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

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There are two figures showing the new north/south split as two different figures, one with $\frac{dh}{dt}$ for only the northern glaciers, one for only the southern glaciers. There is a discussion of uncertainty due to our choice of maximum allowed deviation on our mass change rate, with three figures that highlight the influence of clouds on ASTER DEMs (figures 3, 4 and 5). This is followed by a brief discussion of ELA vs. AAR for Marinelli, CDI-08 and Garibaldi glaciers, along with figures 6, 7 and 8 that highglight the differences between those three glaciers.

1 New North/South Split

The new north/south split is done only using glacier outlines (not an arbitrary line). Figure 1 shows the "northern" glaciers, figure 2 shows the "southern" glaciers.

2 Mass Change Rate - Uncertainty Due to Maximum Allowed Deviations

We only incorporate elevations into our pixel-by-pixel regression that deviate by less than +5 and -10/-30 (accumulation/ablation) m yr^{-1} from the first elevation (from the SRTM DEM 94% of the time). The upper limit of +5 m yr^{-1} is based on estimates of precipitation in this region (e.g. 4000 to 6000 m yr^{-1}, Fernandez et al., 2011), accounting for the fact that year-to-year thickening will be less than precipitation due to compaction and ablation. Allowing a deviation of -30 m yr^{-1} is necessary in the ablation zone to capture maximum thinning, which is more than -25 m yr^{-1} over areas of Marinelli (the wiggle room accounts for the uncertainty on individual ASTER elevations, which is 8-20 m). Restricting the maximum negative deviation to -10 m yr^{-1} in the accumulation zone produces a smooth transition in $\frac{dh}{dt}$ at the ELA, indicating that we are not excluding large areas of real thinning in the accumulation zone (i.e. there are no large areas of thinning greater than -10 m yr^{-1} in the accumulation zone). This removes splotches of incoherent, negative noise that would make our mass change rate more negative than it should be.

Changing the maximum allowed deviations significantly alters the mass change rate. For example, increasing the maximum allowed positive deviation from +5 to +10 m yr^{-1} decreases the mass loss rate from -3.9 Gt yr^{-1} to -1.8 Gt yr^{-1}. Which is closer to the real mass change rate, and how do we account for the uncertainty due to our choice of maximum allowed deviation? Because we do not know the actual mass change rate, we cannot test different deviations against it.

We cannot assume the ice has a $\frac{dh}{dt}$ of 0 m yr^{-1}, so we cannot apply the maximum deviations we use on the ice to off-ice areas to assess any possible bias. In fact, warming in the region (e.g., Holmlund and Fuenzalida, 1995; Koppes et al., 2009), retreat at many glaciers (e.g., Holmlund and Fuenzalida, 1995; Koppes et al., 2009; Lopez et al., 2010; Davies and Glasser, 2012) and shrinkage from the LIA to the present (Davies and Glasser, 2012) suggest the ice has a negative $\frac{dh}{dt}$. Besides the likelihood that the actual average ice $\frac{dh}{dt}$ is negative, there is also a disproportianate number of positive outliers due to clouds. Therefore, the distribution of elevation differences with cloud-cover is not Gaussian. This is apparent in figure 3, which shows a typical distribution of ASTER - SRTM elevation differences for the 15/01/2011 ASTER DEM where cloud cover is present.

The problem of positive outliers obviously becomes more pronounced at larger elevation differences. We demonstrate the influence of positive outliers by calculating the average off-ice $\frac{dh}{dt}$ for maximum allowed deviations of ±5, ±10 and ±30 m yr^{-1}, which result in $\frac{dh}{dt}$ of -0.04, +0.10 and +0.82 m yr^{-1}, respectively. Figure 4 shows off-ice elevation differences within ±30 m yr^{-1} for the 15/01/2011 ASTER DEM that illustrate this pattern for a single ASTER DEM. A simi-

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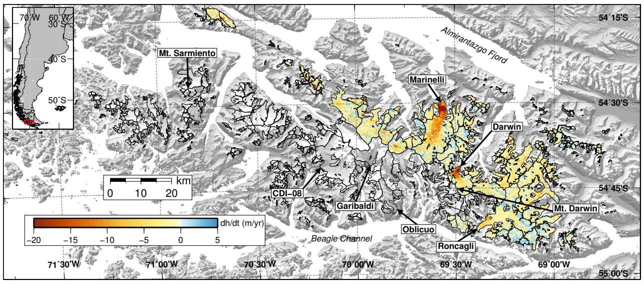

Fig. 1. $\frac{dh}{dt}$ of northern glaciers only.

