Geodetic corrections to Amazon River water level gauges using ICESat altimetry

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[1] Gauge stations are vital for monitoring water levels worldwide. However, many remote basins suffer from having gauges that are not tied to a common datum, making it impossible to know absolute water elevations, and therefore slope. This problem is known to exist on the River Amazon, for example, where water flux modeling efforts have been hampered by inconsistently leveled gauge data that serve as boundary conditions for these models. This paper presents a methodology for using Ice, Cloud, and land Elevation Satellite (ICESat) laser altimetry observations to geodetically level gauge stations. A proof-of-concept study was carried out to ascertain the feasibility and accuracy of the approach, and a mean absolute error of 19 cm was found. Once this was established, gauges within the Amazon Basin were geodetically leveled. This produced offsets for six gauges using a method that can be transferred to other locations and allows slope and discharge estimates to be calculated. The results are significant, with offsets as large as 13.37 m being added. The approach could provide improvements in modeling floodplain flow, processes, and fluxes in the Amazon Basin and worldwide.

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1. Introduction

[2] Throughout the world in situ gauge data are used to monitor and model river systems. However, in many remote or large scale catchments, gauges are few and far between [*Alsdorf and Lettenmaier*, 2003]. In addition, the gauges that are present are often not tied to a standard vertical datum. Although relative changes in water level can be observed from the gauging stations, absolute water level elevations and, more importantly, gradients cannot be assessed and are thus of limited value for driving model simulations. Being unable to calculate the water surface slope also means that accurate discharge estimates cannot be made, yet discharge is required to understand global freshwater storage [*Alsdorf et al.*, 2007].

[3] The Amazon Basin is a catchment where all of the gauge stations have local datum levels. The River Amazon is the largest river in the world by discharge, accounting for ~20% of the total runoff discharged into the world's oceans [*Richey et al.*, 1989]. The river has a catchment of ~6 million km^2 [*Richey et al.*, 1989], and the main channel can be up to 6 km wide [*Filizola et al.*, 2009]. The lack of a common datum means that the use of water level data from gauges in hydrodynamic models, such as LISFLOOD-FP [*Bates et al.*, 2010] or HEC-RAS [e.g., *Trigg et al.*, 2009], would not be meaningful. Therefore, these gauges cannot be used unless they are tied to a common datum. This is commonly done using land-based survey methods, such as a Differential Global Positioning System (DGPS); however, in large catchments such as the Amazon these methods are hampered by expense, difficulties with access, and the size and remoteness of the area to be surveyed. Also, dense forest canopies reduce the precision and accuracy of DGPS data and increase acquisition times [*Deckert and Bolstad*, 1996]. In order to overcome the fundamental issue of unleveled gauge stations, vertical offsets are needed to tie the water elevation data to a common datum.

[4] The Ice, Cloud, and land Elevation Satellite (ICESat), which carries the Geoscience Laser Altimeter System (GLAS), was designed primarily to monitor changing elevations of ice sheets [*Zwally et al.*, 2002]. In this study, ICESat has been used to create a reliable set of geodetic level offsets to tie a set of Amazon gauges to a common datum. Calculating offsets for Amazon gauges has previously been investigated by *Kosuth et al.* [2006] using TOPEX/Poseidon (T/P); from 1993 to 2002 they used maximum water level comparisons between gauge and T/P observations. Using a polynomial interpolation of the T/P elevations a consistent network referenced to the EGM96 geoid was created across the Amazon Basin. These offsets were used by *Trigg et al.* [2009] to model the Amazon flood wave; however, limitations with the T/P data are a potential source of uncertainty in the modeling process. The kilometer scale footprint of T/P [*Calmant et al.*, 2008] is not ideal for obtaining land-free observations for the majority

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of river channels. *Birkett et al.* [2002] found that the minimum river width to be used with T/P, to avoid footprint contamination, is ~1 km. Although suitable for some Amazonian river channels, this greatly limits its use elsewhere or during periods of low water. Other problems associated with using radar altimeters such as T/P are that multiple bright sources in a footprint can cause multiple peak returns [*Birkett*, 1998]. Interference from the forest canopy, wind fetch, and land contamination can also affect the altimeter return, particularly at low water [*Birkett*, 1998].

