Glacier monitoring at Popocatépetl volcano, Mexico: glacier shrinkage and possible causes

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Abstract

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Glaciers in combination with volcanoes may represent an important hazard for human settlements. As Popocatépetl volcano is located in the vicinity of highly populated areas monitoring its glaciers is a vital part of the surveillance system of the volcano.

Popocatépetl hosts two small glaciers that are monitored mainly by aerial photographs taken nearly on a monthly basis. Using this data, maps and digital elevation models were generated with photogrammetrical and further image processing methods. The study of the glaciers has then focused on changes in area, morphology and ice thickness (i.e. accumulation and ablation).

Different reasons for the observed intense glacier shrinkage are proposed here: local to regional and global climate changes, a response to the eruptive activity of Popocatépetl and topographic changes of the volcanic edifice due to inflating or deflating effects related to volcanic activity.
Keywords: glacier, volcano, surveillance system, glacier shrinkage, climate change, volcanic activity

1 Introduction

The three largest volcanoes of central Mexico: Pico de Orizaba, Popocatépetl and Iztaccíhuatl are capped by glaciers. Besides the importance of studying tropical glaciers, the observation of ice masses on active volcanoes is of the utmost relevance for hazard evaluations as showed dramatically the 1985 tragedy on Nevado del Ruíz where more than 20,000 people died in a lahar formed by pyroclastic flows and subsequent melting of glacier ice (Williams 1989). The current eruption of Popcatépetl is of particular interest due to the presence of highly populated areas in the vicinity (Fig. 1), and, thus, special attention is focused on the glaciers.

Popocatépetl volcano hosts two small glaciers which actually could be considered as one single glacier system except for the fact that they have different drainage systems. Ventorillo glacier is located on the northern side of Popocatépetl and drains northward whereas Noroccidental glacier extends to the northwest and drains westward.

Both glaciers start at 5452 m.a.s.l. and have their terminus at about 4800 m.a.s.l. (Ventorillo) and 5130m.a.s.l. (Noroccidental). Noroccidental glacier is considered as being passive while Ventorillo glacier shows a range of indications of activity (Delgado 1997).

The terminus of Ventorillo glacier is divided into three separate tongues (Herradura, Tezcalco, Ventorillo), all draining into the same downflow system. Both glaciers are nested at the top of the volcano, and as a result, they are steep glaciers with a mean slope of approximately 36º. This fact is of great importance for stability considerations.

Since the nineteenth century repeated observations of Popocatépetl's glaciers have been reported (i.e. Alzate 1831; Aguilera and Ordóñez 1895; Weitzberg 1923), and later studied in greater detail by Lorenzo (1964) who carried out an extensive glacier inventory on all three of Mexico's glacier-clad volcanoes.

Unfortunately, the efforts of Lorenzo did not found continuity until investigation has been reinforced by Delgado et al. (1986) and Delgado and Brugman (1995).

