# Improving Model Projections and Vulnerability Assessments by Adapting Land Surface Feedback within Regional Climate Studies over the Western Himalayas

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## 1 Introduction

Snow cover over the Hindu Kush Himalayan (HKH) region is of vital importance for northern Indian water resources. Important North Indian river basins, viz. Indus, Ganges, and Brahmaputra have their headway origin there and rely on the ablation period snow melt. Agriculture, animal husbandry, habitat, and regional socio-economic aspects traditionally depend on the snow cover and winter water storages. On the other hand, heavy snowstorms cause rapid river flooding in the hilly regions as well as avalanches. These disasters not only affect human lives and property but also have a significant negative impact on local businesses and tourism. Understanding the evolution, trend, and spatial distribution of accumulation and/or ablation of snow mass over the HKH region thus remains an important issue. Regional assessments are challenging due to the remote and often inaccessible, complex topography which pose difficulties in conducting measurements and maintaining long- term observations that are regionally representative. Also, in addition to assessing the traditional climatological parameters such as temperature and precipitation, for the HKH region, snow depth measurements and the snow to snow water equivalent estimation become critical parameters to gauge the regional hydroclimatic changes across the HKH.

In this paper, we present a perspective on the climatic impacts reported over the HKH region. This is then followed by a focus on the need for considering land surface and local-scale feedbacks in developing an enhanced regional understanding. The final section highlights the need to consider a local or a bottom-up feedback not just into the dynamic processes but also for assessing vulnerability to different stressors in developing regionally sustainable policy input.

## 2 Large-Scale Feedbacks on the HKH Region

The IPCC (2007) reported that mountain ranges and their downstream areas are particularly vulnerable to climatic changes. Using multi-decadal climate model predictions, temperature increases are projected to be larger in high mountains than at lower altitude (Bradley et al. 2006). Also, mountain areas exhibit a large spatial variation in climate zones due to large differences in altitude over small horizontal distances (Beniston et al. 1997). Documenting the relations with elevation and warming trends in the Indus basin, Immerzeel et al. (2009) reported an increase from 0.028$^{o}$C/yr at 2000 m to 0.043$^{o}$C/yr at 5000 m. Such changes are also reported by Bradley et al. (2006) for the Andes Mountains.

Within the context of global changes, different global modeling studies indicate a pronounced reduction in seasonal snow cover for the Himalayan region (Watson et al. 1996; Aizen et al. 1997). However regional exceptions are also hypothesized with higher snowfall during warming climate in the cold regions (Houghton et al., 1996). The patterns of expected changes in snow cover are thus highly uncertain. This uncertainty is even higher for snow depth projections and for regional-scale estimates.

Similar to the snow cover changes, retreating glacier extents have also been reported by a number of researchers. In the Himalayan context, Koul and Ganjoo (2010) have shown negative mass balance based on a three year study on Naradu Glacier. Similar conclusions are provided by Bhutiyani (1999) for Siachen Glacier and by Wagnon et al. (2007) for Chotasigri Glacier. For the Siachen Glacier, however, Raina and Sangewar (2007) report that its retreat has halted since about 1958. Studies by Qin et al. (2000), Ren et al. (2004), and Jin et al. (2005) have shown large area shrinkage in the Himalayan glaciers. A study by Shi (2001) concluded that regional warming is causing increased glacier shrinkages in mountainous areas. Others have proposed the deposition of black carbon from biomass burning and industrial and vehicular emissions as causing this shrinkage (Menon et al. 2010). Similarly, due to increase in temperature patterns around the Siachen and Chotasigri Glaciers, it is hypothesized that regional warming will cause increasing ablation. As a result, Dimri and Dash (2010) suggested that the equilibrium line altitude will be at a higher altitude in the future. Hence ablation in the tongue zone will exceed the ice amount moved from the accumulation zone leading to glacier thinning and retreat.

