Memorias de la Primera Conferencia Internacional de Cambio Climático: Impacto en los Sistemas de Alta Montaña

Proceedings of the First International Conference on the Impact of Climate Change: on High-Mountain Systems

Suiza.

IDEAM
INSTITUTO DE HIDROLOGÍA, METEOROLOGÍA Y ESTUDIOS AMBIENTALES

UNIVERSITAS TURICENSIS

2007

Climate change vs. Volcanic activity: Forcing Mexican glaciers to extinguish and related hazards

Hugo Delgado Granados[1]

Abstract

Glaciers in México have shown a retreat pattern along the last decades as a consequence of climate change. However, since these glaciers are capping active volcanoes with a variety in activity level, their changes are not only the result of climatic interactions but also the consequence of volcanic activity. Relations between the volcanic activity and the presence of glaciers have several aspects to study, among them: ice melting provoked by eruptive products and heat flux, glacier extinction, and debris flow generation.

Small-sized glaciers can be found at Iztaccíhuatl, Popocatépetl and Citlaltépetl whose volcanic activity is characterized by a different level of activity. Popocatépetl volcano's glaciers have been influenced by the changing climatic conditions, the regional warming due to the presence of largely populated settlements in the surroundings, and the eruption of the volcano; whereas Iztaccíhuatl volcano's glaciers have been influenced by the same factors except the eruption. Citlaltépetl volcano's glaciers have been just affected by climatic changes. Available meteorological data suggests that a decrease in precipitation is the main climatic factor influencing the glacier's retreat.

In spite of the activity state of the volcanoes (erupting, fumarolic, or dormant), we know that one of the main consequences of the ice-volcanic activity interactions is the generation of lahars. So, one of the motivations to study those interactions is to prevent the possibility for having this kind of devastating events at any volcano in México, especially because some of the explosive events at Popocatépetl volcano have generated lahars during the past eleven years. In order to better assess the laharic hazards, an updated inventory of the glaciers is mandatory.

Introduction

The glaciers of México have been present during the last century on top of the three highest moun-tains of the country (figure 1): Iztaccíhuatl (5.286 m.a.s.l.), Popocatépetl (5.420 m.a.s.l.), and Citlaltépetl (5.640 m.a.s.l.). All these mountains are active volcanoes. The term active volcano is applied to those volcanoes with eruptive activity within the last 10.000 years, and all three highest volcanoes of México had at least an eruption within this term.

Mexican glaciers were studied for the first time in 1958 as part of the activities of the International Geophysical Year (Lorenzo, 1964). At that time, the total glaciated surface was reported in 0,89 Km^2. Delgado-Granados et al. (1985a and 1985b) raised the need for an updated inventory of the glaciers of México after two decades without glaciological studies and initiated the work at the glaciers of Popocatépetl and Iztaccíhuatl.

[1] Universidad Nacional Autónoma de México, Instituto de Geofísica, Departamento de Vulcanología, México, D. F., México; hugo@geofisica.unam.mx

Delgado-Granados (1997) presented an updated inventory of Popocatépetl volcano's glaciers, along with field observations made between 1977 and 1992. In this work, two glaciers (0,559 Km^2) and four permafrost fields (0,239 Km^2) were reported. When comparing the total glaciated area reported in 1964 with that reported in 1982, a reduction in the total glaciated area of 22% was observed. The retreat of the glaciers at Popocatépetl volcano was evidenced not only in terms of the total glaciated area, but also, it was demonstrated in terms of the tongue's altitude position. All tongues at Popocatépetl retreated in terms of distance and altitude along the decades. This retreat was speculated to be originated by: an increase of the volcano's heat flow; local climatic changes; global climatic changes; or a combination of all these factors.

Figure 1: Location of the three highest mountains of México: 1) Popocatépetl volcano, 2) Iztaccíhuatl volcano, and 3) Citlaltépetl volcano, also known as Pico de Orizaba.

On December 21, 1994, Popocatépetl started an eruption that has lasted for more than 12 years (Delgado-Granados et al., 2001). The eruption was characterized by vulcanian explosions that cleared out the conduit system over the end of 1994, the entire 1995, and the beginning of 1996. In early March 2006, the eruption turned to be bimodal: effusive and explosive. On March 27, 2006, a lava dome appeared inside the crater of the volcano, but on April 30, 2006 the lava dome was de-stroyed by an energetic explosive event. Ever since, events of lava dome construction alternated with destructive explosive vulcanian events constitute the main eruptive pattern at the volcano. The eruptive activity has affected the glacial regime.

Since the beginning of the eruption, the presence of ice masses near the vent became a matter of concern for the authorities (Delgado-Granados and Brugman, 1995). The concern was focused on the likely production of laharic flows due to the interaction between the eruptive products of the volcano and the ice, especially because of the presence of important laharic deposits in the stratigraphic record (Delgado-Granados and González-Huesca, 1994; Delgado-Granados et al., 1994), and the sad historic precedent of Nevado del Ruíz in Colombia in 1985 (Thouret, 1990). Huggel and Delgado (2000) mentioned that glaciers in combination with volcanoes may represent an important hazard for human settlements. They stressed that, since Popocatépetl volcano is located in the vicinity of highly populated areas, monitoring of its glaciers had to be considered as a vital part of the surveillance system of the volcano. Therefore, more attention was devoted to the measurement of the glaciers. The two small glaciers were monitored mainly by aerial photographs taken nearly on a monthly basis. Using these data, maps and digital elevation models were generated with photogrammetrical and further image processing methods. The results threw impressive retreat figures after the eruption of the volcano started. In 1996 the total glaciated area was reported to be 0,54 Km^2, and 0,42 Km^2 by 1999.

Even though the main interest was put in laharic hazards evaluation (Delgado-Granados et al., 1994; Palacios et al., 1998; Delgado-Granados et al., 2000; Sheridan et al., 2001; Julio-Miranda and Delgado-Granados, 2003; Bursik et al., 2003; Capra et al., 2004; Julio-Miranda et al., 2005), the retreat of the glaciers was outstanding. The retreat was observed long before the eruption started (Delgado-Granados, 1997) and thus, not only an eruptive forcing of the retreat had to be causing the shrinkage of the glaciers but also the climate should have been acting. The only way to test this was to accomplish the study of all the glaciers in México. The study of the glaciers of México has relevance in terms of laharic-hazards evaluation (because all glaciers are settled on active volcanoes), and in terms of climate change.

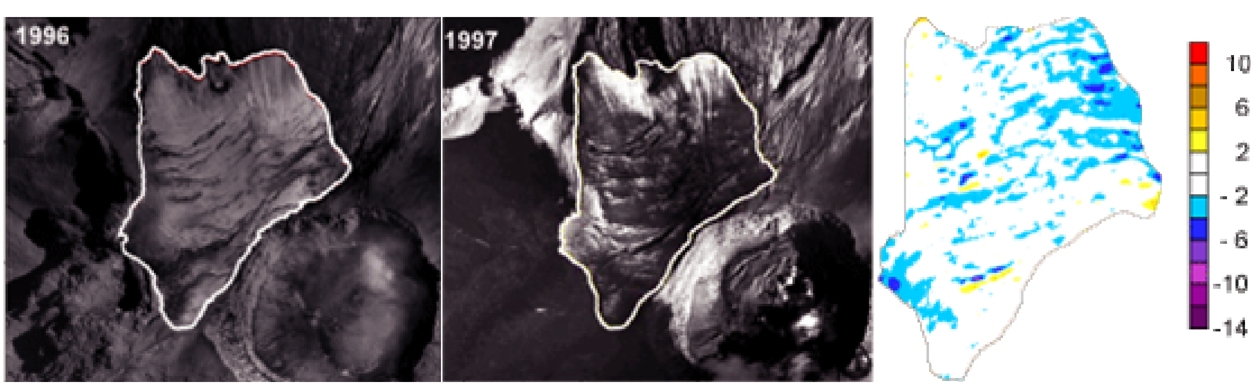
Mexican glaciers offer a rare opportunity for glaciological studies. The glaciers of Popocatépetl volcano were affected by the 12 years-long eruption, but also could be affected by the pollution from the largely populated and industrialized areas nearby (such as México and Puebla cities). These glaciers however, have been affected by the climatic change documented elsewhere (Haeberli et al., 2002). On the other hand, Iztaccíhuatl volcano is not under eruptive conditions but its glaciers could be affected by the other two effects. Finally, Citlaltépetl volcano is not erupting, and no large settlement is located nearby. If there is a possibility to study the global climatic effects on Mexican glaciers, it is at this volcano.

