Climate Change Impact and Vulnerability in the Eastern Himalayas – Technical Report 1

ICIMOD

FOR MOUNTAINS AND PEOPLE

Climate Change in the Eastern Himalayas: Observed Trends and Model Projections

MacArthur Foundation

Preface

Mountains are among the most fragile environments on Earth. They are also rich repositories of biodiversity and water and providers of ecosystem goods and services on which downstream communities (both regional and global) rely. Mountains are home to some of the world's most threatened and endemic species, as well as to some of the poorest people, who are dependent on the biological resources. Realising the importance of mountains as ecosystems of crucial significance, the Convention on Biological Diversity specifically developed a Programme of Work on Mountain Biodiversity in 2004 aimed at reducing the loss of mountain biological diversity at global, regional, and national levels by 2010. Despite these activities, mountains are still facing enormous pressure from various drivers of global change, including climate change. Under the influence of climate change, mountains are likely to experience wide ranging effects on the environment, natural resources including biodiversity, and socioeconomic conditions.

Little is known in detail about the vulnerability of mountain ecosystems to climate change. Intuitively it seems plausible that these regions, where small changes in temperature can turn ice and snow to water, and where extreme slopes lead to rapid changes in climatic zones over small distances, will show marked impacts in terms of biodiversity, water availability, agriculture, and hazards, and that this will have an impact on general human well being. But the nature of the mountains, fragile and poorly accessible landscapes with sparsely scattered settlements and poor infrastructure, means that research and assessment are least just where they are needed most. And this is truest of all for the Hindu Kush-Himalayas, with the highest mountains in the world, situated in developing and least developed countries with few resources for meeting the challenges of developing the detailed scientific knowledge needed to assess the current situation and likely impacts of climate change.

The International Centre for Integrated Mountain Development (ICIMOD) undertook a series of research activities together with partners in the Eastern Himalayas from 2007 to 2008 to provide a preliminary assessment of the impacts and vulnerability of this region to climate change. Activities included rapid surveys at country level, thematic workshops, interaction with stakeholders at national and regional levels, and development of technical papers by individual experts in collaboration with institutions that synthesised the available information on the region. A summary of the findings of the rapid assessment was published in 2009, and is being followed with a series of publication comprising the main vulnerability synthesis report and technical papers on the thematic topics climate change projections (this publication), biodiversity, wetlands, water resources, hazards, and human wellbeing.

Clearly much more, and more precise, information will be needed to corroborate the present findings. Nevertheless, this series of publications highlights the vulnerability of the Eastern Himalayan ecosystems to climate change as a result of their ecological fragility and economic marginality. It is hoped that it will both inform conservation policy at national and regional levels, and stimulate the coordinated research that is urgently needed.

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Climate Change in the Eastern Himalayas: Observed Trends and Model Projections

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Introduction

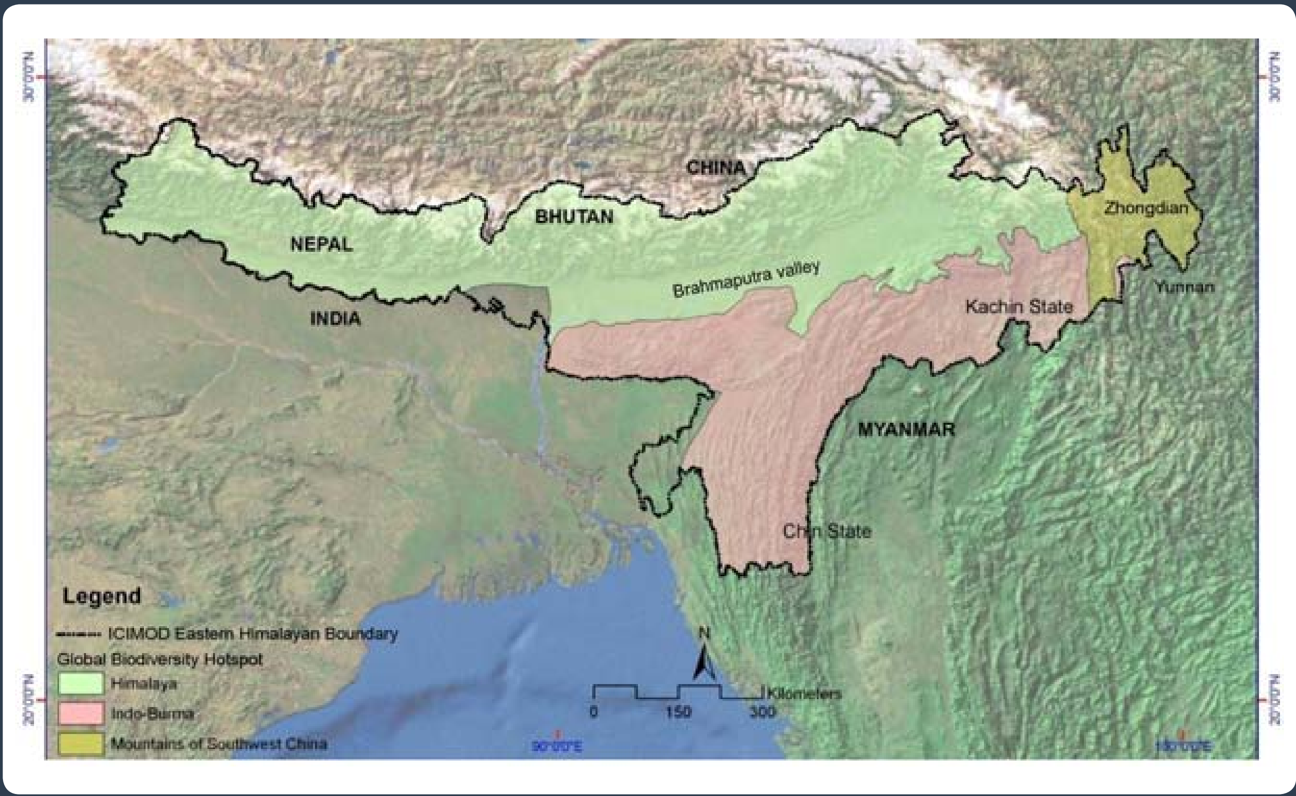
The Eastern Himalayan region

The Eastern Himalayan region covers a broad spectrum of ecological zones in eastern Nepal, northeastern India, Bhutan, the Tibet Autonomous Region and Yunnan of China, and northern Myanmar (Figure 1). The topography varies significantly over the area, and besides atmospheric circulation, the climate in this region is influenced by a variety of physiographic features. The region is dominated by a monsoon climate from June to September and by westerly disturbances in the remaining months. Mani's (1981) study shows that the eastern Himalayas have about eight months of active rainy season (March-October); monsoon activity in the northern mountain region is not well defined as pre-monsoon thunder activities gradually merge with it. The region hosts the wettest spot in the world, Cherrapunji. Chalise (1994) emphasised the role of the Himalayan region as a climate barrier between lower and mid-latitudes in the global atmospheric circulation systems; this means that the Himalayan regions are responsible for the moist summers and mild winters in South Asia.

