Bulletin of Glaciological Research 22 (2005) *31–37*

Slope lapse rates of temperature in Din Gad (Dokriani Glacier) catchment, Garhwal Himalaya, India

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(Received August 20, 2004; Revised manuscript received November 22, 2004)

Abstract

Temperature lapse rate studies of Din Gad catchment in Garhwal Himalaya were carried out during the ablation period (May-October) in 1998, 1999 and 2000. Temperature data for this study was collected from the meteorological stations established at three altitudes (2540, 3483 and 3763 m a.s.l.) in the Din Gad catchment. This data has been analysed to determine suitable lapse rate of slope temperature for temperature index modeling of snow/glacier runoff and mass balance of Dokriani glacier. Station pair within the alpine zone (3483 and 3763 m a.s.l.) of the catchment shows distinct variations in lapse rate as compared to the valley scale (2540 and 3763 m a.s.l.) lapse rate. Yearly variations in the lapse rate within the alpine zone of the catchment were higher than the variations of valley scale lapse rate, which show 40–50% reduction in the lapse rate in 1999 and 2000 as compared to 1998. It is also observed that in the valley scale, lapse rate values were lower during the monsoon months, compared to the rest of the ablation months. However this trend is absent between the station pair located within the alpine zone. Due to non-linearity of lapse rate of Din Gad valley as observed in this study, it is suggested that the lapse rate of the alpine zone is most representative of the glacier catchment, suitable for snow/glacier melt runoff and mass balance models. It is suggested that the lapse rate of alpine zone of the catchment have to be monitored for modeling hydrological processes of Himalayan glaciers, rather than adopting the lapse rates of mountain areas of other geographical locations or extrapolating lapse rate values of lower elevations of the Himalayas, as being practiced today.

Keywords: Garhwal Himalaya, Dokriani glacier, Lapse rate, Monsoon, Mountain meteorology.

1. Introduction

Slope lapse rate of temperature is one of the most important variables for modeling meltwater runoff from a glacier catchment using temperature index method. It is also an important variable for determining the form of precipitation and its distribution characteristics during summer ablation months over the glaciers under the monsoonal regime (Higuchi *et al.,* 1982; Thayyen, 1997; Thayyen *et al.,* in press). Temperature lapse rate values are also critical in the study of accumulation characteristics of the glaciers under the influence of monsoon (Ageta and Higuchi, 1984). Barry (1992) discussed the complex processes influencing the temperature lapse rate in the mountain catchments and its variations. Hence region specific information of temperature lapse rate and its variations are essential requirement for temperature index modeling of hydrological processes of the Himalayan glaciers. Studies on slope lapse rate of temperature are sparse from the Himalayan region. A study of de Scally (1997) from Punjab Himalaya, Pakistan suggests that the lapse rate in this region is generally higher than the values reported from other studies ranging from 0.48 to 0.78℃ $100^{-1}\,m^{-1}$. Researchers have used wide-ranging lapse rate of slope air temperatures ranging from 0.65 to 0.98℃ $100^{-1}\,m^{-1}$ for runoff modeling studies (Bagchi, 1982; Dey *et al.,* 1989; Upadhyay, 1995). Many other snowmelt runoff models from various regions used range of values close to the environmental lapse rate ranging from 0.55 to 0.65℃ $100^{-1}\,m^{-1}$ (Martinec, 1975; Ageta *et al.,* 1980; Rango, 1983; Ikebuchi *et al.,* 1986; Kayastha *et al.,* 1999). This paper investigate the validity of these slope lapse rate values for modeling glacial hydrological processes of Garhwal Himalaya, where the influence of monsoon during summer ablation period is very prominent.

