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# *Interactive comment on* "Hybrid inventory, gravimetry and altimetry (HIGA) mass balance product for Greenland and the Canadian Arctic" *by* W. Colgan et al.

**W. Colgan et al.**

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We thank Reviewer 2 for their interest in our work. We greatly appreciate the thoughtful review and constructive feedback they have provided. Here we discuss the general comments raised by Reviewer 2, as well as the few specific comments with which we disagree.

**General Comments**

*1. Gibbs phenomenon (or "ringing effect")*

Reviewer 2 makes a sound case that the residual difference between the observed



spherical harmonic and inferred Gaussian smoothed mass change fields shown in Figure 6 of Colgan et al. (2013; and denoted as "$\Delta$ij") is consistent with the Gibbs phenomenon (or "ringing effect"; Swenson et al., 2002). We note, however, that the spherical harmonic mass trend field we invert is solved to degree/order 60 (Luthcke et al., 2013), rather than solved to a higher order and then truncated to degree/order 60. Figure 1 of Reviewer 2 suggests that with the 200 km Gaussian filter we employ in our present study, a non-trivial signal weight is contained beyond degree/order 60. Thus, "ringing" results from a difference in the effective degree/order of the observed and inferred fields, whereby the latter has a greater effective degree/order than the former.

In a revised manuscript we will acknowledge that "ringing" went unidentified in the Colgan et al. (2013) companion paper to this present study. In terms of addressing "ringing", we are reluctant to increase the degree/order of the GRACE-derived mass trend solution above its fundamental resolution of 60, and computing spherical harmonics to subsequently truncate at degree/order 60 in each iteration of each simulation is computationally intractable. Therefore, as we cannot expect to eliminate "ringing", we intend to acknowledge the uncertainty associated with "ringing" by introducing an additional error term. The ensemble mean absolute residual field ("$\Delta$ij") has a domain wide mean value of 0.042 mWE/a (Figure 1 of this comment). We propose to take this mean residual as characteristic of the uncertainty associated with "ringing". At the local scale, we will combine this characteristic "ringing" uncertainty with existing local uncertainty (discussion paper Figure 10). At the sector scale, we will integrate this error to yield the estimates shown in Figure 2 of this comment, which we will then combine with existing uncertainties (discussion paper Table 1). We will also clearly articulate that the implication of "ringing" on our geophysical implications, namely that mass change may be over- (under-) estimated in peripheral (interior) areas of Greenland.

Finally, we note that the potential biases introduced by "ringing" are on the magnitude of the uncertainty associated with in situ measurements of mass balance in interior Greenland.

*2. Firn density correction*

Reviewer 2 is correct in asserting that our redistribution of coarse resolution mass change using higher resolution volume changes implicitly assumes that the effective density of volume change is equivalent between adjacent cells. We would contend, however, that this does not compel us to assume that firn characteristics (e.g. density and rate of density change) are correlated over the 400 km spatial resolution of GRACE, but rather the 26 km spatial resolution of the inversion grid we adopt. Firn compaction is primarily driven by changes in air temperature and accumulation, both of which vary over spatial scales greater than 26 km (Zwally et al., 2011). Employing the Zwally et al. (2011) 50 km dataset, differences in rates of both surface elevation (dH/dt) and firn compaction (dC/dt) indeed increase with separation distance between grid points. On average, however, the change in dH/dt with separation distance is just over an order of magnitude greater than the change in dC/dt with distance ($8.7*10^{-4}$ versus $6.4*10^{-5}$ m/a/km, respectively; Figure 3 of this comment). Thus, spatial variability in dC/dt is an order of magnitude smaller than spatial variability in dH/dt. Simply put, the "fingerprint" of mass change is more dependent on observed dH/dt, rather than modelled dC/dt.

In a revised manuscript we will explicitly acknowledge that our approach assumes that: (1) firn characteristics are spatially correlated at 26 km resolution, and (2) changes in dH/dt with distance are an order of magnitude greater than changes in dC/dt with distance. We will also more clearly state that we term the altimetry-derived omega coefficient "relative", as it has been normalized and appears in the inversion algorithm as a dimensionless successive-over-relaxation-type parameter, rather than an absolute unit of elevation change (discussion paper Equation 3). We will clarify how using altimetry information in an inversion to reproduce observed mass-change differs from the conventional combination of altimetry information with forward firn modelling to infer mass-change. In the latter, mass change is essentially the "free" variable to be solved, while in the former the density of volume change essentially serves of the "free"



variable, as mass change is constrained by observation (e.g. Zammit-Mangion et al., 2013).

Finally, we note that our redistribution of observed mass changes in a spatial pattern consistent with observed volume changes potentially allows an independent estimate of the density associated of elevation change. An empirical estimate of the effective density associated with volume change is desirable, as elevation changes cannot be easily converted to mass changes when and where the surface mass balance and dynamic elevation changes are of opposite sign (Li and Zwally, 2011).

