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Key Points:

- Space geodetic data are employed to constrain a global model of glacial isostasy
- The GPS-refined model is verified using GRACE time-dependent gravity data
- The spherically symmetric model of the GIA process is confirmed

Supporting Information:

- Figures S1–S4 and Tables S1, SS1, S2, and SS2
- Data Set SStokes

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Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model

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Abstract A new model of the last deglaciation event of the Late Quaternary ice age is here described and denoted as ICE-6G_C (VM5a). It differs from previously published models in this sequence in that it has been explicitly refined by applying all of the available Global Positioning System (GPS) measurements of vertical motion of the crust that may be brought to bear to constrain the thickness of local ice cover as well as the timing of its removal. Additional space geodetic constraints have also been applied to specify the reference frame within which the GPS data are described. The focus of the paper is upon the three main regions of Last Glacial Maximum ice cover, namely, North America, Northwestern Europe/Eurasia, and Antarctica, although Greenland and the British Isles will also be included, if peripherally, in the discussion. In each of the three major regions, the model predictions of the time rate of change of the gravitational field are also compared to that being measured by the Gravity Recovery and Climate Experiment satellites as an independent means of verifying the improvement of the model achieved by applying the GPS constraints. Several aspects of the global characteristics of this new model are also discussed, including the nature of relative sea level history predictions at far-field locations, in particular the Caribbean island of Barbados, from which especially high-quality records of postglacial sea level change are available but which records were not employed in the development of the model. Although ICE-6G_C (VM5a) is a significant improvement insofar as the most recently available GPS observations are concerned, comparison of model predictions with such far-field relative sea level histories enables us to identify a series of additional improvements that should follow from a further stage of model iteration.

1. Introduction

During the Late Quaternary era of Earth history, beginning approximately 900,000 years ago, climate variability was dominated by an almost metronomic cycle of glaciation and deglaciation with a characteristic timescale near 100,000 years [e.g., Shackleton et al., 1990]. During each successive cycle, Northern Hemisphere continental ice volume increased nonmonotonically during a glaciation phase that lasted approximately 90,000 years and then collapsed during an ensuing "termination" that lasted approximately 10,000 years [Broecker and Van Donk, 1970]. The initial inception phase of each glacial cycle appears to be explicable solely as a consequence of variations in the orbit of the Earth around the Sun caused by the action of gravitational n-body effects in the solar system [Berger, 1978; Laskar, 1989; Quinn et al., 1991]. The rapidity of the buildup of ice on the continents and the associated fall of sea level, however, are thought to require the action of important positive feedbacks involving migration of the tundra-taiga boundary [Gallimore and Kutzbach, 1996] and/or an adjustment of the general circulation of the oceans [Khodri et al., 2001] or a combination of such influences [Vettoretti and Peltier, 2003]. Simple ice sheet coupled climate models have been successful in explaining the origins of this 100 kyr cyclic behavior [Tarasov and Peltier, 1997; Peltier, 2002b], but only if the known covariation of atmospheric carbon dioxide is directly employed in addition to orbital insolation change as an input to the model, rather than explaining this as a consequence of coupling to an explicit model of the carbon cycle. A viable ocean carbon chemistry coupled climate model remains to be developed that is able to explain the systematic ~80 ppmv drawdown of atmospheric carbon dioxide concentration that has accompanied the full glacial state of each of the Late Quaternary glacial cycles [e.g., Petit et al., 1999].

Since modern coupled atmosphere-ocean models of climate system evolution are as yet not integrable over ice age cycle timescales, their application has remained restricted to the inference of climate state at discrete intervals of time for which sufficiently accurate knowledge is available of the surface boundary conditions

[e.g. Vavrus, 1999; Vettoretti and Peltier, 2003; Peltier and Solheim, 2004; Vettoretti and Peltier, 2013] or to investigation of the transient response of the system to known (or suspected) forcings [Stouffer et al., 2006; Peltier et al., 2006; Liu and Otto-Bliesner, 2009; Vettoretti and Peltier, 2013; Peltier and Vettoretti, 2014]. Primary targets for the inference of climate state at fixed intervals of time include the Last Glacial Maximum (LGM), which is usually taken to have occurred at 21,000 years before present (B.P.), the mid-Holocene warm period at ~6000 years B.P. and the previous (Eemian) interglacial at ~120,000 years B.P. A primary target for the investigation of the transient response has involved analysis of the reaction of the meridional overturning circulation of the Atlantic to a sustained injection of freshwater over the region where deep water would otherwise form, normally the Greenland-Iceland-Norwegian and Labrador Seas [eg Stouffer et al., 2006]. More recent analyses of the transient response of the thermohaline circulation to freshwater inputs have focused upon the Younger Dryas event. These analyses have demonstrated that the freshwater input responsible for this millenial cooling of the Northern Hemisphere that interrupted the transition to full Holocene warmth occurred through the Mackenzie River outlet into the Arctic Ocean [Tarasov and Peltier, 2005, 2006; Murton et al., 2010]. More recent analysis has focused upon the dynamical processes responsible for the so-called Dansgaard-Oeschger oscillations that are such a prominent feature of climate variability during Marine Oxygen Isotope Stage 3, and these analyses have already made use of the boundary conditions provided by the model whose construction is described herein [Peltier and Vettoretti, 2014].

This new model of the evolution of surface boundary conditions throughout the glaciation and deglaciation process is intended to service the requirements of both steady state and transient analyses of climate state. To this end, it will be accompanied not only by time-dependent continental paleotopography and ocean paleobathymetry from Last Glacial Maximum (LGM) to the present but also by time-dependent land ice and land sea masks and a complete field of land ice thickness variations through this period of time, for which purpose LGM is taken to have occurred at approximately 26,000 years before present [*Peltier and Fairbanks*, 2006] rather than the conventional 21 ka age. These data sets are available through the web site of the senior author (www.atmosp.physics.utoronto.ca/~peltier/). One of the most important data sets describing the model from a geodetic perspective, however, namely, the Stokes coefficients in terms of which the time dependence of geoid height is described, is provided as Data Set SStokes in the supporting information that accompanies the present paper.

The distribution of ice on the continents under both modern and LGM conditions is shown qualitatively in Figures 1a and 1b, respectively. These plates also illustrate qualitatively the topography of the non-ice-covered land with respect to sea level as well as the bathymetry of the oceans at these two epochs according to the existing ICE-5G (VM2) model of surface conditions that it is the purpose of the analyses to be presented in the present paper to refine. Superimposed upon the regions of continental ice cover are also shown as thickness contours for the ice sheets themselves. Comparison of the data in Figures 1a and 1b over both Greenland and East Antarctica will show that in these regions, the changes are inferred to have been modest. The greatest changes of ice cover were those that occurred over both North America and Northwestern Eurasia where the extensive Laurentide/Cordilleran/Innuitian and Fennoscandian/Barents Sea/British Isles ice sheet complexes, respectively, were fully developed by the LGM. Somewhat less evident from Figure 1 is the fact that the West Antarctic lce Sheet was also considerably more massive at LGM than it is at present. The LGM mass of the West Antarctic ice sheet has recently been the focus of considerable debate [*Whitehouse et al.*, 2012a, 2012b; *Argus et al.*, 2014], and further discussion of this component of the LGM state of ice cover will be provided in the present paper.

The primary constraint upon the net volume of ice that disappeared from the continents during the deglaciation process subsequent to LGM is provided by records of relative sea level change from sites in the "far field" of the ice sheets themselves. The most important of such records is that based upon samples of coral drilled from the ocean floor proximate to the island of Barbados in the Caribbean Sea [*Fairbanks*, 1989; *Bard et al.*, 1990; *Peltier and Fairbanks*, 2006]. The complete set of data from this site is shown in Figure 1c where it is compared to the prediction of the relative sea level history at this site for the previous ICE-5G (VM2) model that will be superseded by the revised model to be presented herein (In this nomenclature, ICE-5G is the model of continental ice sheet thickness variations, whereas VM2 is the model of the radial variation of the viscoelastic properties of Earth's interior.). In the age range from 21,000 years ago to 26,000 years ago, the only constraint upon sea level at this site is that provided by samples of the coral species *Montastrea Annularis (Ma)* for which the attached error bars on relative sea level are 20 m in length. This error bar is accurately determined on the basis of a morphological transition that occurs when the coral grows at a depth greater than 20 m



Figure 1. (a) Global ice cover and surface topography and bathymetry under modern climate conditions. (b) Same as Figure 1a but for Last Glacial Maximum conditions according to the ICE-5G (VM2) model. Ice thickness contours at 500 m spacing are superimposed upon the areas shown as ice covered. (c) The fit of the ICE-5G (VM2) model to the coral-based record of relative sea level history from the island of Barbados in the Caribbean Sea. The two major meltwater pulses are noted. (d) Fits of the ICE-5G (VM2) model to the records of Holocene relative sea level history at sites near the centers of rebound of the Laurentide (d1) and Fennoscandian (d2) ice sheets.

[*Fairbanks and Dodge*, 1979]. Since all of these samples are of the shallow water morphology, sea level in this range of time is constrained to lie between the depth from which the samples were raised, shown by the horizontal bar, and the tip of the error bar that extends to shallower depth. The ICE-5G (VM2) model prediction of sea level history passes near the shallow water tips of the error bars provided by the *Ma* samples. The model so tuned must therefore be accepted as a minimum mass model although it will be noted that there also exists a cluster of *Ma* samples in the vicinity of 12,000 years age which is the approximate midpoint age of the Younger-Dryas event. All of the *Montastrea annularis* samples in the Y-D interval are such that the *Acropora Palmata* samples which provide the tightest bounds on sea level at Barbados, those having the smaller 5 m error bars, lie slightly above the shallowest water tips of the *Ma* range. Clearly, the fit of the prediction of the ICE-5G (VM2) model to the complete Barbados record is of rather high quality, recognizing that the model is a minimum mass models but one which is nevertheless expected to be very close to reality. The manner in which the Barbados record is employed to tune the new model is discussed in the following section of this paper. This new model, which we are denoting by ICE-6G_C (VM2), although the viscosity model

VM5a is simply a multilayer fit to VM2 (a figure comparing these two viscosity profiles is provided in Figure S1 in the supporting information). The delimiter "_C" in the name of the new model is employed to denote the fact that the Antarctic component of the model [*Argus et al.*, 2014] has been fully iterated in order to obtain a best fit to the available GPS observations from Antarctica. Also identified in Figure 1c are meltwater pulses 1A and 1B first identified in *Fairbanks* [1989] during which the rate olf meltwater addition to the oceans became especially high. Although the issue of origins of the stronger MWP 1A event is believed to be the Northern Hemisphere [*Peltier*, 2005], this issue continues to be debated.

