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Abstract

In this work an attempt is made to explain a case of the water circulation in the North Aegean shelf based on a set of oceanographic and meteorological measurements. It is argued that hydrodynamic conditions created by the meteorological fields of surface wind and pressure, force the renewal of the waters in the coastal area of Kavala Bay. It is shown that, although the mean horizontal water velocity is estimated at about 7cm/sec providing a time period of water renewal of the bay at about 4 days, the geostrophic circulation of the wider area in the North Aegean, controlled by the geometry of the local area, accelerates the water movement in the bay decreasing the time required for the renewal to less than one day.

Keywords: Water circulation; Kavala Bay; North Aegean; Greece.

Introduction

The study area of interest is part of the North Aegean shelf. Kavala Bay covers an area of 261 km^2 with a flat bottom, forming a small inclination in the northern and eastern parts. In the southwestern part of the bay, a basin is formed with a maximum depth of 46m, closed in the south by a small ridge of 10m height and crossed in the central part by a channel of 1 km wide (Fig. 1). The oceanographic knowledge of the wider area of the North Aegean is summarized in the work of Georgopoulos (GEORGOPOULOS, 2002). Specifically, the hydrology of the North Aegean was studied by LACOMBE *et al.,* 1958; THEOCHARIS & GEORGOPOULOS, 1993; UNLUATA, 1986; ZODIATIS, 1994 and by ZERVAKIS & GEORGOPOULOS, 2002 .

Following the above studies, three major water masses can be identified in the area: The Black Sea Water, (BSW) exiting the Dardanelles with salinity less than 30 psu, which forms a surface layer of less than 40 m thickness. The BSW characteristics are modified by the prevailing meteorological conditions and the vertical diffusion through mixing with the underlying waters. BSW in its cyclonic route in the North Aegean gains salt and the salinity gradually increases from 37 psu to more than 38 psu. The intermediate depths range below the surface layer and above the sill depths that separate different basins and sub-basins, are occupied by water whose characteristics suggest Levantine ori-

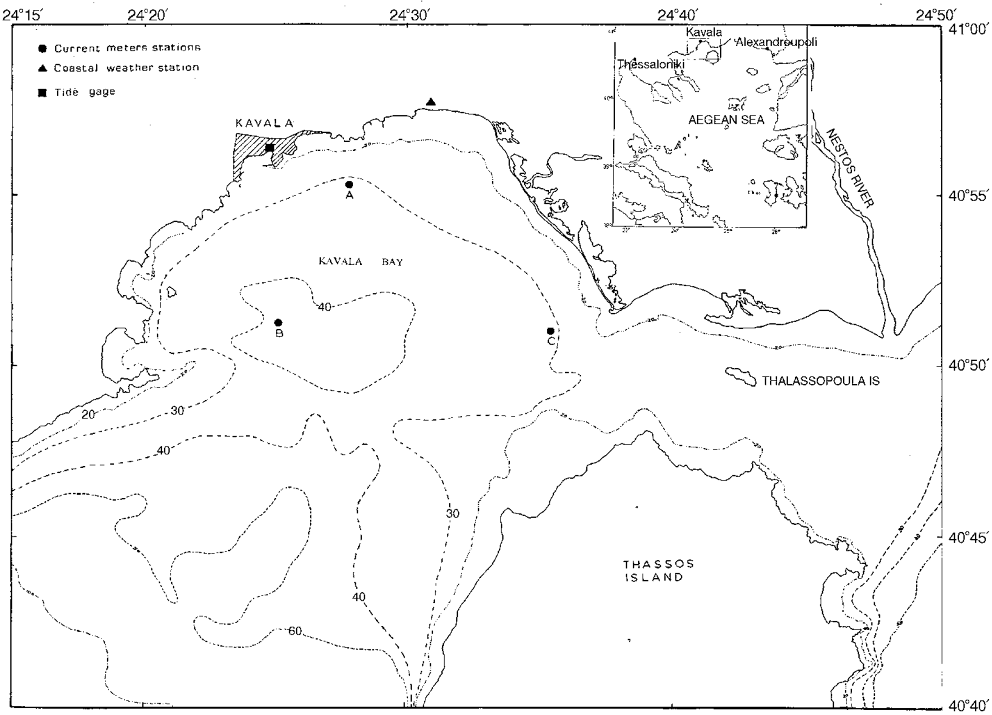

Fig. 1: The wider area of Kavala bay (North Aegean).

gin. Below 400 meters, the presence of saline and dense waters, with slightly different hydrological characteristics per basin, suggest local formation and limited communication between the basins.

