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The recent retreat of Mexican glaciers on Citlaltépetl Volcano detected using ASTER data

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Abstract

Satellite imagery and net radiation data collected between 2001 and 2007 for Citlaltépetl Volcano confirm the dramatic shrinkage of Glaciar Norte and the elimination of Jamapa and Chichimeco glacier tongues. The Glaciar Norte rapidly retreated between 2001 and 2002 while for 2007 this retreat decreases considerably. Jamapa and Chichimeco tongues disappeared by 2001 as compared to the geometry shown for 1958. The Glaciar Norte lost about 72 % of its surface area between 1958 and 2007. Recently, the ice loss appears to be accelerating as evidenced by the 33 % areal loss in just 6 yr between 2001 and 2007. At this shrinkage rate the glaciers would be gone from the volcano by the year 2020, which is decades earlier than previously estimated. The net radiation from ASTER images and the energy fluxes calculated via the meteorological data at the glacial surface show the close relationship between glacial shrinkage and surface energy balance. The magnitude of changes in the net radiation balance allows improved understanding of glacial retreat in Mexico.

1 Introduction

Mexico is a country with glaciers because of the very high altitude of its volcanoes. Only three Mexican volcanoes are currently high enough to allow accumulation of snowfall sufficiently deep to sustain glaciers. These are Popocatépetl, Iztaccíhuatl and Citlaltépetl Volcanoes. The tropical geographic location makes the existence of these ice bodies puzzling. To-date there is insufficient understanding of these glaciers to know why they exist and how long they will survive. Despite their small areal extent, these glaciers are important for Mexico since they provide critical storage of water in the form of ice that feeds the surrounding areas in times of need. The glaciers accumulate snow during the wet season when summit temperatures are near or below freezing and precipitation is abundant, and release water at all times when temperatures are warm enough for melt to occur. Without the water supplied from these glaciers during the dry season it is possible there could be water shortages in the surrounding areas. In the future, water shortages near these ice-clad volcanoes could become more severe if global warming enhanced water stress during dry periods.

Recent studies on Popocatépetl and Iztaccíhuatl volcanoes in Mexico have demonstrated a notable retreat of the glaciers (Delgado-Granados and Brugman, 1995; Alvarez and Delgado-Granados, 2002). Currently, most glaciers around the world show that recent climatic changes have made glaciers more vulnerable to the thinning and shrinkage (Oerlemanns and Fortuin, 1992; Oerlemanns, 1994, 2005; Haeberli and Beniston, 1998). Eruptive activity at Popocatépetl Volcano has already contributed to the near extinction of its glaciers (Julio-Miranda and Delgado-Granados, 2003; Julio-Miranda et al., 2008). Prior to this volcanic activity in 1999, the glacier changes at Popocatépetl (Delgado-Granados et al., 2007) appear to reflect the influence of historical climate fluctuations. In comparison, the glaciers of Citlaltépetl lie on a dormant volcano farther away from highly populated and polluted areas (see Fig. 1). The polar-type climatic conditions that permit glaciers to exist in Mexico at high elevations also permit a unique view of global warming impacts at 19° north latitude.

Although previous studies have been carried out on Citlaltépetl's glaciers (i.e. Lorenzo, 1964; Palacios and Vazquez-Selem, 1996) information is incomplete for comparison of glacier areal extent through time. In this study we have used corrected previous data on these glaciers and added recent information to evaluate the current situation of these glaciers after recent climatic warming as evidenced by the Intergovernmental Panel of Climate Change Report (2007).

Recently, remote sensing tools allow us to examine glacial surfaces to quantify the magnitude of recent changes (Kääb, 2005). Here we investigate the rapid retreat of Glaciar Norte on Citlaltépetl reported first by Lorenzo (1964) and later by Palacios and Vázquez-Selem (1996). The results developed in this study are used to create a new glacier inventory for Citlaltépetl Volcano; this study shows how the survival of glaciers in Mexico is directly related to high elevation weather conditions in the tropics. The areal changes of Glaciar Norte are documented in this paper for the years 2001 to

2007 using analysis of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite images. This data was available through Global Land Ice Measurements from Space (GLIMS) project. Remote sensing techniques and algorithms were developed to calculate the spatial distribution of net radiation on the glacier. To further support the findings reported by Ontiveros-González (2007), in this work the relationship between net radiation and glacial retreat was established for the entire glacier surface.

2 Glaciers of Citlaltépetl Volcano

The Citlaltépetl Volcano (so-called Pico de Orizaba) lies at an altitude of 5675 meters a.s.l. and is a stratovolcano located in the eastern part of the Trans-Mexican Volcanic Belt at 19° 02′ N; 97° 17′ W which is about 200 km east of the Mexico City and 100 km west of the Gulf of Mexico. This volcanic cone lies upon the Sierra Madre Oriental mountain range that is aligned north-south to create a topographic barrier separating the dry Central Mexican plateau and the moist coastal plains along the Gulf of Mexico. Citlaltépetl is the highest volcano in North America. The volcanic debris covers an area of about 1000 km^2. The most recent eruption occurred in 1687 and volcanic activity during the fifteen and sixteen centuries continued until that year (Carrasco-Nuñez, 2000). The Citlaltépetl Volcano erupted during the late Pleistocene and the Holocene, so there is a long history of volcanic and glacial interactions (Palacios and Vázquez-Selem, 1996).

