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The impact of water loading on postglacial decay times in Hudson Bay

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ABSTRACT

Ongoing glacial isostatic adjustment (GIA) due to surface loading (ice and water) variations during the last glacial cycle has been contributing to sea-level changes globally throughout the Holocene, especially in regions like Canada that were heavily glaciated during the Last Glacial Maximum (LGM). The spatial and temporal distribution of GIA, as manifested in relative sea-level (RSL) change, are sensitive to the ice history and the rheological structure of the solid Earth, both of which are uncertain. It has been shown that RSL curves near the center of previously glaciated regions with no ongoing surface loading follow an exponential-like form, with the postglacial decay times associated with that form having a weak sensitivity to the details of the ice loading history. Postglacial decay time estimates thus provide a powerful datum for constraining the Earth's viscous structure and improving GIA predictions. We explore spatial patterns of postglacial decay time predictions in Hudson Bay by decomposing numerically modeled RSL changes into contributions from water and ice loading effects, and computing their relative impact on the decay times. We demonstrate that ice loading can contribute a strong geographic trend on the decay time estimates if the time window used to compute decay times includes periods that are temporally close to (i.e. contemporaneous with, or soon after) periods of active loading. This variability can be avoided by choosing a suitable starting point for the decay time window. However, more surprisingly, we show that across any adopted time window, water loading effects associated with inundation into, and postglacial flux out of, Hudson Bay and James Bay will impart significant geographic variability onto decay time estimates. We emphasize this issue by considering both maps of predicted decay times across the region and site-specific estimates, and we conclude that variability in observed decay times (whether based on existing or future data sets) may reflect this water loading signal.

1. Introduction

Glacial isostatic adjustment (GIA) is defined as the response of the solid Earth surface and gravitational field to ice-age surface mass (ice and water) loading. Ongoing GIA associated with the last deglaciation, extending from the Last Glacial Maximum (LGM, ∼21 ka) when ice sheets were at their maximum extent (Clark et al., 2009), to ∼6 ka when major deglaciation ended globally (Denton et al., 2010), has been contributing to sea-level changes throughout the Holocene (i.e. the current interglacial). In regions like North America and Fennoscandia that were heavily glaciated during the LGM, GIA effects make a significant contribution to local sea-level change through solid Earth deformation, but the impact of GIA on sea level is global in extent (Mitrovica and Peltier, 1991).

Constraining the sea-level changes associated with GIA is challenging because the spatial and temporal distributions of these changes are sensitive to the ice history and the rheological structure of the solid Earth, both of which are poorly constrained. One approach to overcoming this challenge is to develop a parameterization of relative sea level i.e., sea level at a time in the past relative to the present (henceforth "RSL"), that are relatively insensitive to the ice history (Andrews, 1970; Cathles, 1975; Forte and Mitrovica, 1996; McConnell, 1968; Mitrovica and Forte, 2004; Mitrovica and Peltier, 1995; Nordman et al., 2015; Walcott, 1972, 1980; Wieczerkowski et al., 1999). (Note that the term RSL is also used in other literature to define the height of sea surface relative to the solid surface, which is what we define here as simply "sea level"). A widely-used example of such a parameterization is the postglacial decay time inferred from RSL curves in previously ice-covered regions.

Postglacial decay times represent, at least in principle, the intrinsic timescale associated with the relaxation of the solid Earth toward isostatic equilibrium after deglaciation (Andrews, 1970; Walcott, 1972, 1980). Pioneering studies (Andrews, 1970; Cathles, 1975; Walcott, 1980) demonstrated that sea-level change after termination of the deglaciation phase in locations near the

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center of previously ice-covered regions is in free decay (i.e. RSL curves follow an exponential form, see Methods). Subsequent numerical studies have shown that the decay time (or e-folding time) associated with this form is relatively insensitive to ice loading history, and therefore predominantly dependent on mantle viscosity (Lau et al., 2016; Forte and Mitrovica, 1996; Mitrovica et al., 2000; Mitrovica and Peltier, 1993; Nordman et al., 2015). Hence, decay times estimated from RSL histories have been used to constrain mantle viscosity under previously glaciated regions such as Hudson Bay and Fennoscandia, and differences in decay time estimates between sites have been considered potentially indicative of lateral variations in mantle viscosity (e.g. Mitrovica, 1996; Mitrovica and Forte, 1997, 2004; Mitrovica and Peltier, 1993, 1995). It is important to note that while decay times are insensitive to the details of the ice history, the maximum depth of mantle at which viscosity profile can be inferred depends on the broad spatial scale of the ice cover at LGM (Mitrovica, 1996).

Decay times have been extensively studied in the Hudson Bay region of North America because the region was straddled by two major domes of the Laurentide Ice Sheet, which covered much of the continent at the LGM. Estimates of decay times at sites in the Hudson Bay region vary widely. For example, Andrews (1970) estimated a decay time of 2 ky for the whole North American region. Walcott (1980) then introduced a modified version of the original methodology developed by Andrews (1970) to take into account uncertainties in absolute age and height of a given geological sea-level record and emphasized the importance of using consistent sea-level markers (e.g., mytilus edilus shells) in determining decay times. He estimated a lower bound on the decay time in southeastern Hudson Bay (i.e. Richmond Gulf and Castle Island) of 5 ky. Peltier (1998) suggested a decay time of 3.4 ky for a region that includes both Richmond Gulf (henceforth RG) and James Bay (henceforth JB). Mitrovica et al. (2000) emphasized the importance of site-specific decay time analysis, showing that a regional decay time estimated by combining RSL data at multiple sites (i.e. calculating a single decay time for a region that includes RG and JB) may be inconsistent with decay times estimated at individual sites. Mitrovica et al. (2000) reappraised decay times at RG and JB with an updated compilation of RSL data, and estimated decay times of between 4–6.6 ky for RG and 2–2.8 ky for JB. Most recently, Lau et al. (2016) computed postglacial decay times of 2.7–4.7 ky for James Bay based on a new RSL curve reconstructed for the last 7 ky by Pendea et al. (2010), who utilized sediments from wetlands in the region.

