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Factors controlling Slope Environmental Lapse Rate (SELR) of temperature in the monsoon and cold-arid glacio-hydrological regimes of the Himalaya

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Abstract

Moisture, temperature and precipitation interplay forced through the orographic processes sustains the Himalayan cryospheric system. However, factors controlling the Slope Environmental Lapse Rate (SELR) of temperature along the higher Himalayan mountain slopes across various glacio-hydrologic regimes remain as a key knowledge gap. Present study dwells on the orographic processes driving the moisture–temperature interplay in the monsoon and cold-arid glacio-hydrological regimes of the Himalaya. Systematic data collection at three altitudes between 2540 and 3763 m a.s.l. in the Garhwal Himalaya (hereafter called monsoon regime) and between 3500 and 5600 m a.s.l. in the Ladakh Himalaya (herefater called cold-arid regime) revealed moistrue control on temperature distribution at temporal and spatial scales. Observed daily SELR of temperature ranges between 9.0 to 1.9 °C km^{-1} and 17.0 to 2.8 °C km^{-1} in the monsoon and cold-arid regimes respectively highlighting strong regional variability. Moisture influx to the region, either from Indian summer monsoon (ISM) or from Indian winter monsoon (IWM) forced lowering of SELR. This phenophena of "monsoon lowering" of SELR is due to the release latent heat of condensation from orographically focred lifted air parcel. Seasonal response of SELR in the monsoon regime is found to be closly linked with the variations in the local lifting condensation levels (LCL). Contrary to this, cold-arid system is characterised by the extremely high values of daily SELR upto 17 °C km^{-1} signifying the extremely arid conditions prevailing in summer. Distinctly lower SELR devoid of monsoon lowering at higher altitude sections of monsoon and cold-arid regimes suggests sustained wetter high altitude regimes. We have proposed a SELR model for both glacio-hydrological regimes demostrating with two sections each using a derivative of the Clausius–Clapeyron relationship by deriving monthly SELR indices. It has been proposed that the manifestations of presence or absence of moisture is the single most important factor determining the temperature distribution along the higher Himalayan slopes driven by the orographic forcings. This

work also suggests that the arbitary use of temperature lapse rate to extrapolate temperature to the higher Himalaya is extremely untenable.

1 Introduction

The Hindu-Kush-Himalayan (HKH) mountain plays a very important role in regulating the climate and hydrology of the South Asian region (Dey and Bhanu Kumar, 1983; Kumar et al.,1999; Zhao and Moore, 2004; Ye and Bao, 2005). Sustenance of a large population of the region also depends on the rivers fed by this mighty mountain chain (Cruz et al., 2007; Bookhagen and Burbank, 2010; Immerzeel et al., 2010; Bloch et al., 2012). Acknowledging these facts, there is an increased focus on the Himalayan cryospheric systems, its response to changing climate and ensuing impact on downstream flow regimes in recent years (Bookhagen and Burbank, 2010; Immerzeel et al., 2010, 2013; Kaser et al., 2010; Thayyen and Gergan, 2010). Empirical evidences of climate change over the Himalaya is being presented and debated under various contexts. Glacier change in the region is found to be comparable with other mountain glacier systems of the world (Zemp et al., 2009) and other manifestations of the climate change such as increase in temperature and decrease in precipitation is also evident in the region (Bhutiyani et al., 2007, 2010; Shrestha et al., 1999; Dimri and Dash, 2012; Shekhar et al., 2010; Duan et al., 2006). Reported mass gains of the Karakoram glaciers (Hewit, 2005; Gardelle et al., 2012, 2013; Kaab et al., 2012; Bambri, 2013) and a decade long positive mass balance regime of upper Chenab glaciers during 1990s (Azam et al., 2012) brings in more uncertainity in the processes driving the climate variability across the Himalayan arc.

One of the key areas of knowledge gap over the Himalayan region is the moisture–temperature interplay at its higher elevations. While latitudinal control on the insolation sustains the polar cryospheric systems, the Himalayan cryospheric system is formed and sustained mainly by its altitude and orographic processes. Hence, over the Himalayan region, the insolation controls could be regulated by the regional physical-dynamical-thermodynamical processes associated with the mountain orography. Therefore, global climate change indicators could get modified through the orographic proceses over the Himalayan slopes and cryospheric systems; making it difficult to establish direct linkages between the two (Thayyen, 2013a). As mountain climate is a balance between free air advective processes and surface radiative effects (Whiteman et al., 2004; Pepin and Lundquist, 2008), unravelling the complex nuances of orographic controls on the Himalayan climate system is central to this understanding.

Many aspectes of altitudinal dependencies of surface temperature variations along the slopes are investigated across various mountain ranges of the world (Stone and Carlson, 1979; Richner and Phillips, 1984; Pepin and Losleben, 2002; Rolland, 2003; Pepin and Seidel, 2005; Lundquist and Cayan, 2007; Marshall et al., 2007; Blanford et al., 2008; Pepin and Lundquist, 2008, 2011; Gardner et al., 2009; Minder et al., 2010; Yang et al., 2011; Kirchner et al., 2013; Kattel et al., 2013). Comparative studies of free air and surface temperature variations amply demonstrated the significant differences between the two (Pepin and Losleben, 2002; Pepin and Seidel, 2005; Pepin et al., 2011). However, while studying the larger tract of the ungauged high altitude Himalayan cryospheric regions, the temperature lapse rates are still used arbitrarily between ~ 6.0 to $\sim 8.9\,^{\circ}\mathrm{C\,km^{-1}}$ to determine the higher altitude temperature values for snow/glacier melt modelling studies (Singh and Bengtsson, 2004; Rees and Collins, 2006; Kaser et al., 2010; Alford, 2010; Immerzeel et al., 2010, 2013). Thayyen et al. (2005) have shown decrease in temperature lapse rate during peak monsoon months in the monsoon regime and suggested that it could be driven by the latent heat release from monsoonal clouds. They have cautioned the use of standard environmental lapse rate for snow and glacier melt studies in the high altitude regions dominated by the monsoon systems, where peak melt period coincides with the peak of monsoon season. Later, Kattel et al. (2013) substantiated this processes with regional scale assessment over the monsoon dominated regions of the Nepal Himalaya. Moreover, they have observed similar response during winter months as well. Earlier, Legates and Willmott (1990), Brazel and Marcus (1991) and De Scally (1997) also looked into the variations in the surface temperature lapse rate along the Himalayan slope which suggested a range of lapse rate extending from 10.8 to 3.0 °C km^{-1}.

Lack of understanding of the factors controlling the temperature variabiltiy over the mountain slopes led to uncertainity over the warming rates of the mountainous region vis-a-vis with the rest of the land surface (Rangwala and Miller, 2012; Beniston, 1997). Moreover, understanding the physical processes controlling the temperature of the Himalayan slopes in different glacio-hydrolgical regimes (Thayyen and Gergan, 2010) is paramount to the understanding of the climate forcing on the Himalayan cryosphere and regional variability of emerging water scenarios. This understanding is also inevitable for climate downscaling over the higher Himalayan region for better estimate of future climate trends.

