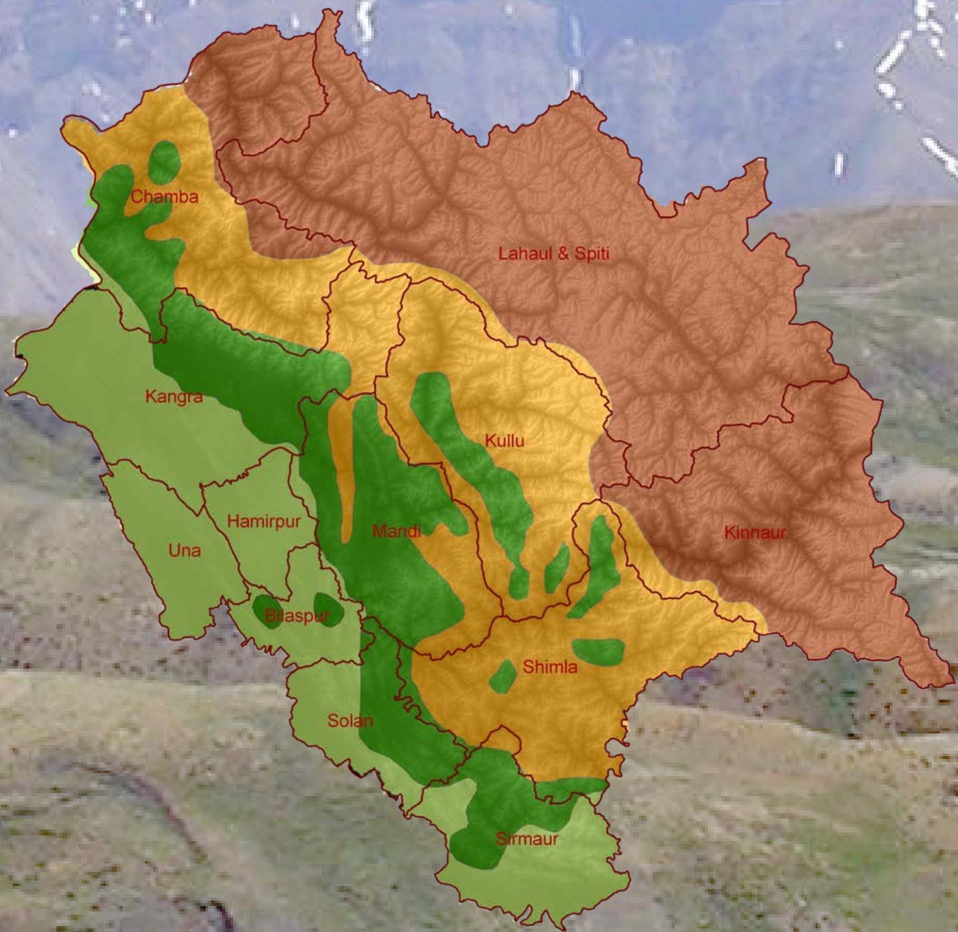
Draft Report

(Prepared by GGGI, South Korea, TERI in association with DEST)

Climate Modelling for Himachal Pradesh



Please send your comments to:

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A Department of Science & Technology (DST), Government of India sponsored programme

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EXECUTIVE SUMMARY

The picturesque state of Himachal Pradesh is located between $30^0$22'40" N latitude to $33^0$12'40" N and $75^0$47'55" to $79^0$04'20" E longitude. It extends over a geographical area of 55, 673 sq. kms, which is 1.69 percent of the country's area and 10.54 percent of the Himalayan landmass. It is surrounded by Jammu and Kashmir in the north, Tibet on north/north east, Uttaranchal in the east/ south east; Haryana in south and Punjab in south west/ west. There are four agroclimatic zones viz. Shivalik Hill Zone, Mid Hill Zone, High Hill Zone and Cold Dry Zone. Shimla, which once was the summer capital of India, now serves as the state capital.

The economy of the State is dependent on sectors like the hydel power generation, horticulture, agriculture, forestry and tourism etc. and these sectors are assumed to be under threat in the present scenario of changing climate. Any change in these sectors due to climate change, in every likelihood, will not only going to affect the livelihood prospects in the agrarian economies of mountain regions, but also everyone living below in the plains.

This report provides an analysis and evaluation of observed climatological information of Himachal Pradesh and assessment of near future climate variability over the State. Analyses methods include review of literature, obtaining the observed climatological data for the State and its trend analyses.

A high resolution dynamical model was used to simulate (under A1B scenario) a baseline run from 1970-2000 and for near future (2030s: 2020-2050) to arrive at future climate variability over the study domain area.

Spatial variation is seen for precipitation projections for near future for different seasons (Fig. A, B, C, D).

Winter months shows the largest changes in the probable ranges for the future (Fig C) and summer season shows an overall increase over the state in the future (Fig. D). The snow and glacier areas have not been taken into block wise analysis plots for rainfall.

Analyses of extreme climate conditions were also performed. Annual mean temperature projected to increase by 1.3-1.9° C for 2021-2050 period relative to 1971-2000 (Fig. E). Relatively larger changes projected for minimum temperatures for the future (Figs. F & G). Extreme rain events will also increase (both frequency and intensity) in the near future (Fig. H).

