C. R. Geoscience 349 (2017) 151–158

Contents lists available at ScienceDirect

Comptes Rendus Geoscience

www.sciencedirect.com

External Geophysics, Climate

Extent and dynamic evolution of the lost land *aquaterra* since the Last Glacial Maximum

Giorgio Spada*, Gaia Galassi

Dipartimento di Scienze Pure e Applicate (DiSPeA), Università degli Studi di Urbino "Carlo Bo", Via Santa Chiara, 27, 61029 Urbino, Italy

ARTICLE INFO

Article history:
Received 29 June 2017
Accepted after revision 30 June 2017
Available online 23 August 2017

Handled by Philippe Cardin

Keywords:
Paleogeography
Sea-level change
Glacial Isostatic Adjustment

ABSTRACT

We study the evolution of a recently recognised global geographical feature, named *aquaterra*, enclosing those lands that in previous glacial cycles have been repeatedly exposed and flooded. So far, the geography of *aquaterra* has been studied as a first approximation neglecting the isostatic effects and assuming globally uniform (*i.e.* eustatic) sea-level variations. Focussing on the last deglaciation and considering both global and regional aspects, we show that isostatic effects related with mantle dynamics have indeed played a significant role in the evolution of *aquaterra.* Our analysis is based upon paleogeographic reconstructions in the framework of well-established Glacial Isostatic Adjustment theories.

1. Introduction

Dobson (1999) has proposed the recognition of a vast geographical Earth feature – named *aquaterra* – encompassing the lands that have been inundated and exposed during the last 120,000 years in consequence of the waxing and waning of the continental ice sheets. The study of the extent and chronology of *aquaterra* impacts various disciplines of Earth sciences and has also a number of cultural aspects. In particular, knowledge of the detailed evolution of *aquaterra* could shed light on the human history and on the occupation of landmasses in the past (Flemming, 1985), also providing clues on the pathways of diffusion of material culture (Cavalli-Sforza et al., 1993). Recently, Dobson (2014) has refined the description of *aquaterra.* Furthermore, he has also outlined possible strategies for the exploration of *aquaterra*, which would demand a major collaboration between geographers and oceanographers for its exploration.

Before a systematic exploration of *aquaterra* may become possible, global models of Glacial Isostatic Adjustment (GIA, see Spada, 2017, for a review) can be used to constrain its evolution in space and time. Since the seminal work of Peltier (1994), methods for the reconstruction of the ice age paleotopography have become available, based on the solution of the so-called "Sea Level Equation" (SLE) first introduced by Farrell and Clark (1976). The SLE, which describes the time evolution of sea level in response to the melting of the late-Pleistocene ice sheets, can be solved to predict the changing shape of the shorelines, employing suitable high-resolution numerical methods (see Spada and Stocchi, 2007; Spada et al., 2012). In GIA models, the history of sea-level change is determined by taking the variations of the equipotential geoid surface into account and reconstructing the paleotopography iteratively. Earth rotation effects are also accounted for. For these reasons, GIA models are "gravitationally" and "topographically self-consistent" (Peltier, 1994). Isostatic effects are of interest in the present context, since Dobson (2014), as a first approximation, did not take them into account. Thus, so far, the spatial and temporal extent of *aquaterra* has been defined with the

---

* Corresponding author.
E-mail address: giorgio.spada@gmail.com (G. Spada).

http://dx.doi.org/10.1016/j.crte.2017.06.004

implicit assumption of eustatic (*i.e.* spatially uniform) sea-level variations.

In this note, following the hint of Dobson (2014), we aim at refining the description of *aquaterra* by means of up-to-date GIA modelling. In particular, we shall consider the role of isostasy on the submergence of *aquaterra* since the Last Glacial Maximum (LGM, ~21,000 years ago). During this period, major cultural innovations (see Fig. 3 in Dobson, 2014) and human dispersal occurred (Flemming, 1985; Lahr and Foley, 2004). Furthermore, after LGM existing GIA models define the history of the ice sheets to a sufficient level of detail. By a global analysis and some regional examples, we shall show that dynamic (*i.e.* non-eustatic) processes associated with isostatic deformation, mantle rheology, Earth rotational fluctuations and time variations of topography have affected significantly the extent and evolution of *aquaterra.*