The region contains parts of three global biodiversity hotspots and hosts an array of unique plants and animals of global importance. Furthermore, the Eastern Himalayan region is the source of many rivers which are the lifeline of downstream provinces and countries. These rivers and landscapes provide valuable ecosystem services, not only by providing water but also by facilitating soil retention, climate regulation, and carbon sequestration, and as reservoirs of pollinators, natural predators, and others. The welfare of approximately 400 million people living downstream is inextricably linked with the natural resources of the Eastern Himalayas. Mountains provide opportunities for both plants and animals to migrate vertically as a coping mechanism and adaptive strategy. Species in high-altitude areas, however, may not have scope for vertical movement upwards after a certain point in the process of climate change; and, hence, their extinction is inevitable if natural or human-induced adaptation to climate change does not take place.

The wetlands are most likely to be the first among the eco-hydrological systems to be affected by climate change. In fact, erratic weather situations are already being observed in many parts of the Himalayas. Water-related hazards (glacial lake outburst floods, flash floods, and landslides) are becoming more frequent at the cost of lives, property, and natural resources and these are likely to be exacerbated by climate change (Xu et al. 2008). It has become imperative to assess the impacts of ongoing changes in the climatic regime and changes that might occur in future.

Figure 1: **The Eastern Himalayan region**



ICIMOD, in partnership with the MacArthur Foundation, has undertaken an assessment of trends, perceptions, and impacts of climate change on biodiversity in the Eastern Himalayan region: in the process it is hoped to achieve a broad consensus on the impacts of climate change on the ecosystem and measures that can be taken to adapt to them. This paper is a part of the broader assessment and includes analyses of contemporary trends in key climatic variables. Further, the paper investigates the likely future climate scenarios using the results of regional climate models (RCMs). Only two variables, temperature and precipitation, are considered in this study: the performance of RCMs in simulating the climate of the region is also assessed. The results of the analyses will be useful for sectoral impact assessment studies and for planning adaptation and mitigation measures.

Methodology

Trend analysis

The study focuses mainly on analysis of contemporary trends in temperature and precipitation in the region and on analysing the scenarios of future climate change. The Climate Research Unit's Times Series' (CRU TS 2.0) data (New et al. 2002) were used to analyse temperature and precipitation trends. The eastern Himalayas were divided into three elevation zones: below 1,000, 1,000 to 4,000; and above 4,000 metres and area-averaged trends were derived for these regions for the period from 1970-2000. The period from 1970-2000 was chosen because after the 1970s the global and regional temperature records show monotonous rising trends, whereas before this period the trends generally descend (Jones and Mann 2004; Shrestha et al.1999).

Analysis of the climate scenario

This study examined the efficiency of HadRM2 and PRECIS models in simulating the mean seasonal present-day as well as the future climate over the Eastern Himalayan region, using monthly precipitation and temperature data. The models are described briefly in the following section.

Models used for analysis of the climate scenario

HADRM2 model – HadRM2 is a high-resolution, limited area, atmospheric regional climate model (RCM) which was developed by the Hadley Centre, UK. The lateral and sea surface boundaries of this model were driven by the output from a general circulation model

(HadCM2). The grid spacing of this regional model is 0.4425° latitude by 0.4425° longitude; and this is kept quasi-regular over the region of interest by shifting the coordinate pole. The time-step of the model is five minutes. Two types of simulated data are available over a period of 20 years. Simulation of control climate was carried out by keeping the constant atmospheric CO_2 at 1990 level, hereafter called control (CTL) simulation (1981-2000). The projected simulation was carried out for a compound increase of one per cent of CO_2 per year from the 1994 level; hereafter called greenhouse gas (GHG) climate (2041-2060). Refer to Jones et al. (1995) for a detailed description of the model.

PRECIS model – PRECIS (providing regional climates for impact studies) was also developed by the Hadley Centre, UK. The model can be run on a personal computer (PC) and can be applied to any area of the globe to generate detailed climate change projections. PRECIS has a horizontal resolution of 0.4425° latitude by 0.4425° longitude with 19 levels in the atmosphere and four levels in the soil. The present version of PRECIS has an option to downscale to a horizontal resolution of 25 km. In addition to a comprehensive representation of the physical processes in the atmosphere and on the land surface, it also includes the sulphur cycle. The Indian Institute of Tropical Meteorology (IITM), Pune, India runs PRECIS with a 50 km horizontal resolution to generate the climate for present (1961-1990, BLA and BLB[1] experiments) and future periods (2071-2100) for two different socioeconomic scenarios, both characterised by regionally focused development but giving priority to economic issues in one (A2 scenario) and to environmental issues in the other (B2 scenario).

Validation and scenarios

Validation of the output of the model is required to assess the result of simulated present and past climates. One of the methods of doing this is by studying the physical basis of the model, including its complexities, which provide parameters for the various processes and interactions. The second method is by quantifying the model errors and assessing causes of errors (Rupa Kumar and Ashrit 2001). Over Indian regions, various general circulation model (GCM) and regional circulation model (RCM) products have been applied in this kind of research (Lal et al. 1994, 1995; Bhaskaran et al.1995; Dümenil 1998; Rupa Kumar and Ashrit, 2001). In this study, the bias of a model was estimated by simply subtracting the value of the current mean climate model simulated from the observations; this represents the quantitative estimation of the uncertainties in the simulated data. The Climate Research Unit's (CRU) TS 2.0 data was used as observed data for bias estimation (New et al. 2002).

[1] BLA means the baseline of the IPCC emission scenario A and BLB means the baseline for the IPCC emission scenario B.

Similarly, the future climate scenarios associated with the perturbed greenhouse gasses are estimated by subtracting the simulated model of the current climate from future values. The simulated climate change applied in the present study covered a period of 20 years (2041-2060) in HadRM2 and 30 years (2071-2100) in PRECIS; evaluation of the models was based on a comparison of statistical parameters for 1981-2000 and 1961-1990 respectively. Hence the future scenarios of HadRM2 and PRECIS models represent, approximately, mean climate changes by the 2050s and 2080s respectively.

