GROUND THERMAL PROFILES FROM MOUNT KENYA, EAST AFRICA

BY

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ABSTRACT. This paper presents and compares ground thermal regimes at 4200 and 4800 m a.s.l. on Mount Kenya's southern aspect. Temperatures were recorded using Tinytalk^{TM} data loggers, installed at the ground surface and at depths of 1 cm, 5 cm, 10 cm and 50 cm. Temperatures were logged at 2-hour intervals over a period of 12 months (August 1998 to July 1999). The study is designed to demonstrate near-surface freeze conditions, which would have implications for contemporary periglacial landform production. Although ground freeze at 4200 m a.s.l. occurs during most nights (*c.* 70% at 1 cm depth), freeze penetration is restricted to the top 2 to 3 cm, such that no freeze was recorded at 5 cm depth. At 4800 m a.s.l., the diurnal frost frequency at the surface is 365 days (100%), whilst that at 10 cm depth is 165 days (45%). The paper demonstrates that a greater longevity of contemporary thin snow cover at 4800 m a.s.l. permits progressive sub-surface cooling with depth. However, the near-surface ground temperature profiles suggest that conditions are not conducive to permafrost development at the sites.

Key words: ground thermal regimes, cryogenic characteristics, Mount Kenya

Introduction

Mount Kenya is located on the East African equator (0°9'S, 37°19'E) and rises to 5199 m a.s.l. (Fig. 1). Despite its equatorial locality, 18 glaciers were recorded during the early 1900s (Hastenrath 1984), yet by the end of the twentieth century only 11 glaciers remained (Young and Hastenrath 1991; Karlén *et al.* 1999). Given such rapid glacial retreat and disappearance, Mount Kenya is an important site for performing global change research. Examples of previous work done on Mount Kenya include studies on glacier mass balances (Haeberli *et al.* 1996), energy balances and hydrological responses (Hastenrath 1983; Hastenrath and Kruss 1988), Late Glacial and Holocene palaeoclimatic change (Mahaney 1985; Karlén *et al.* 1999), and the altitudinal advance of alpine plants in response to glacier retreat (Mizuno 1998). It is apparent that strong altitudinal gradients occur on hydrological, vegetational, climatic and cryospheric processes, making it relatively easy to detect change at various altitudes. The intensity, duration and depth of ground freeze is likewise expected to change altitudinally, impacting on the effectiveness of cryogenic processes and consequent landform development and seedling establishment.

Near-surface soil temperatures are important considerations, in that they are the upper boundary condition for sub-soil temperatures (Kane *et al.* 2001). Here we present data on the near-surface ground thermal regime at two sites (4200 and 4800 m a.s.l. respectively) on the southwestern flank of Mount Kenya. The objective is to provide an understanding of near-surface cryo-thermal dynamics in this equatorially driven climate, which would differ from those in higher latitude mountains.

Few published accounts on ground temperature data are available for Mount Kenya. Winiger (1981) provides the most detailed examination of the altitudinal and topographic variability of ground temperatures recorded at 50–70 cm depth during 1976–1979. Grab (1996) produced a single-recorded vertical thermal profile to 1 m depth at 4750 m a.s.l., on 8 July 1995. The present study provides two vertical thermal profiles to 0.5 m, recorded continuously over 12 months (1998/99) at two-hour intervals. Making a ground thermal comparison to the previous studies is difficult owing to the highly variable nature of surface temperatures (cf. Winiger 1981). Whilst it is important to recognize the complexity of such ground temperature

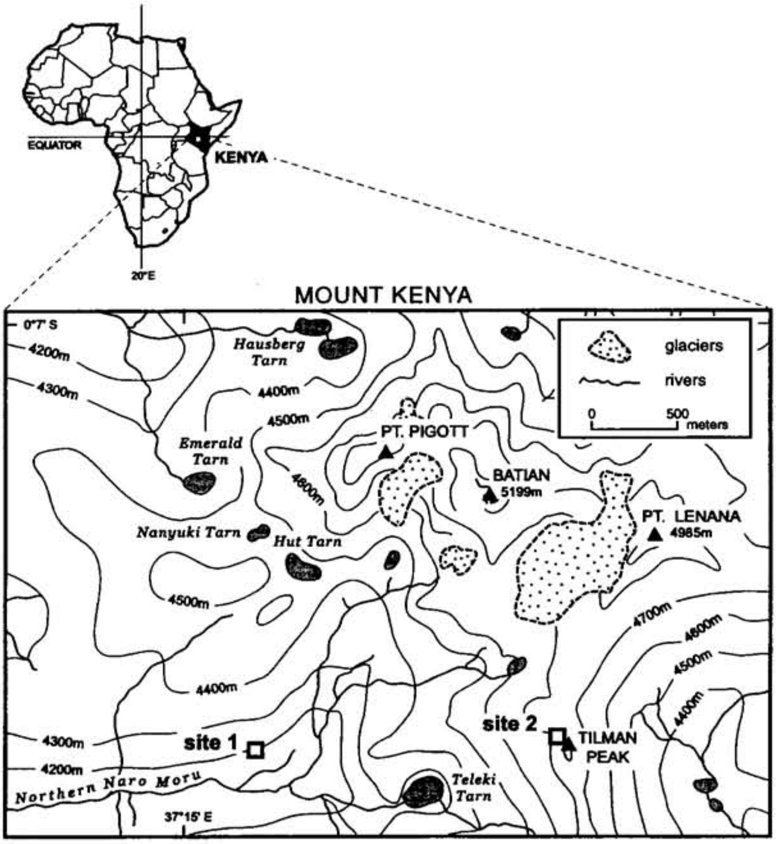

Fig. 1. Study localities on Mount Kenya, East Africa.

