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SEASONAL VARIABILITY OF SURFACE CURRENT IN THE EASTERN MEDITERRANEAN SEA

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Key words: ***Eastern Mediterranean, Geostrophic current circulation.***

ABSTRACT

The geostrophic current has been calculated in the eastern Mediterranean Sea using the objectively analyzed hydrographic data. The surface circulation of the eastern Mediterranean is quite steady during the four seasons. In the northern part of the Ionian Sea the circulation is seasonal. It changes from cyclonic circulation in winter and spring to anticyclonic and cyclonic in summer and autumn seasons. PELOPS anticyclonic gyre appears off the southwest coasts of Peloponnisos in Greece in winter and summer. There is a strong cyclonic circulation in the central part of Levantine basin can be identified in all seasons. Its size changes from season to season, occupying the region between Crete and Cyprus some of time and shrinking toward Rhodes at other time. Mid Mediterranean Jet, partly flows around Rhodes Gyre eventually to join the westerly flow (Asia Minor current) along the southwest Anatolian coast. Mersa-Matruh cyclonic gyre appears off the western Egyptian coast in winter and autumn seasons. An anticyclonic gyre is found off the western Egyptian coasts in spring and summer. Shikmona gyre appears off Lebanese coast in the four seasons. Clear cyclonic gyre appears in the southeastern corner of Levantine in the four seasons. The current in the north Levantine is westward parallel to its northern coasts. The most interesting feature of the current regime in Otranto Straits is the inflow of the current to the Adriatic Sea through Otranto Straits in all seasons except summer. In summer the current flows out of the Adriatic Sea through Otranto Straits.

In the Aegean Sea, the circulation is seasonal. In winter, there are two cyclonic circulations off the northern coasts of Crete, and another *cyclonic one in the central part in winter. In spring, the whole Aegean Sea is occupied by cyclonic circulation. In summer, there are four gyres, two anticyclonic gyres and two cyclonic ones. In autumn there are two cyclonic circulations, one is in the southern part and the other occupies its northern and central parts.*

INTRODUCTION

The shallow and narrow straits of Sicily (300 m depth) separate the Mediterranean Sea into the western and eastern basins. The eastern Mediterranean Sea is almost an isolated basin, within which a wide range of oceanic processes and interactions of global interest occur. Such processes are driven by all major forcing mechanisms including momentum flux induced by surface winds, bouncy flux, water mass formations and lateral exchange of masses. The eastern Mediterranean is composed of four sub-basins: Ionian, Adriatic, Levantine and Aegean,.

The Ionian Sea is located in the central part of the Mediterranean Sea. It is connected to the Adriatic Sea by the strait of Otranto. Levantine Sea is the second largest basin of the eastern Mediterranean. Asia Minor, the northeast African mainland and the Cretan Archipelago encircle the Levantine Sea. Narrow passages (straits of Rhodes, Scarpanto and Kassos) allow connection to the Aegean Sea, and the connection to the Ionian Sea occurs through the Cretan Passage (south west of Crete). Aegean Sea is located between Greece and Turkey mainlands. The Adriatic Sea is situated between the Italian Peninsula and the Dalmatian coast of Albania and Yugoslavia.

Direct current measurements in the eastern Mediterranean Sea are very scarce, so the current pattern computed from the oceanographic data provides information on the general circulation in the eastern Mediterranean.

The circulation in the east Mediterranean is dominated by small sub-basin gyres. Sharaf-El-Din and Karam (1976) studied the geostrophic currents in southeast Mediterranean. They determined the reference level for some offshore stations by Defant's method and for some coastal stations by Groen's method. Gerges (1976) studied the general circulation using the observed density and wind fields. Dzhioyev and Drozdov (1977) computed the current in the eastern Mediterranean. May (1982), calculated the climatological wind stress averages for the Mediterranean Sea. El-Gindy (1982), made a comprehensive hydrographic and dynamical study of the eastern Mediterranean and Aegean seas. Said (1984), used the hydrographic data collected in the period 1963-1982 as well as the meteorological data to investigate the circulation in the central and eastern Mediterranean. Maiyza (1986) studied the hydrographic characteristics of the eastern Mediterranean Sea in warm and cold winters. Tziperman and Malanotte-Rizzoli (1991), calculated the Mediterranean horizontal circulation of the upper 800 m from a seasonal climatological hydrographic data set using a simple inverse model. Ozsoy ***et. al***. (1993) studied the circulation and hydrography of the Levantine basin. Bergamasco ***et. al.*** (1993) determined the steady seasonal circulation of the eastern Mediterranean using adjoint method. Kamel (1993) computed the wind driven current in the eastern and western Mediterranean Sea. Kamel (1998) showed the circulation pattern of the Mediterranean Sea through the distribution of salinity and density fields.

