Preparation of
Hazard, Vulnerability & Risk Analysis atlas and report for the state of Himachal Pradesh

Climate Change & Flood Hazard Risk Assessment

Composite Final Draft Report

(T6)

Prepared for

Disaster Management Cell, Department of Revenue

Government of Himachal Pradesh, Shimla

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New Delhi and Ahmedabad, India

March 2015

VOLUME GUIDE

This series of reports present detailed technical and methodological documentation of the study entitled "Preparation of Hazard, Vulnerability & Risk Analysis Atlas and Report for the State of Himachal Pradesh" for DM Cell, Revenue Department, Himachal Pradesh.

Volume
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Hazard Risk

This volume contains Technical papers on hazard risk assessment due to natural and man-made hazards within Himachal Pradesh as presented below.

1. Avalanche Hazard Risk
2. **Climate Change & Flood Hazard Risk**
3. Drought Hazard Risk
4. Earthquake Hazard Risk
5. Environmental & Industrial Hazard Risk
6. Forest Fire Hazard Risk
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Vulnerability and Risk

This volume contains Technical papers on the Vulnerability and Risks to key elements at risk within Himachal Pradesh as presented below.

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Volume

1

Hazard Risk

Climate Change & Flood Hazard Risk Assessment

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Abbreviations

%	Percentage
0C	Degree Celsius
2D	2 Dimensional
a.m	Ante Meridian
A1B	Balanced on all energy sources (IPCC scenarios)
A1FI	Fossil - fuels intensive (IPCC scenarios)
A1T	Non - fossil energy sources (IPCC scenarios)
amsl	Above mean sea level
AR4	Fourth Assessment Report
ASCII	American Standard Code for Information Interchange
ASTER	Advanced Spaceborne Thermal Emission and Reflection radiometer
CAESAR	Cellular Automaton Evolutionary Slope and River
CDD	Consecutive dry days
CSDI	Cold spell
CV	Coefficient of Variation
CWD	Consecutive wet days
DEM	Digital Elevation Model
DTR	Diurnal temperature range
EC	End Century
ETCCDI	Expert Team on Climate Change Detection and Indices
FP	Flood plain
GCM	Global Circulation Models
GLOFs	Glacial Lake Outburst Floods
ha	Hectare
HadAM3	Hadley Centre Atmospheric Model version 3
HadCM3	Hadley Centre Coupled Model, version 3
HEC	RAS - Hydrologic Engineering Centre - River Analysis System
HP	Himachal Pradesh -
HPPWD	Himachal Pradesh Public Works Department
HRTC	Himachal Road Transport Corporation
IITM	Indian Institute of Tropical Meteorology
IMD	Indian Meteorological Department

IPCC	Intergovernmental Panel on Climate Change
JF	January, February
JJAS	June, July, August, September
Km	Kilometre
LEM	Landscape evolution models
m	Meter
MAM	March, April, May
MC	Mid Century
MCM	Million cubic meters
mm	Millimeters
NH	National Highway
NJPC	Nathpa Jhakri Power Corporation
OND	October, November, December
p.m	Post Meridian
PPE	Perturbed Physics Ensemble
PRCPTOT	Wet - day precipitation
PRECIS	Providing REgional Climates for Impacts Studies
QUMP	Quantifying Uncertainty in Model Predictions
R10mm	Heavy precipitation days
R20mm	Very heavy precipitation days
R95p	Very wet day precipitation
R99p	Extremely wet day precipitation
RCM	Regional Climate Models
RR	Rainfall Rate
RX1day	Max 1 - day precipitation
RX5day	Max 5 - day precipitation
SDII	Simple daily intensity index
SWAT	Soil and Water Assessment Tool
TN10p	Cool night frequency
TN90p	Hot night frequency
TNn	Coolest night
TNx	Hottest night
TX10p	Cool day frequency
TX90p	Hot day frequency
TXn	Coolest day

TXx	Hottest day
U.S	United States
UK	United Kingdom
WSDI	Warm spell

Glossary and Abbreviations

Glossary[1]

Basin

An aquifer or aquifer system whose boundaries are defined by surface-water divides, topographic barriers

Boundary condition

Specified conditions at the edges or surfaces of any system.

Calibration

The adjusting of parameters of numerical model input data until model output matches a set of field observations with some degree of accuracy.

Climate change

A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.

Climate extreme (extreme weather or climate event)

The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as ‘climate extremes.

Climate model

A numerical representation of the climate system that is based on the physical, chemical, and biological properties of its components, their interactions, and feedback processes, and that accounts for all or some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical, or biological processes are explicitly represented, or the level at which empirical parameterizations are involved. Coupled Atmosphere-Ocean Global Climate Models (AOGCMs), also referred to as Atmosphere-Ocean General Circulation Models, provide a representation of the climate system that is near the most comprehensive end of the spectrum currently available. There is an evolution toward more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal, and inter-annual climate predictions.

Climate projection

A projection of the response of the climate system to emissions or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate

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[1] https://www.ipcc.ch/pdf/special-reports/srex/SREX-Annex_Glossary.pdf

predictions in order to emphasize that climate projections depend upon the emission/ concentration/radiative-forcing scenario used, which are based on assumptions concerning, e.g., future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty.

Climate scenario

A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate.

Climate variability

Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate at all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Coefficient of variation (CV)

It is defined as the ratio of the standard deviation to the mean

Cold days/cold nights

Days where maximum temperature, or nights where minimum temperature, falls below the 10th percentile, where the respective temperature distributions are generally defined with respect to the 1961-1990 reference period.

Emissions scenario

A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as technological change, demographic and socioeconomic development) and their key relationships. Concentration scenarios, derived from emissions scenarios, are used as input to a climate model to compute climate projections. In the IPCC 1992 Supplementary Report, a set of emissions scenarios was presented, which were used as a basis for the climate projections in the IPCC Second Assessment Report. These emissions scenarios are referred to as the IS92 scenarios. In the IPCC Special Report on Emissions Scenarios, new emissions scenarios, the so-called SRES scenarios, were published. SRES scenarios (e.g., A1B, A1FI, A2, B1, B2).

Flood

The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods.

Flood flow

The stream discharge during periods of flood.

Flood peak

The highest stage or discharge during a given flood event.

Floodplain

The low-lying areas adjacent to a stream that are occasionally, are predicted to be, or have been covered by water when the stream overflows its banks.

Flow

The rate of water discharges from a source expressed as a volume per unit time. Synonymous - discharge.

Flow capacity

The maximum amount of water any particular Hydrogeologic environment can accept and transmit

Flow path

The path a molecule of water takes in its movement through a porous medium.

Gauging station

A specific location on a stream where systematic observations of hydrologic data are obtained.

Geographic Information System (GIS)

A computer-based software package for storing, displaying, and querying location and attribute data.

Glacial lake outburst flood (GLOF)

Flood associated with outburst of glacial lake. Glacial lake outburst floods are typically a result of cumulative developments and occur (i) only once (e.g., full breach failure of moraine-dammed lakes), (ii) for the first time (e.g., new formation and outburst of glacial lakes), and/or (iii) repeatedly (e.g., ice-dammed lakes with drainage cycles, or ice fall).

Glacier

A mass of land ice that flows downhill under gravity (through internal deformation and/or sliding at the base) and is constrained by internal stress and friction at the base and sides. A glacier is maintained by accumulation of snow at high altitudes, balanced by melting at low altitudes or discharge into the sea.

Hydraulic conductivity (K)

The volume of fluid that flows through a unit area of porous medium for a unit hydraulic gradient normal to that area.

Hydrograph

It is a graph showing changes in the discharge of a river over a period of time.

Inundation

The submergence of land by water

Mean sea level

Sea level measured by a tide gauge with respect to the land upon which it is situated. Mean sea level is normally defined as the average relative sea level over a period, such as a month or a year, long enough to averageout transients such as waves and tides.

Overland flow

The flow of water over the land surface created by direct precipitation.

Percentile

A percentile is a value on a scale of 100 that indicates the percentage of the data set values that is equal to or below it. The percentile is often used to estimate the extremes of a distribution. For example, the 90th (10th) percentile may be used to refer to the threshold for the upper (lower) extremes

Percolation

Gravity flow of groundwater downwards through the unsaturated zone.

Perennial stream

A stream that flows all year.

Precipitation

Precipitation is any product of the condensation of atmospheric water vapour that falls under gravity. The main forms of precipitation include drizzle, rain, sleet, snow, graupel and hail.

Probability

It is measure of how likely event will occur.

Rating curve

A curve that relates the discharge of a stream to the gage height

Recharge

The process by which water enters the groundwater system or, more precisely, enters the phreatic zone.

Return flow

That water which is pumped from a stream, an aquifer, or a basin that is not consumptively used and which returns to the stream, aquifer, or basin.

Return period

It is the average time interval between occurrences of a hydrological event of a given or greater magnitude, usually expressed in years.

Runoff

Water from precipitation, snowmelt, or irrigation running over the surface of the Earth

Saturation

When all the pores are filled with water.

Streamflow

Water flow within a river channel, for example, expressed in m3 s-1 A synonym for river discharge.

Terrain

A region, tract, or environment under observation.

Tributary

A stream that flows into another body of water or into a (larger) stream.

Uncertainty

An expression of the degree to which a value or relationship is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. Uncertainty may originate from many sources, such as quantifiable errors in the data, ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgment of a team of experts.

Unit hydrograph

The response of a direct runoff streamflow hydrograph generated by 1 inch (or 1 centimetre) of excess rainfall generated uniformly over the drainage area at a constant rate for an effective duration.

Virgin flow

Streamflow that existed or would exist in the absence of human actions.

Vulnerability

The potential of a system to suffer loss or damage.

Warm days/warm nights

Days where maximum temperature, or nights where minimum temperature, exceeds the 90th percentile, where the respective temperature distributions are generally defined with respect to the 1961-1990 reference period.

Warm spell

A period of abnormally warm weather. Heat waves and warm spells have various and in some cases overlapping definitions. See also Heat wave

Watershed

The area of land drained by a single stream or river. Watershed and catchment are equivalent terms.

Chapter 1: Climate – Current Baseline and Climate Projections

The long term trends in observed seasonal precipitation and temperature over Himachal Pradesh using IMD gridded rainfall and temperature at daily time scales has been performed to arrive at current baseline climatology for the state. Summary is presented in the following paragraphs.

1.1 Data used

- IMD gridded rainfall at 0.5 degree spatial resolution for the time period 1971-2005 (35 years).This data set has been then analysed further for two periods-1971-1990 (20 years) and 1991-2005 (15 years).
- IMD gridded maximum and minimum temperature at 1 degree spatial resolution for the time period 1969-2005 (37 years). This data set has been then analysed further for two periods-1971-1990(20 years) and 1991-2005(15 years).Two time periods have been analysed for comparison between them.

1.2 Limitations

- In the absence of observed station data for the state of Himachal Pradesh gridded daily data has been used.
- Orographic corrections has not been applied..

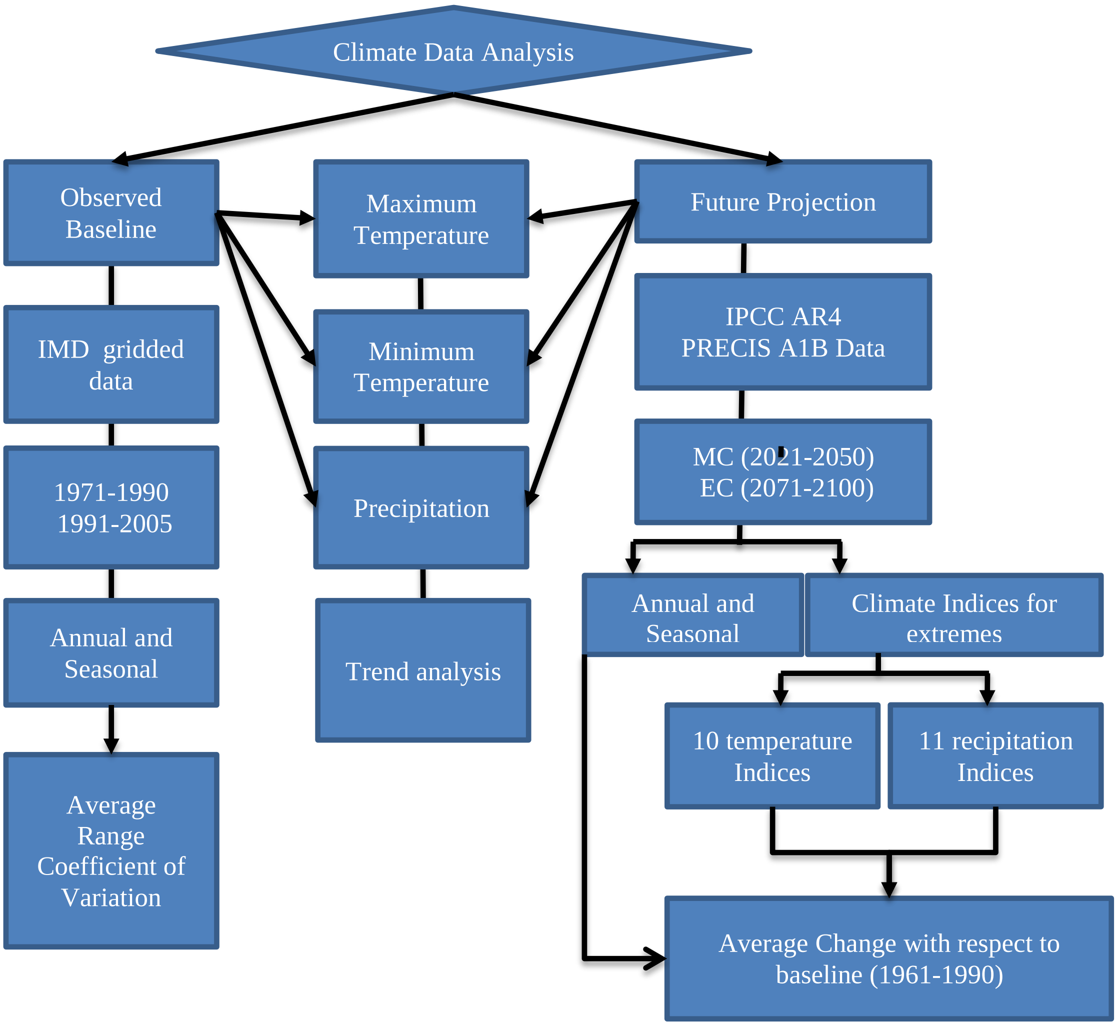
1.3 Methodology

The steps followed to analyse the climate data has been described below. The same is represented in (Figure 2):

- IMD gridded data for the baseline observed temperature data (1969-2005-37 years) and rainfall data (1971-2005-35 years) were used and analysed. This data set were then analysed further for two periods-1971-1990 (20 years) and 1991-2005 (15 years) for comparison.
- A1B PRECIS data for the future projected climate data analysis (Mid-century-2021-2050 and End century-2071-2100) were used.
- The gridded daily data of the Himachal Pradesh state have been used in public domain available software R to summarize the basic statistics of precipitation and temperature. Then using Microsoft excel the basic statistics (Average, Range, Coefficient of Variation) were tabulated at the state level.
- Descriptive statistics along with the long term trend analysis were performed on the daily observed rainfall and temperature data.
- Trend analysis was done using Mann-Kendall analysis using R software.
- Maximum and minimum temperature and precipitation results are presented annually and for the 4 seasons-JF, MAM, JJAS and OND.
- Rainy days analysis for the observed data for South West Monsoon Season (JJAS) was also done.

- RClimDex (1.0)[2]which is designed to provide a user friendly interface to compute indices of climate extremes, was used to derive 10 temperature and 11 climate indices for Himachal Pradesh. Mid-century and end century change with respect to baseline are graphed using Excel.

Figure 1 : Climate Data Analysis Flowchart



Source: INRM analysis

[2]http://cccma.seos.uvic.ca/ETCCDI/software.shtml

1.4 Observed Precipitation trends (1971-2005)

Rainfall in the state of Himachal Pradesh varies considerably both in space and time from year to year. Table 1 gives the summary of observed rainfall statistics for Himachal Pradesh.

Table 1: Observed Rainfall Statistics for Himachal Pradesh (1971-2005)

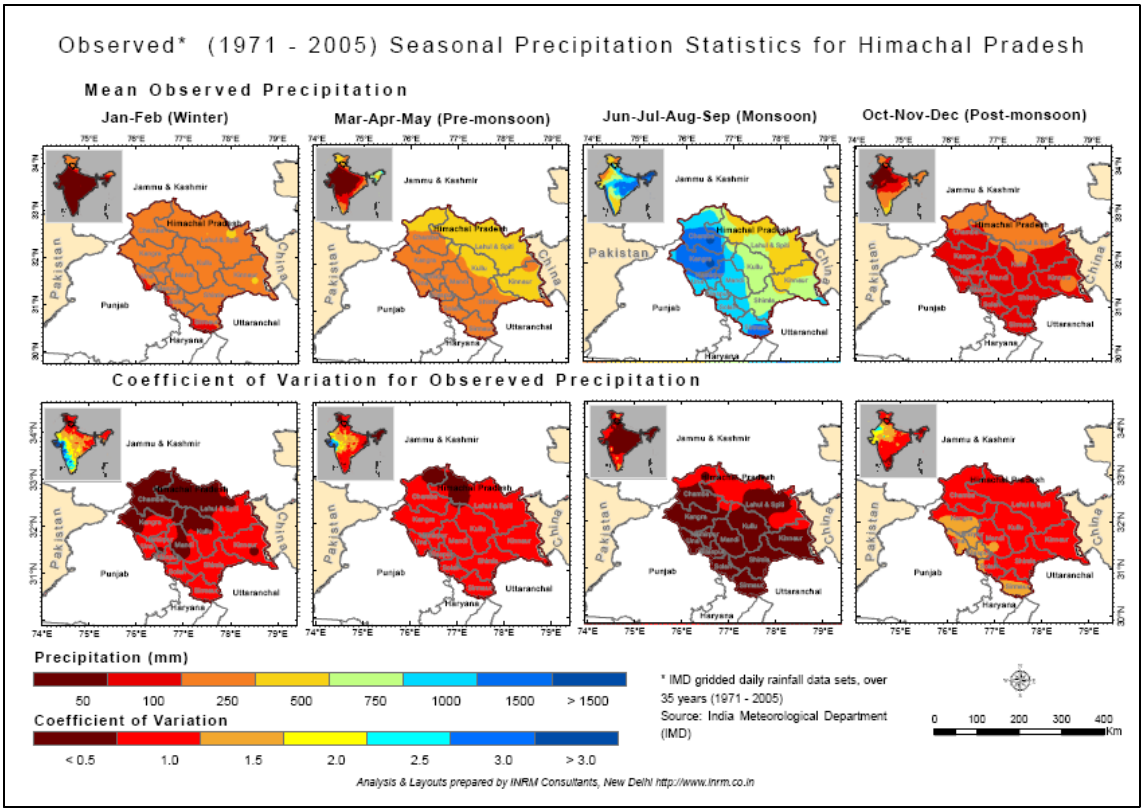
Season	Statistics	Value	Contribution in Annual Rainfall (%)
Annual	Average (mm)	1294.3	
	Range - Average (mm)	782 - 2118.3	
Winter (JF)	Average (mm)	85.6	6.6
	Range - Average (mm)	62.6 - 124.3	
Pre Monsoon	Average (mm)	230.1	17.8
	Range - Average (mm)	100.7 - 341.4	
Monsoon (JJAS)	Average (mm)	802	62
	Range - Average (mm)	292.1 - 1625.5	
Post Monsoon	Average (mm)	176.5	13.6
	Range - Average (mm)	91.3 - 259.9	
Annual	Range- Inter-annual	0.3 - 0.4	
Winter (JF)	Range- Inter-annual	0.7 - 1.2	
Pre Monsoon	Range- Inter-annual	0.4 - 0.9	
Monsoon (JJAS)	Range- Inter-annual	0.3 - 0.8	
Post Monsoon	Range- Inter-annual	0.3 - 0.9	

Source: IMD Gridded rainfall data (1971-2005)

Annual average rainfall for Himachal Pradesh from 1971-2005(35 years) is1294.3 mm. The mean south-west monsoon (June, July, August and September) rainfall (802 mm) contributes 62% of annual rainfall. Mean monthly rainfall during July (286 mm) is highest and contributes about 22% of annual rainfall, followed by August (279 mm) which contributes about 21.5%. The mean rainfall during June is slightly lower and contributes about 8.5 % of annual rainfall. September rainfall contributes 9.9 % of annual rainfall. Contribution of pre-monsoon (March, April and May) rainfall and post-monsoon (October, November and December) rainfall in annual rainfall is 17.8% and 13.6% respectively. Rainfall is highest during the monsoon season (June, July, August and September) and coefficient of variation[3] the lowest (Figure 2).

[3]Coefficient of Variation (CV): A statistical measure of the dispersion of data points in a data series around the mean. The coefficient of variation represents the ratio of the standard deviation to the mean, and it isa useful statistic for comparing the degree of variation from one data series to another, even if the means are drastically different from each other. Higher the CV, greater is the dispersion in the variable.

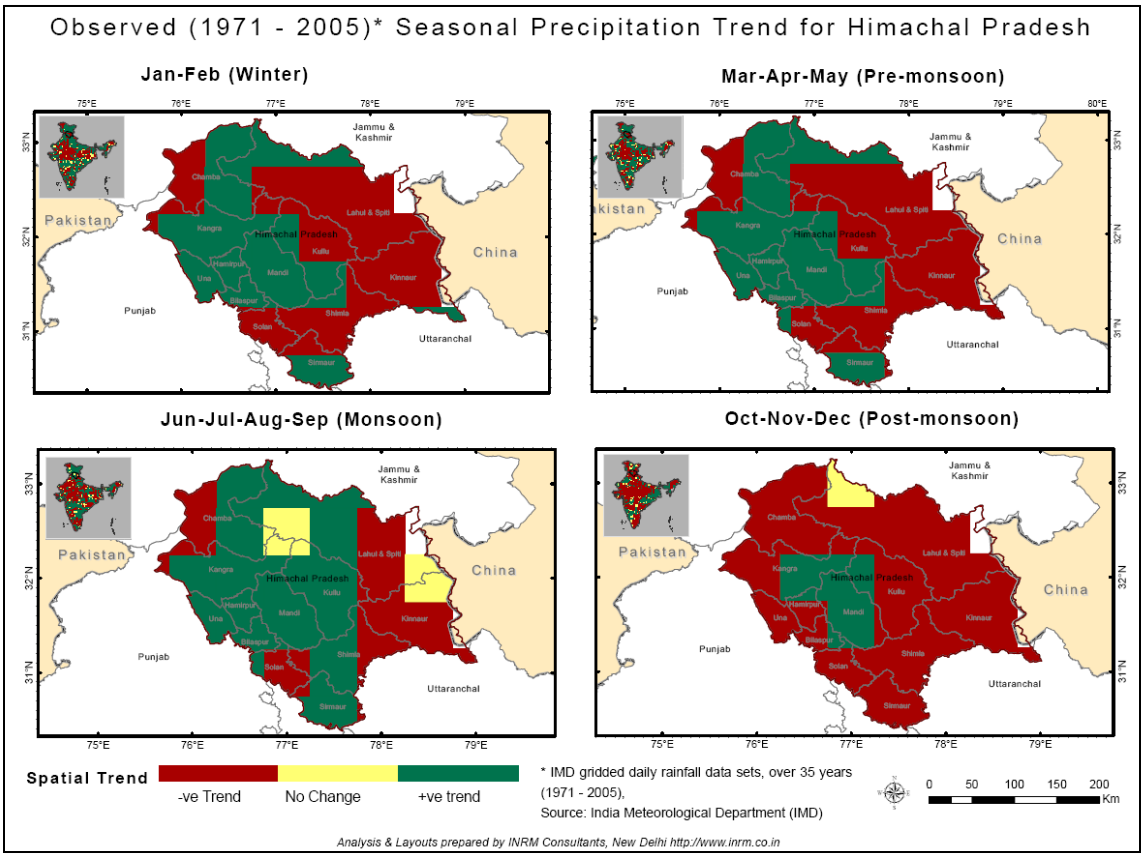
Figure 2 : Mean and Inter annual variation in seasonal rainfall in Himachal Pradesh



Source: INRM analysis

Temporal variation in monthly, seasonal and annual rainfall over IMD grids belonging to Himachal Pradesh has been made for the period from 1971 to 2005. Long term changes in rainfall determined by Man-Kendall rank statistics and linear trend has also been carried out. Figure 3 shows the spatial variation in the trend in seasonal precipitation.

Figure 3 : Observed seasonal rainfall trend in Himachal Pradesh



Source: INRM analysis

From Figure 3 it's seen that there is a general positive trend in most part of Himachal Pradesh barring parts of Chamba, Solan, Kinnaura and Lahul and Spitiwhich show increasing trend in the monsoon rainfall. While in the post monsoon season most parts of Himachal Pradesh show decreasing trend in rainfall barring parts of Kull, Mandi and Kangra.

1.5 Observed Precipitation trends (1971-1990 and 1991-2005)

Rainfall in the state of Himachal Pradesh varies considerably both in space and time from year to year. Table 2gives the summary of observed rainfall statistics for Himachal Pradesh for periods 1971-1990 and 1991-2005.

Table 2: Observed Rainfall Statistics for Himachal Pradesh (1971-1990 and 1991-2005)

Season	Statistics	Value (1971-1990)	Value (1991-2005)
Annual	Average (mm)	1135.4	1123.1
	Range - Average (mm)	531.6-2006	577.6-1795.5
	CV - Coefficient of variation	0.34	0.34
	Trend	Significant Positive trend	Insignificant Negative trend
Winter (JF)	Average (mm)	160.7	155.7
	Range - Average (mm)	45.1-370.1	0-323.7
	CV - Coefficient of variation	0.56	0.58
	Contribution in Annual Rainfall (%)	14.2	13.9
	Trend	Insignificant Positive trend	Insignificant Negative trend
Pre Monsoon (MAM)	Average (mm)	231.7	182.8
	Range - Average (mm)	59.4-586.6	58.4-352.5
	CV - Coefficient of variation	0.69	0.52
	Contribution in Annual Rainfall (%)	20.4	16.3
	Trend	Significant Positive trend	Insignificant Negative trend
Monsoon (JJAS)	Average (mm)	647.8	722.7

Source: IMD Gridded rainfall data (1971-1990, 1991-2005)

Annual average rainfall for Himachal Pradesh from 1971-1990(20 years) is1135.4 mm while for 1991-2005(15 years) is 1123.1 mm (Table 2). Though for the period 1991-2005 annual average rainfall is lower than 1971-1990 annual average rainfall but the JJAS month's contribution in annual rainfall is higher for the period 1991-2005 than 1971-1990. Mean south-west monsoon (June, July, August and September) rainfall for periods 1971-1990 and 1991-2005contributes 57.1% and 64.3% in annual rainfall respectively. Contribution of pre-monsoon (March, April and May) in annual rainfall is 20.4% and 16.3% for period's 1971-1990 and 1991-2005respectively. Rainfall is highest during the monsoon season (June, July, August and September) while coefficient of variation[4] the lowest (Figure 5).Contribution of post-monsoon (October, November and December) and winter rainfall (January and February) is the least in annual rainfall for both the periods. Coefficient of variation is also very high.

[4]Coefficient Of Variation (CV): A statistical measure of the dispersion of data points in a data series around the mean. The coefficient of variation represents the ratio of the standard deviation to the mean, and it isa useful statistic for comparing the degree of variation from one data series to another, even if the means are drastically different from each other.Higher the CV, greater is the dispersion in the variable.

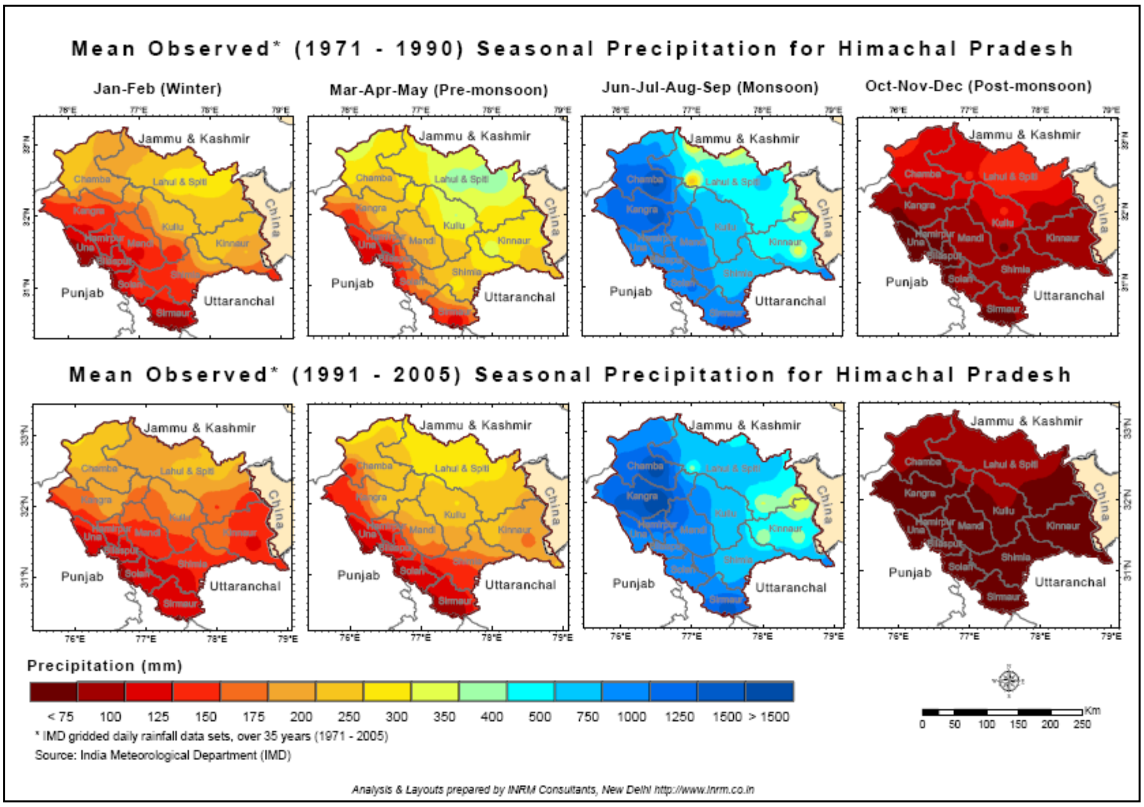
Maximum mean observed annual rainfall is observed in Chamba and Kangra districts for both the periods. Trend is considered to be statistically significant if confidence level is greater than or equal to 90% else it's considered as insignificant. Annual average rainfall for Himachal Pradesh show significant positive trend in period 1971-1990 while insignificant negative trend in 1991-2005.

Figure 4 and Figure 5shows the spatial variation in Mean Observed Rainfall and Coefficient of Variation in seasonal precipitation for both the periods for comparison.

