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How robust and (un)certain are regional climate models over the Himalayas?

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Abstract

Regional Climate Model(s) (RCMs) are sensitive towards presentation of regional climate of Indian winter monsoon (IWM) over the western Himalayas (WH). They illustrate robust nature in representing regional climate at mountain scale and even at event scale. While downscaling outputs, from these models, at basin level for hydrological and glaciological studies, it is found that RCMs fail to provide realistic figures. And hence, in the present paper, using the Siachen glacier basin as a reference, debate and deliberation on RCMs' uncertainly and high order of deviation from real observations is presented. Results from RCMs thus need "further tuning" if they are used for hydrological and glacier studies. Reasons for such uncertainties could be due to the improper representation of topography, missing subgrid scale processes, surface flux characteristics, various physical processes etc. at such finer model resolution and scale. At present, this paper only deliberates and brings out issues pertaining to such complexities to provide an insight for future course of studies, if understood correctly.

1 Introduction

In the recent decades changes in Himalayan glaciers (Bolch et al., 2013) and hydrological balance (Moors et al., 2011) have drawn attention. Regional assessments at basin level thus become important for socio-economic reasons. Regional climate model (RCM) representation could provide a benchmark feeds for such regions primarily as they are data void. RCM simulations and corresponding sensitivity studies over the Indian subcontinent have been carried out by various researchers. Important issues like poor, or no, representation of important feedbacks within RCMs (Lucas-Pitcher et al., 2011); improved framework for RCMs to capture the fundamental structure of the south Asian summer monsoon (SASM) system (Saeed et al., 2012); downscaling at the sub-regional scale with an RCM simulation (Bhaskaran et al., 2012); comprehensive feedback for adaptation studies over Indo-Gangetic plain (Mathison et al., 2012); and regional climate of Indian winter monsoon (IWM) over the western Himalayas (WH) (Dimri and Niyogi, 2013; Dimri et al., 2013) have been discussed. Particularly over mountainous regions RCMs have proven to well represent regional climate at mountain and even at event scale (Dimri, 2013). However, use of regional model outputs “without tuning” to evaluate hydrological and glacier responses to climate change in the Himalayan high mountains is still problematical (Yasunari et al., 2012). And thus it is imperative to assess the sensitivity of RCMs for hydrological and glaciological studies at basin level. In the present paper these aspects are looked into for further investigation.

Therefore, the sensitivity of RCMs at glacier basin level, with the Siachen glacier as a representative glacier, in the WH region is evaluated to provide an insight on sensitivity/uncertainty of RCMs for hydrological/glaciological study over one of glacier basin. This glacier basin is chosen as it is one of the longest glaciers outside the polar region, also provides inflow to the Indus river tributaries and situated in the cold arid desert region of the WH. For having a comprehensive characteristic understanding of these processes model outputs from three RCMs are chosen and discussed. A brief detail of these models is provided in the following section under Methodology.

2 Study area

The topography of the WH, map and schematic illustration of the Siachen glacier region used in the present study are shown in Fig. 1a–c respectively.

3 Models, experimental design and observations

3.1 Models

For the present paper, three “available” RCM simulations from HadRM3 (Buonomo et al., 2007, upgraded to include the MOSES 2.2 land surface scheme, Essery et al., 2003) and RegCM3 (Pal et al., 2007) were used. HadRM3 simulations were forced with global ERA-Interim reanalysis data (Dee et al., 2011) and sea surface temperature taken from ERA-40 was considered in the model physics. RegCM3 was forced with NNRPII reanalysis data (Kanamitsu et al., 2002) to supply large-scale boundary information and the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation Sea Surface Temperature (OISST) dataset over the ocean areas. In case of HadRM3, the 1984 US Navy 10′ orography was used as lower surface boundary. In case of RegCM3, GTOPO30 topography of USGS was used. HadRM3 RCM simulates the regional climate with a spatial resolution of 0.23° (∼ 25 km) whereas RegCM3 simulate the regional climate with a spatial resolution of 60 km (CONT experiment) and 10 km with subgrid scheme (SUB experiment). For such studies over complex topographical regions, ideally very high resolution, explicit convection resolving simulations will be preferred (Medina et al., 2010), but due to computational limitations for multidecadal regional climate assessment subgrid scheme of Seth et al. (1994) within a framework of a RegCM3 (Pal et al., 2007) was used. Model details are provided in Table 1.

