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Wintertime Seasonal Scale Simulation over Western Himalaya Using RegCM3

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Abstract—The Himalayan region of north India is composed of complex mountain ranges with different altitudes and orientations, causing prevailing weather conditions to be complex. Wintertime eastward moving synoptic weather systems 'Western Disturbances' (WDs) yield large amounts of precipitation over this region. Numerous micro/mesoscale circulations become generated along with prevailing weather due to surface heterogeneity and land-use variability of the Himalayan region. WDs along with these circulations may give rise to very adverse weather conditions over the region. Intraseasonal variability of surface climate over the Himalayas is studied using regional climate model (RegCM3) with 60 km resolution. A 6–month (Oct. 1999–Mar. 2000) period, as this period has received an enormous amount of precipitation in the form of snow, is considered to study surface climate variability in terms of temperature, precipitation and snow amount. Model simulations show cold bias over the Himalayan region and warm bias over northwest India. Average monthly distribution of temperature indicates that a controlled experiment could capture the areas of lowest temperature regime. Precipitation fields could be simulated only up to a certain degree of satisfaction and the influence of topographic elevation and valleys needs to be seen. RegCM3 provides a representation of resolvable atmospheric circulations that results in explaining mean variability during winter.

Key words: Snow, seasonal scale simulation, Western Himalaya.

1. Introduction

The Indian part of the Himalayas is composed of complex mountain ranges with different altitudes and orientations, which causes the prevailing weather conditions to be complex. Surface weather elements such as precipitation and temperature are intensely governed by local topography (Dimri, 2004) and local atmospheric circulations (Mohanty and Dimri, 2004) by virtue of thermodynamical and dynamical forcings. Also, numerous micro/mesoscale circulations in the narrow valleys and rugged hills are generated due to surface heterogeneity of northern Indian

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Himalaya. This heterogeneity determines the precipitation and temperature pattern over the region (DIMRI and MOHANTY, 1994). Topography exerts a strong dynamical forcing on the atmospheric circulations and land surface exchanges. As a result, land atmosphere interactions substantially impact weather and climate patterns and the water and energy cycles of the climate systems (DICKINSON *et al.*, 1995; PIELKE and AVISSAR, 1990).

To study the impacts of various forcings at the regional scale, regional climate models (RCMs) are useful tools for studying mesoscale climatic processes. These previous multilayered experiments, over the united states (GIORGI *et al.*, 1993a), eastern Asia and Japan (HIRAKUCHI and GIORGI, 1995), and Europe (MARINUCCI and GIORGI, 1992; JONES *et al.*, 1995), have shown that RCMs have worked well over various domains over the globe. Also, various researchers have carried out regional climate simulation to study monsoon behavior over the Indian region. BHASKARAN *et al.* (1996) has compared seasonal simulation of the Indian Summer Monsoon with a set of three RCMs, which shows the strong orographically forced mesoscale component. Similarly, GOSWAMI and SHUKLA (1984) have studied quasi-periodic oscillation in a symmetric general circulation model and have demonstrated the impact of large-scale dynamics on the strength of the monsoon. Though numerous studies were carried out by various researchers over the Indian region they mainly pertained to the summertime monsoon phenomena and considerably less studies on multilayer integrations/simulation with RCMs during winter over the complex Himalayan region have been reported.

Therefore, in the present work an attempt is made to simulate the wintertime weather over the Indian region with a focus on mean climate conditions and intraseasonal variability. Further, most of the RCM studies have been focused on mean climate conditions and much less is known about interannual and intraseasonal variability. Therefore, the goal of this study is to provide details of intraseasonal variability. This is important for several reasons. First, the degree of similarity between modeled and observed intraseasonal precipitation variability is an important model diagnostic, as it is one way of putting sensitivity testing of a RCM to a range of meso/microscale atmospheric conditions. Second, change in precipitation has substantial socio-economic impact at the regional scale. Therefore, it is critical to evaluate when and where climate anomalies are predictable and to assess the performance of RCMs in reproducing them. Third, the intraseasonal variability of precipitation may change due to anthropogenic increases in atmospheric Greenhouse gases.