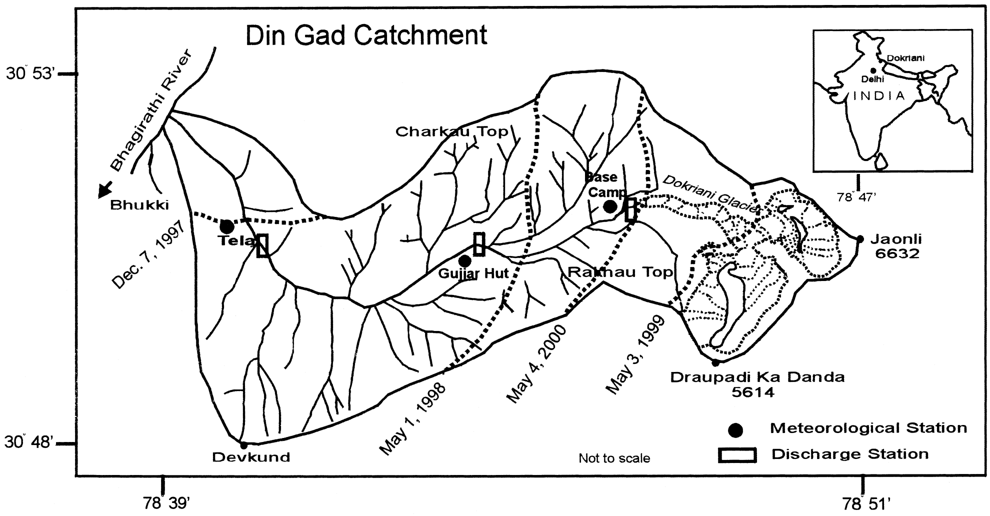


Fig. 1. Location map of Din Gad catchment showing Tela, Gujjar Hut and Base camp meteorological observatories. Figure also show snow line positions in the Din Gad catchment in the first week of May during different observation years.

Table 1. Characteristics of climate stations in the Din Gad catchment.

Station	Elevation (m a.s.l.)	Aspect	Site description	Surface type	Possibility of Katabatic effect
Tela	2540	NE	Opening in the conifer forest	Sparse grass	No
Gujjar Hut	3483	Plain ground	Meadow close to the forest	Grass	Moderate
Base Camp	3763	Plain ground	Meadow above the tree line	Sparse grass	Yes

This study focuses on the monthly and yearly variations in the lapse rate of slope air temperature between three station pairs during 1998,1999 and 2000 ablation months.

2. Study area

Din Gad valley is part of headwater catchment of Ganga river in the Garhwal Himalaya. This catchment has NW aspect and lies between latitude 30°48′ to 30°53′N and longitude 78°39′ to 78°51′E. Forested area of the catchment cover 54% and Alpine meadows and glaciers cover 31% and 15% respectively (Fig. 1). Total catchment area is 77.8 km^2. Din Gad joins with Bhagirathi River near Bhukki village. Monsoon hits Din Gad catchment after June 15 and prevail till mid September. July and August account for nearly 40–50% of rainfall during the ablation months. Din Gad catchment is one of the glaciated catchments in the Garhwal Himalaya, which first encounters monsoon winds as it moves up to the higher reaches of Bhagirathi catchment. Hence Din Gad catchment experience good monsoon rainfall (1100 to 1600 mm, during May-October). Din Gad catchment extended from 1800 m to 6600 m and seasonal snow cover generally reaches up to 2300–2500 m in winter. During the years of normal winter snowfall snowline recedes to 3800 m a.s.l. in the beginning of the month of May.

3. Methods

Three meteorological stations were established in the Din Gad catchment in 1998 to monitor the meteorological variables. Air temperature data at these stations were collected during the summer ablation months (May to October). These stations were established along the 23 km trekking route to Dokriani glacier from the road head at Bhukki village. The first station at Tela is located at a height of 2540 m a.s.l., in a large open space surrounded by the Oak and Pine forest on the valley slope having NE aspect. The second station at Gujjar Hut (3483 m a.s.l.) has been established on alpine meadows close to the conifer forest. This station is on the plain ground well above the valley bottom. The third station at Dokriani glacier Base camp (3763 m a.s.l.) is on the alpine meadows above the tree line. Detailed topographic descriptions of meteorological stations are given in Table-1. These stations were monitored from 3 May to 23 November in 1998, 8 May to 15 November in 1999 and 15 May to 23

Table 2. Average monthly Lapse rate °C (100m)$^{-1}$ for different station pairs during three years of observation.

