HOLOCENE SEA-LEVEL CHANGES IN THE MEDITERRANEAN SEA: THE ROLE OF REMOTE AND NEAR-FIELD ICE SHEETS

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INTRODUCTION

The sea-level change attributed to the melting of continental glaciers is the result of global eustatic, local glacio-hydro-isostatic and geoidal contributions. The relative importance of each factor depends upon the distance between the investigated site and the centers of the ice-sheets, and from the details of the load time-history. The global solution of the sea-level equation (Clark et al., 1978) evidences six zones on the Earth's surface showing characteristic post-glacial relative sea-level (RSL) curves. Here we have solved the sea-level equation for a spherically symmetric visco-elastic Earth to study the existence and contours of the Clark's regions in the Mediterranean Sea. At first we have implemented the complex ICE1 and ICE3G models and we have compared the RSL predictions of the two models at various times. Subsequently, we have considered the ocean load associated with single sub–aggregates of ICE1 and ICE3G and we have addressed how uncertainties on the time–history of Antarctica map onto the RSL curves for the Mediterranean and the shape of the Clark's regions. Our study enlightens the role of the melting of Antarctica on the RSL observed in the Mediterranean, showing that the late–Holocene high-stand observed in this region is mainly caused by the continental levering due to the meltwater load of Antarctica.

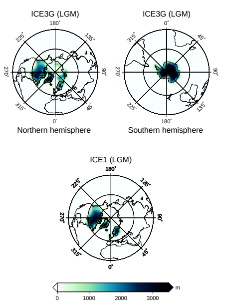
METHOD

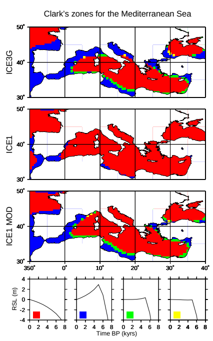
A five-layer model with 100 km thick elastic lithosphere, three-layer Maxwell viscoelastic mantle, and homogeneous inviscid core is assumed. The viscosities in the shallow upper mantle and transition zone are both kept fixed to 1.0×10^{21} $Pa \cdot s$, while for the lower mantle a value of 2.0×10^{21} $Pa \cdot s$ is assumed. The relative sea-level curves and the Clark's zones are obtained solving the sea-level equation (SLE) for a viscoelastic Earth (Farrell and Clark, 1976) trough a pseudo-spectral algorithm. If S denotes the sea-level variation at a given place and time, and I is the change in ice thickness, the SLE reads:

$$S = \frac{\rho_i}{\gamma} G_s \underset{i}{\circledast} I + \frac{\rho_w}{\gamma} G_s \underset{o}{\circledast} S - \frac{m_I}{\rho_w A_0} - \frac{\rho_i}{\gamma} \overline{G_s \underset{i}{\circledast} I} - \frac{\rho_w}{\gamma} \overline{G_s \underset{o}{\circledast} S}$$

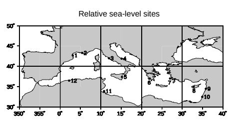
ICE MODELS AND RSL PREDICTIONS

We have employed three distinct ice chronologies: the ICE1 model (Peltier and Andrews, 1976), the ICE3G model (Tushingham and Peltier, 1991) and the ICE1 MOD model, where the Antarctic component of ICE3G has been included into the ICE1 model. The basic features of these glaciers at the LGM are shown in the bottom figure.

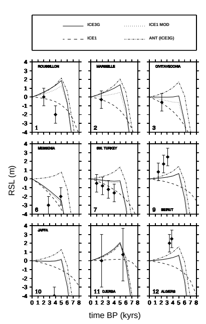


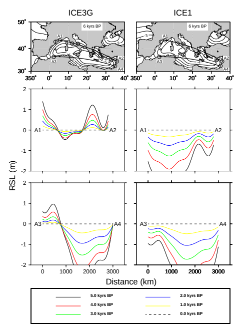


The solution of the SLE for the three models reveals complex patterns of the post-glacial RSL curves according to their geographical location. The most significant difference between the outcomes of ICE3G and ICE1 concerns the extent of the blue zone that is characterized by a late Holocene high-stand and corresponds to the Zone VI of Clark (1978). The solution for ICE1 MOD shows that the presence and the geographical extent of zone VI is to be attributed to the melting of the remote Antarctic component.



The predictions of the RSL variations expected from the melting of ICE3G and ICE1 MOD in specific sites contained in the Peltier database (Tushingham & Peltier, 1992) show a general sea-level high-stand at 5 kyrs BP. When ICE1 is considered instead, the computed RSL curves clearly show a monotonous increase. The only RSL observations an high-stand in the last 5 kyrs correspond to site #9 (Beirut), #11 (Djerba), and #12 (Algiers).