Now determination of the manner in which mass is distributed within the known margin positions of the glaciated regions is, in fact, the primary aim of the analyses to be presented herein. Although Figure 1b accurately depicts the geographical regions covered by grounded ice at LGM and Figure 1c quite accurately depicts the history of the addition of melt water to the global ocean due to the collective effects of the melting of all ice sheets, the manner in which ice thickness varied as a function of time within the individual ice-covered regions can be constrained only by the addition of further information. The data that have been previously employed for this purpose have consisted of calibrated ¹⁴C-dated relative sea level histories from within the ice-covered regions themselves. Examples of such data and of the fit of the previous ICE-5G (VM2) model to them are shown in Figures 1d1 and 1d2 from sites near the centers of rebound in North America and Fennoscandia [Peltier, 1998]. Where such data are available, they enable us to "weigh" the ice that must have been removed from the proximate region but only if the history of load removal has been accurately constrained. It is therefore fortunate that reasonably accurate ¹⁴C-dated ice sheet margin chronologies now exist for both North America [Dyke et al., 2002] and for Northwestern Eurasia [Gyllencreutz et al., 2007]. These chronologies will be discussed in what follows in the appropriate subsections of the paper for each of these specific geographical regions. Although relative sea level histories from the ice-covered regions are extremely important to the process of model development, they are clearly available only from coastal locations. Yet much of the grounded ice cover over the continents was located over regions well removed from current coastlines. Such regions include the vast interior of the North American continent as well as all of Greenland and much of Antarctica. Additional information is therefore required in order to constrain the model in these regions, and such information is now becoming available from a variety of different space geodetic systems. It is these geodetic data, including that from Global Positioning System (GPS) receivers, both permanent and campaign based, and related systems, as well as time-dependent gravity observations from both surface measurements and those which are now available from the space-based Gravity Recovery and Climate Experiment (GRACE) dual satellite system which are providing the necessary additional information. These data will play the most important role in enabling us to refine the previous ICE-5G (VM2) model of Peltier [2004] to produce ICE-6G_C (VM5a).

In order to test the hypothesis that a spherically symmetric model of the internal viscosity structure of the mantle is adequate insofar as most Glacial Isostatic Adjustment (GIA) observations are concerned, both the VM2 and VM5a models have been constructed by making use of the different dependence on radial viscosity structure of the isostatic rebound induced by ice sheets of differing horizontal scale. To this end, the following Late Pleistocene ice sheet complexes along with additional constraints based upon Earth rotation observations have been employed, which provide primary constraints on the noted depth intervals of mantle viscosity: the Scottish ice sheet [e.g., *Peltier et al.*, 2002], primarily sensitive to the elastic thickness of the lithosphere; the Fennoscandian/Barents sea ice sheet complex [e.g., *Peltier*, 1998], sensitive to both lithospheric thickness and to the viscosity of the upper mantle and transition zone to a depth near the 660 km transition of mineral phase; the Laurentide ice sheet [e.g., *Peltier*, 1998], sensitive primarily to the viscosity of the upper part of the lower mantle in the depth range from ~660 km to ~1250 km; and the rotational observables of true polar wander and the nontidal acceleration [e.g., *Peltier*, 1983; *Wu and Peltier*, 1984; *Peltier and Luthcke*, 2009; *Roy and Peltier*, 2011; *Peltier et al.*, 2012], sensitive primarily to the viscosity of the deepest mantle from midmantle depth to the core-mantle boundary itself, with maximum sensitivity near the core mantle boundary.

The totality of these rebound data therefore provide sensitivity to viscosity at all mantle depths. Previous work at Toronto has suggested that all of the associated data *from the once ice-covered regions* could be quite well fit by the same radial viscosity structure. Furthermore, much of the data pertaining to relative sea level history observations from what are referred to as "far-field sites" remote from these ice-covered regions is also fit by the same model (e.g., see *Peltier* [2004] for examples), although in these remote regions anomalous results have been identified. One of the purposes of this paper is to test the extent to which the same model is exportable to a further geographic region, namely, Antarctica, which also experienced

partial deglaciation in the period subsequent to LGM but from which data have not been employed in the construction of the VM2-VM5a viscosity structures. This region is especially interesting because very few relative sea level observations are available, as recently discussed in *Argus et al.* [2014], which may be invoked to provide an independent inference of local viscosity structure.

2. Theoretical Preliminaries and Model-Tuning Strategy

In order to refine the original model of continental glaciation history so as to eliminate the most apparent misfits to the newly compiled set of geodetic data to be discussed below, our purpose in this paper is to proceed by assuming that all of the error is associated with flaws in the space-time distribution of land ice thickness, while keeping the viscosity structure fixed. This revision requires application of the detailed theory of ice-Earth-ocean interactions, up-to-date reviews of which have recently been made available [Peltier, 2007b; Peltier and Luthcke, 2009; Peltier et al., 2012]. We keep the viscosity structure fixed in this iteration step as it has been constrained by employing data from the ice-covered regions that are essentially independent of errors in ice thickness history. The data on the basis of which this fact is demonstrated consist of the exponential relaxation times that may be inferred on the basis of data from the centers of previously ice covered regions. These relaxation times, measured during the Holocene interval of time, when the surface ice load had ceased to vary, are determined almost entirely by the radial structure of the mantle viscosity profile. It is because of the variation of the sensitivity of these exponential relaxation times as a function of the horizontal scale of the ice load from the center of which the relaxation times are measured that one is able to obtain resolving power on the depth variation of mantle viscosity over a wide range of depths. The rebound in response to removal of the Scottish ice sheet is sensitive primarily to uppermost mantle viscosity and lithospheric thickness, that to removal of the Fennoscandian ice sheet to the viscosity of the upper mantle and transition zone and that to removal of the Laurentide ice sheet to the viscosity of the uppermost part of the lower mantle. This is clearly established by the Frechet derivatives in terms of which these sensitivities may be quantified (see Peltier [1998] for a detailed discussion).

2.1. Mathematical Methods

The theory we employ to fit observations of relative sea level history provides predictions of postglacial relative sea level history that are produced by solving an integral "Sea Level Equation" in which relative sea level history, $S(\theta, \lambda, t)$, say, where the independent variables are latitude, longitude, and time respectively, is expressed as follows:

$$S(\theta, \lambda, t) = C(\theta, \lambda, t) \left[\int_{-\infty}^{t} dt' \iint_{\Omega} d\Omega' \left\{ L(\theta', \lambda', t') G_{\phi}^{L}(\gamma, t - t') + \Psi^{R}(\theta', \lambda', t')_{R} G_{\phi}^{T}(\gamma, t - t') \right\} + \frac{\Delta \Phi(t)}{g} \right]$$
(1)

In (1) C (θ , λ , t) is the "ocean function" which is unity over the oceans and zero over the land. This is time dependent because of the migration of the coastlines that occur as water is added to (or removed from) the ocean basins. A highly accurate iterative method for the computation of the time dependence of "C" is available [*Peltier*, 1994]. Also in (1), the space- and time-dependent function L is the surface mass load per unit area which may be decomposed to write

$$L(\theta, \lambda, t) = \rho_I I(\theta, \lambda, t) + \rho_w S(\theta, \lambda, t),$$
(2)

in which ρ_l and ρ_w are the densities of ice and water, respectively. In the Green functions G^L_{ϕ} and $_R G^{TR}_{\phi}$, the angle ϕ is the angular separation between the source point with coordinates (θ' , λ') and field point with coordinates (θ , λ). These impulse response functions [*Peltier*, 1974] depend only upon this angle when the viscoelastic Earth model is assumed to be spherically symmetric. Their time dependence is determined by this radial structure which, in the new ICE-6G_C (VM5a) model, is VM5a, a model recently demonstrated to eliminate what had been a serious flaw concerning the predictions of horizontal motion over the North American continent [*Peltier and Drummond*, 2008]. The explicit forms of the Green functions that appear in (1) are as follows:

$$G_{\phi}^{L}(\phi,t) = \frac{a}{m_{e}} \sum_{l=0}^{\infty} \left(1 + k_{l}^{L}(t) - h_{l}^{L}(t) \right) P_{l}(\cos\theta)$$
(3a)

$${}_{R}G_{\phi}^{T}(\phi,t) = \frac{1}{g} \sum_{l=0}^{\infty} \frac{(2l+1)}{4\pi} \left(1 + k_{l}^{T}(t) - h_{l}^{T}(t) \right) P_{l}(\cos\theta)$$
(3b)

$$k_{l}^{T}(t) = k_{l}^{T, \mathcal{E}} \delta(t) + \sum_{j=1}^{M} q_{j}^{I} e^{-s_{j}^{t} t},$$
(4a)

$$\boldsymbol{h}_{l}^{T}(t) = \boldsymbol{h}_{l}^{T,\mathcal{E}}\delta(t) + \sum_{j=1}^{M} \boldsymbol{r}_{j}^{J}\boldsymbol{e}^{-s_{j}^{t}t}, \tag{4b}$$

$$k_I^L(t) = k_I^{L,E} \delta(t) + \sum_{j=1}^M q_j^L e^{-s_j t},$$
(4c)

$$\boldsymbol{h}_{l}^{L}(t) = \boldsymbol{h}_{l}^{L,E} \delta(t) + \sum_{j=1}^{M} \boldsymbol{r}_{j}^{L} \boldsymbol{e}^{-\boldsymbol{s}_{j}^{t} \boldsymbol{t}}. \tag{4d}$$

In these normal mode expansions, the $k_I^{T,E}$, $h_I^{T,E}$, $k_I^{L,E}$, and $h_I^{L,E}$ are the elastic surface mass load and tidal potential loading Love numbers of Farrell [1972], the s_i are the inverse relaxation times of a discrete set of normal modes of viscoelastic relaxation determined as the zeros of an appropriate secular function [Peltier, 1985] or by collocation [Peltier, 1974, 1976], and the amplitudes q_i^l, r_i^l, q_i^l , and r_i^l are the residues at these poles. In so far as understanding the polar wander component of the rotational response of the planet to the GIA process is concerned, the parameter k_{2}^{T} plays an especially crucial role as has recently been discussed in detail in *Peltier and* Luthcke [2009] and Peltier et al. [2012]. An important difference between previous formulations of the sea level equation and that to be employed herein concerns the Green function denoted as ${}_{R}G_{a}^{TR}(\gamma, t)$. This is the "renormalized" form that is required in order to ensure that the impact of rotational feedback upon sea level history, which acts through a variation of centrifugal potential, exerts only local influence, which is to say that the variation of the centrifugal potential at one point on the Earth's surface exerts no influence upon the centrifugal potential at any other point. This clearly differs from the manner in which surface mass loads function as a surface mass load at any point on the Earth's surface influences the gravitational potential at all other points. This issue has been recently discussed in detail in Peltier et al. [2012] and will not be further discussed here, but the interested reader should also refer to Chambers et al. [2010]. The remaining function that appears in the Sea Level Equation (1), $\Psi^{R}(\theta, \lambda, t)$, is the variation of this centrifugal potential due to the changing rotational state of the planet which may be written to first order in perturbation theory as [Dahlen, 1976]

$$\Psi^{R}(\theta,\lambda,t) = \Psi_{00}Y_{00}(\theta,\lambda,t) + \sum_{m=-1}^{+1}\Psi_{2m}Y_{2m}(\theta,\lambda,t)$$
(5)

with

$$\Psi_{00} = \frac{2}{3}\omega_3(t)\Omega_o a^2 \tag{6a}$$

$$\Psi_{20} = -\frac{1}{2}\omega_3(t)\Omega_0 a^2 \sqrt{4/5}$$
(6b)

$$\Psi_{2,-1} = (\omega_1 - i\omega_2) \left(\Omega_o a^2/2\right) \sqrt{2/15}$$
(6c)

$$\Psi_{2,+1} = -(\omega_1 + i\omega_2) \ (\Omega_o a^2/2) \sqrt{2/15} \tag{6d}$$

The ω_i (*t*) in equations (6a)–(6d) represent the time-dependent variations in the three Cartesian components of the angular velocity vector of the planet, whereas Ω_o is the unperturbed angular velocity of the Earth and "a" is the mean radius. This is the theoretical structure that will be employed to perform the necessary calculations of GIA influence in the remainder of this paper. Initial solutions of the Sea Level Equation in the absence of the influence of rotational feedback were those discussed by *Farrell and Clark* [1976], *Clark et al.* [1978], and *Peltier et al.* [1978].

