A Combined use of ERS-1 and TOPEX/POSEIDON data to study the mesoscale dynamics in the Mediterranean Sea

Salvatore Marullo	Centro Ricerche Casaccia, ENEA, Rome, Italy Via Anguillarese, 301, 00060 S. Maria di Galeria, Rome, Italy salva canaletto.ifa.rm.cnr.it
Simona Zoffoli	Istituto di Fisica dell'Atmosfera, CNR, P.le L. Sturzo 31, 00144 Roma, Italy simona oceano.ifa.rm.cnr.it
Rosalia Santoleri	Istituto di Fisica dell'Atmosfera, CNR, P.le L. Sturzo 31, 00144 Roma, Italy lia oceano.ifa.rm.cnr.it
Daniele Iudicone	Istituto di Fisica dell'Atmosfera, CNR, P.le L. Sturzo 31, 00144 Roma, Italy daniele oceano.ifa.rm.cnr.it
Bruno Buongiorno Nardelli	Istituto di Fisica dell'Atmosfera, CNR, P.le L. Sturzo 31, 00144 Roma, Italy bruno oceano.ifa.rm.cnr.it

Abstract

TOPEX/Poseidon and ERS-1 altimeter data have successfully been used to study the mesoscale field in the Mediterranean Sea and to investigate the seasonal variability of the Sea Level and eddy statistics in this basin. The comparison between the two altimiter performance is very good and underline importance to combine the information of TOPEX/Poseidon and ERS-1 to study the Mediterranean mesoscale eddy field. Sea level anomalies maps every five days were produced using the both data sets by means of sub-optimal interpolation. A comparison between mesoscale features detected by the two altimeters and contemporaneous features observed using Sea Surface Temperature maps definitively proves the direct relation between sea level anomalies and the Mediterranean eddy field.

Keywords: Mediterranean, altimeter, TOPEX/POSEIDON, ERS-1, mesoscale, SST.

Introduction

Earth observing satellites are providing a significant quantity of high quality synoptic data for the investigation of oceanographic phenomena on spatial and temporal scales unattainable with in situ measurements. Satellite altimeter provides a direct measurement of the sea surface slope associated with the geostrophic current variability. Altimeter data have already proved to be able to resolve sea surface variability in regions corresponding to the major western boundary currents (Gulf Stream, Kuroshio, Malvinas and Angulhas) and the Antarctic Circumpolar Current. On the contrary very few works have been done on studies of ocean areas characterized by small sea level slopes or on small semi-enclosed seas like the Mediterranean. This lack of research effort could be probably due to the poor precision of radar altimeters operating before ERS-1 and TOPEX/POSEIDON.

In this paper we examine the sea level variability of the Mediterranean Sea during the year in which the T/P and ERS-1 oceanographic missions were operated contemporaneously. The paper is organized as follows. Section 2 describes the data processing. Section 3 deals with sea level observed combining T/P and ERS-1 data. The Algerian Basin dynamics is analyzed in section 4 looking to the Sea Level Anomalies (SLA) maps resulting from the merging of T/P and ERS-1 data and to some particularly interesting tracks that cross the basin. The results are summarized in the conclusions.

The main goal of this work is to verify if T/P and ERS-1 concurrent measurements are compatible and can be merged to describe the sub-basin and mesoscale dynamic features of the Mediterranean circulation and to compare the resulting picture of the surface circulation against observational evidence.

There are many reasons that suggest the concurrent use of the two data-sets. First of all the two satellites have a significantly different repeat period. The ERS-1 repeat period is 35 days, for its oceanographic phase, while T/P has an high frequency repeat cycle (about 10 days). Consequently the separation between sub-satellite ERS-1 track (65 Km at 38° lat) is more proper to couch the Mediterranean mesoscale features, that are characterized by a space scale of 30-100 km. On the other hand the size of Mediterranean Sea although relatively small is sufficient so that circulation may be governed by large scale ocean dynamics, that can be studied using T/P altimeter.

