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Storm surges in the Mediterranean Sea: Variability and trends under future climatic conditions

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ABSTRACT

The trends of storm surge extremes in the Mediterranean Sea for a period of 150 years (1951–2100) are explored, using a high-resolution storm surge model. Numerical simulations are forced by the output of regional climate simulations with RegCM3, which uses IPCC's historical data on greenhouse gasses emissions for the (past) period 1951–2000, and IPCC's A1B climate scenario for the (future) period 2001–2100. Comparisons between observations and modeling results show good agreement and confirm the ability of our model to estimate the response of the sea surface to future climatic conditions. We investigate the future trends, the variability and frequency of local extremes and the main forcing mechanisms that can induce strong surges in the Mediterranean region. Our results support that there is a general decreasing trend in storminess under the considered climate scenario, mostly related to the frequency of local peaks and the duration and spatial coverage of the storm surges. The northward shift in the location of storm tracks is a possible reason for this storminess attenuation, especially over areas where the main driving factor of extreme events is the inverted barometer effect. However, the magnitudes of sea surface elevation extremes may increase in several Mediterranean sub-regions, *i.e.*, Southern Adriatic, Balearic and Tyrrhenian Seas, during the 21st century. There are clear distinctions in the contributions of winds and pressure fields to the sea level height for various regions of the Mediterranean Sea, as well as on the seasonal variability of extreme values; the Aegean and Adriatic Seas are characteristic examples, where high surges are predicted to be mainly induced by low pressure systems and favorable winds, respectively.

1. Introduction

Low-elevation areas along the Mediterranean coastline are at high risk in cases of extreme storm surge events; extreme storms may induce significant direct (*e.g.* flooding, coastal erosion, damage to property) and indirect (*e.g.* salt intrusion, land subsidence, water supply contamination, vegetation destruction) impacts to the coastal zone (White, 1974). The existence of numerous coastal cities, river deltas, islands, low land elevation coastal areas and topographically complicated regions

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(*e.g.* Adriatic Sea, Aegean Archipelago) over the Mediterranean coastal zone, support the need to consider possible climate change impacts in coastal planning. Nicholls and Hoozemans (1996) argued that coastal management in the Mediterranean Sea needs to address long-term problems and, especially, the impact of climate change on the sea level elevation. Although the tidal signal is an important sea level height factor, the Mediterranean basin's sea level extremes are mainly related to storm surges rather than to the combination of tides and surges (Marcos et al., 2009). The aim of the present paper is to investigate the interannual, seasonal and spatial variability of storm surges in the Mediterranean for the 21st century under specific climatic conditions (A1B scenario, IPCC, 2001), to assess the frequencies of surge maxima and to identify the main driving mechanisms of the latter, in different regional seas.

Storm surges may have significant differences between the various Mediterranean regions, due to the topography of each area and the storm characteristics. There is a high correlation between the surges over the western and central Mediterranean and the North Atlantic Oscillation (Marcos et al., 2009), while its relation with surges in the eastern Mediterranean is also significant but weaker due to the distance from the atmospheric (pressure) action centers. Storm surge events in the Aegean Sea generally exhibit low magnitude and occurrence frequencies of extreme events (Krestenitis et al., 2011). Tsimplis et al. (2009a) investigated the relationship between extreme sea levels and estimated return periods over a temporal span of 14 years, based on measurements from tide-gauges of the Southern European Seas (Iberian, Atlantic and Mediterranean stations); they found significant differences between the various sub-regions. Tsimplis and Blackman (1997) also analyzed tide-gauge data to estimate the return periods of extreme sea levels in the Aegean and Ionian Seas over a period of eight years. Satellite altimetry data for the 1993–2000 period (Tsimplis et al., 2009b) and numerical simulations for the 2000–2004 period (Krestenitis et al., 2011), showed that the increasing gradient of the sea level trend is steeper over the eastern than the western Mediterranean coasts. Significant spatial variability was identified in observations from all seasons (Tsimplis and Shaw, 2010). Regarding the North (N) Adriatic basin, its shape determines unique sea surface dynamics with seiches, surges, astronomical tides, and the long fetch of strong southeasterly winds (Sirocco) that may favor intense storm surge conditions (Lionello et al., 2012a). According to Marcos et al. (2009), the tidal effects may add up to 30 cm in the N. Adriatic coastal region. Another region with intense atmospheric cyclogenesis in the Mediterranean is the Levantine basin (Campins et al., 2011).

