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Chronicle of a death foretold: Extinction of the small-size tropical glaciers of Popocatépetl volcano (Mexico)

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Abstract

The large ice masses of the world are claimed to be affected by global warming and local climatic variations. Tropical glaciers as those on Popocatépetl volcano can be affected also by the same processes but are more vulnerable because of their size and eruptive processes. Even though their extinction might not have a global impact, their disappearance deprives us of important climatic "gauges" at the ~20° north latitude and impacts strongly the local environment. This is an account of the eruption-forced extinction of the glaciers of Popocatépetl volcano. We show that 40% of climatic-related shrinkage occurred in 4 decades whereas 32% of eruption-related shrinkage occurred in 4 yr. Long-term effects of glacier extinction include an imbalance between recharge and extraction of groundwater at surrounding aquifers provoked by the disappearance of glacier-related melt water. Events like this may occur at other tropical glaciers worldwide.

Keywords: glacier; extinction; Popocatépetl; volcano; lahar; Mexico; eruption

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1. Introduction

Study of glaciers' changes is one of the best means to document global change (IPCC, 2001; Haeberli et al., 2002). Currently, most glaciers of the world are retreating strongly as a result of global warming (Oerlemanns and Fortuin, 1992; Oerlemanns, 1994; Haeberli and Beniston, 1998; Oerlemans, 2005). Special attention is put on large ice masses where changes are evident and measurable from the ground or space (Bindschadler and Vornberger, 1998; Kieffer et al., 2000; Pelto and Hedlund, 2001; Bindschadler and Rignot, 2001). Less attention is paid to the behavior of intertropical glaciers (Kaser and Osmaston, 2001), particularly small and vulnerable (Ramírez et al., 2001), but important for local environments. A large number of intertropical glaciers are of small-size (Haeberli et al., 1998) and thus, largely sensitive to climate changes and vulnerable to events such as volcanic eruptions. Study of extinction events is crucial to understanding possible future environmental effects in proximal areas and may reveal the high impact on society. In the case of glaciers on volcanoes, laharic or debris-flow-related disaster

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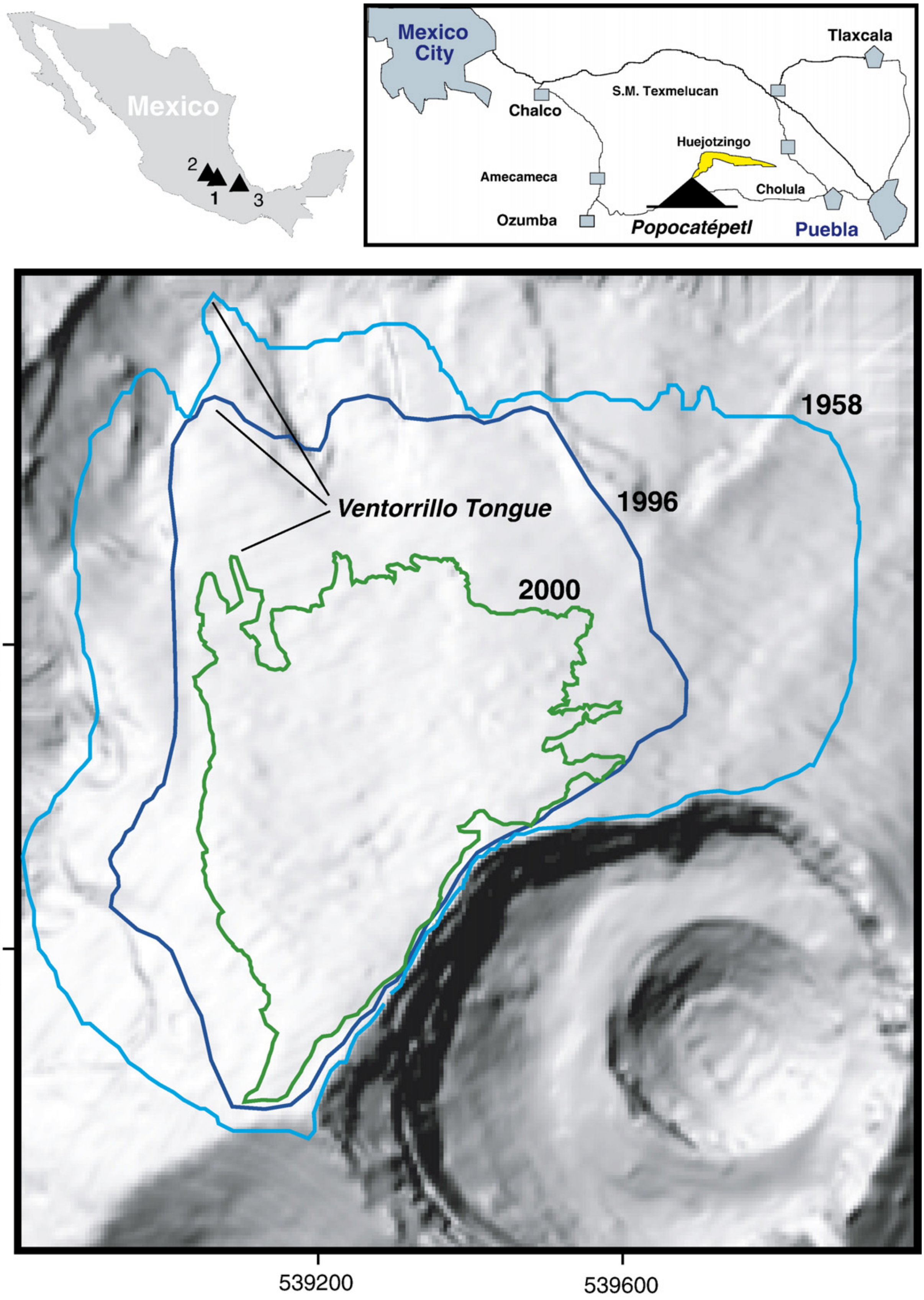
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prevention can be assessed (Julio-Miranda et al., 2005; Delgado-Granados et al., 2005; Schneider, 2005).