The analysis of altimeter data of the Mediterranean can be useful to study the variability of the Mediterranean circulation on the global scale and identify its main characteristics. Recently Larnicol et al. (1995) and Iudicone et al.(1997) have analyzed T/P data over the Mediterranean and found that most of the large scale structure of the circulation have a signature on T/P data.

Altimeter data processing

Three years of T/P altimeter data over the Mediterranean Sea, starting from October 12, 1992 (i.e. from cycle 3 to 112), were processed for this study.

Data were initially edited based on quality flags and parameter ranges as recommended in the user handbook (AVISO, 1992). The following corrections were applied to both TOPEX and POSEIDON data: water vapor from the on-board radiometer, TOPEX dual-frequency ionospheric correction, dry troposphere, inverted barometer, electromagnetic bias, center of gravity, solid Earth tide, pole tide, and net instrument correction. The ocean tide model suggested by the user handbook for the Mediterranean Sea (Canceil et al., 1994) was used to subtract the main ocean tide constituents. Finally the JGM-2 precise orbit was subtracted. In order to evaluate the mean sea level, altimeter passes were interpolated to a fixed grid defined by each first satellite track free of gaps. The resulting mean grid size was approximately 6 km. Interpolated altimeter data were used to compute a mean sea level that was subtracted from each single altimeter pass obtaining SLA data.

On the contrary, high-level altimeter data processed by the CLS Space Oceanography Group from CERSAT OPRs have been used for ERS-1 (AVISO, 1995). The CLS data processing consists in a preliminary quality control, validation and application of instrumental and geophysical corrections and a precise orbit correction. Orbits errors have been estimated by a global minimization of T/P and ERS-1 crossover differences, providing orbits with accuracy similar to T/P orbits. SLA are finally calculated, after a resampling every 7 km, using repeat-track analysis. We extract the SLA relative to the Mediterranean Basin to this data-set.

The following data processing was applied to both T/P and ERS-1 SLA.

Due to the very low sea level signal of oceanographic features in the Mediterranean Sea, a particular attention has been paid to the outliers detection phase. Following Iudicone et al. (1996) the objective analysis estimates was used to discriminate the outliers. The objective analysis method for outliers detection, even if rather time consuming, worked extremely well in all the cases. A visual inspection of data samples confirmed that the algorithm is really able to individuate the same outliers that a "manual editor" would individuate but definitively more quickly (and more objectively).

Finally, bias has been subtracted from each track in order to separate the variability, due to steric effects induced by seasonal warming, and seasonal variations, due to large scale quasi-stationary currents, from mesoscale variability. The removal of bias, even if not strictly necessary owing to precise orbit determination, also contributed to remove the relative bias found between TOPEX and POSEIDON altimeters (Nerem et al., 1994) and to eliminate bias due to the occasion features of inverse barometric corrections (Larnicol et al., 1995).

The SLA were used to compute sea level variability (SLV) and eddy kinetic energy (EKE) maps of the entire Mediterranean. The maps were obtained by binning the data on a .5°x.5° grid and then applying an objective analysis algorithm. The used covariance function computed directly from the data is:

$$f(x) = a_1 e^{-(x/b_1)^2} + a_2 e^{-(x/b_2)^2}$$

where a1=0.825, a2=0.175, b1=90 km, b2=20 km and x is the distance.

The results presented in the following have been deduced by the analysis of one year of data starting from November 10 1992 (i.e. from cycle 7) for ERS-1 and from November 21 1992 (i.e. from cycle 7) for T/P.

The objective analysis method (following Larnicol et al., 1995) was used to merge ERS-1 and T/P data and SLA optimal maps every 5 days was computed.