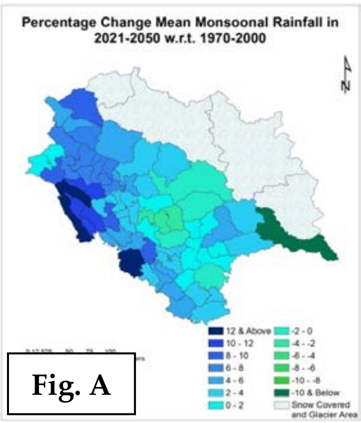


Fig. A

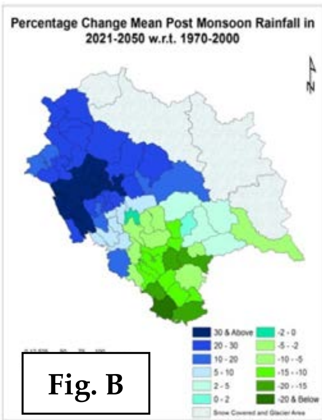


Fig. B

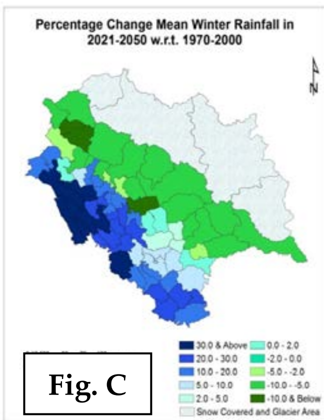


Fig. C

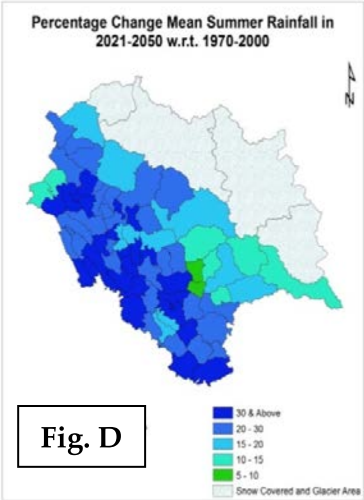


Fig. D

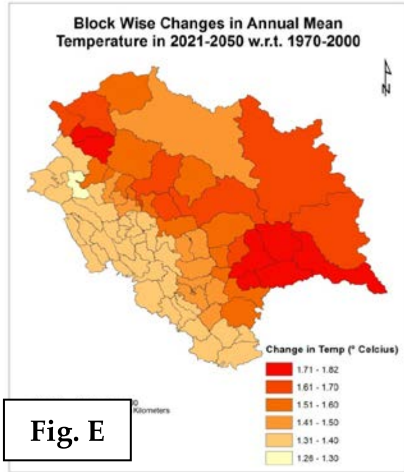


Fig. E

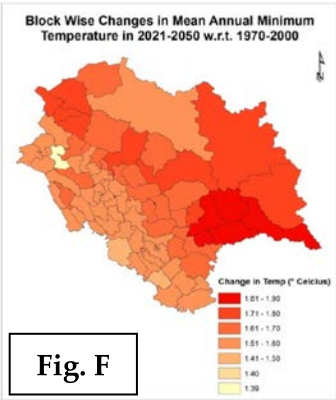


Fig. F

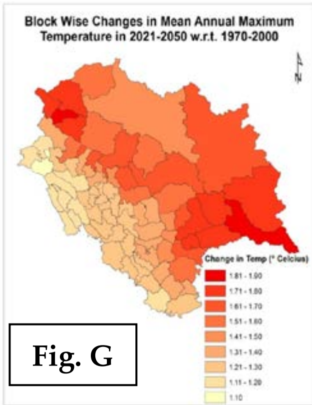


Fig. G

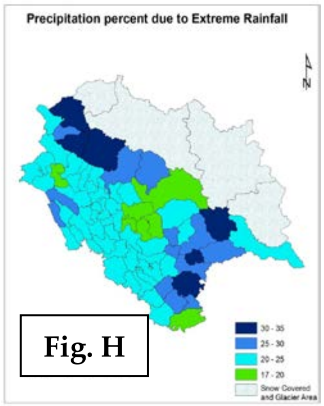


Fig. H

1. Introduction

The climate modelling component involves establishing climatological information of Himachal Pradesh and assessing near future climate variability over the State.

To establish the climatological information for the State of Himachal Pradesh, historical trend analysis of the meteorological data and literature review has been carried out. Review on the latest available literature for the climatological trends for basic meteorological parameters over Indian domain and on sub-divisional scale has been done as the first step towards understanding the climate of the region.

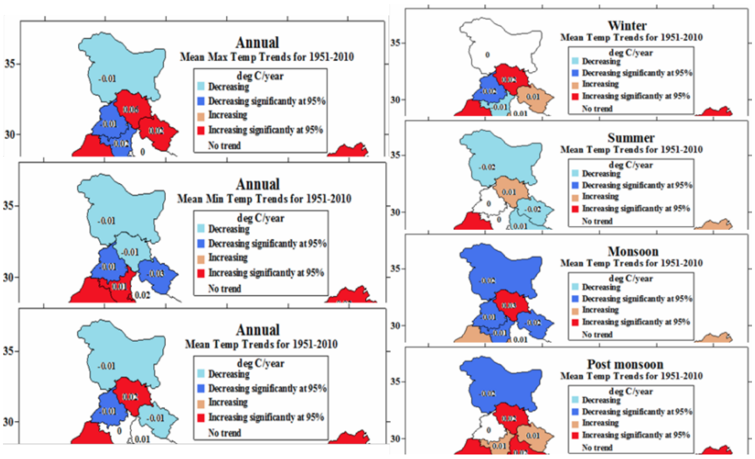
Post literature analysis and historical data analysis, the model identification was carried out and a high resolution dynamical model was run under A1B SRES[1] scenario that simulates baseline run from 1970-2000 and near future time scale run from 2020-2040 (2030s) to arrive at future climate variability over the State. Analyses of extreme climate conditions were also performed.

1 SRES: Special report on emission scenarios, IPCC, 2000: http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0

2. Observed climatological trend over Himachal Pradesh

2.1 Temperature

The state of Himachal shows a significant increasing trend of 0.06°C/yr on annual mean maximum temperatures and 0.02°C/yr on annual mean temperatures for the 1951-2010 time period. The annual mean minimum temperatures have shown a decreasing (-0.01°C/yr) trend over the state for the same time period (Rathore *et al.*, 2013) (Figure 1 left). The seasonal mean temperature trends for the 1951-2010 period shows a significant increasing trend for most seasons *viz.* winters (0.02°C/yr), monsoons (0.03°C/yr) and post-monsoon (0.02°C/yr) but not significantly increasing for summers (0.01°C/yr) (Rathore *et al.*, 2013) (Figure 1 right).



Source: IMD monograph: ESSO/IMD/EMRC/02/2013

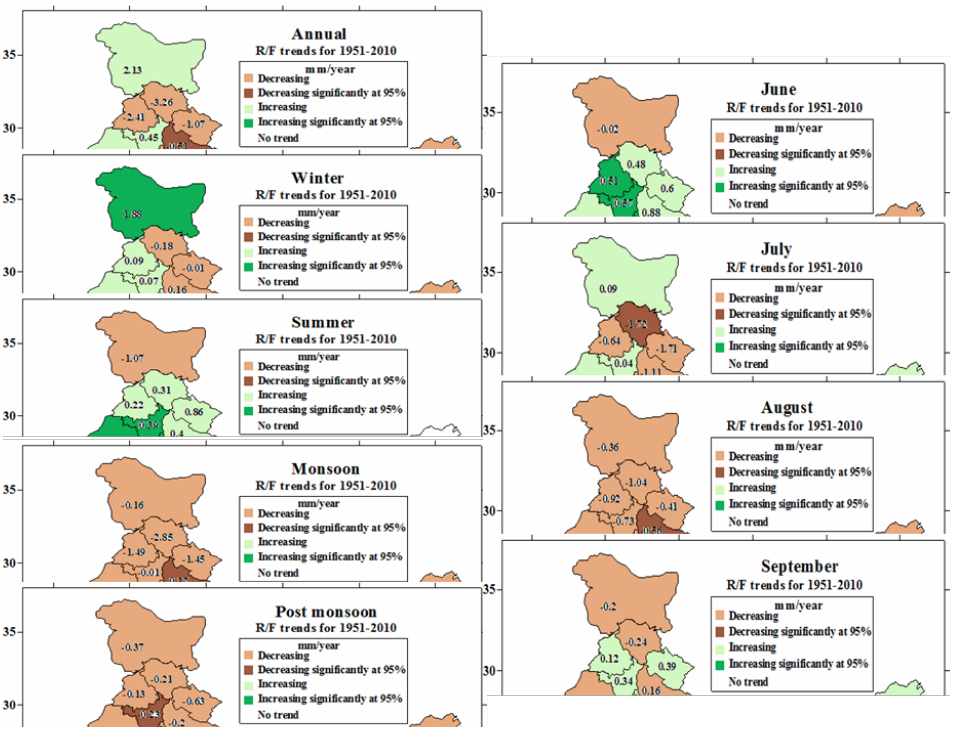
Figure 1 : Trends in annual maximum, minimum and mean temperatures (on left) and trends in seasonal mean temperatures (on right) for 1951-2010 period

The short term analysis has shown that the rate of increase in maximum temperature is observed to be greater over higher latitudes as compared to lower latitudes and the rate of warming in north western Himalayan region have been significantly higher than the global average. The winter air temperature in the last two decades has also shown a clear increasing trend over the observation stations of Shimla and Solang and over the entire state region as well (Bhutiyani *et al.*, 2007) (HP-SAPCC, 2012).

2. 2 Rainfall

The annual average rainfall over the state of Himachal Pradesh for the period 1951-2010 indicates a decreasing trend (-3.26 mm/yr). The seasonal rainfall for summer (0.31 mm/yr) shows an increasing trend for the same time period whereas the winter, monsoon and post-monsoon seasons show a decreasing trend of -0.18 mm/yr, -2.85 mm/yr and -0.21 mm/yr (Figure 2 left). For the individual monsoon months, the trend for the time period of 1951-2010 shows a decreasing trend for July at -1.72 mm/yr (significant at 95% level), August (-1.04 mm/yr) and September (-0.24 mm/yr) whereas June rainfall have shown an increasing trend of 0.48 mm/yr for the 1951-2010 period (Figure 2 right).

