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Ten years of monthly mass balance of Conejeras glacier, Colombia, and their evaluation using different interpolation methods

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ABSTRACT

Understanding global climate change and its impacts on glaciers in the inner tropics is challenged by an absent climate seasonality that requires glacier monitoring at increased frequencies. Conejeras glacier in Colombia has been monitored monthly for 10 years, contributing to the limited knowledge of glacier mass development in this region. We acquired a terrestrial Lidar digital elevation model (DEM) and performed a full homogenization of the time series. Applying a number of interpolation methods, we calculated glacier-wide balances and deduced respective uncertainties. All interpolation methods revealed comparable variations in monthly surface mass balance, but the profile method failed in certain cases. We recommend using the Index-site method for monthly and annual and the Contour-line method for annual surface mass balances. Even when strongly reducing the stake network, the Index-site method and geostatistical interpolations (Kriging and Topo to Raster) showed robust and reliable results. Conejeras glacier is strongly down-wasting with a mass loss of 29 400 mm w.e. and an area shrinkage of 20% within 10 years. Surface mass balance variations were strongest from November to February and depend largely on the intensity of El Niño Southern Oscillation. With a repeat DEM in the near future the glaciological time series could be validated with the geodetic mass balance. We recommend continuing the monthly monitoring programme, but complementing it with an energy balance study using additional meteorological data to better explain the glacier–climate interactions. However, to track the glacier's mass variations, a monitoring network with lower measurement frequency and stake density would be sufficient.

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1. Introduction

Tropical glaciers are relevant indicators to document and understand climate variability. To achieve this, it is important to monitor their mass changes over long time periods, typically 30 years. Climate changes are global, and thus worldwide data on glacier changes are necessary. Before the mid-1990s, glaciers in the inner tropics of South America have not been represented by a continuous mass balance programme (Francou et al. 2000), although glaciers and glacial discharge are important for the páramo ecosystems (Jacobsen et al. 2012; Vuille 2013). This gap has hampered the understanding of glacio-climatic processes in the humid inner tropics without a clear temperature and precipitation seasonality (Vuille et al. 2008) in contrast to the outer tropics with a marked dry and wet season

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(Kaser 1999; Francou et al. 2004). It was unclear whether the common accumulation–ablation balance monitoring strategy with two measurement campaigns per year would have sufficient time resolution to infer a glacier's relation to weather patterns. Therefore, Ecuador has started the first inner-tropical mass balance programme with monthly measurements on Antisana 15α, an outlet glacier of the ice cap on Volcán Antisana in 1994 (Francou et al. 2000). Initially motivated by natural hazards on ice-capped volcanoes (Thouret 1990, Huggel et al. 2007), glacier monitoring in Colombia started in 1985 and was expanded in the 2000s to a Colombia-wide monitoring programme. Measurements showed a massive glacier area loss in the twentieth and the beginning of the twenty-first century, but knowledge about short-term mass changes and the relation to climate variability was still missing (Ceballos et al. 2006, Poveda & Pineda 2009). In 2006, the national meteorological institute of Colombia (Institute for Hydrology, Meteorology, and Environmental Studies, IDEAM) in collaboration with the University of Zurich set up a glaciological mass balance programme based on monthly measurements on Conejeras glacier. The international project 'Capacity building and twinning for climate observing systems' (CATCOS) by the Swiss Agency for Development and Cooperation has supported the programme since 2011.

One decade of monthly mass balance measurements had been compiled, but the results were heterogeneous because (1) inter- and extrapolation methods were inconsistently used and (2) glacier extents as well as the glacier hypsometry had been uncertain. These issues were the main sources of systematic errors of the glacier-wide mass balance and a homogenization of the time series was needed to solve them. The continuous changes in glacier extent as well as the interpolation method can lead to large uncertainties (Zemp et al. 2013; Basantes-Serrano et al. 2016), but only few studies have systematically quantified them (e.g. Funk et al. 1997, Sold et al. 2016).

This study aimed at homogenizing 119 months of glacier surface mass balance data to reveal the general trend of mass changes on Conejeras glacier, including the annual and sub-seasonal spatial mass change patterns. A major objective was to investigate the impacts of using different methods for the spatial interpolation of point observations to calculate glacier-wide surface mass balances in order to retrieve the most robust data series and its respective uncertainties. Thus, a high-resolution Lidar digital elevation model (DEM) was generated *in situ* to provide the necessary precise elevation information. We also assessed the effect of a smaller stake network for a possible effort reduction of the monitoring programme. In addition, we wanted to establish the link between monthly surface mass balances and the seasonal climate cycle of the inner tropics.

2. Study area

Colombia hosts four glacierized regions between 3 and 11 degrees North. All of them are located in the inner tropics that are characterized by year-round precipitation (Troll 1941) with two small peaks and by almost uniform air temperatures (Kaser and Osmaston 2002; Braitmeier 2003). Conejeras glacier is located on the western side of Volcán Santa Isabel, the lowest of three neighbouring glacierized volcanoes (North-South: Nevado del Ruíz, Nevado Santa Isabel, Nevado del Tolima) in the Cordillera Central, about 140 km west of Bogotá (Figure 1). Daily minimum air temperatures occur in July–August (~0°C) and daily maximum temperatures in April and November (~1.6°C). Total precipitation reaches ~1500 mm in the lowlands (Manizales, 2160 m a.s.l.; IDEAM 2005) and much lower values close to the glacier (390–1130 mm; Laguna Verde Station, 4304 m a.s.l.; similar values in Braitmeier 2003), as is typical for high elevations in the inner tropics (Weischet 1996). North-western South America is heavily influenced by the El Niño Southern Oscillation (ENSO) phenomenon, which is caused by variations in sea surface temperatures (SSTs) in the equatorial Pacific. Its warm and cold phases cause positive and negative temperature and precipitation anomalies in the tropical Andes (Vuille et al. 2000, Garreaud & Aceituno 2001, Francou et al. 2004), the intensity of which depends on the strength of SST variations (McPhaden et al. 2006; Rabatel et al. 2013). During the *in situ* monitoring period, two intense El Niño events took place in 2009/2010 and in 2015/2016.

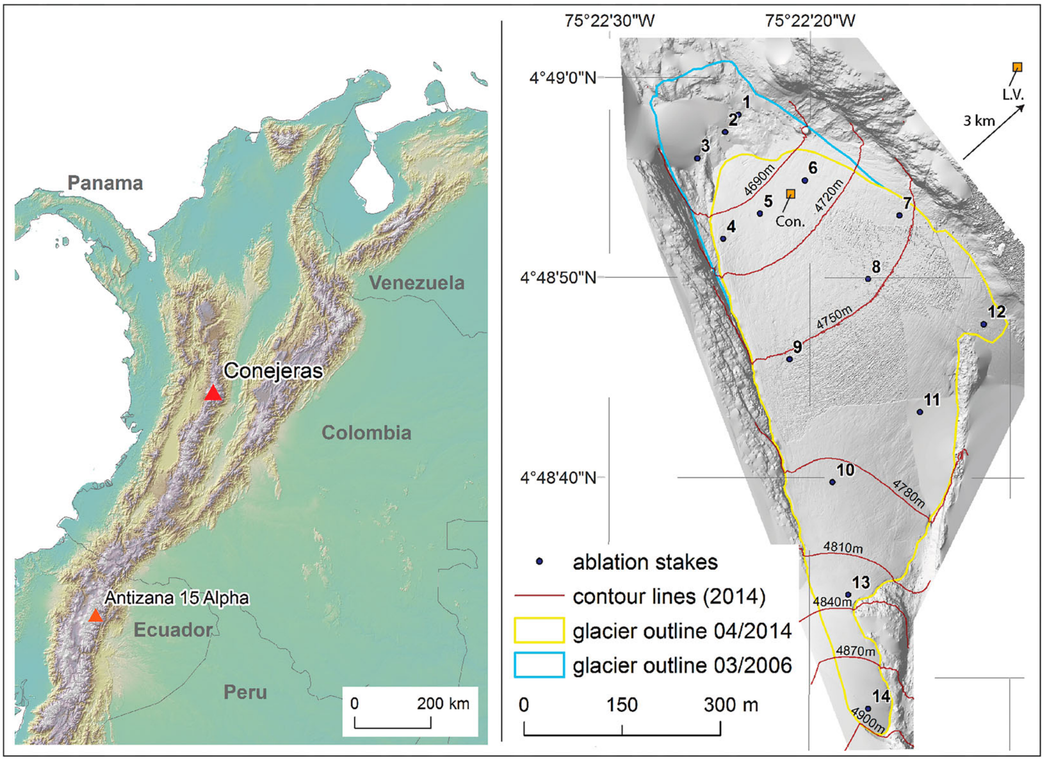

Figure 1. Left: Location of the two mass balance glaciers in the tropical Andes: Conejeras and Antizana 15α. Right: A hillshade of the Lidar DEM of Conejeras glacier and glacier outlines from 2006 and 2014 overlaid by Lidar DEM contour lines and the stakes network. The orange rectangles indicate the locations of the two meteorological stations: Conejeras (Con.) and Laguna Verde (L.V.).