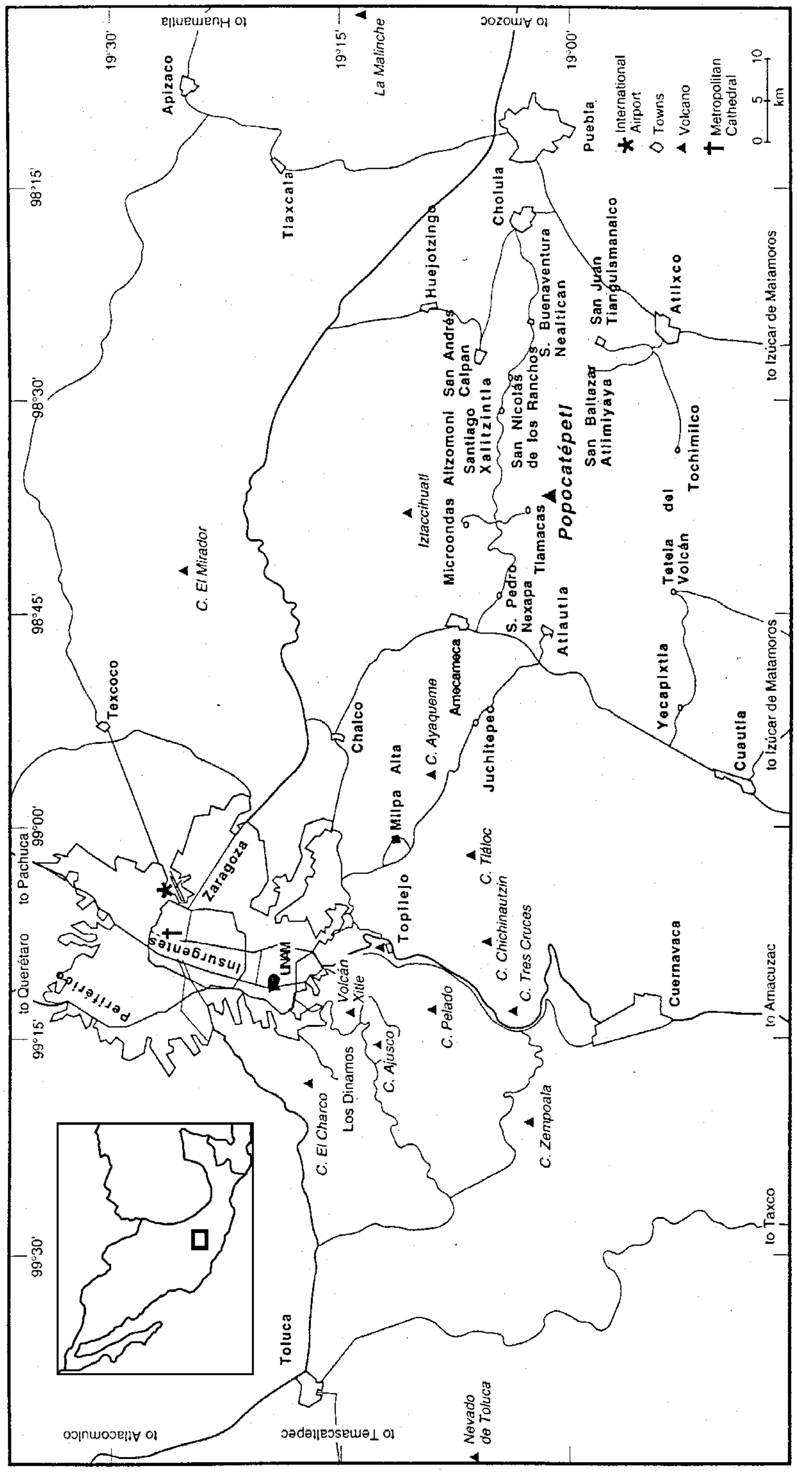

Fig. 1: Location map. Popocatépetl volcano lies 40 km southeast of Mexico City.

2 Observations and methodology

Data and results presented in this study basically stem from the monitoring activities of Popocatépetl volcano. Hereby, aerial photographs were taken on a nearly monthly basis. Flying heights vary between 500 m and 1000 m above the summit.

For each date the aerial photographs were restitued and orthorectified using a photogrammetrical station and a set of ground control points (GCP) which were previously established and measured with the aid of a Global Positioning System (GPS). Altitude contour lines extracted during the photogrammetrical processing were spaced every 10 m. A weighted average interpolation algorithm (Kriging) was then applied to interpolate the contours and to calculate a rectangular grid with 5 m spacing. Thus, for each date covered by aerial photographs an orthophoto and a corresponding map with the precise glacier extent as well as a digital elevation model (DEM) were computed.

However, in the case of Popocatépetl, the precision of the DEM´s is less than for DEM´s established under favourable conditions, i.e. an altitude precision of 0.1‰ of the flying height above ground (Kraus 1990). In addition to the rugged terrain, the problem merges mainly because of Popocatépetl´s high eruptive activity. This may cause alteration and destruction of established ground control points. Field campaigns enabling the measurement of new GCP's are currently too hazardous due to volcanic activity.

Lack and minor alteration of GCP's may provoke a slight shift in the DEM ranging up to 1.5 m in a horizontal sense. The resulting errors inherent to the generated DEM´s are thus calculated as up to ± 1.25 m in a vertical sense depending on the surface slope.

Glacier changes are studied in terms of area, ice thickness and additional morphological characteristics such as slope, etc. Slope calculations are thereby based on an algorithm taking into account the adjacent 8 pixels of each center pixel of the grid.

As far as glacier area changes are concerned the above-mentioned errors can be neglected, for ice thickness changes, however, they have to be taken into consideration in order to obtain significant results.

