Sea-level change model predictions based on geomorphological data in Cyclades (Greece) and Tunisia

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1 General aim

The geomorphological and archaeological relative sea-level indicators from the Mediterranean coasts witness the sea level change that accompanied and followed the melting of the late Pleistocene continental ice sheets. Being reasonably distant from the previously glaciated regions, the Mediterranean sites may provide constraints on the volumes of melt–water that have been globally released through time, and therefore on the consequent crustal deformation. In this context a comparative analysis between observed relative sea–level changes from different areas and sea–level predictions from glacio–hydro–isostatic models is useful to investigate the effects and consequences of different ice chronologies and to point out their failures in terms of lack of fit with the data. The latter in fact may be in general the result of underlying, long-term vertical crustal movements related to tectonics. Marking the collisional boundary between African and Eurasian plates, the Mediterranean Sea is in fact affected by complex geodynamical processes which are are driven by lithospheric blocks showing different structural and kinematic interactions

2 Investigated areas

In this study we investigate the late Holocene relative sea-level changes in the central Mediterranean Sea (Fig. 1a) by comparing SE Tunisia (Fig. 1b) and the Cycladic archipelago (Fig. 1c). The occurrence of the Last Interglacial marine deposits at a few meters above the current sea–level confirm the long–term tectonic stability the Gulf of Gabes and Djerba island (Jedoui et al. 2003; Morhange and Pirazzoli 2005). The lack of Holocene uplifted sea–level indicators in the Cyclades rules out the occurrence of long–term uplift or short–term coseismic displacements [Pirazzoli, 2005], but cannot exclude the occurrence of long–term subsidence.

