Impact of resolution and radar penetration on glacier elevation changes computed from DEM differencing

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Accepted as a correspondence to the ***Journal of Glaciology*** *(http://www.igsoc.org/journal/)*

1. Introduction

Digital elevation models (DEMs) are now frequently used to calculate elevation changes and regional mass balances of glaciers, for example in the Alps (Berthier and others, 2004; Paul and Haeberli, 2008; Huss and others, 2010), Alaska and Canada (Larsen and others, 2007; Schiefer and others, 2007; Berthier and others, 2010), Patagonia (Rignot and others, 2003) or High Mountain Asia (Surazakov and Aizen, 2006; Berthier and others, 2007; Bolch and others, 2011). Geodetic mass balance measurements from space-borne imagery are indeed useful to assess glacier changes in remote or wide areas and thus, better constrain glacier losses and contribution to sea level rise (Cogley, 2009). Previous studies have demonstrated that a thorough processing strategy is mandatory (i.e. a proper horizontal and vertical adjustments of the two DEMs to be substracted) to compute unbiased elevation changes from multi-temporal space-borne DEMs (e.g. Nuth and Kääb, 2011).

The 90-m freely available SRTM (Shuttle Radar Topography Mission) DEM was derived from C-Band SAR imagery acquired in February 2000 and, due to its wide coverage, is often used in regional mass balance studies. It has been suspected to cause an altitude-dependent vertical bias in the elevation changes when differentiated with others DEMs derived from aerial photographs or satellite optical imagery (Berthier and others, 2006). Subsequently, Paul (2008) attributed this bias to a difference in the original spatial resolution of the DEMs and concluded that this bias, estimated on the surrounding ice-free terrain, should not directly be applied to glaciers. However, it is still under debate whether this bias should be corrected or not, and whether it is similar on and off glaciers (Berthier and others, 2006; Larsen and others, 2007; Möller and others, 2007; Schiefer and others, 2007; Huss and others, 2010; Möller and Schneider, 2010). In addition, the C-band radar penetration of SRTM can reach up to 10 m in snow and ice (Dall and others, 2001; Rignot and others, 2001). Thus, the SRTM DEM (or any other DEM derived from C-Band radar data) may actually map a surface which is below the real surface, especially in accumulation areas (Langley and others, 2008), leading to biased estimate of the glacier elevation changes (Berthier and others, 2006, Figure 4).

To explore the impact of DEM resolutions and radar penetration, we used three different DEMs over the Karakoram region (Pakistan/China): a 40 m SPOT5 DEM of December 2008 derived from optical imagery (Korona and others, 2009), a 90 m SRTM DEM acquired in C-band (Rodriguez and others, 2006) and a 30 m SRTM DEM, acquired in X-band, both in February 2000. In addition, we produced a glacier inventory based on Landsat-5 imagery from August 1998. Our Karakoram study site (75°02’E-76°29’E; 35°08’N-36°55’N) exhibits one of the steepest relief on Earth and includes 5615 km^2 of glaciers whose altitude ranges from 2700 to 7900 m a.s.l.

2. Impact of DEM resolution

Following the experiment suggested by Paul (2008), we resampled the 90 m SRTM C-band DEM to 40 m, resampled it back to 90 m and subtracted it from the original (90 m) one. Elevation changes were averaged in 100 m altitude bins and a bias with altitude similar to Paul (2008) was found on and off glaciers, with higher values off glaciers (not shown here). Paul (2008) suggested that terrain slope determines the amplitude of the elevation differences and that plan curvature (the second derivative of the topography) determines the sign of this difference. Here, we build on these previous findings but show that terrain maximum curvature can be used to correct those elevation biases (Fig. 1a and b). The curvature used in this study is computed with a 5x5 kernel size (in this regard, it is only a local derivative of the slope) and defined as the maximum curvature in any plane intersecting the surface (Wood, 1996). The computation was done with the IDL/ENVI software, but is also implanted in the open source GRASS GIS software.