In this work (1) the mean climatic conditions and (2) the intraseasonal variability of temperature and precipitation during a particular winter season, Oct. 1999–Mar. 2000, over the western Himalayas is studied. These two issues are studied by simulating the Abdus Salam International Center for Theoretical Physics (ICTP)—RegCM3 model driven by the National Center for Environmental Prediction, US, (NCEP) observed boundary conditions. Hence, a series of regional climate simulations of six months duration over the Himalayan region is tested. The focus of the study is particularly on the Indian Himalayan region, where the heterogeneity is maximum.

In section 2, a brief description of the model and experimental design is presented. The results are discussed in section 3 and final remarks are given in section 4.

2. Model and Experimental Design

The regional climate model used in the present work is the version of RegCM developed by GIORGI *et al.* (1993a,b) with some of the updates discussed in GIORGI and SHIELDS (1999). The dynamical core of the RegCM is equivalent to the hydrostatic version of the fifth-generation Pennsylvania State University—National Center for Atmospheric Research (NCAR), US, Mesoscale Model (MM5). For the present simulation, the standard model configuration is used with 23 sigma levels, with the medium resolution PBL scheme with five levels in the lowest 1.5 km of the atmosphere, at approximately 40, 110, 310, 730 and 1400 m above surface (GIORGI and BATES, 1989). The physics parameterization employed in the simulations includes the radiative transfer package of the NCAR Community Climate Model version 3 (CCM3, KIEHL *et al.*, 1996), the nonlocal boundary scheme by HOLTSLAG *et al.* (1999) and mass flux cumulus cloud scheme of GRELL (1993).

Land-surface processes are described via Biosphere-Atmosphere Transfer Scheme or BATS (DICKINSON *et al.*, 1993). BATS is a state-of-the-art land-surface model that has been used for many years by a wide research community. It consists of a vegetation layer, three soil layers for soil water content calculations and a force restore method to calculate the temperature of a surface soil layer and a subsurface soil layer. At each model grid point a vegetation class is assigned as dependent on seasonal parameters including roughness length, maximum and minimum leaf area index, stem area index, vegetation albedo and minimum stomatal resistance. The parameter values are given by DICKINSON *et al.* (1993) for 18 land-surface classes.

In the presence of the vegetation, the temperature of canopy air and canopy foliage is calculated as demonstrated from the canopy energy balance. Sensible heat, water vapor and momentum fluxes at the surface are computed using a standard surface drag coefficient formulation based on a surface layer similarity theory. Surface evapotranspiration accounts for evaporation from the soil and the wet portion of the canopy and transpiration from the dry portion of the canopy. Ground evaporation and transpiration rates depend on the soil water content, which is a prognostic variable.

The soil hydrology calculations include predictive equations for the water content of the surface soil layer, the root zone, and a deep soil layer characterized by depths of 10 cm, 1–2 m, and 3 m, respectively. These equations account for precipitation, snowmelt, canopy foliage drip, evapotranspiration, surface runoff, infiltration below

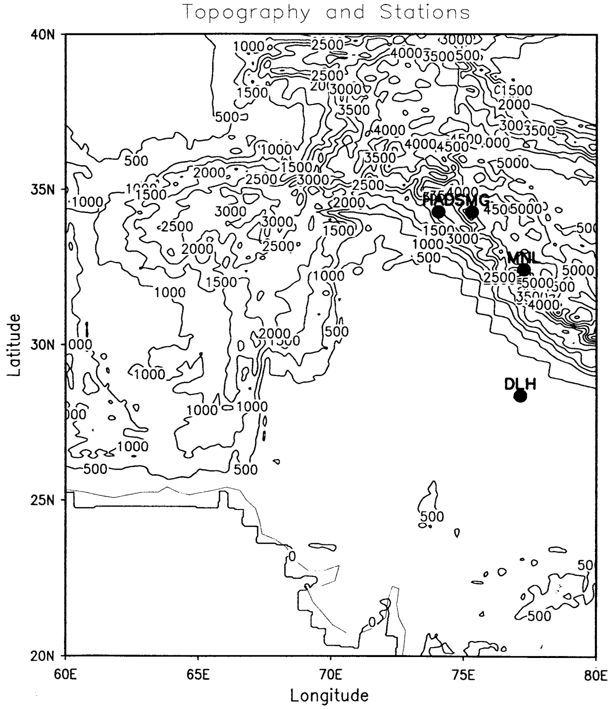

Figure 1
Domain topography (km) in the control simulation. The model grid cell size is 60 km.

the deep soil (which we refer to as base flow), and soil water movement under gravitational and capillary forces. The surface runoff rate is proportional to the precipitation + snowmelt rate and the degree of soil water saturation. Snow depth is prognostically computed from snowfall, snowmelt and sublimation.