Mexican glaciers (Fig. 1) are settled on the high altitude volcanoes: Citlaltépetl, Popocatépetl and Iztaccíhuatl (Lorenzo, 1964), all of them with different levels of activity and climatic conditions. Glaciers of Citlaltépetl are on a dormant volcano far from highly populated and polluted cities. The glaciers of Iztaccíhuatl are on a dormant volcano between largely inhabited and industrial areas. The glaciers of Popocatépetl top an erupting volcano between the basins of Mexico and Puebla (Fig. 1). Distinction of global and regional climatic conditions, anthropogenic, and volcanic effects on glacier behavior is a difficult task that should be achieved. These glaciers are unique, representing the only ice masses and natural "gauges" to study global warming at around 20° north latitude (Delgado-Granados, 1996). Additionally, studies of ice-volcanic activity interactions recognize their impact on glaciers and serve for catastrophic-flows prevention (Williams, 1990; Julio-Miranda and Delgado-Granados, 2003).

We document an eruption-forced extinction of the glaciers on Popocatépetl volcano in late 2000, together with a possible combination of global change. Due to a lack of a comprehensive meteorological and glaciological data, this is a report of facts rather than an exhaustive study of the processes that lead to the extinction. Extinction of these glaciers may pose a strong impact on the local environment and may chronicle the fate of similar glaciers around the world (as in Ecuador, Colombia, Bolivia, among other places).

2. Glaciers of Popocatépetl volcano

Popocatépetl (19.023°N, 98.622°W), a volcano with an altitude of 5426 masl (meters above sea level), had two glaciers on its northern flank, with four tongues (Delgado-Granados, 1996). Ventorrillo tongue was both the largest and the best known for centuries.

According to Delgado-Granados (1996) 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 fills 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). The glacier ice of Popocatépetl had temperatures ranging from −3.3 to −0.5 °C (at depths of 9–6 m 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 the extraction of the data and resetting the instruments) installed at different depths in two sites over the glacier where stakes were emplaced at altitudes of ~5000 masl. Maximum thicknesses measured in 1995 were 40–70 m depending on the site (Delgado-Granados and Brugman, 1995).

No measurements of solar radiation have been carried out in order to confirm its importance in the ablation process during the dry season and its role in the formation of penitents. In addition, no meteorological database exists for the altitude of the glaciers in order to elucidate the conditions for the melt water to refreeze. 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.

Fig. 1. Location of Popocatépetl volcano and shrinkage of its glaciers. Volcanoes covered by glaciers in central Mexico are: Popocatépetl (1), Iztaccíhuatl (2), and Citlaltépetl (3) (upper left corner). Mexico City and Puebla are 40 km from Popocatépetl volcano (upper right corner). The image shows the uppermost part of the volcano. Lines on the map depict glacierized area extent for 1958, 1996, and up to late 2000 (Lorenzo, 1964; Huggel and Delgado-Granados, 2000; Julio-Miranda and Delgado-Granados, 2003). The two glaciers of Popocatépetl volcano are shown as a single area for clarity. Notice the proximity of the glaciers to the crater of the volcano.