Conejeras glacier (4°48.8′N, 75°22.3′W) is small (~0.2 km^2) with a low mean elevation (~4750 m a.s.l.) and a small elevation range (4600 m–4900 m a.s.l.). Its surface is homogenous with few crevasses and no avalanche-prone areas, allowing the set-up of a representative and dense stake network (Figure 1). Conejeras glacier is located on the main mountain ridge between two higher peaks, facing the North-West, and is the remnant of a former outlet glacier of an ice cap covering Santa Isabel, which has disintegrated into several small glaciers. Its geometry is somewhat cone-shaped, with just a small elongated extension reaching elevations above 4800 m a.s.l. Due to its small altitudinal range and its small share of high-elevation areas, the glacier is highly sensitive to changes in meteorological conditions. The glacier is generally debris-free, but impacted by ash fallout during active phases of neighbouring volcano El Ruíz (~10 km from the glacier). A peculiar feature of the glacier is the large number of dead birds that are found on the surface as well as in the ice, for which we do not have any explanation.

Conejeras is the only glacier in the inner tropics with a monthly monitoring time series of both the lower and higher regions of the glacier, while Antisana 15α (660 km distant, Figure 1) and mass balance glaciers in the outer tropics are being monthly monitored in the ablation area only (Rabatel et al. 2013). The Conejeras programme is, therefore, an important extension and contributes to the picture of glacier development over the tropical Andes.

3. Data and methods

3.1. Stake data

In March 2006, a network of 12 stakes was installed on the glacier to measure both ablation and accumulation. The 6–12 m long stakes consist of PVC pipes of 2 m length with chain links. They are equipped with barbed hooks of spring steel to avoid floating in the steam-drilled hole and with cutting marks showing the stake number. These 12 stakes are roughly organized in 4 cross profiles at about 4670, 4700, 4750, and 4780 m a.s.l. (Figure 1). In April 2007, two more stakes were placed at 4830 and 4885 m a.s.l. to cover the upper reaches of the glacier. Glaciologists from IDEAM carry out the measurements in the first week of every month. Typical measurements of the field surveys include stake readings (monthly), density measurements in snow and firn pits (about three times a year), and redrilling of stakes (if required) at the former position.

The stake network density is 46–58 stakes km^{-2}, that is, ~1 stake per 2 hectares. This value is high compared to other well-established networks, for example, on Storglaciären (~15 stakes km^{-2}, Zemp et al. 2010) or Silvrettagletscher (12 stakes km^{-2}, Huss et al. 2009).

3.2. Elevation data

While a high-resolution DEM had not been available for Conejeras glacier, it represents a necessary input for the surface mass balance analysis and can serve as a reference for future geodetic mass balances. Until recently, calculations have been made with coarse topographic data from the National Geographic Institute and few point measurements from topographic surveys. Accordingly, a terrestrial laser scanning survey was carried out in January 2014 to create a precise base-line data set. An ultra-long-range RIEGL VZ-6000 device was used (near-infrared laser beam at 1064 nm) and represents an ideal choice for glacial studies requiring high-accuracy and precision geodetic data, as demonstrated by recent studies (Gabbud et al. 2015, Fischer et al. 2016).

Reflector targets for georeferencing purposes were fixed on stakes or rocks around the glacier and measured using differential GPS. Three distinct scan positions were set to achieve good coverage of the whole glacier and its surroundings. Using the software RiSCAN PRO, the data processing consisted in a filtering of points (e.g. due to atmospheric reflections caused by dust or moisture), a unification of the point clouds from the three different scan positions, and the georeferencing of the final grid using the target reference points. The final DEM has a spatial resolution of 0.5 m and was projected to MAGNA Colombia Bogotá (EPSG 3116), the official georeference system of Colombia. The Lidar DEM provided precise (0.04 m) elevation information. Elevation bins of 30 m were derived and used for the calculation of the specific net balance, consistently for the whole time series.

3.3. Meteorological data

The IDEAM has set up several weather stations on and around the glacier. Two of these recorded temperature and precipitation data with high quality over a longer period. The 'Laguna Verde' station was erected ~3 km from the glacier at 4304 m a.s.l. in May 2008 to measure hourly precipitation and temperature. Another station was installed in spring 2009 on the glacier tongue at 4700 m a.s.l. measuring temperature and humidity. From these stations, temperature and precipitation data are available for the periods May 2008–January 2016 (precipitation) and March 2009–January 2016 (temperature), including some periods with data gaps. The overlapping period shows a temperature difference of 1.7°C (lapse rate of 4.25°C km^{-1}).

The multivariate ENSO index (MEI) was considered (Wolter and Timlin 2011) as a variable reflecting the intensity of El Niño/La Niña. The MEI is based on several variables observed over the tropical Pacific, including sea-level pressure, zonal/meridional surface wind, SSTs, surface air temperature, and total cloudiness fraction (Wolter & Timlin 1993).

3.4. Methodology for the time series homogenization

The homogenization of the surface mass balance time series followed recommendations by Cogley et al. (2011) and Zemp et al. (2013) and contained the following steps: (1) Snow density correction of stake data, (2) use of an accurate DEM for defining the size of elevation bins used for interpolation,

(3) correction of measurement periods to monthly intervals, (4) glacier outline correction, (5) detection and filling of outliers, (6) application of a selected interpolation method, and (7) assessing of random errors.

Homogenization of the stake values. In the first step, the data series of each stake was homogenized to reduce errors and uncertainties. Field measurements indicated high values and very low variations of snow density throughout the seasons, possibly due to high temperatures during snowfall events (see also Francou et al. 2004). Thus, a stake value correction was performed when snow accumulation was present using a constant for snow density (450 kg m^{-3}).

Due to weather and logistics, it is not possible to perform the measurements on the same day every month; hence, monthly stake values were adjusted by linear interpolation. A fixed-date system was applied for calculating monthly and annual surface mass balances. The latter are calculated for calendar years, which roughly fit to the onset of the strong ablation period.

From five dates of glacier boundary surveys (03/2006, 11/2009, 10/2012, 01/2014, and 04/2014), glacier area and area share per elevation bin were linearly interpolated for each month. This synthetic time series of glacier extents is used for the calculation of glacier-wide surface mass balances on a monthly basis.

The subsequent analysis revealed some unusual mass balance patterns caused by individual and possibly wrong stake values. These presumably originate from wrong stake readings or the field-office transfer and need to be adjusted or removed from further analysis. Earlier studies recommended filtering accumulation point values before the spatial interpolation (Rotschky et al. 2007) and we used a modified Thompson Tau Test (outlier if $x \geq 1.5 * \tau * std$; $\tau = 1.8498$ for 14 stakes; Anbarasi et al. 2011) to identify 18 outliers (0.01% of all values). The new values were derived from interpolating neighbouring values or from the linear correlation with elevation (uppermost stake #14).