Maximum mean observed monsoon rainfall is observed in North Western districts of Himachal Pradesh namely, Chamba, Kangra, Sirmaur and Hamirpur districts for both the periods. Lahul and Spiti receives the least rainfall. While in winter and pre monsoon seasons South Western districts show comparatively higher rainfall as compared to the other districts (Figure 4).

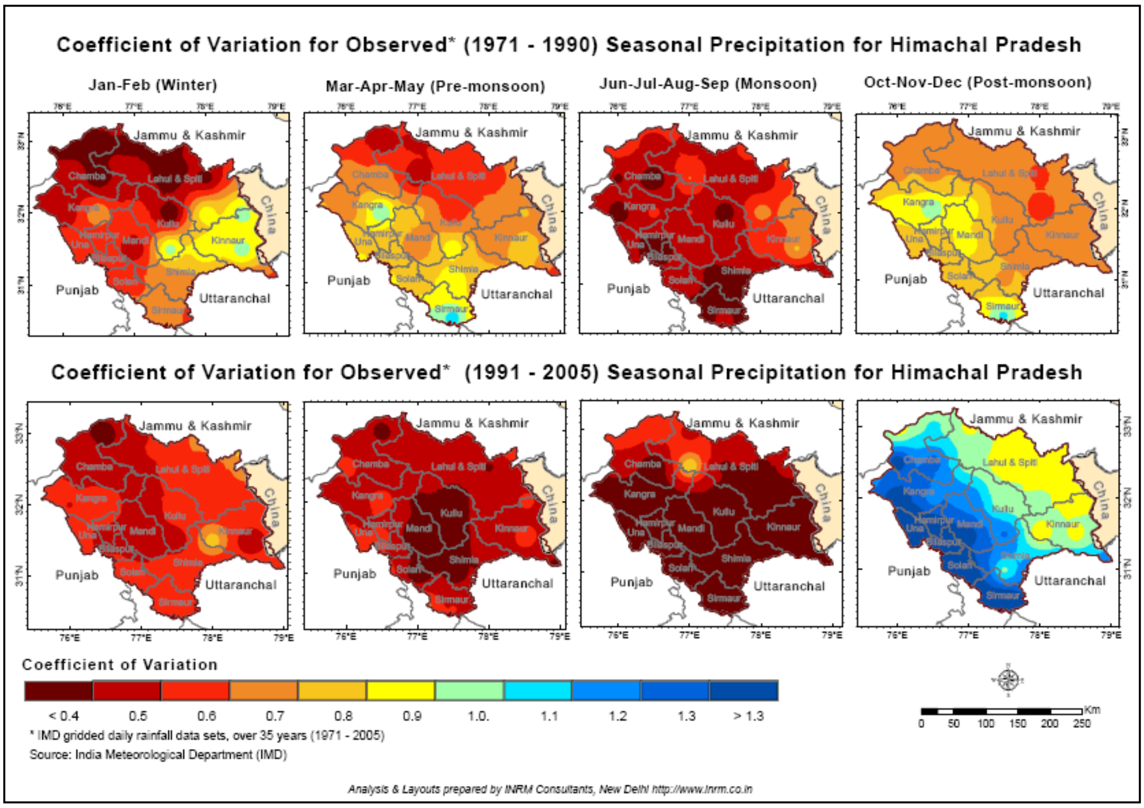
Maximum variability is observed in post monsoon rainfall in South Western districts while least variability is observed in the monsoon months for the period 1991-2005 compared to 1971-1990 (Figure 5).

Figure 4 : Observed mean seasonal rainfall in Himachal Pradesh (1971-1990 and 1991-2005)



Source: INRM analysis

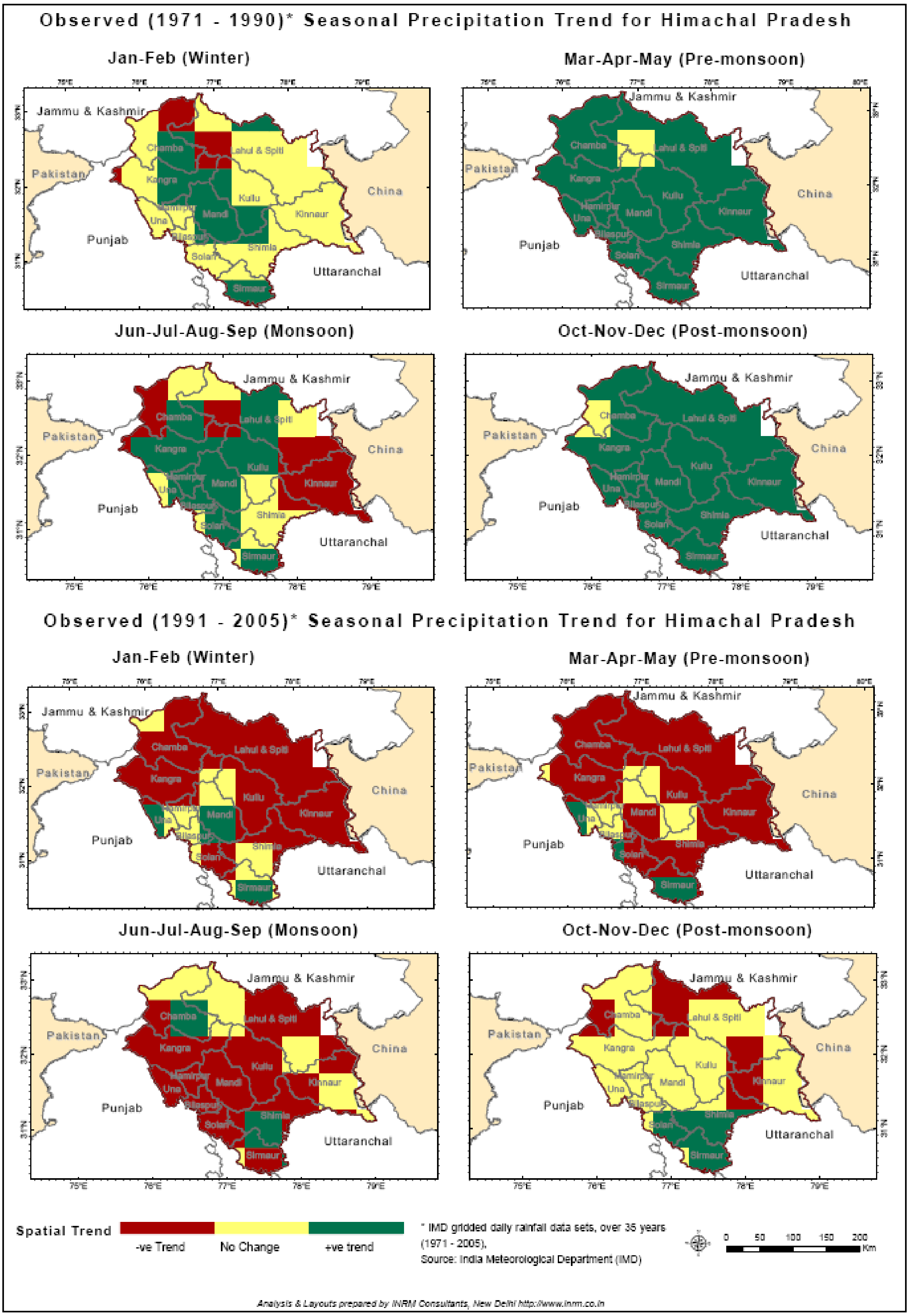
Figure 5 : Inter annual variation in seasonal rainfall in Himachal Pradesh(1971-1990 and 1991-2005)



Source: INRM analysis

Temporal variation in seasonal and annual rainfall over IMD grids belonging to Himachal Pradesh has been made for period's 1971-1990 and 1991-2005. Long term changes in rainfall determined by Man-Kendall trend statistics has also been carried out. Figure 6 shows the spatial variation in the trend in seasonal precipitation for both the periods.

Figure 6 : Observed seasonal rainfall trends in Himachal Pradesh (1971-1990 and 1991-2005)



From Figure 6 it's seen that in 1971-1990 there is a general positive trend in most part of Himachal Pradesh barring parts of Kinnaur, Chamba, Solan, Kullu, Kangra and Lahul and

Spiti which show decreasing trend in the monsoon rainfall. While in the latter period (1991-2005) general decreasing trend is seen in most part of Himachal Pradesh barring Shimla and Chamba

In general period 1971-1990 show positive trend in most parts of the State for all 4 seasons while 1991-2005 show negative trend.

Annual average rainfall for Himachal Pradesh show significant positive trend in period 1971-1990 while insignificant negative trend in 1991-2005.Maximum mean observed monsoon rainfall is observed in North Western districts of the state namely, Chamba, Kangra, Sirmaur and Hamirpur districts for both the periods. Lahul&Spiti receives the least rainfall.

1.6 Observed Rainy days (1971-2005)

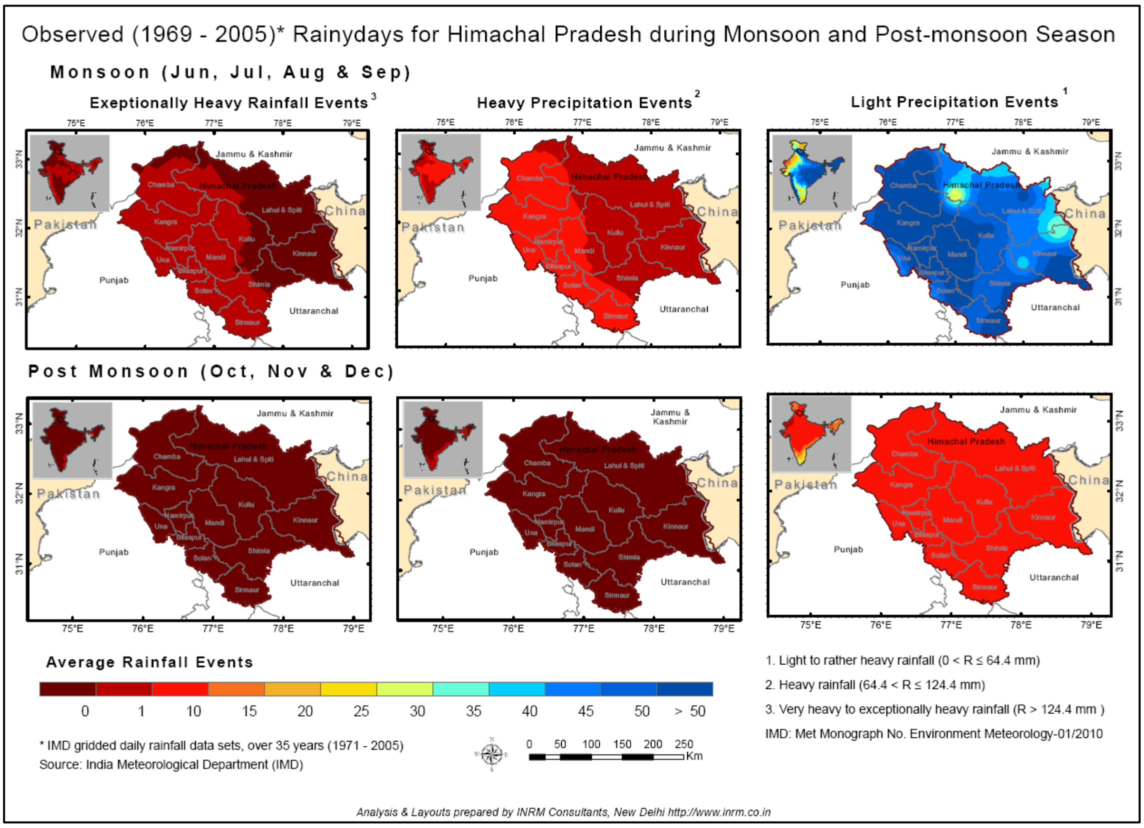
Rain has been regrouped into three broad categories (Pattanaik and Rajeevan, 2010[5]) for calculating extreme rainfall, i) light to rather heavy rainfall ($0 < R \leq 64.4$ mm), ii) heavy rainfall ($64.4 < R \leq 124.4$ mm) and iii) very heavy to exceptionally heavy rainfall ($R > 124.4$ mm). Rainfall > 124.4 mm is referred as extreme rainfall events. Figure 7 shows these events during monsoon and post monsoon period.

Average number of rainy days in Himachal Pradesh during the south west monsoon is about 50 days and varies from 25 days to 69 days. Days when there are heavy precipitation events range from 0 to 4 days and similarly the exceptionally heavy rainfall days are less and is about 1 day.

Average number of rainy days in the state during the post monsoon (winter) is about 7 days and varies from 3 days to 9 days. Days when there are heavy precipitation events and exceptionally heavy rainfall events are negligible.

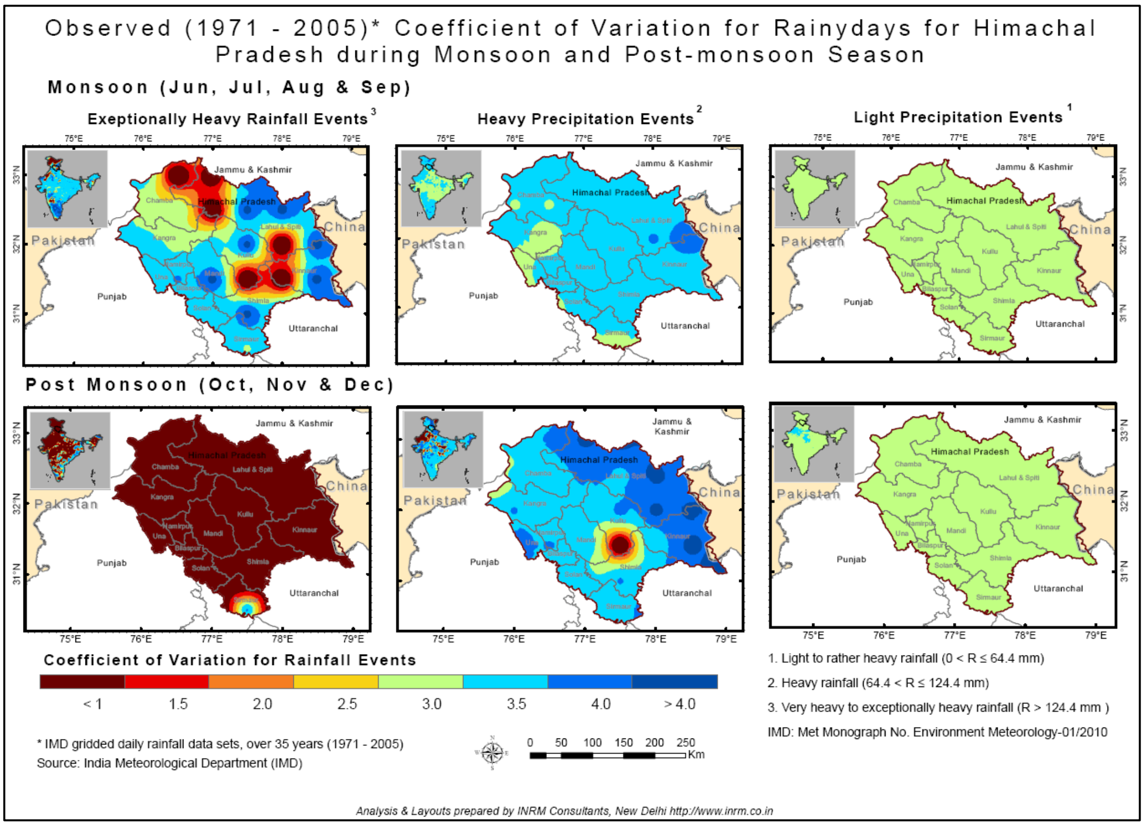
[5] Pattanaik, D. R. and Rajeevan, M., 2010, Variability of Extreme Rainfall Events over India During Southwest Monsoon Season; 2010, Meteorological Applications Vol. 17, 88-104

Figure 7 : Observed rainfall Statistics –Average Seasonal rainy days during Monsoon and Post-monsoon season



Source: INRM analysis

Figure 8 : Observed rainfall Statistics – Inter annual variation in rainy days during Monsoon and Post-monsoon season



Source: INRM analysis

There is a large inter annual variation in heavy precipitation days. Light precipitation days shows relatively less inter annual variation (Figure 8).

1.7 Observed Rainy days (1971-1990 and 1991-2005)

Rain has been regrouped into three broad categories (Pattanaik and Rajeevan, 20106) for calculating extreme rainfall, i) light to rather heavy rainfall (0 < R ≤ 64.4 mm), ii) heavy rainfall (64.4 < R ≤ 124.4 mm) and iii) very heavy to exceptionally heavy rainfall (R > 124.4 mm). Rainfall > 124.4 mm is referred as extreme rainfall events. Figure 9shows these events during monsoon period (JJAS) for the periods 1971-1990 and 1991-2005 respectively.

Average number of rainy days (when daily rain >2.5 mm) in Himachal Pradesh during the south west monsoon is about 43 days and varies from 17 days to 71 days for 1971-1990.

Average number of rainy days (when daily rain >2.5 mm) in Himachal Pradesh during the south west monsoon is about 45 days and varies from 17 days to 78 days for 1991-2005.

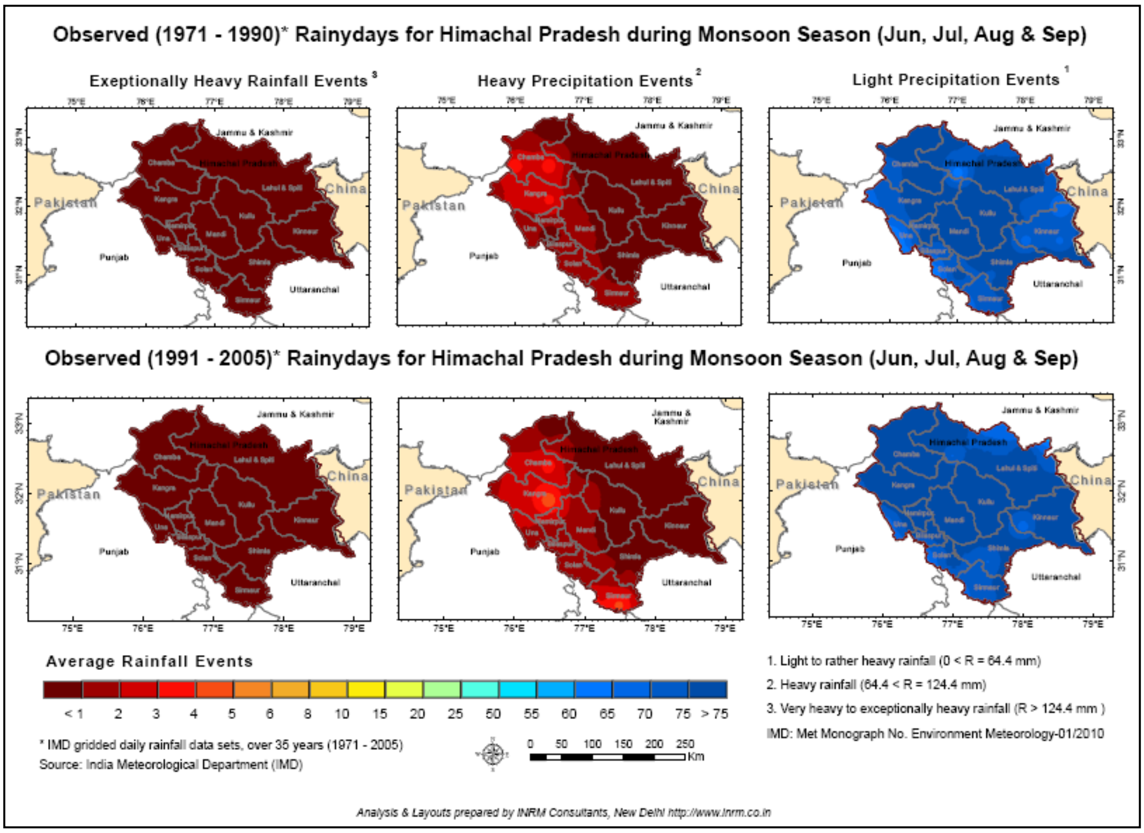
During monsoon months for the period 1971-1990, light to rather heavy rainfall (0 < R ≤ 64.4 mm) events is 75 on average for districts of Himachal Pradesh, and ranges from 67 to 79 days. Similarly, days when there are heavy rainfall (64.4 < R ≤ 124.4 mm) events is 1 on average and ranges from 1 to 2 days for the districts, and the exceptionally heavy rainfall (rainfall > 124.4 mm) days are negligible.

During monsoon months for the period 1991-2005, light to rather heavy rainfall (0 < R ≤ 64.4 mm) events is 78 on average for districts of Himachal Pradesh, and ranges from 73 to 84 days. Days when there are heavy rainfall (64.4 < R ≤ 124.4 mm) events is 1 on average and ranges from 1 to 2 days for the districts and the exceptionally heavy rainfall (rainfall > 124.4 mm) days are negligible.

Thus it's seen that in monsoon months in period 1991-2005 light to rather heavy rainfall days have increased by 3 days on average compared to 1971-1990 while the extreme and heavy rainfall days show no change.

[6] Pattanaik, D. R. and Rajeevan, M., 2010, Variability of Extreme Rainfall Events over India During Southwest Monsoon Season; 2010, Meteorological Applications Vol. 17, 88-104

Figure 9 : Observed rainfall Statistics –Average Seasonal rainy days during Monsoon season (1971-1990 and 1991-2005)



Source: INRM analysis

Average number of rainy days (when daily rain >2.5 mm) in Himachal Pradesh during the south west monsoon is about

43 days and varies from 17 days to 71 days for 1971-1990.

45 days and varies from 17 days to 78 days for 1991-2005.

In monsoon months in period 1991-2005 light to rather heavy rainfall days ($0 < R \leq 64.4$ mm)have increased by 3 days on average compared to 1971-1990 while the extreme and heavy rainfall days show no change.

1.8 Observed Temperature trends (1969-2005)

The state of Himachal Pradesh shows a spatial as well as temporal variability. Table 3 gives the summary of annual and seasonal temperature statistics.

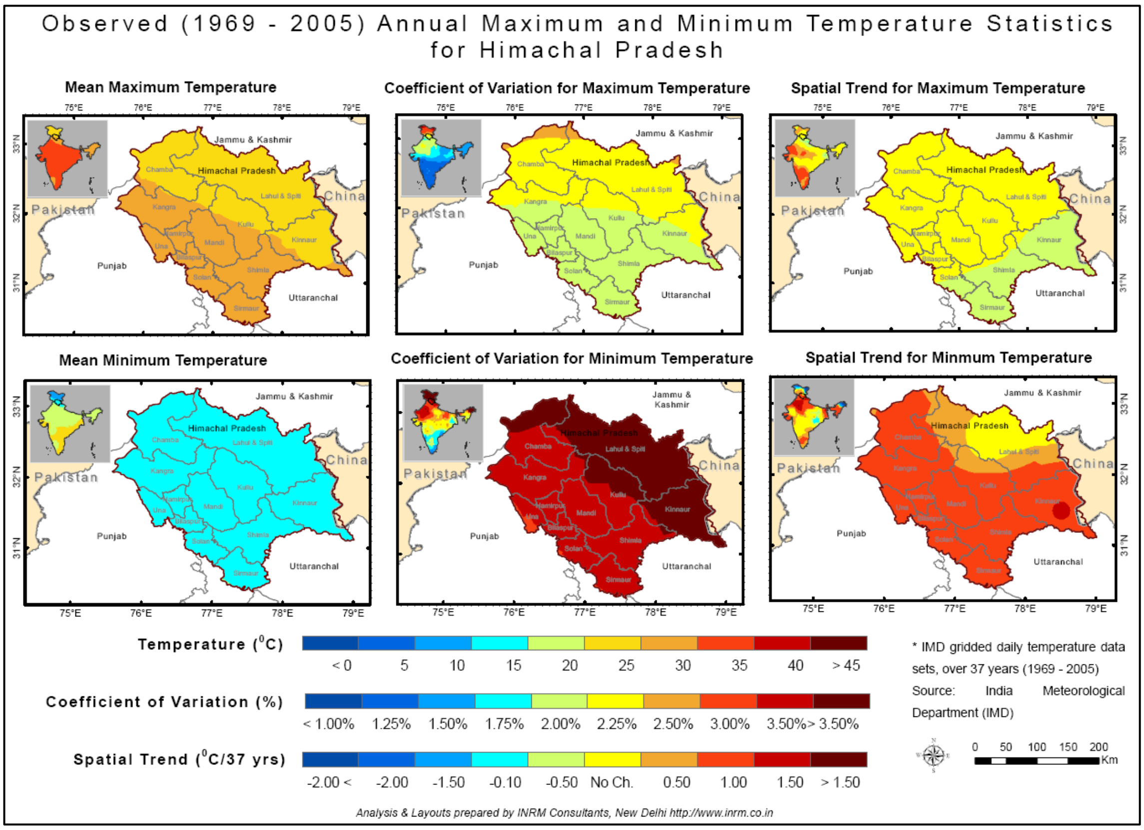
Table 3: Observed Temperature Statistics (1969-2005)

Season	Statistics	Maximum Temperature (^oC)	Minimum Temperature (^oC)
Annual	Average (mm)	25.2	13
	Range - Average (mm)	23 - 26.9	10.7 - 14.8
Winter (JF)	Average (mm)	16.3	4.4
	Range - Average (mm)	13.7 - 18.4	1.9 - 6.1
Pre Monsoon (MAM)	Average (mm)	27.5	13.7
	Range - Average (mm)	24.7 - 30	11.2 - 15.8
Monsoon (JJAS)	Average (mm)	30	20
	Range - Average (mm)	28.6 - 31.6	18 - 21.8
Post Monsoon (OND)	Average (mm)	22.5	8.6
	Range - Average (mm)	20.2 - 24.1	6.3 - 10.4
Annual	Range- Inter-annual variation	0.02 - 0.02	0.03 - 0.04
Winter (JF)	Range- Inter-annual variation	0.04 - 0.06	0.13 - 0.39
Pre Monsoon (MAM)	Range- Inter-annual variation	0.04 - 0.05	0.05 - 0.07
Monsoon (JJAS)	Range- Inter-annual variation	0.02 - 0.02	0.02 - 0.02
Post Monsoon (OND)	Range- Inter-annual variation	0.03 - 0.04	0.06 - 0.09

Source: IMD Gridded temperature data (1969-2005)

From Table 3 it can be seen that annual average maximum and minimum temperature for Himachal Pradesh from 1969-2005 is 25.2^{0}C and 13.0^{0}Crespectively. Figure 10 depicts spatial variation in the long term statistics for mean maximum and minimum temperatures.There is no change in trend in mean maximum temperature for all the districts except for Kinnaur, Shimla, Solan and Sirmaur which shows decreasing trend ofabout0.3^{0}C while minimum temperature shows an increase of about 0.3^{0}C to 0.9^{0}C in 37 years. Southern Himachal Pradesh districts show higher increase in the minimum temperature (0.8^{0}C to 0.9^{0}C). Inter annual variation is higher for minimum temperature than maximum temperature. Spatial variation in mean maximum and minimum temperature is found to be around 4^{0}C.

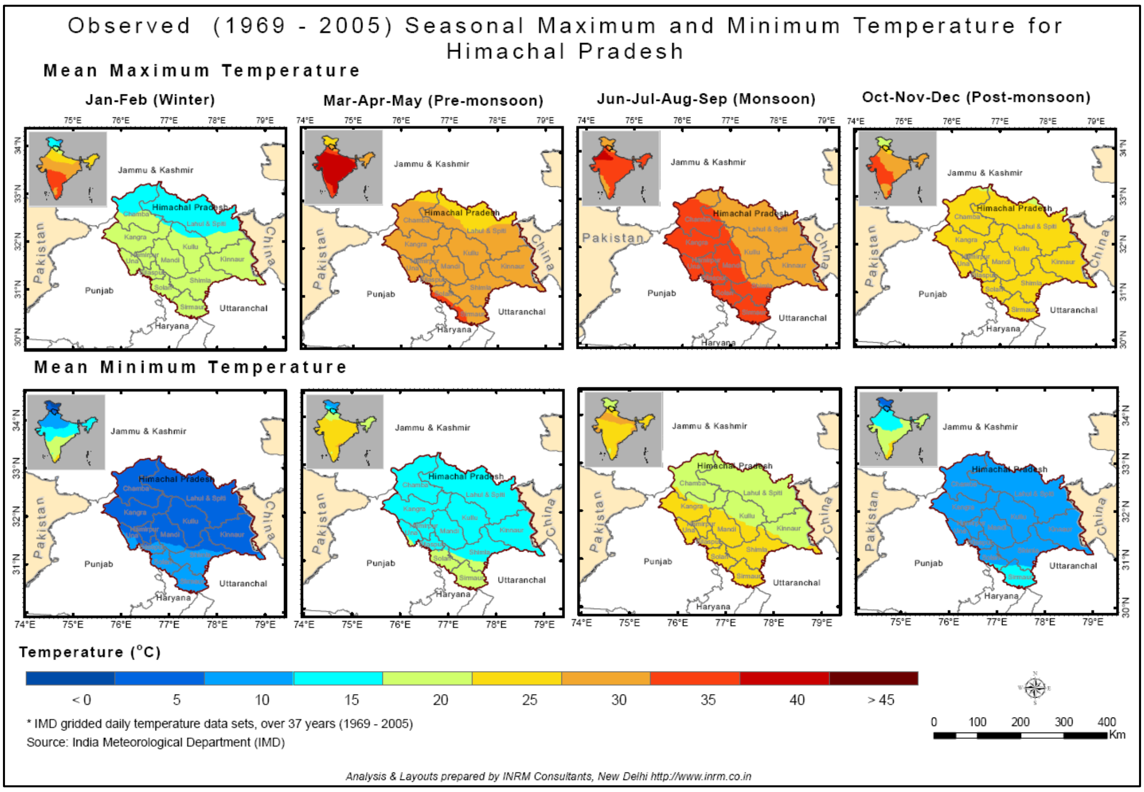
Figure 10 : Observed annual maximum and minimum temperature statistics in Himachal Pradesh



Source: INRM analysis

As seen in Table 3, seasonal average maximum temperature is higher during monsoon season (30.0^{0}C) and ranges between 28.6^{0}C to 31.6^{0}C. Similarly seasonal average minimum temperature is lowest during winter period (4.4^{0}C) and ranges from 1.9^{0}C to 6.1^{0}C. Figure 11 shows the observed seasonal maximum and minimum temperature for Himachal Pradesh. Western, South Western and North Eastern districts of Himachal Pradesh have the highest average maximum temperature in the monsoon season.

Figure 11 : Observed seasonal maximum and minimum temperature in Himachal Pradesh



Source: INRM analysis

1.9 Observed Maximum Temperature trends (1971-1990, 1991-2005)

The state of Himachal Pradesh shows a spatial as well as temporal variability. Table 4 gives the summary of annual and seasonal maximum temperature statistics for periods 1971-1990 and 1991-2005.

