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Seasonal and Spatial Variation in Sea Surface Temperature in the South-East Mediterranean Sea

Mohammed Abudaya[1]*

1. Engineering Faculty, University of Palestine, PO box 1219, Rimal-Gaza, Palestine.

* E-mail of the corresponding author: dr.m.abudaya@hotmail.com

Abstract

A seven-year dataset of Advanced Very High Resolution Radiometer-Sea Surface Temperature AVHRR-SST during (1998-2004) was used to study the annual and seasonal variability in Sea Surface Temperature in the Levantine Basin of the Eastern Mediterranean Sea.

The time analysis revealed the presence of a strong seasonal signal characterized by two main seasonal extremes, winter and summer. The transition between the winter and the summer occurs very rapidly in May and October. The space analysis shows that the dominant scale is the sub-basin scale and the sub-basin gyres are very well resolved allowing the identification of permanent and semi permanent structures.

The seasonal and monthly SST distributions are strongly correlated with the dynamical structure of the basin upper thermocline circulation. Furthermore, comparison of the SST monthly climatologies with the POEM circulation scheme shows that all the major currents and the sub-basin gyres are also found consistently in our patterns.

A general warming trend appeared in the time series of SST data, and the seasonal cycles and their linear fit, suggesting an increase of about 0.5^{o}C in 7 years, although during the period under consideration, no systematic increase or decrease of the maximum summer SST was observed. This increase is essentially due to a steady rise of winter (December, January, February, and March).

Keywords: SST; spatial; seasonal; mesoscale; AVHRR, gyre, eddy

1. Introduction

Since the beginning of this century, the Mediterranean Sea has been the site of a continuous effort from the oceanographic community to improve the understanding of the circulation, production, transformation and spreading of the water masses, and to identify the associated forcing mechanisms (Ozsoy et al., 1993).

The Mediterranean Sea is land-locked and relatively small, yet it is of sufficient size of for its circulation to be governed by large-scale ocean dynamics mainly linked to climate. It is among the most interesting of the semi enclosed seas because of the great range of processes and interactions that occur within it (Robinson et al., 1992; Brankart and Brasseur, 1998). In fact most of the physical process that characterize the global general ocean circulation, occurs analogously in the Mediterranean, all the major forcing mechanisms surface wind and buoyancy fluxes and lateral mass exchange-all being evident (Marullo et al., 1999).

Intensive cyclone activity over the Eastern Mediterranean sea creates significant- space–time variability in the meteorological conditions, causing a local wind field driven by the compounded effects of climatic

contrasts and land topography (Reiter, 1975; Brody and Nestor, 1980). This heterogeneity in wind field causes a complex spectrum of water movements in the synoptically and mesoscale space–time ranges, resulting in temperature fronts with gradients exceeding 0.1°C km-1 in the north Levantine Basin (Ozsoy et al., 1993).

A series of previous observational based on in situ hydrographic measurements and climatological analysis produced significant amount of multidisciplinary hydrographic data in the Eastern Mediterranean. Individual hydrographic experiments were specifically designed to investigate physical process and the impact on nutrients and biological production. Nutrients enrichment has been observed during winter season in the area of the northern Levantine occupied by the cyclonic Rhodes Gyre encountered with low temperature at the surface (Yilmaz and Tugrul, 1998); whereas low nutrient values have been detected in the neighboring anticyclones gyres (Kress and Herut, 2001). Recent analysis of in situ data provided a general structure of the local oceanic circulations in the Eastern Mediterranean Sea (Ozsoy et al., 1989; POEM Group, 1992; Robinson et al., 1992; Ozsoy et al., 1993). The major elements of the Levantine Basin circulation include: the Rhodes Gyre, of which the multiple centers are located south-east of the island of Rhodes and extend towards Cyprus; the intense Mersa

Matruh Gyre south of Rhodes; the Shikmona Gyre complex with a number of separate centers in the south-eastern Levantine Basin; and a coherent mid-basin jet, identified as the Central Levantine Bain Current, flowing eastwards amongst these vortices. Some of these eddies change their intensity and position by about 50–100 km during the same season. However, the inter-annual variability of the dynamic features is not known clearly, because in situ measurement data in the Levantine Basin with timescales longer than a few years are yet to be made available.