3 Glacier area and terminus changes

Lorenzo (1964) was the first to carry out exact area measurements of Popocatépetl´s glaciers, actually being based on the glacier extent of 1958 (Fig. 2). Later on, White (1981) reports changes in terminus altitude from 1968 and 1978, but gives no indication of the areal extent. Lorenzo (1964) distinguishes three glaciers on Popocatépetl. The third glacier named Glaciar Norte was observed later to be part of Ventorillo glacier (Delgado 1997). The former area of the so called Glaciar Norte is now actually covered by a permafrost field consisting of volcanic ash and debris, cemented by ice. During the dry season and the beginning of the rainy season superficial ice is melted, and solifluction processes are indicated by the high solid concentration of mud.

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 (Fig. 3).

Monitoring activities at Popocatépetl were largely intensified since the beginning of the eruptive phase starting in 1994. Therefore, data availability on glaciers became much denser, especially since 1996, measurement intervals became much closer and glacier fluctuations can be studied on a more convenient scale.

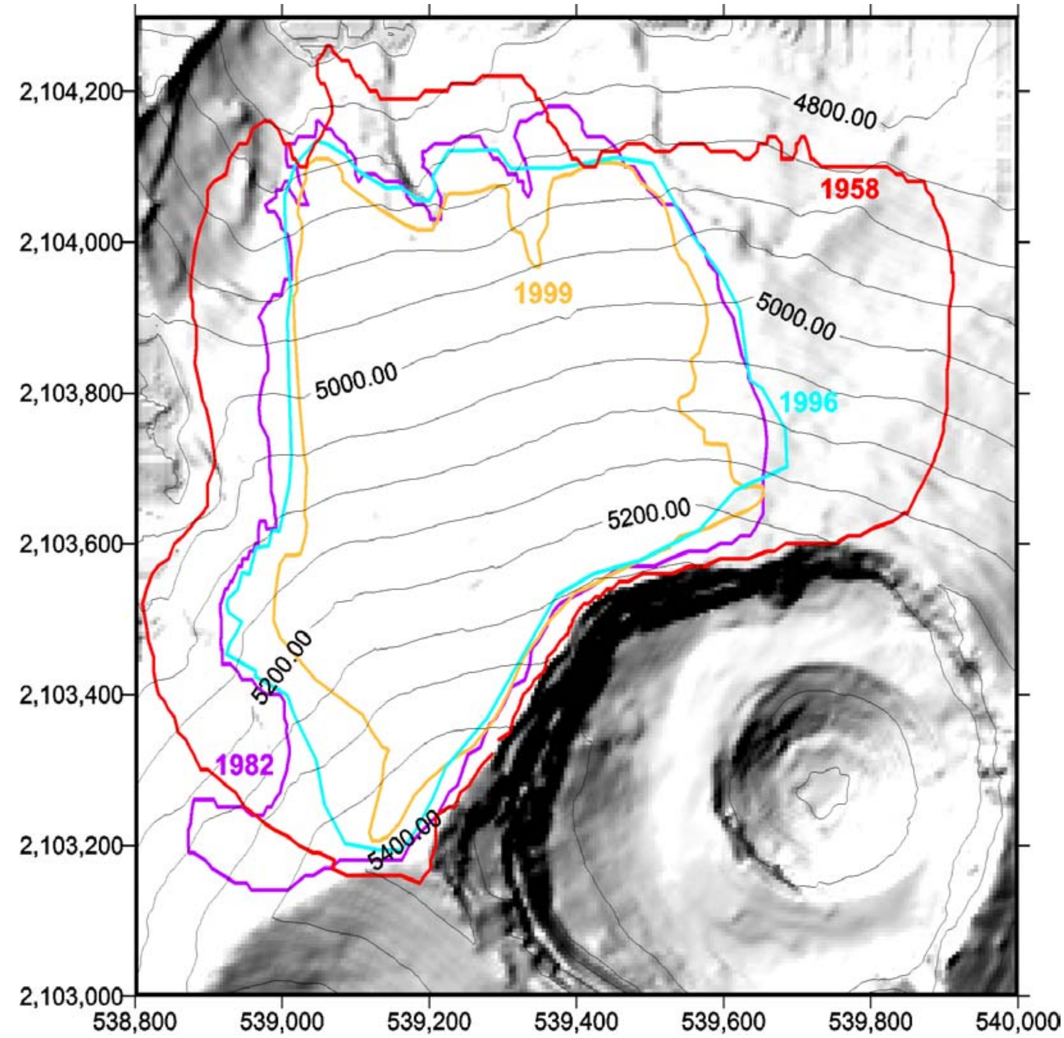

Fig. 2: Glacier extents in 1958, 1982, 1996 and 1999 shown over a digital elevation model including the crater of Popocatépetl. Geographic reference is indicated by the national Mexican coordinate system.

