layer on the western shelf of relatively fresh and cold outflowing water which is separated from that in the center of the strait by a coastal front. A tongue of fresh ASW (T<13.0°C, S<38.2) protrudes seaward amidst the warmer and more saline surface and intermediate Ionian waters. The ASW reduces its spatial extension going southward and the surface jet detaches from the coast when reaching the northern Ionian (transect not shown). The summer situation shows a reduced horizontal variability in the surface layer which is partly associated to the minimum river runoff. The presence of the seasonal thermocline is clearly visible. In deeper layers the pattern remains qualitatively unchanged; however, the signal associated to the ADW is weaker. Differences between summer and winter in the LIW signal are not so evident.

In order to give a more precise definition of the two water masses and to follow more closely their temporal variability, average T, S and σ_θ were calculated for parts of the sections where σ_θ is larger than 29.20 kg/m^3 for ADW and where S is higher than 38.75 for LIW. Also, the area occupied by waters having these characteristics for each season was computed. This represents then a quantitative measure of the volume of the two water masses. Average thermohaline properties of the surface water masses were not calculated because of their large temporal variability.

The average values of temperature and salinity for ADW and LIW are presented graphically in Figure 4 for all six cruises, together with some historical data obtained from some other campaigns in the area (project POEM – Physical Oceanography of the Eastern Mediterranean). Standard deviations within each season (not shown here) are smaller than the instrumental errors. The temporal variability in both ADW and LIW was very small during the entire Otranto project period. The only exception is the T-S relationship for LIW in spring 1995 when the average salinity is substantially higher than for the preceding seasons. In general T-S characteristics of the ADW are more variable on the seasonal scale than those of LIW. Also, differences between historical data points and Otranto data are typically larger than differences within the Otranto data set. This would suggest that the interannual signal in thermohaline properties of both LIW and, to a lesser extent, of ADW is significantly stronger than the seasonal one.

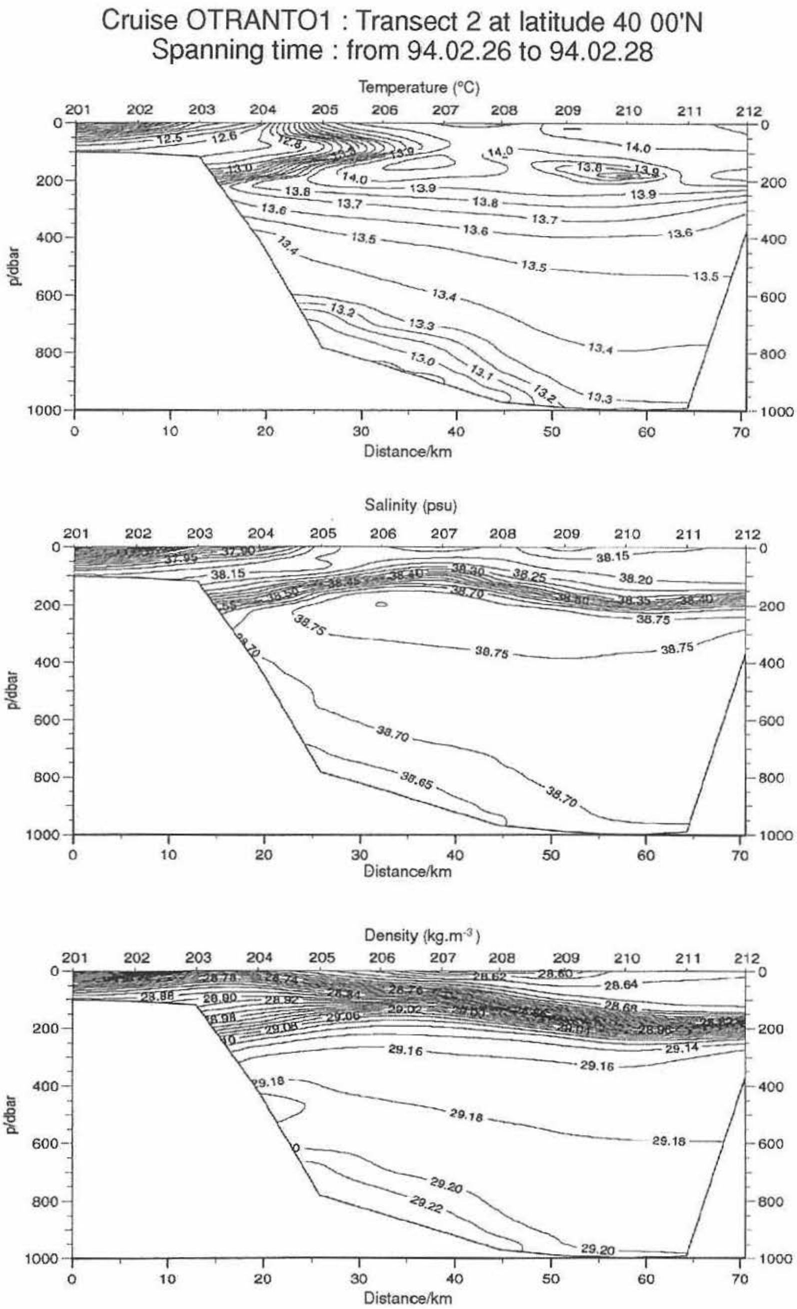

Figure 3a – Vertical sections of potential temperature (upper panel), salinity (middle panel) and density excess (lower panel) for the winter 1994 survey at transect 2. The hydrographic stations are indicated by numbers at the top of the layout.

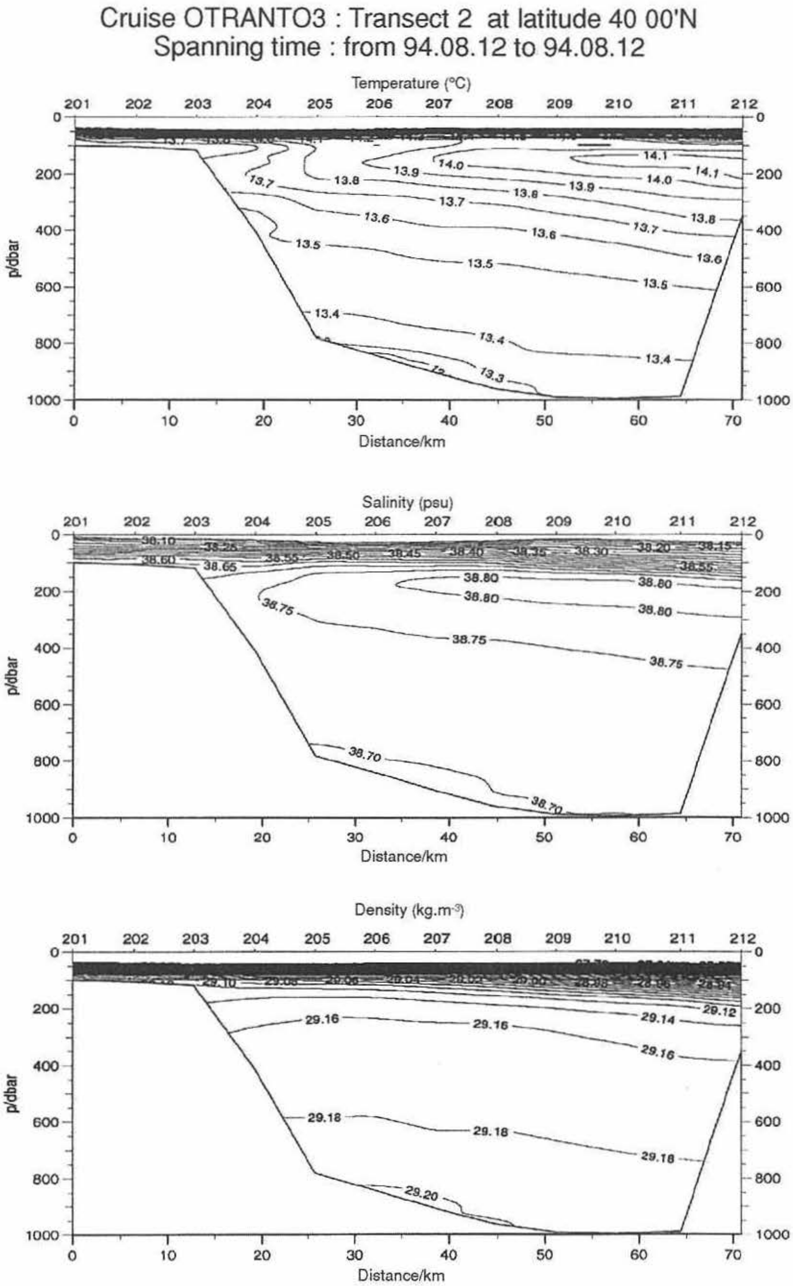

Figure 3b – Vertical sections of potential temperature (upper panel), salinity (middle panel) and density excess (lower panel) for the summer 1994 survey at transect 2. The hydrographic stations are indicated by numbers at the top of the layout.