Variability of the dynamic ocean topography

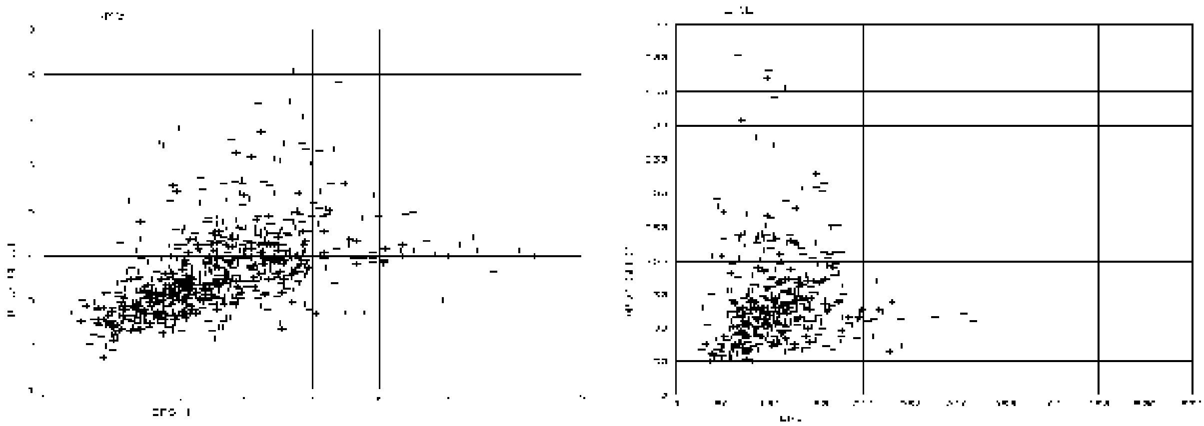

Figure 1:Scatter-plots of the SLV and EKE for T/p e ERS-1 data.

To compare quantitatively the performance of two altimeter data sets, the SLV and EKE maps from ERS-1 and T/P data were computed separately. The resulting scatter-plots are shown in fig. 1. The two SLV data-sets present a practically zero Mean Bias Error (MBE) and also the Root Mean Square Error (RMS) is very small (less than 1 cm). On the contrary, T/P EKE values are generally above the ERS-1 ones (MBE=28 cm2/s2). Consequently, the SLV shows a high degree of coherence while the EKE is much more scattered. The main reason is to ascribed to the characteristics of the Mediterranean mesoscale features that have time scale between 10 days to 3-4 months, a space scale of 30-100 km and are mainly due to instability of the coastal jets. Consequently, the low sampling time of ERS-1, combined with the discard of coastal data applied by CLS in ERS-1 data processing, results in the observed difference between the two altimeter results. Moreover the more accurate T/P mean sea level can also contribute. The results of this intercomparison indicate that the merging of the two altimeters measurements is possible.

The SLV map obtained using the two data sets is showed in figure 2. The SLV ranges from a minimum value of 1-2 cm, located in the area south of Cyprus, in several small cells in the Ionian Sea and in the area offshore the Gulf of Lyon, and maximum values of 5-8 cm in the areas of the Rhode Gyre and in the Algerian Basin for T/P. There are also maxima in the Tyrrhenian, in the Alboran sea and in the Adriatic Sea. The pattern of the contour lines clearly reveals the major structures of the Mediterranean circulation and the description is more accurate and realistic respect on the map obtained with T/P data alone (not shown).

In the Alboran sea, the high activity, in the SLV map, may be related to the presence of the Alboran gyre system while at its eastern margin there is a clear indication of the presence of the Almeria-Oran front. More east, the line connecting the Spain coast to the African coast should essentially be due to the return flow of the surface MAW.

High values of SLV can be found in the Algerian Basin, where eddies, characterized by a diameter of approximately 100 Km, are known to be formed and to move northward (Millot, 1991). The SLV reaches its maximum along the African coast. This particular area will be more closely discussed later taking into account the variability of the along track SLA and the combined maps of the two altimeter.