Until recent years, the eastern Mediterranean and in particular the Levantine Basin has remained one of the least understood parts of the world ocean. However as a result of the work of POEM (Physical Oceanography of the Eastern Mediterranean) programme, it became clear that current patterns in the Eastern Mediterranean are very complex (Robinson et al., 1991; POEM Group, 1992; Robinson and Golnaraghi, 1994). Specifically there appear to be series of persistent sub-basin scale gyres interconnected by a meandering current, as well as and energetic mesoscale field consisting of warm and cold core eddies. Because of the scale of these features, the terms gyre and eddy are often used interchangeably in the eastern Mediterranean. Some of these features appear to be very persistent, e.g. the cold-core eddy situated southwest of Rhodes (Rhodes gyre), and the warm-core eddies south of Cyprus (Cyprus eddy). Such features can have a major effect on biogeochemical process occurring within basin.

More recently it has become possible for sea surface temperature has been measured from satellite orbiting around the earth, with similar accuracy to the surface temperature measured by conventional sensors installed in merchant vessels. Furthermore, these satellite have global geographic coverage, unlike merchant vessels that are concentrated into the main shipping routes (Folland et al., 1993). The most widely used satellite sensor to measure Sea surface Temperature is the Advanced Very High Resolution Radiometer (AVHRR) installed in the National Oceanic and Atmospheric Administration’s (NOAA) series of satellites. The detailed structure and the seasonal cycle of SST derived from (AVHRR) permit researchers to identify the meso-and basin-scale oceanographic and their annual variation. This paper presents a study of the seasonal and spatial variation of the sea surface temperature (SST) of the Levantine Basin, as inferred from the remote sensing record. In particular, a time series of satellite images collected by the Advanced Very High Resolution Radiometer (AVHRR), in the period 1998-2004 is analyzed. In addition, major features of the surfaces circulation detected and inferred from the satellite data were compared with evidence from the previous in situ observations.

2. Material and methods

2.1 Study area

The area covered in this paper is the south-east basin (Levantine Basin) in the Eastern Mediterranean Sea, a semi-enclosed basin characterized by rough bottom topography with a narrow continental shelf (<200 m) and a step continental slop. It is bounded in the south by the coasts of Libya and Egypt, in the east by the coasts of Israel, Palestine, Lebanon and Syria, and in the north by Turkey and the islands extending from Rhodes to Crete (Figure 1).

The Mediterranean Sea, located at mid-latitudes, is characterized by a rather sub-tropical climate with two well-defined seasons, winter and summer, and short periods of transition between them. The Levantine Basin is characterized by a typical Mediterranean-type of climate. The annual climatic variability can be divided into two main periods: (i) November to March, which is cool and rainy; and (ii) May to September, which is a hot and rather dry season. October and April an be characterized as intermediate months, between these two distinctive periods (Zabakas, 1981; Poulos et al., 1997).

Table 1: Upper thermocline features in results from the POEM general surveys. The Table shows the mesoscale features and gyres found by the modelling of the sampling hydrographic in situ data during 1985-1987 by cooperating scientists.

No.	Feature	No.	Feature
1	Mid-Mediterranean Jet MMJ	4	Greaten Cyclone CC
2	Rhodes Gyre RG	5	Mersa-Matruh Gyre MMG
3	West Cyprus Gyre WCG	6	IeraPetra Anticyclone IPA

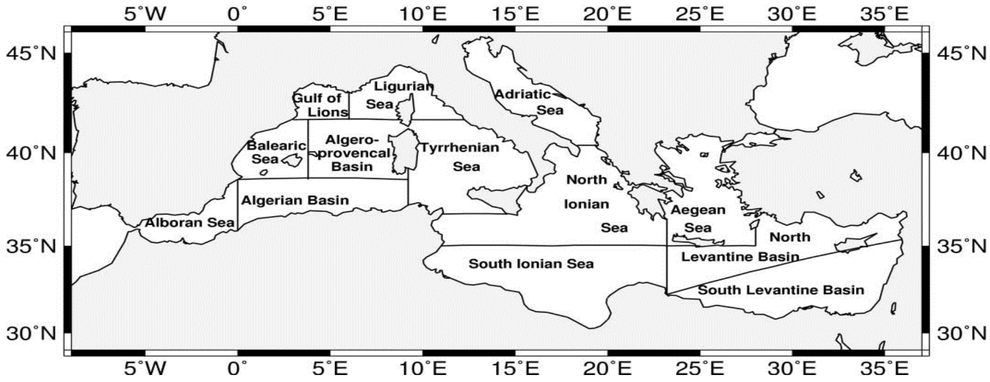

Figure 1: Map of the Mediterranean Basin showing the south-east Basin (Levantine Basins).

