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Comment on “Ocean mass from GRACE and glacial isostatic adjustment” by D. P. Chambers et al.

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[1] The modern global theory of the glacial isostatic adjustment (GIA) process is a theory that directly addresses the extent to which the geoid of classical geodesy is impacted by this phenomenon. Because the geoid is, by conventional definition, the surface of constant potential that overlaps the surface of the sea in the absence of currents and tides, we may determine the impact of the GIA process upon it only by explicit analysis of the manner in which mass is redistributed among the ocean basins and the level of the sea is thereby influenced. Although the dominant contribution to GIA is that associated with the transfer of mass between the oceans and the continents, there is an additional influence due to the variations in Earth’s rotational state. This influence “feeds-back” onto the geoid. In the recent paper by Chambers et al. (2010), several arguments were presented that question earlier attempts to discuss the consequences of this feedback. These arguments are interesting and we address them in what follows.

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1. Introduction

[2] The issue of the importance of rotational feedback upon the GIA process emerged with the launch of the Gravity Recovery and Climate Experiment (GRACE) satellites in March 2002. GRACE was designed to deliver a time-dependent gravity field for the planet by producing a new global field every month during the lifetime of the mission (see *Tapley et al.* [2004] for a discussion of the GRACE system). At approximately the same time, one of us (WRP) was approached by NASA with a request to provide a global map of the expected time dependence of geoid height that would be expected to be observed due to the influence of GIA, a primary target for which the mission was designed. At that time it was imagined that the GIA phenomenon would be dominated by the lingering influence of the Late Quaternary ice-age. The prevalent model of this process at that time remained the ICE-4G (VM2) model of *Peltier* [1994, 1996] the geoid height time dependence prediction for which is shown as Figure 1 (see http://www.csr.uteas.edu/grace/publications/brochure/page6.html). Notable by inspection of this figure is the large amplitude anomaly over the east coast of the continental United States. This is one of the four extrema of the degree two and order one spherical harmonic pattern that the theory predicted to exist as a consequence of the rotational feedback phenomenon whereby, as a consequence of the changes in the rotational state of the planet induced by the GIA process, a redistribution of water was induced in the ocean basins. That the dominant contribution of rotational feedback upon the geoid should consist of a degree two and order one overprint was established by *Dahlen* [1976] to be a consequence of the influence of polar wander, although his analysis was undertaken in the different context of a discussion of the “pole tide” raised in the oceans by the Chandler wobble.

[3] The issue of the strength of the rotational feedback process that the ICE-4G (VM2) model predicted arose once sufficient GRACE data became available to allow an estimate of the amplitudes of the degree two and order one “Stokes coefficients” in geoid height time dependence to be obtained. The existence of a possible problem with the predictions of these coefficients by the ICE-4G (VM2) model and its successor ICE-5G (VM2) of *Peltier* [2004] was clearly exposed in the recent paper by *Peltier and Luthcke* [2009] (hereafter PL09) who noted that, of the two geoid height Stokes coefficients of degree two and order one, although one, $\dot{C}_{21}$, was close to that which being suggested by the GRACE analysis centers, the other, $\dot{S}_{21}$, differed so significantly from the GRACE inference as to suggest a fundamental problem with the quality of the GIA models. It was hypothesized that the explanation of any such misfit could simply be a consequence of the fact that the GIA models contained no contribution from the ongoing melting of land ice due to the global warming process.

[4] In the paper by *Chambers et al.* [2010] (hereafter C10) the authors have provided a series of arguments which question some aspects of this previous work. We see their issues as being three in number, as follows and in order of decreasing importance: (1) that the computation of the geoid Stokes coefficients of degree two and order one may have been insufficiently accurate, (2) that the hypothesis of PL09

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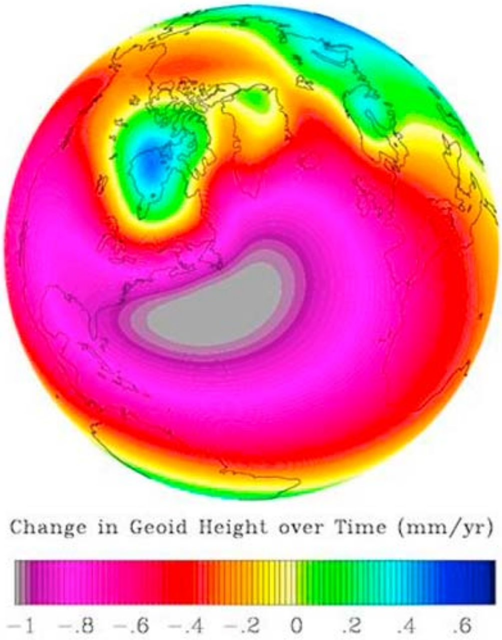