[5] With the aim of creating more reliable offsets for the Amazon gauges using ICESat, a proof-of-concept study was first carried out over the Danube and Mississippi Rivers to assess the accuracy of ICESat for this application. These two rivers were chosen as they are both large enough to obtain land-free ICESat observations and have reliable, geodetically leveled gauges. From the early ICESat campaigns, height accuracies as low as 2–3 cm were found over terrestrial water bodies [*Harding and Jasinski*, 2004; *Urban et al.*, 2008]. However, here we use all of the ICESat campaigns, since the mission has now ended. Once the accuracy of ICESat was confirmed the Amazon gauge stations within our study area were leveled.

2. Methods

2.1. ICESat

[6] ICESat GLAS was the first spaceborne Earth orbiting laser altimeter and operated from 2003 to 2009. The instrument had a footprint of ~70 m and made an observation every 172 m along track [*Carabajal and Harding*, 2005]. This makes it more suitable for observing river water levels than radar altimeters as contamination from surrounding land and vegetation is less likely with the small footprint, and smaller rivers can be observed. In comparison, T/P, designed to observe the oceans, has an ~1 km footprint and makes along-track observations approximately every 596 m [*Leon et al.*, 2006]. ICESat data were acquired from the National Snow and Ice Data Centre (NSIDC) website (available at http://nsidc.org/data/icesat/). The product used was the GLA14 Land Elevation Product, Release 31 and covers all campaigns carried out during the ICESat mission. The campaigns cover high, low, and rising water levels, allowing offsets to be calculated that are temporally independent. The data were extracted using the Interactive Data Language (IDL) code provided by the NSIDC, which also converted the data from the T/P ellipsoid to the World Geodetic System of 1984 (WGS84) ellipsoid. During this process the elevation-use flag (i_ElvuseFlg) was used to identify suitable observations. The saturation index was also used to remove or correct saturated observations. Observations with an index of three or above were removed. An index of zero or one is suitable for use without correction as there is no saturation or an inconsequential level of saturation, respectively. Those with an index of two had the saturation correction applied to them. Then, to convert the elevations to the vertical datum Earth Gravitational Model of 1996 (EGM96), the geoid conversion tool, F477, provided online by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA) was used (available at http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm96/egm96.html). The EGM96 geoid was chosen for this study due to its common usage, particularly in hydrodynamic modeling of large river floodplains where Shuttle Radar Topography Mission (SRTM) data, which is also referenced to WGS84 EGM96, is commonly the only source of topographical data.

2.2. ICESat and Gauge Comparison Method

[7] The ICESat and gauge comparison method used in the proof-of-concept study and for the Amazon Basin is outlined below. First, all available gauge station data within the study areas (Figure 1) were acquired for the operational time period of ICESat. To ensure that the river channel is wide enough for ICESat to get water surface observations, only gauges on the main channels and larger tributaries were identified. The gauge locations were mapped over Landsat Thematic Mapper (TM) images of the study areas, which were downloaded from the U. S. Geological Survey (USGS) Earth Explorer website (available at http://earthexplorer.usgs.gov). The ICESat ground tracks were also plotted over the Landsat TM images to identify gauges with nearby ICESat passes. Daily gauge measurements allow in situ water level observations to be found for the same day as the ICESat pass. The gauge observation nearest in time to any given ICESat pass was the observation used during the comparisons. However, before comparing these data, we had to ensure that the ICESat returns were from the water surface only. Therefore, the number of peaks detected in the lidar return had to be one. More than one peak usually represents various layers of vegetation, which causes more than one return signal to be received by the sensor. However, since most land surfaces can also return a single peak a secondary measure was introduced. A buffer of 80 m was used to exclude all ICESat observations that could contain land surface within their footprint. This buffer included the footprint of ICESat (35 m radius), and the geolocation errors of ICESat (2.4 ± 7.3 m [*Carabajal and Harding*, 2005]) and Landsat TM (30 m). All ICESat observations within 80 m of the riverbank, identified using the Landsat TM images, were excluded. Once this buffer had been applied, the gauge data could be compared to the remaining ICESat observations. This was done by identifying the gauge level closest in time to the ICESat observation and directly comparing the two elevations, given that in very large rivers flow does not vary markedly between gauge readings. For example, the River Amazon water levels at Anamã varied on average by 5.35 cm during the 24 h around the gauge level used for comparison with ICESat. This methodology for identifying ICESat observations over water bodies is transferrable to any location, and can be used in rivers of relatively narrow widths ($\geq$170 m).