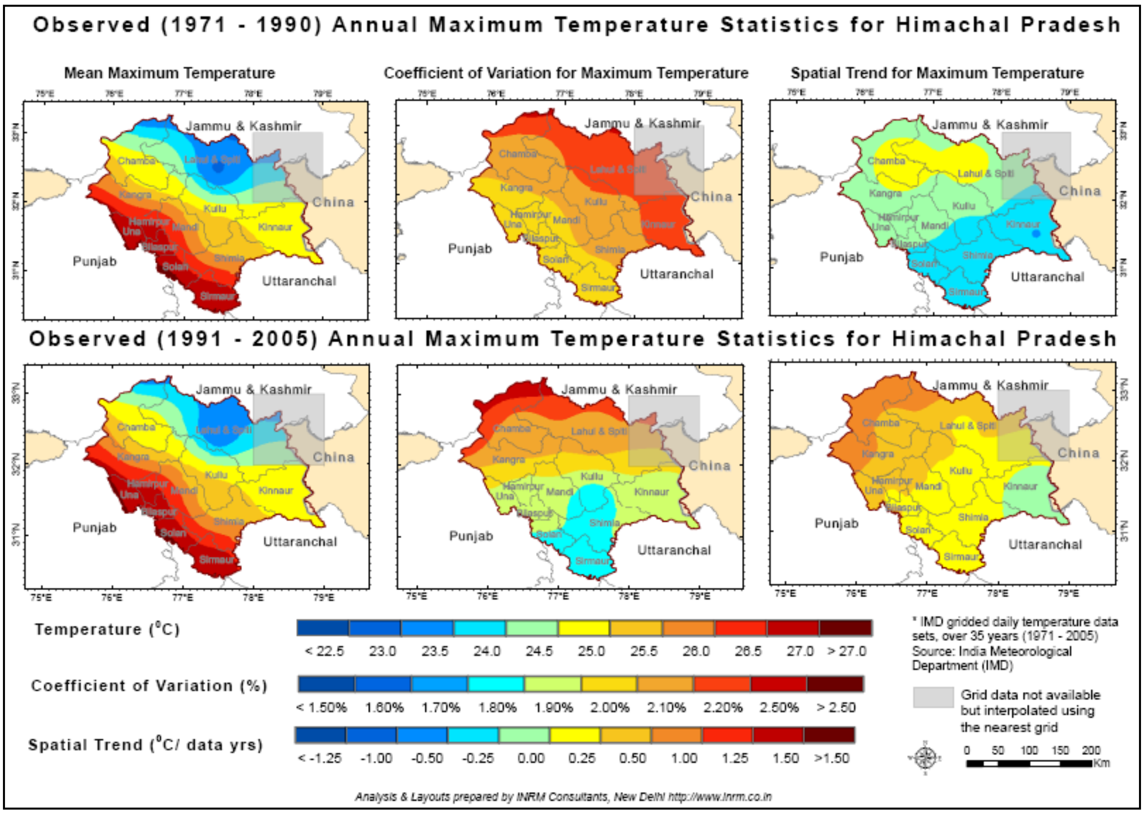
Table 4: Observed Maximum Temperature Statistics (1971-1990 and 1991-2005)

Season	Statistics	Maximum Temperature (1971-1990-20 years)	Maximum Temperature (1991-2005-15 years)
Annual	Average (mm)	25.2	25.3
	Range - Average (mm)	24.2-25.9	23.9-26.1
	CV	0.02	0.02
	Trend(0C/data years) period	0	0.41
Winter (JF)	Average (mm)	15.9	15.9
	Range - Average (mm)	14.4-17.6	14.5-18.1
	CV	0.05	0.05
	Trend(0C/data years)	0.7	-0.43
Pre Monsoon (MAM)	Average (mm)	27.2	27.5
	Range - Average (mm)	24.2-29.1	25.9-29.6
	CV	0.05	0.04
	Trend(0C/data years)	-1.63	2.07
Monsoon (JJAS)	Average (mm)	30.6	30.5
	Range - Average (mm)	29.8-32.5	29.7-31.2
	CV	0.02	0.01

Source: IMD gridded temperature data (1971-1990, 1991-2005)

From Table 4 it can be seen that annual average maximum temperature for Himachal Pradesh from 1971-1990 and 1991-2005is 25.2^{0}C and 25.3^{0}C respectively. Figure 12 depicts spatial variation in the long term statistics for mean maximum temperatures. Southern Himachal districts show decline of about 0.25^{0}C in 20 years (1971-1990). Chamba and Lahul and Spiti show increase of about 0.25^{0}C/20 years while other Northern districts show no change in trend While in the latter period 1991-2005 its seen that all districts show positive trend. Chamba and Kangra show increase of about 1^{0}C/15 years while other districts show increase of about 0.25 to 0.5^{0}C/15 years. Thus it's observed that annual maximum temperature show increase of about 0.41^{0}C in 1991-2005 while in 1971-1990 it shows no change. Inter annual variation is higher in 1971-1900 than 1991-2005.Spatial variation in mean maximum temperature is found to be around 2^{0}C.

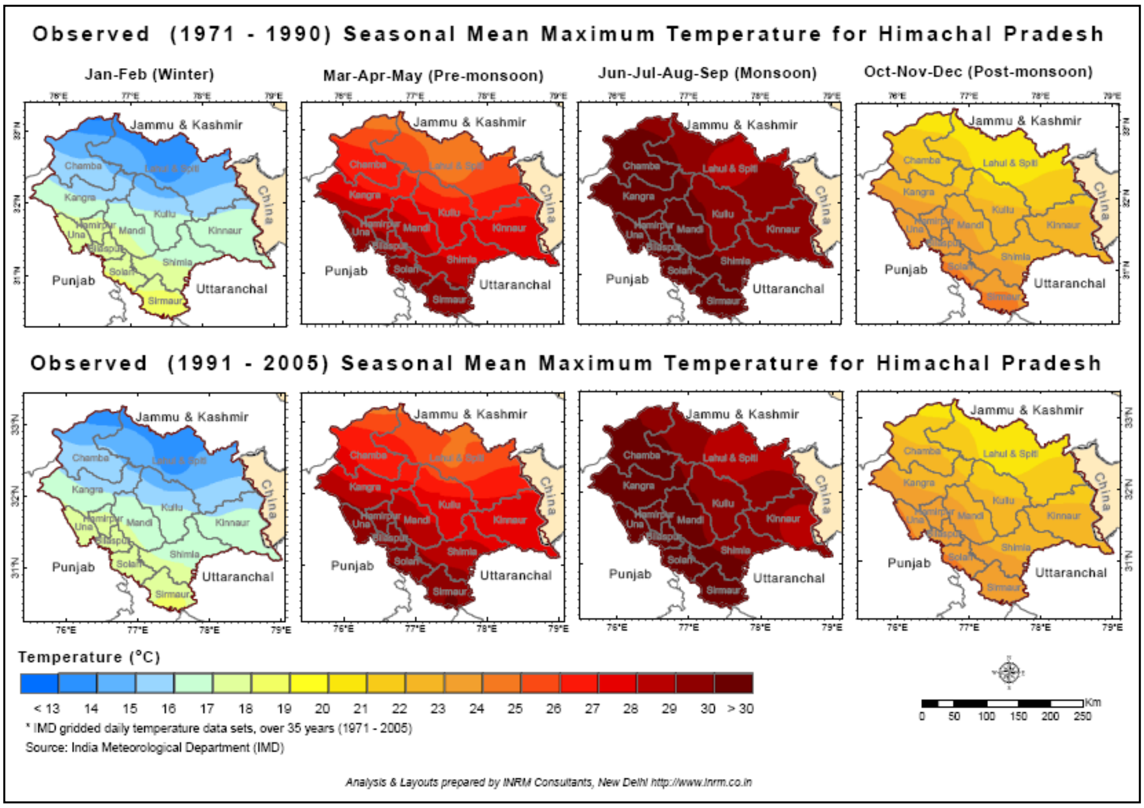
Figure 12 : Observed annual maximum temperature statistics in Himachal Pradesh (1971-1990 and 1991-2005)



Source: INRM analysis

As seen in Table 4, seasonal average maximum temperature during the period 1971-1990 is higher during monsoon season (30.6^{0}C) and ranges between 29.8^{0}C to 32.5^{0}C. Similarly, seasonal average maximum temperature during the period 1991-2005 is higher during monsoon season (30.5^{0}C) and ranges between 29.7^{0}C to 31.2^{0}C. Figure 13 shows the observed seasonal maximum temperature for Himachal Pradesh for 1971-1990 and 1991-2005. Western, South Western and North Western districts of Himachal Pradesh have the highest average maximum temperature in the monsoon season.

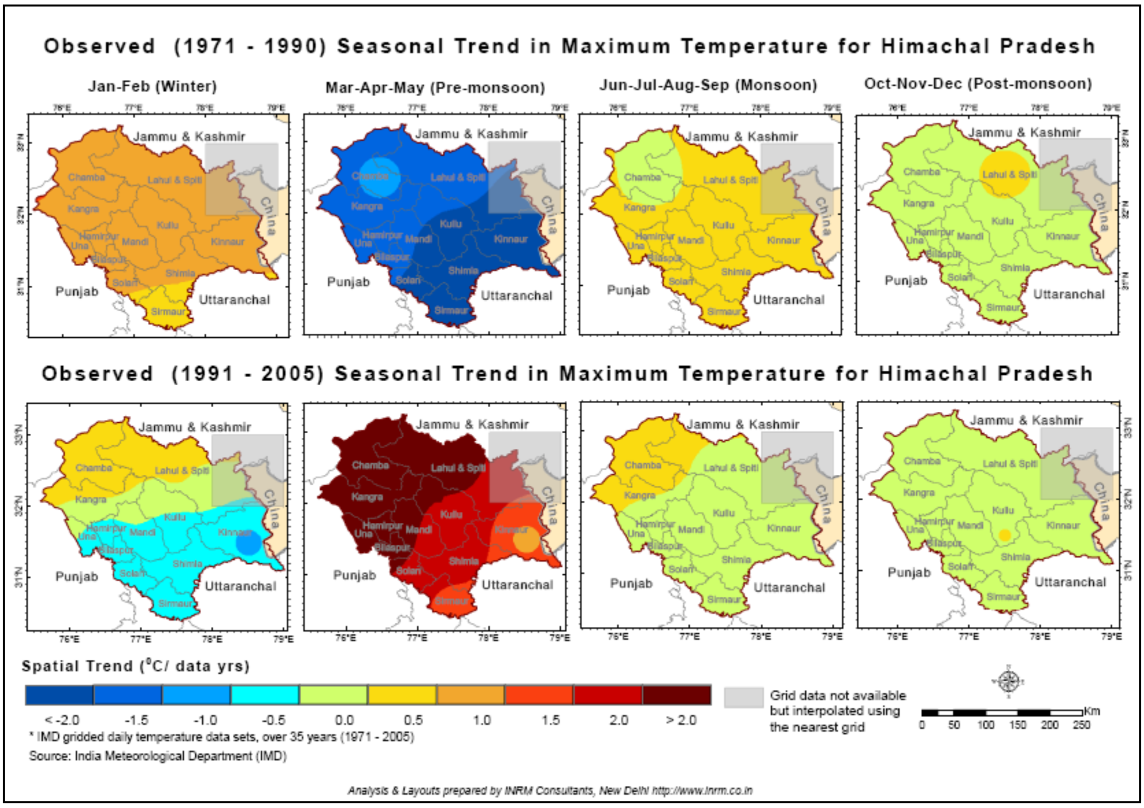
Figure 13 : Observed seasonal maximum temperature in Himachal Pradesh(1971-1990 and 1991-2005)



Source: INRM analysis

Figure 14 shows the spatial variation in the trend in maximum temperature for both the periods. In pre monsoon season difference in trend between the periods is more pronounced compared to the other seasons. In the period 1971-1990 average maximum temperature is expected to decline for all parts of the State while in 1991-2005 it is expected to increase over the years. North western and Western districts show greater increase in 15 years compared to the other parts. Thus in pre monsoon season for Himachal Pradesh state maximum temperature show decline of about 1.63^{0}C in 1971-1990 while increase of about 2.07^{0}C in 1991-2005 (Table 4) The grey portion in Figure 14 grid data is not available but has been interpolated using the nearest grid.

Figure 14 : Observed seasonal maximum temperature trends in Himachal Pradesh (1971-1990 and 1991-2005)



Source: INRM analysis

1.10 Observed Minimum Temperature trends (1971-1990, 1991-2005)

The state of Himachal Pradesh shows a spatial as well as temporal variability. Table 5 gives the summary of annual and seasonal minimum temperature statistics for periods 1971-1990 and 1991-2005.

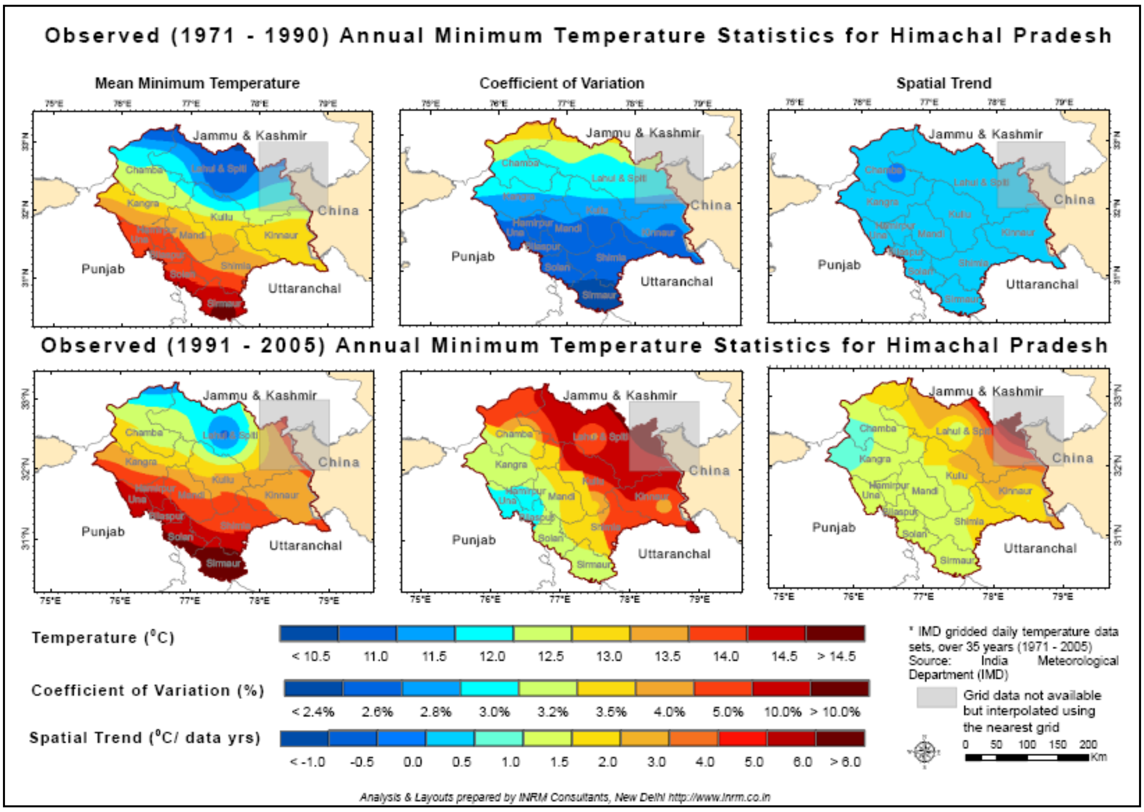
Table 5: Observed Minimum Temperature Statistics (1971-1990 and 1991-2005)

Season	Statistics	Minimum Temperature (1971-1990-20 years)	Minimum Temperature (1991-2005-15 years)
Annual	Average (mm)	12.5	13.7
	Range - Average (mm)	11.9-13.1	12.3-15.6
	CV	0.03	0.09
	Trend(0C/data years)	0.19	3.6
Winter (JF)	Average (mm)	3.6	4.1
	Range - Average (mm)	2.2-5	2.7-5.3
	CV	0.22	0.15
	Trend(0C/data years)	1	0.54
Pre Monsoon (MAM)	Average (mm)	13.1	13.7
	Range - Average (mm)	11.7-14.4	12.5-15.3
	CV	0.06	0.06
	Trend(0C/data years)	-0.67	2.32
Monsoon (JJAS)	Average (mm)	20	22
	Range - Average (mm)	19.5-20.9	19.9-24.8
	CV	0.02	0.1
	Trend(0C/data years)	0.46	6.49
Post Monsoon (OND)	Average (mm)	7.9	9.2
	Range - Average (mm)	7-8.9	7.3-11.3
	CV	0.07	0.16
	Trend(0C/data years)	0.35	3.88

Source: IMD gridded temperature data (1971-1990, 1991-2005)

From Table 5 it can be seen that annual average minimum temperature for Himachal Pradesh from 1971-1990 and 1991-2005is 12.5^{0}C and 13.7^{0}C respectively. Thus it can be observed that minimum temperature has grown in the period 1991-2005 by about 1.2^{0}C compared to 1971-1990. Figure 15 depicts spatial variation in the long term statistics for mean minimum temperatures. Southern districts namely, Sirmaur, Solan, Una, Bilaspur and Hamirpur show higher observed annual minimum temperature than the Northern parts for both the periods. Himachal Pradesh districts show decline of about 0.5^{0}C in 20 years (1971-1990). While in the latter period 1991-2005 it's seen that all districts show positive trend. Maximum increase in minimum temperature in 1991-2005 is observed for North Eastern districts highlighted in grey portion in the layout.The grey portion in Figure 15 grid data is not available but has been interpolated using the nearest gridThus it's observed that annual minimum temperature show increase of about 0.19^{0}C in 1991-2005 while in 1971-1990 it shows a much higher increase of about 3.6^{0}C. Inter annual variation is higher in 1991-2005 than 1971-1990.

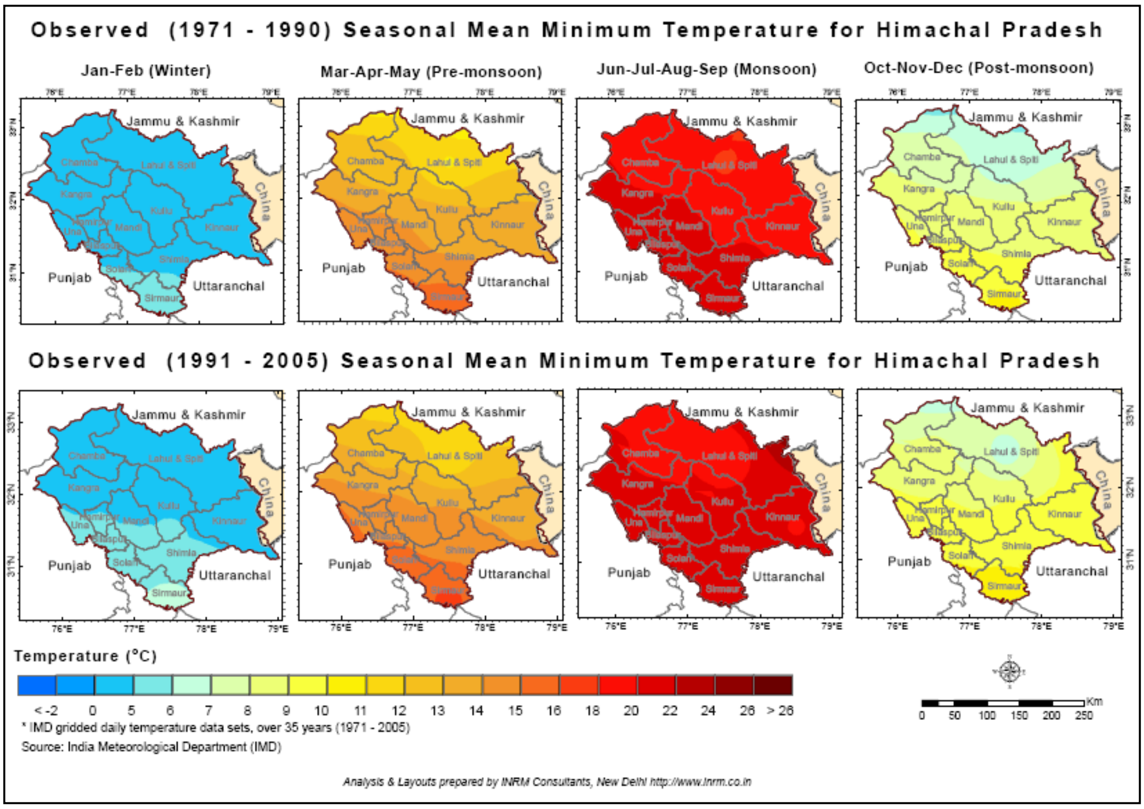
Figure 15 : Observed annual minimum temperature statistics in Himachal Pradesh (1971-1990 and 1991-2005)



Source: INRM analysis

As seen in Table 5, seasonal average minimum temperature during the period 1971-1990 is higher during monsoon season (20.0^{0}C) and ranges between 19.5^{0}C to 20.9^{0}C. Similarly, seasonal average minimum temperature during the period 1991-2005 is higher during monsoon season (22.0^{0}C) and ranges between 19.9^{0}C to 24.8^{0}C. Figure 16 shows the observed seasonal minimum temperature for Himachal Pradesh for 1971-1990 and 1991-2005. South districts of Himachal Pradesh show higheraverage minimum temperatures than the Northern districts in the pre monsoon season while in monsoon season not much variability is observed for both the periods.

Figure 16 : Observed seasonal minimum temperature in Himachal Pradesh (1971-1990 and 1991-2005)

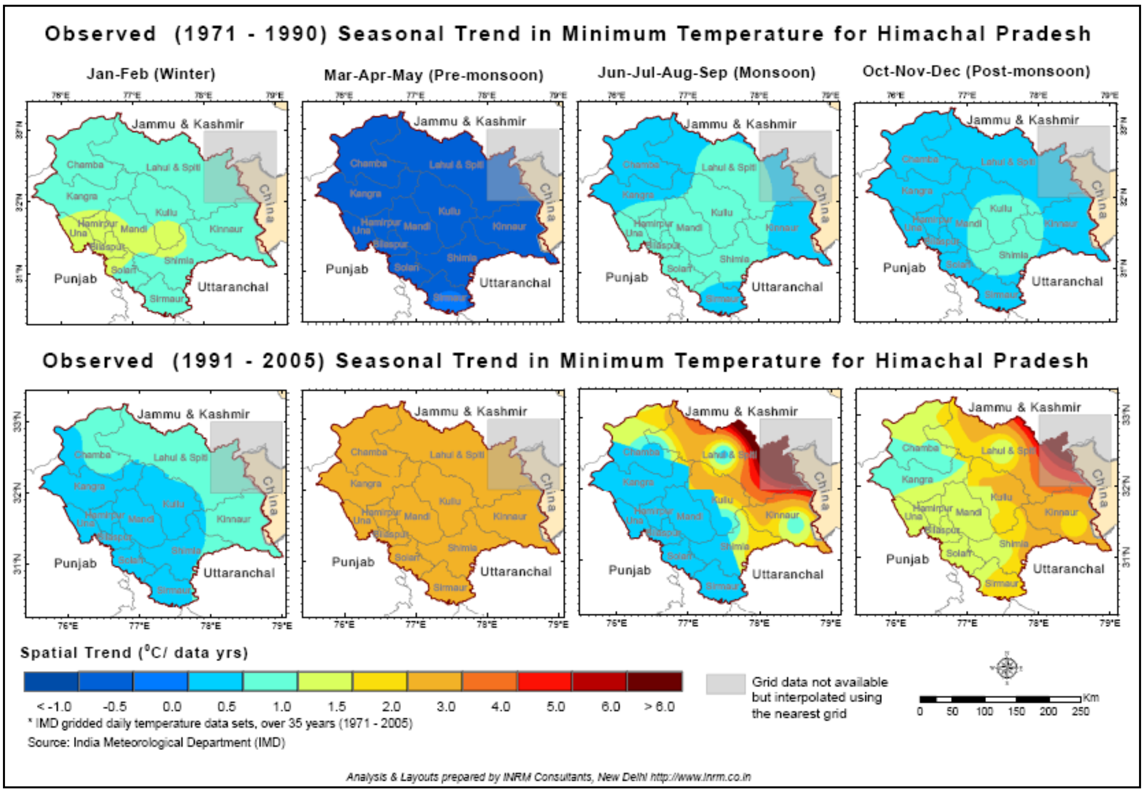


Source: INRM analysis

Figure 17 shows the spatial variation in the trend in minimum temperature for both the periods. In pre monsoon season, monsoon and post monsoon season's trend difference between the two periods is very high. In the period 1971-1990in Pre monsoon season average minimum temperature is expected to decline for all parts of the State while in 1991-2005 it is expected to increase for all districts. In monsoon season North Eastern districts show greater increase in 15 years compared to the other parts. While in post monsoon season all parts of the State show much higher increase in minimum temperature in 1991-2005 than 1971-1990, specially the North Eastern districts. Thus in pre monsoon, monsoon and post monsoon seasons for Himachal Pradesh state minimum temperature show decline of about 0.67^{0}C, increase of about 0.46^{0}C and increase of about 0.35^{0}C respectively in 1971-1990 while increase of about 2.32^{0}C,6.49^{0}C and 3.88^{0}C respectively in 1991-2005 (Table 5).This it can be concluded that minimum temperature has grown over the recent years,1991-2005 in Himachal Pradesh compared to the earlier years (1971-1990).

The grey portion (North Eastern) in Figure 17 grid data is not available but has been interpolated using the nearest grid.

Figure 17 : Observed seasonal minimum temperature trends in Himachal Pradesh (1971-1990 and 1991-2005)



Source: INRM analysis

Annual maximum temperature for Himachal Pradesh shows increase of about 0.41^{0}C in 1991-2005 while in 1971-1990 it shows no change. In pre monsoon season, state maximum temperature show decline of about 1.63^{0}C in 1971-1990 while increase of about 2.07^{0}C in 1991-2005.

Annual minimum temperature for Himachal Pradesh shows increase of about 0.19^{0}C in 1991-2005 while in 1971-1990 it shows a much higher increase of about 3.6^{0}C. State shows much higher increase of minimum temperature in pre monsoon, monsoon and post monsoon seasons in 1991-2005 in comparison to 1971-1990.

1.11 Climate Change Scenarios

The IPCC scenarios provide a mechanism to assess the potential impacts on climate change. Global emission scenarios were first developed by the IPCC in 1992 and were used in global general circulation models to provide estimates for the full suite of greenhouse gases and the potential impacts on climate change. Since then, there has been greater understanding of possible future greenhouse gas emissions and climate change as well as considerable improvements in the general circulation models. The IPCC, therefore, developed a new set of emissions scenarios, published in the IPCC Special Report on Emission Scenarios (IPCC SRES November 2000). These scenarios provided input into the Third and Fourth Assessment Reports and were the basis for evaluating climatic and environmental consequences of different levels of future greenhouse gas emissions and for assessing alternative mitigation and adaptation strategies. These scenarios refer to the predictions made for future conditions mainly related to precipitation, sea level rise and temperature changes based on 'storylines' of the alternate greenhouse gas emissions. There are four storylines (A1, A2, B1 and B2) identifying alternate states of future economic and technological development that takes place over the next few decades as summarized in Table 6.

Table 6: Summary of IPCC SRES Scenarios

A1	**A2**
WORLD: MARKET ORIENTED ECONOMY: RAPID ECONOMIC GROWTH. POPULATION: PEAKS IN 2050 AND THEN GRADUALLY DECLINES. GOVERNANCE: A CONVERGENT WORLD - INCOME AND WAY OF LIFE CONVERGE BETWEEN REGIONS. EXTENSIVE SOCIAL AND CULTURAL INTERACTIONS WORLDWIDE. TECHNOLOGY: THERE ARE THREE SUBSETS TO THE A1 FAMILY A1FI - FOSSIL-FUELS INTENSIVE. A1B - BALANCED ON ALL ENERGY SOURCES. A1T - NON-FOSSIL ENERGY SOURCES.	WORLD: DIVIDED WORLD ECONOMY: REGIONALLY ORIENTED, LOWEST PER CAPITA INCOME POPULATION: CONTINUOUSLY INCREASING POPULATION. GOVERNANCE: INDEPENDENTLY OPERATING, SELF-RELIANT NATIONS TECHNOLOGY: SLOWER AND MORE FRAGMENTED
B1	**B2**
WORLD: CONVERGENT ECONOMY: SERVICE AND INFORMATION BASED, LOWER GROWTH THAN A1 POPULATION: SAME AS A1. GOVERNANCE: GLOBAL SOLUTIONS TO ECONOMIC, SOCIAL AND ENVIRONMENTAL STABILITY TECHNOLOGY: CLEAN AND RESOURCE EFFICIENT TECHNOLOGIES	WORLD: LOCAL SOLUTIONS ECONOMY: INTERMEDIATE LEVELS OF ECONOMIC DEVELOPMENT POPULATION: CONTINUOUSLY INCREASING POPULATION, BUT AT A SLOWER RATE THAN IN A2. GOVERNANCE: LOCAL SOLUTIONS TO ECONOMIC, SOCIAL AND ENVIRONMENTAL STABILITY TECHNOLOGY: MORE RAPID A2, LESS RAPID MORE DIVERSE A1/B1

Source: IPCC 4th Assessment Report (2007)

Climate models are mathematic models used to simulate the behaviour of climate system. They incorporate information regarding climate processes, current climate variability and the response of the climate to the human-induced drivers. These models range from simple one dimensional models to complex three dimensional coupled models. The latter, known as Global Circulation Models (GCM), incorporate oceanic and atmospheric physics and dynamics and represent the general circulation of the planetary atmosphere or ocean. The GCMs are usually run at very course grid (about 30 X30) resolution whereas the processes that are of interest for studies such as this one, such as precipitation, are highly influenced by the local features namely orography and land use. These local characteristics are not properly represented at the coarse scale of GCM and contribute to prediction errors on the impact of climate change at the sub-grid scale. Therefore, these GCMs are strengthened with the incorporation of local factors and downscaled, in general with a grid resolution of about 0.50X0.50 or less. The downscaling can be of dynamic or statistical type. These models are referred to as Regional Climate Models (RCM) and improve the quality of climatic prediction for specific local areas.

A RCM is a model of the atmosphere and land surface which has high horizontal resolution and consequently covers a limited area of the earth's surface. A RCM cannot exist without a 'parent' GCM to provide the necessary inputs. The RCMs provide an opportunity to dynamically downscale global model simulations to superimpose the regional detail of specified region. RCM provide climate information with useful local detail including realistic extreme events and also they simulate current climate more realistically.

A regional climate model:

- Is comprehensive physical high resolution (~50km) climate model
- Covers a limited area of the globe
- Includes the atmosphere and land surface components of the climate system
- Contains representations of the key processes within the climate system (e.g., cloud, radiation, rainfall, soil hydrology)

Advantages of Regional climate models include

- highly resolved information
- physically based character
- many indicators
- better representation of the mesocale and weather extremes than in GCMs.

