Final response : Factors controlling Slope Environmental Lapse Rate (SELR) of temperature in the monsoon and cold-arid glacio-hydrological regimes of the Himalaya by Thayyen and Dimri

Thayyen and Dimri

We thank the reviewer for his/her elaborate and very useful constructive comments. We are certain that these inputs will help us in improving the manuscript. The comments are marked 'C' and followed by our response.

C1: We know very few information about the observational data used in this study. This paper cannot be published without more details on how are measured precipitation, temperature and moisture. The author should also detail the uncertainties associated with these observations. Does observations come from a specific Indian network? Or is this observational data collected specifically for this study? In addition, you should explain the possible uncertainties associated with this data, in particular those related to the difficulty to measure snowfall with rain gauges. Please refer to previous papers dealing with observational and modelling approaches showing that precipitation is potentially under-estimated in high altitude areas (e.g. Palazzi et al., 2013, Dimri et al. 2013). Ménégoz et al. (2013) estimated that that more than half of the total annual precipitation occurs as snowfall on average over a region located higher than 2500 m. a.s.l. at the border between Nepal and India. Shrestha et al. (2012) strongly corrected local measurements of precipitation considering snow depth and snow albedo measurements.

Response: The data used in this study was collected under two separate projects under the Indian Himalayan Glaciology programme by the Department of Science & Technology (DST). Govt. of India. The Dingad catchment is monitored under Dokriani glacier research programme by using the standard India Meteorological Department (IMD) equipment. These were manual stations operated to cater to the multidisciplinary expedition to Dokriani glacier during 1998-2004 periods. The data for the cold-arid region (South Pullu and Glacier stations) is collected from Ganglass catchment during 2010-2013 period. Data of Leh station (3500 m a.s.l.) is collected from IMD. This data is monitored by an AWS operated by the Indian Air Force. Data available with us from this station is limited to mean daily temperature and precipitation. The South Pullu station (4700 m a.s.l.) and the and Glacier station (5600 m a.s.l.) is operated by National Institute of Hydrology (NIH) under the Phuche glacier Project funded by the DST. The AWS at 4700 m a.s.l. is of Sutron make and AWS at 5600m a.s.l. is of Waterlog. Details of the temperature and humidity sensors will be added to the revise MS. We fully appreciate the problems associated with the precipitations measurements. Precipitation data is used only for describing the regional climatology and a section describing the specific humidity variation will be introduced. The methodology section will be strengthened by adding the station details, instruments and associated uncertainties.

C2: Observational data is not sampled during the same periods for the two different regions. It would have been better to use observations sampled at the same time for the two regions. If such observations are not available, the authors should investigate how the climate inter-annual variability may have affected their comparisons between the SELR observed in the two regions?

Response: The glacio-hydrological regimes of the Himalaya is primarily forced by the topography and presence or absence of large scale circulation of summer and winter monsoons. This regional climate prevail over these regions for centuries and have its imprint on all glacio-hydrological system components including glacier distribution. Here we are discussing the factors controlling the SELR variations under the regional climate perspective. Inter-annual variations are embedded in the regional climate characteristics of these two extreme glacio-hydrological regimes of the Himalaya. In general, the data availability of the monsoon regime is significantly higher than that of cold-arid regime. The regional and temporal extend of the role of the monsoons in SELR is evident from the work by Kattel et al. (2013) which also suggests persistent (1984-2004) monsoon lowering of SELR in the region dominated by the monsoon. Here we are evaluating (not comparing) the factors controlling the SELR variations of two distinct glacio-hydrological regimes of the Himalaya forced by the presence/absence of large scale weather systems in each region. Hence we feel that the inter-annual variations do not have significant influence on the processes governing SELR pattern of these regions.

C3: How is applicable such model in other hydrological catchments? What can we think about using it for Himalayan regions located at higher altitudes? This new calibrated model is certainly strongly dependent on the local atmospheric circulation. I am not sure that it can be used directly used in other Himalayan basins. The authors should explain more in detail the limits of the application of such a model in other regions. In addition, the authors should detail their calibration methodology to allow the use of their method by author scientists in other catchments of the Himalaya. Similarly, they should have to provide all the needed parameters and constants to the reader.

