Response to 'Volume loss from Bering Glacier, Alaska, 1972–2003' by E. Berthier

Berthier and others (2010) attempt to reproduce the sequential digital elevation model (DEM) analysis of Muskett and others (2009) for the Tana Glacier and Bering Glacier arm. They find total volume losses four times lower than found by Muskett and others. Berthier (2010) claims their estimates may be more reliable than those of Muskett and others, based on three main points. I respond to each of the points below.

RESPONSE TO POINTS 1 AND 2

A single-valued offset adjustment presumes the material properties of ice, water, snow and rock (silicate, carbonate and their sediments) are the same, linear and uniform and that there are no dynamics and that the error sources of the earlier DEMs (i.e. maps) are the same and uniform. This is not the case.

Ice, Cloud and land Elevation Satellite (ICESat) positions (World Geodetic System 1984 (WGS84) ellipsoid heights) were used in the first part of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) terrain model processing, directly. The ASTER terrain model was then transformed into a DEM using geoid heights, GEOID99. Next, a 9 m mean (standard deviation $\sigma = \pm 28$ m) value adjustment (offset) was removed based on non-glacier vertical mismatch. In addition, there is a 4 m mean ($\sigma = \pm 3$ m) value removed due to cartographic errors from the 1972 compilation of the contour plates. Not all the DEMs (i.e. provisional US Geological Survey (USGS) topographic maps at 1 : 63 360, from which the DEMs (i.e. US National Elevation Dataset (NED)) were derived in the early 1980s) covering the Bering Glacier system have the same photo-compilation date (most are 1972/73, with two from 1972). This means the different dates and compilation dates capture different aspects of the dynamics of the Bering Glacier system, as the dynamics change in time. Additional information regarding the USGS provisional maps (source of the DEMs), their errors and reference frame can be found at http://research.iarc.uaf.edu/IRG/GRACE/Notes/manuscript_datums.pdf.

In addition, we need to keep in mind that the Bering Glacier system (as well as the Malaspina Glacier system) deforms the geoid, i.e. the gravity geopotential with additional small undulations bordering it in the non-glacier terrain. A single-value adjustment is insufficient given the definition of elevation (ellipsoid height and geoid height together from the formal definition) and the problems with the early-date cartographic sources.

A definition is now required. The relationship for elevation in a terrestrial reference system (orthometric) is given by

$$\text{Elevation} = \text{Ellipsoid Height} - \text{Geoid Height}$$

at geocentric latitude, longitude and time locations. The polarity of the geoid height can be positive (+) or negative (–). The terrestrial reference system can be one of three classes: non-tide (i.e. tide-free), mean tide or zero tide. The class depends on how direct and indirect tide forces are modeled and removed, if at all or in part, from the reference system. The World Geodetic System, in addition to its network stations, consists of a reference ellipsoid, WGS84, and a geoid, Earth Gravity Model 1996 (EGM96). In its definition, WGS84/EGM96 is a non-tide reference system. This is still the case for WGS84/EGM08 (2008). The TOPEX/Poseidon reference ellipsoid is part of a mean tide system. Along ocean–continent plate boundaries with mountains and glaciers (e.g. southeastern Alaska; Patagonia), the geoid polarity is positive, with a magnitude of tens of meters, and somewhat spatially non-uniform given the distribution of mass and changes thereof. Ignoring the contribution of the geoid and its changes in time has been a serious flaw in many investigations.

An example will help. Let us consider performing a difference of 'elevations' (two) at the same geodetic coordinates but which derive at two different times. The difference we will designate Δ in the arithmetic. For argument, let E_1 and E_2 be elevations measured at times 1 and 2, with 2 being newer than 1. In our argument, our investigator does not realize that E_1 is actually an ellipsoid height, H_1, whereas E_2 ($=H_2 - G_2$) is an elevation. G_2 is the geoid height at time 2. We now set the argument as follows:

$$\Delta = E_2 - E_1$$

and, upon substitution for E_2,

$$\Delta = (H_2 - G_2) - H_1.$$

In this case, we assume for argument that $H_1 = H_2$. Therefore the difference becomes

$$\Delta = -G_2.$$

If the value of the geoid height at time 2 is positive, relative to its reference ellipsoid, our investigator would interpret an apparent 'elevation decreasing'. If, on the other hand, the value of the geoid height at time 2 is negative, our investigator would interpret an apparent 'elevation increasing'. However, both interpretations are false. In reality, the Δ we estimate is a mixture of ellipsoid height change, geoid height change, random errors, and systematic errors within a common reference system.