variations in the context of the Mount Kenya data, our aim is rather to compare two site-specific situations and determine their implications for the surrounding slopes.

Study area

The summit area consists mostly of basalt and hosts nepheline-syenite volcanic plugs (Baker 1967). Several small but rapidly retreating glaciers still remain, of which the Lewis glacier is the largest (*c.* 850 m×65 m). The periglacial morphology consists of a variety of actively forming miniature frost-induced landforms such as sorted patterned ground, turf-exfoliated terraces and fine earth flags between 4300 and 4800 m a.s.l. (Hastenrath 1973). The occurrences of an inactive/relict rock glacier and protalus rampart at *c.* 4750 m a.s.l., indicate that periglacial macro-forms developed in the recent past during the Holocene (Grab 1996).

The climate of the Mount Kenya region is primarily controlled by the continental northeastern monsoon bringing dry conditions, whilst the southeastern monsoon brings moisture from the Indian Ocean. However, topographic control permits orographic precipitation throughout the year, thus reducing the potential seasonal trends found in the surrounding lowlands. The two wet periods are generally referred to as the '*long rains*' (March to May) and '*short rains*' (October/November), separated by somewhat drier months (Hedberg 1964; Hastenrath 1981; Ogallo 1990). Maximum precipitation (2500 mm a^{-1}) occurs along the southern and eastern slopes between 2500 and 3000 m a.s.l., whilst the drier northern slopes receive about 1000 mm a^{-1} and altitudes above 4500 m regularly receive solid forms of precipitation amounting to *c.* 700–800 mm a^{-1} (Hastenrath 1981). Air temperatures in the alpine zone are characterized by a very low mean seasonal range (*c.* 2°C), but high diurnal range (10 to 20°C) (Hastenrath 1981, 1984). The 0°C isotherm is estimated at *c.* 4750 m a.s.l. (Hastenrath 1984), which marks the equilibrium line for the Lewis Glacier (Haeberli *et al.* 1996). Temperatures in the afro-alpine belt are affected by a typical daily cycle of clear mornings and cloudy afternoons (Gatebe *et al.* 1999).

Altitudinal vegetation belts on the southern slopes of Mount Kenya have been classified as the Montane Forest Belt below 3400 m a.s.l., the Ericaceous Belt between 3400 and 3600 m a.s.l., and the afro-alpine belt above 3600 m a.s.l. (Hastenrath 1984). Although vegetation becomes increasingly sparse above 4400 m a.s.l., Winiger (1981) reports the occurrence of *Senecio keniophytum* to 4930 m a.s.l.

Methods

Site 1 is located on a colluvial terrace at 4200 m a.s.l. (0°10'S, 37°15'E), *c.* 13 m above the Teleki Valley floor (Fig. 1). The monitoring site is an extensive area of bare soil, surrounded by slopes of *Festuca* grass. Site 1 was represented by relatively dry uniform sediment to 50 cm depth (as observed during two field visits), averaging 34% gravel, 52% sand and 14% silt/clay (fines). The sediment composition was determined from samples collected at the monitoring localities. The unvegetated *Site 2* is located *c.* 10 m below a southwest facing interfluve at 4800 m a.s.l. (0°09'S, 37°18'E; Fig. 1). The gravel constituents increased towards the surface and the profile averaged 47% gravel, 42% sand and 11% silt/clay. The percentage of fines at both sites is sufficiently high (>10%) to be frost susceptible (cf. Meentemeyer and Zippin 1981). The entire profile was saturated during excavations in 1998 and 2000. Tinytalk^{TM} data logger probes were calibrated in ice baths and obtain an accuracy of *c.* 0.1°C. Probes were placed into fixed positions at the surface, and at 1 cm, 5 cm, 10 cm and 50 cm depths. We chose a two-hour logging interval to allow for a two-year continuous recording. The loggers were inserted two weeks prior to the first readings taken from 12 August 1998. Owing to logger failures and disruptions, only 12 months of data are included in this study (i.e. August 1998 to July 1999). Surface and 5 cm depth data were also interrupted and thus only a few months' data are available for these recordings. The emphasis of the presented results and subsequent discussion is thus primarily based on the data obtained from 1 cm, 10 cm and 50 cm depth. Given the risk of equipment being vandalized, climate parameters such as precipitation, air temperature and snow depth could not be recorded.