In this paper, a control simulation is made over the domain and topography as shown in Figure 1. The computational domain is considered from the Mediterranean Sea to India using a Lambert conformal projection with grid cells of 60 km $\times$ 60 km size to understand the flow pattern of the wintertime synoptic weather system called 'Western Disturbance (WD)'. However, in the present work discussion is mainly associated with surface parameter variabilities over the Indian Himalayan and surrounding areas. The topography for control grids is obtained from a 30" (about 1 km) resolution global data set produced by the Geological U.S. Survey (USGS). The land-use distribution for the control experiments is also obtained from a 30" landuse data set produced by USGS (LOVELAND *et al.*, 1991). A version of this data set is already available in the form of BATS surface types. From the 30" data set we calculate the fractional cover of different surface types for each cell of the different model grids, and the grid cell is then assigned the surface type with the largest fractional cover and henceforth considering landuse and soiltype.

A 6-month simulation for the period starting from October 1, 1999, and ending on March 31, 2000, which encompasses a full winter season, is made. This particular period is chosen for the study, as an enormous amount of precipitation in the form of snow was received/recorded at SASE observatories located in the Indian part of the western Himalayas. Hence, most of the discussion pertains to surface parameter variabilities during this period. Further, lateral meteorological boundary conditions for the simulations are obtained from analyses of observations by the NCEP (KALNAY *et al.*, 1996) and therefore the model results can be directly compared with the observations for the simulated period. Soil temperatures are initialized with the temperature of the bottom model level and soil water content is initialized as a function of vegetation type (GIORGI and BATES, 1989).

3. Results

Overall evaluation of the model performance is provided within this section. A detailed analysis and comparison of control simulation with observation over the Himalayan region is presented. Observed surface air temperature and precipitation needed for the comparison with the simulated fields are obtained from 0.5° resolution global land data sets developed by the Climate Research Unit (CRU) of the University of East Anglia (NEW *et al.*, 2000) and station data from the Snow and Avalanche Study Establishment (SASE), Chandigarh, India. Results of control run simulations with observations are discussed, based on seasonal and monthly averages and variabilities of temperature, precipitation and snow depth amount. In addition to this, comparison is drawn at three stations, viz., Haddantaj (lat 34°18′43″, lon 74°02′42″. alt 3080m), Banihaltop (lat 33°31′17″, lon 75°12′00″, alt 3250m) and Manali (lat 32°16′33″, lon 77°09′03″, alt 2192m), situated in the Indian Himalayan region. These stations are chosen in such a way that they represent different climatic and geographic conditions of the region and have recorded data.

(a) Surface Air Temperature

Observed temperature (CRU) and simulated surface air temperature in control experiments averaged during the period Oct. 1999–Mar. 2000 over the region are presented in Figures 2(a,b). In addition, Figure 3(a) represents seasonal averaged observed (SASE) surface air temperature over the Indian Himalayan region. A comparison shows that the model has a warm bias over the Indian Gangetic plain and a cold bias by a few degrees over the complex mountainous region. It is likely that the model bias is artificially enhanced by a temperature overestimate/underestimate in the observed data set induced by the relatively low density of high elevation stations. Observations tend to show finer scale structure, in particular over the main mountainous ranges, which are represented well by model integrations up to a certain