From 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 diminished by 8 m and Noroccidental tongue by 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 whereas a greatly accelerated glacier retreat was observed on a worldwide scale for the same period including tropical glaciers such as those on Mt. Kenya or in Peru (Haeberli and Hoelzle 1993; Oerlemans 1994; Hastenrath and Ames 1995). This suggests that Popocatépetl regional or local climate trends were considerably different compared to many mountain ranges over the world.

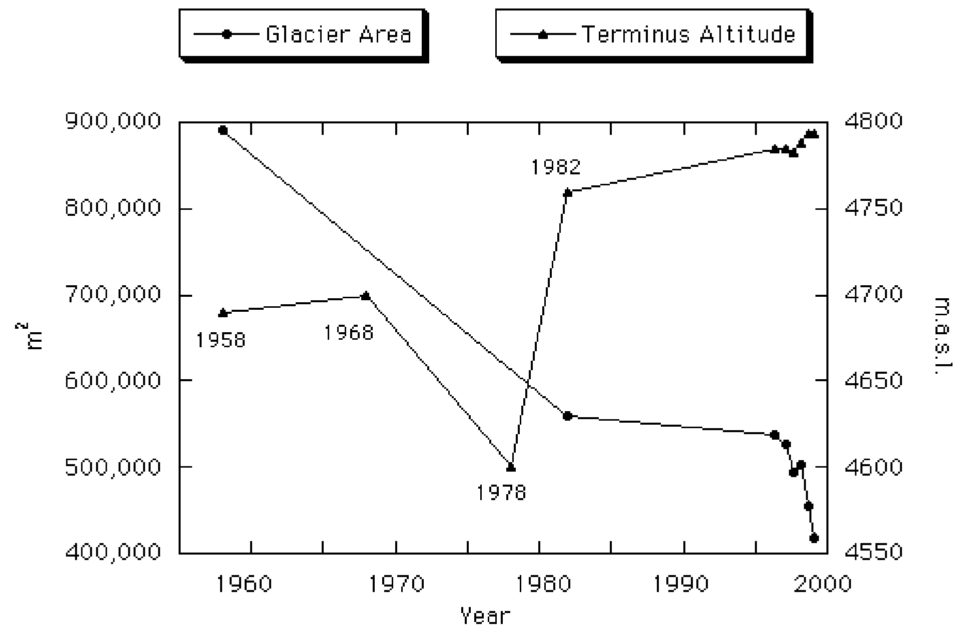

Fig. 3: Changes in glacier terminus (Ventorillo tongue) and area between 1958 and 1999. Data prior to 1996 from White (1981) and Delgado (1997).

Still, a loss of 22% of the area during 3 years indicates an extraordinarily high glacier shrinkage since 1996. Causes and processes behind this phenomena are not yet completely understood, but it is postulated that it has to be related to the volcanic activity since 1994/1995. An exclusively climate-induced loss of this order of magnitude seems rather unlikely.

4 Ice thickness changes

The measurement of glacier mass changes is generally a far better method to investigate a glacier's 'health' than is the change of terminus positions (Paterson 1994). Linking glacier fluctuations to climate, mass balance is the direct response whereas length variations are an indirect and delayed response such that climatic variations are best represented by mass balance studies (Haeberli and Hoelzle 1993).

Although small glaciers show much faster length variation responses to climate changes than large valley glaciers do, the study of terminus variations alone does not allow a closer insight as needed for a deeper understanding of the behaviour of the glaciers of Popocatépetl. Therefore, efforts have been undertaken to study the changes in the mass regimes of these glaciers.