The variability of the area occupied by the two water masses displays a strong seasonal signal (Figure 5). The largest cross-sectional area occupied by ADW is found in winter, *i.e.* immediately after the vertical convection period. On the other hand, the minimal area occupied by ADW occurs in summer, which can be explained in terms of the draining of the south Adriatic reservoir. In the autumn the area occupied by ADW increases again. The only possible explanation for the occurrence of an increased volume of the ADW that overflows the sill of the Otranto Strait in autumn can be found in an increased contribution of the much colder and less saline North Adriatic Dense Water. This water overflows the Palagruza Sill, follows isobaths in the form of a vein until it encounters a transversal sub-marine canyon off Bari (BIGNAMI *et al.*, 1990) where a vigorous mixing occurs. The North Adriatic Dense Water reaches the South Adriatic Pit only in autumn triggering again ADW overflow while also partially mixing with it. Seasonal variability of the area occupied by LIW displays a maximum in summer. In addition, an overall increase throughout the study period is evident, suggesting an increased

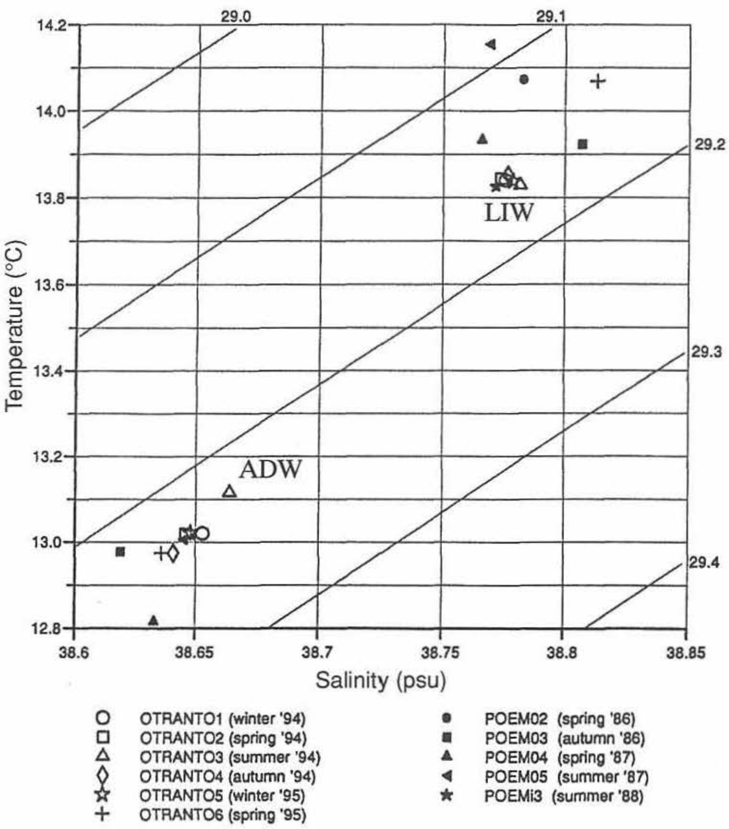

Figure 4 – Average values of temperature and salinity for LIW and ADW from data collected during the seasonal surveys within the OTRANTO project and from some historical data in the same area.

Mediterranean water influence in the Strait of Otranto. It is important to notice that the ADW and LIW volume changes are complementary both on seasonal and longer time scales, *i.e.* in summer when there is a minimum of ADW, the LIW reaches its maximum. Also, when in spring 1995 LIW shows a maximum for the entire period considered, ADW area decreases to its minimum. This may suggest that the LIW inflow is not compensated by the ADW outflow. Thus, one can conclude that the compensating outflow for stronger LIW inflow should occur in the surface layer. It is important to mention that the area occupied by a determined water is not necessarily related to the amount of water transported across the strait, but can also reflect its accumulation. The variability of the transport and of the volume of the water present can also be dictated by sub-basin scale circulation features not necessarily associated with a seasonal time scale. This applies more likely to the LIW since it is shallower and since sub-basin scale structures are prevalently baroclinic. In fact, the area occupied by LIW shows large spatial changes which are consequence of the sub-basin circulation features.

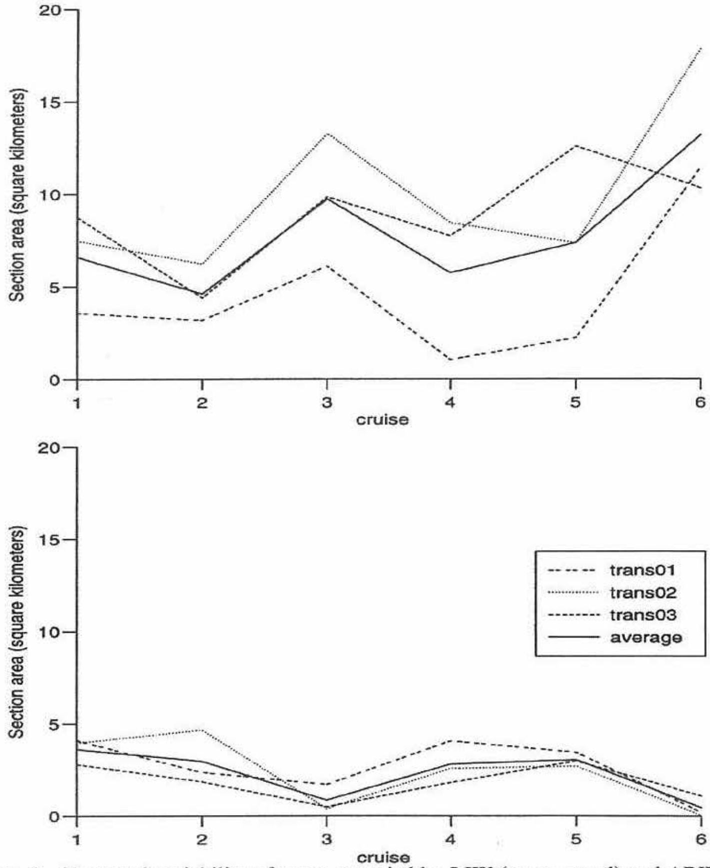

Figure 5 – Temporal variability of areas occupied by LIW (upper panel) and ADW (lower panel) in each transect and for each cruise (1 – winter 1994, 2 – spring 1994, 3 – summer 1994, 4 – autumn 1994, 5– winter 1995 and 6 – spring 1995).

The summer and winter upper thermocline geostrophic shear field, as well as corresponding surface layer temperature and salinity distributions, were compared. Geopotential anomalies of the sea surface were computed with respect to the 100 dbar reference level. This reference level is chosen in order to obtain a geostrophic shear in the layer above the seasonal thermocline. Winter pattern (Figure 6) shows a strong horizontal shear between the eastern and western portions of the strait with a well pronounced meandering large-scale inflow stream. Both inflowing and outgoing current patterns are only modified by the sub-basin scale features. On the other hand, in summer the upper thermocline water exchange across the Strait of Otranto is completely blocked by a large sub-basin scale anticyclonic eddy (Figure 6). Winter horizontal distributions of temperature and salinity show clearly a narrow stream of ASW leaving the Adriatic in winter (Figure 7). The major portion of the strait surface (eastern and central part) is characterized by the presence of a homogeneous warmer and more saline water of Ionian origin. Summer horizontal variability of both temperature and salinity (Figure 7) is mainly characterized by sub-basin scale closed features and by the absence of a basin-wide structure. Thus, the essential difference between summer and winter horizontal distributions of thermohaline properties is in the importance of sub-basin scale features, which during winter can only modify the basin scale flow pattern, but in summer can completely block the upper thermocline water exchange between the Ionian and Adriatic seas.