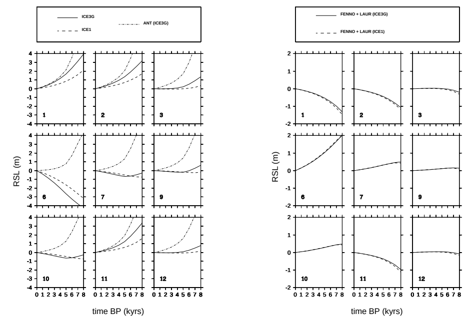


When ICE3G is employed, high-stands are predicted along the continental margins, whereas for ICE1 only monotonous sealevel increases are expected in the whole Mediterranean basin.

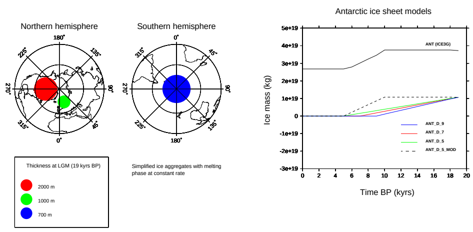
If the Antarctic component of ICE3G is considered separately, a neat high-stand is observed at 5 kyrs BP, when this aggregate completely disappears. This effect is responsible for the high-stands that characterize the whole ICE3G.

RESULTS

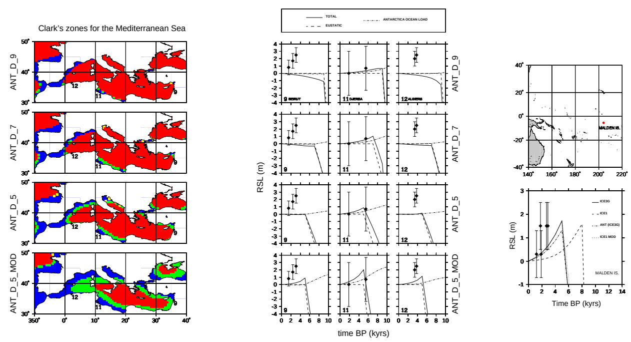
Here we completely neglect the ice–load effect ($I = 0$) and we compute $S = S^H - S^E$, where S^H is the sealevel change arising from the deformation and gravitational effects from the loading of ocean meltwater, and S^E is the eustatic sealevel variation. The contribution of Antarctica is uniform across the Mediterranean (dash–dotted, left frame). Differences in the results obtained for ICE3G and ICE1 reflect differences in the global distribution and time–histories of the two ice complexes. The Laurentian and Fennnoscandian portions of ICE3G and ICE1 produce comparable results (right frame), thus showing that the melting of Antarctica has a major effect on the differences shown in the left frame. A minor role is played by the other small ice aggregates of ICE3G.



To gain a better insight into the role of Antarctica, we now consider a set of simplified disc loads of uniform thickness characterized by a linear deglaciation. Their thickness at the LGM is shown below. While the end of deglaciation for the Laurentian and the Fennoscandia ice loads is kept constant at 6 kyrs BP, this parameter is varied for Antarctica as shown in the figure, thus giving a suite of deglaciation models for this aggregate. In ICE3G Antarctica melts in a period of 5 kyrs, and the mass loss varies almost uniformly in time. In the following we account for both the ocean and the ice loads.



The shape of the Clark's zones for the Mediterranean vary significantly according to the Antarctic deglaciation model assumed. With increasing length of the melting phase, from ANT_D_9 to ANT_D_5, the zones that are characterized by a late–Holocene sealevel high-stand (blue) tend to be enlarged. This is also observed for the transition RSL curves that fall in the green regions. When a time history that closely mimics that of ICE3G is employed, an high-stand is predicted almost everywhere along the continental margins, and the transition region is significantly enhanced. By predictions pertaining to the three sites where high-stands are suggested by the available observations, we observe that with increasing length of the melting phase the timing of the high-stand is delayed with respect to the LGM and its amplitude tend to increase. Qualitatively, the best fit with the observations is obtained for an Antarctic ice sheet similar to that of ICE3G (ANT_D_5_MOD). This is an indication that the RSL observations in the Mediterranean can constrain the timing and extent of the melting of Antarctica.



CONCLUSIONS

The shape and time evolution of the Clark's zones are known to be dictated by the shape of the ice loads and by their time–history. In the case of the Mediterranean region, the observed RSL is expected to stem from various factors, including the collapse of the northern hemisphere forebulges and possibly the meltwater load effect from distant ice aggregates. As we have explicitly shown, the melting of Antarctica causes the RSL curves to look similar to those pertaining to far–field equatorial sites such as Malden Island. However, differently from Malden Island, where the RSL curve is determined by equatorial ocean syphoning that characterizes the zone V (Mitrovica and Milne, 2002), the Mediterranean late–Holocene high-stand can be mostly attributed to the phenomenon of continental levering driven by the ocean load associated to the melting of Antarctica.

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