The maximum advance of the glaciers on Citlaltépetl Volcano occurred between 10 000 to 8500 yr before present. Also, there is evidence of two important Neoglacial (5000–100 yr before present) advances. The first advance is identified by the moraine chains at the base of the volcanic cone at elevations of 4000 to 4400 m a.s.l. These moraines were deposited at between 3000 to 2000 yr before present (Heine, 1983, 1988). The second advance corresponds to the Little Ice Age (LIA), which ended in Mexico during the mid nineteenth century. Evidence of this second advance is shown

TCD
6, 3149–3176, 2012

by a series of moraines that lie at elevations between 4400 to 4800 m a.s.l. on Citlaltépetl (Heine, 1983). In both Neoglacial episodes the glaciers advanced principally across the northern and western slopes. More over, the last eruptive phase of Citlaltépetl corresponds to the beginning of the LIA so that, the climate conditions were cool enough to allow the ice bodies to remain without melting despite the volcanic activity (Palacios and Vázquez-Selem, 1996).

Lorenzo (1964) reported four principal glaciers existed on Citlaltépetl during 1958. These were Glaciar Norte, Glaciar Oriental, Glaciar Occidental and Glaciar Suroeste, and his report included their many glacial tongues (Fig. 1), which descend over the northern and northwestern slopes. The longest on the North Slope is called “Jamapa tongue” which extended down to an elevation of 4395 m a.s.l. during the LIA. According to Palacios et al. (1999) the glacial front has been retreating during the last decades, also during the last century the glacial shrinkage gradually exposed valleys and basins at lower elevations as the ice melted away (Palacios and Vázquez-Selem, 1996). Glaciar Norte is one of the few survivor glaciers on Citlaltépetl Volcano, perched between 5000 m a.s.l. and the summit. The formerly impressive Jamapa glacial tongue had actually disappeared by the year 2001 together with the Chichimeco tongue (Figs. 1 and 2).

Recent studies on the glacial surface of the Citlaltépetl Volcano show the seasonality of the local weather; where the temperature and the relative moisture determine the annual dry and wet seasons on the glacier (Ontiveros-González, 2007). Furthermore, the net radiation on the surface impacts this seasonality, and can increase ablation causing enhanced ice loss or decrease ablation, allowing preservation of the ice during the driest season on the glacier. The glaciers of Citlaltépetl Volcano are the biggest glaciers in Mexico; the climatic change has a direct effect on the glacier health and appears to have caused ice loss even though there is low volcanic activity and the volcano is far from major air pollution sources such as Mexico City (also see Delgado-Granados et al., 2007).

TCD
6, 3149–3176, 2012

3 Data and methods

3.1 Meteorological data

In May 2006 two automatic weather stations (AWS) were installed on the glacial surface and on a moraine over the Glaciar Norte on Citlaltépetl Volcano. The first one called "Glaciar" is located at 5100 m a.s.l. on the ablation zone of the glacier, the second one called "Morrena" was installed 100 m from the Glaciar AWS on a moraine close to the glacier's limits. Air temperature, relative humidity, ice temperature, snow accumulation and net radiation over the surface were the principal meteorological parameters measured by these AWS since May 2006. The data is sufficient to allow determination of the annual surface energy balance of the glacier and allow comparison to the glacier changes measured using the ASTER images.

Incoming long wave radiation data set of the North American Regional Reanalysis (NARR) was used to calculate the spatial distribution of net radiation on the glacier surface. These data were interpolated in an area covering the extension of the glacier on the date and time of image acquisition. The interpolated value was obtained directly from the website of NARR data where is possible to establish date, time and the geographic grid of interest.

Since the installation of the AWS there was a test period to determinate the reliability of the data and the proper functioning of the instruments. Due to the harsh weather conditions at the Glaciar AWS its meteorological data set was strengthened using a combination of the Morrena data that was used to replace some gaps within the Glaciar's data set. Unfortunately at the beginning of the implementation the functioning of the sensors were not the optimum because some of the AWS components were coated with a shield of rime ice during a few major storms at these high altitudes, which decreased the ability of data acquisition due in part to the loss of solar power and in part due to compromised sensory quality. Thereafter, the stable operation of sensors at both AWS sites allowed the climatic studies at the Glaciar Norte to proceed.

TCD
6, 3149–3176, 2012

The good quality data set covers the period from 17 September 2006 to 15 October 2009. Into this period, the barometric pressure data of Glacier AWS was patched by the Morrena AWS data set since in the most of this period the barometric pressure sensor failed.

3.2 Glacier mapping from ASTER

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite images were employed to map the glacier outlines of Glaciar Norte on Citlaltépetl Volcano. Six images from 2001–2007 were geometrically corrected using ground control points located close by and on the volcanic cone, and also using a SRTM digital elevation model with a resolution of 90 m. The ground control points were acquired through a Panchromatic Landsat ETM+ image and a 1 : 50 000 scale map. Since the complex topography was difficult to view from satellite, the horizontal error attached for the orthorectification process was ∼ 40 m. Errors are expected to largest when the steepest slopes on north part of the volcano are considered. Sometimes, these steep areas are imperceptible to the drawing sensor due to shadows on the ground (Kääb, 2002), which increases the RMS error in the orthorectification process.

