ICESat sea level comparisons

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Received 4 August 2005; revised 25 October 2005; accepted 28 October 2005; published 3 December 2005.

[1] ICESat calculations of sea level and mesoscale variability are demonstrated and compared to calculations from TOPEX altimetry. In particular, we examine the accuracy of the ICESat Laser 2a Release 21 GLA15 ocean elevations. A global ICESat ocean elevation bias of -10.0 ± 1.0 cm (low) was found with respect to TOPEX, obtained with a reference mean sea surface (MSS). Dual-satellite (ICESat - TOPEX) crossovers independently verify this bias, having a mean of -11.7 ± 1.8 cm. The origin of this bias is unknown, although it may be related to sea state. Release 21 improvements have mitigated ICESat's thermally-induced day/night laser pointing variations to 1 to 2 cm in elevation. The average daily single-satellite internal crossover RMS is 12 cm for ICESat, 7 cm for TOPEX. ICESat laser altimetry is able to match TOPEX detection of major sea level anomaly and mesoscale variability features on a global scale. **Citation:** Urban, T. J., and B. E. Schutz (2005), ICESat sea level comparisons, *Geophys. Res. Lett.*, *32*, L23S10, doi:10.1029/2005GL024306.

1. Introduction

[2] ICESat's Geoscience Laser Altimeter System (GLAS) emits ~3.4 million laser pulses per day. Typically one third of ICESat's laser pulses occur over land and ice, and about half of the ocean surface is obstructed by opaque cloud cover, yielding ~1 million valid ocean elevations per day. Limited sets of these ocean elevations are routinely used for improving ICESat laser pointing determination, incorporated through the use of high-angle ocean and around-the-world scans [*Luthcke et al.*, 2005], but little research has been presented or published on ocean science. In this paper, we apply ICESat data products to global mean sea level (GMSL) and mesoscale variability and compare them to calculations from TOPEX altimetry. We evaluate the existence of an elevation bias and assess the accuracy of the ICESat elevations in ocean areas.

2. Data

[3] ICESat Release 21 (R21) ocean data (GLA15) from all 55 days of the Laser 2a (L2a) campaign are examined. Coarse editing has been performed where ICESat elevations deviate more than 10 m from a reference mean sea surface (MSS). L2a encompasses both 8-day and 91-day exact repeat orbits; however, no statistical differences in elevation between data collected from the two orbits are observed. We consider deep-water data (depth > 500 m) independently from shallow, and consider shallow waters as a proxy for coastal areas. ICESat data from 65°S to 65°N (±65°) within the TOPEX latitude range (±66°) are examined separately from the global data set (±86°). ICESat elevations are edited where the spacecraft off-nadir pointing angle is large (>0.5°) due to increased geolocation elevation error.

[4] Two key differences between ICESat laser and radar altimetry are data rate (40 Hz for ICESat, pulse-averaged 1 Hz for TOPEX) and footprint size (65 m for ICESat, several km-scale for TOPEX). Though very precise (<3 cm over flat areas) (e.g., C. Shuman et al., Ice sheet elevations from ICESat: 2003–2005, submitted to *Geophysical Research Letters*, 2005), the ICESat full-rate 40-Hz ocean data are inherently noisier than the 1-Hz TOPEX data due to the laser mission's much finer sampling of ocean waves, wind effects, and swell [*Zwally et al.*, 2002]. To compensate, we compute an ICESat 1-Hz normal point product that is more consistent with TOPEX, and which provides a fairer basis for comparison. A 1-second (40-point-maximum) along-track averaging window is used to create each ICESat normal point, chosen to approximate the TOPEX data rate. Several averaging window durations were tested from 0.25 to 3 seconds, with differences at or below 1 mm for initial TOPEX comparisons. Recursive three-sigma editing is performed over the 1-second span, excluding spurious 40-Hz points. After convergence, the normal point is not created if fewer than 20 of the 40-Hz points remain. The following comparisons are performed with ICESat 1-Hz normal points except where indicated.

[5] For this study, TOPEX radar altimetry is used as the primary reference because 1) the TOPEX altimeter is the recognized leader in satellite sea level measurement [*Fu et al.*, 1994] and 2) fixed references, such as the MSS used in this investigation [*Tapley and Kim*, 2000], do not account for sea level rise or seasonal signals measured by altimetry. The TOPEX data (altimeter side B, in use since February 1999) are modified versions of the Merged Geophysical Data Records [*Benada*, 1997] distributed by the Jet Propulsion Laboratory Physical Oceanography Distributed Active Archive Center. The TOPEX data have been updated with a wet troposphere correction [*Keihm et al.*, 2000] and a side-B-specific sea state bias (SSB) model [*Chambers et al.*, 2003].

