Correspondence

Volume loss from Bering Glacier, Alaska, 1972–2003: comment on Muskett and others (2009)

Alaskan glaciers have experienced rapid and accelerating wastage over the past four to five decades (Arendt and others, 2002) and accounted for 0.12 ± 0.02 mm a^{-1} (7.5%) of total sea-level rise between 1962 and 2006 (Berthier and others, 2010). Ice loss in Alaska is dominated by a few large glaciers located in the vicinity of the Gulf of Alaska (e.g. Columbia, Malaspina and Bering Glaciers). Among them, the Bering Glacier system (BGS) is often regarded as the largest glacier system in North America, with an area of nearly 4400 km^2 (Beedle and others, 2008), or >5000 km^2 if the accumulation area of Tana Glacier is included (Molnia, 2007).

The elevation change and volume loss of the BGS have been estimated by different authors using remote-sensing techniques. They all used the 1972 US Geological Survey (USGS) map as a reference topography. For a 2190 km^2 sub-area of the BGS, Arendt and others (2002) found mass loss of 2.3 ± 0.5 km^3 w.e. a^{-1} between 1972 and 2000. They carefully restricted their analysis to the lower part of Bering Glacier where they flew airborne laser altimetry profiles in 1995 and 2000. Berthier and others (2010) estimated the mass loss of the complete BGS (following the definition of Beedle and others, 2008) as 2.6 ± 0.5 km^3 w.e. a^{-1} by comparing recent (2003–07) digital elevation models (DEMs) derived from SPOT-5 and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite imagery to the US National Elevation Dataset (NED) DEM derived from the 1972 topographic maps. Muskett and others (2009) also compared recent (2000–03) DEMs generated from air- and spaceborne sensors to the 1972 map-derived DEM to estimate the total volume loss of a 3560 km^2 sub-area of the BGS. For comparability with other estimates, we converted the Muskett and others (2009) volume loss (191 ± 17 km^3, or 6.2 ± 0.5 km^3 a^{-1}) to mass loss, assuming a density of 900 kg m^{-3} for the material gain/loss by the BGS (the same assumption was used by Arendt and others (2002) and Berthier and others (2010)). Although measured during a similar period, the Muskett and others (2009) mass loss, 5.6 ± 0.5 km^3 w.e. a^{-1}, is more than twice as large as other estimates (Arendt and others, 2002; Berthier and others, 2010). In this correspondence, we demonstrate that this discrepancy is due to overestimation by Muskett and others (2009) of the volume loss for Tana Glacier and the Bering Glacier arm, a region that concentrates 60% (114 ± 4 km^3) of their overall BGS loss (their table 2 and fig. 5). We also show that this overestimation originates from a vertically biased ASTER DEM.

We reproduced the Muskett and others (2009) sequential DEM analysis for Tana Glacier and the Bering Glacier arm by comparing the same original data: the 1972 USGS map-derived DEM and a pair of ASTER optical stereo images acquired on 8 August 2003. Details of the methods we used to calibrate the USGS and ASTER DEMs can be found elsewhere (Berthier and others, 2010). Elevation changes during 1972–2003 are shown in Figure 1b for the whole ASTER scene. Only part of this map was used by Muskett and others (2009) to measure volume changes (their fig. 5b, box b, reproduced here in our Fig. 1a) and it is not straightforward to extract exactly the same sub-region as them (thick black polygon in our Fig. 1b). Conservatively, we analyzed an area of 1112 km^2, which is larger than the 1015 km^2 area considered by Muskett and others (2009). The glacier and nunatak outlines used here (Berthier and others, 2010) differ from those used by Muskett and others (2009) and may explain part of this difference in areal extent. Over this 10% larger ice-covered area, the total volume loss is 28.6 ± 5.5 km^3 (corresponding to an area-average thinning of 26 ± 5 m), four times lower than the 114 ± 4 km^3 volume loss reported by Muskett and others (2009, table 2).

There are several reasons why our new estimate for Tana Glacier and the Bering Glacier arm may be more reliable than Muskett and others' (2009) value:

1. Our mean elevation difference between the ASTER and USGS DEMs on the ice-free terrain is small, –1.4 m. The standard deviation of the elevation differences is relatively large (±30 m), but expected given the respective uncertainties of the USGS (±15 m) and ASTER (±15–20 m) DEMs. Muskett and others (2009) did not report those statistics on the ice-free terrain.