Classification of the glacial limits could be made by a manual delimitation especially in zones where the ice cover is not very extensive and there are strong differences between different surface cover types. While the digital treatment is almost based on the radiometric intensity of the pixel (within the corresponding spectral band), the visual analysis can use other elements present in the image as textures, footprints, sites and locations, which are more difficult to classify in digital form (Chuvieco, 1996). In order to enhance the visual classification of the ice and snow we applied a band ratio of the near-infrared and the short-wave-infrared bands (NIR and SWIR, respectively). The interpolator employed to resample the SWIR band for this band ratio was the nearest neighborhood. This treatment is based on the snow/ice reflectivity contrast that can be distinguished using the difference between the NIR and SWIR electromagnetic wavelengths. Also, we applied to each image a contrast stretch and a pseudo color display to distinguish the limits between the snow and the ice in the scene. All of this work and the calculation of the net radiation distribution on the surface were done employing the software ENVI 4.3 which was used to restore the images, orthorectify, map and remove atmospheric effects. Ground control points, satellite images and topographic maps were used in this work and the data projected into the UTM zone 14N with a WGS-84 datum. Finally, that information was processed using a geographic information system (GIS) to determine the areal changes of the glacial surface.

3.3 Spatial distribution of the net radiation

A simple transformation algorithm was implemented to calculate the distribution of the net radiation over the glacial surface (see Roerink et al., 2000). Atmospheric corrections were required using the parameters for each band of the sensor taken from the ASTER Users Guide (Abrams et al., 2002) and processing separately the solar to the thermal bands via ENVI 4.3. For this algorithm three images were taken in March 2002, 2004 and 2007 during the driest season of the year. This net radiation transformation algorithm originally used the Landsat TM images, but the similarity of the spectral ranges used allow use of the ASTER images in order to calculate the albedo, surface temperature and the outgoing long-wave radiation. There are only two missing parameters that we required for this algorithm, and these are the extraterrestrial solar radiation and the incoming long-wave radiation on the surface. The extraterrestrial solar radiation ($K^{\downarrow}_{\text{sun}}$) required for this method was taken from Alonso (2007) and the incoming long-wave radiation ($L^{\downarrow}$), from the North American Regional Reanalysis data. NARR data are available at http://nomads.ncdc.noaa.gov/data.php?name=access{#}narr_datasets (Eq. 2).

The accuracy of the present method is based on the atmospheric and geometric corrections of the images. Atmospheric corrections were made it for the solar bands employing the routine FLAASH from ENVI 4.3, which uses the DISORT algorithm to calculate the atmospheric conditions at the acquisition moment. The dispersion of radiation through the atmosphere is made it by the MODTRAN subroutine of DISORT.

Here, we apply the FLAASH routine considering a tropical atmosphere, a rural zone, and a clear sky conditions on the scene. The net radiation is defined as:

$$R = (S^{\downarrow} - S^{\uparrow}) + (L^{\downarrow} - L^{\uparrow}) \quad (1)$$

where $S^{\downarrow}$ and $S^{\uparrow}$ are the short-wave radiation incident and reflected, respectively; $L^{\downarrow}$ and $L^{\uparrow}$ are the incoming and outgoing long-wave radiation. This equation can be expressed as:

$$R = (1 - r_0)\tau K_{\text{sun}}^{\downarrow} - \sigma \varepsilon_0 T_0^4 + L^{\downarrow} \quad (2)$$

here the net short-wave radiation is calculated as function of the albedo (r_0) and the transmissivity of the atmosphere (τ), both were calculated directly from the ASTER images. The net long-wave radiation is calculated by differencing the outgoing long-wave radiation expressed by the Stephan Boltzmann law and the value of the incoming long-wave radiation ($L^{\downarrow}$) for each date. The surface temperature (T_0) and the emissivity of the atmosphere (ε_0) also are calculated directly from the ASTER images; σ is the Boltzmann constant.

In order to get the albedo of the glacial surface from each ASTER image, we made a numerical transformation from the raw image pixel values to the irradiance values through the following equation:

$$L(\lambda) = \frac{(DN - 1) \times C}{10} \quad (3)$$

where

$L(\lambda) \rightarrow$ is the spectral radiance for each long-wave $\lambda \rightarrow \left[\frac{\text{mW}}{\text{cm}^2\,\mu\text{m}\,\text{sr}}\right]$

$C \rightarrow$ is the transformation coefficient for each band of ASTER [–].

TCD
6, 3149–3176, 2012

The value of C can be acquired from the ASTER user manual (Abrams, 2002) and which is a function of the gain and offset parameters of the image. Before the transformation to radiative values, each image is corrected for the atmospheric influence, using the algorithm of ENVI for the ASTER images as it was explained before. After that, following the methodology developed by Roerink et al. (2000) only the planetary albedo and the surface albedo are required and these can be obtained through the calculation of the reflectance of each spectral range in the ASTER images (for more detail see Roerink et al., 2000). The transmissivity of the atmosphere was made by a linear regression between the planetary albedo and the surface albedo.

The surface temperature is calculated from the corrected atmospheric data obtained from the thermal bands of the ASTER imagery. Those bands were corrected by the thermal atmospheric correction algorithm of ENVI. This algorithm is different from that of the solar bands since this only uses the bands in the thermal spectra to calculate the brightness temperature. From the brightness temperature and the radiance values of the thermal bands the algorithm makes a linear regressions to correct the effect of the atmosphere. Following the algorithm described by Roerink et al. (2000) only the ASTER thermal bands 13 and 14 (10.25–11.65 µm) were used. As a result of the atmospheric correction, it was possible to derive the long-wave radiation values at the top of atmosphere ($L_{(13,14),\mathrm{TOA}}(\lambda)$), in the spectral range considered (10.25–11.65 µm). Thus, it was possible to derive the temperature measured by the satellite as (for more detail see Markham and Baker, 1987):

$$T_{\mathrm{sat}} = \frac{1260.56}{\ln\left(\frac{60.776}{L_{(13,14),\mathrm{TOA}}(\lambda)} + 1\right)} \tag{4}$$