2.2. The Role of the Barbados Sea Level Record in Tuning the Model

The tuning strategy to be employed in the construction of the new model will heavily rely upon the validity of the Barbados record of relative sea level history as an approximate record of eustatic (globally averaged) sea



Figure 2. (a) Map of the island of Barbados in the Caribbean Sea in which are shown the geographical locations of the traverses along which the coral samples have been collected on the basis of which the uplift of the island due to tectonic processes can be reconstructed. (b) Reconstructed uplift histories of Barbados based upon the dated coral samples from the three regional traverses denoted by St. Georges Valley, Clermont Nose, and Christ Church. (c) The Barbados relative sea level history based upon the data set of *Peltier and Fairbanks* [2006] prior to correction for the influence of tectonic uplift. The inset of this figure illustrates the linear uplift correction based upon the data in Figure 2b that is characterized by an implied uplift rate of 0.34 mm/yr. (d) The relative sea level curve for Barbados in Figure 2c after the correction for tectonic uplift of the crust has been applied is shown as the individual data points. The black curve is the fit to these data predicted by the new ICE-6G_C (VM5a) model. The step discontinuous red curve is the ice equivalent eustatic sea level history for this new model as discussed in the text. In the inset of this figure that is shown, as the red line, the ice equivalent eustatic sea level for a full 100 kyr glacial cycle for the ICE-6G (VM5a) model. This full glacial cycle history of ice equivalent eustatic sea level is compared with the inset to that inferred on the basis of temperature-corrected benthic oxygen isotopic data by *Waelbroeck et al.* [2002]. It is notable that the two curves quite closely agree in terms of the LGM depression of sea level when the tectonic correction to the coral derived Barbados record is applied.

level change over the deglaciation phase of the most recent glacial cycle. Since the validity of this assumption has recently been questioned by Austermann et al. [2013], it will be important to review its basis. In Figure 2a we show a map of this island on which we have placed the locations of the traverses along which the height of individual coral samples have been measured with respect to present-day sea level. Figure 2b plots the height of the individual coral samples for the three sequences from which data have been taken as a function of the age of the individual samples. The three sequences are, respectively, those from St. Georges Valley, Clermont Nose, and Christ Church whose locations are denoted in Figure 2a. The former record, in which the age of the individual samples has been determined by Uranium series dating, is from Bender et al. [1979] and is the longest record which therefore best constrains the rate of uplift of the island with respect to sea level. As indicated in the figure, the rate inferred for the St. Georges Valley location is approximately 0.34 mm/yr. The records for the Clermont Nose and Christ Church traverses are from Radtke et al. [1988], and for these records, the individual coral samples have been dated using the electron spin resonance methodology. Because one of these records is characterized by a slightly higher rate of uplift than that for St Georges Valley and the other a slightly lower rate, the average of the three rates is essentially identical to the St. Georges Valley rate of 0.34 mm/yr. Because the island of Barbados is being continuously uplifted tectonically with respect to sea level at this rate, in order to infer the actual amount by which sea level has risen at this location, every sample in the offshore depth versus age data set that makes up the raw record of post LGM sea level history here must be displaced downward by a depth correction equal to the product of sample age and uplift rate. Since the age for samples in the offshore data set of Fairbanks [1989] and Peltier and Fairbanks [2006] is determined by U/Th dating, the sample ages are essentially sidereal. Figure 2c shows the uncorrected data as a plot of depth of the individual samples versus age. The inset to this figure shows, as the straight line, the time-dependent correction that must be applied to the raw depths in order to account for the ongoing tectonic uplift of the island at the rate of 0.34 mm/yr due to the continuing long-timescale tectonic action of the subduction zone above which the island is located, near the boundary between the Caribbean and North American Plates. Austermann et al. [2013] believe that an additional correction to these raw data should be applied due to the lateral variations of viscosity in the vicinity of the subduction zone. They believe this to be a cyclic correction that would require that actual sea levels would have to be corrected upward during the glacial phase of the glaciation cycle but downward during the deglaciation phase. In their view, the additional downward correction has an average rate of change that is identical to the rate associated with the long timescale continuing uplift of the island itself. Since we do not have access to coral samples from the glaciation phase of the last 100,000 year ice cycle, it is not possible to directly test the validity of the Austermann et al. [2013] conjecture; however, the robustness of their model will require further assessment as it involves a large number of additional degrees of freedom.

Figure 2d shows the same data as in Figure 2c after the traditional tectonic correction for the ongoing uplift of the island has been applied. Also shown in Figure 2d, as the black line, is the prediction of the new ICE-6G_C (VM5a) model for the history of relative sea level change at this location. The step discontinuous red line also shown in the figure is what will be referred to as the "ice equivalent" eustatic curve of this new model of deglaciation history. By the "ice equivalent" eustatic sea level curve, we mean the globally averaged sea level history that would be inferred on the basis of the time-dependent volume of meltwater produced by the melting of land ice divided by the surface area of the oceans into which the meltwater is discharged under the assumption that the surface area of the oceans does not change from modern. Inspection of Figure 2d demonstrates that for the new ICE-6G_C (VM5a) model, the ice equivalent eustatic sea level history tracks the sea level equation-based prediction for this site quite accurately. This is the reason why the Barbados record plays such an important role in the tuning of the model. It provides a good approximation to the net mass of ice that must have melted across the glacial-interglacial transition. If we were to include the impact upon the eustatic curve predicted by the deglaciation model due to the changing area of the ocean basins that accompanies the isostatic adjustment process, as discussed in Peltier [2007a, 2007b], this would further depress the sea level equation-based Relative Sea Level (RSL) prediction by approximately an additional 10 m at LGM. It is also important to directly compare the fit of the ICE-6G_C (VM5a) model to the tectonically corrected Barbados record with that provided by the previous ICE-5G (VM2) model for which the result has been shown in Figure 1c. Comparison of the latter to the former shows that there has been some degradation of the fit provided by the new model over the range of time extending from the time of meltwater pulse 1A (MWP 1A) to a time significantly later than MWP 1B, the timing of these pulses having been explicitly noted previously in Figure 1.

Also shown as the inset to Figure 2d is a comparison between the eustatic sea level history inferred by *Waelbroeck et al.* [2002] and that of the ICE-6G_C (VM5a) model. The *Waelbroeck et al.* [2002] reconstruction was based upon the use of measurements of $\delta^{18}O$ on benthic foraminifera obtained from deep sea sedimentary cores, which generally provide very useful information on the mass of land-based ice present on the continents at the time in the past represented by the depth in the core from which the "forams" are extracted. Because this isotopic signal is also influenced by temperature as well as land ice volume, the *Waelbroeck et al.* [2002] inference of eustatic sea level is based upon the application of an appropriate temperature correction. Inspection of the comparison shown in the inset of Figure 2d will demonstrate that the ICE-6G (VM5a) model eustatic sea level curve matches that of *Waelbroeck et al.* [2002] quite accurately, further reinforcing the importance of the Barbados constraint for the tuning of total deglacial ice mass.

Another brief comment is warranted concerning the additional correction to the Barbados record of relative sea level change recently suggested in the Austermann et al. [2013] paper. The magnitude of this correction is essentially identical at the LGM to that for the action of vertical uplift of the island due to the action of subduction zone tectonics, i.e., at 21 ka it amounts to an additional 7 \pm 1 m according to the authors, the same as the tectonic correction computed as 0.34 mm/yr × 21,000 years! It is unclear based upon the detail provided in the Austermann et al. paper how robust this estimate could be given the very large number of parameters that have been required to fix the lateral heterogeneity of viscosity that characterizes their model, but it is not our purpose to challenge the reasonableness of this additional correction here. We simply note that this additional correction to the Barbados curve would simply provide the additional room required in the global LGM ice inventory to allow for the known additional inputs that originated from low-latitude high-elevation regions (e.g., the Himalayas, the Alps, the Caucasus, the Andes, etc.). The meltwater that inputs from the collectivity of these regions is expected to have provided an additional 5 m or so of global sea level rise. By excluding explicit incorporation of these additional sources of meltwater from the model and tuning it to the data set that includes only the correction for tectonically induced island uplift, we expect that the error incurred in the inventory of LGM ice mass will be of minor consequence to the glacial inventories in the three major regions upon which our analyses are focused.

In the following three sections of this paper, we will discuss the manner in which the space geodetic constraints may be brought to bear to refine, either radically or minimally, as required, the detailed space-time distributions of ice thickness in the North American, Northwest Eurasian, and Antarctic regions which were the locations of the largest accumulations of land ice during the LGM. This will be followed by a discussion of specific RSL and other data from regions remote from these main centers of glaciation that may be employed to confirm or to deny the viability of the model.

3. The Glaciation History and Isostatic Adjustment of the North American Continent

The methodology we will employ to refine the glacial history of this region is to seek a variation of the ice thickness field $I(\theta, \lambda, t)$ such that the previously identified misfits [Argus and Peltier, 2010] of the predictions of the precursor model ICE-5G (VM2) to the space geodetic constraints are eliminated. This requires predictions of both the rates of horizontal and vertical motion of the crust, formulae for which have been previously provided that include the influence of both ice sheet and ocean loading as well as the influence of rotational feedback (e.g., see Peltier [2004], but note that the renormalization factor is required in all terms involving the rotational feedback process). In Argus and Peltier [2010] an initial data base of space geodetic measurements of both vertical and horizontal motion of the crust as well as the time dependence of the planet's gravitational field as measured using surface-based instruments was provided. These data included very long baseline radio interferometric (VLBI) measurements, Satellite Laser Ranging (SLR) measurements, and Global Positioning System (GPS) measurements, as well as measurements derived from Doppler Orbitography and Integrated Radio-positioning by Satellite (DORIS) observations, all of which were employed to constrain present-day vertical and horizontal motion at specific points on the Earth's crust. In order to provide useful contributions to the refinement of ice sheet thickness distributions within the formerly glaciated regions, these data require that appropriate account be taken of the nature of the reference fame with respect to which the data are represented [Argus, 2007; Argus and Peltier, 2010; Argus et al., 2010; Argus, 2012], as well as, in the case of horizontal motion measurements, of the motion of the tectonic plates upon which the Late Quaternary cycle of glaciation and deglaciation has been recurring [Argus et al., 2010].

In order to produce the best possible refinement of the North American ice sheet complex, we have constructed a further improved global inversion of the totality of the GPS data currently available. The main basis of the current work consists of the global reanalysis of GPS data for the time period 1994 to 2012 at the Jet Propulsion Laboratory [Desai et al., 2011]. First, satellite orbits, clocks, and a subset of 80 GPS global site positions are estimated on each day. A series of Helmert transformations consisting of a scale, a translation, and a rotation are determined to transform the GPS position estimates into the IGS08 reference frame. (IGS08 is a realization of ITRF2008 [Altamimi et al., 2011].) The International Earth Rotation Service (IERS) standards [Petit and Luzum, 2010] for the solid Earth and pole tides are followed. In this first step the GMF (Global Mapping Function) [Boehm et al., 2006a] and Global Pressure and Temperature troposphere models [Boehm et al., 2006b] are used. Second, the positions of several thousand GPS sites are determined using the point positioning method of Zumberge et al. [1997]. The VMF1 (Vienna Mapping Function 1) and zenith height delay models from the ECMWF model are used in this second step [Boehm et al., 2006b, 2007]. This method realizes the advantage in position determination of the VMF1 observational model over the GMF empirical model [Tregoning and Watson, 2009]. The pole tide correction accounts for (following the IERS 2010 standards) solid Earth's deformation due to deviations of Earth's spin axis from a constant velocity (at 3.5 milliseconds of arc per year toward 80°W) but does not account for solid Earth's deformation due to this spin axis wander itself. Therefore, the GPS rates of vertical motion must be compared with a postglacial rebound model that includes the effect of rotational feedback.

