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The contrasting effect of increasing mean sea level and decreasing storminess on the maximum water level during storms along the coast of the Mediterranean Sea in the mid 21st century

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ABSTRACT

The maximum level that water reaches during a storm along the coast has important consequences on coastal defences and coastal erosion. It depends on future sea level, storm surges, ocean wind generated waves, vertical land motion. The future sea level in turn depends on water mass addition and steric contributions (with a thermosteric and halosteric component). This study proposes a practical methodology for assessing the effects of these different factors (which need to be estimated at sub-regional scale) and applies it to a 7-member model ensemble of regional climate model simulations (developed and carried out in the CIRCE fp6 project) covering the period 1951–2050 under the A1B emission scenario. Sea level pressure and wind fields are used for forcing a hydro-dynamical shallow water model (HYPSE), wind fields are used for forcing a wave model (WAM), obtaining estimates of storm surges and ocean waves, respectively. Thermosteric and halosteric effects are diagnosed from the projections of sea temperature and salinity. Steric expansion and storminess are shown to be contrasting factors: in the next decades wave and storm surge maxima will decrease while thermosteric expansion will increase mean sea level. These two effects will to a large extent compensate each other, so that their superposition will increase/decrease the maximum water level along two comparable fractions of the coastline (about 15–20%) by the mid 21st century. However, mass addition across the Gibraltar Strait to the Mediterranean Sea will likely become the dominant factor and determine an increase of the maximum water level along most of the coastline.

1. Introduction

This paper proposes a practical methodology for computing the maximum water level that will be reached along the coast and estimates how it will change in the future because of global climate change. The study consists in a sequence of three steps that from the outputs of regional climate models i) produce an estimate of the various factors responsible for the water level ii) add the different contributions iii) build indicators of water level maxima, whose values are used for estimating the climate change signal.

The maximum level that water reaches during a storm along the coast is expected to change in future with potentially important consequences on coastal populations and structures (e.g. chapter 5 of IPCC AR5). Results of this study are expected to be relevant for planning coastal and harbor defenses, such as dams, sea walls, breakwaters and structures such as jetties and docks. The analysis is applied to the Mediterranean sea leading to an estimate of future maximum water level along its whole coastline, whose vulnerability has been recognized since long time (e.g. Nicholls and Hoozemans, 1996).

In spite of the relevance of the issue, it appears that no study has so far attempted a comprehensive estimate of the maximum water level including the superposition of the different relevant factors: mass addition, changes of density (steric effects), vertical land motion, changes of storm surges and of wind generated surface waves. All these factors need to be estimated at sub-regional scale as they are characterized by a large variability in space and time.

The mean sea level of the Mediterranean Sea has shown, in the recent past, substantial deviations from the global values at decadal time scales. In the period 1960–1990 the mean Mediterranean sea level actually decreased, mainly because of a persistent positive anomaly of sea level pressure (Tsimplis et al., 2005; Marcos et al., 2011a). Later, during the 1990s, it increased at a speed greater than the global one, and subsequently stopped from 2002 onwards (Marcos et al., 2011a, 2011b, 2011c). This behavior can be due to mass exchanged with the Atlantic across the Gibraltar strait, to change of volume because of change of temperature and salinity, or, more in general to a combination of both. A mean flow of mass across Gibraltar can be the consequence of ice

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melting, which increases globally the mass of the oceans, or/and of changing sea level pressure distribution over the North Atlantic and Mediterranean regions. Calafat et al. (2010) have estimated the mass contribution to Mediterranean Sea level variability for the period 1948–2000. They found that the mass content of the Mediterranean basin has increased at a rate of 0.8 ± 0.1 mm/yr for the period 1948–2000 and that it increases up to 1.2 ± 0.2 mm/yr if the effect of the atmospheric surface pressure is removed. The steric contribution has been estimated to contribute about 20% of sea level variance (Tsimplis et al., 2008) in model simulations and it is clearly smaller than the effect of mass addition, which is the real cause of the observed increase of the Mediterranean sea level (Jordà and Gomis, 2013a, 2013b). Its estimate, which is affected by the uncertainty of oceanographic observations containing dubious records and holes during the 20th century, indicates that a small steric sea level increase could eventually have been driven mainly by warming of the upper waters (Tsimplis and Rixen, 2002). However, concerning long-term trends (1960–2000), even the sign of the thermosteric component is uncertain and ranges from -0.06 to $+0.09$ (Jordà and Gomis, 2013b). Halosteric trends are negative for all products, but the magnitude and spatial patterns provided by available hydrographic datasets are statistically inconsistent among them.

The future evolution of Mediterranean Sea level is uncertain. Some regional studies have focused on the steric contribution. Marcos and Tsimplis (2008) have used a large set of global climate models (GCMs) for computing the steric effect on Mediterranean sea level. They have found a large spread among model results (from -22 to 31 cm at the end of the21st century), with density increase (due to the projected increase of salinity) compensating the thermosteric expansion (due to the projected warming) in some models. These estimates have been recently reconsidered using the CIRCE simulations (Gualdi et al., 2013), which provided estimates of the 2021–2050 mean steric sea level rise with respect to the reference period (1961–1990) in the range from 2 to 7 cm. All these estimates are valid under the hypothesis that the total water mass in the Mediterranean will not change, which seems dubious if salinity will change. An attempt to consider the total sea level using a statistical model has been done by Scarascia and Lionello (2013), but only at sub-basin scale for the Adriatic Sea under the A1B scenario, where they estimated a total sea level rise in the range from 14 cm to 49 cm at the end of the century. The future effect of the atmospheric mechanical forcing has been estimated by Jordà et al. (2012) suggesting a sea level decrease in winter, with trends of up to -0.8 ± 0.1 mm/year in the central Mediterranean under the A2 scenario, and a small increase in summer (0.05 ± 0.04 mm/yr).