The annual precipitation, winter and monsoon precipitation for the long time period (1866-2006) over the stations of Shimla have also shown a decreasing trend at 95% confidence level (Bhutiyani *et al.*, 2007). The trend over the district rainfall in the last 25 years have shown increasing trend of 33.5%, 54.3% and 51.5% for Kinnaur, Chamba and Lahul & Spiti respectively whereas a decreasing trend of 8.7%, 13.3% and 26.6% for Solang, Shimla and Sirmour respectively (HP-SAPCC, 2012).



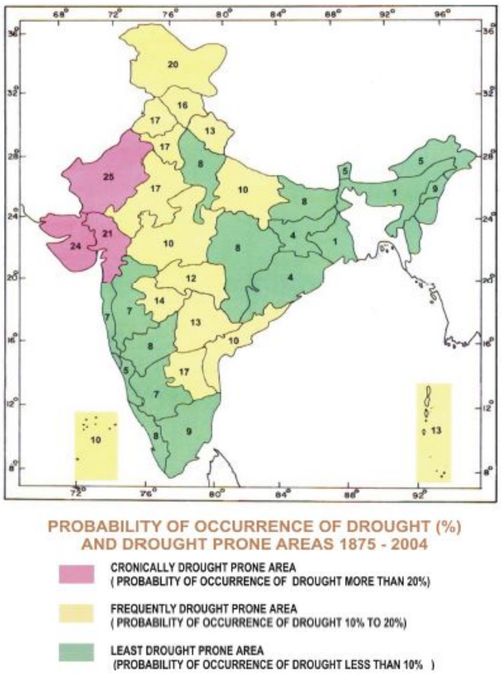
Source: IMD monograph: ESSO/IMD/EMRC/02/2013

Figure 2: Trends in annual and seasonal rainfall (on left) and trends in monthly rainfall (on right) for 1951-2010 period

2.3 Drought

Himachal Pradesh is enlisted under the frequent drought (10-20% probability) prone areas as per Indian Meteorological Department's (IMD) classification of drought incidences from 1875-2004 period (Figure 3). A total of 23 droughts[2] have occurred in the state of which 20 were moderate and 3 have been severe over the 1879-2009 time period with the drought probability of 17 % and with four instances of consecutive droughts over two years (Shewale and Kumar; 2005, Attri and Tyagi; 2010, IMD met monograph 21/2005 and 01/2010).

[2] Drought: Meteorological drought over an area is defined as a situation when the monsoon seasonal (June-September) rainfall over the area is less than 75% of its long-term average value. Moderate drought: if the rainfall deficit is 26-50% and Severe drought: when the deficit exceeds 50% of the normal. A year is considered as a 'drought year' when the area affected by moderate and severe drought either individually or together is 20-40% of the total area of the country and seasonal rainfall deficiency during southwest monsoon season for the country as a whole is at least 10% or more



Source: IMD meteorology monograph - 2010

Figure 3: Probability of occurrence of drought (%) and drought prone areas 1875-2004

Cold Waves and snow fall: De *et al.* 2005 documented the cold waves[3] for different Indian states and it was found that the epochs of 1901-99 have seen occurrences of 22 cold waves of which the 1978-99 epochs have seen 18 incidences. The analysis on different altitudes in Himachal have shown a decreasing trend of snow fall at Bhang, Solang, Dhundi and Patseo station for recent 20 years of observations.

3 Cold waves: Occurrences of extreme low temperature in association with incursion of dry cold winds from north into the sub-continent are known as cold waves. The northern parts of India specially the hilly regions and the adjoining plains are influenced by transient disturbances in the mid latitude westerlies which often have weak frontal characteristics and are called as western disturbances.

3. Approach

3.1 Climate Model

Objective: To analyze the future climate over the state the regional model simulations at 25km × 25km resolution are being carried out. The model used in the study is PRECIS model.

Model setup: The model used in the study is PRECIS - Providing Regional Climates for Impacts Studies. It is developed at UK Met Office Hadley Centre. PRECIS is an atmospheric and land surface model of limited area and high resolution. Dynamical flow, the atmospheric sulphur cycle, clouds and precipitation, radiative processes, the land surface and the deep soil are all formulated, while the boundary conditions at the limits of the model's domain are required to be specified. It gives a comprehensive representation of physical processes in atmosphere and on land in terms of:

1. dynamics - atmospheric circulations, cyclones, fronts
2. radiation - effects of greenhouse gases and aerosols
3. clouds - radiative effects, sulphate aerosol effects
4. precipitation - convection, large-scale condensation
5. land-surface - soil hydrology (4 levels), vegetation

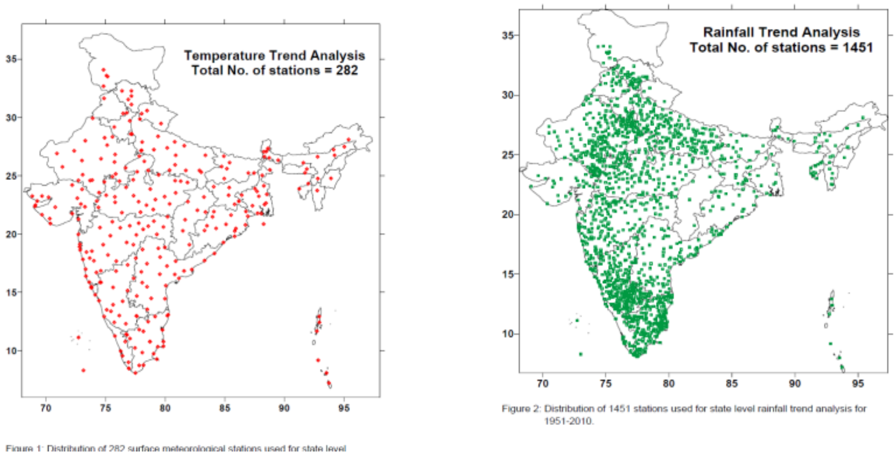
The typical horizontal grid size is 50km which can be lowered as per the user. It has 19 levels in hybrid vertical coordinate (Simmons and Burridge, 1981; Simon *et al.*, 2004) with variable thickness. The sea surface boundary conditions would be taken directly from ocean component of the ECHAM05 model. The model has been tuned to simulate the baseline runs from 1970-2000 and future runs of 2030s (2020-2040) under the A1B SRES[4] scenario. PRECIS is highly relevant for scientists involved in vulnerability and adaptation studies particularly for national communication documents and have been extensively used throughout the world in numerous regional modelling experiments.

3.2 Sources of uncertainty/data gaps

For building a climate profile over a region, studying historical trends and undertaking model validation, the long term observational data from the station or from an observational gridded dataset is essential. It's a direct relation between the number of station data used and the quality of the dataset. The IMD stations used in the 1951-2010 analysis as shown earlier are 5 for temperature and 36 for rainfall (Figure 4a). Also, for the gridded dataset, the methodology is restricted over an area with less number of stations and hence, more approximations and interpolations are done to arrive at datasets. All these factors should be noted as the key factors for uncertainty in observational data and resulting model analysis. Figure 4b below shows the data gaps in the analysis for meteorological

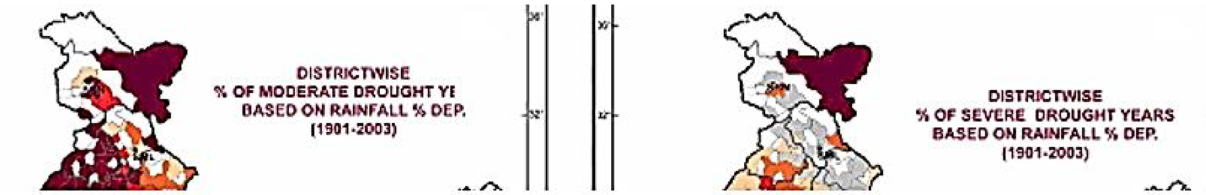
4 SRES: Special report on emission scenarios, IPCC, 2000: http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0

droughts.