Results and Discussion

Temperature and precipitation trends

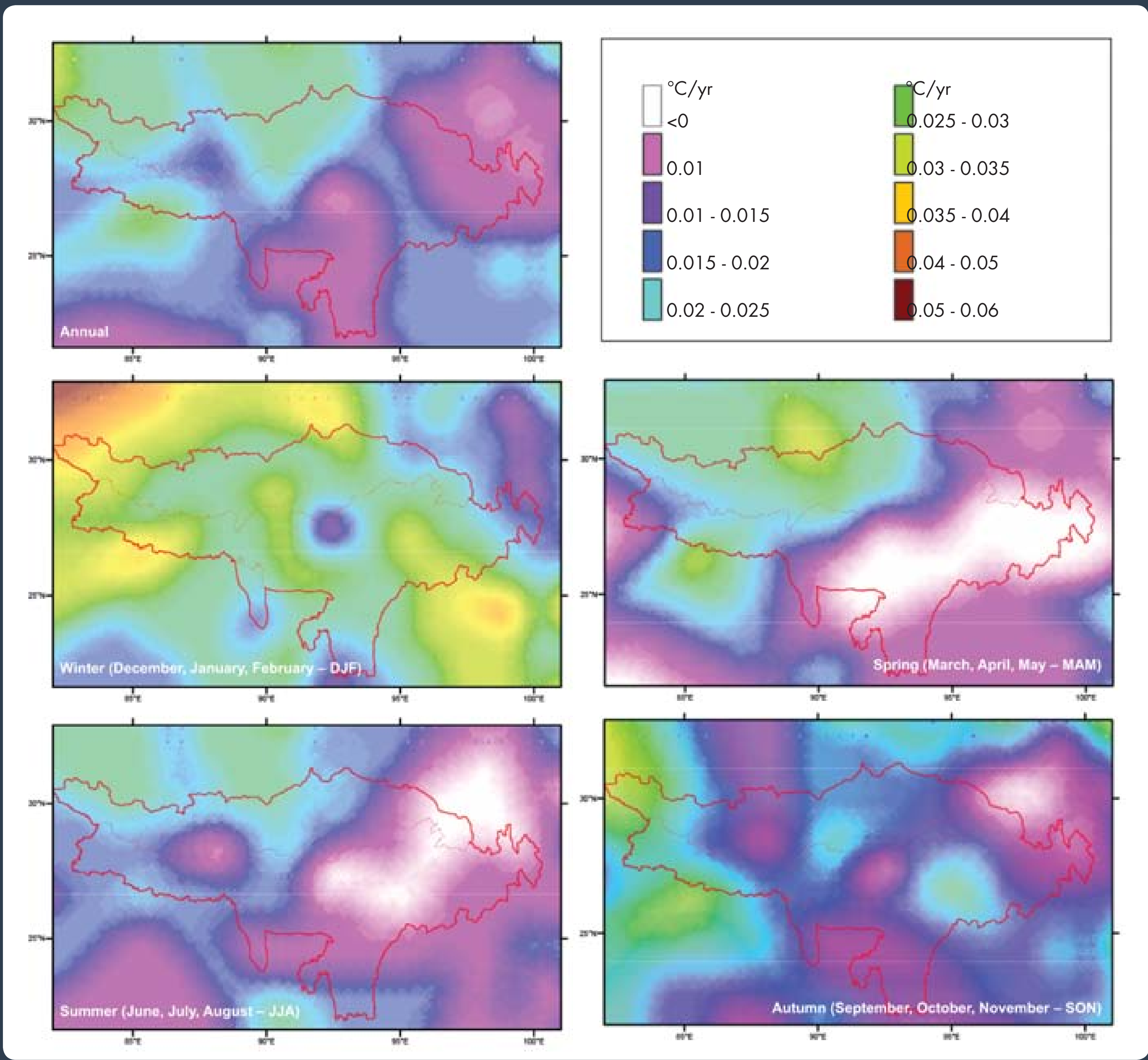
The spatial distribution of trends in annual and seasonal temperature is illustrated in Figure 2: it is clear that major parts of the region are undergoing warming trends. Annual mean temperature is increasing at the rate of 0.01°C/yr or more. In general, for annual and seasonal trends there is a diagonal zone with a southwest to northeast trend with relatively less (0 to 0.02°C/yr) or no warming. This zone encompasses the Yunnan Province of China, part of the Kachin State of Myanmar, and the northeastern states of India and Assam. The area to the upper left of this zone, which includes eastern Nepal and eastern Tibet, shows relatively greater warming trends (>0.02°C/yr). The warming in the winter (December, January and February; DJF) is much greater, about 0.015°C/yr more than the annual trends and more widespread by comparison. The diagonal zone of less warming is significantly small and limited to Yunnan and Arunachal Pradesh.

The temperature trends in the three elevation zones are provided in Table 1. The analysis suggests that i) the Eastern Himalayan region is experiencing widespread warming and the warming is generally greater than 0.01°C/yr; ii) the highest rates of warming are occurring in the winter December, January, February (DJF) season

Table 1: **Temperature trends (°C/yr) by elevation zones**

	Annual	DJF	MAM	JJA	SON
Level 1 (<1000 m)	0.01	0.03	0.00	-0.01	0.02
Level 2 (1000-4000 m)	0.02	0.03	0.02	-0.01	0.02
Level 3 (>4000 m)	0.04	0.06	0.04	0.02	0.03

Figure 2: **Spatial distribution of temperature trends** (Change in annual and seasonal temperatures. The red line shows the border of the Eastern Himalayan region plus parts of the Brahmaputra and Koshi basins.)



and the lowest or even cooling trends are observed in the summer (June, July and August; JJA) season; and iii) warming increases progressively with elevation, with areas >4,000 m experiencing the highest warming rates. The results suggest that seasonal temperature variability is increasing and the altitudinal lapse rate in temperature is decreasing. Unlike temperature, precipitation does not demonstrate any consistent trends.

Validation of model results

Validations was carried out for the area-averaged data. Quantification of biases for mean temperature per area and precipitation series was also carried out. In addition, biases were evaluated over all grids within the regions and spatial distributions of these quantities presented.

Comparison of model-simulated and observed data

Area-averaged temperature data were obtained based on the CRU TS 2.0 data series and compared with the model-simulated data for the base periods. Figure 3 shows the area-averaged annual cycles of observed and simulated current mean temperatures for HadRM2 and PRECIS over the Eastern Himalayan region. The annual cycles typically have the highest temperatures during summer and minimum temperatures in winter and are well represented by the models. Compared to observed data, the simulated current mean temperatures are of smaller amplitude in the annual cycle, which means the model generally features cooler than observed mean temperatures throughout the year.

Correlation coefficients between observed and PRECIS-simulated (BLB) current mean winter, summer, and annual temperatures are respectively 0.61, 0.75, and 0.68, which are significant at a level of one per cent. In addition, the HadRM2 simulation of current mean temperature over this region is found to be closer to the observations in warmer than in cooler months.