Mass balance can be determined by several methods, for instance the hydrological or the glaciological method. In this study, the photogrammetrical method has been applied, mainly due to its independence from field stays once the GCP's have been established. In fact, this is a major prerequisite since measurements in the field such as those necessary for other methods are not possible currently due to the high eruptive activity.

Net balance can be measured comparing surface altitude of the entire glacier for two consecutive years. Elevation differences determined by the photogrammetrical method can only be related to mass balance taking into account the entire glacier surface. Considering part of the glacier may not be accurate since ice thickness changes can also be the result of processes not directly related to mass changes (e.g. changes in ice flow).

Aerial photographs should be taken at the end of the balance year, i.e., at the end of the ablation season, in order to obtain glaciologically significant results (Paterson 1994). Accordingly, a few important restrictions have to be made for the glaciers of Popocatépetl. Firstly, two DEM´s from the end of the ablation season are needed to compare and calculate glacier thickness changes. However, due to data limitations resultant of unfavourable flight or visibility conditions, this is not always possible for Popocatépetl.

Secondly, Mexican glacier regimes are characterized by ablation seasons beginning in November and ending in July while accumulation seasons last from August to November. Yet, the timing of accumulation and ablation seasons of intertropical glaciers is poorly defined. In addition, accumulation processes at intertropical glaciers provoke that overlying layers may be very inhomogeneous making difficult the exact reconstruction of water equivalents generally used in mass balance studies (e.g. Kaser et al. 1990). Results presented here are limited to changes in ice thickness.

