Guide for Applying ICESat Inter-campaign Bias Corrections (ICBs)

Using ICESat GLAS altimetry data to assess temporal elevation changes requires consideration of long-period variations in range measurements that manifest themselves as constant elevation biases over each of the mission campaigns. These "inter-campaign biases" (ICBs) have been evaluated by several research groups using a variety of approaches. In this document, NSIDC DAAC lists several available ICB corrections and provides self-reported information about how they were calculated. No ICESat ICB correction is endorsed by the ICESat Science Team, NASA, or NSIDC DAAC. Users may decide whether or not to apply ICBs to their data and, if so, which ICB correction set is most appropriate for their particular application.

In general, all the ICB corrections have been determined by measuring apparent elevation change over a nearly-unchanging 'reference' surface spanning a wide area that includes a large number of GLAS laser shots for most or all of the ICESat campaigns. The reference surface is assessed with either an independent measurement of that surface's elevation through time or a well-founded assumption of near-zero change.

Two important corrections for ICESat data were recognized and assessed late in the mission that had a large effect on the apparent ICBs: 1) the range correction for GLAS detector saturation effects on the waveform (the 'saturation correction' – see Saturation Correction Guidance; and 2) a data processing error arising from two different methods of determining the reference point in the outgoing and received GLAS waveform (geoid minus centroid, or 'G-C' correction; Borsa et al. 2014). Products through Release 633 had been incorrectly calculated from the centroid (amplitude-weighted center of leading and trailing edge thresholds) of the transmitted laser pulse to the center of the Gaussian fit of the return pulse (Zwally, 2013; Borsa et al., 2014). Applying the range correction for the G-C offset improved the range precision by 1.7 cm to <2 cm, and changed (but did not eliminate) ICBs.

Although the net effect of using ice-sheet data without the G-C corrections applied is very small if compatible bias corrections are applied (that is, if the ICBs were constructed so that the effect of G-C error is incorporated in them, unknowingly), the error in trends can be significant. Errors in an elevation trend without G-C correction have been assessed at –1.29 cm/yr for the L2a to L3j campaigns.

Users of ICESat data should note that in Release 634, the G-C correction is already applied on a shot-by-shot basis. [The revised saturation correction is available but not applied to the data].

Evaluation of ICBs

Following completion of the ICESat mission in 2009, ICB's were estimated by various investigators using differing reference surfaces, data releases, corrections, and other variations in methods. A summary of various ICBs is given in Scambos and Shuman (2016); however this did not include a full evaluation of the ICB methodologies. The purpose of this document is to discuss some evaluation criteria to five recent ICB studies, presented in spreadsheets in NSIDC Criteria for Evaluation of ICESat Inter-campaign Biases. These criteria provide a basis for evaluation of other ICBs previously published or not yet produced.

The six ICB studies we highlight are: 1) Borsa et al., 2017 (submitted): Stable terrestrial reference surface at the Salar de Uyuni, Bolivia with Rel 634; 2) Felikson et al., 2017: Global ocean mean sea surface with Rel 634; 3) Zwally et al., 2015: Ocean level within leads in Arctic and Antarctic Sea Ice with Rel 634; 4) Richter et al., 2014: Ice surface above subglacial Lake Vostok, Antarctica with Rel 633 and G-C applied, 5) Hofton et al., 2013, Ice surface in East Antarctica (two regions) with Rel 633; 6) Schröder et al., Validation of satellite altimetry by kinematic GNSS in central East Antarctica. Evaluation details for each of the six methods are given below.

ICB corrections for these studies are shown in Table 1.

Table 1. Published ICESat Intercampaign Bias Assessments: Sources and magnitudes of ICB (cm)

	Hofton and others [2013][1]		**Richter and others [2014][1,2]**	**Urban and others [2013][1,3]**	**Zwally and others [2015][4]**		**Schröder and others [2017]**	**Borsa and others (in prep) [2017]**
ICESat Campaign	(86°S orbit ring)	(EA Divide)	(Vostok area)	(Ocean)	DSL, D	(Polar Oceans)	(Vostok region)	(Salar de Uyuni)
L1A	-1.1 ±1.6	-5.1 ±5.5	-2.8 ±1.4	-4.7 ±3.6	--	--	-3.2 ±1.0	--
L2A	+3.2 ±1.8	+0.4 ±5.5	+2.1 ±1.2	+4.8 ±1.3	+4.6	-3.9	+3.6 ±0.9	+4.9 ±3.9
L2B	-1.0 ±4.3	-1.6 ±4.3	-0.7 ±1.1	+0.5 ±1.3	+10.4	0.9	-0.1 ±0.9	+0.4 ±3.0
L2C	+7.1 ±5.5	+2.4 ±5.7	+6.3 ±1.0	+4.1 ±0.9	+11.4	0.1	+5.2 ±0.8	+5.9 ±5.8
L3A	-2.7 ±4.0	-6.7 ±3.9	-3.2 ±0.9	+1.0 ±1.3	+5.7	-2.4	-3.1 ±0.9	+0.6 ±3.7