At each of 1000 available global GPS sites, we fit estimates of position as a function of time from 1995 to 2012 with a position (at an epoch), a velocity, a sinusoid with a period of 1 year, and offsets when and where needed. In the present work, we have continued to employ the methods we have used on previous occasions [e.g., *Argus et al.*, 2010, appendix B] which are further discussed in *Argus et al.* [2014]. The interested reader is referred to the latter paper for a more detailed description of the methodology employed to reduce this GPS data set. In that paper the analysis of the Jet Propulsion Laboratory (JPL) data set has been restricted to the available observations from Antarctica. The North American and Northwest European data will be uniquely discussed in the present paper where they will be employed in the construction of the Northern Hemisphere component of ICE-6G_C (VM5a).

For the purpose of our analysis, we have placed JPL's GPS results in a global reference frame following the methods of *Argus et al.* [1999, 2010] and *Argus and Peltier* [2010]. Although JPL's GPS results constitute the main basis for this study, we have also performed an inversion of solutions from six institutions based on four space techniques. The data input for these additional analyses consist of the velocities of the following: 509 GPS sites from JPL's solution; the 52 VLBI, 20 SLR, and 37 DORIS sites employed in *Argus et al.* [2010]; 36 GPS sites in Fennoscandia (BIFROST data from 1994 to 2006, analyzed by *Lindberg et al.* [2010]); and 142 GPS sites in the Canadian Base Network (estimated using four campaigns from 1996 to 2011 by M. Craymer (electronic communication, 2012)).

The estimated parameters consist of the rotational and translational velocities between the original reference frames of the four space techniques, the angular velocities of the major plates, and the velocities of sites on plates moving significantly due to postglacial rebound or current ice loss. The velocities of other sites on plates are deduced from their residuals [*Argus and Peltier*, 2010]. Data from the same inversion of the GPS observations will be employed for the analysis of the glaciation history and isostatic adjustment of each of the regions in which we are interested. In Table S1 of the supporting information accompanying this paper, we have tabulated the inferred rates of vertical and horizontal motion at each of the locations in North America that are employed for the purpose of our analyses together with the predictions of the ICE-6G_C (VM5a) model as well as the 2 sigma confidence limits on the observations.

Figure 3 provides the set of deglaciation isochrones from *Dyke et al.* [2002] that are employed to constrain the temporal evolution of the area of the North American continent that was covered by land ice from LGM until the present. These isochrones are currently available at approximately 1000–500 year intervals on the sidereal timescale with their ages having been originally determined on the basis of radiocarbon dating and then transferred into sidereal time using the conventional calibration process [*Reimer et al.*, 2009]. When we adjust ice thickness over North America so as to eliminate the misfits to the data previously identified in *Argus and Peltier* [2010], we only modify the thickness of the ice within regions in which it is known to have existed at the time for which the adjustment is made. To the extent that there are inaccuracies in the margin chronology, these will propagate into the refinement of the glaciation history.



Figure 3. Deglaciation isochrones for the Laurentide, Cordilleran, and Innuition ice sheet complex of North America according to *Dyke et al.* [2002]. These ice margin locations are the constraints applied in the construction of both the ICE-5G and ICE-6G_C deglaciation chronologies.

For the North American region, Figure 4 shows the present-day-predicted map of vertical motion that is obtained following the adjustment of the ice thickness versus time data so as to eliminate the misfits of the predictions of the previous ICE-5G (VM2) model of Peltier [2004] to the data obtained from the new global GPS inversion. Also shown in Figure 4 are the positions of these North American sites, for each of which the radius of the circle is indicative of the accuracy of the vertical motion observation available from it, the larger the radius of the circle, the higher the accuracy. Notable is the fact that in addition to the very large number of GPS sites from the Canadian land mass which was once covered by ice, we now also have available an extremely large number of sites from the continental United States that lay south of the LGM ice margin. Since the strategy we are employing is one in which only the ice thickness history in the ice-covered region is being adjusted in the process of refining the model, the data from the sites south of the ice-covered region will provide us with a check on the quality of the refined model in terms of data not employed in the refinement process. This process simply consists of iteratively modifying the ice thickness history in the regions previously identified in Argus and Peltier [2010] as being locations where significant misfits of ICE-5G (VM2) model predictions to the GPS observations existed. Inevitably, once appropriate adjustments were introduced in these regions, further errors were introduced as a result because the response to load removal is not entirely local to the region in which the adjustment is made. The refinement of the model therefore involves a tedious process which we have not attempted to automate using the previously developed methodology involving an explicit model of ice sheet dynamics [e.g., Tarasov et al., 2012]. We have learned to eschew that process as it is strongly restricted in its skill by virtue of the fact that it relies upon the use of an overly simple model of ice mechanical behavior that also requires inputs which are themselves subject to significant error, related, for example, to climate forcing, mass balance response, subglacial processes, etc. The methodology we are employing to refine the model is therefore a "GIA only" methodology. Once this



Figure 4. The predicted present-day rate of vertical motion of the crust for the ICE-6G_C (VM5a) model of the global glacial isostatic adjustment process is represented by the background map in which amplitude in mm/yr is represented by the color bar. Superimposed upon this map are the locations of the sites, shown as the open circles, from which GPS measurements of vertical motion are available. The radii of these circles are inversely proportional to the standard error of the individual measurements. Also shown are the traverses along which comparisons are shown in Figures 5a–5c between the predictions of several of the available models including the new model ICE-6G_C (VM5a).

iterative process of model refinement has converged to a final time-dependent thickness distribution, we may proceed to assess its quality. It is this converged thickness history that has been employed to predict the map of vertical displacement rate in Figure 4. The glaciological self-consistency of the models so produced will be addressed elsewhere.

Also depicted in Figure 4 are a series of 11 transects across the model predicted rate of vertical motion field for which we may produce quantitative comparisons of observations to model predictions. These transects are labeled AA'–KK' in the figure. Figures 5a–5c illustrate the quality of the model fits to the observed rates along these three sets of transects. Comparisons of model predictions to the observations along these transects are shown not only for the new ICE-6G_C (VM5a) model but also for the predictions of the previous ICE-5G (VM2) model and an additional model denoted in the figure as *Geruo et al.* [2013], the latter being a reconstruction of the prediction of the ICE-5G (VM2) model by *Geruo et al.* [2013] based upon the identical loading history for North America as that of the ICE-5G (VM2) model and an essentially identical radial profile of viscosity. Inspection of this sequence of comparisons of model fits to the newly constructed GPS vertical motion data set shows that the reconstruction of the ICE-5G (VM2) predictions by Geru et al. are essentially identical to our own predictions even though the numerical methodology they are employing is distinct from our own. As stated in section 1, our analyses are based upon the theory of viscoelastic normal modes that was originally developed in *Peltier* [1974, 1976] and *Clark et al.* [1978] with the rotational feedback contribution calculated as described in the preceding theory section of this paper. Clearly on all traverses, the misfits of the ICE-5G (VM2) model to the data are highly significant. Equally significant, however, is the fact that the misfits of



Figure 5. (a) Comparisons between GPS observed and GIA model predicted rates of vertical motion along the traverses AA', DD', and GG' shown in Figure 4. Blue sites are from locations that were once ice covered, red sites were never ice covered, and white sites are sufficiently far removed from the line of the traverse that misfits to the data may be ascribable to that source of error. (b) Same as Figure 5a but for the traverses BB', CC', EE', and FF'. (c) Same as Figure 5a but for the traverses HH'–KK'.

this model to the data on all eleven traverses are essentially eliminated by the new ICE-6G_C (VM5a) model. Furthermore the new GPS data set includes results for a very large number of sites from the United States where land ice at glacial maximum was absent. Since this region is under the control of the process of glacial forebulge collapse, rather than the process of postglacial rebound of the crust that is characteristic of the region that was once ice covered, the fact that the model is also fitting the data from this region, data that were not employed to constrain the model, provides further and independent confirmation of its validity.

Additional independent confirmation of model validity is available from the GRACE time-dependent gravity observations, further observations that have not been employed to tune the model parameters. Figure 5 provides a comparison between the fits to the GRACE gravity observations for ICE-5G (VM2) as compared to the new ICE-6G_C (VM5a) model. The GRACE inference of the signal over North America in time-dependent gravity is shown on the top left frame of Figure 5 labeled "GRACE" in which the time dependence of the gravitational field is represented as the time rate of change of the thickness of a layer of water on Earth's surface in units of mm/yr. The Release 5 GRACE product from the U.S. Center for Space Research has been



Figure 5. (continued)

employed in producing this figure, and a Gaussian filter of half width 300 km has been applied but no correlated error filter has been invoked. The GRACE field has the form of a double bull's-eye pattern consisting of two prominent extrema straddling Hudson Bay. This differs from the result first documented in *Peltier and Drummond* [2008], *Peltier* [2009], and *Peltier and Luthcke* [2009] in which the Release 4 product, which was processed using the correlated error filter and the same Gaussian filter, was characterized by a single elliptical anomaly trending northwest and southeast centered upon Hudson Bay. The possible reasons for this difference are that for the purpose of the present analysis, the correlated error filter previously employed to eliminate "striping" of the signal is apparently no longer needed and/or that the Release 5 product is



Figure 5. (continued)

comprised of time series of monthly reconstructions of the field that is now sufficiently long and/or of increased accuracy so as to eliminate artifacts of this kind. In the previous analysis, the double bull's-eye pattern only appeared once the correction due to surface hydrology variations was applied. The same result as that first published in Peltier and Drummond [2008] was also obtained independently by Tregoning et al. [2009] in their analysis of the Release 4 GRACE product. When the hydrology correction is applied to the Release 5 data, it converts the GRACE signal into that labeled GR-GL where the hydrology correction has been based upon the Global Land Data Assimilation System (GLDAS-NOAH) model [Rodell et al., 2004] that has been denoted as "GL." This is observed to amplify the strength of the double bull's-eye pattern rather than being required for it to emerge. Of primary importance, however, is the fact that the prediction of the signal over North America in time-dependent gravity by the previous ICE-5G (VM2) version of the model is not consistent with this double bull's-eye pattern whereas the prediction of the new ICE-6G_C (VM5a) version of the model is (also shown). The improvement of the GIA model introduced by improving the ice loading history so as to better fit the GPS observations of the rate of vertical motion of the crust is therefore confirmed as a significant improvement by this independent check. It is interesting to note in this regard that the newly refined model of the GIA process fits the low-pass filtered version of the Release 5 GRACE data well, whereas application of the hydrology correction somewhat degrades the fit in the formerly ice-covered region while improving it in the region south of the ice margin, perhaps implying that the hydrology correction in the former region requires further improvement or that further adjustment of the GIA model may be warranted. Also shown in Figure 5 are the differences between the different GIA predictions of the impact of ancient ice age influence on gravity field time dependence and the complete GRACE signal over North America and Greenland. By subtracting the prediction of the GIA model from the modern observed signal, we see clearly revealed the signals centered on Greenland and the high topography of Alaska and the Canadian Yukon Territory associated with modern global warming-induced loss of land ice. Evident by inspection of these difference fields is the fact that the ICE-6G_C (VM5a) model is a superior filter of the influence of ancient ice age influence from GRACE than is the previous model. An initial version of Figure 6 was first published in Peltier [2010] demonstrating the significant improvement of the fit to GRACE data achieved when the GPS observations were taken fully into account.

