OnLine Journal of Earth Sciences 1 (4): 180-187, 2007
ISSN: 1991-7708

Seasonal and Inter-Annual Variations of the Sea Surface Circulation in the Central Mediterranean Sea Derived from 11 Years of Topex/Poseidon and ERS-1/2 Data

Jihène Abdennadher and Moncef Boukthir
UR1304, Institut Préparatoire aux Etudes d'Ingénieur de Tunis,
2 rue Jawaher Lel Nehru, 1089 Montfleury, Tunisia

Abstract: Seasonal and inter-annual variations of the surface circulation in the central Mediterranean Sea are examined. Sea level anomaly variations are obtained using 11 years of merged data from two altimeters (TOPEX/Poseidon and ERS-1/2). It is first shown that the surface circulation pattern is characterized by an intense eddy activity. This is supported by high values of eddy kinetic energy, particularly in the Strait of Sicily and in the eastern part of the basin. Moreover, the month-to-month changes of the basin-integrated sea level show a strong seasonal cycle with amplitude of nearly 16 cm month^{-1}. We also observed a substantial inter-annual variation with amplitude of nearly 5 cm year^{-1}. The surface geostrophic current anomalies deduced from the satellite sea level anomaly as well as the total current confirmed the observed high spatial variability of the sea surface circulation and particularly reproduced with some realism the meanders of the Libyan coastal current. Present results confirm the capability of the satellite altimeter data to reproduce the main features of the surface circulation and its ability to measure accurately the variable part of the sea surface topography.

Key words: Sea circulation, satellite, altimeter, scatterometer, current, Mediterranean sea

INTRODUCTION

Available *in situ* oceanographic data are sparsely scattered both in time and space, which, in the past, was an obstacle to the large efforts deployed to understand the world's ocean circulation. Such observations are not sufficient to depict synoptic-ocean variability over the world ocean. In this respect, satellite altimeter has unique capabilities to measure the sea level of the world ocean and therefore produces a global and synoptic view of the oceans. Indeed, satellite altimeter can accurately measure the variable part of the sea surface topography. Synoptic mapping of sea surface height variability is now available, for example, from satellite missions such as TOPEX/POSEIDON, ERS-1/2 and JASON.

Several investigators (Wunsch, 1991; Fu and Pihos, 1994; Chao and Fu, 1995; Larnicol *et al*., 2002) discussed the use of the altimeter data. It is shown that it was possible to employ altimetry to produce global, time varying, large-scale charts of the sea surface topography. Moreover, several studies have already examined the possibility of dynamically transferring information on topographic height into the deep ocean flow (Holland and Malanotte-Rizzoli, 1989; Boukthir *et al*., 1991; De Mey, 1997; Brasseur *et al*., 1999; Boukthir and Abdennadher, 2003). They showed that the reliability of the altimeter data is adequate for constraining the ocean eddy variabilities. Larnicol and Le Traon (1995) described the circulation and mean sea level variations of the Mediterranean Sea from 2 years of TOPEX/POSEIDON altimetric data. Particularly, they succeeded to recover the Mediterranean surface circulation, despite low signal-to-noise ratio (the rms of sea level variability is less than 10 cm).

The variability of the Mediterranean general circulation is mainly inferred from modelling results (Pinardi and Navarra, 1993; Beckers *et al*., 2002) and also from *in situ* observations (Robinson and Golnaraghi, 1994; Millot, 1999; Hamad *et al*., 2004). Although this approach allowed to understand a lot about this circulation, some interrogations remain without convincing answers. One of the main objectives of this study is to examine the seasonal and inter-annual variations of the surface circulation in the central Mediterranean Sea. We focus our attention on the south part of the basin where very little is known about the surface circulation because of the rarity of observations. This study can also be viewed as an attempt to show that the main features of the sea surface circulation and probably new features can emerge from altimeter data

Corresponding Author: Moncef Boukthir, Department de Physique, Institut Préparatoire aux Etudes d'Ingénieur de Tunis, 2 rue Jawaher Lel Nehru, 1089 Montfleury, Tunisia

analysis even in the coastal regions. In this study, we use 11 years of satellite altimeter data provided by TOPEX/Poseidon and ERS-1/2. We believe that continuous coverage provided by satellite altimetry helps to elucidate the transient and/or permanent character of features over the 11 years of the study.

