Satellite-Derived Volume Loss Rates and Glacier Speeds for the Cordillera Darwin Icefield, Chile

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Summary: This paper gives a nice overview of observational changes occurring in the Cordillera Darwin Icefield, Chile. The authors use a suite of remote sensing platforms to quantify ice velocity, elevation change, and volume loss from 2000-‐2011. The authors have compiled an impressive data set of ice velocity and elevation change in the CDI. They display the results clearly and with the thoughtful consideration of uncertainties and biases. The figures are, for the most part, easy to follow and impressively displayed. I recommend publishing, but with some major revisions.

Major concerns:

My major complaint about this paper is that it is a bit skimpy on the glaciological analysis. The bulk of the paper describes the setting, methodology and results, with very little interpretation. The methodology is similar to previous papers by the same authors, and lacks a clear science focus. While the dataset is valuable in and of itself, the paper could be strengthened with additional glaciological or climatological analyses.

We have expanded our glaciological and climatological analyses and tried to better emphasize the interpretation that is already in the text.

We have re-organized and refined the discussion of Marinelli Glacier in section 4.2 to better explain how we connect velocity and elevation change measurements for this glacier (e.g. section 4.2.5).

Added/changed, section 4.2.1, "Marinelli Glacier – Overview"
Added/changed, section 4.2.2, "Marinelli Glacier – Flux"
Added/changed, section 4.2.3, "Marinelli Glacier – Comparison with Previous Results"
Added/changed, section 4.2.4, "Marinelli Glacier – Thinning Gradient Maintains Surface Slope at the Front"
Added/changed, section 4.2.5, "Marinelli Glacier – Tidewater Cycle"

We have also reworked the abstract and conclusion to better illustrate several points, which we outline below:

1) Contrast between the "northern" and "southern" side of the icefield, with different average thinning rates and different behavior (e.g. retreat at Marinelli Glacier, advance at Garibaldi). This is consistent with climate trends for the region and changes in glacier length presented by Holmlund and Fuenzalida (1995). We note that given the warming trend, it is unlikely that

there will be periods of sufficient snowfall in the near future to compensate the thinning and retreat at glaciers like Marinelli.

a. Added, abstract: "Splitting the CDI along the main, east-west oriented highest divide results in a northern/eastern part with an average thinning rate of -1.8±0.2 m w.e. yr^{-1} and a southern/western part with an average thinning rate of -1.0±0.2 m w.e. yr^{-1}."
b. Added, introduction, first paragraph: "Throughout the paper the "southern" part or side of the CDI refers to southern and western glaciers, and the "northern" part or side of the CDI refers to northern and eastern glaciers. The green line in figure 1 shows the divide we use to distinguish between the "north" (1475 km^2) and ``south'' (1130 km^2)."
c. Added, section 3.1, second paragraph: "Splitting the CDI roughly along the main, east-west oriented highest-altitude divide produces an average thinning rate of -1.0±0.2 m w.e. yr^{-1} for the southern side, significantly lower than the northern side (-1.8±0.2 m w.e. yr^{-1}). The contrast between north and south is most likely due to an increased orographic effect (Holmlund and Fuenzalida, 1995)."
d. Added, conclusion, first paragraph: "The average thinning rate is -1.0±0.2 m w.e. yr^{-1} for the southern part and -1.8±0.2 m w.e. yr^{-1} for the northern part."

2) We find that the front speed in 2003 is slightly higher than 2001, and the front speed in 2011 as high or higher than 2003. We estimate flux using our 2001, 2003 and 2011 and find that flux in 2001 is the same as 2011, and slightly higher in 2003. We do not see similar large thinning signals at adjacent glaciers with similar settings, and given that the flux does not drop from 2001 to 2011 we attribute thinning at Marinelli to the glacier dynamics, driven by the fjord bathymetry.

3) Other glaciers (Darwin, CDI-08) show a similar pattern of retreat, rapid thinning near the front, and higher speeds at the front (with the front speed at Darwin in 2001 higher than Marinelli). However, we do not have enough glacier velocity measurements or enough knowledge of the fjord bathymetry at these glaciers to attribute this to dynamic thinning caused by recession of the terminus into deeper water, as we think is the case for Marinelli.

4) We put our results for the CDI into a larger context, comparing our results with the other Patagonian icefields (NPI, SPI) and (at the suggestion of the other reviewer) with other southern hemisphere glaciers in the same latitude belt. Warming is occurring in all of the regions we mention, as is glacier thinning and retreat. Gordon et al. (2008) discuss the potential for rapid retreat of calving glaciers from topographic pinning points due to warming and consequent thinning. The "tidewater-cycle" is a mechanism that can cause very rapid ice loss, and using velocity and thinning estimates to identify glaciers that are in the "retreat phase" of the tidewater-cycle is a

valuable contribution to the literature. We present velocity results over the past decade that support this hypothesis for Marinelli Glacier, and consider it as an analogue to Jorge Montt on the SPI. Two other glaciers, CDI-08 and Darwin, exhibit similar behavior, and identifying these two glaciers as worthy of additional investigation via velocity measurements is also a useful contribution to the literature.

