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Relative sea level in the Western Mediterranean basin: A regional test of the ICE-7G_NA (VM7) model and a constraint on late Holocene Antarctic deglaciation

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ABSTRACT

The Mediterranean Basin is a region of special interest in the study of past and present relative sea level evolution, given its location south of the ice sheets that covered large fractions of Northern Europe during the last glaciation, the large number of biological, geological and archaeological sea level indicators that have been retrieved from its coastal regions, as well as its high density of modern coastal infrastructure. Models of the Glacial Isostatic Adjustment (GIA) process provide reconstructions of past relative sea level evolution, and can be tested for validity against past sea level indicators from the region. It is demonstrated herein that the latest ICE-7G_NA (VM7) model of the GIA process, the North American component of which was refined using a full suite of geophysical observables, is able to reconcile the vast majority of uniformly analyzed relative sea level constraints available for the Western part of the Mediterranean basin, a region to which it was not tuned. We also revisit herein the previously published interpretations of relative sea level information obtained from Roman-era coastal Mediterranean “fish tanks”, analyze the far-field influence of the rate of late Holocene Antarctic ice sheet melting history on the exceptionally detailed relative sea level history available from southern Tunisia, and extend the analysis to complementary constraints on the history of Antarctic ice-sheet melting available from islands in the equatorial Pacific Ocean. The analyses reported herein provide strong support for the global “exportability” of the ICE-7G_NA (VM7) model, a result that speaks directly to the ability of spherically symmetric models of the internal viscoelastic structure to explain globally distributed observations, while also identifying isolated regions of remaining misfit which will benefit from further study.

1. Introduction

The intense glaciation-deglaciation cycles that dominated climate system variability over the past several hundred thousand years were associated with significant variations of global sea level, not only through the direct impact of these large redistributions of mass between the oceans and the continental cryosphere, but also due to the time-dependent response of the Earth's shape to these varying surface loads, a process commonly referred to as Glacial Isostatic Adjustment (GIA). Careful analysis of the extensive suite of geophysical observables influenced by this process may be employed to generate global reconstructions of continental ice sheet thickness evolution (and corresponding ocean bathymetry changes) and models of the viscosity of Earth's interior. These models of the GIA process may then be employed to provide boundary conditions for coupled climate model reconstructions of past climate conditions (e.g. in the context of the Paleoclimate Modeling Intercomparison Project (PMIP), as discussed in Abe-Ouchi et al., 2015; Ivanovic et al., 2016). Examples of such work based upon the ICE-NG (VMX) sequence of models from the University of Toronto include that on the El Niño Southern Oscillation (ENSO) phenomenon at Last Glacial Maximum (Peltier and Solheim, 2004), that on the strength of the Atlantic Meridional Overturning Circulation (AMOC) at the Last Glacial Maximum (LGM) of Vettoretti and Peltier (2013) and on the Dansgaard-Oeschger Oscillation of Marine Isotope Stage 3 (MIS3) of Peltier and Vettoretti (2014) and Vettoretti and Peltier (2015, 2016).

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Among the wide range of geophysical observables currently being employed to construct models of the GIA process, the extensive databases of geological and biological inferences of past Relative Sea Level (RSL) history that are currently available from numerous coastal regions have been especially critical. In particular, the joint use of high-quality sea level data from the U.S. East coast (Engelhart et al., 2011; Engelhart and Horton, 2012), together with the vast network of precise space-geodetic observations of crustal motion over North America, has led to the latest ICE-7G_NA (VM7) model (Roy and Peltier, 2017), which resulted from further refinement to the precursor model ICE-6G_C (VM5a) model of Argus et al. (2014) and Peltier et al. (2015). Among the many regions from which such detailed knowledge of past sea level evolution is available, the Mediterranean Basin is of particular interest due to its location south of the ice sheets that formerly covered Northwestern Eurasia and to the large amount of both archaeological and geological evidence that is available to provide accurately datable sea level inferences recording relative sea level position over much of the Holocene interval of time. One may reasonably think of the Mediterranean Basin as providing similarly strategic information concerning post-Last Glacial Maximum (LGM) deglaciation as does the U.S. Atlantic coastal region, in terms of the evolution of the nearby Northwestern Eurasian ice sheet complex and of the far-field influence of the Laurentide, Greenland and Antarctic ice sheets.

In the analysis to be reported in what follows, the global "exportability" of the ICE-7G_NA (VM7) model (significantly driven by tuning to the high-quality data from the U.S. East coast), will be tested against the independent, uniformly analyzed data set of geological and biological reconstructions of past RSL evolution covering the Western part of the Mediterranean Basin (Vacchi et al., 2016). This comparison is of substantial interest because of the extensive geographical coverage of the data set and its use of an International Geological Correlation Programme (IGCP) protocol, as opposed to the limited number and/or geographical coverage used in some previous regional GIA analyses (Lambeck & Purcell 2005; Lambeck et al. 2011). The quality of the fit provided by the new model to geophysical observations from a region remote from the area of focus of Roy and Peltier (2017) (and to which that model was not tuned) will be shown to provide further confidence in the global quality of the results achievable based upon application of a spherically-symmetric model of the viscosity of the Earth's interior such as Viscosity Model 7 (VM7).

