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Circulation and hydrological characteristics of the North Aegean Sea: a contribution from real-time buoy measurements

K. NITTIS and L. PERIVOLIOTIS

National Centre for Marine Research
Institute of Oceanography
Agios Kosmas Elliniko, 16604 Athens, Greece

e-mail: knittis@ncmr.gr

Abstract

In the framework of the POSEIDON Project, a network of open sea oceanographic buoys equipped with meteorological and oceanographic sensors has been operational in the Aegean Sea since 1998. The analysis of upper-ocean physical data (currents at 3m, temperature and salinity at 3-40m depths) collected during the last 2 years from the stations of the North Aegean basin indicates a strong temporal variability of flow field and hydrological characteristics in both synoptic and seasonal time scales. The northern part of the basin is mainly influenced by the Black Sea Water outflow and the mesoscale variability of the corresponding thermohaline fronts, while the southern stations are influenced by the general circulation of the Aegean Sea with strong modulations caused by the seasonally varying atmospheric forcing.

Keywords: Monitoring systems, Buoys, Satellite sensing, Ocean circulation, Mesoscale features.

Introduction

The increasing demand for high quality real-time observations and forecasts of the marine environmental conditions and the fast progress in the field of marine technology and numerical modeling have contributed to the development of Operational Oceanography as a main priority for the Marine Sciences (STEL 1996). The Global Ocean Observing System (GOOS) is an international initiative that coordinates efforts for the development of local, regional or global monitoring and forecasting systems (IOC 1996). The POSEIDON system, (SOUKISSIAN *et al.,* 1999) which was developed during a 3 year project (1997-2000), is an operational monitoring, forecasting and information system for the Hellenic Seas that contributes to the efforts of GOOS and its Mediterranean component MedGOOS.

The observational basis of the POSEIDON system is the network of 10 oceanographic buoys installed in the Aegean Sea. Fixed oceanographic buoys are probably the most widely used platforms for real-time observations. The TAO (Tropical Atmosphere Ocean) array of the Equatorial Pacific is the

biggest and most well known buoy network (McPHADEN *et al.,* 1998). It was developed for a continuous monitoring of the El-Nino Southern Oscillation and uses the ATLAS buoys that collect meteorological data as well as physical parameters (temperature and salinity) for the upper 500m of the ocean. The SeaNet network of the North Sea is the largest network of buoys and fixed stations in Europe and it is mainly oriented towards meteorological and sea level measurements. Small buoy networks have been recently developed in Germany and France (the Marnet and Marel networks respectively) for monitoring of biochemical parameters in coastal areas (TZIAVOS & FLEMMING, 1998).

The POSEIDON network uses the Seawatch buoys that were developed for multi-parametric measurements, and can be exploited for a wide range of marine environmental applications (HANSEN & STEL, 1997). The buoys collect meteorological and upper ocean data every 3 hours and transmit them in real-time to the operational center of NCMR. Forecasts of meteorological, wave and hydrological conditions are also provided daily by the POSEIDON numerical forecasting system. Buoy data and forecasts are available in real-time to the public through the system's Internet Web page (http://www.poseidon.ncmr.gr). A more in-depth description of the POSEIDON system and its applications is provided by SOUKISSIAN *et al.* (1999) and NITTIS *et al.* (2001).

An analysis of physical oceanographic data from the POSEIDON buoys located in the North Aegean Sea is presented in this paper. The study is focused on the temporal and spatial variability of general circulation structures and hydrological properties of the basin. A secondary goal of this paper is to demonstrate that the value of operational monitoring systems is not limited to the production of services and products for the end-users, but their data may contribute towards a better understanding of the marine ecosystem function.

Materials and Methods

The Seawatch buoys are equipped with meteorological sensors (wind speed and direction, atmospheric pressure, air temperature) as well as oceanographic sensors for physical (current speed and direction, temperature and salinity) and biochemical variables (light attenuation, chlorophyll-a, dissolved oxygen). The current meter is located at 3m depth and is also equipped with conductivity, temperature and pressure sensors (Sensortec UCM-60 with Aanderaa 2990 conductive cell, Kistler pressure sensor and CS4-1/10 temperature sensor). Additional CT (Conductivity – Temperature) sensors are placed at 10m, 20m, 30m and 40m depthS (Seamos CTD string equipped with conductivity cell Aanderaa 2994 and temperature sensor Fenwall GB 32JM19). In order to maintain the high quality of measurements, the stations are visited every 3 months for regular maintenance to prevent the growth of "bio-fouling" effects. During the maintenance procedure the sensors of chlorophyll-a, oxygen, salinity and temperature are calibrated against reference in-situ measurements (NITTIS *et al.* 2001).