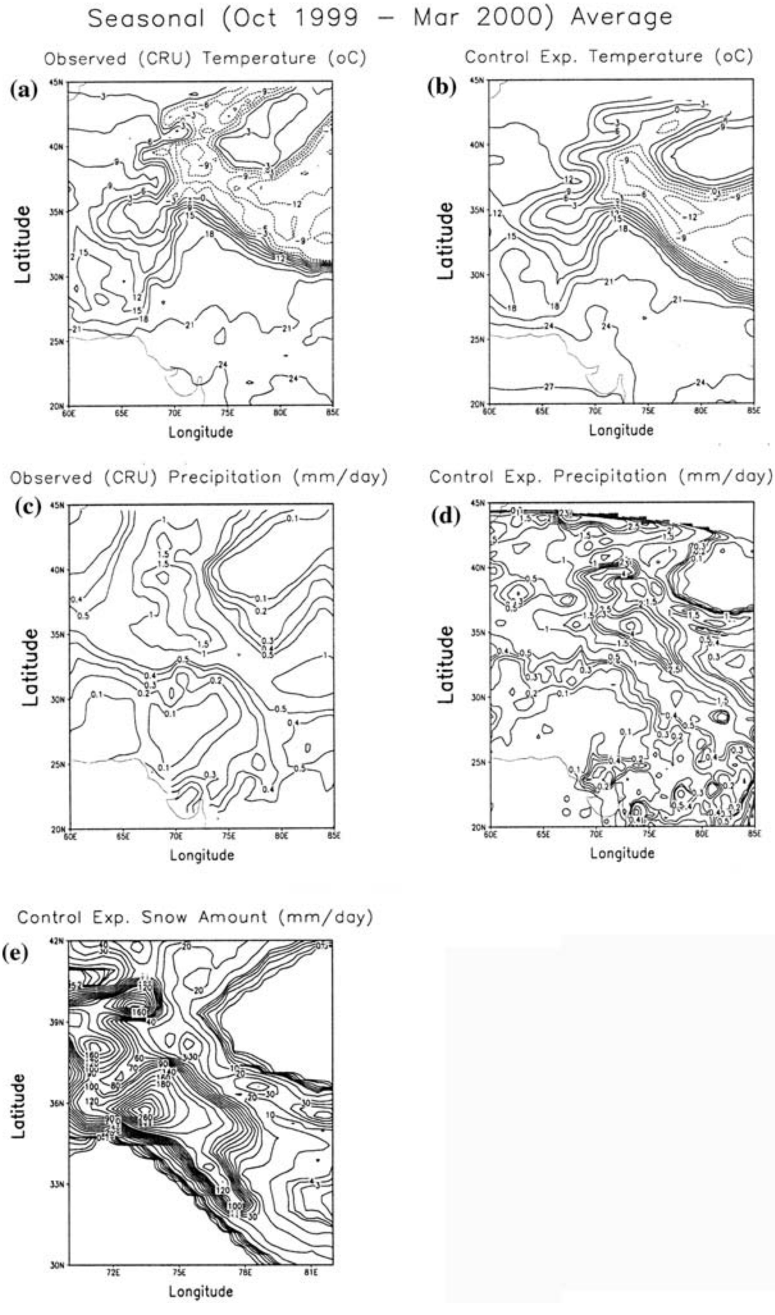

Figure 2

Seasonal (Oct 1999–Mar 2000) average:(a) Observed (CRU) and (b) simulated (control run) surface air temperature (^{o}C); (c) observed (CRU) and (d) simulated (control run) precipitation (mm/day); (e) simulated (control run) snow amount (mm/day) over the Himalayan region.

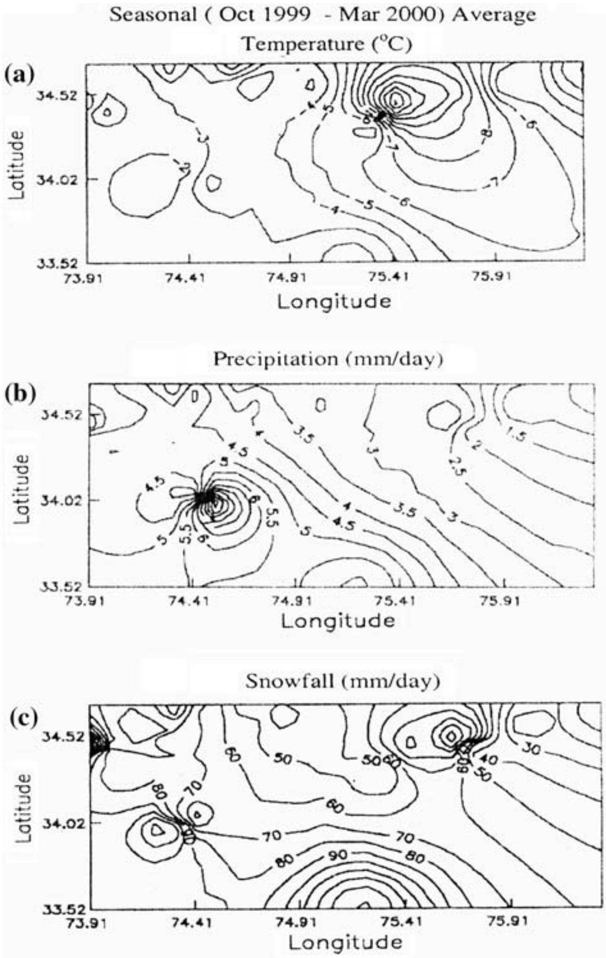

Figure 3
Observed (SASE) seasonal (Oct. 1999–Mar 2000) average:(a) Surface air temperature (°C), (b) precipitation (mm/day), (c) snowfall (mm/day) over the Himalayan region.