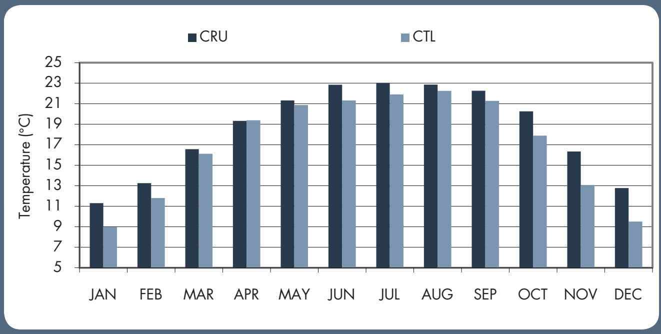
Both models reproduce patterns of annual cycles of mean temperature very well over the Eastern Himalayan region. In general, HadRM2-simulated current mean temperature over this region is found to be comparatively closer to the observed data than PRECIS-simulated values.

Data for area-averaged annual cycles of observed and HadRM2- simulated current and projected precipitation over the Eastern Himalayan region are given in Figure 4. The mean annual cycle is of great amplitude due to the fact that most of the annual precipitation occurs during the monsoon season (June through September); this is well captured. The HadRM2 model overestimates the amount of precipitation in this region compared to the observed data for all twelve months, and this is particularly so for the months of May, June, September, and October.

Figure 4 indicates that both models reproduce the patterns of annual precipitation cycles reasonably well over the Eastern Himalayan region. Simulation of current precipitation in this region is found comparatively closer to the observations in the HadRM2 model than in the PRECIS model from the months of January to May, however.

Figure 3: **Comparison of average annual cycles of current mean temperatures over the Eastern Himalayan region**

Observed and HadRM2-simulated (1981-2000)



Observed and PRECIS- simulated (1961-1990)

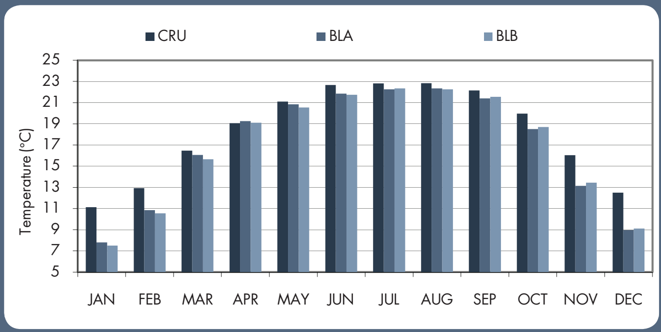
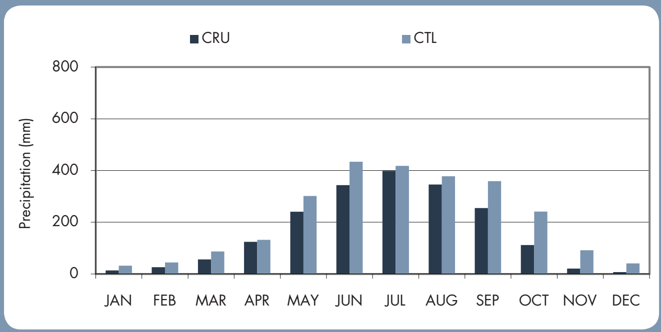
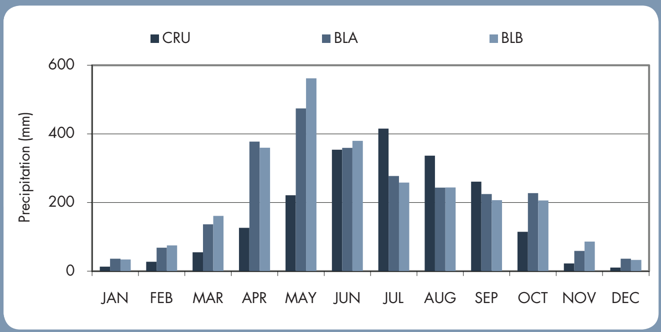


Figure 4: **Comparison of average annual cycles of current precipitation over the Eastern Himalayan region**

Observed and HadRM2-simulated (1981-2000)



Observed and PRECIS-simulated (1961-1990)



Biases of simulated results

Tables 2 and 3 show the area-averaged seasonal and annual biases and sensitivities of the HadRM2 and PRECIS simulated mean temperatures over the Eastern Himalayan region. Both models indicate cooler climates than those of the observed data during all seasons and annual periods. Further, both models show the greatest bias during winter (DJF) and the least during pre-monsoon (March, April and May; MAM) over the region. Comparing Tables 2 and 3, the biases in the PRECIS simulation are greater than those in the HadRM2 simulation by 0.8°C in DJF and 0.1°C in MAM. Whereas, the biases in the HadRM2 simulation are greater than those in the PRECIS simulations by 0.5°C in summer (JJA) and 0.7°C in the post-monsoon (September, October and November; SON) period. It may thus be concluded, in general, that over the Eastern Himalayan region the performance of HadRM2 is better during winter and that of PRECIS is better during the summer and post-monsoon (SON) seasons. During the pre-monsoon (MAM) and annual periods, both models perform more or less uniformly.

Spatial variation in the annual, winter, and summer biases (°C) of the HadRM2 and PRECIS simulated mean temperatures over the Eastern Himalayan region are presented in Figures 5 and 6 respectively. In general, both models simulate cooler current climates than the observed in higher-altitude regions (above approximately 2000 masl) and warmer than observed in regions lower than this. Comparing the magnitude of such biases in these models, it is found that the cold bias in higher-altitude regions is lower in PRECIS than in HadRM2 simulations of annual and summer mean temperatures and remain almost identical during winter. Similarly, the warm bias at lower altitude (below approximately 2000 masl) is less in the PRECIS than in the HadRM2 simulation of annual and winter mean temperatures, whereas the warm bias at lower altitude is smaller in the HadRM2 than in the PRECIS simulation during summer.