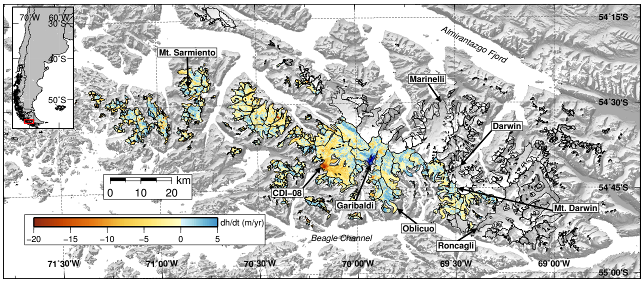

Fig. 2. $\frac{dh}{dt}$ of southern glaciers only.

lar pattern is observed for the ice elevation differences (figure 5), though with a more negative peak and more negative values closer to the peak than positive values (which we take to be indicative of real thinning).

The mean and the median are both affected by the choice of maximum deviation, however, the mode (the most commonly occurring value, i.e. the peak in a peaked distribution) is not affected by the choice of maximum deviation or by the disproportianate number of positive outliers. Taking the mode of elevation differences to be either the "actual" average $\frac{dh}{dt}$ (or at least a lower bound on the mass loss), we first compare (for each ASTER DEM) the mode of ASTER - SRTM elevation differences off-ice to the on-ice mode. For 26 out of 32 applicable DEMs, the on-ice mode is more negative than the off-ice mode, indicating that the ice has a negative $\frac{dh}{dt}$ (given that we know the off-ice areas must have a real $\frac{dh}{dt}$ of effectively 0 m yr^{-1}).

It is important to remember that the modes are not affected by the choice of maximum deviation, unless the maximum deviation does not include the mode. This is not the case for any of our ASTER DEMs, even when the maximum allowed positive deviation is limited to +5 m yr^{-1}. Therefore, we take the mode of the on-ice elevation differences as a deviation-independent measure that is representative of the average $\frac{dh}{dt}$ (i.e. it would be the mean if the distribution were Gaussian).

Taking the elevation differences from all of the ASTER DEMs, normalizing by converting to rates, then determining the mode gives a $\frac{dh}{dt}$ of -1.3 m yr^{-1} for the ablation zone and -0.9 m yr^{-1} for the accumulation zone. These are almost certainly less negative than the real $\frac{dh}{dt}$, because there is thinning in the -20 to just over -25 m yr^{-1} range at the front of three glaciers (which the regression-based $\frac{dh}{dt}$ include, but the mode does not). It is true that positive $\frac{dh}{dt}$ in the +20 to +25 m yr^{-1} are similarly excluded, but coherent thickening in the +20 to +25 m yr^{-1} range would be far outside the realm of possibility suggested by precipitation data for this region (e.g., Fernandez et al., 2011).

Multiplying these rates by the areas of the ablation and accumulation zone and assuming a density of 900 kg m^{3} gives a mass change rate of 2.54 Gt yr^{-1}. We do not consider this the "actual" mass change rate, but do take it as a deviation-independent measure that is a lower bound on the mass loss occurring. The difference between 2.54 Gt yr^{-1} and our mass change rate of 3.76 Gt yr^{-1} (excluding sub-aqueous and using the same assumptions regarding density, penetration depth, etc.) is taken as an estimate of the possible uncertainty due to the choice of maximum deviation. Adding all of our sources of uncertainty together in quadrature yields a total uncertainty of $\pm$1.5 Gt yr^{-1}.

Ignoring the possible influence of ELA on our results and assuming zero meters of penetration, the mode of normalized elevation differences for the entire icefield is -1.1 m yr^{-1}, which would yield a mass change rate of -2.86 Gt yr^{-1} (the more negative rate is due to the fact that the frequency of points tends to be "heavier" just negative of the mode for both the accumulation and ablation zones). We use the rate of -2.54 Gt yr^{-1} given above that is obtained using the same assumptions that yield the -3.76 Gt yr^{-1} estimated via pixel-by-pixel regression.

