

ГОДИШНИК НА СОФИЙСКИЯ УНИВЕРСИТЕТ „СВ. КЛИМЕНТ ОХРИДСКИ“  
ФИЗИЧЕСКИ ФАКУЛТЕТ

Том 108

ANNUAL OF SOFIA UNIVERSITY “ST. KLIMENT OHRIDSKI”  
FACULTY OF PHYSICS

Volume 108

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EOF ANALYSIS OF BLACK SEA SURFACE HEIGHT  
ANOMALY USING ALTIMETER DATA

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*Милена Миланова, Елисавета Пенева.* АНАЛИЗ С ЕОФ НА АНОМАЛИЯТА НА СВОБОДНАТА ПОВЪРХНОСТ НА ЧЕРНО МОРЕ, ИЗПОЛЗВАЙКИ АЛТИМЕТРИЧНИ ДАННИ

Основните елементи на изменчивостта на свободната повърхност на Черно море са изследвани чрез алтиметрични данни от архива AVISO. Продуктът SALTO/DUAC на AVISO е компилация на измервания от няколко алтиметрични мисии и дава аномалиите на морската повърхност с пространствена резолюция  $1/8^\circ \times 1/8^\circ$  (приблизително 10 km) и времева резолюция от 1 седмица. Извършеният анализ с ЕОФ показва, че главната изменчивост (78%) е свързана с пресноводния баланс на морето и стеричните ефекти. Следващите по значение компоненти отразяват влиянието на сезонното усилване на главното течение и еволюцията на квазистационарните вихри.

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The near-real time data from AVISO archive are used to identify the principle components in the variability of the Black sea surface height. The AVISO product SSALTO/DUAC compiles measurements of several altimeter missions and gives the sea level anomalies with spatial resolution of  $1/8^\circ \times 1/8^\circ$  degrees (approximately  $\sim 10$  km) and temporal resolution of 1 week. The performed EOF analysis indicates that the main variability (78%) is related to the fresh water input in the sea and the steric effects. Other components reflect the influence of the seasonal intensification of the Rim current and the evolution of the quasi-stationary eddies.

**Keywords:** altimeter data, EOF analysis

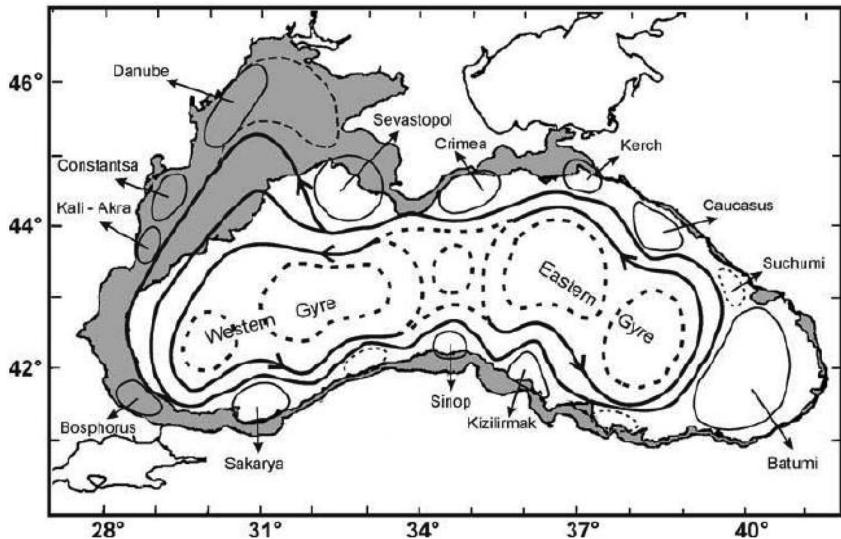
**PACS numbers:** 92.10.ab, 92.10.ak

## 1. INTRODUCTION

The Black Sea is one of the largest inland basins of the world with a surface area of  $\sim 4.2 \times 10^5$  km<sup>2</sup> (zonal and meridional dimensions  $\sim 1000$  km and  $\sim 400$  km), and a maximum depth of  $\sim 2200$  m. It is almost completely isolated from the world oceans; it is connected to the Sea of Azov via the Kerch Strait in the North and to the Marmara Sea (which is connected to the Aegean Sea through Dardanelles Strait) via the Bosphorus in the southeast.

