Twenty-first Century Glaciers and Climate in the Prokletije Mountains, Albania

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Abstract

At least four active glaciers are present in the Prokletije Mountains of northern Albania. These glaciers exist at altitudes between 1980 and 2420 m a.s.l.—well below the regional equilibrium line altitude—on shaded northeast-facing slopes prone to avalanche. Glacier-climate modeling suggests that these glaciers require annual accumulation of between 4137 and 5531 mm (water equivalent) to balance melting. A significant proportion of this accumulation is likely to be sourced from windblown snow and, in particular, avalanching snow. It is estimated that the total accumulation needed to balance melting is potentially up to twice the value received from direct precipitation. The presence of these glaciers—some of the southernmost in Europe—at altitudes well below the regional equilibrium line altitude, highlights the importance of local controls on glacier development.

Introduction

Pleistocene glaciation was common in the Mediterranean mountains (Hughes et al., 2006a), although modern glaciers are rare and exist under conditions marginal for glaciation (Fig. 1). In the mountains of the peninsulas of southern Europe, such as Iberia, Italy, and the Balkans, the regional equilibrium line altitude is situated at >3000–3500 m (Messerli, 1980). However, glaciers are present in areas where mountains do not reach this theoretical equilibrium line, and the contradiction of glaciers in the warmest parts of Europe has been the subject of curiosity of numerous researchers over the past 100 years (see Hughes and Woodward, 2009, and references therein). This paper presents new data on the Prokletije glaciers of northern Albania. The aims of the paper are to: (1) describe the evidence of modern glacier activity in the Prokletije; (2) apply a degree-day melt model to understand the accumulation required to balance melting; and (3) assess the local topographic and climatic factors contributing to glacier activity in these mountains.

Study Area

The Prokletije Mountains (translated as "cursed mountains") are situated on the border between Montenegro and Albania (Fig. 2) and the highest peak is Maja Jezerce (2694 m). The bedrock of this area is dominated by Jurassic and Triassic limestones, many of which are metamorphosed, with granites and other intrusive volcanics present locally. At Plav (980 m a.s.l.), c. 20 km northeast of Maja Jezerce, the mean annual precipitation is 1986 mm (Bošković and Bajković, 2004). The mean annual temperature at Vermosh (1152 m) in the same valley as Plav, but on the Albanian side of the border, is 6.7 °C (Palmentola et al., 1995). The Prokletije supported some of the largest Pleistocene glaciers in the Balkans, although Milivojević et al. (2008) have recently suggested that Pleistocene glaciation may have been more restricted in this area than previously thought.

Methods

The valleys and cirques surrounding Maja Jezerce were visited at the very end of the summer melt season in September 2006 and October 2007, prior to new winter snow accumulation. Glacier limits were traced in the field and plotted onto 1:50,000 topographic base maps with 20 m contour intervals. Glacier areas were then calculated from these maps. Altitudinal positions were taken using a handheld global positioning system and an aneroid (barometric) altimeter.

The median elevation of the glaciers (Braithwaite and Müller, 1980) was used to estimate the equilibrium line altitude (ELA) in this study. Braithwaite and Raper (in press) found that there was strong correlation between observed steady-state ELA and median glacier elevation on 94 glaciers around the world. The median glacier elevation divides the glacier surface into two equal parts and reflects the statistical median of the glacier surface area–altitude distribution. This is not the same as the median elevation of glaciers as described in Meierding (1982) and Benn and Lehmkuhl (1998) in which a toe-to-headwall-ratio is used to obtain the so-called "median" elevation. On very small glaciers with little altitudinal variation, such as those in Albania, it could be argued that whichever method is applied to estimate the ELA the range of values is trivial.

