The Cryosphere Discuss., 8, C501–C509, 2014
www.the-cryosphere-discuss.net/8/C501/2014/

The Cryosphere
Discussions
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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.

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Received and published: 23 April 2014

We thank Reviewer 1 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 1, as well as the few specific comments with which we disagree.

General Comments

1. Incorporation of altimetry data:

Reviewer 1 questions whether biases in firn compaction and regional hypsometry limit

the utility of incorporating altimetry data, especially in the Canadian Arctic. We note that altimetry information enters the iterative update term (discussion paper Equation 2) as a normalized or dimensionless value, rather than a length scale (i.e. meters). Given this nuance, multiplying this dimensionless "omega" value by fractional ice coverage does not offer a coarse approximation to forward calculate absolute mass balance. By employing an inversion approach, essentially taking mass balance as a "given" rather than "free" parameter, similar to Zammit-Mangion et al. (2013) we are permitted to allow firn compaction to be a "free" parameter.

In a revised manuscript we will emphasize the contrasting roles of firn compaction and mass balance as given (free) and free (given) parameters, respectively, in a forward (inverse) approach. We will also clarify that in comparison to Greenland there is a paucity of airborne altimetry data over the Canadian Arctic (which was only collected in 2005 during the study period), and remind readers that while the dynamic drawdown of outlet glaciers is a major mechanism of mass loss in Greenland (Joughin et al., 2010), the majority of mass loss in the Canadian Arctic occurs via surface mass balance (Gardner et al., 2011), which generally exhibits weaker spatial gradients than ice dynamics. We will, however, be more candid in stating that the Canadian Arctic has more variable glacier hypsometries, and is therefore more sensitive to spatial sampling biases, than Greenland.

Finally, we note that the uncertainty assessed to "omega" is substantially greater throughout the Canadian Arctic than Greenland (see 2A below). This discrepancy, while influenced by the potential bias sources described above, primarily acknowledges greater rate of elevation change noise in the Canadian Arctic than Greenland.

2A. Altimetry data processing:

Reviewer 1 highlights several areas in which the processing of the altimetry data is not sufficiently described. In a revised manuscript, we would clarify that the only altimetry data used (both satellite and airborne) was collected during the ICESat IMBIE period

(09/2003 - 10/2009), and that only ATM, not LVIS, airborne altimetry data are used over Greenland. While Gaussian-Centroid offsets are not employed by Schenk and Csatho (2012), these cm-scale corrections have a minimal impact on the spatial variation of surface elevation change. Although the absence of Gaussian-Centroid corrections can influence mass loss trends by up 2 cm/a (Borsa et al., 2014), in our present work mass loss trends are ultimately constrained by gravimetry. We will also clarify that airborne altimetry data has only been collected in the Canadian Arctic in 1995, 2000, 2005 and 2011, which does not permit repeat-airborne elevation changes to be computed for the ICESat IMBIE period. Gardner et al. (2011) similarly omit ATM data from their 2004 to 2009 mass balance assessment of the Canadian Arctic, while Gardner et al. (2012) assess mass balance between ATM surveys.

We contend that additional airborne altimetry sampling would not fundamentally change our results. We note that Gardner et al. (2012) estimate the uncertainty associated with extrapolating all available ICESat-observed elevation changes to all ice in the Canadian Arctic South as 10

2B. Altimetry data processing:

Reviewer 1 seeks further detail on employing the method of Gardner et al. (2011), specifically regarding fitting polynomial equations to elevation changes as a function of elevation, and applying these functions over various regions. While we follow the methodological "first step" of Gardner et al. (2011), and estimate secular elevation rates from planar surface fits to repeat-tracks at 700 m resolution, we do not follow the "second step", whereby these elevation rates are extrapolated to regions not sampled by ICESat. In a revised manuscript, we will explicitly state that we are only calculating mean elevation changes from all available repeat-observations within 2 km bins, rather than extrapolating observed elevation changes to all ice coverage.

We will also clarify that we do not take the 1-sigma standard deviation of all elevation changes within a 26 km grid cell as characteristic of uncertainty in elevation changes at

26 km, but rather initially bin elevation changes at 2 km resolution, and take the 1-sigma standard deviation across the 169 (where available) 2 km elevation change bins as the uncertainty in elevation changes at 26 km. The fundamental spatial scale of correlation of ICESat dh/dt estimates is difficult to quantify because there is both observational and natural spatial correlation in dh/dt. Gardner et al. (2011; 2012) assumed an along-track correlation length of 5 km and no correlation between different sets of repeat-tracks. In our present work, we assume full correlation within 2 km grid cells (which may contain multiple sets of repeat-tracks or ATM profiles) and no correlation between them. Our altimetry-related uncertainties are therefore roughly consistent with previous studies. We will update the main text to clarify this uncertainty assumption.

While we employ the previously published raw altimetry data of Gardner et al. (2011), we do not employ the full mass balance calculation of Gardner et al. (2011), as we seek to create an independent estimate of the spatial distribution of mass balance that is consistent with satellite gravimetry observations. In a revised manuscript, we will explicitly compare and contrast our estimated uncertainty with that of previous assessments (e.g. Gardner et al., 2011). We would argue, however, that a "reconciling" of the intermediate terms of our respective error calculations is not possible, given fundamental differences in the terms employed in forward and inverse mass balance assessments.