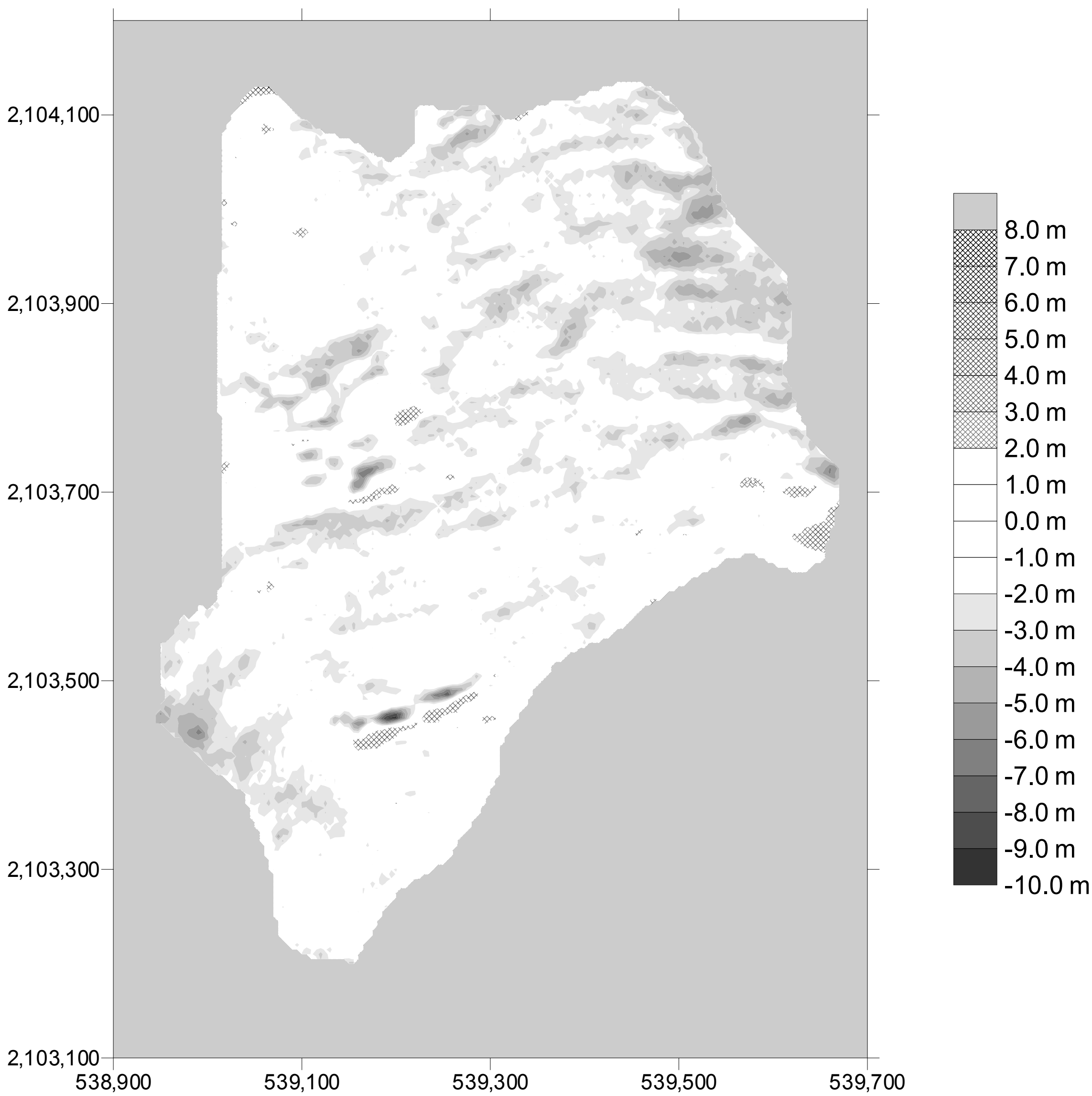

Fig. 4: Ice thickness changes in meters between May 1996 and February 1997.