[8] In the Amazon, satellite observations were used to create an offset for each gauge in order to level them to the EGM96 geoid. The method used by *Kosuth et al.* [2006] has here been expanded and improved with the use of ICESat altimetry. The method described above was used to identify suitable ICESat elevations. The gauge and ICESat elevations were directly compared. The gauge water levels were then subtracted from the ICESat elevations to find the mean difference and produce an offset. The mean offset and the standard deviation of all of the observations over the main channel were calculated for each gauge. If more than one pass was available for comparison with a gauge

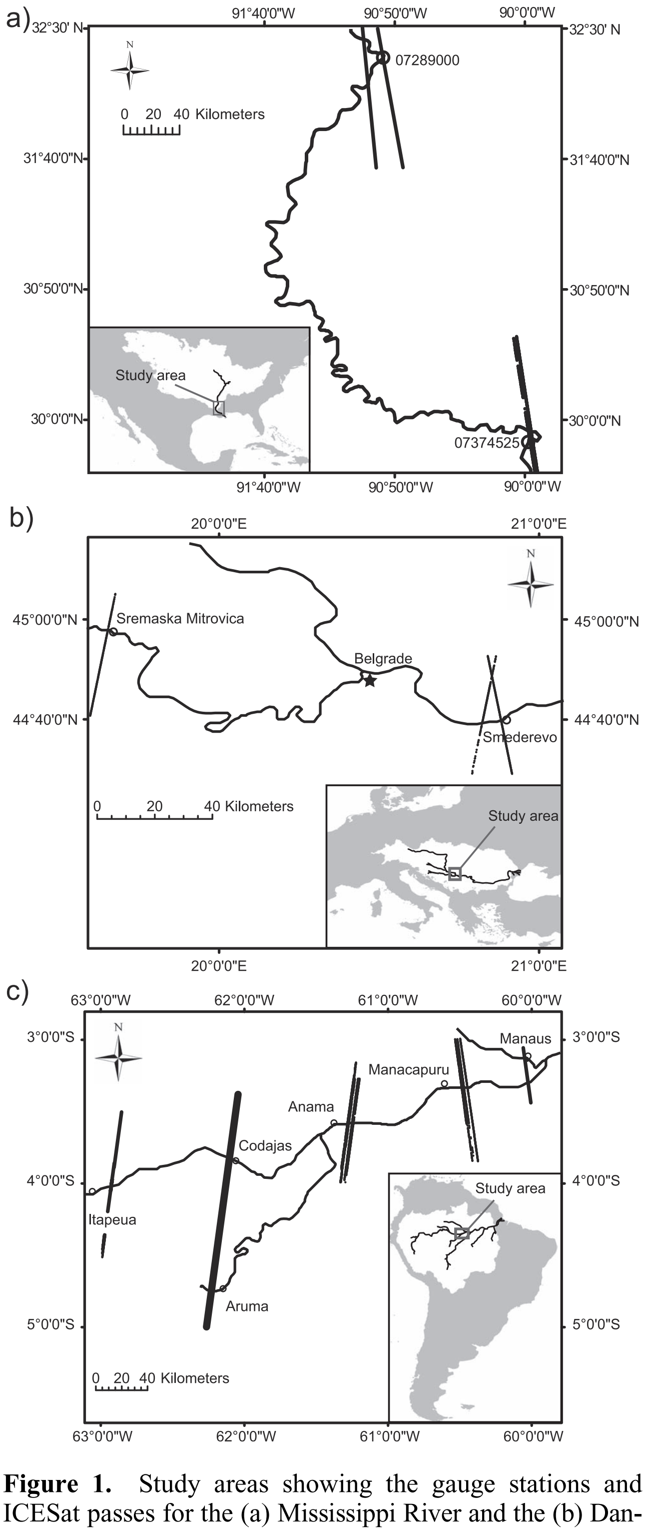

Figure 1. Study areas showing the gauge stations and ICESat passes for the (a) Mississippi River and the (b) Danube River) used in the proof-of-concept study, and the used ICESat passes and gauges in the (c) Amazon Basin that were geodetically leveled. Images created using data from USGS HydroSHEDS website (available at http://gisdata.usgs.gov/website/HydroSHEDS/).

station then the mean offsets for all of the tracks were used. Because of the width of the reach considered (3.4 km [*Trigg et al.*, 2009]) one satellite pass could provide many observations of water level to compare to a gauge observation. For full details of all ICESat and gauge observations used in the Amazon and proof-of-concept study, please refer to the auxiliary material.[1]

2.3. Proof-of-Concept Study

[9] The gauge data for the Mississippi were acquired from the USGS Water Data for the Nation website (available at http://waterdata.usgs.gov/nwis/) and the above process was applied. However, the north-south flow direction of the Mississippi main channel means that few ICESat passes go over the river at a suitable distance from a gauging station. Two suitable gauging stations were located: the first, 07289000 at Vicksburg and the second, 07374565 at Belle Chasse (Figure 1a). The gauge levels provided at these gauges were daily values; hourly observations were not provided. The gauges were converted from their American datums to EGM96 before comparison with the ICESat data. Where ICESat passed over the river to the north and south of the gauge, the gradient between the two locations was used to calculate