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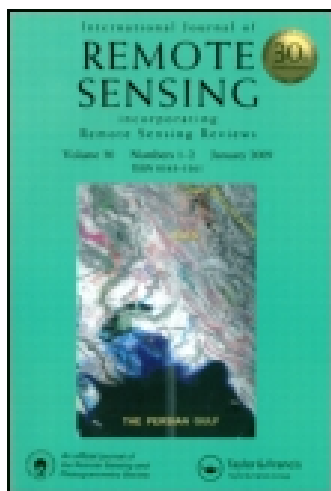
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Accuracy assessment of SRTM v4 and ASTER GDEM v2 over the Altiplano watershed using ICESat/GLAS data

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The new Global Digital Elevation Model (GDEM v2) has been available since 17 October 2011. With a resolution of approximately 30 m, this model should provide more accurate information than the latest version of Shuttle Radar Topographic Mission (SRTM v4) with a resolution of 90 m outside of the USA. The accuracies of these two recently released digital elevation models (DEMs) were assessed over the Altiplano watershed in South America using ICESat/GLAS data (Ice, Cloud and Land Elevation Satellite/Geoscience Laser Altimeter System). On the global scale, GDEM v2 is more accurate than SRTM v4, which presents a negative bias of approximately 8.8 m. Strong correlations between the DEMs' accuracies and mean slope values occurred. Regarding land cover, SRTM v4 could be more accurate or easier to correct on a smaller scale than GDEM v2. Finally, a merged and corrected DEM that considers all of these observations was built to provide more accurate information for this region. The new model featured lower absolute mean errors, standard deviations, and root mean square errors relative to SRTM v4 or GDEM v2.

1. Introduction

Digital elevation models (DEMs) are widely used in geological, glaciological, and hydrological studies. In hydrological studies, DEMs are used to extract watershed and drainage systems using numerical methods (Jenson and Domingue 1988; Mackay and Band 1998; Martz and Garbrecht 1999; O'callaghan and Mark 1984; Planchon and Darboux 2002 among others) that rely on cell-to-cell slope to retrieve the flow direction.

In large and poorly monitored areas, the topography may be extracted from DEMs based on remotely sensed observations, such as SRTM Shuttle Radar Topography Mission (Farr et al. 2007) and GDEM (Global Digital Elevation Model) (ASTER GDEM Validation Team 2009), which offer nearly global coverage. Spaceborne interferometric synthetic aperture radar (SAR) technology was used to acquire the SRTM elevation data. In addition, InSAR equipment obtained a nearly global

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elevation dataset [60° N to 56°S] with a spatial resolution of 30 m × 30 m and a global vertical precision of 16 m. However, several studies have reported errors, particularly related to vegetation (Sun et al. 2003). Stereo-pair images obtained in the visible and near-infrared (VNIR) bands collected by the ASTER instrument were used to generate a GDEM elevation dataset [83° N to 83° S]. One of the drawbacks of this technology is its sensitivity to clouds and the presence of bump and pit artefacts (Arefi and Reinartz 2011).

In case of an inaccurate DEM, numerical algorithms may fail or lead to erroneous flow direction; as a result, unrealistic hydrological analysis may occur (Tsanis et al. 2013). DEM accuracy is particularly crucial in flat regions (Getirana et al. 2009).

Elevation datasets for specific regions around the world have been analysed in numerous studies. One commonly used method is to compare the DEM with high-quality ground control points (GCPs). The GCPs can be obtained using global positioning system (GPS) measurements (Hirt, Filmer, and Featherstone 2010; Zhao et al. 2011), topographic maps (Zhao et al. 2011), or high-quality radar altimetry data, such as ICESat/GLAS (Billemont 2010; Carabajal et al. 2011; Enslé, Heinzl, and Koch 2012; Zhao, Xue, and Ling 2010). Alternatively, remotely sensed DEMs can be compared with high-quality DEMs (Forkuor and Maathuis 2012; Sertel 2010). Based on one of these two methodologies, several studies have already addressed the evaluation of the first version of GDEM (v1) and various SRTM products in different regions of the world, including Turkey (Sertel 2010), China (G. Zhao, Xue, and Ling 2010; Zhao et al. 2011), Australia (Hirt, Filmer, and Featherstone 2010), and Ghana (Forkuor and Maathuis 2012) (Table 1). In these studies, good agreement was generally observed between the remotely sensed DEMs and the ground truth data.

Since October 2011, a new GDEM version (GDEM v2) has been freely available to the public (<https://reverb.echo.nasa.gov>). Apart from the studies led by the GDEM v2 team on a global scale (Carabajal 2011) and across the USA (Gesch et al. 2011), only a few studies have addressed the accuracy of GDEM v2. Assessments have been conducted in Germany (Enslé, Heinzl, and Koch 2012), China (Li et al. 2012), and Indonesia (Suwandana et al. 2012) (Table 1). Based on these studies, GDEM v2 is generally more suitable than GDEM v1. However, this suitability is not evident based on comparisons with SRTM products. More suitable DEMs depend on the region and final purpose. Thus, the accuracy of GDEM v2 is still debated, and its evaluation in different regions of the world remains of interest to the scientific community.

As reported in many previous studies, a DEM's horizontal accuracy may range from a few metres to hundreds of metres (Table 2). The horizontal accuracy is important for understanding and interpreting the vertical accuracy (Nikolakopoulos, Kamaratakis, and Chrysoulakis 2006). Horizontal accuracy assessments have been provided for various GDEM and SRTM versions in different regions of the world.

Generally, the horizontal offset between DEMs is represented by a sub-pixel length and could be absent (Hirt, Filmer, and Featherstone 2010). The high values found by Nikolakopoulos, Kamaratakis, and Chrysoulakis (2006) could be linked to the old version of the ASTER-derived DEM that was assessed in this study. In the event of horizontal bias, a DEM could provide good elevation data that are associated with the wrong locations; thus, the DEM is inaccurate. Based on this hypothesis, the horizontal shift estimation represents a primordial step in the evaluation of DEM accuracy.

Table 1. Summary of previous studies focused on GDEM v1, GDEM v2, and various SRTM products' horizontal accuracy.

Authors	DEMs assessed	GC/PS used	Results
Zhao et al. (2011)	GDEM v1/SRTM v4	Derived from topographic Map	In Loess plateau, GDEM v1 and SRTM v4 accuracies are similar whereas in North China Plain SRTM v4 is more accurate than GDEM v1.
Sertel (2010)	GDEM v1	DEM generated from topographic maps	GDEM v1 is found suitable to characterize topography in Turkey.
Hirt, Filmer, and Featherstone (2010)	GDEM v1/SRTM v4/GEODATA DEM-9S ver3	GPS	Better accuracy for SRTM v4 and GEODATA DEM-9S ver3. GDEM v1 should be improved as was done for the SRTM previous version.
Zhao, Xue, and Ling (2010)	GDEM v1	ICESat/GLAS/SRTM v2/SRTM v4	GDEM v1 performs better in flat regions than in mountainous areas. GDEM v1 presents fewer voids than SRTM v2 but presents many artefacts.
Forkuor and Maathuis (2012)	GDEM v1/SRTM v4	DEM generated from topographic maps	Better vertical accuracy is found for SRTM v4, which tends to overestimate elevation while GDEM v1 underestimates it. SRTM v4 is found more suitable for hydrological applications.
Billemont (2010)	GDEM v1/GDEM v2	ICESat/GLAS	GDEM v1 accuracy is very good in flat regions and decreases with increasing mean slope. The presence of artefacts alters GDEM v1 accuracy.
Carabajal et al. (2011)	GDEM v2/SRTM v2	ICESat/GLAS	Regarding global statistics, over South America, SRTM v2 and GDEM v2 seem to be in pretty good agreement.
Li et al. (2012)	GDEM v2/GDEM v1/SRTM v4	GPS/SRTM v4	Lower values of both RMS and mean difference are found for GDEM v2 than for GDEM v1 and SRTM v4.
Enslie, Heinzel, and Koch (2012)	GDEM v2/SRTM v4/SRTM 25	ICESat/GLAS	The better DEM for mountainous areas is the GDEM v2 whereas SRTM products are more suitable for flat areas.
Suwandana et al. (2012)	GDEM v2/SRTM v4	GPS/ DEM generated from topographic maps	SRTM v4 is more accurate in terms of elevation but GDEM v2 remains more suitable for inundation area delimitation.
Gesch et al. (2011)	GDEM v1/ GDEM v2 /SRTM 1/NED	GPS	GDEM v2 shows a global enhancement in comparison with GDEM v1. NED is the more accurate DEM following SRTM.