The POSEIDON network has been operating in the Aegean Sea since November 1998 and up to now Seawatch buoys have been installed in the following areas of the North Aegean Sea (Table 1, Fig. 2): northwest of Lesvos Island, south-east of the Athos peninsula, north of Lemnos Island, north of Skiathos Island and east of Mykonos Island. The oceanographic data used in this study are from the Lesvos, Athos and Mykonos stations

Table 1
Operation of buoys in the North Aegean Sea.

Station	Position	Depth	Period
Lesvos	39.15N, 25.81E	130	6/12/98-todate
Athos	39.96N, 24.72E	215	25/5/00-todate
Mykonos	37.51N, 25.46E	140	28/5/99-todate
Skiathos	39.22N, 23.43E	155	30/5/99-14/10/99
Lemnos	40.00N, 25.00E	220	6/12/98-15/2/99

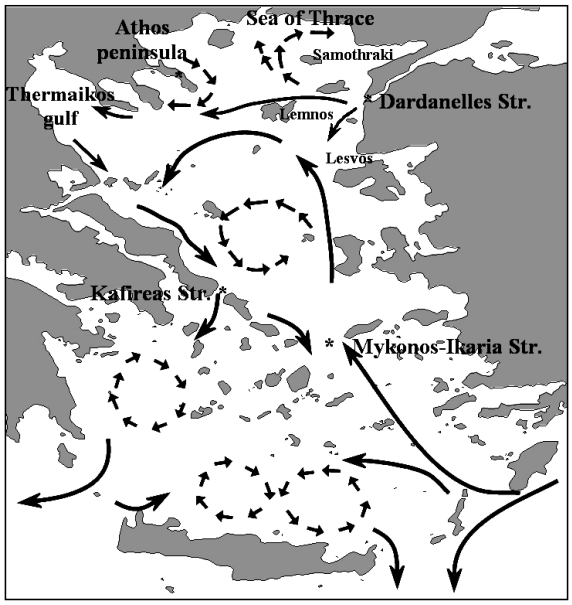

Fig. 1: Schematic representation of the Aegean Sea upper circulation (following THEOCHARIS *et al.,* 1993 and 1999, THEOCHARIS & GEORGOPOULOS 1993; ZODIATIS, 1994, ZERVAKIS & GEORGOPOULOS, 2002).

that have the longest records, covering a period of more than 2 years. At these 3 mooring sites the depth is 150-250m while the average depth of the North Aegean is approximately 300-400m (maximum depth above 1200m in the western part -North Aegean Trough- and minimum depth in the extended plateau along the northern coast). SST (Sea Surface Temperature) maps are used to complement the in-situ data sets and demonstrate the synergy between remote sensing and buoy data. They are derived from infrared remote sensing images processed by DLR (Deutsches zentrum fuer Luft-und Raumfahrt e.V., German Aerospace Research Establishment) to produce Multi Channel SST products.

Discussion

The general circulation of the Aegean Sea (Fig. 1) is characterized by a multiple scale pattern that includes a basin scale cyclonic flow, sub-basin scale recurrent gyres and a number of transient eddies. The northern part of the basin is dominated by the presence of the low-salinity Black Sea Waters (BSW) that enter the Aegean through the straits of Dardanelles and influence its hydrology and circulation. This water mass occupies the surface layers and can be traced by its low temperature and salinity values (Fig. 2 for an SST map of February 1999 that shows the distribution of BSW in the North Aegean). After their entrance into the Aegean, the BSW flow westwards with bifurcations to the north, towards the Sea of Thrace, and to the southwest reaching the south Aegean through the Kafireas and Mykonos - Ikaria straits. The NW part of the Aegean is also influenced by the fresh water discharge of major rivers in the Thermaikos Gulf. A large part of the NE Aegean (south of the Dardanelles straits) is occupied by warm and saline waters since this area is influenced by the branch of Asia Minor that enters the Aegean Sea from the eastern straits transferring Levantine waters towards the north. The presence of such different water-masses creates strong temperature and