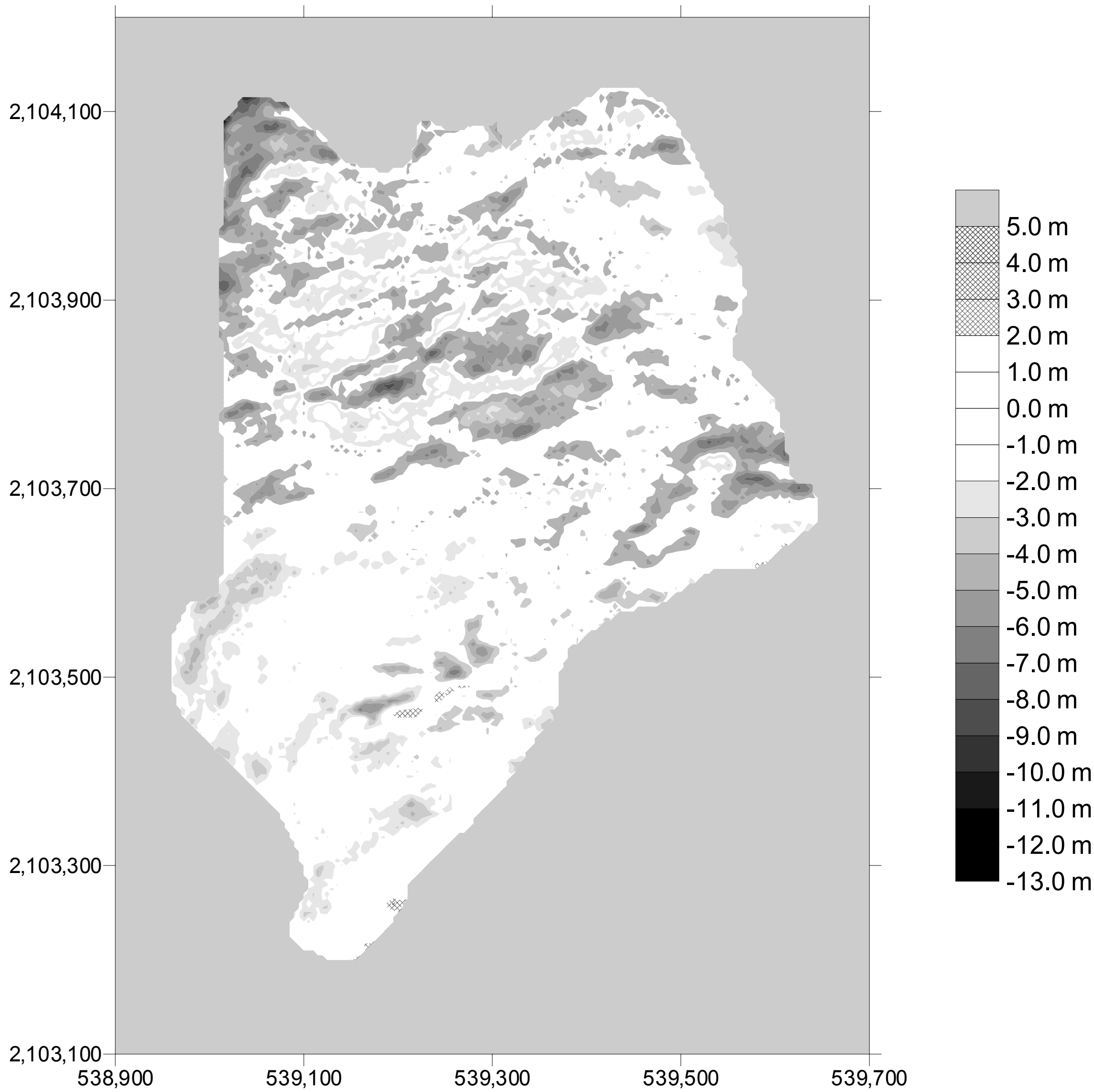

Fig. 5: Ice thickness changes in meters between February 1997 and February 1998.

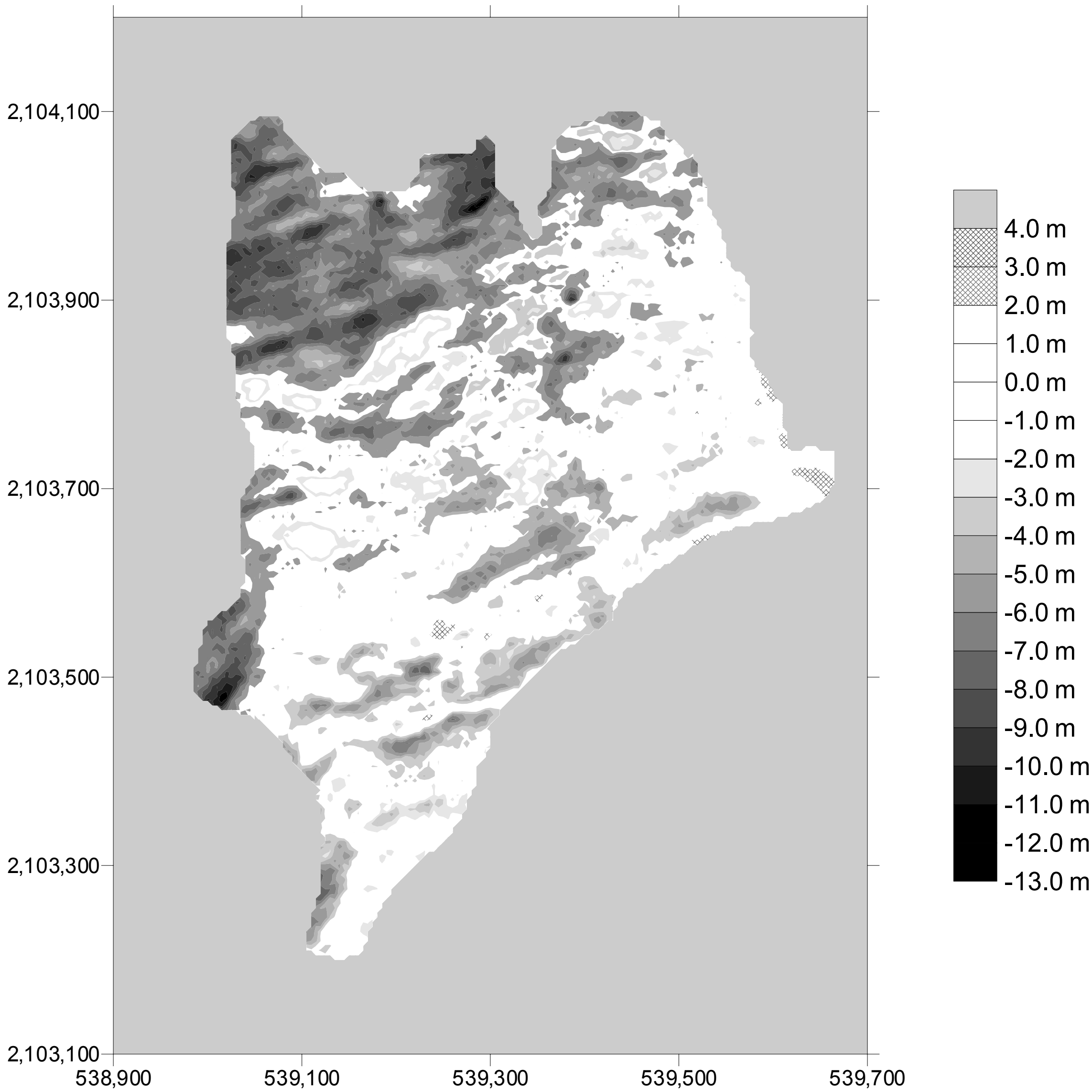

Fig. 6: Ice thickness changes in meters between January 1998 and January 1999.