the level at the gauge for a direct comparison. There were 80 ICESat observations meeting the above criteria for the Mississippi. The same methodology was then applied to the Danube. Because the majority of gauges on the Danube were further inland on small tributaries, a total of five suitable ICESat observations at two gauge locations remained for comparison (Figure 1b). The gauge at Smederevo provided a daily observation, whereas the Sremaska Mitrovica gauge provided hourly data. It should be noted that although the saturation correction is applicable to single peak returns it has not been fully tested over water surfaces; therefore, the analysis of the proof-of-concept results has been carried out both including and excluding the saturation corrected observations.

[10] From the results of this proof-of-concept study it is clear that ICESat can observe water levels to a decimetric level of accuracy. The mean difference between the ICESat and gauge water levels of all the 85 observations, which includes those that have been corrected for saturation, from the Mississippi and Danube Rivers is -16 ± 73 cm with a mean absolute error of 54 cm. When observations requiring saturation correction were excluded, the mean difference of the remaining 32 observations was -10 ± 27 cm with a mean absolute error of 19 cm. The ICESat elevation was greater than the gauge level in most cases.

[11] The difference between the ICESat and gauge levels could be due to the vertical error of the ICESat (0.04 ± 0.13 m per degree incidence angle [*Carabajal and Harding*, 2005]) and the gauging stations (likely only a few cm for standard river gauges). However, the incidence angle of ICESat over flat surfaces, which includes water, can be considered to be the ICESat nominal pointing angle of 0.3° [*Urban et al.*, 2008]. *Carabajal and Harding* [2005] state that the nominal pointing angle of ICESat will translate into a 0.01 ± 0.04 m vertical error. Unusually large differences between the gauge and ICESat may be due to wind action on the water surface, increased incidence angles due to water slope, or to the time difference between the ICESat observation and the daily gauge reading. The mean difference from day to day at the 07289000 gauge on the

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011WR010895.