DATA PROCESSING

The satellite altimeter data used are provided by TOPEX/Poseidon (CNES/NASA) and ERS-1/2 (ESA). The record spans the period between 1993 to 2003 and we use the sea level anomaly. Sea level anomaly measurements were obtained by removing the 11-year mean. The second satellite data sets we used are scatterometer winds given by Quikscat. The Seawinds on Quikscat level 3 data set consists of daily gridded values of scalar wind speed, the meridional and zonal components of the wind velocity and the wind speed squared derived from the NASA Quick Scatterometer.

RESULTS

Seasonal variations: Seasons are defined as follows: the winter includes December, January and February; the spring, March, April and May; the summer, June, July and August; and the autumn includes September, October and November. Time mean over the 11 years of the Sea Level Anomaly (SLA, hereinafter) is defined as climatological. The estimates relative to the 3-month spatial averages of the SLA are presented in Fig. 1. Remember that altimetric maps only give the variation relative to the mean circulation. It is important to note that the SLA is negative within the basin in spring and positive in autumn. In particular, SLA varies from -4.5-3.5 cm in winter, from -11 to -4 cm in spring, from -4-3 cm in summer and from 3 to nearly 10 cm in autumn. In winter, two eddies (cyclonic and anticyclonic) develop along the Tunisian eastern coast. In summer the situation reverses completely, showing the cyclonic eddy at the place of the anticyclonic one and vice-versa. However, these eddies disappear in spring and autumn, which means that these structures are not permanent. It is also interesting to note the presence of several cyclonic and anticyclonic structures along the Libyan coasts during the four seasons, which is a signature of the Libyan coastal current already mentioned by previous studies based on *in situ* measurements and numerical simulations.

The climatological seasonal cycle of the basin-averaged SLA (Fig. 2) shows a strong seasonal cycle with amplitude of nearly 16 cm month^{-1}. It varies from -9 cm in March to 7 cm in October-November period. The root-mean-square (rms) of the month-to-month change of SLA is nearly 6 cm, which confirms the high seasonal variability of SLA in the basin. Shown in Fig. 3 is the month-to-month change of the basin-averaged SLA

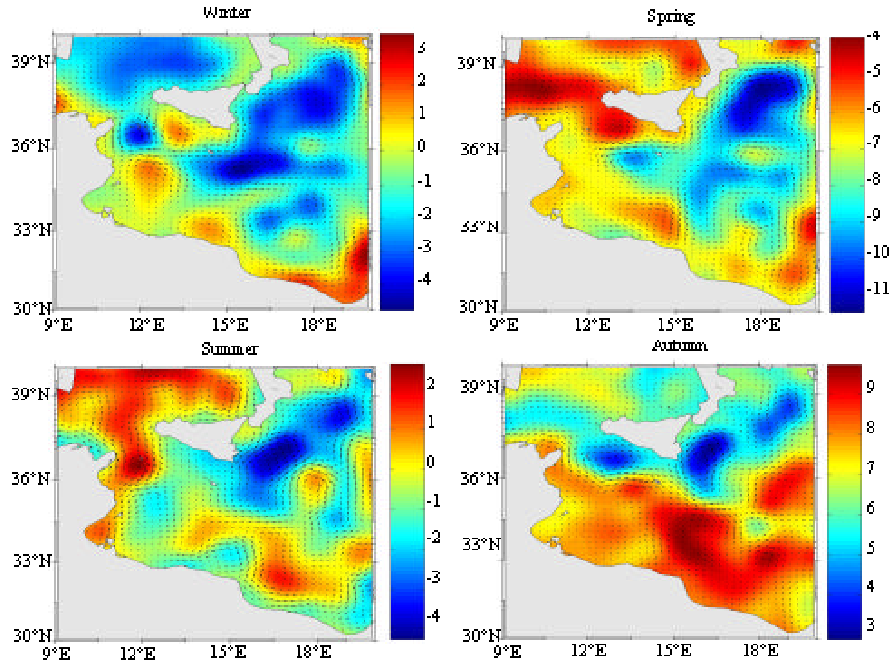

Fig. 1: Distribution of the sea level anomaly (in cm) and the associated geostrophic current anomalies for winter, spring, summer and autumn