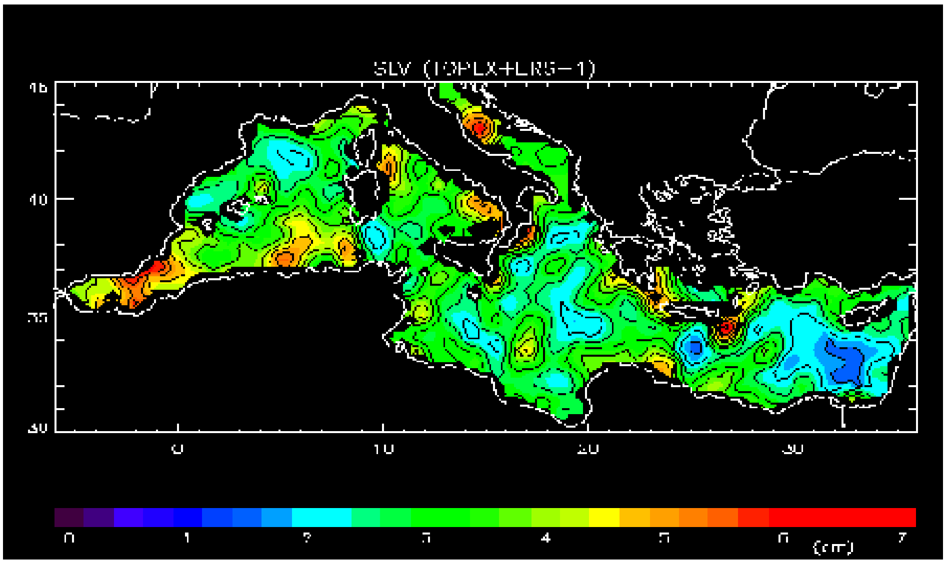

Figure 2: Combined T/P and ERS-2 SLV of SLA

The area of the gulf of Lyon is characterized by a minimum in SLV (1-2 cm). It is due to the Liguro-Provencal current and to a local cyclonic circulation which are known to be permanent.

In the Tyrrhenian basin two distinct area of high variability are visible. The north-west area is located off the Sardinian coast and is related to the variability of the North Tyrrhenian Eddy and the Tyrrhenian anticyclone. These cyclonic and anti-cyclonic gyres undergo significant seasonal changes that cause a strong variability in intensity orientation and location (Marullo et al., 1994). On the contrary, the large values in SLV map in the south-east Tyrrhenian are reached near the coast in an area characterized by very low dynamics. This large value of variability can be ascribed either to tidal correction error or to steric effect. In fact, SST maps and climatological data reveal a quite evident summer warming of sea water temperature in this area.

In the Levantine Basin the area around Crete displays a complex pattern. South-east of the island the SLV reaches the highest values of the entire Mediterranean (over 7 cm). These high values are clearly due to the variability in shape, in strength and location of gyres, which are a characteristic of this part of the Basin: the cyclonic Rhode Gyre and the Iera Petra Anticyclone. A low value of all the parameters characterize almost all the rest of the basin, comprised the area of the Rhode gyre, suggesting a low variability of its core.

This map underlines how is important the ERS-1 contribute to describe the mesoscale field between the T/P ground-tracks. On the contrary ERS-1 contribution has no effect underneath T/P tracks where T/P data are preferably and mainly selected because of their greater accuracy and higher repetitivity.

The Algerian Basin

The Algerian basic dynamic was investigated using both altimeter and AVHRR data. The objective SLA maps were computed every 5 days (see $2) and compared to the cloudy free AVHRR images corresponding to altimeter passage. Moreover a comparison between altimetric signal and SST field has been done superimposing along track sea level anomalies and corresponding residual geostrophic velocities to the images. This allows to better understand links between SLA derived from T/P and ERS-1 data and dynamical features of the Mediterranean circulation.