3.2 Experimental design

In HadRM3 experimental strategies, simulations for a continuous 18 year period from 1990–2007 were made. In the case of RegCM3 simulations were made continuously for 22 year period from 1981–2002. In addition, in later experiment two sets of model simulations were designed. (i) A control run (RegCM3-CONT), in which the fine scale BATS scheme was not used and therefore the land surface had the same resolution as the atmosphere, and (ii) a fine scale subgrid-scale based run (RegCM3-SUB), in which the BATS scheme was used. So, in RegCM3-CONT experiment each coarse grid cell of 60 m horizontal model resolution was divided into 36 subgrid cells of 10 km each in RegCM3-SUB experiment.

3.3 Observations

RCMs results were verified with corresponding verification reanalysis of the ERA-Interim (Dee et al., 2011), NCEPII (Kanamitsu et al., 2002), CRU (Mitchell and Jones, 2005) etc. Precipitation fields were compared with APHRODITE (Yatagai et al., 2009) and CRU (Mitchell and Jones, 2005) observational gridded data sets. These multiple observations were used to assess the uncertainty in the downscaled outputs of the RCMs over the Siachen glacier region in the WH region. For more in-depth analysis, in-situ observations at Base Camp or A1 (lat 35°11′49″ N, lon 77°12′28″ E, alt 3570 m), A2 (lat 35°29′32″ N, lon 76°57′14″ E, alt 5215 m) and A3 (lat 35°15′49″ N, lon 76°47′32″ E, alt 5995 m) of the Snow and Avalanche Study Establishment (SASE), Chandigarh, India were used. These are the only stations with longest records available over the Siachen glacier so far.

4 Results and discussion

In this section, issues pertaining to the uncertainties associated with model precipitation and temperature fields over the Siachen glacier basin are emphasized and discussed.

4.1 Precipitation

Precipitation in regional simulations by HadRM3, RegCM3-CONT and RegCM3-SUB show biases over higher elevation of the Himalayas; the Deccan plateau in the middle of Indian subcontinent and along the Western Ghats (Mathison et al., 2013). Detailed analysis over the WH shows a similar spatial distribution in precipitation bias in all the three RCM simulations (Dimri and Niyogi, 2012; Dimri et al., 2013). Over higher elevation regions RCMs indicate a wet bias, but over the plain regions of the Indian subcontinent RCMs perform better (Dimri and Niyogi, 2012; Dimri et al., 2013). It should be noted here that due to the lower number of observations over the mountainous region represented within the precipitation reanalyses fields, there could be an under-representation of the precipitation scale over the mountainous region as compared to plain regions. And hence observed precipitation bias over the WH could be enhanced by the lack of a gauge under-catch correction in the measurements, which is likely to be an important issue over the WH region. Roe et al. (2003), Dimri and Niyogi (2012) and Dimri et al. (2013) performed experiments that suggested a possible mechanism, which is more apt for topographic situations where a model cannot capture the full complexities of orographic precipitation. Error analysis shows the relative importance of using RegCM3-SUB over RegCM3-CONT as it improves representation of topography in model which can provide an extension to the Lang and Barros (2004) where they have discussed storm climatology over central Himalayas.