Presence and/or absence of moisture is key to the distribution of temperature and precipitation in an orographic system which drives the climate of the mountain slopes (Dimri and Niyogi, 2013). The central and eastern Himalaya is impounded by moisture through Indian summer monsoon (ISM) during summer months (June–September: JJAS) (Kumar, 1999, 2006) and western and central Himalaya by Indian winter monsoon (IWM) during the winter months (November–March: NDJFM) (Dimri, 2013a, b). As these two systems negotiate the Himalayan region from opposite directions, topography regulates these flows and produces seasonal moisture surplus and deficient zones across the Himalayan arc forming distinct climate and hydrological zones. These climate and hydrological zones of the Himalaya are broadly classified into three; (1) Himalayan system with dominant ISM, (2) alpine system with dominant IWM and (3) cold-arid system characterised by the absence of ISM in summer and subdued influence of IWM in winter (Thayyen and Gergan, 2010). In this paper we analyse the role of orography-moisture interplay in controlling the temperature distribution along the Himalayan slopes and high altitude cryospheric regions under monsoon and cold-arid systems. These two regions with extreme climate variability highlight various nuances of orographic processes under dry and wet conditions on the temperature distribution along the Himalayan slopes. To model the slope environmental lapse rate (SELR) we have proposed process based monthly indices for different altitude sections under monsoon as well as cold-arid system for the first time to discontinue the practice of arbitrary use of environmental lapse rates for temperature extrapolation to the higher altitude as practiced. The understanding developed in this study could improve the efficiency and efficacy of climate and hydrological models by better represention of the climate along the Himalayan slopes and cryospheric systems.

2 Study area and climate

Among the three dominant glacio-hydrologic regimes of the Himalaya, present study focus on the wet monsoon regime of the Garhwal Himalaya and the cold-arid region of Ladakh (Fig. 1). The wet system studies are carried out in the Dingad catchment of Garhwal Himalaya. Dingad catchment covers an area of 77.8 km^2 and extends from 2360 to 6000 m a.s.l. and has 9.6 % glacier cover (Fig. 2a). The general aspect of this valley is north-west and lies between latitude 30°48′ to 30°53′ N and longitude 78°39′ to 78°51′ E. Dingad is a typical "Himalayan catchment", where climate is dominated by the ISM in summer and IWM embedding western disturbances (WDs) in winter (Kumar et al., 1999, 2006; Dimri, 2009; Thayyen and Gergan, 2010). The cold-arid system studies are carried out in the Ganglass catchment situated on the southern slopes of the Ladakh range (34°06′ to 34°17′ N and 77°30′ to 77°40′ E) (Fig. 2b). While the Dingad catchment on the southern slopes of the great Himalayan range receives huge amount of monsoon moisture, Ladakh range is far away from the normal course of monsoon trajectory. However, monsoon moisture do penetrate into the Ladakh region occassionaly as observed during the August 2010 cloudburst events (Thayyen et al., 2013b). Precipitation from IWM is also significant over the Dingad catchment while the Ladakh range lies in the shadow zones of the WDs limiting its influence over the mountain top. Moisture deprivation from both monsoons over the Leh region manifests into a very low mean annual precipitation resulting to cold-arid climate. While long-term mean annual precipitation at Leh (3500 m a.s.l.) is limitted to 115 mm, the mean annual precipitation at Dingad (3763 m a.s.l.) at comparable altitude is around 1400 mm. The annual precipitation and temperature distribution (Fig. 3) illustrates these divergent climatic characteristics over the two regions. Monsoon regime experiences very high monsoon precipitation and lower summer temperature as compared to the cold-arid region. Mean monthly temperature during July and August over Leh is almost double that of the wet monsoon system at corresponding elevation. During the core winter months of January and February, Ladakh region is much colder as compared to its wet counterpart in the Garhwal Himalaya.

3 Methodology

In the present work we analyse the altitudinal control on temperature among three stations in the Dingad catchment (in the Garhwal Himalaya: monsoon regime) and Gangalss catchment (the Ladakh region: cold-arid regime). In the Dingad catchment, three stations are located at Tela (2540 m a.s.l.), Gujjarhut (3483 m a.s.l.) and Basecamp (3763 m a.s.l.) (Fig. 2a). In the Ganglass catchment, Leh meteorological station (3500 m a.s.l.) is paired with the stations at South Pullu (4700 m a.s.l.) and Phuche glacier (5600 m a.s.l.) (Fig. 2b). Air temperature data of Dingad stations were collected during the summer ablation months (May–October) of 1998–2004 (with an exception in 2002). For deciphering temperature lapse rate characteristics of the winter months, data collected during 2002–2004 period was used. For the Ganglass catchment, data collected during 2010–2013 period is used in the study.

For a short period within the study of Dingad catchment, mean daily temperature was calculated from the 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 °C higher than the mean daily values derived from hourly temperature at Basecamp and 0.5 °C higher at Tela stations. In this paper lapse rate has been calculated from the mean daily temperature derived by averaging the dry bulb temperatures measured at 05:30, 08:30, 11:30, 14:30, 17:30 and 20:30 IST at three stations to maintain the consistency of the data throughout the study period. The mean daily temperature for Leh, South Pullu and Glacier stations were calculated from daily maximum and minimum temperatures during the 2010–2013 periods. All the temperature measurements were carried out following India Meteorological Department (IMD) standards. Measurements were carried out using calibrated thermometers and identical passive ventilation shields were used for stations in each region. Hence, relative observational errors between the stations in each region are expected to be minimal. In addition, SELR is calculated as a difference of temperature between two elevation points and hence influence of marginal measurement errors get minimized further in this analysis.

The average temperature decrease with height in the free atmosphere is generally called "environmental lapse rate" (Berry, 2008) which usually approximate between 6–6.5 °C km^{-1}. The temperature lapse rate along the mountain slopes significantly differ from the free atmosphere or environmental lapse rate (Pepin and Losleben, 2002; Pepin and Siedel, 2005). This temperature lapse rate along the mountain slope is termed here as the slope environmental lapse rate (SELR). The SELR is driven by naturally occurring orographic factors whereas environmental lapse rate of the free atmosphere is driven by vertical displacement of the air parcel. SELR between the station pairs are calculated by the equation,

$$\mathrm{SELR}(^\circ\mathrm{C\,km}^{-1}) = \left(\frac{T_1 - T_2}{H_2 - H_1}\right) \times 1000$$

where T_1 and T_2 are the mean daily temperature of lower and upper stations respectively, and H_1 and H_2 are the elevation of the lower and upper stations in meter. SELR is calculated for different altitude ranges in the Dingad and Ganglass catchment to understand elevation dependency of slope lapse rate values of temperature vis-a-vis with the moisture regimes. The lower and upper stations (2540 and 3763 m a.s.l.) in the Dingad catchment are paired to deduce the SELR across the valley and termed as Section-1M. Higher altitude stations in the catchment are paired (3483 and 3763 m a.s.l.) to calculate the SELR of nival-glacier regime and termed as Section-2M. Similarly, in the cold-arid system, lower and intermediate stations paired (3500 and 4700 m a.s.l.) to calculate SELR is termed as Section-1A and higher altitude station pair representing the nival-glacier regime (4700 and 5600 m a.s.l.) is termed as Section-2A. Hereafter, these terms will be used as defined in the following discussion.

4 Results

4.1 Temperature variations in monsoon and cold-arid regimes

In the monsoon regime (Dingad catchment), highest mean monthly temperature recorded at different altitudes during the study period was 18.6 °C in June 1998 at 2540 m a.s.l. followed by 13.4 °C in July at 3483 m a.s.l. and 11.4 °C in July at 3763 m a.s.l. All these high values were recorded during the El-Nino year of 1998. During normal years, highest monthly temperatures of 17.4, 12.4, 11.3 °C were recorded at 2540, 3483 and 3763 m a.s.l. respectively. In summer (May–October) mean monthly temperature ranged between 18.6 to 9.6 °C at 2450 m a.s.l., 13.4 to 4.9 °C at 3483 m a.s.l. and 11.4 to 2.3 °C at 3763 m a.s.l. In winter (November–April) mean monthly temperature ranged between 13.0 to 2.8 °C at 2540 m a.s.l. and −4.6 to 4.3 °C at 3763 m a.s.l. Gujjarhut station at 3483 m a.s.l. was not monitored during the winter months.