Further commentary is warranted concerning the fit of the new model to the GRACE observations in connection with the fact that these observations are generally considered to be accurate only to degree and order 60 in spherical harmonics. In Data Set SStokes in the supporting information, we provide a listing of the geoid Stokes coefficients for the ICE-6G_C (VM5a) model to degree and order 256. Purcell et al. [2011], improving upon the earlier suggestion of Wahr et al. [2000], have suggested that an empirical relation may be employed to directly predict the vertical motion of the crust from such GRACE observations of gravity field time dependence as represented by the geoid Stokes coefficients. Because the GIA model is complete to degree and order 256, we are in a position to fully test the accuracy of the Purcell et al. [2011] suggestion. Such a test for the North American sector of the model is provided in Figure S2 in the supporting information where we show the ICE-6G_C (VM5a) prediction of the rate of vertical crustal motion for the complete model in (a), the approximation to this provided by application of the Purcell et al. [2011] empirical expression based upon the geoid Stokes coefficients listed in Data Set SStokes to degree and order 60 which is the restricted range over which it usually believed GRACE to be accurate in (b), as well as the prediction using the same empirical expression using all of the Stokes coefficients to degree and order 256 in (c). Also shown are the differences between these two empirical estimates and the exact model solution in (d) = (b) – (a) and (e) = (c) – (a), respectively. Inspection of the results presented in the latter figures demonstrates that there is a highly significant error in the empirical prediction, irrespective of the resolution of the empirical solution employed. This error is centered upon the region of Hudson Bay in which, because of the ongoing postglacial rebound of the crust that is occurring in this region, the water load is continuing to vary thereby violating one of the assumptions on which the Purcell et al. empirical result is based, namely, that no changes in surface loading on the target region has occurred for the last 6000 years. There are additional errors evident in this comparison that are due to the fact that important changes of loading have also occurred on spatial scales that are not resolvable even at the highest resolution for which the empirical model has been employed, e.g., in the Fox Basin region off the coast of Baffin island and in the Queen Elizabeth Islands in general. Additional comparisons of the same kind for Fennoscandia and Antarctica are shown in Figures S3 and S4, respectively, in the supporting information. Important errors in the empirical formula are clearly evident in both regions, for these same reasons, e.g., see the



Figure 6. Shows GRACE observations labeled "GRACE" of the time dependence of the gravitational field over North America and Greenland based upon Release 5 data from the center for Space Research (CSR) for the period January 2003 to October 2013. No correlated error filter has been employed in producing the results shown on this plate of the figure, but a spatial filter with a Gaussian half width of 300 km has been applied. Also shown are the predictions of the ICE-6G_C (VM5a) model of the GIA process (labeled ICE-6G). In both graphics, the gravity field time dependence is represented as the time rate of change of a layer of water on the Earth's surface in mm/yr. The degree 2 and order 0 and degree 2 and order 1 coefficients in the ICE-6G_C (VM5a) prediction are replaced by those from *Roy and Peltier* [2011] for the period prior to the early 1990s. The plate labeled GR-GL is that generated by applying the GLDAS hydrology correction of *Rodell et al.* [2004] for the gravity field time dependence due to changes in the surface hydrology of the continent (here GR = GRACE and GL = GLDAS). Also shown is the field-labeled ICE-5G which shows the predicted results for gravity field time dependence for the ICE-5G (VM2). The fields labeled GR-GL-16 and GR-GL-15 represent the residual fields for gravity time dependence associated with the modern influence of global warming which is leading to the meltback of the Greenland ice sheet and the high-altitude ice catchments on the mountains of the U.S. state of Alaska and the Yukon Territory of Canada.

misfits in the Gulf of Bothnia and Scotland regions of Northwestern Europe and in the regions of West Antarctica where the most intense unloading of the crust has occurred since Last Glacial Maximum. Especially in Antarctica, these errors of the predictions of the Purcell et al. empirical model are particularly severe which strongly suggests that it not be employed at all for analyses of vertical motion observations in this critical region.

Now the two data sets discussed above (GPS and GRACE) that have been employed to demonstrate that the new model is a significant improvement on its precursor are both data sets that involve present-day measurements of the rates of continuing ice age influence. It is equally important, however, to demonstrate that there has been no sacrifice of the accuracy of fits to data that constrain the history of the evolution of this influence, the primary data that may be invoked for this purpose being relative sea level histories determined by the radiocarbon dating of geomorphological features indicative of past levels of the sea at different spatial locations. Although the existing data base of such information for the North American continent is voluminous, we will content ourselves here by providing only a limited number of illustrations from sites that were previously covered by the now vanished Laurentide, Cordilleran, and Innuition ice sheets, as well as representative sites from locations south of the ice margin at the LGM. Maps showing the locations of the selection of sea level sites (for each of our primary target regions of North America, Fennoscandia, and



Figure 7. Locations from which representative relative sea level data are available for North America, Fennoscandia, and Antarctica that are employed to test the quality of the new model of the glacial isostatic adjustment process that is produced by the refinement process described in this paper that is primarily based on the application of GPS measurements of the rate of vertical motion of the crust.

Antarctica) are shown in Figure 6, and a listing of the site names and references for the data from each of the North American locations is provided in Table SS1. Discussion of the sea level data from the Antarctica locations has been previously discussed in *Argus et al.* [2014] and will not be repeated in what follows, but it is important to recognize for present purposes that very few such data are, in fact, available.

Figure 7 shows a sequence of 18 intercomparisons between RSL observations and predictions of the ICE-5G (VM2) and ICE-6G C (VM5a) models at North American sites. Sites in Canada are for locations that were once covered by ice and which have been employed to tune the model, whereas sites in the United States primarily lay external to the previously ice-covered region and were not employed to tune the model. Inspection of the comparisons in Figure 7 for the Canadian sites will show that at four sites (Eclipse Channel, Churchill, Bella Coola, and Squamish), the ICE-6G_C (VM5a) model provides an improved fit to the data. At an additional three sites (St. Anthony, Fort George, and Kugluktuk), the fit of the two models to the data is similar, both models being acceptable. At the remaining two Canadian sites (Ungava Bay and Deception Bay), the fit of the earlier model to the data is somewhat better than that of the new model. Turning to consideration of the comparisons shown in Figure 7 for the additional nine sites that were not ice covered, it will be observed that the fit of the new model to the data at most locations is also an improvement to the fits delivered by the earlier model ICE-5G (VM2) of Peltier [2004]. However, it is also clear that certain characteristic misfits remain, especially at sites that lie along the East Coast of the continental United States. For example, at many such locations (e.g., New York and South Carolina), the misfit is such that the oldest data consistently lie above, i.e., at shallower depth, than the predictions of the model. In work, to be described elsewhere (K. Roy and W. R. Peltier, Glacial isostatic adjustment, relative sea level history and mantle viscosity: reconciling relative sea level model predictions for the U.S. East Coast with geological constraints, submitted to Geophysical Journal International, 2014), a detailed analysis is presented of the further adjustments to the model, especially involving the radial profile of mantle viscosity, that may be invoked to remedy this characteristic misfit to data from sites beyond the ice margins. At those sites in Figure 7 that were near the southern margin of the North American ice sheet complex at LGM, however (S. (Southern) Massachusetts, S. (Southern) Maine, Moncton, and Riviere-du-Loup), the new model appears to provide an improved fit to the data.

A final characterization of the properties of the new model for the North America region compared with the previous version at 21,000 years before present is shown in Figure 8. In this figure we compare the topography of the region with respect to sea level near the time of the Last Glacial Maximum for the two models, ICE-6G_C (VM5a) (shown in the upper plate) and ICE-5G (VM2) (shown in the center plate). The difference between them is shown in the bottom plate. This "paleotopography" field is extremely important from the perspective of our ability to construct well-constrained inferences of the ice age climate regime using coupled atmosphere-ocean general circulation models. Inspection of the difference between these two paleotopography fields will show that to achieve the dramatically improved fit to the GPS data, we have had to substantially reduce the thickness of ice to the west of Hudson Bay and to somewhat increase its thickness over northern Quebec and in the region near the northern border between the Canadian provinces of Alberta and British Columbia. These requirements were suggested on the basis of the misfits identified to

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Figure 8. Predicted relative sea level histories for the ICE-6G_C (VM5a) and ICE-5G (VM2) models for the sequence of 18 locations shown in Figure 6 which were either covered by or outboard of the North American ice sheet complex.

the earlier compilation of GPS data discussed in *Argus and Peltier* [2010]. Our more accurate data set provided in Table S1 in the supporting information has simply reconfirmed the necessity of these modifications to the model. Insofar as the application of these, as yet unpublished, data sets to the problem of climate reconstruction is concerned, analyses have already begun to be published using them, examples of which will be found in *Vettoretti and Peltier* [2013] and *Peltier and Vettoretti* [2014]. The data sets needed for use by others will be made available from http://www.atmosp.physics.utoronto.ca/~peltier/.

4. The Glaciation History and Isostatic Adjustment of Northwestern Eurasia

The quality of the ICE-5G (VM2) model, at least insofar as Fennoscandia and the Barents Sea regions are concerned, was far superior to that for North America. Figure 9 shows the map of ice margin locations for this region recently produced by Gyllencreutz et al. [2007], and Figure 10 shows the map of the predicted vertical motion of the crust provided by the new ICE-6G_C (VM5a) model, superimposed upon which, in a format identical to that employed for the analysis of the North American results in the previously discussed Figure 4, is the set of locations from which GPS estimates of the rate of vertical motion of the crust are available. The inferred rates of vertical motion of the crust at each of these locations, as well as the model predicted rates, are listed in Table S2 in the supporting information. Also shown in the figure are the locations of three traverses across the region (RR'-TT') along which we will proceed to compare model predictions with GPS observations. These comparisons are shown in Figure 11. On the cross sections RR' and TT', it would appear that the new model is somewhat superior to its precursor ICE-5G (VM2). However, in section SS' there clearly exists a large misfit at the Ny Alesund location which is undoubtedly associated with the fact that this site in the Spitzbergen Archipelago is in a region that is currently experiencing ice loss due to the global warming process and therefore is uplifting at a rate considerably in excess of that predicted to be occurring solely as a consequence of the ice loss that occurred during the deglaciation phase of the most recent Late Quaternary ice age cycle. Also notable in section SS' are the misfits evident at Bodo and Vilhelmina, although these sites are actually significantly distant from the cross section itself, and so it is unclear whether the associated misfits might simply be a consequence of the inaccuracy of the projection of the data onto the cross section. All in all, we conclude that insofar as Northwestern Eurasia is concerned, GPS data from both sites within the ice-covered region and from sites beyond the ice margins that have not been employed in tuning the model is providing an



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Figure 9. Paleotopographies of the North American ice sheet complex that would be seen by the CESM1 global climate model [e.g., *Meehl et al.*, 2013], whose resolution is approximately 1° in both latitude and longitude, for either the new ICE-6G_C (VM5a) or the precursor ICE-5G (VM2) model. Also shown is the difference between these two predicted paleotopographies.