Source: IMD Meteorological Monograph No. ESSO/IMD/EMRC/02/2013

Figure 4a: Distribution of met stations used for temperature trend analysis (on left) and rainfall analysis (right)



Source: IMD Meteorological Monograph 2010

Figure 4b: The white gaps show that the datasets were not available for the long term drought intensity and frequency analysis

It may be noted that all the studies involving modelling assessments are probabilistic which provide us the best indicator on how the climate has been evolving in the past and in coming future. The degree of certainty depends on many factors like input data and the boundary forcings used, the parameter being modelled, the type of models used, resolution and domain utilized. Considering the recent studies around the world and scale of the present study area, it is advised to use a multi-model ensemble study and a much higher resolution to arrive at probabilistic climate projections over a district wide scale.

4. Trend Analyses

4.1 Rainfall

The long period 1901-2013 annual accumulated rainfall over Himachal has been trendless although a slight decreasing trend has been observed for long term monsoon accumulated rainfall. However, the rainfall variability has been very significant (Figure 5) in the past as well as in recent years. To analyze long period and the seasonal rainfall trends over the state, latest IMD high resolution gridded rainfall dataset (Pai et al, 2014) have been utilized. The spatial resolution of these datasets is 0.25^{o}x0.25^{o} in the horizontal. The data has been extracted over the state and post-processed for the analysis. Since the dataset has square grids which do not necessarily match with the irregular state boundaries, this may result in some minor mismatch with station data analysis as reported earlier.

As can be seen from Figure 6 (a,b,c) the seasonal climatologies for winter (December, January & February), pre-monsoon (March, April & May) and post-monsoon (October & November) season show a decreasing trend for the 1970-2013 period using the IMD gridded dataset. A slight increasing trend is seen for the monsoon (June, July, August & September) season (Figure 7a) relative to other seasons. As seen from anomalies in Figure 7b, the recent years have experienced more negative rainfall signifying poor monsoon than the long term normal. Spatially the model simulated baseline shows that high rainfall bands over the state are mainly concentrated over the northern part of the state. Overall, the model is able to capture the observed rainfall spatially but overestimating a bit at some regions (Figure 8).

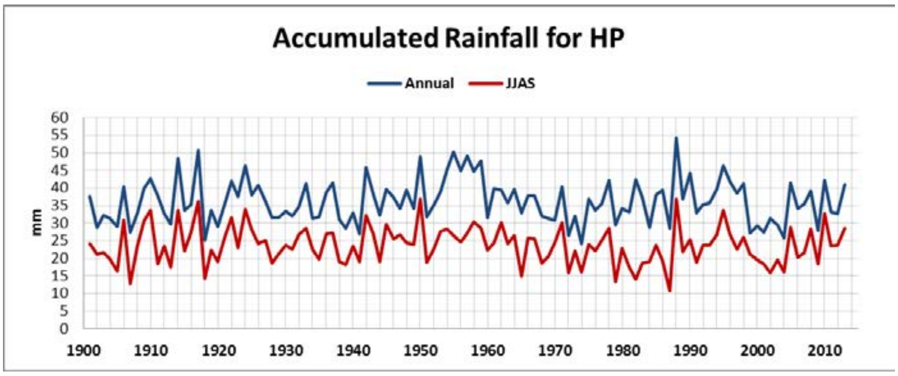


Figure 5: Annual and June, July, August, September accumulated rainfall over Himachal Pradesh for the 1901-2013 period showing year to year variability

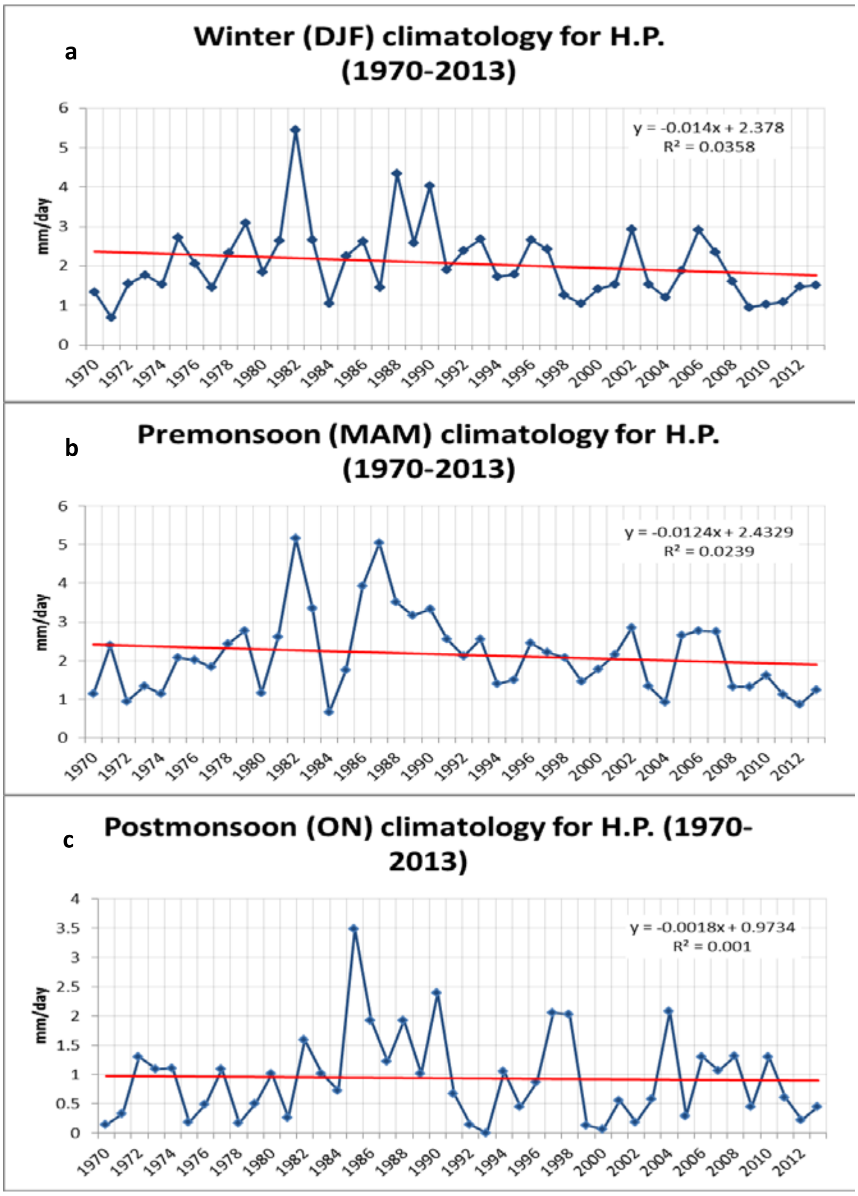


Figure 6: Rainfall climatologies for Himachal for (a) winters (b) pre-monsoon (c) post-monsoon for the 1970-2013 period

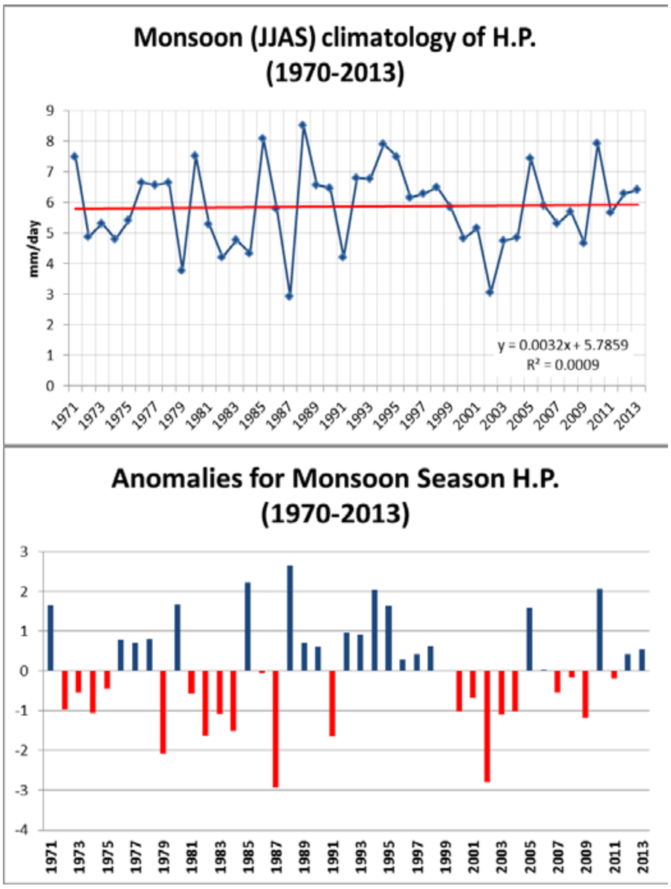


Figure 7: June, July, August and September rainfall (a) climatology and (b) anomaly over Himachal Pradesh for the 1970-2013 period

