Air temperature environment on the debris-covered area of Lirung Glacier, Langtang Valley, Nepal Himalayas

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Abstract Meteorological observations have been carried out for different surface covers (grass, debris-free glacier and rock-covered glacier ice in Langtang Valley, Nepal Himalayas. Change in the daily mean lapse rate over debris-covered ice shows a significantly larger fluctuation compared with over debris-free ice. An analysis of the daily mean lapse rate reveals that a "low" ["high"] lapse rate appeared under dry [wet] conditions on the debris-covered area even though the opposite result was expected for the lapse rate of a free atmosphere. It is considered that less evaporation under dry condition would bring about high surface and then warm air temperatures. Diurnal changes in the lapse rate over debris-covered ice suggests that the air temperature changes less over the debris-covered ice than over grassland and debris-free ice. Perhaps heat stored in the debris layer would prevent large diurnal changes in air temperature. Both seasonal and diurnal changes in lapse rate suggest the strong effect on air temperature of the complex topography of the debris-covered area and the presence of the debris layer. This fact suggests that air temperature cannot be simply estimated by a constant lapse rate as in previous studies.

INTRODUCTION

One of the most common characteristics of glaciers in the Himalayas is the presence of a debris mantle masking a large portion of their ablation areas. Reports have consistently indicated that this debris cover exerts a tremendous influence on the ablation process itself. Several studies on the ablation process under the debris layer have been carried out in the Himalayas (e.g. Mattson & Gardner, 1989; Mattson *et al.*, 1993; Rana *et al.*, 1997; Nakawo & Rana, 1999). The meteorological environment over the debris has not been discussed in previous studies, though it has been treated as input data for the calculation. In this investigation, we present the seasonal and diurnal changes in air temperature over different surfaces such as grassland, debris-free glacier ice and debris-covered glacier ice by using the lapse rate.

OBSERVATIONS AND ANALYSIS

Meteorological observations were carried out at the grass-covered site of Base House (BH, 3878 m a.s.l.), the debris-covered site on Lirung Glacier (LR, 4153 m a.s.l.) and at a site of debris-free snow on Yala Glacier (YL, 5350 m a.s.l.) from May to October

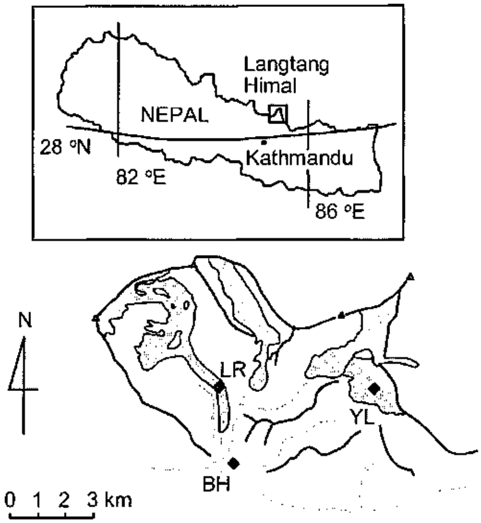

Fig. 1 Location of Langtang Valley. Meteorological observations were conducted at the grass-covered site of Base House (BH), the debris-covered site of Lirung Glacier (LR) and the debris-free snow of Yala Glacier (YL) situated in a valley.

1996. The locations of each site are shown in Fig. 1. The altitudes of each site were surveyed by a laser distance finder in 1996 (Aoki & Asahi, 1998; Fujita *et al.*, 1998). Daily mean meteorological data were summarized by Fujita *et al.* (1997).

The lapse rate (l_a, °C km^{-1}) at a certain site (subscript a) is the air temperature difference per unit elevation from a reference site (subscript r) described as:

$$l_a = \frac{(T_r - T_a)}{(h_a - h_r)} \times 1000 \tag{1}$$

where, T and h are air temperature (°C) and altitude (m a.s.l.) at each site. Air temperature was measured at a height of 1.5 m, and the sensor was shaded from solar radiation. The site BH was selected as the reference site because of the meteorological data collected there since 1985 and its location at the bottom of the main valley.

CHANGES IN DAILY MEAN LAPSE RATE

Variations in the daily mean lapse rate at LR (l_L), YL (l_Y) and BH are shown in Fig. 2. The average lapse rates at LR ($\overline{l_L}$) and at YL ($\overline{l_Y}$) were 5.1 and 5.4 (°C km^{-1}), respectively. It was reported that the lapse rate was about 10.0 (°C km^{-1}) at Chongce Glacier, which is located in the West Kunlun Mountains, on the northern side of the Tibetan Plateau, because the air mass was cooled by the glacier (Ohata *et al.*, 1989). On Yala Glacier, however, no cooling effect by the glacier can be seen in the lapse rate because its area (2.5 km^2) is considerably smaller than that of Chongce Glacier (16.4 km^2; Zhang & Jiao, 1987). Figure 2 clearly shows that the fluctuation of l_L is significantly larger than that of l_Y. Standard deviations of the lapse rate at LR (σ_L) and YL (σ_Y) are 2.1 and 0.8 (°C km^{-1}), respectively. The smaller deviation of l_Y is

