

Correspondence

Volume change at Gran Campo Nevado, Patagonia, 1984–2000: a reassessment based on new findings

Möller and others (2007) calculated the volumetric glacier change of the ice cap Gran Campo Nevado (GCN), southernmost Chilean Patagonia, during 1984–2000. Their analysis was based on a digital elevation model (DEM) created from aerial photographs (1984 DEM) and the Shuttle Radar Topography Mission (SRTM) DEM (2000 DEM). In that analysis an elevation-dependent correction to the SRTM elevations was applied, as suggested by Berthier and others (2006).

Recently, considerable disagreement has arisen as to whether there exists an elevation-dependent bias in the SRTM DEM and whether, if it does exist, a correction to calculations of volumetric glacier changes is required. Different studies have led to different findings on this matter (e.g. Berthier and others, 2006; Larsen and others, 2007; Schiefer and others, 2007; Paul and Haeberli, 2008; VanLooy and Forster, 2008). Finally, Paul (2008) presented a possible explanation of the nature of the bias. Mountainous terrain tends to have a more pronounced relief with increasing elevation; it forms ridges and peaks with steep slopes. These sharp forms are frequently underestimated by

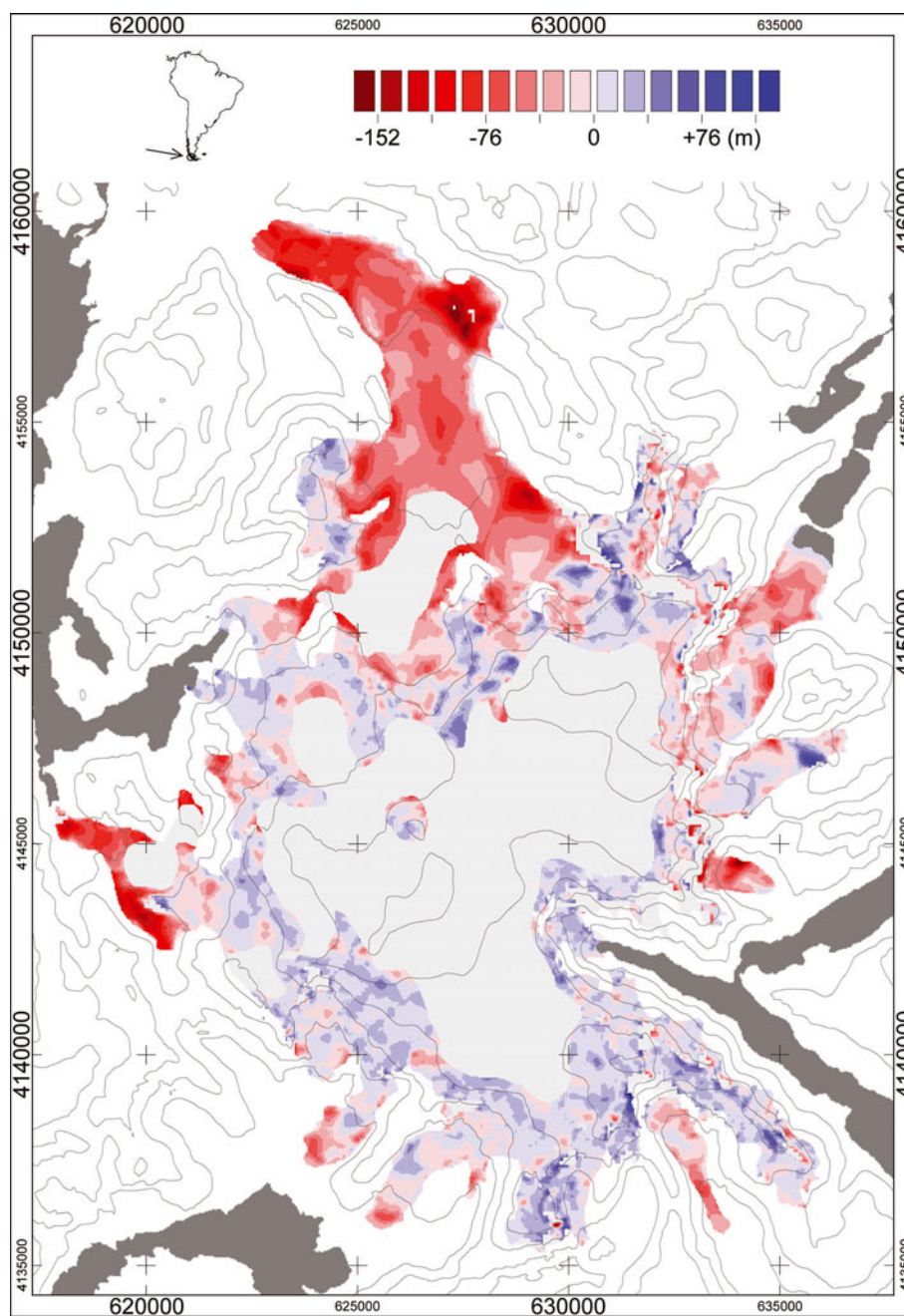


Fig. 1. Surface-elevation changes for GCN in 1984–2000. Light-grey colours throughout the glacier area represent data voids in the 1984 DEM. Dark-grey shading represents the sea surface. Contour spacing is 250 m. Coordinates correspond to Universal Transverse Mercator (UTM) zone 18S.

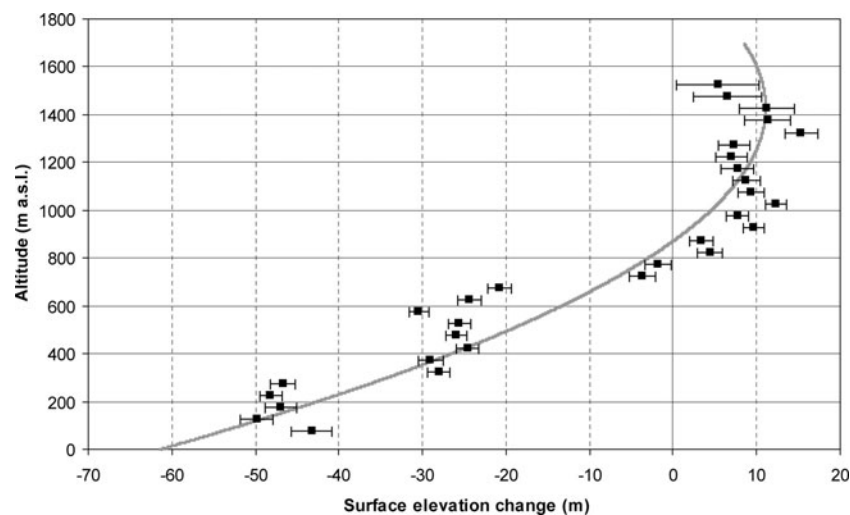


Fig. 2. Hypsometry of glacier surface-elevation changes at GCN in 1984–2000 and polynomial fit used to fill data voids in the volumetric analysis. RMS errors (error bars) show an increase with terrain elevation. They thus reflect a decreasing pixel basis due to extensive data voids in the 1984 DEM throughout the low-contrast regions of the ice plateau (cf. Möller and others, 2007).