Mississippi, during 2003 to 2007, was 20 cm showing that this is a river with rapidly varying flow. It should also be noted that large elevation differences between gauge and ICESat (up to ~2 m) can be seen in those observations that required a saturation correction to be applied, indicating that the saturation correction is likely not reliable over water bodies.

2.4. Leveling the Amazon Gauges

2.4.1. Study Area

[12] The study area is a 400 km reach of the River Amazon between the gauges at Itapéua at the upstream end, and Manaus at the downstream end (Figure 1c). This area contained sufficient gauges for this study and relates to previous hydraulic modeling work. For example, *Trigg et al.* [2009] carried out flood modeling of this reach using the T/P gauge offsets mentioned previously. There are five gauges on the main channel, three on the River Purus, the tributary entering the Amazon main stem (termed the Solimões above the confluence with the River Negro) from the south, and one on the River Negro at the city of Manaus at the downstream end of the study area. Because Manaus is only 17 km upstream of the confluence of the Solimões and the Negro it can be considered representative of water levels in the main stem [*Meade et al.*, 1991]. However, when these gauges were compared to the ICESat ground track locations, only six had nearby passes: four gauges on the main stem, one on the River Purus, and one on the River Negro at Manaus (Figure 1c). Data for these gauges were downloaded from the Agência Nacional de Águas (ANA) Hidroweb website (available at http://hidroweb.ana.gov.br/), however, no information is provided relating to the gauges' vertical datum.

2.4.2. Gauge Offsets

[13] The six Amazon gauges in Figure 1c were corrected using the method previously described. Observations at these gauges were collected at 07:00:00 GMT-4 and 17:00:00 GMT-4, with mean levels interpolated for midday and midnight. This allows the gauge water level to be within a maximum of 3.5 h of the ICESat pass, which is suitable due to slowly varying water levels of the Amazon. The Manaus gauge is an exception with only one gauge level provided for each day with no indication of the observation time. The number of suitable ICESat tracks ranged from two at Manaus to 13 at Anamã, whereas the number of actual along-track observations ranged from nine at Arumã to 173 at Anamã.

[14] The distance between the gauge and the ICESat tracks used in the offset calculations needed to be accounted for. This was done by using ICESat tracks that passed over the river in two different locations within a day of each other to calculate the river slope. There were 23 such pairs of tracks from 2003 to 2009. The water level change at a nearby gauge from the first day to the next was used to correct for the tracks being on different days. The gradients were split into three seasons: rising, high, and low water, as the gradient changes during the year. The mean gradient for each season was found. In order to substantiate the suitability of this method of finding the gradient, the relative daily change in slope between gauges was investigated. The mean daily change in slope was small, as expected ($\leq$0.02 cm km^{-1}). Therefore, the ICESat gradients were used to correct for the distance between gauge and ICESat pass by multiplying the distance by the gradient for the appropriate season.

2.5. Model Setup

[15] Analysis of the gauge offsets produced by ICESat was carried out by inputting the leveled gauge data into the Hydraulic Engineering Centers River Analysis System (HEC-RAS) (v4.1.0), a 1-D hydrodynamic model developed by the U.S. Army Corps of Engineers (available at http://www.hec.usace.army.mil/software/hec-ras/hecras-download.html). The model was run using the same initial conditions as in the previous study [*Trigg et al.*, 2009], with irregular cross-sections, except here we use the ICESat offsets (including the saturation corrected observations) rather than the T/P-derived offsets. The model's upstream boundaries on the Amazon and the Purus used a flow hydrograph. For the downstream boundary, 12 km downstream from Manacapuru, the leveled stage hydrograph is used. Because the ICESat offsets were spatially and temporarily independent we simulated the same time period as *Trigg et al.* [2009]: from 1 June 1995 to 31 March 1997.