The area-averaged seasonal and annual biases and sensitivities of the HadRM2 and PRECIS simulated

Table 2: **Area-averaged observed climate (CRU) and HadRM2 simulated mean temperature statistics by area over the Eastern Himalayan region, where CTL stands for twenty-year simulations of current climate (1981-2000) and GHG for model-projected climate (2041-2060)**

	DJF	MAM	JJA	SON	Annual
CRU (°C)	12.4	19.1	22.9	19.6	18.5
CTL (°C)	10.1	18.8	21.8	17.4	17.0
GHG (°C)	13.3	20.8	24.8	20.6	19.9
CRU minus CTL (°C)	2.4	0.3	1.1	2.2	1.5
GHG minus CTL (°C)	3.2	2.0	3.0	3.2	2.9

Table 3: **Area-averaged CRU and PRECIS simulated mean temperature statistics over the Eastern Himalayan region, where BLA and BLB stand for simulated current climate (1961-1990) and A2 and B2 for model-projected climate (2071-2100)**

	DJF	MAM	JJA	SON	Annual
CRU (°C)	12.2	18.9	22.8	19.4	18.3
BLB (°C)	9.0	18.5	22.2	17.9	16.9
BLA (°C)	9.2	18.7	22.2	17.7	17.0
CRU minus BLB (°C)	3.2	0.4	0.6	1.5	1.5
CRU minus BLA (°C)	3.0	0.2	0.6	1.7	1.4
B2 (°C)	12.5	21.0	25.0	20.4	19.7
A2 (°C)	14.5	22.5	25.9	22.0	21.2
B2 minus BLB (°C)	3.5	2.6	2.8	2.5	2.9
A2 minus BLA (°C)	5.3	3.8	3.8	4.3	4.3

Figure 5: **Spatial distribution of biases (°C) of the HadRM2-simulated annual, winter, and summer mean temperatures over the Eastern Himalayan region (1981-2000)**

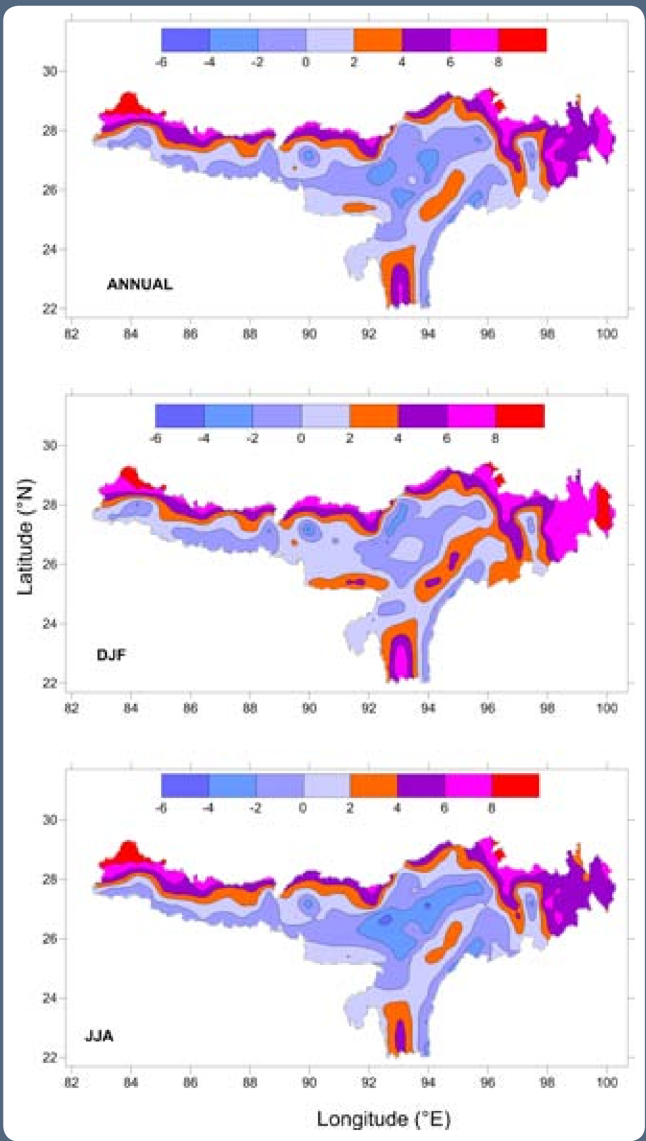
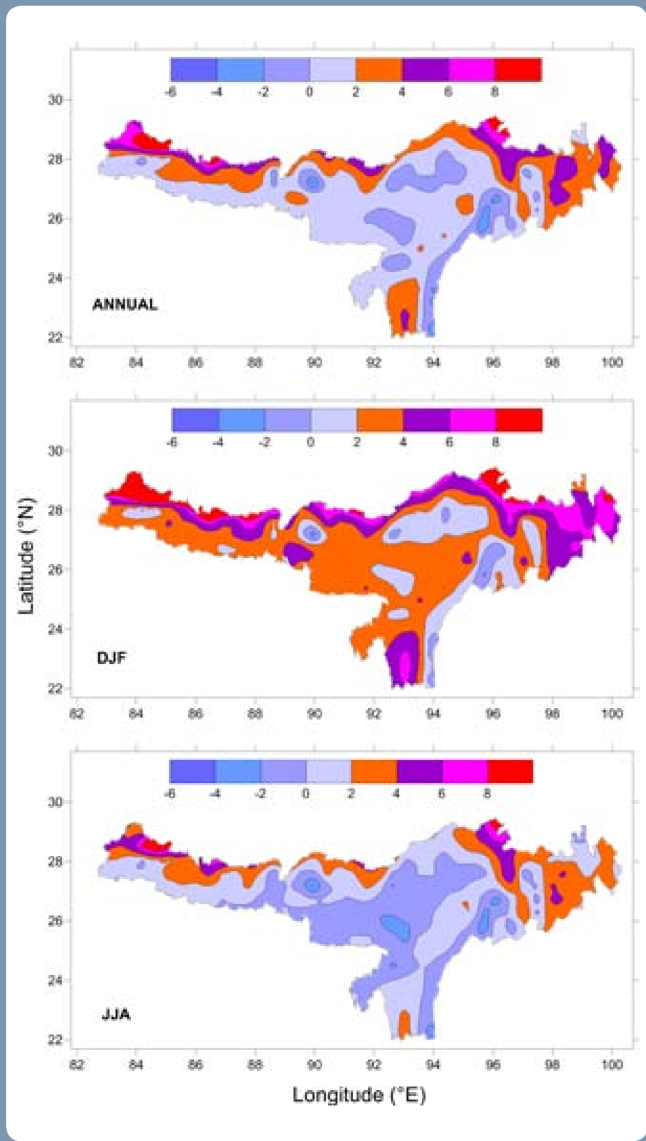


Figure 6: **Spatial distribution of biases (°C) of the PRECIS-simulated annual, winter and summer mean temperatures over the Eastern Himalayan region (1961-1990)**



precipitation over the Eastern Himalayan region are given in Tables 4 and 5. Both the models generally overestimate both seasonal and annual precipitation in comparison to the observed data, except during the monsoon, during which the PRECIS model slightly underestimates precipitation compared to the amount observed. Further, in most cases, both models indicate an inverse relationship between seasonal rainfall and the biases. Comparing Tables 4 and 5, over the Eastern Himalayan region HadRM2 overestimates monsoon precipitation by 18% and PRECIS underestimates it by 20% compared to the observed data.

