The recent retreat of Mexican glaciers on Citlaltépetl volcano detected using ASTER and Landsat 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 disappearance of Jamapa and Chichimeco glacier tongues. The Glaciar Norte rapidly retreated between 2001 and 2002 and then slowly retreated during 2007. Jamapa and Chichimeco tongues were prominent during 1958 but had completely disappeared by 2001. The Glaciar Norte lost about 72% of its surface area between 1958 and 2007. Recently, the ice loss has accelerated as evidenced by the 33% areal loss in just six years between 2001 and 2007. If this rapid shrinkage rate continues, the glaciers will be gone from the volcano by the year 2020, which is decades earlier than previously estimated. The net radiation from ASTER images and energy fluxes calculated using surface meteorological data show the close relationship between glacial shrinkage and surface energy balance. This study of net radiation balance improves understanding of recent glacial retreat in Mexico.

1. Introduction

Mexico has glaciers only because of the very high altitude of its volcanoes. Only three Mexican volcanoes have summits that are currently high enough (above 5 km a.s.l.) to allow accumulation of snowfall sufficiently deep to sustain glaciers. These are Popocatépetl (5,465 m a.s.l.), Iztaccíhuatl (5,230 m a.s.l.) and Citlaltépetl (5,675 m a.s.l.) volcanoes. The tropical geographic location makes the existence of these ice bodies unique. To-date there is insufficient knowledge of these glaciers to know why they exist and how long they will survive. Despite their small areal extent, these glaciers are important for the surrounding areas since they provide critical storage of water in the form of ice that feeds the surrounding areas especially during 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 the water shortages may occur 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; Haeberli and Beniston, 1998; Oerlemans, 2005). 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 distant 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 documented 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 1958 to 2010 using analysis of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite images, Landsat images, and data from the work of Lorenzo (1964). This data was available through Global Land Ice Measurements from Space (GLIMS) project. Remote sensing techniques and algorithms were used to calculate the spatial distribution of net radiation on the glacier using ASTER data. 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 (also called Pico de Orizaba) lies at an altitude of 5,675 meters above sea level 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 1,000 km^2. The most recent eruption occurred in 1687 and the volcano was active during the fifteen and sixteen centuries (Carrasco-Nuñez, 2000). The Citlaltépetl volcano erupted during the late Pleistocene and the Holocene, and provides 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 8,500 years before present (Heine, 1983). Also, there is evidence of two additional advances at 5000-100 yr before present (Heine, 1983; 1988). The first advance is identified by the moraine chains at the base of the volcanic cone at elevations of 4,000 to 4,400 m a.s.l. These moraines were deposited between 3,000 to 2,000 years before present (Heine 1983; 1988). The second advance corresponds to the Little Ice Age (LIA), which ended in Mexico during the mid nineteenth century (Heine, 1983). Evidence of this second advance is shown by a series of moraines that lie between 4,400 to 4,800 m a.s.l. on Citlaltépetl (Heine, 1983). In both Neoglacial episodes the glaciers advanced principally across the northern and western slopes. The last eruptive phase of Citlaltépetl corresponds to the beginning of the LIA, (Palacios and Vázquez-Selem, 1996).

Lorenzo (1964) reported four principal glaciers existed on Citlaltépetl in 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 glacier on the North Slope is called "Jamapa tongue" which extended down to an elevation of 4,395 m a.s.l. during the LIA. According to Palacios et al. (1999) the glacial front has been retreating during the last decades, also glacial shrinkage and thinning during the last century has gradually exposed valleys and basins at lower elevations (Palacios and Vázquez-Selem, 1996). Glaciar Norte is one of the few surviving glaciers on Citlaltépetl volcano, perched between 5,000 m a.s.l. and the summit. The formerly impressive Jamapa glacial tongue together with the Chichimeco tongue had disappeared by the year 2001 (Figures 1 and 2). The strong retreat of Jamapa and Chichimeco tongues culminated in 2007 as shown on Figure 1, because these tongues completely disappeared from Glaciar Norte.

Recent glacial surface studies on Citlaltépetl Volcano show the seasonality of the local weather where the temperature and the relative moisture conditions reflect the annual dry and wet seasons on the glacier (Ontiveros-González, 2007). Furthermore, the net radiation on the surface impacts the glacier balance 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. Climatic change can directly affect glacier health and has lead to major ice loss in Mexico during the last century (Delgado-Granados et al., 2007).