	Hofton and others [2013][1]		**Richter and others [2014][1,2]**	**Urban and others [2013][1,3]**	**Zwally and others [2015][4]**		**Schröder and others [2017]**	**Borsa and others (in prep) [2017]**
L3B	-2.5 ±3.1	-5.1 ±4.6	-4.0 ±0.9	+0.2 ±1.1	+3.4	-7.4	-1.7 ±0.8	+5.4 ±9.9
L3C	-3.6 ±3.9	-6.2 ±4.7	-2.9 ±0.8	+1.0 ±1.5	+6.3	-1.3	-2.1 ±0.7	+1.8 ±3.0
L3D	+1.6 ±2.5	-3.2 ±4.2	+0.4 ±0.8	+0.4 ±1.0	+0.3	-5.3	+1.9 ±0.7	-0.6 ±3.9
L3E	+1.8 ±1.6	-1.1 ±4.5	-1.1 ±0.8	+0.3 ±0.7	+3.9	-3	+0.2 ±0.7	-1.7 ±6.9
L3F	-2.2 ±2.3	-4.9 ±4.9	-1.7 ±0.8	+0.1 ±0.9	+1.2	-5.6	-1.0 ±0.6	-2.4 ±8.8
L3G	+3.2 ±0.8	-1.1 ±4.9	+2.4 ±0.8	+1.9 ±0.7	+0.3	-3.2	+2.4 ±0.6	-2.3 ±6.3
L3H	+1.2 ±1.8	+0.1 ±3.0	-1.0 ±0.8	+1.2 ±0.9	+5.4	-2	0.0 ±0.6	-0.4 ±9.5
L3I	0.0 ±3.2	0.0 ±3.3	0.0 ±0.9	0.0 ±0.9	0	0	0.0 ±0.6	0.0 ±3.4
L3J	+3.5 ±2.3	+1.3 ±5.2	+3.1 ±1.0	-1.2 ±1.4	+1.0	-2.6	+2.5 ±0.6	-1.3 ±6.3
L3K	+6.2 ±2.6	+3.1 ±3.4	+4.3 ±1.2	-0.7 ±2.0	+1.8	-6.1	+3.7 ±0.6	+2.8 ±3.6
L2D	+7.7 ±1.5	+7.3 ±4.5	+5.0 ±1.2	+5.7 ±1.7	+1.8	-6.1	+5.9 ±0.6	+3.7 ±4.4
L2E	+14.7 ±3.0	+13.9 ±4.9	+5.6 ±1.3	+11.2 ±7.3	--	--	+8.7 ±0.6	+6.6 ±9.9
L2F	+7.4 ±2.8	+4.2 ±4.4	+6.0 ±1.3	+4.9 ±1.2	--	--	+6.1 ±0.6	+1.2 ±7.6

All published IC biases presented here have been adjusted to be relative to the Laser 3I campaign (zero). Uncertainties (±) are included if available.

[1] These data were based on Release 633 but include the Gaussian minus Centroid (G-C) correction. All other analyses used Release 634 data. See the original references for additional details.

[2] Ewart and others [2012] was updated for Helm and others [2014] and then Richter and others [2014] by including the G-C correction (see their Table 3, ΔHGC column). L2A value excludes the 8-day data early in that campaign.

[3] These bias numbers have been updated by Urban, pers. comm. [2015] as published in Scambos and Shuman [2016].

[4] From Zwally and others [2015], DSL equals the D value plus an Envisat-derived correction for sea level variations.

A critically important criteria is the correction for vertical movement of the reference surface, listed in item 6 of the evaluation tables included in the Appendix. This requires either an independent method of measurement or a well-justified assumption of near-zero vertical movement of the reference over the ICESat campaign period. We review this for the five highlighted ICB approaches here.

Borsa et al., 2017 (dry lake bed) use GPS measurements on a dry salt lake to establish that the surface exhibits little seasonal deformation and that the mean interannual deformation is near zero. However, the total number of shots over the lake bed is far fewer than the other assessments, raising concerns that the few tracks involved may not represent other regions well. Urban et al. 2015 (mean ocean surface) apply a constant 3 mm/yr correction for global sea level rise, but do not correct for concurrent variations in ocean dynamic topography, which can be significant (e.g., Rio and Hernandez, 2004). These variations may be on the order of 10 cm/yr in some ocean regions; however, the study assumes that these dynamic effects have a near-zero mean over the global ocean. Wave effects are similarly not corrected, but are assumed to have near-zero mean impact because of the very large averaging area and the smaller footprint and waveform approach to elevation determination for ICESat (relative to radar altimetry). This method includes only unsaturated laser returns over the ocean, so any saturation correction effects are minimal.

In Zwally et al., 2015 (polar ocean leads), corrections are made for ocean level changes by using concurrent Envisat radar altimetry of the same surface in leads and polynyas within the Arctic and Antarctic sea ice pack. A similar approach is routinely used for detection of leads and measurement of sea ice freeboard (e.g., Kwok et al., 2007), but concerns have been raised about its accuracy for measurement of an absolute sea level surface (Kern and Spreen, 2015) owing to the sensitivity to parameters used to subset the leads-only surface. These concerns and others were discussed in Scambos and Shuman, 2016 and Zwally et al., 2016. The measured reflectivity over leads and polynyas in Zwally et al. is 0.42, and 0.53 on adjacent sea ice. Effects from saturation should be small. This approach should also account for seasonal and inter-annual temporal variations and for spatial variations in ocean dynamic typography, which can be significant (e.g., Giles et al., 2012). Longterm changes in global sea level due to changes in the gravitational field rise also vary regionally, particularly near polar ice sheets, and the method makes an adjustment intended to correct for that as well. Further, leads and small polynyas have generally low wave heights.