Ground thermal characteristics

The mean annual ground temperature varies between 8.8°C (1 cm depth) and 7.8°C (50 cm depth) at 4200 m a.s.l., and 2.7°C (1 cm depth) and 0.9°C (50 cm depth) at 4800 m a.s.l. (Table 1). Soil surface temperatures at 4800 m a.s.l. reflect low seasonal (max = 3.1°C) but very high diurnal (mean = 27.4°C) fluctuations (Table 1, Figs 2 and 3). The most notable characteristic is the high daily maximum and nightly frost cycle, which is maintained during all seasons of the year (Fig. 3). The mean diurnal range at 1 cm depth is 27.9°C (4200 m) and 21.1°C (4800 m), with absolute maxima of 40.7°C and 38.3°C respectively (Table 1).

The typical daily cycle of late-morning cloud buildup and afternoon snowfall throughout much of the year on Mount Kenya helps reduce potential evaporation and maintain high soil moisture at 4800 m a.s.l. Fig. 4 presents measurements of mean monthly maximum and minimum time-lag effects from 1 to 10 cm depth at the two study sites (located at 4200 and 4800 m a.s.l.). At 4200 m a.s.l., the daily minima at 10 cm depth lag on average by 1.9 hours, whilst the daily maxima lag on average by 2.1 hours. The slightly faster penetration of cooling may account for the somewhat cooler mean temperatures at 10 cm depth (8.1°C) than at 1 cm depth (8.8°C) (Table 1). It is important to note that the sediment at 4200 m a.s.l. is considerably drier and has an impeded intensity and duration of freeze over that at 4800 m a.s.l. Given the drier soil conditions, the heat capacity is expected to be lower than at 4800 m a.s.l., but would have a higher diffusivity, thus accounting for the short time-lag effects at 4200 m a.s.l. The time-lag effects are considerably increased at 4800 m a.s.l., averaging 5.9 hours (minima) and 4.9 hours (maxima) (Fig. 4). The occurrence of water-filled soil pores at 4800 m a.s.l. (personal observations during two field visits) would lower the thermal diffusivity due to a greater heat capacity (cf. Hinkel *et al.* 1993). Nocturnal phase shifts are about 1 hour slower than those during the day, which may be accounted for by wet and freezing soil conditions promoting the upward movement of water toward the downward advancing nocturnal freezing front, causing latent heat of fusion to be released. This dissipation of heat slows the rate of sub-surface freeze penetration (Kane *et al.* 2001). In the absence of snow, rapid daily heat penetration may also be in response to the high positive temperatures at 1 cm depth (frequently over 30°C). Nevertheless, the longer-lasting daily neg-

Table 1. Ground thermal characteristics for the two study sites on Mount Kenya (August 1998–July 1999). Temperature (°C).

	Ground depth				
Caracteristic	Surface*	1 cm	5 cm†	10 cm	50 cm
Altitude 4200 m					
Mean	6.7	8.8	8.8	8.1	7.8
Mean min.	–3.7	–1.5	3	4.4	7.6
Absolute min.	–7.2	–7.7	0.2	1.9	5.6
Mean max.	26	26.7	16	12.4	7.9
Absolute maa.	42.8	40.7	25.2	19.3	9.5
Mean diurnal range	29.6	27.9	11.8	8	0.2
Max. diurnal range		43.3		13.9	2.1
Max. monthly range		5.1		3.9	2
Monthly deviation		1.27		1.03	0.65
Frost days (%)	98	70.2	0	0	0
Number of frost cycles		291	0	0	0
Altitude 4800 m					
Mean	2.6	2.7	1.5	2.1	0.9
Mean min.	–6.3	–4.3	–0.6	0.1	0.7
Absolute min.	–14	–10.1	–2.6	–1	0
Mean max.	21.2	16.8	5.5	5.1	1
Absolute max.	43.2	38.3	13.3	11.8	2.5
Mean diurnal range	27.4	21.1	6.3	4.9	0.2
Max diurnal range	52.5	42.9	13.7	11.3	1.2
Max monthly range	3.1	2.9		2.2	1.1
Monthly deviation	0.93	0.93		0.68	0.32
Frost days (%)	100	100	95	53	8
Number of frost cycles		359		186	26
Ground lapse rate (°C/100 m) (4200–4800 m)	0.8	1		1	1.2

* August to December only for 4200 m a.s.l.

† August to November only for 4200 m a.s.l.; August to October only for 4800 m a.s.l.

ative temperature cycles (mean = 13–14 h) at the surface, helps dampen the warming effect into the sub-layers.