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 5,100 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 (Fig. 1). 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 (used NARR data has a resolution of 32 km, the method of interpolation is a bilinear interpolation which is used for surrounding grid points to get the interpolated value. The grid used for this study was: -97.333° to -97.25° longitude and 19° to 19.08° latitude). 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.

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 (see Table 1), and also using a SRTM digital elevation model with a resolution of 90 m and horizontal accuracy of ±20 m and vertical absolute accuracy of ±16m (Rabus et al., 2003). 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. It is possible to extract Digital Elevation Models (DEM) from ASTER images using stereoscopic pairs with their 3N and 3B bands. However, Cortés-Ramos (2009) determined the accuracy of these DEM comparing SRTM and ASTER derived DEM and concluded that SRTM DEM is better since topographic errors on the ASTER DEM are very high in the glacierized area.

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.

The altitude of the glacier front for each date was delimited using the limit of the glacier where Jamapa glacier was located. This altitude was obtained from a 1:20,000 DEM produced by photogrammetric methods using air photos (SIGSA: Sistemas de Información Geográfica, S. A). This DEM was interpolated with a spatial resolution of 2 m using nearest neighbor interpolation.

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 ($K^{\downarrow}_{\mathrm{sun}}$) 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); last access, 30 October 2012.

The accuracy of the present method is based on the atmospheric and geometric corrections of the images. Atmospheric corrections were made 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 date. The dispersion of radiation through the atmosphere is made by the MODTRAN subroutine of DISORT. Here, we apply the FLAASH routine considering a tropical atmosphere, a rural zone, and clear sky conditions on the scene.

The net radiation is defined as:

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

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:

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

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 Stefan-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 Stefan-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:

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

where

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

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

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 regression 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 ($L_{(13,14),TOA}(\lambda)$), 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):

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

Now, if apply the Stefan-Boltzmann law is applied,

$$L^{\uparrow} = \sigma T_{sat}^{4} \quad (5)$$

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

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

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:

$$T_0 = \sqrt[4]{\left(T_0^{R\,4}/\varepsilon_0\right)} \quad (7)$$

Once the albedo, the surface temperature, the transmissivity and the emissivity are derived, then equation 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% (~90,000 m^2) with respect to 2001. Whereas a marked decrease in the glacial retreat rate for 2007 (-9,185 m^2/year) and two positive retreat rates for 2009 and 2010 (see Table 2). The area loss between November 2005 and March 2007 was just of ~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.

This retreat is evident from Landsat and ASTER images. Figure 3 shows the glacial shrinkage of Glaciar Norte since 1973 to 2010, including the disappearance of Jamapa and Chichimeco tongues. During the period of 1973-2010 the glacial front steadily retreated to high altitudes. This reflects the changing glacier sizes, which varied in accordance with the general worldwide trend of glacier shrinkage (Zemp et al., 2007; Schneider et al., 2008). As shown in Table 2, the shrinkage rate gives an average glacier loss of 26,272 m^2/year for the last ten years, which is 3% of the glacial area per year. For the end of the LIA the glacial limit was around 4,395 m a.s.l. (Palacios and Vázquez-Selem, 1996), while Lorenzo (1964) reported for 1958 an altitude of the glacial front about 300 meters higher at 4,695 m a.s.l. Figure 4 shows the major glacial retreat that happened in the last decade, where during 2003 the glacier terminus extended below 5,000 m a.s.l. and just in 2 years the lower limit only to 5,050 m a.s.l.

4.2. Surface distribution of net radiation

The energy balance model developed for Ontiveros-González (2007) was used to 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 were used to calculate the energy balance at the glacial surface. From these results, this study determined the radiative fluxes are the main factors to the energy balance, and the net radiation is most important (Cortés-Ramos, 2009). According to the results of Ontiveros-González (2007), the energy exchanges at the glacier surface are reliable indicators of the mass loss of the glacier. The net radiation is the principal component of the energy balance and also the mass loss at the glacier surface. The presence of a uniquely tropical-type ablation season was identified by Ontiveros-González (2007) for the winter season (beginning on January) when the air temperature and humidity reach their minimum values. This period is accompanied by an increasing of net radiation values at the glacial surface, which causes enhanced ablation during mid-winter in Mexico.

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. 5). 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 (Delgado-Granados et al., 2007). March is a period previous to the formation of penitents over the Glaciar Norte glacier (Lliboutry, 1954). If the penitents are formed, then the average albedo will change with the surface roughness and all factors that control glacier surface net radiation adsorption and reflectivity. A low albedo (such as for coarse, dirty, damp and rough ice) will increase the net radiation on the surface because more solar energy is absorbed. The increased energy adsorption at the surface leads to a more positive the energy balance and causes more ice ablation (melting, sublimation and fracturing), and thus a more negative glacier mass balance..

