Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

Future relative sea level for the Mediterranean Sea

Ensemble projections combining terrestrial ice melt, high resolution steric effects, tectonics, and glacial isostatic adjustment

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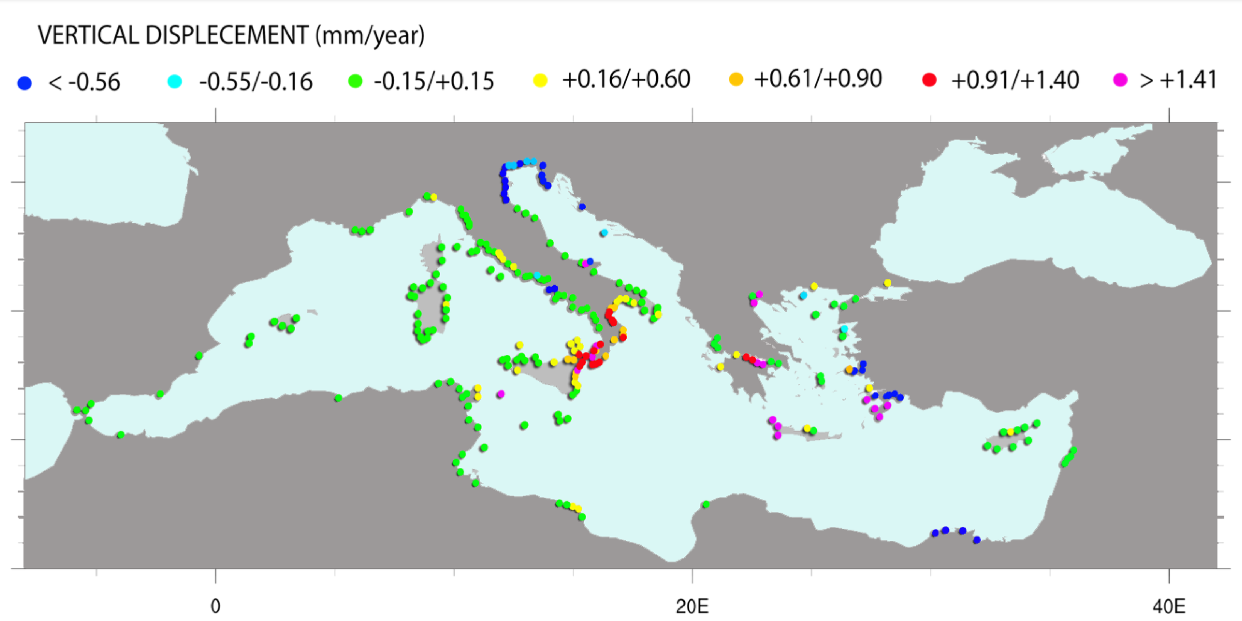
1. Introduction

Climate change-induced variations in local sea level are expected to expose coastal areas to increased risks of extreme flooding and erosion, threatening the health and well-being of inhabitants and damaging coastal ecosystems. Predicting relative sea level rise at the local level is an extremely complex task, as such process is the result of the interaction of a variety of factors occurring on a wide range of temporal and spatial scales. The **Mediterranean Sea** is expected to be particularly vulnerable to future sea level rise, also due to the high population density along its coasts. Future sea levels in the Mediterranean Sea are affected by long-term vertical **tectonic movement**, glacial isostatic adjustment (**GIA**) in response to the melting of the late-Pleistocene ice sheets, and by the elastic contribution of terrestrial ice melt (**TIM**). In addition, rising water temperatures and altered salinity are expected to induce **steric variations** in water volumes, a major component of sea level projections in the Mediterranean. Finally the role of the **hydraulic control** in the Strait of Gibraltar might prove to be a relevant additional factor. The contributions from **GIA** and **TIM** are linearly combined with the **steric effects** projected by the regional oceanographic model **MedBs16**.

2. Tectonics



Present day vertical tectonic movement

Figure 1 Long term geological vertical tectonic movements along the Mediterranean coasts. Data (mm\years) was calculated using

- Long term geological data (since MIS 5.5, 125 ka Bp, with a seal level of 7 ±2 m),
- Short term geological data (since Holocene, 10 ka cal BP, using *Lambeck et al. 2011* model for isostasy).