Coming particularly to the analysis over the Siachen glacier basin, Fig. 2a and b presents HadRM3 simulated and corresponding observed APHRODITE area averaged monthly precipitation over the Siachen glacier region (35° N 75° E–36° N 80° E). Comparison between Fig. 2a and b very clearly show that HadRM3 could simulate similar interannual precipitation variability in its 18 years' simulation over the Siachen glacier region. The model captures the highs and lows in monthly averaged precipitation over the region too. It suggests that the model very adequately captures higher and lower precipitation years, as seen in the corresponding observation (Fig. 2b). Higher precipitation variabilities particularly during 1996, 2002–2004 and so the lower precipitation variabilities were very well captured. Such representation of precipitation within the model framework could be excellent information on interannual variability at glacier scale. However, simultaneous higher simulated precipitation over the region could be erroneous if glacier studies are forced with such precipitation values. Such increased model precipitation, Fig. 2a, cannot ideally be used for studies such as seasonal evolution/decay at glacier basin level as it will provide inflated inputs for such studies. Similarly, such precipitation will not provide a correct indicator for glacier melt/thaw. And hence at glacier scale/level RCMs become very uncertain in their ability to provide reasonable precipitation values.

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Further, Fig. 2c shows the distribution of daily precipitation frequency vs. intensity for the winter season for the RegCM3-CONT and RegCM3-SUB simulations and station observations at Base Camp. Note that the distributions were normalized by the number of daily events, which was different for simulations and observations, as one is at grid points and the other at station points. Daily precipitation for all grid points included in the WH was collected and the relative percentile was calculated by dividing the total number of events in the samples contributing to the distributions. For precipitation frequency vs. intensity distribution, we defined a precipitation event as such if a daily precipitation value was greater than or equal to 1.0 mm. At present the experimental model configuration of snow drift accumulation and rain shadow effects were not treated. These are important mountainous physical processes which need explicit driving mechanism in the model physics (Leung and Ghan, 1995). Fractal interpolation based orographic rainfall disaggregation scheme had shown about 50 % improvement of total precipitation amount in quantitative precipitation forecasting (Bindlish and Barros, 2000). Figure 2c shows that for low intensities the simulated distributions match the observed station data reasonably well. But in the middle and high intensity range, the model overestimates. Distribution of model precipitation overestimation was clearly seen in the intensity distribution. While comparing this distribution with seasonal distribution of precipitation at station level it was seen that the model's higher value events were not always well matched with that in the observations. Hence, it can be stated that both experiments simulate the lower value events with higher accuracy than the higher value events. Additionally, the RegCM3-SUB experiment simulates higher values with more accuracy than the RegCM3-CONT experiment. Especially, during winter precipitation generation mechanisms are mainly of dynamical orographic forcing in nature over WH. Small differences across the simulation could essentially be due to the internal model variability (Giorgi and Bi, 2000). In contrast, during summer a greater effect of the subgrid scheme is expected as disaggregation procedure is used for convective precipitation and because of which greater forcings by the surface fluxes are expected by subgrid scheme. Detailed investigations indicate high altitude (mountainous) regions correspond to convergence zones, and the lower altitude (valley) regions correspond to divergence zones (Dimri et al., 2013).

4.2 Temperature

During winter (December, January and February: DJF), surface air temperature in the WH region often remains below sub-zero in the WH. Spatial distribution of mean seasonal (DJF) temperature biases shown, Fig. 3a and b based on RegCM3-CONT and RegCM3-SUB minus CRU respectively, that the model tends to underestimate temperature over high elevation areas in the WH and hence shown a cold bias except over the region of maximum topographic heterogeneity where the bias was typically less than 2 °C (Dimri and Niyogi, 2012). Dimri and Niyogi (2012) have shown that the RegCM3-SUB simulation, although retaining the basic patterns of the RegCM3-CONT simulation (and thus the similar bias patterns) exhibited much finer resolution information. The bias distribution showed that the RegCM3-SUB experiment could produce better simulation than the RegCM3-CONT experiment over high elevation points. The subgrid scheme mostly redistributed the grid-scale temperatures according to the fine and coarse topographical information without introducing systematic differences. Here, the SUB simulation could produce the lowest temperature range that could not be produced well in the CONT simulations. Also, the effect of subgrid topography could be clearly seen in the spatial temperature distribution across the WH. Though overall, topographically-induced spatial temperature distribution was seen, but this discrepancy could be partially due to the relatively low density of high elevation stations in the observed dataset, where the data probably underestimates temperature over the WH.