The Black Sea has been an object of exploration and intensive scientific research for a historically long period of time. Its unique hydrographic structure originates from a combination of restricted exchange with the Mediterranean Sea through Bosphorus Straits, supplying a source of salty water, and large fresh water input in the northern shelf part. This determines the strong stratification, and as a consequence a permanent poor on oxygen deep layer is formed which makes of the Black Sea the largest anoxic body in the world. Thus the basin is an excellent case study for the oceanographers to observe and investigate the manifestation of many physical processes. One of the long studied problem is the variability of the surface and deep sea circulation.

It is known that the Black Sea has a basin-wide cyclonic boundary current (Rim Current) driven by the curl of the wind stress field, which is also affected by the fresh water discharges from rivers (buoyancy forces), bathymetry and thermohaline fluxes [1, 2]. In addition to the Rim Current, the Black Sea circulation system contains many mesoscale eddies (see Fig. 1), meanders and filaments spread over the basin [3]. The Rim Current separates the cyclonically dominated inner basin from the anticyclonically dominated coastal zone [1]. The Sinop and Kizilirmak [1], Batumi, Bosphorus, Sukhumi, Kerch, Sevastopol, Danube, Caucasus, Constanta, Crimea and Sakarya eddies reside on the coastal side of the Rim Current zone. In the inner basin, two cyclonic cells (Western Gyre and Eastern Gyre) are formed [4].



**Fig.1.** Classical view of the Black sea surface circulation

However, this picture is not static: the Rim current meanders and eddies evolves in time and space with different scales: global to mesoscale, seasonal to interannual. Until recently the lack of reliable information about the surface state with fine resolution both in time and space prevented the derive of the principles and conclusions about the evolution of the sea surface currents. Since the satellite era has begun we have now more than 20 years of regular satellite altimeter measurements. Our first objective in this paper is to summarize and analyze the information coming from the near-real time AVISO altimeter data. Then we will try to identify the principal components in the variability and to attribute them to the basin-scale or mesoscale variability of sea surface.

## 2. AVISO DATA ARCHIVE USED IN THE STUDY

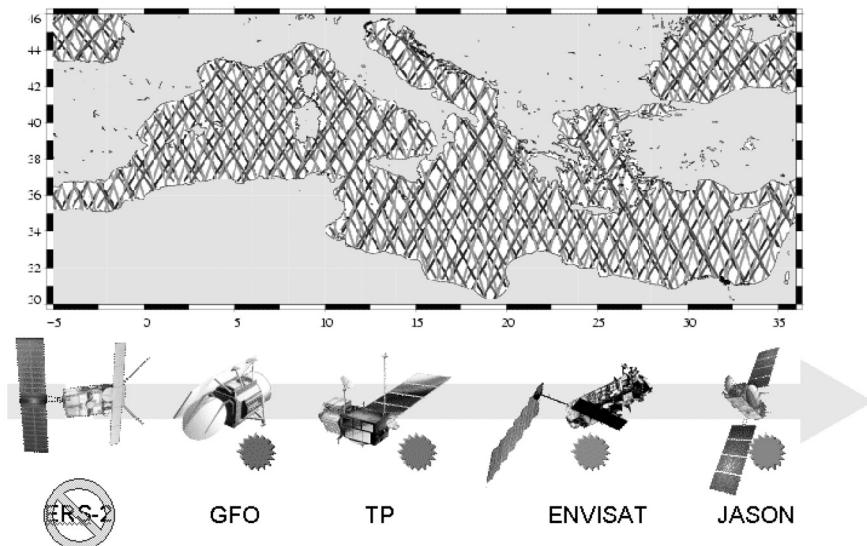
The source of the data is the near-real time altimeter data from AVISO regional product for the Black Sea SSALTO/DUAC, which is a compilation of several altimeter missions (Topex/Poseidon, ERS 1 and 2, Jason-1 and 2, Envisat, Cryosat-2) ([www.aviso.oceanobs.com](http://www.aviso.oceanobs.com)). The altimeter data are usually measured along track and each satellite mission follows different tracks in different moments of time (the tracks for the Mediterranean region are shown in Fig. 2). That is why it is very difficult to work with the raw along-track data. Aviso has developed a more user-friendly product, entitled SSALTO/DUAC: the along-track data are merged in gridded data with optimal time and space interpolation [5]. This product gives the sea level anomalies and calculated geostrophic currents anomalies for ~20 year

period October 1993 to 2012 (Table 1) with spatial resolution of  $1/8^\circ \times 1/8^\circ$  degrees (approximately  $\sim 10$  km) and temporal resolution of 1 week.