Marine storminess in the Mediterranean region is associated with a well-defined sub-branch of the mid-latitude storm track and a consensus on a decrease of its intensity has progressively emerged in the literature (Lionello et al., 2006, 2008a; Lionello and Giorgi, 2007; Zappa et al. 2013), which is especially evident considering the RCP8.5 scenario in the latter study. Correspondingly, significant wave height and storm surges are projected to decrease (Lionello et al., 2008b; Marcos et al., 2011b; Conte and Lionello, 2013). For both wave and surge maxima the value of the reduction varies depending on the basin in the range from 2% to 5% in the period 2021–2050 with respect to 1971–2000 for the A1B scenario.

This study differs from previously published studies because it aims at computing the maximum level that water can reach during a storm considering simultaneously various factors, that were considered separately in previous studies: storm surges, ocean wind generated waves, steric effects on sea level. Further its output is designed in such a way to focus on the coastline (Fig. 1a), where effects of water level maxima are most important and it is essential to adapt to their eventual future variation. The goal is to assess the climate change effect on marine storminess along the coast of the Mediterranean Sea in the next decades. A multi-model approach is adopted by using the forcing fields provided by a new generation of coupled regional atmosphere-ocean models that were developed in the CIRCE FP7 project (Gualdi et al., 2013). However, this study does not include land vertical motions (which need a completely different set of models and information) and the effect of mass addition caused by melting of polar and continental ice caps, which is an essential, but complicated issue in its own (Church et al., 2013).

The organization of this paper reflects the different factors that are included in this analysis. Section 2 (Data and methods) lists the climate model projections (Section 2.1) providing the sea level pressure (SLP) and surface wind fields and describes briefly the models used for computing the surge levels and the wind wave spectra (Section 2.2). The following two Sections (2.3-2.4) describe how the contribution of wind generated waves and steric effects to the maximum water level are computed. Section 2.5 describes the indicators that are used to describe climate change. Section 3 analyzes the results of the simulations considering first separately the role of waves (Section 3.1) and surges (Section 3.2), and then adding them to compute the maximum water level reached by wave crests during a storm. Initially the analysis considers the average annual maximum water level. Results for other indicators are described in Section 3.4 (the average 10 independent annual maxima, the 5 and 50 years return values) and in Section 3.5 (storm duration). Steric effects are described in Section 3.6. The discussion (Section 4) describes the net effect of storminess (waves and surges) and steric effects on the maximum water level. The study is summarized in the conclusion Section 5.

2. Data and methods

2.1. Climate model projections

Input data for this analysis are provided by a set of climate simulations that have been produced within the CIRCE fp6 project (Climate Change and Impact Research: the Mediterranean Environment) and cover the period 1951–2050 under the A1B emission scenario (Gualdi et al., 2013). Seven simulations have been considered, labeled CMCC-LR, CMCC-HR, MPI, ENEA, CNRM, IPSL3, IPSL2. All simulations except CMCC-HR are carried out with coupled atmosphere ocean models including a high resolution model of the Mediterranean Sea circulation.

- The CMCC-LR (Euro Mediterranean Centre for Climate Change Low Resolution) datasets produced using the global climate model CMCC-Med, whose atmospheric component is ECHAM5 in its T159 configuration (~150 km) and ocean component is OPA8.2 at 2° resolution. Over the Mediterranean basin ECHAM5 is fully coupled with NEMO-MFS at a 6.7 km resolution (Oddo et al., 2009).
- The CMCC-HR (Euro Mediterranean Centre for Climate Change High Resolution) datasets produced using the CMCC-CLM Regional Climate model downscaling of the CMCC-LR simulation and it represents its dynamical downscaling to an horizontal grid resolution of $0.12 \times 0.12°$.
- The MPI (Max Plank Institute-Germany) dataset, which is produced using REMO (REgional Model) which is a dynamical downscaling of the CMCC-LR model at a spatial resolution of $0.22 \times 0.22°$ coupled to the Max-Planck-Institute for Meteorology ocean model (MPI-OM). The boundary conditions are extracted from CMCC-LR simulation (Elizalde et al., 2010).
- The ENEA (Italian National agency for new technologies, Energy and sustainable economic development) dataset, which is produced using the RegCM3 regional atmospheric model coupled to the MITgcm model in the Mediterranean Sea (Carillo et al., 2012). This dataset is a downscaling of ECHAM5-MPIOM at resolution of 30 km for the atmospheric component and 1/8° for the ocean component.
- The CNRM (Centre National de Recherches Météorologiques - MeteoFrance) dataset, which is produced using the ARPEGE atmospheric circulation model (Déqué and Piedelievre, 1995), whose stretched grid reaches a 50 km resolution over Europe-Mediterranean-North Africa) coupled to OPA9 at 2° resolution for the global

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