Global and Planetary Change 124 (2015) 10–21

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Ocean bottom pressure variability in the Mediterranean Sea and its relationship with sea level from a numerical model

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ARTICLE INFO

Article history:
Received 1 April 2014
Received in revised form 6 November 2014
Accepted 20 November 2014
Available online 27 November 2014

Keywords:
Mediterranean Sea
sea level
ocean bottom pressure

ABSTRACT

The spatial and temporal scales of variability of ocean bottom pressure (P_b) in the Mediterranean Sea are characterized and their relationship with sea level was assessed using a high resolution eddy-permitting regional ocean model spanning the period 1999–2011. It was found that rapid (periods of a few days) bottom pressure fluctuations are coherent with sea level and are decoupled between the eastern and western basins as a result of topographic constraints. In the longer periods, steric processes gained relevance away from the coast and partially broke the coherence between sea level and P_b, especially on the western basin. Results confirm that sea level changes are predominantly barotropic over most of the basin and at all time scales, except for the annual cycle. Along the coasts sea level fluctuations reflected local steric processes taking place in their vicinity. This effect was stronger on the western basin, whereas the coasts of the Eastern Mediterranean arise as the most suitable proxies for basin wide long term (>60 days) mean sea level (or ocean bottom pressure) changes at non-seasonal periods.

1. Introduction

Knowledge of ocean bottom pressure (P_b) variability in combination with sea level changes provides information on the vertical structure of the ocean and on the water mass distribution. Not surprisingly, the number of studies on the relationship between P_b (or ocean mass) and sea level has grown in the last decade thanks to the confluence of various factors: on the one hand, the increasing availability of long term three-dimensional numerical simulations that provide joint P_b and sea level fields; on the other, an increasing number of P_b observations, including point-wise open ocean sensors but also the valuable and fruitful space gravimetry observations from the Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al., 2004); and in addition to that, the maturity reached by the processing and analysis of nearly global sea level altimetric measurements, starting in 1992. The relationship between P_b and sea level depends on the oceanic response to a given forcing; in a homogeneous ocean (no density changes in the water column) such response is depth-independent (Gill and Niiler, 1973). The relative weight of this barotropic response with respect to the depth-dependent (steric) processes changes with latitude and time scales. Earlier model based studies have established that at short time scales (<~100 days) sea level and P_b are very much related everywhere in the global ocean, with some exceptions as in the Tropics and in strongly eddying regions (Vinogradova et al., 2007; Bingham and Hughes, 2008; Quinn and Ponte, 2012). Conversely, at longer (intra- to interannual) time scales sea level variance is not generally explained by P_b variance as ocean variability is mostly related to steric processes over most parts of the ocean (Vinogradova et al., 2007; Köhl and Stammer, 2008; Bingham and Hughes, 2012). This was also confirmed by the combination of monthly altimetric and space gravimetry observations at inter-annual time scales (Piecuch et al., 2013). It must be mentioned here that, at certain spatial and temporal scales, steric processes can also impact P_b (e.g. Song and Zlotnicki, 2004). Some regions have, however, been identified where P_b and sea level changes show a correspondence even at long time scales, namely shallow and shelf areas and semi-enclosed basins (Piecuch and Ponte, 2011). This is the case of the Mediterranean Sea, which has been identified as one of the few regions worldwide where basin average water mass (P_b) changes explain to a large extent sea level variability (Bingham and Hughes, 2008; Piecuch et al., 2013).

The Mediterranean Sea is a semi-enclosed basin located at mid-latitudes and connected to the Atlantic Ocean through the narrow Strait of Gibraltar. Given its relatively well monitored coastal sea level, it has been an important region for the assessment of global sea level trends, glacio-isostatic adjustment and tectonic processes, among other issues. Mean sea level variability in this region has been extensively investigated based on in-situ and remote observations (Tsimplis and Baker, 2000; Tsimplis and Rixen, 2002; Fenoglio-Marc, 2002; Criado-Aldeanueva

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http://dx.doi.org/10.1016/j.gloplacha.2014.11.009
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et al., 2008; Marcos and Tsimplis, 2008; Calafat and Gomis, 2009; Marcos and Tsimplis, 2008; Tsimplis et al., 2013) as well as using numerical models (Gomis et al., 2008; Somot and Colin, 2008; Sannino et al., 2009; Calafat et al., 2012). Consequently, it has been well documented that basin wide inter-annual and longer term mean sea level oscillations are mostly driven by mass variations (Fukumori et al., 2007; Calafat et al., 2010; Landerer and Volkov, 2013) attributed to exchanges through the Strait of Gibraltar. These are forced either by local processes such as winds at Gibraltar or steric changes in the nearby Atlantic, or by a remote forcing, like changes in the atmospheric pressure over the North Atlantic Ocean or mass addition from land-based ice melting (Fukumori et al., 2007; Calafat et al., 2012; Tsimplis et al., 2013; Pinardi et al., 2014). Indeed, earlier works addressing mass variability, or alternatively P_b changes, in the Mediterranean Sea have mostly addressed basin average changes, despite the Mediterranean Sea being a deep basin with its own ocean circulation and dynamics (see e.g. Schroeder et al., 2013). Fukumori et al. (2007) is one of the exceptions, since their study made use of an ocean circulation model covering the Mediterranean Sea and a sector of the Northeast Atlantic. However, the coarse model resolution (1° × 1°) impeded accounting for the steric processes dominated by mesoscale signals. Other works with a global focus have also provided insight into the relationship between P_b and sea level in the Mediterranean (Vinogradova et al., 2007; Bingham and Hughes, 2008).