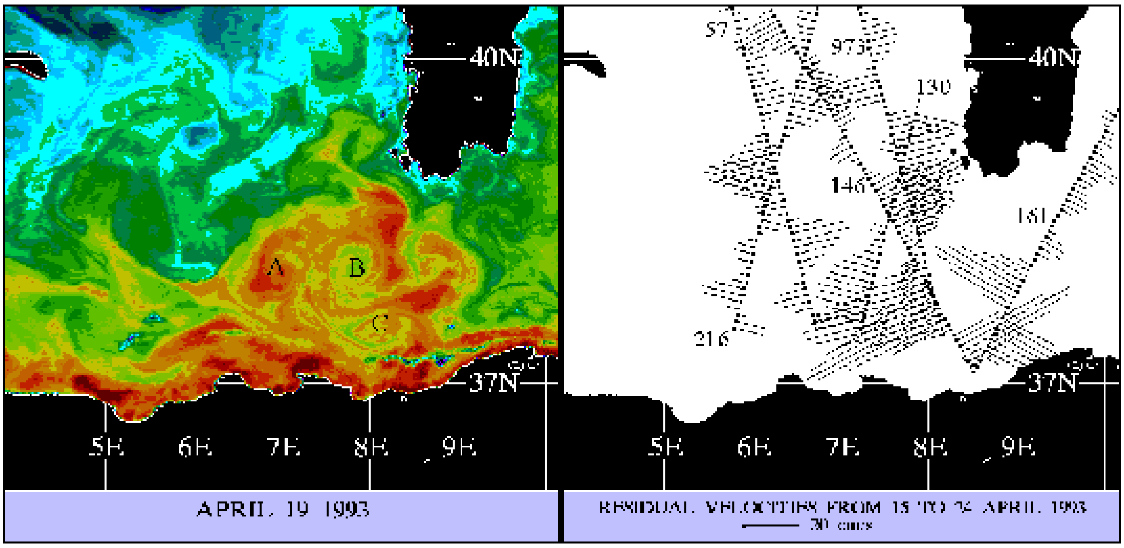

Figure 3: AVHRR image of April 19, 1993 (Ch., 4, NOAA 11)(on the left). Vectors for the estimated geostrophic velocity orthogonal to the ERS-1 and T/P tracks (on the right).

In Fig.3 (NOAA-AVHRR image of 19 April 1993)we show the most representative example of this comparison. The track analyzed are the 146 and 161 (cycle 21,15 April) from T/P and the 973 (15 April), the 57 (18 April), the 130 (21 April) and the 216 (24 April), all during cycle 11 of ERS-1. In April, the Algerian basin images reveal the appearance of a very complex feature in the south-eastern part of the basin. The image of 19 April 1993 shows an organized structure covering the area between 6.5° E - 8.5° E and 37.2° N - 38.5° N (fig. 3). This area is delimited south by the African coast and east by the rising of bottom topography in the Sardinian channel. This structure seems strictly connected with the eastward flowing Algerian Current, constituted by MAW. It has the shape of three highly convoluted spiral eddies, two of them zonally aligned (A centered at 38.0°N 7.0°E and B centered at 38.1°N 7.9°E respectively) and the third one (C centered in 37.5°N 8.1°E) located South-East of the first two. The eddies have an almost uniform SST of 14.7°C with some colder patches of entrained water. Their mean radius is about 30 km, even if A and C are elliptical. Their spiraling shapes suggest a cyclonic circulation for A and C and an anti-cyclonic circulation for B. The system appears as two coupled mushrooms sharing the middle eddy (B). East of this structure, the eastward MAW flux seems to be limited to a narrow band close the coast.

SLA along T/P track 146 shows a minimum of ~12 cm in correspondence of the C eddy and a maximum of 14 cm for the B one (see fig 4 for the SLA profile and fig.3 for the ground-tracks). The same characteristic is also detected in the SLA along ERS-1 track 973, that has a maximum of 18 cm in correspondence of the B core. The top of the anticyclonic doming have not a regular shape. This could be the result of the entertainment of outer water, as seen in the image. Along the T/P 146 and ERS-1 973 tracks the maximum velocity is between B and C suggesting a westward jet-like flow of ~ 50 cm/s. The idea of the westward flux is validated also from the analysis of velocity along the others westward ERS-1tracks. In particular they suggest that the flux follows the semi-circular structure westward of the tripole. The velocity along ERS-1 130 track, that pass between the two structure A and B, is slower than 973. This could suggests a northward direction of the velocity field in this area, as seems from SST map. No one track give us information on the versus of rotation of A, while they indicate an cyclonic circulation of the tripole. The T/P 161 track is important to characterize the eastward boundary of the structure , the only velocity truly different from zero is near the African coast. It is remarkable that ERS-1 57 and 216 tracks contribute to describe a zone where T/P do not give any information. SLA along these tracks (fig.4) show a maximum near the zone of the core displaced at 39.1 N and 9.3 E. The velocity , about 30 cm/s, reveals that the zone is interested by an anticyclonic circulation with an odd cold core.