Comparing model simulated temperature probability density function (pdf) at glacier basin, Fig. 3c showed shift towards lower values and hence a cold bias. Pdfs based on model simulations were slightly wider as well, indicating a higher variance when compared to pdfs based on station observation. While looking for the reasons for this cold bias and shift towards the colder mean value, it was seen that model simulations could not reproduce corresponding mean values. Although the model could well reproduce variances in the pdfs, it could not simulate observed mean values which were higher (Fig. 3c). However, the description of how temperature varied with elevation was crucial. Corresponding temperature analysis with available in situ temperature records at three stations, A1, A2 and A4 as marked in Fig. 4a, at and along the glacier surface illustrated that RCMs provided much cold biases over the glacier region (Fig. 4b–d). Comparison with corresponding reanalysis forcing and with limited in situ observations showed similar interannual variability in seasonal temperatures. Similar winters with higher and lower temperature were evolved by the model. Role of higher elevation was also well represented in model simulations. As we moved higher up along the elevation of glacier slope we found that model performance was maintained as compared with the corresponding observations. Similar cold bias of surface temperature up to $\sim -4\,^{\circ}\mathrm{C}$ in model simulation was seen all along as we moved up along the elevation. To investigate this large deviations in model – corresponding reanalysis – and observations further we looked into the temperatures in upper atmospheric levels. Corresponding area averaged monthly temperature over the Siachen glacier region (35° N 75° E–36° N 80° E) at 700 hPa is shown in Fig. 5a and c in HadRM3 and corresponding observation of ERA-Interim respectively. Similarly Fig. 5b and d represent 500 hPa temperature. Figure 5 depicts that RCM have warming at these mid-atmospheric levels. As we saw in Fig. 3a and b that model simulations provide colder surface temperature than the corresponding observation. This shows that model environment is colder at surface and warmer at mid atmospheric levels. Thus it suggests that vertical temperature threshold over glaciated region in model physics is still elusive and needs careful approach while interpreting over the glacier basin. This is also debated with in situ observations by Thayyen and Dimri (2014) (see Fig. 5) and Fiddes and Gruber (2014). To investigate it further, we looked into temperatures in vertical levels. Figure 6 represents temperature distribution with elevation within the model grid considered for the study (Fig. 1c). A total of 117 model grids are represented here with their corresponding model height. As per physical laws, it correctly shows that as the elevation increases temperature decreases. However, in such topographic regions free atmospheric lapse rate will be in-correct to take into consideration for any hydrological/glaciological studies. It is more appropriate to consider slope environmental lapse rate (Thayyen and Dimri, 2014). Thus with height corrections based on slope environmental lapse rate it is shown in Fig. 5 that influence of such flawed lower (higher) elevation increased (decreased) cooling in model simulations is corrected with improved correlation of 0.8 within them.

5 Conclusions

This study debates on the issues of whether RCMs could be as good over hydrological/glacier basins as they are over the mountainous region. RCMs were found to realistically representing the regional climate over the Indian Himalayan region and Indian winter monsoon and show its variability well. However these models are very uncertain when scaled down to glacier basin level. It is seen here that without doing any "further tuning" RCMs' results cannot be very favorable for hydrological and/or glacier studies. Such deviation from realistic representation could be due to underrepresentation of glacier surface within the model physics. Model simulation of precipitation very much depends on how model topography is represented within the models' physical and dynamical parameterization schemes. Variability in these factors will lead in defining internal model variability. A corrections with slope environmental lapse rate is employed with better results.

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Table 1. Features of the experimental design of the Regional Climate Models used in the present study.

	HadRM3	RegCM3
Nonhydrostatic	No	No
Grid size	114 × 92	51 × 61
Vertical levels	19	23
Buffer zone	8 cells	8 cells
Spatial resolution	0.23° (∼ 25 km)	60 km
Land surface scheme	MOSES (Cox et al., 1999)	BATS1E (Dickinson et al., 1993)
Convection scheme	Mass flux (Gregory and Rowntree, 1990)	Grell Scheme (Grell, 1993)
Microphysics	Smith (1990)	SUBEX (Sundquist et al., 1989)