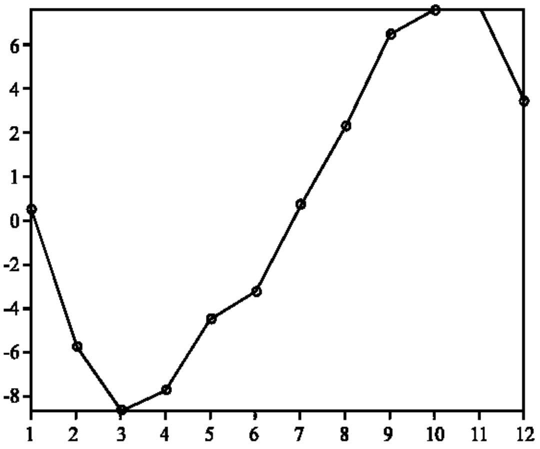

Fig. 2: Climatological seasonal cycle of the basin-averaged sea level anomaly in cm/month

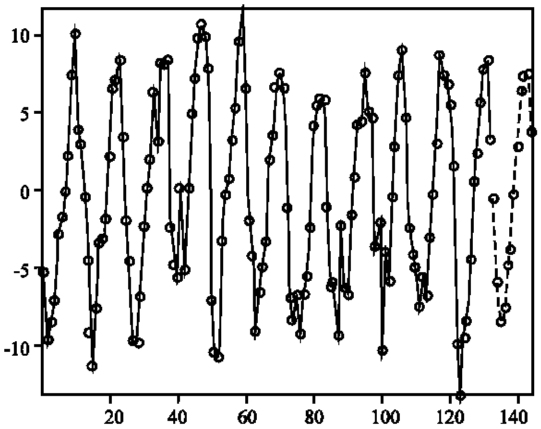

Fig. 3: Month-to-month changes of the basin-averaged sea level anomaly from 1993 to 2003 (in cm/month). The last twelve values (dashed line) correspond to the climatological months

over the 11 years of the analysed data. SLA varies from -13-14 cm month^{-1} and the seasonal cycle changes from one year to the next suggesting an important inter-seasonal variability. This is confirmed by the maps of the SLA where the structures change their shape, location and even intensity.

The EKE (Eddy Kinetic Energy) for four seasons is displayed in Fig. 4. High values of EKE correspond to areas of intense activity. The maximum value of EKE occurs in winter with 40 cm^2 s^{-2} and the weakest one in summer with 17 cm^2 s^{-2}. It clearly appears that the sea surface circulation is intensified in winter, while summer appears to be quiet. Autumn and spring seasons seem to be a transition period. For all seasons, high values of EKE are found in the Strait of Sicily particularly off the Tunisian coasts and also in the eastern basin. The first observed maximum of EKE is probably the signature of the Atlantic current entering the Strait of Sicily and flowing off the Tunisian coasts. The intense activity in the eastern basin was already mentioned in some previous studies using *in situ* measurements and numerical models (Malanotte-Rizzoli and Hecht, 1988; Robinson and Golnaraghi, 1994; Pinardi and Navarra, 1993; Wu and Haines, 1998).

Inter-annual variations: The spatial distribution of the annual mean of SLA (Fig. 5) shows that the major part of the domain is dominated by a sea level low extending from 9°E to 13°E. The rest of the domain is characterized by two maximums, one off the eastern Italian coasts and the second off the Libyan ones. However, a good inspection of Fig. 5 shows some important differences from one year to the next. Indeed, the structures change their shape, location and intensity and can even show a reversed signature with respect to the mean. For example, along the eastern coasts of Italy the SLA is mainly positive from 1993 to 1995 but becomes negative from 1998 to 2000. The same conclusion holds off the African coasts, where the SLA is rather negative from 1993 to 1995 and becomes positive from 1998 to 2000. Thus, we expect the presence of important interannual signals.