*3. Canadian Arctic altimetry*

Reviewer 2 suggests we should employ airborne altimetry data over the Canadian Arctic to validate HIGA-inferred mass balance in the Canadian Arctic. We note that we do attempt to validate inferred mass balance in the Canadian Arctic at two spatial scales. We compare sector-scale inferred mass balance with previously published estimates (Gardner et al., 2011; Schrama and Wouters, 2011), the latter of which incorporates satellite altimetry information, and we also compare 26 km scale inferred mass balance with previously published in situ measurements (Burgess and Sharp, 2008). To our knowledge, the most recent airborne altimetry-derived mass balance assessment of all major Canadian Arctic ice caps is Abdalati et al. (2004), which does not employ a firn correction. While we acknowledge that an independent airborne altimetry-derived mass balance dataset would be extremely valuable for validation, creating such a dataset is a non-trivial undertaking.

*4. ICESat spatial sampling*

We agree with Reviewer 2 that using one sigma standard deviation of all elevation rates within a 26 km grid cell gives an indication of the spread of observed rate of volume change. We note that we assess dH/dt trends and variability at 2 km scale, before aggregating these 2 km bins to 26 km resolution. In a revised manuscript we will explicitly state that we are assuming systematic errors in altimetry-derive dH/dt are smaller than the spatial variability at 26 km scale that we take as one sigma standard deviation in dH/dt.

We acknowledge under-sampling of outlet glaciers by ICESat can be an issue in Greenland, where outlet glaciers can experience rapid dynamic drawdown. In the Canadian Arctic, however, mass loss occurs primarily through surface mass balance (Gardner et al., 2011). Hurkmans et al. (2012) suggest sparse dH/dt sampling in the lower reaches of Jakobshavn Isbrae can result in ordinary space-time kriging underestimating Jakobshavn mass loss by up to 20

In a revised manuscript, we will more clearly discuss the potential implications of under sampling Greenland outlet glaciers and describe how our ensemble framework accommodates uncertainty in the spatial pattern of mass balance. In contrast to Hurkmans et al. (2012), rather than deriving mass balance by spatially integrating km scale volume changes, the ensemble of mass balance fields we infer are ultimately constrained by satellite gravimetry, with the ensemble mean reflecting the most likely spatial distribution at 26 km that matches both gravimetry and altimetry constraints. We note that our present inversion acknowledges the unique volume and mass change setting of Jakobshavn, with ensemble spread in local mass balance ($\pm$ 0.5 mWE/a) equal to 30

Finally, we will also acknowledge that the potential bias stemming from under sampling outlet glaciers results in mass balance being over- (under-) estimated in the periphery (interior) of the ice sheet, which is the opposite of the spatial distribution of the potential bias stemming from "ringing" (c.f. general comment 1).

*5. Altimetry and gravimetry time periods*

Presently, we combine mass changes observed during the IMBIE GRACE period (12/2003 - 12/2010) with volume changes observed during the IMBIE ICESat period (09/2003 - 10/2009; Shepherd et al., 2012). Reviewer 2 illustrates that Greenland mass trend patterns are non-stationary, with Greenland mass loss accelerating in the Northwest and decelerating in the Southeast during the 2009-2010 period covered by



the GRACE IMBIE period, but not the ICESat IMBIE period. Reviewer 2 is correct that our motivation in assuming ICESat period volume changes are characteristic of GRACE period mass changes is to facilitate direct comparison with IMBIE results. We acknowledge that this assumption can be avoided by adopting a GRACE period that is consistent with the ICESat IMBIE period. In a revised manuscript, we would perform the hybrid inventory, gravimetry and altimetry inversion over the common 09/2003 - 10/2009 period.

*6. Canadian Arctic surface mass balance*

Reviewer 2 points out that mass loss in the Canadian Arctic is primarily driven by surface mass balance (Gardner et al., 2011), and thus a comparison between HIGA inferred mass balance and modelled surface mass balance offers potential for validation of the inversion method we present. While the MAR v.3.2 surface mass balance product we employ in the discussion paper covers only Greenland (and not the Canadian Arctic), the recently released MAR v.3.3 surface mass balance product does cover both the Canadian Arctic and Greenland at native 15 km resolution. In a revised manuscript, we would therefore be able to compare HIGA-inferred mass balance with MAR-modelled surface mass balance at an interpolated resolution of 26 km throughout the Canadian Arctic.

*7. Zammit-Mangion et al. (2013)*

Reviewer 2 draws our attention to a recent paper that employs a Bayesian framework to solve a system of stochastic partial differential equations to resolve the magnitude and spatial distribution of elevation changes due to: (1) glacio-isostatic adjustment, (2) firn compaction, (3) ice dynamics and (4) surface mass balance in West Antarctica (Zammit-Mangion et al., 2013). Similar to our discussion paper, this work seeks to concurrently match trends in both altimetry and gravimetry observations. In contrast to our discussion paper, however, it also seeks to match trends in bedrock elevation (as observed by GPS) to infer a glacio-isostatic adjustment field. In a revised manuscript we would compare and contrast our methodology and data requirements with that presented by Zammit-Mangion et al. (2013). For the purposes of this brief response comment, however, we will note that Zammit-Mangion et al. (2013) also forego the inclusion of a forward model to estimate firn compaction, and instead leave firn compaction as a free parameter to be evaluated through their Bayesian framework (c.f. general comment 2 above).