One might note that a major change occurs in the period 2002–2005: the end of ERS mission and the introduction of Jason. In 2005 T/P mission ended. Due to the merging of different sources of data some of the studied effects might reflect this change rather than a manifestation of a physical process. For the purposes of this study, we will consider the data consistent in time.

**Table 1.** Data from the satellite missions included in AVISO SSALTO/DUAC merged product

Satellite mission	Type of data	Duration
Cryosat-2	along-track	April 2012 – ongoing
Jason-2	along-track	October 2008 – ongoing
Jason-1	along-track	August 2002 – ongoing
Envisat	along-track	June 2003 – ongoing
TOPEX/Poseidon	along-track	September 1992 – October 2005
ERS-1	along-track	October 1992 – May 1995
ERS-2	along-track	May 1995 – June 2003
Merged	gridded	October 1992 – ongoing

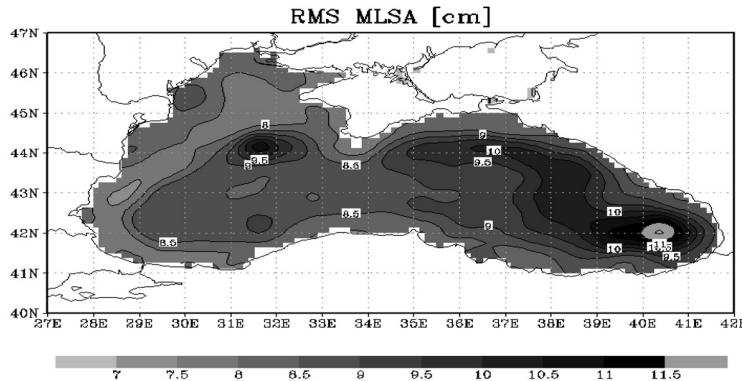


**Fig. 2.** Trajectories of the satellites

### 3. VARIABILITY OF THE SEA SURFACE ANOMALY

The data archive presents a great amount of data, every week for 20-years period. In order to identify the zones where the sea surface height varies most we

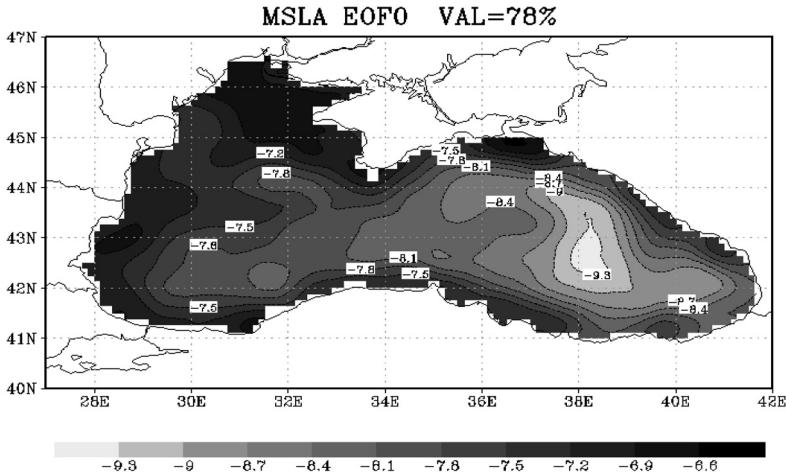
have calculated the root mean square deviation for each point regarding the mean for the whole period. The result is shown in Fig. 3. The most variable zones are the areas of the quasi permanent eddies – Batumi and Sevastopol ( $\sim 12$  cm amplitude). It's impressive to note the asymmetry between west and east parts: along the western coast the scale of variations is about half in respect to the eastern part.



**Fig. 3.** RMS of the sea surface height anomaly

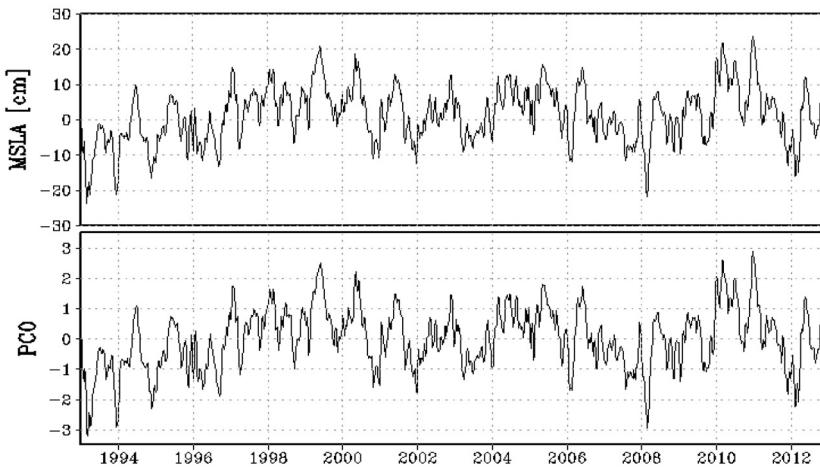
#### 4. EOF ANALYSIS OF SURFACE SEA HEIGHT ANOMALY