The year-to-year change in the basin-averaged SLA shown in Fig. 6 is substantial since it exceeds the climatological mean. SLA shows an inter-annual variation with amplitude of 5 cm year^{-1}. Nevertheless, the rms of the year-to-year change of SLA is about 1.4 cm year^{-1}. The high deviation with respect to the climatology mean occurs in 1997 with 3 cm year^{-1} and in 2000 with -2 cm year^{-1}. Pinardi *et al.* (1994) have simulated the Mediterranean circulation forced by realistic winds and heat fluxes from January 1980 to November 1988 and have show an important interannual variations which are attributed to the atmospheric variability. These variations are found to be the strongest in the eastern Mediterranean, which is in agreement with the spatial distribution of the SLA.

Surface currents: Surface geostrophic current anomalies (u'_g,v'_g) are calculated from the gridded surface altimetric slope anomalies, using the geostrophic approximation:

$$\begin{cases} u'_g = -\dfrac{g}{f}\dfrac{\partial h'}{\partial y} \\ v'_g = \dfrac{g}{f}\dfrac{\partial h'}{\partial x} \end{cases} \quad (1)$$

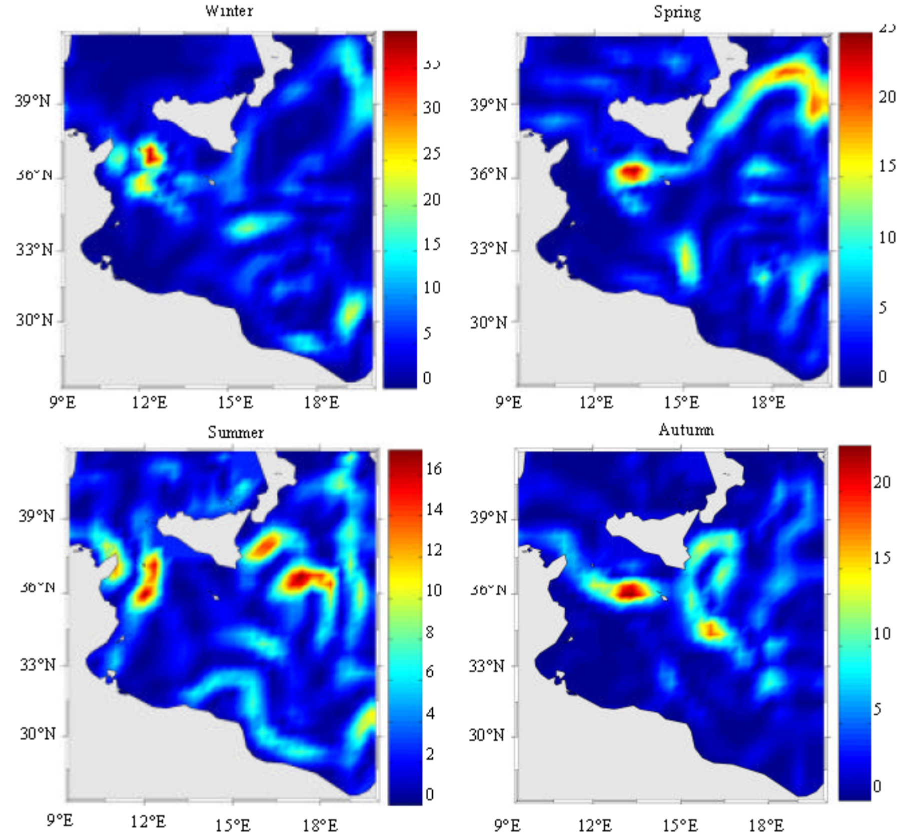

Fig. 4: Eddy kinetic energy (in cm² ⁻s²) for winter, spring, summer and autumn

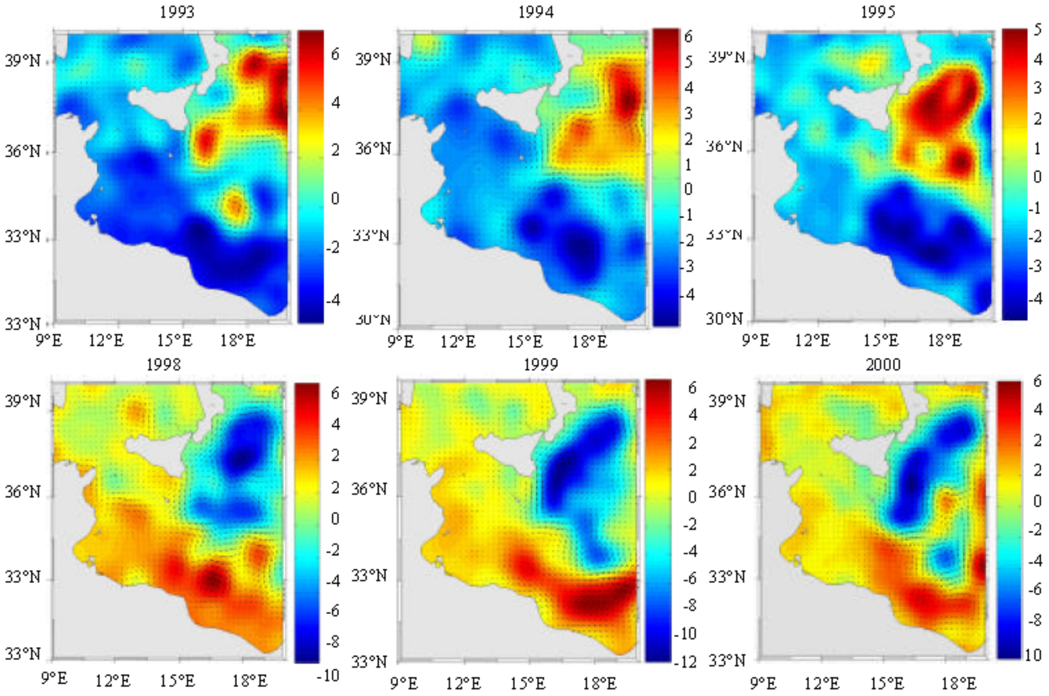

Fig. 5: Annual mean of the sea level anomaly (in cm) and the associated geostrophic current anomalies

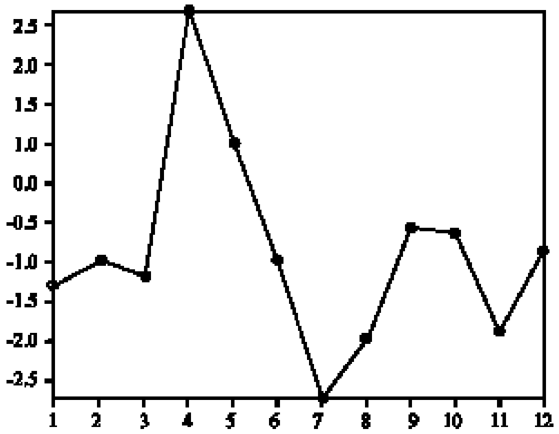

Fig. 6: Annual mean of the sea level anomaly (in cm/year) for each individual year. The year-twelve corresponds to the climatology