Figure 1. Geoid height time-dependence, according to the ICE-4G (VM2) model of the glacial isostatic adjustment process as produced by WRP for the original NASA GRACE brochure.

concerning the origin of any discrepancy between the GIA predicted and GRACE inferred values of the critical Stokes coefficients was questionable, and (3) that the suggested value of the required GIA correction to the GRACE inferred rate at which mass is being added to the ocean basins, might also be suspect.

2. Discussion

[5] Our purpose in this comment is to address each of *Chambers et al.*'s [2010] contentions in turn. Detailed discussion is available as Texts S1–S5 in the auxiliary material.[1] An additional file (Text S6) is also available in the auxiliary material detailing the accuracy of a critical part of the analysis. The most important points touched upon are as follows: theoretical preliminaries (Text S1); comparison of methods for estimating geoid height time dependence (Text S2); geoid height time-dependence based upon the sea level equation, focusing on analytical results for the degree two and order one stokes coefficients (Text S3); testing the land–ice melting explanation of the "Stokes coefficient conundrum" (Text S4); and the accuracy of the GIA correction to GRACE for the rate of Mass addition to the ocean basins (Text S5).

[6] Figure 2 shows examples of the global fields $S^{\bullet}$, $R^{\bullet}$ and $dGeoid\ /\ dt$ for the ICE-6G (VM5aD1) model (note: these results incorporate the correction to the rotational component highlighted in section 4 in Text S3).

[7] Figure 3 illustrates the impact upon the $\dot{J}_2$ parameter of the surface load perturbations due to the collective effect of present-day land ice melting from Greenland, Antarctica and Alaska. Figure 4 illustrates the "opposite hemisphere effect" on sea level rise due to polar land ice melting.

3. Conclusions

[8] In the auxiliary material of this paper we have addressed in sequence the three issues raised in C10 concerning the analyses presented in *Peltier* [2009], PL09, and *Peltier* [2007]. The first of these was the suggestion that there could be a flaw in the methodology employed to compute the values of the degree two and order one Stokes coefficients for the ICE-5G (VM2) model of *Peltier* [2004]. Through the construction of an analytical solution for the degree two and order one terms of the SLE this issue has been successfully resolved. We demonstrated that the relationship between the Stokes coefficients of the true geoid and the time derivatives of the products of inertia, as this is embodied in the formulation employed by *Chambers et al.* [2010], is not compatible with the Sea Level Equation and is therefore incorrect. The use of that formula causes an error in the predicted values of both of these coefficients of magnitude 2.06 with the incorrectly predicted values being smaller than the correct values by this factor.

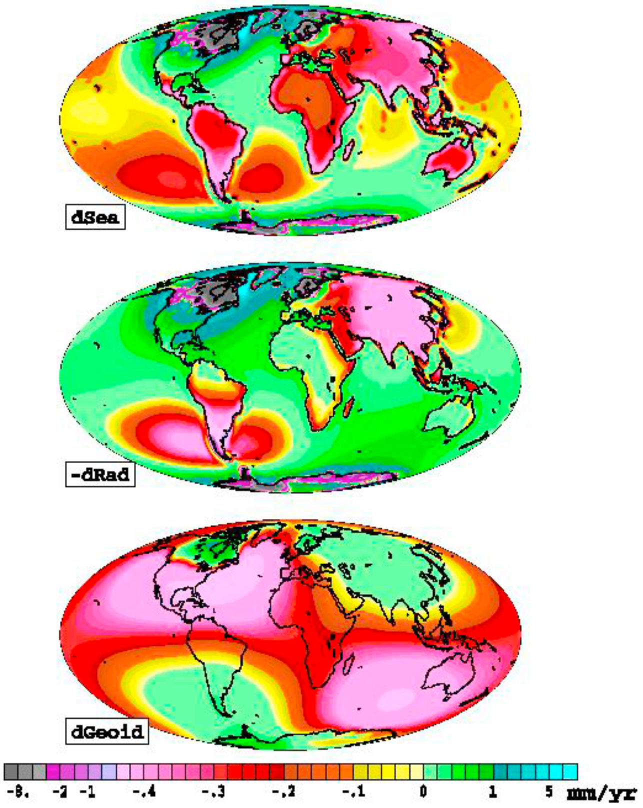

Figure 2. Prediction for the ICE-6G (VM5aD1) model of the fields that contribute to the prediction of geoid height time dependence for the present-day. (a) Rate of change of sea level with respect to the deforming surface of the solid Earth. (b) Rate of change of the local radius of the solid Earth. (c) The sum of Figures 2a and 2b which is the time rate of change of geoid height.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011JB008967.