Glacier volume was estimated using an empirical volume-area relationship that is widely applied in glacier inventory and water resources estimation. Based on data from 63 mountain glaciers, Chen and Ohmura (1990) found that:

$$V = 28.5S^{1.357} \qquad (1)$$

where V is glacier volume (10^6 m^3) and S is glacier surface area (10^6 m^2). From this, the *average* glacier depth (h) was then calculated as:

$$h = 28.5 \, S^{0.357} \qquad (2)$$

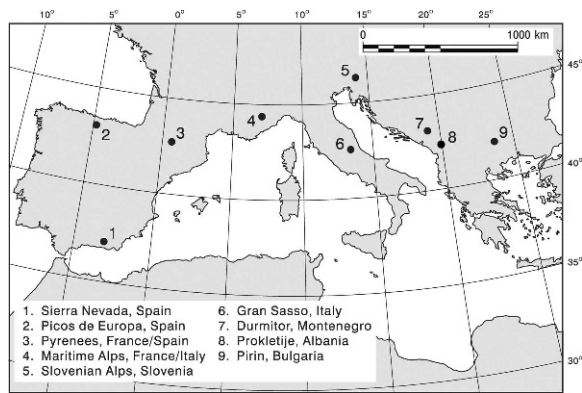This second scaling coefficient estimates the *average* glacier depth

FIGURE 1. Locations of the southernmost glaciers and ice patches in Europe (based on data in Grunewald et al., 2006; González-Trueba et al., 2008; Hughes and Woodward, 2009).

and this value may be substantially less than the *maximum* glacier depth. The scaling coefficients in Chen and Ohmura (1990) are based on a large data set (63 glaciers) that includes very small glaciers like those in Albania.

A simple degree-day model was used to calculate the amount of accumulation required to sustain the glaciers in the Prokletije. The mean annual temperature of 6.7 °C at Vermosh (1152 m) was extrapolated to the median elevations of the Prokletije glaciers using a lapse rate of 0.6 °C per 100 m. These annual temperatures were then distributed over a sine curve to provide daily temperature means using the following equation (from Brugger, 2006):

$$T_d = A_y \sin(2\pi d/\lambda - \Phi) + T_a \quad (3)$$

where T_d is the mean daily air temperature, A_y is the amplitude of the yearly temperature (half of the annual temperature range; the annual mean monthly temperature range at Vermosh is 18.6 °C), d is the day of the year (1 to 365), λ is the period (365 days), Φ is the phase angle (taken as 1.93 radians to reflect the fact that January is the coolest month), and T_a is the mean annual air temperature.

The annual accumulation required at the equilibrium line altitude to balance melting equals the sum of daily snow melt, using a degree-day factor. Braithwaite (2008) found that degree-day factors for snow on 66 glaciers worldwide had averages of 3.5 ± 1.4 and 4.6 ± 1.4 mm day^{-1} K^{-1} in low- and high-accumulation conditions, respectively, with an overall mean of 4.1 ± 1.5 mm day^{-1} K^{-1}, in accordance with earlier values reported in the literature (e.g. Braithwaite et al., 2006). However, it is important to be aware that degree-day factors for snow can vary quite significantly between individual sites, and degree-day factors for snow have been reported ranging from 2.5 to 11.6 mm day^{-1} K^{-1} (Hock, 2003). Nevertheless, the mean degree-day factor for snow of 4.1 ± 1.5 mm day^{-1} K^{-1} (standard deviation 2σ: ±36%) in Braithwaite (2008) is representative of most glaciers and is applied to the Albanian glaciers in this study.