Altitudinal ground temperature cooling between 4200 and 4800 m a.s.l. averages 5.9°C at 1 cm depth and 6.9°C at 50 cm depth (Fig. 5). Ground temperature lapse rates average 0.8 to 1.2°C/100 m over the monitoring area and would be influenced by topographic position. The near-surface (1 cm depth) ground lapse rate averages 1°C/100 m, which is considerably steeper than the mean global free-atmospheric lapse rate of 0.55°C/100 m (Meyer 1992). Owing to the insulating effects of regular thin snow cover at 4800 m a.s.l. and temperature inversions, the mean annual nocturnal lapse rate is only 0.4°C/100 m. Daytime lapse rates are exceptionally high (1.6°C/100 m) due to more frequent snow and cloud cover reducing solar radiation input at the ground surface of the upper afro-alpine belt. Altitudinal ground temperature lapse rates steepen at 50 cm depth, which may be associated with stronger vertical ground temperature gradients at 4800 m a.s.l. (Table 2). The vertical temperature gradient in the upper 10 cm varied from 0.01 to 0.13°C/cm (mean = 0.08°C/cm) and decreased to between 0.01 and 0.05°C/cm (mean = 0.03°C/cm) from 10 to 50 cm depth (Table 2). The temperature gradients at corresponding depths at 4200 m are on average reduced by 0.02°C/cm.

The amplitude of daily temperature cycles near the soil surface decreases with the accumulation of snow (cf. Hinkel *et al*. 2001). The longest estimated duration of continuous snow cover at 4800 m a.s.l. (based on low (0.5 to 7.8°C) daily temperature ranges at the surface) during the 12 month monitoring period is 9 days in March 1999 (Fig. 6). The high midday surface temperatures throughout the year (Fig. 3) prevents seasonal ground freeze or the progression of a freezing front to depths beyond *c*. 10 cm. Fig. 6 indicates the impact that

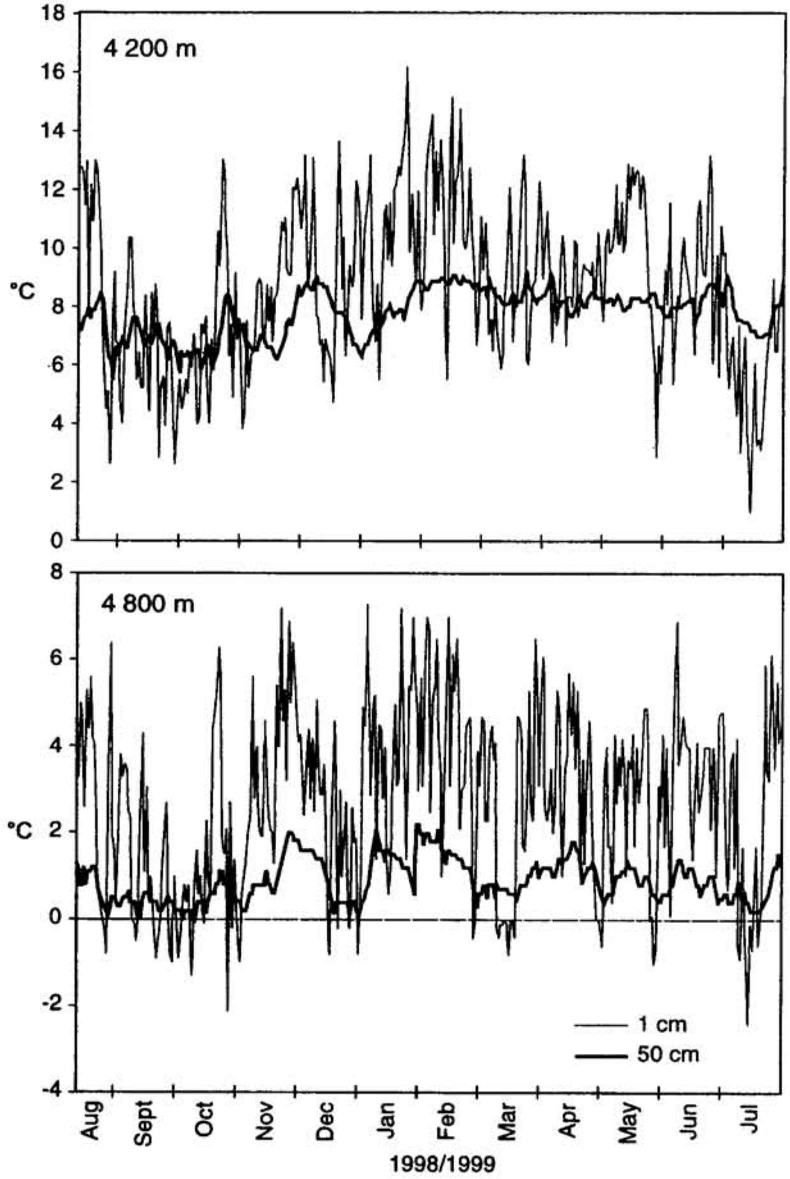

Fig. 2. Mean daily ground temperatures recorded at 4200 and 4800 m a.s.l. from August 1998 to July 1999.

Table 2. Annual vertical temperature gradients for the two study sites on Mount Kenya.