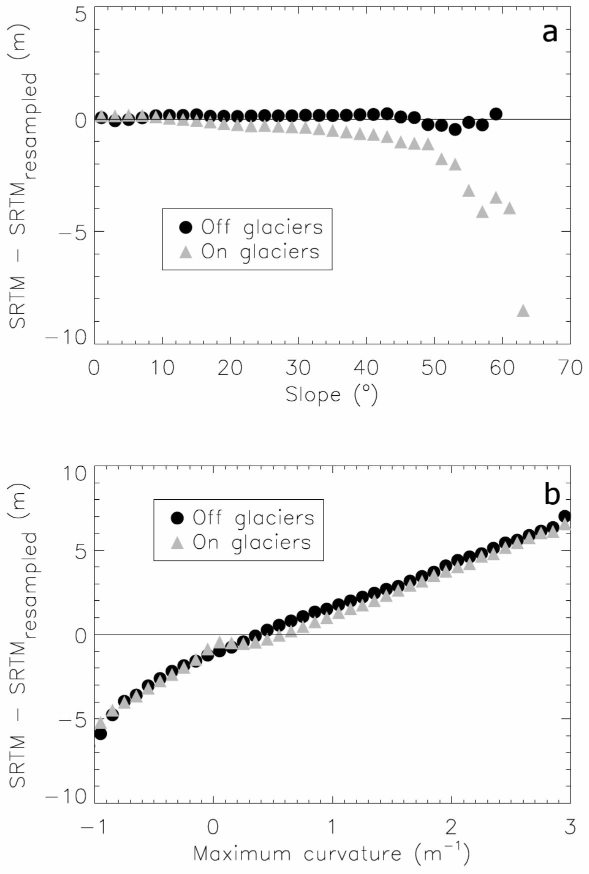

Figure 1: *Relation between (a) the terrain slope or (b) maximum curvature and the elevation differences computed from the original 90 m C-band SRTM and the one resampled from 40 m (see text). Grey triangles represent glacier pixels, black circles non-glacier pixels.*

The link between the maximum curvature and the elevation bias can be qualitatively illustrated if we consider how slopes are represented by low and high resolution DEMs. A slope constant over numerous continuous coarse pixels (which means low curvature values in the direction of the slope), will be equally represented by the low and high resolution DEM. On the opposite, a slope that is constant only over few high resolution pixels (i.e. high curvature values in the direction of the slope) will be better estimated by the high resolution DEM than by the coarser one (Kervyn and others, 2008).

Importantly, the relation between the elevation differences and the terrain maximum curvature from our experiment (Fig. 1b) is similar over and outside glaciers, a key condition to use it confidently to correct the elevation differences on glaciers. Conversely, elevation differences as a function of altitude (not shown here) or elevation differences as a function of slope (Fig. 1a) differ strongly on and off glaciers, because of different curvature distributions. We also tested other definitions of curvature for correcting this bias, which revealed that the plan curvature has also a clear relationship with the elevation difference, but does not fully compensate the bias, as the maximum curvature do (see squares in Fig.2).

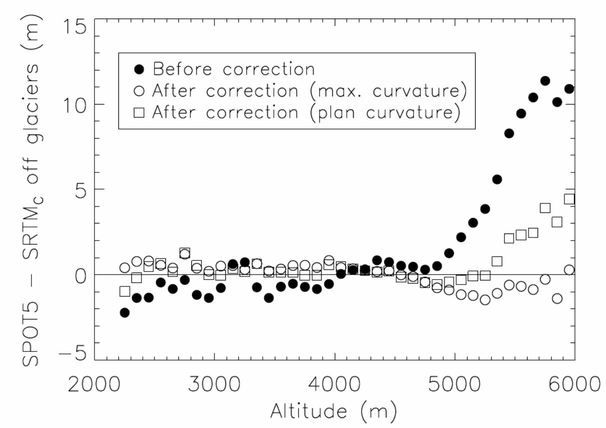

Figure 2: *Elevation differences off glaciers between SPOT5 and SRTM C-band DEMs as a function of altitude. Filled circles represent the raw elevation differences, open circles represent the elevation differences after a correction based on terrain maximum curvature and squares the ones after a correction based on terrain plan curvature.*