Now, if apply the Stephan Boltzmann law is applied,

$$L^{\uparrow} = \sigma T_{\mathrm{sat}}^{4} \tag{5}$$

TCD

6, 3149–3176, 2012

The recent retreat of Mexican glaciers on Citlaltépetl Volcano

J. Cortés-Ramos and H. Delgado-Granados

Then the temperature without the effect of surface emissivity is given by:

$$T_0^R = \sqrt[4]{(L\uparrow/\sigma)} \tag{6}$$

Considering that the surface has different values of emissivity for different covers, the method of the vegetal cover given by Valor and Caselles (1996) may be used to calculate the emissivity. For this the normalized vegetation index (NDVI) of each scene was used. Finally the surface temperature is given as:

$$T_0 = \sqrt[4]{(T_0^{R4}/\varepsilon_0)} \tag{7}$$

Once the albedo, the surface temperature, the transmissivity and the emissivity are derived, then Eq. (2) can be used to obtain the net radiation on whole glacial surface.

4 Results

4.1 Areal changes of Glaciar Norte

After correcting the cartographic error in the glacial outline determined by Lorenzo (1964) by digitizing and geocoding his map it was possible to determine the 1958 area for Glaciar Norte in 2.23 km^2. Figure 2 shows the areal changes of the Glaciar Norte extent determined from ASTER images for 2001, 2003, 2005 and 2007. Between 1958 and 2007 the glacial area decreased considerably, around 72 % to the total area of 1958. For 2002, the glacial area suffered a loss of 9.5 % ($\sim$ 90 000 m^2) with respect to 2001. Whereas a marked decrease in the glacial retreat rate for 2007 (–15,267 $m^2\,yr^{-1}$, see Table 1), the area loss between November 2005 and March 2007 was just of $\sim$ 20 000 m^2. The total area lost during the period of 2001 and 2007 was of 33 %, which reflects the strong ablation occurred in recent decades.

During the period of 2001–2007 the glacial front moved back to high altitudes steadily; reflecting the changes on the limit of the glacier, which is in accordance with the general worldwide trend of glacier shrinkage (Zemp et al., 2007; Schneider et al., 2008). As shown in Table 1, the shrinkage rate averaged about $-70\,701\,\mathrm{m^2\,yr^{-1}}$ for the last 6 yr is extraordinarily high compared with the size of that glacial area. For the end of the LIA the glacial limit was around 4395 m a.s.l. (Palacios and Vázquez-Selem, 1996), while Lorenzo (1964) reported for 1958 an altitude of the glacial front about 300 m higher at 4695 m a.s.l. Figure 3 shows the major glacial retreat that happened in the last decade, where during 2005 the lower limit of the glacier was below 5000 m a.s.l. and just in 2 yr the lower limit reached 5050 m a.s.l.

4.2 Surface distribution of net radiation

The energy balance model developed for Ontiveros-González (2007) transform the meteorological parameters from the AWS to values of latent and sensible heat fluxes through the glacial surface. Those values together with net radiation lead us to calculate the energy balance at the glacial surface. From these results, it could be obtained that the radiative fluxes are the main factors to the energy balance, all of them involved into the net radiation (Cortés-Ramos, 2009). According with the results of Ontiveros-González (2007), the energy exchanges on the glacier surface are good indicators of the mass loss of the glacier. In his work, the net radiation is the principal component on the energy balance and then of the mass loss on the glacier surface. That work mentioned the presence of an ablation season during the first half of the year (beginning on January) where the air temperature and humidity rise their minimum values. This period is accompanied by an increasing of net radiation values on the glacial surface.

The net radiation data of Glaciar AWS during September 2006 to July 2007 (Ontiveros-González, 2007) shows the maximum values between February and April 2007, and the highest value was observed in March 2007 (Fig. 4). February to April are within the dry season (January–May), formation of penitents takes place in the April–May period (Delgado-Granados et al., 2007). A strong sublimation occurs due to the intense radiation in spite of the prevailing cold temperatures of this season (Delgado-Granados et al., 2007). March is a period previous to the formation of penitents over the Glaciar Norte glacier. That means an absence of sublimation that may enhance the effects of radiation making the mass balance more negative.

Mölg and Hardy (2004) documented that the strong ablation changes on a glacier surface result from the differences of the albedo distribution over the surface. Using the net radiation distribution calculated over the glacial surface with the ASTER scenes, we are able to say that the more vulnerable zones for glacial shrinkage (mass loss) are those where the net radiation has the highest differences. This is valid considering that net short-wave radiation depends on the albedo over the glacier surface and net short-wave radiation has a stronger effect on the radiative balance (Ontiveros-González, 2007). In addition, the increase of the incoming short-wave radiation due to decreases in cloudiness in the dry season plays a decisive role for the glacier retreat by increasing ablation, as demonstrated for Mount Kenya and Rwenzori (Kruss and Hastenrath, 1987; Mölg et al., 2003).

As we can see in Fig. 5, the northwest, west and southwest zones have a big contrast in net radiation values, with more than 100 $W\,m^{-2}$ difference between the southwestern and northern parts of the glacier. Since the images were selected into the driest month of the year in Mexico, this could be considered as representative of the ablation season in a balance year. This would mean that net radiation is then the controlling factor for ablation on the glacial surface. The net radiation values for 2007 are in agreement with the values measured on the same day of the year by the Glaciar AWS.