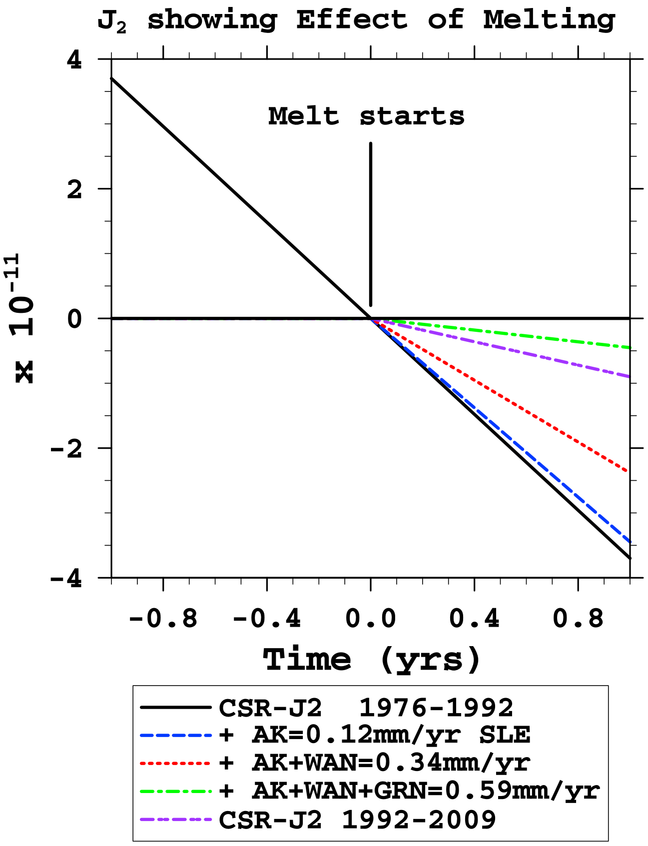

Figure 3. Present-day secular variations of J_2 both prior to and after the break in the time series identified in the analyses of *Roy and Peltier* [2011]. The post 1992 change is adequately explained by the action of land ice melting from the polar regions if the pre-1992 rate is assumed.

[9] This flaw in the *Chambers et al.* [2010] analysis led to a significant exaggeration of the flaw in the analysis of *Peltier* [2007, 2009] and PL09 which involved an amplification of the values of these coefficients by a factor of 2.51). Even after incorporation of the required "renormalization" of the theoretical structure employed in the construction of the ICE-5G (VM2) model, however, the predicted values of the critical Stokes coefficients continue to differ significantly from the GRACE inferences These inferences do appear to be seriously compromised, however, as demonstrated by the analysis of Earth orientation data by *Roy and Peltier* [2011] who have shown that a profound shift in the components of the velocity of polar wander had occurred a decade prior to the launch of the GRACE satellites. We suggest that the *Roy and Peltier* [2011] inferences of the rotational observables should be employed to replace those published by the analysis centers. This includes the value for the $\dot{C}_{20}$ coefficient which is simply equal to $-\dot{J}_2/\sqrt{5}$.

[10] The specific flaw in the previously computed values of the true Stokes coefficients of degree 2 and order 1 for the ICE-5G (VM2) model turns out to have only a modest impact on the strength of the influence of rotational feedback on predicted sea level histories. In particular the feedback is found to persist in its importance along the east coast passive continental margin of the South American continent based upon the data compiled in *Rostami et al.* [2000] as will be discussed in detail elsewhere.