This bias due to DEMs of different resolutions can thus be corrected on and off glaciers, based on the maximum curvature of each pixel (taken from the high resolution DEM) and using the relation between elevation differences and maximum curvature established off glaciers. As the curvature varies within a glacier, the correction will introduce local modifications of elevation changes. How this correction will influence the individual glacier (or glacier complex) mass balance will depend on the curvature distribution, which varies from one glacier to another.

This validity of the curvature correction has been tested in a real case study involving a SPOT5 DEM from December 2008 and the SRTM C-band DEM from February 2000 over the Karakoram. The raw elevation differences (SPOT5 – SRTM$_{\text{C-band}}$) off glaciers exhibit a positive elevation bias above 5000 m that reaches up to 11 m at 6000 m (black circles in Fig.2). The relation between the maximum curvature and the elevation differences has been computed on ice-free terrain and used to correct the elevation bias. The differences SPOT5 – SRTM$_{\text{C-band}}$ after correction show that the elevation bias has been properly removed (open circles, in Fig. 2). A correction based on plan curvature as also been tested (squares, in Fig.2). Part of the bias is corrected but the adjustment is not as good, with a 5 m bias remaining at 6000 m in our case study.

3. Accounting for radar penetration

Another artefact that can affect the glacier elevation changes computed with, at least, one radar DEM (e.g. SRTM C-Band) is the penetration of the radar signal into snow and/or ice. The comparison of the SRTM X-band (9.7 GHz) and C-Band (5.7 GHz) DEMs permits to quantify this penetration, as it is much smaller in the X band than in the C band. Those two DEMs were acquired simultaneously so that no “glaciological” elevation change is expected. However, the coverage of the SRTM X-band DEM is not continuous. The swath width is narrower (~50 km) and the resulting DEM is available along selected strips only.

The C-band DEM has been resampled to 30 m and substracted from the X-band DEM. First, because of the difference in the original DEMs resolution, a correction according to the terrain maximum curvature has been applied, with the method described above. Then, in addition to the glacier inventory, we identified the snow-covered areas (both on and off glaciers) on a Landsat image from the 24th February 2000, just a few days after the acquisition of both SRTM DEMs. The $\mathrm{SRTM}_{\text{X-band}}$ – $\mathrm{SRTM}_{\text{C-band}}$ differences as a function of altitude (Fig. 3) show no significant bias over debris-covered parts of glaciers or bare ice-free terrain, confirming the efficiency of the curvature correction.

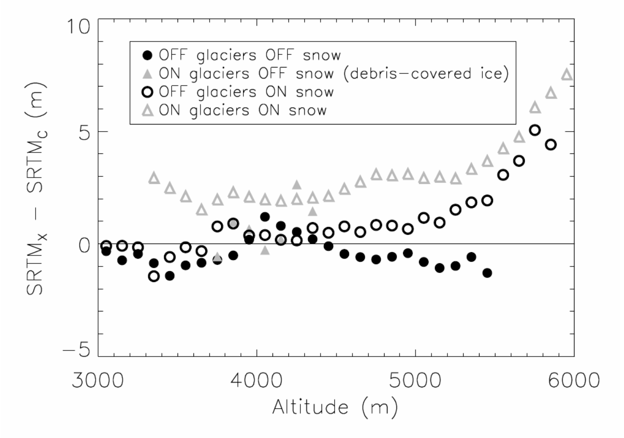

Figure 3: *Elevation differences between* $\mathrm{SRTM}_{\text{X-band}}$ *and* $\mathrm{SRTM}_{\text{C-band}}$ *as a function of altitude.*