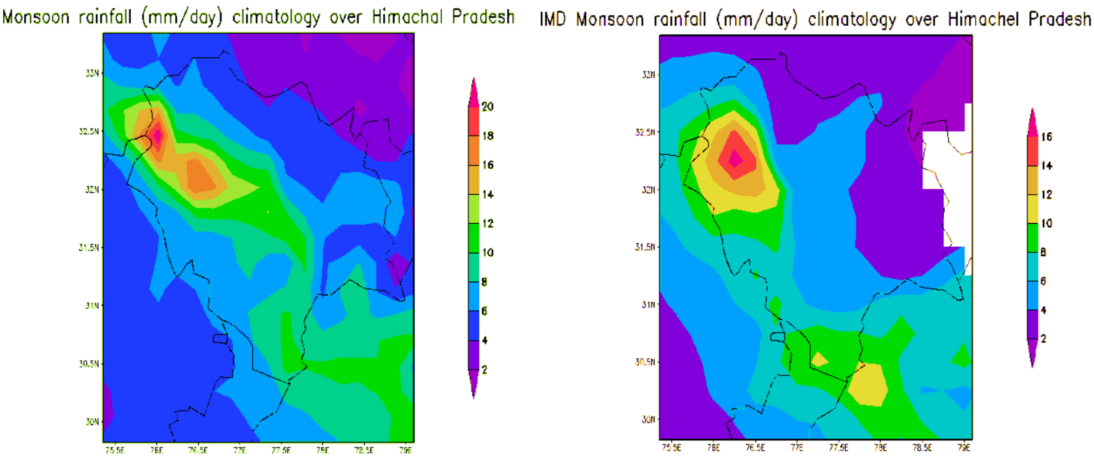


Figure 8: Monsoon (JJAS) rainfall climatology from IMD (left) and PRECIS (right) for the baseline period 1970-2000 both showing a high rainfall zone in the north

4.2 Temperature

The annual mean temperatures from the gridded IMD temperature datasets (Srivastava *et al.*, 2008) have been plotted (Figure 9 left) along with the model baseline (on right). It's observed that the model is able to capture the east-west oriented temperature gradient but has a comparatively colder bias over the state. Currently various methods are being researched to minimize the model bias over the area which is topographically complex.

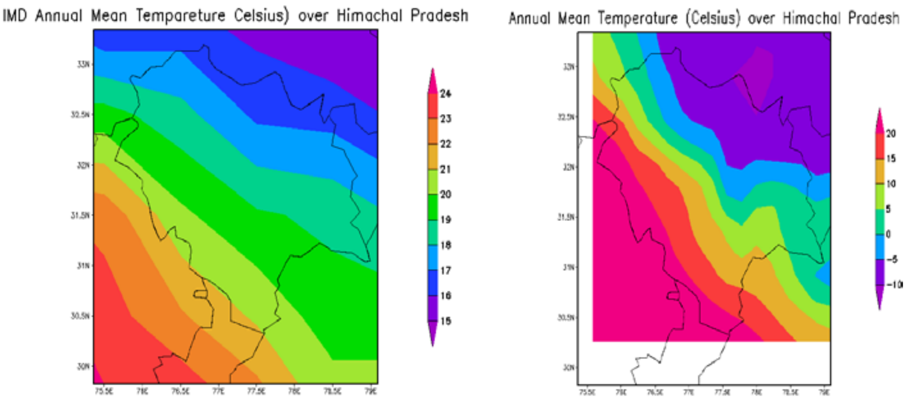


Figure 9: Annual mean temperatures from IMD (left) and model (right) for 1970-2000 baseline period over Himachal Pradesh

5. Climate projections

5.1 Rainfall

Owing to variable terrain and inconsistency in long term observations over the entire State, spatial variation is seen for precipitation projections for near future. Model projects the percentage precipitation change for monsoon months between the range -8% to 12% (Figure 10a). This change for winter months of December, January and February show a much larger variation i.e. from less than -10% to over 30% in some areas (Figure10b). The whole state shows a positive change for summer rainfall (Figure 10c) whereas post monsoon season also shows a variation in the changes of precipitation percentage in the range of less than -15% in some areas to more than 30% in others (Figure 10d).

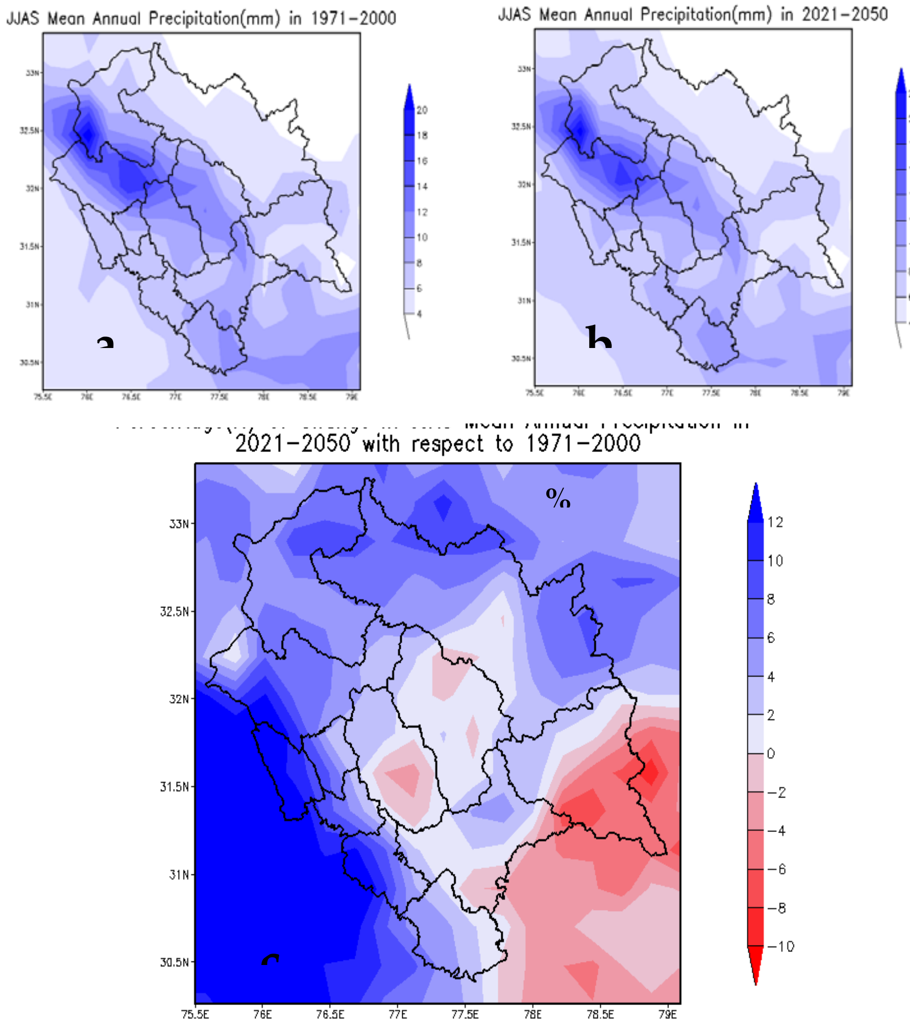


Figure 10a. Mean annual summer monsoon precipitation for baseline period (a), near future(b) and change in near future (c) relative to baseline period