Interpolation method. Earlier investigations showed that the interpolation method is a major source of uncertainties (Zemp et al. 2013; Basantes-Serrano et al. 2016). Hence, different interpolation methods were compared to identify the differences and select the most appropriate one. Good coverage of the glacier surface with stakes allowed for the related testing. As a reference data set (e.g. geodetic mass balance) is not yet available, the range of results from the various interpolation methods is used as uncertainty estimation for the final surface mass balance series.

Initially, the surface mass balance following the direct glaciological method (e.g. WSB, Paterson 1994) was calculated using the original profile method (e.g. Escher-Vetter et al. 2009). The surface mass balance B is calculated for each elevation bin (N = number of elevation bins) from the simple linear regression function $f(z)$ based on a correlation between local stake values (accumulation/ablation) and elevation using the area–elevation distribution $A(z)$ of the respective period of record (PoR).

$$B = \frac{\sum_{i=1}^{N} f(z_i)A(z_i)}{\sum_{i=1}^{N} A(z_i)}. \tag{1}$$

Applying this method to Conejeras glacier, a major drawback appeared when we analysed the values for equilibrium line altitude (ELA) and surface mass balance gradient ($\mathrm{d}b/\mathrm{d}z$). The mass balance gradient is often small or even negative, revealing a low correlation between stake values and elevation. As a consequence, in some months both the ELA and the specific balance showed implausible values.

Thus, we compared the original profile method (*O-Profile*) to an adapted version of it (*A-Profile*), to the contour-line method (*Contour*), and to the index-site method (*Index*). In the *A*- and *O-Profile*, the surface mass balance value per elevation bin is calculated from the linear regression between stake values and elevation, but for the *A-Profile* the linear regression $f(z)$ is based on the arithmetic mean of stake values in the same elevation bin; thus, only 6 instead of 14 values are used to derive the regression parameters for $f(z)$.

The *Contour* method is the suggested standard method (Østrem & Brugman 1991; Cogley et al. 2011) and has proven to provide best results in its traditional and in distributed model applications. It consists in contours of mass balances that are based on point observations (stakes) and expert knowledge, for example, specific accumulation/ablation patterns or the location of the snow-line (Østrem & Brugman 1991; Escher-Vetter et al. 2009; Sold et al. 2016). Compared to other methods, including expert knowledge represents the big strength of the Contour method for the spatial interpolation of surface mass balances. The *Contour* method was applied in 500 mm w.e. intervals to derive annual mass balances using the annual sum of stake values.

The *Index* method was first used on Gulkana glacier by March and Trabant (1998) and documented again by van Beusekom et al. (2010). In our adapted form, the stake values x on similar elevations (see Figure 1) are averaged to calculate the surface mass balance per elevation bin that is summed up and divided by the total glacier area to arrive at B.

$$B = \frac{\sum_{i=1}^{N} (\overline{x_i}) A(z_i)}{\sum_{i=1}^{N} A(z_i)}. \tag{2}$$

The values for elevation bins without measurements are interpolated from the two neighbouring bins or calculated from the linear relation between averaged stake values and elevation (for the highest and lowest bins).

In order to find the most suitable geostatistical interpolation method, we calculated surface mass balances for a number of test months with the following methods: Inversed Distance Weighting, Natural Neighbor, Ordinary Kriging (Spherical, Circular, Exponential, Gaussian, and Linear), Universal Kriging (Linear Drift and Quadratic Drift), Spline, and Topo to Raster (TTR). The results were compared regarding spatial homogeneity, deviation from max/min stake values, and their robustness in different situations (test months with varying stake value distributions). Ordinary Kriging (Spherical) has been used in previous studies (e.g. Bales et al. 2001; Rotschky et al. 2007), and showed good and robust results, together with TTR, another global interpolation method that is based on thin plate smoothing splines and aims for a connected drainage structure of the resulting raster (Hutchinson 1989). Thus, both (*Kriging* and *TTR*) were used for generating monthly surface mass balance maps over the whole time series.

The investigation intentionally excludes any comparison to modelling approaches as applied in earlier comparisons of glaciological surface mass balance (Escher-Vetter 2009; Sold et al. 2016). Because of the high-observation frequency and the capacity-building nature of the project, the set of applied methods should be simple to use and not require high technological input from the investigator, thus adding to the longevity and independence of the programme carried out by IDEAM. Finally, the following methods were used for comparison: (1) *O-Profile*, (2) *A-Profile*, (3) *Contour*, (4) *Index*, (5) *Kriging*, and (6) *TTR*.

3.5. Calculation of uncertainties

Estimating uncertainties is essential for evaluating the significance of and bias detection in glaciological observation series. A first comprehensive overview over potential error sources including suggestions to overcome and assess them has been provided by Zemp et al. (2013). We followed those suggestions to the extent possible to come up with a sound uncertainty estimation. A drawback is that due to missing reference data from the onset of the observations, it was not possible to validate the glaciological time series with an independent data set.

Random error sources. The random error sources were divided into the three classes: *point measurements: stake readings* (σ_{pt}), *point measurements: density conversion* (σ_{dens}), and *spatial interpolation* (σ_{int}). Uncertainties for each PoR (one month) are calculated according to the law of error propagation:

$$\sigma_{\text{total}} = \sqrt{\sigma_{pt}^2 + \sigma_{\text{dens}}^2 + \sigma_{\text{int}}^2}. \tag{3}$$

During the homogenization process, the error sources were taken care of: stake measurements were investigated and filtered, a homogeneous snow density was used, glacier area changes were reconstructed and accounted for, the time system was standardized, and a consistent interpolation method was used. Considering stake readings, a random uncertainty of 20 mm for ablation and 50 mm for accumulation measurements was assumed. These values were applied when monthly surface mass balances were negative or positive. The conversion of the stake readings into millimetre water equivalent by assuming a certain snow/ice density is another major error source. The density of ice (900 kg m^{-3}) is close to stable; therefore, an uncertainty of ±10 kg m^{-3} was assumed for ice ablation measurements. Based on a number of field surveys, the density of heavy snow (450 kg m^{-3}) was used when converting accumulation measurements. The related uncertainty is much higher and was set to ±100 kg m^{-3}. The uncertainty related to the interpolation of the stake data is among the highest in the glaciological surface mass balance (Soruco et al. 2009; Basantes-Serrano et al. 2016). We estimated it based on the results of a range of applied interpolation methods. The *Index* method results were chosen as the reference. The uncertainty is estimated as 1.96 times the standard deviation of all methods, which provides a value range for mass balance results being inside a 95% confidence interval and is thus considered statistically similar.

The annual surface mass balance can be calculated from the sum of the 12 monthly surface mass balances or from the sum of the 12 months of stake values and a subsequent interpolation. Analogously, the uncertainty calculation for annual surface mass balances was adapted to these two alternatives. Equation (4) describes the uncertainty calculation for the annual surface mass balance interpolated from the sum of stake values ($\sigma_{a.stk}$):

$$\sigma_{a.stk} = \sqrt{\sum_{1}^{N} t\,(\sigma_{pt.t}^2) + \sigma_{\text{int}}^2 + \sigma_{\text{dens}}^2}\;. \tag{4}$$

Equation (5) describes the same for the annual surface mass balance calculated from the sum of monthly mass balances ($\sigma_{a.mt}$):

$$\sigma_{a.mt} = \sqrt{\sum_{1}^{N} t\,(\sigma_{pt.t}^2 + \sigma_{\text{int}}^2 + \sigma_{\text{dens}}^2)}\;. \tag{5}$$

4. Results

4.1. Comparison of different interpolation methods

Monthly mass balance. Figure 2 summarizes the results from the different methods used to compute the monthly glacier-wide surface mass balance from the available stake data set and the respective cumulative surface mass balance over the full period.

All methods exhibit very similar overall trends and agree well in most observation periods. In certain cases, the *O-Profile* method leads to implausible specific surface mass balances and ELA values (e.g. a positive surface mass balance even though most stake values are negative), which is due to a low or negative surface mass balance gradient. In some months, the discrepancy to other methods is >200 mm w.e. (e.g. November 2006, December 2008, and May 2009). Applying the *A-Profile* method (averaging the stake values over the respective elevation bin) attenuated the influence of single stakes and thus improved the consistency significantly. In comparison with other methods, however, it yields more negative surface mass balances on average, with large deviations for some months.