Interestingly, the Himalayan snow cover also has important dynamical feedbacks on the HKH climate (Bamzai and Shukla 1999; Liu and Yanai 2002; Zhao and Moore 2006). HKH is in a low latitude region and the magnitudes of insolation and shortwave radiative forcings are large. Glaciation also plays an important role in the regional radiation budget. The cryosphere-atmosphere interactions over HKH can bring dynamical perturbations at the regional scale. Paleoanalysis suggests that the expansion of the continental ice sheet during ice ages has illustrated such extreme changes in boundary conditions which force the atmosphere (Broccoli and Manabe 1987; Manabe and Broccoli 1985; Hall et al. 1996; Weaver et al. 1998; Bush and Philander 1999). Both dynamical steering of atmospheric winds and changes in the radiation budget due to topographic HKH snow cover can provide a positive snow albedo feedback (Crowley 1984; Crowley and North 1991). At a shorter time scale, the snow albedo feedback will play an important role in regulating the annual mean regional climate over the HKH region. Also, the albedo feedback can influence regional temperature as strong radiative cooling or warming of the atmosphere can provide a forcing mechanism for driving atmospheric circulation. Since the subtropical region of the HKH receives more solar radiation than that at higher latitudes (Kuhle 1988), such feedback over the HKH can produce stronger cooling of the atmosphere resulting in atmospheric circulation anomalies through Rossby waves which could potentially influence the moisture source for the region. Such changes can possibly influence both the summer and wintertime monsoon circulations and thus regulate the regional climate over south Asia (Hahn and Shukla 1976; Dickinson 1984; Dey and Bhanu Kumar 1982; Dey et al. 1985; Ropelewski et al. 1984; Benn and Owen 1998).

## 3 Regional Variability in Climatic Patterns

The HKH region has pronounced topographic variability and is characterized by different land use from west to east and a large corresponding variation in precipitation and temperature patterns. Over the western part, almost two-thirds of the annual precipitation is received via cyclonic storms in the westerlies and the remaining from the summer monsoon (Wake 1989). Over the central HKH region, for both the winter and summer seasons, and over the east Indian summer, the monsoon rainfall is the dominant contributor. Over the west, a warming of 1.6$^{o}$C in last century, with faster winter warming has been observed (Bhutiyani et al. 2007). Similar increases in maximum and minimum temperature of 1$^{o}$C and 3.4$^{o}$C is observed in the western Himalayas (Shekhar et al. 2010; Dimri and Dash 2011). In contrast, the Karakoram Range has experienced a decreasing trend in maximum and minimum temperatures (Dimri and Dash 2010; Shekhar et al. 2010) along with an increase in winter precipitation. In the central Himalayas, precipitation has decreased in Uttarakhand regions with dramatic shifts in the precipitation regimes rather than a gradual decrease (Basistha et al. 2009). However, in the Nepal region of the central Himalayas no distinct long-term trend in precipitation has been reported. The Nepal monsoon record also shows large variability and is highly correlated with the Southern Oscillation Index (SOI) (Shrestha et al. 1999). In the case of temperature, a warming trend of 0.06 to 0.12$^{o}$C/yr and 0.03$^{o}$C/yr is seen over the Himalayan and Siwalik regions, respectively (Shrestha et al. 1999; Baidya et al. 2008). In the eastern part of the Himalayas, larger variability is noted with some stations showing increasing, while some others showed decreasing trends in the observed diurnal temperature range (Jhajharia and Singh 2010). However, a much more robust warming pattern has been observed during monsoon and post monsoon seasons. Possibly as a thermodynamic feedback of the warming, Dahe et al. (2006) has shown that western China snowfall has consistently increased, but they caution that the mechanisms underlying this phenomenon warrant further study on a regional scale. Dahe et al. (2006) also found that the eastern part of the Qinghai-Xizang (Tibet) Plateau is affected by the most substantial year-to-year fluctuation in snow depth. Similar variation in Eurasian snow cover is found by Vernekar et al. (1995).

Immerzeel et al. (2009) has shown significant negative trends for winter snow cover in the upper Indus basin based on observations between 2000 and 2008. A similar decreasing trend with -0.34%/year is seen over the Tibetan Plateau (Pu et al. 2007). Gurung et al. (2011) concluded that the amount of annual snowfall is correlated with annual seasonal snow cover for the western Himalayas indicating that changes in snow cover are due to interannual variations in circulation patterns. They found a linear trend in annual snow cover in the HKH region from 2000 to 2010 of –1.25±1.13%, which is significantly less than reported for the period between 1990 and 2010 (Menon et al. 2010).