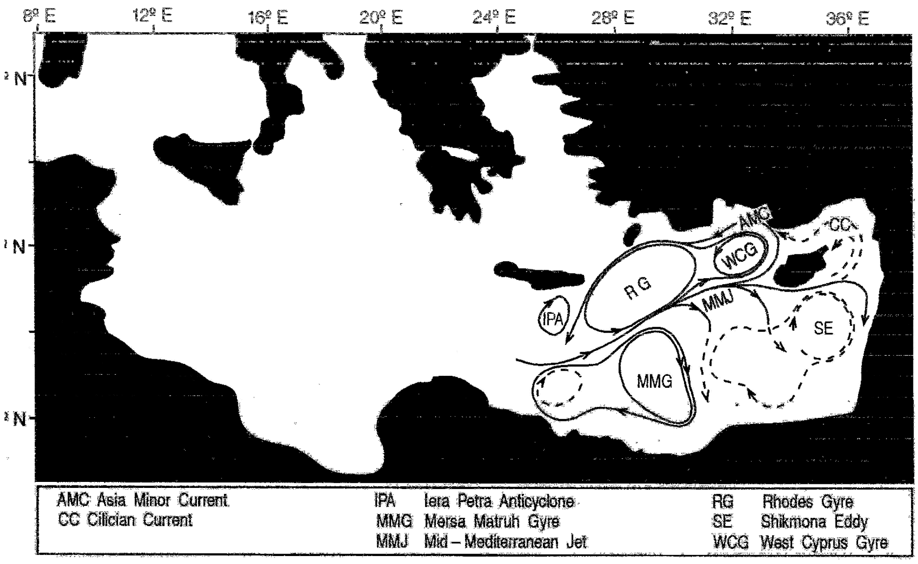

Figure 2: Schematic map showing the upper circulation patterns of the south-east Mediterranean Basin (The Poem Group, 1992; Robinson and Golnaraghi, 1994).

2.2 SST data

In this study, a systematic analysis of the AVHRR data of the Eastern Mediterranean Sea is carried out. A global Multi-channel Sea Surface Temperature (MCSST) data set based on measurements by an Advanced Very-High-Resolution Radiometer (AVHRR) on board NOAA satellites (McClain et al., 1985; McClain, 1999). The daily SST local area coverage dataset (LAC) collected by the various versions of the AVHRR carried on-board the NOAA satellites used in the present work area 1.1X1.1 km SST images for the period 1998 January to December 2004 obtained from NOAA Satellite Active Archive and processed at Plymouth Marine Laboratory (PML). The first stage of the images processing was to mask the land and clouds cover areas and masked out in black. The sea surface temperature values were estimated by using the latest Non-Linear SST (NLSST) algorithm has been used for SSTs estimation (McClain, 1999).

The night time images were used only in estimation of SST in order to exclude the solar heating effect evident in daytime images. Averaging all the available image values produced the monthly and seasonal images for the period 1998-2000 and to investigate the inter annual variation in the mesoscale features in the averaged SST's during the period 1998-2004, seasonal averages for individual years were calculated by subdividing each year in four intervals of three months each. Each season has been defined as the average of the three successive months traditionally associated with the four seasons in oceanography, i.e., January-February-March for winter, April-May-June for spring, July-August-September for summer and October-November-December for autumn (Levitus, 1982). The monthly and seasonally maps were compared with evidence from the previous in situ comprehensive pooled hydrographical data base collected during 1985-1987 by cooperating scientists from several institutions and nations, the POEM Project (Physical Oceanography of the Easter Mediterranean) which was established to determine the circulation of the Eastern Mediterranean Sea. The results and observations of the POEM programme are shown in Table 1 and Figure 1.

3. Results

The time series of the monthly mean SST values averaged over the entire Levantine Basin are shown in Figure 3, which illustrates both, intra-annual and inter-annual variation in temperature and its term trend from January 1998 to December 2004. The seven annual cycles of SST averaged over the entire Basin in Figure 4 clearly show the annual patterns through the months and seasons.

The seasonal images have been used to extract the seasonal SST values in the Levantine Basin in the eastern Mediterranean Sea for 1998-2004 (Table 2). SST varies from a maximum around 24.9 ± 0.85 in summer, though 21.6 ± 1.50 in the autumn, to a minimum 17.3 ± 1.20 during winter, before rising again to 20.5 ± 0.90 in the spring,. The highest monthly average summer SST was 25°C registered in 2002 (25.0 °C); and the lowest 23.7 °C in 2001. The lowest winter SST value was 17.3 °C, in 2004.

Table 2: mean season surface temperature for 1998-2004.

