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Sea-level rise in the Mediterranean Sea by 2050: Roles of terrestrial ice melt, steric effects and glacial isostatic adjustment

Gaia Galassi, Giorgio Spada *

Dipartimento di Scienze di Base e Fondamenti (DiSBeF), Università degli Studi di Urbino "Carlo Bo", Urbino, Italy

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ABSTRACT

To assess the regional pattern of future low-frequency sea-level variations in the Mediterranean Sea, we combine the terrestrial ice melt, the glacio-isostatic and the steric sea-level components. The first is obtained from global scenarios for the future mass balance of the Greenland and Antarctica ice sheets, glaciers and ice caps. The second is based on modeling, using different assumptions about the Earth's rheology and the chronology of deglaciation since the Last Glacial Maximum. The third is obtained from published simulations based on regional atmosphere–ocean coupled models. From a minimum and a maximum scenario by 2040–2050, we find that the total, basin averaged sea-level rise will be 9.8 and 25.6 cm. The terrestrial ice melt component will exceed the steric contribution, which however will show the strongest regional imprint. Glacial isostatic adjustment will have comparatively minor effects. According to our estimates, at the Mediterranean Sea tide gauges, the rate of sea-level change will increase, by 2050, by a factor of ~1–6 relative to the observed long-term rates.

1. Introduction

Contemporary sea-level rise (Cazenave and Llovel, 2010), either caused by density or mass variations of the world's oceans, is one of the key indicators of global warming. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) has projected, under the Representative Concentration Pathway scenario RCP6.0 (Moss et al., 2010), a global average sea-level rise in the likely range of 38 to 73 cm between 1986–2005 and the end of current century (2081–2100), with a corresponding increase of rate of sea-level rise between 4.7 and 10.3 mm yr^{-1} (Church et al., 2013). As for all the AR5 scenarios, for RCP6.0 the major contribution to future sea-level rise is that associated with terrestrial ice melt (TIM), through surface mass balance variations and rapid ice sheet dynamics, which would cumulatively contribute 25 cm in 2081–2100 (median of the possible values). According to this scenario, about 50% of this sea-level rise will be due to the melting of glaciers and ice caps (GIC), in a likely range of 6 to 19 cm. Projections for the large continental ice sheets are subject to large uncertainties. The Greenland Ice Sheet (GIS) contribution is assessed in the range between 2 and 15 cm (considering both the dynamics and the surface mass balance components), and the Antarctic Ice Sheet (AIS) between −6 and 15 cm of projected sea-level rise, and negative values for the surface mass balance component. The contribution associated with thermal expansion has, for the RCP6.0 scenario, an estimated range of 15 to 24 cm by 2081–2100, with a median value of 19 cm.

The AR5 projections above represent globally averaged sea-level variations which cannot be immediately translated into regional scenarios. Indeed, all the processes responsible for future sea-level rise are characterized by a strong regional signature, which makes local projections particularly challenging (Meehl et al., 2007). These, however, are of fundamental importance for the possible impact of sea-level rise on society and to improve management and planning of coastal defense. Several contributions to sea-level rise which have small or negligible globally averaged effects, can indeed have a significant amplitude on regional scale. This occurs, for example, for the sea-level changes expected from salinity variations (Antonov et al., 2002) or for those associated with glacial isostatic adjustment (GIA), originated by the ongoing mass redistribution still caused by the melting of the late-Pleistocene ice sheets (Farrell and Clark, 1976). GIA effects average to zero across the surface of the oceans, but they will be the source of local and regional sea-level variations, both in the formerly glaciated areas at the Last Glacial Maximum (LGM, ~21,000 years ago) and in key-areas such as the Mediterranean Sea (Stocchi and Spada, 2009). The pattern of the sea-level change expected from future mass loss from GIC and continental ice sheets shows significant variations even at the 100-km spatial scale (Spada et al., 2013). These will add up to the spatially heterogeneous contribution expected from the ocean response to global warming that includes thermosteric, halosteric and dynamic effects (Spada et al., 2013).