The aim of the present work is to explore and quantify P_b variability in the Mediterranean Sea at different time scales and to clarify its relationship with sea level at the regional and local scales. The presence of steric processes, especially in some parts of the basin where active mesoscale variability with the presence of eddies takes place, is expected to break the coherence observed between spatially averaged P_b and sea level, at least at the inter-annual and longer time scales. To achieve this goal an eddy-permitting numerical ocean model has been used. The high spatial resolution in the model is required to resolve the small scale structures in the Mediterranean Sea, where the baroclinic Rossby radius is only a few tens of kilometres, and to explore the relationship between sea level and P_b at different spatial and temporal scales. In this sense, the present work represents a step further with respect to the aforementioned studies by Fukumori et al. (2007), Vinogradova et al. (2007) and Bingham and Hughes (2008), in which the horizontal resolution was between 0.25° and 1° and did not allow for a proper representation of the topography of the Mediterranean Sea.

This paper is organized as follows: in Section 2 the numerical model is presented together with the methodology used throughout the paper. Section 3 is devoted to the results, which include the characterization of the P_b variability in the Mediterranean Sea, the rapid P_b fluctuations, the seasonal cycle of P_b and the low frequency behaviour. The last section summarizes the major findings and discusses its implications as well as the limitations of the present work.

2. Numerical model and methods

Daily outputs of temperature (T), salinity (S) and sea surface height (ssh) fields were obtained from an ocean reanalysis for the period 1999–2011 carried out by the Mediterranean Forecasting System at INGV and freely available at the MyOcean web site (http://www.myocean.eu/, product ID MEDSEA_REANALYSIS_PHYS_006_004). In this particular simulation the ocean model NEMO was implemented in the Mediterranean Sea and a nearby sector of the Atlantic Ocean with a spatial resolution of 1/16° × 1/16° in latitude and longitude and 72 unevenly spaced vertical levels (Oddo et al., 2009). The regional model was nested to a global model (Drevillon et al., 2008) in the Atlantic box using the Flather boundary conditions (Flather, 1976) for vertically integrated velocities. This implies that the regional model is not conserving its volume and mass. In order to ensure global mass conservation the global spatial mean steric anomalies should be added to ssh at each time step (Greatbatch, 1994; Ponte, 1999; Griffies and Greatbatch, 2012). Unfortunately this correction for the global model was not available and therefore was not applied. Nevertheless, it is expected to be small in comparison with regional changes and minimized by the fact that the analyses have been performed on detrended time series. This numerical setup has been evaluated in earlier works. Oddo et al. (2009) compared modelled T with Argo data and modelled ssh with tide gauge and satellite altimetry and demonstrated the improvement in the nesting with respect to a closed model in terms of the characteristics of the outflow waters and the seasonal sea level variability. Adani et al. (2011) assessed the quality of an 18-year simulation in terms of hydrographic properties and sea level anomalies with the aim of exploring two different data assimilation schemes. Their analyses resulted in a preferred scheme that was then used in this product.

Daily fields of ocean bottom pressure P_b were computed at each grid point as:

$$P_b = \int_{-H}^{0} \rho g dz + \int_{0}^{\eta} \rho_0 g dz = \int_{-H}^{0} \rho g dz + \rho_0 g \eta \tag{1}$$

where ρ is the ocean density, computed using T and S, ρ_0 is the density at the sea surface, H is the water depth, η is the sea surface elevation and g is the gravity acceleration. Neither the regional model nor the global model to which it is nested at the boundaries is forced by atmospheric pressure and, therefore, the term is not accounted for in this equation. The first term in the right hand side of Eq. (1) corresponds to the steric contribution. Likewise, the thermosteric (halosteric) term is defined using the same expression but with ρ determined only by T (S) changes and S (T) being kept constant at its initial value. P_b anomalies are computed by removing its time-mean field and are then normalized into water height equivalent as:

$$\frac{P_b - P_b^G}{\rho_{0g}}.$$

The percentage of variance of sea level explained by P_b was computed as:

$$\frac{1 - var(\mathrm{ssh} - P_b)}{var(\mathrm{ssh})} \times 100.$$

When stated in the text, as part of the analysis daily values of ssh and P_b fields were high-pass filtered using a Butterworth filter of order 2. The low-passed component of each variable was then estimated by subtracting the high-pass filtered series to the total signal. The mean seasonal cycle was obtained by fitting an annual and a semi-annual signal to the low-passed component using harmonic analysis.

Additionally, daily 10-m wind fields were obtained from ERA-Interim (European Centre for Medium-Range Weather Forecasts — ECMWF — Re-analysis), available at the ECMWF web site (http://data-portal.ecmwf.int/data/d/interim_daily/). The wind fields are the same as those that were used to force the model.

3. Results

3.1. Scales of variability of P_b in the Mediterranean Sea

Standard deviations of detrended daily P_b and sea level anomalies are mapped in Fig. 1. P_b variability ranges between 4 and 8 cm, whereas sea level presents higher values up to 12 cm. These results are qualitatively in agreement with those inferred for the Mediterranean Sea in the global analyses of Vinogradova et al. (2007) and Bingham and Hughes (2008). Spatially averaged sea level variability is higher (7.9 cm) than P_b variability (6.2 cm). According to numerical results, the Mediterranean Sea is a region with large P_b variance in comparison with the global ocean, where the range of P_b anomalies is around 1 cm