2. Our ice-elevation changes (Fig. 1) are consistent with the elevation changes measured by Muskett and others (2009) using laser altimetry profiles along the Bering Glacier arm (fig. 6a in Muskett and others, 2009). When projected in their figure 6a, the elevation changes derived from the ASTER DEM correspond to abscises 50–95 km. Our Figure 1 reveals the same pattern as the 1972–2003 curve in figure 6a by Muskett and others (2009), with thinning by 60–70 m in the lower part (abscise 50 km), evolving to no elevation change around abscise 85 km and then to slight thinning again at higher elevations (abscise 95 km and further up in Bagley Ice Valley). On the other hand, figure 5b of Muskett and others (2009) indicates strong thickening (120 m) in the lower part (abscise 50 km), then a maximum thinning of about 150 m and small thickening again at higher elevations (abscise 95 km). Thus, there are strong discrepancies between figures 5b and 6a in Muskett and others (2009). It is striking that the average thinning for the Bering Glacier arm and Tana Glacier derived by Muskett and others using sequential DEM analysis, 112 m (Muskett and others, 2009, table 2), is higher than the maximum thinning they measured by differencing laser altimetry profiles and the USGS DEM over the Bering Glacier arm during the same period (1972–2003).

3. There are glaciologically unrealistic discontinuities in the different ice-elevation change maps that were assembled from different elevation datasets by Muskett and others (2009; see the different panels in their fig. 5). At the transition between the Bering Glacier arm and the Bering Lobe, there is a sharp shift from strong thickening (by about 120 m) to moderate thinning (by about 60 m). This vertical step (nearly 200 m) is located at the southwest boundary of their ASTER-based map of elevation changes. It cannot be explained by the 4 year difference between the two surveys (1972–2003 for the arm, 1972–99 for the lobe), given that no surge is known to have affected the lower part of Bering Glacier between

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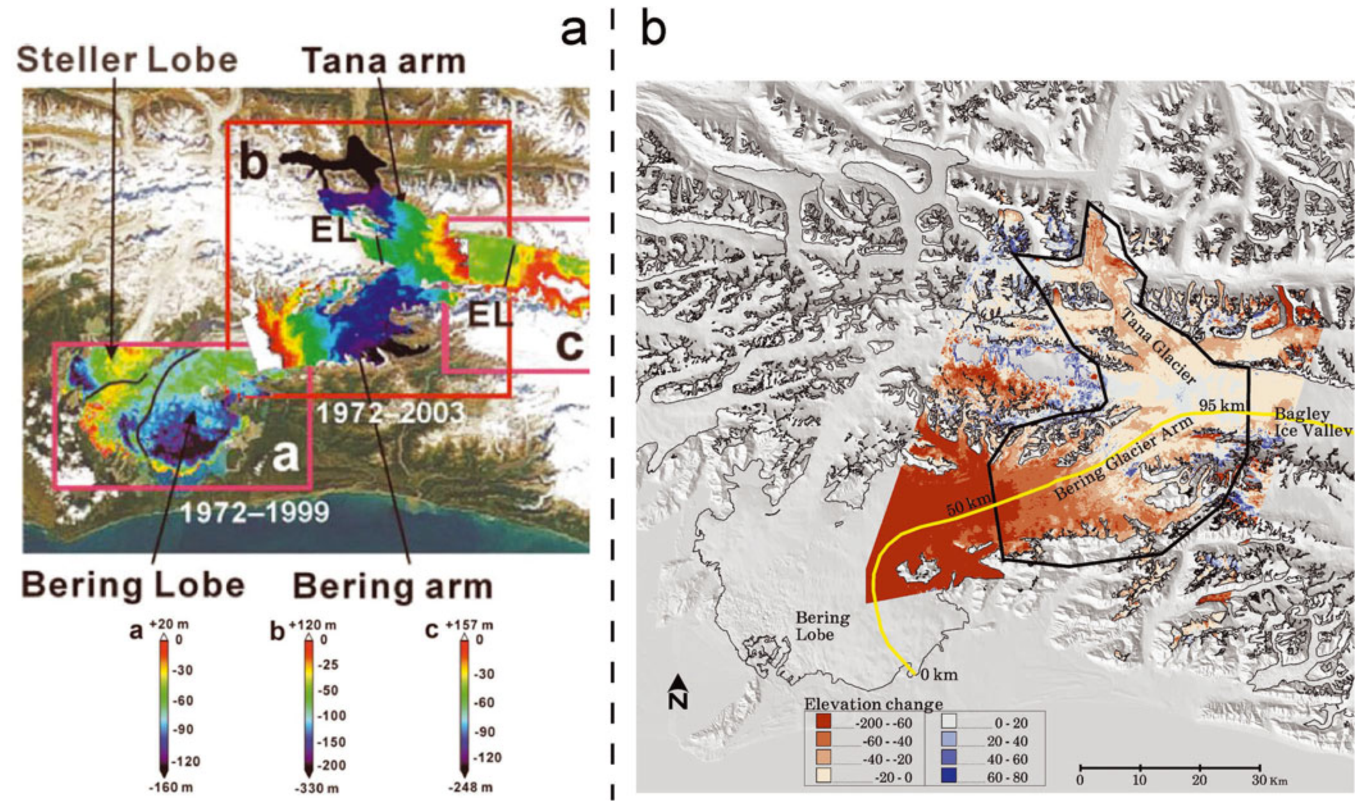