3. Methods

Oerlemans et al. (1998) found no straightforward relationship between glacier size and fractional change of ice volume emerges for any given climate scenario. Also, they found that hypsometry of individual glaciers plays an important role in their response. Furthermore, Khun et al. (1985) found that length and mass balance of glaciers might follow different trends, and topography or area/altitude distribution as the most important factor determining the different variations of mass balance and length at some glaciers. Accordingly, in this study we use altitudinal variations of a selected glacier tongue of Popocatépetl volcano and the changes through time in glacierized area to document the retreat of Popocatépetl volcano's glaciers until their extinction. Determination of area/altitude distributions was carried out using topographic maps at a scale of 1:2000 (horizontal and vertical accuracy within 2 m due to uncertainties induced by the eruptive activity). Maps obtained from photogrammetric restitution of vertical aerial photographs were used as the basis for the construction of digital terrain models (DTMs) of glacierized areas after their definition on the photographs and confirmation by field observations (Kraus, 1987; Fig. 1). The maps were elaborated by the Secretaría de Comunicaciones y Transportes as part of the activities of the Mexican government devoted to monitor the eruptive activity of the volcano. Because the glaciers were near the summit of the erupting volcano, it was needed to choose the best topographic maps, based on aerial photographs free of the influence of volcanic clouds. In order to study the annual changes of the glacier's surface, the maps for January or February between 1996 and 1999 were digitized. Distinction of the glacierized areas was facilitated by the lack of snow cover during the dry season. After digitizing the topographic maps, DTMs were constructed by using Surfer® 8 software with a horizontal resolution of $\sim$7 m, and a vertical resolution within 2 m.

Table 1
Altitude retreat and glacierized area change rates for Ventorrillo Tongue

Year	Ventorrillo Tonge		Glaciers of Popocatépetl	
Data	Altitude	Retreat rate	Total glacierized area	Surface area change rate
	(m)	(m/yr)	(m^2)	(m^2/yr)
1519	4150			
1906	4335	−0.5		
1910	4390	−13.8		
1920	4435	−4.5		
1950	4573	−4.6		
1958	4690	−14.6	892,011	
1968	4700	−1.0		
1978	4600	10.0		
1982	4760	−40.0	559,000	−13,866
1996	4785	−1.8	536,869	−1536
1997	4783	2.0	527,363	−12,480
1998	4788	−5.0	503,005	−25,115
1999	4803	−15.0	416,706	−89,998
2000	4925	−122.0	255,310	−86,251

The altitude positions are listed together with calculated retreat rates based on long-standing observations (Delgado-Granados, 1996). 1982 retreat rate might be associated to a response after an "El Niño" event. Retreat rates after 1996 are related to an acceleration of the extinction process by the volcanic eruption (see text). Total glacierized area retreat rate is strongly enhanced after 1996.

Table 2
Average thickness and water equivalent lost per period. Calculation of differences in altitude at every pixel from one DTM to the other can be readily done and an average loss in thickness can be estimated

Period	Thickness (m)	Water equivalent (m^3)
1996–1997	−1.00	−474,627
1997–1998	−2.13	−964,261
1998–1999	−3.19	−1'206,431

By using subtraction of areas and differences in thickness, volumes are estimated accurately and approximate mass balances for a budget year. These volumes are expressed as water equivalent (an ice density of 900 kg/m^3 was used).

Based on DTMs, precise determination of the altitudes of Ventorrillo tongue was accomplished digitally and some of them confirmed by GPS determinations in the field. These data complemented previous databases (Delgado-Granados, 1996; Palacios, 1996) in order to observe altitude variations of the glacier tongue through time since the 16th century allowing calculation of retreat rates, starting in the 20th century (Table 1). Glacierized area determinations were performed by using commercial software (PCI Geomatics® combined with Surfer® 8), for plane view and the real inclined area. Plane areas are 80–82% of glacierized surfaces on the steep slopes of the northern flank of the volcano. GPS occupations of several sites on the glacier's surface were carried out in 1995, 1996, and 1999.