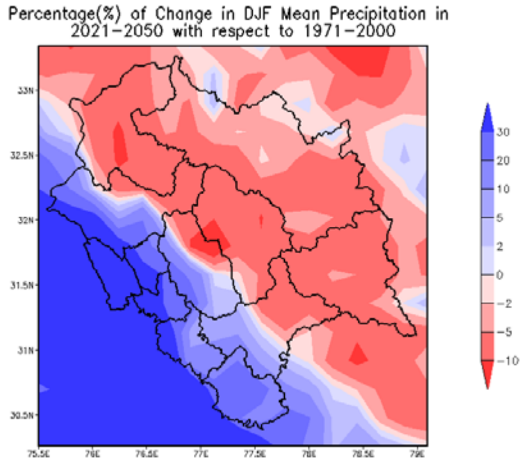


Figure 10b: Mean winter precipitation change for near future (2020-2050) relative to 1970-2000

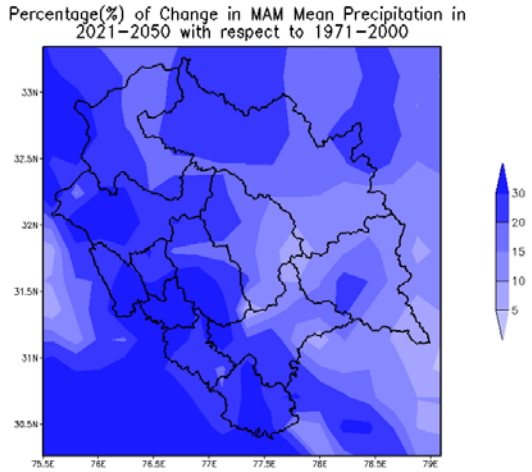


Figure 10c: Mean summer precipitation change for near future (2020-2050) relative to 1970-2000

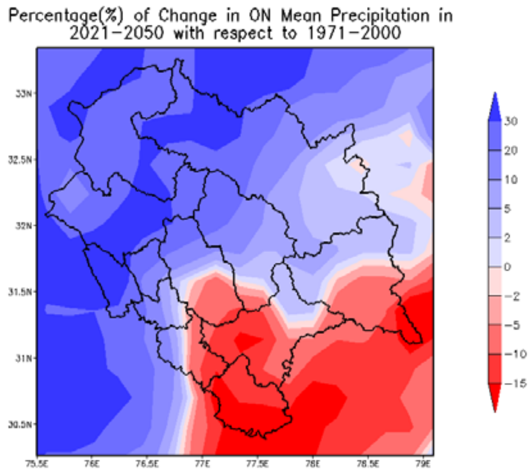


Figure 10d: Mean post monsoon precipitation change for near future (2020-2050) relative to 1970-2000

5.2 Temperature

Overall warming projected over the State in the near future with respect to the baseline period (Figure 11). Annual mean temperature projected to increase by 1.3-1.9 □2021-2050 relative to 1971-2000.

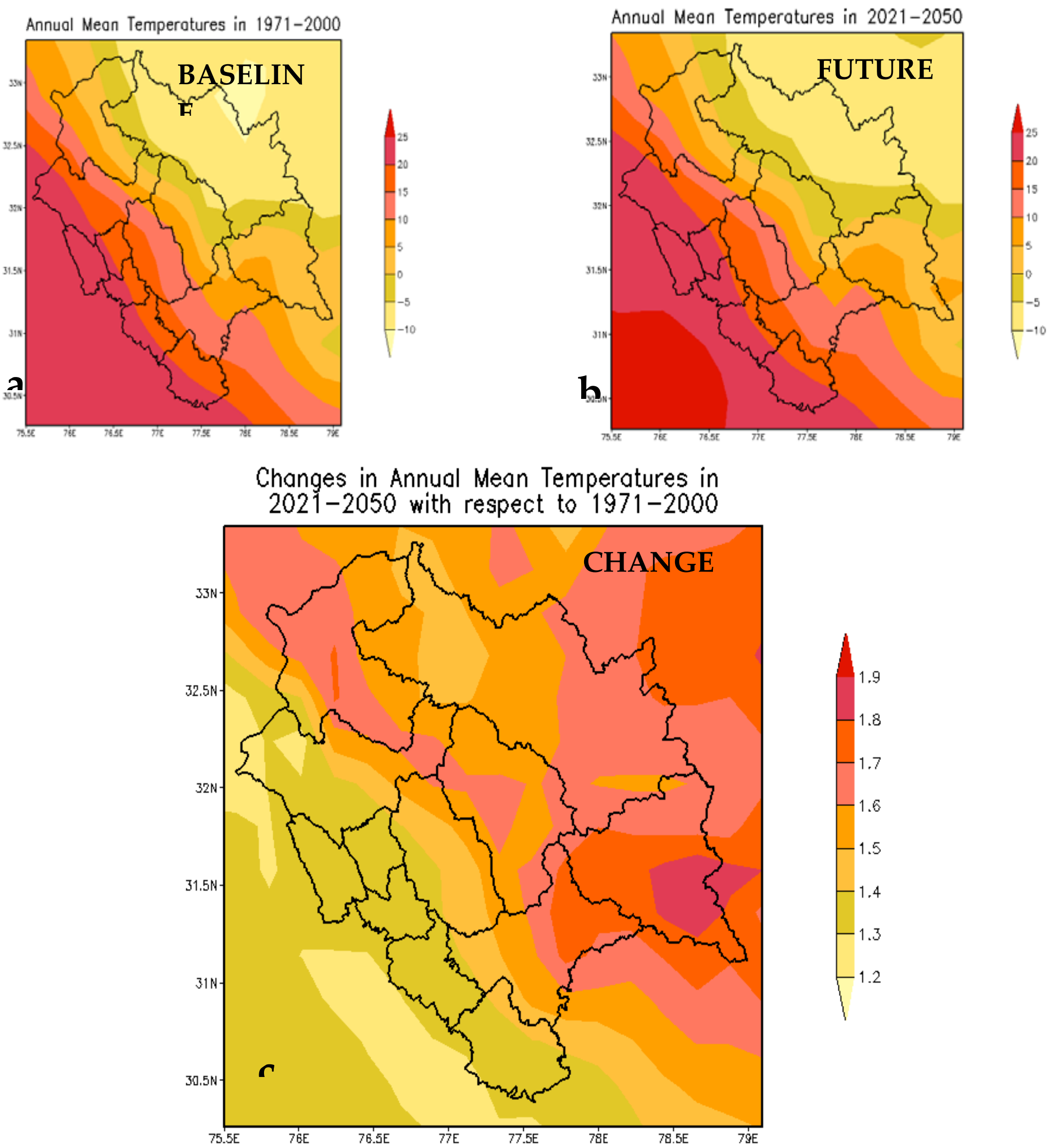


Figure 11: Mean annual temperature for baseline period (a), near future (b) and change in near future (c) relative to baseline period

5.3 Temperature extremes

Mean Annual Maximum temperature (**Tmax**) over the State is projected to increase by 1.1-**1.9** □ C (Figure 12). The Mean Annual Minimum Temperature (**Tmin**) also is projected to increase over the Study domain area in the range **1.5-1.9 deg C**(Figure 13). Relatively larger changes projected for minimum temperatures for the future. Corroborates with the historical trends over India, which have seen increase in Minimum Temperature to contribute more than Maximum Temperature for the increase in Mean Temperature over the baseline period (1970-2000). (ref. INCCA report, MoEF, 2010)

Increase in Minimum Temperature has many impacts not only over plants, crops but over human comfort as well. This also indicates that night time temperatures also will increase in the near future relative to the baseline period.