	4200 m a.s.l.			4800 m a.s.l.		
Depth	Mean	Min.	Max.	Mean	Min.	Max
Surface to 50 cm (°C/0.5 m)				1.7	0.3	2.5
1–50 cm (°C/0.5 m)	0.9	−1.8	2.9	1.9	0.8	2.7
1–10 cm (°C/cm)	0.06	0.01	0.12	0.08	0.01	0.13
10–50 cm (°C/cm)	0.01	0.01	0.05	0.03	0.01	0.05

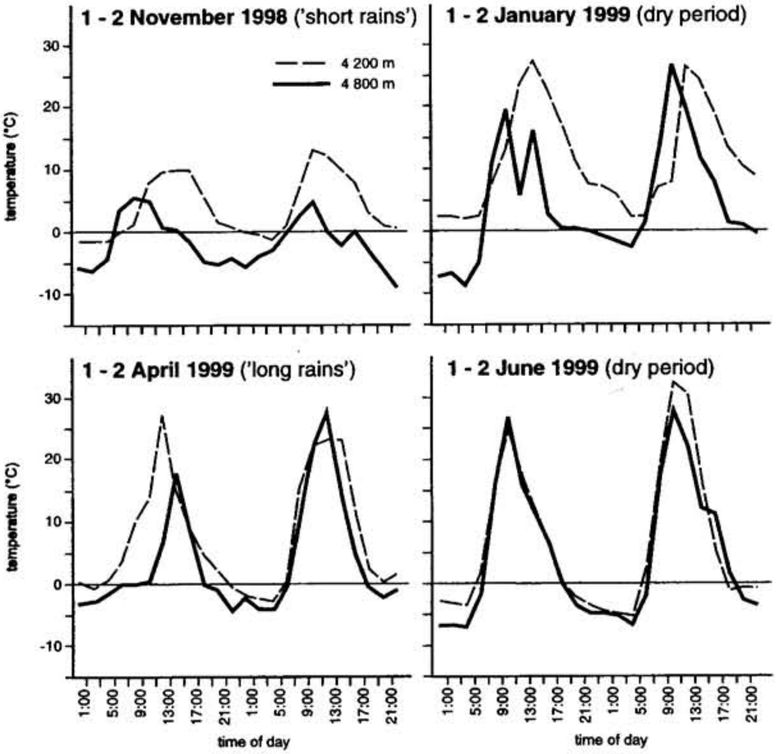

Fig. 3. Ground surface temperatures (first two days per month) for the various seasons on Mount Kenya.

equatorial snow cover has on reducing high daily surface temperatures (by 20–30°C), whilst daily minimum temperatures are only increased by 5–7°C in response to the insulating snow cover. It is only under such snow covered conditions that the mean daily surface temperature drops below 0°C (Fig. 6, Table 3). Snow cover lasting several days permits cooling into the sub-layer, such that at 10 cm depth the mean temperatures are significantly lower (0.4°C) during the 9 days of snow cover than the 4 days preceding (2.8°C) or the 4 days after snow cover (1.1°C; Fig. 6, Table 3). Although the temperature at 10 cm depth did not fall below 0°C during this snow cover, it remained between 0.4 and 0.2°C for several days and may represent a period of gradual phase change (Fig. 6). Given that snow cover reduces the rate of latent heat release stored within the soil, and significantly lowers surface temperatures, negative vertical temperature gradients occur during the period of snow cover (Table 3).

Discussion

Cryogenic characteristics

4200 m a.s.l. Although ground freeze at 4200 m a.s.l. occurs during most nights near the surface (98% at the surface, 70% at 1 cm depth), frost penetration is restricted to the upper 2–3 cm of soil, such that no freeze was recorded at 5 cm depth (Ta-

Table 3. Comparison of mean temperatures and vertical temperature gradients before, during and after snowcover in March 1999, at 4800 m a.s.l., Mount Kenya.

	Mean temperature (°C)			Vertical temperature gradient (°C/cm)	
	Surface	10 cm	50cm	Surface to 10 cm	10 to 50 cm
4 days before snow cover	4.3	2.8	0.8	0.15	0.04
9 days snow cower	–0.6	0.4	0.6	–0.1	0
4 days after snow cover	3.1	1.1	0.6	0.2	0.01
Average for month	2.5	1.8	0.8	0.07	0.02