Generated DTMs were used to determine mass balances. Subtraction among DTMs allowed calculation of gain or loss of ice mass per pixel in meters. Every DTM describes the relief of the glacier's surface and then, we were able to calculate precise volumes of ice and estimate water equivalent volumes (Table 2) using the measured ice densities. Fig. 2 shows the resulting maps of DTM subtractions. Taking into account the involved vertical error (σ), when subtracting DTMs the volume described by the area with thicknesses of $0\pm\sigma$

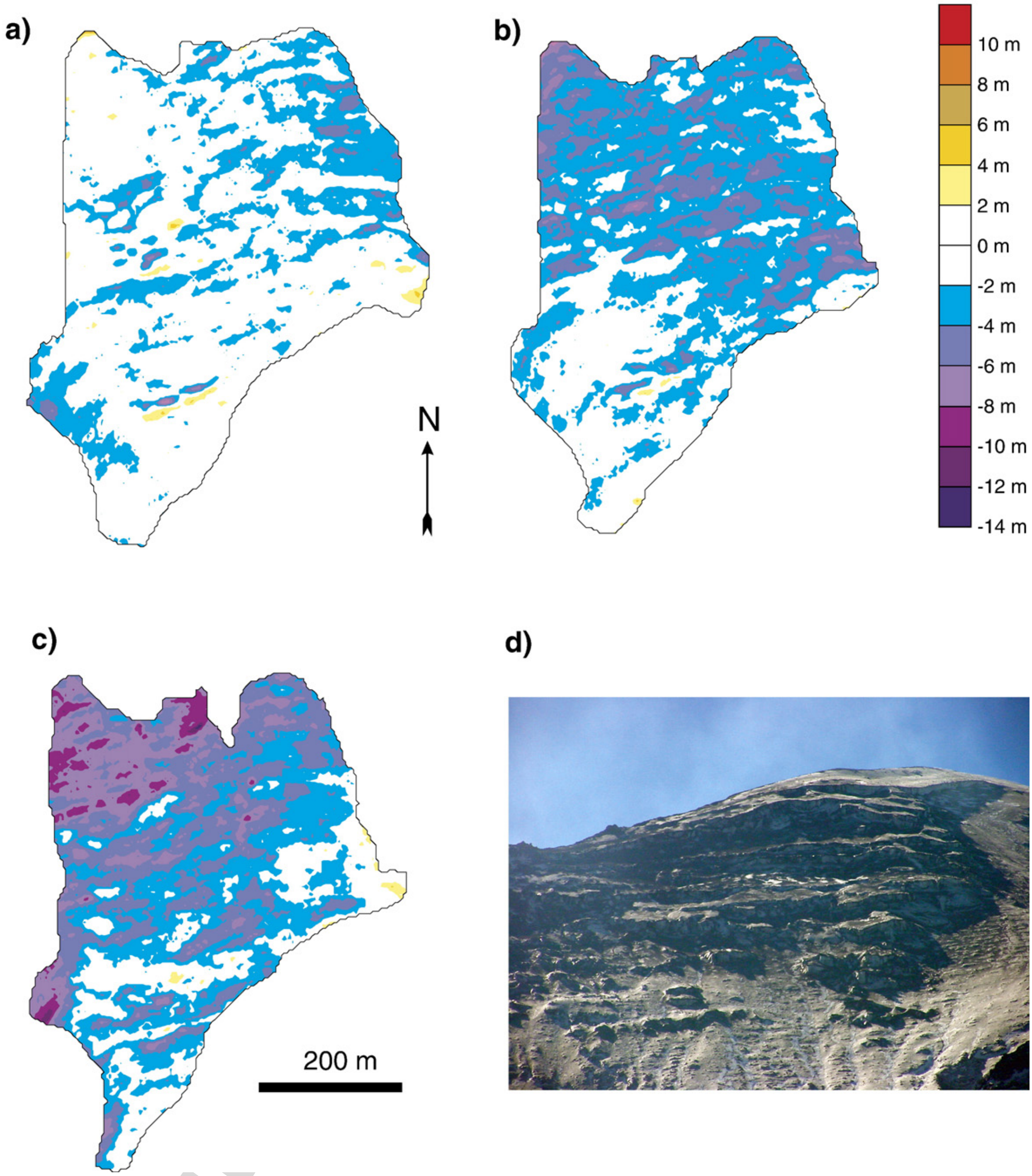

Fig. 2. Detailed mass-balance maps. Distribution of "cold" and "warm" colors indicates lost and acquired ice mass in terms of thickness according to scale bar and estimated error (see text). (a) 1996–1997 color distribution mainly implies ice mass loss, especially at the eastern edge of the glacier due to the influence of hot ashfall. (b) Much larger mass loss is seen in 1997–1998 all over the north flank, particularly at Ventorrillo tongue and crevasses. (c) In 1998–1999 mass loss is almost ubiquitous but enhanced at the tongues. (d) Photograph showing the glaciers on December 02, 2002, bedrock is exposed in between séracs. The glaciers were already extinct.

was not considered in the ice mass calculations (shown as a white band of 2σ in the column and white areas in the maps of Fig. 2). Because the time period between DTMs is ~1 yr, the total-ice mass balance of a budget year was obtained for every couple of DTMs. The pronounced effects of the seasonal cycle of ablation and accumulation over an entire year are considered by the volumetric estimates.