The ratio between the drainage area leading directly onto the glacier surface and the total glacier surface area (*drainage ratio*) was used to provide an indication of the possible contribution of windblown and avalanching snow onto the entire glacier surface. The influence of avalanche on accumulation was isolated further using a separate *avalanche ratio*. This is the ratio between the total area susceptible to avalanche, which is defined here as slopes >30° leading directly onto the entire glacier area, and the total glacier surface area. The entire glacier area is used in these ratios because, as noted earlier, very small glaciers such as these can experience
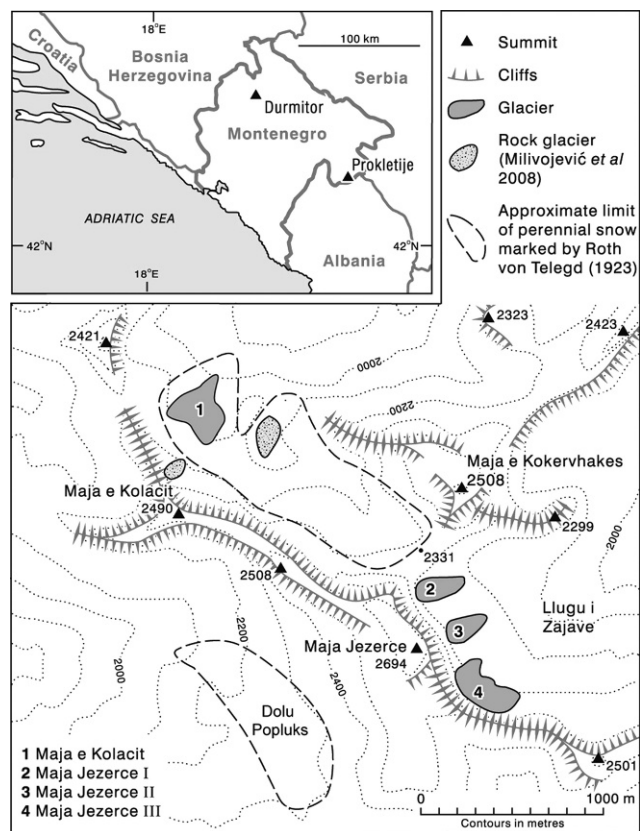

FIGURE 2. Glacier locations in the area around Maja Jezerce, the highest peak in the Prokletije Mountains.

positive or negative mass balance over the entire glacier surface in different years (Hughes, 2007).

Results: Evidence of Modern Glaciers in the Prokletije

A glacier is present at the base of the north-facing cliffs of Maja e Kolacit (2490 m) (Fig. 2). This glacier was recognized by Milivojević et al. (2008) and is the largest of the Prokletije glaciers covering an area of c. 5.4 ha between altitudes of 1980 and 2100 m. Moraines are present only several meters from the glacier margin and the lack of lichens on boulders on the crests of these moraines suggests that they have formed recently. Older moraines are situated 25–50 m down-valley and may correlate with late 19th century moraines identified in front of the Debeli Namet glacier on Durmitor in Montenegro (Hughes, 2007).

Milivojević et al. (2008) mentioned the presence of two rock glaciers close to the glacier described above (Fig. 2). The areas that they described are indeed admixtures of ice and rock debris. However, they lack the clear lobate form of rock glaciers and these features may not be actively moving and thus may be better described as patches of sporadic permafrost rather than true rock glaciers.

Three glaciers are present in the cirque of Llugu i Zajave below the northeastern cliffs of Maja Jezerce (2694 m) (Fig. 2). The two northernmost glaciers were described in Milivojević et al. (2008). These glaciers (Maja Jezerce I and II) covered areas of c. 2.4 and 2.0 ha between 2220 and 2320 m altitude and were bounded by very clear moraine ridges. Another, larger glacier was present to the southeast of Maja Jezerce summit (Maja Jezerce III) below the ridge leading to spot height 2501 m (Fig. 2) and Maja e Rogomit (2472 m). Ice and firn covered an area of c. 4.9 ha

TABLE 1

The dimensions of the Prokletije glaciers including the drainage and avalanche ratios and glacier median elevations (see text for details).

Glacier (ha)	Glacier area	Glacier volume (m³)	Average glacier depth (m)	Drainage ratio	Avalanche ratio	Glacier median elevation (m)
Maja e Kolacit	5.4	542,879	10.1	2.0	1.9	2040 m
Maja Jezerce I	2.4	180,631	7.5	1.2	0.6	2260 m
Maja Jezerce II	2.0	141,040	7.1	1.2	0.8	2280 m
Maja Jezerce III	4.9	475,818	9.7	0.7	0.5	2340 m

between 2270 and 2410 m and, like all the other Prokletije glaciers, was bounded by clear moraines close to the ice margins. Older moraine ridges up to 100 m beyond the modern glacier margins in the Llugu i Zavaje cirque may correlate with late 19th century moraines recognized on Durmitor in Montenegro, as mentioned above for the Maja e Kolacit glacier. No other glaciers were found in the cirques and valleys surrounding Maja Jezerce. In the Dolu Popluks cirque, to the south of Maja Jezerce summit (Fig. 2), no glaciers were found, although large snowfields were present in September 2006.