coarse-resolution DEMs. In contrast, finer-resolution DEMs can represent such structures more accurately. Therefore, a comparison of DEMs with different spatial resolution, i.e. cell size, leads to increasing biases in the uppermost terrain regions when analysing non-glacierized surfaces. However, for glacier-covered alpine terrain the effect is less pronounced. Ice-covered mountain terrain usually occurs at less steep slopes where even a coarse-resolution DEM can capture the relief adequately. This marked morphological contrast between glacierized and non-glacierized terrain implies that it is impossible to assign a bias that suits both terrains.

GCN is situated in the fjord-dominated region of the southern Chilean Andes, covering an area of $>190\text{ km}^2$. Its morphology is almost exclusively dominated by a large, smoothly shaped ice plateau with several outlet glaciers reaching to sea level. Hence, the situation is nearly the opposite of that for alpine terrain: steep slopes are found at low elevations and gentle slopes dominate the highest elevations. For this reason, the bias found by Möller and others (2007) shows characteristics inverse to those described by Berthier and others (2006) for alpine terrain. Due to its morphological characteristics, the majority of the ice-covered area of GCN can be represented by either a coarse- or a fine-resolution DEM with almost equal quality. Possible differences might only arise within the steep parts forming the transition zone between the flat ice plateau and the likewise flat outlet glacier tongues. Nevertheless, when calculating the volumetric glacier change of GCN, Möller and others (2007) applied a correction to the assumed elevation-dependent bias of the SRTM DEM, based on the morphologically different non-glacierized terrain, as suggested by Berthier and others (2006). Thus an artificial error was introduced in the derived elevation changes of the ice cap.