Table 2. Summary of previous studies focused on horizontal offset estimation between DEMs.

Authors	Regions	DEMs assessed	Absolute mean west/east shift	Absolute mean north/south shift
Nikolakopoulos, Kamaratakis, and Chrysoulakis (2006)	Greece	DEM derived from ASTER/SRTM 3	6.66" (200 m)	13.33" (400 m)
Reuter, Nelson, and Jarvis (2007)	4 GDEM v1 tiles over the world: N05W02, N40E023, N14W087, N45E008 and S02W079	GDEM v1/SRTM 3	<1" (<30 m)	<1" (<30 m)
Hirt, Filmer, and Featherstone (2010)	Australia	GDEM v1/SRTM v4	0" (0 m)	0" (0 m)
Tachikawa et al. (2011)	Japan	GDEM v2/GSI (Geographical Survey Institute) DEM	0.13" (3.9 m)	0.19" (5.7 m)
NGA (National Geospatial-Intelligence Agency)	284 GDEM v2 tiles over 20 sites over the world	SRTM DTED2/GDEM v2	0.104" (3.12 m)	0.175" (5.25 m)

In the present study, we have evaluated SRTM v4 and GDEM v2 for the Altiplano watershed region in South America. This region includes emblematic ecosystems, such as Lake Titicaca and Poopó Lake. The water resources in this region are under increasing anthropic pressure with several conflicting uses by the international boundary watershed countries (Molina Carpio, Cruz, and Alurralde 2012; Urquidi Barrau 2012) and mining areas (Moran 2009; Molina Carpio 2007). The regional topography is very flat, but the areas are surrounded by the two highest mountain ranges (cordilleras) in South America. The best available topographic information for the Altiplano region consists of topographic maps (1:50 000) from the IGMB (Instituto Geográfico Militar Bolivia). The Altiplano watershed includes three countries (Bolivia, Peru, and Chile) with their own topographic information sources. These information sources may not be consistent with each other due to their different information processing methods, resolutions, and formats. Consequently, the compilation of topographic data is a difficult task that can be easily bypassed using a DEM.

Thus, a quality assessment of the available DEMs is crucial before considering regional hydrological modelling. Our methodology is based on using the ICESat/GLAS data as GCPs for comparison purposes at the basin scale. In addition, our method considers different ranges of slope and land cover, and provides a general framework for DEM quality assessments in large and remote regions.

2. Materials

2.1. Study area

The Altiplano watershed is an endorheic system located between latitudes of 22° S and 14° S and longitudes of 71° W and 66° W, with a total area of approximately 192,390 km². The Altiplano watershed is shared by three countries, Bolivia (70%), Peru (26%), and Chile (4%). The climate of this region is semi-arid with low precipitation, and the total amount varies strongly between the north (approximately 750 mm year⁻¹) and south (160 mm year⁻¹) (Condom et al. 2004). The elevation dataset was generated using 33 GDEM v2 tiles for the GDEM version and 5 SRTM v4 tiles for the SRTM version. The elevations of the region varied between 3500 and 6500 m, with a mean elevation of 4700 m. The region includes the TDPS system, which is composed of Lake Titicaca, the Desaguadero River, Poopó Lake, and the Coipasa Salt Pan (or Salar) Basin. The lowest elevations are mainly located in the southern portion of the region and in the floodplain of the Desaguadero River. This river serves as a surficial connection between Lake Titicaca in the north and Uru-Uru and Poopó lakes in the central portion of the basin. The Altiplano Plateau is a very flat region with a mean slope value of approximately 2°. High reliefs are found in two cordilleras (Occidental and Royal) that form the western and eastern borders, respectively, of the watershed. In addition, our study area includes Uyuni Salar, which is located south of the TDPS system but is not part of the same watershed (Figure 1).

2.2. SRTM version 4

The SRTM is a joint product of the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). Data were collected over 11 days in February 2000 using dual spaceborne imaging radar (SIR-C) and dual X-band synthetic aperture radar (X-SAR). From these data, a near-global DEM was generated that spanned 60° N to 56° S. The SRTM DEM data featured two different resolutions. One dataset featured a resolution of 1 arc-second (30 m near the equator) (SRTM1) and was only available for the USA, and the other featured a resolution of 3 arc-seconds (90 m near the equator) (SRTM3). These products were released in 2003 by the United States Geological Survey (USGS) and have been freely available to the public since September 2003.

Since their release, the quality of SRTM3 has progressively improved. The SRTM research team made several improvements to the first version by correcting spurious points, such as spikes and wells, and has aimed to better represent waterbodies and coastlines. A second version was released in 2006 that is still freely available on the USGS website (USGS 2014). The absolute vertical error is 12.6 m in South America for SRTM3 (Rodríguez, Morris, and Belz 2006). More recently, the Consortium for Spatial Information (CSI) of the Consultative Group of International Agricultural Research (CGIAR) released the last official version of SRTM3, which includes several additional improvements (Jarvis et al. 2008). Particularly, the interpolation method described by Reuter, Nelson, and Jarvis (2007), in combination with an auxiliary DEM, allowed the remaining data gaps to be filled. The definition of the waterbodies and coastlines was clarified using the Shorelines and Water Bodies Database (SWBD) produced by the USGS (2003). The final product (SRTM v4) was released in August 2008 and is freely available on the USGS website (CGIAR 2014). The data are delivered in tiles of 5° by 5° that are referenced to the WGS84 ellipsoid and the

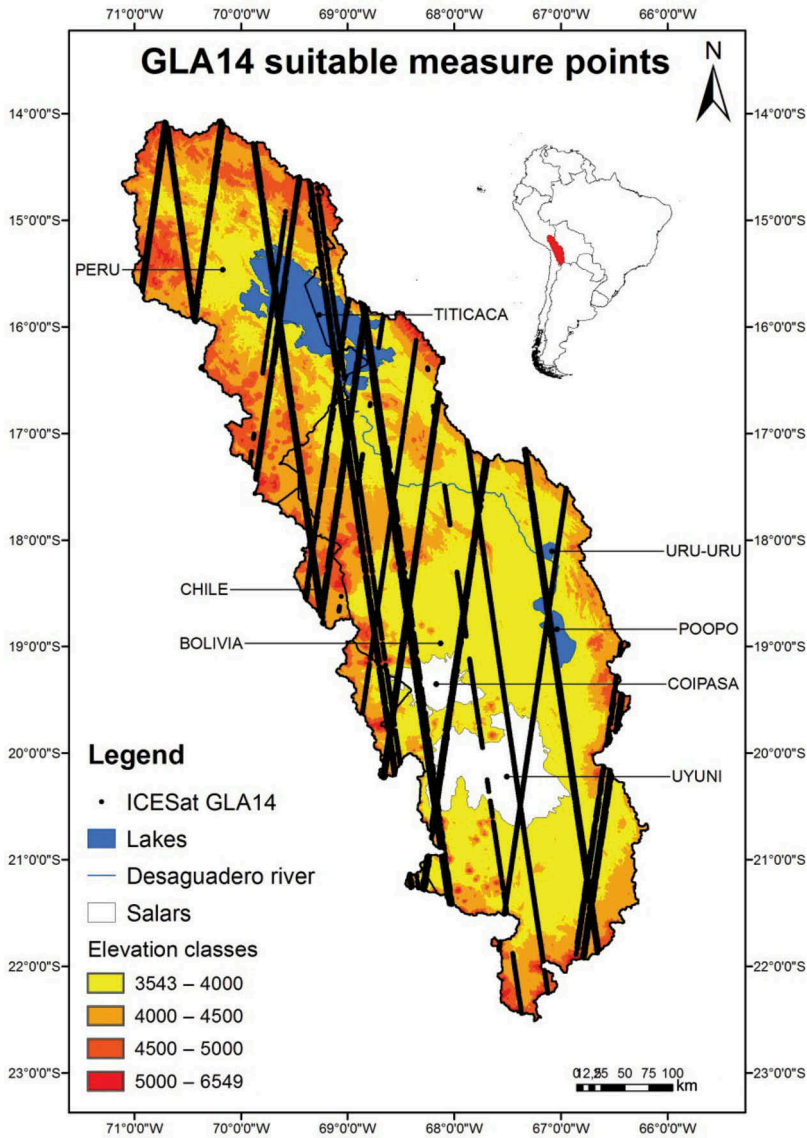


Figure 1. Study area.