Cold-arid regime studies were carried out during 2010–2012 period. During these three years, daily minimum and maximum temperature recoded at Leh station (3500 m a.s.l.) was in the range of −23.4 to 33.8 °C. Highest temperatures were recorded in the month of July and August and mean monthly temperature during these months ranged from 20.1 to 22.5 °C (July 2011). During winter (November–April) lowest mean monthly temperature recorded was −8.5 °C in January 2011. As compared to this, higher elevation station South Pullu (4700 m a.s.l.) recorded the lowest mean monthly temperature of −16.3 °C in January 2012 and highest mean monthly temperature of 9.74 °C in August 2012. Temperature during July and August months range between 8.6 to 9.7 °C. Lowest daily minimum and maximum temperature recorded at South Pullu station was −27.3 and 21.9 °C respectively. During summer months, Leh station (3500 m a.s.l.) in cold-arid regime experiences higher temperature than that at comparable elevations at Dingad in the monsoon regime. It demonstrates the role of moisture and plateau effect on ambient temperature. Over the mountain top at 5600 m a.s.l. instantaneous minimum and maximum temperature ranges between −27.4 and 13.6 °C and the mean monthly temperature ranges between −21.0 and 2.8 °C.

4.2 Precipitation variations in monsoon and cold-arid regimes

One of the most prominent divergences of monsoon and cold-arid regime is the amount and distribution of precipitation along the mountain slopes. Stations in the Dingad catchment experienced rainfall during 57–65 % of summer days (May–October) and the rainfall amount in these stations did not show much variation at different altitudes. Gujjarhut at 3483 m a.s.l. received highest mean summer rainfall of 1350 mm in the catchment followed by 1238 mm at the 3763 m a.s.l. (Basecamp station) and 1183 mm at 2540 m a.s.l. (Tela station). In winter (November–April), precipitation at 3763 m a.s.l. ranges between 512 mm water equivalent (w.e.) to 380 mm w.e. and mean annual precipitation recorded is 1669 mm. The cold-arid regime is characterized by very low precipitation. Long term mean annual precipitation at Leh (3500 m a.s.l.) is only 115 mm (Thayyen et al., 2013b). However annual precipitation at the higher altitudes of the cold-arid regime (South Pullu station, 4700 m a.s.l.) varied between 285.6 to 207.4 mm during the study period suggesting that the annual precipitation at 4700 m a.s.l. is nearly double that of 3500 m a.s.l. Winter precipitation over the glacier could be still higher as indicated by the winter mass balance estimates of the Phuche glacier ranging from 590–660 mm w.e. (paper under preparation). This signifies the role of orography in temperature–moisture dynamics over the mountain slopes. It may be noted that the spatially homogenous precipitation distribution observed in the Dingad catchment could be an aberration than a norm in the monsoon dominated areas as other studies has suggested declining monsoon precipitation at higher altitudes of the monsoon regime (Bookhagen and Burbank, 2006).

4.3 SELR variations in the monsoon regime

Daily SELR of temperature at Section-1M, between the extreme lower (Tela, 2540 m a.s.l.) and higher (Basecamp, 3763 m a.s.l.) stations ranged from 9.0 to 1.9 °C km^{-1} during the observation period. This station pair showed consistent SELR lowering in association with moisture influx to the region during peak winter and summer months (Fig. 4a). We call this process as “monsoon lowering” of SELR as this process occurs during peak winter and summer monsoon period. Followed by Thayyen et al. (2005), similar response of SELR is reported from a large number of station pairs in Nepal as well (Kattel et al., 2013). Hence we strongly believe that this phenomenon is a characteristic of Himalayan catchments. Winter (November, December, January) and summer (July and August) experienced comparable low mean monthly SELR ranging from 4.9 to 5.8 °C km^{-1}. Post monsoon period (September and November) also occasionally experienced lower lapse rates. During the rest of period mean monthly SELR of Section-1M ranged from 7.1 to 6.0 °C km^{-1} (Table 1). May and June in 1998 recorded the highest mean monthly valley scale lapse rate of 7.1 and 7.0 °C km^{-1} during the 6 year observation period. SELR between lowermost (2540 m a.s.l.) and intermediate (3483 m a.s.l.) station (SELR-TG) also shown the monsoon lowering of SELR consistently during the summer monsoon months (Table 2). SELR variations in the winter months between these station pairs could not be compared as there was no winter monitoring commissioned at the Gujjarhut station due to logistic reasons.

The SELR of Section-2M representing the nival-glacier regions (3483–3763 m a.s.l.) showed a very different patterns of variation through the ablation months as compared to Section-1M (2540–3483 m a.s.l.). Absence of “monsoon lowering” of SELR during July and August months is the most significant deviation observed for Section-2M (Fig. 4b). Another significant characteristic of the Section-2M was the lower mean monthly SELR observed for this station pair which ranged between 2.1 to 4.6 °C km^{-1} with few exceptions (Table 2). SELR of Section-2M showed consistent response through summer months (May to October) during 1999 to 2003 period. The only exception was in 1998, when SELR of Section-2M was significantly higher than other years (3.6 to 7.1 °C km^{-1}) during the ablation/monsoon months (June–September). As mentioned earlier, 1998 was an El-Nino year and there could be large scale teleconnection pertaining to this relation, which however, is not dealt in the present paper. This station pair also reported temperature inversion almost every year in the month of November.

4.4 SELR variations in the cold-arid regime

Temperature measurements in the station pairs of the cold-arid system have been carried out from May 2010 onwards. Data of 2010, 2011 and 2012 of Section-1A (3500–4700 m a.s.l.) and 2012–2013 data of Section-2A (4700–5600 m a.s.l.) are presented in the paper. Data of Section-2A is available only for a year, generated by two automatic weather stations installed in September 2012. The foremost observation from these data is the steep daily SELR of the cold-arid system ranging from 2.8 to 17.0 °C km^{-1} with consistently higher SELR during summer months clearly reflecting the characteristics of the arid conditions. In fact, Section-1A started experiencing higher SELR from March onwards (9.5 to 11.0 °C km^{-1}) (Table 3). However, SELR of core winter months (November–January) showed striking similarity with the monsoon regime with winter lowering of the SELR. Daily SELR during this period ranged between 5.8 to 7.5 °C km^{-1} (Fig. 4c), which clearly indicates the role of moisture influx and low temperature combination controlling the SELR of cold-arid regime mountain slopes during these months. During winter, both the regions fall under the influence of the WDs forcing the similar SELR response for both the regions. During winter months, Section-2A of the cold arid regime mimics the SELR variations of Secion-1A (Fig. 4c). However, SELR of Section-2A during summer months is characterized by lower daily SELR ranged between 7.4

to 6.5 °C km^{-1} as compared to the higher values of the Section-1A, which recorded summer SELR consistently > 9.8 °C km^{-1}.