Year	May	June	July	August	Sep.	Oct.	Nov.
Base Camp-Gujjar Hut							
1998	0.36	0.71	0.71	0.67	0.70	0.56	−0.13
1999	0.58	0.37	0.35	0.40	0.36	0.21	0.28
2000	0.44	0.42	0.44	0.34	0.30	0.38 (1–14) −0.22 (14–25)	—
Tela-Base Camp							
1998	0.71	0.70	0.58	0.55	0.61	0.63	0.54
1999	0.67	0.60	0.52	0.55	0.56	0.62	0.66
2000	0.60	0.56	0.51	0.50	0.56	0.57	—
Tela-Gujjar Hut							
1998	0.81	0.70	0.55	0.52	0.58	0.65	0.74
1999	0.70	0.67	0.58	0.59	0.61	0.74	0.77
2000	0.67	0.60	0.53	0.55	0.64	0.71	—

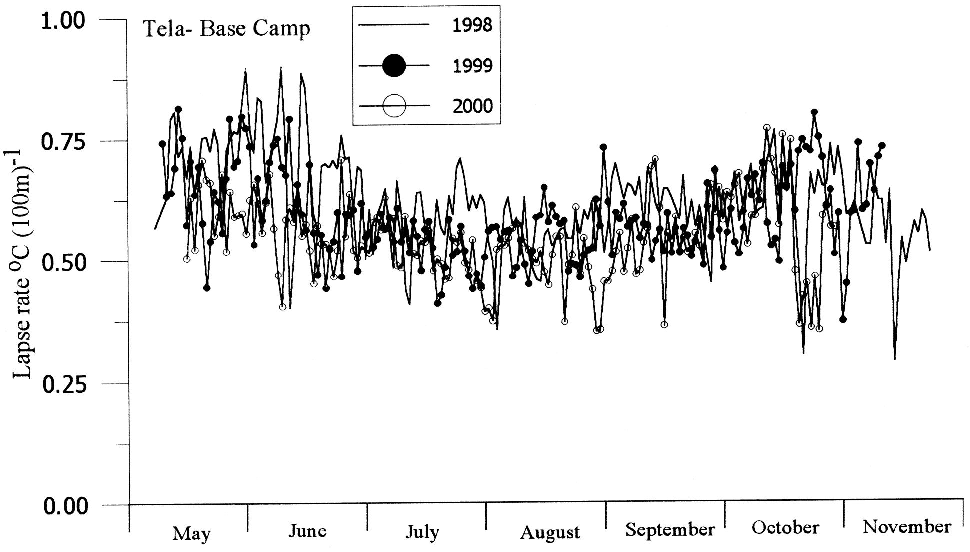
October in 2000. Air temperature measurements in these three stations were carried out from 0530 hrs to 2030 hrs with three-hour interval. The instruments were placed inside the Stevenson screen at 1.6 m above the ground. In 1999, thermographs were installed at Tela station between 25 June and 16 November and at Base camp from 7 July to 13 November for continuous recording of temperature. Mean daily temperature for these periods were calculated from hourly temperature record from the thermograph and compared with the mean daily temperature calculated from dry bulb temperatures. On an average mean daily temperature derived from dry bulb temperature is 1.0℃ higher than the mean daily values derived from hourly temperature at Base Camp and 0.5℃ at Tela. In this paper lapse rate has been calculated from the mean daily temperature derived from dry bulb temperature by averaging the temperatures measured at 0530, 0830, 1130, 1430, 1730 and 2030 hrs. at three stations. This data has been collected consistently during May - November period from all the three stations for three consecutive years.