EGM96 geoid. Because this version is the last result of a long enhancement process that began with the release of the first SRTM3 version in 2003, SRTM v4 was chosen for this study.

2.3. ASTER GDEM version 2

The ASTER GDEM was jointly developed by the Ministry of Economy, Trade, and Industry (METI) of Japan and NASA. Approximately 1,200,000 scenes of stereoscopic data were collected by the advanced spaceborne thermal emission and reflection

radiometer (ASTER) aboard the NASA Terra spacecraft. These data were used to develop a DEM known as GDEM version 1 (GDEM v1). This freely available version was released in June 2009 with a horizontal resolution of 1 arc-second (30 m near the equator) and covered land between 83° N and 83° S. However, according to the ASTER validation team, GDEM v1 should be considered at the research level (ASTER Global DEM Validation 2009), and methodologies have been developed to improve its quality (Arefi and Reinartz 2011). A second version (GDEM v2) was developed by the ASTER GDEM research team. This version relies on a larger number of stereoscopic scenes than the first version (260,000 more scenes have been used). Zhao, Xue, and Ling (2010) showed that the accuracy of GDEM v1 was better for areas where more scenes were used for its production. Consequently, we could expect an accuracy enhancement in this new version. In addition, this practice led to a significant decrease in the number of anomalies and artefacts, such as residual clouds, bumps, and pits occurring in GDEM v1. In some areas, the artefacts were entirely eliminated (Tachikawa et al. 2011). In addition to the higher number of scenes, a smaller correlation kernel was used (5×5 vs. 9×9 pixels) to yield higher spatial resolution. An improved water mask enabled a more accurate definition of the water surface. Finally, the negative overall bias that was estimated by Zhao et al. (2011) and the ASTER GDEM team to equal approximately 5 m was removed. Overall accuracy shifted from 20 to 17 m at 95% confidence level (ASTER GDEM Validation Team: USGS/EROS METI/ERSDAC NASA/LPDAAC 2009). The GDEM v2 was released on 17 October 2011 and is freely available on the NASA website (NASA 2014b). The data are delivered in tiles of 1° by 1° that are referenced to the WGS84 ellipsoid and EGM96 geoid.

2.4. ICESat/GLAS

The ICESat/GLAS data were produced by NASA. The data were collected between 12 January 2003 and 11 October 2009 by the geoscience laser altimeter system (GLAS) aboard the Ice Cloud and Land Elevation Satellite (ICESat). The footprint size is approximately 70 m, and the inter-track spacing is 30 km (near the equator). The elevation was calculated every 172 m for each track. The altimeter measures the two-way travel time of a pulse that is reflected by the ground. The height is determined by considering the actual velocity of the signal due to propagation in the atmosphere. The ICESat/GLAS mission was initially launched for monitoring the icecaps. This mission had a nearly global coverage, and many studies have considered its capability for monitoring other types of land cover. For example, in Bolivia, Fricker et al. (2005) assessed the performance of the ICESat/GLAS over the Uyuni Salar. The data were compared to a local DEM that was derived from kinematic GPS measurements. The absolute vertical accuracy was within 2 cm over the salar. Baghdadi et al. (2011) demonstrated the satellite's ability for monitoring a French lake with a vertical accuracy of 5 cm relative to automatic *in situ* water-level measurements. Zwally et al. (2002) showed that the vertical accuracy was approximately 15 cm under good conditions at the global scale. Regarding the absolute height error of 12.6 m in South America for SRTM3 and an overall accuracy of 17 m at the 95% confidence level for GDEM v2, the accuracy of ICESat/GLAS can be used as GCPs data. The data are referenced to the TOPEX/Poseidon ellipsoid and EGM96 geoid and can be downloaded through the NASA website (NASA 2014b). The National Snow and Ice Data Centre (NSIDC) provides an IDL routine for reading ICESat/GLAS data and for extracting information in an easy array format with the latitude, longitude, elevation and geoid of each measured point. Thus, this script was used in this study.

Various ICESat/GLAS products are available. These products are referenced from GLA01 to GLA15, and each one is more suitable for a specific task. For this study, we used the latest release (v33) of the GLA14 Global Land-Surface Altimeter data, which is specifically for land-surface elevations (referred to as GLA14 hereafter).

2.5. *GlobCover Land Cover*

With a spatial resolution of 1 km at the equator, the Vegetation Map of Latin America over South America (Eva et al. 2002) was the first accurate description for land cover over this area. Recently, the European Space Agency (ESA) with the help of the Joint Research Center, European Environmental Agency, Food and Agriculture Organization of the United Nations (FAO), United Nations Environment Programme (UNEP), Global Observation for Forest Cover and Land Dynamics, and International Geosphere–Biosphere Programme developed the GlobCover Land Cover (GCLC). This product is the result of an interpretation of data collected by the ENVISAT Medium Resolution Imaging Spectrometer (ENVISAT-MERIS) between 1 December 2004 and 30 June 2006. With a spatial resolution of 300 m, the GCLC presents the most accurate description of land cover ever released. The classification was performed according to the Land Cover Classification System (LCCS) and was developed jointly by the FAO and the UNEP. Overall, 22 different classes are described. Over South America, a more detailed classification based on accurate regional observations is also available. The number of descriptions increases from 22 classes to 52 (Bicheron et al. 2008). The data are freely available on the ESA website (ESA 2014) and are referenced to the GRS80 ellipsoid of WGS84. Due to its greater accuracy, this dataset was used in this study. The study area counts with 22 classes from the 52 defined for South America.

The three most represented classes are bare areas (31%), closed to open shrubland (17%), and sparse vegetation (16%). These classes represent 64% of the entire coverage. According to the GCLC class distribution, the Altiplano can be described as a desert region with only a few urbanized areas (0.1%), and waterbodies and salt areas account for considerable percentages (3.5% and 5.3%, respectively) of the entire surface area.

3. Data processing

3.1. *Preprocessing of DEM data and GPCs selection*

The first step consisted of referencing all elevation data to the same ellipsoid and geoid systems. The SRTM v4 and GDEM v2 data are referenced to the same ellipsoid (GRS80 of WGS84) and geoid (EGM96). However, the ICESat/GLAS dataset is referenced to the T/P ellipsoid. To make the references coherent between the three elevation products, we used the NSIDC-provided IDL tool called ‘IDL Ellipsoid Conversion’, which enables the conversion of the GLA14 array of latitude and elevation from T/P to WGS84 (NSIDC 2014). At each ICESat/GLAS measurement location, the EGM96 was computed using the interpolation program available on the NGA website (NGA 2014) and subtracted from the GLA14 elevation to obtain the GLA14 value referenced to the same system (WGS84/EGM96) as GDEM v2 and SRTM v4. Using a two-dimensional linear interpolation tool available in Matlab software, the elevation of each DEM was computed for all GLA14 points.

Overall, 381,289 GLA014 points are available in the study region. The NSIDC provides quality control based on several flags from which we selected four as follows:

I_elvuseFlg: indicates whether the value should be used or not. Only the data with this flag set 'on' were selected.