Response: Since we first reported the monsoon lowering of SELR in 2005 (Thayyen et al., 2005) for Dingad catchment, Kettel et al., 2013 have showed that the phenomena is indeed have region wide response covering large part of Nepal under the influence of Winter and summer monsoons. This shows that the observed SELR variations derived for Dingad catchment is forced by the orographic lifting associated with large scale circulations rather than local circulation. Figure 4D conclusively demonstrate this fact with similar response of cold- arid and monsoon regime SELR in response to winter monsoon covering both the regimes. Hence, it is prudent to conclude that the proposed relationship could be used in other regions under the winter/summer monsoon regimes. High altitude temperature measurement in the cold-arid region of Ladakh is really sparse. Some years of measurement by Snow & Avalanche Study establishment (SASE) at Patsio glacier in Spiti region also showed similar SELR response (personnel communication H.S Negi, SASE). Given the large scale circulation control on regional SELR under winter and summer monsoons regions point towards regional influence on summer SELR of cold- arid regime as well.

Data of higher altitude regimes of the Himalaya is further sparse. Existing research show declining precipitation of higher altitude region (Bookhagen and Burbank, 2010). Our data also shows reduction in the specific humidity at higher altitude of the monsoon regime. However, observed SELR of the highest altitude segment of both the regimes moved closer to the SALR and at the same time higher reaches experienced higher and steady humidity during the monsoon months indicating cooler and prolonged wet regimes, irrespective of the precipitation amount. Reduced SELR of higher altitudes of the both the regimes indicate that the basic orographic process is same under varying climate regimes. Study by Immerzeel et al. (2014) also showed SELR as low as 3.4^{o}C/km at higher altitude regions of Nepal Himalaya. However, more research under varying moisture conditions of the higher Himalaya is necessary to build a conclusive answer to this question. We hope that the present paper may trigger more such research in the higher Himalayan region.

The equations part is supplemented by the all necessary parameters and constants as suggested by the reviewer.

C4. The authors are using too few references to other studies estimating lapse rates over other mountains range. They should look for other studies based both in observational data and modelling approaches to check if similar findings have been found in other places, or to get a clearer idea of the specificity of the Himalayan region. As an example, Minder et al. (2010) and Feld et al. (2013) estimated lapse rates in other mountains. Regarding other modelling studies, the authors should consider both in the introduction and in the conclusion the limits of the application of a simplified model in comparison to full regional climate models. In addition, the authors should quote other studies based on the developments of large number of automatic weather stations (e.g. Whiteman et al., 2014).

Response: We have referred number of publications from other mountain ranges in the introduction (p 5648 lines 5-15). We will improve upon this by adding more studies and perspectives as suggested. As far as the limits of the application of a simplified model in comparison to full regional climate models are concerned, we hold the view that the incorporation of the new insights and modelling solution suggested in this paper may improve the performance of the RCM's.

C: Introduction, P5647,L.14: Ân Glacier change in the region is found to be comparable with other mountain glacier systems of the world (Zemp et al., 2009) Â˙z: Himalayan glaciers respond on a very different way to climate variations depending on their location along the mountain range (Kääb et al., 2012), so please modify this too vague statement.

Response: The sentence modified as follows

"IPCC (2007) report indicated higher rate of glacier melting in the Himalayan region. Systematic studies later shown that the glacier change in the Himalayan region is comparable with other mountain glacier systems of the world except that of Karakorum region (Zemp et al.,2009, Bolch et al., 2012). Reported mass gains of the Karakoram glaciers (Hewit,2005; Gardelle et al., 2012; Kaab et al.,2012; Gardelle et al., 2013; 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. 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; Bhutiyani et al., 2010; Shrestha et al., 1999; Dimri and Dash, 2012; Shekhar et al.,2010; Duan et al.,2006).”

C: P 5646, L17: focred * L.7, P 5649 : glacio-hydrolgical: Response : Implemented

C: P5650: Please, could you quickly describe the different sections of the paper at the end of the introduction?