Spatial variation of bias (in percentages of the observed data) of the HadRM2 and PRECIS simulated monsoon (June-July-August-September; JJAS) precipitation over the Eastern Himalayan region is presented in Figure 7. In general, both models simulate greater amounts of monsoon precipitation than the observed amounts in higher-altitude regions (wet bias) and lower than the observed (dry bias) at lower altitudes. The wet bias of HadRM2 at higher altitude is suppressed significantly in the PRECIS simulation of monsoon precipitation. Similarly, the dry bias at lower altitude is relatively more reduced in the PRECIS than in the HadRM2 simulation of monsoon precipitation.

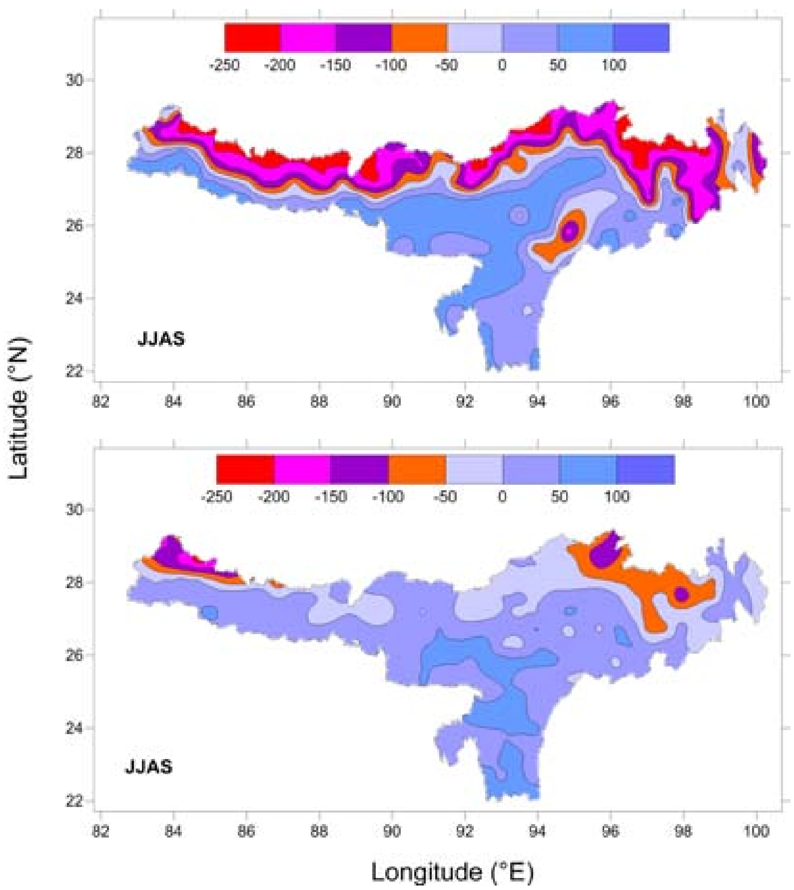
Table 4: **Area-averaged CRU and HadRM2 simulated precipitation statistics over the Eastern Himalayan region, where CTL stands for twenty-year simulations of current climate (1981-2000) and GHG for model-projected climate (2041-2060)**

	DJF	MAM	JJAS	ON	Annual
CRU (mm)	47	422	1344	133	1945
CTL (mm)	118	520	1589	333	2559
GHG (mm)	185	761	1701	381	3028
CRU minus CTL (% of CRU)	-150	-23	-18	-150	-32
GHG minus CTL (% of CTL)	57	46	7	15	18

Table 5: **Area-averaged CRU and PRECIS simulated precipitation statistics over the Eastern Himalayan region, where BLA and BLB stand for simulated current climate (1961-1990) for A2 and B2 projected emission-scenario climate (2071-2100), respectively**

	DJF	MAM	JJAS	ON	Annual
CRU (mm)	51	403	1367	138	1959
BLB (mm)	143	1083	1090	292	2607
BLA (mm)	139	989	1105	286	2520
CRU minus BLB (% of CRU)	-179	-169	20	-112	-33
CRU minus BLA (% of CRU)	-172	-145	19	-108	-29
B2 (mm)	176	1165	1276	328	2944
A2 (mm)	189	1440	1413	339	3381
B2 minus BLB (% of BLB)	23	8	17	12	13
A2 minus BLA (% of BLA)	35	46	28	18	34

Figure 7: **Spatial distribution of biases (% of observed) of the HadRM2 (upper panel for 1981-2000) and PRECIS (lower panel for 1961-1990) simulated monsoon precipitation over the Eastern Himalayan region**



Climate-change scenarios

Temperature

The area-averaged sensitivity of the simulated seasonal and annual mean temperatures expressed in terms of degrees Celsius over the Eastern Himalayan region is shown in Tables 2 and 3. HadRM2 simulation over the region projects the highest mean temperature increase of 3.2°C during DJF and SON, the lowest increase of 2°C during MAM, and a 2.9°C increase in the annual mean temperature by the 2050s. Similarly, B2 (A2) scenarios from PRECIS simulation over the same region project the highest mean temperature increase of 3.5°C (5.3°C) during DJF, the lowest increase of 2.5°C (3.8°C) during SON (MAM and JJA), and a 2.9°C (4.3°C) increase in annual mean temperature by the 2080s.

The area-averaged annual cycles of HadRM2 and PRECIS-simulated current and projected mean temperatures over the Eastern Himalayan region are shown in Figure 8. For PRECIS simulation two types of emission scenario are considered, BLA and BLB. In both types the simulated current mean temperature generally underestimates the observed values throughout the year. The projected mean temperature, however, is higher in the A2 than the B2 scenarios, and this is particularly prominent during the cooler months (e.g., DJF)

The spatial variation of annual, winter, and summer sensitivities (°C) of the HadRM2 and PRECIS simulated mean temperatures over the Eastern Himalayan region are shown in Figure 9. The greenhouse warming scenarios of the HadRM2 model predict an increase in annual mean temperature by 2 to 3°C over most parts of the region; the PRECIS model predicts an increase in annual mean temperature by 2.5 to 3.5°C.

The high warming tendency of the HadRM2 model, particularly over high-altitude regions, is suppressed in PRECIS simulations. The future simulations of both models indicate a little greater warming in winter than in summer precipitation over the Eastern Himalayan region.