Investigators need to keep in mind that ASTER oblique-stereo photogrammetry, and other like sensors and techniques, renders the surface as ellipsoid heights, not elevations, relative to the reference ellipsoid of choice, which would preferably be geocentric. Investigators need to be aware that non-geocentric ellipsoids exist, and to understand which are of which type. GPS receivers and their software are now beginning to incorporate geoid models such as EGM96 in rendering surface elevations (orthometric) as given by the definition. Investigators need to be aware that other *locally* and globally defined geoids exist and could cause confusion for those unaware.

Another issue that can confound investigators when using DEMs created from historical maps is that of systematic errors from lack of elevation control, non-geocentric datums and leveling networks, and contour misplacement from poor photographic contrast and resolution over relatively flat terrain relative to the photographic field of view of the camera that was used.

RESPONSE TO POINT 3

In Muskett and others' table 2, for brevity, 'Bering and Tana Glaciers' refers to the parts of Bering and Tana Glacier arms and parts of associated tributary glaciers within the ASTER DEM (this DEM incorporates EGM96 in the definition of

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surface elevation given above), which does not include upper Bering or upper Tana Glacier. These are included in Bagley Ice Valley (Muskett and others, 2009). Areas given are those of the parts of the system that adjoin and do not overlap. Of course, our analysis is of the *glacier system* and its component glaciers as our multi-spatial and -temporal datasets allow.

Surface-elevation changes in their time frames are illustrated by Muskett and others' (2009) figures 5–7, by DEM differencing, airborne-laser differencing, map profile comparison and ICESat differencing. These indicate that a region of elevation increase post-2000 to late 2003 was near upper Tana–lower Bagley Ice Valley (center-right, Muskett and others' fig. 5b) and were corroborated by altimeter differencing (Muskett and others' fig. 6a; 80–90 km on the profile) and ICESat differencing (Muskett and others' fig. 7, track 1279). This region on upper Tana was one of the three regions of elevation increase shown in figure 5c on Bagley Ice Valley (1972–2000). The region of elevation increase on lower Bering Glacier (Fig. 5b, lower-left) is not corroborated by our other elevation changes and therefore appears an anomaly. Except for ICESat, our time frames are much too coarse in time increment and insufficient to address this anomaly. However, the surface geometry is consistent with the post-surge stage (Post, 1960, p. 3705 for an illustration). Muskett and others' figure 6a does illustrate this effect along the profiles, from about 40 to 90 km (a relative rise near mid-lower Bering, relative low up-glacier, then relative rise near the distributary).

By fall 2006 the increased-elevation region on upper Tana/Bagley Ice Valley had moved down-glacier to the lower Bering Glacier section (the location of the previous anomaly in Fig. 5b) as shown in the ICESat difference profiles (fig. 7, track 0185). The 2006 summer flooding (basal; fig. 8) from the east side of the Bering Lobe was without significant terminus advance at that time.

These observations point to basal/englacial water transfer and dynamics as the cause of the surface-elevation and volume changes. Furthermore, these dynamic changes are in preparation for the next major surge of the Bering Glacier system.

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REFERENCES

Berthier, E. 2010. Correspondence. Volume loss from Bering Glacier, Alaska, 1972–2003: comment on Muskett and others (2009). *J. Glaciol.,* **56**(197), 555–557.

Berthier, E., E. Schiefer, G.K.C. Clarke, B. Menounos and F. Rémy. 2010. Contribution of Alaskan glaciers to sea-level rise derived from satellite imagery. *Nature Geosci.,* **3**(2), 92–95.

Muskett, R.R. *and 6 others*. 2009. Airborne and spaceborne DEM- and laser altimetry-derived surface elevation and volume changes of the Bering Glacier system, Alaska, USA, and Yukon, Canada, 1972–2006. *J. Glaciol.,* **55**(190), 316–326.

Post, A.S. 1960. The exceptional advances of the Muldrow, Black Rapids, and Susitna Glaciers. *J. Geophys. Res.,* **65**(11), 3703–3712.

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