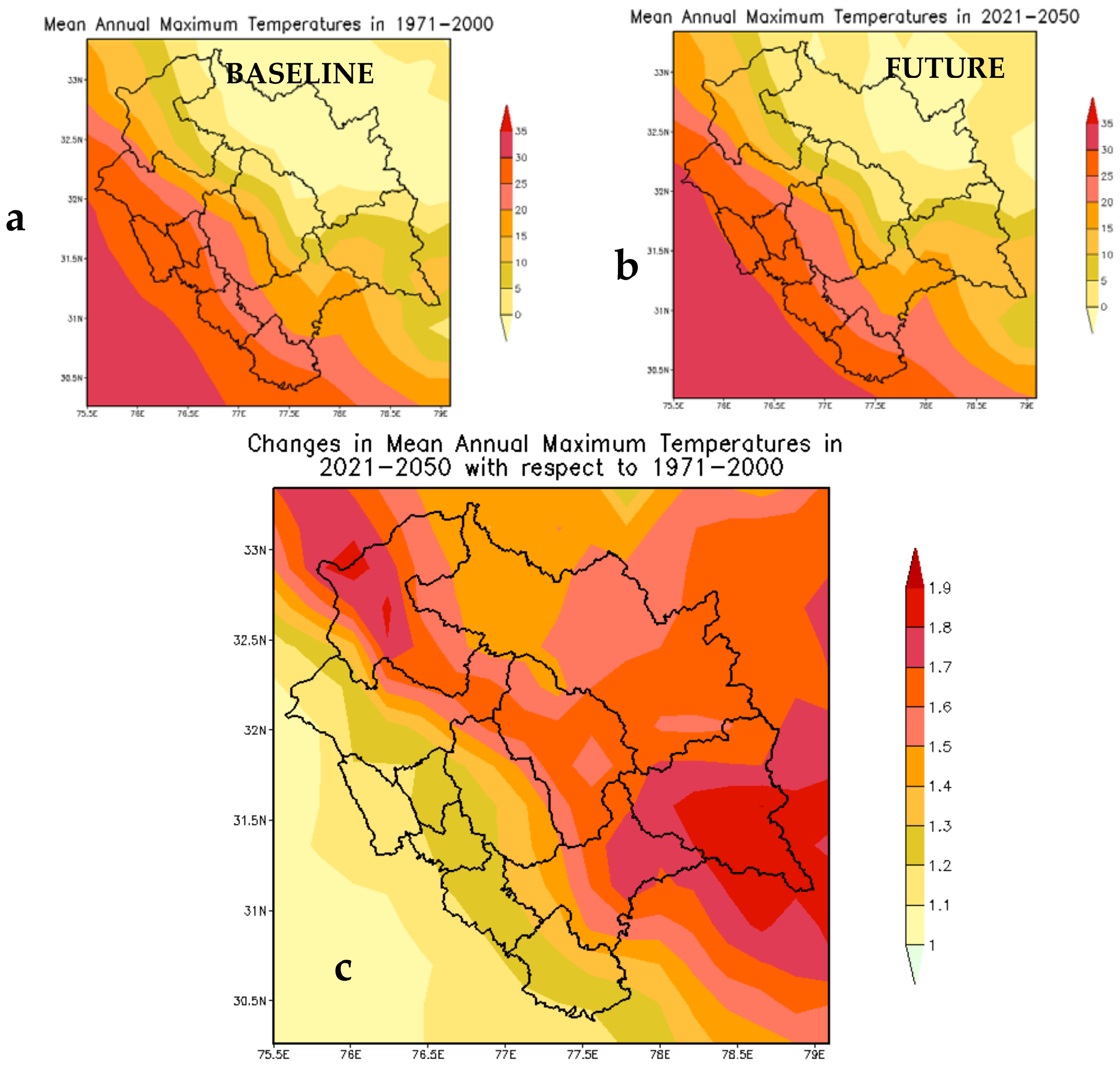
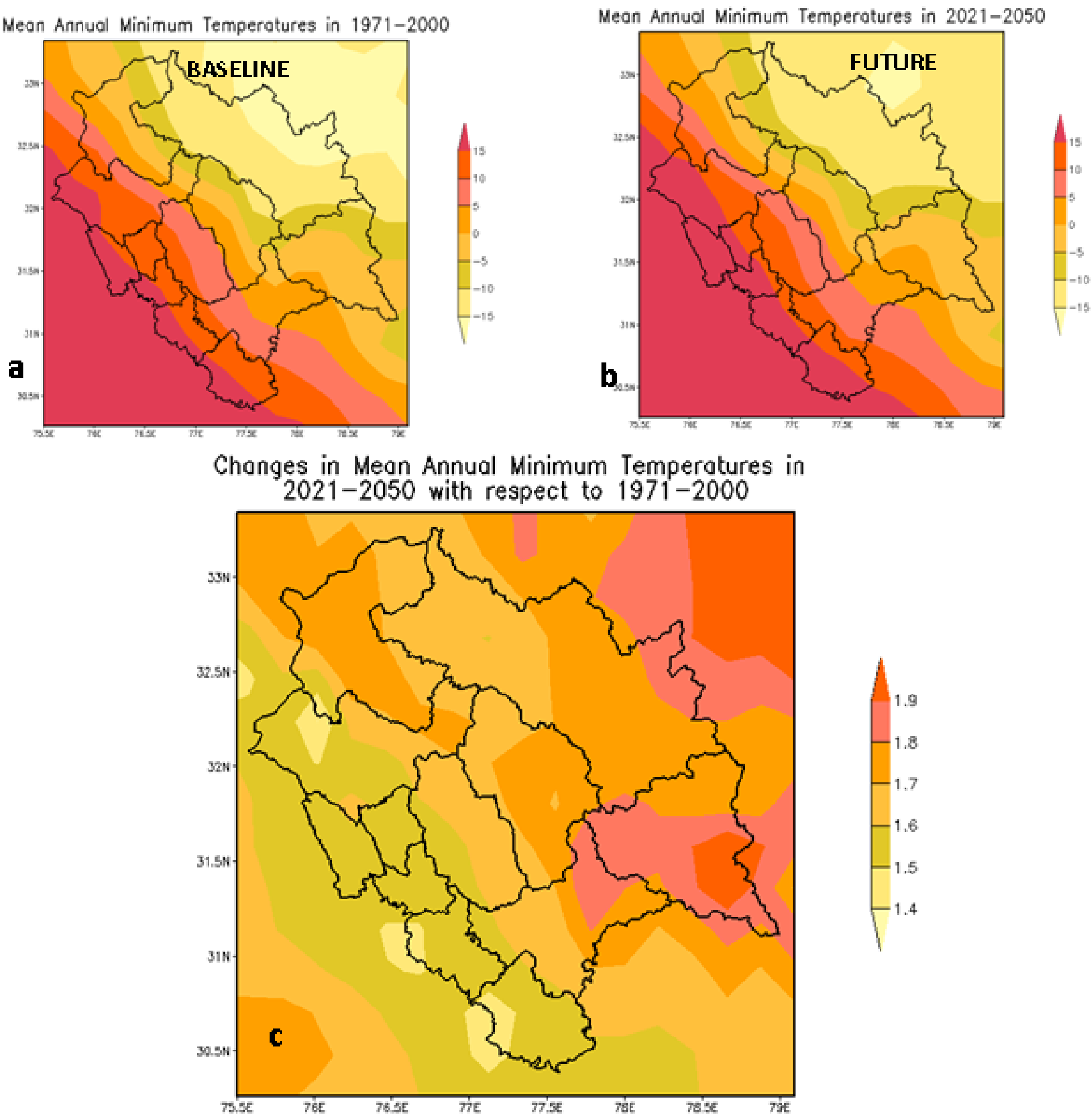


Figure 12: Mean Annual Maximum Temperature (Tmax)

Figure 13 : Mean Annual Minimum Temperature (Tmin)



5.4 Rainfall Extremes

Extremely wet days were calculated as those days when the rainfall amounts exceed 99th percentile of the rainfall amounts in baseline period. This analysis provides us information on the contribution of extreme rainy days to the total rainfall in the near future. Figure 14 shows the precipitation amount (in percentage) of the total precipitation in future that is due to extremely wet days.