This work is a progress report on the different studies made at the Mexican volcanoes, in order to elucidate the causes that provoked the shrinkage of their glaciers. The entire study would document the extinction of the Mexican glaciers in the first half of the 21st century.

Methods

Study of Mexican glaciers needs the following lines of action: a) glacier inventory update; b) determination of thicknesses; and glacier characterization.

Glacier Inventory Update. It is needed to know the total glaciated area at the three mountains. For this end, topographic maps published in previous years are useful, as well as aerial photomaps (i. e. INEGI, 1982). Also, a comprehensive compilation of aerial photographs has been made for the three volcanoes, and their original acquisition data has been obtained in order to carry out photogrammetrical restitution (applying digital photogrammetry). Orthorectified aerial photographs (figure 2) can be used, together with precise ground control points determined by using double-frequency GPS, to produce digital elevation models (DEM). DEM allow the determination of glaciated surfaces within reasonable accuracy (Julio-Miranda and Delgado-Granados, 2003).



(A) (B) (C)

Figure 2: Examples of aerial photographs from Popocatépetl volcano. The restituted photographs (A and B) allow the construction of DEM. Subtraction of DEM permit the calculation of differences in area but also in altitude, those differences are in fact, thickness losses. In (C) the scale of the resulting differences in thicknesses after subtraction of DEM are indicated.

Thickness Determination. Thickness is needed to be known for volumetric calculations. An inventory is more complete if we know the volume and not only the area of the glaciers. Evaluation of laharic hazards is more viable if the volumes are known. There are four ways to make thickness observations. The first is through direct observations in the field at exposed sites where the upper glacier surface and the bedrock are seen. The second method uses the information provided by DEM. When two or more DEM are available, subtraction among them result not only in areal differences but also in altitude differences. These altitude differences are, in fact, thickness losses between the dates of the concerned DEM (figure 2C). The third method is by drilling through the ice (figure 3A). Mexican glaciers are not so thick so, regular drilling devices may get to the bottom of the glaciers. The fourth method is by carrying out ground penetrating radar (GPR) profiling (figure 3B). Profiling has been carried out by using two different instruments: an Ekko IV radar system with 100 MHz antennas, and a Geophysical Survey System SIR 2000 with a mono static antenna of 200 MHz (GSSI-5106).


(A)


(B)

Figure 3: (A) Drilling through the ice at Ayoloco Glacier at the site known as “La Panza”, using a vapor drill. (B) GPR profiling on the slopes of Citlaltépetl volcano.

Glacier Characterization. Up to now, most of the knowledge on Mexican glaciers comes from glacier inventories but no quantitative data existed about the meteorological conditions at the high-mountain environment. The available meteorological data come from stations located 15 - 30 Km from the mountains. Even though some scarce data on ice temperature existed, no systematic glaciological data was acquired ever. Currently, research of the Mexican glaciers comprises: meteorological data acquisition, mass, energy and hydrological balance determinations. For meteorological data acquisition two stations have been installed at ~5.000 m.a.s.l. on Citlaltépetl volcano.

(A) (B)

Figure 4: (A) “Moraine” meteorological station at Citlaltépetl volcano. (B) “Glacier” meteorological station at Citlaltépetl volcano.

One of the stations was settled on the hump of a moraine (figure 4A), whilst the other was put on the glacier surface (figure 4B). Both are equipped with sensors for recording air temperature, humidity, pressure, wind speed and direction, precipitation (liquid and solid), and radiation (using a pyranometer and a radiometer). The station installed on the glacier has two additional thermistors at 0,5 m, and 1,0 m for ice temperature acquisition. In the near future, an additional meteorological station will also be installed at ~5.000 m.a.s.l. on Iztaccíhuatl volcano with a similar setting as the moraine station of Citlaltépetl. The three stations are planned to be transmitting data in near-real time. Energy balance will be determined by using radiation data from the stations. Mass balance will be determined by using the DEM, GPS surveying, and the measurement of stakes installed on Citlaltépetl’s North Glacier. Hydrological balance is currently evaluated for Iztaccíhuatl volcano by using existing hydrological data.

Resultados

Iztaccíhuatl volcano’s glaciers.

Glacier Inventory Update. Iztaccíhuatl volcano (White Woman in náhuatl language, also known as the Sleeping Woman), is located 45 Km southeast of México City (figure 5). Even though Iztaccíhuatl has been considered for a long time an extinct volcano (Mooser, 1958), recent reports on diffuse degassing and seismic events at the volcano and its vicinity indicate that this is, in fact, an active, dormant volcano (Delgado-Granados, 2001). Lorenzo (1964) measured for the first time the size of twelve glaciers on Iztaccíhuatl volcano by using aerial photographs restituted photogrammetrically obtaining 1,21 Km^2. Delgado-Granados et al. (1985b) found that three glaciers were extinct, and the rest were described and classified. Delgado-Granados et al. (2005) reported for 1982 a total glaciated area of 0,97 Km^2, an area loss of 20% in 24 years. Delgado-Granados et al. (2005) studied one of the most representative glaciers of Iztaccíhuatl: Ayoloco Glacier, reporting an area of 218.340 m^2 for 1982, and 140.890 m^2 for 1998, which compared to the reported area by Lorenzo in 1968 of 247.500 m^2 threw a glacial area retreat of 43% in 30 years for this glacier. More recently, Schneider et al. (in press) reported an update of the glaciated areas of Iztaccíhuatl using ASTER imagery data. In spite of differences, all the studies point to the strong retreat of Iztaccíhuatl’s glaciers. It has been hypothesized that a possible volcanic reactivation may produce a basal increased heat flow that may produce more melting than the originated by climatic factors.