I also recommend the authors revisit the organization of the paper/sections. For example, volume change is discussed in the elevation change rate section (which makes it a bit confusing, especially since the topics jump around a lot); results and interpretations of individual glaciers are discussed in a number of places, which makes an overall analysis hard to follow. A stronger interpretation of the data can be achieved by discussing the interconnectedness of velocity and elevation changes for individual glaciers.

First, we calculate elevation change rates at each pixel using a weighted linear regression applied to elevations from stacked DEMs (see figure 10). The volume change rate is the sum of the elevation change rate at each pixel multiplied by the area of the pixel (section 2.2, paragraph 6).

See discussion above for other examples of how we related the interconnectedness of velocity and elevation change.

The title implies that the paper is about volume loss rates, but in fact volume is the least discussed and most poorly measured variable here. I'm also not clear on the methodology for calculating the flux (p3518, line 6). Is the ice thickness adjusted for the observed thinning? What's the basis for the average front wall height and total glacier thickness? How were the errors estimated?

Fluxes are now estimated by measuring the glacier height from the nearest DEM (in time) and adjusting based on dh/dt if necessary.

Added/changed, section 4.2.2 – "Marinelli Glacier – Flux": "We calculate flux along transects perpendicular to glacier flow (as close as possible to the front) for velocities from 07/09/2001 to 25/09/2001, 06/09/2003 to 13/09/2003 and 30/07/2011 to 16/08/2011. The height of the glacier is determined from the 25/09/2001 ASTER DEM, 13/09/2003 ASTER DEM, and the 13/11/2007 ASTER DEM (adjusted using our dh/dt) respectively, we assume an average glacier depth below water of 150 m (see Koppes et al., 2009, figures 4a and 4b). Adding this to the height gives an approximate thickness. We multiply the glacier thickness by the perpendicular velocity along the transect to calculate flux. Sources of uncertainty that we include in the uncertainty for our flux estimates are the uncertainties on the speed, uncertainty on the depth below water (±50 m), and uncertainty on the DEMs used to obtain elevations.

We estimate a flux of 0.5±0.2 $km^3\ yr^{-1}$ for the 2001 pair, 0.7±0.2 $km^3\ yr^{-}1$ for the 2003 pair and 0.5±0.2 $km^3\ yr^{-1}$ for the 2011 pair. Flux is highest in 2003 (due to higher speeds than 2001 and a larger front than 2011), but the important point is that the 2011 flux has not dropped relative to 2001 due to speeds at the 2011 front that are higher than 2001 and as high as 2003.

…"

Additional concerns:

I had trouble following the description of sub-aqueous volume calculations. Perhaps simply rewording this paragraph, and/or the organization of the section will help. It seems out of place and the methodology here is hard to follow.

Section 2.2, ninth paragraph has been changed to better explain our purpose and method in estimating sub-aqueous volume change.

Sub-aqueous volume change is a component of the overall volume change, and it is important to have at least a general idea of its magnitude relative to the volume change we obtain from our dh/dt (which are surface elevation change rates derived from data acquired by satellite/spaceborne instruments). We provide an estimate for sub-aqueous volume change in this paper and find it to be an order of magnitude less than the volume change we derive from our dh/dt.

Sub-aqueous volume change is estimated by measuring the area of ice lost/gain at the front of the most rapidly-changing glaciers (identified by retreat/advance history and our dh/dt map) that terminate in water (Garibaldi, Marinelli, Darwin, CDI-08, identified in figure 1, original manuscript). The area lost/gained at the front is very well measured, the uncertainty is entirely from the lack of knowledge regarding the ice depth below water. We use 150 m for Marinelli from fjord bathymetry by Koppes et al. (2009), we use 60 m for the other glaciers (we assume that the Marinelli fjord is deeper, given that Marinelli's rapid retreat is attributable to the depth of the fjord and the other glaciers are not retreating/advancing nearly as rapidly, though this is merely a supposition). An uncertainty of ±50 m is assigned to all depths.

I understand the rationale for adding 2m to the C-band derived SRTM elevations for CDI, but I'm not entirely sure it's valid. Especially since, based on the blue dv/dt trends in Figure 10, that first SRTM data point really dictates the trend in some areas.

Previous reviewers have insisted that this effect holds for temperate icefields, e.g. the SPI. We note in section 2.2, tenth paragraph that adding 2 m to the SRTM elevations increases the mass loss rate by 13%.

Some of the figure captions are misleading, or need to be better described in the text. For example, Figures 5 and 6 show maximum dh/dt at ~2 km from the terminus. This is merely a function of the terminus retreat, not that thinning really is maximal at this odd distance up-stream. This should be pointed out somewhere.

Retreat and thinning go hand-in-hand, in the case of Marinelli we attribute thinning to the maintenance of high front speeds and therefore flux. Measuring terminus retreat does not capture the total volume loss occurring over the glacier during the study period, whereas our dh/dt provide an estimate of the icefield's contribution to sea level. Also, thinning is measured during the study period, we are not measuring the present thinning rate but rather the average thinning rate over the study period. Present thinning is not necessarily maximum over the location where the most thinning occurred during our study period.

References

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