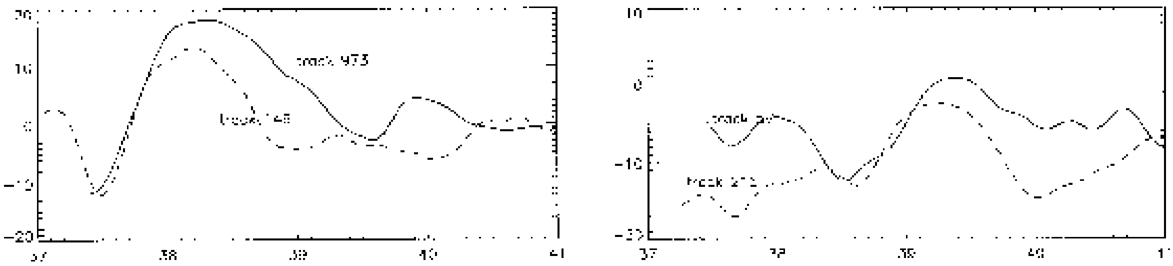

Figure 4: SLA along T/P and ERS-1 ground tracks

The analysis of the combined T/P and ERS-1 SLA maps reveal a strong mesoscale activity associated to the formation of large meanders and eddies due to the instability of the Algerian current. This phenomenon is persistent all along the year. The SLA intensity is higher in winter than in summer reaching values greater then 15 cm from January to April. The analysis of the SLA maps shows an anticyclonic structure south-west of Sardinia locatized at 8°E at end of March (fig. 5). The intensity and shape of this eddy increases with time reaching their maximum between 8-19 April. The pattern of this maps is very similar to the SST field observed in the AVHRR images. In particular the eddy B and C are clearly recognizable in the 19 April map while eddy A is visible on the 14 April map.

The study of the time evolution of SLA (not shown) field clearly shows a migration of the mesoscale features that from the Algerian current moves northwestward with a velocity of approximately 3 km/day until they reach 39 ° N were they lose their energy and slowly disappear.

