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Research paper

Last deglacial relative sea level variations in Antarctica derived from glacial isostatic adjustment modelling

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ABSTRACT

We present relative sea level (RSL) curves in Antarctica derived from glacial isostatic adjustment (GIA) predictions based on the melting scenarios of the Antarctic ice sheet since the Last Glacial Maximum (LGM) given in previous works. Simultaneously, Holocene-age RSL observations obtained at the raised beaches along the coast of Antarctica are shown to be in agreement with the GIA predictions. The differences from previously published ice-loading models regarding the spatial distribution and total mass change of the melted ice are significant. These models were also derived from GIA modelling; the variations can be attributed to the lack of geological and geographical evidence regarding the history of crustal movement due to ice sheet evolution. Next, we summarise the previously published ice load models and demonstrate the RSL curves based on combinations of different ice and earth models. The RSL curves calculated by GIA models indicate that the model dependence of both the ice and earth models is significantly large at several sites where RSL observations were obtained. In particular, GIA predictions based on the thin lithospheric thickness show the spatial distributions that are dependent on the melted ice thickness at each sites. These characteristics result from the short-wavelength deformation of the Earth. However, our predictions strongly suggest that it is possible to find the average ice model despite the use of the different models of lithospheric thickness. By sea level and crustal movement observations, we can deduce the geometry of the post-LGM ice sheets in detail and remove the GIA contribution from the crustal deformation and gravity change observed by space geodetic techniques, such as GPS and GRACE, for the estimation of the Antarctic ice mass change associated with recent global warming.

1. Introduction

An important source of information on the ice thicknesses and extents since the Last Glacial Maximum (LGM) is the changes in the relative sea level (RSL). In regions where high-quality RSL data are available, these data can be used to constrain past ice sheet changes (e.g., Zwartz et al., 1998), mantle viscosity (e.g., Nakada and Lambeck, 1989), or both. In Antarctica, however, there are few geological and geographical RSL observations, largely due to the lack of coastal ice-free areas where organic material for radiocarbon dating can accumulate. Thus, RSL curves have been obtained at a small number of sites on the Antarctic Peninsula (Bentley et al., 2005); on the coast of East Antarctica in the Vestfold Hills (Zwartz et al., 1998), Sôya Coast (Miura et al., 2002) and Windmill Islands (Goodwin, 1993); and in the Ross Sea region (Baroni and Hall, 2004). Nakada et al. (2000) demonstrated RSL variations along the coast of Antarctica from glacial isostatic adjustment (GIA) modelling and constrained the maximum (ANT5) and minimum (ANT6) models of the ice-loading histories of the Antarctic ice sheet during the last deglaciation by comparing the modelling results and field observations. Furthermore, Ivins and James (2005) improved the reconstruction of the Antarctic ice sheet history using both RSL data and space-based geodetic observations (GPS and GRACE) and proposed a new ice load model (IJ05) that is consistent with both the geologic and geodetic observations in Antarctica.

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Far-field sea level observations from Barbados, the Sunda shelf and Tahiti (Fairbanks, 1989; Hanebuth et al., 2000; Deschamps et al., 2012) show a large and rapid rise in sea level approximately 14 calibrated kilo-years before present (cal. kyr BP). This event, described as meltwater pulse IA (MWP-IA), is considered to represent a eustatic sea level (ESL) rise of approximately 20 m over 500 yr. Clark et al. (2002) suggested that the Antarctic ice sheet melting contributed to the MWP-IA event, and the results contribute to the controversy regarding whether the MWP-IA event was sourced primarily from the northern or southern hemisphere (Clark et al., 2002; Bassett et al., 2005; Peltier, 2005). Recently, Bassett et al. (2005) extended the work of Clark et al. (2002) to consider the full viscoelastic solid earth response to MWP-IA. Comparing the GIA modelling and far-field observations from Tahiti, Barbados and Sunda indicated that a dominant Antarctic contribution to MWP-IA (ca. 15 m eustatic equivalent) is required to fit the far-field observations with a single ice history and earth model. Accordingly, the estimation of the Antarctic ice sheet history during the last deglaciation provides an important clue to understand the mechanism of the abrupt climate change.

In this study, we present the RSL predictions along the coast of Antarctica using the typical ice-loading models and earth structure models, which are characterised by the lithospheric thickness (effective elastic thickness: T_e), to validate the permissible combinations of conventional ice and earth models.

