

REPLY

10.1002/2017JB014930

This article is a reply to comment by Peltier et al. (2018) <https://doi.org/10.1002/2016JB013844>.

Key Points:

- The empirical relationship of Purcell et al. (2011) is validated
- The excessive uplift across the Antarctic continental shelves in (ICE6G_C) has been mitigated in ICE6G_D
- High power at high degrees persists in the ICE6G_D Stokes' coefficients of Peltier et al. (2017)

Supporting Information:

- Supporting Information S1
- Data Set S1
- Data Set S2
- Data Set S3
- Data Set S4
- Data Set S5
- Data Set S6

Correspondence to:

A. Purcell,
Anthony.Purcell@anu.edu.au

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Reply to Comment by W. R. Peltier, D. F. Argus, and R. Drummond on "An Assessment of the ICE6G_C (VM5a) Glacial Isostatic Adjustment Model"

A. Purcell¹ , P. Tregoning¹ , and A. Dehecq^{1,2} 

¹Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia, ²Jet Propulsion Laboratory, Pasadena, CA, USA

Abstract The empirical approximation of Purcell et al. (2011, <https://doi.org/10.1029/2011GL048624>) has been validated by Peltier et al. (2018, <https://doi.org/10.1002/2016JB013844>). In their Comment they introduced new results derived from the same ice/rheology models of ICE6G_C (VM5a) but using a different model for Antarctic bathymetry. This has greatly reduced the differences in predicted Antarctic uplift rates relative to those of Purcell et al. (2016, <https://doi.org/10.1002/2015JB012742>). In fact, with a ~50% reduction in uplift rate in the Weddell Sea, the results of Peltier et al. (2018, <https://doi.org/10.1002/2016JB013844>) now agree more closely with the predictions of Purcell et al. (2016, <https://doi.org/10.1002/2015JB012742>) than with the original ICE6G_C values. Peltier et al. (2018, <https://doi.org/10.1002/2016JB013844>) state that the high power in their high-frequency spherical harmonic coefficients remains in their new calculations. They also claim that Purcell et al. (2016, <https://doi.org/10.1002/2015JB012742>) used an inaccurate loading history in deriving their velocity field. In fact, the ice load history was unchanged; to remove any ambiguity, the ice and water load histories used in the CALSEA calculations are provided in the supporting information.

1. Introduction

This comment/reply cycle has come about as follows:

Purcell et al. (2011) presented an empirical approximation for calculating GIA-induced vertical uplift rates from Stokes' coefficients for the GIA-induced rate of change in gravity. This approximation was shown to be accurate to ~1 mm/yr in regions where there has been no change in load for 6,000 years. Peltier et al. (2015) applied this empirical approximation to the spherical harmonic coefficients of their ICE6G_C (VM5a) model and found that it produced a spurious high-frequency signal around Antarctica. They concluded that "the errors of the predictions of the Purcell et al. empirical model are particularly severe, which strongly suggests it should not be employed at all ...".

Purcell et al. (2016) investigated the cause of this high-frequency signal using the CALSEA software (Lambeck et al., 2003). The empirical relationship of Purcell et al. (2011) worked well when applied to the CALSEA-derived spherical harmonic coefficients for the ICE6G_C (VM5a) model but did not work well for the coefficients provided by Peltier et al. (2015). This misfit resulted from much higher power at high degrees in the published ICE6G_C (VM5a) Stokes' coefficients than in the CALSEA-derived Stokes' coefficients. Moreover, the CALSEA-produced radial velocity field (derived from a rigorous calculation, not relying on the empirical approximation) differed from that presented by Argus et al. (2014) and Peltier et al. (2015), especially across the Antarctic continental shelves. On closer examination, the published ICE6G_C (VM5a) radial velocity field seemed inconsistent with the change in surface load dictated by the ICE6G_C model. As a result of this investigation, Purcell et al. (2016) concluded the following:

1. The empirical relationship presented in Purcell et al. (2011) is correct under the conditions originally specified.
2. The dimensionless Stokes' coefficients presented by Argus et al. (2014) and Peltier et al. (2015) for ICE6G_C (VM5a) are inconsistent with the corresponding radial velocity field and are unexpectedly large at high degree.