I_FRir_gaFlg: indicates the presence of clouds. Only the data with this flag set 'off' were selected.

I_rng_UQF: indicates the quality of the flags. Only the data with good flag quality were selected.

I_satCorrFlg: indicates whether saturation phenomenon occurred during the acquisition and if it was corrected. Only the non-saturated data were selected.

Approximately 50% of the points were unreliable based on the quality control results provided by NSIDC, demonstrating that the quality control is necessary. Thus, 183,713 data points were kept. Another flag called '*i_DEM_hires_elv*' was used by Ensle, Heinzel, and Koch (2012) to remove the ICESat/GLAS data with absolute differences of more than 100 m with respect to a high-quality DEM. Following a similar approach, we computed the absolute difference between GLA14 for both SRTM v4 and GDEM v2 data. Overall, the 116 GCPs had an absolute difference of 100 m or more in comparison to the two DEMs, and 654 GCPs had an absolute difference of 50 m. Considering the small proportions of these data points, we kept the 50 m threshold to ensure a very-high-quality GCP database. The repetitive cycle of ICESat can lead to numerous measurements at the same location. Only one measurement based on location was kept for the database. Because the precision of ICESat is approximately 15 cm and the precisions of GDEM v2 and SRTM v4 are approximately 17 m and 12.6 m, respectively, such a selection will not affect this comparison. According to these criteria, we recorded a data decrease from 183,059 to 157,254 points. The GCLC class was extracted, and the mean slope was computed using the ArcGIS Spatial Analyst tool for each GCP location. Ultimately, the constructed database contained the latitude and longitude, the GLA14, GDEM v2, and SRTM v4 elevations, and the GCLC class and mean slope values for each selected GLA14 point.

3.2. Horizontal accuracy assessment

Our study area includes 33 GDEM v2 tiles and five SRTM v4 tiles. In some of these tiles, only a few square kilometres were included in the TDPS watershed. The horizontal accuracy assessment was applied to only 21 GDEM v2 tiles with at least 50% of their area within the Altiplano watershed. The total considered area included 210,000 km² and covered 84% of the study area. First, we set the two DEMs to the same spatial resolution. The 3" resolution of SRTM v4 was kept, and we aggregated the GDEM v2 pixels from the original 1" resolution to the 3" resolution by computing the mean value of the nine original cells. For each GDEM v2 tile and SRTM v4 tile, we extracted six elevation profiles, three east–west profiles, and three north–south profiles (Figure 2).

Second, assuming that the elevation between two successive DEM points follows a linear equation, the variation in the horizontal position of an elevation increment of 1 m was computed for both DEMs (Figure 3) along each profile. Then, along each profile, the same elevation for both DEMs was detected and the mean horizontal shift was computed. Finally, a mean horizontal shift was computed for both directions by considering all profiles.

ICESat does not present continuous measurements along its footprint; the measurement points are spaced 175 m apart, and some of them are missing due to the quality assessment.

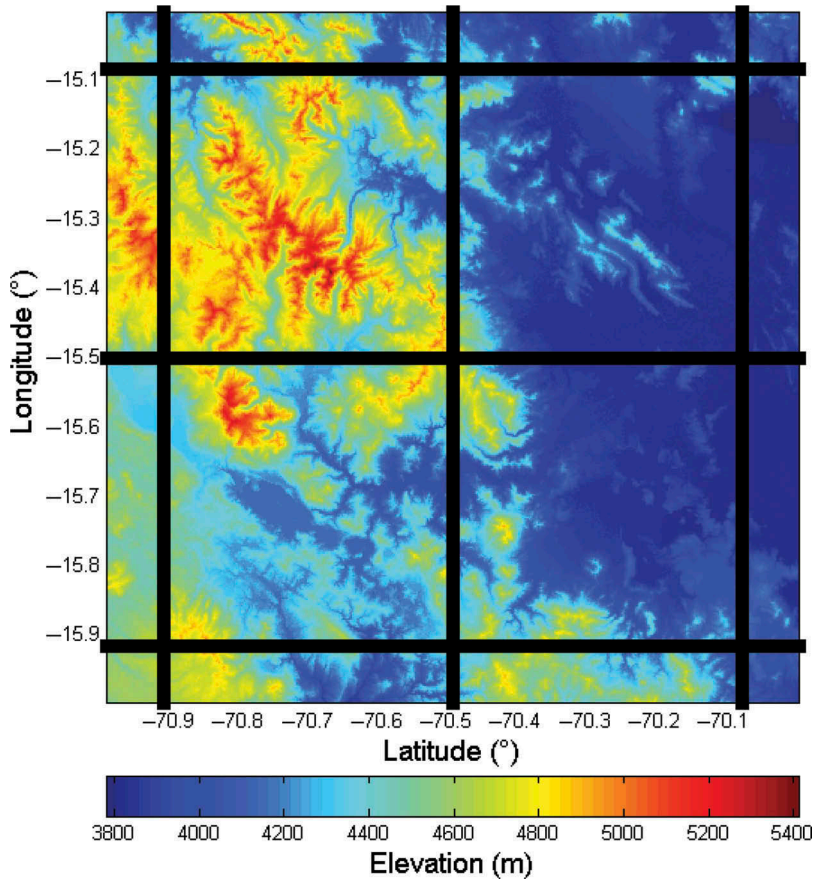


Figure 2. Aggregated GDEM v2 tile with transect locations.

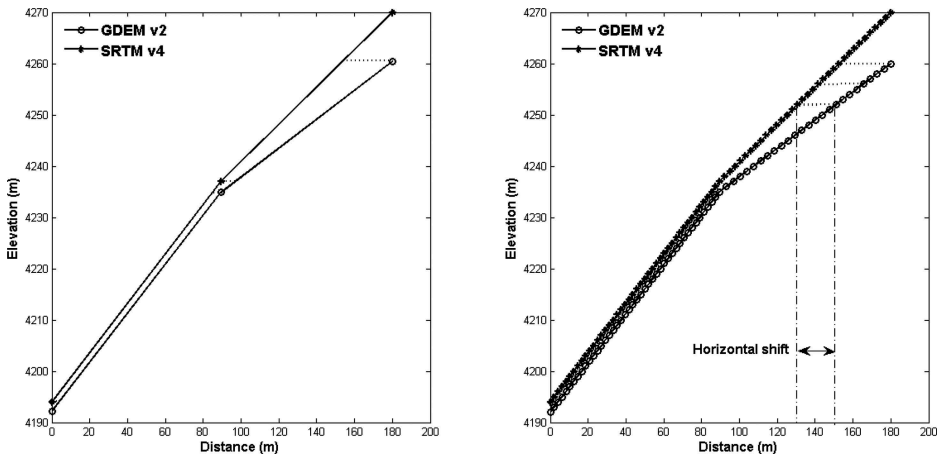


Figure 3. Original elevation profile on the left and elevation profile with increment computation of 1 m to the right.

To assess the DEMs' horizontal shift compared to the GCPs, we extracted eight elevation profiles from an area where the ICESat data were the most homogeneous, with four profiles oriented northwest–southeast and four oriented northeast–southwest.

3.3. Vertical accuracy assessment

To assess the DEMs' qualities, we computed different statistical parameters, including the absolute mean error (AME), standard deviation (STD), and root mean square error (RMSE) (Equations (1)–(3)).

$$\text{STD} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n [(x_i - y_i) - (\bar{x} - \bar{y})]^2}, \quad (1)$$

$$\text{AME} = \sum_{i=1}^n |(x_i - y_i)|, \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n [(x_i - y_i)^2]}{n}}, \quad (3)$$

where n is the number of values; x is the GLA14 value in metres; and y is the DEM value in metres.