3. Sea Surface Anomaly (SSA)

[6] The SSA is computed as altimeter-derived elevation minus the reference MSS height, and will reflect seasonal, interannual, and all other sea level variations. The daily-averaged SSA for ICESat and TOPEX are computed similarly (±65°, depth > 500 m) and plotted in Figure 1. This figure shows the daily GMSL time series during L2a, with corresponding statistics in the first row of Table 1. While no mission has been designed to accurately detect daily GMSL variations, this analysis is useful for detecting

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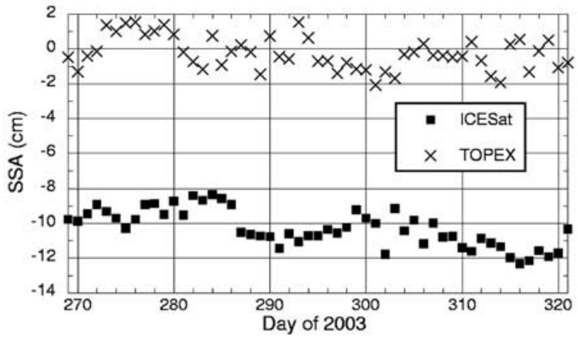

Figure 1. Daily SSA during L2a.

daily changes in ICESat performance. Daily variations observed in each time series of Figure 1 are caused by measurement errors, sampling effects, and real oceanographic changes. Note that the MSS has been adjusted to match the average TOPEX SSA, to remove the average seasonal signal and sea level rise since the MSS was computed.

[7] The overall mean SSA of ICESat is the ICESat ocean elevation bias. This bias is -10.0 ± 1.0 cm (formal uncertainty), with day-to-day variations of the same magnitude as TOPEX (± 2 cm). This bias is not consistent with recent L2a R21 comparisons over flat land ($\sim$0 cm by *Fricker et al.* [2005]; $\sim$2 cm by *Martin et al.* [2005]).

[8] Significant onboard events can change the day-to-day ICESat elevation bias. For example, large onboard temperature changes between days 286 and 287 and between days 301 and 302 cause small (1 to 2 cm), detectable jumps in the ICESat curve of Figure 1. The suspicion is that some thermally-induced pointing variation remains in the data.

[9] Computations using ICESat 1-Hz normal points are comparable to using the 40-Hz full-rate data. Table 2 shows statistics for days 270 and 307. Daily mean differences between 40- and 1-Hz data are 0 to 1 cm, less than the ± 2 cm daily changes observed in both ICESat and TOPEX 1-Hz data in Figure 1. The 40-Hz ICESat daily RMS is much larger (30 cm) than the 1-Hz data RMS (14 cm), as expected from high-resolution wave sampling. TOPEX provides nearly twice as many 1 Hz points as ICESat due to cloud cover obstructing the ocean surface.

[10] Figure 2 shows maps of the average L2a SSA for ICESat and TOPEX ($\pm 65°$, depth > 500 m) gridded in 1° bins using minimal Gaussian smoothing for both spacecraft. The two maps are similar, displaying the same high and low features. ICESat anomalies appear up to 5 cm lower than TOPEX throughout the southern oceans and near the Gulf Stream and Kuroshio western boundary currents, all areas

Table 2. Examples of Daily SSA from 40-Hz and 1-Hz ICESat and TOPEX Data ($\pm 65°$, depth > 500 m)[a]

DOY	40 Hz ICESat			1 Hz ICESat			TOPEX		
2003	Mean	RMS	Points	Mean	RMS	Points	Mean	RMS	Points
270	−8.7	29.8	703,012	−9.7	14.0	19,042	−1.1	11.9	36,864
307	−9.6	30.7	640,873	−9.8	14.5	17,222	−0.2	12.0	37,015

[a]Mean, RMS in cm.

having larger ocean waves and variability. The ICESat map displays erroneously high SSA values in the coastal Antarctic due to contamination from sea ice. Strict edit criteria based on the SSA cannot eliminate this contamination; more investigation is needed.