Although sea-level rise is generally considered a relatively slow process on human time scales (but see Cronin, 2012), it has a very significant long-term impact, influencing the dynamics of coastal erosion, groundwater salinization and change in natural ecosystems (Nicholls and Cazenave, 2010). In view of the high and increasing population density

* Corresponding author.
E-mail address: giorgio.spada@gmail.com (G. Spada).

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(Cori, 1999) and of the numerous coastal areas potentially vulnerable to flooding, erosion and loss of wetlands (Nicholls et al., 1999), in the Mediterranean region the problem of future sea-level rise is particularly felt. In key zones, like the Moroccan coast (Snoussi et al., 2008) and the Venetian Lagoon (Carbognin et al., 2010), future sea-level rise will exacerbate existing human pressure, will impact the development of tourism (Cori, 1999) and will influence the migration fluxes (Black et al., 2011). Because of ~46,000 km of populated coasts belonging to 22 countries, the socioeconomical and political implications of a growing risk of inundation demand, for the Mediterranean countries, serious consideration of long term sea-level variability into costal planning (Nicholls and Hoozemans, 1996). Low-elevation coastal zones (LECZs, see Fig. 1) have a considerable extension in the Mediterranean basin and are highly vulnerable to environmental events, like floods, which can directly or indirectly affect the coastal community. Some Mediterranean densely populated areas are LECZ. For example ~30% of the Egyptian population (about 27 million people) lives in the LECZ of the Nile delta (Black et al., 2011) and highly populated cities, as Tunis (~2.2 million inhabitants) are in LECZ.

Previous investigations on the future sea-level rise across the Mediterranean Sea (Marcos and Tsimplis, 2008; Tsimplis et al., 2008; Carillo et al., 2012; Jordà and Gomis, 2013) have mainly focused on the modeling of the steric component of sea-level change, which describes the effects of water density variations. At first order, these can be separated into thermosteric and halosteric components, where the first accounts for temperature variations assuming a constant salinity, and the second represents the effect of salinity variations at constant temperature (Jordà and Gomis, 2013). While at global scale the thermosteric effects dominate the steric sea-level variations (Antonov et al., 2002), at a regional scale and in particular in the Mediterranean Sea halosteric and thermosteric effects can be comparable (see e.g. Tsimplis and Rixen, 2002). It has been recently pointed out, however, that neglecting the contribution of the salinity increase to the mass component could lead to a severe underestimation of total sea-level rise, especially within semi-enclosed basins (Jordà and Gomis, 2013).

A common feature to all previous approaches to the problem of future sea-level rise in the Mediterranean Sea has been the adoption of simplified models for the mass component. This term accounts for the effect of melting glaciers, ice caps, and ice sheets (Antarctica and Greenland) and of terrestrial mass exchange, including dam impoundment and groundwater variations (Slangen, 2012). Tsimplis et al. (2008), who have first tackled the problem of future sea-level changes in the Mediterranean Sea, have used the IPCC AR4 projections for the mass term (Meehl et al., 2007) and modulated it according to the amplitude of the GIA "sea-level fingerprint" (Mitrovica et al., 2001) predicted for the Mediterranean region as a whole, thus neglecting possible spatial variabilities at a sub-basin scale. An even more simplified approach has been adopted by Marcos and Tsimplis (2008), who only accounted for a globally-averaged mass term according to the IPCC AR4 SRES A1B and A2 scenarios (Meehl et al., 2007). In Carillo et al. (2012), no attempts have been made to combine estimates for the mass-induced term to their projections of steric variations by 2050. Furthermore, none of the above studies have considered nor realistically modeled the effects on future sea-level change expected from GIA, in spite of its recognized importance in the Mediterranean basin at decadal and secular time scales (Stocchi and Spada, 2009). A notable exception is the study of Lambeck et al. (2011), who projected future sea-level combining GIA effects (including glacio- and hydro-isostatic components) to the IPCC AR4 and Rahmstorf (2007) scenarios to 2100, also estimating the future relative sea-level variations of tectonic origin. The study of Lambeck et al. (2011), however, is limited to the Italian coasts.