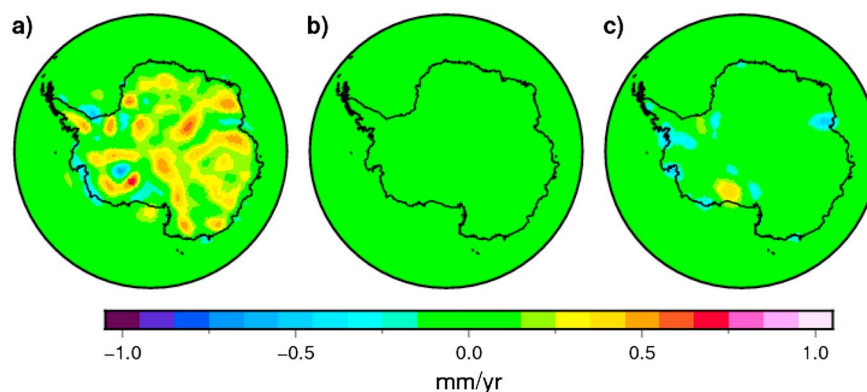


Figure 1. Differences in present-day uplift rate predictions brought about by using (a) the pre-LGM ice history described in Peltier et al. (2018) rather than the ramp-up model assumed in Purcell et al. (2016), (b) the ice history of Peltier et al. (2018), incorporating the extra time steps between 26 ka B.P. and the present rather than the time steps in Peltier et al. (2015), (c) BEDMAP2 bathymetry values rather than BEDMAP bathymetry values.

3. The radial velocity field presented by Argus et al. (2014) and Peltier et al. (2015) is in error in locations that experience an ice-load to water-load transition, and this error is particularly large in the Weddell Sea.

In their comment on Purcell et al. (2016), Peltier et al. (2018) make the following points:

1. "There is therefore nothing wrong with the Purcell et al. (2011) empirical formula." The empirical approximation is thus validated. Figures 3 and 4 of the Comment of Peltier et al. (2018) confirm the limitations of the empirical approximation as described in Purcell et al. (2011).
2. The ice history of ICE6G_C prior to 26 kaBP had not been made available and was different in the computations of Peltier et al. (2015) than that assumed by Purcell et al. (2016).
3. The high power in the high-degree terms in the published Stokes' coefficients of Peltier et al. (2015) "is physical" and a consequence of the interaction between the rotational component of sea level change and ice sheet grounding line migration. The CALSEA software contains both grounding line migration and rotational effects, and yet the ICE6G_ANU spherical harmonic coefficients of Purcell et al. (2016) do not have high power at high degrees. It is unclear how the combination of rotational component and grounding line migration can produce a signal in the gravity Stokes' coefficients but not in the corresponding velocity field as in Peltier et al. (2015) and Peltier et al. (2018). It is left to the reader to make their own determination.
4. The difference between the ICE6G_C (VM5a) CALSEA-derived radial field and that published by Peltier et al. (2015) is due to "the use by Purcell et al of a loading history for the embayments which differs significantly from that of our model." Purcell et al. (2016) used the ice load history described in Peltier et al. (2015). Gridded data of ice thickness, water depth, sea level change, and paleotopography are provided in the supporting information for this reply.

2. Updated Computations

The ice history file provided in the supporting information of Peltier et al. (2018) differs in two ways from that provided by Peltier et al. (2015). First, the ice thickness values prior to 26 kaBP are now included. Second, there are more time steps provided from 26 kaBP to the present. This extended ice history has been used in this study to recalculate present-day uplift rates. Peltier et al. (2018) stated that the difference in ice history has negligible effect on the computations of present-day GIA signals, and we confirm that changing the ice history for those early epochs causes uplift rates to change by less than 1 mm/yr (Figure 1a). The extra time steps between 26 kaBP and the present-day change present-day uplift rate predictions by less than 0.1 mm/yr (Figure 1b).

In performing the recomputations, it was realized that the Antarctic bathymetry model used in Purcell et al. (2016) was, in fact, BEDMAP, not BEDMAP2 as was originally claimed. The difference in present-day uplift rates produced by using BEDMAP2 as against BEDMAP is less than 0.5 mm/yr in the Antarctic region (Figure 1c). To make our computations consistent with those of Peltier et al. (2018), BEDMAP2 has been used as the default Antarctic topography for this study. The new computations are labeled ICE6G_ANU_D, and gridded uplift rates as well as spherical harmonic coefficients are provided in the supporting information.