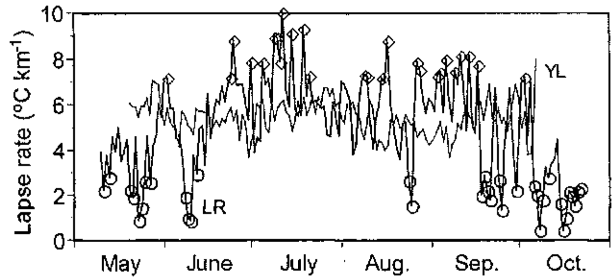

Fig. 2 Daily mean lapse rate at the debris-covered site on Lirung Glacier (LR, black line) and debris-free site on Yala Glacier (YL, grey line) compared with that for the grass-covered reference site at Base House (BH). Symbols denote "high" (rhombuses) and "low" (circles) lapse rates.

considered to be associated with the location of YL and BH. Since YL is located at the upper part of an open slope above BH, it is expected that the change in air temperatures at both sites would be that of the free atmosphere. The cold snow surface would also suppress variations and calm the atmosphere. The larger fluctuation of l_L, on the contrary, is thought to be affected by complex air flow, such as greater convection in the debris-covered area, because LR is located in the bottom of a deep valley and surrounded by heterogeneous debris topography. Figure 3 shows that at BH the wind is mainly from west-southwest toward YL (valley breeze), while the wind at YL mainly blows from north-northeast toward BH (slope wind). Although it is difficult to explain

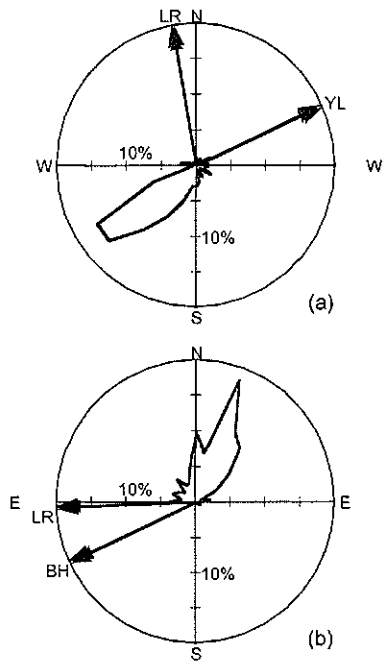

Fig. 3 Frequencies of wind direction at Base House (a) and Yala Glacier (b). Arrows denote the directions at the debris-covered site on Lirung Glacier (LR), the debris-free site on Yala Glacier (YL) and the grass-covered reference site at Base House (BH) from Base House (a) and Yala Glacier (b), respectively.

the more complex air flow at LR by the simple air flows at BH and YL, it is rare for the wind to blow from both sites toward LR. It is considered that the air temperature at LR is strongly controlled by the surface and topographical features around the site.

In order to understand which meteorological variables affect the large variation of the lapse rate at LR (l_L), three types of lapse rate were selected (Fig. 2): "high" (l_L higher than $\overline{l_L}+\sigma_L$; 26 days), "normal" (l_L within $\overline{l_L}\pm\sigma_L$; 106 days) and "low" ($l_L$ lower than $\overline{l_L}-\sigma_L$; 34 days). Daily mean values of air temperature, wind speed, solar radiation, relative humidity, precipitation and surface temperature at LR and BH under each condition are summarized in Table 1. The table clearly shows that a "low" lapse rate at both sites was due to lower air temperature, higher wind speed, greater solar radiation, the smallest precipitation and the lowest relative humidity. Surface temperature at LR, on the other hand, does not seem to affect the lapse rate, while surface temperature at BH has the same effect as air temperature. The "low" lapse rate would appear under less cloudy, less precipitation and drier atmosphere conditions even though the air temperature was relatively low. Since an arid environment would bring about less evaporation, radiative fluxes absorbed at the debris surface, such as net shortwave radiation and downward longwave radiation, should be released by upward longwave radiation, sensible and ground heat fluxes except for latent heat. Because these fluxes are strongly associated with surface temperature, a higher surface temperature is expected with a dry surface, when the cooling effect on surface temperature by latent heat (evaporation) is small. As Table 1 shows, a higher surface temperature at LR appeared at a "low" lapse rate, while the air temperature was lower at LR even though both air and surface temperatures at BH were lower at a "low" lapse rate. The higher surface temperature for dry conditions would result in a relatively higher air temperature and lower lapse rate at LR. Mattson & Gardner (1989) have suggested that latent heat had an important role in the heat balance on the debris-covered glacier in the Karakoram, though it has been consistently ignored in previous studies (e.g. Rana *et al.*, 1997; Nakawo & Rana, 1999). Figure 2 shows the occasional "low" ["high"] lapse rates during the pre- and post-monsoon [mid-monsoon] season, though a dry [wet] adiabatic lapse rate (large [small] value) is expected in the dry [wet] season. This also supports the

Table 1 Daily mean variables at the debris-covered site on Lirung Glacier (LR, upper rows) and the grass-covered reference site (BH, lower rows) for three conditions.