Response: Modified the last part of the introduction to describe different sections of the paper as suggested.

C: P5650, L10: “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.” Please indicate the exact location of Garhwal, Ladakh and Dingad region on Fig. 1.

Response: Figure will be updated as suggested

C: P 5651: In Section “methodology”, Could you add more details concerning the description of the meteorological stations used for this study? (See major comment 1).

Response: Methodology section will be improved by adding the descriptions of meteorological stations as suggested.

C: P5651, L2: Please detail where do come from the observations showed in Fig. 3. (Major comment 1).

Response: This data comes from the present study as detailed in the methodology. Please also see the response to major comment 1.

C: P5651: Methodology: Could you discuss the uncertainties induced by the fact that observational data is not sampled during the same periods for the two different regions? (See major comment 2).

Response: Please see the response to the major comment -2.

C: P5652, L25: Why Section-1M has been computed with the lower and upper stations (2540 and 3763ma.s.l.) whereas Section-1A has been computed with the lower and intermediate stations (3500 and 4700ma.s.l.)?

Response: As stated; the sections were selected based on the data availability. There is no winter data available at intermediate station of Dingad at 3483 m a.s.l. The glacier station at 5600 m a.s.l. in commissioned only in 2012 and have only one year of data. However, it is seen that the Lower and Upper stations and lower and intermediate station have same SELR response. Distinction is between lower and upper/intermediate station pairs and intermediate and upper stations.

C: P5654: Section 4.2: Precipitation: If rain gauges do not catch snowfall, it is tricky to discuss the vertical gradient of precipitation. What do you think about the quality of snowfall measurements that you used? You find that precipitation is not varying with the altitude in the Dingad catchment, what do you think of the uncertainty related to this finding?

Response: All the precipitation data used in the study comes from the rain/snow captured in the standard rain gauges with its inherent uncertainty for snow fall data. Summer rainfall indeed show differences with higher precipitation at the intermediate station. Please note that the altitude range we are discussing in this paper in the Dingad catchment is rather small (2540-3763 m a.s.l.) for the precipitation regime to introduce significant variations. Moreover, significant amount of precipitation at lower station Tela (2540 m a.s.l.) occur as rainfall in winter and as snowfall at higher stations. In summer, all the stations experiences rainfall. This allows a credible comparison between these stations. Snowfall data is not used for any calculation or interpretation in the paper but to describe the general climatic characteristics of the two regions. We will be upgrade this section by discussing the specific humidity variations along with precipitation as suggested by the reviewers.

C: P5655: L13: “Hence we strongly believe that this phenomenon is a characteristic of Himalayan catchments.” Do you think such phenomenon cannot be observed over other mountain ranges?

Response: Yes. The data presented by Kettle et al (2013) clearly suggests that it is a regional phenomena governed by the large scale weather systems. Comparable SELR response of cold- arid and monsoon regimes during winter months in response to the winter monsoon also suggests the same. Distinction between ‘Himalayan catchments’ versus ‘Alpine catchment’ and ‘Cold-arid catchment’ is Indian Summer Monsoon. Please see the definition of “Himalayan catchment” in Thayyen and Gergan (2010). In general, the statement holds good for any mountain region with prominent summer monsoon moisture inflow.

C: P5658, L15: Please, could you explain in details how was constructed the theoretical SALR curves in Fig.6? You should indicate both in the text and in the caption if you used the equation (2). In addition, could you indicate the full description of vertical axis of this graph? It would be also relevant to show a similar graph for DALR for a better comprehension of your analysis. Some references to SALR and DALR, based on both theoretical and experimental approaches should be added in the manuscript.

Response: Theoretical SALR curves in Fig.6 is calculated by equation -4. This will be indicated in the caption and text. Vertical axis title is updated as ‘Saturated Adiabatic Lapse rate’ and Y2- axis title (Temperature ^{o}C) will be added. As DALR did not have either pressure or temperature control we thought of avoiding the cold-Arid system SELR distribution on the SALR- Pressure graph. Section-1A during winter months and Section 2A during winter and summer months (cold-arid system) indeed influenced by the moisture. We will plotted the Cold-arid SELR on the SALR- atm. Pressure-Temperature graph for comparison as suggested and will present as Figure 6b.