## 4 Considering Regional Land Surface Feedbacks

To model regional climate feedbacks, a number of methodologies are being suggested including multiple nesting (Leung and Qian 2003; Christensen et al. 1998) or parameterization of subgrid-scale processes (Giorgi and Avissar 1997) to account for local-scale processes and optimize the computational needs. Employing such downscaling methods provide finer representation of climate at the regional scale. Moreover, it is assumed that with correct representation of complex and variable topography in the HKH, regional simulations are needed in order to have statistically meaningful results and to be able to compare simulated and observed precipitation and temperature anomalous for specific months and seasons (Luthi et al. 1996; Jenkins and Barron 1997; Walsh and McGregor 1997).

Land surface heterogeneity due to topographic and land use variability can modulate the regional climate by regulating the land-atmosphere exchanges of heat, water, and momentum (Giorgi and Mearns 1991; Feddema et al. 2005; Giorgi and Avissar 1997; Pielke Sr. 2001; Dimri, 2009; Im et al. 2010; Pielke and Niyogi 2010). For example, during winter, high amounts of precipitation, mostly in the form of snow, is caused by eastward moving low-pressure synoptic weather systems called Western Disturbances (WDs) (Pisharoty and Desai 1956; Rao and Srinivasan 1969; Singh 1979; Kalsi 1980; Kalsi and Haldar 1992; Dimri and Mohanty 2009). Mesoscale processes including the land surface and topographical feedbacks can directly impact the structure of propagating synoptic systems and trigger convective and organized circulation patterns that can affect the location and amount of winter precipitation.

Recently, Dimri and Niyogi (2011) conducted experiments with a combination of the subgrid scheme of Seth et al. (1994) within a framework of a regional climate model (the RegCM3, Pal et al. 2007). They conducted an experimental suite with twenty two (22) years (1980 – 2001) of winter season (DJF) simulations to assess the effect of fine-scale subgrid land scheme on the regions precipitation and temperature patterns. Analysis of two simulations: a control run (CONT), in which the sub-BATS scheme is not used and therefore the land surface has the same resolution as the atmosphere (grid intervals of 60 km), and subgrid scale run (SUB), in which each coarse grid cell is divided into 36 subgrid cells (with 10 km grid increments), was conducted. The model was forced with interpolated, 6-hourly intervals from the National Centers for Environmental Prediction (NCEP) Reanalysis II data (Kanamitsu et al. 2002). The SST over the ocean areas is obtained from the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) SST dataset with a horizontal spacing of 1-degree at a weekly time interval. Two observational datasets were used for the evaluation of the seasonal (DJF) precipitation and surface air temperature simulations. These included the 0.5 degree spatial increment global land datasets developed by the University of East Anglia Climate Research Unit (CRU) (New et al. 2000); and station observations from the Snow and Avalanche Study Establishment (SASE), Chandigarh, India at three WH stations: Gulmarg (34$^{o}$30’00”N, 74$^{o}$29’00”E, alt 2800 m), Bhang (32$^{o}$16’33”N, 77$^{o}$09’03”E, alt 2192 m), and Base Camp (34$^{o}$11’49”N, 77$^{o}$12’28”E, alt 3570m). These stations represent different climatic and geographic conditions of the WH and have the longest records available.

Model simulations show that topographic forcing on the precipitation and temperature is an important driver for capturing regional snow cover changes. CONT simulation was able to reproduce the climatology of the simulated region well both in the spatial and temporal patterns of precipitation and temperature over the WH. Simulations with the SUB experiment produced finer and more realistic details of temperature variations in response to the topographic disaggregation. Considering the fine-scale surface features also produced improvements in the precipitation statistics and particularly the snow amounts. Other components of the hydrologic cycle were also found to be strongly affected by the fine-scale representation. The improvements in the model results occurred because of the ability to resolve mesoscale convection as well as capturing many of the circulation patterns that have been observed in satellite and observational analysis (e.g., Lang and Barros 2002; Medina et al. 2010).

Thus, topography and land use information can especially be of use in understanding the precipitation and temperature variability over the complex terrain of the WH, which is poorly represented in coarse resolution models. Inclusion of this should lead to a better understanding of seasonal evolution of precipitation and temperature patterns. Further, while it is difficult to separate out effects of subgrid scale topography and land use from model simulations, it appears that the main forcing for the sensitivity towards wintertime weather – WDs- in mid-latitude domain is topographic variability. Overall, the consideration of fine-scale processes is assumed to provide a useful improvement in the model results.