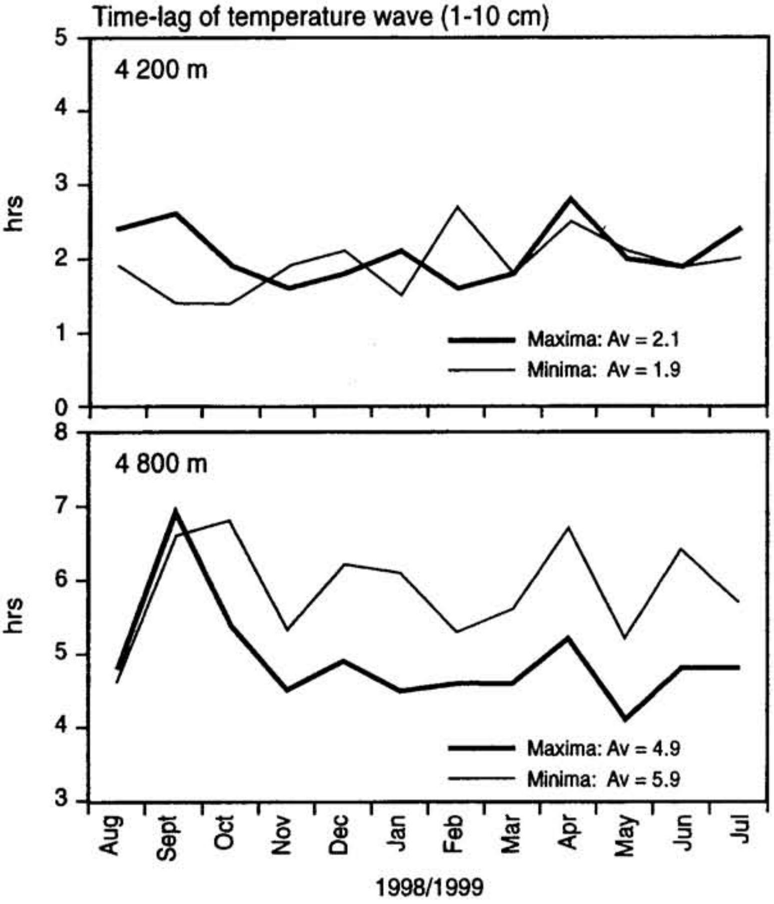

Fig. 4. Mean monthly time-lag effects for *maximum* and *minimum* temperature waves between 1 and 10 cm depth.

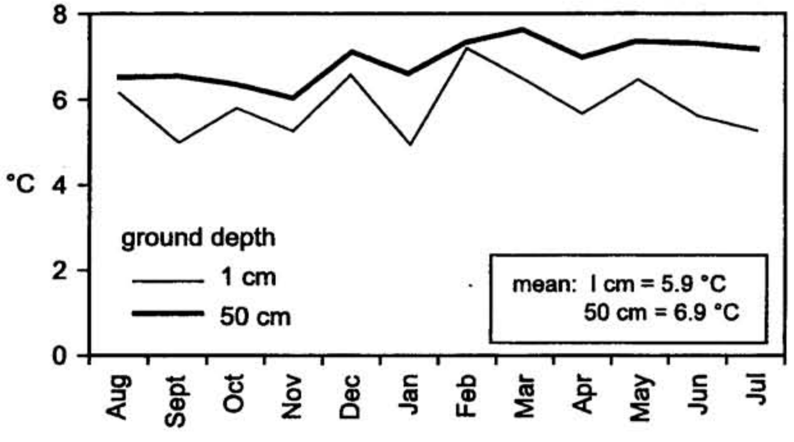

Fig. 5. Altitudinal ground temperature cooling between 4200–4800 m a.s.l. for the two study sites (mean monthly values).