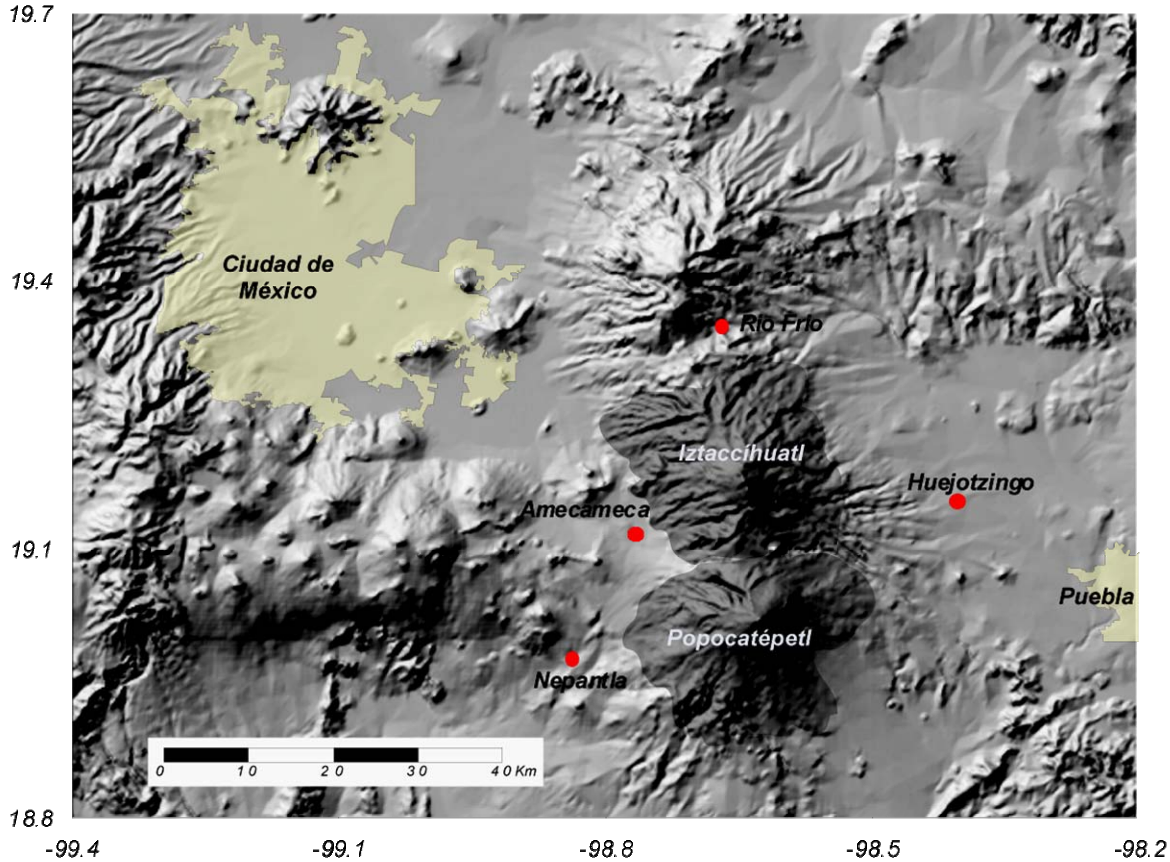


Figure 5: Location map of Iztaccíhuatl and Popocatépetl volcanoes. Red dots are location of meteorological stations.

Thickness Determination. Álvarez and Delgado-Granados (2002) applied ground penetrating radar (GPR) techniques to study the morphology of the ice at depth and investigated the buried volcanic landforms (figure 6). Delgado-Granados et al. (2005) found at Ayoloco Glacier a maximum thickness of more than 70 m with an estimated average of ~20 m. With these figures a volume of the glacier was calculated in 4.516.400 m^3. A stake network was deployed on the surface of the upper Ayoloco Glacier at the site known as La Panza, and even though the network was ephemeral and lasted less than a year, it was possible to observe that the stakes at the uppermost part of the glacier showed little horizontal displacement but a vertical movement was observed (sinking) which evidenced the thinning of the glacier (Luna-Alonso, 2002; Luna-Alonso et al., 2002).

Glacier Characterization. Most of the snow precipitation extensively melts during the dry season (January-May) due to the intense radiation at this altitude. Part of the snow on the surface sublimates resulting in ice conical shapes (penitents) and water ponds at their base. The resulting water progressively refreezes during the night and is thus converted into glacier ice. Such glacier ice has no internal structure, and is rather a glass-type glacier ice. The average temperature of the glacier ice is ~-1,5 ºC (ranging from -2,0 ºC to 0,5 ºC) and therefore, existence of englacial water bodies (de-scribed as water pockets by Álvarez and Delgado-Granados (2002) is not unlikely inside the upper-most part of Ayoloco Glacier as revealed by the GPR profiling (figure 6). Notwithstanding, the aver-age density of glacier ice was measured in ~910 Kg/m^3.

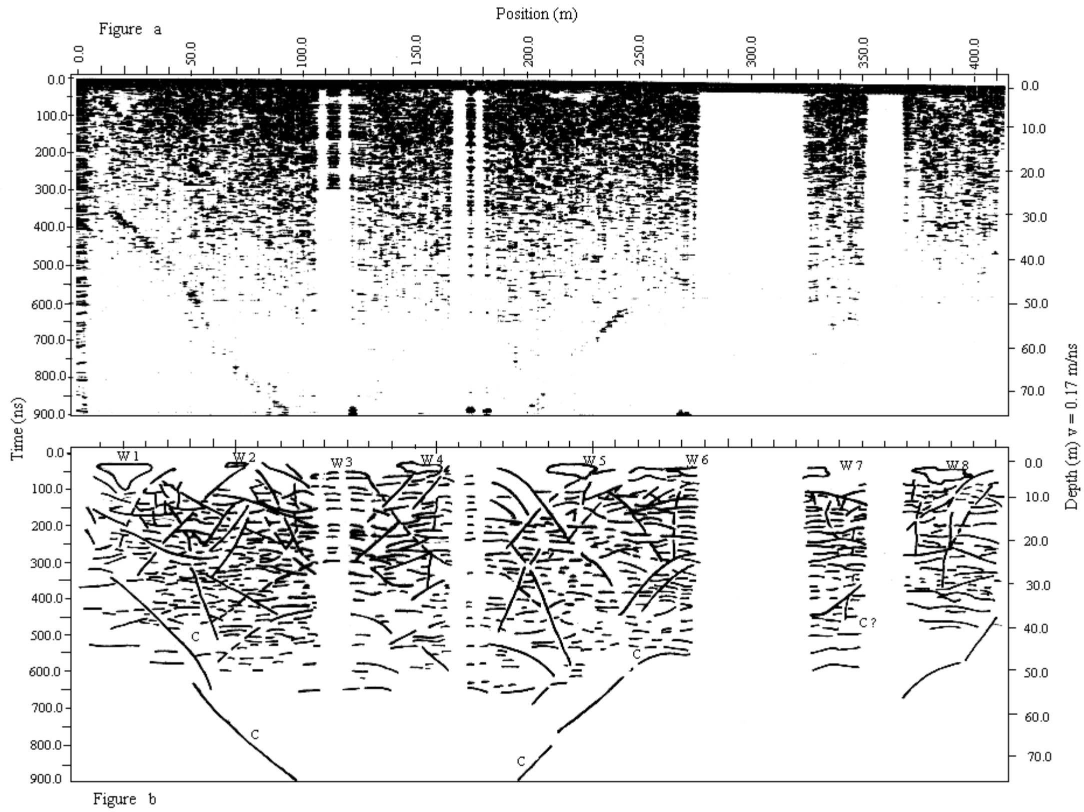
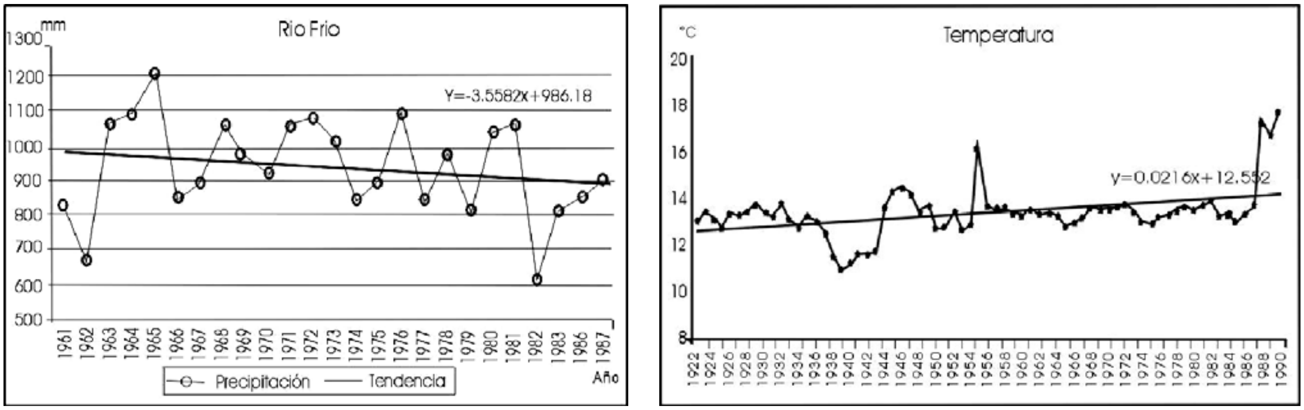


Figure 6: a) GPR profile of Ayoloco Glacier at “La Panza”; b) profile’s interpretation, showing intense fracturing at the uppermost part of the glacier (0 - 10 m deep) where water pockets can also be seen an intermediate part (10 - 50 m) with thicker ice layers, and a more ductile, less fractured lower part (50 - 85 m). W1 to W8 are water pockets interpreted along the profile.