4.5 Free environment temperature lapse rate of the study areas

Environmental lapse rate of the free atmosphere is calculated from the ERA-interim reanalysis (Dee et al., 2011) (https://apps.ecmwf.int/auth/login/), and compared with the observed SELR from station data. In the region of study, so far no radiosonde ascents are performed. Vertical temperature profiles of point location are extracted from ERA-interim reanalysis. It is important to mention here that various reanalysis are amalgamation of observed station records, satellite information etc. use different mathematical and statistical algorithm to generate the reanalysis data. It is not discussed here in detail as it is out of the scope of the present work. However, ingenuity of the ERA-interim data over other reanalysis data is proven as it uses observed surface temperature records during its preparation (Simmons et al., 2004, 2010). This particular fact is very important for the Himalayan region due to paucity of observation network and may give a benchmark for future research in the absence of such records. ERA-interim data records for the period 1998–2004 for monsoon regime at Tela (30°51′26.22″ N, 78°40′39.96″ E) and for 2010–2013 period for cold-arid regime at Leh (34°07′33.93″ N, 77°32′17.33″ E) are extracted to compare with the corresponding station observation. Averaged monthly environmental lapse rate for the respective periods were calculated for monsoon and cold arid regimes and compared with the station records (Fig. 5) In monsoon regime, comparison shows that ERA-interim environment lapse rate matches with the observed SELR variability of summer monsoon lowering well. However, it is insensitive to the changes occurring during winter lowering and remains higher than the corresponding SELR from the station observations. In cold arid regime, environmental lapse rate based on ERA-interim analysis is closer to the observed SELR of Section-1A during November, December and January but as seasons advances it remains much lower than the SELR of Section-1A and but much closer to the SELR of Section-2A. It is important to mention here that ERA-interim is at 1° × 1° lat/lon horizontal resolution which is too coarse over region of study with heterogeneous land use and variable topography. It could be inherent that during the preparation of the reanalysis, most of the subgrid scale processes are not being captured within the resolution of reanalysis. But it is obvious that environmental lapse rate based on ERA-interim is sensitive to moisture in both monsoon and cold-arid regime. Use of gridded reanalysis data is capable of providing enhanced understanding in the regions with limited observations. Fiddes and Gruber (2014) have extensively shown the downscaling method of climate variables from coarser to finer resolution over heterogeneous topographic regions.

5 Discussions

Most prominent distinction between SELR of monsoon regime and cold-arid regime were observed during the peak summer ablation months (June–September) (Fig. 4d). In the monsoon regime, daily SELR during summer ablation months range between 9.0 to 1.9 °C km^{-1}, while in the cold-arid regime SELR is in the range of 17.0 to 2.8 °C km^{-1}. In the monsoon dominant region, summer SELR is skewed towards saturated adiabatic lapse rate (SALR) (Fig. 6). Influx of monsoon moisture into the "Himalayan catchments" and its orographic lifting and resultant latent heat release during condensation is dictated by varying atmospheric vertical pressure at different altitudes. This led to the significant proximity of SELR of Section-1M during the monsoon months with the theoretical SALR. On the contrary, absence of moisture influx deep into the trans-Himalayan region forces the SELR of Section-1A of the cold-arid regime to follow the dry adiabatic lapse rate (DALR). This emerged as one of the dominant characteristics distinguishing these two glacio-hydrological regimes proposed by Thayyen and Gergan (2010). In winter months, both the regions receive moisture from the IWM. Combined with the prevailing low temperature environment in winter, SELR show closer values with that of corresponding SALR in both the regions.

Another important characteristic common to both the regions pertinent to the cryospheric system modelling is the significantly lower SELR at the higher altitude nival-glacial regimes as compared to the respective lower sections (Fig. 4d). In the case of monsoon regime, SELR of Section-2M is very close to the plausible SALR for corresponding pressure levels in summer months (Fig. 6). In the cold-arid regime, SELR of the lower section (Section-1A) in summer is consistently $> 9.8\,^{\circ}\mathrm{C\,km^{-1}}$, while at nival-glacier region (Section-2A), SELR was predominantly $< 9.8\,^{\circ}\mathrm{C\,km^{-1}}$. Winter lowering of SELR leading to lesser temperature difference between lower and higher elevation do not have significant influence on the regional hydrology or glacier characteristics because the ambient temperature in these region is well below the freezing point in winter and the snow and glacier regions remain under the non-melt regime. But in summer, SELR lowering forced by the moisture influx and orographic up draft greatly influence the melt processes of glaciers and snow cover by facilitating incremental energy during the melt regime. In the case of displacement of air parcel along a vertical air column, such variations in the lapse rate occur above and below the lifting condensation level (LCL) (Ahrens, 1991). Analysis suggests that the same processes are followed by the air parcel while being lifted along the mountain slopes by the orography as well. ($\mathrm{LCL} = (T_\mathrm{o} - T_\mathrm{do})/(9.8 - T_\mathrm{d}^2/158T)$, T_o and T_do are temperature and dew point temperature at the surface and T and T_d are temperature changing with the altitude (Salby, 1996). Here in the absence of free atmosphere higher altitude temperature values, surface values are used with little error). Significant correlation between LCL at 2540 m a.s.l. and SELR of Section-1M (r^2, 0.47 to 0.72, $P < 0.001$) in the monsoon regime during the observation years suggests that the seasonal LCL height variation plays a dominant role in determining the SELR in the monsoon regime. The LCL in summer/monsoon months is found to be closer to the land surface forcing SELR towards SALR (Fig. 7a). On the contrary, LCL shifts to the higher altitudes during moisture deficit months of April, May and June in the pre-monsoon period and October and November in the post-monsoon period forced higher SELR for Section-1M shifting towards the DALR. A major process consuming significant energy within the parcel is the re-evaporation of condensed precipitation while falling through the warmer layers below (Dolezel, 1944). We propose that the rate of re-evaporation of water droplet, governed by the seasonal variations in the LCL could be playing an important role in determining the seasonal variations in the valley scale (Section-1M) SELR. Hence we believe that the net energy released through condensation of winter and summer monsoon moisture is the prime driver of the SELR along the Himalayan slopes. The distinction between higher Himalayan glacier regimes (Section-2M) with that of the lower section is explained by the seasonal humidity variations at lower (Tela, 2540 m a.s.l.) and higher (Basecamp, 3763 m a.s.l.) altitude stations. At lower elevations, day-to-day humidity variation is significant even during the monsoon period, while at the higher elevations, mean daily humidity consistently remains above ~ 80 % throughout summer months (Fig. 7c). This indicates that the higher elevation cryospheric regions in the monsoon regime are predominantly above LCL during most part of the year and explains the steady SELR close to SALR of Section-2M throughout the year. Distinctly different SELR of Section-1A and Section-2A of the Ganglass catchment also suggests atmospheric pressure–moisture–temperature interplay in the higher altitude region of the cold-arid system as well. In the cold-arid system, lowest LCL at 4700 m a.s.l. was experienced during winter months and most of the time stayed around a kilometer and above. Hence, influence of LCL on SELR of Section-2A of the cold-arid system probably limited to winter months (Fig. 7b). These results indicate the role of the atmospheric pressure of the altitude sections in determining the SELR variations, especially at the higher altitude cryospheric regions. Till date, no distinction is made for the selection of SELR based on the base station altitude or atmospheric pressure levels. The results presented here suggest that it is highly inappropriate to use standard environmental lapse rate or even observed SELR between two lower elevation stations to extrapolate the temperature measured at the higher altitude nival-glacier regions of the Himalaya. Even in the cold-arid system, the glacier regions are in the wetter regimes as compared to the arid lowlands which forces a lower SELR along the nival-glacial regime. High variability of daily SELR values with a SD ranging from 1.09 to 0.84 °C km^{-1} for monsoon regime and 1.08 to 2.98 °C km^{-1} for cold-arid regime for daily values is common to both the regions and sections. This high variability of daily SELR is characteristic to other mountain regions as well (Kirchner et al., 2013).

These results questions the veracity of the use of standard environmental lapse rate for extrapolating the temperature to the higher altitudes for snow and glacier melt calculations irrespective of the glacio-hydrological, seasonal and altitude regimes under consideration and highlight the need for a SELR model to address this issue.

Modelling SELR for monsoon and cold-arid regimes

The results discussed above suggests that the SELR model should take into account the variability of SELR under different glacio-hydrologic regimes of the Himalaya and the variability induced by the orographic dynamics along the mountain slopes at different altitudes. It calls for integrating various processes controlling the SELR such as the atmospheric pressure, moisture conditions and the prevailing temperature of the base station, above which the temperature extrapolation is intended.