5 Discussion

The glacial shrinkage of the Glaciar Norte at Citlaltépetl is evident from the analysis of the changes within the period of 2001–2007. Figures 2 and 3 show how the glacier shrank during recent years, where the variations in terminus altitude and areal extent are strongly correlated. During these 6 yr, the glacier lost an area of 33 %, which reflects the recent strong ablation as compared to the 43 yr since 1958 when the glacier lost an area of 58 %. At the current rate the glacier could disappear by 2020, which is 20 yr faster than the previous estimates (Delgado-Granados, 2007).

Since this analysis was limited to the available ASTER images and the beginning of the ASTER project in 2000, the knowledge of the glacial retreat within 1958 to 2001 is based on the altitudinal changes documented for the glacial front. In Mexico as in most glaciers around the world the glacial retreat and the movement of the glacial front to high altitudes starts at the end of the LIA (e.g. Schneider et al., 2008; White, 2002; Palacios and Vázquez-Selem, 1996); this frontal retreat, as in the case of the Glaciar Norte where the volcanic activity is negligible, has a close relationship to climatic fluctuations.

Considering the glacial retreat from the end of the LIA until 1994 (Fig. 6) spanning about 100 yr, it is possible to observe a change in altitude of around 400 m. For comparison, during 2001–2007, a time span of only 6 yr, the corresponding glacial retreat was 100 m in altitude. This recent rapid glacial retreat was preceded by Jamapa and Chichimeco tongues complete disappearance. This is evident if we consider that the magnitude of retreat, occurred in just 6 yr, is the same order-of-magnitude than the retreat occurred in ~ 150 yr. The timing of these events suggests a close relationship between the local and global climatic changes and the glacial retreat. Glaciar Norte behaves as other glaciers on Popocatépetl and Iztaccíhuatl Volcanoes, showing similar magnitudes of retreat rates and the areal changes (Delgado-Granados, 1997; Delgado-Granados et al., 2005).

Particularly, the geometry of the glacial cover on Citlaltépetl has changed more in some places than in others. Taking into account all zones where areal changes have occurred the possible effects of net radiation on glacial surface can be seen. In Fig. 5 the strong ablation on the glacier surface is located principally at the low altitude zones where the temperature warming effects were apparently the greatest in the recent decades. Additionally, the net radiation in these zones as Jamapa and Chichimeco tongues presents high values in comparison to the high altitude zones and the eastern part of the glacier. Net radiation has a close relationship to the surface albedo and the

TCD
6, 3149–3176, 2012

changes in surface albedo are generally the result of climate change. As shown on Fig. 5, the year 2007 was when the highest values of net radiation were measured over glacial surface; which indicates strong ablation was occurring on the glacier.

Well-documented examples of these relationships are those for the Citlaltépetl Volcano's Occidental and Oriental glaciers. Glaciar Occidental covered 89 455 m^2 of the volcano surface during 2001 while during 2007 this glacier only had covered 23 268 m^2. This means a loss of 74 % of the glacial area occurred between 2001 to 2007 on Glaciar Occidental. In contrast, for the Glaciar Oriental where the net radiation is low, the glacial area lost only a 13 % during this same period (2001–2007).

If we consider each image as representative of one year (the acquisition year), and normalizing the rate by the days (in years) after two different images, it is clear that the shrinkage (or retreat) rates given in Table 1 show a great contrast between the years 2002 and 2007. The retreat rate for 2007 (–15 267 $m^2\,yr^{-1}$) decreased considerably compared with the retreat rate of only a period of 160 days between 2001 to 2002 where the retreat rate presented a large areal loss value (–209 302 $m^2\,yr^{-1}$). This contrast could be the result of local climate variability or perhaps reflects global climatic changes. The ablation processes on the Glaciar Norte must be determined using net radiation factors with careful consideration of weather seasonality and climatic changes around the glacier. In general, the ablation processes occur along the year, however in this work is not possible to conclude if ablation is more prevalent in one season than another. But it is possible to establish a scenario based on the influence of net radiation into the energy balance of the glacier.

Considering that the glacier surface is susceptible to radiative energy fluxes enclosed into the net radiation, it is clear the relationship between net radiation and the ablation/accumulation processes. This is true even when the strong ablation is inhibited by sublimation (as in the outer tropic glaciers, see Vuille et al., 2008), which allows formation of penitents over the glacial surface producing differential ablation processes. From Fig. 5, it is possible to identify two areas where the net radiation has the strongest values on the image. One of them covers the glacier head and the other one covering the western part of the glacier. In this sense, the western side of the glacier is more irradiated than the rest of the glacier which makes more difficult the permanence of snow. Therefore, the energy budget is spent on melting process which enhances the ablation on the glacial surface. In contrast, the eastern side of the glacier corresponding mainly to Glaciar Oriental does not present significant values of net radiation which is reflected in the permanence of that glacier at the present.

Moreover, the path of the sun in these latitudes causes the west remains largely radiated by the radiative fluxes throughout the day. Either when the sky is clear or if there are presence of clouds, radiation will be as short or long-wave radiation, respectively. This may mean that the results obtained in this study are representative of energy expenditure in the rest of the year.