4. Glacier retreat and extinction

Glaciers of Popocatépetl volcano were retreating before the eruption of Popocatépetl volcano started in December 1994. The altitude of Ventorrillo tongue retreated in elevation at a rate of 0.5 m/yr before the 20th century (Table 1). Only two measurements exist for this average that might seem meaningless because of the complex behavior of other glaciers around the world during this period (see Oerlemans, 2005). However, these two elevation data indicate a minor change in the position of the tongue in almost four centuries. In contrast, the retreat average rate for 1906–1982 was of ~10 m/yr (see Fig. 3). The altitudinal change in four centuries before 1906 was 185 m, whereas from 1906 to 1982, the altitudinal change was 425 m. Areal change rate during the period 1958–1982 was $\sim 10^4$ m^2/yr.

Review of the eruptive activity of Popocatépetl volcano is important in order to understand the glacier's behavior after 1994. First signals of volcanic unrest started in the fall of 1990 increasing gradually with time (Delgado-Granados et al., 2001). Eruption started on December 21, 1994 after ~70 yr of dormancy. The first eruptive stage (December 1994–March 1996) consisted of vulcanian explosions that cleared the conduit system. Explosions were very frequent in December 1994–January 1995, becoming less frequent with time and by August 1995 stopped. This explosive activity produced ash layers that mantled the glaciers several times. Eruptive activity resumed in March 1996 when eruptive style changed, and effusive and vulcanian explosive events alternated. Since then, eruptive activity has maintained the same style with variations in magnitude of explosivity, lava volume and effusion rate. During this stage, hot ballistic projectiles impacted the glaciers' surface and thick layers of hot tephra covered the ice repeatedly. 117 major and 435 minor explosions occurred between 1994–2000.

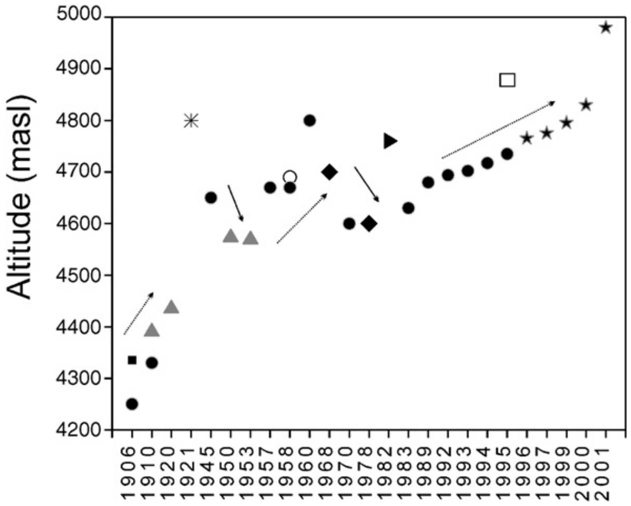

Fig. 3. Altitudinal evolution of Ventorrillo glacial front over the 20th century. Solid arrows indicate advance whereas dashed arrows indicate retreat. [■] - Anderson (1917); [✳] - Waitz (1921); [▲] - White (1954); [○] - Lorenzo (1964); [◆] - White (1981); [●] - Palacios (1996); [▶] - Delgado-Granados (1996); [□] - Delgado-Granados and Brugman (1996); [★] - present work.

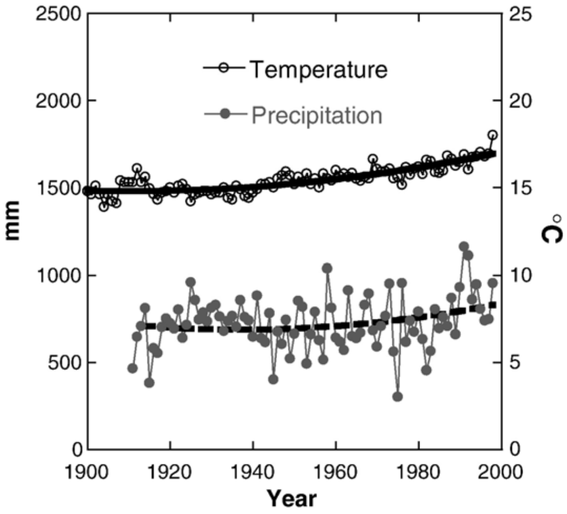

Fig. 4. 100-yr-long annual mean temperature and precipitation. Data belongs to the nearest database weather station (60 km to the northwest), the Tacubaya Station (19.638°N, 99.127°W, at 2260 masl). A sustained temperature increase is shown by the polynomial fitting curve.