**Specific Comments**

We thank Reviewer 2 for their detailed comments. In a revised manuscript we would incorporate all suggestions through additional clarification or novel discussion, except:

P.539, L.23: Similar to Zammit-Mangion et al. (2013), we would argue that leaving firn compaction as a free parameter avoids dependence on forward modelling firn density.

P.551 L.20: We would maintain that this is indeed the first time a GRACE-derived product has been directly compared with point measurements of mass balance.

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**Figure Captions**

**Figure 1** - **Left:** The ensemble mean absolute residual field ("Δij" in kg/m2/a), which depicts the discrepancy between the observed spherical harmonic representation and the simulated Gaussian-smoothed mass trend fields. **Right:** The associated histogram of domain wide absolute residuals ("|Δij|"; in kg/m2/a). The vertical line denotes a mean residual value of 0.042 mWE/a.

**Figure 2** - Sector-scale estimates of the uncertainty associated with "ringing" based on the characteristic uncertainty of Figure 1.

**Figure 3** - Differences in surface elevation rate (dH/dt; **Left**) and firn compaction rate (dC/dt; **Right**) with separation distance in the 50 km Zwally et al. (2011) Greenland ice sheet dataset. While differences in both dH/dt and dC/dt increase with separation distance, changes in dH/dt with distance are, on average, an order of magnitude greater than changes in dC/dt with distance (dashed lines denote $8.7*10^{-4}$ and $6.4*10^{-5}$ m/a/km, respectively). Note the left y-axis is an order of magnitude greater than the right y-axis.

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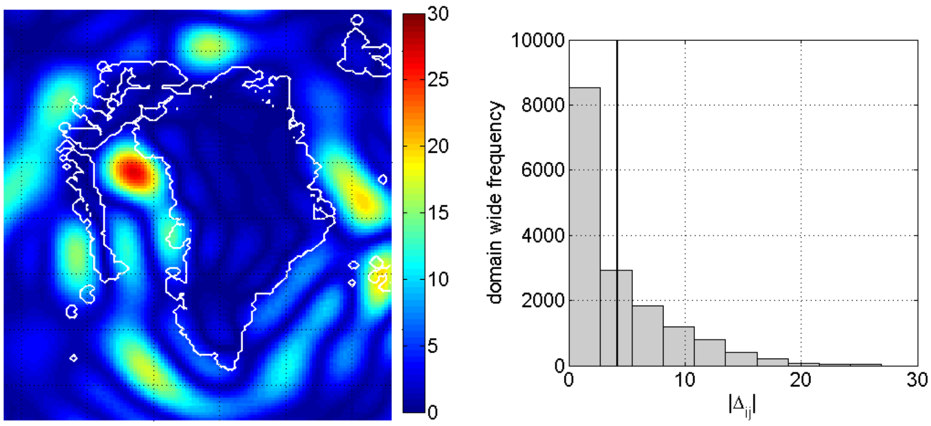


**Fig. 1.** see figure caption following references.

| Sector | Ice Sheet (Gt/a) | Glaciers (Gt/a) | Total (Gt/a) |
|---|---|---|---|
| 1 | ±1.4 | ±0.6 | ±2.1 |
| 2 | ±1.7 | ±0.1 | ±1.8 |
| 3 | ±1.5 | ±0.4 | ±1.9 |
| 4 | ±0.8 | ±0.1 | ±0.9 |
| 5 | ±0.3 | ±0.1 | ±0.4 |
| 6 | ±1.0 | ±0.1 | ±1.1 |
| 7 | ±1.1 | ±0.2 | ±1.3 |
| 8 | ±1.4 | ±0.1 | ±1.5 |
| 9 | ±0.0 | ±1.3 | ±1.3 |
| 10 | ±0.0 | ±0.7 | ±0.7 |
| Total | ±9.2 | ±3.8 | ±13.6 |

**Fig. 2.** see figure caption following references.



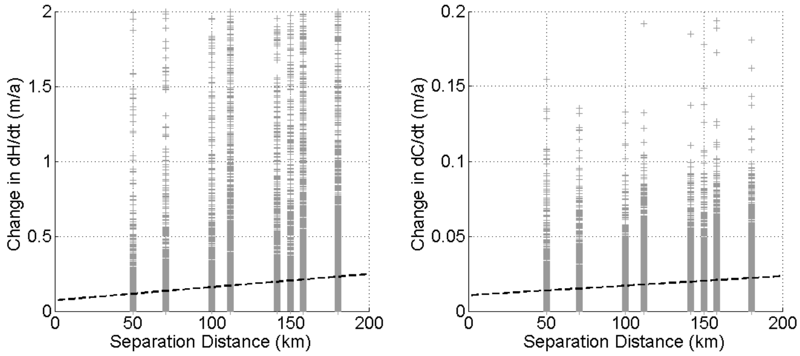


**Fig. 3.** see figure caption following references.