This assessment was first performed at a regional scale and considered all available comparison points. However, a global assessment cannot indicate the limitations of DEMs due to their acquisition mode. In rugged regions, the SAR interferometry used to construct the SRTM DEM may fail because the radar backscatter is disrupted in mountainous areas. Because the elevation calculation is based on the delay between emissions and reception, we could expect DEM inconsistencies in such regions. In addition, problems can occur with the GDEM v2 data during the interpretation step of the scenes used for DEM construction due to, for example, shading effects. Consequently, the slope and land use could represent potential influence factors on DEM quality. Therefore, we assessed the DEMs' accuracy with regard to the mean slope value and land cover.

The Altiplano is a very flat region, where 67% of the measured points have a slope value less than or equal to 5°, but there are also areas with rough relief.

To assess the DEMs' accuracy as a function of the mean slope, we developed a frequency histogram based on the mean slope value (Table 3). The first and second intervals account for approximately 55% and 16%, respectively, of the entire dataset. The third and fourth intervals account for approximately 14% and 13%, respectively, of the dataset. The fifth interval accounts for only 2% of the dataset.

To assess the DEMs' quality as a function of the land cover, we selected the six most representative land-cover classes (bare areas, sparse vegetation, closed to open shrubland, mosaic grassland/forest-shrubland, mosaic forest-shrubland/grassland, and waterbodies) and two additional classes (salt hardpans and permanent snow and ice) for their physical particularities. A field investigation showed inconsistencies in the GCLC classifications for these two last classes. Below an altitude of 4500 m, many salt areas were defined as permanent snow and ice instead of as salt hardpans. No permanent snow or ice was found at this elevation in this region. To remain near the ground truth data, we merged these two classes into a single class, salt hardpans, below 4500 m. First, we accounted for all of the GCPs to compute the

Table 3. Computed AME, STD, and RMSE value for GDEM V2 and STMV4 in function of slope ranges.

Classes (°)	Number of points	Area (%)	AME (m)				STD (m)				RMSE (m)			
			GDEM v2	SRTM v4	MERGE DEM	GDEM v2	SRTM v4	MERGE DEM	GDEM v2	SRTM v4	MERGE DEM	GDEM v2	SRTM v4	MERGE DEM
0-2	86,595	55	5.2	7.2	3.7	6.6	4.1	5.3	6.6	8.1	5.3	6.6	8.1	5.3
2-5	24,583	16	6.0	8.5	6.0	8.0	6.8	8.0	8.0	10.2	8.0	8.0	10.2	8.0
5-10	22,143	14	7.8	9.9	7.8	10.2	10.5	10.2	10.2	12.6	10.2	10.2	12.6	10.2
10-20	20,144	13	10.8	13.4	10.8	13.8	15.6	13.8	13.9	16.9	13.9	13.9	16.9	13.9
>20	3789	2	14.6	17.0	14.6	18.0	20.7	18.0	18.2	21.1	18.2	18.2	21.1	18.2
TOTAL	1,57,254	100	6.6	8.8	5.8	9.0	8.6	8.5	9.0	11.1	8.5	9.0	11.1	8.6

AME, STD, and RMSE for these eight classes. Then, to avoid any influences of the mean slope values, the STD and RMSE were computed for the GCPs with mean slope values between 0° and 2° and for the GCPs with mean slope values of between 10° and 15° . For this second step, the classes were ordered as follows according to the GCLC classification system from the sparser and lower classes to the denser and higher classes: bare areas, sparse vegetation, mosaic grassland/forest shrubland, closed to open shrubland, and mosaic forest-shrubland/grassland. These categories are numbered 1 to 5 in [Figure 9](#). Because of their particularities, salt hardpans and waterbodies were not considered ([Table 4](#)).

4. Results and discussion

4.1. Horizontal accuracy

From a visual perspective, no significant horizontal shift was observed between the DEMs. Regarding the bias computation from the elevation profiles with respect to SRTM v4, GDEM v2 shifted by an average of 13.3 m (0.44') east–west and 2.5 m (0.08') north–south. For example, a GDEM v2 shift of 0.104' (east–west) and 0.175' (north–south) was observed relative to SRTM DTED2 (Tachikawa et al. 2011). This difference could be linked to the use of a different DEM as the reference and due to the use of a homogenous region when comparing the 20 sites around the world studied by Tachikawa et al. (2011).

As described in [Section 3](#), the horizontal shift with respect to the GCPs was computed along 8 profiles. We computed mean average shifts of 5.1 and 2.8 m for GDEM v2 and 3.7 and -7.3 m for SRTM v4 in the northeast–southwest and northwest–southeast directions, respectively.

The shift values between the two DEMs and the DEMs with respect to the GCPs remained lower than the DEM resolutions and consequently should not have a significant effect on the vertical assessment of this study.

4.2. Regional Altiplano scale

Overall, 157,254 GLA14 points are available to assess the DEMs' quality in the study area. A significant negative bias was found when comparing the GLA14 and SRTM V4 elevations, with approximately 140,000 negative differences between the two series ([Figure 4](#)). The differences are better distributed around zero when comparing with the GDEM v2 and GLA14 elevation series.

The statistics of the comparisons are reported in [Table 3](#). The AME values between the DEM and GCP elevations were 6.7 and 9.6 m for the GDEM v2 and SRTM V4 products, respectively. The STD is approximately similar for both DEMs, whereas the RMSE is lower for GDEM v2 than for SRTM v4. In previous studies, the RMSE values found for the GDEM v2 products relative to the ICESat data were 6.3 m for Germany (Enslé, Heinzl, and Koch 2012) and 8.8 m for the entirety of South America (Carabajal 2011). A RMSE value of 8.68 m for GDEM v2 was found for the USA in comparison with the GPS benchmark (Gesch et al. 2011). The RMSE computed in this study was similar to the values computed for South America, Germany, and the USA and was lower than the values reported when using GDEM v1. For example, the reported values were 13.1 m (using GPS points as GCPs) and 17.3 m (using ICESat as GCPs) for China and Australia, respectively (Hirt, Filmer, and Featherstone 2010; Zhao, Xue, and Ling 2010). In this case, the GDEM v2 STD was equivalent to the STD of 8.5 m that was computed for South America by Carabajal (2011).

Table 4. Computed AME, STD, and RMSE values for GDEM V2 and STMV4 in function of GCLC classes.

Classes	Number of points	Area (%)	Mean slope (°)	AME (m)						STD (m)						RMSE (m)					
				GDEM v2	SRTM v4	MERGE DEM	GDEM v2	SRTM v4	MERGE DEM	GDEM v2	SRTM v4	MERGE DEM	GDEM v2	SRTM v4	MERGE DEM	GDEM v2	SRTM v4	MERGE DEM			
Bare areas	58,265	31	0.34	5.0	7.6	5.0	7.1	6.1	6.1	6.1	6.1	7.1	8.9	7.1	8.9	7.1					
Sparse vegetation	22,383	16	7.5	8.1	10.6	8.1	10.9	11.3	11.3	11.3	11.3	10.9	13.6	10.9	13.6	10.9					
Closed to open shrubland	22,504	17	3.7	7.1	10.7	7.1	9.7	10.1	10.1	10.1	10.1	9.7	12.9	9.7	12.9	9.7					
Mosaic grassland/Forest-shrubland	7643	5.7	3.5	6.2	11.6	6.2	8.7	8.6	8.6	8.6	8.6	8.7	13.3	8.7	13.3	8.7					
Mosaic forest-shrubland/grassland	7269	4.3	6.0	7.8	10.7	7.8	10.5	10.5	10.5	10.5	10.5	10.5	13.2	10.5	13.2	10.5					
Salt hardpans	9243	5.3	0.6	5.8	4.8	2.1	8.0	2.5	2.5	2.5	2.5	8.0	5.3	8.2	5.3	3.0					
Waterbodies	12,363	3.5	0.03	8.5	3.7	0.9	2.4	1.8	1.8	1.8	1.8	2.4	4.1	8.8	4.1	2.3					