4. Results and discussion

4.1. Monthly and yearly variations in slope lapse rate

Figure 2 shows the daily lapse rate variations between the selected station pairs from which the monthly mean values were calculated. Summary of monthly lapse rates in three observation years are given in Table 2. During this period monthly variations of lapse rate in summer months have been minimum between the Tela- Base Camp station pairs, ranging between 0.71–0.50℃ $100^{-1}\,m^{-1}$, with an average lapse rate of 0.59℃ $100^{-1}\,m^{-1}$. Lapse rate between these two stations represents the valley scale lapse rate of Din Gad catchment. Highest mean monthly lapse rate value recorded among the station pairs was 0.81℃ $100^{-1}\,m^{-1}$ in May 1998 between Tela and Gujjar hut stations. Monthly variations in lapse rates between Gujjar Hut and Base camp station was highest, within the range of 0.71℃ $100^{-1}\,m^{-1}$ in June and July of 1998 to 0.21℃ $100^{-1}\,m^{-1}$ in October 1999 with certain periods in October and November experiencing temperature inversion characteristics (Table 2). These station pair in the alpine zone of the Din Gad catchment show distinctly lower lapse rate in 1999 and 2000 as compared to the 1998 values. Lapse rate in peak ablation months of June, July and August in 1999 and 2000 was 40–50% less compared to the values calculated for the same months in 1998. Large variations in the lapse rate between Base Camp - Gujjar Hut pair is possibly due to the variations in the distribution of snow cover in these years. Figure-1 shows the snowline positions observed in the month of May during the observation years. The year 1998 experienced heavy snowfall during December to March as compared to 1999 and 2000. In fact, the year 1999 experienced lowest snowfall (144 mm w.e.) at the Base camp since the studies started on the Dokriani glacier in 1992. Where as in 2000, winter snow precipitation at the Base camp was 210 mm w.e. in which most of the winter snowfall occurred in the last quarter of the winter season and melted away fast from the lower reaches of the Gujjar Hut catchment due to the higher temperatures in April.

Mean monthly lapse rate of June, July and August months in 1999 and 2000 were close to the lapse rate reported by Legates and Willmott (1990), 0.30℃ $100^{-1}\,m^{-1}$ for July at an altitude of 3010 m in Himalaya. It could be possible that the sparse snow cover resulted in more homogenous warming in the higher altitude, resulting in lower temperature variations be-



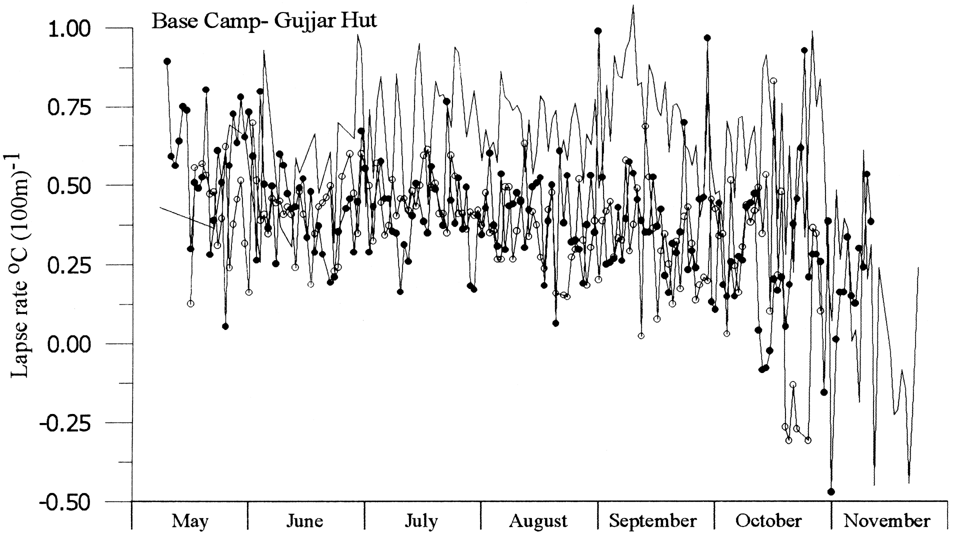


Fig. 2. Daily variations in the lapse rate values in summer months within the Alpine zone and in the valley scale during the three years of observation.

tween the meteorological stations. Temperature at meteorological stations located at the lower altitude seems to be unaffected by the variations in the snow cover at higher altitude. This is evident from the lower monthly variations in lapse rate during these three years between Tela- Base camp and Tela- Gujjar hut pairs, except in the month of May, 1998. Higher lapse rate value in May 1998 between Tela- Gujjar Hut pair was resulted due to the closeness of Gujjar hut station to the snow line in the month of May, which offers greater temperature variations between these stations with respect to the Tela station. Hence it can be suggested that the closeness of snow to the meteorological stations, lateral extent of snow cover and depth of snow influences the lapse rate between the stations in the alpine catchment.