## 5 Regional Analysis is Useful but not Sufficient

While in the above section we discussed the use of a regional model to downscale the past climatic patterns and understand the processes, there are inherent limitations and problems that need to be highlighted. Understanding these limitations is important because statistical and dynamic downscaling from the multi-decadal global model predictions is the dominant approach of developing regional and local impact assessments decades into the future. Thus, even though the downscaling approaches provide information at regional and finer scales, the results need to be evaluated using different measures for their robustness. One inherent problem over the WH is that, due to limited observations, the validation of the performance of the different models and modeling approaches cannot be rigorously pursued. Moreover, the models need to only be able to skillfully predict the current climatology of the HKH region, but they must skillfully predict the changes in this climatology due to human climate forcings. Evaluation of such a test, of course, can only be pursued in hindcast model runs. .

Further, building off the analysis presented in Pielke et al. (2011), the downscaled analysis needs to have following features:

(i) Representation of all processes that are important at the different scales. For the HKH region and the Indian monsoon region these include explicit consideration of the aerosols as well as land surface feedbacks [see for example: NRC 2005].

(ii) Recognition that global multi-decadal predictions are generally unable to skillfully simulate major atmospheric circulation features such the Pacific Decadal Oscillation [PDO], the North Atlantic Oscillation [NAO], El Niño and La Niña, and the South Asian monsoon that have high relevance to the hydroclimatology of the HKH region (Pielke Sr. 2010; Annamalai et al. 2007; Compo et al. 2011).

(iii) Recognize that while dynamic regional downscaling yield higher spatial resolution, the regional climate models are strongly dependent on the lateral boundary conditions and interior nudging by their parent global models (e.g., see Rockel et al. 2008). Large-scale climate errors in the global models are retained and could even be amplified by the higher spatial resolution regional models.

(iv) The regional models themselves do not have the domain scale (or two-way interaction) to skillfully predict the larger-scale atmospheric features such as ENSO/SOI, PDO, and NAO, as well as the dynamical feedbacks caused by landuse changes (Pongratz et al. 2011).

(v) There is also typically one-way interaction between regional and global models which may not be physically consistent. If the regional model significantly alters the atmospheric and/or ocean circulations, this information is typically not transmitted to alter the larger-scale circulation features which are being fed into the regional model through the lateral boundary conditions and nudging.

Additionally, when higher spatial analyses of land use and other forcings are considered in the regional domain, the errors and uncertainty from the larger model still persists thus rendering the added complexity and details ineffective (Ray et al. 2010; Mishra et al. 2010). Indeed, there is a value for predicting climate change from global models so as to help frame the issue and identify one set of plausible future climates for regional decision makers, it needs to be recognized that there has been no demonstrated demonstration of skillful predictability in translating the model results into changes in seasonal to weather scale climatological patterns from what currently exist using historical and recent paleo-record climate data. As highlighted in Dessai et al. (2009) the finer and time-space based downscaled information can be "misconstrued as accurate", but the ability to get this finer-scale information does not necessarily translate into increased confidence in the downscaled scenario (Wilby 2010).

Due to these limitations of providing skillful regional and local climate impact assessments based on global climate models, as well as the limited range of plausible climate conditions that they predict, a vulnerability based approach would be of value to the HKH region, and is discussed in the following section.

## 6 From Climate Projections to Vulnerability Assessment

Pielke et al. (2011) identify two approaches to assess the vulnerability of a region to climate variability and longer-term change. The following text follows closely from that paper. The two approaches to assess vulnerability of the HKH region are to apply a top-down global climate model driven assessment (referred to as outcome vulnerability) and/or to apply a bottom-up, resource-based focus assessment (referred to as contextual vulnerability).

The current scientific perspective is dominantly top-down and greenhouse gas emission centric, and focuses on multi-decadal global climate model predictions. This typically involves using the global model results downscaled to regional and local scales for societal and environmental impact models. In general terms, this follows the results typically developed for the IPCC multi-model ensembles i.e. Working Group 1 (Solomon et al. 2007) to the Working Group 2 reports (Parry et al. 2007), which culminate in the Working Group 3 studies (Metz et al. 2007) within the IPCC framework. This approach is useful for global policymakers and has also been adopted in a number of studies at regional and local scales (e.g., Schroter et al. 2005; Metzger et al. 2006; Schneider et al. 2007).