References

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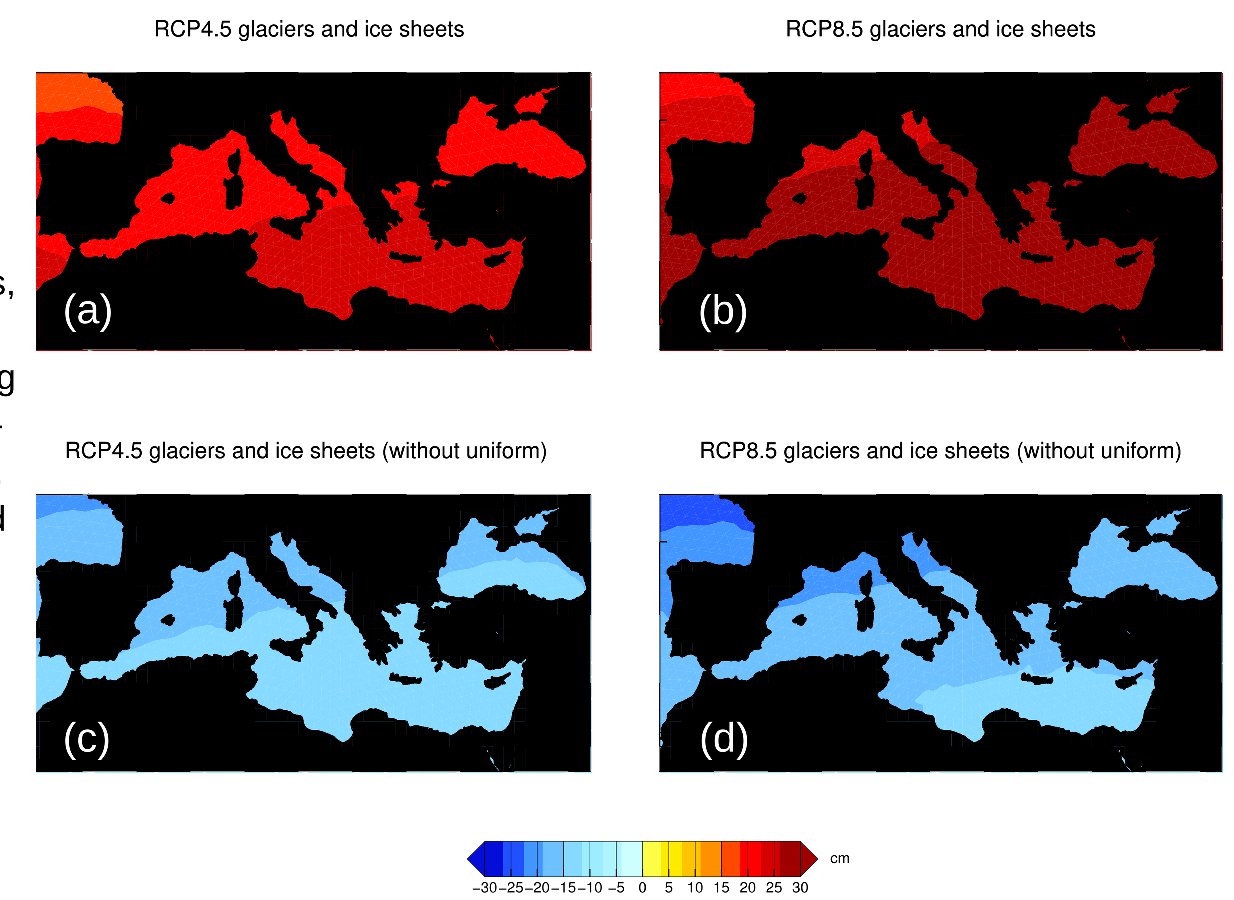
3. GIA and TIM

Figure 2 (a, b) shows the terrestrial ice melt (**TIM**) contribution to future sea-level rise. TIM includes the effects of surface mass balance variations and ice dynamics for the Greenland and the Antarctic ice sheets, and of glaciers and ice caps, for scenarios **RCP4.5** and **RCP8.5** (*Slangen et al. 2014*), corresponding to 35 cm and 43 cm of eustatic sea-level rise to year 2100, respectively. The Sea Level Equation was solved via the **SELEN** code (*Spada and Stocchi, 2007*) (maximum harmonic degree lmax=128), adopting an elastic Earth model with PREM properties; isostatic and rotational effects are accounted for.