Richter et al. 2014 (Antarctic Lake Vostok) rely on repeat measurements of a GPS stake network, and kinematic profile resurveys, to conclude near-zero surface elevation change and hydrostatic equilibrium (Ewert et al., 2012) for the snow surface above Sub-Glacial Lake Vostok and its surroundings in East Antarctica. However, the accuracy of those measurements and conclusions have been disputed (Zwally et al., 2015; Zwally et al., 2016a; Zwally et al., 2016b). Richter et al. (2016) discussed the disputed aspects, and further work with continued GPS measurements still indicates near-zero vertical motion for the region (Schroeder et al., 2016). Some (Zwally et al., 2015) but not all (Helm et al., 2014; McMillan et al., 2014) radar altimetry analysis of the region shows elevation increase in the area of >1 cm/yr. While the saturation correction was applied in the Richter et al. analysis (and related earlier work by Ewert et al., Gunther et al.), there are remaining concerns that residual effects of saturation even after correction could remain. Borsa et al., 2016, have concluded that these are negligible.

Hofton et al. 2013 (stability of East Antarctic plateau) calculate ICBs beginning with the assumption that two broad regions in East Antarctica have near-zero elevation change over the ICESat campaign periods, and apply a saturation correction to Rel. 633 with G-C applied, and use cross-over analysis to extract ICB numbers for the different campaigns. They reference the elevations collected. While this assumption is supported by other studies, Zwally et al. 2015 report a significant elevation increase for the region.

For further details on each of these methods, see the NSIDC Criteria for Evaluation of ICESat Inter-campaign Biases assessment tables in the Appendix of this document (on page 14).

Brief Review of All Past Published ICB assessments

Below we list a literature review of all efforts to assess absolute or relative campaign biases for the period 2005-2017, in reverse time order. **Note that any table or figure number referenced below refers to entries in the original publication.** This listing compiles the known ICB assessments for the user to refer to and investigate, but makes no evaluation of accuracy, quality, or appropriateness for a particular application. See the documents below for information on ICESat Data Releases:

- Release Schedule
- YXX Release Numbers

Borsa et al., 2017 (submitted)
Intercampaign biases for saturation-corrected Release 634 ICESat data are determined by differencing ICESat elevations from a GPS-derived digital elevation model (DEM) over the Salar de Uyuni, Bolivia. The survey area covered by the DEM is 45 x 54 km, has no visible relief, and is

stable at the cm level on annual timescales. Aside from transformations into the GPS frame of reference, no adjustments are made to the ICESat data.

Felikson et al., 2017 (doi: 10.1109/TGRS.2017.2709303)
Intercampaign biases are estimated using release 634 GLAS data over the global oceans (Urban and Schutz, 2005). A bias is estimated for each campaign as the mean difference between ICESat elevation measurements and a reference mean sea surface, including a constant sea level rise rate of 3 mm/year, over the global oceans.

Urban et al. 2015 (doi: 10.1017/jog.2016.59)
ICESat biases are determined using Release 634 data, following the methodology of Urban and Schutz (2005), i.e., by taking the difference between ICESat elevations and mean global sea surfaces. A constant mean sea level rise rate of 0.3 cm/year is also included in the biases. ICESat bias values are reported in Scambos and Shuman (2016), Table 1. The values are updated from previous work by Urban et al. (2012).

Zwally et al. 2015 (doi: 10.3189/2015JoG15J071)
ICESat biases were determined by comparing sea surface heights over open water and thin ice in leads and polynyas in the Arctic and Antarctic sea-ice packs with ICESat data from Release 634. Additionally, adjustments were made for sea surface height variations measured by Envisat radar altimetry, and gathered concurrently with ICESat. Values are found in Table 6, for both the ICESat-measured and Envisat adjusted biases.

Helm et al. 2014 (doi: 10.5194/tc-8-1539-2014)
ICESat biases are determined following the work of Ewert et al. (2012), using Release 633 data (with G-C). The values can be found in Table 1.

Gunter et al. 2014 (doi: 10.5194/tc-8-743-2014)
ICESat biases were determined following the methodology of Gunter et al. (2009) and Riva et al. (2009), by choosing a low-precipitation region in East Antarctica. This was defined as all high-elevation regions with less than 21.9 mm Equivalent Water Height/year snow accumulation. The value was set by selecting a continuous low-precipitation zone isolated from areas of steep topography. Repeat-track ICESat footprints from release 633 having at least 80% laser spot overlap in the low-precipitation zone were used to generate biases. Additionally, an firn density model, or FDM, (based on RACMO2; Lenaerts et al., 2012) was used to adjust the median elevation change in the low-precipitation zone, accounting for firn height changes. The results are found in Table 1.

Richter et al. 2014 (doi: 10.1002/2014JF003228)
Relative ICESat biases were determined by a regional crossover adjustment (7559 crossovers)

over the ice surface within the area of subglacial Lake Vostok, East Antarctica. Repeated GNSS observations at 56 sites distributed all over the lake area (2001-2013) as well as repeated kinematic GNSS profiling around Vostok station (2001-2013) have shown independently and consistently that the ice surface elevation above the lake has not changed significantly throughout the ICESat mission. Moreover, the ice above the lake has been shown to be in hydrostatic equilibrium (Ewert et al. 2012) and this allows them to extrapolate the stability of the ice surface from the GNSS observation sites over the entire lake area. Data used were from Release 633, with and without G-C correction applied. Results are shown in Table 3.

Hofton et al. 2013 (doi: 10.1002/2013GL057652)

Two sets of ICESat biases were independently determined from comparison of inter-mission (LVIS to ICESat) and intra-mission (ICESat to ICESat) crossovers in Antarctica. For both estimates, ICB's were estimated using only data from areas where spatial and temporal variations due to climate related surface processes were minimal. For ICB's estimated from inter-mission crossovers this was the area along 86S between 110E and 155E. For ICB's estimated from intra-mission crossovers, this was an area of 393,765km^2 of East Antarctica. For both comparisons, the elevation differences between near-coincident footprints were obtained and ICB's calculated from the average value in a cell. The ICB values are determined from Release 633 data, corrected for G-C and saturation effects, and are adjusted for the effects of climate related processes, and can be found in Table 2 for each study region. The comparison involving LVIS had long wavelength topography removed from the elevations prior to extracting differences between overlapping footprints. The author's preferred solution for the ICESat ICB's are those from the 86S study region using intersensor differences from which long-wavelength topography is removed and to which corrections for ICESat elevation errors and elevation changes due to climate-related surface processes.