3 Accumulation Area Ratios - Marinelli, Garibaldi and CDI-08 glaciers

Figures 6, 7 and 8 show the accumulation area ratio (AAR) vs. elevation for Marinelli, CDI-08 and Garibaldi glaciers, respectively (elevations from the SRTM DEM). Marinelli Glacier, with an AAR of 0.38 at an ELA of 1100 m, has the lowest AAR of the three glaciers. Marinelli has already gone through the “flat” part of the curve (where small changes in the ELA cause large changes in the AAR) and is not in balance, contributing to the large negative mass balance and recent rapid retreat (e.g., Koppes et al., 2009).

CDI-08, with an ELA of $\sim$640 m, is still in the flat part of its curve and is more sensitive to a change in ELA than Garibaldi. The AAR of CDI-08 at its ELA of 640 m is 0.71, shifting the ELA up to 840 m would give an AAR of 0.46, a reduction of 25%. Garibaldi is comparatively insensitive, changing its ELA by the range we use for the entire icefield (650 m to 1090 m, more than 400 m) reduces the AAR from 0.89 to 0.67 (22%).

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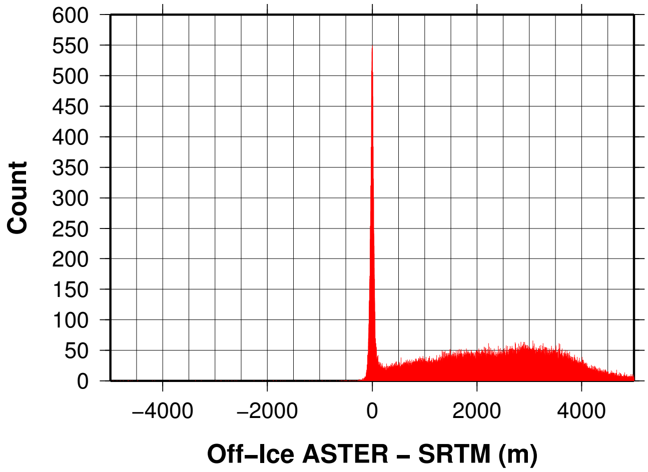

Fig. 3. 15/01/2011 ASTER DEM off-ice elevations minus SRTM DEM off-ice elevations (after vertical and horizontal coregistration of the ASTER DEM). There is a positive ”tail”, primarily due to the presence of clouds in the optical imagery used to generate the DEM. The mode of the distribution is approximately zero.

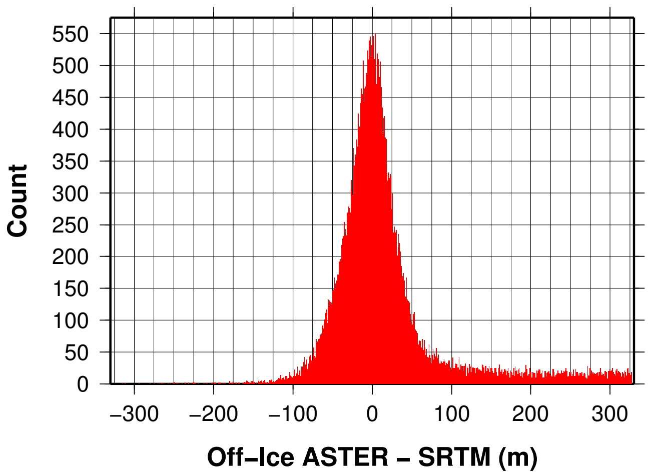

Fig. 4. 15/01/2011 ASTER DEM off-ice elevations minus SRTM DEM off-ice elevations (after vertical and horizontal coregistration of the ASTER DEM), excluding ASTER elevations that deviate more than ± 30 m yr^{-1} from the SRTM DEM. The positive tail is still apparent.