extent. The reason for not being able to delineate finer details of temperature distribution can be attributed to the fact that the model is provided with 1.5° resolution data, which happens to be considerably coarser from a topographic variability point of view. In addition to this, observed extreme temperatures, say 12°C, are well captured in the control experiment and the areas of lowest temperature details are well indicated over the mountainous region. Further comparison with real-time seasonal averaged observed (SASE) surface air temperature, Figure 3(a), shows that, though Figure 3(a) represents a very small area of the Himalayas, temperature distribution of the warm and cold regions is well captured by model experiments. Areas of lowest temperature are well depicted by the control experiment.

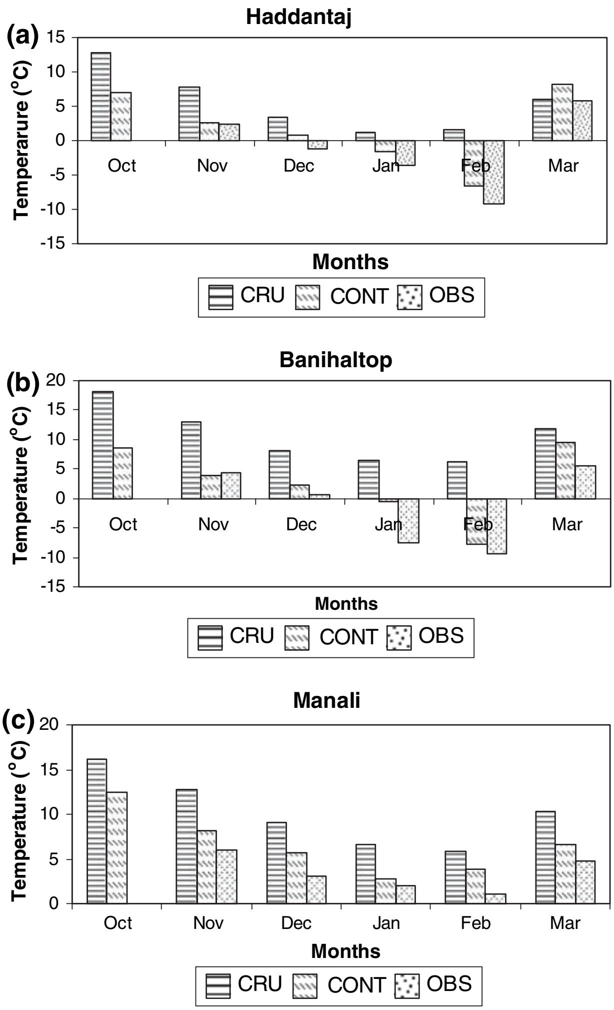

Figure 4

Comparison of monthly average surface air temperature (°C) at (a) Haddantaj, (b) Banihaltop and (c) Manali.

Further, Figures 4(a-c) represent monthly averaged observed surface air temperature of SASE and CRU and simulated surface air temperature in the control run at three of the stations located in the Indian Himalayas. Temperature value of the grid in which these stations fall is considered from CRU data and the control experiment for comparison. It should be noted that temperature data for October is not available at SASE stations. Figure 4 shows that the control experiment could capture the temporal variability and spatial variability of cold temperature over the region. In addition, control runs could produce the negative temperature distribution than the observed CRU data. It could be attributed to the fact that finer details of heterogeneity in topography and land-use are represented in the model with finer scale. Whereas in CRU observations representation of density of high elevation and low elevation stations may not be that homogeneous so that fine resolution resolvable scale circulations are not reproduced. Further, comparison shows that the model has a tendency to overestimate the cold region temperatures and underestimate the warm region temperatures by a few degrees. These biases can be attributed to the facts that they are due to the relatively low density of high elevation stations in observed data sets. Overall, the comparisons of the figures indicate that the model reproduced the observed regional temperature pattern over the Himalayan region generally well.