4.2. *Lapse rate variation in monsoon months*

In the valley scale, prominent and consistent variations in the slope lapse rate of temperature during the monsoon months have been observed during the study period. The results show lower lapse rate during the monsoonal months between Tela- Base camp and Tela- Gujjar Hut station pairs (Fig. 2 and Table-2). However alpine zone (Gujjar Hut- Base camp) of the catchment did not show such a trend. Station pair within the alpine zone shows higher yearly variations but lesser monthly variations during the monsoon months. From these observations it can be suggested that the lapse rate between the station pair, in which at least one of the stations is uninfluenced by the snow cover (outside the alpine zone), show reduced lapse rate in monsoonal months, especially in July and August, which ranged between 0.59–0.50℃ 100^{-1} m^{-1}. All the three stations recorded high relative humidity values in monsoon months ranging from 69 to 95%, suggesting upward movement of air under saturated adiabatic conditions and large quantities of latent heat release during condensation and rainfall (de Scally, 1997). This conditions probably leads to a more homogenous temperature distribution resulting in reduced valley scale lapse rate in monsoonal months. The absence of such a trend in lapse rate derived from the stations within the alpine zone suggests homogeneity of thermal regime of alpine zone through the ablation months that persisted even during the monsoon months.

4.3. Selection of slope lapse rate for modeling glacier hydrological processes

The results of this study raises a pertinent question about the selection of suitable altitudinal range for monitoring slope lapse rate for snow/glacier melt runoff models, which would be most representative of the glacier catchment. Comparison of monthly lapse rates derived from three station pairs show considerable variation in the lapse rate values between different station pairs. Three year average of summer lapse rate between Tela- Base camp and Tela - Gujjar hut station pairs are 0.59℃ and 0.65℃ $100^{-1}m^{-1}$ respectively, where as average summer lapse rate of Gujjar Hut- Base camp pair in 1998 was 0.62℃ 100^{-1} m^{-1} and average of 1999 and 2000 was 0.36℃ $100^{-1}m^{-1}$. Hence it can be suggested that the use of valley scale lapse rate to determine the point temperatures at higher altitude may be feasible but calculation of temperature distribution over the glacier by extrapolation as required for distributed glacier runoff models using valley scale lapse rate may introduce large errors. This study suggests a change in the lapse rate above 3000–3500 m of the Din Gad catchment along the main axis of the valley. Lapse rate below this elevation shows less monthly and yearly variation and the station pair above this zone shows substantial monthly and yearly variations, mainly attributed to the snow cover variations and related manifestations. Considering these altitudinal variations in lapse rate, it is suggested that the lapse rate observed in the alpine zone of the catchment (Gujjar hut- Base Camp pair) is the most representative of the lapse rate of the glacier catchment. However extrapolation of these values over the glacier is bound to generate some errors due to the fact that both these stations are in snow/ice free zone in the summer ablation months. However it is prudent to assume that the lapse rate between the station pair over the glacier will be less than the lapse rate of closest pairs in ice free area, especially when the glacier catchment experience heavy monsoonal rains in the summer ablation months. Hence most accurate lapse rate values for snow/ice melt model only can be derived from station pair established over the glacier itself, but has operational difficulties in the field conditions of Himalayan glaciers. Hence it can be suggested that the future lapse rate studies for glaciological studies in the Himalaya needs to be concentrated in the alpine zone of the catchment. More comprehensive studies are required to establish the control of snow cover, slope, aspect, rainfall and wind etc. on slope lapse rate of temperature to develop predictive model for temperature lapse rate variations in a glaciated Himalayan catchment. While considering the range of yearly variation observed in the lapse rate within the alpine zone, modeling slope lapse rate is an important objective to be achieved for the successful modeling of hydrological processes of Himalayan glaciers.

