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Letter

Comment on Zwally and others (2015)-Mass gains of the Antarctic ice sheet exceed losses

In their article 'Mass gains of the Antarctic ice sheet exceed losses' Zwally and others (2015) choose Vostok Subglacial Lake as an exemplary region to demonstrate their inference of surface height change rates from a portion of the ICESat mission's laser altimetry data (2003–08). In their appendix, they discuss some of the remarkable differences between their results and those reported by Richter and others (2008, 2013, 2014). However, the selective consideration of our works and the misleading or incorrect interpretation of our results call for clarification.

1. Richter and others (2014) present results of in-situ observations of surface height changes in the area of Vostok station, by repeated kinematic GNSS profiling. These observations were first carried out in 2001 and were repeated in 2012 and 2013. In 308 crossovers, covering an area of ~6 km^2, a mean value of surface height change of 1 ± 5 mm a^{-1} was determined, indicating a stable surface height for more than a decade including the entire ICESat mission period. This observational result contradicts the conclusion of Zwally and others (2015), of a sustained increase of surface height over Vostok Subglacial Lake. The claimed mean rate of +20.2 mm a^{-1} implies a surface rise exceeding 20 cm between our kinematic surveys. This is not reconcilable with the accuracy of our surface height profiles. Although Zwally and others (2015) cite the Richter and others (2014) work in their review, at no point do they address this discrepancy.

2. Richter and others (2014) discuss in detail, the fact that the ice sheet above Subglacial Lake Vostok is in hydrostatic equilibrium (also Ewert and others, 2012; Schwabe and others, 2014). This means that the local surface height change observed at a point within the lake area reflects primarily the mean ice-thickness change over the lake area. Spatial variations in the ice-thickness change are attenuated by a factor $(\rho_w - \rho_i)/\rho_w$ (with water density ρ_w and ice density ρ_i), thus propagating only 8% of the difference between the local and the mean ice-thickness change to the surface height.

The stability of the surface height observed around Vostok station is therefore to a large extent valid for the whole lake. In particular, it would require an implausibly large local anomaly in ice-thickness change close to Vostok station to counterbalance a mean ice-thickness growth of 2 cm a^{-1} implied by the remote sensing results as interpreted by Zwally and others (2015).

In the light of the hydrostatic balance, the significant spatial variation in height change rates across the lake area in Figure 5 of Zwally and others (2015), e.g. the jumps in ICESat profile 0330 and slopes in profiles 1312 and 0077, need further explanation.

3. Zwally and others (2015) misinterpret Figure 4 of Richter and others (2014) writing: 'Similarly, ΔH_i (i.e. $\Delta H(t_i)$ in Figure 4 of Richter and others, 2014) mostly overlap rather than separate in time as they would if bias adjustments were applied.' This figure is intended to reveal surface deformations instead of height changes over time. Therefore, any effect of inter-campaign biases is eliminated beforehand. Richter and others (2014) explain this in detail.

4. Richter and others (2008) document the accumulation rates and snow densities observed in-situ around Vostok station. These are challenged by Zwally and others (2015). It may be that the authors prefer models and remote sensing results rather than local observations. We prefer long-term, solid field observation as evidence of actual behaviour of the system for the following reasons.

First, the accumulation map derived by Arthern and others (2006) and evoked by Zwally and others (2015) has already been reported to overestimate the accumulation rates in the Vostok Subglacial Lake region by ~10 mm w.e. a^{-1} (i.e. by 25–50%), thus underestimating the regional N–S accumulation gradient, and providing error estimates by a factor of 2–5 too small in this region (Richter and others, 2013).

In addition, Zwally and others' statement, 'Richter and others (2008)… did not actually measure the rise of the snow surface in the vicinity of their GPS markers' is not true. However, given the stochastic nature of the spatio-temporal distribution of snow buildup, especially in an area affected by snow dune drift and anthropogenic activity, the local snow heights measured at a few GPS markers over a few years is unlikely to yield a snow build-up rate of adequate precision and reliability for a comparison with the much more homogeneous, densification driven vertical particle velocity. Robust long-term accumulation rates from dated tephra layers in snow pits or snow build-up rates observed over decades in the array of 79 accumulation stakes at Vostok are far better suited for this purpose. Instrumental accumulation monitoring (e.g. in arrays of accumulation stakes) is usually too limited in its spatial extension and resolution to account rigorously for the spatial component of snow build-up variation. A pragmatic approach to reduce the noise introduced by this spatial variation is to increase the temporal integration interval. For this reason, and considering the significant 50 a period in temporal accumulation variation established in the Vostok station area (Ekaykin and others, 2004), Richter and others (2008) preferred the 200 a mean accumulation rate over that derived from 25 a of stake measurements.