The available meteorological data from nearby meteorological stations is quite interesting (Ortega, 2001). At Río Frío station, ~20 Km from the mountain (figure 7), the temperature shows an increasing pattern whilst the precipitation shows a decreasing pattern. Precipitation pattern is opposite at Huejotzingo station (~25 Km from the mountain), although the temperature pattern increases (figure 8). Another nearby station (Amecameca at ~15 Km from the mountain), shows a different trend with a decreasing pattern of both, precipitation and temperature (figure 12). Decrease in precipitation, and increase in temperature at two nearby stations may explain the retreat of glaciers. Unfortunately, these stations no longer exist and no recent data is available. More conclusive data will come from the forthcoming meteorological station.



(A) (B)

Figure 7: Río Frío meteorological station (see location in figure 5). A) Plot of the precipitation data showing a decreasing pattern. B) Plot of the temperature data, showing an increasing pattern.

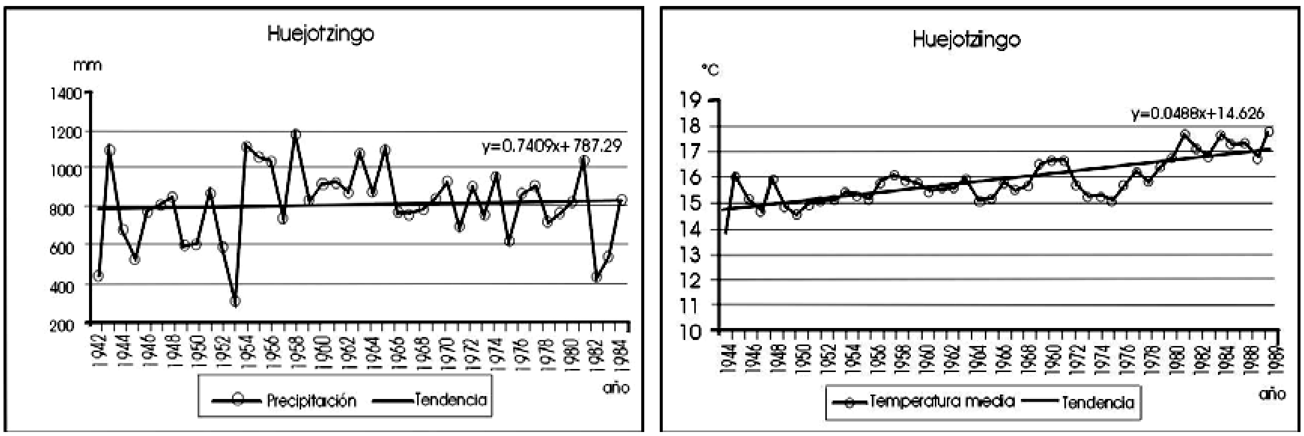


Figure 8: Huejotzingo meteorological station (see location in figure 5). A) Precipitation data showing an increasing pattern. B) Plot of an increasing pattern of the temperature data.

Popocatépetl volcano's glaciers.

Glacier Inventory Update. Lorenzo (1964) was the first to carry out exact area measurements of Popocatépetl´s glaciers, based on the glacier extent of 1958, distinguishing three glaciers on Popocatépetl. Glaciar Norte was, in fact, part of Ventorillo glacier (Delgado-Granados, 1997). Compared to the areal extent of 1958 the total area of Ventorillo and Noroccidental glacier diminished by 1996 in 0,36 Km^2 which is equivalent to a loss of 40% of the 1958 area (0,89 Km^2) with a mean retreat rate of 0,01 Km^2a^{-1}. Glacier terminus retreat (Ventorillo tongue) for the same time is given as 95 m in altitude or as a mean rate of 2,5 ma^{-1}. The continuous retreat pattern was interrupted between 1968 and 1978 by a considerable advance of about 100 m in altitude (White 1981). Photographs taken at that time show a glacier tongue characteristic of advancing glaciers. A strong retreat observed after 1978, resumed the retreat observed since the fifties in a more or less linear way. From 1996 to early 1999 glaciers suffered a loss of 0,12 Km^2 or 22% of the 1996 area (0,54 Km^2) resulting in a retreat rate of 0,045 Km^2a^{-1}. During the same interval, Ventorillo tongue retreated 8 m and Noroccidental tongue 28 m (retreat rates of 3 ma^{-1} and 10,5 ma^{-1}, respectively). The strong loss in area was most pronounced on either flank of the glacier. Remarkably, glacier changes between 1982 and 1996 were minimal in terms of area. Still, a loss of 22% of the area during 3 years indicates extraordinarily high glacier shrinkage since 1996 (Huggel and Delgado-Granados, 2001).

Even though Popocatépetl volcano was erupting since 1994, glaciers only responded after resumption of the eruptive activity in March 1996. The eruptive activity during the initial stage (1994 - 1995) did not affect much the glaciers (the small tongue retreated at a rate of 1.8 m/year and the glacierized area changed at a rate of ~103 m^2/year). After resumption of eruptive activity in March 1996, the re-treat rate of Ventorrillo tongue increased three-fold in 1998, an order-of-magnitude by 1999 and two orders-of-magnitude in late year 2000. Areal change rate in the period 1996 - 1997 is similar to the rate before the eruptive activity but mass loss consistently increased between 1996 and 1999, and maintained the same order-of magnitude surface area change rate in 1999 - 2000. The glaciers of Popocatépetl volcano became extinct in the year 2000 (Delgado-Granados et al., in press) because the ice masses lost the characteristics of a glacier when the ice became stagnant, attached to the steep slope, and the bedrock was exposed in between ice blocks. Crevasses were the sites where thinning took place in a way that bedrock became visible at their previous locations, leaving behind a series of “ice stripes”.