	Location	High	Normal	Low
Air temperature (°C)	LR	7.4	7.3	6.0
	BH	9.6	8.8	6.6
Wind speed (m s^{-1})	LR	1.0	1.2	1.4
	BH	1.3	1.7	2.1
Solar radiation (MJ m^{-2} day^{-1})	LR	12	17	25
	BH	18	20	26
Precipitation (mm water equivalent day^{-1})	LR	7.2	5.8	0.2
	BH	4.4	5.1	0.0
Relative humidity (%)	LR	98	92	74
	BH	94	89	71
Surface temperature (°C)	LR	8.7	10.5	9.4
	BH	16.1	15.7	12.4

idea that the lapse rate between LR and BH is not associated with the air temperature of the free atmosphere, but rather with the air temperature at LR, which would be strongly controlled by the local heat balance.

DIURNAL CHANGES IN LAPSE RATE

Figure 4 shows diurnal changes in hourly mean lapse rate at LR (l_L) and YL (l_Y) averaged for the period from May to October, 1996. The diurnal change in lapse rate at LR is obviously larger than that at YL. The stable l_Y suggests that the air temperature at YL and BH fluctuate synchronously. As mentioned above, the changes in air temperatures at both BH and YL would have synchronicity because of their location on an open slope and the dominant wind directions at both sites. The larger [smaller] lapse rate in daytime [night-time] at LR suggests that air temperature at LR is cooler [warmer] than at BH in daytime [night-time]. Figure 5 shows the diurnal variation of hourly mean air temperatures at BH and LR. The variation of air temperature estimated from air temperature at BH and the constant lapse rate (5.1 °C km^{-1}) is also shown in the figure. The figure suggests that the fluctuation of air temperature at LR is smaller (more stable) than at BH. Mattson & Gardner (1989) reported that 60–80% of the energy entering the debris cover was stored and used to change the temperature in the debris, and that the residual energy was used to melt ice under the debris. Their result suggests a stable fluctuation of air temperature at LR by the following process.

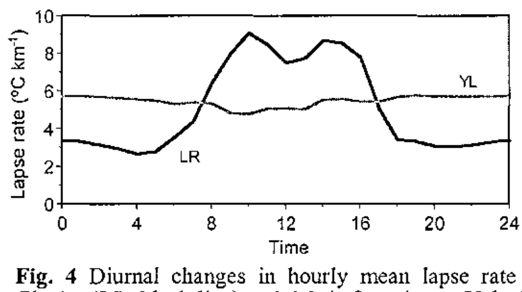

Fig. 4 Diurnal changes in hourly mean lapse rate for the debris-covered Lirung Glacier (LR, black line) and debris-free site on Yala Glacier (YL, grey line) from the grass-covered reference site at Base House.

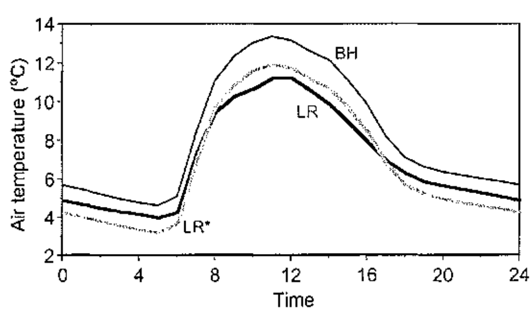

Fig. 5 Diurnal changes in hourly mean air temperature at the grass-covered reference site at Base House (BH, thin black line) and at the debris-covered site on Lirung Glacier (LR, thick black line). The grey line (LR*) denotes the diurnal change in hourly mean air temperature estimated from that at BH and the constant lapse rate (5.1 °C km^{-1}).

Increase of surface and air temperatures would be prevented in daytime by heat absorption into the debris. Then, on the following night, debris would prevent the lowering of surface and air temperatures by releasing the stored energy.

CONCLUDING REMARKS

A significant difference in seasonal and diurnal changes in air temperature in the debris-covered area is demonstrated in this study. This fact suggests that air temperature cannot be simply estimated by a constant lapse rate as in previous studies (e.g. Rana *et al.*, 1997; Nakawo *et al.*, 1999). It is considered that the large fluctuation in the lapse rate at the debris-covered site compared with the reference site are caused by the local heat balance in the complex topography of the debris-covered area. Hence, the relatively stable air temperature at the debris-covered site would be caused by the storage and release of heat in the debris layer. The heat balance for different surface conditions should be examined in further detail to find the effects on air temperature of the complex topography of the debris-covered area and the presence of the debris layer.

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