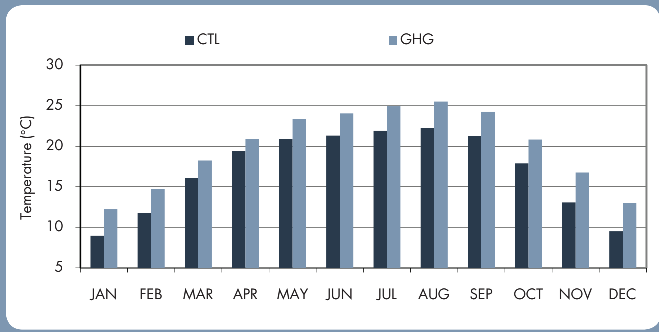
Precipitation

Tables 4 and 5 give the area-averaged sensitivity of the simulated seasonal and annual precipitation expressed in terms of percentages of the current simulation over the Eastern Himalayan region. The HadRM2 model projects an increase of monsoon precipitation by 7% of the current simulation; the B2 (A2) scenarios of the PRECIS model predict an increase of monsoon precipitation by 17% (28%) of the baseline simulation.

Spatial variation of sensitivities (in percentage of current simulation) of the HadRM2 and PRECIS simulated summer precipitation over the Eastern Himalayan region are presented in Figure 10. The greenhouse warming scenarios of both models predict an enhancement of monsoon precipitation of up to 30% over most parts of this region and even up to 40% over a few high-altitude pockets. Reduction in HadRM2 simulated summer precipitation over northern high-altitude regions, however, is lower in the PRECIS simulation.

Figure 8: **Comparison of area-averaged annual cycles of mean temperatures over the Eastern Himalayan region**

HadRM2-simulated control (1981-2001) and projected (2041-2060)



PRECIS- simulated baseline (1961-1990) projected (2071-2100)

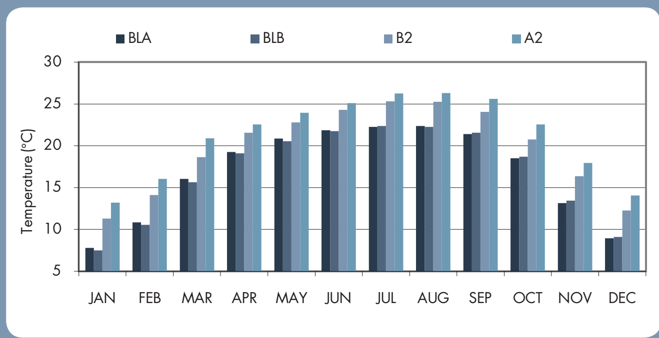
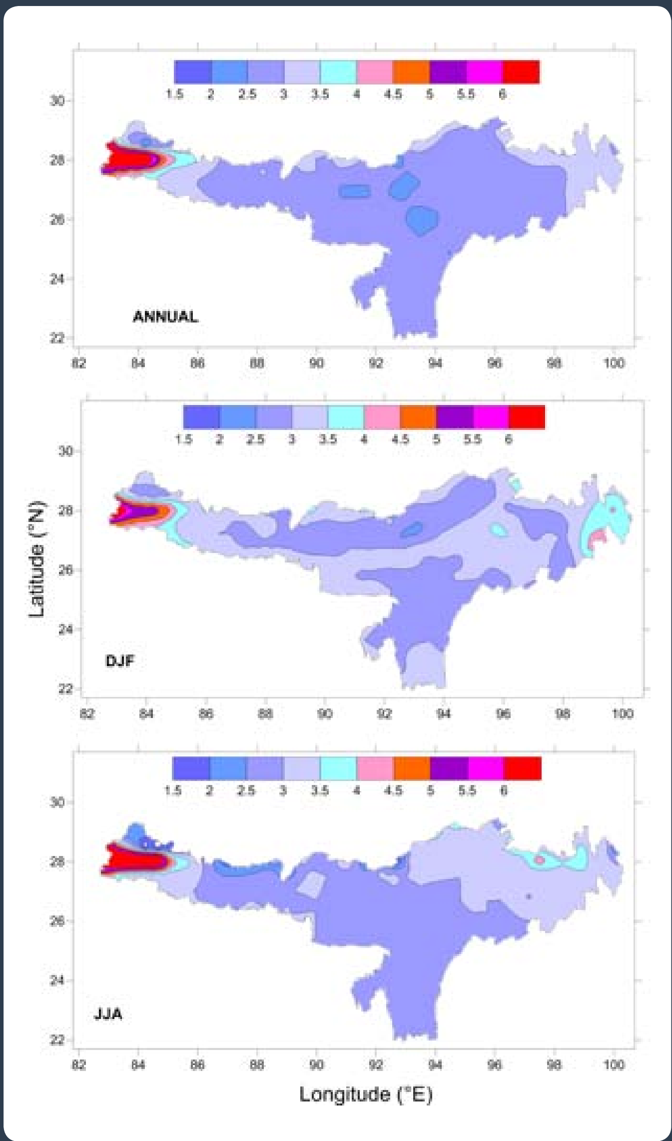


Figure 9: **Spatial distribution of scenarios (°C) of the simulated annual, winter, and summer mean temperature over the Eastern Himalayan region**

HadRM2 (2041-2060)



PRECIS (2071-2100)