The western part of the bay of Kavala is covered by volcanic (granite and diorite) and metamorphic rocks (marble and gneisses). The eastern coastal area is flat, formed by the alluvial of the Nestos River. The river outflows 13 km east of the bay (Fig. 1), with a mean annual output of 850x 10^6 m^3/y and maximum values between January and May. Based on the outflow data for the Nestos River provided by the Public Power Corporation, the time series diagrams with the mean annual outflow were constructed for the years 1981 throughout 1986 (Fig. 2).

From the geological studies it was shown that fine-grained material, originated from Nestos River output, predominates all over the area (LYKOUSIS, 1984). The conclusion was reached by combining:

a. The low values of transparency found in the eastern part of the bay especially during the periods of the maximum river outflow.
b. The noticeable high concentration of mineral illite in the surface bay sediments which is characteristic of river's outflow material.
c. The observed eastern transport of the suspended material of the river outflows from the river's mouth and near shore sands' formations, using aerial and satellite images.

The general surface structure of the water masses in the North Aegean shelf is characterized by the very low salinity values due to the presence of BSW and riverine waters. A series of oceanographic measurements made by the Hellenic Navy Hydrographic Service

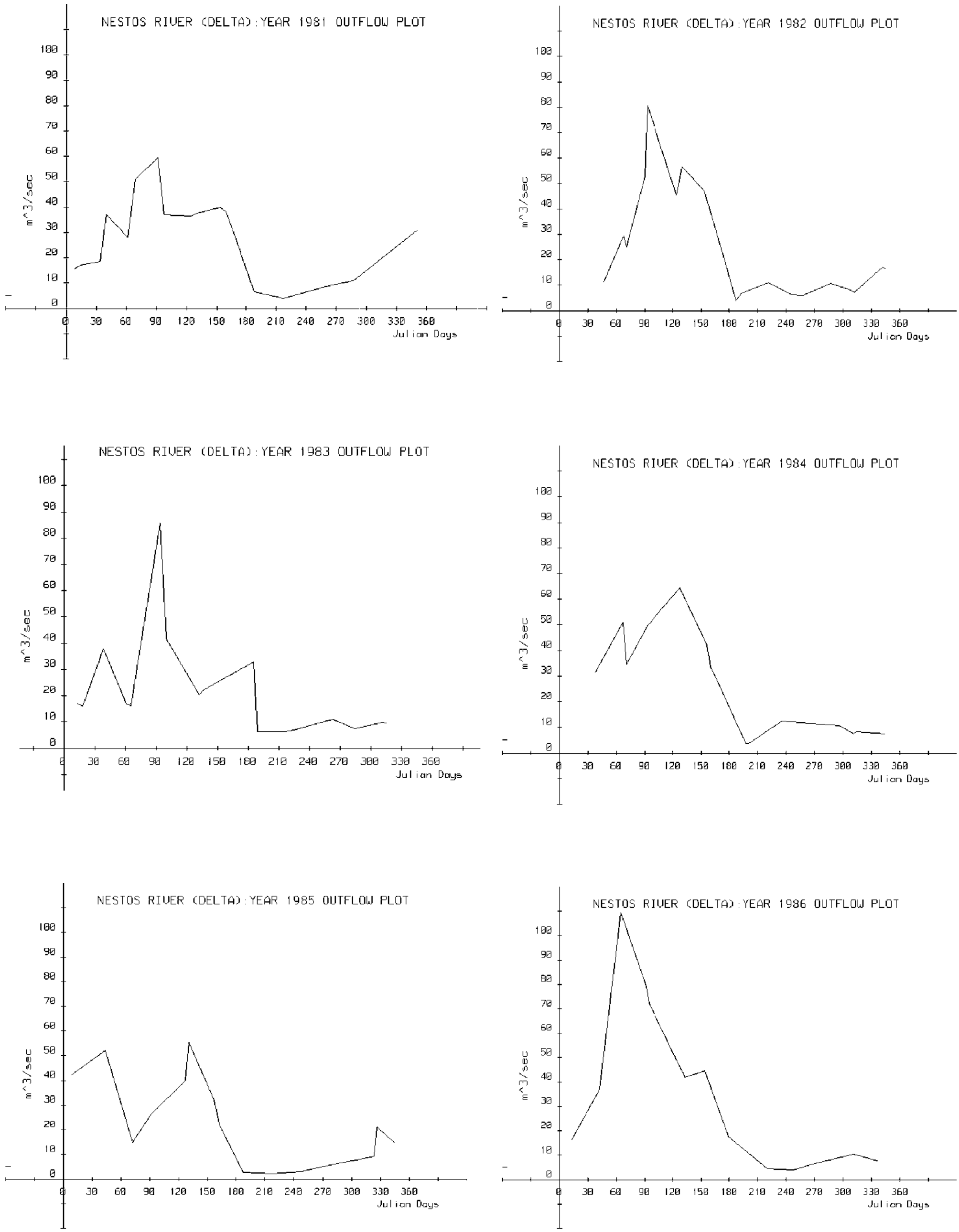

Fig. 2: Nestos river outflow time series with the mean annual value for the years 1981 throughout 1986.

during the years 1965 to 1983 leads to the conclusion that during the winter and spring, the Nestos River provides the area of Kavala Bay with cold and fresh waters. On the contrary, during the summer and autumn period, the influence of the low salinity water masses from the Dardanelles is the prevailing factor in the wider area of the North Aegean shelf, including Kavala Bay (KARDARAS, 1998).

In the first section of this work the oceanographic and meteorological data used are presented, in the second the results are discussed and finally, an attempt is made to draw the conclusions and to describe the mechanism about the water circulation in the bay.

Data

For the purpose of this work, data used are collected from 18/5/1983 to 7/6/1983. They consisted of current meter measurements in Kavala Bay and the available meteorological and sea level data for the extended area of the North Aegean (KARDARAS, 1998).

At each location A, B and C in Figure 1,

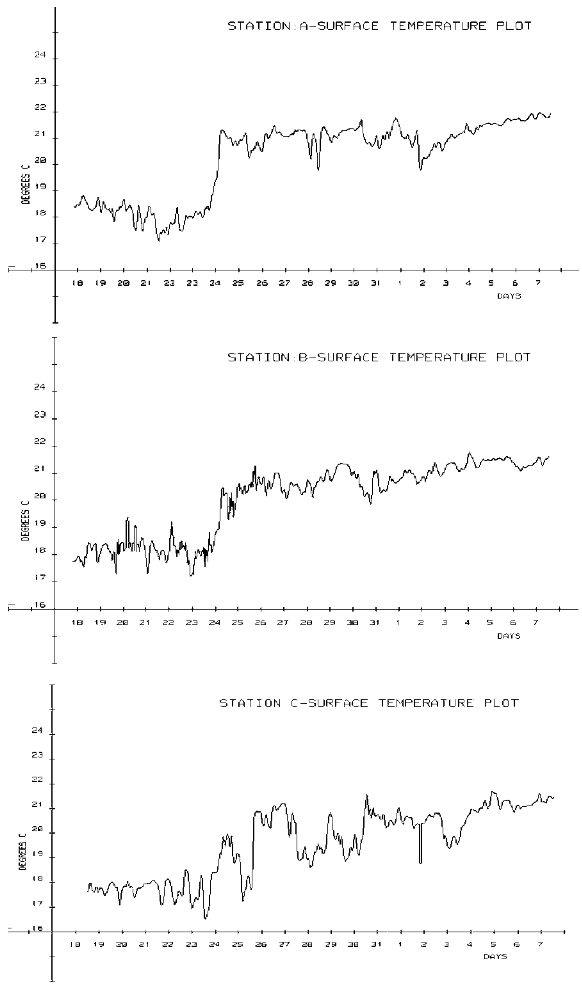

Fig. 3: The filtering time series of the recorded values of temperature at the top current meter of each mooring A, B and C (Fig 1).