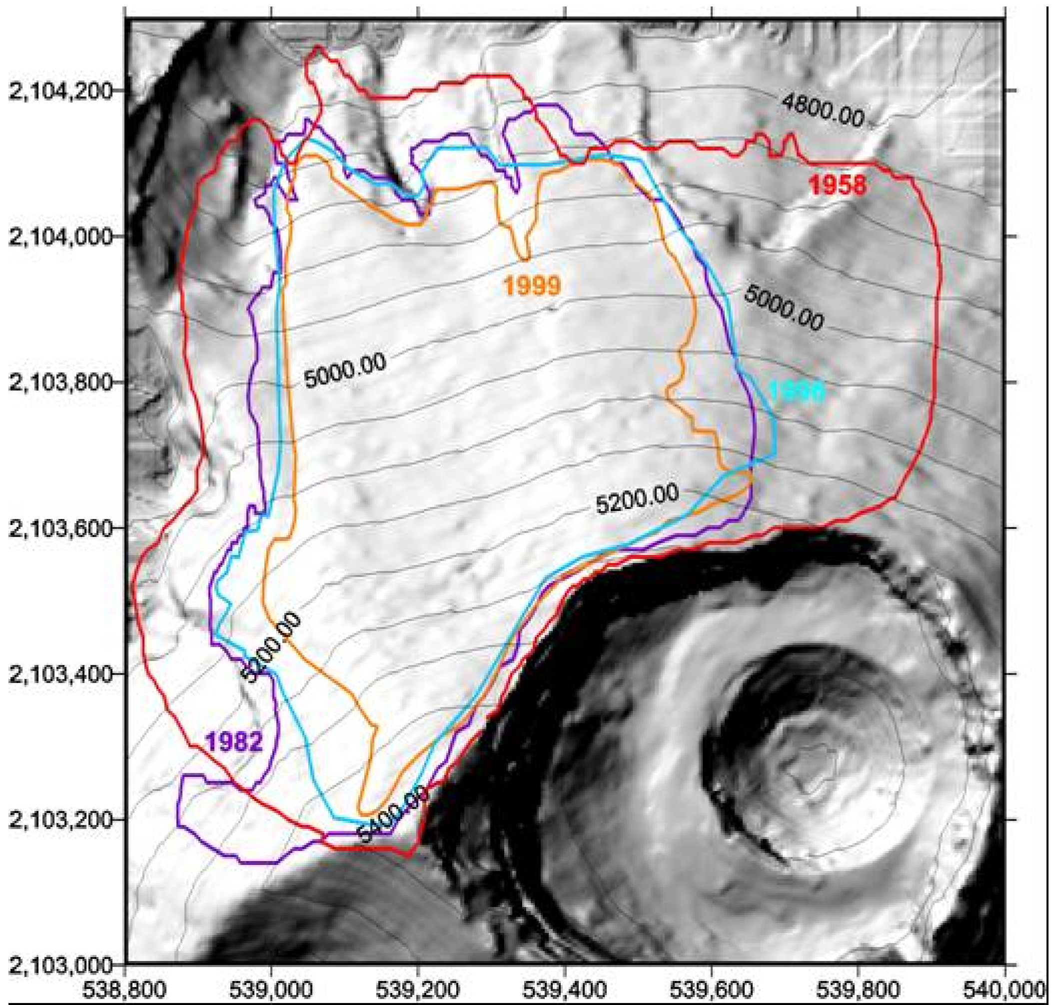


Figure 9: Glacier extents in 1958, 1982, 1996 and 1999 shown over a digital elevation model including the crater of Popocatépetl. Geographic reference is indicated by the national Mexican coordinate system (from Huggel and Delgado-Granados, 2001).

Thickness Determination. Maximum thicknesses measured in 1995 were 40 – 70 m depending on the site over the Ventorrillo Glacier (Delgado-Granados and Brugman, 1995). However, the glacier regime was disrupted by eruptive activity since mid-1996. Maps and data show the distribution patterns of mass losses, in area (figure 9), thickness and volume (figure 10). Average thickness and mass losses increased every year, and accumulation was strongly inhibited because new snowfalls melt under volcanic ejecta.

Glacier Characterization. According to Delgado-Granados (1997) the major sources of nourishment for Popocatépetl glaciers were snow, hail, refrozen rain, hoar frost, and rime. Summer in this region is characterized by the rainy season (starting in May - June) when precipitation is predominantly snow and hail at the high altitude, and sometimes also rain. Field observations noticed that snow and hail melt and together with rain percolate down through porous snow or into the crevasse system. Also, it was observed that water refreeze at night (for instance, outwash from beneath the glacier stops flowing in the evening). Thus, the summer season can be considered an ablation-accumulation season. In August - October heavy snowfalls occur associated with the hurricane season. This snow remains during November - February when additional snowfalls contribute to the system. During part of the dry season (February - March to April - May) penitents formed and grew up to 2 m high. This suggests a strong ablation possibly due to an intense radiation in spite of the prevailing cold temperatures of this season. The melt water becomes stagnant between penitents and refreezes during the night. At the end of May-early June, the new snow precipitation fill the spaces left between penitents and the cycle is repeated. In this way, glacier ice is quickly formed and acquires an average density of 900 Kg/m^3 in less than a year (measurements made in July, 1995).

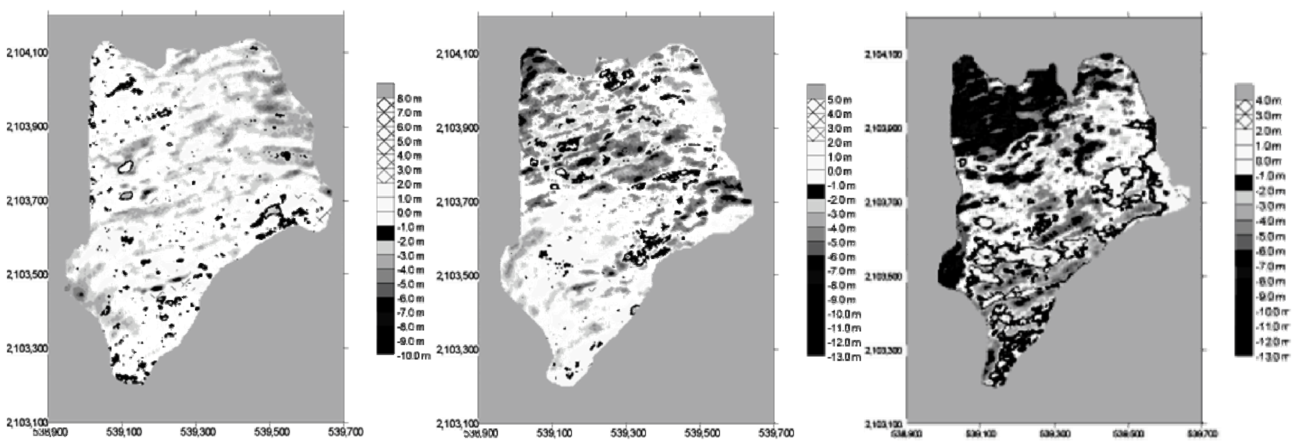
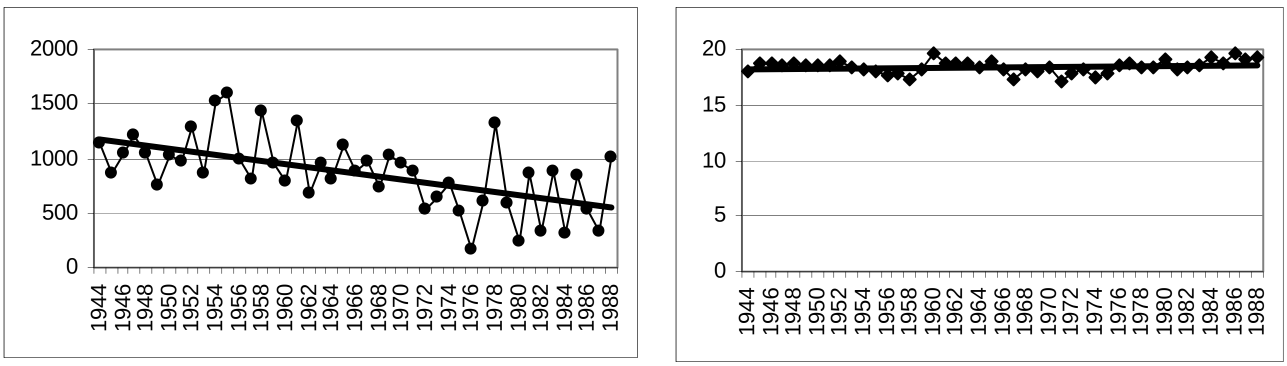


Figure 10: A) Ice thickness changes in meters between May 1996 and February 1997. B) between February 1997 and February 1998. C) between January 1998 and January 1999 (from Huggel and Delgado-Granados, 2001).

The glacier-ice of Popocatépetl had temperatures ranging from –3,3 to -0,5 ºC (at depths of 9 - 6 meters respectively) as revealed by several measurements obtained between 1995 and 1996 using thermometers (commercial thermometers suited to record maximum and minimum temperatures, and visited on a monthly basis for extraction of the data and reset the instruments) installed at different depths in two sites over the glacier where stakes were emplaced at altitudes of ~5.000 m.a.s.l. A stake network was installed in 1995, in order to acquire accumulation data and record the movement of the ice mass. This network however, was difficult to visit due to the risks imposed by the volcanic eruption, and eventually, the eruptive products from Popocatépetl destroyed the network. Radiation, meteorological, and accumulation measurements were strongly needed to better assess the glaciological processes but the eruption imposed a serious restriction to the study. Notwithstanding, there is some meteorological data from stations nearby the volcano. Figure 11A shows a decreasing pattern in the precipitation regime at Nepantla (20 Km from the volcano, whereas figure 11B shows an increasing pattern in temperature. Precipitation at Amecameca (figure 12A) shows a similar pattern but temperature has a decreasing pattern. Despite differences in trends, decrease in precipitation may account for the retreat of glaciers.