excellent fit to the vertical motion observations. Since we are employing not only the BIFROST data from the ice-covered region but also that from the surrounding region of forebulge collapse, we have been able to significantly extend the region of applicability of the model beyond that which was the focus of the original BIFROST analysis of Milne et al. [2001, 2004]. This is important as the viscosity model which we show to be applicable to this entire region differs significantly from that inferred on the basis of this early analysis. In the work of these authors, it has been suggested that there was strong preference in the data for a lower mantle viscosity that was in excess of an order of magnitude higher than that of the upper mantle. Insofar as upper mantle viscosity is concerned, however, there is general agreement among those who have seriously considered the problem that the average viscosity of the upper mantle and transition zone is 0.4–0.5 \times 10^{21} Pa s, as in Peltier [1996] and in Lambeck et al. [1998a, 1998b]. The lower mantle value was claimed in Milne et al. [2004] to lie within the 95% confidence range 5×10^{21} Pa s to 5×10^{22} Pa s. It is notable that although the upper mantle viscosity in VM5a is 0.5×10^{21} Pas, the viscosity of the upper part of the lower mantle is significantly lower than the lower bound inferred in both the work of Milne et al. [2001, 2004] and that of Lambeck et al. [1998a, 1998b]. This is simply a consequence of the fact that the horizontal scale of the Fennoscandian ice sheet complex is insufficiently large to provide resolution into even the upper part of the lower mantle. As has been demonstrated elsewhere [e.g., Peltier, 1996, 1998] in terms of the Frechet kernels for the individual wave number components of the Fennoscandian relaxation spectrum, the resolving power of these data is essentially negligible for depths much below the 660 km depth seismic discontinuity that marks the base of the mantle transition zone. In VM5a the viscosity in this region is fixed by relaxation time data derived from relative

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Figure 10. Margin positions for the Fennoscandian and Barents sea ice complexes from LGM to present day according to the compilation of *Gyllencreutz et al.* [2007].

sea level records near the previous center of the Laurentide ice sheet complex of North America which surrounded Hudson Bay as previously discussed above (e.g., see *Peltier* [1998] for a review).

As in the case of North America, we may check the quality of the Northwest Eurasian component of the model by invoking the GRACE observations of the time dependence of the gravitational field over this region. This comparison is shown in Figure 12 which is focused upon Fennoscandia. The format of the presentation is identical to that employed for the North American data. Here when the correction of the GRACE data for the influence of hydrology is performed using the GLDAS-NOAH data set, the GRACE signal centered on the Gulf of Bothnia is actually diminished in amplitude rather than amplified as was the case for North America. Also in this region, as was the case for the fits of the model to the GPS observations, there is very little difference between the results for ICE-5G (VM2) and the new model ICE-6G_C (VM5a) insofar as the signal over the Gulf of Bothnia is concerned.

As also was the case in the discussion of the North American data, the above comparisons focus entirely upon data that record the strength of the continuing uplift of the crust due to the deglaciation phase of the most recent Late Quaternary ice age cycle. In order to assess the quality of the model's representation of the history of this response, we once more invoke the RSL records at a number of sites from this region in order to provide the needed further assessment. The locations of the sites we have selected for this purpose are shown in the previous Figure 6, and the data from them have been compiled from the references listed in Table SS2 with the detailed bibliographic materials once more provided together with the table. The comparisons between the ICE-5G (VM2) and ICE-6G_C (VM5a) predictions and the observations are shown in Figure 13 for the 12 locations we have selected. Inspection of these comparisons will demonstrate that the quality of the fit of our GIA model to the RSL data from this region are inferior to those for the North American sites even though the fits to both the GPS and GRACE data are of high quality. The reason for this diminished capability insofar as the historical data are concerned has to do with the complexity of the mass unloading process that occurred in this



Figure 11. Map of the predicted rate of vertical motion of the crust in Northwestern Europe/Eurasia for the ICE-6G_C (VM5a) model. Also shown as the closed circles are the locations from which GPS observations of the vertical motion are available as well as three traverses of the landscape along which comparisons are shown in Figure 11 of predictions compared with observations for this GIA model and its precursor ICE-5G (VM2). The radius of the circles showing the locations of the available GPS measurements is inversely proportional to the standard error of the measurement at each site.

region that was associated with the development of the Baltic Lake that existed ephemerally during the deglaciation process, the establishment of which led to a shift of the surface mass load in the form of ice from one spatial location to that in the form of meltwater to another region prior to the time when the lake was finally connected to the ocean and discharge occurred. Further discussion of the complexity of the relative sea level records from Fennoscandia will be found in *Lambeck et al.* [2006].

As a further check on the ability of the model to reconcile the ongoing rebound of the crust in this region, it is useful to focus upon the associated rate of relative sea level change as this is recorded on the many tide gauges that are located throughout the region, many of which have been operated for more than 100 years. If we restrict attention to the data from such gauges, there are 26 such installations whose locations are shown in Figure 14 where the individual sites are assigned a letter. Parts a and b of Figure 15 compare the data from a subset of 12 of these locations to the predictions of two different version of the GIA model which differ only in the assumed viscosity profile, which is fixed either to VM5a or VM5b, the latter model, introduced in *Engelhart et al.* [2009] to test its influence on RSL predictions at U.S. East Coast locations, differing from VM5a only in the upper mantle and transition zone where VM5b is assumed to have half the viscosity (0.25×10^{21} Pa s) of VM5a (0.5×10^{21} Pa s). In Figure 15b the sites correspond to locations that were once covered by the Fennoscandian ice sheet, whereas in Figure 15b the sites correspond to locations of the new ICE-6G_C (VM5a) model (shown as the red lines) fit the observed rates of relative sea level fall (represented by the black linear least squares fits to the tide gauge data) well, whereas the predictions of the model with



Figure 12. Comparisons between the observed and predicted vertical motion of the crust along the traverses RR'-TT' for both ICE-6G_C (VM5a) and ICE-5G (VM2).

the softer viscosity in the upper mantle and transition zone (VM5b) significantly misfit the observations. The comparisons in Figure 15b, which are for sites in which relative sea level is generally rising, as most of these locations are found in the region of glacial forebulge collapse, display considerably more variability insofar as the quality of the model fits to the data is concerned. At four of the sites, where the signal is as much as 10 times weaker than is characteristic of the rate of sea level fall characteristic of ice-covered locations, the fits are equally good, whereas at two of these additional six locations the fits are poor suggesting that the location of the LGM margin of the ice cover or the timing of deglaciation is in error. These data will therefore prove useful in further refinement of the GIA model in this region. At all of these additional sites, the fit of the softer VM5b model continues to be inferior to that of VM5a when the ICE-6G_C loading history is assumed.

The final illustration of the new model we will provide for Northwestern Europe/Eurasia, which parallels our discussion of the new North American component, is of the LGM topography with respect to sea level that would be represent in this region if the model were employed to fix the surface boundary conditions of a modern coupled atmosphere ocean general circulation model of LGM climate. Once more, we employ the U.S. National Center for Atmospheric Research Community Earth System Model version 1 (CESM1) for this purpose, the horizontal resolution of which is approximately 1° by 1°. Figure 16 compares this characteristic of the ICE-6G_C (VM5a) model to that of the precursor ICE-5G (VM2) model in the same format as employed previously for North America. Inspection of the results for this region will show that the Greenland component of the model remains the same as that described in *Tarasov and Peltier* [2002], which was constrained by an explicit model of ice sheet dynamics trained to fit relative sea level histories from sites located along the coastline of Greenland. Modest changes in the loading history that are not clearly visible for the British Isles were, however, required to fit the records of relative sea level change from the ice-loaded region of Scotland discussed in *Peltier et al.* [2002], in order to account for the effective thinning of the lithosphere characteristic of the VM5a viscosity structure described in *Peltier and Drummond*



Figure 13. Same as Figure 5 but for Fennoscandia.

[2008]. Insofar as the core regions of the Fenoscandian ice sheet are concerned, however, the required modifications of the ice cover are very modest, amounting to a slight shift westward toward the high mountains of Norway of the region of maximum paleotopographic height. We conclude that the model in this region constitutes a more modest improvement compared to the radical improvement that has been achieved for North America.

5. The Glaciation History and Isostatic Adjustment of Antarctica

The application of space geodetic measurements to the refinement of the deglaciation history of Antarctica is more challenging than for either North America or Northwestern Europe/Eurasia. There are many reasons for this, not the least of which concerns the difficulty of making the needed GPS measurements in an environment that is as hostile as that of Antarctica. However, the most significant challenge is actually associated with the fact that the entire continent has remained ice covered over most of its surface during the most recent deglaciation event of the current ice age and that the relative sea level histories that are available are, of course, all confined to sites along the current coastline. This means that unlike the case of the two Northern Hemisphere regions of significant continental glaciation, which are now inland seas (Hudson Bay and the Gulf of Bothnia) whose coastlines record the history of relative sea level change subsequent to deglaciation, the relative sea level histories that are available from Antarctica cannot be invoked to provide an independent inference of the effective viscosity beneath the Antarctic Plate, the rebound of the crust in these locations being dominated by what we might refer to as "edge effects." Most of the available GPS observations are also available only from such edge locations, although these are much more numerous now compared with the sites from which multimillennial sea level histories have been constructed. However, an additional data set has recently become available [*Whitehouse et al.*, 2012a], consisting of exposure age dates on "trimline elevations"

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Figure 14. Comparisons between predicted and observed sea level histories of the sites in Fennoscandia, whose locations are shown in Figure 6.

which can be interpreted as constraints on the time-dependent thickness of ice at the locations from which such data are available. Although these data are also primarily from edge sites, they do constitute a useful additional set of constraints that any successful model should strive to accommodate.

All three of these data types have very recently been employed as a basis for the refinement of the ICE-5G (VM2) model of the glaciation history over the Antarctic continent [*Argus et al.*, 2014], and so it will not be necessary in this paper to do more than briefly review, and somewhat expand upon, the conclusions



Figure 15. Map of the predicted rate of relative sea level rise for the Fennoscandian region on which is superimposed the locations of tide gauges of more than 100 years seniority on which the secular rates of relative sea level change are recorded which may be compared with the predictions of GIA models for the region.

previously reached. The primary data set employed for this purpose has been that consisting of vertical rates of motion of the crust determined by the same JPL global inversion of GPS measurements as that which formed the basis of the analysis of sites from North America and Northwestern Europe/Eurasia and which was discussed in section 2 of this paper and applied in the previous sections 3 and 4. Table 1 of Argus et al. [2014] has provided a listing of the GPS observed rates of vertical motion of the crust in this region as well as the predictions of the ICE-6G_C (VM5a) model. There are at least two important characteristics of the revised model for Antarctica which require comment herein for completeness sake. First, the net loss of mass from the southern continent across the glacial-interglacial transition in the new model [see Argus et al., 2014, Figure 2] is approximately 13.6 m in eustatic sea level rise equivalent terms

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Figure 16. (a) Comparison of the tide gauge observed and GIA predicted rates of relative sea level rise at six of the locations noted in Figure 14, all of which are located in the region that was once ice covered and which is now experiencing postglacial rebound of the crust and thus relative sea level fall. The thin black line on each plate represents, in its slope, the present-day rate of RSL fall determined by a linear least squares fit to the annually averaged tide gauge data. The red lines represent the prediction of the new ICE-6G_C (VM5a) model, whereas the green lines represent the prediction of a modified version of the GIA model in which the viscosity of the upper mantle and transition zone has been reduced by a factor of 2 from the value of 0.5×10^{21} Pa s value characteristic of the ICE-6G_C (VM5a) model. This modification to the radial viscosity structure is denoted as VM5b in the literature *Engelhart et al.* [2009]. (b) Same as Figure 15a but for six additional sites shown in Figure 14 that are located outside of the region that was once covered by the Fennoscandian ice sheet complex.

rather than the 17.5 m that was characteristic of the precursor model ICE-5G (VM2). The second difference between the new model and ICE-5G (VM2) concerns the contribution of Antarctica to the meltwater pulses during which global sea level has been inferred to have risen very rapidly on the basis of the Barbados record of sea level history. These are labeled MWP 1A and MWP 1B in Figure 1 of this paper. Also notable is the fact that both ICE-6G_C and ICE-5G contain sharp inputs of meltwater from Antarctica associated with meltwater pulse 1B in the Barbados record of relative sea level rise illustrated previously in Figures 1 and 2 of this paper, whereas the old model ICE-5G contained no contribution to meltwater pulse 1A from Antarctica. On the contrary, the W12 model contains no contribution to either of these meltwater pulses from Antarctica.