Season/Year	1998	1999	2000	2001	2002	2003	2004	Mean
Winter	18.01	18.10	17.81	18.23	17.98	18.12	17.70	18.00±0.19
Spring	20.05	20.49	20.23	20.29	20.28	20.14	19.84	20.19±0.22
Summer	24.30	24.43	24.11	24.4	24.56	24.37	23.98	24.30±0.20
Autumn	21.51	21.55	21.36	21.24	21.43	20.95	21.36	21.34±0.21

The seasonal SST values were estimated by averaging the three successive months associated with the four seasons in oceanography, i.e., January-February-March for winter, April-may-June for spring, July-August-September for summer and October-November-December for autumn. The monthly SST values determined from AVHRR satellite images at 1km resolution.

Although it is difficult to be conclusive about any long-term trends, from only seven years of data, monthly values are plotted against time, a statistically significant general warming trend is evident (ANOVA: d.f.= 6, F= 3.39; $p<0.01$), suggesting an increase of about 0.6°C in seven years (Figure 3). The monthly SST distribution maps for 1998 are shown in Figure 5.

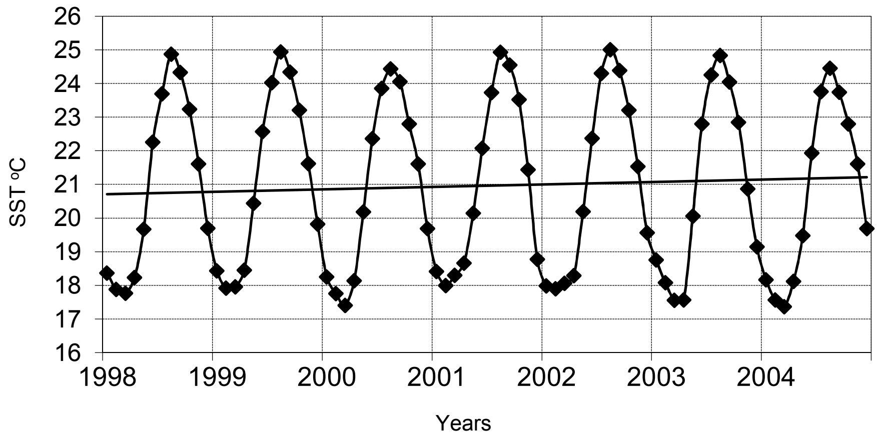

Figure 3. Patterns of monthly mean SST over the entire Levantine Basin for January 1998-Deember2004. The trend line shows the regression of the mean SST. The monthly mean SST values were estimated from AVHHR satellite images at 1.1km resolution by using the least Non-Liner regression.

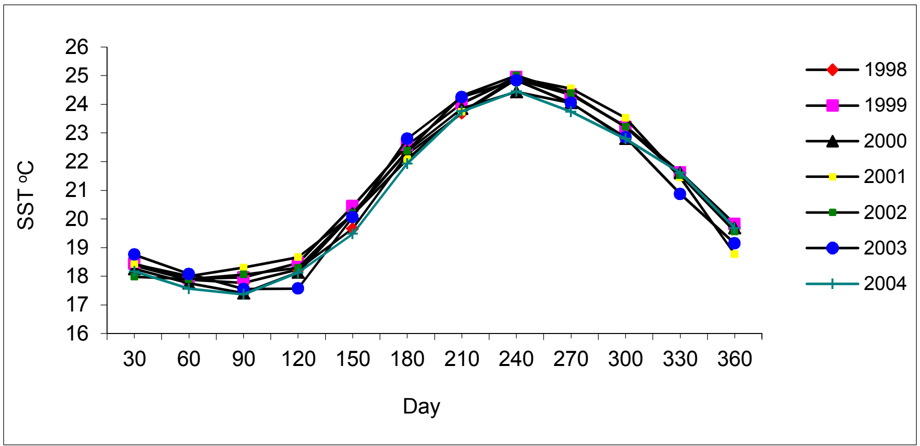

Figure 4. Seven annual cycles of the monthly mean SST averaged through the entire Levantine Basin from the years 1998-2004. The monthly mean SST values were estimated from AVHHR satellite images at 1.1km resolution by using the least Non-Liner algorithm over the Levantine Basin of the Mediterranean Sea.