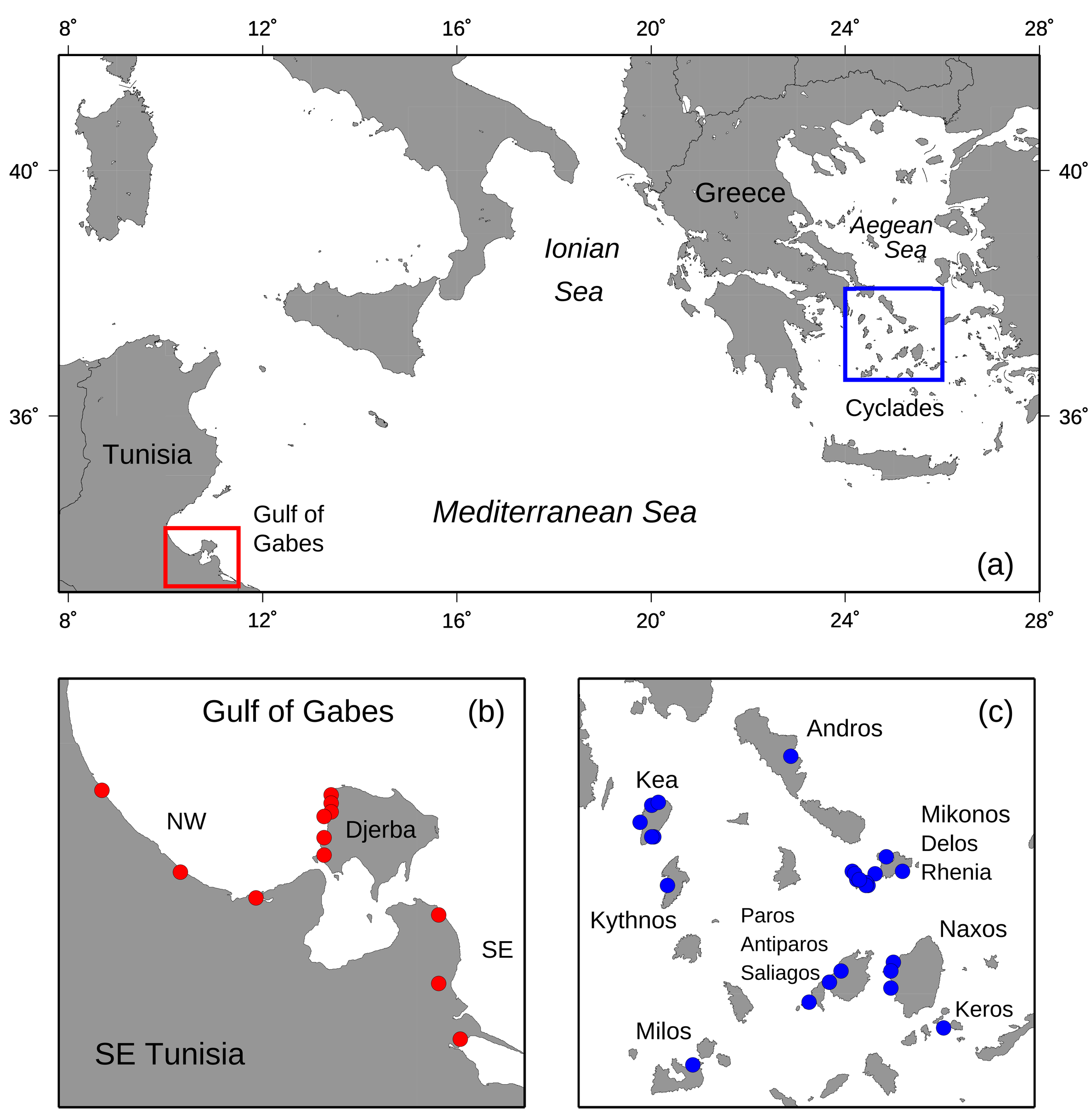

Fig. 1: (a) Central Mediterranean Sea and investigated areas (red and blue boxes). (b) Zoom on the Gulf of Gabes and Djerba island (SE Tunisia). (c) Zoom on Cyclades islands (Aegean Sea).

3 Relative sea-level data

We present a collection of revised published and new relative sea-level data from the Gulf of Gabes in SE Tunisia (Fig. 1a) and from Cyclades islands in the Aegean Sea (Fig. 1b). The palaeo indicators consist of geomorphological markers, biological deposits and archaeological remains covering the last 8.000 years (Fig. 2).

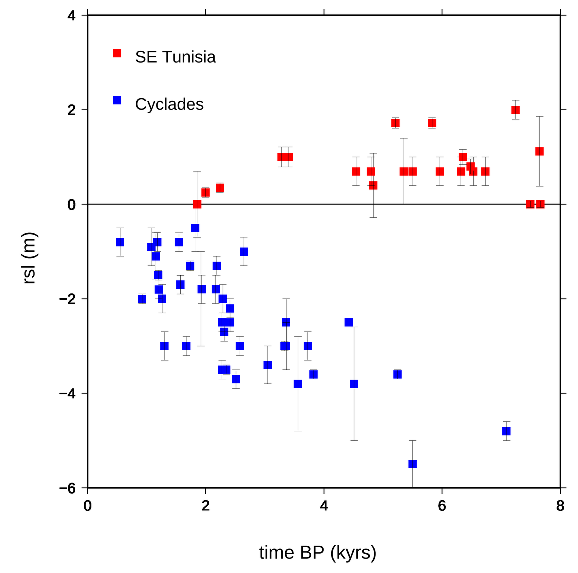

Fig. 2: Collective plot of relative sea-level data from SE Tunisia (red squares) and Cyclades (blue squares) spanning the last 8.000 years (calibrated ages).

SE Tunisia and the Cycladic archipelago show two opposite relative sea-level change trends during the late Holocene. While the absence of higher than present–day Holocene sea–level markers in the Aegean Sea is a common feature shared by the majority of non–upliftfing areas in the Mediterranean, the ∼ 2.0 m sea-level highstand observed in the Gulf of Gabes is the only clear evidence of the occurrence of sea–level fall driven by Glacial–Isostatic Adjustment (GIA)(Morhange and Pirazzoli 2005; Stocchi et al. 2009).