The time derivative of the sea level history record from Barbados much more clearly shows the occurrence of both meltwater pulses and the results of such an analysis based upon the excellent fit to the Barbados record shown previously in Figure 1 of this paper are shown in Figure 17. Superimposed upon this time series and denoted as solid squares with attached error bars are the times of the onset of deglaciation at a large number of sites from the shelves surrounding Antarctica within which thick ice was grounded in what are now regions of deep water (E. Domack, 2010, and A. MacIntosh, 2012, personal communications to W.R.P.).



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Anomaly (ICE6G C - ICE5G) 500





These estimates of the timing of deglaciation are based upon carbon dating [Domack et al., 1989] of the recommencement of marine sedimentation which could not begin until the ice had pulled back from the shelf break, out of which it had apparently extended at LGM. In each of the sedimentary cores raised from these continental shelf sites, there is a hiatus in the sedimentation record. Below the hiatus, evidence of marine sedimentation is absent. Above the hiatus, it is present. The hiatus therefore occurs at the time that grounded ice disappeared from the location from which the core was raised. Inspection of the timing of deglaciation at the locations from which the sedimentary cores were raised shown in Figure 17 demonstrates that deglaciation at the vast majority of sites occurred coincident (within the error of the carbon dating) with the timing of meltwater pulse 1B in the Barbados record. This is a primary constraint employed in the construction of the history of Antarctic deglaciation of the ICE-6G_C (VM5a) model. As also shown in Figure 2 of Argus et al. [2014], however, and suggested by at least one of the deglacial timing results in Figure 17, the new model of Antarctic deglaciation also contains a modest input of deglacial meltwater at meltwater pulse 1A time. In Argus et al. [2014] this was argued for on physical grounds. Given that the majority of meltwater pulse 1A is derivative of Northern Hemisphere sources and given that the gravitationally self-consistent theory for postglacial relative sea level history predicts that the resulting sea level rise would be especially strong in the opposite hemisphere, it was suggested that all grounded shelf ice that was sufficiently thin to be unable to resist the buoyancy associated with the MWP 1A-induced rise of local relative sea level would have disintegrated into gloating icebergs. In fact, analyses of an ice-rafted debris layer in sedimentary records from a region referred to as "iceberg alley" has recently been reported that is consistent with this proposed contribution to meltwater pulse 1A [Weber et al., 2012].

Although we were able to check the quality of the refinement of model ICE-5G (VM2) represented by the new model ICE-6G_C



Figure 18. Time derivative of the Barbados record of relative sea level rise of *Peltier and Fairbanks* [2006] documenting the occurrence of the two meltwater pulses 1A and 1B. The black squares, each with an appropriate error bar, denote the age of the hiatus in each sedimentary core which corresponds to the time of recommencement of marine sedimentation at the corresponding location. This is interpreted as the timing of the "pull back" of grounded ice from the proximate continental shelf. At the majority of such sites, grounded ice is eliminated at the time of meltwater pulse 1B in the Barbados record. Also shown in the figure are the locations of each of these sites together with the list of references in which the data for each site can be found. The radiocarbon dates for the hiatus in the sedimentation record at each site has been determined using the pyrolysis technique discussed in *Rosenheim et al.* [2008]. This figure has been provided courtesy of Andrew Mackintosh. See *Mackintosh et al.* [2011, 2013] for further discussion.

(VM5a) using the GRACE time-dependent gravity observations over both North America and Northwestern Europe/Eurasia, this is not possible insofar as Antarctica is concerned. This is a consequence of the fact that not only is Antarctica still ice covered but it is currently experiencing rapid ice loss during the ongoing Anthropocene era of global warming. In this region the GRACE observations can (and must) be employed, however, to constrain the rate at which this mass loss is occurring, but this is only possible if an accurate model of Late Quaternary deglaciation and GIA response is available to produce an accurate reconciliation of data unambiguously connected to the GIA process. Such a model may then be employed as a filter with which to eliminate the contamination of the GRACE signal due to ancient ice age influence. The guality of the new model in this regard is therefore especially important. Although it is not our purpose in the present paper to employ the new model to address this question in detail, we will record its influence when applied to the available GRACE observations. The predicted GIA signal in terms of time-dependent gravity for model ICE-6G_C (VM5a) compared to that for the precursor model ICE-5G (VM2) is shown on the two central graphics of Figure 18. This figure shows not only these alternative GIA predictions but also the Release 5 GRACE product, low-pass filtered by application of a Gaussian filter with a half width of 300 km, as inferred by the two primary analysis centers, respectively, the U.S. Center for Space Research at the University of Texas in Austin and the German Deutsches GeoForschungsZentrum (GFZ) Laboratory in Potsdam. Our analysis of the satellite data covers the period of approximately 11 years extending from January 2003 to October 2013. Notable is the fact that over this period, the inferences of the spatial variation of gravity field time dependence over the southern continent produced by the two analysis centers are extremely similar. Comparing the two GIA predictions for models ICE-5G (VM2) and ICE-6G_C (VM5a), however, makes it clear that these two models differ in several important respects. First, although both models are characterized by the same two primary extrema in the



Figure 19. Comparison between GRACE observed and GIA predicted time rate of change of the gravitational field over Antarctica. The raw GRACE observations are shown as an average rate of change over the time period January 2003 to October 2013 from both the U.S. Center for Space Research (CSR) and the German GFZ Laboratory at Potsdam. The GFZ data employed are those based upon the most recently corrected analyses. The latest GIA-predicted gravity field time dependence is shown on the central plates for both the ICE-6G_C (VM5a) and ICE-5G (VM2) models in terms of the time rate of change of the thickness of a layer of water at Earth's surface. The difference between the GRACE Release 5 data and the GIA predictions for the rate of change that should be observed if the only process involved were the influence of the last deglaciation event of the Late Quaternary ice age is also shown for both GIA models. This difference, over the primary centers of past continental glaciation is attributed to the modern influence of global warming of the lower atmosphere and the surface ocean.

vicinity Ross Sea and Wedell Sea ice shelves, the magnitudes of these extrema are inverted between the two models. Whereas the extremum close to the Wedell Sea is stronger in ICE-5G (VM2), that near the Ross Sea is stronger in ICE-6G_C (VM5a). Also notable is the evident difference between the two models in the interior of East Antarctica. Whereas in ICE-5G (VM2) it was assumed that some ice loss would have occurred from the central plateau of East Antarctica, in the new model ICE-6G_C (VM5a) it has been assumed that no significant ice loss occurred in this central region. This issue is still actively debated in the community, and there is a body of opinion, based upon the approximate accumulation records that are available from the few deep ice cores that have been drilled in East Antarctica (e.g., Vostock, EPICA Dome C, and Dome Fuji) to the effect that additional mass accumulated in this region over the Holocene.

That ice loss has, in fact, not been the sole mode of mass variation over the entire Holocene interval in Antarctica is also clear on the basis of Figure 19. This shows that for the GIA-corrected Release 5 GRACE data, substantial accumulation of mass has occurred over the 11 year GRACE interval along the coastline of East Antarctica east of the Wedell Sea. That this has been a relatively recent phenomenon, however, is established by the sequence of GIA-filtered GRACE data for the series of overlapping 7 year intervals beginning in January 2003 (Since the GRACE satellites were launched in March 2002, we start our analysis in January 2003 because Release 5 data for 2002 are not available from the GFZ analysis center and we have also been interested in comparing the CSR and GFZ interpretations.). We end our analysis in October 2013 because this is the last time for which GLDAS hydrology correction data were available to us for analysis of Northern Hemisphere data. Evident by inspection of this figure is the fact that mass did not begin to accumulate along the coast of East



Figure 20. This figure shows a sequence of 7 year overlapping averages of the rate of change of the gravitational field over Antarctica over the period January 2003 to October 2013 in which each frame shows the version of the GRACE field from which the ICE-6G_C (VM5a) prediction has been subtracted. Noticeable is the fact that following the first several years, there begins to appear a significant increase of mass along the coast of East Antarctica east of the Wedell Sea. This is interpreted to imply an increase of solid precipitation in this region.

Antarctica until approximately the middle of the 11 year GRACE period but continued to increase more rapidly as time progressed. The final plate in Figure 19 shows the average GIA-filtered field for the entire 11 year period, obtained by fitting a single rate of secular variation to each of the spherical harmonic amplitudes in terms of which the time dependence of the gravity field is constructed. It is therefore clear that insofar as the understanding the contribution of Antarctica to the ongoing rate of global sea level rise is concerned, we will be obliged to explicitly recognize that it will not be sufficient to represent this process by a single rate that may be taken to apply over the entire GRACE interval.

The final results that we will show for the Antarctic component of the new model as compared with that of the old is that for the LGM topography of the model with respect to sea level as compared to that for the ICE-5G precursor. This comparison is shown in Figure 20 in exactly the same format as was employed for North America and Northwestern Europe/Eurasia. Once more, this paleotopography with respect to sea level is that which would be seen by the coupled climate model CESM1 of the U.S. National Center for Atmospheric Research (NCAR). The primary differences in the topography with respect to sea level in the two models are that the topography of the East Antarctic plateau is lower in the new model than it was in the old because no ice is now assumed to have been lost from this region during deglaciation; furthermore, insofar as coastal locations are concerned, more ice is assumed to have been lost from these regions in the new model and this is evident in the paleotopography field as higher LGM elevation with respect to sea level in coastal regions.