The main goal of this study is to identify the components in the variability of the Black Sea surface height and to attribute them to the real physical processes manifestation. When a great amount of data is to be analyzed, the Empirical Orthogonal Function (EOF) Analysis is very powerful method to identify the principal modes in the variability and their overall contribution [6, 7]. In brief, the method is to construct the initial data matrix  $F(x,t)$ , where  $x$  is the space index and  $t$  is the time index, then to calculate the covariance matrix  $R = F^T F$  and to find its eigen vectors and values. In fact this is a decomposition of the initial data, the eigen vectors are EOFs and each eigen values show the contribution of the corresponding eigen vector to the variance. Thus we order the EOFs by the respective eigen values: EOF1 corresponds to the largest eigen value and so on. The EOF analysis is performed and it shows the mode with largest contribution in the variability 78% in Fig. 4, we named it EOF0. The values are all negative, they do not change sign, and so the variations of this mode are almost synchronous in the whole sea, with small horizontal gradients. Same values are observed in the areas of largest fresh water input: rivers Danube, Dniepr, Dniestr, Sakarya and the Kerch Strait (reflecting Don river).



**Fig. 4.** EOF0 of the sea surface anomaly from AVISO SSALTO/DUAC

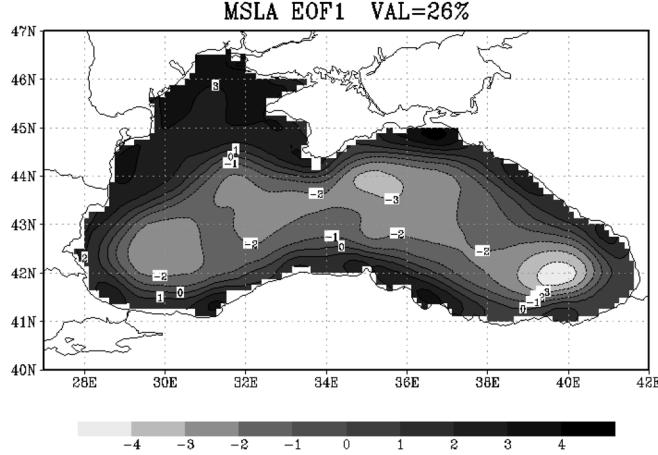
In order to understand the meaning of the most frequent mode we have to look at the time projection of EOF0, e.g. its principal component time series PC0, which is basically the matrix multiplication of  $F(x,t)$  and EOF0( $x$ ). The graphics is very similar to the evolution of the surface mean sea level anomaly, as seen in Fig. 5.



**Fig. 5.** Mean Black Sea level anomaly [cm] and PC0 for the period 1993–2012

Thus the conclusion is that the main mode in the variability is related to the mean sea level variability which is dependent on the fresh water input in the sea and the seasonal variation due to thermal expansion, e.g. steric effects. [8] The Fig. 4 also shows that the fresh water input enters simultaneously, e.g. all the rivers are under similar climatic conditions.

As the fresh water input governs the processes of the sea surface variation, in order to remove this effect we have constructed another initial data matrix  $F_A(x,t) = F(x,t) - Fav(t)$ , where  $Fav(t)$  is the surface area mean sea level anomaly in every moment of time. The EOF analysis is performed for the  $F_A$  matrix, and the first EOF with contribution of 26% is shown in Fig. 6.