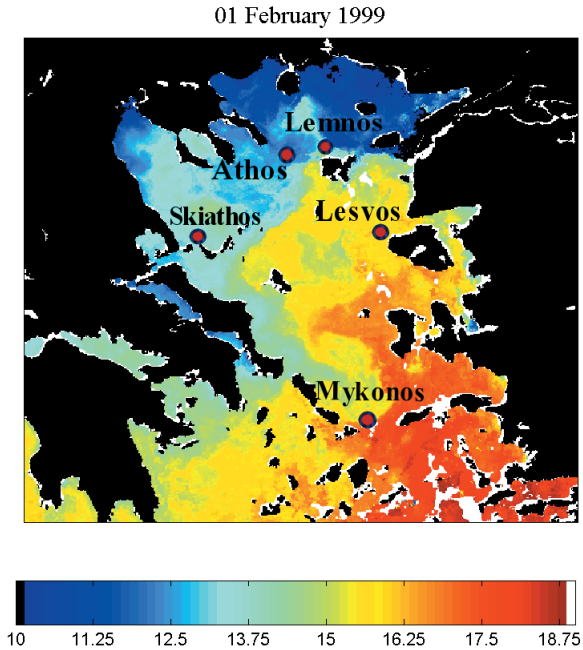

Fig. 2: Sea Surface Temperature field in the north Aegean Sea, derived by NOAA/AVHRR image of 1 February 1999. The positions of selected POSEIDON buoys are superimposed.

salinity contrasts between the N-NW cold and fresh areas and the S-SE warm and saline parts of the North Aegean basin.

The above circulation pattern inferred by the surface temperature map of figure 2 is a typical situation for the Aegean Sea, in agreement with previous oceanographic observations in the area (THEOCHARIS & GEORGOPOULOS, 1993; THEOCHARIS *et al.,* 1993 and 1999; ZODIATIS, 1994; ZERVAKIS & GEORGOPOULOS, 2002). This pattern of hydrology and circulation is also reproduced by the buoy data that, in addition, provide a detailed description of its temporal variability. The surface salinity values recorded in Lesvos station (the easternmost buoy) are higher than all the other stations of the North Aegean. An average salinity value during the summer period in Lesvos is 38.8, while in Athos (an area mainly affected by BSW) this value drops to 34.1 and in Skiathos (located further to the west) the average salinity is 35.9. At Mykonos station, which is the southern-most station for the North Aegean but lies on the pathway of BSW outflow to the south, the average salinity during summer is 38.4. These average values were estimated for the summer period when the BSW have the minimum salinity and the highest outflow rate (UNLUATA *et al.,* 1990).

The salinity and current speed time-series at Mykonos station appear to be influenced by the strong seasonal signal of BSW outflow and the seasonal variability of local winds (Fig. 3). A clear seasonal cycle is observed in the salinity records with maximum values above 39.1 during winter and minimum values below 38.0 during summer. This variability is related to the seasonal cycle of BSW outflow but is further intensified by the seasonal modulations of surface currents. The dominant direction in this area is to the S-SE (Fig. 4) since the Mykonos-Ikaria strait together with the Kafireas strait are the two areas from where