[11] Ocean mesoscale correlations between ICESat and radar altimetry were first noted by *Leben et al.* [2003] in the Gulf of Mexico. Figure 3 shows the RMS about the mean of each 1° grid of Figure 2, illustrating global mesoscale variability. Again, both maps are similar, with all the major currents observable. ICESat variability is 2.7 cm higher than TOPEX globally, reflecting a slightly higher noise level for the normal points. Also visible in the ICESat map are several local spots of high variability requiring further investigation. A number of differences observed between the ICESat and TOPEX maps in Figures 2 and 3 may be due to sampling. TOPEX is in a 10-day exact repeat orbit, while ICESat did not repeat its ground track during L2a, giving ICESat a $\sim$5 times denser ground track spacing at the equator.

[12] Various subsets of global ICESat data were examined including latitudes poleward of $\pm 65°$ and coastal waters, with statistics filling out Table 1. The standard data subset ($\pm 65°$, depth > 500 m) was previously compared to TOPEX and has a mean SSA (ICESat elevation bias) of -10.0 cm. By including either high latitude or coastal data, the bias changes to -9.5 cm; with both areas included (global case), the bias is -9.0 cm. While relatively fewer points per day fall into each of these areas, high-latitude and coastal SSAs have larger mean and RMS values than the standard cases, and therefore skew the global results. One reason that ICESat performance appears adversely affected in the coastal and high-latitude areas stems from limitations of radar altimetry: the latitude ranges of radar satellites are all less than ICESat; and radar and radiometer footprint land contamination eliminate coastal areas from their reliable data products. Consequently, MSS and ocean tide models, which rely heavily on radar data, are weakest in those areas, and so SSAs calculated from any satellite can be expected to be noisier there. Even TOPEX shows a 50% higher RMS in shallow areas (18 cm) than globally (12 cm). Additionally, high-latitude ICESat data suffer from sea ice contamination

Table 1. Average Statistics of Daily Global SSA Solutions[a]

Case	Latitude, Depth Bounds	ICESat Mean	ICESat RMS	TOPEX Mean	TOPEX RMS
Standard	±65°, >500 m	−10.0	13.9	0.0	12.2
Standard plus High Latitudes	±86°, >500 m	−9.5	14.7	0.0	12.2
Standard plus Coasts	±65°, >0 m	−9.5	14.5	0.3	12.6
Global (All Data)	±86°, >0 m	−9.0	15.9	0.3	12.6
Only High Latitudes	±65° to ±86°, >500 m	21.2	65.9	-	-
Only Coasts	±65°, 0 to 500 m	−2.0	20.1	6.2	18.0

[a]Mean, RMS in cm.

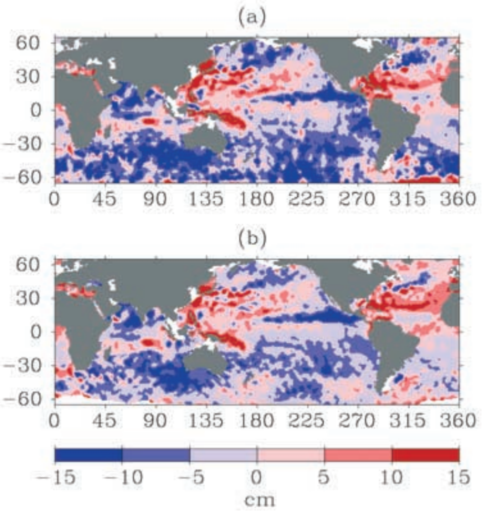

Figure 2. L2a SSA from (a) ICESat (−10.0 cm elevation bias removed) and (b) TOPEX.

by erroneously including sea ice elevations, which artificially increases the average SSA mean and RMS. The mean SSA of the coastal areas is much closer to zero (−2.0 cm) than the global statistics, albeit noisier, suggesting a possible systematic difference between deep waters and shallow coastal areas, such as a possible SSB effect.

[13] Thermally-induced elevation variations observed in earlier ICESat data releases were detected, in part, through the examination of SSAs. Most significantly, a large day/night difference was discovered by independently comparing ascending and descending passes. During L2a, the average local solar time of ICESat descending passes was ~8 hours (day) and ascending was ~20 hours (night), with ICESat having a slowly varying node rate. Meanwhile, TOPEX nearly completed a 60-day node cycle during L2a, passing through all local solar times. The differences between ascending and descending (A-D) daily global

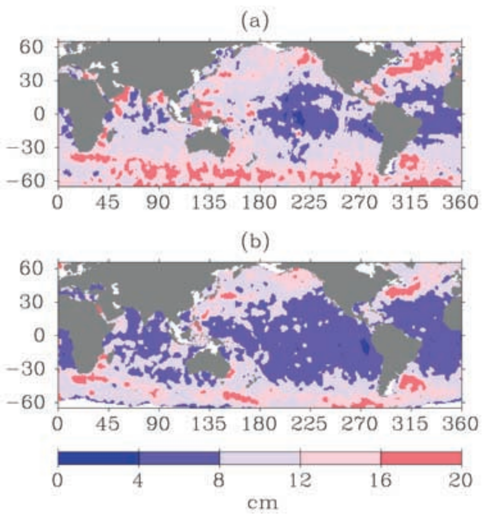

Figure 3. Mesoscale variability: RMS of 1° gridded L2a SSA from (a) ICESat (average = 11.6 cm) and (b) TOPEX (average = 8.9 cm).