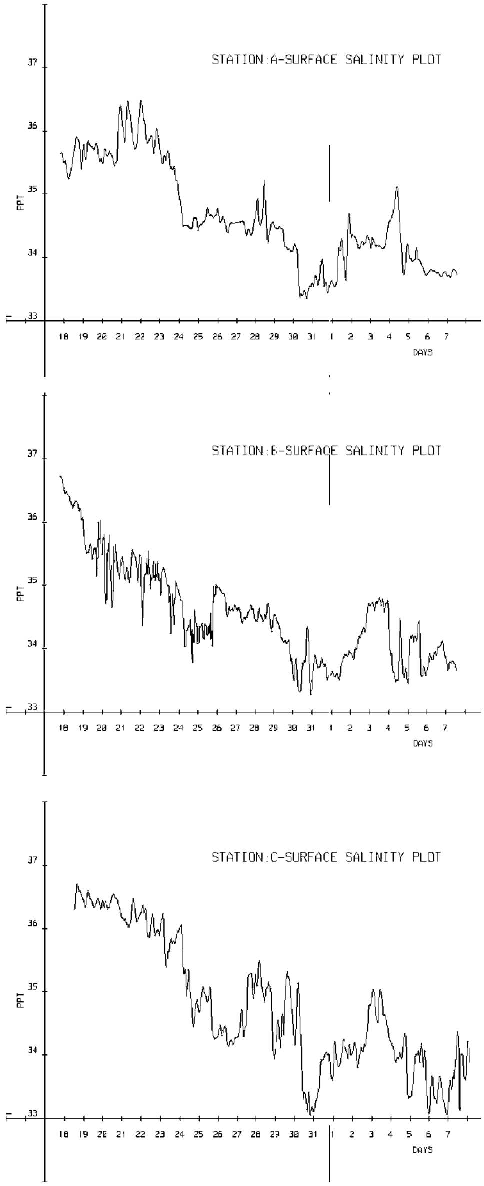

Fig. 4: The filtering time series of the calculated salinity at the top current meter of each mooring A, B and C (Fig 1).

one subsurface mooring was deployed, which carried two AANDERAA model RCM4 current meters at depths 9m below MSL and 5m above the bottom, recording at ten minute sampling intervals, the horizontal velocity components, temperature, conductivity and hydrostatic pressure of the water column.

During the current meters' recording period, hourly values of the wind field (direction, speed and barometric pressure) and heights of sea level were recorded at coastal stations, which are operated by the North Aegean Petroleum Company (Fig.1). In order to define a more comprehensive picture, as far as the prevailing environmental conditions in the area during the given period are concerned, the meteorological data (wind field parameters, barometric pressure and weather maps) as well as the sea level recordings of the extended area of the North Aegean were also taken into account. Specifically, data recorded at Thessaloniki, Alexandroupoli and Chios meteorological and tidal stations were considered (enclosed map of the North Aegean area in Fig. 1), which were provided by the Hellenic National Meteorological Office and the Hellenic Navy Hydrographic Service.

Results and Discussion

Figures 3 and 4 show the filtering time series of the recorded values of temperature and the calculated salinity at the top current meter of each mooring A, B and C (Fig. 1).

Two noticeable events are observed in the above time series both associated by an intrusion of warmer and less saline waters, in the time periods between 23 to 24 and 28 to 31 May 1983. Specifically, during the first event the temperature was increased by to 2^{o} C to 3^{o} C (from about 18^{o} C to 21^{o} C) and the salinity was decreased by about 1.9 psu (a change from 36.4 psu to 34.5 psu), as the waters were intruded into the bay from eastern and southern directions. From the Public Power Corporation archive, a recorded mean temperature of about 17^{o}C was derived at the river mouth for May 1983. During the second event a further drop in the salinity was noticed by about 1.2 psu (recorded value 33.3 psu) that was accompanied by a strong anticyclonic flow of the waters into the bay.