3. Terminology:

Reviewer 1 points out a potential inconsistency in terminology between that originally adopted in Colgan et al. (2013) with the convention established by Cogley et al. (2011). Essentially, mass balance can either be expressed as the mass balance within a given grid cell, or the mass balance per unit ice area within a given grid cell. When the spatial resolution of a binary ice mask is identical to the spatial resolution of a mass balance grid this is not an issue. As we employ a fractional ice mask, at peripheral cells where fractional ice coverage is < 1, mass balance and mass balance per unit ice area are not equivalent. In a revised manuscript, we will adopt the terms "mass balance per unit area" and "mass balance per unit ice area" to distinguish these two properties. While Cogley et al. (2011) do not explicitly deal with the issue of fractionally ice-covered nodes, we feel these terms are broadly consistent with the spirit of Cogley et al. (2011).

Reviewer 1 also points out a potential inconsistency between our interchangeable use of m-dot and H-dot. As H-dot reflects changes in ice equivalent thickness and m-dot reflects mass balance (the sum of both surface mass balance and divergence of flux), we would contend that m-dot and H-dot are functionally equivalent at the scale of entire ice column thickness. The m-dot measured by GRACE, or the coffee-can and strain network in situ approaches, implicitly corresponds to the mass balance over the entire ice thickness. In a revised manuscript we will only employ m-dot, and reformulate and describe Equation 6 of the discussion paper in a fashion that is consistent with this terminology.

4. In situ observations:

Reviewer 1 highlights difficulties associated with comparing in situ point mass balance observations with mass balance observations inferred at 26 km resolution from remotely sensed data. We acknowledge that the 26 km product inherently averages out substantial local variability in mass balance processes that may otherwise be reflected in point observations. We also acknowledge that apparent discrepancies stemming from local variability are likely greater in the Canadian Arctic than Greenland. We note, however, that only six in situ observations are available from the Canadian Arctic, all from the Devon Ice Cap not smaller local glaciers (Burgess and Sharp, 2008). While these in situ observations are insufficient to generate a glacier wide mass balance estimate, we do compare our remotely sensed mass balance estimate with other estimates within ten sectors across Greenland and the Canadian Arctic.

In a revised manuscript we would consider limiting our in situ comparison to in situ data collected more than 26 km inland from the margin of the Greenland ice sheet (if advised

by the editor). While only comparing remotely sensed mass balance values to interior ice sheet observations would limit the potential influence of local variability, we contend there is merit in comparing remotely sensed mass balance to all available observations. Following an appeal to Cryolist, we now have collected 40 previously published in situ mass balance observations with which to validate our remotely sensed data product (17 more than in the discussion paper). We would also clarify that the nature of cryospheric research often necessitates large scale remotely sensed data products to be validated against sparse in situ observations, with local noise conventionally assumed to be a component of apparent discrepancy (e.g. Stroeve et al., 2013).

Specific Comments

We thank Reviewer 1 for their detailed comments. In a revised manuscript we would incorporate all suggestions through additional clarification or novel discussion, except:

P.551 S.4: We contend that the calibration / validation of HIGA inferred mass balance against in situ observations is more of a discussion point than a result. We acknowledge, however, that describing the conversion of previously published geodetic-derived estimates is somewhat tedious for a discussion section. In a revised manuscript we would excise this description to an appendix. We may then provide further details on this conversion as well (re: P.553).

P.555 L.27-28: At the urging of Reviewer 2, we will pursue comparing HIGA mass balance was MAR surface mass balance over the Canadian Arctic. We will, however, acknowledge potential issues and biases stemming from interpreting mountain glaciers at regional climate model / HIGA resolution.

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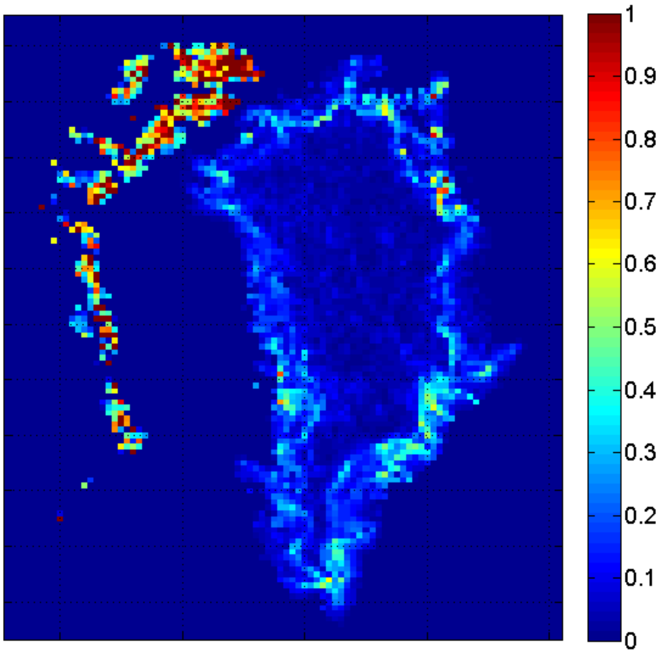

Fig. 1. Fractional uncertainty in "omega" (unitless), calculated as $\delta\omega/\omega$ (discussion paper Figure 3), across the Canadian Arctic and Greenland.