The present study represents an attempt to illustrate the surface circulation of the eastern Mediterranean Sea for the four seasons using geostrophic method; trying to determine the areas in which the circulation is steady and those in which the seasonal signal has significant magnitude.

MATERIALS AND METHODS

Seasonal climatological hydrographic data, covering the eastern Mediterranean Sea up to 1995 are used. These data are obtained from the project entitled 'Mediterranean Oceanic Data Base', undertaken at the University of Liege, Belgium. The data is made to be a quarter degree squares latitude horizontal resolution.

Geostrophic velocity profiles were made for different pairs of tations nd were plotted for the four seasons. The dynamic computation depends to a great extent on the choice of the reference level. The first dynamic topography charts for the whole Mediterranean Sea were obtained for the surface and 500 m level relative to 1000-decibar surface for winter and summer seasons by Ovchinnikov and Feodosyev (1965). In the present study the reference level is taken at 1000m level.

The method of computation of geostrophic current used is described in detail in Pond and Pickard (1983). The geostrophic x- and y-equations can be summarized as follows:

$2\Omega \sin\varphi v = \alpha \partial p / \partial x$

$2\Omega \sin\varphi u = - \alpha \partial p / \partial y$

Introducing $\Delta\Phi = \alpha \partial p$ (the change of geopotential over the vertical distance ∂z)

Then,

$2\Omega \sin\varphi (v_1 - v_2) = \partial(\Delta\Phi) / \partial x$ *and*

$2\Omega \sin\varphi (u_1 - u_2) = - \partial(\Delta\Phi) / \partial y$

Then:

$(v_1 - v_2) = (1/2\Omega \sin\varphi) \partial(\Delta\Phi) / \partial x$

$(u_1 - u_2) = -(1/2\Omega \sin\varphi) \partial(\Delta\Phi) / \partial y$

Where:

α is the specific volume.

u_1 and u_2 are the velocity components in x (west-east) direction (in m/s), subscripts *1* and *2* refer to depth levels z_1 *and* z_2

v_1 and v_2 are the velocity components in y (south-north) direction (in m/s), subscripts *1* and *2* refer to depth levels z_1 *and* z_2

$\partial p / \partial x$ and $\partial p / \partial y$ are the pressure gradient in the x- and y-directions respectively, $\partial p = \rho g \partial z$

φ is the geographic latitude.

Ω is the angular speed of rotation of earth, its magnitude is 7.29×10^{-5} rad/s.

$\Delta\Phi = \alpha \partial p$ is the change of geopotential over the vertical distance ∂z, $(z_2 - z_1)$.

RESULTS AND DISCUSSION

The circulation in the Mediterranean Sea is slightly different in general nature from season to season and can be stable due to predominance of northwesterly winds throughout the year, (Ovchinnikov, 1966). Gerges (1976) mentioned that the gradient currents in the eastern Mediterranean Sea are dominating at the surface. The surface circulation of the eastern Mediterranean, as shown in figures (2-5), is quite steady during the four seasons.

In the Ionian Sea the eastward inflow of Atlantic water through Sicilian Straits, is directed parallel to southern coasts of Sicily Island, with average speed of 7 cm/sec in winter (Fig. 2). In spring, its speed reaches 10 cm/sec; while in summer and autumn it is higher (13 cm/sec) as shown in figures 3,4 & 5. Part of this current meanders to the south then to the west with speed of 6 cm/sec in winter, making anticyclonic circulation (south Sicilian anticyclonic gyre). The northward current turns east to make an anticyclonic circulation off the western Tunisian coast (southern Ionian anticyclonic circulation). The magnitude of this circulation differs from 8 cm/sec in winter and spring to 11 cm/sec in autumn (as shown in table 1). In the northern part of the Ionian Sea the circulation is seasonal. It changes from cyclonic circulation in winter and spring to two gyres in summer and autumn seasons (anticyclonic and cyclonic ones). This result agrees with the work of Bergamasco *et. al*., 1993, who mentioned that the northern half of the Ionian Sea is occupied by anticyclonic gyre in winter and a cyclonic one in summer. This north Ionian gyre is of magnitude from about 2 cm/sec in winter to 7 cm/sec in summer and autumn seasons (as shown in table 1). In summer (Fig. 4) the surface circulation is characterized by an anticyclonic movement and small scale cyclonic and anticyclonic eddies in the northern Ionian. This finding agrees well with Ovchinnikov (1966) and Dzhioyev & Drozdov (1977). They showed that there are different gyres of different scales in this area. Off the southwest coasts of Peloponnisos, there is anticyclonic gyre appears in winter and summer (PELOPS Gyre). It had shown also in the work of Robinson *et. al*., 1991. In the area to the southwest of Crete, there is a cyclonic circulation which can be identified in the four seasons. This cyclonic circulation appeared also in the work of Gerges, 1976. Sharaf-El-Din and El-Gindy (1986) showed that in winter there were two cyclonic motions, one in the Ionian Sea and the other to the south of Crete Island.