4 1D pseudo–spectral method for GIA

We solve the gravitationally self–consistent Sea Level Equation (SLE) for a spherically symmetric Maxwell Earth to predict the GIA–related relative sea–level changes at the investigated sites [Farrell and Clark, 1976]. The SLE, which accounts for the effects of glacio– and hydro–isostasy, is solved by the "pseudo–spectral" method of Mitrovica and Peltier [1991], assuming a time–dependent ocean function (i. e., variable coastlines and bathymetry).This implies a spatio–temporal discretization in which the distribution of ice sheets varies step–wise and the basic unknowns (i. e., sea–level change S, surface displacement, and geoid height change) are decomposed in series of spherical harmonics.
We adopt the VM2 mantle viscosity profile (Fig. 3c) and compare two different ice chronologies: ICE-5G [Peltier, 2004] and ANU [Lambeck et al., 2004]. Both models share ∼127m of equivalent sea–level at the LGM, but show different melting rates during the last 20.000 years (Fig. 3a). In particular, while the ICE-5G melting phase ends ∼ 5.000 BP, the ANU deglaciation, driven by the melting of Antarctica, continues up to the present–day (Fig. 3b). All computations are performed using the public domain program `SELEN 2.7` by Spada and Stocchi [2007].

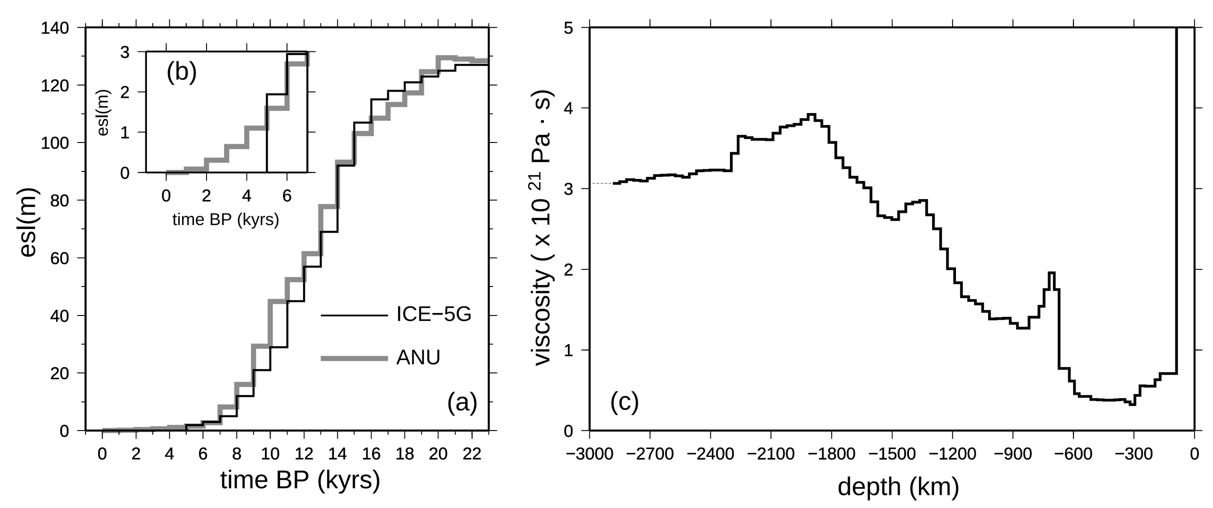

Fig. 3: (a-b) Ice volumes in equivalent sea–level (m) for the ice chronologies ICE-5G [Peltier, 2004] and ANU [Lambeck et al., 2004] used in this study. (c) VM2 mantle viscosity profile used in this study [Peltier, 2004]