[11] The second of the issues raised by C10, namely that it is possible on a priori grounds to rule out the plausibility of the hypothesis in PL09 as to the origin of the misfit of these coefficients to GRACE observations, has been addressed by providing a counterexample. The simple counterexample constructed to investigate this possibility employed six sources of land ice melting, three of which, Greenland, Antarctica and Alaska, have their melt rates directly constrained by GRACE measurements. The remaining three are sources known to be

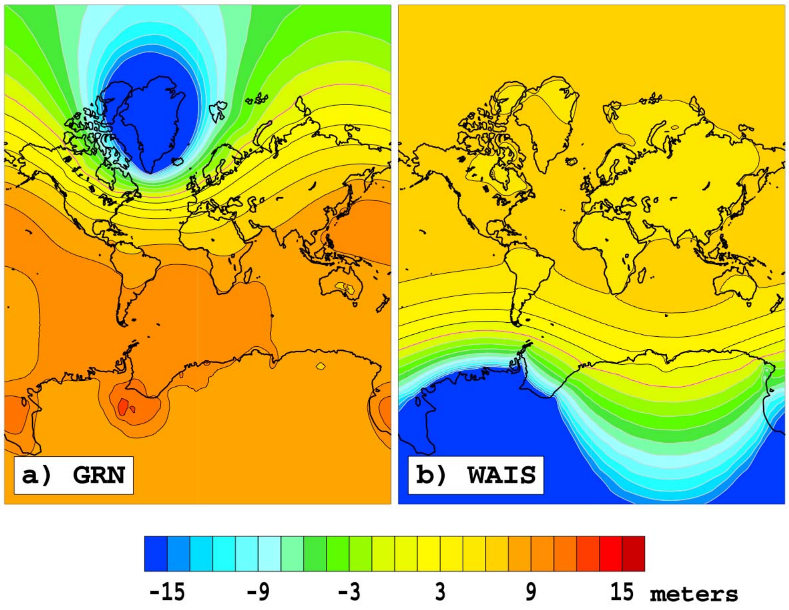

Figure 4. Predicted rise of relative sea level (a) due to complete melting of the Greenland ice sheet (GRN) and (b) due to complete melting of the West Antarctic ice sheet (WAIS) over a century.

active on high topography but at much lower latitudes, namely the Andes, the Himalayas and the Western Cordillera. It was shown that this model could provide an accurate fit to the rotational constraints for the post 1992 period according to the analyses by *Roy and Peltier* [2011]. The total sea level rise equivalent melt rate of ~2.6 mm/yr from the six sources of the counterexample is in excess of that estimated for all land ice sources by either *Church et al.* [2011] (1.73+−0.27 mm/yr) or by *Jacob et al.* [2012] (1.44+−0.19 mm/yr) but close to earlier estimates . The counterexample also predicts excessive geoid height anomalies over the mountain sources of melting. It does suffice, however, to demonstrate that the modified rotational state of the planet during the GRACE era provides a strong constraint upon such scenarios as argued in *Roy and Peltier* [2011]. The flaw in the second of the contentions of C10, that such modern sources of land ice melting could not be invoked to reconcile any misfit between model predicted and observed Stokes coefficients, may be due to their having missed the marked change in the rotational state that had occurred prior to the launch of GRACE.

[12] The third of the issues raised in C10 concerned the value of the correction that should be applied to GRACE data in estimating the rate at which mass is being added to the oceans. We agree with them that the time dependence of the mean field should not have been incorporated in this estimate. It was not immediately obvious (to us) that the rate of change of the mean field was entirely due to the conservation of mass term in the Sea Level Equation but our detailed analysis has demonstrated this to be so.

[13] The new value for the mass rate correction based upon the revised analyses reported herein depends somewhat upon the "flavor" of geoid to which the analysis is applied. The two flavors for which we have provided data in Table S2 in Text S5 include that for the conventional geoid which is defined in terms of sea level and that for the approximation to the geoid that GRACE is restricted to observing. In the first case the mass rate correction is found to be −1.09 mm/yr and in the latter −1.0 mm/yr. These numbers are smaller than the previously published value of −1.4 mm/yr (reduced from the initial value of −1.8 mm/yr by eliminating the mean field effect). The latter value is identical to the value assumed in the paper by *Leuliette and Miller* [2009]. It is significantly lower that the more recent value of −1.29 mm/yr which appears to be the preferred value of C10. It is clear, however, that the last chapter on the important issue of sea level budget closure, which depends significantly upon the value of this correction, has yet to be written.

[14] **Acknowledgments.** We are indebted to Yonggang Liu of Princeton University who provided the "fresh pair of eyes" needed to effectively sleuth the version of the numerical solver employed to construct solutions to the Sea Level Equation for the ICE-5G (VM2) model. One of us, WRP, has also benefited directly from a series of exchanges with John Wahr. The computations described in this paper were performed on the SciNet facility for High Performance Computation at the University of Toronto [*Loken et al.*, 2010]. SciNet is a component of the Compute Canada national HPC platform Additional support was provided by NSERC Discovery Grant A9627 and by NOAA (NA110AR4310101).

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