Glaciers strongly retreated after resumption of 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/yr and the glacierized area changed at a rate of $\sim 10^3$ m^2/yr, Table 2). After resumption of eruptive activity in March 1996, the retreat 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 1996–1999, and maintained the same order-of-magnitude surface area change rate in 1999–2000 (Table 1).

The glacier regime was disrupted by eruptive activity since mid-1996. Maps and data show the distribution patterns of mass losses (Fig. 2) in thickness and volume. Average thickness and mass losses increased every year, and accumulation was strongly inhibited because new snowfalls melt under volcanic ejecta.

The remaining ice mass no longer behaves as a glacier. At the end of the year 2000, ice masses were still present on the northern slope of the mountain (Fig. 2d).

However, these ice masses do not move, crevasses disappeared, and glacier regime was disrupted. The ice is stagnant, attached to the steep slope. 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”. Soundings made in 1995 (Delgado-Granados and Brugman, 1995) revealed at least 40 m of ice at the middle part of the glacier, but on May 26 1999, during drilling activities at the same site, the ice was found to be 1.5–2 m thick. The ice stripes divided as melting continued and formed a series of static ice-blocks or *séracs* (Fig. 2d), further exposing the bedrock. Hence, the glaciers of Popocatépetl volcano became extinct in late year 2000.

5. Discussion

Glacier extinction was a foretold process (Delgado-Granados, 1996; Huggel and Delgado-Granados, 2000) but the eruption accelerated the process substantially. Considering the glacierized area reported in 1958, 40% disappeared in 38 yr (1958–1996) and 32% disappeared in only 4 yr (1996–2000).

Observations on several glaciers at the mountains of Mexico indicate a strong retreat during the last decade. At the neighboring Iztaccíhuatl volcano strong glacier retreat is observed, although 40–70 m thick glaciers still existed by the year 2000 (Alvarez and Delgado-Granados, 2002; Delgado-Granados et al., 2005). The glaciers on Citlaltépetl volcano also showed a strong shrinkage (Delgado-Granados, unpublished data). At Popocatépetl volcano retreat data previous to 1996 suggested a climate-related extinction process. Unfortunately, no meteorological data exists for the surroundings of the glacierized areas. However, a long climatological database exists for Mexico City (60 km from the volcano). The database indicates a warming process during the 20th century (Fig. 4). Long-term temperature increase seemed to be the responsible for the retreat patterns previous to 1996. Interestingly, precipitation data show an increase after 1996. This is explained as the urban influence on these climatic records as documented by Jáuregui (1995, 1996).

Glacial regimes at Popocatépetl (and other Mexican mountains) contrast with glaciers at similar settings. At Popocatépetl, ice mass loss is important during the winter/spring dry season, as well as during the summer warm/wet period, when strongly positive long and shortwave radiative balance with high humidity levels