CURRENT FIELD VARIABILITY

In this chapter certain characteristics of the sub-inertial current field variability in the Strait of Otranto will be summarized, analyzing data from an array of current meters spanning the strait over a period of approximately a year and a half (see Figure 8 for mooring locations and time-series available), and from surface drifters released in the eastern part of the strait in December 1994 and May 1995.

From all Eulerian current measurements mean hourly current vectors were calculated and then low-passed using a digital filter (THOMPSON, 1983) to remove tidal and other high-frequency variations. A geographic coordinate system is used since the along-strait axis is oriented approximately in a north-south direction and thus, north current component is a good approximation of the inflowing current component. Average north and east current components as well as their standard deviations are calculated for each current meter location and for each month. Also, kinetic energy of the mean motion and fluctuations is calculated.

Seasonal changes as well as the high-frequency sub-inertial variability on a weekly time scale, which appears rather energetic over the entire strait (Figure 9), will be described. In fact, inspection of the time-series reveals that the temporal variability on a weekly time-scale is sometimes even more prominent than the seasonal variations.

Analyzing the two winter months, with a good spatial coverage of the strait by current measurements, a comparison of the eddy kinetic energy of the east and north current components reveals a north-south polarization of the flow field which is especially prominent near the strait bounda-

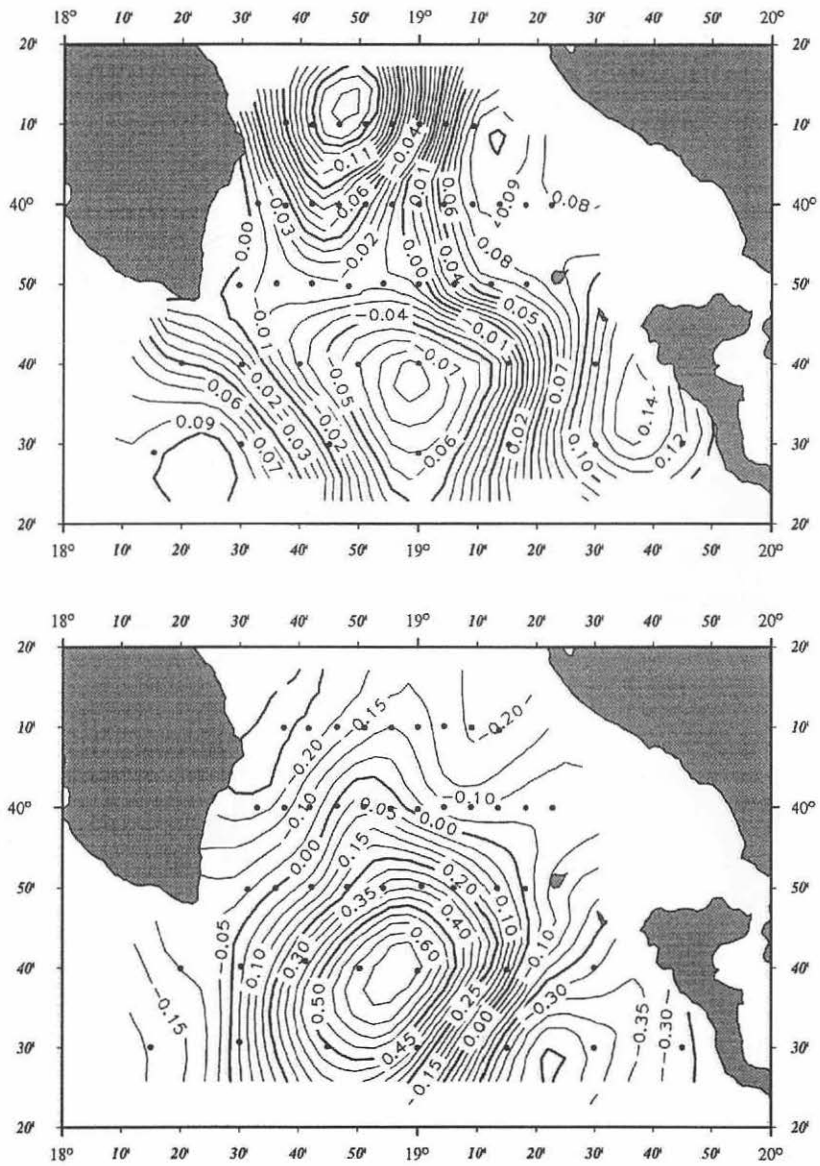

Figure 6 – Geopotential anomaly (m^2/s^2) at surface referenced to 100 dbar for both winter (upper panel) and summer (lower panel) surveys.

ries (Figure 10, upper panel). Moving away from the boundaries the difference in the eddy kinetic energy between the east and north current components diminishes and transversal (east-west) velocity fluctuations can even exceed the longitudinal ones (station 306 and 308). Furthermore, comparison of the eddy and mean kinetic energy in the north current component

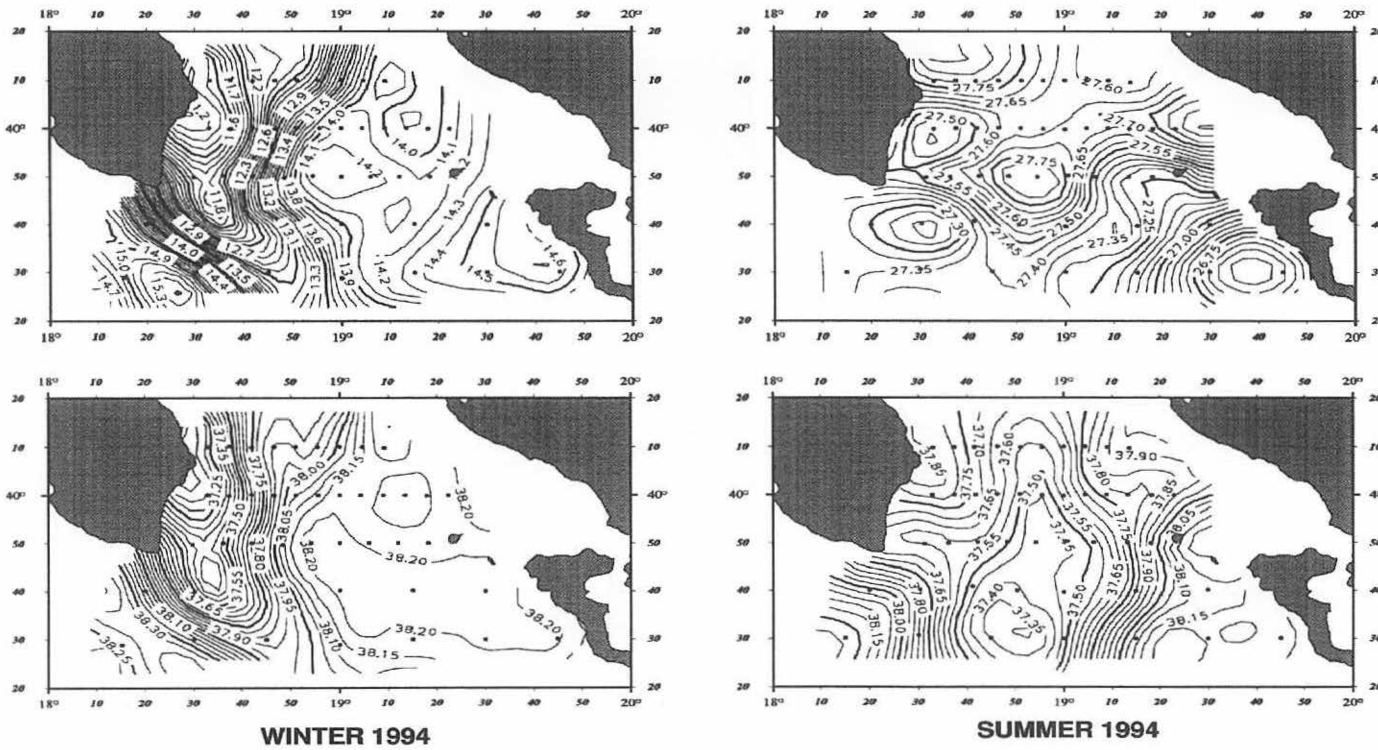

Figure 7 – Distribution of surface temperature (upper panel) and salinity (lower panel), averaged in the layer between 0 and 10 dbar, for the winter 1994 surve (left) and for the summer 1994 survey (right).