Figure 15 shows the percentage of wet days in future where the daily precipitation amount is greater than extremely wet days of the baseline period. The wet days doesn't show any trend for the State, although the 3-point moving average indicates higher number of extreme wet days frequency around 2035-2045 time period.

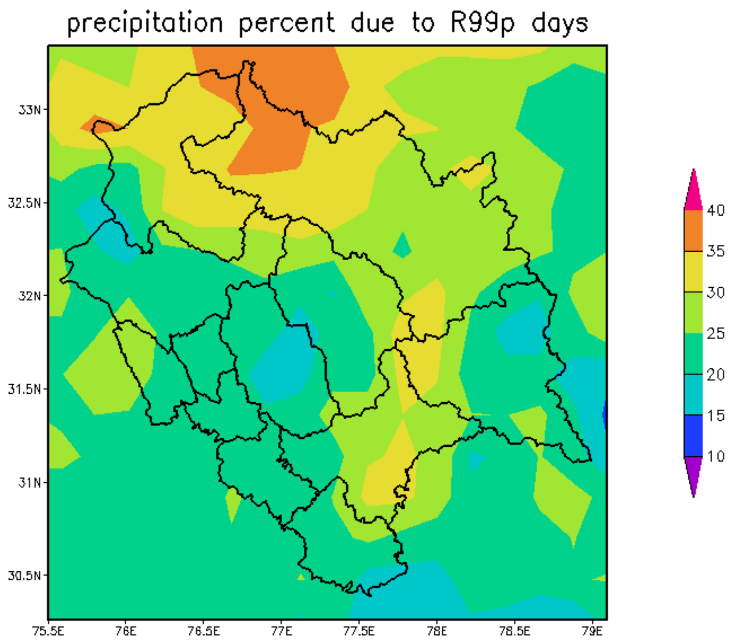


Figure 14: Extreme wet days contribution to the total rainfall – near future

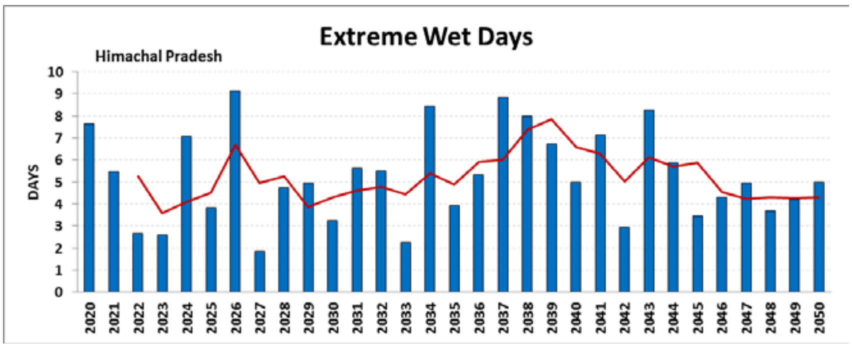
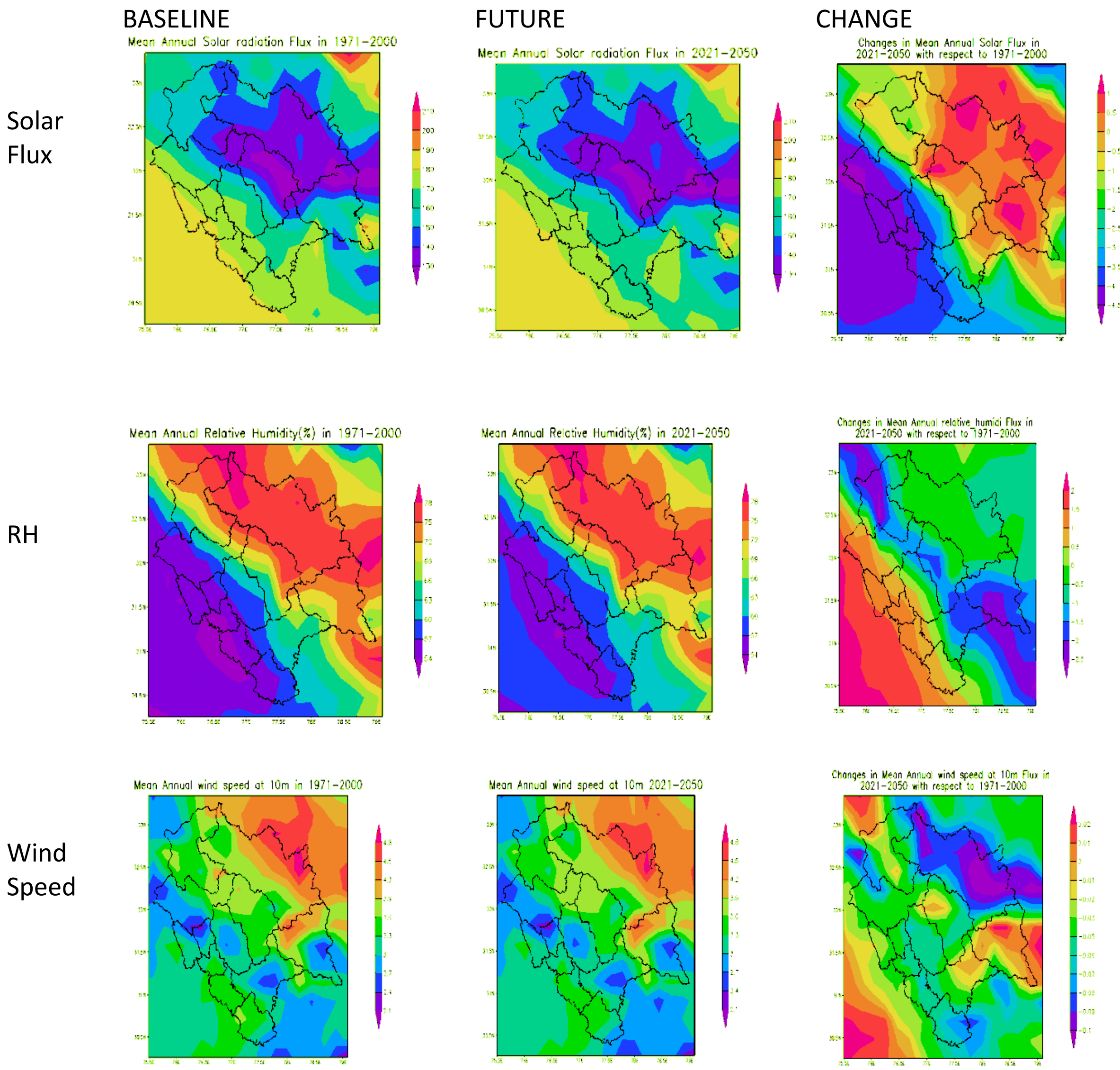


Figure 15: Extreme Wet days in future relative to extreme rainfall in baseline

Analysis of other major climate variables Solar Flux, Relative Humidity and Wind Speed were also performed (Figure 16) which also showed inconsistency owing to the effects of irregular terrain.



Fundamental physics, approximated equations and empirical estimates of unresolvable sub-grid scale processes are fused together in climate models. So the models do have computational constraints. Hence, being probabilistic, the ranges in climate projections should be taken as indicative.

Figure 16: Spatial pattern of Solar Flux (top panel), Relative Humidity middle panel) and Wind speed (bottom panel) and the change in near future relative to the baseline period.

6. Discussion

The following key points emerge:

- The study projected changes in spatial distribution of summer monsoon (June-September) precipitation in the near future (2030s) relative to the baseline period. Spatial variations in ranges also seen for other seasons over the state.
- Annual mean temperature projected to increase by 1.3-1.9° C
- Relatively larger changes projected for minimum temperature (Tmin) which may adversely affect plants, crops and human comfort.
- There will not be much changes in the occurrences of extreme rain events during the summer monsoon season in the near future from the baseline period. The temporal distribution of rainfall will be different.

7. References

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