The snow-covered ice-free terrain exhibits a strong bias with altitude above 5000 m that reaches ~5 m at 6000 m. The bias on snow-covered glacier parts is similar but is about 2 m higher at all altitudes. We interpret the bias above 5000 m as a differential penetration in snow between C-band and X-band radar. The 2 m systematic bias on snow-covered glaciers is attributed to the differential penetration in ice, C-band having a larger penetration than X-band. Little is known about the absolute value of X-band penetration into snow and glacier ice, but it decreases as temperature and water content rise (Surdyk, 2002; Ulaby and others, 1986). In Antarctica, Davis and Poznyak (1993) measured penetration depths at 10 GHz from 2.1 m to 4.7 m, and Surdyk (2002) reported a 4 m penetration depth at 10.7 GHz at -8°C. However, the ice and snow conditions in winter in the Karakoram are not identical to those in Antarctica: temperature is probably higher, snow is less dry, and ice is dirtier (presence of debris) so penetration depth in X-band should be less than the values found in the literature. As a first approximation, we assume no penetration of the X-Band signal and consider that the value $\mathrm{SRTM}_{\text{X-band}}$ – $\mathrm{SRTM}_{\text{C-band}}$ corresponds to the C-band penetration. Clearly, this hypothesis needs to be further validated, especially with the German Aerospace Center (DLR) TanDEM-X mission, which will release high resolution DEMs from X-band radar data.

Comparing C-Band and X-Band DEMs is a mean to better take into account and correct for the SRTM penetration into snow and ice. We stress that the amplitude of penetration will likely be peculiar to each region as snowfall seasonality and snowpack characteristics were different among glacierized areas in February 2000, when SRTM was flown. One limitation of the proposed methodology to account for C-Band penetration is the limited coverage of the X-Band DEM, restricted to some stripes.

4. Conclusion

Our correspondence analyzed and proposed corrections for two issues that can lead to altitude-dependant bias between DEMs and thus, erroneous measurements of glacier elevation and volume changes. The first issue concerns the comparison of DEMs of different original resolutions. Building on previous findings (Paul, 2008), we found that those biases are directly explained by variations in terrain maximum curvature and that, importantly, the relationship is unchanged on and off glaciers. Thus, the relationship between elevation differences and maximum curvature can be established off glaciers and applied to the ice-covered areas. The second issue is related to the penetration of the radar signal into ice and snow, a penetration that can reach several meters in the case of the SRTM C-Band DEM. We showed here that analyzing the elevation differences between the two SRTM DEMs (30 m X-Band and 90 m C-Band acquired simultaneously in February 2000) can provide a first-order estimate of C-band penetration. A 3 m average penetration of the SRTM C-Band signal was found for the Karakoram but must be recalculated for each ice-covered region.

It is known that DEMs should be corrected prior to their comparison but we stress here that the elevation differences on the ice free terrain cannot be readily use to correct the ice/snow elevation changes. Together with other processing steps (Nuth and Kääb, 2011), particular attention should be paid to the two additional corrections proposed in this correspondence when the forthcoming 30 m global TanDEM-X DEM will be compared to the SRTM 90 m C-band DEM or to any other earlier DEMs acquired with different resolution and/or in a different wavelength of the electromagnetic spectrum. In addition, we recommend to investigate the potentially strong impact of such corrections on previously published mass balance estimates (Berthier and others, 2007; Larsen and others, 2007; Möller and others, 2007; Paul and Haeberli, 2008; Schiefer and others, 2007; Surazakov and Aizen, 2006).

Acknowledgments

We thank F. Paul and N. Barrand for their excellent reviews which helped to improve the quality of this correspondence. J. Gardelle acknowledges a PhD fellowship from the French Space Agency (CNES) and the French National Research Center (CNRS). E. Berthier acknowledges support from the French Space Agency (CNES) through the TOSCA and ISIS program and from the Programme National de Télédétection Spatiale (PNTS). We thank the United State Geological Survey (USGS) for allowing free access to their Landsat archive, CIAT for SRTM C-band data, and DLR for SRTM X-band data. This work was supported by Agence Nationale de la Recherche (reference ANR-09-320 CEP-005-01/PAPRIKA).

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