In Levantine basin a cyclonic circulation is found in the area between Crete and eastern Libyan coast in all seasons (Cretan Circulation). Its magnitude is 7,5,9 and 10 cm/sec in winter, spring, summer and autumn seasons respectively. To the southeast of this circulation, off the western Egyptian coast, there is a cyclonic gyre appears in the four seasons. The current velocity of this gyre is higher in winter and summer (11 & 10 cm/sec respectively), as shown in

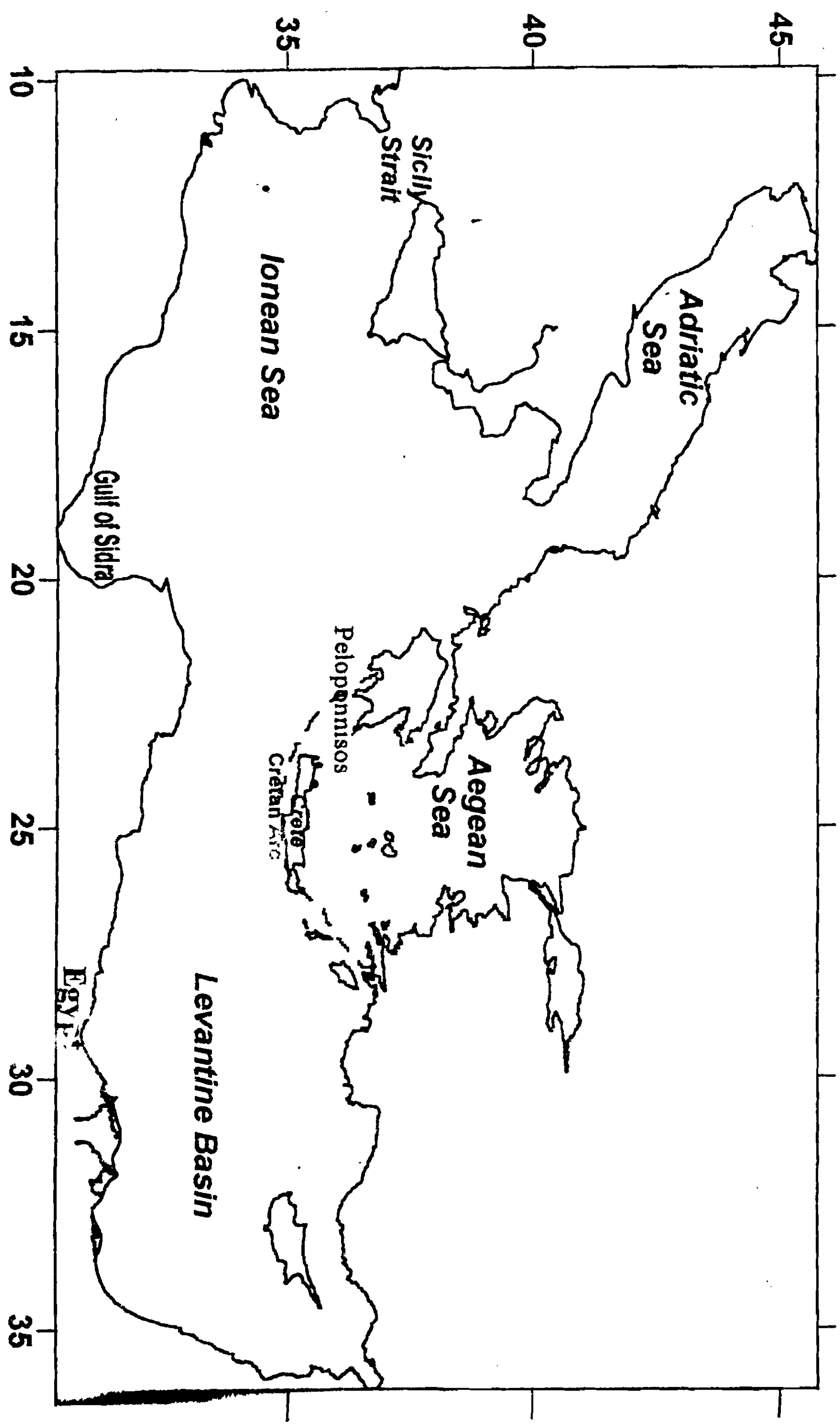

Fig. (1): Eastern Mediterranean basin.