The aim of this work is to estimate the future sea-level variations in the Mediterranean Sea by 2040–2050 relative to 1990–2000, combining the patterns of TIM, GIA, and steric components of sea-level change, following the approach first outlined on a global scale by Slangen et al. (2012) and later adopted by Spada et al. (2013). The chosen time frame is dictated by the specific projections employed for the steric component of sea-level rise. Up to now, for the Mediterranean Sea these components have only been considered separately, and often their spatial variations have been neglected across this relatively small, semi-enclosed basin. Although Tsimplis et al. (2008) have recognized the importance of the mass addition into the oceans due to the future melting of the GIC, up to now a realistically modeled TIM component has not been included in the future sea-level budget of the Mediterranean Sea. Similarly, as far as we know, the future effect of GIA has never been evaluated before at the Mediterranean scale using different models. Recent projections for the twenty-first century by Slangen et al. (2014) have emphasized the regional patterns of all the sea-level components, but have not provided clues on the Mediterranean Sea.

The manuscript is organized into three sections. In Section 2, estimates for each of the sea-level components relevant for the Mediterranean Sea are separately described; namely, the TIM, the terrestrial mass exchange (TME), the GIA and the ocean response (OR) contributions. These are combined in Section 3, where the total sea-level variation by 2040–2050 relative to 1990–2000, is estimated across the whole basin, at sub-basin scale, and at specific locations as tide gauge sites and LECZ. In Section 4 we draw our conclusions.

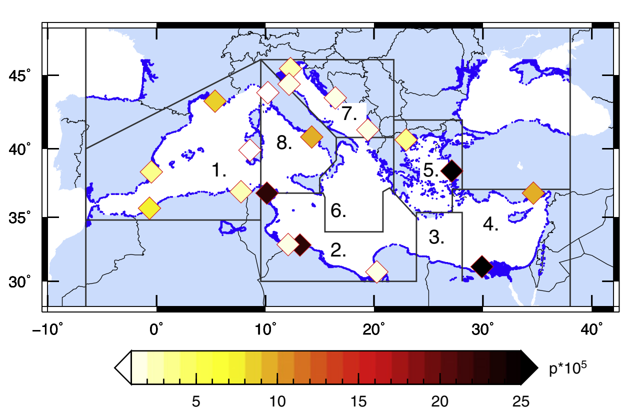

Fig. 1. LECZs (defined as lands with an elevation < 10 m relative to present sea-level, see McGranahan et al., 2007 and http://sedac.ciesin.columbia.edu/data/collection/lecz) along the coasts of the Mediterranean Sea (blue, obtained from model ETOPO2, see http://www.ngdc.noaa.gov/mgg/fliers/06mgg01.html), with principal cities in LECZ marked by diamonds (the population is color-coded in units of 10^5 inhabitants). Also shown are the political boundaries and the Mediterranean Sea sub-basins outlined by Carillo et al. (2012). This same partitioning is adopted in the body of the paper to facilitate an intercomparison of the various components of sea-level change. The Western Mediterranean (1.) is the largest sub-basin, adjacent to the Tyrrhenian Sea (8.). This latter is connected with the Southern Central Mediterranean (2.) through the Channel of Sicily. The Adriatic Sea (7.) extends northwards between Italy and the Balkans and communicates with the Ionian Sea (6.) through the Strait of Otranto. The Aegean Sea (5.) extends between Greece and Turkey, and is connected to the South Crete (3.) and the Levantine Seas (4.) through several straits in the Grecian Island Arc.

2. Sea-level components

The long-term sea-level variations at a given place and time result from the combination of several contributions. Assuming that these are acting independently, following the general approach outlined by Mitrovica et al. (2001), the total variation is

$$s^{TOT}(\theta, \lambda, t) = s^{GIA} + s^{MAS} + s^{OR} + s^{OTH}, \quad (1)$$

where s is the relative sea-level, θ and λ are the co-latitude and longitude, respectively, t is the time, s^{GIA} is the GIA component of sea-level change, s^{MAS} is the contribution associated with mass exchange, s^{OR} is the component due to the ocean response (this includes the ocean circulation contributions and thermosteric and halosteric effects), and s^{OTH} represents the contribution of other factors (including, for instance,