Citlaltépetl volcano's glaciers.

Glacier Inventory Update. Citlaltépetl (Mountain of the Star) or Pico de Orizaba is located at the eastern part of the Trans-Mexican Volcanic Belt (figure 13) and at the south of a N-S-trending chain of volcanoes, the Cofre de Perote-Las Cumbres-Pico de Orizaba-Sierra Negra volcanic chain. Situated at the limit of the states of Puebla and Veracruz, some 1,3 million people live within the hazard zone (Höskuldsson and Cantagrel 1994). Three major cities are located in the eastern part of the hazard zone: Orizaba, Cordoba and Fortin. On the west flank of the volcano are the towns of Ciudad Serdán and Tlachichuca. The rivers (Rio Jamapa, Rio Tilapa, Rio Orizaba etc.) are mainly distributed on the western more humid mountain side.



(A) (B)

Figure 11: A) Precipitation pattern at Nepantla meteorological station (see location in figure 5). B) Temperature data at the same station.

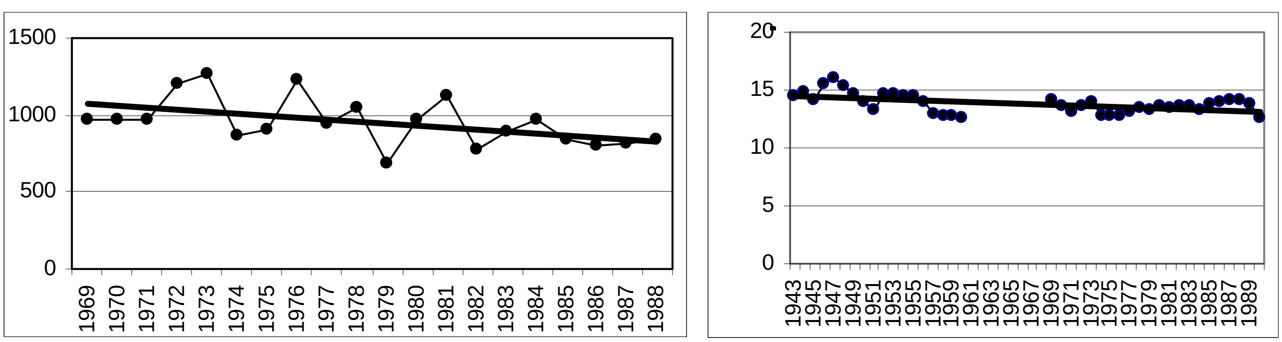


Figure 12: A) Precipitation pattern at Amecameca meteorological station (see location in figure 5). B) Temperature data at the same station.

The glaciers of Citlaltépetl volcano are still the largest ice bodies of the country. Volcanic activity is not as important as in the case of Popocatépetl or Iztaccíhuatl although there is some low-temperature fumarolic activity near the summit. Even though the influence from the volcanic activity is not important at Citlaltépetl, the glaciers have also retreated strongly. Citlaltépetl is not surrounded by large cities as in the case of the other two volcanoes. Thus, the main reason for the retreat has to be mainly with changing climatic conditions. Lorenzo (1964) reported the existence of 8 glaciers on this volcano with a total glaciated area of

9.5 Km^2. In fact, all glaciers share the same accumulation area, and can be divided in 3 main systems. The inventory update at this mountain is in progress by applying digital photogrammetry.

Glacier Characterization. Even though the inventory update is in progress, some meteorological data can be discussed. As in the case of the other volcanoes, meteorological data from nearby stations is shown at Figures 14. The closest is Tlalchichuca station, 17 Km from the mountain (figure 14A), showing a decrease in the precipitation pattern through the decades accompanied by a slight in-crease in temperature (figure 14B), as in previous cases. Ciudad Serdán station, 18 Km from the mountain (figure 5 and 15A), shows and increasing pattern in precipitation but accompanied by an increase in temperature (figure 15B). The most striking behavior can be seen at Coscomatepec station (22 Km from Citlaltépetl), where a decreasing pattern in precipitation (figure 16A), and temperature is observed (figure 16B). Decrease in precipitation should account for the retreat of glaciers, because the increase in temperature is very small or even decreasing at Coscomatepec.

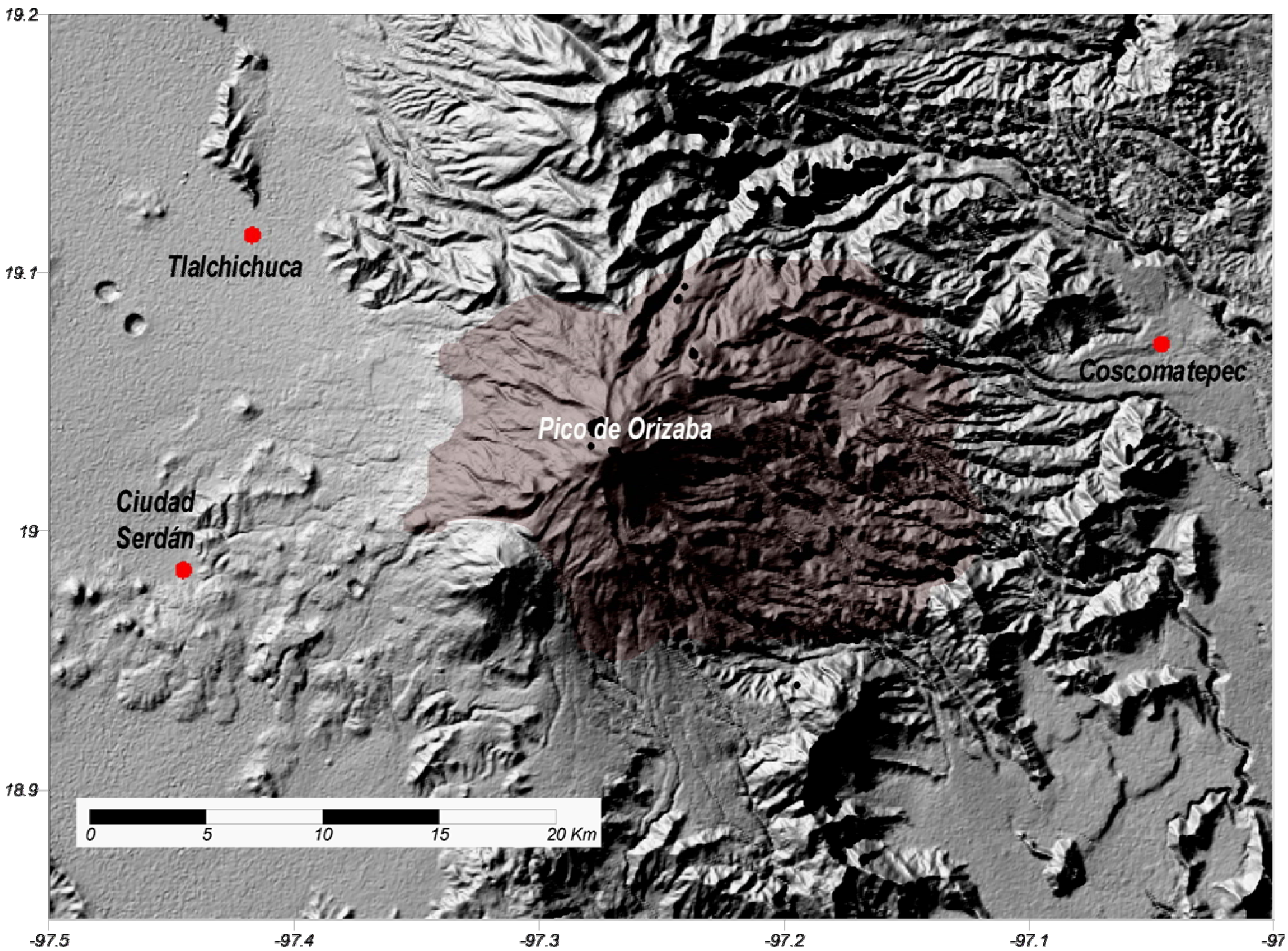


Figure 13: Location of Citlaltépetl volcano. Red dots are location of meteorological stations.