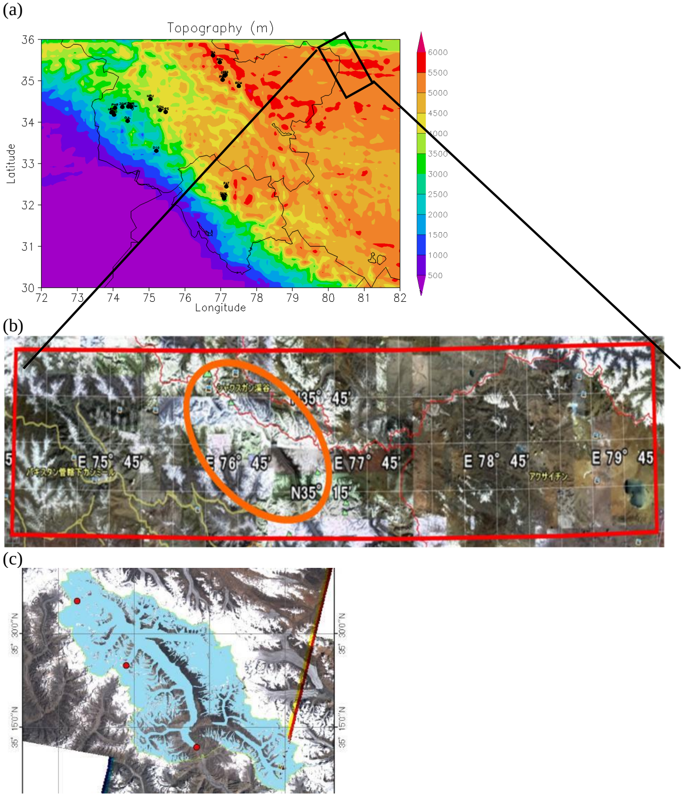

Figure 1. (a) Topography (m: shade) of the WH region considered in the study, **(b)** Google map marked with the Siachen glacier region considered in the present study and **(c)** schematic representation of the Siachen glacier with stations marked with red dot at elevation 3570 m (Base Camp or A1), 5215 m (A2) and 5995 m (A3).

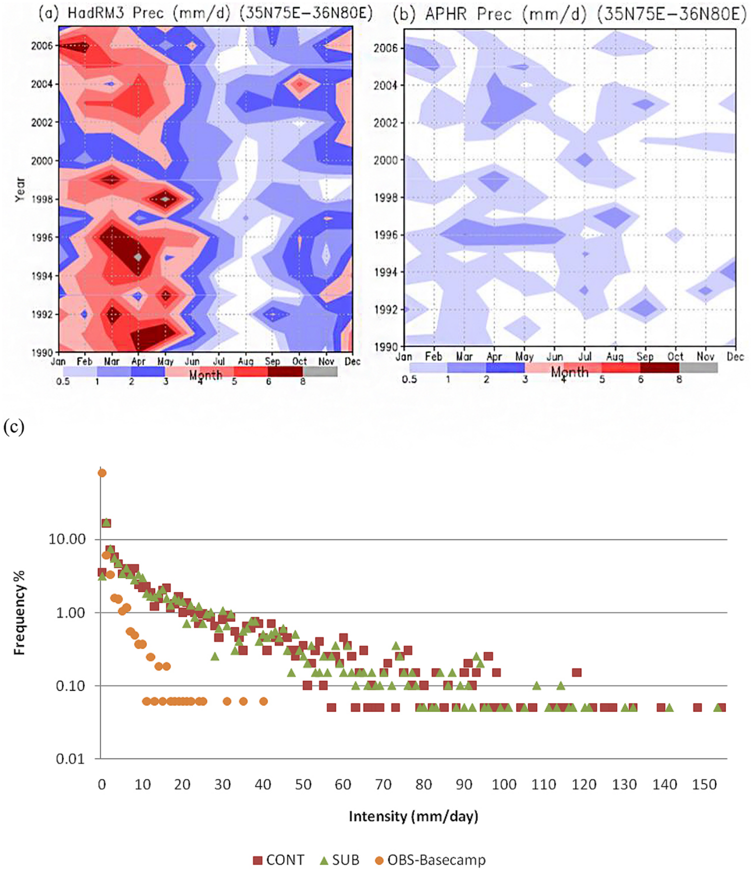

Figure 2. Area (30° N 72° E–37° N 82° E) averaged monthly precipitation (mm d^{-1}) in **(a)** HadRM3 and **(b)** APHRODITE observations and **(c)** frequency distribution of daily precipitation in the RegCM3-CONT and RegCM3-SUB experiment with insitu observation at Base Camp.