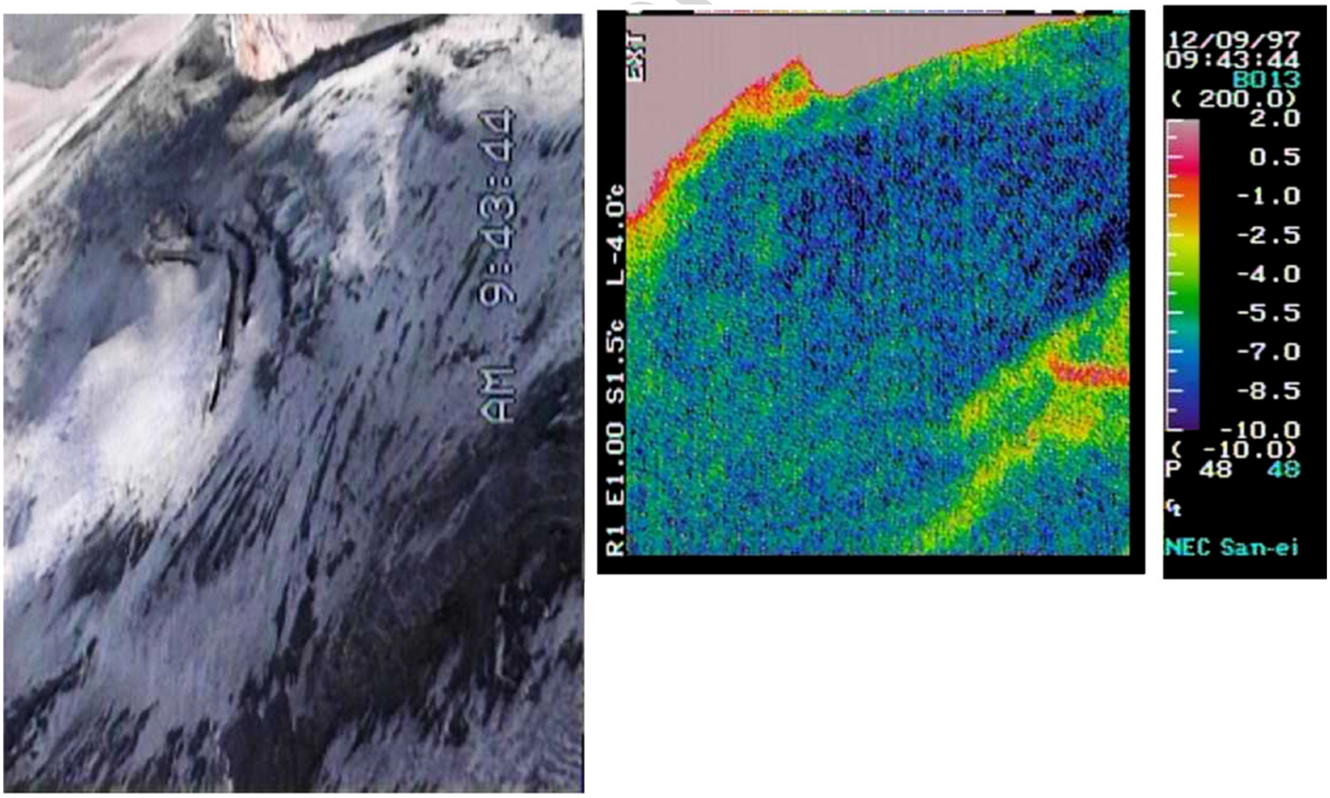

Fig. 5. Visible and thermal IR image obtained from a helicopter on September 12, 1997. The visible image shows a detail of Ventorrillo glacier and the upper crevasse system whilst the IR image shows a thermal anomaly at the right of the glacier (in red). Although the image is not calibrated (due to the impossibility to approach the volcano to measure ground-temperature data at the fumarolic site and glacier, it allows to see a thermal anomaly nearby the glacier.

are expected to lead to high melt rates. In contrast, on subtropical glaciers in the southern hemisphere, major ablation takes place during the (austral) summer–wet season (e.g. Francou et al., 2003). High ablation rates during dry and cold periods with formation of penitents are an indication for significant mass loss due to sublimation. As known from many tropical glaciers, other factors beside the sensible heat flux, such as near-surface humidity, through its partitioning of the available energy into melt and sublimation, the amount and timing of precipitation through its impact on albedo and the persistence of cloud cover through its impact on the net radiation balance may be equally important factors (M. Vuille, pers. Comm., 2006). In order to confirm this, it is strongly needed to establish a meteorological network on the Mexican mountains and better assess the role of temperature and radiation in the ablation and retreat processes.

Influence of pollutants from nearby anthropogenic sources on the mountain environment has been suggested by isotopic and chemical data (Goff et al., 1998). As a consequence, it was speculated that pollution in the surroundings of Popocatépetl might be the cause for a local warming (Delgado-Granados, 1996), in order to explain the retreat of the glaciers before 1994. However, no further discussion on this can be done due to a lack in radiation or high altitude data.

The volcanic eruption affected the glaciers in several ways. One was the immediate thermal effect of hot falling ash on snow and ice, although once deposited, several-centimeters-thick ash layers begin to insulate the snow and ice pack (could not produce further ablation) as observed elsewhere. Observations made during the eruption of Mt St. Helens in 1980 in the United States (Driedger, 1981) indicate that a thick ash layer reduces ablation, and ever since, it has been shown by many others (e. g. Rhodes et al., 1987). Ballistic projectiles are also hot, but in addition, their high kinetic energy ($\sim 10^6$–10^9 kJ considering major explosions during 1994–2000) produced melting restricted to the impact areas. Every event that deposits 1 cm of ash over the glacierized area represents a heavy load of $\sim 10^2$–10^4 t that modify glacier's sliding regime. Besides, fumaroles of <100 °C on cracks beneath the glacier provoked continuous melting at the base of the glacier even during the winter. Occasional observations of tiny vapor columns coming out from the crevasses suggest the continuation of a crack-associated anomaly beneath the glacier (Fig. 5).