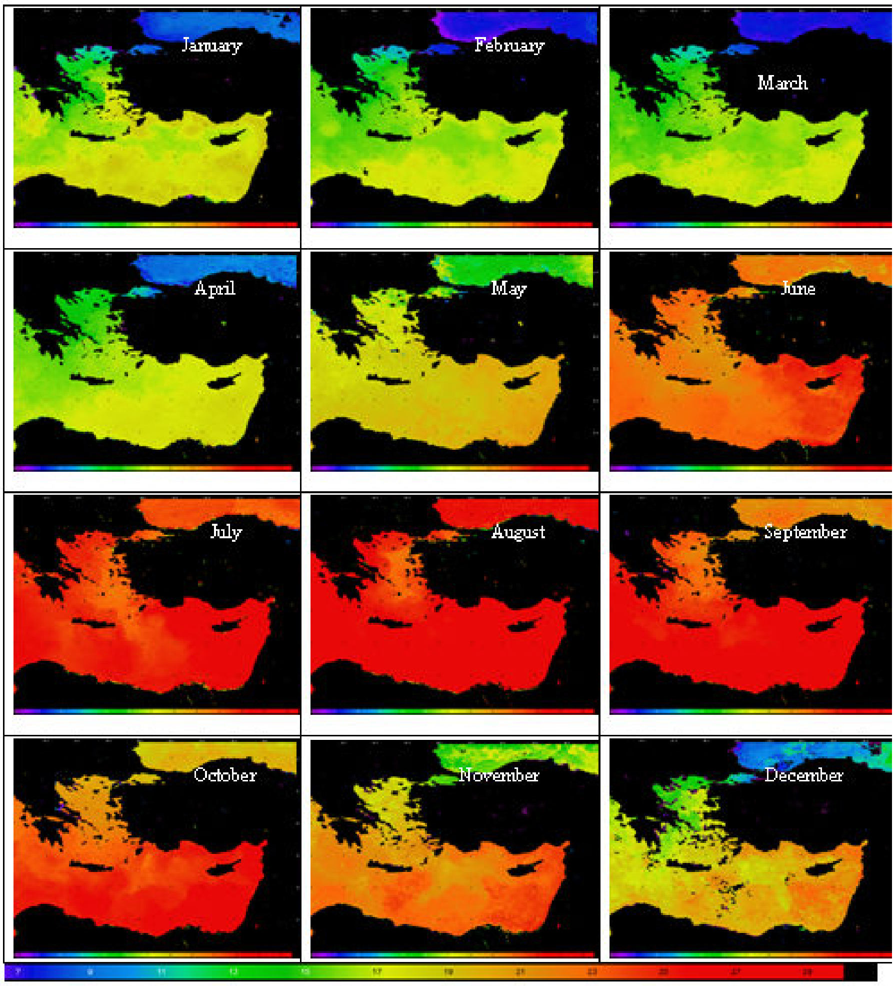

Figure 5. Monthly mean images of SST distribution for the year 1998. The colour scale shows ^{o}C. The monthly mean SST values were estimated by averaging the daily images of AVHRR satellite images at 1.1km resolution.

3.1 Mesoscale features in SST images

The SST images provided further oceanographic information on surface water structures visible as patterns of temperature distribution. The SST satellite imagery shoed a drop of 5 ^{o}C between the east and west Levantine Basins, and a strong SST front crossing the basin as far as Cyprus, thus separating the entire Levantine basin from its eastern-most warm part (Figure 6), the discontinues nature of the thermal structure, as opposed to smooth gradients, being evidence of meso-scale and associated currents. The thermal front was quite evident in the Levantine Basin and was associated with Mid-Mediterranean Jet (MMJ) that is the continuation of the North African Current. The MMJ al constituted the southern boundary of the Rhodes Gyre (Figure 7). The MMJ front was always well defined up to Cyprus and defected northward west of Cyprus. However, in other images instead the MMJ front bifurcated into two branches that turn northward, on passing to the east Cyprus and the other to the west (Figure 6).

The Sea Surface Temperature satellite imagery clearly shows a series of sub-basin scales and mesoscale consisting of warm and cold eddies. Some of these mesoscale features are very persistent. There are almost no areas of the Basin, which are not part of some mesoscale feature or other (Figures 6). Inspection of some daily and monthly SST images revealed that three main features are present: the cold Rhodes Gyre east of Crete, the Cretan Gyre and the warm Ierapetra Anticyclone southeast of Crete.

The SST satellite imagery also clearly showed the sub basin features between Cyprus and Rhodes. The most striking, remarkable permanent feature was the Rhodes Gyre (RG) south of Rhodes. Although present at all times of the year, its shape, position and strength change monthly. In March the intense cold core of the gyre was oriented north-west/south-east and acquires a plume like shape, while in June and August the major axis of the cold core was oriented in the north-south and became weaker than in March. In the monthly mean SST images of winter (November, December, January and February) the gyre was still present but the cold core moved westward (Figure 6, 7).