Past ICB assessments, citations below from earlier work, provided for background:

Urban et al. 2012 (http://adsabs.harvard.edu/abs/2012AGUFM.C13H..03U)

Abstract: This paper summarizes inter-campaign bias estimation methods and results developed in support of Ice, Cloud and land Elevation Satellite (ICESat-1) mission validation. ICESat-1 made more than 2 billion laser altimeter measurements from 2003-2009. Due to laser lifetime issues, while continuing to address the mission's primary goal of detecting long-term ice sheet changes, data were collected in 18 distinct campaigns - approximately 33-day periods two or three times per year. The overall mission has met the requirement for delivering elevations with an accuracy of 15 cm or better; however, verification studies at several calibration/validation sites have detected significant inter-campaign elevation biases. Additionally, inter-campaign biases vary in different regions, over different surface types, different analysis methods, and data-release versions.The biases are summarized and evaluated for consistency of potential trends in residual bias in the final data Release 633 that would affect estimates of long-term elevation change rates.

Ewert et al. 2012 (doi: 10.1111/j.1365-246X.2012.05649.x)

Relative ICESat biases were determined by a regional crossover adjustment over the ice surface within the area of subglacial Lake Vostok, East Antarctica. Repeated GNSS observations at 56 sites distributed all over the lake area (2001-2013) as well as repeated kinematic GNSS profiling around Vostok station (2001-2013) have shown independently and consistently that the ice surface elevation above the lake has not changed significantly throughout the ICESat mission (Richter et al. 2008; Richter et al. 2014). Moreover, the ice above the lake has been shown to be in hydrostatic equilibrium (Ewert et al. 2012) which allows to extrapolate reliably the stability of the ice surface from the GNSS observation sites over the entire lake area. All data are GLA12, from Release 531. Note that the biases in the original publication are given with reverse sign with respect to the “conventional sign definition” in the Evaluation Criteria table.

Pritchard et al. 2012 (doi: 10.1038/nature10968)

ICESat biases were calculated from comparison between ICESat elevation data and mean sea surface elevations using Release 428 data. The values were provided through a personal communication with Tim Urban (2009) and can be found in the supplementary Table 2.

Shepherd et al. 2012 (doi: 10.1126/science.1228102)

ICESat biases were calculated from comparison between ICESat elevation data and mean sea surface elevations using both Release 633 and 428 data. The values were provided through a personal communication with Tim Urban and can be found in the supplementary Table 5.

Schutz et al. 2011 (https://nsidc.org/sites/nsidc.org/files/files/inter-campaign_bias_notice_v1.pdf)

ICESat Science Team members have detected inter-campaign elevation biases from different areas and various surface types across the globe. The Release 33 data reprocessing (elevation level 633) includes the parameter i_ElevBiasCorr on GLA06/12/13/14/15 products. However, this bias has not been classified: different groups estimate different biases. Therefore, this parameter should not be used.

Siegfried et al. 2011 (doi: 10.1109/TGRS.2011.2127483)

This work estimates ICESat biases for mission phases L3I, L3J, L2D and L2E using GPS measurements and GLA12 data from Release ?31. The values can be found in Table 3, along with a comparison to biases from previous studies (Fricker et al. 2005, Wesche et al. 2009, and Urban (2010, personal communication).

Sorensen et al. 2011 (doi: 10.5194/tc-5-173-2011)

ICESat bias trend is estimated by O.B. Andersen and T. Bondo (Personal Communication, 2010), through comparison between Release ?31 GLA15 ocean altimetry data and the DNSC08 mean sea surface topography model. The trend is reported as 1.59 ± 0.4 cm/year (1.29 ± 0.4 cm/year after correction for sea level rise determined as 0.3 cm/year by Leuliette et al. (2004)). No individual mission campaign bias values are reported in this work. However, in the 2010 dissertation by Sorensen, individual campaign elevation bias values are shown in Figure 8.7 but not tabulated.

Zwally et al. 2011 (doi: 10.3189/002214311795306682)

ICESat biases are determined for 12 mission phases between L2A and L3I (fall 2003 to fall 2007), using data from Release 428 except for phase L2C where data from release 128 were used. Elevation measurements are compared to elevations of open water between sea ice in the Arctic Ocean. The bias values are adjusted for a sea level rise rate of 0.3 cm/year.

Gunter et al. 2010 (doi: 10.1007/978-3-642-10634-7_75)

This approach determines ICESat elevation biases by assuming that height changes in parts of East Antarctica are flat. Determination of a flat region uses ECMWF (European Centre for Medium-Range Weather Forecasts) mean solid precipitation data over Antarctica from January 2003 to December 2007. The region is shown in Fig. 75.3 and roughly corresponds to the same area outlined by Hofton et al. (2013). The bias rate calculated from this region, between 2003 and 2007, is 2.1 cm/year for crossover data (4.7 cm/year for repeat track data). No individual mission phase data are presented in this source. Release?

Urban 2010 (doi: 10.1109/TGRS.2011.2127483)

These ICESat bias values are found in Siegfried et al. (2011), Table 3, and are reported for mission phases L2a to L2f. The values were calculated following a sea surface model method outlined in Gunter et al. 2009, and reported by Tim Urban through personal communication to the author (Siegfried). All values are from Release 431 data.