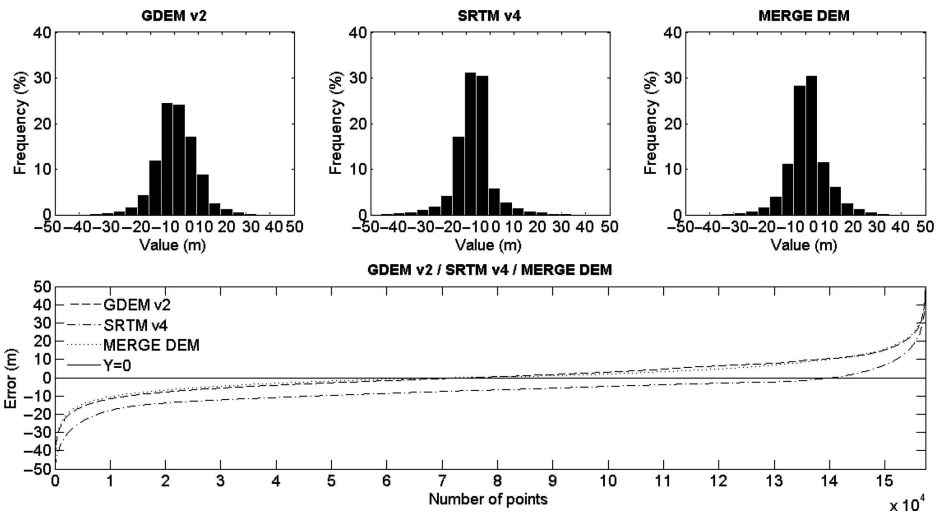


Figure 4. Error distribution of GDEM v2 (top left) and SRTM v4 (top middle) and MERGE DEM (top right) and error distribution of GDEM v2, SRTM v4, and MERGE DEM (bottom).

The good performance of GDEM v2 can be explained by the large number of scenes used in its construction for the Altiplano region. As presented in Carabajal (2011), the study region includes a large number of scenes (between 20 and 60 scenes). Previous studies on the GDEM v1 show that the GDEM v1 quality increases with the number of scenes used (Billemont 2010; Zhao, Xue, and Ling 2010). This result partly explains the good results obtained for GDEM v2.

4.3. Mean slope

As reported in Table 3, the AME increases from 5.2 to 14.6 m for GDEM v2 and from 7.2 to 17.0 m for SRTM v4 but remains lower for GDEM v2. The STD value increased from 6.6 to 18.0 m for GDEM v2 and from 4.1 to 20.7 m for SRTM v4. The regions with gentle relief present a lower STD for SRTM v4. The RMSE values increased from 6.6 to 18.2 m for GDEM v2 and from 8.1 to 21.1 m for SRTM v4. For both DEMs, the AME, STD, and RMSE increased with the mean slope value. The accuracies of the DEMs were clearly linked to the mean slope values (Figure 5).

Regions with low mean slopes presented lower STD and higher RMSE values for SRTM v4. These results are consistent with those obtained for different GCLC classes. The low mean slope areas are primarily bare areas, closed to open shrubland, mosaic grassland/forest-shrubland, salt hardpans, and waterbodies (Table 4). For all of these classes, the STD values were lower for SRTM v4 than for GDEM v2, or the values were very similar for both DEMs. Higher RMSE values were observed for SRTM v4 and for all land-cover classes, except for salt hardpans and waterbodies, which are less representative of the studied regions. Consequently, a lower mean STD and a higher RMSE were observed for the low mean slopes for SRTM v4.

The negative bias of 8.8 m occurred for all classes when comparing the entire GCPs dataset with the SRTM v4 elevations. Because of the small STD and RMSE values of the first two classes, the negative SRTM v4 bias is clearly identifiable in these classes (Figure 6).

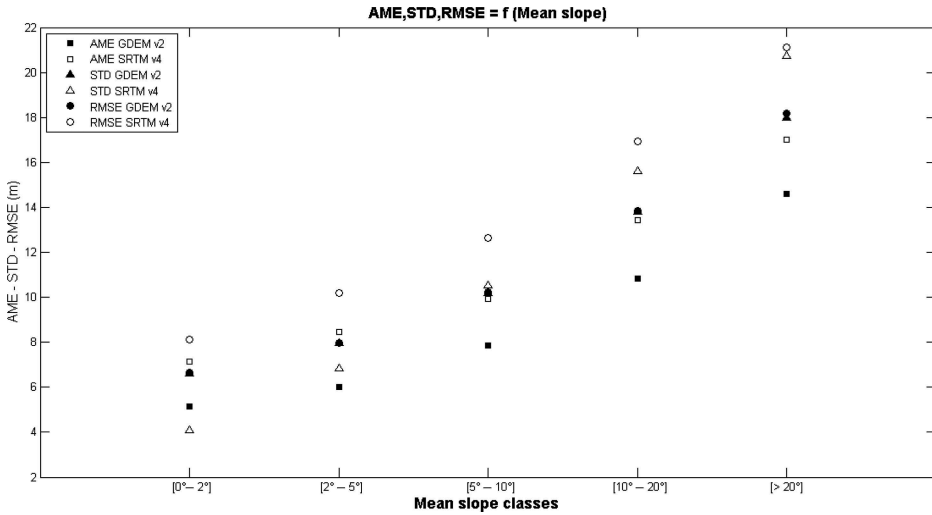


Figure 5. STD (top) and RMSE (bottom) distribution in function of the slope range for SRTM v4 and GDEM v2 DEMs.

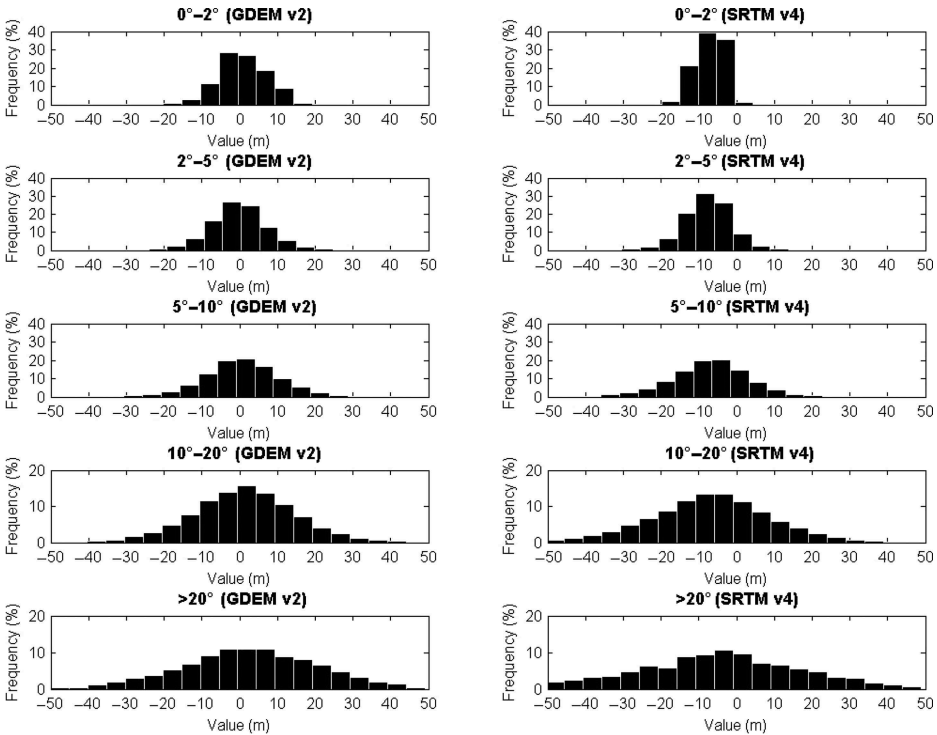


Figure 6. Error distribution for GDEM v2 (left) and SRTM v4 (right) for increasing slope range (from top to bottom).

4.4. Land cover

The negative bias observed for SRTM v4 at the regional scale is confirmed in every type of cover. For salt hardpans and waterbodies classes, the negative bias was very noticeable (Figure 7 and 8).

The AME and RMSE values were lower for GDEM v2 than for SRTM v4, except for the salt hardpans and waterbodies classes. The STD values were lower for SRTM v4, except for sparse vegetation and closed to open shrubland, but the values were very similar to those of GDEM v2 (Table 4).