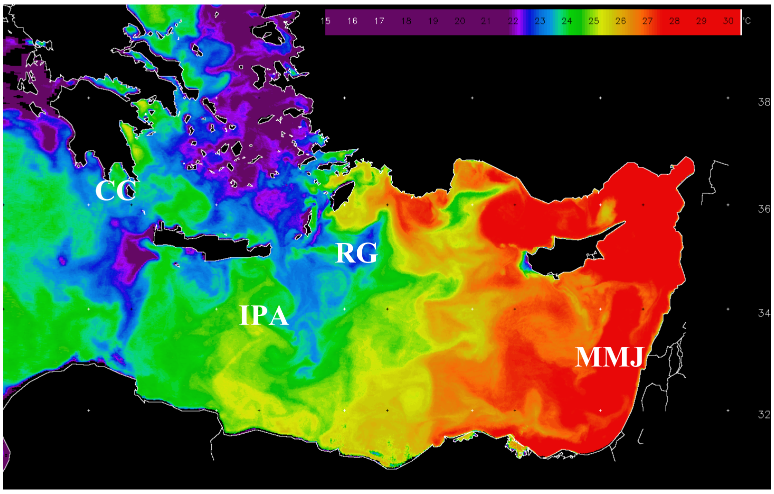

Figure 6. AVHRR 4-km Sea Surface Temperature image for 4th August 2002 showing mesoscale structure in the Eastern Mediterranean Sea.

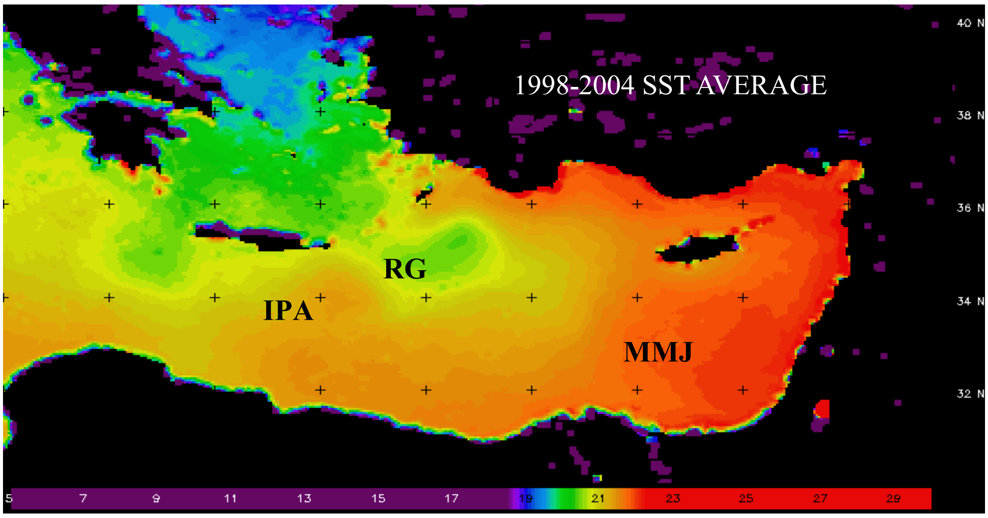

Figure 7. Time average of the Sea Surface Temperature from the entire time series.

Inspection of monthly mean SST images showed a second cold feature was the Cretan Gyre, west of Cretan Arc Straits. This is a quasi-permanent cold gyre, present mainly in the period from January to April in the monthly averages SST. The gyre shape, position and strength change monthly. The Cretan Gyre could intensified and occupied the entire Cretan passage, strongly reducing the exchange between the Ionian and Levantine basins and its southern boundary almost reached the African coast, pushing the Mid Mediterranean Jet towards the African coast (Figure 6).

The warm Ierapetra Anticyclone (IPA) southeast of Crete is a quasi-permanent structure (Figure 6). The warn signature of the (IPA) was detectable because the eddy was almost completely surrounded by the cold side of the thermal front associated with the MMJ and the Rhodes Gyre to the east. The warm Ierapetra Anticyclone (IPA) from November to March is shown in the monthly mean SST images. The anticyclone Mersa-Matruh Gyre never appeared in the daily or the monthly mean SST satellite images. The inspection of the SST images did not reveal the presence of the Mersa-Matruh Gyre as noted in Figure 6. The SST map of the overall mean temperature obtained by averaging the 84 monthly images is shown in Figure 7. The monthly SST mean SST maps clearly shows the principal series of sub-basin scales features consisting of warm and cold Gyres.