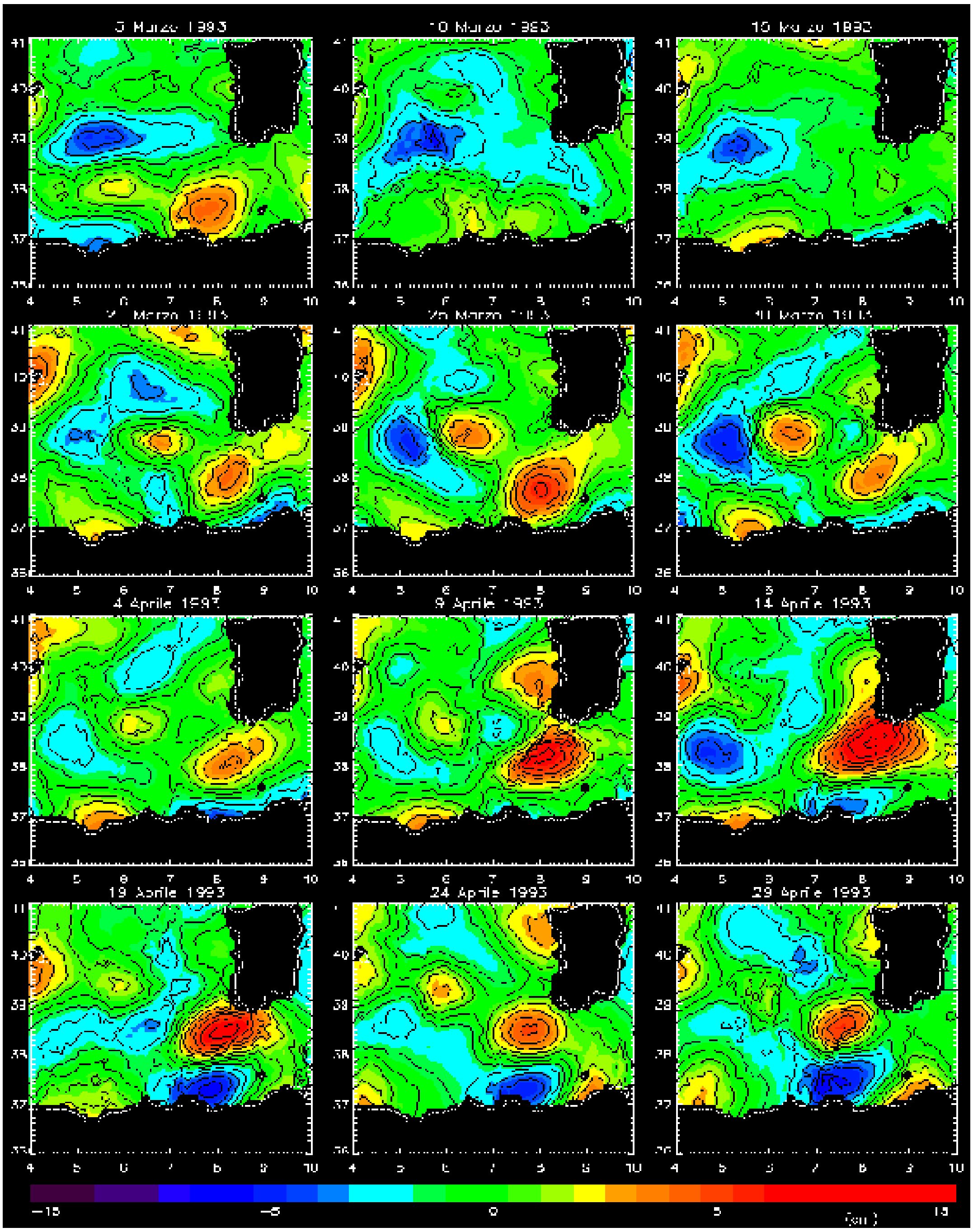

Figure 5: Combined T/P and ERS-1 SLA during March and April, 1993.

Conclusions

In this paper we compared the results of the T/P and ERS-1 altimeter measurements over the Mediterranean. The year in which both satellite were acquiring data simultaneously were analyzed and combined to study the sea level variability of the Mediterranean Sea. The analysis of the SLV map obtained using both satellite clearly reveals the main structures of the Mediterranean circulation and points out two areas of strong sea level signal in the eastern part of Algerian basin and south east of Crete Island.

The inter comparison between the two data-sets is quite good, the mean bias error between the two SLV maps is 0.1 cm indicating that the merging of the two altimeters measurements is possible. The SLV map obtained using the two altimetric data sets underlines how is important the ERS-1 contribute to have knowledge on the mesoscale field between the T/P groundtracks. On the contrary, in corrispondence of T/P ground tracks due to the major accuracy and the elevate repeat cycle of this satellite, the contribution of ERS-1 data is not evident.

The objective analysis method was used to merge the two data sets and SLA maps of entire Mediterranean, and in particular of the Algerian basin, were produced.

The comparison between SLA and AVHRR data relative to 1993 was made to better understand which particular dynamic structure is responsible for the observed altimeter signal. This combined analysis allowed also to integrate two-dimensional horizontal information provided by AVHRR with the one-dimensional vertical view offered by the altimeter. This work successfully demonstrated the capability of T/P and ERS-1 to correctly detect dynamical information over the Mediterranean Sea even if the signal to noise ratio is relatively low.

Moreover, this comparison gives us the opportunity to understand that the intensification of the SLV in the Algerian basin in winter is due to the occurrence of a complex structure of interacting mesoscale eddies appearing in April. The analysis of the residual geostrophic velocity along the ground tracks of both satellite give us the opportunity to have information on the velocity field connected to this complex structures and to identify without error the rotational versus of the complex structure and its interactive eddies. This information is essential to identify the physical process of its formation.

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