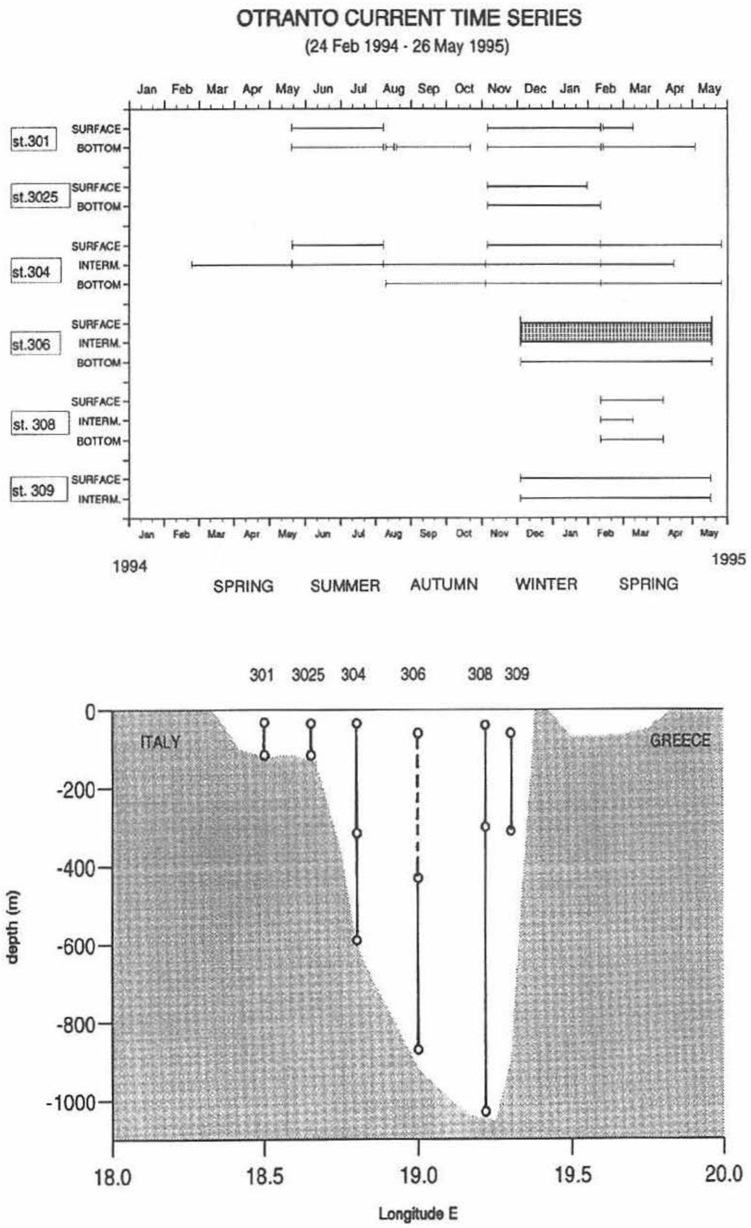

Figure 8 – Schematic diagram (upper panel) of all available current-meter data and the locations of the six moorings with instrument positions (lower panel) deployed along the 39 50' N section in the Strait of Otranto. The shadded area in the upper panel and the vertical dashed line at the station 306 in the lower panel denote the layer for which the measurements were carried out by Acoustic Doppler Current Profiler (ADCP) with vertical resolution of 8 m. Other series were obtained by classical self-recording instruments.

at various points of the transect for the surface layer (Figure 10) shows the prevalence of the mean over the eddy kinetic energy at the eastern and western boundaries of the strait. Also, the total kinetic energy reaches a maximum at both sides of the strait. Since the kinetic energy is calculated on a monthly basis, the eddy kinetic energy is mainly associated with the high-frequency current variability on the time-scale of several days. This suggests therefore that the quasi-steady motion prevails over the transient motion in the surface layer on both flanks of the strait. In contrast, in the central portion of the strait the eddy kinetic energy is larger than or equal to the kinetic energy of the mean flow. This pattern in the surface flow field is especially prominent in December 1994 and January, February and March

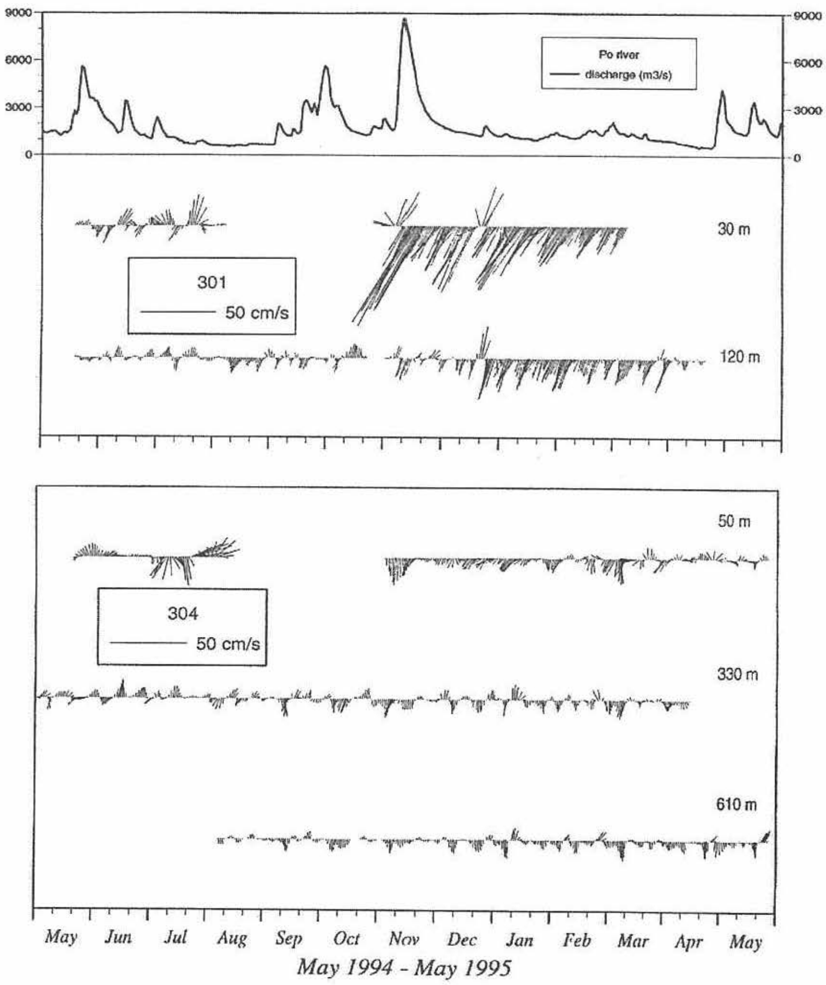

Figure 9 – Low-pass current vector time-series (subsampled at 12.00-noon of each day), at station 301 (upper panel, together with the daily Po river discharge rate), and at station 304 (lower panel).

1995 (Figure 11), *i.e.* after the strong buoyancy input in early November 1994 which generated a geostrophically balanced outflowing surface current along the western shoreline. The strong buoyancy input by the river runoff is well illustrated by the Po river discharge rate time-series (Figure 9) which in early November 1994 reached the value of almost 10.000 m^3/s, which is an order of magnitude larger than the long-term average of 1450 m^3/s. Near the eastern boundary of the strait the strong surface inflowing current probably represents the compensating current to the western surface outflow.