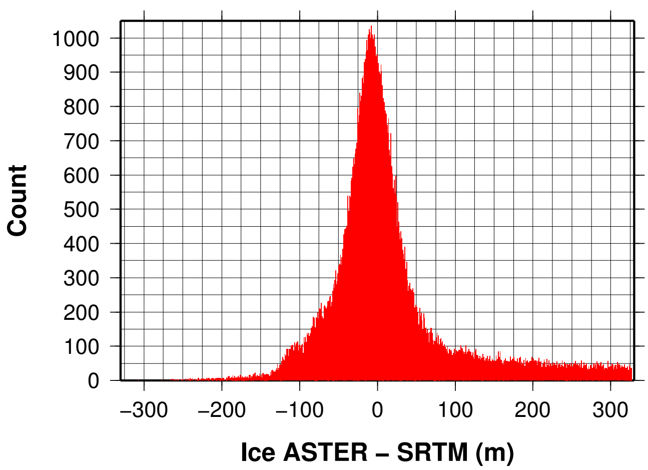

Fig. 5. 15/01/2011 ASTER DEM ice elevations minus SRTM DEM ice elevations (after vertical and horizontal coregistration of the ASTER DEM), excluding ASTER elevations that deviate more than ± 30 m yr^{-1} from the SRTM DEM. The positive tail is still apparent.

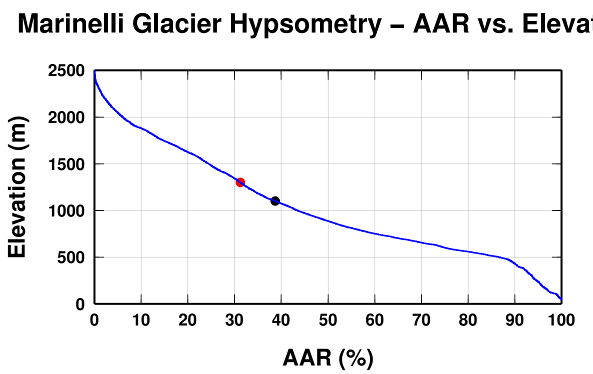

Fig. 6. Hypsometry for Marinelli Glacier from the SRTM DEM. The curve indicates what the AAR would be for the corresponding elevation. The black dot indicates the current ELA (1100 m), the red dot indicates a 200 m upward shift (1300 m). This would reduce the AAR from 0.39 to 0.31.

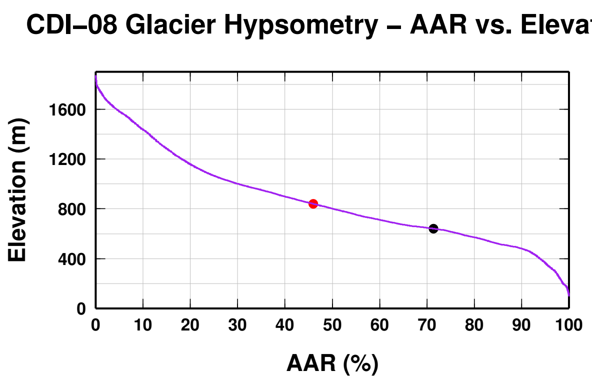

Fig. 7. Hypsometry for CDI-08 Glacier from the SRTM DEM. The curve indicates what the AAR would be for the corresponding elevation. The black dot indicates the current ELA (640 m), the red dot indicates a 200 m upward shift (840 m). This would reduce the AAR from 0.71 to 0.46.

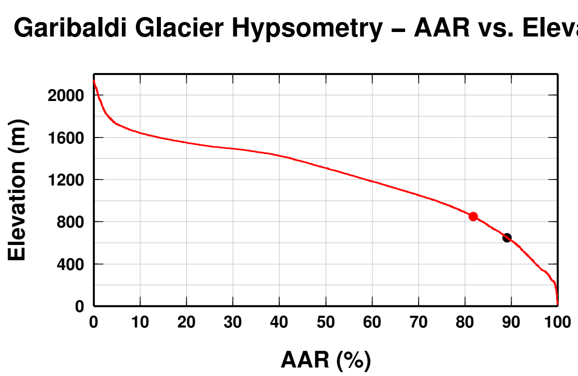

Fig. 8. Hypsometry for Garibaldi Glacier from the SRTM DEM. The curve indicates what the AAR would be for the corresponding elevation. The black dot indicates our best guess of the current ELA (650 m), which we have not estimated but is typical for southern and western glaciers (Bown et al., in press) The red dot indicates a 200 m upward shift (850 m). This would reduce the AAR from 0.89 to 0.32.