6. Implications of ICE-6G_C (VM5a) for the Understanding of Far-Field RSL Observations: The Case of the South American Continent

Figure 21 shows the locations of sites from the east coast "passive" continental margin of the South American continent from which RSL data were compiled in *Rostami et al.* [2000] and employed in a series of analyses directed toward understanding the extent to which a signal associated with the process of rotational



Figure 21. Paleotopography of the continent of Antarctica at Last Glacial Maximum that would be seen by the CESM1 coupled climate model of the U.S. National Center for Atmospheric Research in which the horizontal resolution is approximately 1° in both longitude and latitude. The figure compares the paleotopography of the earlier ICE-5G (VM2) version of the model with that of the ICE-6G_C (VM5a) version and also explicitly illustrates the difference.

feedback could be isolated. The possibility that this region might prove useful for this purpose will be clear of the basis of Figure 22 which shows the present-day time rate of change of geoid height for the new model together with its constituent parts, namely, the present-day rate of relative sea level rise (labeled dSea in the figure) and the present-day rate of change of the local radius of the solid Earth (labeled dRad in the figure), the sum of which equals the present-day time rate of change of geoid height (dGeoid). As it is by now well known, dGeoid is seen to be dominated by the degree 2 and order 1 pattern that is derivative of the action of rotational feedback, a quadrapole pattern, one of whose four extrema is located on the southern tip of the South American continent. It is important to note that the degree 2 and order 1 Stokes coefficients that exert primary control over the amplitudes of these four extrema in Figure 22 are those for the geoid defined in terms of sea level rather than simply in terms of mass. This difference appears to have been discussed in detail for the first time in Peltier et al. [2012]. There, it is shown that the connection between these coefficients and the elements of the changes in the moment of inertia tensor associated with the rotational response to the GIA process are the following:

$$\dot{C}_{21} = g_1 \left(1 + \frac{1}{k_f} \right) \left(\frac{\dot{I}_{xz}^{\text{LOAD}}}{(C-A)} + \frac{\dot{I}_{xz}^{\text{ROT}}}{(C-A)} \right) \quad (7a)$$

$$\dot{S}_{21} = g_1 \left(1 + \frac{1}{k_f} \right) \left(\frac{\dot{I}_{yz}^{\text{LOAD}}}{(C - A)} + \frac{\dot{I}_{yz}^{\text{ROT}}}{(C - A)} \right)$$
 (7b)

In equations (7a) and (7b) the constant $g_1 = -\sqrt{3/5}((C - A)/M_e a^2)$. The critical feature of equations (7a) and (7b) is the term $1/k_f$ in the first bracket. This represents the increased amplitude of the Stokes coefficients that arises when the geoid is properly defined in terms of sea level. Since $k_f \cong 0.94$ (which is the so-called fluid Love number; see, e.g., Peltier and Luthcke [2009] and Peltier et al. [2012] for detailed discussions), this more than doubles the values of these coefficients that appear in the sea level-based definition of geoid height time dependence compared to those that would be determined by the shift in surface mass load alone. It is this definition of the geoid that has been employed in producing Figure 22.



Figure 22. Location map for RSL sites along the east coast of the South American continent. The individual site numbers correspond to the last two digits of those shown adjacent to the site names in the comparisons of observed to predicted Holocene RSL histories in Figure 23. The site numbers in Figure 23 are those from the University of Toronto global data base of relative sea level histories.

Figure 23 presents a comparison of the predictions of the previous ICE-5G (VM2) model with enhanced rotational feedback together with the predictions of the new ICE-6G_C (VM5a) model both with and without rotational feedback for all sites along the coast beginning with the site on the coast of Venezuela and ending with the site on the southernmost tip of the coast in Tierra del Fuego and that in Chile. A detailed discussion of the data will be found in the original paper of *Rostami* et al. [2000]. Inspection of the results of these comparisons will demonstrate that the influence of rotational feedback along this coast at sites south of the equator is to elevate the predictions of the GIA models above those that would be made in the absence of an accounting for this influence. In general, the strength of this influence is greater in ICE-5G (VM2) than in the new model which is a direct consequence of the overly large values of its degree 2 and order 1 Stokes coefficients. In fact, the results for the new model with feedback are very similar to those previously obtained in Peltier [2002a, 2002b] in which the ICE-4G (VM2) model with feedback was employed. The primary conclusion to be drawn on the basis of this sequence of analyses is that the influence of rotation feedback along this coast is readily apparent and necessary if the data are to be adequately explained (e.g., see the comparisons for

the B. Samborombon and Pedro Luro locations where the predictions of ICE-5G (VM2) are excessively high, whereas the ICE-6G_C (VM5a) prediction with rotation fits the data). Although the amplitudes of the mid-Holocene highstands from sites farther south along the coast are well fit by the ICE-5G (VM2), we must now accept that this is a consequence of the inflated values of the degree 2 and order 1 Stokes coefficients of this model. The issue remains as to whether the expected change in tidal range will suffice to explain the extreme amplitude of these high-latitude highstands or whether they will have to be recognized as being storm beach deposits, a possibility that was considered to be ruled out by *Rostami et al.* [2000] but which remains outstanding.

7. Discussion and Conclusions

In the previous sections of this paper, we have described the development of a new global model of the glacial isostatic adjustment process that we have labeled ICE-6G_C (VM5a). The refinement of the previously developed model of this process, ICE-5G (VM2), has been achieved primarily by invoking the new analysis of Global Positioning System observations recently produced by the Jet Propulsion Laboratory for the period 1994–2012 [*Desai et al.*, 2011]. The GPS data from this period were augmented by additional space geodetic constraints from complementary systems. The misfits to these vertical motion observations characteristic of the ICE-5G (VM2) model, which were found to be similar to those previously identified in *Argus and Peltier* [2010],



Figure 23. Illustration of the components of the prediction of the ICE-6G_C (VM5a) model of the predicted time derivative of geoid height (denoted as dGeoid in the figure). This field is the algebraic sum of the field for the present-day time rate of change of relative sea level (denoted as dSea in the figure) and the time rate of change of the local radius of the solid Earth (denoted as Drad in the figure). Notable is the fact that dGeoid is dominated by the degree 2 and order 1 pattern due to the action of rotational feedback.

were employed as the primary basis on which to further adjust the model. In this process, it was assumed that the simple VM5a model of the depth dependence of mantle viscosity [*Peltier and Drummond*, 2008] could be held fixed in the adjustment process, and these misfits mapped solely into modifications to glaciation history. That this strategy has led to a significant improvement to our model of the GIA process is documented in Figures 24 and 25 where we show the chi-square misfit to the totality of the GPS observations for models ICE-5G (VM2), Geruo A, and ICE-6G_C (VM5a) and, in the case of Antarctica, for the additional models of *Whitehouse et al.* [2012a] and *lvins et al.* [2013]. In the caption of this figure, we also provide standard *F* test statistics that further document the improvements in the model over its competitors. Especially for North America, the improvement of the fit provided by ICE-6G_C (VM5a) over the other models is very evident. Since the model was tuned so as to achieve this improvement of fit in the previously ice-covered region, however, the result for this subset of the data cannot be construed as supporting the validity of the reconstruction in its entirety. Nevertheless, the GPS observations from the U.S. portion of the surface of this continent were not employed to tune the model of glaciation history, yet the data from this region, from which a very large number of GPS measurements are now available, are also very well fit by the new model. This is important. For example, if the

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Figure 24. Comparisons between relative sea level history predictions for the ICE-5G (VM2) model with rotational feedback and those of the ICE-6G_C (VM5a) model with and without rotational feedback for sites along the east coast of South America with the single exception of a site of the west coast. The last two digits of the number associated with the site name correspond to the site number of the location in Figure 21.

influence of lateral heterogeneity of viscosity and/or lithospheric thickness was an important contribution to the deglaciation-induced change of planetary shape over this region, one might have expected this to become apparent in a differential pattern of misfit between the once ice-covered portion of the surface and that which always lay beyond the ice margin. There is no evidence of any such characteristic pattern of misfit, either in North America or in Northwestern Europe/Eurasia. The same laterally homogeneous viscoelastic model fits the data well in both regions.

A further data set was also invoked in our analysis to provide additional confidence in the quality of the new model, namely, the time-dependent gravity data being delivered by the GRACE dual satellite system. The most gratifying result achieved with the new model in this regard is certainly that for the North American continent. Whereas the GRACE data demonstrate that the time-dependent gravity field over this region is dominated by a "double bull's-eye" pattern of extrema that straddle present-day Hudson Bay, the ICE-5G loading history did not accurately fit this pattern, whereas the prediction of the new model very definitely does. This is important because the GRACE data were not employed in the construction of the new model but rather as a means of confirming or of denying its validity. The new model also does well over Fennoscandia. In both regions we have also provided a suite of comparisons of the predictions of the new and old models to relative sea level histories. Generally speaking, these additional constraints were quite well fit by the new model with improvements being more apparent for North America than for Northwestern Europe/Eurasia.

The most significant challenge in the design of ICE-6G_C (VM5a) concerned its Antarctic component. This component has been discussed in detail in the recent paper of *Argus et al.* [2014], and so in the present paper we have simply reviewed its properties for completeness sake and more fully discussed its implications. In this region, we focused upon comparison of the new model with that recently proposed by *Whitehouse et al.* [2012a, 2012b] who had suggested that the ICE-5G (VM2) model was significantly in error for Antarctica because of its reliance upon an incorrect profile for the depth dependence of mantle viscosity. Our analyses demonstrated this suggestion to be incorrect.

In *Argus et al.* [2014] we also argued, and have more fully documented herein, that there is clear evidence that the primary deglaciation of Antarctica did not begin until the time of meltwater pulse 1B in the



Figure 25. Misfit of postglacial rebound models to the GPS vertical rates on the North America, Eurasia, and Antarctic Plates. The height of the bars is the (normalized) chi-square misfit; the values printed near the top of each bar are the normalized sample standard deviation (NSSD), which is the square root of reduced chi-square. If the model was perfect and the data errors were properly estimated, we would expect to find an NSSD of 1 (heavy dashed horizontal line). An NSSD value of larger than 1 indicates that the model poorly fits the data. An NSSD value of less than 1 suggests that the data errors are smaller than estimated. The NSSD for North America is 60% less for ICE-6G_C (VM5a) than for the model of Geruo et al. [2013]. An F ratio test [following Argus and Peltier, 2010, Table 3] indicates that substituting ICE-6G_C (VM5a) for the model of Geruo et al. [2013] results in a misfit decrease that is extremely significant for North America ($p = 1.2 \times 10^{-9}$), significant for Antarctica (p = 0.0052), and insignificant for Eurasia (p = 0.12). ("p" is the probability of obtaining the misfit reduction by chance.) For Antarctica, the F ratio test furthermore indicates that substituting ICE-6G_C (VM5a) for W12A [Whitehouse et al., 2012b] results in a significant (p = 0.022) misfit reduction, as does substituting ICE-6G_C (VM5a) for IJ05 R02 [Ivins et al., 2013] (p = 0.036). Specifics of the F tests for the comparison of the model of Geruo A et al. with ICE-6G C (VM5a) are the following: (North America) 466° of freedom, F = 1.607, $p = 1.2 \times 10^{-9}$; (Eurasia) 242° of freedom, F = 1.164, p = 0.12; and (Antarctica) 104° of freedom, F = 1.659, p = 0.0052. Specifics of the two other F tests in Antarctica are the following: (W12A versus ICE-6G (VM5a)) 104° of freedom, F = 1.489, p = 0.022 and (JJ05 R02 versus ICE-6G (VM5a)) 104° of freedom *F* = 1.479, *p* = 0.036.

Barbados record of *Peltier and Fairbanks* [2006]. We repeated this argument in the current paper by providing a more detailed presentation than that shown in *Argus et al.* [2014] of data constraining the timing of recommencement of marine sedimentation at sites around the Antarctic shelf that occurred upon shelf deglaciation. Such data had also been employed in the construction of the Antarctic component of the ICE-5G (VM2) model. Although the new model of the deglaciation of Antarctica is one that loses somewhat less ice than did this earlier model, a far more significant change in the deglaciation history of ICE-6G_C compared to that of ICE-5G is the introduction of a modest Antarctic contribution to meltwater pulse 1A. Although we are unable to accurately constrain the amplitude of this contribution, a recent suggestion that such a contribution must have existed has recently been provided in *Weber et al.* [2012].

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