3. Results

[16] The Amazonian gauge offsets, and their associated errors, calculated including and excluding observations requiring saturation corrections, were leveled to the EGM96 geoid and are provided in Table 1, with the gauges presented in a downstream direction. It should be noted that, as all Arumã elevations were saturated, excluding the saturation-corrected observations means that an offset cannot be calculated here. Two more recent geoids derived

Table 1. Amazon Gauge Station Offsets and Errors Derived From ICESat Referenced to the EGM96 Geoid[a]

Gauge	Offsets Including Saturated Points ± SD[b] (m)	Observations	Offsets Excluding Saturated Points ± SD[b] (m)	Observations
Itapéua	13.37 ± 0.16	81	13.25 ± 0.21	41
Codajás	11.11 ± 0.15	61	11.04 ± 0.12	30
Arumã	**6.88 ± 0.16**	**9**		**0**
Anamã	8.37 ± 0.14	173	8.28 ± 0.23	97
Manacapuru	3.54 ± 0.06	67	3.53 ± 0.06	61
Manaus	**−7.82 ± 0.78[c]**	**28**	**−7.82 ± 0.78[c]**	**28**

[a]The gauge stations in boldface are those that are not in the main channel, however, Manaus is considered to be representative of water levels in the Solimões [*Meade et al.*, 1991].

[b]These offsets have no spatial or temporal variability as the mean offset was found using water levels across the channel and through time.

[c]This high SD in the offset for Manaus is unexpected and is thought to be attributed to the gauge readings as there is no direct evidence of a physical reason for it and ICESat has been reliable in all other locations.

from the Gravity Recovery and Climate Experiment (GRACE) mission were also investigated, EIGEN-51C [*Bruinsma et al.*, 2010] and GGM02C [*Tapley et al.*, 2005], the results of which have been included in Table 2. It should be noted that intercampaign biases of $\sim$2 cm yr^{-1} [*Riva et al.*, 2009] exist between the different ICESat campaigns. No accepted values for these biases exist, however, so no correction for this is currently available in the products (data are from B. Schutz, J. DiMarzio, S. Luthcke, D. Hancock, and T. Urban, Notice concerning detection of ICESat/GLAS inter-campaign elevation biases, NSIDC, 2011; available at http://nsidc.org/data/icesat/pdf/inter-campaign_bias_notice_v1.pdf). If the Arumã tributary gauge is ignored, it can be seen that there is a clear relationship between the offsets on the main channel, which decrease in the downstream direction. The standard deviations of the offsets are low and within the vertical accuracy of ICESat, except at Manaus (79 cm). The high standard deviation here is due to a large difference in the offset for the gauge found from each of the two available ICESat tracks; however, as the same two ICESat tracks have been used to calculate offsets for two other gauges in different locations further upstream without any noticeable discrepancies, this difference could be attributed to a change at the gauging station.

[17] The implication of using unleveled gauges becomes clear when the gradient of the river is investigated. A mean slope of -0.96 cm km^{-1} is observed between the four unleveled gauges in the main channel, a value which is meaningless, as it suggests that water is flowing upstream. However, after adding the ICESat offsets to the gauges the mean water surface gradient becomes 2.21 cm km^{-1}, which is hydraulically meaningful and closer to what might be expected, according to Table 1 in the work of *Trigg et al.* [2009]. The mean water surface found using the T/P offsets [*Kosuth et al.*, 2006] was similar to the ICESat gradient at 2.24 cm km^{-1}. Analysis of these new ICESat offsets for the modeling period of 1 June 1995 to 31 March 1997 was carried out. The mean water gradients between gauging stations for this time period were calculated and can be seen in Table 3. The gauge data were then input into HEC-RAS using the ICESat offsets to level them. Example discharge estimates were found using Manning's equation for open channel flow,