2. Methods

We follow the GIA theory illustrated by Mitrovica and Milne (2003), which generalises the original formulation of the SLE due to Farrell and Clark (1976). The SLE is obtained by imposing mass conservation within the system composed by the Solid Earth, the oceans and the ice sheets, keeping at the same time the sea surface equipotential. The resulting sea-level variations are not uniform across the oceans because of the effects of gravity and deformation, which are delayed as a consequence of the viscoelastic response of the mantle (*e.g.*, Spada, 2017). In the generalised formulation, the SLE accounts for the horizontal migration of shorelines, for the presence of marine-based ice (distinguishing between grounded and floating conditions) and for the effects of rotational feedbacks on sea-level change (Milne and Mitrovica, 1998). The SLE is solved numerically by an improved version of program SELEN (Spada and Stocchi, 2007; Spada et al., 2012), employing an icosahedron-based equal-area grid (Tegmark, 1996) with a spacing of ~20 km, sufficient to describe the isostatic effects on the global distribution of *aquaterra* in detail. The length of the integration time step is 0.5 kyr.

In this study, following the suggestion by Dobson (2014), we account for glacial isostasy adopting the global deglaciation chronology ICE-5G(VM2) of Peltier (2004) for the continental ice complexes. It assumes isostatic equilibrium before the LGM, and no deglaciation during the last 4 kyr. ICE-5G(VM2) is constrained to fit a global set of relative sea-level (RSL) data and represents a refinement of previous ICE-X models developed by W. R. Peltier (see, *e.g.*, Peltier, 2004, and references therein). The ice thicknesses of continental ice sheets at the LGM and at present time according to ICE-5G(VM2) are shown in Fig. 1. In this work, we adopt a volume-average of the original multilayered viscosity profile VM2 (Peltier, 2004), with a viscosity of 2.7, 0.5, and 0.5×10^{21} Pa·s in the lower mantle, transition zone and shallow upper mantle, respectively. The thickness of the elastic lithosphere is 90 km. It is worth noting that GIA models are affected by some uncertainty, associated with limited knowledge about the melting history of the ice sheets and the rheology of the Earth. As a consequence, it should be taken into consideration that different GIA models can provide slightly different predictions for the history of sea-level change, which will also affect the features and evolution of *acquaterra.*

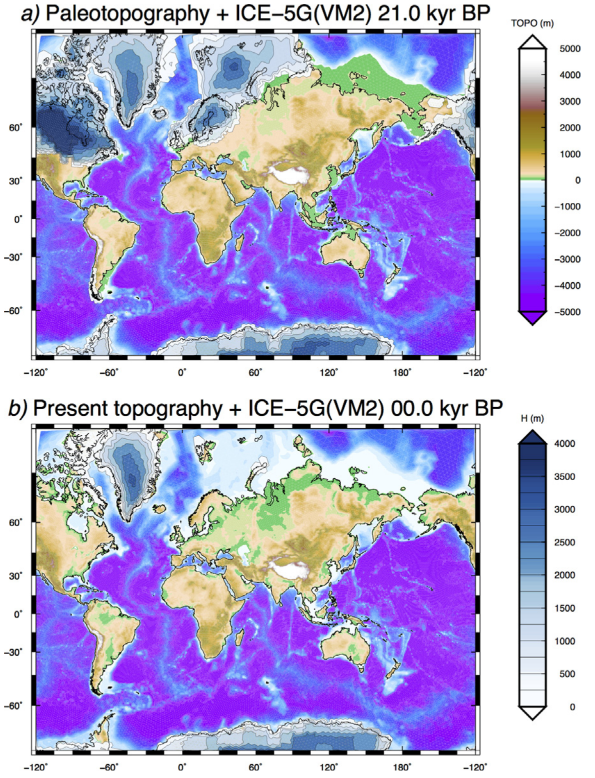

Fig. 1. Paleo-topography al the LGM, reconstructed solving the SLE (a). The present-day topography, corresponding to ETOPO1, is shown in (b). The global ice thickness distribution according to the GIA model ICE-5G(VM2) is also shown.

Following Mitrovica and Milne (2003), paleobathymetry is reconstructed by performing two nested iterations of the SLE. In the internal iteration, the SLE is solved for a given *a priori* distribution of bathymetry; in the external one, the bathymetry is updated be means of the pattern of relative sea-level change obtained in the internal iteration. This procedure is performed adopting the “bedrock version” of the one arc-minute resolution ETOPO1 global relief (Amante and Eakins, 2009) as the present-day condition. The Earth’s topographies at the LGM and at present time are shown in Fig. 1.

3. Results

We first consider the evolution of *aquaterra* from a global viewpoint; then we show results obtained for a few regional case studies.

3.1. A global view

A first guess of the global distribution of *aquaterra* since the LGM is shown in Fig. 2a, where blue pixels mark a grid cells belonging to *aquaterra.* To obtain this map, which is