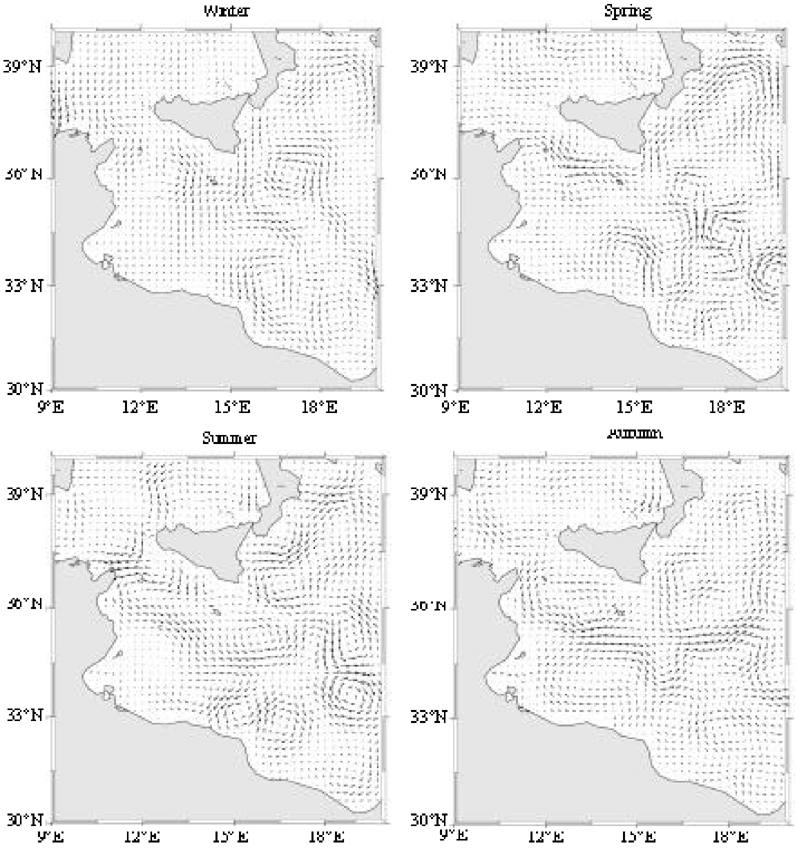

Fig. 7: Total current for winter, spring, summer and autumn

In the above equations a coordinate system with x positive eastward and y positive northward is used. Let u'_g and v'_g be the zonal and meridional velocities, h' is the sea level anomaly, g is the gravity acceleration and f is the Coriolis parameter.

Shown in Fig. 1 are the surface geostrophic current anomalies for winter, spring, summer and autumn. The strongest current which is about 28 cm s^{-1} occurs in winter. The surface circulation is characterised by many eddies whose intensity and size vary from one season to another. In the north of the Strait of Sicily, there is a permanent eddy since it is present during the four seasons. However, it is cyclonic during autumn-winter seasons and becomes anticyclonic in spring and summer. In the Gulf of Hammamet, we found a permanent cyclonic eddy. Another important feature of the surface circulation is the presence of an anticyclonic eddy along the Libyan coasts.

The total current ($\vec{u}_t$) is the sum of the gridded altimetric geotrophic current ($\vec{u}'_g$), the mean surface current ($\vec{u}_E$) and the Ekman current at 15 m depth ($\vec{\bar{u}}$):

$$\vec{u}_t = \vec{\bar{u}} + \vec{u}'_g + \vec{u}_E \tag{3}$$

Van Meurs and Niiler (1997) and Lagerloef *et al.* (1999) propose a regression model between the Ekman currents at 15 m depth (u_E,v_E) and the surface wind stress (τ_x, τ_y). Outside the equatorial band, they propose a two-parameter model:

$$u_E + iv_E = \frac{\beta}{\rho} e^{i\theta} \left[\tau_x + i\tau_y \right] \tag{4}$$

Where, the amplitude $\beta \sim 0.3$ m s^{-1} and θ is the turning angle relative to the wind direction : 60° to the right (left) of the wind in the northern (southern) hemisphere at 15 m depth.

The resulting Ekman currents at 15 m depth (u_E, v_E) are:

$$\begin{cases} u_E = \frac{\beta}{\rho} e^{i\theta} \left[\tau_x \cos\theta - \tau_y \sin\theta \right] \\ v_E = \frac{\beta}{\rho} e^{i\theta} \left[\tau_x \sin\theta + \tau_y \cos\theta \right] \end{cases} \tag{5}$$

Ekman currents were computed using scatterometer winds given by Quikscat. Their spatial distributions for 4 seasons showed that the strongest was in winter with a maximum of 9 cm s^{-1}, the weakest is about 3 cm s^{-1} in summer. The Ekman currents in winter season, compared to spring are reversed and they flow southward.