Ice thickness changes were studied over three consecutive years starting in 1996. According to the size of the above-mentioned potential errors inherent to the DEM´s, the values in the range of ± 2 m are blanked. Thus, areas with values major or minor than ± 2 m reflect significant ice thickness changes.

Between 1996 and 1997 mass loss is most pronounced in the lower eastern part of Ventorillo glacier and on the lower Noroccidental glacier and some few spots show a slight positive change (Fig. 4). Ice thickness changes from 1997 to 1998 reveal a strongly accelerated mass loss and virtually no areas with positive thickness changes are found (Fig. 5). Ice thickness changes are particularly negative at Ventorillo tongue and on the lower to middle part of Ventorillo glacier. Ice thickness changes of the most recent balance year (1998 to 1999) show a similar pattern as the previous years, the loss, however, is further intensified, mainly on Ventorillo and Noroccidental tongues (Fig. 6). As in former years, mass loss on the upper part of the glaciers is less intense, but over all a glacier under negative mass balance condition is revealed.

5 Discussion

The interpretation of such extraordinary glacier shrinkage can not be trivial in this context. Basically, three different explanations are proposed here:

- local to regional climate change;
- increased melting at the surface and base of the glacier by volcanic activity;
- changes in topography of the volcanic edifice due to in- or deflating effects resulting in significant alterations of the DEM´s.

Slight temperature increase was observed in areas close to Popocatépetl such as Mexico City (Urrutia 1991). However, the existing climatological data for Mexico City must be handled with care because they may reflect local climatic conditions and greenhouse effects commonly attributed to pollution of such large cities. It is possible that the vicinity of one of the world´s largest cities influences the climate pattern of Popocatépetl. Unfortunately, not enough climatic records do exist for the area under investigation, a quantitative evaluation of the different influences is presently hindered.

Intensified melting at the base of glaciers due to geothermal heatflow or fumarolic activity was reported worldwide at several volcanoes (Major and Newhall 1989) and observed at Popocatépetl by one of the authors. Even though no precise data exist, we think that a fumarolic zone might be present in the middle to upper part of the glacier. This is furthermore confirmed by infrared images taken in December 1997 showing a thermal perturbation zone in the above-mentioned part of the glacier.

Regarding superficial melting, several ashfall events on the glacier surface have been reported at Popocatépetl. Studies on Mt. St. Helens following the 1980 eruption indicated that traces of ash of few millimeters increased the rate of snowmelt by as much as 20-30% whereas ash layers of 25 mm and more reduced melting due to insulation effects (Brugman and Post 1981). Both cases are present at Popocatépetl, however, the later inhibits snow permanency accelerating the melting rate and provoking negative accumulation rates.

There is no evidence to support the hypothesis of morphological changes in the volcanic edifice. But the magnitude of the observed ice thickness changes is very remarkable for the glacier's small size and might lead to speculations about raising or lowering of surface caused by processes such as magma intrusions related to volcanic activity. Still, as the observed thinning of the glacier is accompanied by strong retreat in area as well, we propose that the observed thickness changes can actually be related to the thinning of the glacier ice.

6 Conclusion

The worldwide glacier retreat of this century is also reflected by the glaciers on Popocatépetl. Different hypothesis for the observed glacier shrinkage have been outlined. In the last three years glacier shrinkage has been of such intensity that a single explanation (i.e. climate change), can hardly account for the whole glacier retreat. The combination of several interacting processes provides a more realistic explanation including a close relationship with the recent eruptive phase of Popocatépetl as the most likely cause of retreat.

For better understanding the phenomena further investigation is needed. Glaciological research on volcanoes is still very scarce and little is known about processes such as geothermal heatflow, basal melting and glacier response. In fact, in view of an improved hazard assessment further studies on ice flow velocity, ice thickness and temperature distribution in the glacier would be very valuable.

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