Disadvantages of Regional climate models include

- computational expensiveness, particularly for long runs
- lack of two way nesting (feedback with the forcing GCM input)
- dependence on usually biased inputs from the forcing GCM
- errors in the GCM fields that could result in errors in the regional climate scenarios
- availability of fewer scenarios.

Providing Regional Climates for Impact Studies (PRECIS) is an atmospheric and land surface model of limited area and high resolution which is locatable over any part of the globe. Dynamical flow, the atmospheric sulphur cycle, clouds and precipitation, radioactive processes, the land surface and the deep soil are all described and lateral boundary conditions (LBCs) are required at the limits of the model's domain. Information from every aspect may be diagnosed from within the model (Noguer et al., 1998[7]).

PRECIS can be applied easily to any area of the globe to generate detailed climate change predictions and is used for vulnerability and adaptation studies and climate research.

1.12 Regional Climate Scenarios for India Using PRECIS

PRECIS is the Hadley Centre portable regional climate model, developed to run on a PC with a grid resolution of 0.44° x 0.44°. High-resolution limited area model is driven at its lateral and sea-surface boundaries by output from global coupled atmosphere-ocean (HadCM3) and global atmospheric (HadAM3) general circulation models. PRECIS captures important regional information on summer monsoon rainfall missing in its parent GCM simulations.

[7]Noguer M, Jones R, Murphy J (1998) Sources of systematic errors in the climatology of a regional climate model over Europe.ClimDyn 14:691–712

Indian RCM PRECIS has been configured for a domain extending from about 1.5°N to 38°N and 56°E to 103°E. IPCC SRES A1B Scenario[8]– Q14 Qump (Quantifying Uncertainty in Model Predictions[9]) for the time slices of present (1961–1990), mid-century (2021-2050) and end century (2071–2100) has been made available by IITM Pune.

Simulations from a seventeen-member perturbed physics ensemble (PPE) produced using HadCM3 under the Quantifying Uncertainty in Model Predictions (QUMP) project of Hadley Centre Met Office, UK have been used as LBCs for 138 year simulations of the regional climate model PRECIS. The QUMP simulations comprise 17 versions of the fully coupled version of HadCM3, one with the standard parameter setting and 16 versions in which 29 of the atmosphere component parameters are simultaneously perturbed (Collins et al. 2006[10]).

Having discussed the RCM scenarios that have been deployed so as to extract input to the hydrological model SWAT, for evaluating the impacts of climate change.

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[8] PRECIS A1B, which is a mid path scenario, a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies, with the development balanced across energy sources

[9] The basic approach involves taking a single

model structure and making perturbations to the values of parameters in the model, based on the

discussions with scientists involved in the development of different parameterization schemes

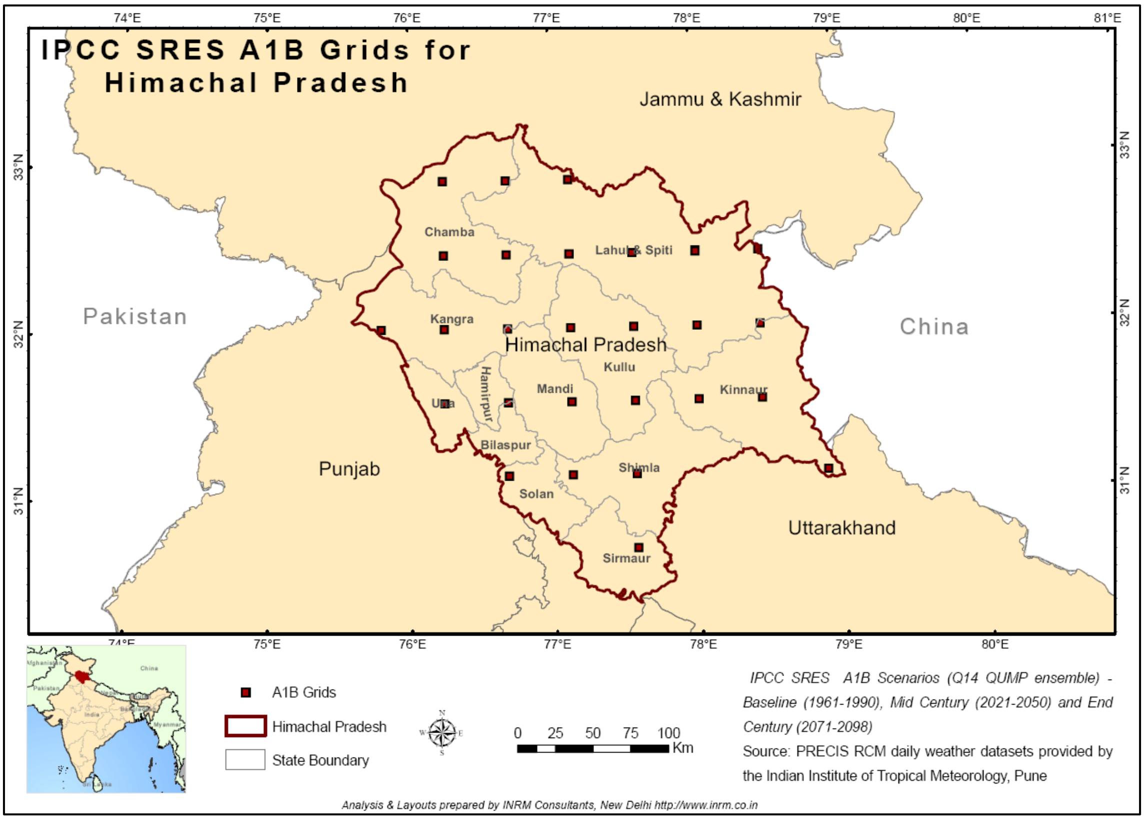
[10] Collins, W.D., V. Ramaswamy, M.D. Schwarzkopf, Y. Sun, R.W. Portmann, Q. Fu, S.E.B. Casanova, J.-L. Dufresne, D.W. Fillmore, P.M.D. Forster, V.Y. Galin, L.K. Gohar, W.J. Ingram, D.P. Kratz, M.-P. Lefebvre, J. Li, P. Marquet, V. Oinas, Y. Tsushima, T. Uchiyama, and W.Y. Zhong, 2006: Radiative forcing by well-mixed greenhouse gases: Estimates from climate models in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). J. Geophys. Res., 111, D14317

1.13 Climate change Data Extraction

Data for many different indicators (Physical quantities, Rainfall, Temperature, Solar Radiation, Relative humidity, Wind speed) at a variety of different timescales; daily, monthly are used for the study area. All model data represent grid cell averages, i.e. an average quantity over a 2500 km2 (50 km X 50 km) and are available in binary format.

Special data extraction software is used to extract the relevant grids (25 grid points) for the study areas. The RCM grids for Himachal Pradesh are shown in Figure 18.

Figure 18 : PRECIS Data grids of Himachal Pradesh

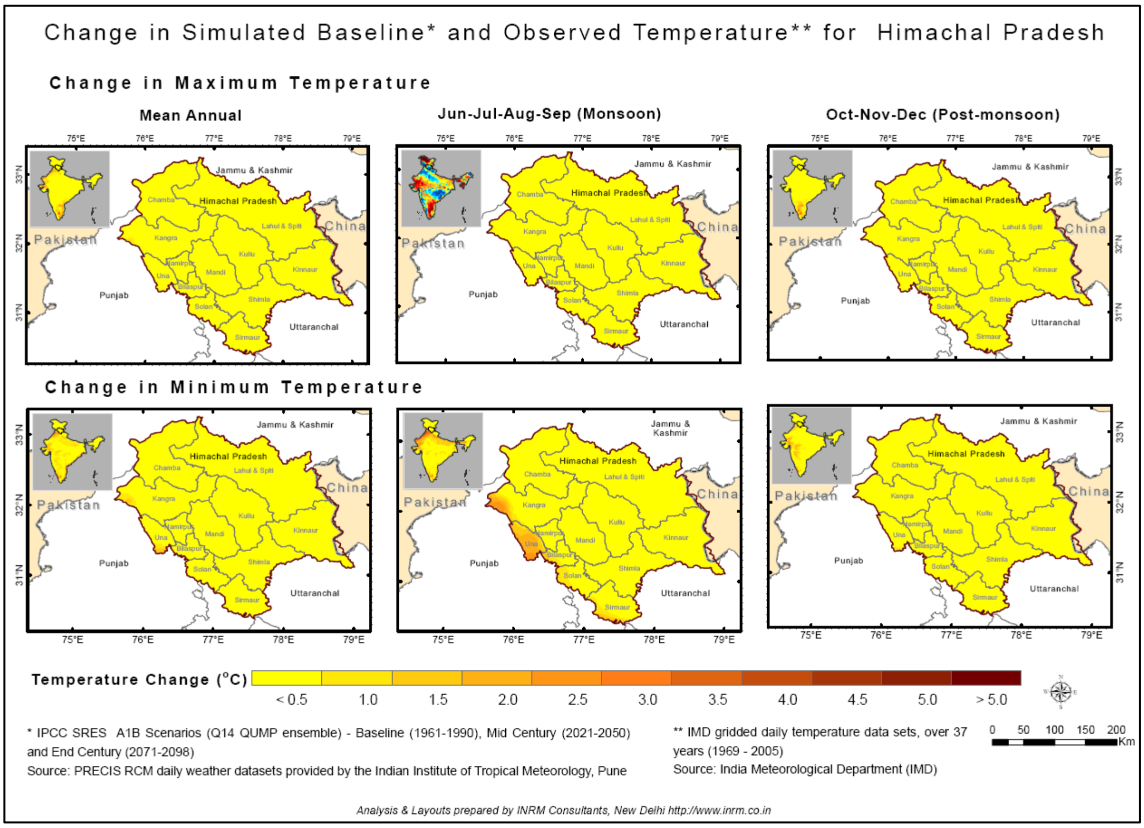


Source: INRM analysis

1.13.1 Comparison of Observed and Simulated Temperature and Rainfall

A comparison of the simulated baseline temperature and rainfall was made to examine the model simulation capability. Figure 19 shows spatial distribution of temperature and rainfall at annual, monsoon (JJAS) and post monsoon (OND) seasons. It can be seen that simulated baseline reproduces the observed temperature statistics well.

Figure 19: Comparison of Simulated Baseline and Observed Temperature and Rainfall for Himachal Pradesh



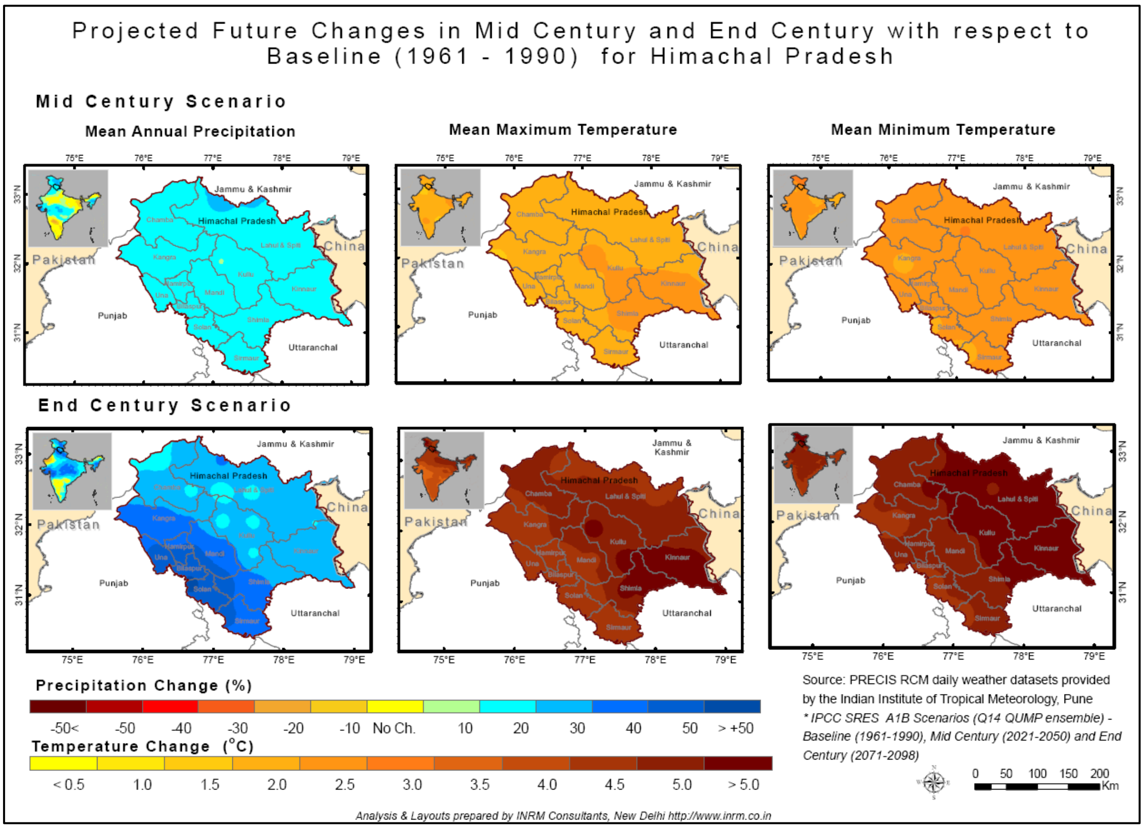
Source: INRM analysis

Simulated baseline annual rainfall shows volumetric difference by about 30 to 40% increase. In monsoon season, Chamba on the North West and parts of Kinnaur district in east of Himachal Pradesh shows under simulation of rainfall in the baseline by about 20 to 30% as compared to IMD rainfall, whereasthe rest of the districts shows no change or over simulation of rainfall in the baseline by 20 to 40% as compared to IMD rainfall. Baseline simulated rainfall show less inter annual variation than IMD rainfall.

1.14 Analysis of the Climate Change Data

The PRECIS data on precipitation, maximum and minimum temperature have been analysed for Himachal Pradesh. Preliminary inferences on the variations of these entities have been presented in Figure 20. Annual maximum temperature is projected to increase by 1.90C and annual minimum temperature by 2.30C towards mid-century. The increase in annual maximum temperature is projected to be 4.60C and annual minimum temperature to be 5.00C towards end century respectively. Increase is projected for average annual rainfall by 15.0% and 28.0% respectively for mid and end century scenarios.

Figure 20: Projected Changes in Mean Annual Precipitation, and Temperature in Himachal Pradesh



Source: INRM analysis

1.14.1 PRECIS Temperature

The HADCM3 simulations downscaled with PRECIS indicate an all-round warming over the Indian subcontinent associated with increasing greenhouse gas concentrations. Seasonal mean daily maximum and mean daily minimum temperatures from the PRECIS simulation of the A1B scenarios are given in Table 7.

Table 7: Characteristics of Simulated Seasonal and Annual Temperature

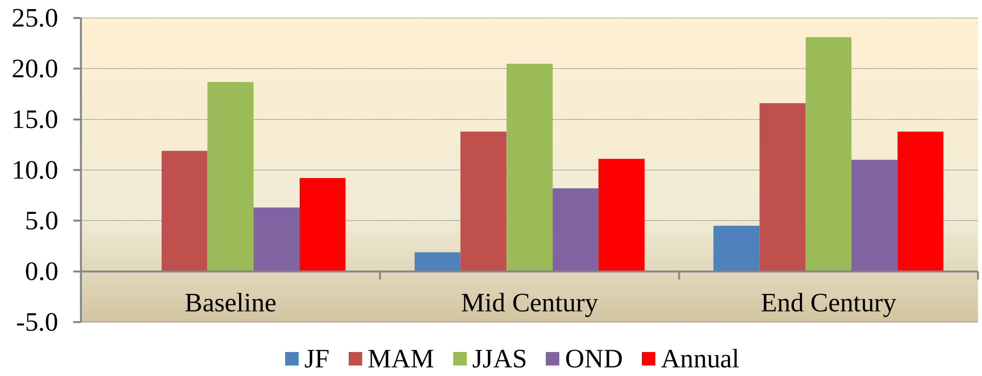
IPCC SRES Baseline and A1B Scenario as Simulated By PRECIS for Himachal Pradesh						
Mean Daily Maximum Temperature (^{0}c)						
		JF	MAM	JJAS	OND	Annual
Himachal Pradesh	1970s	-0.1	11.9	18.7	6.3	9.2
Himachal Pradesh	2050s	1.9	13.8	20.5	8.2	11.1
Himachal Pradesh	2080s	4.5	16.6	23.1	11.0	13.8
Mean Daily Minimum Temperature (^{0}C)						
Himachal Pradesh	1970s	-12.0	-0.9	10.4	-5.7	-2.1
Himachal Pradesh	2050s	-9.9	1.3	12.4	-3.1	0.2
Himachal Pradesh	2080s	-7.0	4.0	15.1	-0.5	2.9
Comparison of projected changes in temperatures for IPCC SRES scenario with respect to baseline for Himachal Pradesh **						

IPCC SRES Baseline and A1B Scenario as Simulated By PRECIS for Himachal Pradesh					
Change in Mean Daily Maximum Temperature (^{0}C)					
	JF	MAM	JJAS	OND	Annual
Change from Baseline to Mid Century	2.0	1.9	1.8	1.9	1.9
Change from Baseline to End Century	4.6	4.7	4.4	4.7	4.6
Change in Mean Daily Minimum Temperature (^{0}C)					
Change from Baseline to Mid Century	2.1	2.2	2.0	2.6	2.3
Change from Baseline to End Century	5.0	4.9	4.7	5.2	5.0
*** Positive change indicates warming in Future and negative change indicates cooling in future*					

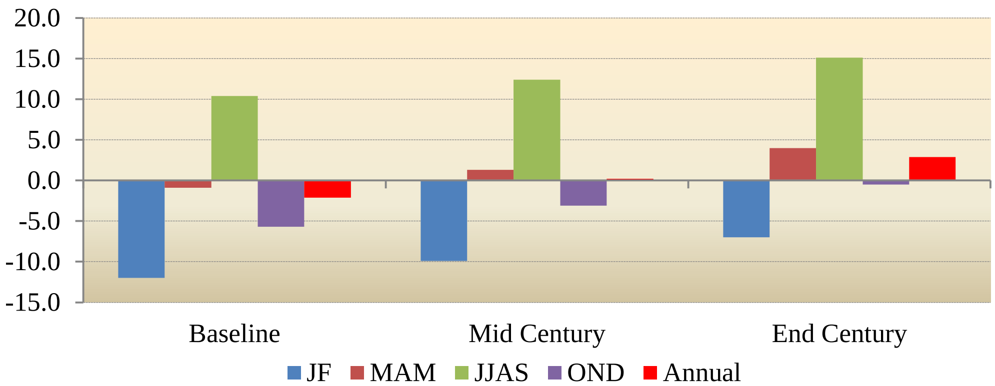
Source: PRECIS A1B data

Both maximum and minimum temperatures are projected to rise significantly under the PRECIS A1B scenario. Increase in the monsoon season would be lower than in the dry seasons. Temperature changes are shown in Figure 21.

Figure 21 : Characteristics of Simulated Seasonal and Annual Temperature in Himachal Pradesh



Maximum temperature in (°C)

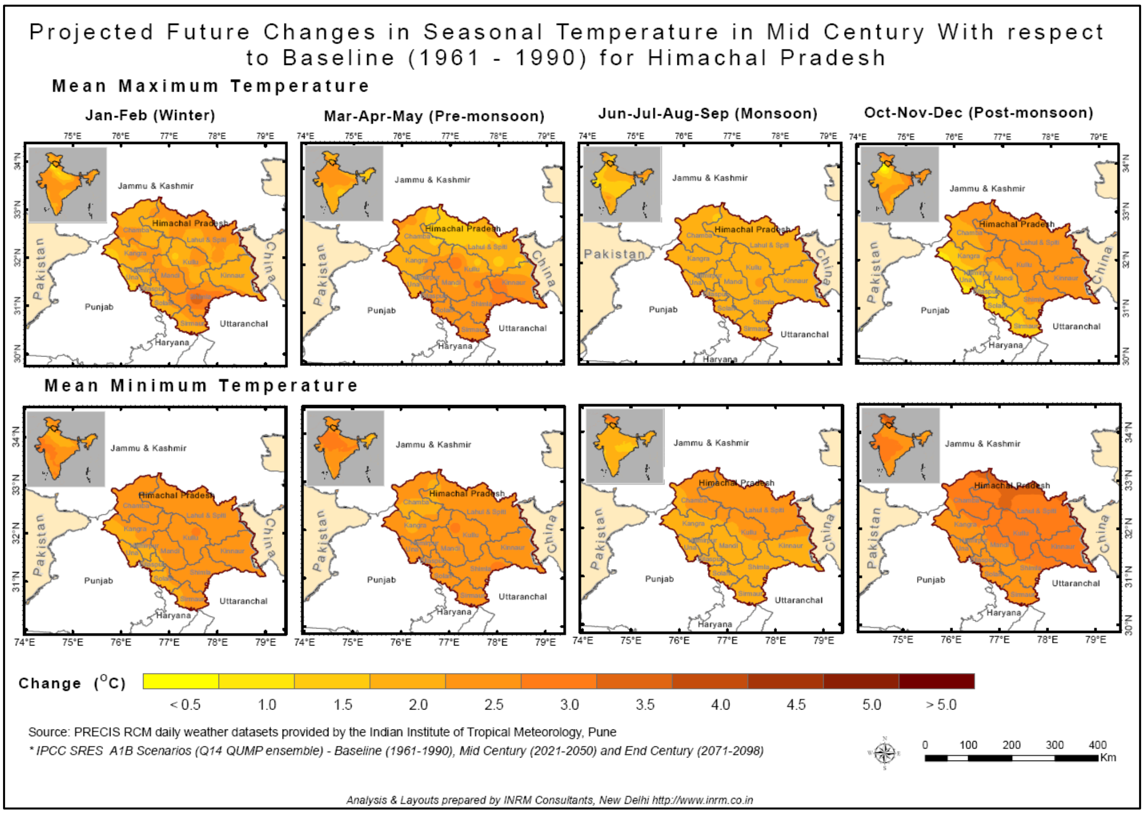


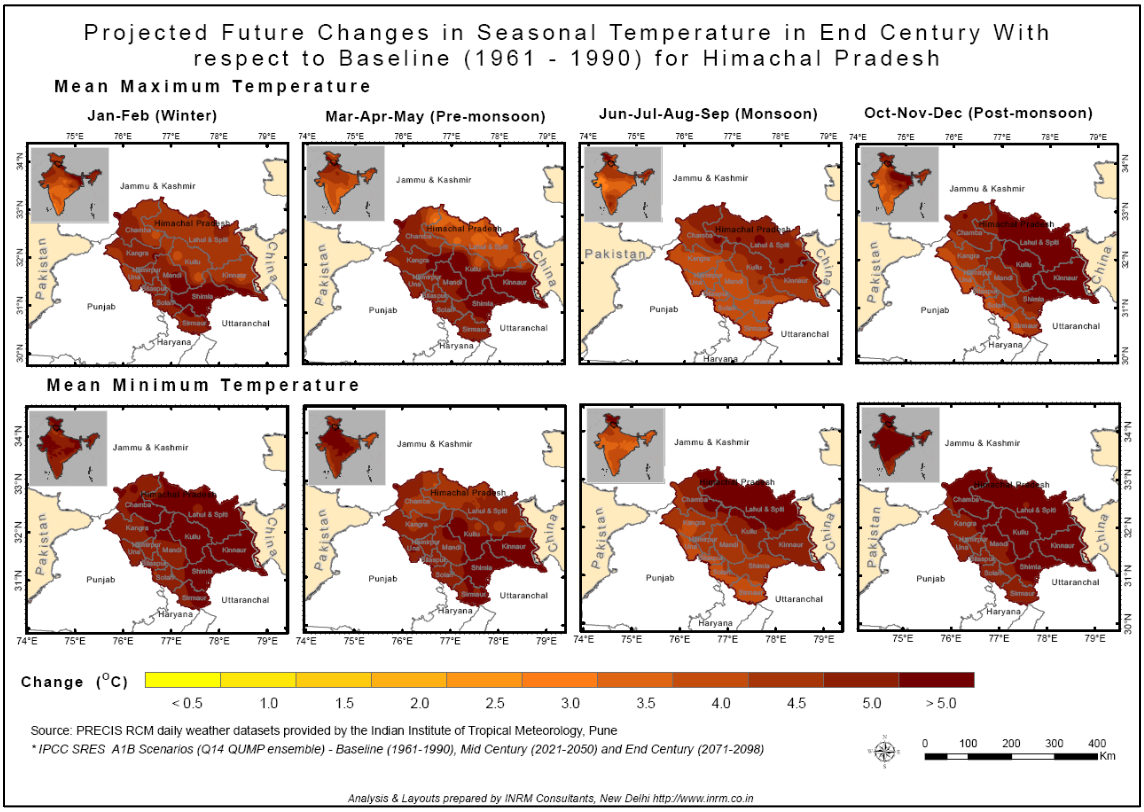
Minimum temperature in (°C)

Source: INRM analysis

Spatial variation in the change in the mean daily maximum and minimum temperature is shown in Figure 22. It can be seen from Figure 22 that the projected change in minimum temperature is higher than the change in maximum temperature in both mid and end century.

Figure 22 : Projected Changes in seasonal temperature in Himachal Pradesh





Source: INRM analysis

1.14.2 PRECIS Precipitation

Himachal Pradeshreceives most of its rain during the monsoon season, which starts in late June. The mean seasonal precipitation amounts simulated by PRECIS are as shown in Table 8. Data are presented for four seasonal periods: JF - January, February; MAM - March, April, May; JJAS - June, July, August, September; OND - October, November, December. Projected changes to mid and end-century is also presented. Under the A1B scenario, rainfall is projected to increase. Mean annual rainfall increases by about313mm (15%) by mid-century and by about 585mm (28%) by end-century under the A1B scenario. Most of the increases occur in the monsoon period. There is a slight decline in JF rainfall towards mid-century under the A1B scenario. Mean monsoon rainfall increases by 182 mm by mid-century and by 384 mm by end century.

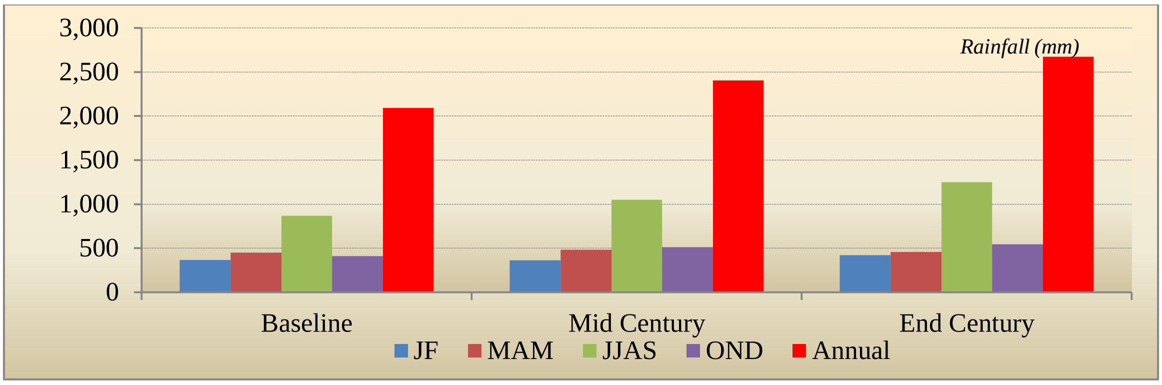
Table 8: Rainfall Statistics for Himachal Pradesh

IPCC SRES baseline and A1B scenario as simulated by PRECIS for Himachal Pradesh						
Rainfall (mm)						
		JF	MAM	JJAS	OND	Annual
Himachal Pradesh	1970s	365.5	447.8	866.6	410.7	2090.6
Himachal Pradesh	2050s	362.7	480.9	1048.7	512.0	2404.3
Himachal Pradesh	2080s	421.0	458.2	1250.9	545.4	2675.5

IPCC SRES baseline and A1B scenario as simulated by PRECIS for Himachal Pradesh					
Comparison of projected changes in seasonal and annual rainfall (mm) for IPCC SRES scenario with respect to baseline for Himachal Pradesh **					
	Change in rainfall (%)				
Change from Baseline to Mid Century	-0.8	7.4	21	24.7	15
Change from Baseline to End Century	15.2	2.3	44.3	32.8	28
*** Positive change indicates increase in future and negative change indicates decrease in future* *JF - January, February; MAM - March, April, May; JJAS - June, July, August, September; OND - October, November, December*					

Source: PRECIS A1B data

Figure 23 : Characteristics of Simulated Seasonal and Annual Rainfall and Temperature

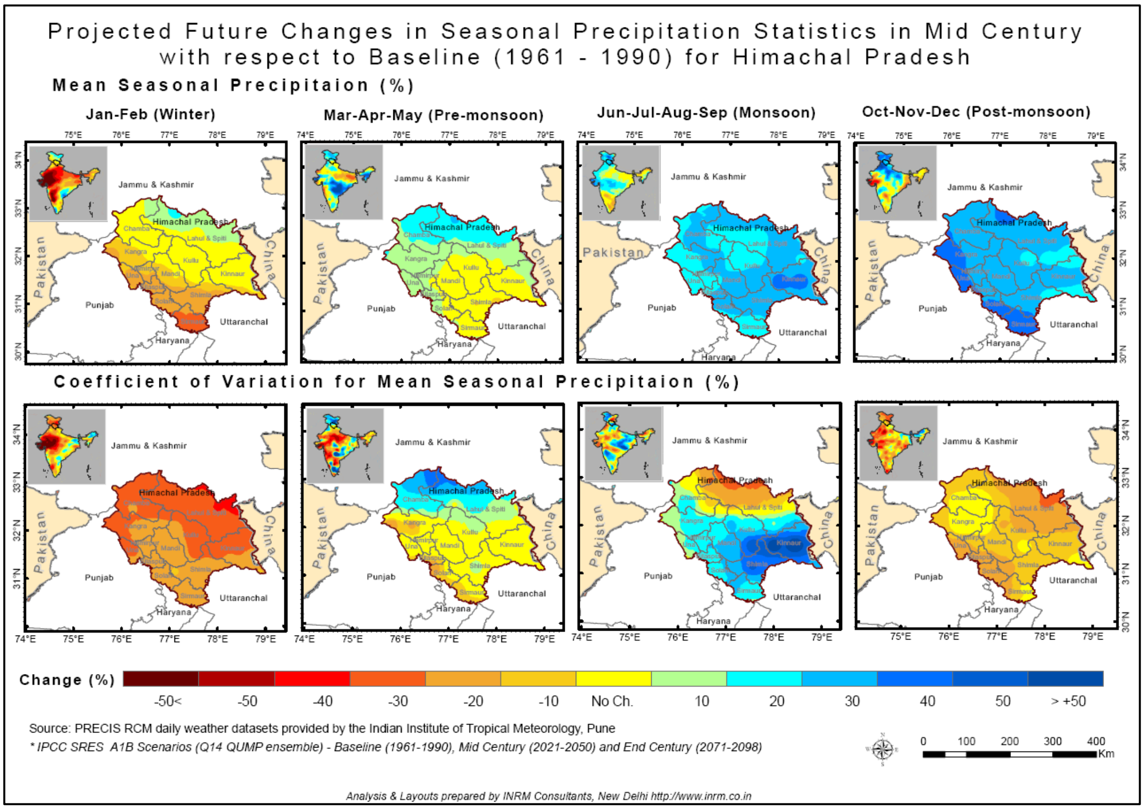


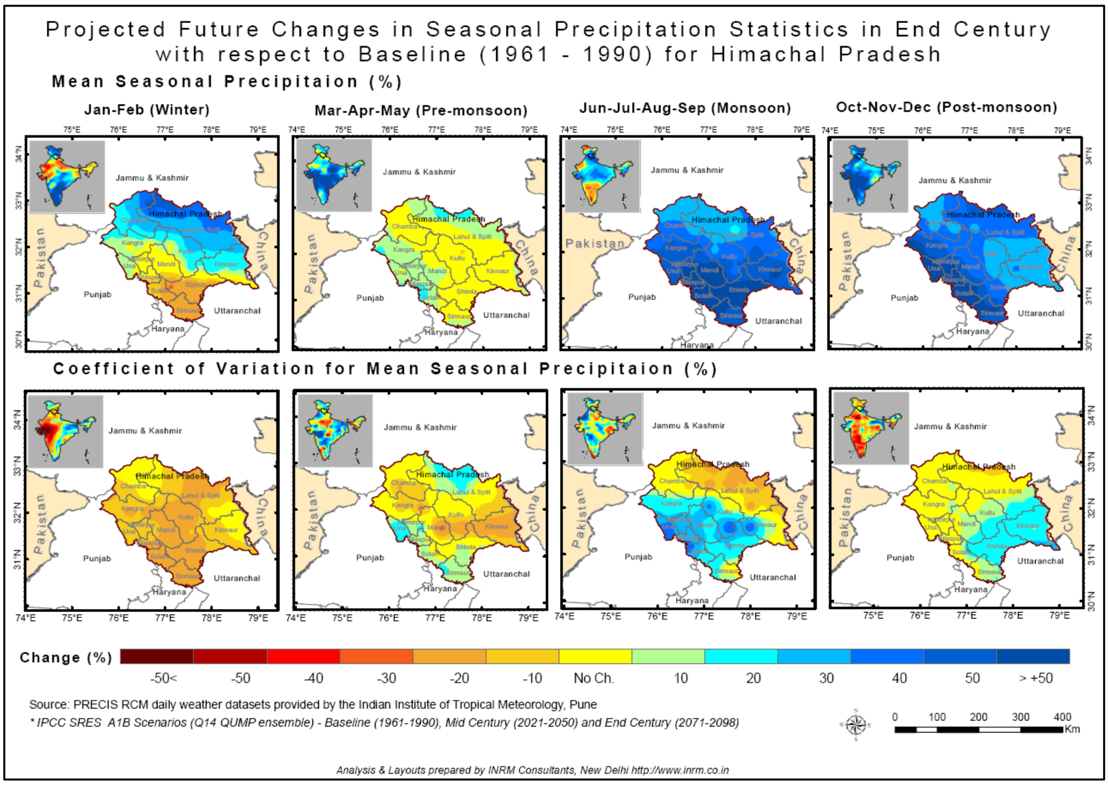
Source: INRM analysis

Above Figure 23 shows the characteristics of rainfall for Himachal Pradesh.