The bare areas class exhibits lower STD and RMSE values in both DEMs. These results agree with the values computed for the same class in GDEM v2 by Carabajal (2011) through the use of ICESat/GLAS data over South America. Carabajal (2011) observed STD and RMSE values of 7.9 and 8 m, respectively. Slightly better scores were observed in our study (STD and RMSE values of 7.1 m) due to the low mean slope value of this class (approximately 0.34°). As previously shown, the qualities of the DEMs increased as the mean slope values decreased.

For low mean slope values and the GDEM v2 data, no significant correlations were observed between the STD and RMSE values and the GCLC classes. Although more variations were highlighted for the SRTM v4 data for both low and high mean slope values, no correlation was found with the cover type. In both cases, for both DEMs and for all of the land-cover classes, the STD and RMSE values increase

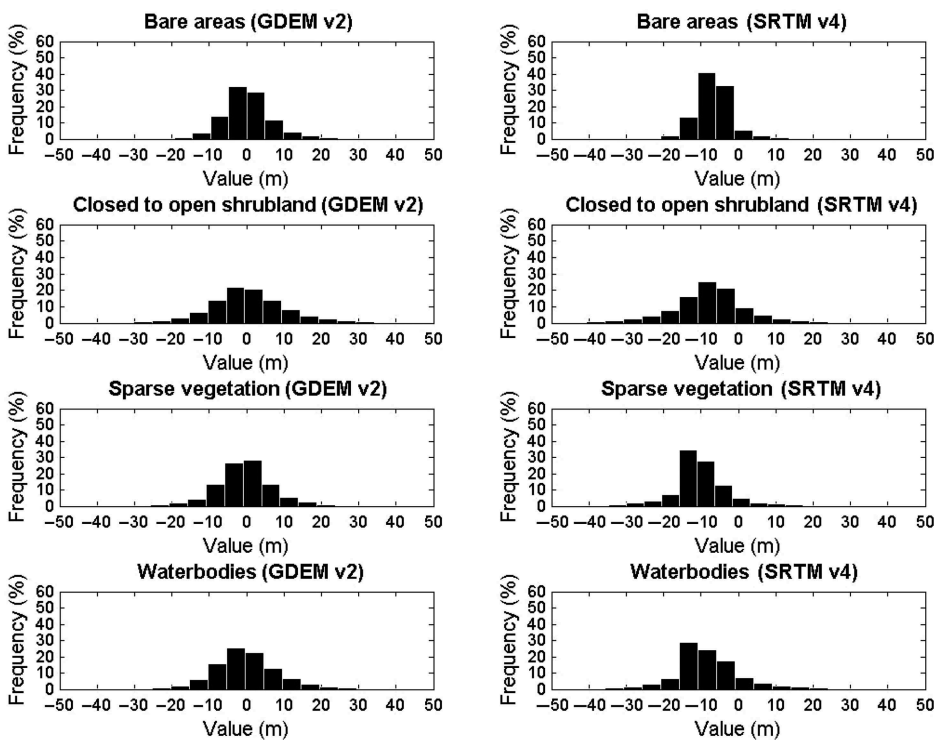


Figure 7. Error distribution for GDEM v2 (left) and SRTM v4 (right) for different land occupation classes (from top to bottom).

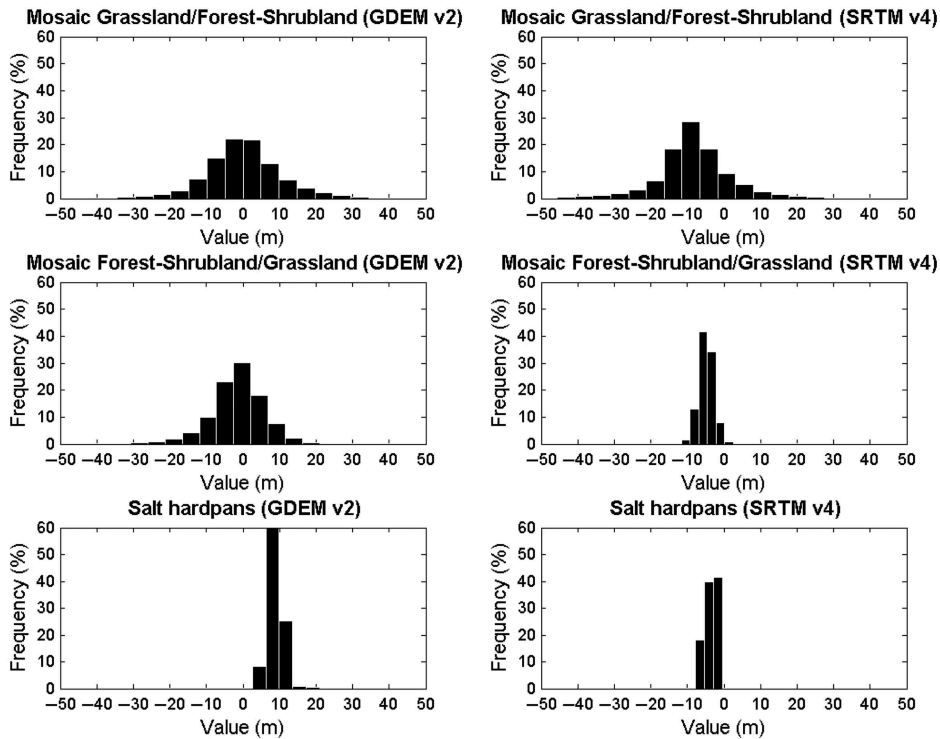


Figure 8. Error distribution for GDEM v2 (left) and SRTM v4 (right) for different land occupation classes (from top to bottom).

considerably as the mean slope values increase (Figure 9). Finally, in the Altiplano region, the DEMs' quality is clearly related to the mean slope value and not to land cover. These results are consistent with the significant homogeneity in land cover that was observed during the field investigation. The entire region could be characterized as a bare to shrub area.

5. Enhancement of SRTM v4 accuracy in specific areas

For SRTM v4, the salt hardpans and waterbodies classes exhibited very small STD values (< 3) and small RMSE values (< 6) (Table 4). Removing the negative bias can enhance the SRTM v4 accuracy for this particular land cover without resulting in additional errors in the data. Due to the hydrological context within this region and the very low slope, these specific areas feature a significant tidal effect. The lake water levels can vary by up to 2 m depending on the season, and the salars can be flooded periodically to a depth of approximately 1 m. The SRTM v4 data were acquired in February 2000, which corresponds to the wet season in this region. Consequently, the high lake water levels were measured, which resulted in negative bias for the lakes and salars. To compute the SRTM v4 bias for these surfaces, we only used the GLA14 data for the dry period to record the low water levels. The dry season occurs between April and October. Unfortunately, the ICESat sensor did not work continuously during this period because of technical problems (NASA 2014a). The data used to compute

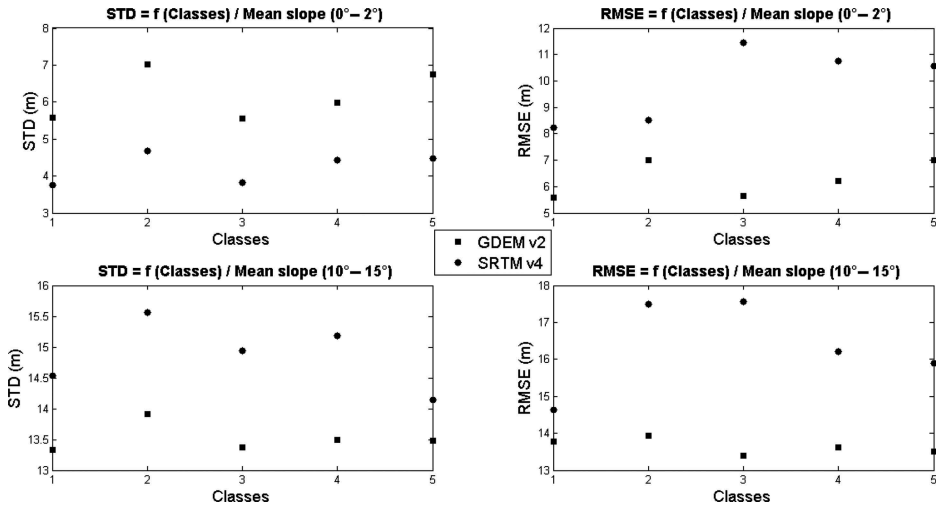


Figure 9. STD (left) and RMSE (right) distribution in function of vegetation height and density for low mean slope value (top) and high mean slope value (bottom) for SRTM v4 and GDEM v2.

the bias on Lake Titicaca, Lake Poopó, and the Uyuni and Coipasa Salars were from the operational periods in May and June.