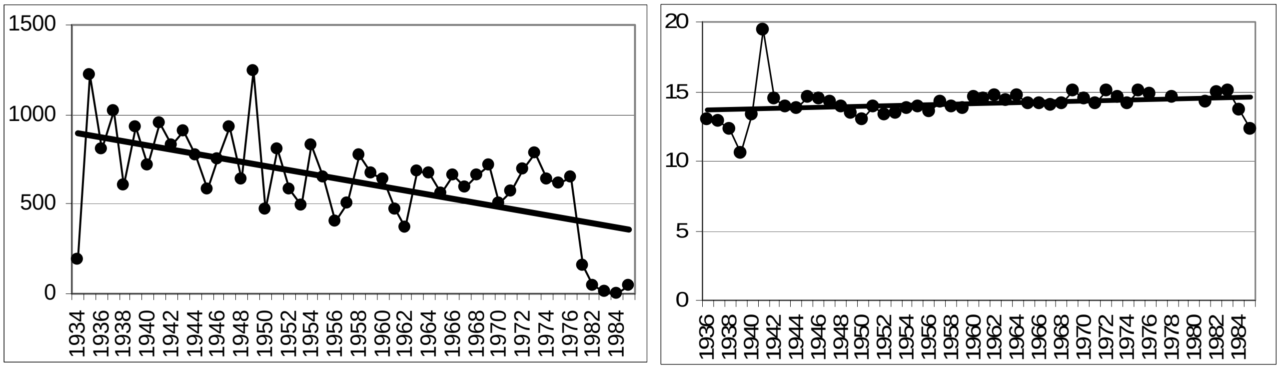
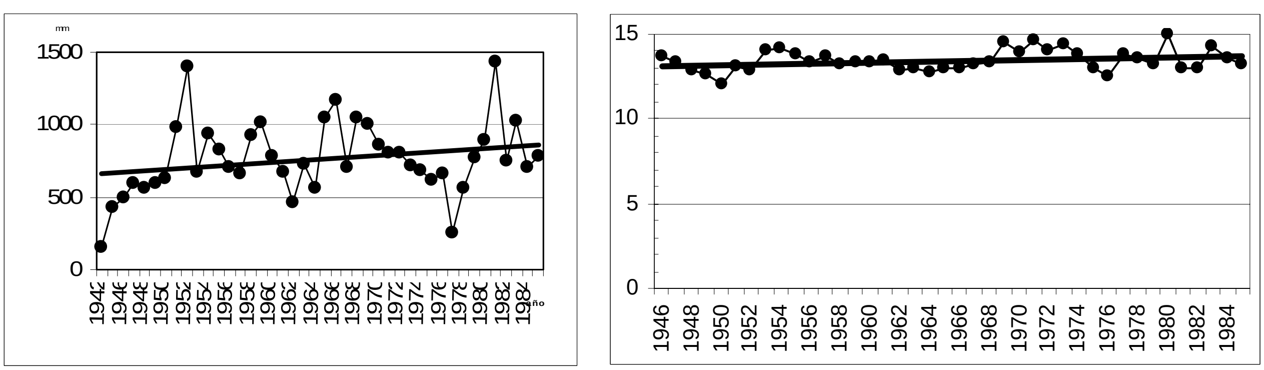


Figure 14: A) Precipitation pattern at Tlalchichuca meteorological station (see location in figure 13). B) Temperature data at the same station.

Conclusions

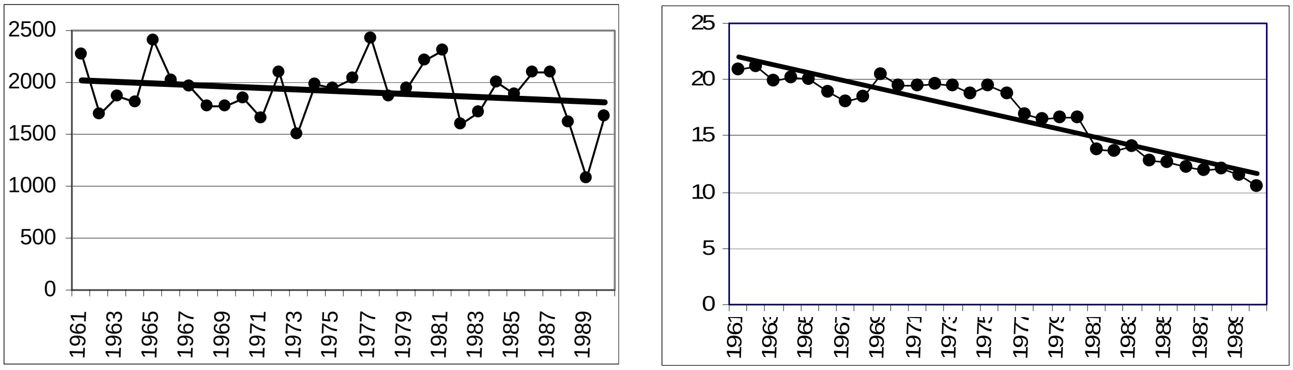
At this stage it is difficult to portray general conclusions but some facts are evident. We know that glaciers at Popocatépetl volcano were retreating before the eruption started, and the volcanic activity accelerated the retreat of the glaciers up to the extinction. At Iztaccíhuatl volcano it has been observed also a strong retreat of its glaciers and it has been hypothesized the possibility of increase of heat flow beneath the ice masses, although no sound data exists to support this speculation. At Citlaltépetl volcano the study is ongoing and not much can be said until data is obtained. The available meteorological data however, points to a generalized decrease in precipitation as the main climatic factor for retreat.

We have the opportunity at these three mountains to study the different effects of the global climate, the influence of local conditions (i. e. proximity to large populated and industrial areas), and the effects of the volcanic eruptions. Even though the study has not been finished, it is anticipated to find a generalized extinction of the glaciers in México within the 21st century. People and authorities of nearby settlements should start to think about the fate of these regions once the glaciers disappear. Environmental effects might be expected, of various magnitudes, but perhaps the most important consequences will be seen in the long term, such as desertification.



(A) (B)

Figure 15: A) Precipitation pattern at Ciudad Serdán meteorological station. B) Temperature data at the same station.



(A) (B)

Figure 16: A) Precipitation pattern at Coscomatepec meteorological station (see location in figure 13). B) Temperature data at the same station.

Acknowledgements

Along all the years these studies have been made several people have participated in the glaciological work both, at the office and the field. Under the risk of being unfair and not naming someone, the author thanks the help and support of: Isaac Abimelec Farraz, Guillermo Ontiveros, José Manuel Álvarez, Enrique Cabral, Oscar Díaz, Brenda Guerra, Ralph Glaus, Simone Fischer, Thomas Berger, Luis Maisincho, Susana Ortega, Lucio Cárdenas, Lorenzo Ortiz, Mario Romero, Juan Manuel Leal, Carlos Linares and José Venegas. Part of the summary on Popocatépetl volcano's glaciers has been worked together with Patricia Julio Miranda whose doctoral thesis deals comprehensively with the interaction of the eruption and the glaciers. Part of the work at Popocatépetl and Iztaccíhuatl was carried out in collaboration with Christian Huggel and Demian Schneider at different times. Simone Fischer made a thorough revision on the bibliography on Citlaltepetl during her stay at UNAM. Some figures were kindly prepared by Isaac A. Farraz. These studies were carried out under the financial support of CONACYT (Grant 45433-F).