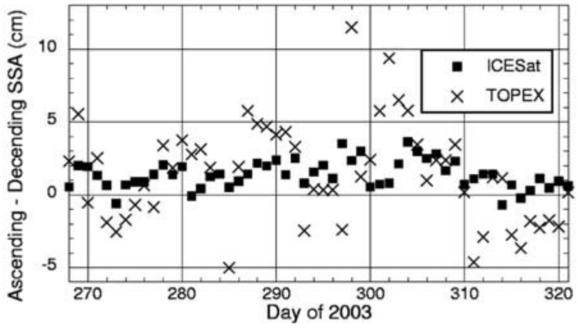

Figure 4. Daily L2a SSA from ascending passes – descending.

SSAs are plotted in Figure 4 (±65°, depth > 500 m). The mean A-D of ICESat is 1.3 cm and for TOPEX is 1.1 cm. The scatter of the daily averages is much larger for TOPEX (4.3 cm) than for ICESat (1.6 cm). We speculate that this is due to radar altimetry's much larger and highly variable wet troposphere and ionosphere corrections, which exhibit large (10–30 cm) spatial and diurnal variations for radar, but are small (<0.5 cm) for laser altimetry.

4. Crossovers

[14] Single-satellite crossovers are computed for ICESat and TOPEX during the L2a campaign, yielding the statistics in Table 3. Crossovers are computed on a strict daily basis and for the whole L2a campaign using a 1-day sliding window (Δt < 1 day) and all data (Δt < 55 days). Crossover height differences are calculated as the ascending pass elevation minus the descending (A-D). For both satellites, the standard cases (±65°, depth > 500 m) have lower RMS values than the global cases. The addition of high-latitude data does not significantly affect the mean crossover difference, but for ICESat significantly increases its RMS and greatly increases the number of crossovers computed (by ~6 times). The strict daily solutions (first two rows) contain few data points, down-weighting their credibility. Conversely, the statistics from the last two rows (Δt < 55 days) were computed from a multitude of crossovers, but will be affected by oceanographic and instrumental changes over the 55-day period. Reporting from the standard (±65°, depth > 500 m) Δt < 1 day case of Table 3, the mean

Table 3. Single-Satellite (A-D) Internal Crossovers Statistics[a]

Case	Latitude, Depth Bounds	ICESat Mean	ICESat RMS	ICESat Points	TOPEX Mean	TOPEX RMS	TOPEX Points
			Average of L2a Daily Solutions				
Standard	±65°, >500 m	2.6	12.0	5/day	0.7	6.2	43/day
Global	±86°, >0 m	1.8	19.3	32/day	0.7	6.4	46/day
			Full L2a Campaign (Δt < 1 Day)				
Standard	±65°, >500 m	1.9	12.5	507	0.5	7.4	4867
Global	±86°, >0 m	2.3	15.7	3206	0.5	7.7	5297
			Full L2a Campaign (Δt < 55 Days)				
Standard	±65°, >500 m	1.2	16.0	11,417	0.2	14.6	145,475
Global	±86°, >0 m	1.3	24.4	85,170	0.2	15.2	160,814

[a]Mean, RMS in cm.

Table 4. Dual-Satellite Ocean Crossovers Statistics[a]

Case	Latitude, Depth Bounds	ICESat - TOPEX Mean	RMS	Points
Average of L2a Daily Solutions				
Standard	±65°, >500 m	−11.3	11.1	47/day
Global	±86°, >0 m	−11.7	11.8	54/day
Full L2a Campaign (Δt < 1 Day)				
Standard	±65°, >500 m	−11.7	11.6	5100
Global	±86°, >0 m	−11.9	12.0	5800
Full L2a Campaign (Δt < 55 Days)				
Standard	±65°, >500 m	−12.2	16.7	153,167
Global	±86°, >0 m	−12.5	17.5	175,349

[a]Mean, RMS in cm.