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 zones prone for glacial mass loss are those where the net radiation has the highest differences in spatial variability. 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 decrease in cloudiness in the dry season plays an important role, because the glacier retreat is accelerated by increased ablation, as demonstrated for Mount Kenya and Rwenzori (Kruss and Hastenrath, 1987; Mölg et al., 2003)

As we can see in Fig. 6, terrain aspect causes big contrast in net radiation values, with net radiation observed on the southwestern and northern glacier surfaces about 100 W/m^2 higher than observed on other compass directions. 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 each balance year. Also, Figure 6 shows how this net radiation ablation pattern prevails even in the rainy season as we can see for November 2005 and December 2008. For October 2001 this was different since the glacier was covered by snow, however the western part of the glacier still had the highest values of net radiation.

This would mean that net radiation is the controlling factor for ablation on the glacial surface and confirm previous findings (see for example Mölg et al., 2003 or Mölg and Hardy, 2004). The net radiation values for 2007 are in agreement with the values measured on the same day of the year by the Glaciar AWS. For March 18, 2007 at 17 hrs UTC, the average value of net radiation for the Glaciar AWS was 239.40 W/m^2 and the value of net radiation with the ASTER images had a value of 229.02 W/m^2 at the same time, while the Morrena AWS had a value of 291.5 W/m^2 and the ASTER image 270.58 W/m^2).

5. Discussion

The shrinkage of the Glaciar Norte at Citlaltépetl is evident from the analysis of the ice extent changes within the period of 2001-2007. Figures 3 and 4 show how the glacier shrank during recent years, where the variations in terminus altitude and areal extent are inversely correlated. The glacier terminus retreated as the area shrank, and indicates little if any response delay in these small and relatively thin ice masses. Between 2001 and 2007 the glacier lost 33% of its area, which reflects the recent strong ablation as compared to the 43 years since 1958 when the glacier lost an area of 58%. At the current rate the glacier could disappear by 2020, which is 20 years faster than the previous estimates (Delgado-Granados, 2007). This estimation could be more effective if the ice thickness changes were recorded together with the volume changes of the glacier. Then, future measurements of thickness should be developed as in the study of Ramirez et al. (2001).

Since this analysis was limited to the available ASTER and Landsat images, the knowledge of the glacial retreat within 1958 to 2010 is based on the altitudinal and areal changes documented in this work. In Mexico as in many regions around the world, the glacial retreat to high altitudes started 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 well documented global climatic fluctuations.

Considering the glacial retreat from the end of the LIA until 1994 (Fig. 7) spanning about a hundred years, it is possible to observe an average terminus change in altitude of around 400 meters for Mexican glaciers (about 1 to 2 meters vertical retreat per year). For comparison, during 2001-2007, a time span of only six years, the corresponding glacial retreat was 100 meters in altitude (about 5 to 10 times faster). This recent rapid glacial retreat was preceded by Jamapa and Chichimeco tongues complete disappearance. The timing observed shows 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. By taking into account all zones where areal changes have occurred, the importance of net radiation (an especially solar radiation) on glacier balance is identified. In Fig. 6 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 near the former Jamapa and Chichimeco tongues was greater in comparison to the high altitude zones and the eastern part of the glacier, further confirming the importance of net radiation for the survival of glaciers in Mexico. Net radiation has a close relationship to the surface albedo and the changes in surface albedo are strongly influenced by climate change. As shown on Fig. 6, the years 2003 and 2007 were when the highest values of net radiation were measured over glacial surface; and when the strongest 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 and 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 2 show a great contrast between the years 2002 and 2007. The retreat rate for 2007 (loss of 9,185 m^2/year) decreased considerably compared with the retreat rate between 2001 and 2002 where the retreat rate presented a large areal loss value (loss of 89,475 m^2/year). 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. The typical mid latitude accumulation/ablation pattern for glaciers does not apply in semi-arid tropical latitudes such as in Mexico. In general, the ablation processes occur along the year, and accumulation typically occurs with the warmest temperatures. In this work it was not possible to conclude if ablation is more prevalent in one season than another, and further studies are required. But we have established the influence of net radiation is important the energy balance, and thus likely important for the Mexican glacier mass balance and retreat rate.