Mean surface currents $\vec{\bar{u}}$ were calculated from the Rio and Hernandez (2004) mean sea surface topography based on available *in situ* data over the upper 700 m. This is comparable to a steric height calculation relative to a chosen reference level at 700 m. Sudre and Morrow (2005) have already used this approach to estimate the total currents in the Agulhas Region. They particularly reproduced the main structures of the Agulhas current with their meanders and instabilities. The spatial distributions of the total current (Fig. 7) for 4 seasons showed that the strongest is in winter with a maximum of 32 cm s^{-1}, the weakest is about 18 cm s^{-1} in summer. The surface circulation is characterised by an intense eddy activity. However, the intensity and size of these eddies vary from one season to another, indicating a strong seasonal cycle.

An important feature of the surface circulation in the eastern basin is the presence of some cyclonic and anticyclonic gyres. A big gyre, in the eastern Italian coast, contributes to and forms a strong SW current, exceeding 20 cm s^{-1} in velocity and almost 150 km in width. In the south, we observe some cyclonic and anticyclonic gyres, probably the signature of the Libyan current with its meanders and instabilities.

The determination of the total current allows not only to depict the spatial and temporal characteristics of the surface circulation but also to validate the results deduced from numerous numerical simulations. In addition, theses currents can be assimilated in the numerical models in order to constrain their solutions.

CONCLUSION

Eleven years of combined maps of TOPEX/Poseidon and ERS-1/2 altimeter data are used to investigate the seasonal and inter-annual variations of the surface circulation in the central Mediterranean Sea. Several mesoscale structures develop in the Strait of Sicily and the adjacent areas. The temporal analysis of the sea level anomaly has shown that the surface circulation is characterized by a strong seasonal cycle with amplitude of nearly 16 cm/month. The distribution of the EKE confirmed the intensification of the sea surface circulation in winter. We also observed an important inter-seasonal variation. Moreover, the spatial distribution of the SLA within the basin shows that the surface circulation is quite different from one year to the next. Indeed, the structures change their shape, location and intensity and can even show a reversed signature with respect to the mean. Thus, we expect the presence of interannual signals. These results are very interesting and must be taken into account, particularly when we analyse *in situ* measurements. Indeed, it is well known that having a long time series of *in situ* measurements is not only a very difficult task but also a very expensive operation. Thus, the analysis of the *in situ* measurements must be done with caution, in particular for time series shorter than one year. Of course, to better enhance our knowledge of the dynamical processes, we need much longer time series to take into consideration the inter-annual variations. In this regard, the altimeter data can be very helpful for analysing the *in situ* measurements since the altimeter data are now available for more than 15 years.

Surface geostrophic current anomalies are computed from the surface altimetric slope anomalies, using the geostrophic approximation. They particularly confirmed the observed high spatial variability of the sea surface circulation. This result is very encouraging for reconstructing the total current which is the sum of the geostrophic current anomalies, the mean current and the Ekman current. The computed total current reproduces with some realism the meanders of the Libyan current. The available long time series of satellites data in addition to their high spatial coverage make now possible a monitoring of the main eddies in the eastern Mediterranean Sea, which was not possible from *in situ* measurements.

A reasonable agreement between the results deduced from satellite altimeter data and those from *in situ* measurements and models illustrates the improved accuracy of TOPEX/Poseidon and ERS-1/2 data and confirms the capability of the satellite altimeter data to reproduce the main features of the surface circulation and its ability to measure accurately the variable part of the sea surface topography. The use of merging SLA from different altimeters, which provides a much denser coverage, improves our knowledge of the sea surface circulation.

ACKNOWLEDGEMENT

This study was supported by Ministère de l'Enseignement Supérieur, de la Recherche Scientifique et de la Technologie through l'Unité de Recherche UR1304. The altimeter products have been produced by the CLS Space Oceanography Division as part of the European Union's Environment and Climate project AGORA (ENV4-CT9560113) and DUACS (ENV4-CT96-0357) with financial support from the CEO programme (Centre for Earth Observation) and Midi-Pyrenees regional council. CD ROMS are produced by the AVISO/Altimetry operations center.

REFERENCES

Beckers *et al*., 2002. Model intercomparison in the Mediterranean: MEDMEX simulations of the seasonal cycle. J. Marine Sys., 33-34, 215-251.