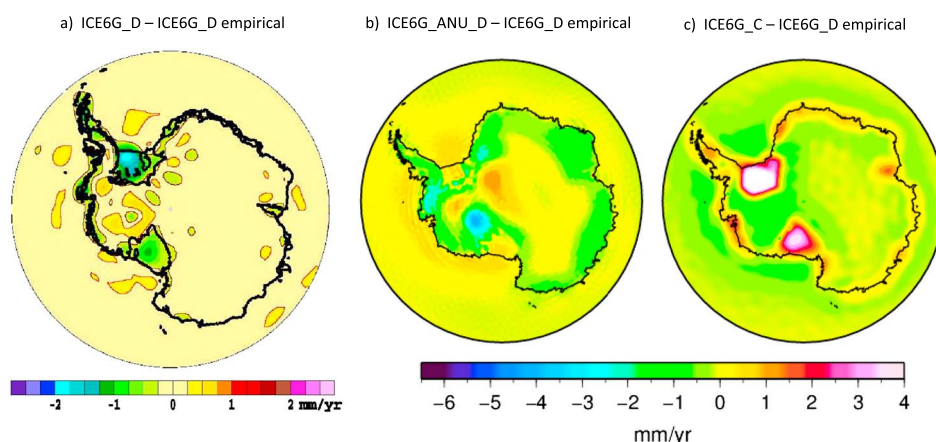


Figure 2. Differences between the uplift rate predictions of (a) ICE6G_D, (b) ICE6G_ANU_D and ICE6G_C (Peltier et al., 2015) compared to the predictions using the spherical harmonic coefficients for ICE6G_D from Peltier et al. (2018) and the empirical approximation of Purcell et al. (2011), evaluated to degree 256. While acknowledging that this is a convoluted way of showing the difference between the three models (ICE6G_D, ICE6G_ANU_D and ICE6G_C), this is the best comparison that can be made at this time, given that a grid of rigorously computed uplift rates for ICE6G_D were not made available. Figure 2a has been modified from Figure 4d of Peltier et al. (2018).

Peltier et al. (2018) have not provided gridded data of present-day uplift rates for ICE6G_D (VM5a). In order to compare the modern uplift rates for ICE6G_D, ICE6G_C, and ICE6G_ANU_D we have applied the empirical approximation of Purcell et al. (2011) to the spherical harmonic coefficients of ICE6G_D (which were provided by Peltier et al., 2018) to obtain a “reference model” against which each model could be compared. This is not an ideal way to make the comparison, since the largest differences pointed out by Purcell et al. (2016) were over the Weddell Sea where potential changes in water load in the past 6,000 years may corrupt the empirical approximation. While acknowledging this, the differences from the empirical reference model computations (Figure 1) can still be compared in order to ascertain how the new model ICE6G_D compares to the other two models.

The comparison between ICE6G_D and the reference model is taken from Figure 4d of Peltier et al. (2018). It is clear that there has been a significant change in the predictions of ICE6G_D compared to ICE6G_C. The significant differences pointed out by Purcell et al. (2016) between their ICE6G_ANU predictions and those of ICE6G_C have been substantially reduced (compare Figure 2a with Figure 2c) and the new ICE6G_D results now agree more closely with ICE6G_ANU_D than with the original ICE6G_C predictions (Figure 2).

The magnitude of these changes can be assessed by comparing Figure 6 in Argus et al. (2014) and Figure 2a from Peltier et al. (2018). In doing so, it appears that changing the bathymetry model from NOCS_ETOP02 to BEDMAP2 has reduced the predicted present-day uplift rate across the Weddell Sea from ~ 12 – 13 mm/yr to ~ 5 – 6 mm/yr between ICE6G_C and ICE6G_D. Across the Ross Sea the uplift rate has been reduced from ~ 7 – 8 mm/yr to ~ 3 – 4 mm/yr. These adjustments directly address the concerns of Purcell et al. (2016) of excessive uplift across the Antarctic continental shelves in ICE6G_C.

3. Conclusion

Peltier et al. (2018) now agree that the empirical relation of Purcell et al. (2011) is “useful because they make it possible for geodesists to make direct comparisons between predictions of global GIA models of vertical motion of the crust without having to perform the complex mathematical calculations that such models require.” This was the intent of Purcell et al. (2011).

The ice load history of the ICE6G_C model of Peltier et al. (2015) was used by Purcell et al. (2016) without alteration, and the ice model of Peltier et al. (2018) was used here without modification. The results of the ICE6G_D model no longer show the significant differences in uplift rates in the continental shelf regions of Antarctica, presumably because of the improved bathymetry model used in the ICE6G_D computations. Thus, there is now general agreement between the two software packages at the ~ 2 – 3 mm/yr level.

Acknowledgments

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