The equations governing the DALR and SALR are well established. However, these equations are generally used in the context of air parcels lifted "vertically" upwards under different moisture conditions. Though various studies pertaining to lapse rate over other mountainous region prevails (Thyer, 1985; Rolland, 2003; Harlow et al., 2004; Mokhov and Akperov, 2006; Blanford et al., 2008; Minder et al., 2010), a model which encapsulates the mountain process remains a challenge. Over central Himalaya, Kattel et al. (2013) has provided lapse rate estimation with functional reference of the elevation. Here, we are proposing a process based relationship of SELR and moisture/water vapor availability along the altitudes.

The DALR and SALR of the free atmosphere is governed by the following equations respectively (Robinson and Henderson-Sellers, 1992),

$$\frac{\mathrm{d}t}{\mathrm{d}z} = -\frac{g}{C_p} \quad (1)$$

$$\frac{\mathrm{d}t}{\mathrm{d}z} = -\frac{g}{C_p} - \left[\left(\frac{L}{C_p}\right) \times \left(\frac{\mathrm{d}w_\mathrm{s}}{\mathrm{d}z}\right)\right] \quad (2)$$

where, $\mathrm{d}t/\mathrm{d}z$ is rate of change of temperature (t) with height (z), g is acceleration due to gravity, C_p is specific heat at constant pressure, L is the latent heat of phase change, w_s is the saturation mixing ratio.

$$w_\mathrm{s} = 0.622\left(\frac{e_\mathrm{s}}{p}\right) \quad (3)$$

where e_s is saturation vapor pressure and p is the station pressure.

To solve this equation, temperature data at two altitudes are required to estimate the change in the saturation mixing ratio. Even though this equation provides valuable insight of processes governing the temperature lapse rate under saturated conditions, this equation do not have the predictive advantage. What is required for a snow/glacier model is a SELR model which delivers the higher altitude temperature distribution based on a single base station temperature data at lower altitude. Following manifestation of the Clausius–Clapeyron relation it is found to be appropriate for this purpose (Peixoto and Oort,1992);

$$\frac{\mathrm{d}T}{\mathrm{d}z} = -\frac{g}{C_p}\left[\frac{(P+N)}{\{P+(\varepsilon L/C_pT)N\}}\right] \quad (4)$$

$$\text{where } N = \frac{\varepsilon L e_\mathrm{s}}{RT} \quad (5)$$

where, T is the base station temperature in Kelvin, P is base station pressure in hPa, ε is the ratio between molecular weight of the water and dry air and R is gas constant.

These two equations were implemented to test its response in the Section-1M/1A and Section-2M/2A for all the years. Year after year, the relationship has given a consistent response as presented in the sample Fig. 8a and b. In the Section-1M, day-to-day variability is more pronounced for the Eq. (2) as it uses the daily estimate of change in saturation mixing ratio between the two stations for calculating the heat generated due to condensation process. Whereas the Eq. (4) is more stable as it uses saturation vapor pressure value of single station for calculating the potential heat generated through condensation processes. It is observed that during winter months, both the models are in better agreement with the observed SELR. May and June months experienced highest deviation between observed SELR and calculated SALR followed by closer relationship during monsoon months. For the Section-1M, observed SELR values were higher than the calculated SALR values, whereas for the Section-2M observed SELR values are lower than the calculated SALR for dominant periods. However, seasonal variability between the two is found to be very less pronounced for this section. Another common response of SALR calculated by Eq. (2) was the lesser deviation of model result during a period of lowest SELR, which got magnified during the seasons experienced higher SELR. This suggests that the heat energy released through condensation as per the Eq. (2) have been expended subsequently for re-evaporation process linked with seasonal variations in LCL as discussed before. These processes probably lead to further cooling and produce the observed SELR.

In the case of cold-arid system, distinction between winter and summer months were more pronounced. In winter, lower section (Section-1A) and higher section (Section-2A) experienced comparable SELR close to the SALR derived by Eq. (4) (Fig. 9c and d). However, during the long dry period from April to October, when SELR were close to or higher than the DALR at Section-1A, Eq. (4) has given a much lower theoretical SALR for the region (Fig. 9c). However, for the Section-2A at the higher altitude, the Eq. (4)

has given a closer estimates with SELR suggesting a wetter regime with sustained lower SELR < 9.8 °C km^{-1}.

We have seen that the processes determining the SELR for different high altitude sections under different glacio-hydrologic regimes vary significantly. However, consistency of the SELR variation through the seasons for six observation years of monsoon regime and four observation years of cold-arid regime suggest that the dynamics governing the SELR variation in each season and each section are unique and consistent. Hence it is found to be necessary to model the SELR for each section under different glacio-hydrologic regimes. To tackle this issue, we propose to modify the equation governing the SALR (Eq. 4) by introducing distinct monthly indices representing the net condensation in each altitude sections in consonance with the station pressure.

SELR variations could also be influenced by the factors such as land surface conditions (Pepin and Losleben, 2002; Pepin and Kidd, 2006). However, Kirchner et al. (2013) found no significance difference between snow and no snow cover days in lapse rate based on daily mean temperature. Since the SELR shows significant year-to-year consistency in seasonal response for both the regions and sections, here we assume that the deviation of SELR from SALR has occurred mainly due to the variations in the moisture availability in each regime and section. The fraction of moisture potentially responsible for the change (dwsf) has been calculated using the observed SELR and estimated SALR using Eq. (2) as described below:

$$\frac{\mathrm{dwsf}}{\mathrm{d}z} = \frac{\left[\frac{\mathrm{d}T}{\mathrm{d}z}\right]_{\mathrm{obs}} - \left[\frac{\mathrm{d}T}{\mathrm{d}Z}\right]_{\mathrm{equ}}}{\frac{L}{C_p}} \tag{6}$$

where, dwsf represent the potential withdrawal/influx of moisture from/to the altitude section with reference to the respective SALR.

By using this information, and utilizing all the data available from the field experiment, we have derived monthly average SELR indices (Mi) for lower and upper sections separately for monsoon and cold-arid regime as follows:

$$\mathrm{Mi} = \frac{\sum_{n=1}^{n} \mathrm{dwsf}}{\sum_{n=1}^{n} \mathrm{dws}}. \qquad (7)$$

Derived monthly SELR indices are given in Table 4. Negative monthly indices during winter months in all the sections and for the Section-2M of the monsoon regime representing the higher altitude nival-glacial systems in summer indicate additional moisture availability at the higher reaches than being assessed at the lower altitude. We presume that the role of local convective systems, land surface conditions and local winds including katabatic and anabatic flows in the region might be influencing these monthly indices systematically in each season.

These monthly indices are applied to the Eq. (5) and modified “N” has been calculated as shown in the Eq. (8) below. Eventually this newly derived “N” is applied to the Eq. (4) to derive the SELR for different sections under different hydrologic regimes.

$$N = \frac{[e_\mathrm{s} - (e_\mathrm{s}\mathrm{Mi})]\varepsilon L}{RT} \qquad (8)$$

The SELR model results using monthly indices showed significant improvement as compared to the Eq. (4) for all sections under monsoon and cold-arid regimes (Fig. 9a–d). Modelling SELR of the mountain slopes on daily basis is a huge challenge due to the influence of numerous factors like local winds, land use, temperature inversion, factors influencing the re-evaporation of condensed droplets etc. However, the present effort provides process based estimates of SELR on a daily basis with reasonable accuracy. Root mean square error (RMSE) for Section-1M is 0.072 °C km^{-1}; for Section-2M is 0.12 °C km^{-1}; for Section-1A is 0.16 °C km^{-1} and for Section-2A is 0.17 °C km^{-1}. The relationship is further improved between monthly mean values of model lapse rate and observed lapse rate (RMSE, for Section-1M is 0.062 °C km^{-1}; for Section-2M is 0.1 °C km^{-1}; for Section-1A is 0.13 °C km^{-1} and Section-2A is 0.14 °C km^{-1}) and the relationship between modelled SELR and observed SELR improved further during the crucial ablation months (June–September). As a general advisory, we propose to apply the monthly indices derived for Section-2M (monsoon regime) for estimating the SELR using the temperature data collected from 3500 m a.s.l. or above. For cold-arid system this critical elevation for the use of monthly indices of Section-2A could be around 4500 m a.s.l. The proposed model with monthly indices provide a process based relationship for SELR of temperature along the mountain slopes at varying atmospheric pressure levels under varying moisture conditions for the first time. This facilitate a significant advancement in our understanding of the process governing moisture–temperature interplay at the higher Himalaya and the SELR variations in two distinct glacio-hydrologic regimes of the Himalaya.