Boukthir, M., J. Verron and B. Barnier, 1991. On the use of satellite data in a general circulation model: Altimeter and scatterometer data. Oceanol. Acta, 15: 507-523.

Boukthir, M. and J. Abdennadher, 2003. Impact of the objective analysis on the assimilation of satellite altimetric data into ocean model. Geophys. J., 24: 67-76.

Brasseur, P., J. Ballabrera-Poy and J. Verron, 1999. Assimilation of altimetric data in the mid-latitude oceans using the singular evolutive extended Kalman filter with an eddy-resolving primitive equation model. J. Mar. Sys., 22: 269-294.

Chao, Y. and L.L. Fu, 1995. A comparison between the Topex/Poseidon data and a global ocean general circulation model during 1992-1993. J. Geophys. Res., 100: 965-976.

De Mey, P., 1997. Data assimilation at the oceanic mesoscale: A review. J. Meteor. Soc. Jap., 75: 415-427.

Fu, L.L. and G. Pihos, 1994. Determining the response of sea level to atmospheric pressure forcing using TOPEX/POSEIDON data. J. Geophys. Res., 99: 24, 633-24, 642.

Holland, W.R. and P. Malanotte-Rizzoli, 1989. Altimeter data assimilation into ocean model. J. Phys. Oceanogr., 19: 1507-1534.

Hamad, N., C. Millot and I. Taupier-Letage, 2004. The surface circulation in the eastern basin of the Mediterranean Sea: New elements. Progress Oceanogr., 44: 65-78.

Lagerloef, G.S.E., G.T. Mitchum, R.B. Lukas and P.P. Niiler, 1999. Tropical Pacific near-surface currents estimated from altimeter, wind and drifter data. J. Geophys. Res., 104: 22313-22326.

Larnicol, G. and P.Y. Le Traon, 1995. Mean sea level and surface circulation variability of the Mediterranean Sea from 2 years of Topex/Poseidon altimetry. J. Geophys. Res., 100: 163-177.

Larnicol, G., N. Ayoub and P.Y. Le Traon, 2002. Major changes in Mediterranean Sea level variability from 7 years of Topex/Poseidon and ERS-1/2 data. J. Mar. Sys., pp: 33-34, 63-89.

Malanotte-Rizzoli, P. and A. Hecht, 1988. Large-scale properties of the eastern Mediterranean: A review. Oceanol. Acta, 11: 323-335.

Millot, C., 1999. Circulation in the western Mediterranean Sea. J. Mar. Sys., 20: 423-442.

Pinardi, N. and A. Navarra, 1993. Baroclinic wind adjustment processes in the Mediterranean Sea. Deep Sea Res. II, 40: 1299-1326.

Rio, M.H. and F. Hernandez, 2004. A mean dynamic topography computed over the world ocean from altimetry, in situ measurements and a geoid model. J. Geophys. Res., 109: 10.1029/2003JC002226.

Sudre, J. and R. Morrow, 2005. Global surface currents from gridded satellite data fields. European Geophysics Sciences colloquium, Vienne.

Robinson, A.R. and M. Golnaraghi, 1994. The Physical and Dynamical Oceanography of the Mediterranean Sea. In: Ocean Processes in Climate Dynamics. Global and Mediterranean examples. Malanotte-Rizzoli and A. Robinson (Edn.). Kluwer Acad., Norwell, Mass, pp: 255-306.

Van Meurs, P. and P.P. Niiler, 1997. Temporal variability of the large-scale geostrophic surface velocity in the northeast Pacific. J. Phys. Oceanogr., 27: 2288-2297.

Verron, J., 1990. Altimeter data assimilation into ocean model: sensitivity to orbital parameters. J. Geophys. Res., 95: 443-459.

Wu, P. and K. Haines, 1998. The general circulation of the Mediterranean Sea from a 100-year simulation. J. Geophys. Res., 103: 1121-1135.

Wunsch, C., 1991. Global-scale sea surface variability from combined altimetric and tide gauge measurements, J. Geophys. Res., 10: 1-49.