$$Q = (1/n)AR^{2/3}S^{1/2},$$

where Q is discharge (m^3 s^{-1}), n is the Manning's roughness coefficient, A is the cross-sectional area (m^2), R is the hydraulic radius (cross-sectional area in m^2/wetted perimeter in m), and S is the river slope (m m^{-1}) calculated from the ICESat offsets. The roughness coefficient, area, and hydraulic radius were taken from the HEC-RAS cross-section (the original data were collected during a field survey). This was combined with the calculated water surface slope to find the discharge at the downstream boundary for the model run period. The mean discharge during this period was 63,106 m^3 s^{-1}. As the Amazon has a very distinct annual flood wave there is a clear minimum and maximum in discharge. The minimum discharge was on 29 October 1995 at 16,223 m^3 s^{-1}. A maximum discharge of 104,162 m^3 s^{-1} was seen on 23 July 1996 at the peak of the flood wave. Therefore, the cycle between 1995 and 1996 saw a change in discharge, between peak and trough, of 87,939 m^3 s^{-1}. This method could potentially be used to estimate discharge at any point along the river.

Table 2. Amazon Gauge Station Offsets for Three Geoids

Gauge	EGM96 Offsets ± SD (m)	GGM02C Offsets ± SD (m)	EIGEN-51C Offsets ± SD (m)
Itapéua	13.37 ± 0.16	13.16 ± 0.16	13.50 ± 0.16
Codajás	11.11 ± 0.15	10.97 ± 0.14	11.08 ± 0.16
Arumã	**6.88 ± 0.16**	**6.64 ± 0.16**	**6.91 ± 0.16**
Anamã	8.37 ± 0.14	8.21 ± 0.15	8.33 ± 0.14
Manacapuru	3.54 ± 0.06	3.29 ± 0.06	3.63 ± 0.07
Manaus	**−7.82 ± 0.78**[c]	**−7.89 ± 0.78**	**−7.93 ± 0.78**

Table 3. Mean Amazon Water Surface Gradients

Offset Method	River Reach Gradient (cm km^{-1})		
	Itapéua–Codajás	Codajás–Anamã	Anamã–Manacapuru
ICESat	2.00	2.35	2.28
T/P	2.54	2.37	1.80

4. Conclusions

[18] Two main conclusions can be drawn from this study. First, that the ICESat mission is a valuable source of data for observing terrestrial river and lake levels from space across the globe; for example, accuracies of 10 ± 27 cm were found in this study. It is a possibility that some of the uncertainty in the results could be due to tidal influences. For example, tidal waves on the River Amazon can travel more than 1000 km upstream [*Kosuth et al.*, 2009]. ICESat's footprint and the distance between observations along track make it suitable for observing rivers and other inland water bodies greater than a few hundred meters wide, particularly those flowing in an east-west direction. Another application for ICESat data would be to create virtual gauging stations across poorly monitored river catchments, as previously done in the Amazon using radar altimetry data [e.g., *Leon et al.*, 2006; *da Silva et al.*, 2010]. The anticipated launch of ICESat-2 in 2016 will continue to provide accurate data for studies of terrestrial water bodies, such as the Amazon and other large river basins.

[19] The second conclusion is that the correction of poorly leveled gauge stations, not just in the Amazon Basin but elsewhere, is essential for accurate discharge estimation and modeling. Leveling gauges with this method will improve all studies using these gauge data. The accurate calculation of water slope impacts upon gauge-based discharge estimates, which are essential for verifying and complementing future satellite missions, such as the Surface Water and Ocean Topography (SWOT) mission [*Durand et al.*, 2010]. There are limitations to this method, however. In particular, the river needs to be wide enough to allow land-free observations of the water surface, and rivers that flow in a north-south direction will have fewer passes over the river due to ICESat's orbital pattern. However, the method used here can be transferred, not only across the Amazon Basin, but to any remote, poorly monitored or unleveled river system.

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