Gunter et al. 2009 (doi: 10.1007/s00190-009-0323-4)

ICESat intercampaign biases were derived over global oceans using a mean sea surface topography model based on TOPEX/Poseidon data, following the procedure of Urban and Schutz (2005). The trend determined for the time period 2003-2007, is 2.3 ± 0.9 cm/year. After adjusting this trend for sea level rise (0.3 cm/yr, following Leuliette et al. (2004)), the final bias correction was reported as 2.0 ± 0.9 cm/year. Individual mission phase values for L1a, L2a, L2b, L3a, L3b, L3c, L3d, L3e, L3f, L3g, and L3h, with associated errors, are shown in Figure 1 but are not tabulated. The companion table to this writeup reports values estimated from reading Figure 1. All data are from Release 428.

Riva et al. 2009 (doi: 10.1016/j.epsl.2009.10.013)

ICESat biases were determined following a similar method to Gunter et al. (2008), by choosing an arid region of East Antarctica where ECMWF data indicate less than 2 cm water equivalent height per year of average solid precipitation between 2003 and 2006. The result was a bias rate of 2.6 cm/year, with a reported uncertainty of 0.3 cm/year. Release?

Wesche et al. 2009 (doi:10.1016/j.isprsjprs.2009.01.005)

ICESat biases were determined in a region of East Antarctica, in Dronning Maud Land. These biases are for mission phases L3G and L3H only, using Release 428 data, and were calculated by differencing crossover elevations in GLA12 data from a DEM constructed from GPS data collected in 1998/99 and 2000/01 campaigns. The bias correction is 11 cm for GPS minus GLA12 data, with a mean error of 23 cm.

Urban et al. 2008 (3645, IEEE Int. Geosci. and Rem. Sens. Symp., Boston, MA, July 7–11.)

ICESat elevation bias rate reported in Gunter et al. 2008 as roughly 2 cm/year. This is determined by Urban et al. (co-author on Gunter et al. 2008) by comparing a global mean sea surface model with ICESat data. It is also reported that this bias rate is only applicable for latitudes below 60 degrees, the coverage boundary for the sea surface models used. Release?

Urban and Schutz 2005 (doi:10.1029/2005GL024306)

Examined the accuracy of ICESat L2a data from GLA15 ocean elevations (Release 421) compared to TOPEX and mean sea surface elevations. This resulted in a mean difference of -11.7 ± 1.8 cm for the L2a period. Data are found in Table 4.

Fricker et al. 2005 (doi:10.1029/2005GL023423)

Obtained differences between GPS reference elevations and ICESat-derived elevations for a region within the Salar de Uyuni, Bolivia for 6 mission phases (L2A, L2B, L2C, L3A, L3B, and L3C). Data come from two different ground tracks (Track 85, descending, and Track 360, ascending). Results are found in Table 1, and also found in Siegfried et al. 2011, Table 3. The results for the standard geolocated product, as well as the same product with the saturation correction applied, are reported as standard mean differences, in cm, and their associated standard deviation values.

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Appendix: NSIDC Criteria for Evaluation of ICESat Inter-campaign Biases

Method Name: Stable terrestrial reference surface at the Salar de Uyuni, Bolivia

1/26/2017 by Adrian Borsa, Helen Fricker, Kelly Brunt

References:

Borsa, A., H.A. Fricker, K. Brunt. (in preparation) "ICESat and CryoSat-2 quality assessment and cross-calibration from a terrestrial reference surface."

Xi,S., J. Abshire, A. Borsa, H. Fricker, D. Yi, J. DiMarzio, K. Brunt, D. Harding, G. Neumann (in review) "ICESat/GLAS Altimetry Measurements: Signal Dynamic Range and Saturation Correction" *IEEE Trans. on Geoscience and Remote Sensing*.

Borsa, A.A., G. Moholdt, H.A. Fricker, K.M. Brunt (2014) "A range correction for ICESat and its potential impact on ice-sheet mass balance studies" *The Cryosphere*, 8, 345-357.

Fricker, H.A., A. Borsa., B. Minster, C. Carabajal, K. Quinn, B. Bills (2005) "Assessment of ICESat performance at the Salar de Uyuni, Bolivia" *Geophysical Research Letters*, Vol. 32, L21S06

Table A - 1. Borsa

Criteria	yes/no/other	Comments/explanation/details
1. Description of method used for determination of the biases.	yes	We compare ICESat elevations directly against a GPS-derived digital elevation model (DEM) of a flat, smooth, and stable terrestrial reference surface, and report summary statistics (median and robust standard deviation) of the difference between ICESat and DEM for each ICESat campaign. This analysis uses data for only the two ICESat tracks that crossed the DEM footprint. We have conducted an additional analysis using additional tracks and data over the broader Salar de Uyuni surface, referenced to elevation averages along track, and obtained similar results in terms of bias values, statistics, and trend.