In (c, d), the global ocean-averages have been subtracted from (a, b) to highlight isostatic and rotational effects. For the two RCPs considered, it is evident that the sea-level rise expected across the Mediterranean Sea and the Black Sea is markedly sub-eustatic, i.e., well below the global average.

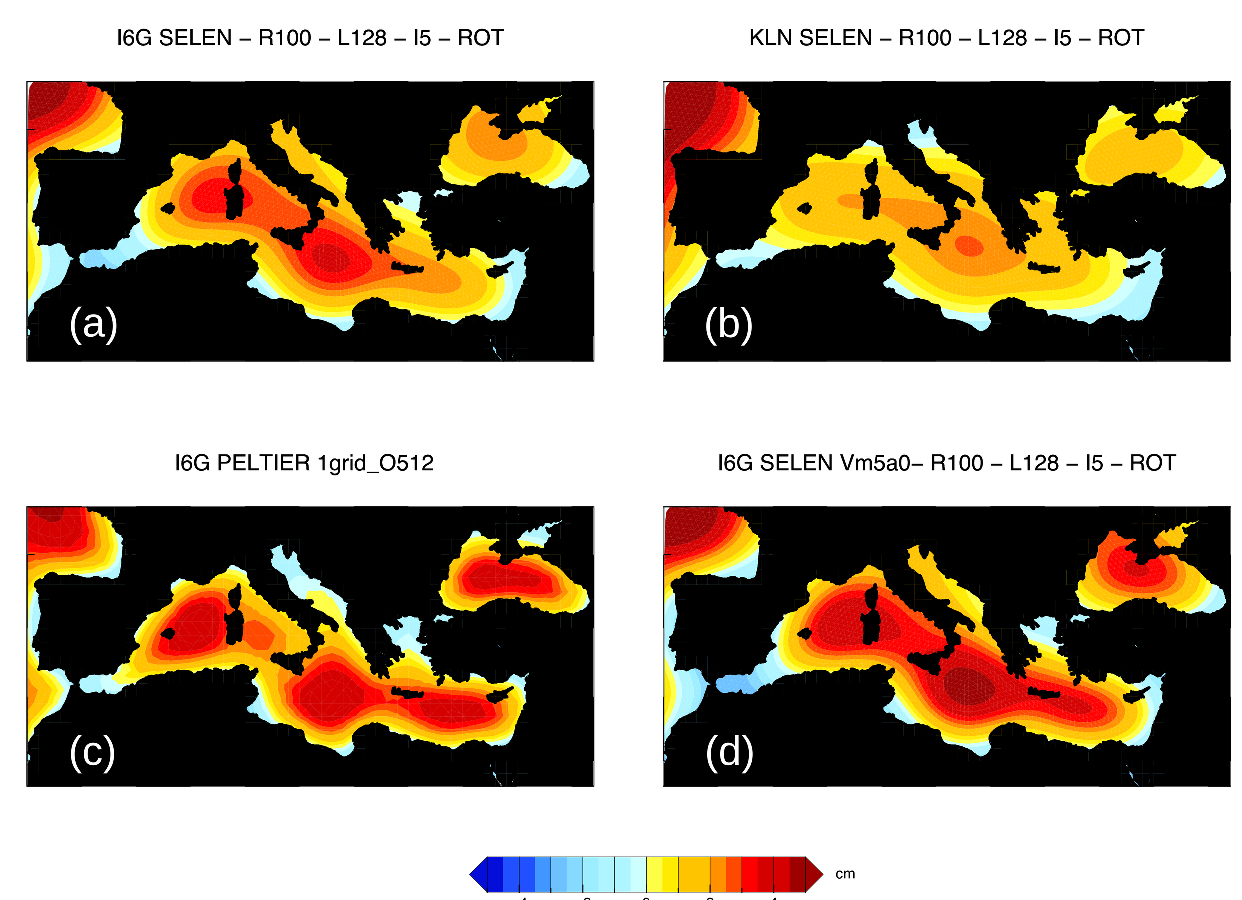


Figure 3 shows the relative sea-level rise induced by glacial isostatic adjustment (**GIA**) in response to the melting of late-Pleistocene ice sheets. Results (a, b, d) are obtained via **SELEN** (lmax=128) taking into account deformational, gravitational, and rotational effects, and assuming incompressibility. In (a) and (c) the **ICE-6G_C**(VM5a) chronology of *Peltier et al. 2015* is employed, assuming volume-averaged mantle densities (c) or the actual density jumps (a). The deglaciation model by *Lambeck et al. 2003* is used in (b), assuming a viscosity jump of a factor 30 across the upper-lower mantle.