Spatial distribution of projected seasonal rainfall is depicted in Figure 24.

Figure 24 : Projected Change in seasonal precipitation in Himachal Pradesh





Source: INRM analysis

It can be seen from Figure 24 maximum changes in projected rainfall are noticed in monsoon and post monsoon seasons. Coefficient of variation is maximum in the winter season.

1.14.3 Climate Indices for extremes

A suite of climate change indices derived from daily data which focus primarily on extremes have been developed by Expert Team on Climate Change Detection and Indices (ETCCDI)[11]. A total of 21 indices are considered to be core indices. They are based on daily temperature values or daily precipitation amount.Some are based on fixed thresholds and some are based on thresholds that vary from location to location (thresholds are typically defined as a percentile of the relevant data series). RClimDex (1.0)[12]which is designed to provide a user friendly interface to compute indices of climate extremes has been used to derive the relevant indices for Himachal Pradesh. RClimDex calculates 10 precipitation and 11 temperature indices (Table 9) at annual and monthly time steps. Most of the indices are defined in terms of counts of days crossing the thresholds which are derived as the percentile (variable thresholds). Since percentile thresholds are expressions of anomalies relative to the local climate, the value of the thresholds is site specific. Indices calculated using variable threshold are most suitable for spatial comparisons, because they sample same part of temperature/precipitation) distributions at each site[13].

Percentile: In statistics, a percentile is the value of a variable below which a certain percent of observations fall. To calculate percentiles, sort the data so that x1 is the smallest value, and xn is the largest, with n = total number of observations.

xi is the p_ith percentile of the data set where: p_i= 100 * i/(n+1).

Percentile is used to calculate the variable threshold. Example: Frequency of maximum temperature > 400C, gives the number of days where the maximum temperature is above 400C. 400C is an absolute threshold value and this may vary at different places (Shimla may be experiencing hot days when maximum temperature exceeds 300C, but for Churu it may be 450C which may be hot day). In order to make the relative threshold based on the prevailing climate parameter, percentile method is adapted. 10th percentile value is the lower threshold and 90th percentile value is the upper threshold. For Maximum temperature 10th percentile value gives cold day and 90th percentile value means hot days. The thresholds are calculated based on the baseline period of 1961-1990.

[11] http://www.clivar.org/organization/etccd

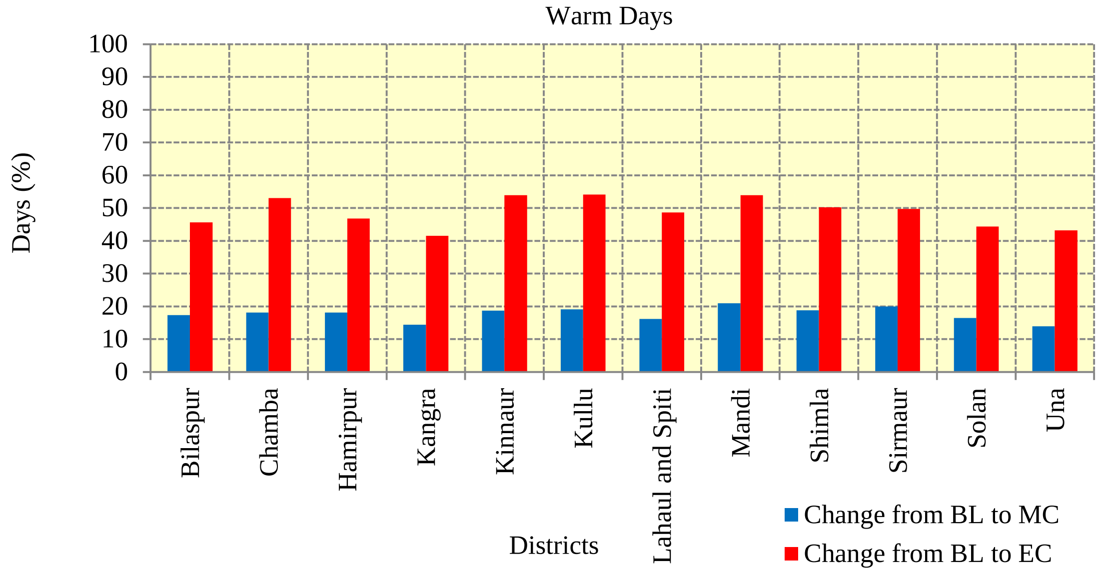
[12]http://cccma.seos.uvic.ca/ETCCDI/software.shtml

[13]Trends in Precipitation Extremes over India.U. R. Joshi and M. Rajeevan. 2006, Research Report No: 3/2006, National Climate Centre. India Meteorological Department,

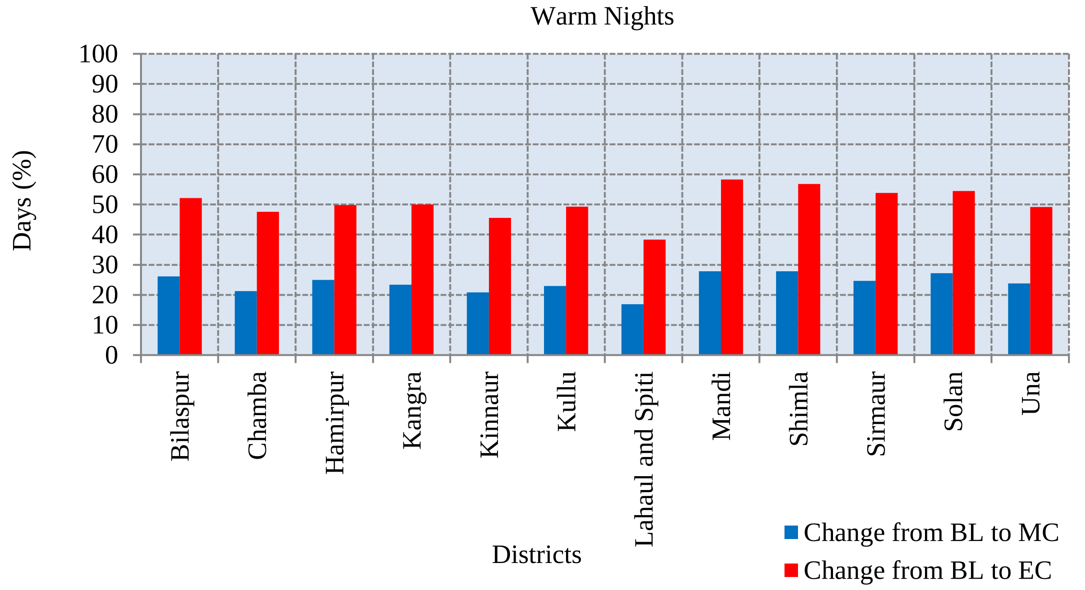
Table 9: List of Climate Indices

Index	Descriptive name	Definition	Units
Temperature indices calculated by RCLIMDEX. (TX is the daily maximum temperature; TN is daily minimum temperature; TG is daily mean temperature.)			
TXX	Hottest day	Monthly highest tx	°c
TNX	Hottest night	Monthly highest tn	°c
TXN	Coolest day	Monthly lowest tx	°c
TNN	Coolest night	Monthly lowest tn	°c
TN10P	Cool night frequency	Percentage of days when tn<10th percentile of 1961-1990	%
TX10P	Cool day frequency	Percentage of days when tx<10th percentile of 1961-1990	%
TN90P	Hot night frequency	Percentage of days when tn>90th percentile of 1961-1990	%
TX90P	Hot day frequency	Percentage of days when tx>90th percentile of 1961-1990	%
WSDI	Warm spell	Annual count of days with at least 6 consecutive days when tx>90th percentile of 1961-1990	Days
CSDI	Cold spell	Annual count of days with at least 6 consecutive days when tn<10th percentile of 1961-1990	Days
DTR	Diurnal temperature range	Monthly mean difference between tx and tn	°c
Precipitation indices calculated by RCLIMDEX. (RR is the daily rainfall rate. A wet day is defined when RR>= 1mm and a dry day when RR<1mm. All indices are calculated annually from January to December.)			
PRCPTOT	Wet-day precipitation	Annual total precipitation from wet days	mm
SDII	Simple daily intensity index	Average precipitation on wet days	mm/day
CDD	Consecutive dry days	Maximum number of consecutive dry days	Days
CWD	Consecutive wet days	Maximum number of consecutive wet days	Days
R10MM	Heavy precipitation days	Annual count of days when rr>=10	Days
R20MM	Very heavy precipitation days	Annual count of days when rr>=20	Days
R95P	Very wet day precipitation	Annual total precipitation when rr>95th percentile of 1961-90 daily rainfall	mm
R99P	Extremely wet day precipitation	Annual total precipitation when rr>99th percentile of 1961-90 daily rainfall	mm
RX1DAY	Max 1-day precipitation	Annual maximum 1-day precipitation	mm
RX5DAY	Max 5-day precipitation	Annual maximum consecutive 5-day precipitation	mm

Figure 25 : Characteristics of Hot Extremes - Warm days and Warm nights



Percentage of days when Maximum temperature>90th percentile of 1961-1990

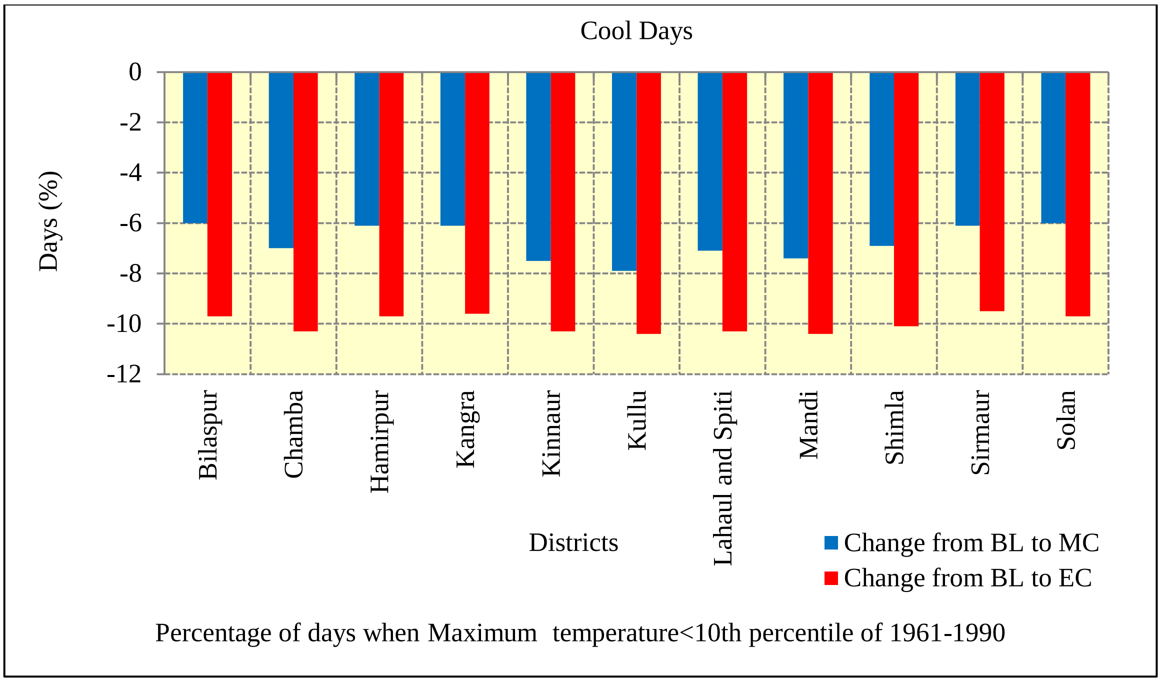


Percentage of days when Minimum temperature>90th percentile of 1961-1990

Source: INRM analysis

Figure 25 shows the characteristic of warm days and warm nights. From the figure it can be seen that percentage of warm days and warm nights is projected to increase for all the districts in MC and EC compared to the BL implying warming up. Towards the end century increase in warm days is more particularly for Kullu, Kinnaur and Mandidistricts and warm nights for Mandi and Shimla compared to the other districtsof Himachal Pradesh. While for Una and Kangra increase in warm days is the least relatively and for Lahul and Spiti increase in warm nights is the least relatively compared to the baseline. It can be inferred that maximum of maximum and maximum of minimum temperatures is consistently increasing, indicating significant warming up over Himachal Pradesh districts.

Figure 26 : Characteristics of Cold Extremes - Cool days and Cool nights



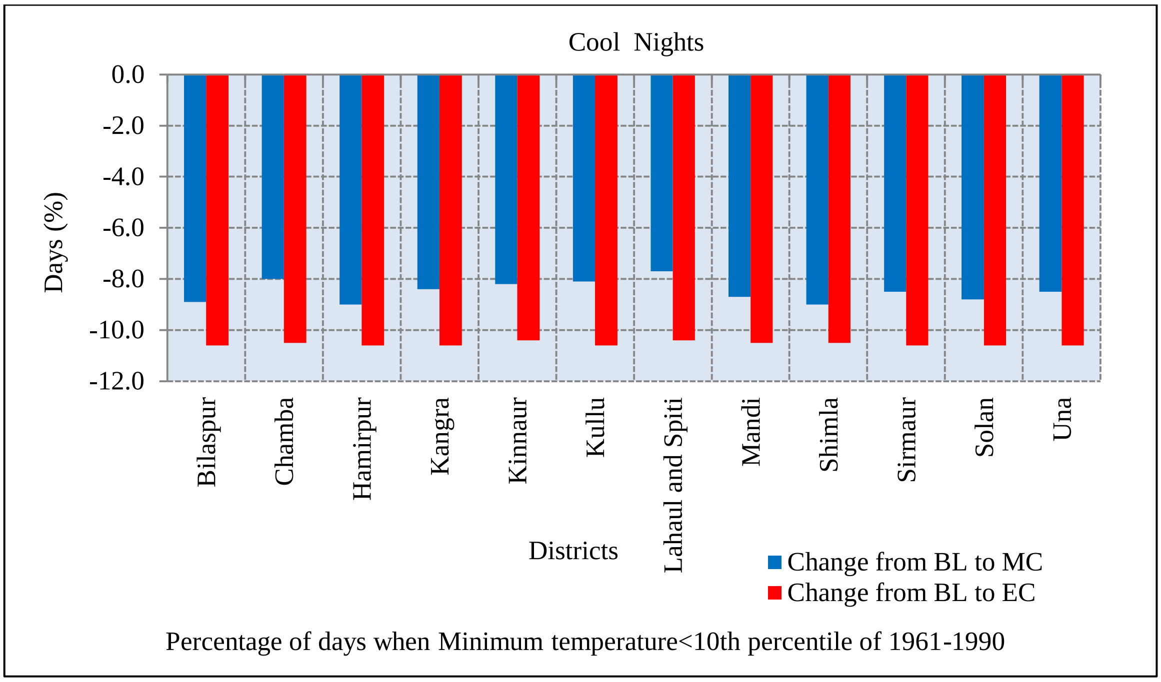
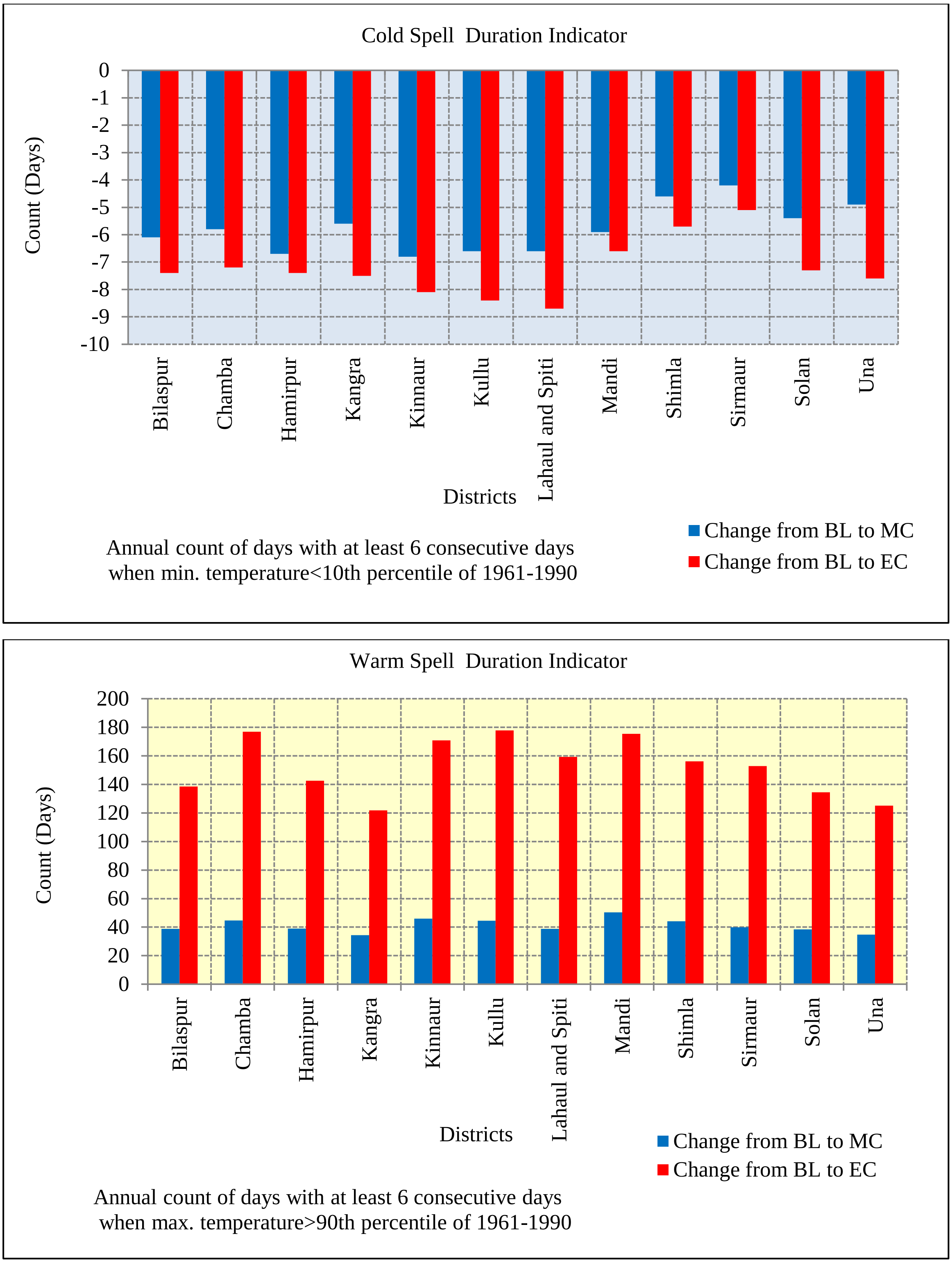


Figure 26 shows the characteristic of cool days and cool nights for Himachal Pradesh districts. From the figure it can be seen that percentage of cool days and cool nights is projected to decrease for all the districts in MC and EC compared to the BL implying warming up.EC decrease is more than that of MC implies that EC would be warmer than MC. Towards the end century percentage decrease in cool days is more particularly for Kullu and Mandi districts compared to the other districtsof Himachal Pradesh thus they are expected to be the warmest compared to the baseline. It can be inferred that minimum of maximum and minimum of minimum temperatures is consistently increasing, indicating significant warming up over Himachal Pradesh districts.

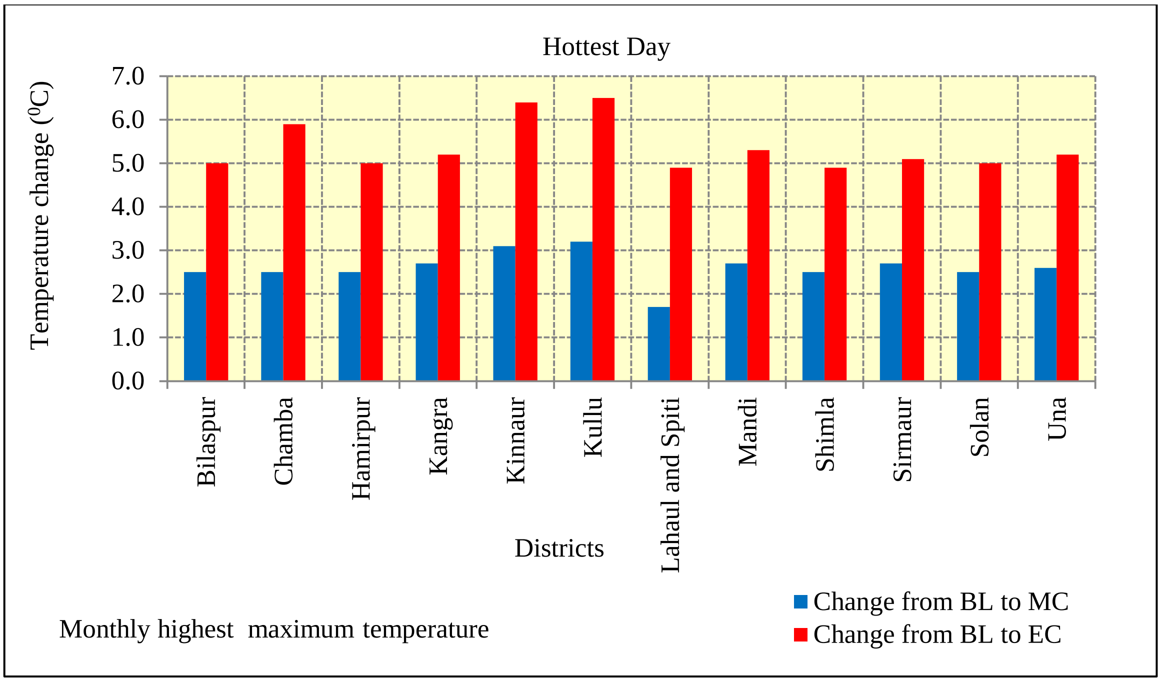
Figure 27 : Characteristics of Cold and Warm Spell duration

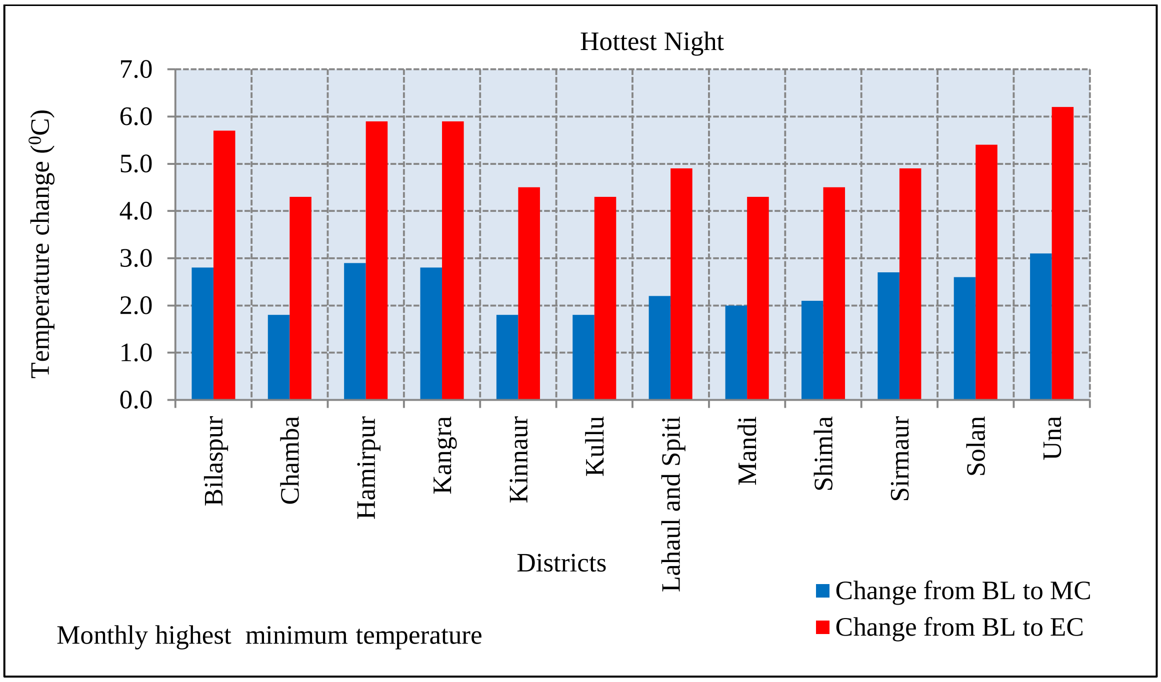


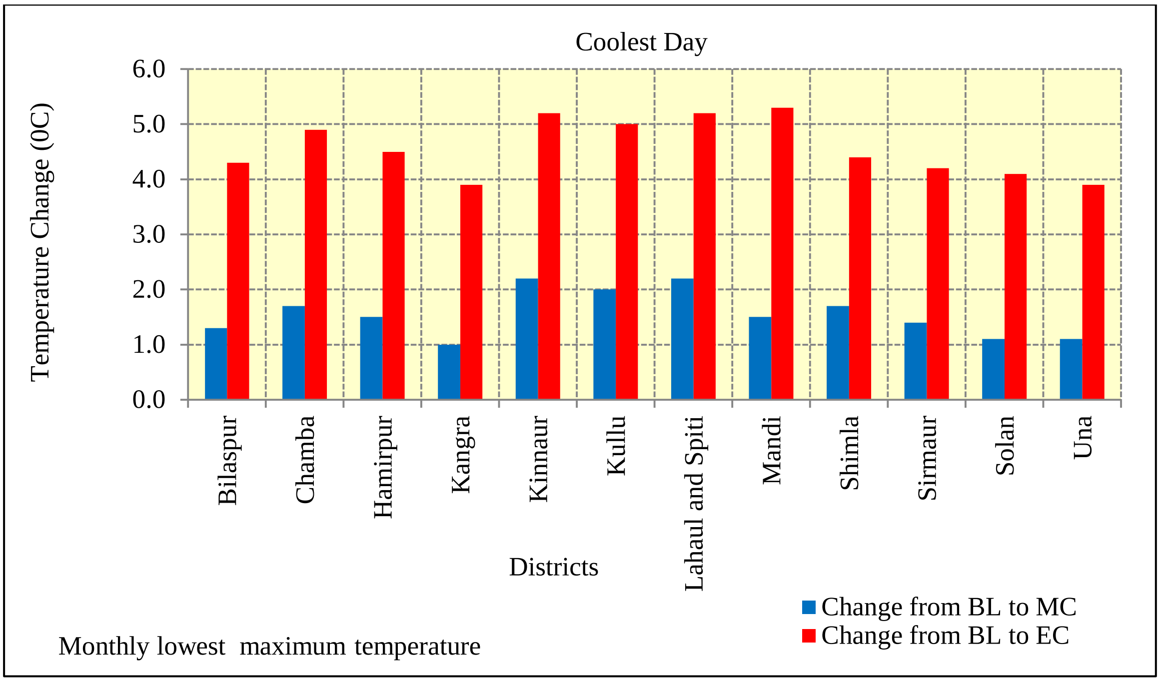
Source: INRM analysis

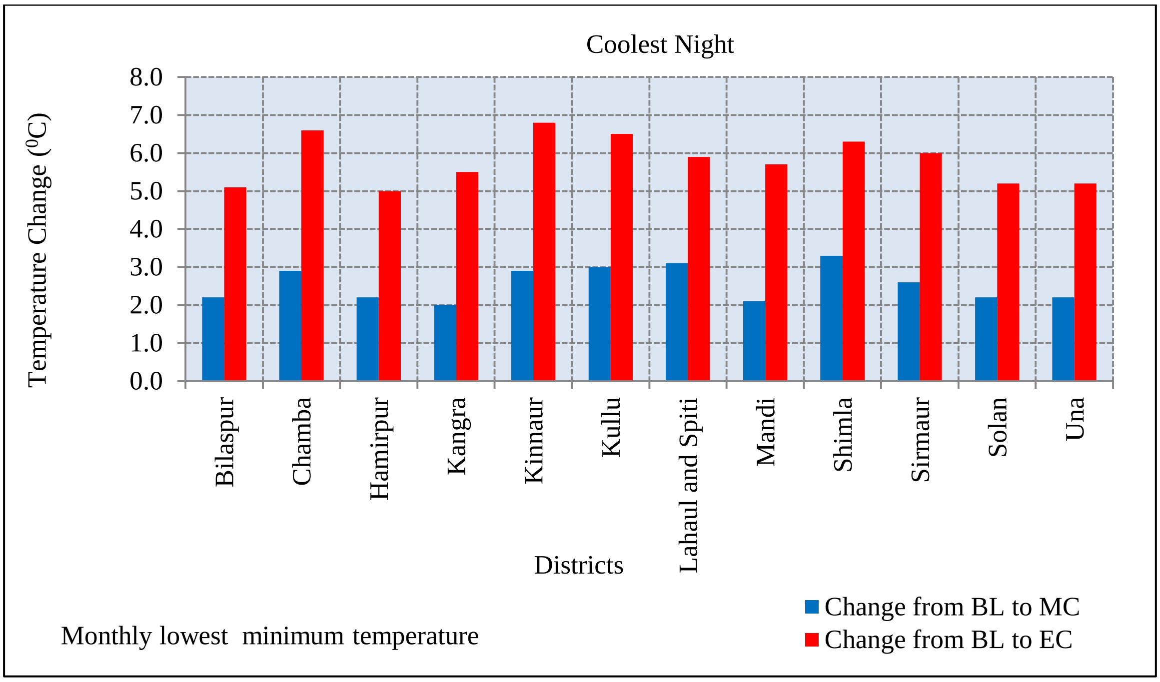
Figure 27 shows the characteristic of warm spell and cold spell duration indicator. From the figure it can be seen that cold spell duration indicator is projected to decrease and warm spell duration indicator is projected to increase for all the districts in MC and EC compared to the BL implying warming up over Himachal Pradesh districts. Towards the end century Kullu, Chamba, Mandi and Kinnaur are expected to have the highest change in warm spell duration while Una and Kangra the least compared to the baseline.