Criteria	yes/no/other	Comments/explanation/details
2. Name and type of reference surface used for bias estimation.		The reference surface is the Salar de Uyuni, a dry salt lake in the Bolivian Altiplano. The overall extent of the lake is roughly 100 x 100 km, and we use a 45 x 54 km region in the eastern basin for the analysis described here. We have surveyed this region three times (in 2002, 2009, and 2011) using both fixed and kinematic GPS, and constructed DEMs from these data for comparison with ICESat and other altimeters. The lake bed is extremely flat and smooth, has a high and stable albedo in the visible/infrared range, and is geometrically stable. It is also located at ~4000 m elevation, which mitigates potential tropospheric effects (clouds, in particular) on the ICESat range measurement.
3. Was GLAS data Release 634 used.?	yes	GLAS Release 634 data were used to determine these biases. Bias calculations for selected earlier releases have been calculated as well, and these yield different results due to SCF (Science Computing Facility) processing changes over time.
4. If not Release 634, was G-C correction applied?	n/a	
5. Was conventional sign (+/-) definition used? i.e. Bias = $H_{meas} - H_{refsurf}$ and $H_{corr} = H_{meas} - \text{Bias}$	yes	A positive (negative) bias indicates ICESat is measuring a higher (lower) elevation than the reference surface. Subtracting the bias from measured elevations lowers (raises) the surface to which the bias is applied.
6. Was a correction made for vertical motion of the reference surface using an independent measurement?	yes	The reference surface was surveyed using fixed and kinematic GPS in 2002 and 2009, with the survey dates bracketing the missions. Subsequent analysis using ALOS InSAR confirmed that the surface exhibits little seasonal deformation and that the interannual deformation is near zero mean and is consistent with the GPS survey results.
7. Were the GLAS saturation range corrections on NSIDC data products applied by the user?	yes	

Criteria	yes/no/other	Comments/explanation/details
8. Errors, error determination?	yes	The inter-campaign biases each have their own error bar, determined from the robust standard deviation of the elevations of the ICESat footprints used in the estimation. In this formulation, the GPS-derived DEM is considered to be error-free.

Method Name: N/A

2/20/2017 by Michelle Hofton

References:

M. A. Hofton, S. B. Luthcke, J. B. Blair (2013), Estimation of ICESat intercampaign elevation biases from comparison of lidar data in East Antarctica, *Geophys. Res. Lett.*, 40, doi:10.1002/2013GL057652.

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Table A - 2. Hofton86S

Criteria	yes/no/other	Comments/explanation/details
1. Description of method used for determination of the biases.		We compute ICESat ICBs using ICESat to LVIS elevation difference observations on the Antarctic ice sheet between 110E and 155E at 86S latitude (dubbed the ICESat Polehole), an area where modeled elevation changes due to climate-related surface processes are small (Ligtenburg et al., 2011). ICESat elevations (corrected for saturation and G-C corrections) are compared to the LVIS Level 2 “low” elevations which represent the mean elevation of the lowest reflecting surface in the footprint. We compute ICESat to LVIS elevation differences between near-coincident footprints binned by ICESat campaign and 2x 50 km long cells along the length of the LVIS swath. Fltering to remove elevations affected by forward scattering or other issues are performed on the differences using a 5sigma edit. To minimize the impact on elevation differences associated with footprint separation and surface slope, we use the LVIS swath surface elevations to correct for long-wavelength topography at 1km resolution prior to extracting the elevation differences between overlapping footprints. We subtract the Ligtenberg et al. [2011] model surface elevation changes at the times and location of each footprint from the lidar elevations before calculating ICESat ICBs. The elevation biases between each ICESat campaign and the LVIS campaign are estimated for each of the seven 2x 50 km cells between 110 E and 155E at 86S. ICESat ICBs are computed for each campaign as the arithmetic average of all the biases estimated for each of the 2x50 km cell relative to L3I. The error estimate for each ICB is computed as the standard deviation of the 2x 50 km cell biases. We apply a GIA correction to trends estimated from the ICBs using the results of the IJ05_R2 model. The average surface elevation trend due to GIA in the study region is – 0.02 +- 0.01 cm/yr.

Criteria	yes/no/other	Comments/explanation/details
2. Name and type of reference surface used for bias estimation.		The reference surface is the ice surface measured by NASA's LVIS during high-altitude flights around 86S (dubbed the ICESat Polehole). A ~2km wide swath of data was collected, using ~20m wide footprints contguous along and across track on 3 separate flights in 2009 and 2010. The segment of the LVIS 86S flight zone between 110E and 155E was identified as likely to be the least influenced by surface elevation changes due to climate-related surface processes using the model results of Ligtenberg et al. [2011]. In addition, we use ice velocity data derived from satellite radar interferometry [Rignot et al., 2011] to apply an additional constraint to minimize the potential influence of velocity variations on surface elevation change.
3. Was GLAS data Release 634 used.?	no	Release 633 was used
4. If not Release 634, was G-C correction applied?	yes	G-C correction was calculated for every ICESat footprint and applied to the elevation prior to comparison
5. Was conventional sign (+/-) definition used? i.e. Bias = $H_{meas} – H_{refsurf}$ and $H_{corr} = H_{meas} – Bias$	yes	Yes.
6. Was a correction made for vertical motion of the reference surface using an independent measurement?	yes	We correct elevation observations for (a) a combination of accumulation, melting, and firn densification processes, and (b) glacial isostatic adjustment. (a) We subtract the Ligtenberg et al. [2011] model surface elevation changes at the times and location of each footprint from the ICESat elevations prior to calculating ICBs. (The surface elevation fluctuations were derived from a firn densification model driven by estimates of surface mass balance, temperature, wind speed, and processes associated with liquid water output by the regional atmospheric climate model RACMO2/ANT, at ~27 km resolution and 48 h intervals for 1979–2010). (b) We apply a GIA correction to trends estimated from the ICBs using the results of the IJ05_R2 model [Ivins and James, 2005] and corresponding to a 65 km thick lithosphere and upper and lower mantle viscosities of 0.2x10^21 Pa s and 1.5x10^21Pa s.

Criteria	yes/no/other	Comments/explanation/details
7. Were the GLAS saturation range corrections on NSIDC data products applied by the user?	yes	
8. Errors, error determination?	yes	The error estimate for each ICB is computed as the standard deviation of the 2x 50 km cell biases.