Figure 2. Comparison of monthly mass balance results from different interpolation methods. The inset table shows the final cumulative results for the full period.

The average absolute difference between all methods is 121 mm w.e. per month, while the median is 47 mm w.e. per month. This emphasizes the strong influence of few months with great differences that originate from implausible results. *Index* and *Kriging* as well as *TTR* showed consistent results. The discrepancy between these three methods is small: on average 23 ± 18 mm w.e. per month.

Annual and total cumulative surface mass balance. The annual surface mass balance (Table 1) can be calculated twofold: (1) as the sum of the 12 monthly surface mass balances derived by one of the interpolation methods or (2) as the sum of the stake values with one subsequent interpolation using one of the different methods. When summed up over a full calendar year, the correlation between stake values and elevation becomes considerably stronger (monthly $R^2 = 0.06–0.97$, mean = 0.7). Method (2) was applied to obtain Figure 3.

The annual surface mass balance gradient is variable and ranges between 1000 and 3200 mm w.e. yr^{-1} 100 m^{-1}. The gradient is shifted in the *x*-direction and tilted around different elevation points. This combination of additive and multiplicative similarity components appears also in seasonal and semi-annual surface mass balance curves and complicates the interpretation of their shape.

In contrast to the monthly surface mass balances, the differences in annual surface mass balance values between the interpolation methods were smaller (Table 1). Only the *O-Profile* results are substantially different from the others in certain years in being considerably more or less negative. In

Table 1. Annual mass balances (mm w.e. yr^{-1}) calculated from summed up monthly mass balances and stake values.

	O-Profile		A-Profile		Index		Kriging		TTR		Contour
	$\sum_{mb}$	$\sum_{stakes}$	$\sum_{mb}$	$\sum_{stakes}$	$\sum_{mb}$	$\sum_{stakes}$	$\sum_{mb}$	$\sum_{stakes}$	$\sum_{mb}$	$\sum_{stakes}$	$\sum_{stakes}$
2007	−1169	−1501	−1579	−1532	−1531	−1531	−1571	−1442	−1369	−1443	−1405
2008	−6404	−349	−360	−542	−348	−324	−255	−255	−236	−245	−245
2009	−3377	−3778	−4352	−3854	−3494	−3443	−3531	−3461	−3434	−3427	−3435
2010	−2894	−3096	−2915	−3182	−3014	−3054	−2944	−2959	−2931	−2948	−2937
2011	−766	−866	−1273	−834	−907	−853	−803	−770	−762	−761	−820
2012	−2945	−2292	−3214	−2868	−2827	−2790	−2961	−2631	−2868	−2880	−2921
2013	−3602	−3843	−3858	−3685	−3541	−3550	−3638	−3333	−3532	−3506	−3599
2014	−4097	−4340	−4450	−4069	−3952	−3947	−4022	−3654	−3960	−3965	−3961
2015	−6218	−6480	−6200	−6254	−6074	−6074	−6191	−5835	−6229	−6194	−6165
Total	−31 472	−26 546	−28 201	−26 820	−25 689	−25 565	−25 916	−24 340	−25 320	−25 369	−25 488

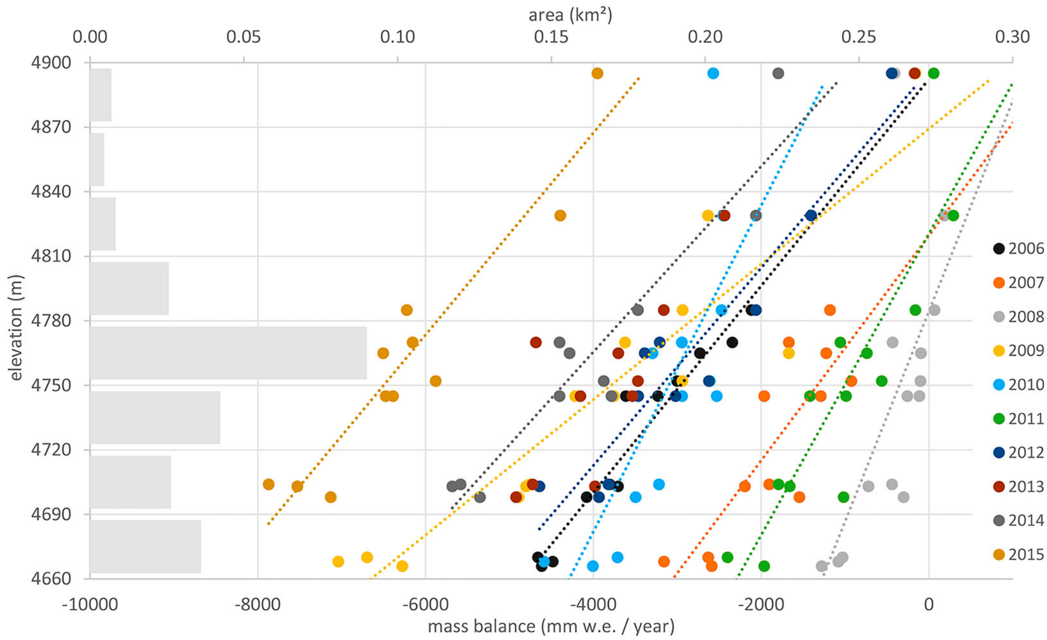

Figure 3. Area-elevation distribution (km^2, upper horizontal axis) and annual stake values (mm w.e., lower horizontal axis).

2008, the value range is about 6000 mm w.e. yr^{-1}, and compared to the stake values (ranging from −1300 to 190 mm w.e. yr^{-1}), the *Index*, *Kriging*, and *TTR* as well as the *Contour* method are the only methods providing reasonable results. In this independent method comparison, the *Contour* method proves its robustness and applicability by being in the range of ±150 mm w.e. of the cumulative surface mass balances of *Index*, *Kriging*, and *TTR*.

The annual surface mass balance as derived from summing up monthly surface mass balances tends to yield more negative results for *O*- and *A-Profile* and *Kriging*. The discrepancy between the two alternatives can be expressed by the sum of absolute differences, which is >8000 mm w.e. for *O-Profile*, 1200 mm w.e. for *Kriging*, but <300 mm w.e. for *Index* and *TTR*.

In theory, the total cumulative surface mass balance for the full time series of 119 months can be calculated in three different ways: (a) as the sum of all monthly surface mass balance values, (b) as the sum of all annual surface mass balance values, and (c) directly interpolated from the sum of stake values. Calculation method (a) yields *O-Profile = −33 527 mm w.e.*, *A-Profile* = 31 900 mm w.e., *Index* = −29 400 mm w.e., *Kriging* = −29 990 mm w.e., and *TTR* = −29 040 mm w.e. Calculation method (b) cannot be applied since the years 2006 and 2016 are incomplete. Thus, a substantial part of the surface mass balance would be missing and the result not comparable. To calculate the surface mass balance according to (c), a correlation between elevation and surface mass balance needs to be established. However, the stake value time series are of different length due to the melt-out of stakes 1–3 during 2011 and 2012 and the correlation will thus not lead to meaningful results. Disregarding stakes 1–3, the correlation between stake values 4–14 and elevation from May 2007 (implementation of stakes 13 and 14) to January 2016 (105 months) yields $R^2 = 0.95$. Similarly, the *A-Profile* method gives $R^2 = 0.92$. This shows that for longer observation periods, the profile method can be a good option to interpolate the glacier-wide surface mass balance. Results of the other interpolation methods for (c) are fairly consistent (±1325 mm w.e.): *Index* = −28 400 mm w.e., *Contour* = −31 050 mm w.e., *Kriging* = −30 000 mm w.e., and *TTR* = −30 000 mm w.e.