In the light of the new findings of Paul (2008), we present a reassessment, i.e. a correction to the calculations of Möller and others (2007). For the renewed analysis we substitute for the formerly used version of the SRTM DEM its latest release (SRTM version 4) and change the technique employed for co-registration of the two DEMs. Co-registration is now done using a standard technique,

i.e. without the originally applied terrain elevation correction. The entire 1984 DEM was shifted until it properly matched its 2000 DEM counterpart, i.e. root-mean-square (RMS) error between the DEMs was minimized. All other processing steps were carried out following the method of Möller and others (2007). The obtained hypsometry of glacier surface-elevation changes (Fig. 1) was again approximated by a polynomial fit ($R^2 = 0.92$). From this fit an estimated mean hypsometry of surface-elevation changes was obtained. This serves to fill data-void areas in the 1984 DEM and derive complete information about volumetric glacier change.

The new results of DEM differencing (Fig. 1) support the overall glacier change pattern presented by Möller and others (2007). A mean glacier thinning of $6.5 \pm 2.5\text{ m}$, corresponding to a mean annual thinning rate of $0.37 \pm 0.14\text{ m w.e. a}^{-1}$, is now derived for the 1984–2000 period. This value is only slightly different from the previous estimate ($0.35 \pm 0.16\text{ m w.e. a}^{-1}$) of Möller and others (2007). However, as expected, our new results for absolute values along the glacier hypsometry differ noticeably (Fig. 2). The outlet glacier tongues show considerably stronger thinning than previously assumed. A negative surface elevation change of almost 50 m is now shown to extend up to elevations of 300 m a.s.l. The former study obtained comparable values only at the lowermost parts of the tongues, well below 200 m a.s.l. Further up-glacier, the new results likewise reveal higher thinning rates as obtained by Möller and others (2007). In contrast, the uppermost central parts of the ice cap show an even more pronounced thickening than was revealed by the previous study. Positive surface-elevation changes are now calculated to reach up to 15.4 m, implying $>50\%$ larger thickening than previously estimated. The new results thus reveal a steeper gradient than estimated by Möller and others (2007). Based on the 1984 glacier area for GCN, of 204.2 km^2 , the new results indicate a total mass loss of $1.2 \pm 0.5\text{ km}^3\text{ w.e.}$ The climate forcing necessary to explain this glacier change for GCN can be attributed to a combined precipitation and temperature offset of $+11\%$ and $+0.35\text{ K}$ from steady-state climate conditions. Thus, the previously estimated deviations of $+7\text{--}8\%$ and $+0.3\text{ K}$

(Möller and others, 2007) turn out to be considerably more pronounced in terms of precipitation offset.

It is concluded that the general thrust of Möller and others (2007) still holds. However, quantitatively marked differences are observed, especially with respect to the accumulation in the uppermost parts of GCN. The results of the presented study strongly encourage future reassessments of past glacier-change calculations using an elevation-dependent correction of SRTM terrain data.

ACKNOWLEDGEMENTS

Comments and manuscript annotations by F. Paul and G. Casassa helped to make this correspondence easier to follow and are gratefully acknowledged.

Department of Geography,
RWTH Aachen University,
Templergraben 55,
D-52056 Aachen, Germany
E-mail: marco.moeller@geo.rwth-aachen.de

Marco MÖLLER
Christoph SCHNEIDER

6 March 2010

REFERENCES

- Berthier, E., Y. Arnaud, C. Vincent and F. Rémy. 2006. Biases of SRTM in high-mountain areas: implications for the monitoring of glacier volume changes. *Geophys. Res. Lett.*, **33**(8), L08502. (10.1029/2006GL025862.)
- Larsen, C.F., R.J. Motyka, A.A. Arendt, K.A. Echelmeyer and P.E. Geissler. 2007. Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise. *J. Geophys. Res.*, **112**(F1), F01007. (10.1029/2006JF000586.)
- Möller, M., C. Schneider and R. Kilian. 2007. Glacier change and climate forcing in recent decades at Gran Campo Nevado, southernmost Patagonia. *Ann. Glaciol.*, **46**, 136–144.
- Paul, F. 2008. Correspondence. Calculation of glacier elevation changes with SRTM: is there an elevation-dependent bias? *J. Glaciol.*, **54**(188), 945–946.
- Paul, F. and W. Haeberli. 2008. Spatial variability of glacier elevation changes in the Swiss Alps obtained from two digital elevation models. *Geophys. Res. Lett.*, **35**(21), L21502. (10.1029/2008GL034718.)
- Schiefer, E., B. Menounos and R. Wheate. 2007. Recent volume loss of British Columbian glaciers, Canada. *Geophys. Res. Lett.*, **34**(16), L16503. (10.1029/2007GL030780.)
- VanLooy, J.A. and R.R. Forster. 2008. Glacial changes of five southwest British Columbia icefields, Canada, mid-1980s to 1999. *J. Glaciol.*, **54**(186), 469–478.