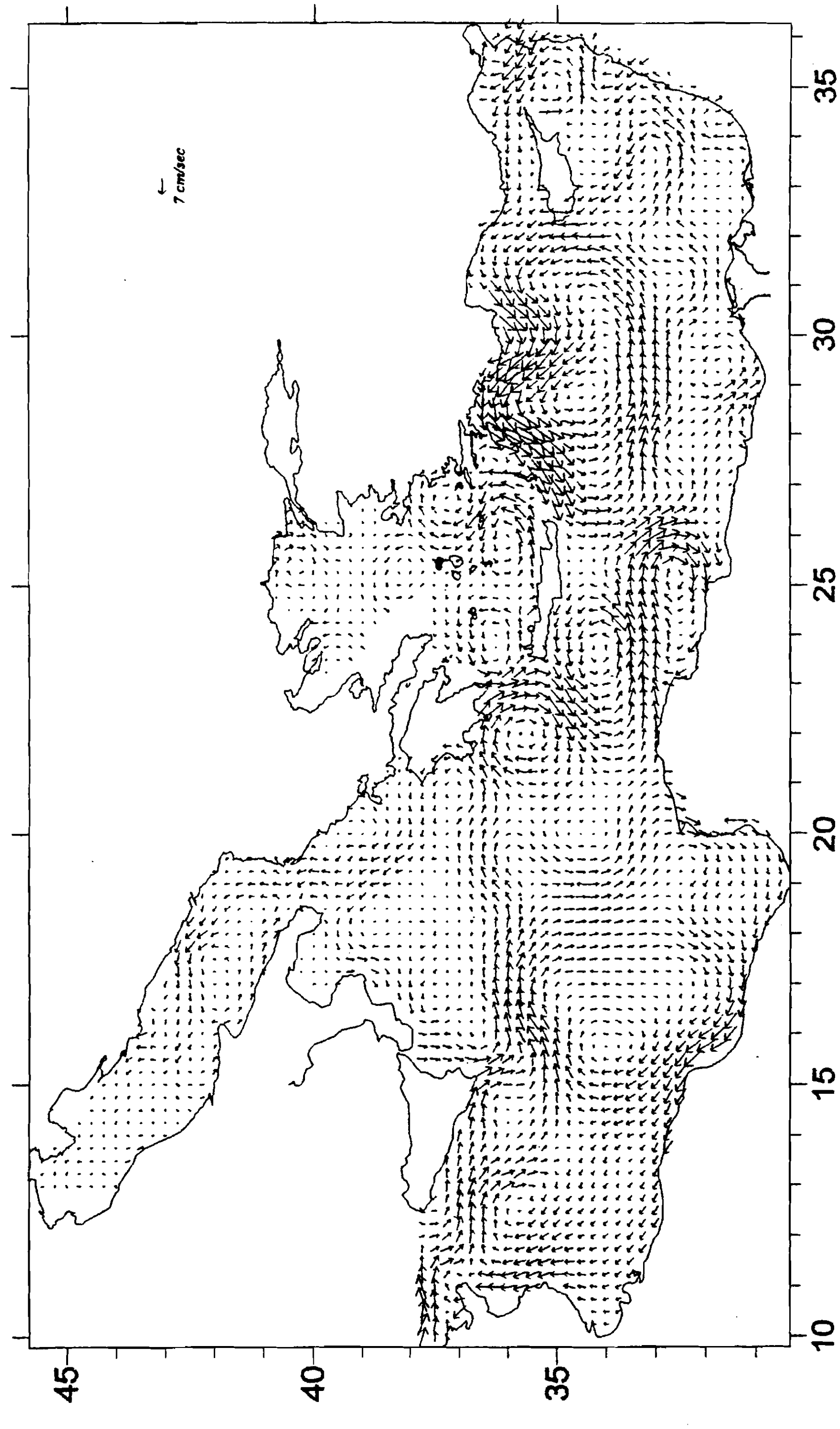

Fig (2): The surface current in the eastern Mediterranean Sea in winter

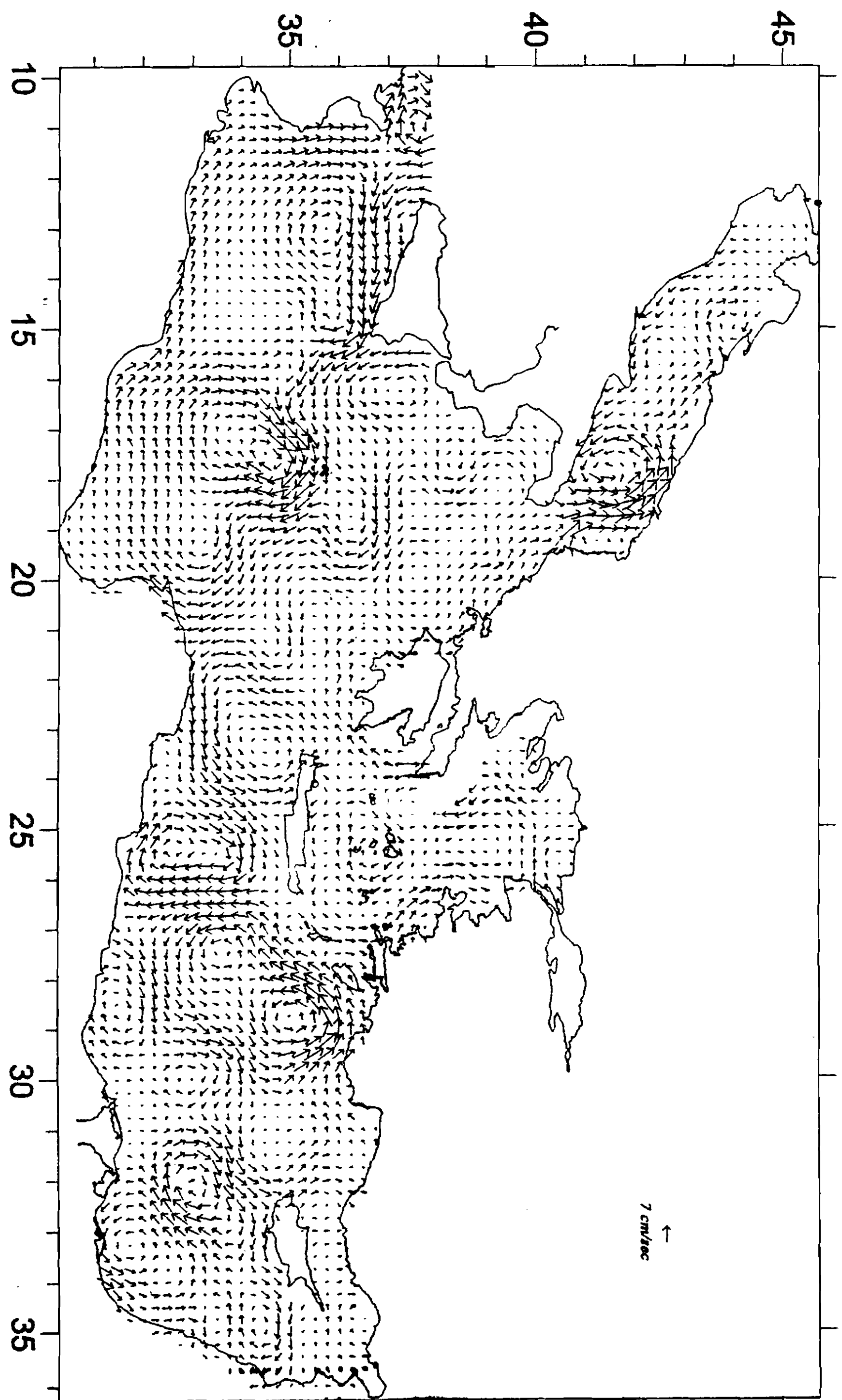

Fig. (3): The surface current in the eastern Mediterranean in spring

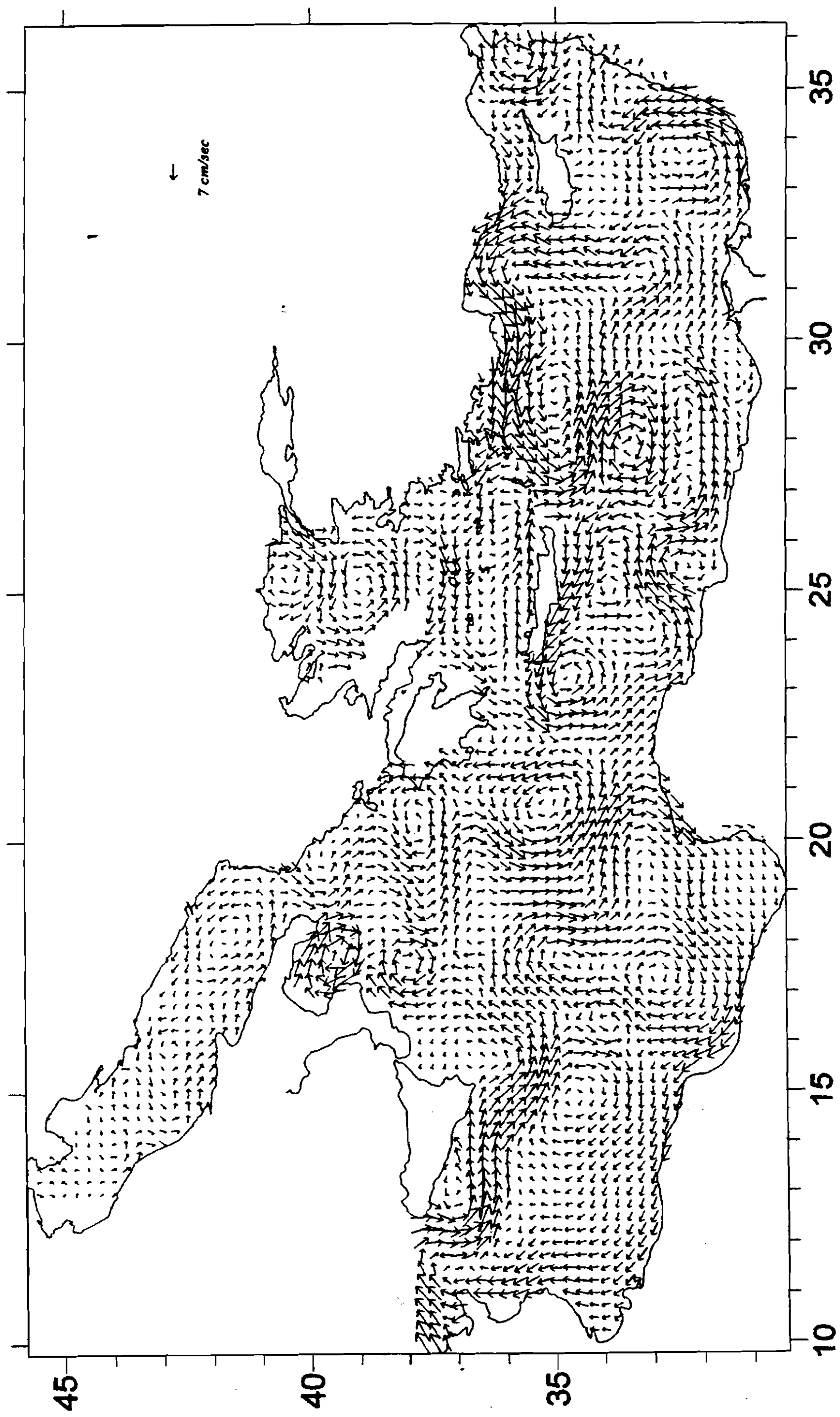

Fig. (4): The surface current in the eastern Mediterranean in summer

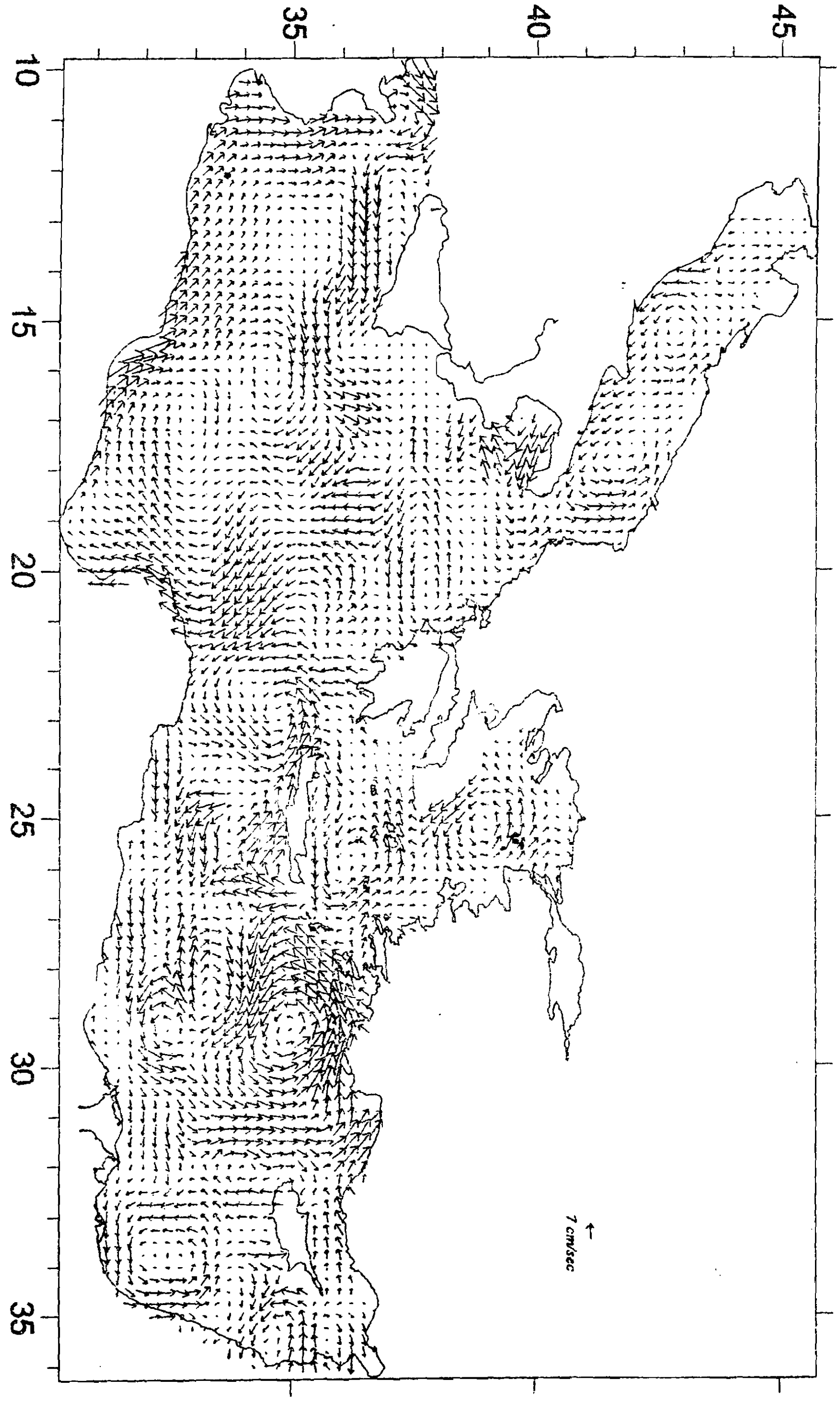

Fig. (5): The surface current in the eastern Mediterranean in autumn

table (1) an lower in spring and autumn (8 & 7 cm/sec). This gyre has been also identified as Egyptian anticyclonic gyre by Said (1984), the Egypt high by Brenner (1989) and Mersa-Matruh gyre by Ozsoy ***et. al.***, (1989); Robinson ***et. al.***, 1991 and Robinson & Galanaraghi, 1993. In spring and summer seasons (Figs. 3 & 4) anticyclonic gyre appears in the Arab Gulf in Egypt. In winter and autumn seasons this gyre is