The requirements for the interpolation method are robustness and consistency as well as a certain technical simplicity in its application. Being in line with these requirements, the results from the

Index method are used for the presentation of further results and analysis as they are more stable and thus more reliable concerning relative changes. In accordance with Cogley et al. (2011) and Østrem and Brugman (1991), we also suggest the use of the *Contour* method, which is in this case only available for annual surface mass balances.

4.2. Ten years of glacier mass balance

The investigated time series lasts from March 2006 until January 2016, that is, 119 months (=observation period). The overall trend of surface mass balance is strongly negative, with a total loss of 29 400 mm w.e. (±1260 mm w.e.) during 10 years, that is, −2965 mm w.e. (±240 mm w.e.) yr^{-1} or −247 mm w.e. (±44 mm w.e.) per month. For 19 of the 119 months, the mass balance was positive, with only 3 of them with values greater than +100 mm w.e. per month. The last month with a positive surface mass balance was March 2012. The series can be divided into five periods of different evolution (Figure 4(a)). From the start of the series until mid-2007, the monthly surface mass balance was mostly negative. From mid-2007 to mid-2009, the glacier was close to a balanced situation. Subsequently, from mid-2009 until mid-2010, the most negative period in the time series prevailed, with monthly surface mass balance values reaching −1000 mm w.e. per month in January and February 2010. This term was followed by about two years of equilibrium and only slightly negative surface mass balances, including the only month reaching a positive mass balance of +200 mm w.e. per month. Since mid-2012, the surface mass balance has again been clearly negative, but exhibiting a seasonal pattern with the strongest monthly mass loss from December to March of each year. In the end of 2015, extreme values of almost −1000 mm w.e. per month were again reached. Surface mass balance values on a monthly and seasonal scale are extremely variable. Annual surface mass balances (calendar year) ranged between −300 mm w.e. yr^{-1} (2008) and −6000 mm w.e. yr^{-1}

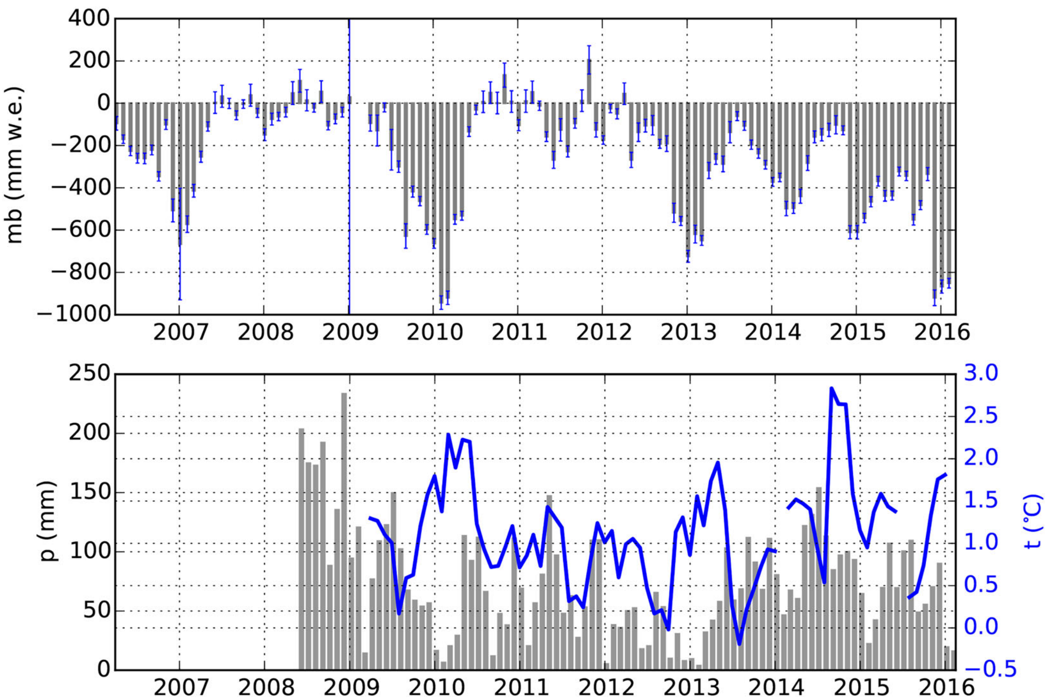

Figure 4. Upper: Conejeras mass balance time series (March 2006–January 2016). The error for December 2008 is 1169 mm. Lower: Monthly mean records of temperature (Conejeras station) and precipitation (Laguna Verde station) for the same period.

(2015). The areal decline between March 2006 and April 2014 was about 14% and almost linear, that is, ~2% per year.

ELA and AAR. Because the highest parts of the glacier are covered by stakes, a highly reliable ELA could be derived for each month with the use of the *Index* method. The lower elevation end of one bin was chosen as ELA if this and all higher successive bins exhibited non-negative values. Figure 5 shows that only rarely the ELA drops below the theoretical equilibrium elevation, where the accumulation area ration (AAR) equals 70% of the glacier surface area, and often rises above the glacier (here indicated as 5000 m, a hypothetical value). The lowest annual ELA was ~4800 m (2008), while on average it was close to the glacier's maximum elevation (AAR = 4%).

4.3. Uncertainties

Monthly interpolation uncertainties mostly range from 20 to 55 mm w.e. per month with 5 outliers over 60 mm w.e. per month (December 2006, December 2008, April 2009, June 2009, and October 2011; see also Figure 4); the median is 27 mm w.e. per month and the mean 44 mm w.e. per month. Outliers originate from months with large discrepancies of the *O-Profile* method and their influence is considerable: removing the two biggest outliers (resulting from a bad performance of the profile method due to the weak correlation between stake values and elevation) reduces the standard deviation from 106 to 14 mm w.e. per month and the mean from 44 to 33 mm w.e. per month. Most important of the three uncertainty sources is the spatial interpolation with a mean value of ±27.5 mm per month. Due to the dense network, however, we estimate it to be relatively small compared to other glaciers and to the other error sources. The stake reading uncertainty is on average responsible for ±25 mm w.e. per month, and the density for ±6 mm w.e. per month.

With Equations (4) and (5), we calculated the annual surface mass balance uncertainties. The uncertainty of the annual surface mass balance calculated from the sum of stake values ($\sigma_{a.stk}$) was expected to be smaller than the one from the sum of monthly surface mass balances ($\sigma_{a.mt}$) because the interpolation needs to be done only once instead of 12 times. However, in the interpolation of the annual stake sum, the standard deviation becomes larger, which influences

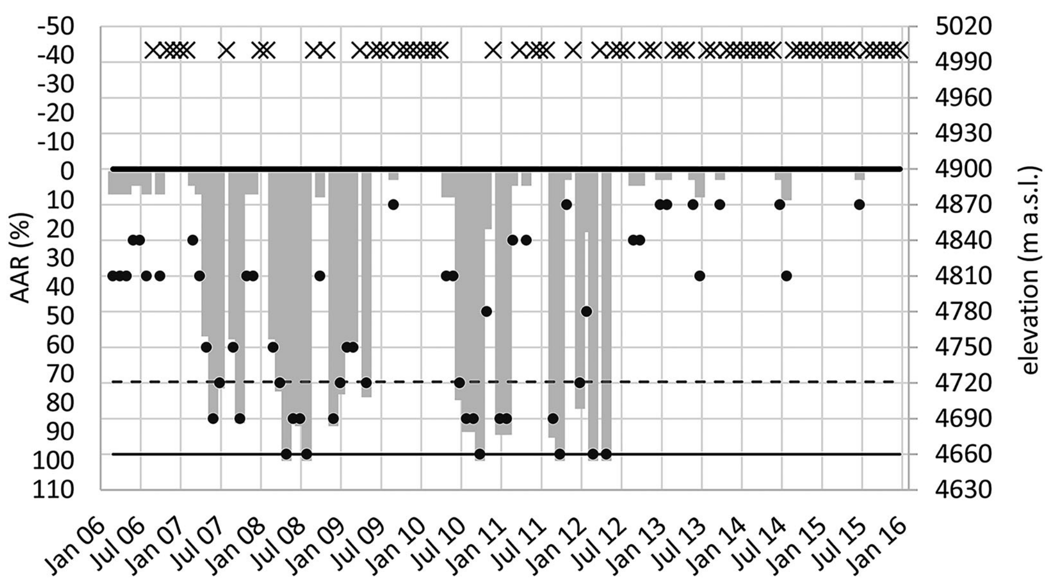

Figure 5. Monthly ELA (dots and crosses) and AAR (grey bars) of Conejeras glacier. Crosses signify an ELA above the glaciers' maximum elevation. The dashed, thick solid and thin solid lines represent the glaciers' balanced-budget equilibrium line, maximum elevation, and minimum elevation, respectively.

the final uncertainty in a way that for most years it is ~90 mm w.e. yr^{-1} greater (see Table 2), which is why we used Equation (5) for the uncertainties of the final results.