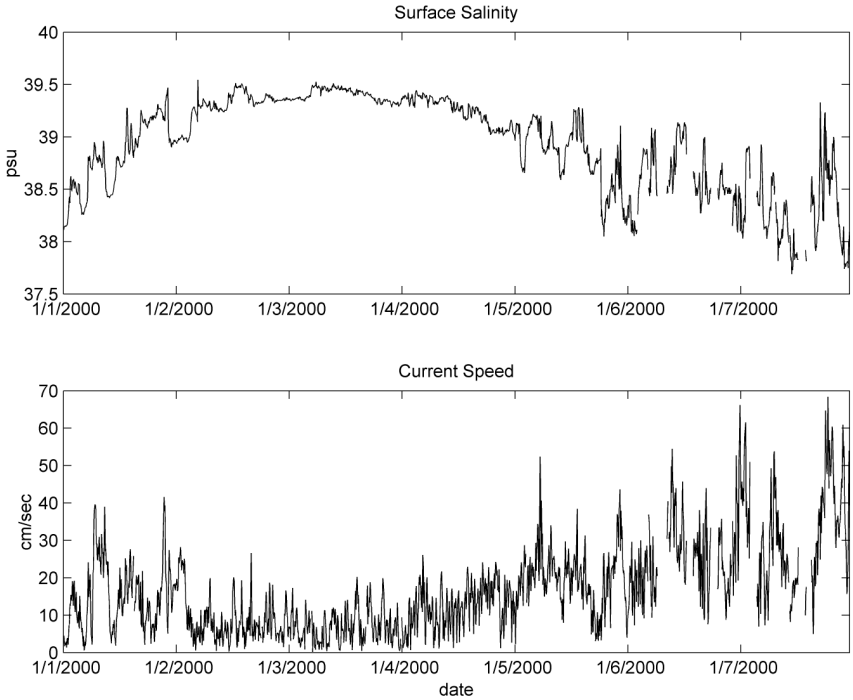

Fig. 3: Time series of surface (3m) salinity and current speed at Mykonos station for the period 1/1/2000 – 31/7/2000.

the surplus of North Aegean fresh water is discharged into the southern basin (Fig. 1). The maximum values of current speed at Mykonos station exceed 50 cm/sec during summer and decrease to 15 cm/sec during winter (Fig. 3). This seasonal variability of current in the central Aegean is associated with the Etesian northerly winds that are intensified during the July-September period (NITTIS *et al.,* 2002). During the summer period the variability in the synoptic time-scale is intensified for both surface salinity and current measurements, indicating a faster response of the stratified shallow upper layer to the synoptic scale atmospheric variability.

At Lesvos station a dominant circulation pattern is also observed, although the flow is less energetic compared to Mykonos (figure 4). The flow direction is to the NW with relatively low variability. This indicates that this area is primarily influenced by the general circulation according to which the warm and saline Levantine water is transported northwards along the eastern coasts of the Aegean Sea (THEOCHARIS & GEORGOPOULOS, 1993). It is interesting to note that during winter 2001 the flow field in both Mykonos and Lesvos stations was more variable and less energetic than the respective period of 2000. This can be attributed to a weakening of the general circulation pattern in the central Aegean Sea.

A different pattern is observed at the Athos station where the flow is much more variable and energetic (Fig. 4). This area is influenced by the westward flow of the BSW as well as by a series of transient mesoscale eddies. These eddies are associated with the strong thermohaline front generated in the area by the entrance of the fresh and cold BSW waters in a saline and warm environment (GEORGOPOULOS *et al.,* 1992). The location and shape of the front are both affected by the wind conditions and the

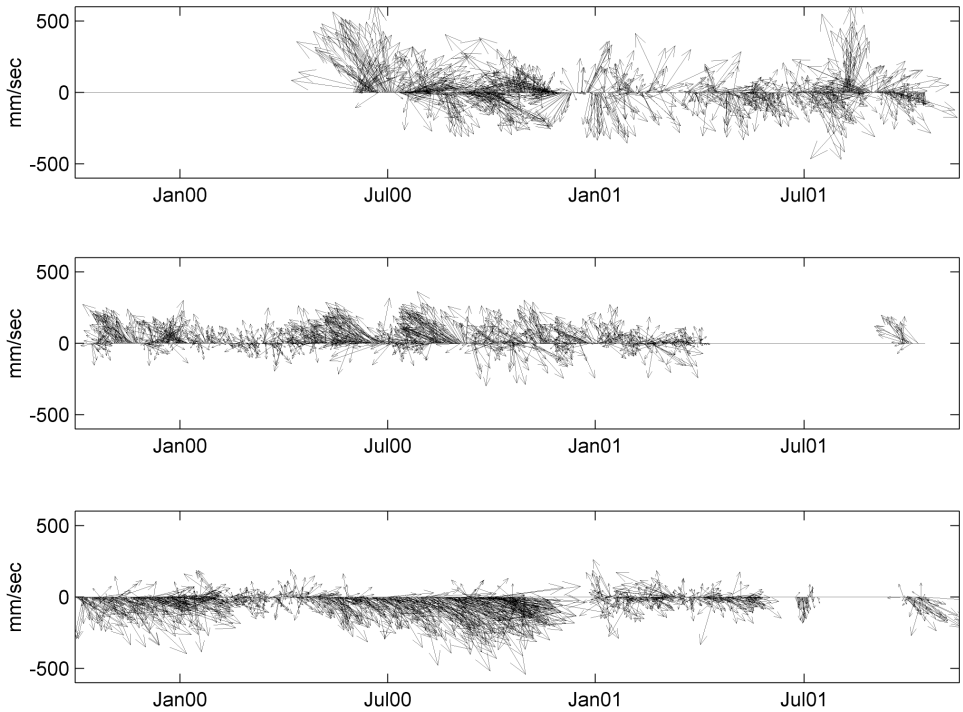

Fig. 4: Stick diagrams of surface (3m) current at stations Mykonos (upper panel), Lesvos (middle) and Athos (lower), for the period 1/10/1999 – 30/9/2001.