Figure 28 : Characteristics of Hottest day and Hottest night, Coolest day and Coolest night





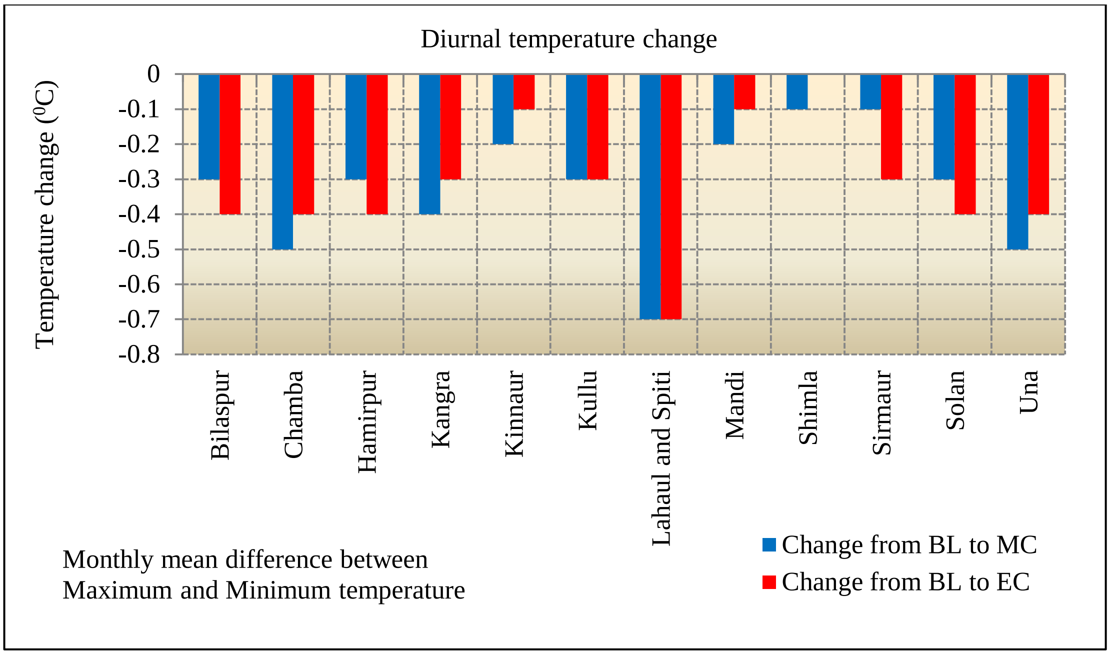




Source: INRM analysis

Figure 28 shows the characteristic of hottest day and hottest night, coolest day and coolest night. From the figure monthly highest maximum and minimum temperature andmonthly lowest maximum and minimum temperature is projected to increase for all the districts in MC and EC compared to the BL implying warming up. Kullu and Kinnaur of Himachal Pradesh district are expected to have the highest maximum temperature increase in EC compared to the baseline and also nights will not be cool as can be seen from the figures. Lahul and Spiti is expected to have least monthly highest maximum temperature increase compared to the baseline.

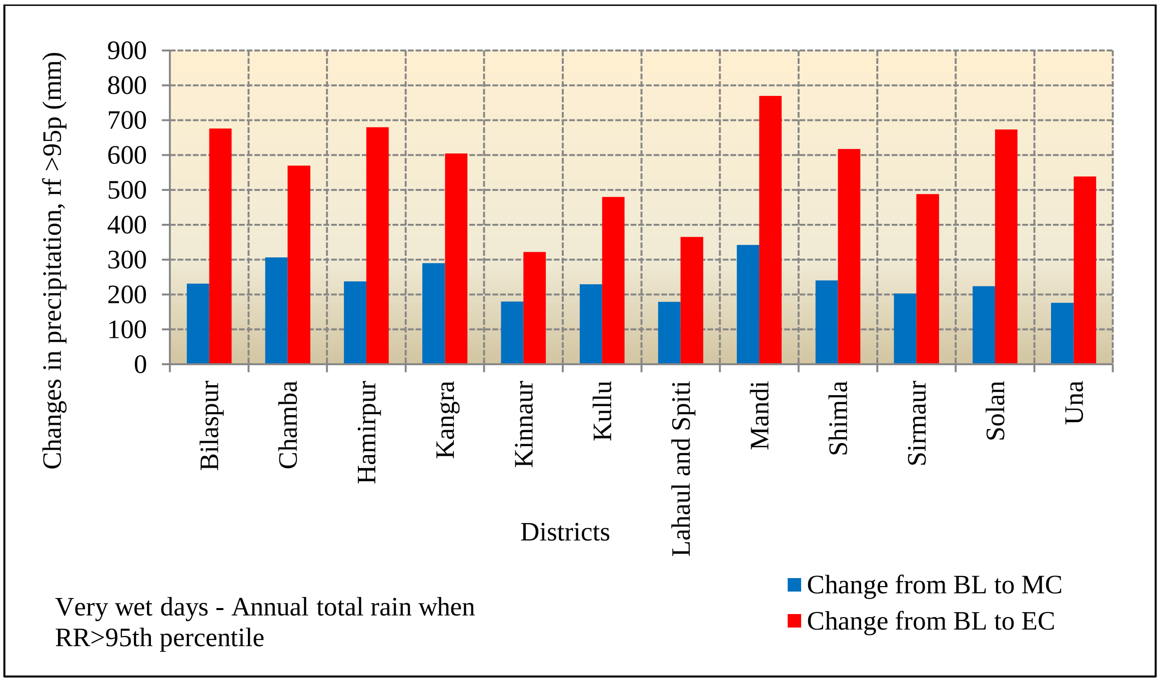
Figure 29 : Characteristics of Diurnal temperature range

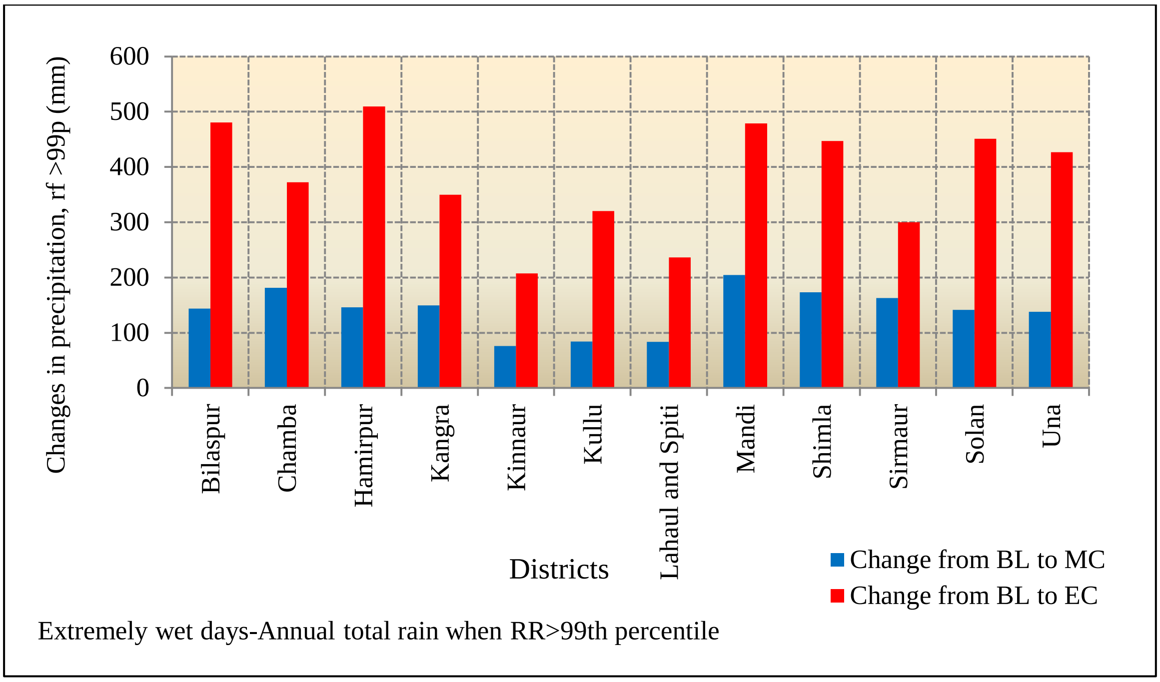


Source: INRM analysis

Figure 29 shows the characteristic of monthly difference between maximum and minimum temperature for Himachal Pradesh districts. From the figure it can be seen that diurnal temperature change is projected to decrease for all the districts in MC and EC compared to the BL implying warming up. Decrease is the maximum for Lahul and Spiti compared to the baseline. Kinnaur and Mandi decrease is the least.

Figure 30 : Characteristics of Precipitation Extremes –Very wet day and Extremely wet day precipitation

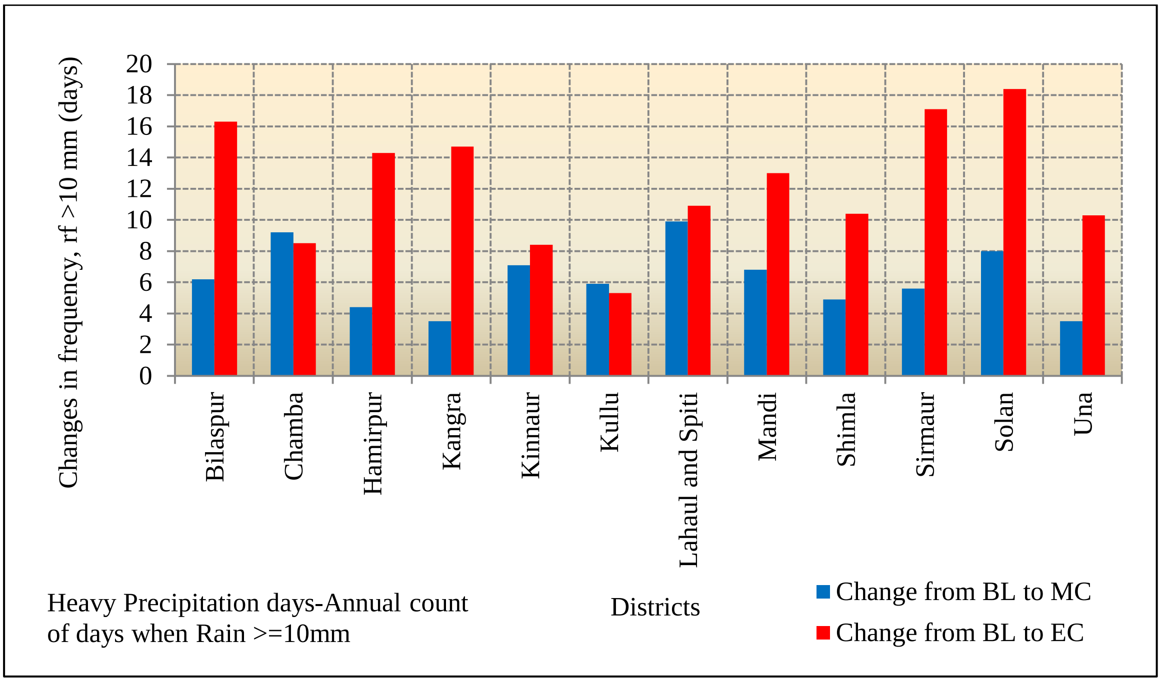


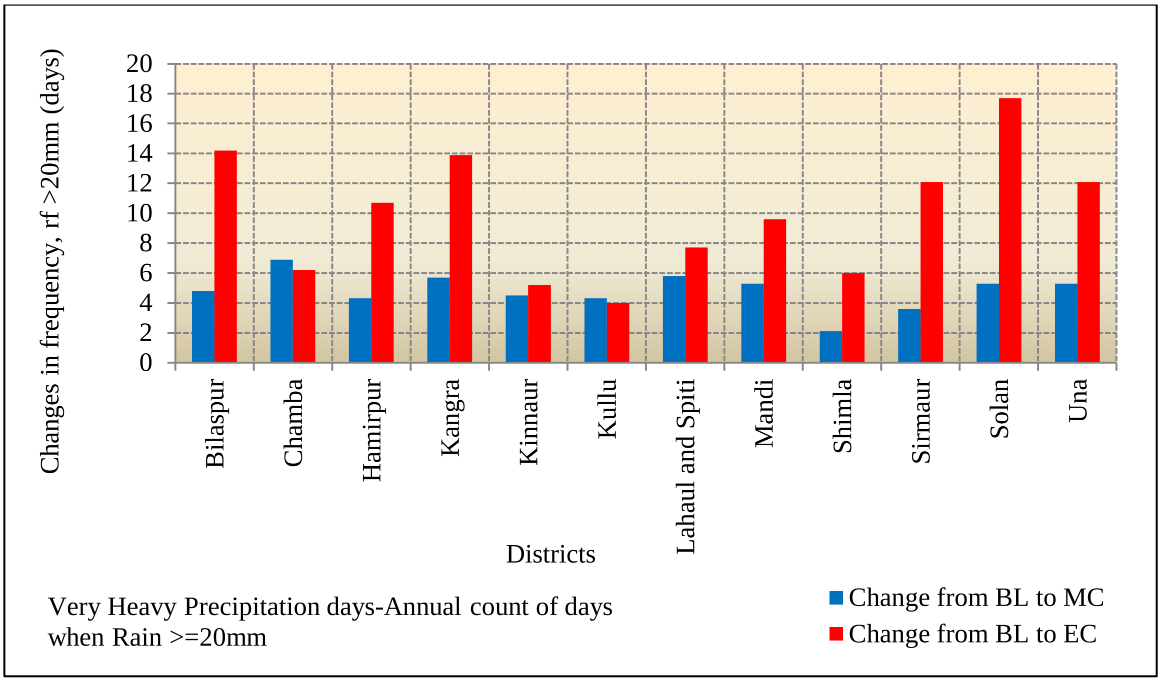


Source: INRM analysis

Figure 30 shows the characteristic of precipitation extremes. From the figure it can be seen that very wet and extremely wet day precipitation is projected to increase for all the districts in MC and EC compared to the BL implying that rainfall and its intensity would increase in the future. But increase in wet days is the maximum for Mandi, Hamirpur and Bilaspurof Himachal Pradesh district compared to the baseline as can be seen from the figures.

Figure 31 : Characteristics of Precipitation Days–Heavy precipitation and very heavy precipitation days

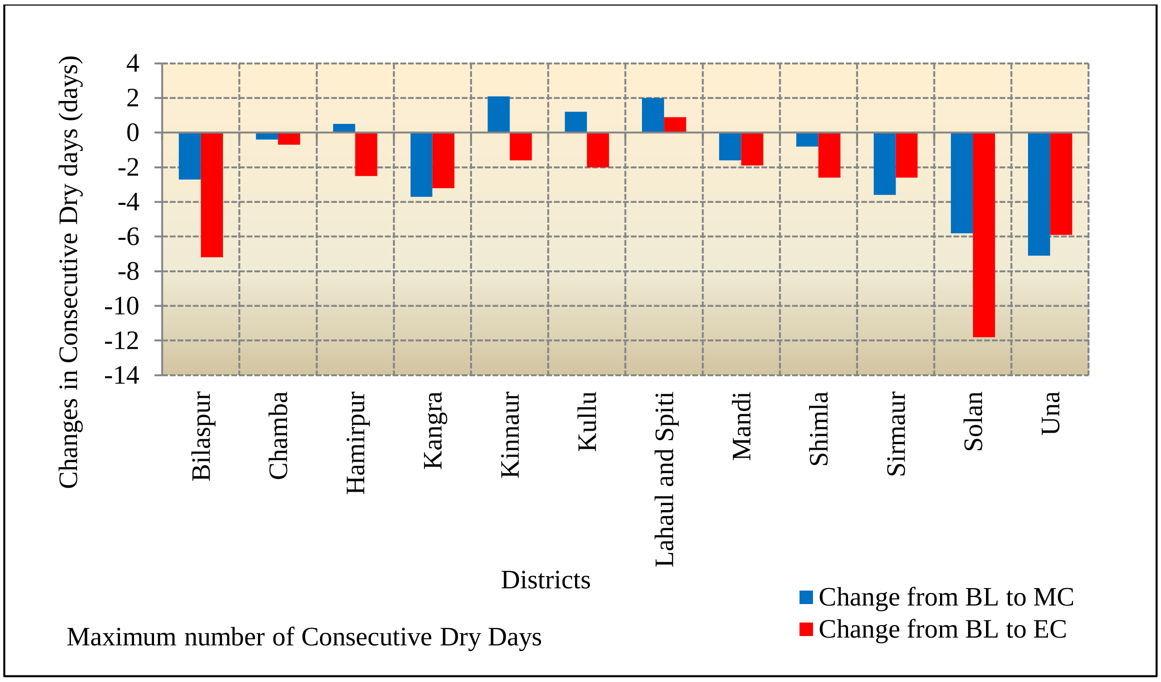


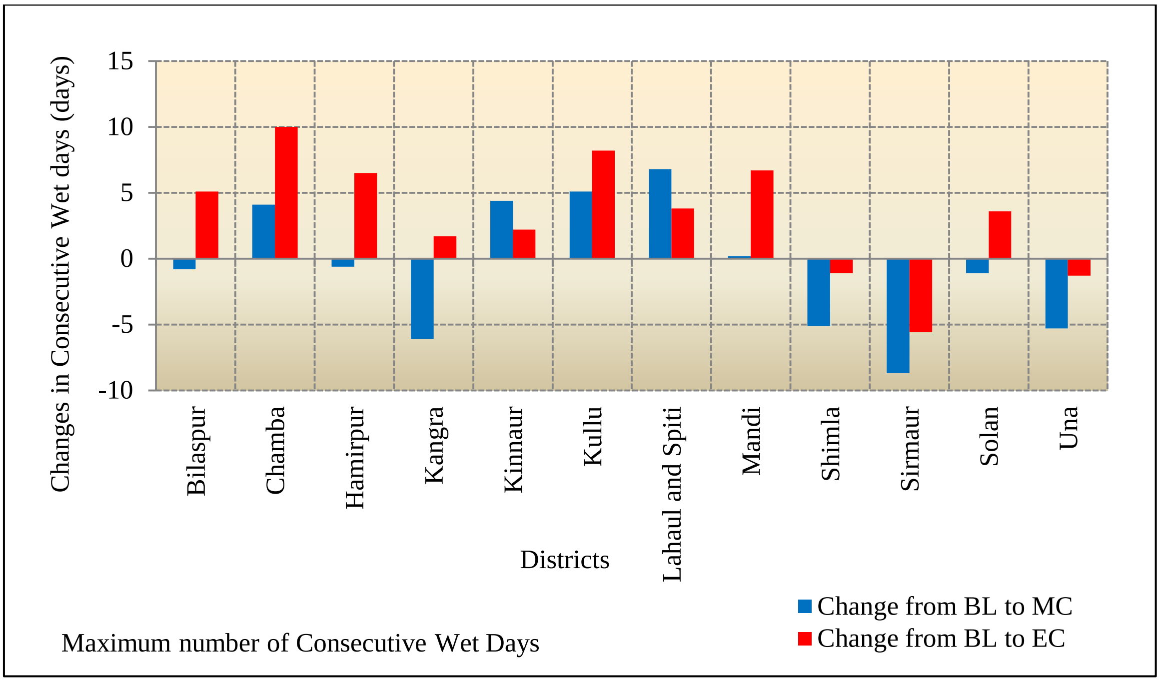


Source: INRM analysis

Figure 31 shows the characteristic of precipitation days. From the figure it can be seen that heavy and very heavy precipitation day is projected to increase for all the districts in MC and EC compared to the BL implying that count of heavy rainy days would increase in the future. Increase in count of very heavy precipitation days is expected to be the maximum for Salon, Bilaspur and Kangra of Himachal Pradesh districts compared to the baseline as can be seen from the figures.

Figure 32 : Characteristics of Precipitation Extremes - consecutive Dry and Wet days

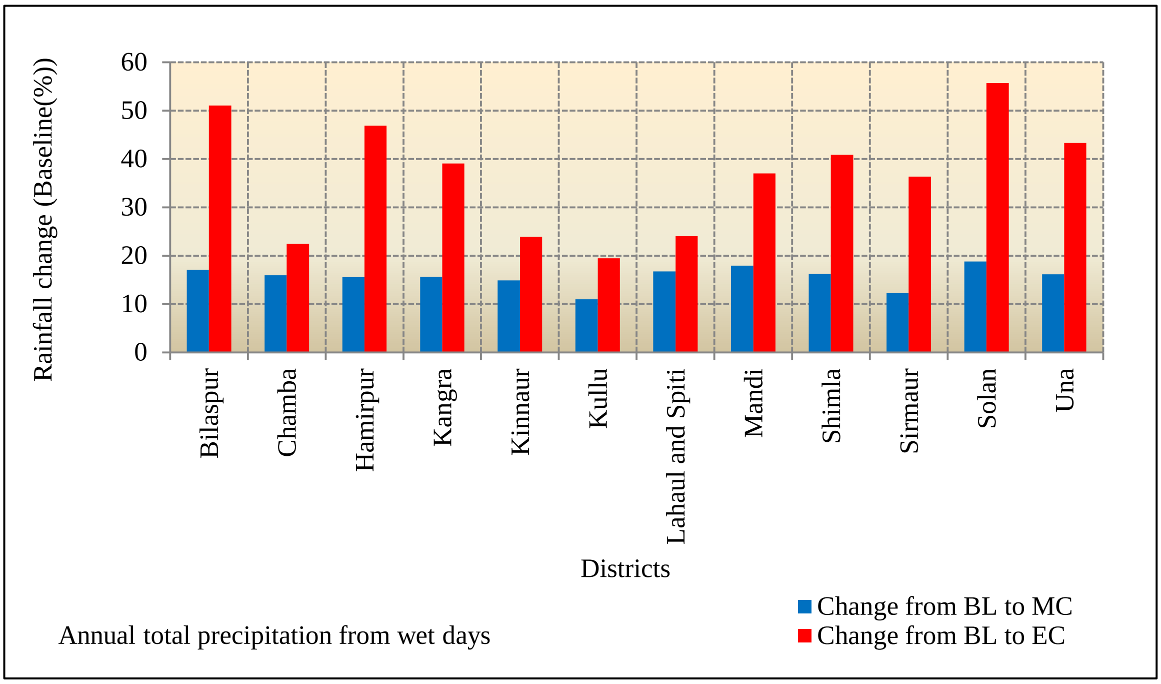


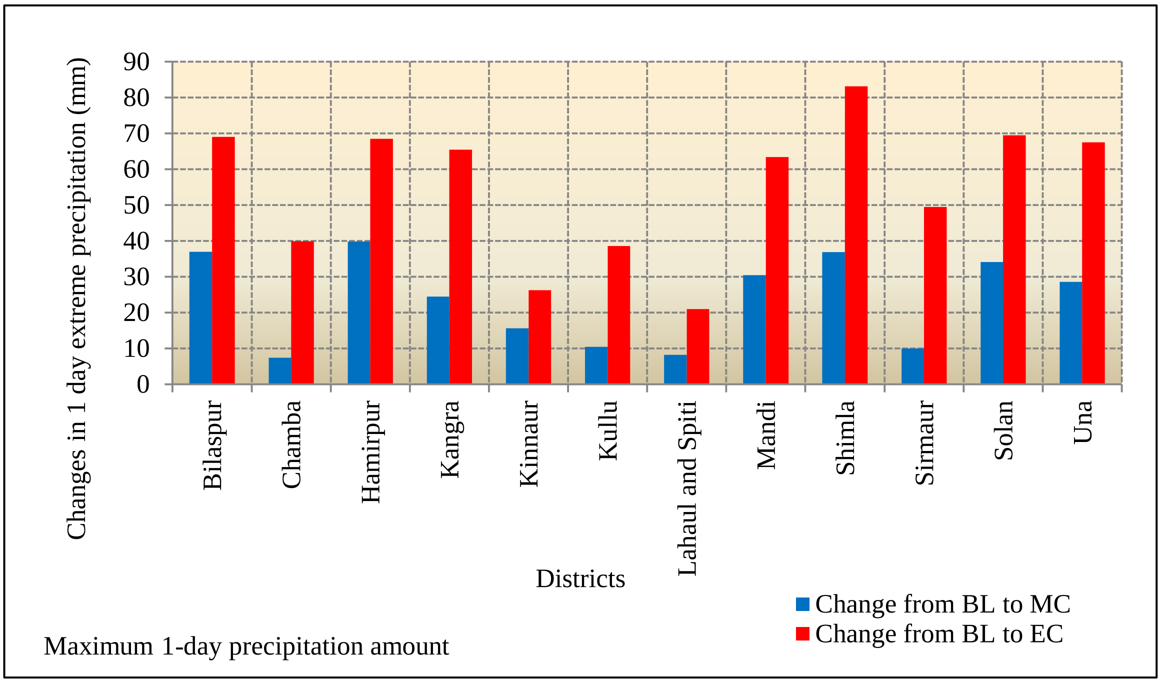


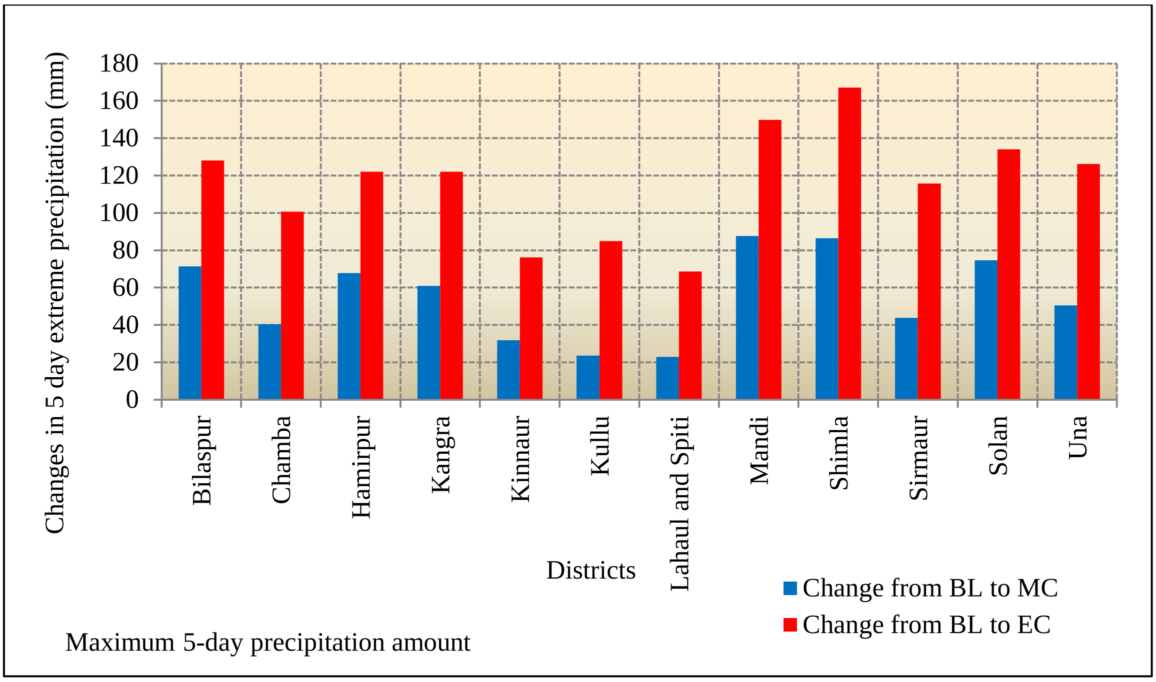
Source: INRM analysis

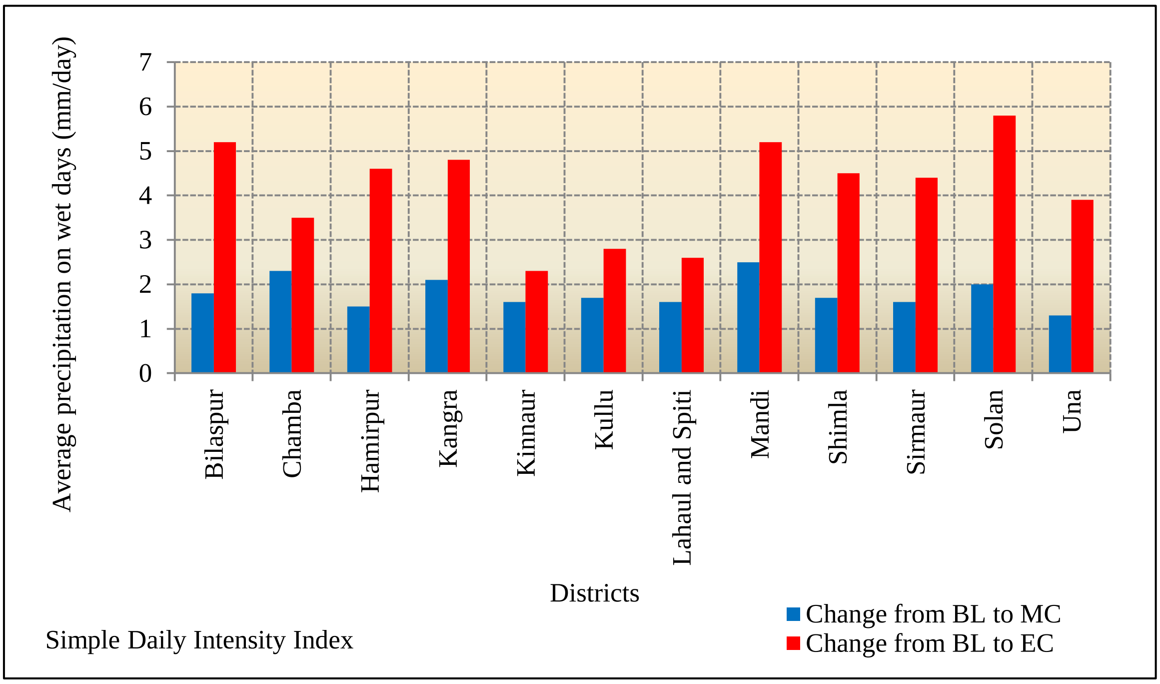
Figure 32 shows the characteristic of Consecutive Dry and Wet days. From the figure it can be seen maximum number of consecutive dry days is declining in MC and EC compared to the baseline except for KInnaur, Kullu and Lahaul and Spiti, whereas maximum number of consecutive wet days is increasing for Bilaspur, Chamba, Kinnaur, Kullu, Lahul and Spitietc while declining for Shimal, Sirmaur, Una, etc compared to the baseline.