Since the errors of PoR cumulate, its importance increases with the length of the time series. With 119 PoRs, Conejeras is among the glaciers with the most surface mass balance observations, making the error estimation especially critical. Following Equation (5) for the full series instead of only one year, an uncertainty of ±1260 mm w.e. is determined.

4.4. Sub-seasonal and spatial patterns of surface mass balance processes

In contrast to high or mid-latitude glaciers, there is no clear distinction between accumulation and ablation seasons in the inner tropics. In one month, both accumulation and ablation can occur and cover parts of or the entire glacier. However, for most of the years, melting is more pronounced from December to March. For 6 out of 10 years (2006/2007, 2007/2008, 2009/2010, 2012/2013, 2013/2014, and 2014/2015; more El Niño influenced), the 3 months from December to February were responsible for 30–50% of the ablation (42% on average); this share becomes larger in higher elevations. Other years showed an opposite pattern, with the highest monthly surface mass balance between September and February and over 50% of the annual ablation in March–May or June–August (2008/2009, 2010/2011, 2011/2012; rather influenced by an ENSO cold phase). Generally, the inter-annual variability of monthly surface mass balance values is smallest in June and July and largest in November to February (standard deviation two to three times larger). The months with the smallest inter-annual variability (June and July) are similar to Antisana 15α (June, July, and November; Basantes-Serrano et al. 2016).

The correlation of monthly stake values with elevation was often weak, the mean R^2 being 0.43 (n = 14, $p < .05\%$). Only for 7 months the R^2 was >0.8; however, in 15 cases it was as low as 0.1 or less. We checked other spatial ablation/accumulation patterns, for example, the correlation between the orographic left and right side of the glacier which was mostly low (average $R^2 = 0.18$). To summarize, the spatial pattern of stake values is highly variable from one month to another and future studies might look deeper into these problems. Over the 10-year period, these local differences were levelled out so that the final cumulative map reveals a clear and strong relation to elevation (Figure 6).

4.5. Possible modification of the measurement network

The density of the stake network is among the highest in the world. Even though the glacier is small, it is laborious and time intensive to read out and redrill the stakes and guarantee their technical operation every month. One goal of this study was to estimate the possibilities to reduce the effort necessary to maintain the mass balance programme in the future. Therefore, the influence of a strongly reduced stake network on the monthly specific surface mass balance was tested for the whole time series. The network was cut down from 14 to 4 stakes (N's. 4, 6, 8, 10), keeping a good distribution over the central part of the glacier, but disregarding the highest and lowest areas. The results were surprisingly consistent for the *Index*, *Kriging*, and *TTR* methods, with a range of results over the full study period of 2600 mm w.e. (i.e. 3–5% difference from the Index method) to the full stake network. Only two months showed surface mass balance differences of over 100 mm w.e. per month, which is due to strongly varying contrasts of single stake values.

Table 2. Annual uncertainties (mm w.e. yr^{-1}) for alternatives (1) and (2) of the annual mass balance calculation.

	2007	2008	2009	2010	2011	2012	2013	2014	2015	Ø	Std
$\sigma_{a.stk}$	142	240	328	211	157	242	227	283	131	218	62
$\sigma_{a.mt}$	119	1175	169	135	143	122	104	106	89	240	331
$\Delta_{stk\text{-}mt}$	22	935	159	75	14	121	123	177	43	185	271

Note: The high value for 2008 is linked to the large error of December 2008.

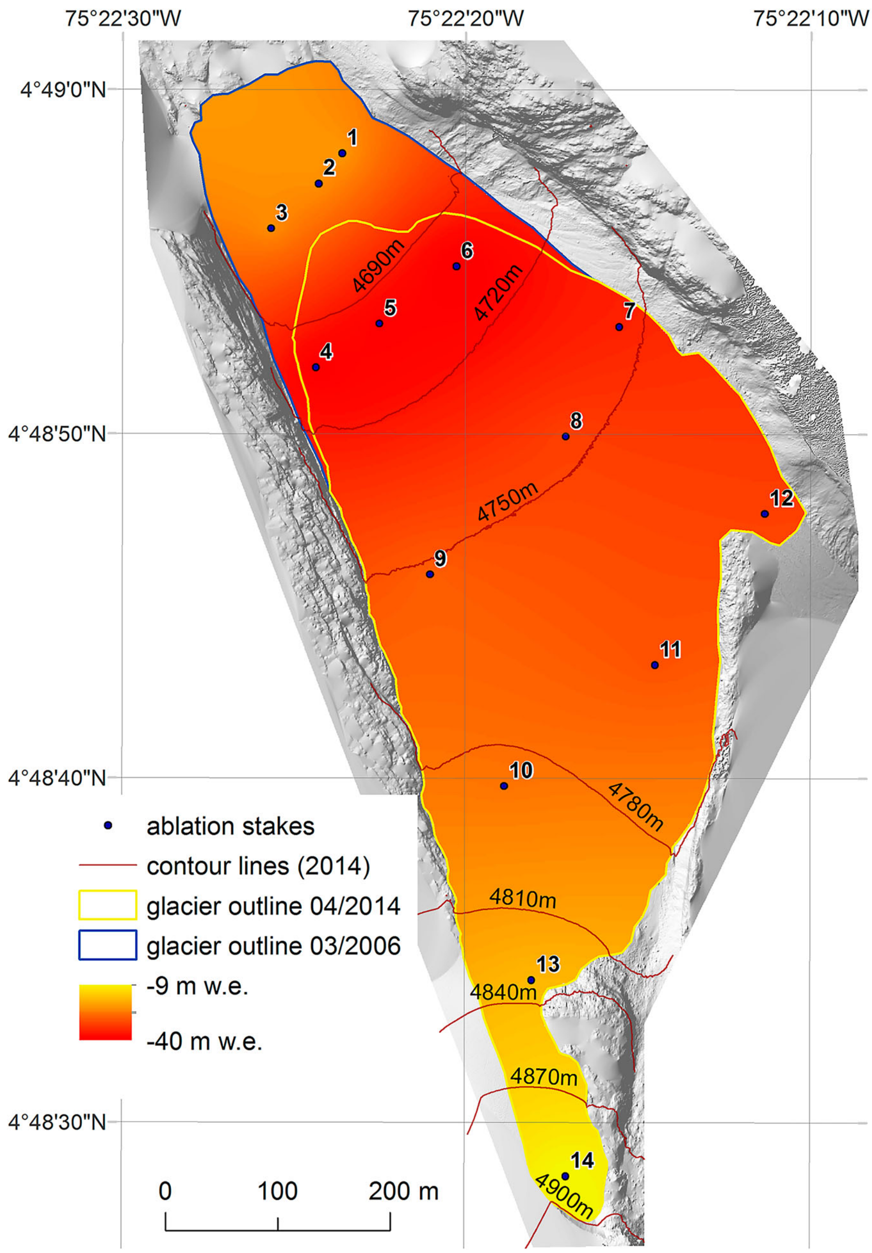

Figure 6. Total mass balance (m w.e.) over 10 years (03/2006–01/2016) according to Topo to Raster interpolation. Due to the continuous retreat, the mass loss is highest in the central parts of the glacier.