seasonal variability of the BSW outflow rate and characteristics (VLASENKO *et al.,* 1996; ZODIATIS, 1994). According to ZERVAKIS & GEORGOPOULOS (2001) the area where the Athos buoy is located was influenced during May 1997 and September 1998 by an anticyclonic eddy associated with the northward flow of the BSW west of Lemnos Island. A similar anticyclonic eddy shifted more to the northeast and attached to the Athos peninsula was observed by THEOCHARIS & GEORGOPOULOS (1993).

The current meter data of the Athos buoy indicate strong mesoscale variability at time scales of 10-30 days. A characteristic example of this variability is given in Figure 5, where a short period of the current time series at the Athos station is presented (detail of figure 4, upper panel). During mid- and end- September 2000 the flow field has a strong SE component with current speed exceeding 50cm/sec. By the end of the month the southward component of the flow is intensified but during the first days of October the flow is reversed and becomes northward for the rest of the month.

This flow reversal is associated with the presence of the anticyclonic gyre of the Athos peninsula. This anticyclone is clearly observed in the SST fields of 25 September 2000 (Fig. 6) south of the peninsula and appears to dominate the circulation in the area where the Athos buoy is located. During the same period, the BSW plume is limited to the east of Lemnos Island, while a well-formed anticyclone is observed in the NE corner of the basin, around the island of Samothraki. This gyre was also observed in 1997 and 1998 (ZERVAKIS & GEORGOPOULOS, this issue) and appears to be a permanent feature of the North Aegean general circulation. Three weeks later (13 October 2000), the Athos anticyclone is hardly observed to the east of

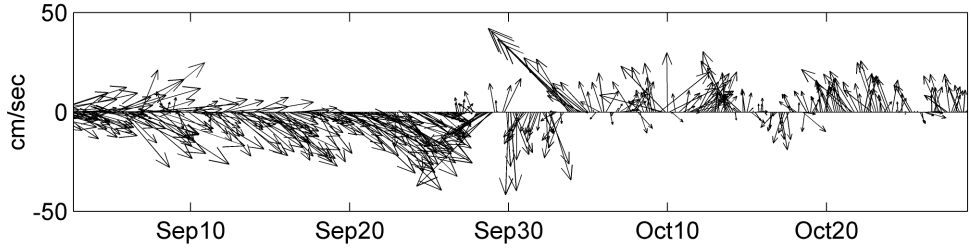

Fig. 5: Detail of figure 4. Stick diagrams of surface (3m) current at Athos station for the period 2/9/2000 – 28/10/2000.

the peninsula as it has been shifted to the north by the BSW plume that now extends up to the Sea of Thrace (Fig. 6). This weakening and shift of the anticyclone due to its interaction with the BSW front is responsible for the reversal of flow recorded by the Athos buoy current-meter at the beginning of October. Similar flow reversals are observed throughout the period 2000-2001.

These changes of circulation patterns also affect the thermohaline structure of the area (Fig. 7). In both temperature and salinity time-series intense high frequency (2-7 days) variability is observed during the end of September 2000, when the above-described flow reversal occurred. The end of September is the period when the surface cooling and the gradual erosion of the seasonal thermocline begin. The upper 40m in the Athos area have typical temperature values of 21-24.5˚C during mid- September and 16-18.5 ˚C by the end of October (Fig. 7). This area is also characterized by its strong halocline created by the presence of the fresh surface BSW. During early August this vertical salinity gradient is maximum, with values of less than 33.0 at surface (3m) and more than 38.0 at 40m depth. This gradient of 5 psu persists until the end of September and then gradually degrades to 2.5-3 psu by the end of October.