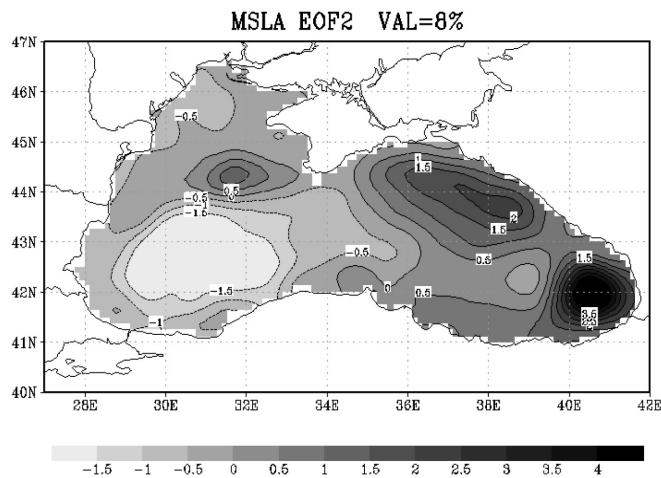
**Fig. 6.** EOF1 of the sea surface anomaly from AVISO SSALTO/DUAC

The values of the EOF1 are positive in the coastal zone and negative in the inner part. This reflects opposite signs of the variations: when one tends to increase, the other tends to decrease. That leads to the conclusion that EOF1 (26%) is related to the seasonal intensification of the Rim current: due to the stronger winds in winter – the cyclonic circulation in the open sea intensifies and the sea surface tends to lower. Thus the difference between sea level of the open sea and sea level in the coastal areas is greater in the winter than in the summer [8, 9].

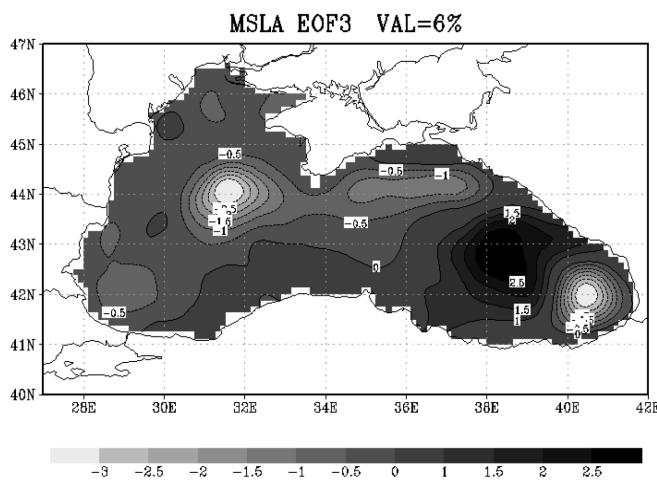
The further analysis shows that EOF2 (8%) (Fig. 7), EOF3 (6%) (Fig. 8) and EOF4 (5%) (not shown here because it does not add significant information) are related to the quasi-stationary anticyclonic eddies: Batumi, Sevastopol, Kerch.

In order to understand the meaning of these modes and to complete the analysis we show in Fig. 9 the time projection of the modes: the principal component time series, e.g. the matrix multiplication of  $F_A$  and the corresponding EOF.

EOF2 indicates opposite phases of the sea surface height anomaly in the Western gyre and the rest of the sea. Most probably this mode is related to the variation in the intensity of the Western and Eastern gyres, which could be due to the wind variability. From the principal component time series PC2 one could note a periodicity of 4–5 years, which might be connected to climate oscillations of such frequency.



**Fig. 7.** EOF2 of the sea surface height anomaly



**Fig. 8.** EOF3 of the sea surface height anomaly

The map of the EOF3 demonstrates that the quasi stationary eddies of Batumi and Sevastopol manifests the same phase but opposite to the central Eastern gyre. The bipolar structure in Batumi area is very interesting and is related to the seasonal transformations of the Batumi eddy: it tends to move from east to west changing the sea surface height anomaly from positive to negative.

## 5. CONCLUSIONS

In this study we use the altimeter data from AVISO SSALTO/DUAC gridded regional product for the Black Sea for the period 1993–2012 in order to investigate the principle components in the variability of the sea surface height. The calculation of the root mean square deviation for each point regarding the mean for the whole period shows that the most variable zones are the areas of the quasi permanent eddies – Batumi and Sevastopol (~12 cm amplitude). The performed EOF analysis indicates that the main variability (78%) is related to the fresh water input in the sea and the steric effects. After the removal of this dominating signal the leading EOF1 (contribution to the variance of 26%) reflects the influence of the seasonal intensification of the Rim current, leading to opposite tendency in the sea level in the coastal areas and open sea. The further analysis shows that EOF2 (8%), EOF3 (6%), and EOF4 (5%) are related to the evolution of the quasi-stationary anticyclonic eddies: Batumi, Sevastopol, Kerch.

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