Method Name: Intra-mission ICESat crossovers in Antarctica

2/20/2017 by Michelle Hofton

References:

M. A. Hofton, S. B. Luthcke, J. B. Blair (2013), Estimation of ICESat intercampaign elevation biases from comparison of lidar data in East Antarctica, Geophys. Res. Lett., 40, doi:10.1002/2013GL057652.

Ligtenberg, S. R. M., et al. (2011)

Table A - 3. HoftonEAIS

Criteria	yes/no/other	Comments/explanation/details
1. Description of method used for determination of the biases.		We estimate ICBs from a comparison of near-coincident ICESat elevation measurements within an 393,765 km^2 area of the East Antarctic ice sheet (EAIS). This area was selected using the model results of Ligtenberg et al. [2011] as being the area where spat
2. Name and type of reference surface used for bias estimation.		The reference surface is the ice surface of a portion of the East Antarcic Ice sheet (EAIS) identified as likely to be the least influenced by surface elevation changes due to climate-related surface processes, based on the model results of Ligtenberg et
3. Was GLAS data Release 634 used.?	no	Release 633 was used
4. If not Release 634, was G-C correction applied?	yes	G-C correction was calculated for every ICESat footprint and applied to the elevation prior to comparison

Criteria	yes/no/other	Comments/explanation/details
5. Was conventional sign (+/-) definition used? i.e. Bias = $H_{meas} - H_{refsurf}$ and $H_{corr} = H_{meas} - \text{Bias}$	yes	Yes.
6. Was a correction made for vertical motion of the reference surface using an independent measurement?	yes	We correct elevation observations for (a) a combination of accumulation, melting, and firn densification processes, and (b) glacial isostatic adjustment. (a) We subtract the Ligtenberg et al. [2011] model surface elevation changes at the times and location
7. Were the GLAS saturation range corrections on NSIDC data products applied by the user?	yes	
8. Errors, error determination?	yes	The error estimate for each ICB is computed as the standard deviation of the values from the 100x100 km cells.

Method Name: Ice surface above subglacial Lake Vostok, Antarctica

12/03/2016 by Andreas Richter, Martin Horwath & Reinhard Dietrich

References:

Richter, A., Popov, S.V., Fritsche, M., Lukin, V.V., Matveev, A.Yu., Ekaykin, A.A., Lipenkov, V.Ya., Fedorov, D.V., Eberlein, L., Schröder, L., Ewert, H., Horwath, M., Dietrich, R. (2014). Height changes over subglacial Lake Vostok, East Antarctica: Insights from GNSS observations, *J. Geophys. Res. Earth Surf.*, 119, 2460-2480, doi:10.1002/2014JF003228

Table A - 4. Richter

Criteria	yes/no/other	Comments/explanation/details
1. Description of method used for determination of the biases.	yes	Method is based on a regional crossover adjustment over a reference surface shown by independent observations to be stable and in hydrostatic equilibrium throughout the ICESat mission time. Relative biases are determined.
2. Name and type of reference surface used for bias estimation.		The reference surface is the ice surface within the area of subglacial Lake Vostok (central East Antarctica).

Criteria	yes/no/other	Comments/explanation/details
3. Was GLAS data Release 634 used.?	no	GLAS release 633 of data product GLA-12 is used.
4. If not Release 634, was G-C correction applied?	yes	In this publication biases for release 633 are shown both with and without application of the G-C correction.
5. Was conventional sign (+/-) definition used? i.e. Bias = $H_{meas} - H_{refsurf}$ and $H_{corr} = H_{meas} - Bias$	yes	Both bias sets for release 633 follow the conventional sign definition: $H_{corr} = H_{meas} - Bias$. In addition, in that publication (Table 3) the ICB derived by Ewert et al. 2012 for release 531 are included but, mistakenly, with inverted sign ($\Delta H = H_{adjusted} - H_{meas}$ for the ΔH_31 column only).
6. Was a correction made for vertical motion of the reference surface using an independent measurement?	no	Different independent observation techniques, namely GNSS observations at 56 sites distributed all over the lake and repeated kinematic GNSS profiling since 2001, have shown consistently that the ice surface elevation above Lake Vostok has not changed significantly throughout the ICESat mission period (Richter et al. 2008; Richter et al. 2014). Moreover, Ewert et al. 2012 have shown that the ice surface above the subglacial lake is in hydrostatic equilibrium. Therefore, the stability of the ice surface can be extrapolated very reliably from the GNSS observation sites over the lake area. This justifies the use of the ice surface within the lake area as reference surface for the ICB determination without need to correct for any vertical motion.
7. Were the GLAS saturation range corrections on NSIDC data products applied by the user?	yes	
8. Errors, error determination?	yes	1-σ bias uncertainties are derived by formal error propagation from the crossover residuals.

Method Name: Global Ocean Mean Sea Surface

12/06/2016 by Tim Urban

References:

Urban, T. J., and B. E. Schutz (2005), ICESat sea level comparisons, *Geophys. Res. Lett.*, 32, L23S10, doi:10.1029/2005GL024306.

Gunter, B., Urban, T., Riva, R. et al. J Geod (2009) A comparison of coincident GRACE and

ICESat data over Antarctica, 83: 1051. doi:10.1007/s00190-009-0323-4.

Scambos, T. and C. Shuman, C., (2016) Comment on ‘Mass gains of the Antarctic ice sheet exceed losses’ by H. J. Zwally and others. *Journal of Glaciology*, Available on CJO 2016 doi:10.1017/jog.2016.59.