5 GIA modeling predictions

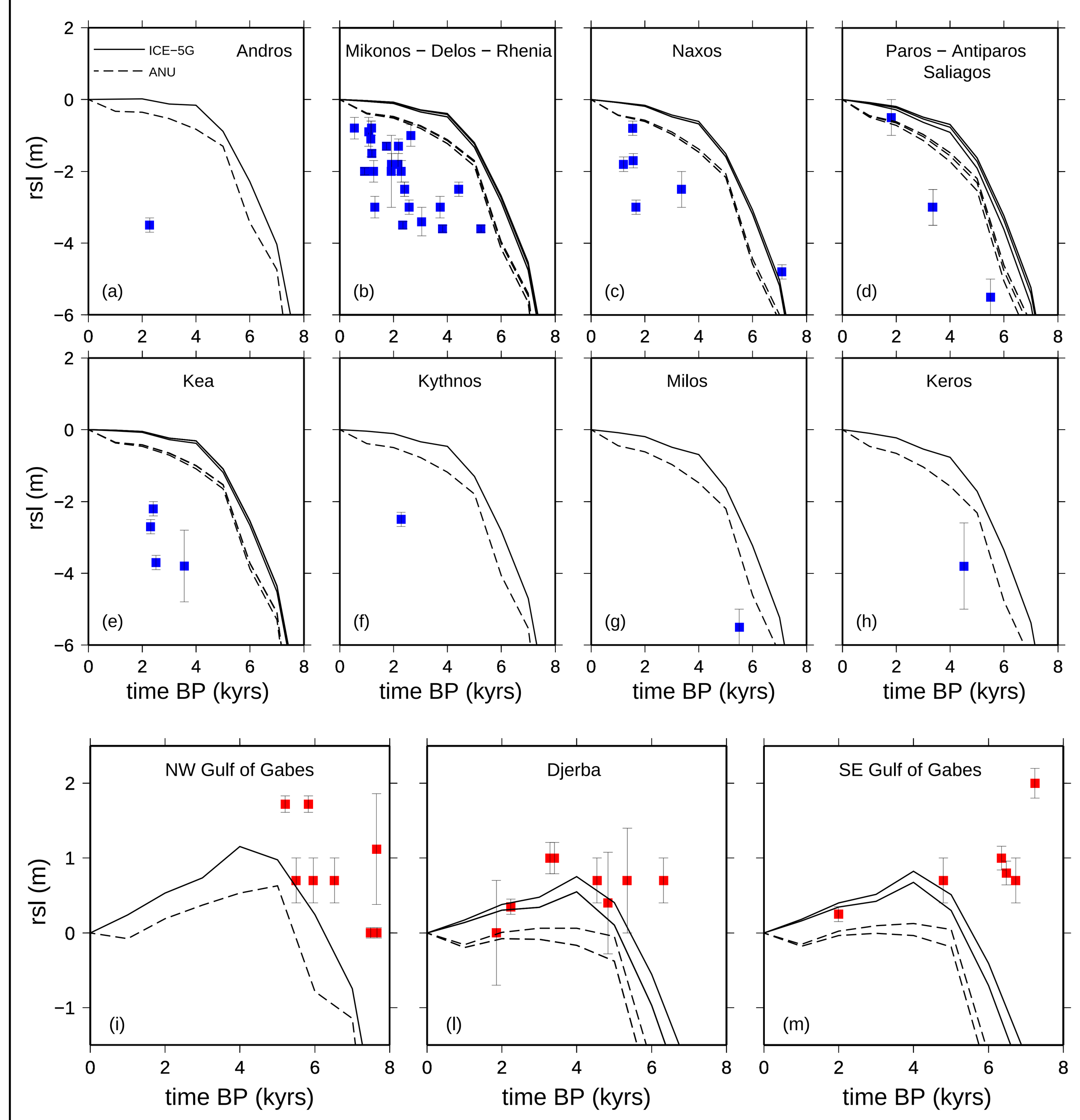

Fig. 4: Relative sea–level curves predicted at Cyclades islands (a to h) and SE Tunisia (i to m) for ICE-5G and ANU chronologies (solid and dashed curves respectively).

The predicted relative sea–level curves broadly confirm the almost opposite Holocene trend observed in SE Tunisia and Cyclades islands (Fig. 4). In the Aegean Sea both ice chronologies result in a relative rising sea–level which never exceeds the present–day level (Fig. 4a–h). Conversely, highstands followed by a sea–level fall are predicted in the Gulf of Gabes (Fig. 4i—m). Despite this general broad agreement, the predicted curves may locally depart significantly from the observations as a consequence of both ice and mantle models parameters and local to regional scale tectonics.