Figure 33 : Characteristics of Annual Precipitation, Maximum 1 day and Maximum 5 day precipitation and Simple Daily Intensity Index









Source: INRM analysis

Figure 33 shows the characteristic of annual Precipitation, Maximum 1 day and Maximum 5 day precipitation and average precipitation on wet days. From the figure they are projected to increase for all the districts in MC and EC compared to the BL implying that rainfall and its intensity would increase in the future. Towards end century increase in precipitation is projected to be the maximum for districts namely Salon, Bilaspur and Hamirpur compared to the baseline. 1 and 5 day extreme precipitation increase is projected to be the maximum for Shimla towards end century as can be seen from the figures.

Climate extremes shows that minimum of maximum and minimum of minimum temperatures is consistently increasing in MC and EC compared to the BL, indicating significant warming up increasing over the Himachal Pradesh districts. Very wet and extremely wet day precipitation is projected to increase for all the districts in MC and EC compared to the BL implying that rainfall and its intensity would increase in the future.

1.15 Conclusions

1.15.1 Observed Temperature and Precipitation

Summary of the long term trends in observed seasonal precipitation and temperature over Himachal Pradesh using IMD gridded rainfall and temperature at daily time scales is:

Rainfall:

- Annual average rainfall for Himachal Pradesh from 1971-2005 (35 years) is1294.3 mm. The mean south-west monsoon (June, July, August and September) rainfall (802 mm) contributes 62% of annual rainfall. Contribution of pre-monsoon (March, April and May) rainfall and post-monsoon (October, November and December) rainfall in annual rainfall is 17.8% and 13.6% respectively.
- Annual average rainfall for the state show significant positive trend in period 1971-1990 while insignificant negative trend in 1991-2005.
- Maximum mean observed monsoon rainfall is observed in North Western districts of the state namely, Chamba, Kangra, Sirmaur and Hamirpur districts for both the periods (1971-1990 and 1991-2005). LahulandSpiti receives the least rainfall.

Rainy days:

- Average number of rainy days in Himachal Pradesh during the south west monsoon is about 50 days for the period 1969-2005and varies from 25 days to 69 days.Average number of rainy days in the state during the post monsoon (winter) is about 7 days and varies from 3 days to 9 days
- Average number of rainy days (when daily rain >2.5 mm) in the state during the south west monsoon is about
  - 43 days and varies from 17 days to 71 days for 1971-1990.
  - 45 days and varies from 17 days to 78 days for 1991-2005.
- In monsoon months in period 1991-2005 light to rather heavy rainfall days ($0 < R \leq 64.4$ mm)have increased by 3 days on average compared to 1971-1990 while the extreme and heavy rainfall days show no change.

Temperature:

- Annual average maximum and minimum temperature for Himachal Pradesh from 1969-2005 is 25.2^{0}C and 13.0^{0}C respectively. Seasonal average maximum temperature is higher during monsoon season (30.0^{0}C) and ranges between 28.6^{0}C to 31.6^{0}C. Similarly seasonal average minimum temperature is lowest during winter period (4.4^{0}C) and ranges from 1.9^{0}C to 6.1^{0}C.
- Annual maximum temperature for Himachal Pradesh shows increase of about 0.410C in 1991-2005 while in 1971-1990 it shows no change. In pre monsoon

season, state maximum temperature show decline of about 1.630C in 1971-1990 while increase of about 2.070C in 1991-2005.

- Annual minimum temperature for Himachal Pradesh shows increase of about 0.19^{0}C in 1991-2005 while in 1971-1990 it shows a much higher increase of about 3.6^{0}C. State shows much higher increase of minimum temperature in pre monsoon, monsoon and post monsoon seasons in 1991-2005 in comparison to 1971-1990

1.15.2 Climate Change Temperature and Precipitation

PRECIS simulations for future indicate an all-round warming over Himachal Pradesh associated with increasing greenhouse gas concentrations.

- The mean minimum and maximum air temperature rise by mid-century is projected to be around 2.3°C and 1.9°C respectively. Change for the same towards end century is projected to be around 5.0°C and 4.6°C respectively. Increase in minimum temperature is projected to be marginally higher than the maximum temperature.
- Precipitation is projected to increase by about 15% and 28% towards mid-century and end Century respectively.

1.15.3 Climate Indices

Climate extremes showsthat minimum of maximum and minimum of minimum temperatures is consistently increasingin MC and EC compared to the BL, indicating significant warming up increasing over the Himachal Pradesh districts.Very wet and extremely wet day precipitation is projected to increase for all the districts in MC and EC compared to the BL implying that rainfall and its intensity would increase in the future.

- Percentage of warm days and warm nights is projected to increase while percentage of cool days and cool nights is projected to decrease for all the districts implying warming up.
- Kullu, Kinnaur and Mandi districts of Himachal Pradesh are expected to get the warmest in MC and EC compared to the BL. while for Lahul and Spiti temperature increase is expected to be the least relatively compared to the other districts.
- Increase in precipitation in MC and EC is projected to be the maximum for Salon, Bilaspur, Hamirpur districts of Himachal Pradesh compared to the BL. while increase in extremely wet days (annual total rain when rainfall is greater than 99th percentile of baseline) is projected to be the maximum for Mandi, Hamirpur and Bilaspur districts.
- Increase in count of very heavy precipitation days is expected to be the maximum for Salon, Bilaspur and Kangra of Himachal Pradesh districts compared to the baseline
- 1 and 5 day extreme precipitation increase is projected to be the maximum for Shimla towards end century

Chapter 2: Glacial Lake Outburst Floods (GLOF)

2.1 Historical Flood and Flood Vulnerability Status in Himachal Pradesh

The Himalayan state of Himachal Pradesh is prone to different kinds of disasters/hazards like floods, earthquake, landslides, snow avalanches, cloudbursts and forest fires etc. Of all the natural disasters that hit the state and cause damage to both life and property, floods are most widespread in the state. However the floods occurring in the state are often in the form of flash-flood and they are interrelated to cloudbursts and landslides. Flood is a temporary inundation of large area/ regions as a result of an increase in reservoir or of rivers flooding their banks because of heavy rains or snow melting or dam bursts[14].

The occurrence of water related natural disasters especially floods and flash floods are common in most of the hilly state including Himachal Pradesh. A flood can be defined as an excess flowing or overflowing of water, especially over land which is not normally submerged. The flow is markedly higher than the usual and this also cause inundation of lowland. The flood can be of various origins, but in a hilly area like Himachal they are the result of some typical reasons. They include cloudburst in the catchment's region, intense and prolonged rainfall, the downstream blocking of river channels by landslides or avalanches or the sudden breach or burst of artificial /natural lakes. In Himachal, the riverine flooding is mostly associated with the rivers having snow fed origin because in summer the snowmelt coupled with heavy rain often triggers a flood. The river Sutlej and river Beas, which are being flooded almost every year, are of this type. Another form of flooding in this hilly state is flash flooding which is principally associated with hydro logically small regions. The duration of this phenomenon is short but can cause extensive damage.

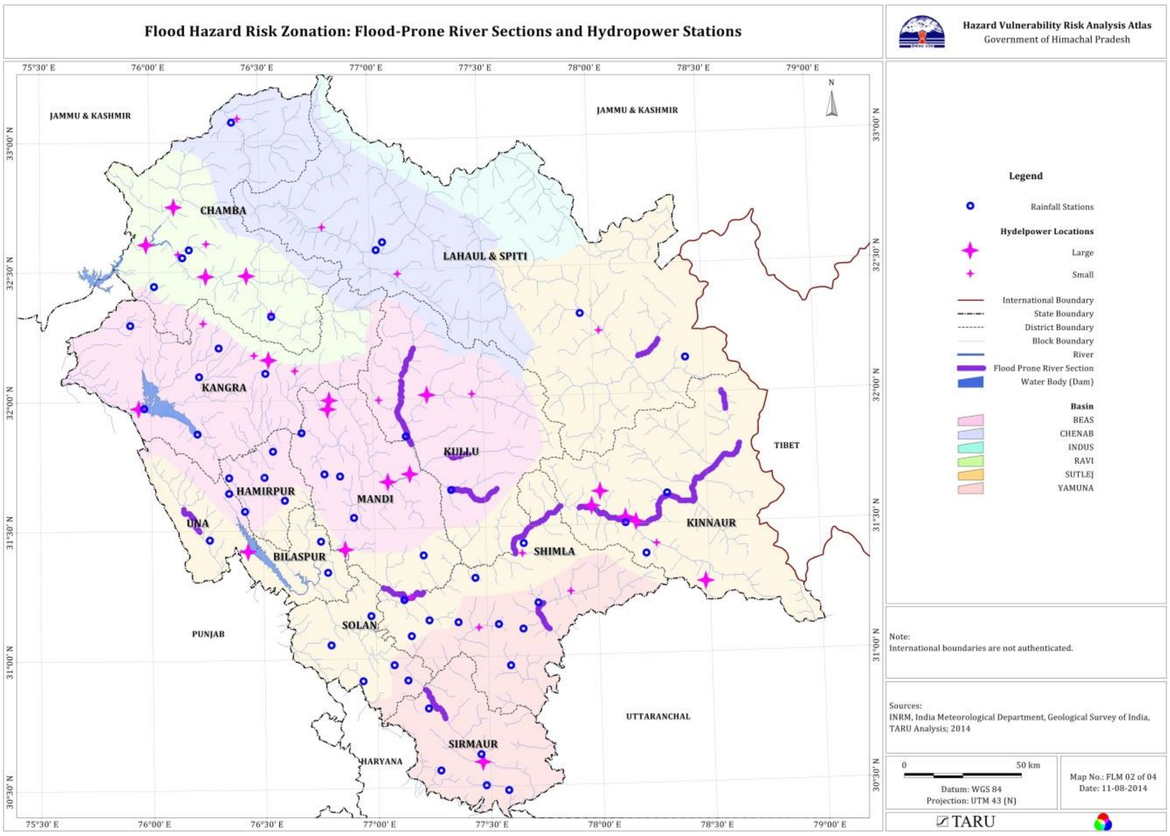
The state of Himachal Pradesh has experienced a large number of incidences of floods since its inception in 1971. Though the state has also faced severe flood disasters in 1975 and 1988 but the last decade (1997-2005) has proved one of the worst decades as both the magnitude and frequency of floods have gone up. There were several incidences of floods / flash floods during and after 1997-2005 and of which about few were really gigantic. These disastrous events have brought heavy toll to the state as the loss was estimated in several thousand millions of rupees and also killed several hundreds of people besides large number of cattle heads. The major causes for floods and flash-floods in Himachal Pradesh include:

- Cloudburst in the catchment's region of the river.
- Heavy rainfall in the upper reaches of the river.
- Sudden breach or bursts of man-made dams or natural lakes.
- Landslides leading to obstruction of flow and change in the river course.
- Tectonic movement leading to slope failure and landslides (e.g. earthquake, Jan.1975).

[14]nidm.gov.in/idmc/Proceedings/Flood/B2-%206.pdf

The problem of flood varies from one basin to another and the magnitude of flood also varies. The most flood prone area in the state are in the Sutlej and Beas rivers (Figure 34). Chenab is more prone to glacier melt and outbursts.

Figure 34 : Flood Prone River Stretches in Himachal Pradesh



Source: TARU Analysis, 2014

High monsoon rains in the area of the Shivalik and lower and mid Himalayan ranges cause extensive floods during rainy seasons. In the upper reaches of the Beas and Satuj valley the main problems are flash floods and bank erosion because of the steep slopes of rivers and high stream flows due to heavy rains. Often the flash caused due to cloudbursts, glacial lake outbursts and temporary blockade of the river channels have been also observed. As a result of breaches in embankments and damage to various utilities such as irrigation/flood control schemes and houses are also observed. According to government of Himachal Pradesh, the rivers prone to flood causing damage are[15]:

- River Sutlej and its tributaries like Spiti, Sanglekhad, Ali khad, Gambharkhad, Sir Khad, and Swan River
- River Beas and tributaries like Uhl and Suketikhads.
- River Ravi and its tributaries like Siul
- River Yamuna and its tributaries like Pabbar, Giri and Bata.

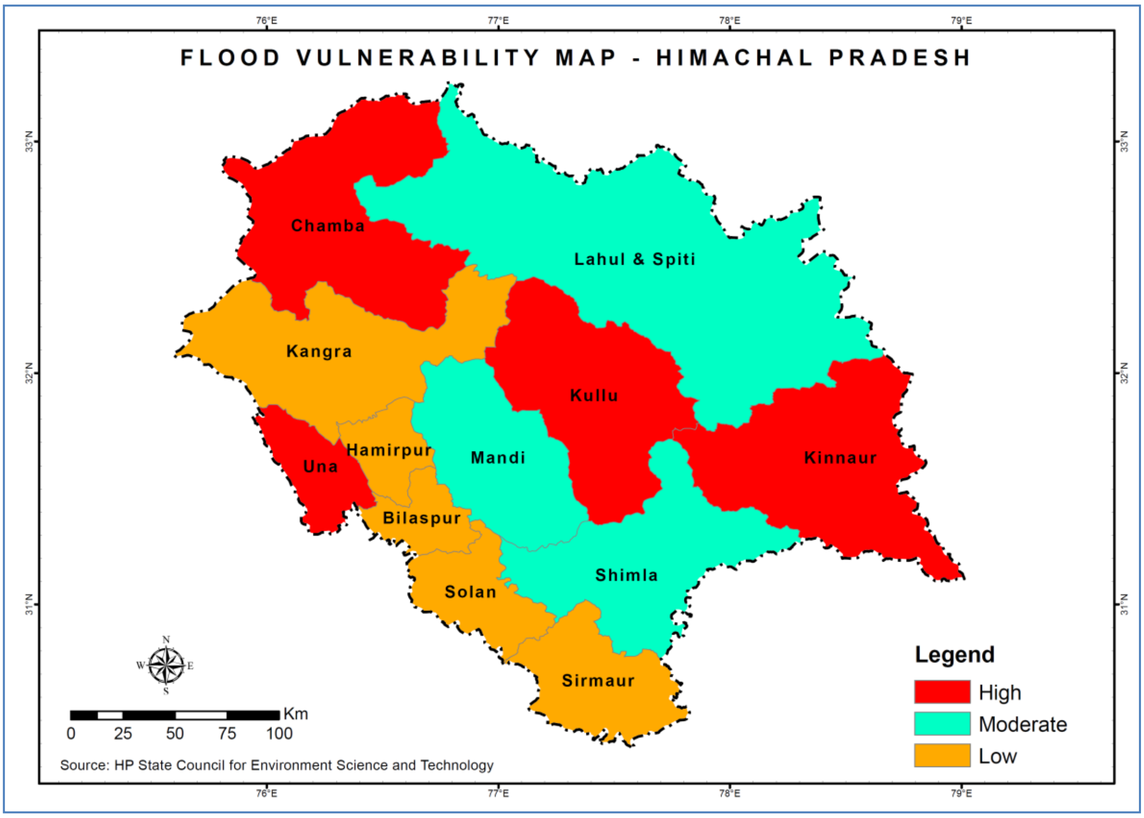
The flood hazard vulnerability map published by HP State Council of Science and Technology[16] (Figure 35) indicates that the areas falling in the districts of Chamba, Kullu ,Una and Kinnaur falls in high vulnerable zone, Lahaul and Spiti, Mandi, Shimla fall in

[15]http://www.hpsdma.nic.in/ProfileOfState/Flood.html

[16]http://hpsdma.nic.in/TNA%20Light.pdf

moderate flood vulnerable zone and Kangra, Hamirpur, Bilaspur, Solan and Sirmour fall in low flood vulnerability zone.

Figure 35 : Flood Vulnerability Map of Himachal Pradesh



2.2 Glacial Lake Outburst Floods - GLOFs

The glaciers are the frozen water reserves in the high altitude and are one of the most important natural resources in the Himachal Pradesh region. Melt water released by the glaciers as well serves as the perennial source for most of the Himalayan river systems. The streams originating from these glaciers are also the source of energy for hydroelectric power plants, which in turn irrigates agricultural lands in the command area especially during the summer period when it is most needed, and also provide water for various other uses.

Natural dams of different size and origin do exist in mountain areas all over the world (Costa and Schuster, 1988[17]). They often retain lakes which, in the case of a dam failure, may drain as powerful floods. If the out bursting lake is located within the glacial or periglacial area, such events are called Glacial Lake Outburst Floods (GLOFs).Richardson and Reynolds[18] (2000) provide an overview of failure mechanisms and case studies. GLOFs often have a highly destructive potential because a large amount of water is released within a short time, with a high capacity to erode loose debris, potentially leading to a powerful flow with a long travel distance. Peak discharges are often some magnitudes

[17]Costa J.E. & Schuster R.l.(1988) - The formation and failure of natural dams.Geol. Soc. Am. Bull.,7: 1054-1068.

[18][2] Richardson S.D. & Reynolds J.M. (2000) - An overview of glacial hazards in the Himalayas. Quatern. Int., 65/66: 31-47

higher than in the case of "normal" floods (Cenderella and Wohl[19], 2001). The source area is usually far away from the area of impact and events occur at very long time intervals or as singularities, so that the population at risk is often not prepared for such events (Schneider et al, 2004[20]). Deficiencies in risk communication are often responsible that events evolve into disasters (Carey, 2005[21]). A number of significant GLOFs resulting in fatalities and severe damage have occurred during the previous decades, particularly in the Himalayas.

The Himachal Pradesh region holds 2554 glaciers with the glacier area of 4160 sq km and 229 lakes including 22 potential GLOF[22].

2.3 Data used

- ASTER[23] digital elevation model of horizontal resolution of the 30 m
- Maximum Glacier volume[24]
- One day discharge for Glacier Lake Outburst routed as flow of single day is spread over complete 24 hrs to release lake complete volume.

2.4 Limitations

- In the absence of high resolution DEM, public domain DEM ASTER has been used, river cross sections derived from ASTER DEM
- Dam break analysis of all eleven lakes has been considered independently, one lake outburst at a time.
- Assumption on Glacier outburst time and outburst sequence, , timing and extent and shape of outburst

[19]Cenderelli DA, Wohl EE. 2001. Peak discharge estimates of glacial lake outburst floods and "normal" climatic floods in Mount Everest region, Nepal. Geomorphology 40:57–90

[20]Schneider, J. F., Gmeindl, M., and Traxler, K.: Risk Assessment of Remote Geohazards in Central and Southern Pamir/GBAO, Tajikistan. Report to the Ministry of Emergency, Tajikistan and the Swiss Agency for Development and Cooperation (SDC), 2004

[21]Carey, M.: Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru, Global Planet. Change, 47, 122–124, 2005

[22]Inventory of Glaciers, Glacial Lakes and the Identification of Potential Glacial Lake Outburst Floods (GLOFs) Affected by Global Warming in the Mountains of India, Pakistan and China/Tibet Autonomous Region Final report for APN project 2004-03-CMY-Campbell, 2005 (https://www.apn-gcr.org/resources/archive/files/d71dea72bc764245642e7d047c095463.pdf)

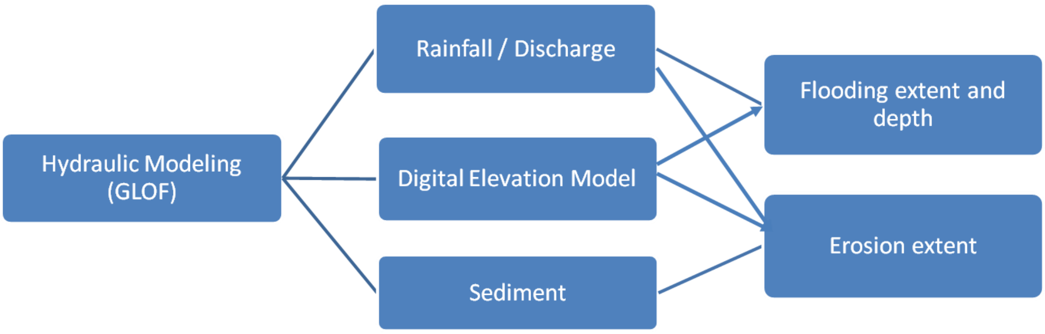
[23] gdem.ersdac.jspacesystems.or.jp/

[24] TARU Field Survey and Analysis

2.5 Methodology

The steps followed to model and analyses impact of GLOF is shown in the flow chart (Figure 36):

Figure 36 : GLOF Modelling Analysis Flowchart

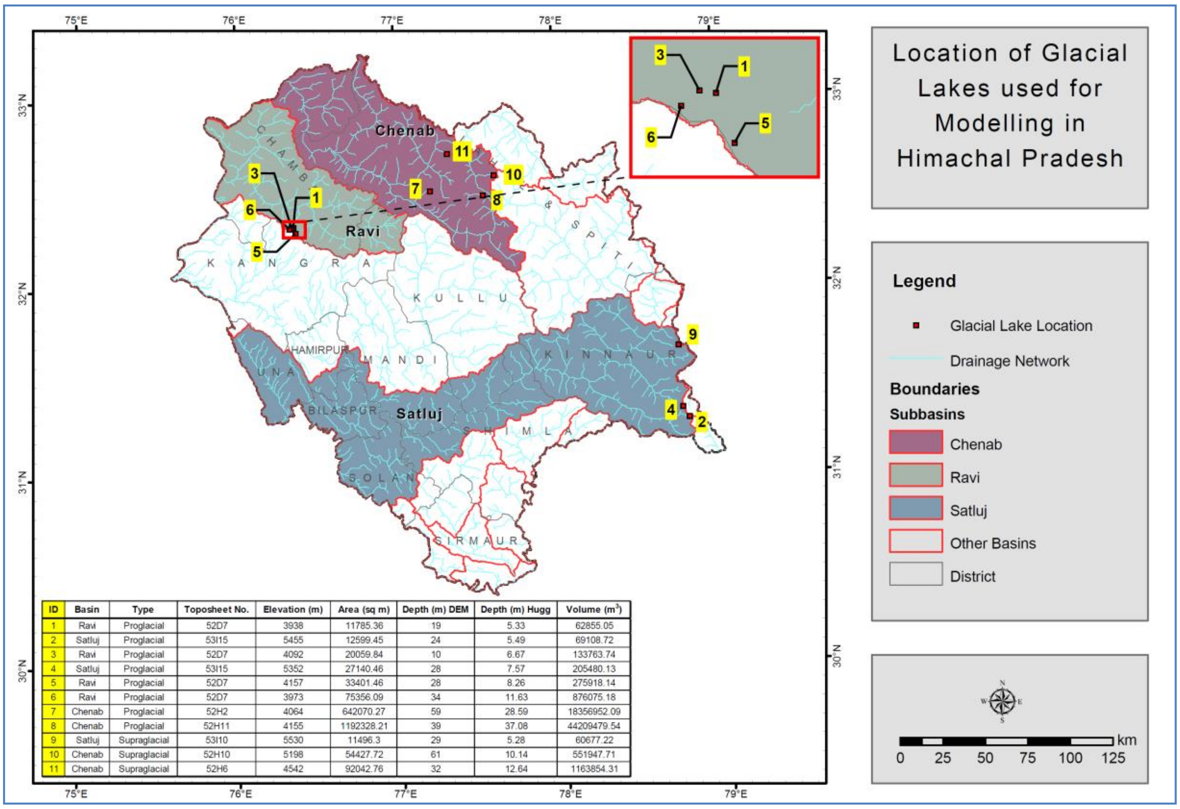


2.6 Modelling GLOF in Himachal Pradesh

The GLOF hazard assessments need to take into account possible interaction of processes or chain reactions as the implications can be complicated and far reaching. One of the many chain reactions that could take place in the Himalayas is that the outburst of a comparably small lake that is situated above another lake or lakes causes a flood and exceptionally large inflow into the other lake or series of lakes, which subsequently burst out. The total discharge of such a chain could be much larger than anticipated from analysing individual lakes only. The triggering lake could even be an erosion lake, considered secure, but squeezed out by an avalanche. This is one of the reasons why smaller lakes can actually pose a large hazard.

A total of 11 lakes within Himachal Pradesh (4 lakes in Ravi basin, 4 lakes in Chenab basin and 3 lakes in Sutlej basin) were identified for the study. Impact of individual glacial lake outburst was considered. Figure 37 shows the location of glacial lakes considered for the modelling.

Figure 37 : Location of Glacial Lakes considered for modeling in Himachal Pradesh



ID	Basin	Type	Toposheet No.	Elevation (m)	Area (sq m)	Depth (m) DEM	Depth (m) Hugg	Volume (m³)
1	Ravi	Proglacial	52D7	3938	11785.36	19	5.33	62855.05
2	Satluj	Proglacial	53I15	5455	12599.45	24	5.49	69108.72
3	Ravi	Proglacial	52D7	4092	20059.84	10	6.67	133763.74
4	Satluj	Proglacial	53I15	5352	27140.46	28	7.57	205480.13
5	Ravi	Proglacial	52D7	4157	33401.46	28	8.26	275918.14
6	Ravi	Proglacial	52D7	3973	75356.09	34	11.63	876075.18
7	Chenab	Proglacial	52H2	4064	642070.27	59	28.59	18356952.09
8	Chenab	Proglacial	52H11	4155	1192328.21	39	37.08	44209479.54
9	Satluj	Supraglacial	53I10	5530	11496.3	29	5.28	60677.22
10	Chenab	Supraglacial	52H10	5198	54427.72	61	10.14	551947.71
11	Chenab	Supraglacial	52H6	4542	92042.76	32	12.64	1163854.31

Source: INRM analysis

2.7 GLOF Modelling using CAESAR

CAESAR-Lisflood[25] (Caesar Lisflood Landscape Evolution and Flow Model) model developed at University of Hull, UK was used for Glacial Lake Outburst for all eleven (11) lakes. Caesar Lisflood is a geomorphological / Landscape evolution model that combines the Lisflood-FP 2d hydrodynamic flow model (Bates et al, 2010) with the CAESAR geomorphic model to simulate erosion and deposition in river catchments and reaches over time scales from hours to 1000's of years.

Landscape evolution models (LEMs) simulate the geomorphic development of river basins over long time periods and large space scales (100s–1000s of years, 100s of km2). The LISFLOOD-FP simplified 2D flow model addresses this issue of shorter term hydrodynamic effects (e.g. the passage of a flood wave). The LEM CAESAR and the hydrodynamic model LISFLOOD-FP were merged to create the new CAESAR-List flood model, and it is tested through a series of preliminary tests showing that using a hydrodynamic model to route flow in an LEM affords many advantages. The new model is fast, computationally efficient and has a stronger physical basis. It allows hydrodynamic effects (tidal flows, lake filling, alluvial fans blocking valley floor) to be represented in an LEM.

Susceptible 11 glacial lakes falling in Ravi, Chenab and Sutlej basin in Himachal Pradesh were identified using expert knowledge, surveys and literatures. The surface of the relevant lakes was computed and the lake volumes were estimated. The peak discharges of

[25]http://www.coulthard.org.uk/CAESAR.html

potential outburst events were estimated. Scenarios of outburst Hydrographs were then created based on the estimated peak discharge and the lake volume. Mapping of the characteristics of the flow path and the area inundation was conducted.

2.7.1 Analysis

Due to the complex nature of GLOFs and the connected uncertainties, particular care is required when interpreting the model results. In the absence of time series data like rainfall, glacier outburst duration, current discharge in river etc, modelling was carried out assuming minimum flow in the river, with no rainfall and runoff generation in the catchment. The glacier lake outburst event was treated to last in a single day. Single day event was modelled for 3 basins (Chenab, Ravi and Sutlej) consisting of all 11 glacier lakes location provided by client. Maximum volume of lake was considered as outburst volume, discharging to the river in single day. Thereafter receding time and duration was estimated. Simulations showed that the glacier lake outburst flood receding time and duration varies from 1 to 3 days.

Maximum glacier volume was routed in one day assuming the glacier burst scenario and inundation area and depth was modelled using CAESAR 2D flow and sediment transport model. Model simulates morphological changes in river catchments or reaches, on a flood by flood basis, over periods up to several days. Model was represented as a landscape with a mesh of grid cells. For each cell, further values were stored representing hydrological parameters, water discharge, grain size, vegetation levels etc. For every model iteration these parameters were altered according to a set of rules, loosely grouped into 1) hydraulic routing, 2) fluvial erosion and deposition and 3) slope processes.

Figure 38 depicts the inundation caused due to three Glacial Lake Outburst in Sutlej basin.