In addition to the ice loading changes in Hudson Bay, regional RSL has been influenced by a history of surface water loading changes. Hudson Bay became mostly ice-free and inundated with a mix of meltwater and water from the open ocean during the early Holocene (∼9–6 ka) (Dyke, 2004). Subsequently, sea level continued to fall in Hudson Bay due to viscous rebound of the solid Earth in response to the collapse of the Laurentide Ice Sheet over the region and viscoelastic deformation in response to ongoing changes in the water loading (Kendall et al., 2005). This water loading perturbs estimates of the decay time associated with the ice collapse in at least two ways. First, it introduces a potentially significant elastic component into the postglacial rebound. Second, it has a spatial scale significantly smaller than the scale of the Laurentide Ice Sheet (i.e. the aerial extent of Hudson Bay is smaller than that of the Laurentide Ice Sheet at the LGM). Both of these effects introduce significant geographic variability in decay times estimated from field data away from an assumption of free decay in response to Laurentide-scale ice unloading.

While many studies have investigated site-specific postglacial decay times in the Hudson Bay region, there has been no analysis of the regional spatial variability of postglacial decay times and how this variability is affected by ongoing water loading in the bay. In this study, we model postglacial sea-level changes over the last 21 ky and compute associated postglacial decay times throughout Hudson Bay. We investigate the spatial pattern of decay times in the region and assess the impact on decay time patterns of both ice and water loading changes during the Holocene (i.e. 8–0 ka). We also consider decay time estimates at a number of individual sites in the region (i.e. Richmond Gulf, James Bay, Churchill, Ottawa Island and Ungava Peninsula), for which there are extensive RSL records (Hardy, 1976; Hillaire-Marcel and Fairbridge, 1976) and corresponding decay times analyses in the literature (e.g. Mitrovica et al., 2000; Mitrovica and Forte, 1997; Mitrovica and Peltier, 1995; Peltier, 1994, 1998; Walcott, 1980). Finally, we highlight sites where the impacts of Holocene water and ice loading changes on decay times are minimized that may be ideal for collecting future RSL observations in the bay.

2. Methods

Andrews (1970) first approximated the postglacial sea-level change at locations near the center of previously glaciated regions with the following exponential form:

$$SL(t) = A \exp\left(-\frac{t}{\tau}\right), \tag{1}$$

where τ is the postglacial decay time, $t = 0$ at the present-day, $t < 0$ at a time in the past, and A is the sea-level change remaining at present-day for the system to reach isostatic equilibrium.

Using equation (1), postglacial RSL changes can be approximated by the following expression:

$$RSL(t) = SL(t) - SL(0) = A\left[\exp\left(-\frac{t}{\tau}\right) - 1\right] + c, \tag{2}$$

where the constant c is an offset that accounts for the uncertainty in present-day absolute age and height of a geological sea-level record (Walcott, 1980). Note that model-generated, synthetic RSL curves are always defined to be zero at present ($t = 0$), which in this case sets the constant c to be zero. One can estimate the postglacial decay time, τ, and remaining sea-level change to reach isostatic equilibrium, A, at a given site by fitting Eq. (2) to the local (modeled or observed) RSL curve.

In order to estimate decay times in Hudson Bay, we generate RSL predictions globally using the postglacial sea-level theory and pseudo-spectral algorithm described in Kendall et al. (2005). Kendall et al. (2005) and Mitrovica and Milne (2003) outline the sea-level theory in detail, and we include the components here that are essential to understanding our methodology. The sea-level theory we implement is gravitationally self-consistent, and it includes migrating shorelines, Earth rotation, and deformation of a Maxwell viscoelastic Earth model with radially varying Earth structure. That is, we solve the generalized sea-level equation (Mitrovica and Milne, 2003; Eq. (39)):

$$\begin{aligned}\Delta S(\theta,\psi,t_j) = {} & \Delta SL(\theta,\psi,t_j)C^*(\theta,\psi,t_j) \\ & - T(\theta,\psi,t_0)\left[C^*(\theta,\psi,t_j) - C^*(\theta,\psi,t_0)\right],\end{aligned} \tag{3}$$

where θ is the colatitude, ψ is the east-longitude, and t_j is the time. The symbol S is the ocean depth, Δ indicates a change in the given field from an initial time t_0 to t_j, SL is globally-defined sea level, T is topography, and C^* is the ocean function defined by the following,

$$C^*(\theta,\psi,t_j) = \begin{cases} 1 & \text{if } SL(\theta,\psi,t_j) > 0 \text{ and there is no} \\ & \quad \text{grounded ice} \\ 0 & \text{elsewhere.} \end{cases} \tag{4}$$