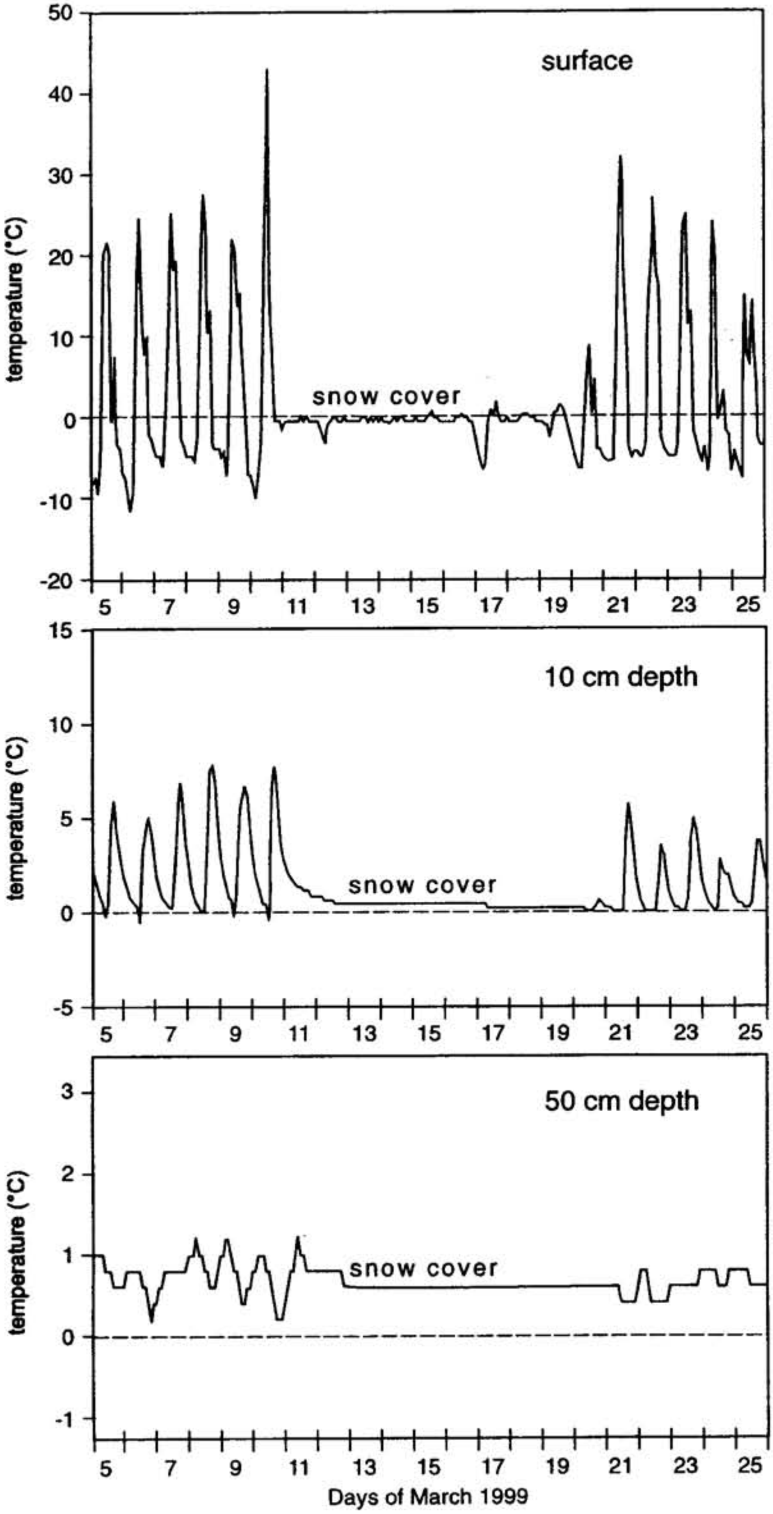

Fig. 6. Impact of snow on ground thermal characteristics at various depths, Mount Kenya, 4800 m a.s.l.

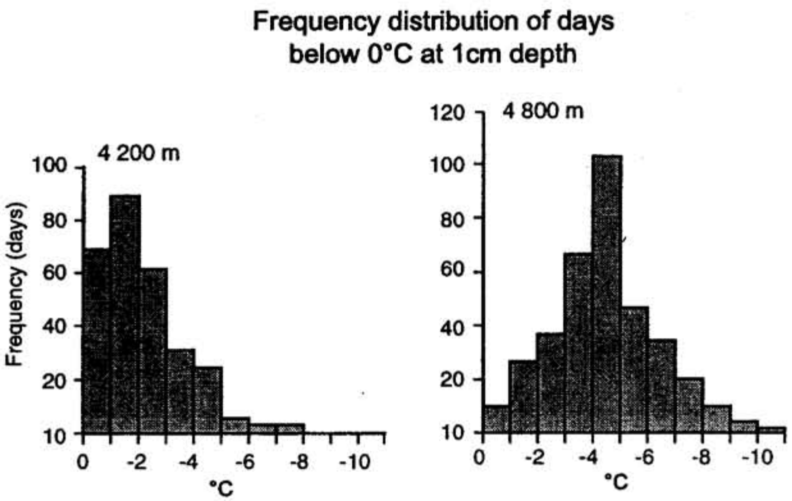

Fig. 7. Distribution of ground frost (1 cm) intensity at 4200 and 4800 m a.s.l., Mount Kenya.

ble 1). Freeze intensity at 1 cm depth is usually between 0°C and –3°C (Fig. 7). In this paper, a *frost cycle* is defined as a fall in temperature to 0°C or lower, followed by a rise above 0°C. Frost occurs throughout the year, permitting a high annual number of frost cycles (291 at 1 cm depth, 1998/99: Table 1).

4800 m a.s.l. Diurnal frost frequency in the upper 1 cm of soil at 4800 m a.s.l. is 365 days (100%), whilst at 10 cm depth it is 165 days (45%) (Table 1). At 50 cm depth, temperatures dropped to 0°C on 25 occasions during the recording year. Freeze intensity at 1 cm depth is commonly between –4°C and –6°C and fell to an absolute minimum of –10.1°C (Fig. 7, Table 1). Due to the thin snow cover and absence of climatic seasonality, 359 frost cycles were measured at 1 cm depth. However, this is rapidly reduced to 186 cycles at 10 cm and 25 cycles at 50 cm depth at the recording sites.

Cryogenic phenomena

Given appropriate soil and hydrological conditions, a maximum of 247 needle ice events would have been possible at 4200 m a.s.l. and 359 events at 4800 m a.s.l during the recording year. However, more important for needle ice growth is the duration of freeze, which largely determines needle ice length and subsequent sediment displacement (Grab 2001). Ground cooling at 4200 m a.s.l. is delayed due to increased amounts of heat storage, which needs to be irradiated. Thus, the short duration (7–8 hours) and low intensity of freeze at 4200 m a.s.l. permits only stunted growth of 8–15 mm, whilst the much longer (13–14 hours) and higher freeze amplitude at 4800 m a.s.l. produces lengths commonly in the range 30–45 mm (personal observations).