The two most important synoptic scale events are observed between 28th September and 9th October, superimposed on this slow variability of the upper layer properties. They have a duration of 2-4 days and their characteristics (increase of salinity and decrease of temperature at the lower layers) indicate a relation to transient upwelling events i.e. vertical advection of colder and more saline water masses from the deeper layers. Similar events were also recorded in Lemnos station during February 1999 (NITTIS *et al.,* 2001), but due to their characteristics (intrusions of cold and fresh water) they were related to horizontal advection of BSW associated with meandering of the thermohaline front.

The first event has a short duration of 2 days (29-30 September) and gives the strongest signal on the salinity time series: more than 2 psu drop at 3 and 10m depth (Fig. 7). During a 30 hour period the current speed rises from 20 cm/sec to 52 cm/sec, drops to 1.6 cm/sec and then rises back to 42 cm/sec while its direction turns from 230˚ to 180˚ (Fig. 5). The vertical velocity associated with this important shear of the horizontal flow field seems to be responsible for the strong pulses of cold and saline water (upwelling from the deeper layers). The second event is almost equally strong and has a duration of 4 days (4-8 October). In the beginning of this event the flow is again intensified from 20 cm/sec to 60 cm/sec (Fig. 5) while its direction turns from S (190˚), to NW (320˚). By October 8th it has turned towards NE (30˚) and its speed is back to low values (15 cm/sec). After this event, the northward flow is established in the area for the rest of the month. A more detailed study of the SST image of 25th September, reveals the presence of a small cyclone southwest of Lemnos Island. This small gyre seems to be generated exactly on the interface between the

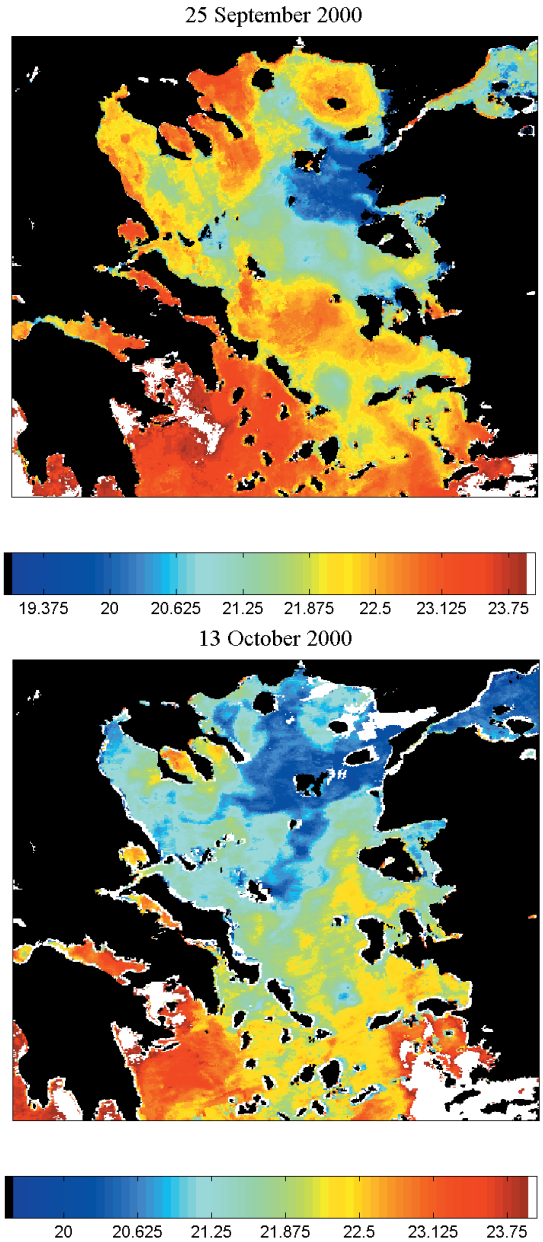

Fig. 6: Sea surface temperature fields in the north Aegean Sea, derived by NOAA/AVHRR images of 25 September and 13 October 2000.

BSW plume and the Athos anticyclone. The generation of such small transient cyclonic features close to the buoy area may explain the above described high frequency variability of 2-4 days duration. A similar mechanism of intense meandering and ring formation due to interaction between strong jets and mesoscale features has been described by GOLNARAGHI (1993) for the Eastern Mediterranean Sea.