The mean annual temperatures at the median elevations of the Prokletije glaciers range from 1.4 to –0.4 °C. Under these temperatures, and an annual range of 18.6 °C (at Vermosh), the degree-day model predicts that the annual accumulation required to offset melting is between 4137 and 5531 mm (standard deviation 2σ: ±36%) water equivalent (w.e.).

The drainage and avalanche ratios for the four Prokletije glaciers are presented in Table 1. The Maja e Kolacit glacier has the largest ratios, while the three Maja Jezerce glaciers (I, II, and III) have progressively smaller drainage and avalanche ratios. In the case of Maja Jezerce III, the drainage ratio is <1, indicating that the potential contribution from windblown and avalanching snow is smaller than the glacier surface area.

Discussion

The Prokletije glaciers remained unknown until recently when Milivojević et al. (2008) reported the presence of three glaciers on the northern cirques of Maja Jezerce (glaciers 1, 2, and 3 in Fig. 2). Earlier reports were made by Roth von Telegd (1923) who noted the presence of "Firnmasse" longer than 1 km in the cirque enclosed by Maja e Kolacit, Maja Jezerce, and Maja e Kokervhakes (Fig. 2). This large area of firn occupied the cirque floor to the east of the modern Maja e Kolacit glacier (Fig. 2). Roth von Telegd also mapped a large perennial snow field in the wide cirque floor south of Maja Jezerce summit in the Dolu Popluks cirque (Fig. 2). However, Roth von Telegd did not mention the Llugu i Zajave cirque and this area remained blank on his maps.

The Prokletije glaciers are some of the lowest altitude glaciers at this latitude (42.5°N) in the northern hemisphere. The glaciers are situated at altitudes between 1980 and 2410 m, similar to the Debeli Namet glacier (2050–2300 m) in the Durmitor massif, Montenegro (Hughes, 2007, 2008). The Prokletije and Durmitor glaciers are much lower than others at a similar latitude in Europe, such as the Calderone glacier in the Italian Apennines (D'Orefice et al., 2000) and the glaciers of the Pyrenees (González-Trueba et al., 2008). The Prokletije and Durmitor glaciers are also at a lower elevation than the Sneschnika glacier in Bulgaria (Grunewald et al., 2006). In Europe, the only ice forms at similar latitude with similar elevations are the ice patches of the Picos de Europa in Spain (González-Trueba et al., 2008). Glaciers in the Caucasus (Russia/Georgia; 41–44°N) are situated at similar latitude to the Prokletije glaciers but the former are much higher, with median elevations ranging between 2530 and 3980 m (Braithwaite and Raper, 2007). Even in the maritime climate of the North Cascade Range in western North America (47–49 °N) most glaciers have mean altitudes that are higher than the median elevations of the Prokletije glaciers, despite the latter being situated several degrees further south (Pelto and Hedlund, 2001). Globally, glaciers at lower altitudes at similar or lower latitudes to the Prokletije glaciers are present only in the southern hemisphere in strongly maritime climates such as New Zealand where glaciers are situated between 41 and 47°N with median ELAs ranging between 1490 and 2440 m (Braithwaite and Raper, 2007). For example, the Franz Josef glacier in New Zealand (43.4°S) has an ELA at c. 1500 m, which is largely in response to direct annual precipitation of c. 5000 mm (Woo and Fitzharris, 1992).

The low altitude of the Prokletije glaciers is due to local topographic and climatic factors such as avalanching and windblown snow, and also shading. Direct meteorological precipitation cannot account for the annual melt at the temperatures at this altitude. Although there are no meteorological records from the highest areas of these mountains, if snow accumulation from direct meteorological precipitation could balance melting at the altitudes of the Prokletije glaciers, then glaciers would be much more widespread with a regional ELA well below the highest peaks.