Analyzing the time history of the relationship between the kinetic energy of the mean motion and the eddy kinetic energy, one notices that the quasi-steady motion prevails over transients in the surface layer on the western shelf area in the period January-March 1995, following the strong freshwater buoyancy input (Figure 11). The coverage of the rest of the observational period is rather incomplete, although summer data (July and August 1994) show relatively low values of the total kinetic energy and negligible values of the kinetic energy of the mean motion. This can be explained in terms of the very low buoyancy input and an almost complete absence of an off-shore baroclinic pressure gradient which otherwise drives the surface long-shore density current. The quasi-steady baroclinic flow, illustrated by the prevalence of the kinetic energy of the mean motion over

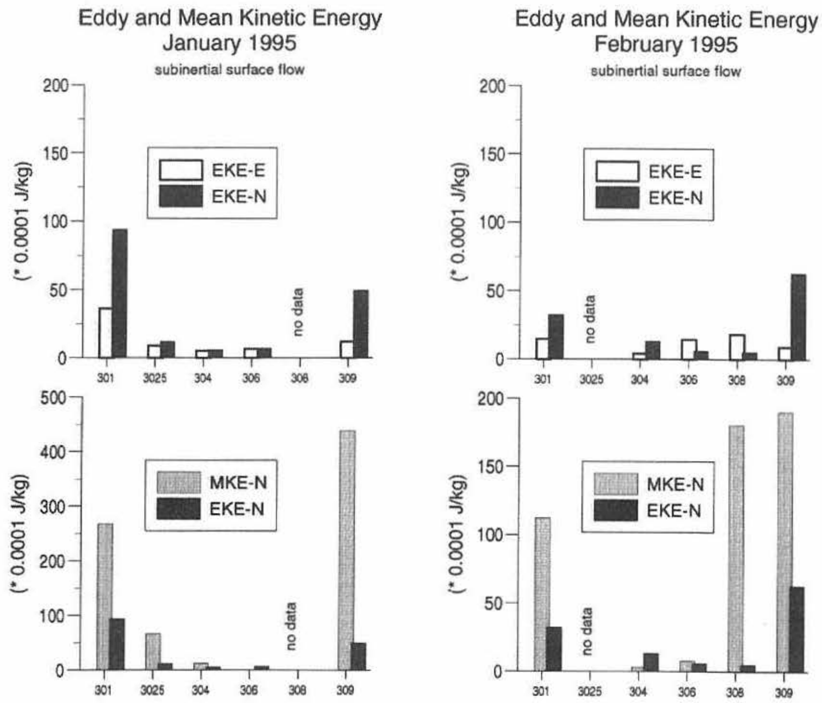

Figure 10 – Spatial distribution of the eddy kinetic energy (EKE) for the east and north current components, and the kinetic energy of the mean motion (MKE) of the north flow for the two winter months. Note the scale change in the lower left panel.

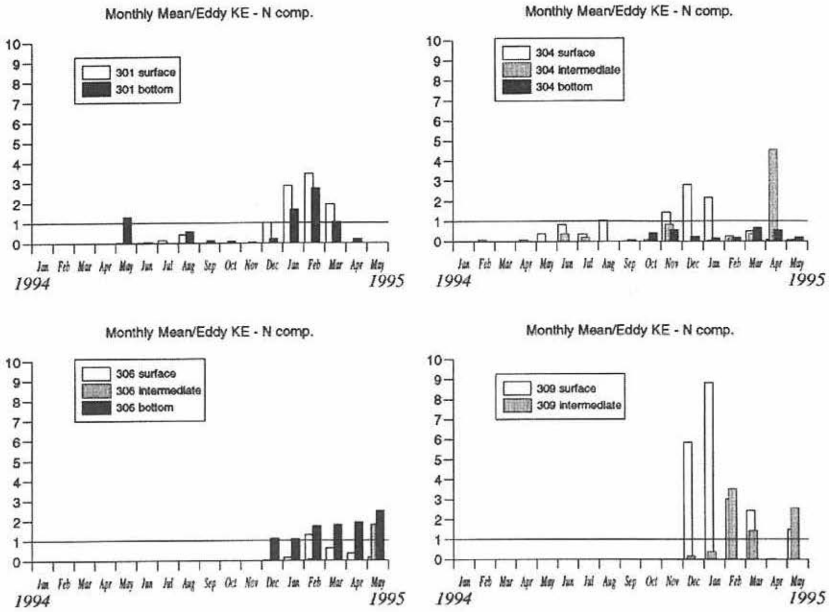

Figure 11 – Time-series of the ratio of monthly values of the kinetic energy of the mean motion and the eddy kinetic energy of the north current component at selected stations (301, 304, 306 and 309).

the eddy kinetic energy, is also prominent in the surface layer at the shelf-break area (station 304). This quasi-steady flow follows the major buoyancy input and occurs contemporarily with the occurrence of the coastal density driven current. In the bottom layer at the western shelf, a quasi-steady flow occurs almost simultaneously with the surface outflow (Figure 11) and consequently the kinetic energy of the mean motion prevails over that of fluctuations during the period January to March 1995. The quasi-steady motion in that layer is probably driven by the offshore baroclinic pressure gradient as it is the case with the surface layer. The strong vertical shear is also associated with the horizontal density gradient. In the rest of the study period the residual flow was weaker than the sub-inertial fluctuations.

The prevalence of the kinetic energy of the mean motion over the eddy kinetic energy occurs also at the 300 m depth near the eastern boundary of the strait (station 309), but with a phase-lag of about two months with respect to the surface layer. In this former layer the mean motion (inflowing current) prevails over the fluctuations in February-March period. This is very likely related to the compensatory inflowing transport along the eastern side. The inflow occurring at the depth of 300 m, *i.e.* near the LIW core depth, and in the upper layer suggests that the baroclinic outflow along the western shore as a response to the buoyancy input, is one of the mechanisms reinforcing the general cyclonic circulation of the Adriatic Sea and consequently the inflow of both ISW and LIW. Moreover, the major buoyancy input into the Adriatic Sea results in an intensification of the Mediterranean influence, bringing more salt and causing a subsequent possible increase of salinity in the Adriatic.

The kinetic energy of the mean motion is more prominent than the eddy kinetic energy also in the central part of the deepest portion of the strait (station 306) in the late winter/early spring, *i.e.* following the deep water formation period. Therefore, this quasi-steady motion is obviously associated with the ADW outflow.

As a conclusion, quasi-steady along-strait flow prevails in the area close to the strait boundaries and it is seasonally modulated and probably driven by a baroclinic pressure gradient set-up by the fresh-water discharge in the north-western coastal area. Another area dominated by a quasi-steady and again seasonally modulated flow is the bottom layer of the deepest part of the strait where the outflow of ADW takes place. Here the intensity of the outflow depends on the availability of ADW and it is the strongest during the spring season, *i.e.* following the deep water formation period. In the remaining transect area the current field is dominated by the sub-inertial variability on the weekly time scale.

The vertical distribution of the inflowing current component together with the ratio of the mean north current component and its standard deviation for February 1995 is shown in Figure 12 and summarizes well the strait flow vertical pattern. The eastern and western boundary surface flows are stable. At the eastern boundary the stable quasi-steady inflow extends up to the intermediate layer. The area of a relatively stable current is also the outflow layer in the central and western part of the bottom layer where ADW leaves the Adriatic. The remaining portion of the transect – the western shelf-break area and the bottom layer near the eastern boundaries – is dominated by the high-frequency transients.

The high-frequency variations may either be generated by atmospheric forcing (wind and atmospheric pressure) or be associated with mesoscale features (eddies, filaments) mainly created by instability of the strong mean shear flow in the strait area. Current field response to a local wind is a baroclinic signal and it is limited to a surface layer. A response to the atmospheric pressure is a barotropic signal while the eddy-associated temporal variability should be prevalently baroclinic.

Wind data were obtained from four Italian land stations (see Figure 1 for locations of wind measurement sites). As they are obviously influenced by local orographic features, wind time-series from various stations were first qualitatively compared in order to eliminate local differences. Then, observing that differences were relatively small, wind velocity vectors from all four stations were averaged and subsequently taken as a wind time-series representative for our current data set. Certainly wind field shear and divergence are not negligible over the width of the strait (75 km) but they are not resolved even with the modern wind measurement methods (remotely measured wind-stress).