cyclonic. This agrees with the study of Moskalenko (1974) who defined two main vortices in the region between Crete and Africa, a cyclonic vortex in the western end and an anticyclonic one to the east. In its central part of the Levantine basin,, there is a strong cyclonic circulation that can be identified in all seasons. Its size changes from season to season, occupying the region between Crete and Cyprus in winter and summer (Figs. 2 & 4) and shrinking towards Rhodes in spring and autumn (Figs. 3 & 5). The velocity of the current of this gyre differs from 10 cm/sec in spring and 15 cm/sec in the other three seasons (Table 1). This gyre has been identified as Rhodes Gyre (Robinson ***et. al.***, 1991 and Robinson & Galanaraghi, 1993). The cyclonic Rhodes gyre was recognized as the dominant circulation in the area between Crete and Cyprus (Ovchinnikov, 1966; Philippe and Harang, 1982; Anati, 1984, & Gerges, 1976). The current in the area off Nile Delta is in the eastward direction but it differs in magnitude. In winter and spring seasons its speed is weak (2 cm/sec), while in summer and autumn (Figs. 4 & 5) it is strong reaching 5 cm/sec. Off Lebanese coast, in the eastern Levantine, anticyclonic gyre appears in all seasons (Shikmona gyre). The average speed of the current in Shikmona Gyre is about 5 cm/sec in all seasons. To the north of Shikmona gyre there is a cyclonic gyre appears in winter and autumn seasons. Brenner ***et. al.***, 1991 and Brenner, 1993 have shown long term persistence of the Shikmona Gyre, despite changes in its structure and position. In the most southeastern corner of Levantine basin, there is a cyclonic circulation appears in all seasons. In winter, this gyre is shifted a little to the north. This cyclonic circulation has been shown also in the work of Gerges, 1976. Various anticyclonic eddies in the southern part of the Levantine basin have been shown by Engel, 1967; Ovchinnikov ***et. al.***, 1976; ; Oren, 1970 & Ovchinnikov, 1984. Off the border coasts between Cyprus and Syria, there is a cyclonic circulation. The current in the north Levantine is westward parallel to its northern coasts. .Anticyclonic gyre appearing off the south eastern coasts of Cyprus in spring and autumn. Mid Mediterranean Jet, partly flows around Rhodes Gyre eventually to join the westerly flow (Asia Minor current) along the southwest Anatolian coast. In winter this jet goes parallel to the northern border of Mersa-Matruh Gyre and to the southern border of Rhodes Gyre. In summer it bifurcates, one branch goes to the south towards Nile Delta, and the other one goes to the north entering Antalia Bay.