The total accumulation required to sustain the glaciers in the Prokletije is estimated at between 4137 and 5531 mm (standard deviation 2σ: ±36%) w.e. Snow avalanche is likely to be a major contribution to glacier mass balance and an avalanche ratio of 1.9 for the Maja e Kolacit glacier indicates that the potential area of avalanching is nearly twice the area of the glacier. This may also explain the low altitude of the glacier (median elevation = 2040 m) compared with the three others in this area. These other higher glaciers, all situated on the northeastern slopes of Maja Jezerce, have avalanche ratios of less than 1 and have median elevations that are more than 200 m higher than the Maja e Kolacit glacier, at between 2260 and 2340 m.

Windblown snow is also likely to be an important contributor to glacier mass balance. In the case of most of the glaciers (Mala e Kolacit, Maja Jezerce II and III) the drainage areas are dominated by steep cliffs and consequently the drainage ratios are only a little larger than the avalanche ratios. However, in the case of Maja Jezerce I, the drainage ratio is double the avalanche ratio (Table 1). This highlights the potential for windblown snow as well as avalanche. Even where the drainage area onto the glacier is dominated by steep avalanche-prone slopes this does not preclude a role for wind in the transfer and redistribution of snow onto the glacier surface. Large accumulation of snow by both wind and avalanche is very common for small glaciers at low altitudes at higher latitudes, such as the Polar Urals, where Dolgushin (1961) called such phenomena "Polar Ural type" glaciers. The low altitude glaciers in the Prokletije (relative to the regional ELA) shows that avalanching and windblown snow also define these "Mediterranean" glaciers, less than 75 km from the Adriatic coast.

In addition to local accumulative inputs as a result of wind and avalanche, shading is likely to be a major influence on the melting of all these northeast-facing glaciers, depressing local ELAs to below the highest peaks. Low insolation due to shading at the glacier sites may reduce air temperatures locally within the cirque. Consequently, temperatures at the altitude of these glaciers may be lower than is suggested when extrapolating temperatures from lower altitudes, such as Vermosh, using a standard atmospheric lapse rate of 0.6 °C per 100 m. This means that the values of accumulation calculated using the degree-day model may be overestimated. The significance of this issue can be tested by monitoring air temperatures at the glacier sites and such local climate measurements will help refine future glacier-climate modeling at these and other sites. This is important not only for understanding the relationship between modern glaciers and climate but also for when applying modern analogs to model glacier-climate conditions on paleoglaciers—especially in the case of former local glaciers that formed under conditions marginal for glaciation (e.g. Sissons, 1979; Hughes, 2002; Hughes et al., 2006b; Sarıkaya et al., 2008)

Local topoclimatic factors may render these glaciers insensitive to regional climatic changes. Warmer air temperatures, which have been predicted for the future decades in the Mediterranean mountains (Nogués Bravo et al., 2008), may increase the avalanche risk on slopes draining onto the glaciers. However, increased regional air temperatures may be dampened by localized shading in cirques and future predictions for high mountain areas such as the Prokletije are difficult. It is clear that the high mountain topoclimate is complex and not always comparable to the regional climate—as is evidence by the presence of glaciers in the Prokletije Mountains, Albania, at altitudes well below the regional ELA.

Conclusions

Four glaciers are present in the Prokletije Mountains of northern Albania, the largest of which covers an area of 5.4 ha. All of the glaciers are present below northeast-facing cliffs near the highest peak of this range, Maja Jezerce (2694 m). It is possible that these glaciers are some of the lowest altitude glaciers (1980–2420 m) at this latitude (42.5°N) in the world. The annual accumulation necessary to sustain these glaciers is in the range 4137–5531 mm w.e. (standard deviation 2σ: ±36%). Such high levels of accumulation are likely to be facilitated by large inputs of snow from windblown snow and especially avalanching snow in addition to direct precipitation.

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