At 25 meters depth (bottom current meters) the corresponding change was from 37.7 psu to 37.2 psu and at 37 meters depth, from 38.3 psu to 37.8 psu.

The above water movements are clearly shown in Figure 5, where the progressive diagrams of the top current meters of each mooring are constructed, describing the directions of the currents' velocity during the period of measurements. In order to emphasize the characteristics of the circulation regime, in Figure 6 the filtered time series of the total horizontal velocity of the current recorded at the top and bottom current meters are depicted. The recorded maximum current speed had a magnitude up to 45 cm/sec in all the top current meters during the second episode between May 28 and May 31, in contrast to the mean current speed 7 cm/sec during the rest of the period. It was noted, that the influence of the wind-wave field, on the current speeds' measurements, was almost null, due to the limited effective fetch for the wind directions considering during the measurement period.

The first of the events coincides with an atmospheric disturbance between May 23, and May 24, 1983 when a cold front passed over the area and easterly winds were recorded at the meteorological station of Kavala, reaching a speed up to 7.7 m/sec. During the second event, observed between May 28 and May 31, 1983, a further drop of salinity was accompanied by very light winds (Fig.6).

Although the water circulation during the first event can be attributed to the prevailing weather conditions in the Aegean, the change of salinity as well as the strong burst of current velocity during the period between May 28 and May 31, 1983, does not appear to have any direct relation to the prevailing wind field over the area and it should be attributed to the water circulation regime of the North Aegean area during the specific time period. Also, the time series comparison between the current meter for each oceanographic parameter suggests that the parameters' quantitative change appeared first at

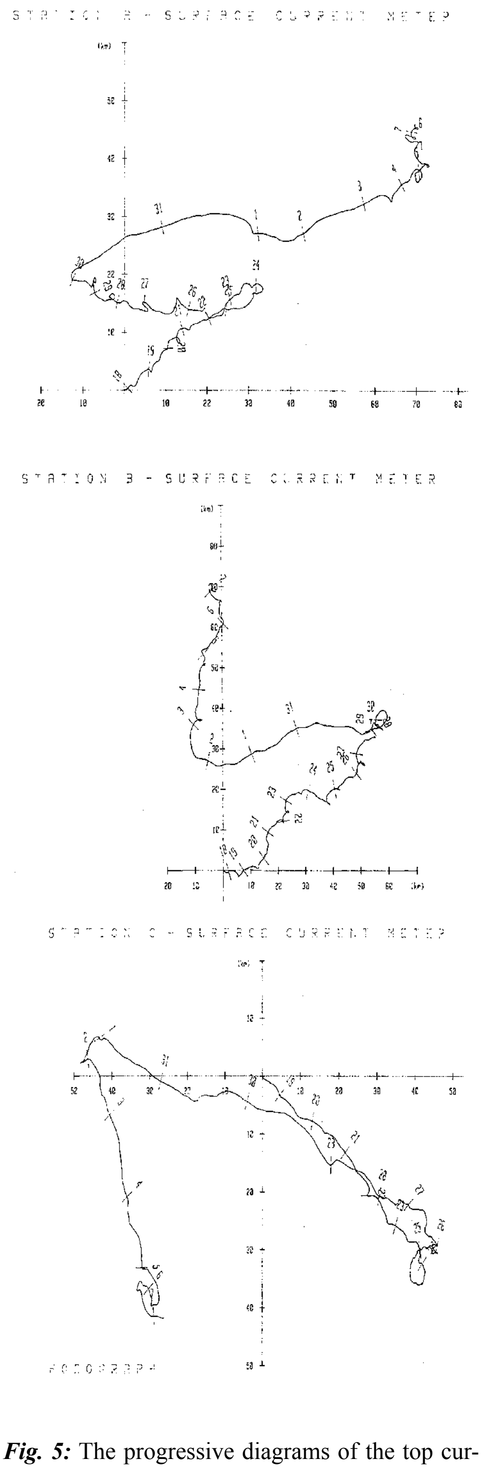

Fig. 5: The progressive diagrams of the top current meters of each mooring A, B and C (Fig 1).