Finally, the sensibility of the energy balance to the net radiation makes more vulnerable the glacier surface to the ablation processes if net radiation presents high values. However, there are more variables that stimulate the ablation on the glacier surface and also there are another ones inhibiting. Something similar happens on Zongo Glacier (16° S) where the ablation is dominated by the net short-wave radiation but is partly compensated by the negative net long-wave radiation. Since the net short-wave radiation is closely related to the albedo, it appears as a central variable controlling the amount of energy available at the surface of the ablation areas on inner and outer tropics (Favier et al., 2004).

6 Conclusions

The recent inventories of the glacial shrinkage at Citlaltépetl Volcano reflect the typical shrinkage behavior of the Mexican glaciers; which has already been reported for Popocatépetl Volcano's glaciers (Delgado-Granados, 2007). The recent glacial retreat and shrinkage documented show how fast the Glaciar Norte is changing and how the wastage varies across the glacier. ASTER image analysis allows quantification of the changes in areal extent, glacier altitude and radiation changes over the whole surface.

TCD
6, 3149–3176, 2012

Although there are not a lot of images available for this volcano prior to 2001, the major problem presented by this kind of methodology is the complex topography of the terrain (Huggel et al., 2008; Schneider et al., 2008). During the 6 yr period between 2001 to 2007, the glacier lost an areal extent of about the same magnitude as the previous 43 yr. This study has shown how the radiation fluxes and the climatic factors likely play fundamental roles in the evolution of the Glaciar Norte. As first reported by Ontiveros-González (2007), the net radiation over the surface correlates directly with the energy balance. Consequently, it makes sense that the spatial distribution of the net radiation corresponds directly to the ablation rate of the glacier. The most vulnerable zone on the glacier is the western part, because this is where the net radiation displays the highest values on the surface and melt rates should be also highest. The great sensitivity of the glacier retreat rates to net radiation variation shows the existence of a close relation of the climatic changes and the shrinkage at the Citlaltépetl Volcano. Perhaps regional climatic variations such as more intense "El Niño" events could be a factor that has accelerated the glacial retreat, or perhaps global warming. An extensive climatic analysis using the high elevation AWS data from this glacier will lead to further understanding about the survivability of the glaciers in Mexico.

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The recent retreat of Mexican glaciers on Citlaltépetl Volcano

J. Cortés-Ramos and H. Delgado-Granados

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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TCD
6, 3149–3176, 2012

The recent retreat of Mexican glaciers on Citlaltépetl Volcano

J. Cortés-Ramos and H. Delgado-Granados

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TCD

6, 3149–3176, 2012

The recent retreat of Mexican glaciers on Citlaltépetl Volcano

J. Cortés-Ramos and H. Delgado-Granados

Table 1. Areal changes and retreat rates of Glaciar Norte from 1958 to 2007.

Year	Time interval years	Altitude of Glacial front m a.s.l.	Glacial area km^2	Retreat rate m^2 yr^{-1}
1958	–	4695	2.23	–
2001	43	4980	0.93	−30 233
2002	0.43	4995	0.84	−209 302
2003	0.85	4998	0.78	−70 588
2004	1.09	5014	0.73	−45 872
2005	1.7	5042	0.64	−52 941
2007	1.31	5065	0.62	−15 267

TCD
6, 3149–3176, 2012

The recent retreat of Mexican glaciers on Citlaltépetl Volcano

J. Cortés-Ramos and H. Delgado-Granados

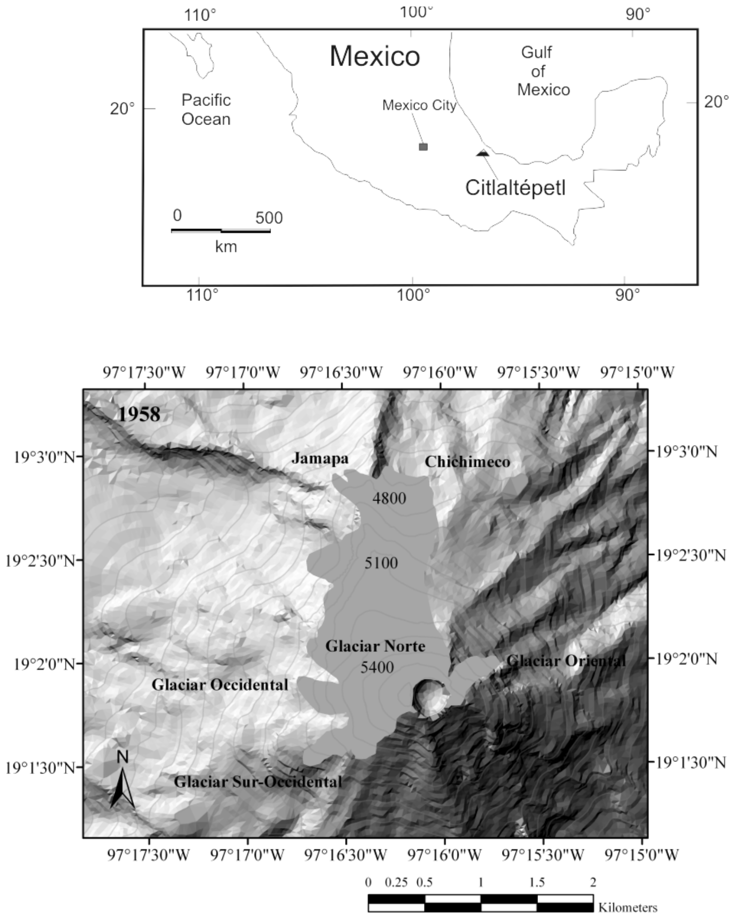

Fig. 1. Location of Citlaltépetl Volcano and extent of the glaciers documented in 1958 by Lorenzo (1964).