5. Discussion

5.1. Interpolation method

Irrespective of the applied interpolation method, the seasonal and total trends changed very little. This can be largely attributed to the extensive point observation network without inaccessible areas that favours the application of traditional and geostatistical methods. In case of such favourable conditions, different interpolation methods can and should be used to receive a robust estimate of the final results as well as of the uncertainties linked to the chosen method. Also, most monthly results of all methods are consistent and significant according to the uncertainty estimation. Whether a certain method is over- or underestimating the mass balance is possible to tell only after acquiring a geodetic mass balance over a comparable period. Some monthly surface mass balance results, however, showed a wide value range. This range is mostly due to the profile method showing deviating results from the other methods and thereby revealing a basic problem in the use of this method. In case the assumption of a strong relationship between stake value and elevation is not valid, the resulting glacier-wide surface mass balances are not meaningful and ought not to be used. It is unclear whether there is a common threshold of correlation, and a comparison to the results from other methods is a most reassuring way of detecting implausible surface mass balance values. According to the Conejeras surface mass balance data, the longer the time series is, the stronger the correlation between stake values and elevation becomes, which in turn reduces the uncertainties that are deviated from the range of results. While the profile methods require this high correlation, the geostatistical methods need a good spatial distribution of stakes and the *Contour* method is based on expert knowledge about the glacier.

Therefore, our findings might not be valid for other glaciers with few stakes and less good spatial coverage (see Basantes-Serrano et al. 2016), and the choice of method needs to be adapted to the existing conditions at the glacier of interest. Examples have shown that a more sophisticated version of the *Contour* method, with additional information and expert knowledge packed into a model, might lead to the most promising results (e.g. Huss et al. 2009, Sold et al. 2016).

5.2. Uncertainties

The representativeness of the stake network is good with no inaccessible areas and high-stake density. Nevertheless, the interpolation method is presumably the largest error source (Basantes-Serrano et al. 2016; Sold et al. 2016). Because of the error propagation, the estimation of uncertainties is especially crucial for a long time series. Since there is no geodetic mass balance available, the application of different interpolation methods can serve as an approximation of the potential surface mass balance range, but not of the correctness of the absolute values.

With ±1260 mm w.e. the uncertainty for the 10-year cumulated time series is rather low, also in comparison to other studies (see Zemp et al. 2013). One reason is clearly the stake network, which is also reflected by a comparatively low interpolation error. Another reason is a low uncertainty for point measurements, even though we assumed rather conservative values. This is because only 18% of all stake values showed accumulation and commonly only of a few centimetres.

We did not consider uncertainties regarding basal and internal melt connected to potential heat conduction by melt water. These terms are usually small to very small (on the order of several millimetre per year, see Zemp et al. 2013 and supplements). Geothermal heat conduction might play a role on this extinguished volcano and should be the subject of future estimations, but can be disregarded when considering the surface mass balance only.

5.3. Patterns of spatial accumulation and ablation

Monthly accumulation and ablation patterns varied much and showed at times a rather homogenous distribution, but in some months a relation to the orographic right/left side of the glacier was evidenced. Generally, if the correlation with elevation is low at monthly scale, there is no clear pattern to be discerned. Future work might concentrate on relating the surface mass balance and weather patterns (e.g. wind measurements) and resulting local accumulation or redistribution patterns (e.g. using time-lapse cameras) or the influence of small-scale but frequent snowfalls that determine short-term albedo changes. Surface albedo in combination with radiation strongly governs ablation, especially in a tropical context (Favier et al. 2004).

5.4. Network reduction

We performed an additional calculation of the surface mass balance time series with a reduced stake network. The results were promising, mostly because the central part of the glacier with the greatest area share was well covered with stakes (Figure 1). Additionally, the analysis of monthly surface mass balances revealed a seasonal distribution with most ablation from December to February and typical accumulation months between June and October. The observation period of 10 years has provided important insights into the monthly surface mass balance variations. There is high potential for saving effort, for example, by extending the PoRs to about four months, with observation dates before the start and at the end of the strong ablation season, that is, in November and March, including one to two observations between May and October to keep track of the accumulation regime variations. Combined with a cutback of the network density that reduces the required field time, the total programme effort could be cut down by 60–80%, which would free capacities of the responsible investigators. This leaves the possibility open to intensify the surface mass balance monitoring again later on, for example, to perform an energy balance study. The density test also suggested a work reduction potential for other surface mass balance programmes, if a meaningful selection of remaining stakes is performed.

5.5. General trend, temporal surface mass balance patterns, and the connection to climate

The cumulative glacier-wide surface mass balance for the 10-year period was almost −30 000 mm w.e. For a small glacier that has been retreating for decades and that is partly situated on a mountain ridge, this is supposedly a substantial part of its total volume. Conejeras glacier is currently highly imbalanced without a permanent accumulation area, and the latest almost balanced period was in 2011. The average altitude of the equilibrium line shows that the committed area loss under the climate conditions of the last 10 years according to Zemp et al. (2015) would be 94%, which practically means that the entire glacier will disappear if the current climate conditions prevail.

The meteorological station data showed that both monthly temperature and precipitation varied strongly throughout the measurement period (Figure 4(b)). Precipitation showed high values from mid-2008 to end-2009 and from mid-2013 to end-2014. The three 6-month periods in between showed strong monthly variations, and several months with precipitation <10 mm per month. Also, temperature showed two outstanding periods of high values in early 2010 and late 2014, with mean monthly values over 2°C. Temperature variations were strong and only two months reached average temperatures below 0°C. The daily temperature amplitude showed a clear seasonal cycle between 3°C in the rainy season (July–September) and 6°C in the drier season (January–March). This evolution is superimposed by small seasonal variations of roughly 1.5°C, with highest (lowest) values in March (July). Precipitation showed a weak seasonal cycle with two peaks in May–June and November. This confirms the expected seasonal climate cycle and underlines the tropical setting of Conejeras glacier where ablation and accumulation conditions can occur throughout the year according to the weather situation. However, the correlation between surface mass balance and the measured temperature and precipitation is weak in certain periods (e.g. during 2012). Nevertheless, the meteorological data revealed some basic relationships: in months with very high precipitation rates (e.g. >100 mm per month), the mass balance is not extremely negative (i.e. not lower than −500 mm w.e. per month). Positive mass balances exist only when the temperature is close to or below the period average (1.2°C). For instance, for some events (e.g. beginning of 2010), high temperatures occurred together with high ablation, although in other cases (e.g. mid-end 2014) this relation did not persist and surface mass balance was less negative while temperatures were exceptionally high. Similar relations were found between surface mass balance and precipitation. This suggests that other factors such as cloud cover (influencing long and short wave radiation), humidity, and albedo strongly influence ablation in certain periods (Sicart et al. 2015).

In the Andean cordilleras of the inner tropics, the ENSO warm phase leads to high air temperatures, weaker and more sporadic snowfalls, low wind speeds and reduced cloud cover, and *vice versa* (Vuille et al. 2000, Garreaud and Aceituno 2001, Francou et al. 2004). For Antisana 15α, Francou et al. (2004) showed a strong correlation of the ENSO signal and the monthly glacier surface mass balance. Conejeras glacier is strongly exposed to westerly winds and its surface mass balance is thus also influenced by ENSO anomalies. Overall, monthly surface mass balances and the MEI are strongly correlated. Figure 7 shows the correlation for the twelve months ranging from R^2 = 0.46 (October) to R^2 = 0.89 (November), with a mean of R^2 = 0.64. The month of May is an exception with a low R^2 of 0.09. Also, the annual surface mass balances and MEI are strongly correlated, even for the calendar year (R^2 = 0.84; without time lag between surface mass balance and MEI data). This is rather surprising, as using the calendar year generally splits the intensive ENSO period in two. A strong positive anomaly is often followed by a negative one and the immediate effects of the switch balance each other out. The correlation for the full year from August to July or June to May is slightly lower (R^2 = 0.71).

The largest inter-annual variations were found from November to February, with a range of >900 mm w.e. per month (std = 290–310 mm w.e. per month). There is a large difference from the other months (350–700 mm w.e. per month, std = 109–220 mm w.e. per month), pointing to a high sensitivity of the surface mass balance during the strong ablation period. The share of annual ablation between December and February depends mainly on the influence of the ENSO warm and cold phases.

