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Glacial isostatic adjustment associated with the Barents Sea ice sheet: A modelling inter-comparison

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ABSTRACT

The 3D geometrical evolution of the Barents Sea Ice Sheet (BSIS), particularly during its late-glacial retreat phase, remains largely ambiguous due to the paucity of direct marine- and terrestrial-based evidence constraining its horizontal and vertical extent and chronology. One way of validating the numerous BSIS reconstructions previously proposed is to collate and apply them under a wide range of Earth models and to compare prognostic (isostatic) output through time with known relative sea-level (RSL) data. Here we compare six contrasting BSIS load scenarios via a spherical Earth system model and derive a best-fit, χ^2 parameter using RSL data from the four main terrestrial regions within the domain: Svalbard, Franz Josef Land, Novaya Zemlya and northern Norway. Poor χ^2 values allow two load scenarios to be dismissed, leaving four that agree well with RSL observations. The remaining four scenarios optimally fit the RSL data when combined with Earth models that have an upper mantle viscosity of 0.2–2 × 10^{21} Pa s, while there is less sensitivity to the lithosphere thickness (ranging from 71 to 120 km) and lower mantle viscosity (spanning 1–50 × 10^{21} Pa s). GPS observations are also compared with predictions of present-day uplift across the Barents Sea. Key locations where relative sea-level and GPS data would prove critical in constraining future ice-sheet modelling efforts are also identified.

1. Introduction

The Barents Sea, bordered by Norway and Russia to the south, Svalbard to the north and Novaya Zemlya to the east (Fig. 1), was extensively covered by an ice sheet during the last glacial cycle and experienced at least three shelf-wide glaciations during that period (Mangerud et al., 1998). Significant debate existed in the past over the extent (restricted to extensive) of the ice cover during the last glacial maximum, or LGM (e.g. Boulton, 1979; Hughes et al., 1977; Grosswald and Hughes, 2002), which occurred in this northerly region slightly later than the global LGM (Clark et al., 2009). It is, however, now more widely accepted that a single extensive grounded ice sheet was present over the Barents Sea during the last glaciation (Svendsen et al., 2004; Patton et al., 2015; Hughes et al., 2016), which fully or partially covered Svalbard, Franz Josef Land and Novaya Zemlya, and coalesced with the Fennoscandian ice sheet in the south. This consensus has been reached following the collection and analysis of a large amount of terrestrial and marine-based geophysical data in recent years (e.g. Mangerud et al., 1999; Ottesen et al., 2005; Andreassen et al., 2008; Hormes et al., 2013). In the western part of the Barents Sea, the extent of the ice sheet and pattern of deglaciation after the LGM is relatively well known (e.g. Landvik et al., 1998; Winsborrow et al., 2010; Ingólfsson and Landvik, 2013). Significant uncertainties, however, still remain regarding its precise extent, its thickness evolution and the timing of deglaciation in the central and eastern sector of the Barents Sea which has received less attention (Polyak et al., 1997, 2008; Bjarnadóttir et al., 2014; Patton et al., 2015; Hughes et al., 2016).

One means to improve the state-of-knowledge regarding the 3D ice extent and deglacial timing is through modelling of the glacial isostatic adjustment (GIA) signal resulting from the ice loading and unloading. We aim here to use a GIA model to test different ice load scenarios so as to better understand former ice extent in the Barents Sea over the last glacial cycle. We achieve this by solving the sea-level equation in the manner of Mitrovica and Milne (2003), using six different ice load scenarios that are available for this region (five published and one currently being developed). We use published relative sea-level (RSL) data bordering the Barents Sea, assembled in a consistent manner into one database, to investigate

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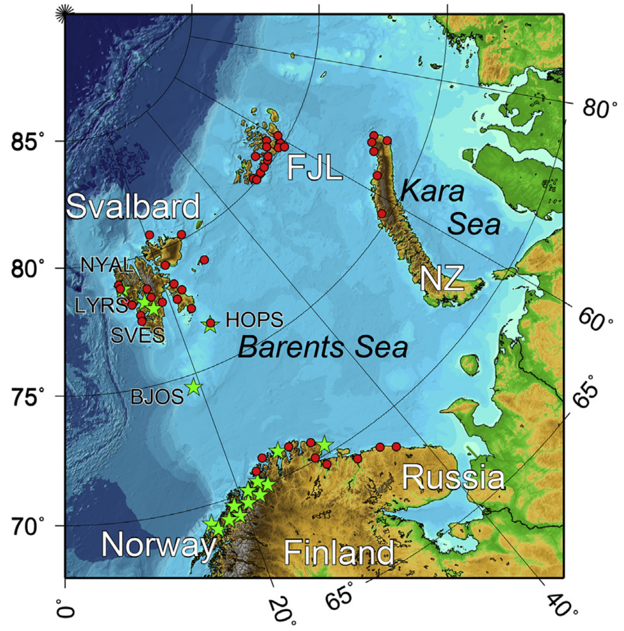

Fig. 1. Bathymetry of the Barents Sea and surrounding land masses (FJL: Franz Josef Land, NZ: Novaya Zemlya). GPS stations (and their names in Svalbard) as well as locations of relative sea-level (RSL) data used in this study are indicated with green stars and red circles, respectively.

the accuracy of the different ice load scenarios available for this area and to infer which one provides an overall best fit to the local sea-level history. By comparing the RSL data with the model predictions, we also solve for the optimal Earth rheology in this region. Finally, we compare the present-day uplift prediction, obtained from our best-fit model, with GPS data from Svalbard and Scandinavia, and identify key locations that can be used in the future to better constrain the ice sheet reconstruction.