For the HKH region, such a top-down approach alone will not be sufficient. This is because, considering the challenging topography and other factors discussed in earlier sections, if the ensemble of GCM projections and actual climate trajectory differ significantly in coming decades, recognition of this error may occur too late for policymakers to realign the adaptation/mitigation strategy in order to respond to the actual state of climate at the local/regional scale. Therefore, if the adaptation strategy considers more scenarios, then it could potentially handle a broader margin of error than the constrained GCM projections centric approach.

Also, GCM-based climate change projections are at relatively coarser resolution (Solomon et al. 2007), whereas the impacts and potential mitigation policies of interest to stakeholders are mostly at local to regional scales (Klein et al. 1999). However, the resilience to such increased occurrence as well as changes in the intensity of such societally important events such as heavy snowfall, droughts etc. is dependent on the local-scale environmental conditions (such as moisture storage and convective rainfall), and farming approaches (access to irrigation, timing of rain or stress, etc). Multi-decadal IPCC-type forecasts, if used without consideration of regional and local vulnerabilities, can lead to misleading outcomes and actions for the impacts and adaptation community as well as for policymakers (Patt et al. 2010; Pielke Jr. et al. 2007).

Thus, while the IPCC Fourth Assessment Report Working Groups (2 and 3) does discuss vulnerability (Pielke Sr. and Niyogi 2010; Schneider et al. 2007) it is based on the multi-decadal global model predictions as the starting point (i.e., a top-down approach). The IPCC identifies seven criteria for “key” vulnerabilities: magnitude of impacts; timing of impacts; persistence and reversibility of impacts; likelihood (estimates of uncertainty) of impacts and vulnerabilities and confidence in those estimates;

potential for adaptation; distributional aspects of impacts and vulnerabilities; and the importance of the system(s) at risk. The IPCC uses the "outcome vulnerability" or a top-down driven perspective to assess these seven criteria.

The contextual vulnerability, assesses risks to key resources by not limiting to subset of threats from the GCM projection but the entire spectrum of risks are considered. There are five broad areas that we can use to define the need for contextual vulnerability assessments: water, food, energy, human health, and ecosystem function. Transportation is often a binding feature of these vulnerabilities and is thus an inherent contextual area as well. Each sector is critical to societal well-being. The vulnerability concept requires the determination of the major threats to these resources from climate, but also from other social and environmental pressures. After these threats are identified for each resource, relative risks can be compared in order to shape the preferred mitigation/adaptation strategy either from past experience, data analysis, and/or expert advice.

The questions to be asked for each key resource are:

a. Why is this resource important? How is it used? To what stakeholders is it valuable?

b. What are the key environmental and social variables that influence this resource?

c. What is the sensitivity of this resource to changes in each of these key variables? (This may include but is not limited to, the sensitivity of the resource to climate variations and change on short (days); medium (seasons) and long (multi-decadal) time scales).

d. What changes (thresholds) in these key variables would have to occur to result in a negative (or positive) outcome for this resource?

e. What are the best estimates of the probabilities for these changes to occur? What tools are available to quantify the effect of these changes? Can these estimates be skillfully predicted?

f. What actions (adaptation/mitigation) can be undertaken in order to minimize or eliminate the negative consequences of these changes (or to optimize a positive response)?

g. What are specific recommendations for policymakers and other stakeholders?

This for the HKH region can be a more inclusive way of assessing risks, including from climate variability and climate change, than using the outcome vulnerability approach alone.

## 7 Summary

Long-term climate change from the diversity of human climate forcings (due to added greenhouse gases, aerosols, land use change) are underway over the HKH region. These forcings occur on a scale larger than the HKH but also regionally. We have highlighted a need to consider the fine-scale/local climate forcings and feedbacks within the dynamical models. We also propose a bottom-up, resource-based vulnerability – adaptation/mitigation perspective. It is anticipated that developing such an approach would complement the top-down global model-based analysis approach and will significantly enhance the information needed by the policy makers over the HKH region.

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