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Reply to Comment by W. R. Peltier Et Al. on “Ocean Mass from GRACE and Glacial Isostatic Adjustment”

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[1] The comment by *Peltier et al.* [2012] validates our original work [*Chambers et al.*, 2010] on two important points: (1) that the global average of the glacial isostatic adjustment (GIA) gravitational signal applied to GRACE data should be zero, and (2) the rates for degree-2, order-1 terms for the *Peltier* [2009] model were erroneously too large. We now agree on the general magnitudes and shape of the GIA correction needed for determining ongoing ocean mass change from GRACE.

[2] We appreciate the opportunity to reply to *Peltier et al.*'s [2012] (hereafter P12) comments regarding our paper [*Chambers et al.*, 2010] (hereafter C10). While P12 extensively discuss many issues, we only address the main points raised in C10. In our paper, we discussed the GIA (glacial isostatic adjustment) correction to GRACE estimates of ocean mass. We noted that a published GIA correction from *Peltier* [2009] (hereafter P09) differed significantly from the correction computed using another GIA model, even though both models were based on the same ice-loading history and a similar Earth viscosity profile. We raised the following three points regarding both P09 and *Peltier and Luthcke*'s [2009] (hereafter PL09) subsequent discussion of P09's results. We showed that when points (1) and (3) are accounted for, P09's corrections fall in line with other estimates.

[3] *Point* 1: P09 incorrectly included a term that implied a nonzero rate of change for the global average of the gravity field, and so violated conservation of the Earth's total mass. While it is appropriate to include this mean for computing the GIA effects on measurements of sea level change measured by tide gauges or altimetry, we argued it should not be used for correcting gravity measurements from GRACE for GIA, since in a gravitational sense the Earth's total mass must be conserved.

[4] *Point* 2: P09 obtained values for $\dot{C}_{21}$ and $\dot{S}_{21}$ (the rates-of-change of the degree-2 order-1 harmonics) that were far larger (by a factor of more than 6 for $\dot{S}_{21}$) than the observed GRACE values for those quantities, or from those of the *Paulson et al.* [2007] model we utilized. To explain the difference, PL09 suggested that the GIA results were possibly being offset by the effects of present-day ice loss somewhere. We argued, though, that any realistically distributed ice loss of the magnitude to cause such a large value for $\dot{S}_{21}$, would cause similarly large signals in other harmonics, which are not present in the GRACE results.

[5] *Point* 3: There was an inconsistency between P09's values of ($\dot{C}_{21}$, $\dot{S}_{21}$) and polar wander rates, which suggested P09 had made an error of some sort. We demonstrated with a simple model that if $\dot{C}_{21}$, $\dot{S}_{21}$ terms consistent with the polar wander rates were used, the inconsistency between GIA models largely disappeared.

[6] We are pleased to see that P12 are now in good general agreement with these points, and we summarize the situation as follows:

[7] *Comment on Point* 1: P12 now agree with this point, stating in Section 6 of their Comment that: "As C10 note, however, it should not be kept in determining the correction to GRACE over the oceans," where "it" refers to the global average term.

[8] *Comment on Point* 3: P12 also reveal that they have uncovered an error in P09's computation of ($\dot{C}_{21}$, $\dot{S}_{21}$), quoting again from Section 4.2 of the Comment: "this constraint must be enforced by imposing an appropriate renormalization of this term (Note: failure to recognize the necessity that this constraint be applied constituted a software bug that has been found in the course of this analytical treatment and fixed. Its impact was to amplify the GIA model predictions of both of the degree two and order one Stokes coefficients by the factor $4\pi/(2\ l + 1) = 4\pi/5 = 2.51..$" We note that the additional factor of $1 + 1/k_f$ (or ≈ 2), discussed in *Tamisiea* [2011] and P12, also contributes to overly large degree-2, order-1 rates in P09. The published rates for these terms in the original model as given in PL09 and summarized in C10, were

$$\begin{pmatrix} \dot{C}_{21} \\ \dot{S}_{21} \end{pmatrix} = \begin{pmatrix} -1.30 \times 10^{-11} \\ 7.67 \times 10^{-11} \end{pmatrix} \quad \text{yr}^{-1}. \tag{1}$$