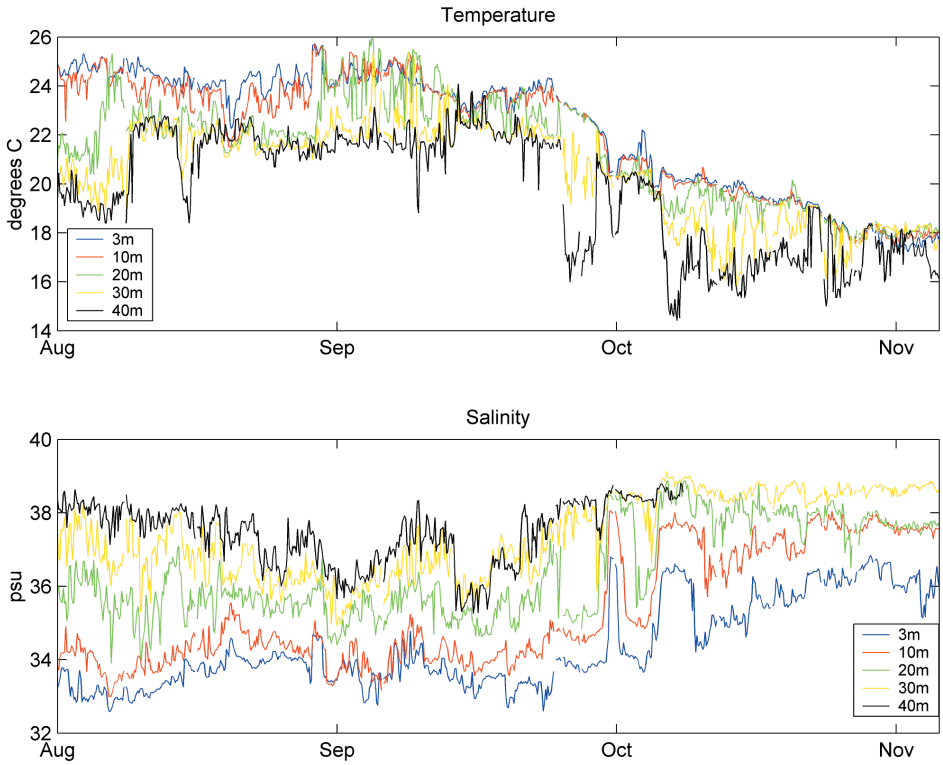

Fig. 7: Time series of salinity (upper panel) and temperature (lower panel) at different depths during August– October 2000 at Athos station.

Conclusions

Time series of physical oceanographic variables from the POSEIDON buoy network and SST maps derived from NOAA/AVHRR images, were used to describe the temporal and spatial variability of the general circulation and hydrological characteristics in the North Aegean Sea. The flow field in the SE part of the basin (Lesvos area) is dominated by the permanent northward propagation of the Levantine waters along the eastern coasts of the Aegean Sea. Under the influence of this water mass, the area is warmer and more saline than the northern and western parts of the basin. The Mykonos station in the central part of the Aegean is dominated by the reverse flow, i.e. the southward flow of the fresher and colder waters of the North Aegean. In both areas, but especially in Mykonos, the flow field is seasonally intensified during summer when the northerly Etesian winds prevail in the whole Aegean Sea. The northern parts of the basin (Athos area) are strongly influenced by the Black Sea Waters that outflow in the basin through the Dardanelles straits. This water mass has a clear signal of low temperature and salinity and occupies the surface layers of the basin creating a strong halocline during summer. The surface currents at Athos station are much more energetic and their variability is intensified in the mesoscale. This area is influenced by the transient Athos anticyclonic eddy and other mesoscale structures generated by the instability of the BSW thermohaline front. The transition between different regimes of the flow field associated with mesoscale variability of local gyres, generates high-frequency (2-4 days) events of strong vertical advection and mixing.

The above results indicate that time series of oceanographic and meteorological data collected by operational networks can be an important source of information, especially for temporal variability studies. The value of such data is increased when combined with other sources of information that provide instantaneous but more detailed pictures of the spatial variability (e.g. remote sensing SST and SSH maps, objective mapping of ship-born CTD casts etc). The POSEIDON buoy network provides data that may contribute towards a better understanding of the Aegean Sea function. The foreseen upgrade of the buoys with additional sensors for deeper measurements is expected to further support this effort.

Acknowledgments

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