2. Glacial isostatic adjustment modelling

2.1. Sea level equation

Sea level variations predicted by the GIA modelling associated with the last deglaciation on a viscoelastic Earth have been formulated by Farrell and Clark (1976). The RSL variation ($\Delta\zeta_{\mathrm{RSL}}$) at site x and time t can be expressed as follows (e.g., Farrell and Clark, 1976; Nakada and Lambeck, 1987):

$$\Delta\zeta_{\mathrm{RSL}}(x,\ t) = \Delta\zeta_{\mathrm{ESL}}(t) + \Delta\zeta_{\mathrm{isos}}(x,\ t) + \Delta\zeta_{\mathrm{local}}(x,\ t) \tag{1}$$

in Eq. (1), $\Delta\zeta_{\mathrm{RSL}}$ represents a change in sea level relative to the present sea level. RSL changes vary both over time (t) and in space (x), and their causes may be divided into three distinct terms. ESL change ($\Delta\zeta_{\mathrm{ESL}}$) is the spatially uniform change in sea level that occurs when a volume of water is released from the ice sheets into the ocean. Sea level change induced by isostatic crustal deformation ($\Delta\zeta_{\mathrm{isos}}$) varies in both space and time and is the result of perturbations to the shape of the solid Earth and the geoid due to temporal variation in the loading by ice and water. These two components represent the changes in sea level that result from GIA. The third term ($\Delta\zeta_{\mathrm{local}}$) in Eq. (1) refers to the local factors that cause sea level change. This term includes the local tidal regime, the consolidation of sediments and tectonic processes. These factors are neglected in this paper, as their contributions to the sea level in the region where we focused are relatively small.

Several important processes are neglected in the original formulation of the sea level equation defined by Farrell and Clark (1976). These processes have been progressively included in subsequent GIA studies. The treatment of shoreline migration, the presence of grounded or floating ice and rotational feedback within the sea level equation are described below.

The first studies to implement time-varying ocean geometry in the context of GIA were performed by Lambeck and Nakada (1990) and Johnston (1993). Subsequent studies have developed increasingly accurate techniques to address shoreline migration (e.g., Milne et al., 1999; Okuno and Nakada, 2001; Lambeck et al., 2003; Mitrovica and Milne, 2003). It has become standard practice to use a time-varying version of the ocean function to obtain precise solutions of the sea level equation. In particular, the evaluation of an ocean function is very important in calculating the sea level changes for the former glaciated regions characterised by both large crustal deformations due to glacial rebound and the existence of ice sheets (e.g., Milne et al., 1999; Okuno and Nakada, 2001). We use a formulation of the water load component introduced by Milne et al. (1999). Milne et al. (1999) used an ocean function based on paleotopography, including the height of the ice sheet, in which they considered the water loads due to the influx of meltwater to subgeoidal solid surface regions previously covered with the marine-based late Pleistocene ice sheets. In fact, the water influx in these regions, including Hudson Bay and the Gulf of Bothnia, contributes significantly to the surface load (e.g., Milne et al., 1999; Okuno and Nakada, 2001).

Further modifications to the extent of the ice- and ocean-loading functions arise in the presence of floating and marine-grounded ice. In previous versions of the sea level equation, ocean-loading has been assumed to be the change in the height of the ocean column. However, in the presence of floating or marine-grounded ice, the water load change will be replaced by the ice load change, and loading at this location will depend upon ice thickness instead of ocean height in the case of floating ice, or only on ice thickness in the case of marine-grounded ice. Special care must be taken when calculating the local changes in RSL following the inundation with water of regions uncovered by retreating marine-grounded ice or the advance of marine-grounded ice into locations with non-zero ocean depth (e.g., Okuno and Nakada, 2002). Ice- and ocean-loading functions must also consider the position of the transition from grounded to floating ice, which is assumed to occur when the mass of the water displaced by the ice is greater than the mass of the ice.

In theory, the sea level equation presented by Farrell and Clark (1976) is based on a non-rotating Earth. Several studies have extended this theory to include rotational effects (e.g., Milne and Mitrovica, 1996, 1998b). Changes in the configuration of the Earth's surface mass load (ice and ocean) perturb the Earth's rotation vector. A change in the rotational state of the Earth deforms both the geoid and the solid surface and hence affects the sea level, thus further reconfiguring the Earth's surface mass load. This feedback process must be incorporated into the sea level equation and will require iterative methods to solve (e.g., Mitrovica et al., 2005).

Neglecting any of the processes described above introduces errors into the GIA calculations. The largest error arises due to the neglect of shoreline migration; the RSL change since the LGM will be over/under-estimated by up to 125 m (i.e., the eustatic change since the LGM) within the region of shoreline migration. Errors of over 10% may also be incurred in regions with broad continental shelves, and late Holocene far-field sea level highstand predictions may contain errors of over 2 m (e.g., Milne and Mitrovica, 1998a; Okuno and Nakada, 1998). The error will be smaller in regions with steep topography at the shoreline, as such topography limits the spatial extent of shoreline migration. The errors can be reduced to approximately 1% using the calculation algorithms developed by Johnston (1993), Milne et al. (1999) and Okuno and Nakada (2001), and will be a function of the time step used.

2.2. Ice histories

In GIA modelling, ice-loading history is defined using temporal step functions; the ice thicknesses at each location are specified at a series of discrete times. The early models used parabolic 'disks' of ice whose thicknesses, but not radius, vary with time. The axisymmetric disks enable the analytical determination of the viscoelastic response to such a load by the spherically symmetric Maxwell Earth (e.g., James and Ivins, 1998 for a thorough analysis). The more recent models specify the ice thicknesses for a given time