(b) Precipitation

Figures 2(c,d) compare seasonal averaged (October 1999 to March 2000) observed (CRU) precipitation and simulated experiments with control runs over the Himalayan region. Also, Figure 3(b) shows observed SASE precipitation. However, the control experiment could reproduce the precipitation distribution pattern, but not at all scales. However, it could generate well the precipitation amount over the northwest Indian region but over the Himalayan region the precipitation patterns are overestimated. This bias may be attributed to the fact that although in general topographically-induced cold season precipitation maxima are reproduced, the corresponding peak precipitation values are somewhat overestimated. This is evidently a problem related to the relatively coarse resolution of observed data set CRU; where over the complex topographical Himalayan region, stations of high elevations are not represented well. Nonetheless, Figures 2(c,d) indicate that model simulations are quite close to the actual precipitation amount of 0.1 to 1.0 mm/day over the western Indian region of Gujrat, Rajasthan and Punjab, whereas, over the Indian Himalayan region the amount of the precipitation is overestimated by the control run experiment. However based on this it could be stated that most of the topographically-induced precipitation is reproduced well by model simulation, therefore, overall the model captures regional topographical forcing. The reason for the model overestimate is that the dominant precipitation process is mostly of a resolvable scale nature and is induced by topographic uplift within eastward moving cyclonic systems (WDs). As a result, precipitation is mostly forced by the topographical gradients and the underrepresentation of these gradients leads to an overestimate of the precipitation maxima. These results are indeed evident from the comparison of the winter precipitation fields in Figures 2(c,d) and Figure 3(b). Small differences across the simulation are essentially due to the internal model variability (GIORGI and BI, 2000).

In addition to this, Figures 5(a-c) represent the monthly averaged observed (SASE and CRU) precipitation and simulated control experiment. Comparison

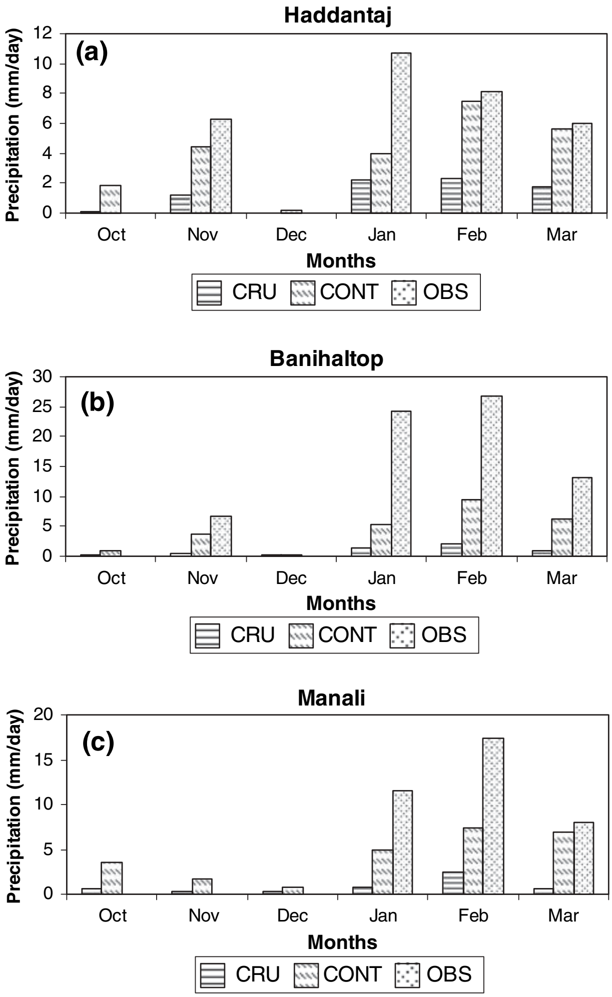

Figure 5
Comparison of monthly average precipitation (mm/day) at (a) Haddantaj, (b) Banihaltop and (c) Manali.

shows that, quantitatively, the control experiment could do better than the observed CRU data set, but still only yield a certain percent of actual precipitation recorded at Haddantaj, Banihaltop and Manali. It can be due to these possible reasons: (i) precipitation amount for control run and observed CRU data set has been considered at the grid where these station fall-–it may happen then that while considering the 60 km resolution many topographical features are not well represented and (ii) the model's internal variability can play an important role.