Third, when determining the accumulation rate – either by stake measurements or from dated layer depths in snow pits and boreholes – the primary, observed quantity is an accumulation layer thickness (corrected for densification). Subsequently, this thickness is converted to an accumulation rate (e.g. in terms of w.e. height a^{-1}) using measured densities. It is therefore inappropriate to choose an arbitrary density value to reconstruct the snow build-up rate from published accumulation rates, as exercised by Zwally and others (2015) in their attempt to invalidate the conclusion of a stable surface height from Richter and others (2008). The density value of 0.33 g cm^{-3} adopted by Richter and others (2008, 2014) represents the best estimate for the surface snow layer combining the results from numerous snow pits and measurements in the Vostok accumulation stake farm (Ekaykin and others, 2003; personal communication from Ekaykin, 2007). This value was used to derive the

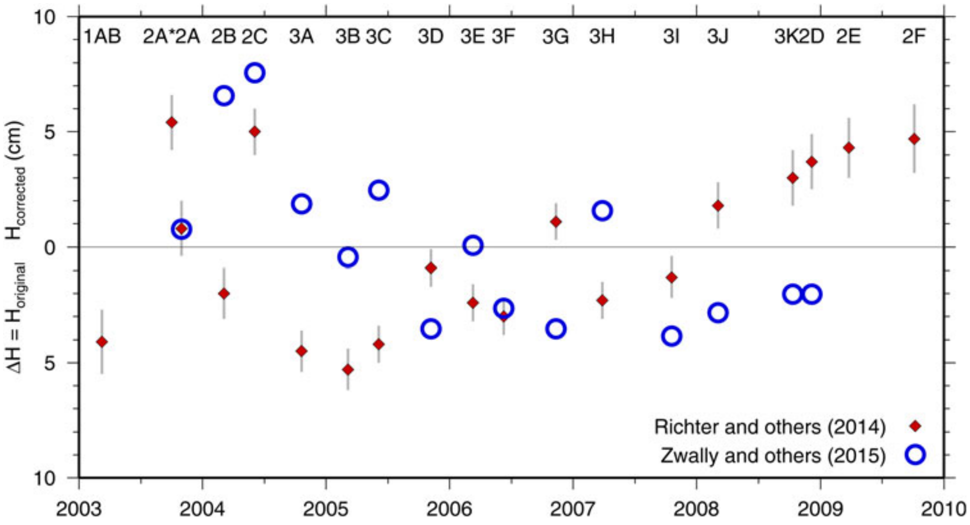

Fig. 1. Comparison of ICESat inter-campaign biases (2003–09) estimated by Richter and others (2014) and those by Zwally and others (2015) after subtraction of their mean value.

accumulation rate of 22.9 ± 1.8 mm a^{-1} from the snow buildup observed in the Vostok stake farm in the period 1970–1995 (Ekaykin and others, 2004), and there is neither reason nor evidence given by Zwally and others (2015) for why a density of 0.30 g cm^{-3} is 'a better value' for the Vostok station area. The density variation within the uppermost 20 cm of the stacked snow-pit profile represents random scatter rather than a dependence on depth (Ekaykin and others, 2003; personal communication from Ekaykin, 2007). The stake farm observations at Vostok, extended to the 40 a period, 1970–2010, yield a mean surface density of 0.335 g cm^{-3} and a (densification-corrected) snow build-up rate of 67.8 mm a^{-1} (Ekaykin and Lipenkov, 2010). If preference is given to this instrumental (in situ) result instead of the long-term mean accumulation rate from snow pits and shallow cores (Ekaykin and others, 2004), the surface height change implied by the GPS observations around Vostok station (Richter and others, 2008) amounts to 67.8 mm a^{-1}–62.1 mm a^{-1} = +5.7 ± 5.2 mm a^{-1}. Accumulation rates and density values that, together with the GPS observed vertical particle velocity of −62.1 mm a^{-1}, yield surface height change rates of +14.2 mm a^{-1} or even +61.2 mm a^{-1} as proposed by Zwally and others (2015) are very much incompatible with the results of decades of high-quality glaciological fieldwork at Vostok.

5. Zwally and others (2015) challenge the stability of the GPS markers presented by Richter and others (2014), describing them as 'poles placed in the firn to some unspecified depths' and claiming: 'An unspecified potential source of error is possible motion of their GPS markers within the firn'. Richter and others (2014) state: 'The markers consist of wooden stakes or aluminum tubes initially emplaced at least 50 cm deep in the snow.' Furthermore, Richter and others (2014) refer their readers to Richter and others (2013) for additional details concerning the marker monumentation and observation procedure. In that paper, it is explained: 'Each of these markers was complemented by two wooden reference stakes (10 m apart) arranged in a triangle. Before and after the GNSS occupations, the stability of the GNSS marker was verified by tape and levelling measurements within the triangle.' These local measurements have proven in all cases that the 'possible motion of their GPS markers within the firn' is indeed zero. Finally, Richter and others (2014) presented vertical velocities of 56 GNSS markers distributed over the whole lake area. The observed velocities are not only consistent between markers close to each other, but reveal a coherent pattern all over the lake. The velocities range from −50 to −60 mm a^{-1} in the southern part of the lake up to −80 to −100 mm a^{-1} in the northern part. Richter and others (2014) discuss in detail that this is a combined effect of a regional N–S accumulation gradient, proven independently by glaciological data and the hydrostatic balance of the floating ice.

6. Based on the observational results demonstrating the stability of the ice surface height above Vostok Subglacial Lake throughout the ICESat mission's duration, Richter and others (2014) derived relative ICESat intercampaign biases within the lake area. They used the GLAS 12 data product in release 633 and applied the G–C correction (Borsa and others, 2014) as mentioned by Zwally and others (2015). This is equivalent to the data release 634 used in the bias estimation by Zwally and others (2015), since some minor additional modifications in the newer release are negligible, at least in their impact on surface elevations over Vostok Subglacial Lake. Both bias sets, however, disagree significantly in their temporal evolution (Fig. 1). In particular, the temporal trend of the biases, which crucially affects the inferred mass-balance rates, differs substantially between both sets. Zwally and others (2015) do not address this discrepancy. In our opinion, estimates of surface height trends and ice-volume change generated for East Antarctica and elsewhere with the inter-campaign biases presented by Zwally and others (2015) are therefore highly questionable.

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