Micro-periglacial phenomena, in particular sorted stripes, are common features of the afro-alpine belt (Fig. 8; Hastenrath 1973; Grab 1996). Most active soil surface patterns on Mount Kenya are a product of needle ice action. Given the shallow freeze depth at 4200 m a.s.l., most patterns at this altitude are restricted to frost-heaved soils, sorted to between 1–2 cm depth. The distribution of larger varieties (20–25 cm in diameter) of stripes sorted to depths averaging 7 cm is extensive on slopes at *c.* 4800 m a.s.l. (Fig. 8). Given the daily frost frequency within the upper soil profile at Site 2, ground thermal conditions are unsuitable for vegetation establishment except around rocks which offer a thermal refugia.

Although the occurrence of a Holocene rock glacier above *c.* 4700 m a.s.l. (Grab 1996) suggests recent permafrost on slopes that were not glaciated, there is no conclusive evidence for contemporary permafrost on Mount Kenya. Schrott (1991) found that ground temperature oscillations come close to zero on approach towards the permafrost table or an ice lens. Given the progressive decrease in ground temperatures towards 50 cm depth at Site 2 (4800 m a.s.l.) on Mount Kenya, where the mean temperature was 0.9°C and oscillates between 0 and 2.5°C, it may reflect a frozen layer at an unconfirmed depth below 50 cm. However, if tempera-

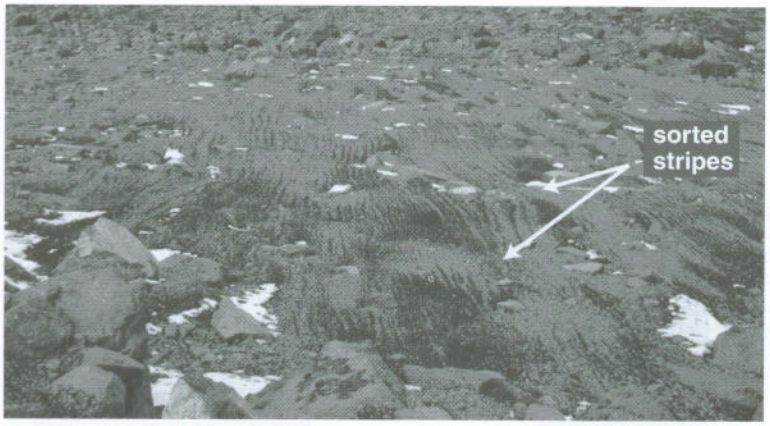

Fig. 8. Periglacial sorted stripes on Mount Kenya, *c.* 4700–4800 m a.s.l.

tures were conducive to contemporary permafrost development at Site 2, then a relatively shallow active layer would be expected to a depth where nocturnal freezing temperature effects overcome daily positive temperature phase shifts, which, however, is not happening.

Snow as an environmental control

The attributes of snow cover would need to be placed in relation to diurnal and seasonal air temperatures to fully understand its likely impact on ground temperatures. This will vary with latitude from equatorial high mountains, to sub-tropical and high latitude mountains. The extent of ground cooling in the Canadian alpine permafrost is found to be more connected to depth and duration of winter snow and spring runoff than to mean annual air temperatures (Harris 2001). Findings from the Central Andes indicate that there is a strong correlation between solar radiation and ground temperatures, whilst the relationship between air and soil temperatures decreases with depth (Schrott 1991, 1998). Cloudy or sunny weather conditions cause direct changes to ground temperatures above 25 cm depth (Schrott 1991) and high global solar radiation reduces waves of low ground temperatures in the Central Andes (Schrott 1998). Similarly, it is expected that high solar radiation budgets and the occurrence of snow on Mount Kenya, exercise considerable control on ground thermal dynamics. Hinkel *et al*. (2001) found that snowmelt can significantly hasten sub-soil warming during the northern hemisphere spring season. Given the frequent cycle of thin snow cover production during the afternoon/evening and subsequent morning thaw at 4800 m a.s.l. on Mount Kenya, snowmelt maintains saturated ground conditions at this altitude and slows down potential soil cooling with depth. An alternative consideration is that the high daily frequency of snow throughout the year substantially reduces solar radiation inputs at the ground surface, thus lowering the intensity and duration of soil warming. Data presented in this study (see Fig. 6, Table 3) indicate that the occurrence of continuous snow cover over several days permits gradual soil cooling (or a potential freeze front penetration) to depths of 10 cm or more.

Conclusions

Recent ground thermal profiles on Mount Kenya offer new insights to cryospheric dynamics in this equatorially driven climate. The data indicate relatively high altitudinal ground thermal lapse rates from 4200 to 4800 m, which are accompanied by substantial increases in frost frequency and intensity. It is suggested that the higher frequency of snow cover at 4800 m a.s.l. is an important factor determining such ground thermal lapse rates. Snow cover lowers solar radiation reaching the ground surface and reduces the intensity and duration of positive day temperatures. The presence of a Holocene rock glacier above 4700 m a.s.l. suggests that permafrost has been present on Mount Kenya (Grab 1996), yet the contemporary near-surface ground temperature profile would imply the degradation of any permafrost during the recent past. We hope that future work will enable a wider distribution of ground thermal monitoring to depths of at least 2 m.

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