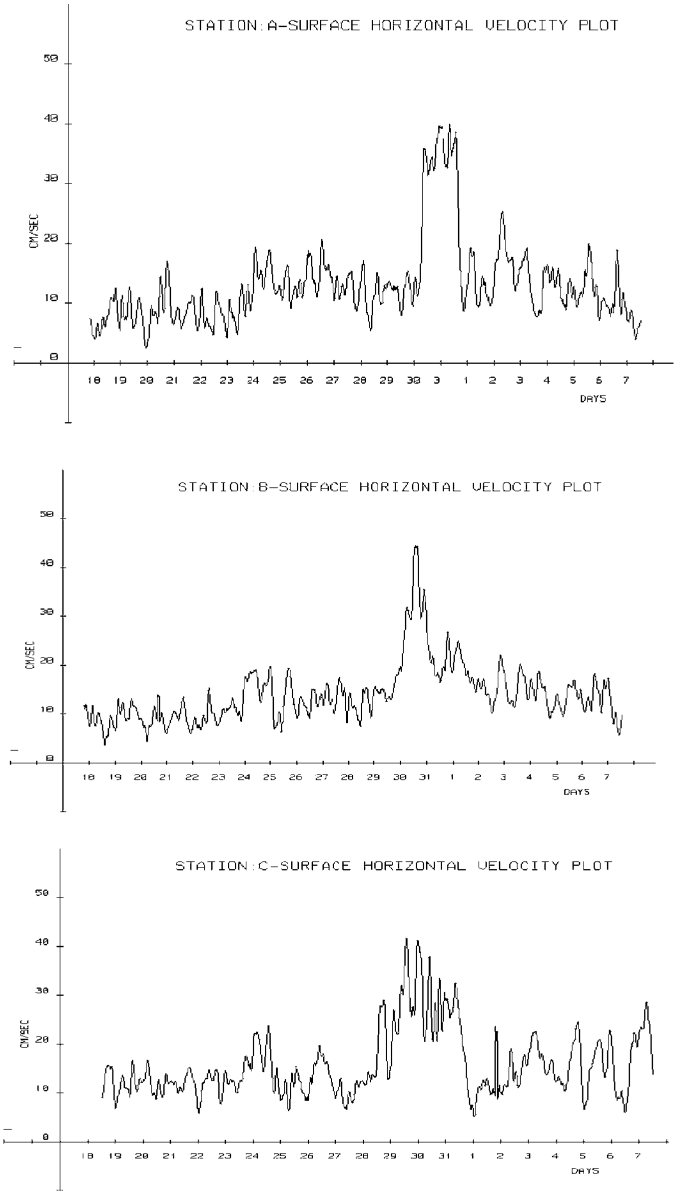

Fig. 6: The filtered time series of the total horizontal velocity of the current recorded at the top and bottom current meters of each mooring A, B and C (Fig 1).

location C (close to the Thassos channel) and subsequently at locations B and A.

In order to further investigate the second and most pronounced event of water circulation in the bay, as it is not apparently related to the prevailing wind field, in Figure 7 the time series of the Adjusted Sea Level (A.S.L.) changes recorded at four tidal stations in the North Aegean area (Thessaloniki, Kavala, Alexandroupoli and Chios, enclosed map in Fig. 1) is presented. A.S.L. parameter can be calculated by adding the correspond-