Result (c), valid to harmonic degree 512, is from the home page of WR Peltier. The four **GIA** realisations shown have similar geometries but different amplitudes, reflecting the modelling assumptions, the viscosity profile adopted and the ice sheets melting histories. Due to the meltwater driven subsidence in the bulk of the Mediterranean and the Black Sea, the **GIA** contribution is estimated to be in range from 2 to 6 cm, while along the continental coastlines it is expected to be comparatively smaller, typically in the range from -1 to 1 cm.

TIM effects clearly dominate those from **GIA** but are characterised by a comparatively smaller regional variability.

4. Steric component

The Mediterranean thermohaline circulation results from the multiple interactions of a variety of mechanisms and processes whose numerical simulation demands adequate model complexity and resolution
Past numerical experiments suggest that any mixing or variations in mixing in the Strait of Gibraltar might have substantial consequences for the budgets of the basin as a whole. Such variations only retain a linear behaviour when induced by small perturbations of present conditions, on the contrary exhibiting strong nonlinearities in the presence of large disturbances (*Myers and Haines 2002*). It cannot be excluded that significant changes in the Atlantic sea level and in the atmospheric forcing over the Mediterranean could trigger hydraulic transitions from **quasi-maximal** to **sub-maximal exchange** in the Strait, affecting mixing between inflowing and outflowing waters and causing a very nonlinear long-term response in the entire Mediterranean system.

Tidal forcing also needs to be explicitly accounted for, as it has been proved to have non negligible effects on the hydraulic control and consequently on the overall simulated circulation (*Sannino et al. 2015*).
Here we present **MedBs16**, an eddy-resolving model which is capable of simultaneously describing relevant processes such as tidally induced hydraulic control (Figure 5), the basin overall hydrological budget (Figure 6), and a realistic response to lateral Atlantic boundary conditions. Model simulations are realized at ENEA on the High-performance Computing Facility **CRESCO**.

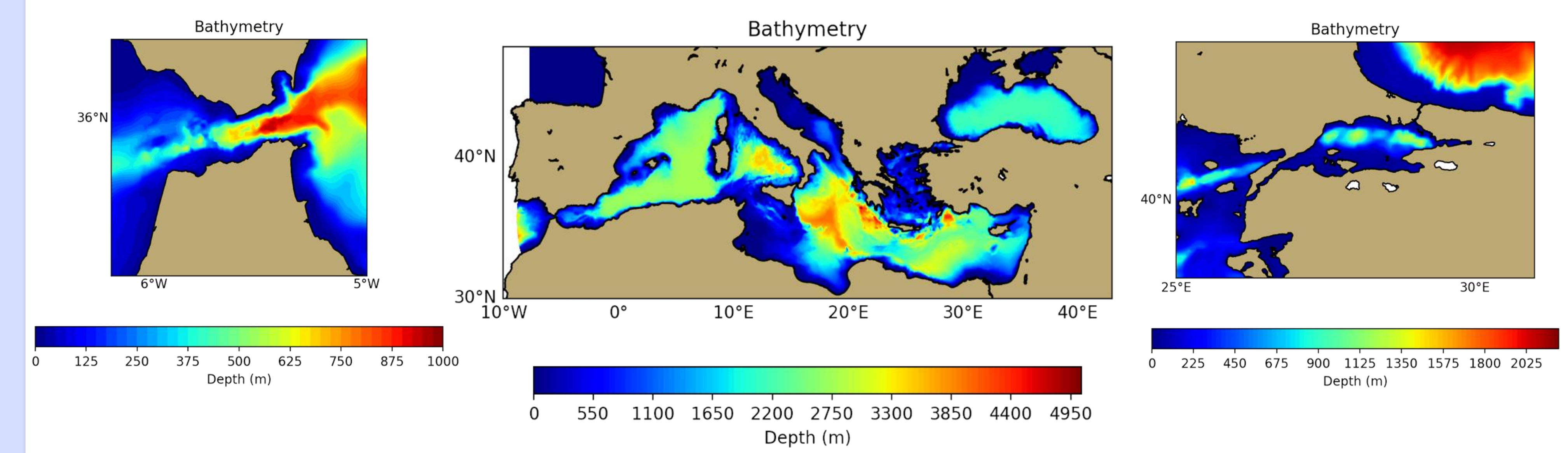


Figure 4: Model bathymetry. Horizontal resolution 1/16° except for Gibraltar and Turkish Straits (1/200). In the vertical 100 unevenly spaced z-levels are prescribed. Partial cell are applied at the bottom.