4. Discussion

The earliest measurements of physical properties in the water of the Levantine Basin were made from the Danish ship RV Thor in 1910. On the basis of these data, the circulation in the upper and intermediate layers of the Levantine Basin was depicted as a simple basin-wide cyclonic gyre. After flowed in along the North African coast and lowed out along the Turkish and Greek coasts (Nielsen, 1912). Data collected subsequently by different group and vessels in the late 1950s through to the early 1970s supported this picture of the large-scale circulation (Lacombe and Tchernia, 1972); however during the 1980s, particularly a result of the work of the POEM (Physical Oceanography of the Eastern Mediterranean) programme, it became clear that the current patterns of the Eastern Mediterranean are more complex than this (POEM Group, 1992). Specifically there appear to be a series of persistent sub-basin-scale gyres interconnected by core eddies. Because of the scale of these features, the terms gyre and eddy are often used interchangeably in the Eastern Mediterranean. Some of these features are very persistent, e.g. the cold-core eddy situated southwest of Rhodes (Rhodes gyre) and the warm-core eddies south of Cyprus (Cyprus eddy). Such features can have a major effect on biogeochemical processes occurring within the basin. The structures found in the POEM general surveys are summarized in Table 1.

4.1 SST record and trends in the Levantine Basin

The analysis of the monthly climatology reveals that the SST distribution is low in the period November to April and high in the period June to September and October are the transition months between the two seasonal extremes. Therefore, low pattern characterize the winter dynamics while a high one is typical of the summer season. Similar seasonal SST patterns were observed from the monthly mean SST calculated by satellite images from 1985-1997 by Kabbara et al. (2002) and Marullo et al. (1999) calculated by satellite images for 1987-1991. Furthermore the Levantine Basin SST absolute monthly values appear to be in a good agreement with the average values reported from in situ measurements by Hecht et al. (1998) and Kress and Herut (2001).

A linear regression of the monthly mean satellite SST values, computed over the Levantine Basin in the Eastern Mediterranean Sea sows a significant increase over the seven years considered. A significant general warming trend shows as increase of about 0.6^{o}C in 7 years for the period from 1998 to 2004. Interestingly, a positive trend of the satellite SST values has been revealed in the western Mediterranean Sea (an increase of SST by 0.5^{o}C in 1984-1990) (Santoleri et al., 1994). Similarly, in the Adriatic Basin of the Mediterranean Sea, an apparent general warming trend of about 2^{o}C in 20 years in a time series for 1981-1999 was found by Barale et al., (2004). Moreover, in the black Sea north of the Eastern Mediterranean Sea a positive trend of the means SST of about 1.8^{o}C over the period (1982-2000) was indicated by Ginzburg et al., (2004).

4.2 Mesoscale features in the Levantine Basin

The SST images provided further oceanographic information on surface water structures visible as patterns of temperature distribution. The Sea Surface Temperature satellite imagery clearly shows a series of sub-basin scales and mesoscale consisting of warm and cold eddies. Some of these mesoscale features are very persistent. There are almost no areas of the Basin, which are not part of some mesoscale feature or other. The major Mid Mediterranean Jet (MMJ) and three main features are present: the cold Rhodes gyre east of Crete, the Cretan gyre, the warm Ierapetra Anticyclone southwest of Crete. The Rhodes Gyre is always present and can be defied as permanent. Two further features, listed in order of decreasing permanence, can be nevertheless classified as quasi-permanent, as they appear in the SST monthly and seasonally climatologies: the Ierapetra Anticyclone and the Cretan Cyclone. This resulting picture of the surface circulation is strongly consistent with the in situ observations publicized by the POEM Group (1992). However, one major discrepancy exists between the AVHHR SST dataset and the in situ observational evidence. The Anticyclone Mersa-Matruh Gyre was never observed in any of the monthly climatologies images, whilst this anticyclone was classified as a permanent feature by POEM Group (1992). A possible explanation for the absence of the Mersa-Matrh Gyre warm gyre in the SST images may be because the gyre was embedded in equally warm surrounding waters so that it was no possible to detect the warm signature of this gyre is almost completely surrounded by the cold side of the thermal front associated with the Mid Mediterranean Jet (MMJ).

The thermal front crossing the Levantine Mediterranean Basin is quite evident and is associated with the Mid-Mediterranean Jet. The MMJ is the continuation of the North African Current (Malanotte-Rizzoli et al., 1996b). The thermal front crossing the Eastern Mediterranean is associated with the dynamical signature of the Atlantic-Ionian Stream (AIS) that enters the basin through the Sicily Strait (Figure 8).