Fig. 1. Elevation changes on the lower parts of Bering and Tana Glaciers between 1972 and 2003: (a) reproduced from figure 5 of Muskett and others (2009; see their legends for details); and (b) calculated in this study. The background image in (b) is a shaded relief USGS DEM. The thin black curve delimits the ice-covered areas extracted from the 1972 USGS maps (Berthier and others, 2010). The thick black polygon limits the area where volume change was derived by Muskett and others (2009) using the ASTER-derived 2003 DEM. The yellow curve locates the laser altimetry profile used by Muskett and others (2009) in their figure 6a. Distances along the laser altimetry profile are indicated.

1999 and 2003. Furthermore, neither a comprehensive map of ice-elevation changes for the whole Saint Elias Mountains (Berthier and others, 2010, supplementary fig. S1f) nor the laser-derived elevation changes (Muskett and others, 2009, fig. 6a) exhibit this vertical step; instead they show a more-or-less regularly increasing thinning toward the Bering Lobe. For similar reasons, the 60–70 m jump in Muskett and others' (2009) elevation changes at the transition between the Bering Glacier arm and Bagley Ice Valley (corresponding to the eastern boundaries of the ASTER-based elevation changes) is not glaciologically realistic. Here the survey periods differ by 3 years: 1972–2003 for the arm, 1972–2000 for Bagley Ice Valley.

The facts that (1) these discontinuities are located at the edge of the ASTER DEM, and (2) the accuracies of the other elevation datasets (Intermap DEM and Shuttle Radar Topography Mission DEM) used by Muskett and others (2009) have been carefully examined, lead to the conclusion that a vertically distorted ASTER DEM is the source of these errors. Muskett and others' (2009) ASTER DEM is too high in its eastern and western parts and too low in its central part. These deviations resemble a cylinder-shaped distortion of the geometric sensor model and, subsequently, of the DEM. Unfortunately, Muskett and others (2009) did not describe their processing of the ASTER images using the ENVI software. For example, it is not stated whether they used ground control points. They simply indicated that the DEM 'was adjusted using airborne laser altimetry acquired August 2003 for vertical bias control' (Muskett and others, 2009, p. 317). Thus, we cannot determine the origin of this vertical distortion in the ASTER DEM, but we speculate that it was introduced during its adjustment to the laser altimetry data.

Due to errors during their processing of the ASTER DEM, we believe Muskett and others (2009) overestimated the volume loss for the Bering Glacier arm and Tana Glacier by about 85 km^3 (300%, or 2.7 $km^3\,a^{-1}$). The systematic errors that led to this overestimation were not included in their small error bar of $\pm 4\,km^3$.

In a context of rapidly evolving ice masses, DEMs derived from satellite imagery are increasingly used to monitor ice-elevation changes on the outlet glaciers of the polar ice sheets (e.g. Stearns and Hamilton, 2007) or on mountain glaciers and ice caps (e.g. Berthier and others, 2004; Kääb, 2008). These spaceborne DEMs are now precise enough to measure the geodetic mass balance at the regional scale (Berthier and others, 2007; Paul and Haeberli, 2008), and can thus be used (1) to complement the limited number of glaciers whose mass balances are monitored in the field, and (2) to provide an improved estimate of land ice contribution to sea-level rise (Cogley, 2009). However, it is crucial that first the potential biases that can affect these DEMs are well understood and corrected. Visual verification that the pattern of ice-elevation changes is consistent with glaciological knowledge is a first means to detect some errors. Analysis of elevation changes on the ice-free terrain and

https://doi.org/10.3189/002214310792447716 Published online by Cambridge University Press

direct comparison with contemporary elevation measurements obtained in the field (e.g. GPS) or from other spaceborne platforms (e.g. ICESat) make it possible to detect and correct these biases.

ACKNOWLEDGEMENTS

Comments by the reviewers A. Kääb and C. Larsen clarified this correspondence. ASTER data were provided at no cost by NASA/USGS through the Global Land Ice Measurements from Space (GLIMS) project (Raup and others, 2007). SPOT-5 data were provided at no cost by the French Space Agency (CNES) through the SPOT-5 stereoscopic survey of Polar Ice: Reference Images and Topographies (SPIRIT) project (Korona and others, 2009). Support from the CNES through the TOSCA (Terre, Océan, Surfaces continentales, Atmosphère) and ISIS (Incentive for the Scientific use of Images from the SPOT system) programs is acknowledged.

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5 January 2010

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