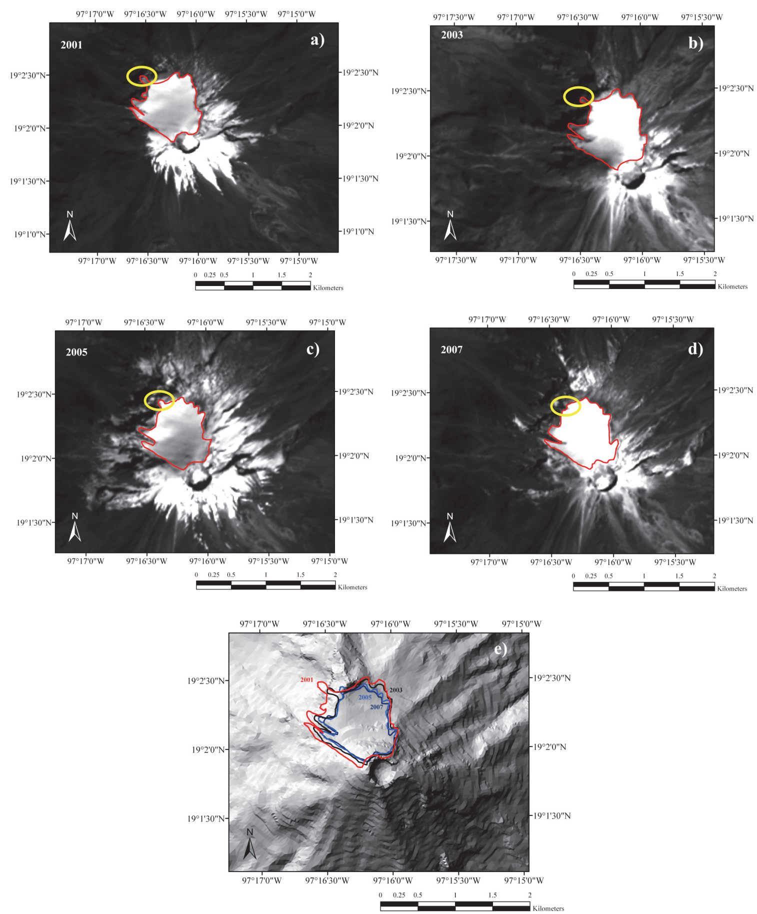

Fig. 2. Ice-coverage changes of Glaciar Norte between 2001 and 2007. **(e)** shows changes of the glacier boundaries through that period. The ellipses make evident the glacial shrinkage.

TCD

6, 3149–3176, 2012

The recent retreat of Mexican glaciers on Citlaltépetl Volcano

J. Cortés-Ramos and H. Delgado-Granados

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄| |►
◄ ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

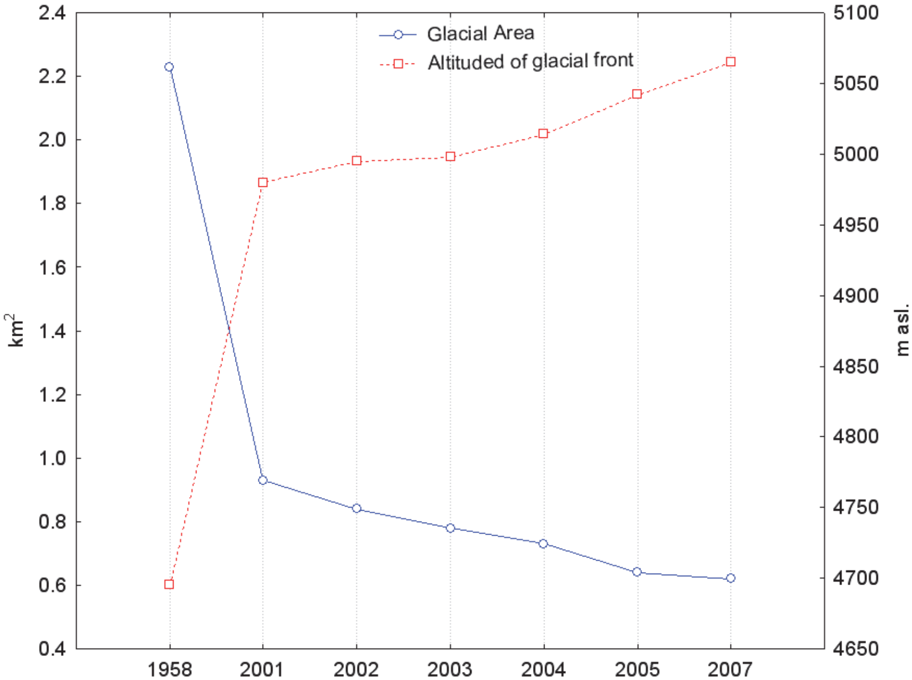

Fig. 3. Glacial area and altitude changes for the period 1958–2007.