References

Álvarez, R. and Delgado-Granados, H. 2002: Characterization of a tropical ice body on Iztaccíhuatl volcano, México. – In: S. K. Koppenjan & H. Lee (eds.): Ninth International Conference on Ground Penetrating Radar. - Proceeding of SPIE, 4758: 438-442.

Bursik, M., Martínez-Kackert, B., Delgado-Granados, H., and González-Huesca, A. 2003: A smoothed-particle hydrodynamic automaton of landform degradation by overland flow, Geomorphology, 53, 25-44.

Capra, L., Poblete, M. A., and Alvarado, R. 2004: The 1997 and 2001 lahars of Popocatépetl volcano (Central Mexico): textural and sedimentological constraints on their origin and hazards: Jour. Volcanol. Res., 131, 351-369.

Delgado-Granados, H. 1997: The glaciers of Popocatépetl volcano (Mexico): changes and causes. Quatern. Int., 43/44: 53-60.

Delgado-Granados, H. 2001: Iztaccíhuatl. In: H. Delgado (ed.): Los Volcanes de México. Chapter "Los Silenciosos", Dirección General de Publicaciones UNAM: 116-119.

Delgado-Granados, H. and Arciniega Dettmer, R. 1985ª: Los glaciares de México: metodologías para su estudio, Memorias de la Reunión Anual de la U.G.M., 194~204.

Delgado Granados, H., Arciniega Dettmer, R. and Calvario Benítez, D. 1985b: Los glaciares del Popocatépetl e Iztaccíhuatl, Memorias de la Reunión Anual de la U.G.M., 178~193, 1985.

Delgado-Granados, H., and Brugman, M. 1995: Monitoreo de los glaciares del Popocatépetl. In: Volcán Popocatépetl, Estudios Realizados durante la Crisis de 1994-1995, CENAPRED-UNAM, México, 221-244.

Delgado-Granados H., and González Huesca, E. A. 1994: Analysis of the historical activity of volcan Popocatépetl and the increase of its activity: implications for a future eruption, Cuarta Reunión Internacional Volcán de Colima, Colima, México, 24-28 de enero, Abstracts, 156.

Delgado-Granados H., González Huesca, E. A. and Abrams, M. 1994: Lahar risk on the NE flank of Popocatepetl volcano, II Simposio Internacional sobre la Tectónica y el Volcanismo Cenozoicos de México, Reunión Anual de la Unión Geofísica Mexicana, 84.

Delgado-Granados, H., González Huesca, E. A. and Oropeza Villalobos, B. 2000: Possible linkage between laharic events and glacier ice melting at Popocatépetl volcano, Mexico, Volcano/Ice interactions on Earth and Mars Workshop, Reykjavík, Iceland, 13-15 de agosto del 2000, 78.

Delgado-Granados H., Julio Miranda, P., Álvarez, R., Cabral-Cano, E., Cárdenas González, L., Correa Mora, F., Luna Alonso, M. and Huggel, C. 2005: Study of Ayoloco Glacier at Iztaccíhuatl volcano (México): hazards related to volcanic activity – ice cover interactions, Zeitschrift für Geomorphologie, Special Issue on Volcanic Geomorphology and Hazards, 140, 181-193.

Delgado-Granados, H., Piedad-Sánchez, N, and Cárdenas González, L. 2001: Sulfur dioxide emissions from Popocatépetl volcano (México): case study of a high-flux passively-degassing erupting volcano: Journal of Volcanology and Geothermal Research, 108, 107-120.

Delgado-Granados, H., Huggel, C., Julio Miranda, P., Cárdenas González, L., Ortega del Valle, S., Alatorre Ibargüengoitia, M. A. in press. Chronicle of a death foretold: extinction of the small-size tropical glaciers of Popocatépetl volcano (México), Global and Planetary Change.

Haeberli, W., Maisch, M., and Paul, F. 2002: Mountain glaciers in global climate- related observation networks: Worl Meteorological Organisation Bulletin, 51, 18-25.

Hoskuldsson, A. and Cantagrel, J. M. 1994: Volcanic hazards in the surroundings of Pico de Orizaba, eastern Mexico, Natural hazards, 10, 3, 197-219.

Huggel, C., and Delgado-Granados, H. 2000: Glacier monitoring at Popocatépetl volcano, Mexico: glacier shrinkage and possible causes, in: Hegg, C., Vonder Muehll, D. (Eds.) Beitraege zur Geomorphologie, Proceedings der Fachtagung der Schweizerischen Geomorphologischen Gesellschaft vom 8.-10. Juli 1999 in Bramois (Kt. Wallis), Birmensdorf, Eidgenoessische Forschungsanstalt WSL, 97-106.

INEGI (Instituto Nacional de Estadística, Geografía e Informática). 1982: Fotomapa del Volcán Iztaccíhuatl, scale 1:20,000.

Julio-Miranda, P., and Delgado-Granados, H. 2003: Fast hazards evaluation employing digital photogrammetry, Popocatépetl glaciers, México: Geofísica Internacional, 42, 275-283.

Julio-Miranda, P., González-Huesca, A. E., Delgado-Granados, H. and Kääb, A. 2005: Glacier melting and lahar formation during January 22, 2001 eruption, Popocatépetl volcano (México), Zeitschrift für Geomorphologie, Special Issue on Volcanic Geomorphology and Hazards, 140, 93-102.

Lorenzo, J. L. 1964: Los glaciares de México. Monografías del Instituto de Geofísica, Universidad Nacional Autónoma de México, 122.

Luna Alonso, M. 2002: Estudios dinámicos en el glaciar La Panza, volcán Iztaccíhuatl. Tesis Ingeniero Geólogo, Facultad de Ingeniería, U.N.A.M. 83 pp.

Luna Alonso M., Delgado Granados, H., Díaz Vera, A., Cabral Cano, E., Correa Mora, F. and Cárdenas González, L. 2002: Estudios dinámicos en el glaciar La Panza del volcán Iztaccíhuatl, Reunión Anual de la Unión Geofísica Mexicana, Puerto Vallarta, México, Noviembre 4-8, 2002, 193.

Mooser, F. 1958: Active Volcanoes of Mexico. In: Meyer, A. H. & A. R. MacBirney (eds.): Catalogue of Active Volcanoes of the World Including Solfatara Fields. – Part VI México and Central America: International Volcanological Association, Naples 6, 36.

Ortega del Valle, S. 2001: Las variaciones climáticas en la región central de México. Tesis Lic. en geografía, Facultad de Filosofía y Letras, UNAM. 79 pp.

Palacios, D., Zamorano, J. J. and Padilla, G. 1998: Proglacial debris flows in Popocatépetl north face and their relation to 1995 eruption. - Z. Geomorph. N.F 42, 273-295.

Schneider D., Delgado-Granados, H., Huggel, C. and Kääb, A. In press. Modeling and assessing lahar hazards under a rapid glacier-melting scenario at Iztaccíhuatl volcano (central México). International Glaciological Society.

Sheridan, M. F., Hubard, B., Bursik, M. I., Abrams, M., Siebe, C., Macías, J. L. and Delgado-Granados, H. 2001: Gauging short-term volcanic hazards at Popocatépetl, EOS, Transactions, American Geophysical Union, 82, 16.

Thouret, J.-C. 1990: Effects of the November 13, 1985 eruption on the snow pack and ice cap of Nevado del Ruíz volcano, Colombia. Journal of Volcanology and Geothermal Research, 41, 177-201.

White, S. E. 1981: Neoglacial to recent glacier fluctuations on the volcano Popocatépetl, México. J. Glaciol., 27, 96, 359-363.