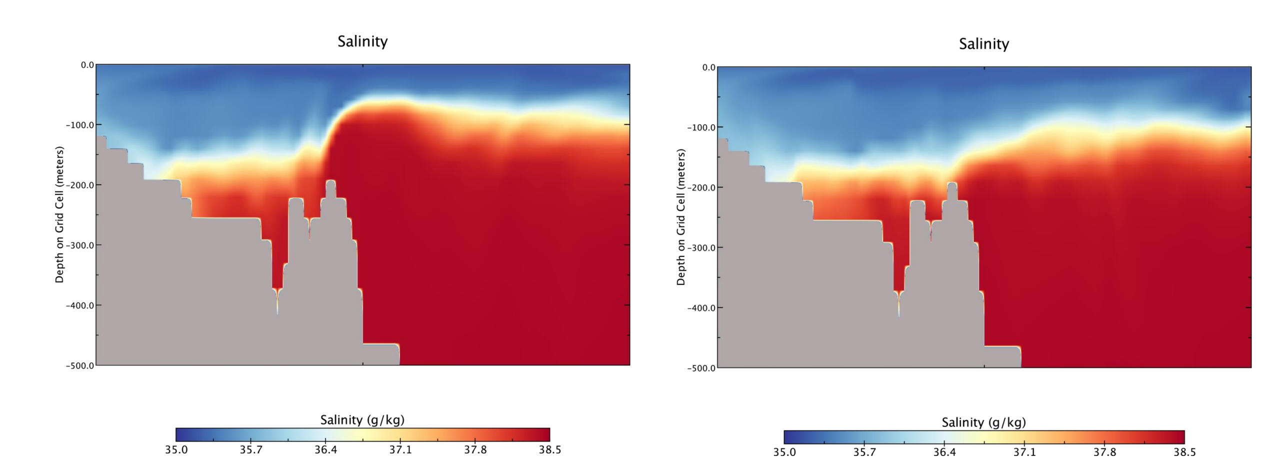


Figure 5: Along-strait salinity section in the Strait of Gibraltar for two instants (6h lag). **MedBS16** is able to simulate the periodic appearance and disruption of the hydraulic jump over Camarinal Sill.

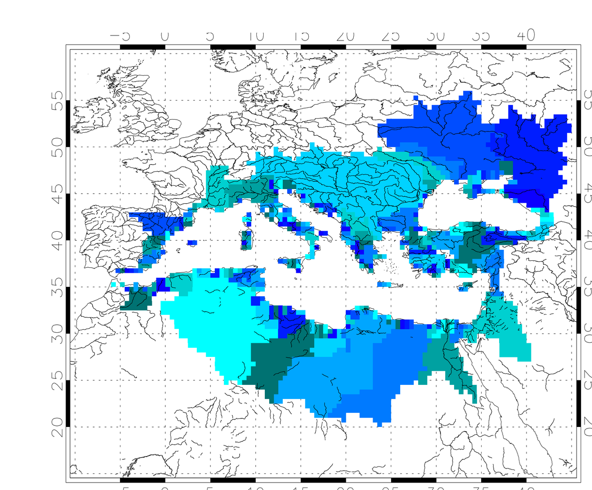


Figure 6: 0.5° x0.5 reconstruction of river basins discharging into the Mediterranean and the Black Sea, extracted from the global data used in *Wisser at al., 2010*. Only the portion of the Nile catchment downstream of the Aswan Dam is accounted for.

MedBs16 is driven by an ensemble of high-resolution regional atmospheric climate simulations performed at SMHI with the RCA4 model (Euro-CORDEX: verification, historical, rcp45, rcp85). These will also provide daily runoff to feed the Water Balance Model routing scheme for river flow computation based on the Muskingum-Cunge river routing method extracted from the Water Balance Model (**WBM**). Boundary conditions in the Atlantic Ocean will be derived by the corresponding driving GCM runs.