C: P5660, L10: Please, could you explain where do come from these humidity observational data sets? It could be introduced in Section 3 for example.

Response: Humidity and specific humidity measurements are detailed in Section-3 and variations in the specific humidity in both the regime is elaborated in the section 4.2.

C: P5661: Modelling Section: Please detail which data has been used to make the graphs 8 and 9. We suppose local temperature observations have been used, but did you also use pressure data? You should also indicate which values were used for all parameters and constants.

Response: Yes. To implement equation-2 for section -1M saturation vapour pressure at lower (2540 m a.s.l.) and upper (3763 m a.s.l.) stations were derived from mean daily temperatures of respective stations. For Section 2M; lower (3483 m a.s.l.) and upper (3763 m a.s.l.) mean daily temperatures are used. Standard station pressure data is used to calculate the Ws, saturation mixing ratio at each station. Values used for parameters and constants are included in the revised text. 'dz' used in the equation consider pressure in vertical co-ordinate systems and hence role of pressure change in the present set of modelling efforts are also considered.

C: P5665, L10: The modelled values seem to have a low standard deviation compared to observations. Is it due to the monthly time-step application of the model? Which results would have got with daily time-step?

Response: No. Model is run on daily –time step as shown in Figure-9. Lower standard deviation of the modelled daily SELR in comparison to the observations is due to the monthly SELR indices used in the model (Eq.8). Monthly mean of observed SELR and that of modelled SELR show further improvement.

C: Conclusion: P5666, L24: "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". Is this remark valid for higher altitude areas of the Himalayan Mountains? If all the moisture is condensate/evaporated at intermediate altitude, could high altitude areas be characteristic of arid regions?

Response: This question has bothered us also for long. If we are discussing the entire vertical extent of the Himalayan orogeny from its foothill zones of Shivaliks to the Great Himalaya or to the Karakorum; it is true that there could be arid regions at higher altitudes. The Cold –arid system of Ladakh exactly represent this phenomena. But here were limiting our discussion to the glacio-hydrologic regimes, meaning we are discussing higher altitude regions of glacial/ Nival systems of the Himalaya, above 3500 m a.s.l. in the Ladakh and above 2000 m a.s.l. in Monsoon systems. An important consideration is the orographic continuum of the mountain slopes as indicated in the Figure-3. Leh region at valley bottom disconnected from the orographic continuum of the lower Himalaya and about 10^{o}C warmer in summer than the station in the monsoon system connected with the orographic continuum. Even in the arid regions, lower lapse rate in the higher altitude region is leading to colder and wetter mountain tops with the presence of glaciers as evident from the Ladakh and Zanskar mountain ranges. We are also aware of the monsoon shadow zones within the monsoon regime, which actually suggests a orographic discontinuity, and may emerge as a distinct glacio-hydrologic regime as research progresses.

C: Please consider in your introduction previous studies based on both observational and modelling approaches that have been performed in other mountain range to estimate lapse rates (see major recommendation 1).

Response: Introduction is updated with more details as suggested

C: References: please check the references.

Response: Implemented

C: Figure 2: Please increase the size of the text on the maps that is difficult to read.

Response: Implemented

C: Figure 6: This Figure is not clear. Please, could you add more information concerning the vertical axis information?

Response: Implemented

C: Figure 8: Please add the horizontal time axis indicating the months for more clarity.

Response: Implemented

C: Figures 4-6-7-9: Please increase the size of the axes captions.

Response: Implemented

References

Immerzeel,W.W., Petersen, L., Ragettli, S., Pellicciotti, F. The importance of observed gradients of air temperature and precipitation for modeling runoff from a glacierised watershed in the Nepalese Himalayas, Water. Resou. Res., 50(3) doi.10.1002/2013WR014506, 2212-2226, 2014

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