The seasonal distribution of sea storms over the Mediterranean region presented significant changes in the last centuries. A change in the seasonal wind patterns may bring storm frequency changes and alter the sea level variations due to meteorological conditions (Camuffo et al., 2000). Such changes in sea storm frequency were strongly associated with tremendous floods in the Spanish Mediterranean coastal zone in the late 16th century, late 17th century, and mid 19th century. Mediterranean surges have a clear seasonal distribution with high positive surges, occurring mostly in winter (Marcos et al., 2011). At the same time, Marcos et al. (2011) also showed an increase in the number of events with higher atmospheric pressure over southern Europe during the 21st century, which are, in turn, linked to fewer number of cyclones over the Mediterranean and, therefore, to a decrease in the number of positive storm surges.

Several global and regional studies showed that changes in atmospheric storminess, predicted for the 21st century, may induce respective alterations to water level heights. According to Giorgi (2006), the Mediterranean is a ‘hot spot’ for climate change. Bengtsson et al. (2006) investigated extensively the storm track changes over the global ocean under the A1B future climatic scenario, used in the current study. Lowe and Gregory (2005) based their work on global climate simulations for 50 or 100 years into the future, and argued that the best practice is to predict the number of events that may exceed a specific height in a fixed length of time. However, global climate models are not sufficient to represent the complexity of the geomorphology of the Mediterranean region (Gualdi et al., 2013). Regional, high spatial resolution models, forced by high resolution atmospheric fields, are required to properly reproduce regional sea level variability processes (Calafat et al., 2012). Recent downscaling techniques improved the simulated trends of atmospheric and oceanic parameters (Somot et al., 2008; Gualdi et al., 2013) over the Mediterranean Sea, by incorporating the small-scale features of the basin. Jordà et al. (2012) investigated the atmospheric contribution to the Mediterranean Sea level variability under three different climate change scenarios (B1, A1B and A2); they found decreasing trends over the western and eastern parts of the basin that range between -0.03 ± 0.03 mm/year and -0.04 ± 0.03 mm/year, -0.16 ± 0.05 mm/year and -0.18 ± 0.04 mm/year and -0.22 ± 0.04 mm/year and -0.25 ± 0.04 mm/year for scenarios B1, A1B and A2, respectively. Similarly, Šepić et al. (2012) found that the sea level trends induced by atmospheric pressure and wind are negative in future climate projections for the medium-emission (A1B) scenario in the Mediterranean Sea. This finding agrees with the analysis of Conte and Lionello (2013), who showed that the climate change, under A1B scenario, may bring a likely attenuation of storminess for the period 1951–2050. However, a localized and/or temporal increase of the mean sea level and land subsidence might still increase the hazard posed by coastal floods due to storm surges. The impact of climate change on the storminess of the N. Adriatic Sea has been examined extensively in numerous recent studies (*e.g.* Lionello, 2005; Nicholls, 2006; Lionello et al., 2003, 2012a,b). Bondesan et al. (1995) showed that, even in the absence of new human activities triggering land-subsidence processes, the additional loss in land level by the year 2100 is expected to vary between 0.5 and 1.5 m in certain areas of the northwestern Adriatic coastal region.

In the present work, we seek to explore the trends of sea level extremes due to atmospheric conditions for a period of 150 years, under a climate scenario with highly increasing concentrations of atmospheric greenhouse gases. The climate change scenario used in our study is A1B, one of the 35 Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC, 2001). The A1B emission scenario is applied on the 3rd version of the Regional Climate Model (RegCM3; Pal et al., 2007). The RegCM3 model's output, in turn, forces a hydrodynamic storm surge model, namely