6 Conclusions

Diverse slope environmental lapse rate (SELR) of temperature for different altitudinal sections of monsoon and cold-arid systems of the Himalaya amply demonstrate that the use of environmental lapse rate or any other temperature lapse rate values arbitrarily for extrapolating the temperature to the Himalayan cryospheric systems is not appropriate. The data presented from two distinct glacio-hydrologic regimes of the Himalaya suggests that the single most important factor determining the temperature of the higher Himalayan mountain slopes including snow/glacier regime is the moisture. Seasonal moisture influx during the winter and summer monsoon period forces lowering of the SELR in the monsoon regime. Whereas cold-arid system SELR is characterized by the winter lowering and steep summer highs due to extremely arid conditions prevailing in summer. Manifestations of atmospheric pressure–moisture variability driven by the orographic lifting lead to greater saturation at the higher altitude regions; resulting into comparatively lower SELR's in the higher Himalaya than the lower sections. Seasonal variations in the height of the lifting condensation level (LCL) and re-evaporation rates are also found to be influencing the seasonal variations of

SELR. Proposed model with monthly SELR indices for higher and lower sections of the monsoon and cold-arid regimes provided a process based solution for calculating SELR. Local surface energy balance including net radiation and turbulent heat fluxes are believed to be the primary determinant of surface temperature and its vertical gradient (Marshall et al., 2007). However, distinct vertical surface temperature gradients observed for the wet and dry systems of the Himalaya and its moisture controlled deviations along the higher altitudes described in the present study clearly indicate that the presence or absence of moisture have an overriding influence in determining the SELR and thereby temperature distribution in an orographically driven system. New insight presented in this work will help to improve our understanding of the climate-cryosphere interaction in the Himalaya and its regional differences, improvement in the snow/glacier runoff modelling in the Himalayan basins, better understanding of the climate change impact on the Himalayan slopes and more realistic climate downscaling. Present study also indicate that the global climate change and its manifestations are impacting the higher Himalayan regions through the orographic modulations. Hence, developing robust understanding of future climate trajectory over the Himalaya require better understanding of this moisture–temperature–orography interplay.

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Table 1. Slope Environmental Lapse rate (SELR) of temperature in the monsoon regime between 2540 and 3763 m a.s.l. (Section-1M) of the Dingad catchment.

	SELR (°C km^{-1}): 2540–3763 m a.s.l.						
Months	1997–1998	1998–1999	1999–2000	2000–2001	2001–2002	2002–2003	2003–2004
Nov	5.4	ND	6.6	ND	5.4	5.5	5.7
Dec	ND	ND	ND	ND	5.3	5.1	5.3
Jan	ND	ND	ND	ND	6.0	4.9	5.7
Feb	ND	ND	ND	ND	6.1	5.6	ND
Mar	ND	ND	ND	ND	ND	6.0	6.5
Apr	ND	ND	ND	ND	ND	5.9	6.2
May	7.1	6.7	6.0	ND	ND	6.5	ND
Jun	7.0	6.0	5.6	5.6	ND	6.4	6.3
Jul	5.8	5.2	5.1	5.0	ND	5.4	5.6
Aug	5.5	5.5	5.0	5.3	ND	5.0	5.3
Sep	6.1	5.6	5.6	6.0	ND	5.5	5.6
Oct	6.3	6.2	5.7	6.5	ND	6.0	6.0

ND: No Data.

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Table 2. Temperature SELR in the monsoon regime between 2540 and 3483 m a.s.l. and 3483 and 3763 m a.s.l. (Section-2M).

	SELR (°C km^{-1}): 2540–3483 m a.s.l.					SELR (°C km^{-1}): 3483–3763 m a.s.l.				
	1998	1999	2000	2001	2003	1998	1999	2000	2001	2003
May	8.1	7.0	6.7	ND	7.1	3.6	5.8	4.4	ND	4.6
Jun	7.0	6.7	6.0	6.2	6.8	7.1	3.7	4.2	3.7	5.2
Jul	5.5	5.8	5.3	5.3	5.7	7.1	3.5	4.4	4.1	4.5
Aug	5.2	5.9	5.5	5.9	5.2	6.7	4.0	3.4	3.4	4.2
Sep	5.8	6.1	6.4	6.9	5.9	7.0	3.6	3.0	3.1	4.0
Oct	6.5	7.4	7.1	7.6	7.0	5.6	2.1	3.8	3.0	2.8
Nov	7.4	7.7	ND	7.4	ND	−1.3	2.8	−2.2	−1.6	ND

ND: No Data.

Table 3. Temperature SELR in the cold-arid regime between 3500 and 4700 m a.s.l. (Section-1A) and between 4700 and 5600 m a.s.l. (Section-2A).

	SELR (°C km^{-1})				
	3500–4700 m a.s.l.			4700–5600 m a.s.l.	
Month	2009–2010	2010–2011	2011–2012	2011–2012	2012–2013
Nov	ND	7.0	7.5	ND	6.9
Dec	ND	6.0	6.0	ND	6.5
Jan	ND	5.8	7.0	ND	5.7
Feb	ND	8.1	9.0	ND	7.9
Mar	ND	9.5	11.0	ND	6.3
Apr	ND	10.0	11.0	ND	7.4
May	10.0	9.9	11.0	ND	7.5
Jun	10.0	10.3	11.0	ND	8.0
Jul	10.0	10.8	11.0	ND	7.8
Aug	11.0	10.2	11.4	ND	6.5
Sep	10.0	10.4	10.6	7.4	9.1
Oct	9.0	8.6	9.9	7.5	ND

ND: No Data.

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Table 4. Monthly SELR indices (Mi) for lower and upper sections in the monsoon and cold-arid regime of the Himalaya.

	Monsoon regime		Cold-arid regime	
months	Section-1M	Section-2M	Section-1A	Section-2A
Nov	0.15	−2.88	0.46	0.16
Dec	−0.14	NA	−0.22	−0.47
Jan	−0.16	NA	−0.87	−1.4
Feb	−0.07	NA	0.72	0.37
Mar	0.44	NA	1.01	−0.11
Apr	0.48	NA	1.05	0.49
May	0.58	0.15	1.04	0.72
Jun	0.59	−0.25	1.01	0.85
Jul	0.42	−0.21	1.03	0.85
Aug	0.36	−0.36	1.03	0.76
Sep	0.44	−0.83	1.03	0.88
Oct	0.44	−1.07	0.94	0.52

NA: Not available.