In the Adriatic Sea, the most interesting feature of the current regime in Otranto Straits is the inflow of the current to the Adriatic Sea through Otranto Straits in all seasons except in summer. In summer the current flows out of the Adriatic Sea through Otranto Straits with speed of about 4 cm/sec. This phenomena may be due to ice melting in the northern Adriatic. Generally the circulation in the Adriatic Sea is quite steady and it is marked by two cyclonic gyres covering its southern and central parts. The cyclonic circulation in the central part is larger in size in spring season and covers the northern and central parts of Adriatic Sea. The current velocity of the southern Adriatic gyre is shown in table (1).

In the Aegean Sea, the circulation is again seasonal. In winter, there are two cyclonic circulations off the northern coasts of Crete, and another cyclonic one in the central part. There is anticyclonic one is found off the southwestern coasts of Turkey. In spring, the whole Aegean Sea is covered by cyclonic circulation. Inside this circulation, in the southern part, there is a small anticyclonic one. In summer, there are four gyres, two anticyclonic gyres and two cyclonic ones. In autumn there are two cyclonic circulations, one in the southern part and the other is in the northern and central parts.

Table (1): The average velocities (cm/sec) of the different gyres in the eastern Mediterranean Sea

	Winter	*Spring*	*summer*	*Autumn*
South Sicilian anticyclonic gyre	5	7	11	11
North Ionian cyclonic gyre	2	3	7	7
South Ionian anticyclonic gyre	8	8	9	11
PELOPS anticyclonic gyre	10		6	
Cretan cyclonic gyre	7	5	9	10
Mersa-Matruh anticyclonic gyre	11	8	10	7
Rhodes cyclonic gyre	15	10	15	15
Arab Gulf cyclonic gyre	5	5	6	7
Southern Cyprus anticyclonic gyre		5		5
South-eastern Levantine cyclonic gyre	4	5	8	4
Shikmona cyclonic gyre	5	4	6	4
Southern Adriatic cyclonic gyre	3	12	5	6

It is to be mentioned that Rhodes cyclonic gyre is the most active one in the Mediterranean Sea from the current velocity point of view as clearly shown in table (1). It is strongly to identfy this area as a site formation of Levantine intermediate and deep waters. There is a general agreement among oceanographer that the northern part of Levantine is the source region of Intermediate water especially in the area to the east of Crete. (Nielsen, 1912; Wust, 1959 and 1961; Lacombe and Tchernia, 1960; Miller, 1963; Ovchinnikov and Fedoseyev, 1965; Moskalenko and Ovchinnikov, 1965; Oren and Engel, 1965; Morcos, 1972; Ovchinnkov, 1984; Ovchinnkov and Plakhin, 1984; Theocharis *et. al.*, 1993; Ozsoy *et. al.*, 1993).

Maiyza, 1984, has identified this area as a site formation of deep water of the eastern Mediterranean.

The high current magnitude in the southern Adriatic in spring, as shown in table (1) and figure 3, which show that this area is a site formation of deep water. This agrees with Pollak, 1951; POEM GROUP, 1992. Birgit *et. al.*, 1999, have described also that the Adriatic Sea is a source of deep water with an additional source in the Aegean.

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