The north current component and the same wind velocity component are well correlated in coastal areas, suggesting that the wind blowing along the strait axis generates a downwind current in the vicinity of the boundaries. These wind-generated events in current field are superimposed to the baroclinic quasi-steady flow and only rarely does the wind-driven current component become so strong as to create a flow reversal. Indeed, only one complete flow reversal occurred during the whole period of measurements. It appeared after the etablishment of the baroclinic outflow along the wes-

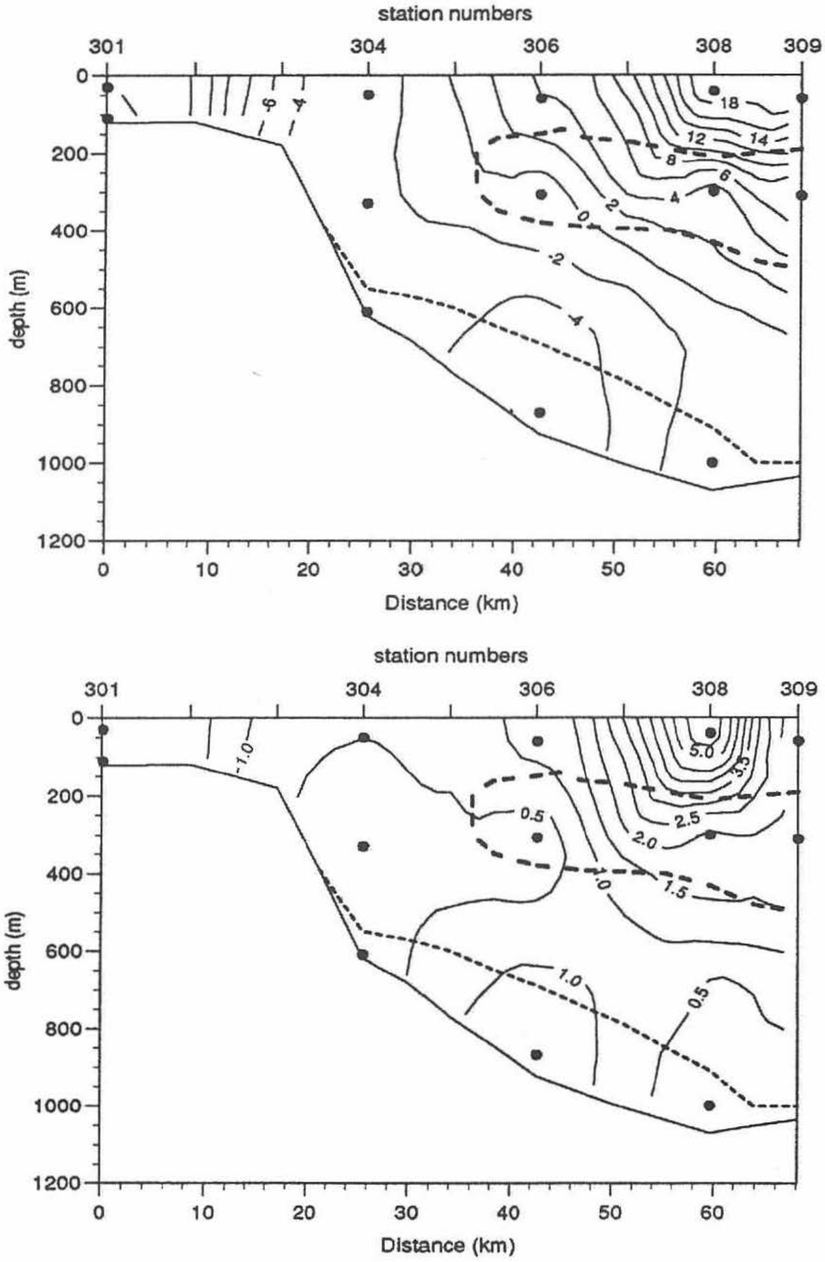

Figure 12 – The February 1995 average north current component in cm/s (upper panel) and the stability calculated as the ratio of the mean current to the corresponding standard deviation (lower panel). The 29.18 kg/m³ density isopycnal, used as the arbitrary limit for calculating the bottom outflow, is denoted by a dashed line. The heavy dashed line is the 38.75 psu isoline delimiting LIW tongue.

tern shoreline (around December 20) and corresponded to a strong southerly wind event in the strait area. In contrast to surface currents in the western shelf area, the currents in the central portion of the strait are very poorly correlated with the wind (Figure 13).

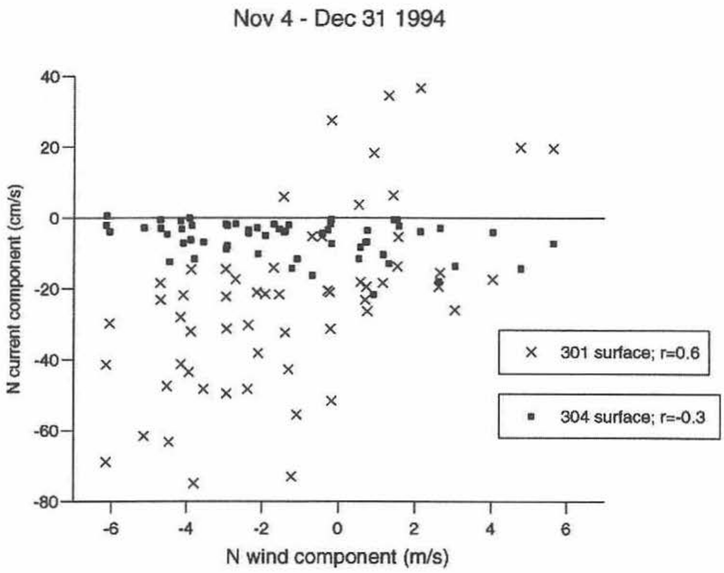

Figure 13 – Dispersion diagram of the north current velocity and north wind components for the surface layer at stations 301 and 304, and the corresponding linear correlation coefficients.

Obviously high-frequency variability in deeper layers is not forced by the local wind. In order to analyze different spatial patterns (baroclinic or barotropic) in relation to various forcing mechanisms, an empirical orthogonal function (EOF) analysis of all available north current component data was carried out. Subsequently, temporal variability of various spatial modes was correlated with the atmospheric pressure and north wind component. Atmospheric pressure in Trieste was expected to represent a signal associated with the sea-level slope and related to the barotropic water exchange. However, since atmospheric pressure and wind time-series are strongly correlated – high pressure coincides with the northerly winds and low pressure with the southerly winds – only wind data were retained. For December 1994 comparison between time-series of amplitudes of various modes and the north wind component variations reveals that the first EOF mode is highly correlated with the wind forcing (Figure 14). This mode explains 60% of the total sub-inertial variance and displays a spatial pattern in which two boundary areas are in-phase; western shelf and slope areas are in-phase with the eastern surface layer. It thus obviously represents a spatial pattern in which current field at the two sides of the strait shows downwind response; as much as 75% of the current field variance in the surface layer on the western shelf is explained by that mode.

In the bottom layer in the same area (~100 m depth) the percentage of the explained variance reduces to about 40%. In the surface layer near the

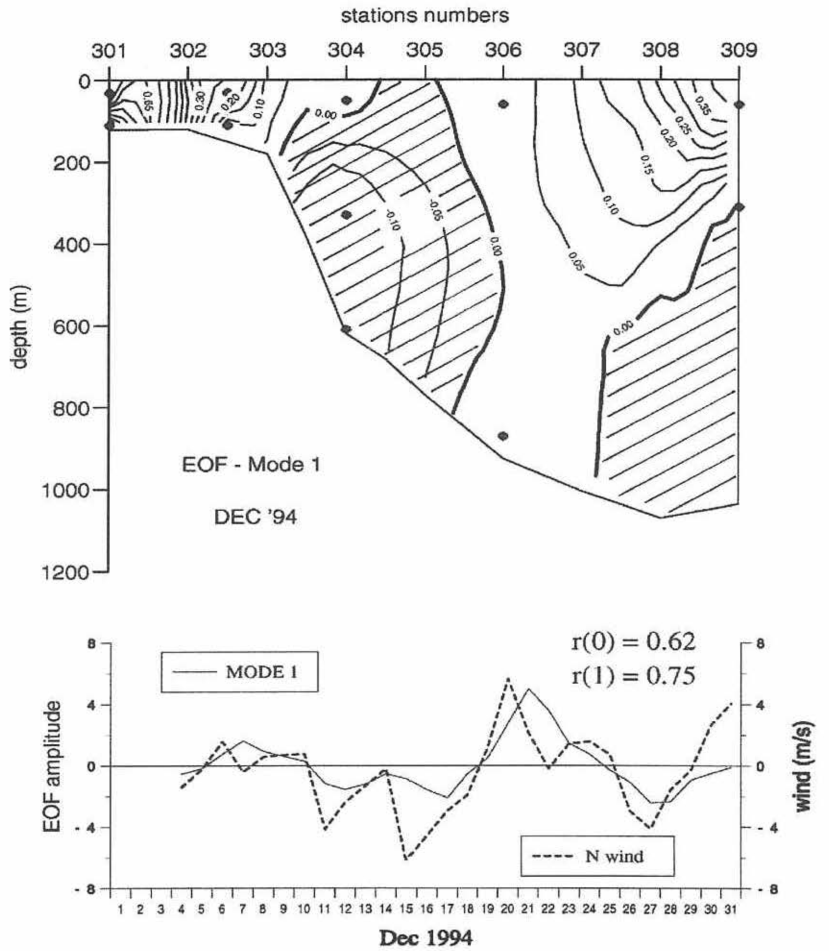

Figure 14 – Spatial distribution of the first EOF mode of the north current component (upper panel). The amplitude of this mode (lower panel) is compared to the north wind component (positive values represent southerly winds). Zero- and one-day phase-lag correlation coefficients are shown.