Table A - 5. Urban

Criteria	**yes/no/other**	**Comments/explanation/details**
1. Description of method used for determination of the biases.	yes	Global unsaturated data are selected for ocean depths > 50m (eliminating coastal area effects) and latitudes within ±66 degrees (maximizing ocean tide and MSS model fidelity from the TOPEX/Jason-series). 40Hz observations are smoothed to 1 Hz and compared with a MSS model to determine the bias. Bias reported is the mean of daily averages. A 3mm/year correction is made for sea level rise. Note: not published, but results including saturated data are available and increase (make more positive) the bias by the following amounts: laser 1 = 4 mm, laser 2 = 2 to 0 mm , laser 3 = 2 to 0 mm. (numbers drop as each laser's energy decays).
2. Name and type of reference surface used for bias estimation.		The reference surface is a Mean Sea Surface. Both the CSRMSS and DMSS have been used. Within the deep ocean and away from the poles, modern models agree very well, within a few mm or better. The MSS includes the geoid and mean dynamic topography components of the ocean surface.
3. Was GLAS data Release 634 used.?	yes	Yes, Release 634 was published in the (2016) reference. Unpublished results are also available for releases 428, 531, 633, and 633 with the G-C correction.
4. If not Release 634, was G-C correction applied?	NA	NA, but available.
5. Was conventional sign (+/-) definition used? i.e. Bias = $H_{meas} - H_{refsurf}$ and $H_{corr} = H_{meas} -$ Bias	yes	Yes.

Criteria	yes/no/other	Comments/explanation/details
6. Was a correction made for vertical motion of the reference surface using an independent measurement?	yes	A 3 mm/year correction is made for sea level rise.
7. Were the GLAS saturation range corrections on NSIDC data products applied by the user?	yes	Saturated data not used for published results.
8. Errors, error determination?	TBD	Errors assigned to each campaign's bias are the standard deviation of the daily biases.

Method Name: Ocean level within leads in Arctic and Antarctic Sea Ice

11/07/2016 by Jay Zwally and John Robbins

References:

Zwally, H. J., J. Li, J. W. Robbins, J. L. Saba, D. Yi, and A. C. Brenner (2015) Mass gains of the Antarctic ice sheet exceed losses, *J. Glaciol*. 61(230), 1019-1035, doi:10.3189/2015JoG15J071

Zwally, H. J. et al., (2016) ibid Response to Comment by T. SCAMBOS and C. SHUMAN (2016) on 'Mass gains of the Antarctic ice sheet exceed losses' doi: 10.1017/jog.2016.91.

Table A - 6. Zwally

Criteria	yes/no/other	Comments/explanation/details
1. Description of method used for determination of the biases.	yes	Method is based on well-established techniques (e.g., Kwok et al., 2009) developed for measuring sea-ice freeboard with ICESat data, which consists of deriving the ocean-reference level in leads and polynyas on along-track segments (tens of km). The average SSH (sea surface height) is measured by ICESat to open water and thin ice in leads and polynyas for each campaign period relative to the mean SSH measured for all campaigns. These ICESat measured values defined as D(t) include temporal variations in ocean dynamic topography as well as the regional sea-level rise, for which a correction is made as described in line 6.

Criteria	**yes/no/other**	**Comments/explanation/details**
2. Name and type of reference surface used for bias estimation.		Lead and polynyas in the sea ice consisting of open water and/or thin ice. GLAS-measured mean reflectivity for the lead and polynya areas used is 0.42. This is close to the 0.53 reflectivity on adjacent sea ice, and closer to the mean reflectivity of ice sheets (~0.8). Open ocean outside of the sea ice edge shows much lower mean reflectivity (~0.1). Both Arctic and Antarctic sea-ice-covered areas are used in the assessment, within the coverage area of ENVISAT radar altimeter data (usd for correcting for inverse barometer and seasonal dynamic sea surface effects). Arctic sea-ice coverage concentrations ≥20% and Antarctic sea-ice-coverage areas of ≥60% were use in all ICESat campaigns up to the maximum latitude (81.5° N) of the Envisat radar altimeter coverage. Lead and polynya measurements are less affected by sea-state biases than open ocean areas.
3. Was GLAS data Release 634 used.?	yes	GLAS Release 634 data over sea ice are used to determine the biases in order to be compatible for correction of Release 634 data.
4. If not Release 634, was G-C correction applied?	NA	
5. Was conventional sign (+/-) definition used? i.e. Bias = $H_{meas} - H_{refsurf}$ and $H_{corr} = H_{meas} - \text{Bias}$	yes	A positive (negative) D(t) bias indicates ICESat is measuring a higher (lower) elevation than the reference surface. Subtracting the D(t) bias correction lowers (raises) the surface to which the D(t) is applied.
9. Was a correction made for vertical motion of the reference surface using an independent measurement?	yes	The average SSH measured by Envisat (defined as $E_{SSH}(t)$) is calculated for the same areas and time periods using 10-day average mappings similar to Giles et al. (2012) that include the same temporal variations in SSH as in the ICESat D(t). Ten-day mappings of $E_{SSH}(t)$ that are within the time of the laser campaigns, weighted by the number of days within the campaign, are used. The resulting campaign biases corrected for concurrent changes in SSH are $D_{SL}(t) = D(t) - E_{SSH}(t)$, which are determined separately over the Arctic and Antarctic sea ice and averaged. The average $D_{SL}(t)$ for each laser campaign is subtracted from the ICESat measured elevations at each laser footprint.

Criteria	yes/no/other	Comments/explanation/details
10. Were the GLAS saturation range corrections on NSIDC data products applied by the user?	yes	
11. Errors, error determination?	TBD	