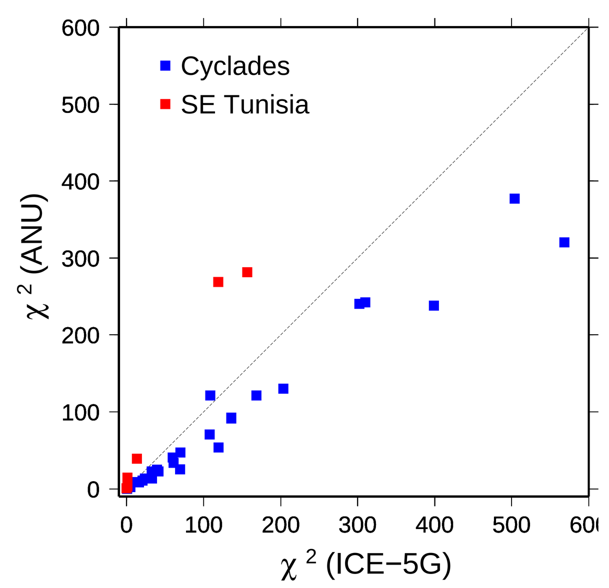

Fig. 5: Site–by–site chi–square misfit analysis

As recently pointed out by Stocchi et al. [2009] the mismatch between predictions and observations in the Gulf of Gabes, which is tectonically stable, may be related to the non realistic melting phase of the Antarctic component of the employed global ice models. In particular the data do not justify a the extended melting phase described by the ANU model (Fig. 3b). The data from Cyclades islands lie sistematically well below the curves predicted for both ice models, and therefore shows an underlying, long–term subsidence related to tectonics.

6 Tectonic deformation at Cyclades

Following Antonioli et al. [2009] we derive the rates of vertical tectonic deformation expected at the Cyclades islands. The tectonic movements are computed at the ages of the different predictions on sea-level position:

$$T = \frac{(H-I)}{G}, \qquad (1)$$

where T is the inferred tectonic rate (mm/yr), H is the observed palaeo sea–level, I is the predicted palaeo sea–level (ICE-5G and ANU), and G is the age of the observed palaeo sea–level.
Errors on tectonic motions are stipulated using an error propagation strategy and provide an upper boundary to the absolute error:

$$\Delta(T) = \frac{\Delta(H)}{G} + \frac{|H-I|}{G}\frac{\Delta(G)}{G}, \qquad (2)$$

where $\Delta(T)$ is the computed uncertainty (mm/yr), $\Delta(H)$ and $\Delta(G)$ are the uncertainties on the measured elevation (m) and calibrated age (years) of the observations. The vertical velocities inferred for the two ice models at each site are then combined to give vertical rates representative of the eight Cycladic islands considered in this study (Fig. 1(c))and of the Cycladic archipelago as a whole. The results are listed in the Table below.

Island(s)	ICE-5G (mm/yr)	ANU (mm/yr)
Total	-0.90 ± 0.20	-0.70 ± 0.2
Andros	-1.50 ± 0.22	-1.36 ± 0.20
Mikonos - Delos - Rhenia	-0.95 ± 0.20	-0.72 ± 0.18
Naxos	-0.82 ± 0.20	-0.60 ± 0.17
Paros - Antiparos - Saliagos	-0.55 ± 0.15	-0.35 ± 0.14
Kea	-1.10 ± 0.17	-0.93 ± 0.16
Kythnos	-1.00 ± 0.22	-0.84 ± 0.16
Milos	-0.70 ± 0.20	-0.50 ± 0.18
Keros	-0.55 ± 0.32	-0.41 ± 0.31

7 Main conclusions

There is a general broad agreement between observed and predicted rates of Holocene relative sea–level change in SE Tunisia and Cyclades islands. Nevertheless, the discrepancies between models and observations have highlighted two main aspects:

- the relative sea–level observations from SE Tunisia may be useful to constrain the late Holocene Antarctic melting, whose end should be placed further back in time (7-8 kyrs BP)
- The Cycladic archipelago is affected by a long–term rate of subsidence between −0.7 and −0.9 mm/yr.

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