eastern boundaries, about 40% of the low-pass current field variance is explained in terms of that mode. On the other hand, high-frequency sub-inertial variations in the central part of the strait and in the intermediate layer near the eastern boundary are completely decoupled from the wind forcing. The wind-driven signal in the coastal area strongly prevails over the background noise as was revealed earlier in this chapter by correlation calculations between the wind and currents (Figure 13). The cross-correlation function between wind and the first EOF modal amplitude shows a maximum for the one-day phase-lag, the wind leading the first EOF mode. This phase lag is close to the geostrophic adjustment time, *i.e.* the time interval in which horizontal pressure gradient, established as a result of the wind forcing generates a geostrophic flow.

Satellite-tracked drifters were deployed in the eastern Strait of Otranto in December 1994 and May 1995 to describe the spatial and temporal variability of the surface velocity and temperature fields. The drifters drogued within the first meter of water were tracked by the ARGOS satellite system. Drifter positions were interpolated on 2-hour regular intervals and low-pass filtered to remove the inertial and tidal current components. The drifter tracks reveal the complex surface circulation in the Strait of Otranto, mainly dominated by mesoscale features. Five-day long track segments are depicted in Figure 15 for consecutive time periods in December 1994 and for the first

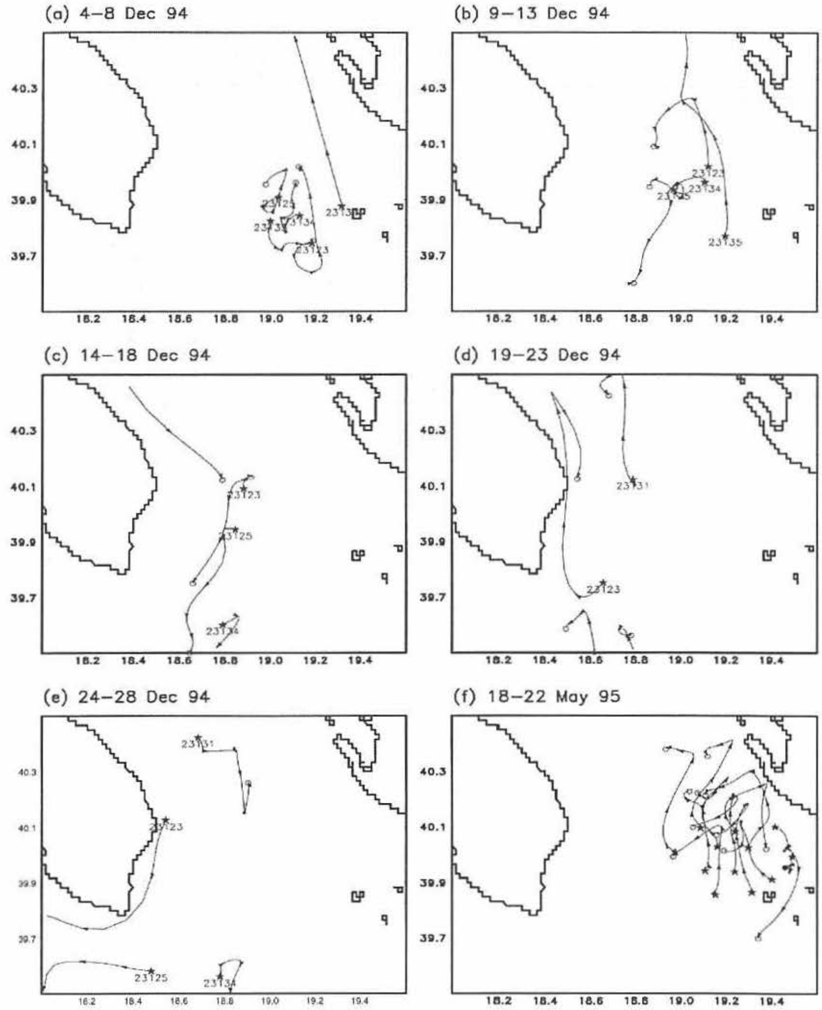

Figure 15 - Five-day long trajectory segments of surface drifters in the Strait of Otranto in December 1994 (a-e) and in May 1995 (f). Start and end locations are denoted by star and circle symbols, respectively. The drifter identification numbers (omitted for panel (f) for clarity) are posted near the start symbols. Arrow symbols plotted along the tracks at daily intervals indicate the direction of drift.

five days after deployment in May 1995. In December, the inflowing surface Ionian water is seen as a narrow quasi-steady stream on the eastern flank of the strait (between 19°10' and 19°20'E) with typical speed of 25 cm/s (see drifters in Figure 15a,b). To the west, the circulation is weak and chaotic. A contemporaneous satellite thermal image (Figure 16) reveals that the transition from swift northward mean flow to weak mesoscale circulation is associated with a strong surface thermal front separating the relatively warm Ionian water to the east from colder Adriatic water in the western and central parts of the strait. By mid-December (Figure 15b,c), some of the drifters became entrained by the outflowing ASW.

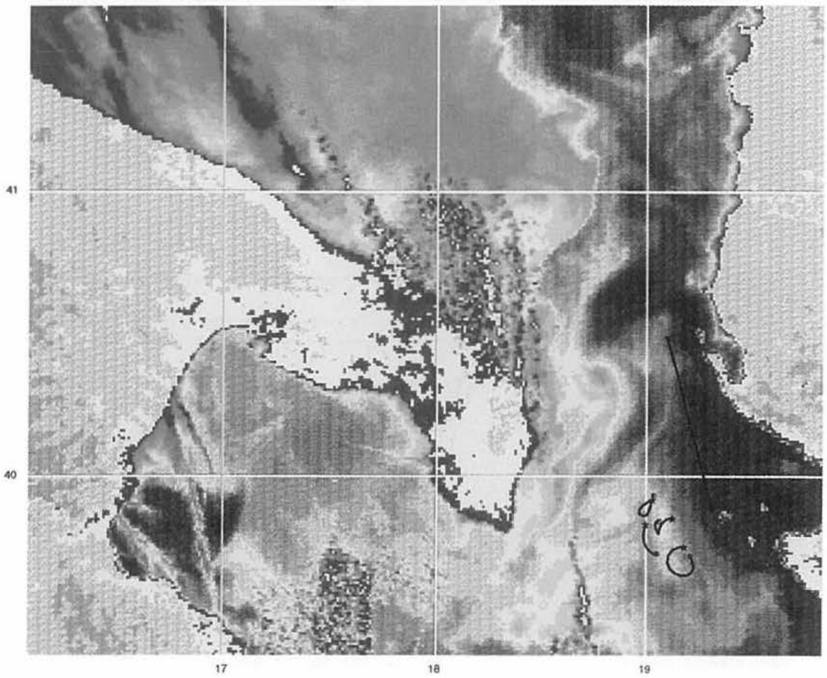

Figure 16 – Satellite thermal image of the Strait of Otranto area on 3 December 1994 at 08:35 UT. Relative warm (cold) surface water is depicted in green (pink). Drifter trajectories for the period 4-6 December are superimposed. Symbols are as in Figure 15.