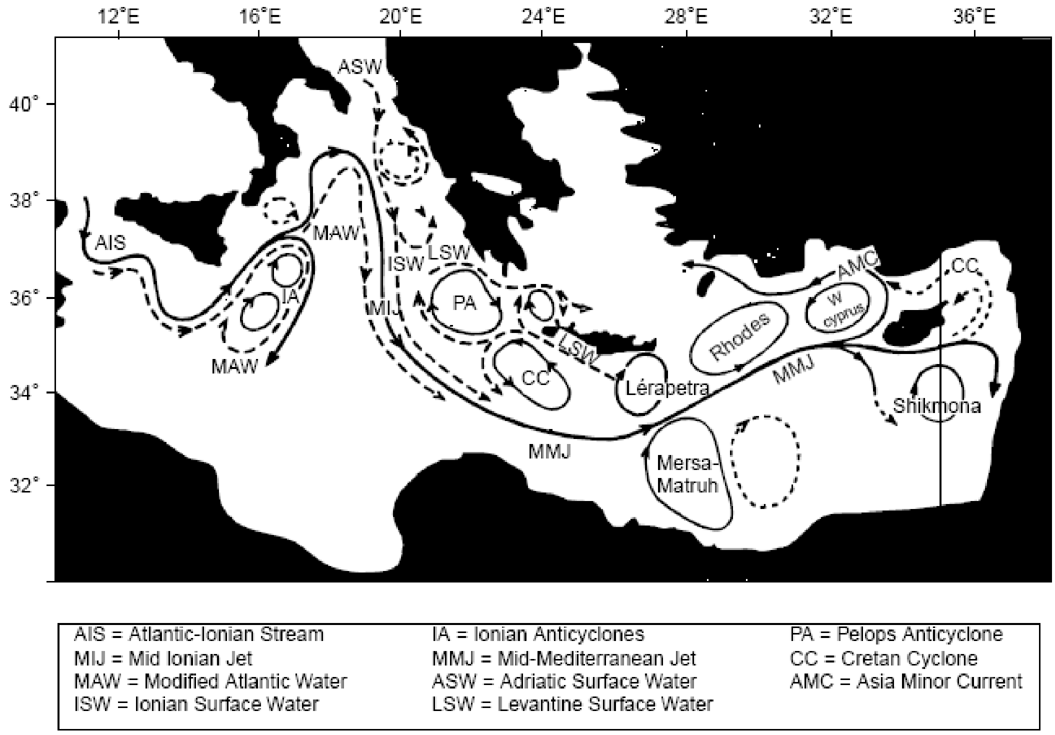

Figure 8. Schematic map of the upper theromcline circulation showing the direction of the Mid Mediterranean Jet and the pattern for the Ionian Sea-Cretan Passage in the Eastern Mediterranean (Malanotte-Rizzoli et al 1996)

The AIS jet follows mainly an eastward path towards the African coast where it becomes the north African current along the Gulf of Sirte, Libya (POEM Group, 1992; Malanotte-Rizzoli, 1994). In the Levantine Basin the front is the constitutes the southern boundary of the Rhodes Gyre (Robinson and Golnaraghi, 1994) and then to west of Cyprus to form the well-defined, semi-permanent Asia Minor and Clinician currents. This picture is quite consistent with both the POEM-Phase 1 observations in the Levantine Sea (POEM Group, 1992) and with modeling simulations (Roussenov et al., 1995; Zavatarelli and Mellor, 1995). The Rhodes Gyre and West Cretan Gyre are cyclonic gyres (Poem Group, 1992); Robinson et al., 1992; Ozsoy et al., 1993) and are fored by anticlockwise water circulation. These are divergent gyres, which tend to draw water up from below the thermocline, this results in an up welling, which results in a decreased temperature of the se surface water an a plentiful supply of nutrients at the surface which should make such areas highly productive. The Ierapetra gyre is anticycloic and formed by clockwise water circulation. This gyre is convergent gyre because the direction of water circulation trends to draw surface water in toward the center and deepen the theromcline due to the convergent tendency of the circulation. In this situation, no new nutrients can come tot eh surface from the deep water and the surface water shows a warm pattern (Lalli and Parsons, 1993; Brown et al., 1994).

5. Conclusion

Two principle objectives have been addressed in this paper. The first was to describe the temporal and spatial patterns of sea surface temperature distributions. The second was to detect and infer major features of the surface circulations. From a seven-year dataset of Advanced Very High Resolution Radiometer-Sea Surface Temperature AVHRR-SST with 1.1km space resolution and monthly frequency during (1998-2004), the following remarks can be made:

- There was evidence of a strong seasonal signal characterized by two main seasonal extremes, winter and summer. The transition between the winter and the summer occurs very rapidly in May and October.

- The monthly mean values showed, a general warming trend appears in the time series of SST data, over the seven years considered. A linear fit, suggesting an increase of about 0.5^{o}C over the years.

- The seasonal and monthly SST distribution is strongly correlated with the dynamical structure of the Basin's upper thermocline circulation. Furthermore, comparison of the SST monthly climatologies with the POEM circulation scheme shows that all the major currents ate the sub-basin gyres are also found consistently in the current images with the only exception of the anticyclone Mersa-Matruh Gyre.

Acknowledgement

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