2. GIA modelling

2.1. Numerical code

We solve the sea-level equation (first derived by Farrell and Clark, 1976) using the implementation from Mitrovica and Milne (2003) and Kendall et al. (2005). Gravitationally self-consistent sea-level changes are computed, taking into account shoreline evolution as well as the time-dependent evolution of marine-based ice margins. The sea-level equation is solved iteratively using an extended pseudo-spectral algorithm.

This numerical code assumes a spherically symmetric Earth, whose properties are based on the Preliminary Reference Earth Model, or PREM (Dziewonski and Anderson, 1981). The Earth model is implemented as an input with three variables: lithosphere thickness and upper and lower mantle viscosities. We use 300 different Earth models, where the lithosphere thickness ranges from 46 to 120 km and the upper and lower mantle viscosities range from 0.05×10^{21} to 5×10^{21} Pa s and 1×10^{21} to 50×10^{21} Pa s, respectively. These Earth models cover the range of Earth parameters generally found or inferred for this area from a range of geophysical techniques (e.g. Steffen and Kaufmann, 2005; Kaufmann and Wolf, 1996; Klitzke et al., 2014). The second input required for the GIA model is the history of ice loading (see Section 2.2), giving the distribution of ice (extent and thickness) at the surface of the Earth at specific times during the last glacial cycle (i.e. 122 ka BP to present).

After solving the sea-level equation, we derive an estimate of the present-day rate of surface deformation across the Barents Sea, and we determine the time evolution of the sea level at specific locations. These are the two main outputs we will utilize in this study for comparison against field data.

2.2. Ice loading scenarios

Six different ice loading scenarios over the Barents Sea area are tested based on: (i) the ICE-5G scenario (Peltier, 2004), (ii) the ICE-6G_C scenario (Argus et al., 2014; Peltier et al., 2015), (iii) the ANU scenario (Lambeck et al., 2010), (iv) the model developed by Näslund et al. (2005); Näslund (2006), henceforth referred to as the N05 scenario, (v) the model developed by Siegert and Dowdeswell (2004), henceforth referred to as the S04 scenario, and (vi) the University of Tromsø, UiT, scenario. The main characteristics of each model are presented in Table 1, including the name given to each model, as used in the rest of the study, and the spatial and temporal coverage of each scenario. Three of the models are only defined locally for Scandinavia and the Barents Sea, while the others (ICE-5G, ICE-6G_C and ANU) define global ice sheet changes. The ICE-5G scenario has a lower spatial resolution (1° grid) than the other models, however, for modelling purposes, all the scenarios are resampled to a spherical harmonic truncation level of degree and order 256.

Each of the ice loading scenarios has been produced using different methods and sets of constraints and it is important to consider the relative merits and limitations of each. In essence though, the six scenarios can be divided into two main types of approach: i) those based on isostatic adjustment modelling (ICE-5G, ICE-6G_C and ANU) that use RSL data and dated margins to inversely constrain an optimal ice loading pattern, and, ii) those based on forward, time-dependent ice flow modelling (N05, S04 and UiT) that are forced by past climate change and mass-balance distribution to yield the free evolution of horizontal ice thickness through time.

The ICE-5G scenario (Peltier, 2004) is constrained by dated observations of ice sheet margins, RSL curves and the global mean sea-level curve. It uses the radial viscosity model VM2 from Peltier (2004). We use the ICE-5G scenario with a wider range of Earth models in our modelling to test the effects of the Earth model chosen and study how well each of our free parameters is resolved by our method and data. Using a different Earth model to VM2 in the far field will not significantly alter the local deformation caused by the far-field loading. Moreover, although ICE-5G is constrained by RSL data, it has not been tested against many of the recently-published data that we include in this study. Thus, although a good fit to RSL data might be anticipated, one should not expect the fit between model predictions and observations to be perfect by default.

ICE-5G has been recently revised and updated to the ICE-6G_C scenario by Argus et al. (2014) and Peltier et al. (2015). It is built mostly on the same principles as its predecessor, but is constrained by an updated data set of geological observations (including relative sea-level data). Compared with its predecessor, the ICE-6G_C reconstruction uses the widest range of GPS observations available to constrain the model. A major improvement from ICE-5G to ICE-6G_C comes from the new definition used for the Stokes gravity coefficients, as described by Chambers et al. (2010). The ICE-6G_C scenario has a higher temporal resolution over the last 26 ka compared with the ICE-5G scenario; and it has been developed in conjunction with the radial viscosity model VM5a. Once again, we tested this scenario against a wide range of Earth models, including an average of VM5a.

The ice extent and thickness of the ANU scenario (Lambeck,