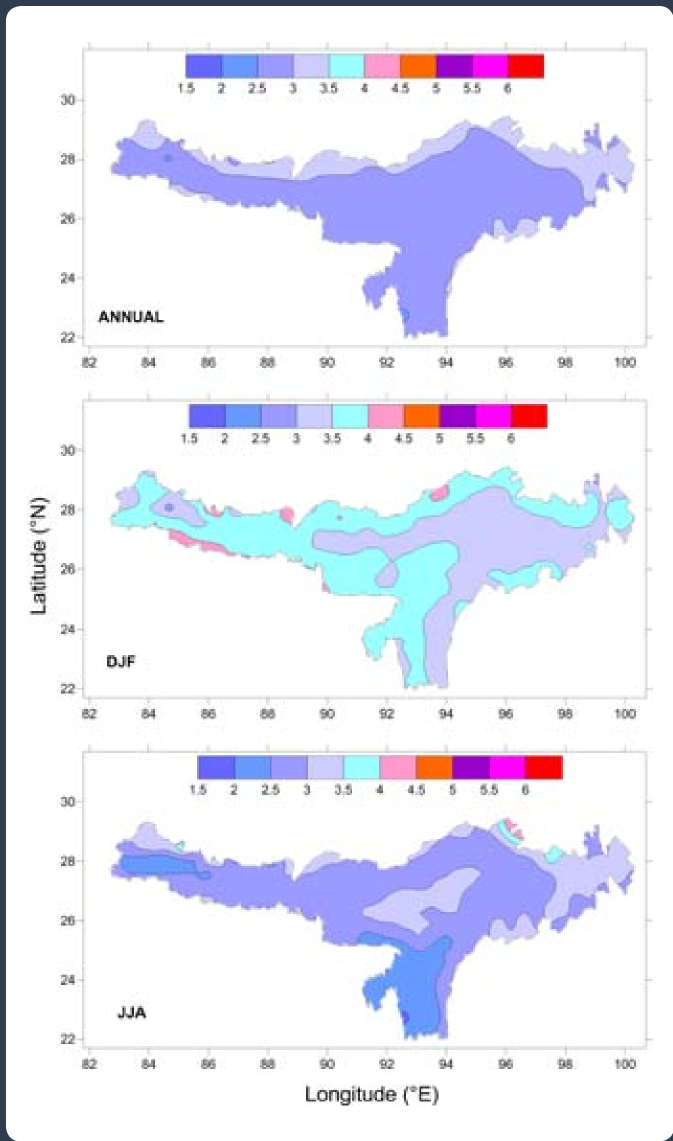
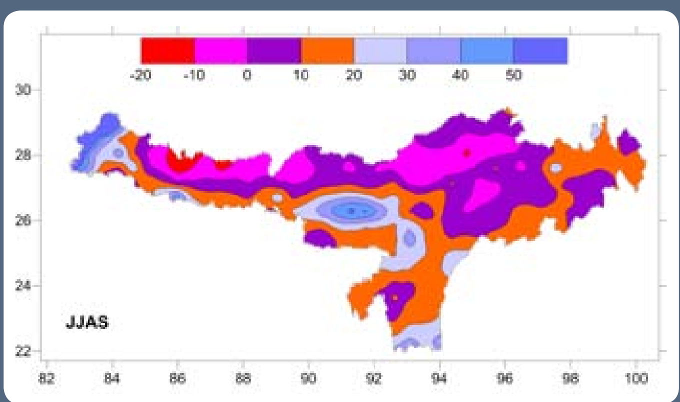
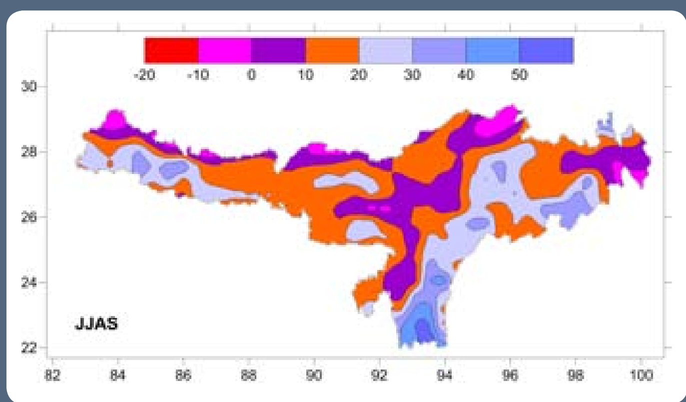


Figure 10: **Spatial distribution of scenarios (% current simulation) of simulated monsoon precipitation over the Eastern Himalayan region**

HadRM2 (2041-2060)



PRECIS (2071-2100)



Conclusion

Summary of the results

The study results lead to the following conclusions:

a) Major parts of the study area are undergoing warming trends: annual mean temperature is increasing at the rate of 0.01°C/yr or more. In general, for annual and seasonal trends, there is a diagonal zone with a southwest to northeast trend where there is relatively less or no warming. There is progressively more warming with elevation, with the areas above 4,000 m experiencing the greatest warming rates. The results suggest that seasonal temperature variability is increasing and the altitudinal lapse rate of temperature is decreasing. Unlike temperature, precipitation does not demonstrate any distinctive trends at present.

b) Both HadRM2 and PRECIS models reproduced the patterns of annual cycles of mean temperature very well over the Eastern Himalayan region. It was found that the influence of the mountains on the local climate is better incorporated in the PRECIS than in the HadRM2 model. Seasonally, over the Eastern Himalayan region, the performance of HadRM2-simulated mean temperature is better during winter and pre-monsoon seasons and that of PRECIS better during summer and post-monsoon season.

c) The HadRM2 simulation over the Eastern Himalayan region projected increases of 3.2, 2.0, 3.0, 3.2, and 2.9°C for DJF, MAM, JJA, SON, and annual mean temperatures, respectively by the 2050s. The B2 scenarios of PRECIS projected increases of 3.5, 2.6, 2.8, 2.5, and 2.9°C for DJF, MAM, JJA, SON, and annual mean temperatures, respectively by the 2080s, whereas the A2 scenario projected increases of 5.3, 3.8, and 4.3°C for the same periods.

d) Both models simulate cooler climates than observed at higher altitudes and warmer than actually observed at lower altitudes of the Eastern Himalayas. The cold and warm biases during winter, summer, and annual periods are less pronounced in PRECIS than in HadRM2, except for the cold bias during winter over the Eastern Himalayan region.

e) Both HadRM2 and PRECIS models reproduced the patterns of annual cycles of precipitation reasonably well over the Eastern Himalayan region. Monthly comparison of observed and simulated current precipitations is, in general, comparatively better in the HadRM2 than in the PRECIS model. Seasonal comparison of observed and simulated current precipitations over the Eastern Himalayan region indicates better performance of the HadRM2 simulation during winter, pre-monsoon, and monsoon seasons and better performance of PRECIS during the post-monsoon season.

f) The HadRM2 simulation of the Eastern Himalayan region projected an increase of winter, pre-monsoon, monsoon, post-monsoon, and annual precipitation by 57, 46, 7, 15, and 18% of the current simulations, respectively, by the 2050s; whereas the B2 scenarios of PRECIS projected an increase of winter, pre-monsoon, monsoon, post-monsoon, and annual precipitations by 23, 8, 17, 12, and 13% of current precipitation, respectively, by the 2080s, and the A2 scenario increases of 35, 46, 28, 18, and 34% for the same period.

g) Both models simulate greater amounts of monsoon precipitation than observed in higher-altitude regions (wet bias) and lower than the observed at lower altitude (dry bias) over the Eastern Himalayan region. In general, these dry and wet biases are less in the PRECIS- than in the HadRM2 simulated monsoon precipitation model. The greenhouse warming B2 scenarios of the PRECIS model project an enhancement of monsoon precipitation of up to 30% of the baseline simulation over most parts and even up to 40% over a few high-altitude pockets in the Eastern Himalayan region.

Both models (HadRM2 and PRECIS) showed significant biases in simulating current climate. This should be considered while interpreting future scenarios.

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Acronyms and Abbreviations

BL	baseline
CRU	Climate Research Unit
CTL	control
DEM	digital elevation model
DJF	December - January - February season
GCM	general circulation model
GHG	greenhouse gas
GLOF	glacial lake outburst flood
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
JJA	June - July - August season
JJAS	June - July - August - September season
MAM	March - April - May season
PC	personal computer
PRECIS	Providing Regional Climates for Impacts Studies
RCM	regional climate model
SON	September-October-November season

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The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush-Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalisation and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. We support regional transboundary programmes through partnership with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream – now, and for the future.

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