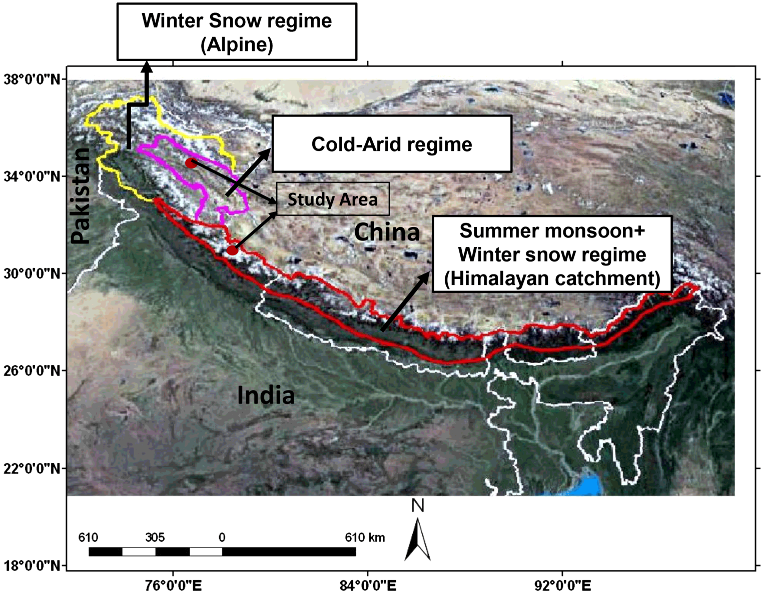

Figure 1. Glacio-hydrological regimes of southern slopes of the Himalaya and study area (after Thayyen and Gergan, 2010).

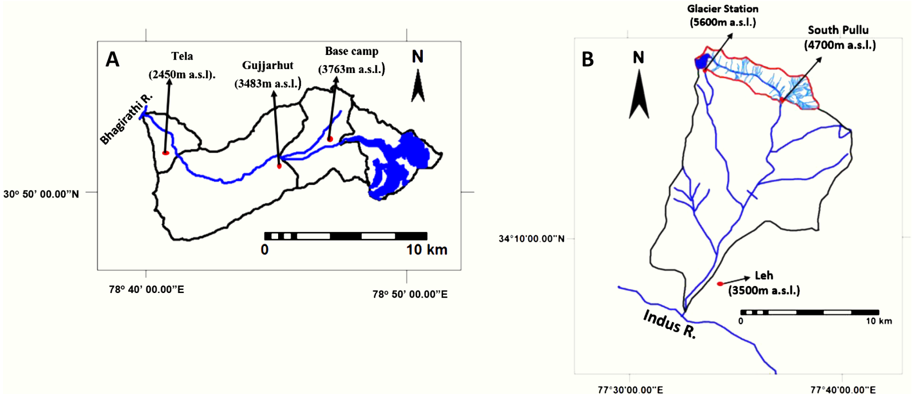

Figure 2. Study catchments: **(a)** Dingad catchment in the Garhwal Himalaya: monsoon regime and **(b)** Ganglass catchment in the Ladakh Himalaya: cold-arid regime.

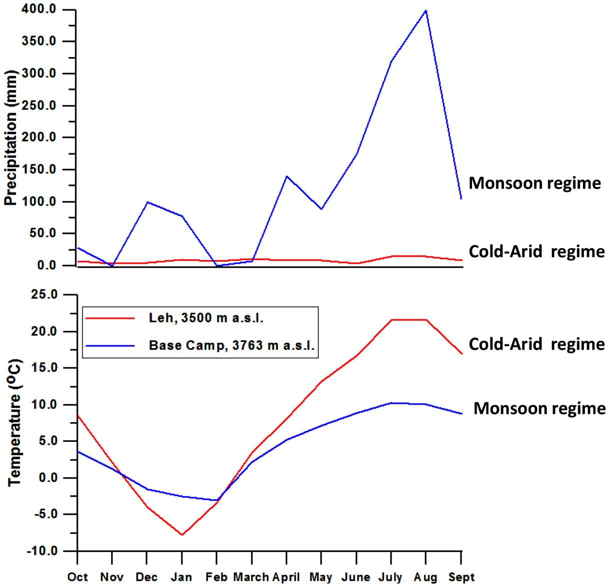

Figure 3. Monthly distribution of temperature and precipitation distinguishing the characteristics of the monsoon and cold-arid regimes. At height range of 3500–3800 m a.s.l., temperature of the monsoon regime (Dingad-1998:2004) (blue) is lower than the cold-arid regime (Leh-2010–2013) (red) during most of the months, except December, January and February. Most remarkable variation is seen in the precipitation.

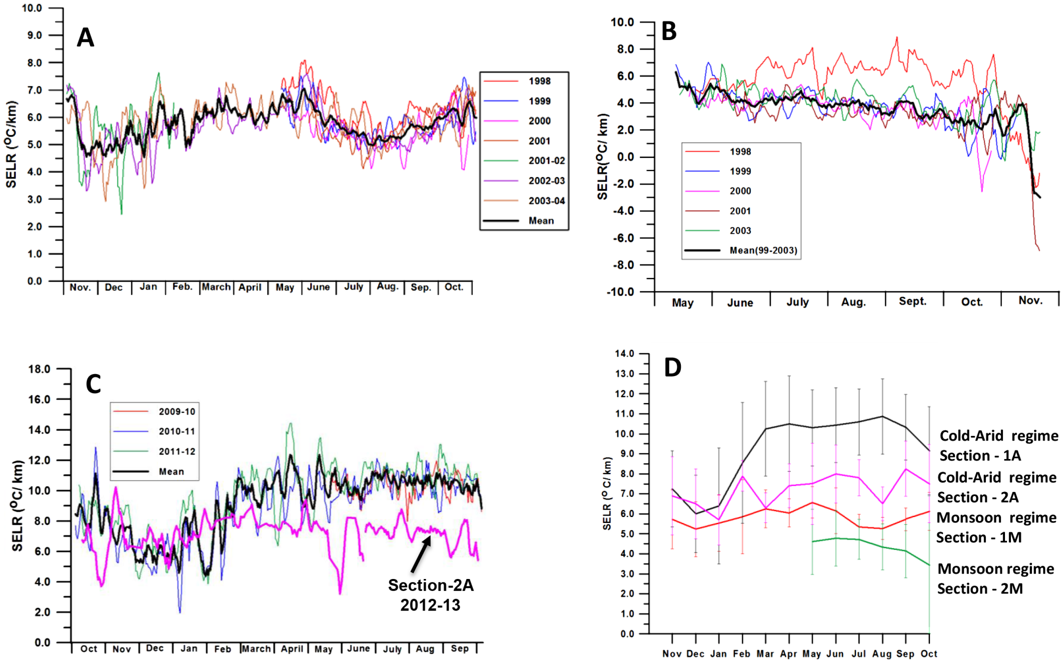

Figure 4. Daily pentad SELR variations at **(a)** Section-1M (2540 m–3763 m a.s.l.), **(b)** Section-2M (3483–3763 m a.s.l.), **(c)** Section-1A (3500–4700 m a.s.l.) and Section-2A (4700–5600 m a.s.l. pink) and **(d)** mean monthly SELR variations summarizing the temporal variations of SELR in the monsoon and cold-arid regimes at different altitude sections.

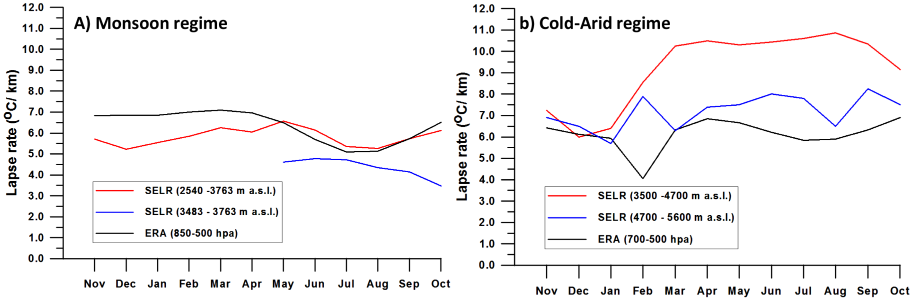

Figure 5. Comparison of ERA-interim free environment lapse rate with SELR of **(a)** monsoon regime and **(b)** cold-arid regime.