The wind-induced reversal event of outflowing ASW around 20 December revealed by the moored current measurements (see above) is corroborated by the drifter observations. Indeed, starting on 20 December, drifters 23123 and 23131 turned to the right and proceeded northward for about two days showing that the reversing currents are essentially concentrated on the Italian shelf and slope (Figure 15d). The maximum northward speed (about 50 cm/s) was observed very close to the Italian coast on 21 December 1994. Southward flow was restored on 22 December as the two drifters reversed their direction (Figure 15e) and moved either south-eastward into the central area of the strait (drifter 23131) or south-westward rapidly escaping into the Ionian basin (drifter 23123). By their Lagrangian nature, the drifters provide more information about the spatial extension of the reversal event (extending at least between 39°45' and 40°30' N and between 19°30' and 19°45' E) than that given by the fixed Eulerian measurements from a limited number of moorings. This example shows, however, that the combination of contemporaneous moored current meter and drifter data helps substantially in describing the spatio-temporal variability of the velocity field considered.

It is interesting to compare the characteristics of the surface velocity field in the eastern Strait of Otranto as sampled by the drifters in December 1994 and in May 1995. In December, the drifters indicate a strong narrow inflow of ISW near the eastern coast (Figure 15b) whereas a broad outflow of the ASW is evident on the western shelf and slope (Figure 15e), in good agreement with the Eulerian measurements. In contrast, the surface circulation in May, at least in the central and eastern portions of the strait, is strongly dominated by mesoscale features and there is no evidence of a significant northward flow, even very close to the eastern coast (Figure 15f). The observed mesoscale structures in the strait are mainly associated with strong upwelling events, which are induced by the prevailing northerly winds, concentrated in specific zones of the eastern coast.

Finally, an attempt is made to estimate the exchange rate as well as the ADW outflow and LIW inflow from monthly means obtained from Eulerian current measurements interpolated over the entire transect. As mentioned before, a satisfactory coverage of the transect with current meter data is obtained only for February and March 1995 and therefore the estimate of transport is reliable only for this period. The exchange rate for both months, *i.e.* the total inflow rate or outgoing transport, is almost the same, and it is slightly larger than 1 Sv (see Table I displaying water mass transports and their sub-inertial variability). The inflow rate appears more stable than the outflow.

TABLE I

Water exchange rate in 10^6 m^3/s with respective standard deviations (February 1995). ADW outflow rate is defined as the bottom outflow of the water mass having density excess larger than 29.18 kg/m^3. LIW inflow rate is defined as an integral over the portion of the transect surface having salinity higher than 38.75 psu.

Total inflow rate	1.67 ± 0.26
Total outflow rate	1.32 ± 0.51
ADW outflow rate	0.27 ± 0.10
LIW inflow rate	0.45 ± 0.16

Using the February'95 CTD measurements, the outflow of water having $\sigma_\theta > 29.18$ kg/m^3 as an indication of the ADW outflow was calculated. Here isopycnal of 29.18 kg/m^3 instead of 29.20 as in the definition of the ADW, was chosen because it fits better to the bottom outflow layer. The obtained bottom outflow amounts to 0.26 Sv which is a lower bound of the estimate mentioned by OVCHINNIKOV *et al.* (1985). On the other hand, the February (winter) values should present a yearly maximum considering that this coincides with a water formation event and the period when the largest volume of the ADW is available in the south Adriatic reservoir. The maximum value of the ADW outflow estimated in OVCHINNIKOV *et al.* (1985) of 1.24 Sv. appears suspiciously high. The total transport estimates given by ZORE-ARMANDA and PUCHER-PETKOVIC (1976) and recalculated by ORLIC *et al.* (1992) are about half of our values obtained from direct current measurements. The estimated LIW inflow is slightly larger than the ADW outflow and the two almost balance each other in these specific circumstances. This is not, however, true over the rest of the year when, as illustrated by the thermohaline data, the seasonal variations of the volume of the two water masses are complementary.

It can be argued that our total transport value is an overestimate since the cross-section presenting the inflow current component was reconstructed without taking into account the bottom boundary layer in which the velocity decreases to zero. This, however, would not introduce an important error since the bottom boundary layer cross-section represents only a small fraction of the entire strait transect area. Thus, the obtained transport values may be considered as rather reliable estimates of the winter water exchange conditions. One must, however, take into considerations the large high-frequency variability associated to these values. One must also bear in mind that water exchange across the Strait of Otranto is subject to strong interannual variability as well.

CONCLUSIONS

The recent long-term Eulerian current measurements along a transect in the Strait of Otranto, accompanied by a Lagrangian experiment and by six CTD surveys, confirm various historical postulations about the flow and associated water mass exchange through the Strait of Otranto, which were based on indirect methods and some very short-term current measurements. These are: prevalent longshore outflow along the western shelf and slope as well as in the bottom layer confined to the western portion (ADW outflow), inflow of ISW and LIW into the Adriatic, presence of transient mesoscale features (eddies) in the central portion of the strait and occurrence of the seasonal signal in both mean and eddy circulation. The seasonal variability is determined by the change in thermal and freshwater buoyancy fluxes over the two adjacent basins, Adriatic and Ionian seas, and by the seasonally modulated wind pattern and air pressure gradient.

In the following paragraph, some conclusions drawn from the results of the 15-month survey carried out within the framework of the OTRANTO Project are summarized.

Quasi-steady sub-inertial flow dominates along both eastern and western boundaries of the strait, contributing to the high total energy exhibited in the north-south direction, especially during the winter. The outflow dominates in the deepest central portion of the strait near the western continental margin, reaches a maximum in winter and it is connected to the newly formed ADW flowing out across the sill. Another maximum of the ADW present in the strait area is evidenced from thermohaline properties in autumn and is associated with the contribution of the North Adriatic Dense Water which reaches the South Adriatic Pit approximately six months after formation.

The spring and summer seasons are characterized more by the energetic eddy transients than by the mean flow. The principal properties of the summer and winter current field are corroborated by the horizontal distribution of thermohaline properties as well, showing that in winter the sub-basin scale structures can only to a small extent modify the large scale flow. On the contrary, in summer smaller scale structures dominate the current field. Wind is identified as the most important mechanism for the synoptic time scale variability of the sub-inertial flow in the strait boundary zones. With a time-lag of one day the wind-driven current pattern is established, showing downwind flow along both eastern and western boundaries. The central portion of the strait appears completely decoupled from the boundaries and dominated by the mesoscale variability.

More details about the circulation in the surface layer are provided by surface drifters. They reveal the narrow strip of inflowing Ionian water, a central zone dominated by mesoscale eddy variability as well as by surface current reversals generated by the wind. The marked seasonal signal observed from drifters manifests itself as a contrast between the dominant quasi-steady alongshore flow near the eastern and western boundaries in winter and the prevalence of mesoscale transients over the entire strait area including boundaries in spring. These seasonal differences are inferred also from the geostrophic shear field as well as from the spatial distributions of thermohaline properties in the surface layer.

The freshwater buoyancy input is shown to be an important mechanism in intensifying the general cyclonic circulation in the Adriatic and, as a consequence, in strengthening Ionian surface and Levantine intermediate waters inflow. In fact, thermohaline properties in the area obtained from a series of CTD surveys display, apart from a seasonal signal, an overall salinity increase of the LIW in the strait area over the study period together with an increase of the volume of this water mass. This phenomenon could be to some extent attributed to the intensification of the Adriatic basin-wide cyclonic circulation and a subsequent Mediterranean waters inflow. Thus, interannual variations of the freshwater buoyancy input could be one of the major causes generating the long-term changes in the water flow through the Strait of Otranto.

From Eulerian current measurements an attempt is made to estimate the water flow rate. Only for one winter month (February) coverage of the strait transect is satisfactory to enable calculations of a reliable estimate of the water flow rate. We obtain slightly more than 1 Sv. for the total inflow or outflow rate, while the ADW outflow rate reaches 0.26 Sv. The LIW inflow rate has the value of 0.3 Sv. These estimates are associated with rather strong high-frequency sub-inertial variability which can be of the same order of magnitude. The obtained estimates of the total inflow or outflow rates are rather high since they were calculated for the period when the cyclonic surface and intermediate circulation in the Adriatic was intensified by the freshwater buoyancy input, and thus they may represent an upper bound to the total flow rates.

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