Influence of the volcanic gases on the surrounding environment and on glaciers is a matter that should be investigated in the future. Popocatépetl volcano has put into the atmosphere a large amount of gases, particularly CO_2 and SO_2 (Delgado-Granados et al., 1998, 2001). Passive volcanic emissions of CO_2 can be up to 10^5 t /d, whereas SO_2 emissions range $\sim 10^3$–10^5 t/d (Gerlach et al., 1997; Delgado-Granados et al., 2001). These gases claimed to have greenhouse and cooling effects (Sigurdsson, 1990), can be widespread over the entire region as reported in Mexico City (Raga et al., 1999) and thus, regional environmental effects are suspected. Future research should be directed to elucidate the impact of volcanic aerosols and ashes on the regional environment and on the glacier energy balance through their change on the glacier albedo.

Global warming has caused glacier retreat worldwide during the last decades (Haeberli and Beniston, 1998). All glaciers in Mexico have retreated strongly: 20% reduction in 24 yr at Iztaccíhuatl volcano, and retreat of Citlaltépetl volcano's glaciers where no influence from eruptive activity can be documented so far (Delgado-Granados et al., 2005). Based on these facts, global warming is still a factor that surely contributes to retreat of Mexican glaciers. It is important to take into account that an exponential increase in glacier shrinkage is also expected once the glacier loses the accumulation area and the glacier becomes so small that edge effects become dominant. A similar phenomenon, without eruptive activity, has been reported on Chacaltaya glacier in Bolivia (Ramírez et al., 2001; Francou et al., 2003).

Study of Mexican glaciers, their changes and disappearance is of large importance at least for two main issues: environmental impact and hazards assessment.

Glacier-related watersheds in the vicinity of the three highest volcanoes of Mexico have recharged aquifers for centuries (Cortés et al., 1997). Yearly melt water contribution from the glaciers of Popocatépetl to the regional hydrologic system used to be at least $\sim 475{,}000$ m^3 (Table 1). Disappearance of the ice bodies during the 21st century can provoke an imbalance between recharge and extraction of groundwater. Since water supply is among the country's strongest problems, this may have important social consequences.

Notwithstanding, the impact of disappearing glaciers on water resources is probably less dramatic when the overall water availability is of concern. More importantly, however, glaciers act as buffers and water storage and thereby increase water availability and discharge during the dry season (due to glacier melt), when otherwise no surface runoff would occur. So the absence of glaciers changes the seasonal distribution of runoff but perhaps not the annual total of available water. In fact, during the period of glacier retreat the imbalance of the glacier and the associated increased melt will lead to a temporary water surplus. This is an important matter for further research.

On the other hand, study of glacier-eruption interactions is very useful for hazards assessment (Julio-Miranda and Delgado-Granados, 2003). Julio-Miranda et al. (2005) described the generation of laharic flows by pyroclastic flows melting part of the ice mass after an explosion occurred in 2001. Glacier-eruption interactions are of large importance when considering the related hazards as discussed by Sheridan et al. (2001), Capra et al. (2004), and Huggel et al. (in press) due to the presence of human settlements at the streams drained by the glaciers. Under the conditions resulting from glacier extinction, unstable *séracs* on the northern slope of Popocatépetl constitute a debris-flow-generation (lahar-generation) hazard, even without eruptions. Thus, countermeasures should be developed to protect villages downstream.

6. Conclusions

The glaciers of Popocatépetl volcano showed a strong retreat prior to 1994, before the initial eruption of the volcano. Retreat can be documented in terms of the altitude of the glacier tongue and the areal extent of the glacier. This retreat was a progressive and continuous process in a way that it was clear that extinction of glaciers was a consequence of it in the following decades. However, the retreat rate increased after the onset of the eruption, accelerating the extinction process. The extinction of these glaciers occurred in late 2000 after an intense eruptive phase. Among the eruptive processes contributing to the extinction of glaciers are: ash burial (although in large quantities it preserves the ice from radiation), ballistic projectile impacts, and volcanic heat flux.

The study of Mexican glaciers, their changes, and possible extinction is important for environmental impact evaluation and laharic hazards assessment. Envionmental effects of the extinction of small-sized glaciers on proximal areas are likely and should be studied in detail. On the other hand, it is crucial to recognize and study similar glacier extinction processes at other latitudes and anticipate the consequences.

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