This study suggests that the valley scale slope lapse rate values do not necessarily represent the lapse rates of the alpine zone. Thermal regime of the alpine zone is probably regulated by the seasonal snow cover extent and its thickness. This study agrees with the general assumption made in many snowmelt runoff models that the lapse rate over the large range of elevation is linear (Dey *et al.,* 1989., Bloschl *et al.,* 1991). But the non-linearity in slope lapse rate observed in this study between the sub zones of the valley suggests that the extrapolation of valley scale lapse rate to the glacier catchment may not yield desired result.

Results reported in this paper have many fold implications in understanding and modeling hydrological processes of Himalayan glacier regimes. Figure 3 demonstrated significant difference between extrapolated degree day values at various altitudinal bands of Dokriani glacier using both standard lapse rate of 0.6℃ $100^{-1}m^{-1}$ and the calculated lapse rate of Alpine zone of the Din Gad catchment in 1998, 1999 and 2000 summer ablation period. If we follow the calculated lapse rate for the Alpine catchment, it is evident that the higher reaches of the Dokriani glacier experienced higher temperature regime in 1999 and 2000 even though the positive degree days of summer months at Base camp in 1998 was much higher than that of 1999 and 2000. This is also reflected in the higher melting of glacier above 4500 m as observed during the stake measurements for mass balance studies of Dokriani glacier in these three years (Dobhal *et al.,* Unpublished). This also enhances the monsoon rainfall component in the glacier discharge (Thayyen *et al.,* in press) and raises serious questions regarding the summer accumulation characteristics of these glaciers. Hence this study suggest that the use of lapse

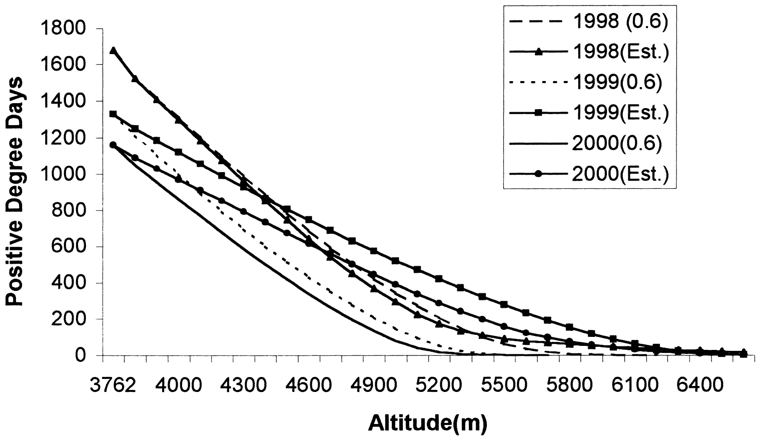


Fig. 3. Distribution of degree days at different altitudinal zones of the glacier by extrapolation of positive degree days at Base camp (3763 m a.s.l.) using standard lapse rate of 0.6℃/100 m and estimated lapse rate of Alpine zone.

rate close to the environmental lapse rate as done in many snow melt models has to be adopted cautiously for Himalayan conditions, especially in the regions under the influence of heavy monsoon activity.

5. Conclusions

1. The slope lapse rate of air temperature in the alpine zone of the Himalayan catchment show distinct variation with the valley scale slope lapse rate. This suggests that the snow/glacier melt runoff and mass balance model by temperature index method may preferably use the lapse rate observed in the alpine zone.
2. Yearly variations in the lapse rate in the alpine catchment were very high, which show 40–50% reduction in slope lapse rate in 1999 and 2000 as compared to 1998. This probably resulted from the variations in snow cover extent and its thickness in the alpine zone and closeness of the stations to the snowline.
3. Valley scale lapse rate show reduced lapse rate during the monsoon months (June, July & August) as compared to the rest of the ablation months suggesting airflow under saturated adiabatic conditions and release of latent heat during condensation. However lapse rate of alpine zone do not show such a trend.
4. Future lapse rate monitoring for glaciological studies in the Himalayas needs to be focused on the alpine zone of the catchment rather than using lapse rate values of lower elevations or valley scale lapse rates.

Acknowledgment

This work was carried out by the financial support of Department of Science and Technology, Govt. of India under the nationally coordinated programme on Himalayan Glaciology. We thank Director, Wadia Institute of Himalayan Geology (WIHG) for providing the institutional facilities.

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