The glacier surface is particularly sensitive to solar radiative energy fluxes so, a relationship between net radiation and the ablation/accumulation processes should exist. This is true even when the strong ablation is inhibited by sublimation (as for subtropical glaciers in dry areas, see Vuille et al., 2008), which allows formation of penitents over the glacial surface producing differential ablation processes. From Fig. 6, it is possible to identify two areas where the net radiation greatest. One area is near glacier head and the other one is the western part of the glacier.. In this sense, the western side of the glacier obtains more net radiation than the rest of the glacier and also shows less snow cover. 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 has less net radiation which is reflected in the greater ice and snow extent of that glacier observed at present, which is likely due to a less negative glacier mass balance.

Moreover, the path of the sun in these latitudes, together with the morphology of the mountain and the orientation of the summit causes the western slopes to remain in direct sunlight throughout the day and especially in dry seasons.

Finally, the sensibility of the energy balance to the net radiation makes the glacier surface more vulnerable to ablation processes when the net radiation is high. However, there are more variables that enhance ablation on the glacier surface and also other factors inhibit ablation. These additional factors are beyond the scope of this study. Similar findings were obtained on Zongo Glacier (16°S) where the ablation is dominated by the net short-wave radiation but there the incoming positive net radiation for melting is partly compensated by the negative net long-wave radiation causing cooling (Sicart et al. 2008). Since the net short-wave radiation is closely related to the albedo, solar radiation 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). For glaciers at mid-latitudes these relationships are different, for that case energy balance is strongly correlated with temperature (Sicart et al. 2008).

6. Conclusions

This new glacier inventory for Citlaltépetl Volcano reflects the typical shrinkage behavior of the Mexican glaciers and is consistent with previous reports for Popocatépetl Volcano's glaciers (Delgado-Granados, 2007). The recent glacial retreat and shrinkage documented in this paper shows how fast the Glaciar Norte has recently changed and how the glacier wastage varies across the volcano. ASTER image analysis allows quantification of the changes in areal extent, glacier altitude and radiation changes over the whole surface. Although available images are rare 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 six year period from 2001 to 2007, the glacier lost an areal extent of about the same magnitude as the previous 43 years. 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 of the glacier is the western part, because this is where the net radiation displays the highest values and where the surface melt rates should be also highest. The great sensitivity of the glacier retreat rates to net radiation variation provides a mechanism to relate climate change to ice loss at 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. This study lays a firm groundwork for understanding last century of glacier variations in Mexico, however if the current seasonality of precipitation and cloud cover changed to allow greater clean snow accumulation (causing higher albedo) and less incoming net radiation (leading to less surface melt), then ice mass growth may result. An extensive climate data analysis using our high elevation Automatic Weather Station on the glacier at 5100 m a.s.l. on Citlaltépetl Volcano can lead to further understanding about the survivability of the glaciers in Mexico.

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Table 1. ASTER scenes used in this study.

Table 2. Altitude of glacier front, areal changes and retreat rates of Glaciar Norte between 1958 to 2010, as obtained from Landsat and ASTER images. 1958 data corrected after Lorenzo (1964; see text).

Fig.1. Location of Citlaltépetl volcano and extent of its glaciers as documented in 1958 (Lorenzo, 1964; grey area) and 2007 (this work; contour in blue). Shaded relief of 1:20,000 DEM from SIGSA (Sistemas de Información Geográfica S. A.). MC: Mexico City; C: Citlaltépetl Volcano.

Fig. 2. Ice-coverage changes of Glaciar Norte between 2001 and 2007 obtained from ASTER images. Figure 2e shows changes of the glacier boundaries through that period. The ellipses make evident the glacial shrinkage. a) 20 October 2001; b) 3 February 2003; c) 23 November 2005; d) 18 March 2007.

Fig. 3. Glacial shrinkage on Citlaltépetl Volcano from 1973 to 2010. Outlines from 1973, 1989, 1999, 2000, 2006, 2009 and 2010 were delimited using Landsat data of the sensors MSS and ETM+. The rest of the outlines are from ASTER data (Figure 2).

Fig. 4. Glacial area and altitude changes for the period 1958-2007.

Fig. 5. Net radiation variability of the Glaciar-AWS data from September 2006 to July 2007 (after Ontiveros-González, 2007).

Fig. 6. Net radiation distribution over Glaciar Norte's surface derived from ASTER imagery. The highest values are observed in February 2003 and March 2007. In almost images is possible to observe the strongest values of net radiation on the western part of the glacier.

Fig. 7. Altitudinal evolution of the glacial front since the end of the LIA. The altitudes of 2001 to 2007 were calculated from ASTER imagery; values for L.I.A., 1945, 1971/1975, 1988, and 1994 were obtained from Palacios and Vázquez-Selem (1996).