ICESat crossover A-D value is 1.9 cm, close to the SSA A-D analysis (1.6 cm); the crossover RMS is 12.5 cm for ICESat, 7.4 cm for TOPEX.

[15] Dual-satellite crossovers are computed as ICESat – TOPEX elevation, with statistics in Table 4. The same six cases as in Table 3 are shown. Again reporting from the standard (±65°, depth > 500 m) Δt < 1 day case, the mean is −11.7 ± 1.8 cm (with deviations within 1 cm for all other cases) and the RMS is 11.6 cm (slightly less for the daily average cases, and much higher for the Δt < 55 days cases). The dual-satellite crossovers independently verify the MSS-estimated bias (−10.0 ± 1.0 cm bias) within their uncertainties.

5. Sea State Bias (SSB)

[16] For radar altimetry, significant wave height (SWH) is derived from the slope of the leading edge of the waveform and corresponds to the peak-to-trough amplitude of the highest third of ocean waves. For ICESat, unfortunately, a SWH parameter is not available from the GLA data. An ICESat 1-Hz normal point encompasses a similar collection of sea states as does the much larger (several km-scale) 1-Hz radar footprint. At its full 40-Hz rate, ICESat samples that area with a finer (170 m) resolution and therefore measures small-scale ocean variability caused by waves, wind effects, and swell. Without derivation, we note that the variability (RMS) of the original 40-Hz data about each 1-Hz normal point is correlated with SWH, finding that TOPEX SWH corresponds to ∼7 times the ICESat L2a R21 RMS at dual-satellite crossover locations. Throughout this paper, several unique attributes have been noted for shallow coastal areas and, if we can assume that coastal areas have different ocean variability than deep waters, this further indicates that an ICESat SSB correction is necessary. Further SSB investigation is warranted, beginning with the radar paradigm using scaled SWH. For ICESat, however, parameters other than SWH appear correlated with SSA, and any laser SSB may ultimately be very different from radar SSB. This is a topic for future research.

6. Discussion

[17] ICESat elevation accuracy over the oceans has been examined and found to have a global bias of −10.0 ± 1.0 cm (low) with respect to TOPEX, with ±2 cm day-to-day variations similar to those observed by TOPEX. ICESat-TOPEX dual-satellite crossovers independently verify this bias. Examining daily A-D SSA variations, ICESat displays a smoother time series than TOPEX, but in general, ICESat data exhibit a noisier performance than TOPEX (∼2 cm higher RMS for daily SSA averages, ∼5 cm higher RMS for single-satellite internal crossovers, and ∼3 cm higher global mesoscale variability). Elevation bias appears to be different over smooth flat land surfaces, and TOPEX and ICESat agree less well in areas having larger waves, suggesting a possible laser SSB correction for future investigtion.

[18] ICESat's data density, coverage, and precision remain superior to radar altimetry: latitudes up to ±86° are sampled at 40 Hz (65 m spots every 170 m); single-shot elevation precision over smooth flat surfaces is <3 cm; laser observations include all shallow waters up to coastlines, whereas radar and radiometer footprint contamination creates coastal exclusion zones. ICESat is unique in its ability to gather high-latitude and coastal data, and holds great potential for generating MSS and ocean tide model improvements [e.g., *Padman and Fricker*, 2005; S. Farrell et al., Sea surface topography in the Arctic Ocean from ICESat, submitted to *Geophysical Research Letters*, 2005].

[19] ICESat laser altimetry matches TOPEX detection of major sea level anomaly and mesoscale variability features. While the conceptual measurement between ICESat laser and typical radar altimetry is very similar, in practice the two remote observation methods have unique characteristics and challenges. Precise geolocation is essential for ICESat, with laser pointing errors being the largest component of the error budget [*Zwally et al.*, 2002]. As demonstrated in this investigation, and given the same ∼1 arcsecond pointing performance as L2a R21, all ICESat campaigns can be expected to provide similar comparisons with TOPEX.

[20] ICESat was designed to meet challenging cryosphere requirements and the rich dataset may also augment oceanography from radar altimetry and provide new insights. Future work will include similar sea level evaluations using other ICESat laser campaigns, examination of a SSB correction, and further investigation of applications for ocean science.

[21] **Acknowledgments.** This work was supported by NASA contract NAS5-99005. ICESat elevation data were provided by the GLAS Science Computing Facility at NASA Goddard Space Flight Center. We also thank our anonymous reviewer for valuable comments, and TOPEX/Poseidon for thirteen years of faithful service.

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