2. The ICE-7G_NA (VM7) model of the GIA process

The ICE-7G_NA (VM7) model of Roy and Peltier (2017) is based upon a detailed analysis of the regional convergence of the iterative procedure that has been used in the generation of global GIA models by the Toronto group, such as the ICE-6G_C (VM5a) model of Peltier et al. (2015) and its precursors (see also Argus et al., 2014 for a discussion of the Antarctic component of this model). This process has most recently benefited from the existence of a high-quality database of uniformly analyzed past relative sea level indicators collected for the U.S. East coast (Engelhart et al., 2011; Engelhart and Horton, 2012). The misfits identified between reconstructions of RSL history along the southern part of the U.S. East coast and model predictions for these regions were originally found to be eliminated by suitable mantle viscosity variations that led to the VM6 viscosity profile (Roy and Peltier, 2015), but it was thereafter found that this simple replacement of the viscosity profile led to unacceptable misfits to the Global Positioning System (GPS)-derived space-geodetic constraints available over the North American continent (the fit to which had been a key strength of the ICE-6G_C (VM5a) model). In Roy and Peltier (2017), it was found that, through further modest adjustments of both mantle viscosity and ice thickness history, a simultaneous fit to both data sets could be obtained. The resulting ICE-7G_NA (VM7) model was also shown to fit other past RSL data from the formerly ice-covered region of the North American continent, additional data from the time-dependent de-levelling of the Great Lakes region, the time-dependent gravitational signal observed by the Gravity Recovery and Climate Experiment (GRACE) satellites over North America and the present-day tilt of former proglacial lake strandlines (Roy and Peltier, 2017). The differences between the VM7 viscosity structure and its precursors are discussed in detail in Roy and Peltier (2017), but it should be noted that the main distinguishing feature between these models is the progressive increase in mantle viscosity with depth found through the lower mantle and the lower part of the upper mantle. The model also fits global constraints on the GIA process, such as the Fennoscandian spectrum of site-specific relaxation times and the coral-based record of relative sea level change from Barbados (Peltier and Fairbanks, 2006; Roy and Peltier, 2017). A detailed review of the mathematical structure underlying the model can be found in Peltier et al. (2015). It will be important in what follows to understand that, in all regions outside of North America, the loading history in ICE-7G_NA (VM7) has been held fixed to that characteristic of ICE-6G_C (VM5a), listed on the web site of WRP. In order to further critically examine the predictive power of the ICE-7G_NA (VM7) model, it is crucial to extend the analysis and comparison of predictions of the model to geophysical observations from other geographical regions from which equivalently high-quality constraint data is available but to which the model has not been tuned. In this context, the Mediterranean basin is of particular interest, because of the extensive number of biological, geological and archaeological indicators that have been collected from the region (e.g. see Lambeck et al., 2004; Antonioli et al., 2001, 2003, 2006, 2009; Vacchi et al., 2016, among many others for detailed discussions of the available information).

3. The Vacchi et al. (2016) data set of Holocene RSL change

The Vacchi et al. (2016) data set of sea-level index points and limiting information that may be invoked to constrain RSL history in the Western Mediterranean Basin is composed of 469 index points (representing local mean sea level as a function of time in the past (e.g. Van de Plassche, 1986)) and 177 terrestrial limiting and marine limiting constraints (which provide upper and lower limits for past relative sea level, respectively), covering the western part of the Mediterranean Basin and which have been separated into 22 individual regional RSL curves (Vacchi et al., 2016). A large fraction of this information was obtained by Vacchi et al. (2016) from re-interpreted ^{14}C-dated biological material and interpretations of archaeological artefacts from historical coastal infrastructure. It is important to note, for the purpose of the interpretation of these data, that the tidal range observed in the Mediterranean basin is of limited amplitude, with tidal components of less than 10 cm of amplitude for much of the basin, except in Southeast Tunisia, in the Aegean Sea and in the northern section of the Adriatic Sea, where they can be significantly greater (Tsimplis et al., 1995; Sammari et al., 2006; Arabelos et al., 2010). The small tidal range has limited the development of salt-marsh environments in much of the Mediterranean region, which have provided such a rich source of past sea-level index points in other regional sea level reconstructions (e.g. Shennan and Horton, 2002; Engelhart and Horton, 2012). In the Mediterranean basin, most sea-level index points must be obtained from other settings, such as past lagoonal environments (dating samples found in open or semi-enclosed brackish lagoons), or beachrocks (sedimentary rock formations cemented by carbonate minerals in coastal