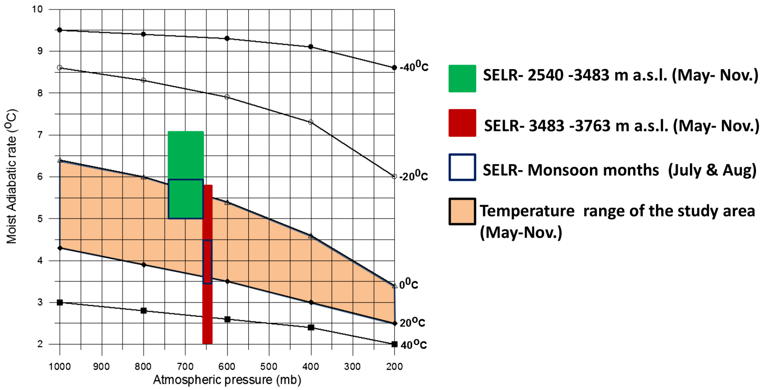

Figure 6. Theoretical saturated adiabatic lapse rate (SALR) under different pressure–temperature combinations and observed SELR under monsoon regime (green and red filled boxes). Blue square showing the extent of SELR during monsoon explains the moisture influx and related monsoon lowering of SELR. Note that the sustained lower SELR close to SALR of higher altitude section during 1999–2003 period.

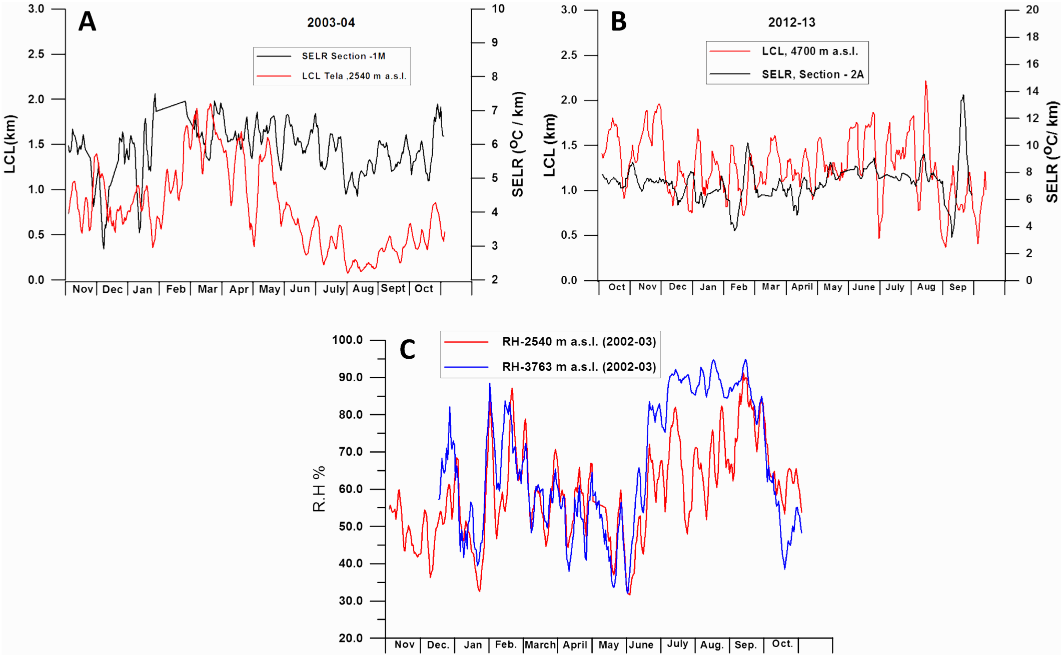

Figure 7. Factors controlling SELR of higher Himalayan region **(a)** relationship between SELR of Section-1M and lifting condensation level (LCL) at Tela (2540 m a.s.l.) for 2003–2004. Other years also mimic this SELR-LCL relationship. **(b)** Weak relationship between SELR and LCL is the characteristics of the cold-arid regime (South Pullu, 4700 m a.s.l.). **(c)** Sustained lower lapse rate observed at higher Section-2M during summer months (June, July, August and September) is explained by the higher humidity regime at Basecamp (3763 m a.s.l., blue line) as compared with that of lower section Tela (2450 m a.s.l.). Plots are 5 day moving average of daily values.

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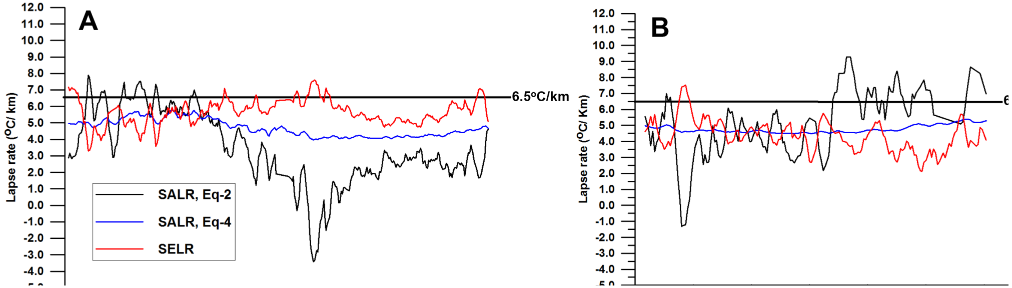

Figure 8. Temperature lapse rate calculated by using the Eqs. (2) and (4) showing significant deviation from the observed lapse rate. **(a)** Section-1M; **(b)** Section-2M. Plots are 5 day moving average of daily values.

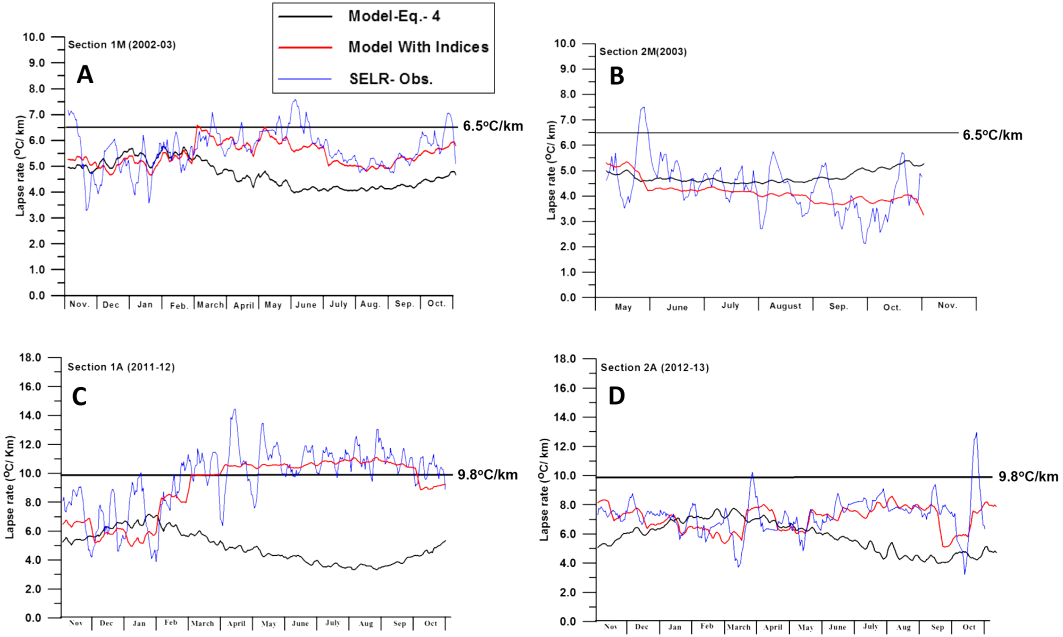

Figure 9. Modeled SELR using monthly indices of monsoon regime in **(a)** Section-1M, **(b)** Section-2M and cold-arid regime in **(c)** Section-1A and **(d)** Section-2A. Observed SELR and lapse rate derived by Eq. (4) are also shown. Plots are 5 day moving average of daily values.