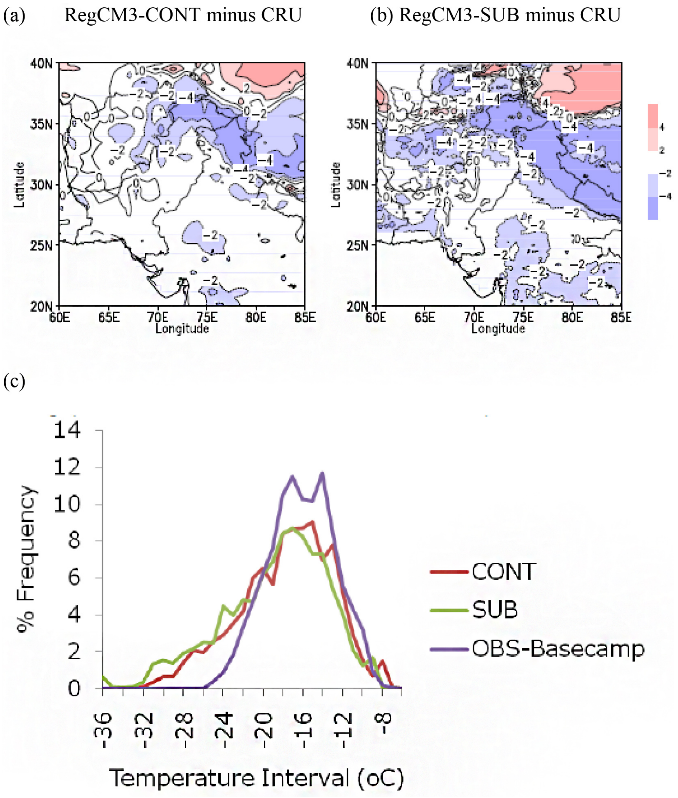

Figure 3. Model simulated 03 month (DJF) average surface temperature biases with the corresponding CRU observations in **(a)** RegCM3-CONT and **(b)** RegCM3-SUB during model simulated period. **(c)** Frequency distribution of daily temperature in the RegCM3-CONT and RegCM3-SUB experiment with in situ observation at Base Camp (A1).