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In C10, we derived a rough estimate for what those rates would have to be if they were consistent with observed polar wander rates, also published in PL09:

$$\begin{pmatrix} \dot{C}_{21} \\ \dot{S}_{21} \end{pmatrix} = \begin{pmatrix} -0.6 \times 10^{-11} \\ 1.4 \times 10^{-11} \end{pmatrix} \quad \mathrm{yr}^{-1}. \qquad (2)$$

[9] The rates computed by P12 after fixing the bug in their code and using a definition of the geoid consistent with GRACE measurements are (from equation (37) in the Comment

$$\begin{pmatrix} \dot{C}_{21} \\ \dot{S}_{21} \end{pmatrix} = \begin{pmatrix} -0.24 \times 10^{-11} \\ 1.24 \times 10^{-11} \end{pmatrix} \quad \mathrm{yr}^{-1}. \qquad (3)$$

The results from the corrected code are, therefore, in line with C10s expectations.

[10] *Comment on Point* 2: Since P12's corrected values of ($\dot{C}_{21}$, $\dot{S}_{21}$) are now much reduced and are no longer in severe disagreement with GRACE observations of those harmonics, there is no need to postulate a large present-day ice loss to explain the original discrepancy, and so Point 2 becomes moot. While there are still differences between the GRACE results and the results of some GIA models, these are of the order that could conceivably be due to present-day mass redistribution as P12 postulate. In C10, we never stated that ongoing ice mass changes could not cause any differences in ($\dot{C}_{21}$, $\dot{S}_{21}$) observed by GRACE and predicted by GIA models, only that they could not explain the factor of 6 difference that was observed in P09.

[11] P12 are also apparently under the mistaken impression that the *Paulson et al.* [2007] model we utilized in C10 does not use the rotational feedback theory of *Mitrovica et al.* [2005], as they state: "It is also extremely important to note that the values being circulated are clearly not based upon the use of the formulation of the rotational response theory advocated in *Mitrovica et al.* [2005] which would reduce them to a further significant degree. We view their modification to the "traditional" form of the rotational response theory originally published by *Peltier* [1982] and *Wu and Peltier* [1984] with skepticism for the reasons discussed in PL09. It is interesting therefore that Wahr and collaborators now seem to have ceased applying this questionable methodology." In fact, the *Paulson et al.* [2007] model does use the modified rotational feedback theory of *Mitrovica et al.* [2005]. *Paulson et al.* [2007] assumed the Earth is incompressible, which leads to larger predicted values of $\dot{C}_{21}$, $\dot{S}_{21}$. We suspect this is the reason for P12's confusion.

[12] In conclusion, we note that P12 now confirm C10s original result that the mass rate correction should be "closer to -1 mm yr^{-1} than -2 mm yr^{-1}." We still must point out, however, that suggesting a single value of the correction is inappropriate, as there are significant differences in the size of the correction (of order 30%) depending on how the ocean averaging area is treated, shown both in Table 1 of C10 and in Table 2 of P12. Instead, the GIA correction should be applied either by subtracting the GIA harmonics from the GRACE coefficients before computing ocean mass trends, or by treating the GIA harmonics with the same processing method used for the GRACE-only calculation, and then subtracting the resulting GIA estimate from the GRACE estimate after analysis. This is especially critical as many studies limit the calculation to latitudes of $\pm 66°$ to be consistent with altimetry, and also exclude regions around the coastline to reduce the leakage from hydrology and ice mass loss [*Chambers*, 2009]. The value recommended by P12 assumes an ocean averaging area that goes right up to coastlines, includes Hudson Bay and the West Antarctic Ice Shelf, and extends to $\pm 90°$.

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