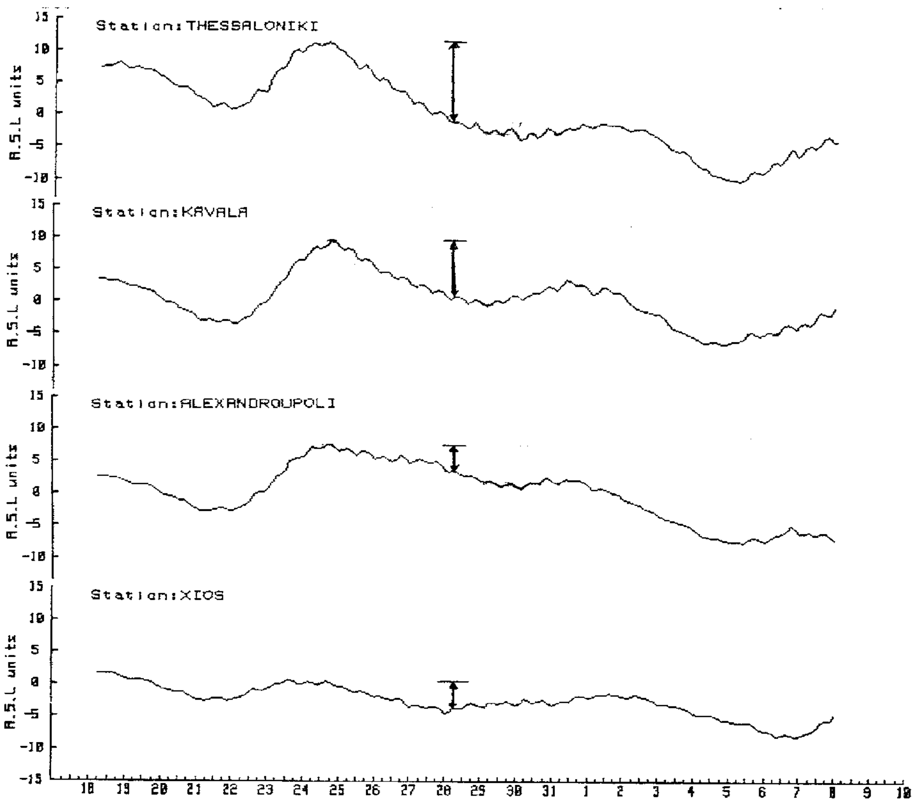

Fig. 7: The time series of the Adjusted Sea Level (A.S.L.) changes recorded at four tidal stations of the North Aegean area (Thessaloniki, Kavala, Alexandroupoli and Chios, enclosed map in Figure 1).

ing barometric pressure value recorded at the local meteorological station, to the sea level height of the tidal station.

The non-tidal variability of the sea level has been extensively studied in the Aegean (ex. KARDARAS & ZOI-MOROU 1987; NITTIS 1993; TSIMPLIS & VLAHAKIS 1994). The works show the very high spatial correlation throughout the Aegean Sea among sea level, atmospheric pressure and north-south wind speed.

Using data from tidal and meteorological stations of the Aegean basin and applying different statistical tools (PCA, regression and spectrum analysis) they mainly found qualitatively and quantitatively among the others that:

a. The Aegean Sea oscillates in the principal modes that together account for ~ 90 % of the total variance. The first mode corresponds to a simultaneous movement of all the Aegean, while the second corresponds to an oscillation with a 180° phase difference between north and south.
b. The sea level is very well correlated to the atmospheric pressure in all the frequencies, although the linear correlation between geostrophic wind and sea level is generally low with the exception of periods of 3-4 days during winter. The phase difference suggested a very fast response of the sea level in synoptic scale,

while in lower frequencies (<10 days), sea level lags 1-1.5 days relevant to the atmospheric pressure. Finally, an over-isostatic response was observed in lower frequencies, while in the higher band the response is near isostatic.

c. The contribution of every mechanism (atmospheric pressure and wind) to the fluctuation of the sea level is explained by 50-80% from the atmospheric pressure and 30-70% from the wind for the winter period in the synoptic scale. Furthermore, the Aegean straits do not impose any restriction on the sea level adjustment due to atmospheric disturbances in synoptic scales.

For all the cases considered above, the existing difference between the geostrophic and the actual surface wind should be taken into account when evaluating the contribution of the wind to the sea level change mechanism.