Simulation shows high intensity of precipitation maxima lying along the orientation of the Himalayan region, which is not shown in observed (CRU) data set. This difference may lie in the fact that topography and vegetation cover is very fast changing within a km over the Himalayan region, whereas the observed data set is presented at 0.5° resolution. Due to smoothing of model topography, micro/mesoscale circulations, which are dominant in the complex topography of the Himalayas, are certainly overlooked in the 60 km simulations for obvious reasons. Apart from this, smoothing of topography and land-use in simulation experiments reduced the impact of orographic lifting due to steep gradients in the Himalayan region. During winter, most of the time orographic lifting is the predominant mechanism to modulate the precipitation amount in the complex topographical region of the Himalayas. In addition, smoothing of land-use type, particularly during winter, it is snow cover which contributes to the over/underestimate of the precipitation amount, by heat-flux exchanges due to solar radiation.

(c) Snow

Figure 2(e) shows simulated averaged (Oct. 1999–Mar. 2000) snow depth over the Himalayan region. As a reference, we also present the corresponding observed snow depths for the simulation period estimated from real time observations of SASE observatories (Figure 3(c)). Here one point to be noted, firstly, is that model calculated snow depth is in terms of the liquid water equivalent, whereas the original observed data is given in centimeters of snow. To obtain equivalent liquid water depth we scaled the snow depth by a factor of 1/3, which is roughly characteristic of the density of the aging snow (DICKINSON *et al.*, 1993). Admittedly, considerable uncertainty is implicit in this assumption because snow density mainly depends on its age, temperature, water content, etc. Second, the station density is irregular in space and it includes a relatively small number of high elevation stations. Third, observed snow depth at a station is strongly affected by processes such as snowdrift and snow sheltering by upwind obstacles, which are not included in the model. For these reasons the comparison with observations is necessarily limited in scope and mostly aims at providing qualitative indications of the model behavior.

Figure 2(e) shows that spatial variability of snow increases substantially with the resolution of the land surface, due to temperature produced such that precipitation can be in the form of snowfall over the higher peaks and rainfall over the valleys. As a result, snow tends to accumulate over the high resolution peaks and melt more effectively over the corresponding valleys over Himalayan topography. Also, limited comparison with observations indicates that the spatial scale of snow depth variability is more in line with observations. Indeed even with the limitations discussed previously, the observations clearly show that snow depth is characterized by pronounced finescale variability. In winter, not only the spatial variability of snow increases, but also do overall snow amounts over the region, i.e., snow amount varies from one region to another. This can be attributed to the inherent nonlinear nature of snow-forming processes. As the temperature threshold for snow-formation reaches, say the high elevation of a peak, snow starts accumulating. Because snow has a higher albedo than bare soil or vegetation, the overall surface albedo increases and this causes a decrease in the absorption of solar radiation at the surface. This in turn inhibits the solar warming of the surface and thus tends to cool the region and increase the lifetime of the snow pack. These feedback processes can be seen by cooling of the Himalayan region in control run and in the greater overall snow amounts.

Averaged monthly snowcover of observed (SASE) is presented in Figure 3(c). Comparison shows that spatial and temporal variability of snowfall amounts needs to be examined in a more realistic manner for assessing the model's behavior, particularly towards snow parameter. However, another feature where model observations appear at least in qualitative agreement is the seasonal evolution of the snowpack. The observations indicate that during winter snow amounts are widespread over the region, but show localized maxima in correspondence to the highest peaks.

4. Discussion and Conclusions

In this paper a regional climate model (RegCM3) is tested for its effects on the surface climate of a simulation for the Himalayan region where both topography and land-use variability are high. In this paper, six months are considered for simulations. The results might thus be sensitive to the initialization of soil variables and depend on the specific simulated year.

Control experiment shows that for temperature field the model represents some cold bias over the Himalayan region and warm bias over the northwest Indian region. However, the model could not capture the extreme temperature values, but definitely could indicate the areas of low temperatures. Also, control run could explain the temporal variability in temperature field based on a comparison with station data. In the case of precipitation field, control experiment could generate the precipitation amount over the northwest Indian region but over the Himalayan region the precipitation patterns are overestimated. In addition to this, snow-pack evolution could be generated by the simulation but has to be seen within its larger nature of complexity.

Keeping the above results in mind, an accurate simulation of the effects of surface climate does require the representation of very finescale surface processes. Also, study of subgrid scale disaggregation processes is planned in future work. In addition to this longer time simulations are planned to understand the variabilities associated with these parameters.

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