We removed the computed bias in the SRTM v4 for these specific areas. The resulting ‘SRTM v4 corrected’ was used for the Titicaca, Poopó, Coipasa, and Uyuni areas, whereas the GDEM v2 was used to characterize all of the other areas. A new DEM (termed MERGE DEM hereafter) was obtained by merging these different areas together. Overall, the GDEM v2 accounted for 90% of the MERGE DEM, whereas the corrected SRTM v4 only represented 10%. To assess the quality of this new DEM, the same statistical approach used for the GDEM v2 and SRTM v4 was used. The results are summarized in [Tables 3 and 4](#).

The AME values were significantly reduced and were well distributed around 0 ([Figure 4](#)). In addition, the RMSE and STD values were reduced, and the correction resulted in a considerable improvement. This MERGE DEM appears to be a more accurate product for characterizing the topography of the Altiplano watershed.

The corrected areas were defined by using the GCLC data, which were not very robust. In addition, the GCLC does not represent Lake Uru-Uru as a continuous surface waterbody. Only a few, unconnected pixels were identified as water areas. Consequently, this lake was not considered in this study. Previously, we observed that problems could also occur in the delineation of salt areas. To enhance the definition of the lake and salt areas, high-resolution satellite imagery is more appropriate.

The differences between the MERGE DEM and the GDEM v2 and SRTM v4 varied between -573.5 and 390.5 m ([Figure 10](#)). This large variation range could be explained by the presence of artefacts, such as clouds, bumps, and pits, which were also detected in the GDEM v1 (ASTER GDEM Validation Team: USGS/EROS METI/ERSDAC NASA/LPDAAC 2009; Arefi and Reinartz 2011; Jarvis et al. 2008; Hirt, Filmer, and Featherstone 2010) and were not totally removed in the processing method of the GDEM v2 (Tachikawa et al. 2011). Because SRTM v4 does not represent the ground truth data, these differences cannot be attributed in their totality to GDEM v2 deficiencies.

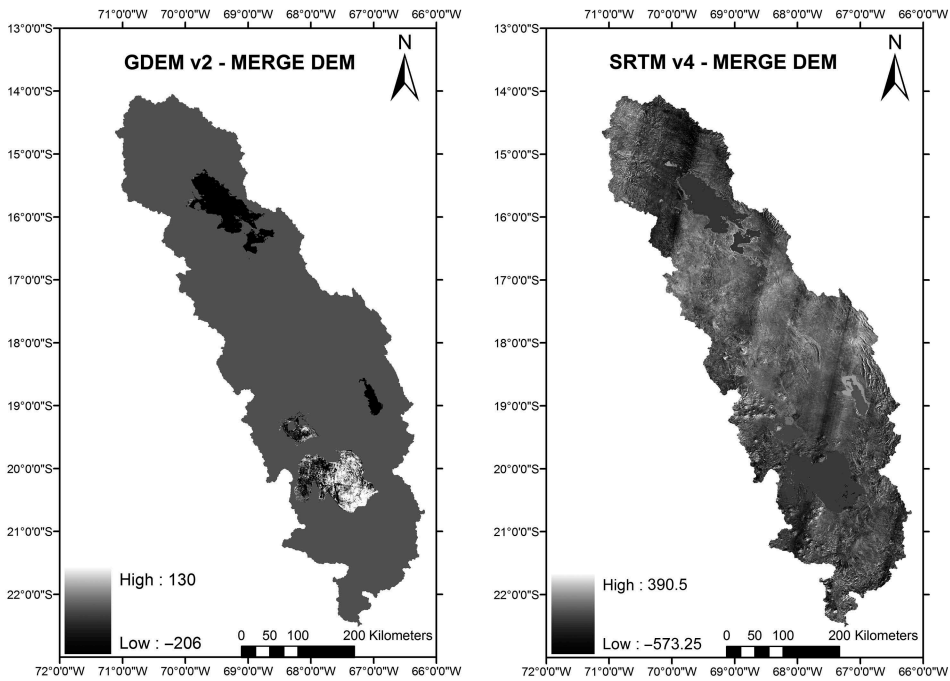


Figure 10. Elevation differences between GDEM v2 and MERGE DEM (left) and between SRTM v4 and MERGE DEM (right).

Due to their small-scale impacts (one to a few pixels), these differences are hardly evidenced through the use of GCPs that consist of point measurements that often do not match these specific areas. Using a high-quality, global-scale dataset, such as a reference DEM, would allow for the characterization of these deficiencies. The method developed by Arefi and Reinartz (2011) to enhance GDEM v1 should be applied to enhance the DEM quality for those specific areas.

6. Conclusions

The quality of the two most commonly used DEMs (SRTM v4 and GDEM v2) was assessed for the Altiplano watershed by using the ICESat/GLAS data as GCPs. A database of approximately 150,000 high-quality GCPs was used. We conducted a quality assessment for each land-cover type encountered in the study area and for different types of relief. A global assessment showed a significantly negative bias in the SRTM v4 data of 8.8 m, whereas the GDEM v2 was well distributed around zero with an AME of 6.6 m. The STD and RMSE values were 9.0 and 9.0 m, respectively; for GDEM v2 and 8.6 and 11.1 m, respectively, for SRTM v4. Although some artefacts were not completely removed from the GDEM v1, the GDEM v2 better represented the topography in this area. A significant correlation occurred between the quality and slope values of the DEMs. The quality decreased when the slope value increased. Considering the techniques that were used in their development, the SRTM v4 should provide information regarding the ground elevation independently of the cover, whereas the GDEM v2 should provide the ground elevation while considering its cover. However, for the Altiplano region, the

vegetation did not impact the accuracies of the DEMs. Finally, we demonstrated that correcting the SRTM v4 for negative bias in specific areas (lakes and salars) and merging it with the GDEM v2 values can be an efficient method for better representing the topography of this region.

From a more general perspective, this study highlights the usefulness of the ICESat/GLAS data for evaluating DEMs for use in remote regions. Due to their accuracy and dense spatial coverage, the ICESat/GLAS data are very well suited for this type of assessment because they provide a large dataset of GCPs. As shown here, this large dataset allows users to split the dataset and combine it with land-cover products to investigate the accuracy of the DEM over several ranges of slope and land-cover type while maintaining a sufficiently large dataset for statistical evaluation.

However, this study is the first step in assessing two commonly used DEMs. The study focuses on horizontal and vertical accuracy using point comparisons. Based on the performance of GDEM v2 and the new MERGE DEM, these DEMs better represent the topography of the TDPS. However, users must remember that this study focused on a point-to-point comparison and does not consider relationships between neighbouring pixels. If an elevation pixel is greater than or lower than the surrounding elevation pixels while the truth data are the opposite, an incorrect topographic shape will result. Hydrological applications are based on mean slope calculations, which involve global topography computations. Even if certain local corrections are possible, errors could remain and result in poor hydrological network extraction and incorrect watershed delimitation. The performances of DEMs in a hydrological application are not linked to the mean elevation error but to the good relative elevation between the pixels. Future DEM studies should focus on this point. However, reference data for the Altiplano are currently missing, which would make such a study difficult. High-quality DEMs, a hydrological network, or watershed delimitation could be used as reference data to compare and assess the results obtained from remotely sensed DEMs.

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