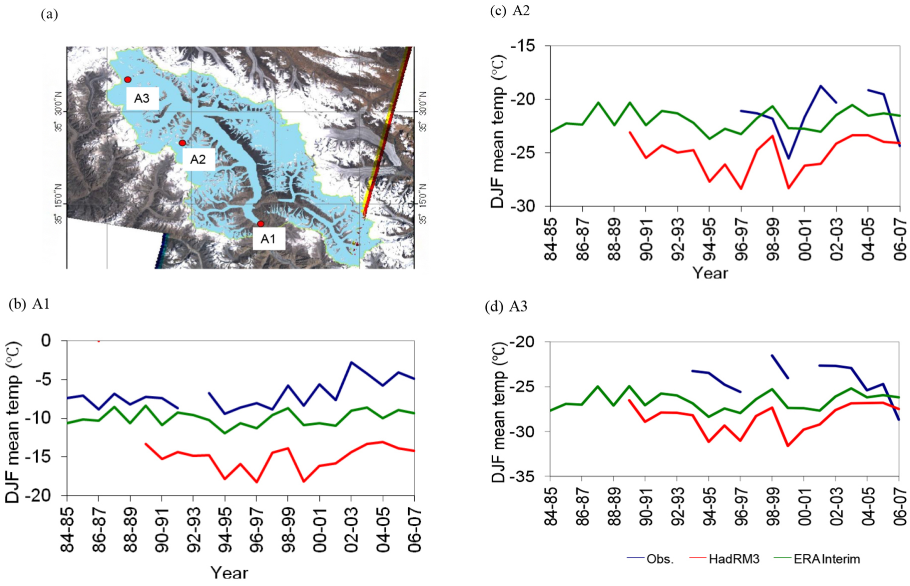

Figure 4. Surface stations where in situ observations are monitored and used in the study as marked in **(a)** A1, A2 and A3, **(b)** in situ surface temperature monitored at A1 compared with HadRM3 model simulated surface temperature and corresponding ERA-interim reanalysis at model grid point location of A1, **(c)** same as **(b)** but at A2 and **(d)** same as **(b)** but at A3.

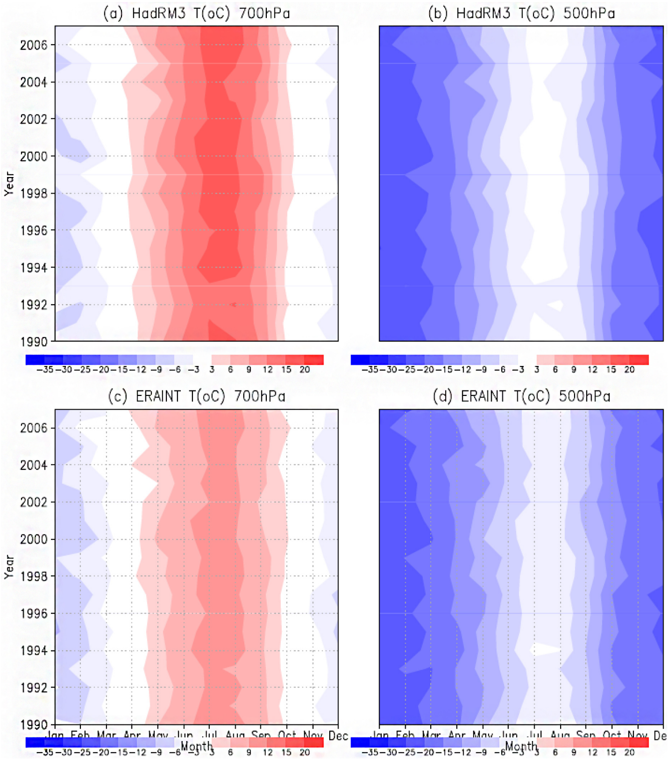

Figure 5. Area (30° N 72° E–37° N 82° E) averaged monthly temperature (°C) in HadRM3 at **(a)** 700 hPa and **(b)** 500 hPa and in corresponding ERA-Interim observations at **(c)** 700 hPa and **(d)** 500 hPa respectively.

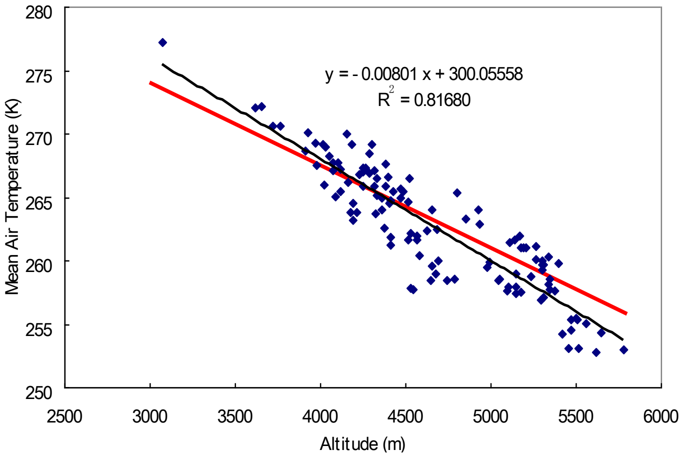

Figure 6. Temperature distribution with elevation within the area (30° N 72° E–37° N 82° E) considered for the study. Total 117 model grids are represented here with their corresponding model height and height corrected distribution. Modeled and corresponding observed gridded values are height corrected (blue line model based and red line slope environmental lapse rate corrected values).