The study of the A.S.L time series, as depicted in Figure 7, combined with the prevailing meteorological conditions taken from the weather maps and the recordings of the meteorological stations all over the area of North and Central Aegean, leads to the following conclusions:

a. During the 23rd to 24th of May 1983 time period, a low-pressure system crossed the Balkans accompanied by a cold front extended down to the Aegean and very strong southerly winds. In the shown A.S.L. time series and for the specific event, a simultaneous and very intense rising of the same magnitude for the stations in the North Aegean is noticed.
b. During the 24th to 27th of May 1983 time period, the A.S.L values are decreased gradually in the North Aegean shelf. The degree of reduction is more intense from the North-West (Thessaloniki) to the North-East Aegean (Alexandroupoli and Chios).
c. For the 29th to 30th of May 1983 time period, two low-pressure barometric systems crossed the Central Aegean Sea combined with very strong southerly winds over the South Aegean and light winds over the North Aegean Sea. The level of A.S.L increases relatively more rapidly at the Chios station followed by a lesser increase from Alexandroupoli to Kavala and Thessaloniki tidal stations.

In each of the four A.S.L time series in Figure 7, a difference of sea level magnitude between the 23-24/5 and 28-30/5 time periods for each area is indicated, which tends to increase starting in turn from Chios and Alexandroupoli, to Kavala and finally to Thessaloniki.

Assuming that a uniform rising of A.S.L. took place in the North Aegean shelf in the period 23rd to 24th of May 1983 due to southerly winds and the low-pressure system passage, in the time period afterwards, the degree of the relative gradual reduction between the stations appears to create a sea surface slope and a pressure gradient in the east-west direction (Fig. 7).

The qualitative approach for the formed sea surface east-west slope in the North Aegean shelf can be quantified by the A.S.L. range difference, as it is indicated in Figure 7, among the Thessaloniki, Kavala and Alexandroupoli stations. The estimated sea surface slope is about $8x10^{-7}$ positive towards the east in the North Aegean area, taking into account the height difference among the A.S.L diagrams between the 25th and the 28th of May 1983 and the mean distance (width) of the North Aegean.

Applying the geostrophic equation:

$$u = \frac{g}{f} \frac{\partial z}{\partial x}$$

where: **u** is the velocity magnitude, **g** the gravity acceleration (9.81 m/sec^2), **f** the Coriolis coefficient ($9.31x10^{-5}$ for $\varphi = 40^o$) and ∂**z**/∂**x** the estimated sea surface slope ($8x10^{-7}$), a mean value of 8.4 cm/sec for a surface northward geostrophic current is calculated. This current balances the created sea surface slope, assuming uniformity of the water.

Based on the relationship of Garret and Majaess (GARRET & MAJAESS, 1984):

$$T = \frac{A.f}{g.H}$$

where **A** is the Kavala Bay area (261x 10^5 m^2) and **H** the mean Thassos Channel depth (about 23 m) and given the geometrical dimensions of the Thassos channel compared to the surrounding area, no geostrophic control is expected on the circulation throughout the channel, for periods **T** greater than 10 sec.

It is argued that the reasoning behind the influx of the water into the Kavala Bay during the period between 28th and 31st of May 1983 is the result of the intrusion of the above created surface geostrophic current throughout the Thassos island channel, which was locally intensified due to the channeling effect.

Conclusion

The study of Kavala Bay current field using data recorded with current meters combined with the available meteorological and sea level data of the extended area of the Aegean showed that prevailing meteorological conditions play a critical role as far as the circulation of the water in the area.

It was shown that, the crossing of the depressions having its axis over the North Aegean results in the formation of sea surface slopes balanced by geostrophic currents. As a consequence, the geomorphological characteristics of the area control the water movement and a new circulation regime is locally formed. The Thassos channel is one of those where the geostrophic currents are amplified because of the channeling effect resulting in sudden intrusions of water masses into the bay having the oceanographic characteristics of the extended area of the North Aegean.

The residual circulation in the bay was calculated several times in the past using various methods (current meters and subsurface drogues, KARDARAS, 1998). The mean current velocity is estimated at about 7cm/sec using the Lagragian approach and therefore, a time period of 4 days is required for the renewal of the bay water.

In the case of the accelerated water forced by the general geostrophic circulation and controlled by the geometry of the area, the time required decreases to less than one day. The estimation is based on a mean horizontal velocity of 40 cm/sec recorded at the level of 9m depth.

Furthermore, from the above mentioned circulation characteristics for Kavala Bay, it is concluded that a decisive factor on the environmental policy for a given area is the time period required for the renewal of the water, which is directly related to the residence time of any suspended material.

Acknowledgements

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