TCD
6, 3149–3176, 2012

The recent retreat of Mexican glaciers on Citlaltépetl Volcano

J. Cortés-Ramos and H. Delgado-Granados

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀▌ | ▶▌
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

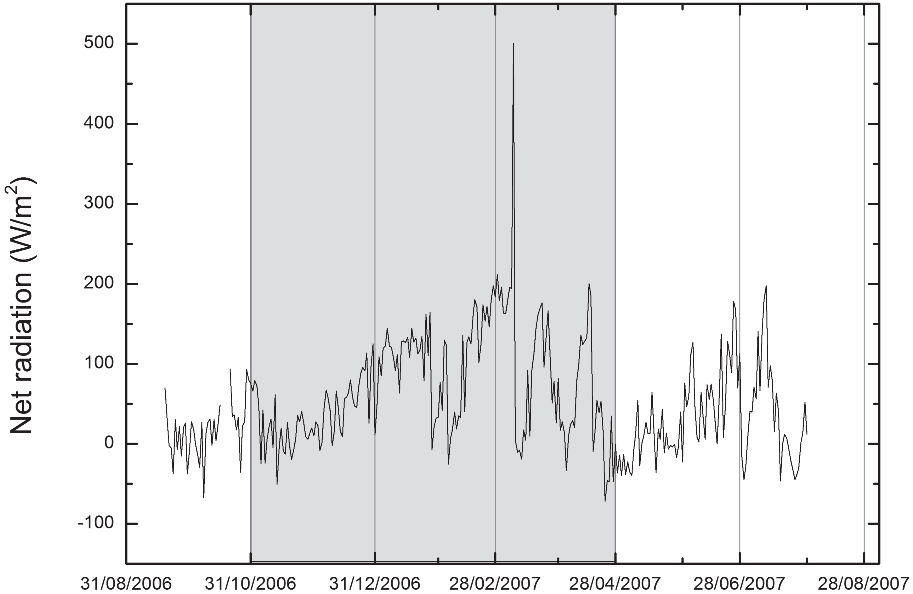

Fig. 4. Net radiation variability of the Glaciar AWS data from September 2006 to July 2007 (after Ontiveros-González, 2007).

TCD

6, 3149–3176, 2012

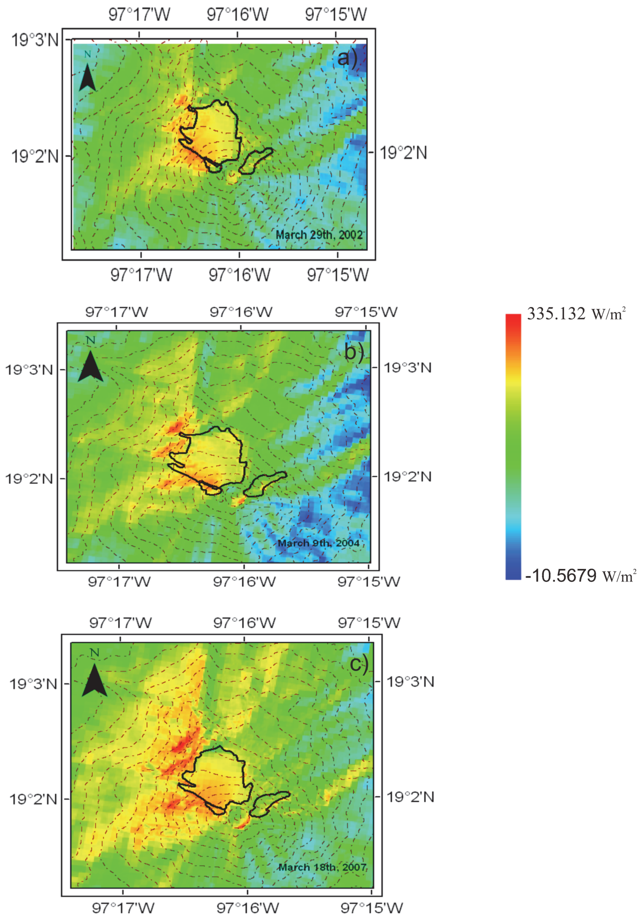

Fig. 5. Net radiation distribution over Glacier Norte's surface derived from ASTER imagery. The highest values are observed in March 2007 **(c)**. Observe the strongest values of net radiation on the western part of the glacier. **(a, c)**.

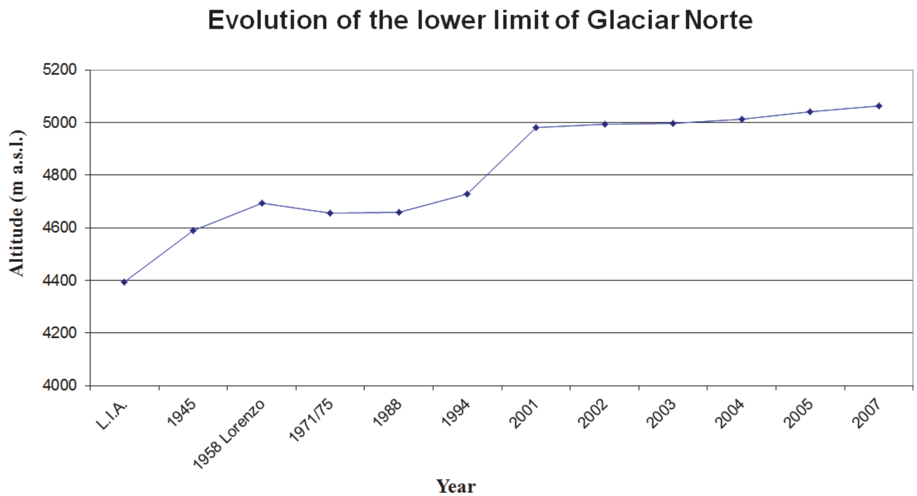

Fig. 6. Altitudinal evolution of the glacial front since the end of the LIA. The altitudes of 2001 to 2007 were calculated from ASTER imagery; previous data are from Palacios and Vázquez-Selem (1996).

TCD
6, 3149–3176, 2012