The changes in precipitation and cloud cover in the tropical Andes since the mid-twentieth century have been minor (Vuille et al. 2003), but temperature and humidity have increased (Vuille & Bradley 2000; Villacis 2008; Gilbert et al. 2010; Rabatel et al. 2013). Combined data from Laguna Verde and Conejeras stations showed that during precipitation events, the temperature at 4700 m a.s.l. oscillated around the freezing point. An elevation increase in liquid precipitation lowers surface albedo (Favier et al. 2004), decreases accumulation amounts, and enhances melt due to the albedo effect and the release of latent heat from rain water. In combination with the temperature increase and the resulting feedback processes, we conclude that temperature is the decisive factor driving the long-term glacier recession of Conejeras.

The intensity of El Niño events has increased since the 1970s (Lee & McPhaden 2010; Cai et al. 2014) and is considered an important factor in the acceleration of glacier retreat in the tropical Andes (Rabatel et al. 2013). The time series of Conejeras glacier supports these findings, also because

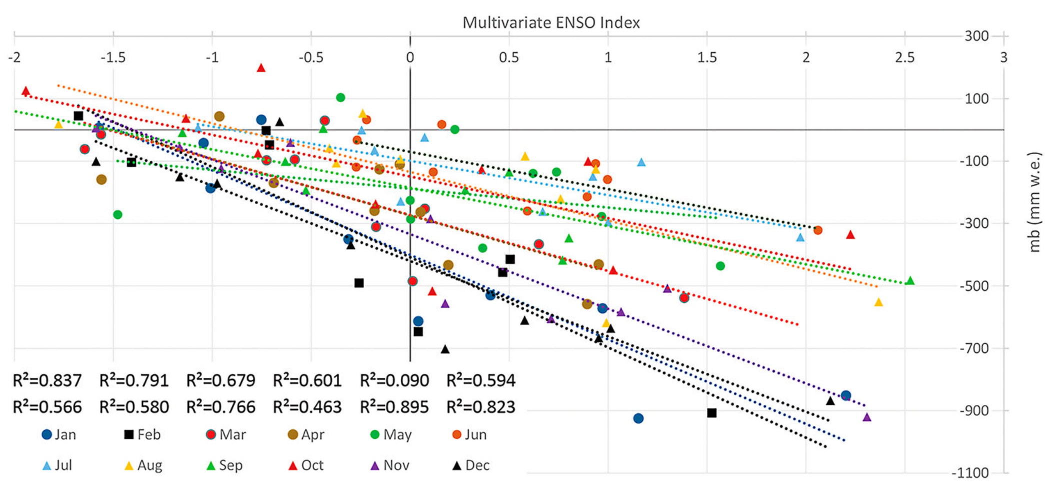

Figure 7. Relation between monthly mass balances and MEI values.

La Niña events seem to have a smaller effect on surface mass balance anomaly than their warm counterparts. Especially under stronger warm phases of ENSO, the surface mass balances of several months can shape the full annual surface mass balance. It remains unclear to what extent the increased El Niño frequency explains an increase in temperature and if the frequency will continue to increase, be constant, or even decrease again, as the theory of the Pacific Decadal Oscillation suggests (Viles & Goudie 2003; Lapp et al. 2012).

5.6. Conejeras glacier changes in a tropical context

In order to evaluate the general trend of surface mass balance and the associated ENSO influence, Conejeras glacier was compared to other glaciers from the tropical Andes. Antisana 15α (Ecuador, see Figure 1) and Zongo (Bolivia) glaciers are being monitored on a monthly basis and their general trends are similar also on a seasonal basis. The trend is also similar for the seasonally monitored Yanamarey and Artesonraju glaciers in Peru. Figure 8 shows their annual surface mass balances and demonstrates roughly the same inter-annual variability for the overlapping period 2007–2013. The influence of ENSO is strong also for Antisana 15α and Zongo, but the positive and negative reactions of Conejeras seem to be more intense.

The glacier-wide surface mass balance of Conejeras glacier is far more negative than that of all other monitored tropical glaciers (see Figure 8). A major reason might be the lower elevation (range) of Conejeras glacier, and the absence of a perennial accumulation area.

6. Conclusions

This study presented a unique 10-year time series of monthly glaciological surface mass balance measurements, performed on the tropical Conejeras glacier in the Colombian Andes. A homogenization of the data series was made possible by the acquisition of a high-resolution Lidar DEM in 2014. We applied different methods to spatially interpolate point observations and could thus reduce the systematic error originating from the choice of the interpolation method as well as estimate-related uncertainties. In this comparison, the *Index* method, the *Contour* method, *Kriging*, and *Topo to Raster* have performed better than the *O-Profile* and *A-Profile* methods, mainly due to the weak correlation between stake values and elevation. Advantages of the *Index* method are the robust performance and technical simplicity. We thus recommend using the *Index* method to calculate monthly and annual as well as the *Contour* method to calculate annual surface mass balance.

A substantial part of glaciological surface mass balance uncertainty is connected to the spatial integration of point data. With the use of different interpolation methods, we were able to provide an approximation of the related uncertainty. Mean monthly uncertainty is estimated at 44 mm w.e.

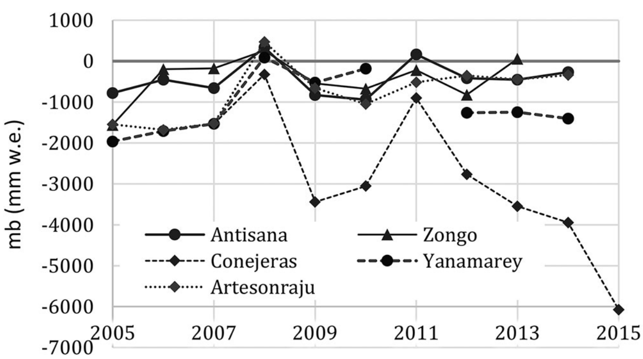

Figure 8. Annual mass balances of the glaciers Conejeras in Colombia, Antisana 15α in Ecuador, Zongo in Bolivia, and Artesonraju and Yanamarey in Peru (World Glacier Monitoring Service 2015).

per month, mean annual uncertainty is 240 mm w.e., and over the cumulated time series the random error is estimated at ±1260 mm w.e.

We could for the first time give insights into the general trend and the sub-seasonal variations of the surface mass balance of a Colombian glacier. In 10 years, Conejeras glacier has lost ice of the equivalent of ~30 m of water (with minimum values of 9 m in the uppermost areas) and accompanied by an area loss of ~20%. There are strong variations in the monthly surface mass balance pattern that cannot be explained by the traditional scheme of annual inner-tropical temperature and precipitation variations. Rather, monthly and seasonal surface mass balances are strongly correlated to the warm and cold ENSO phases that can greatly determine the annual surface mass balance, mainly from December to February. Local meteorological data stress that temperature is the more important variable driving glacier ablation. The relation between ENSO phases and meteorological variables at high elevations is not clearly revealed here and further analysis of existing meteorological station data is needed.

Regarding the future of the programme, we recommend choosing one of the two following options. This study revealed that the surface mass balance measurements could be continued even with a greatly reduced stake network. *Index*, *Kriging*, and *TTR* showed stable and consistent results when reducing the stake network from 14 to 4 stakes with a small effect on the cumulative surface mass balance. Combined with a lower temporal resolution of the measurements, a considerable effort reduction could be achieved, without greatly increasing the uncertainties. With 3–4 annual measurements, this option is sufficient to capture the surface mass balance trends and variations. On the other hand, the monthly monitoring could be continued but complemented by extending the existing meteorological station network to capture the atmospheric conditions on and around the glacier to be used for a glacier surface energy balance study combined with a surface mass balance model. It will help to explain the glacier variations with local and regional meteorological conditions, but it is more labour-intensive. Either way it is necessary to acquire a second DEM within the next 5–10 years to perform a full reanalysis.

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