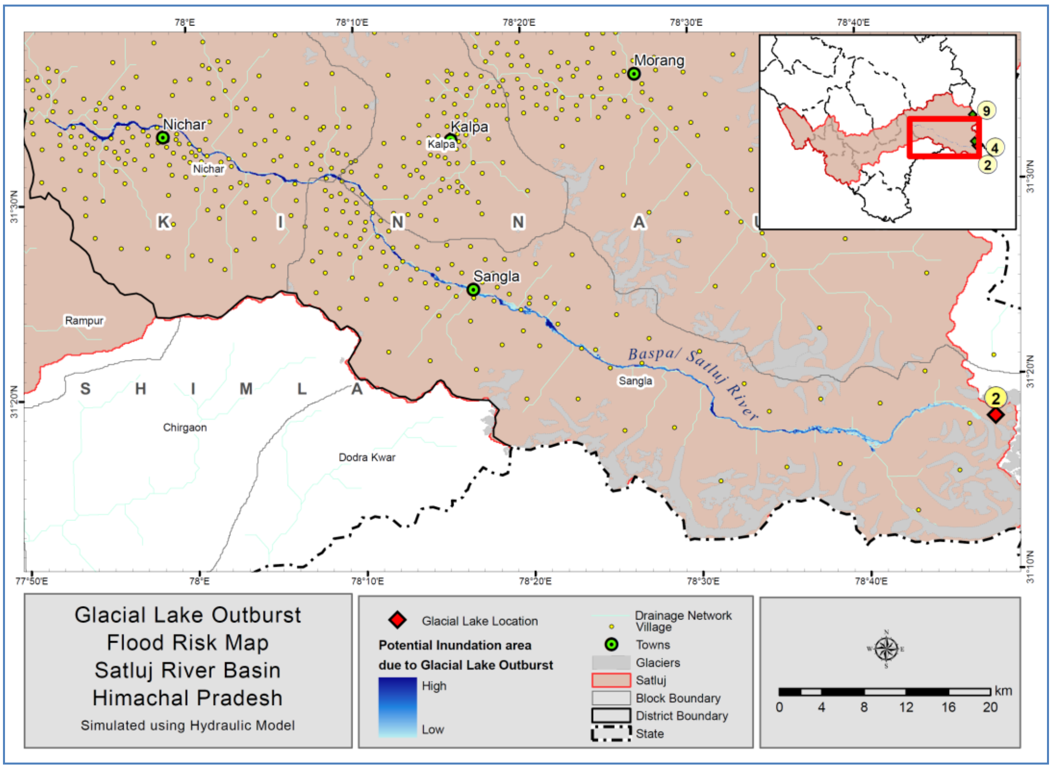
Lake 2 is situated at an elevation 5455 m amsl with an area 1.26 ha and volume 0.07 MCM, at the head Stream of Sutlej River. It can be seen that the flooding caused by this lake outburst affects a stretch of 137 km and covers a part of the flood plain of 50 m - 450 m width.

Lake 4 is situated at an elevation 5352 m amsl covering an area of 2.71 ha and volume 0.21 MCM, at the head Stream of Sutlej River. It can be seen that the flooding caused by this lake outburst affects a stretch of 138 km and covers a part of the flood plain of 50 m - 500 m width.

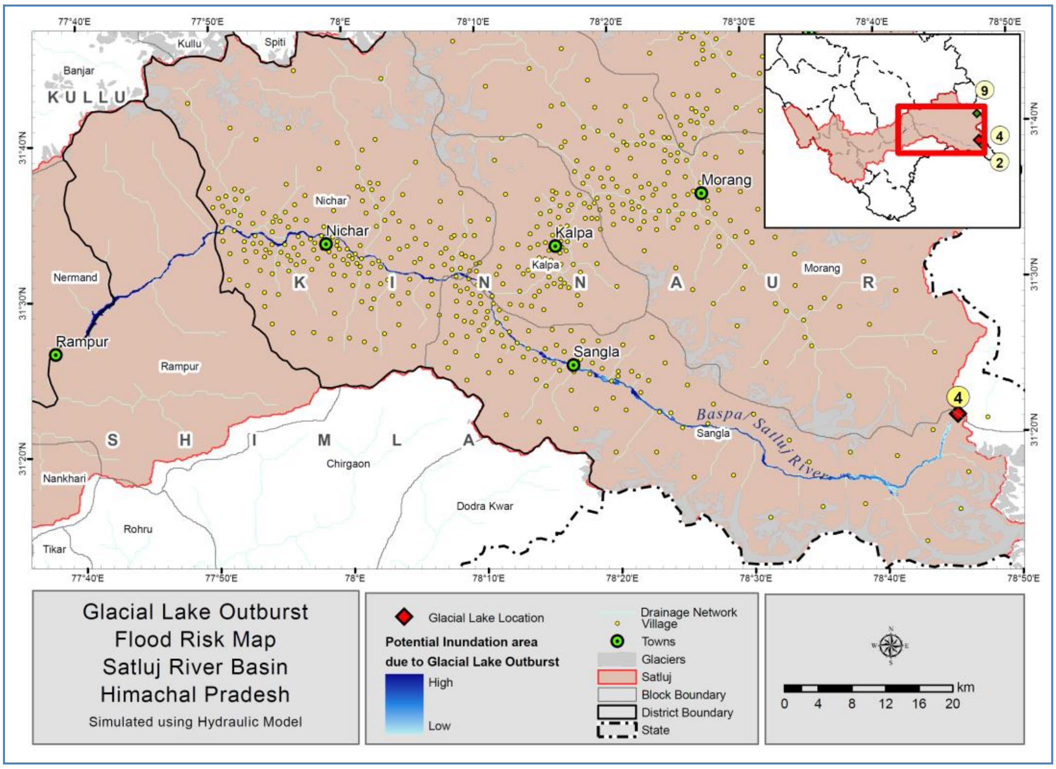
Lake 9 is situated at an elevation 5530 m amsl having area 1.15 ha and volume 0.06 MCM, at the head of Sutlej River. It can be seen that the flooding caused by this lake outburst affects a stretch of 21 km and covers a part of the flood plain of 50m to 200 m width.

Figure 38 : Simulated Inundation caused due to Glacial Lake Outburst Flood in Sutlej basin (Himachal Pradesh)

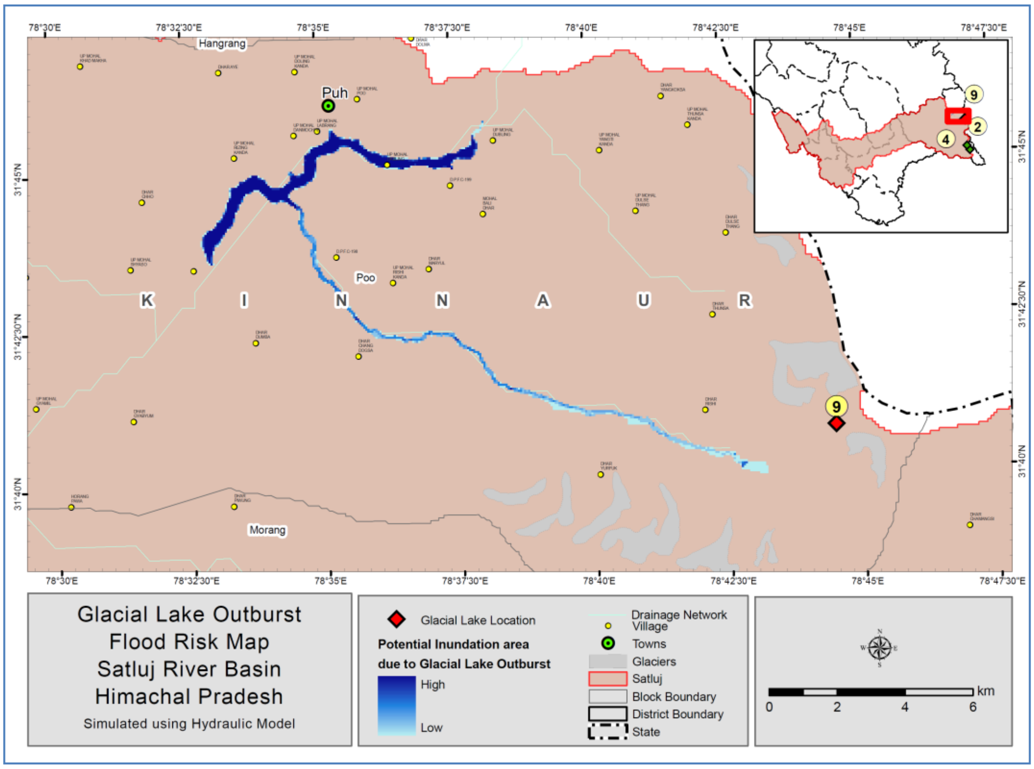
Lake 2 in Sutlej Basin



Lake 4 in Sutlej Basin



Lake 9 in Sutlej Basin



Source: INRM analysis

About 49 number of villages 51 number of villages and about 10 number of villages in Sutlej basin come under potential risk zone due to GLOF of Lake 2, Lake 4 and Lake 9 respectively.

Figure 39 shows the inundation caused due to Glacial Lake Outburst of 4 lakes in Ravi basin.

Lake 1 is situated at an elevation 3938 m amsl having area 1.18 Ha and volume 0.06 MCM, at the head Stream of Ravi River. It can be seen that the flooding caused by this lake outburst affects a stretch of 72 km and covers a part of the flood plain of 50 m to 900 m width.

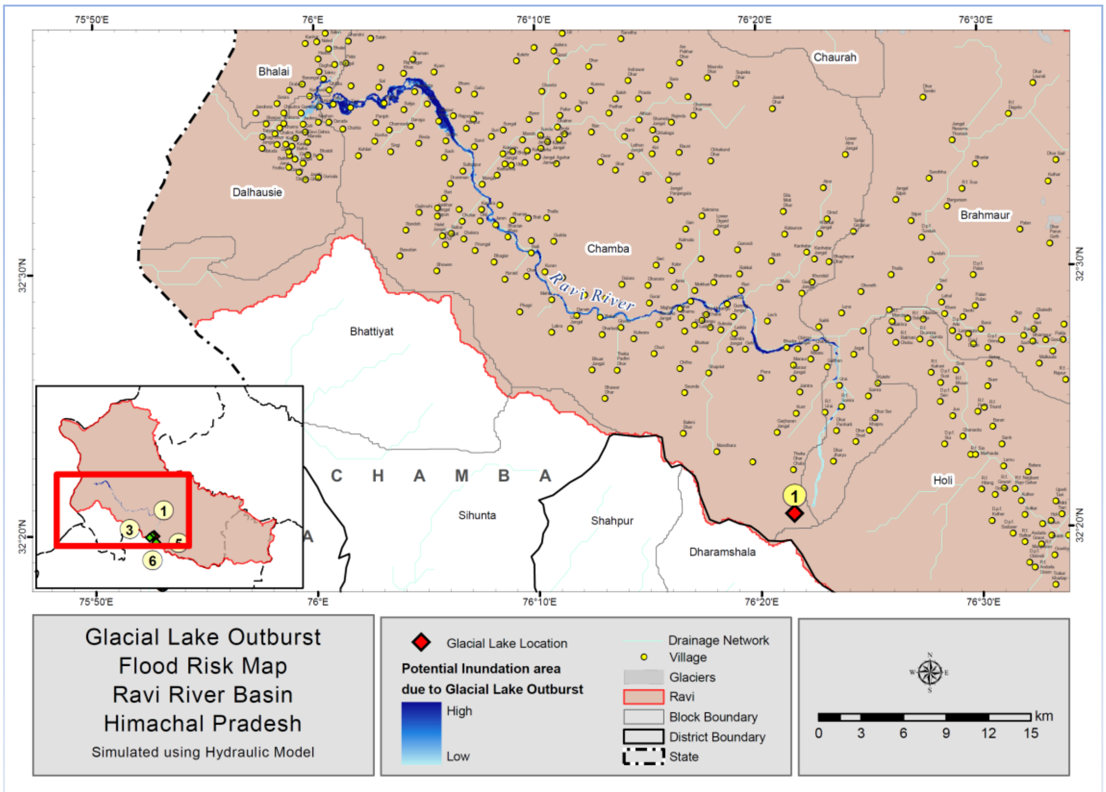
Lake 3 is situated at an elevation 4092 m amsl having area 2.01 ha and volume 0.13 MCM, at the head Stream of Ravi River. It can be seen that the flooding caused by this lake outburst affects a stretch of 132 km and covers a part of the flood plain of 50 m to 1500 m width.

Lake 5 is situated at an elevation 4157 m amsl having area 3.34 ha and volume 0.28 MCM, at the head Stream of Ravi River. It can be seen that the flooding caused by this lake outburst affects a stretch of 132 km and covers a part of the flood plain of 50 m to 1800 m width.

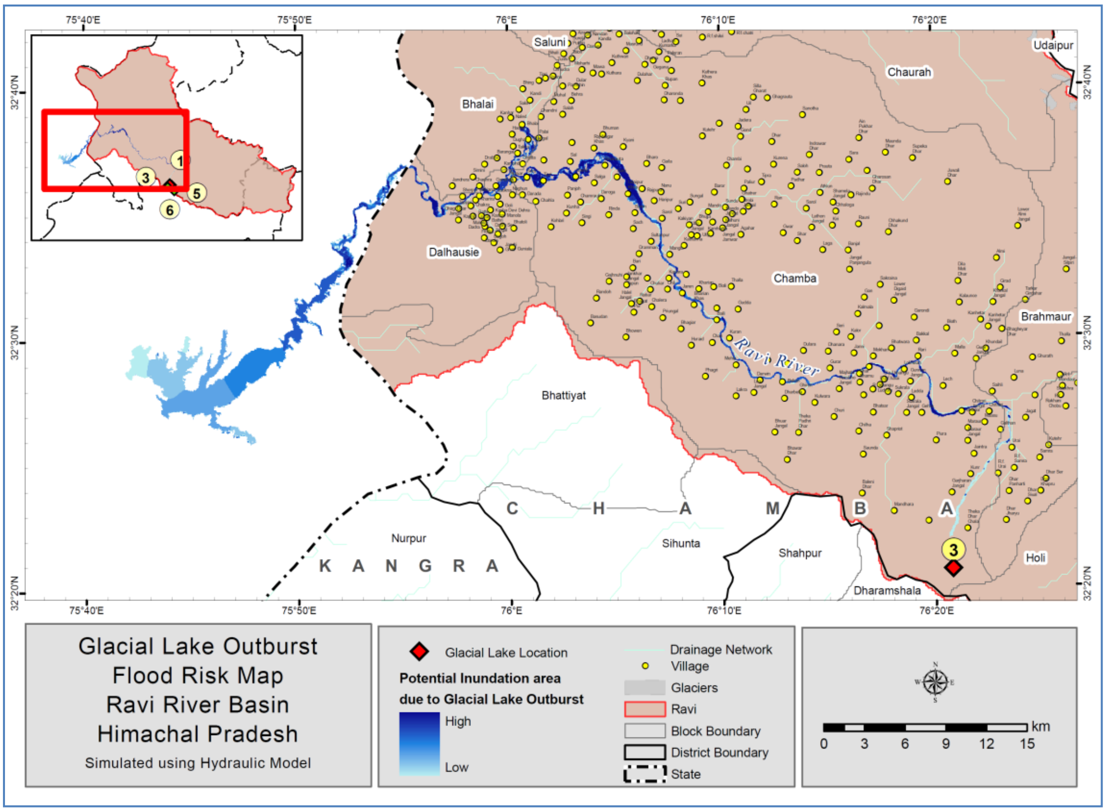
Lake 6 is situated at an elevation 3973 m amsl having area 7.54 ha and volume 0.88 MCM, at the head Stream of Ravi River. It can be seen that the flooding caused by this lake outburst affects a stretch of 132 km and covers a part of the flood plain of 50 m to 2100 m width.

Figure 39 : Simulated Inundation caused due to Glacial Lake Outburst Flood in Ravi basin (Himachal Pradesh)

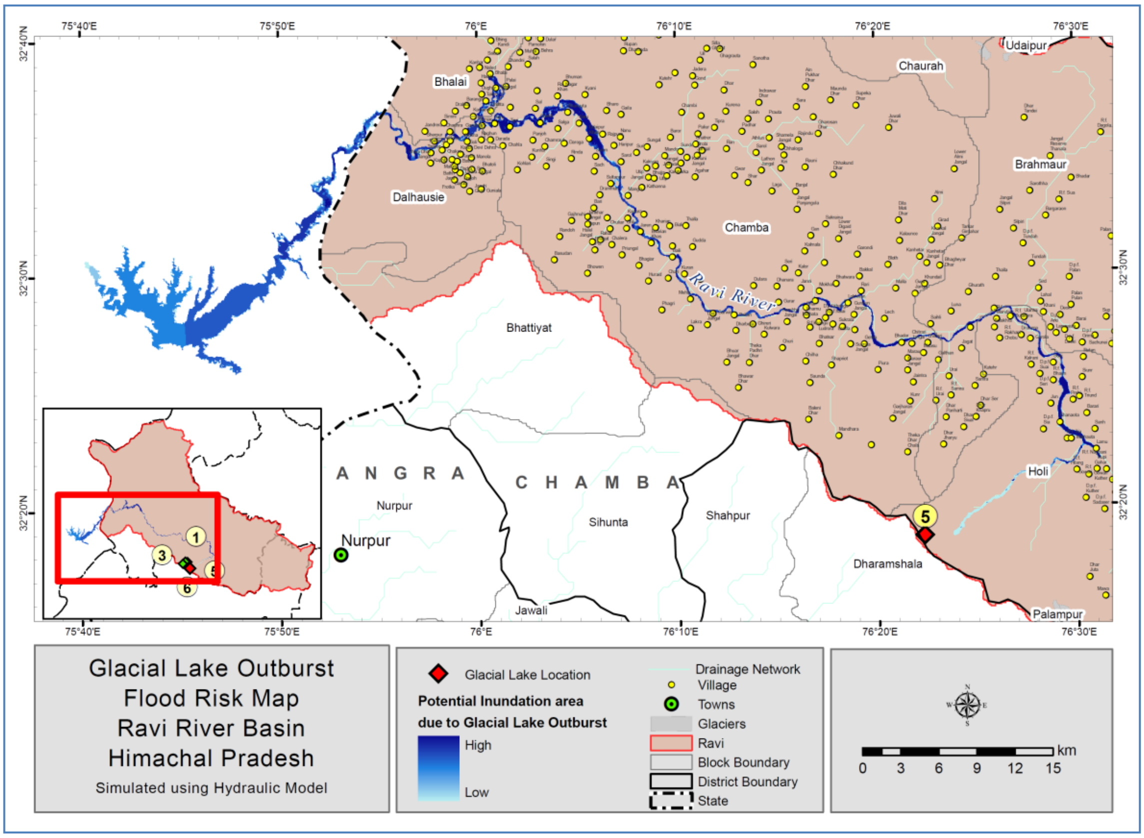
Lake 1 in Ravi Basin



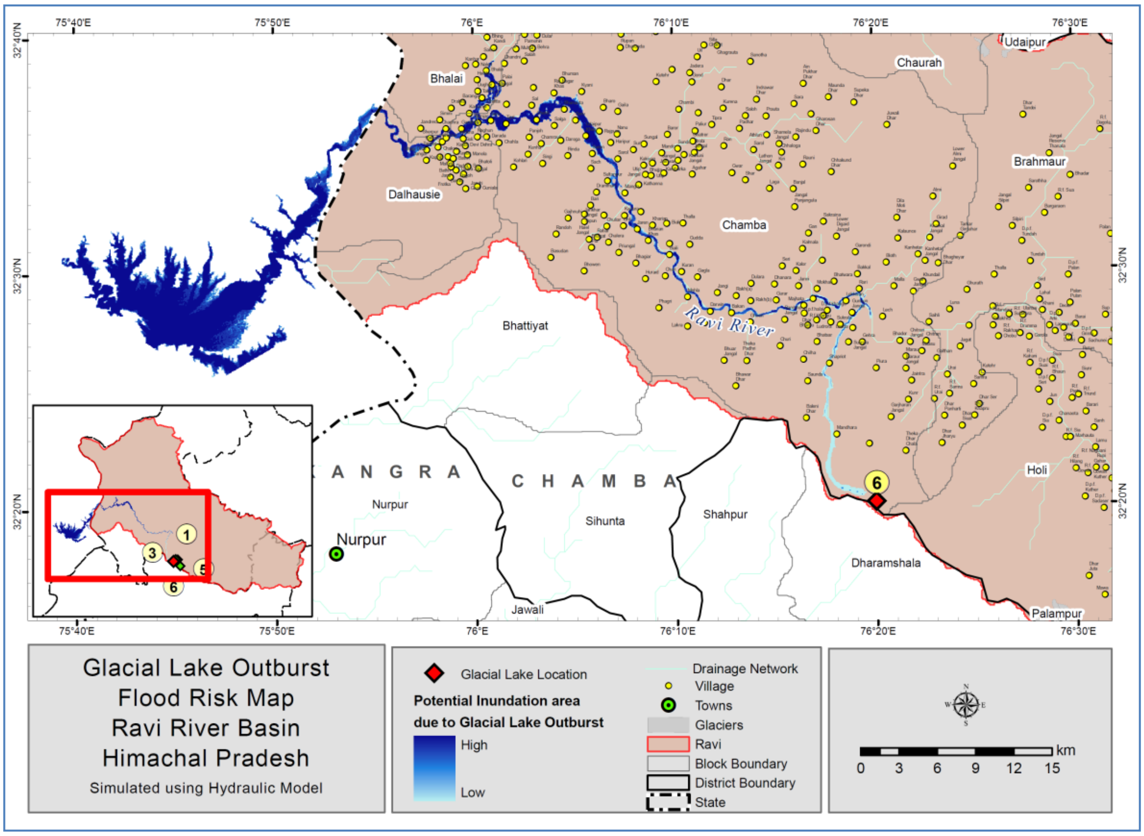
Lake 3 in Ravi Basin



Lake 5 in Ravi Basin



Lake 6 in Ravi Basin



Source: INRM analysis

39, 64, 59 and 65 villages in Ravi basin come under potential risk zone due to GLOF of Lake1, Lake3, Lake5 and Lake6 respectively.

Error! Reference source not found. shows the inundation caused due to Glacial Lake Outburst in Chenab basin. Lake 7 is situated at an elevation 4064 m amsl having area 64.21 ha and volume 18.36 MCM, at the head Stream of Chenab River. It can be seen that the flooding caused by this lake outburst affects a stretch of 190 km and covers a part of the flood plain of 50 m to 4000 m width.

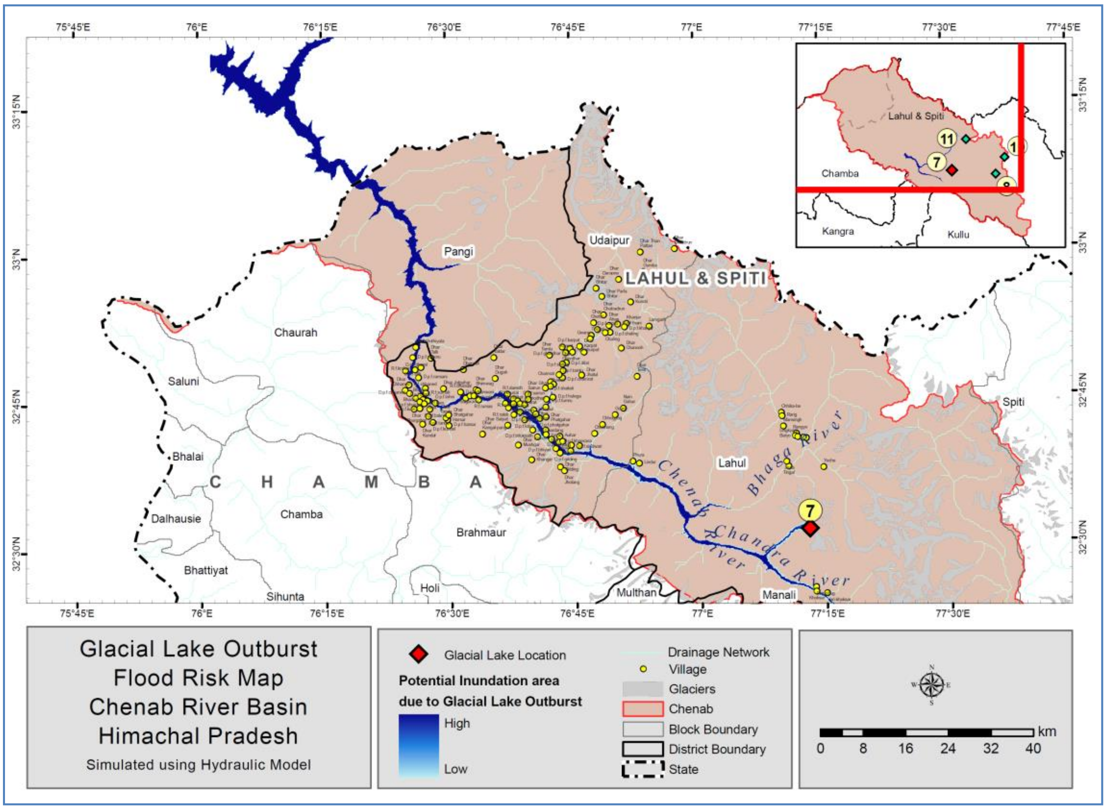
Lake 8 is situated at an elevation 4155 m amsl having area 119.23 ha and volume 44.21 MCM, at the head Stream of Chenab River. It can be seen that the flooding caused by this lake outburst affects a stretch of 260 km and covers a part of the flood plain of 50 m to 4500 m width.

Lake 10 is situated at an elevation 5198 m amsl having area 5.44 ha and volume 0.55 MCM, at the head Stream of Chenab River. It can be seen that the flooding caused by this lake outburst affects a stretch of 140 km and covers a part of the flood plain of 50 m to 1500 m width.

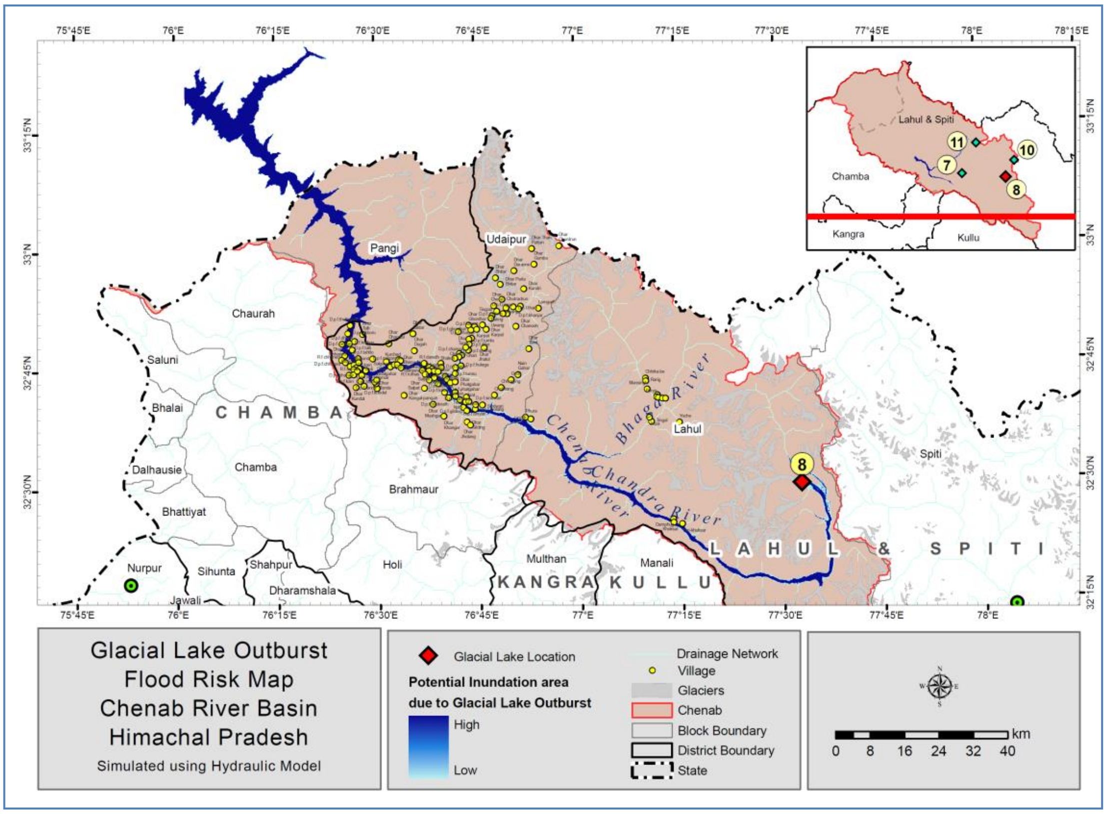
Lake 11 is situated at an elevation 4542 m amsl having area 9.2 ha and volume 1.16 MCM, at the head Stream of Chenab River. It can be seen that the flooding caused by this lake outburst affects a stretch of 62 km and covers a part of the flood plain of 50 m to 1500 m width.

Figure 40: Simulated Inundation Caused Due to Glacial Lake Outburst Flood in Chenab Basin

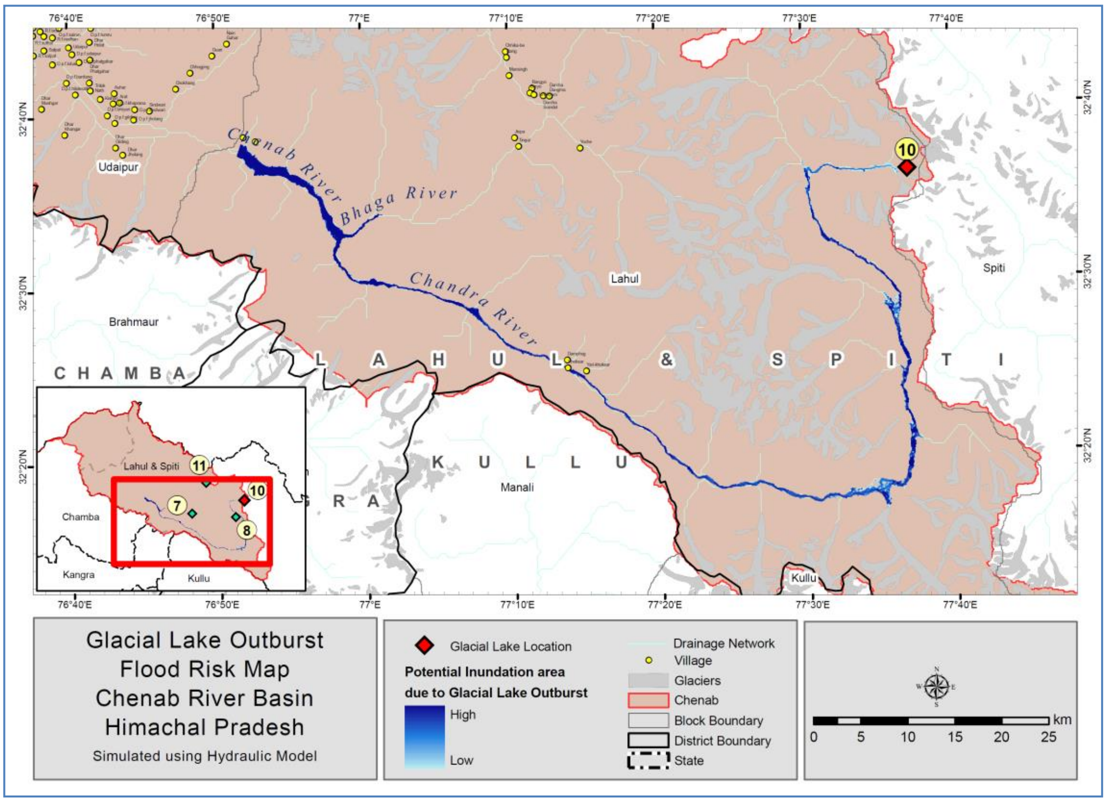
Lake 7 in Chenab Basin



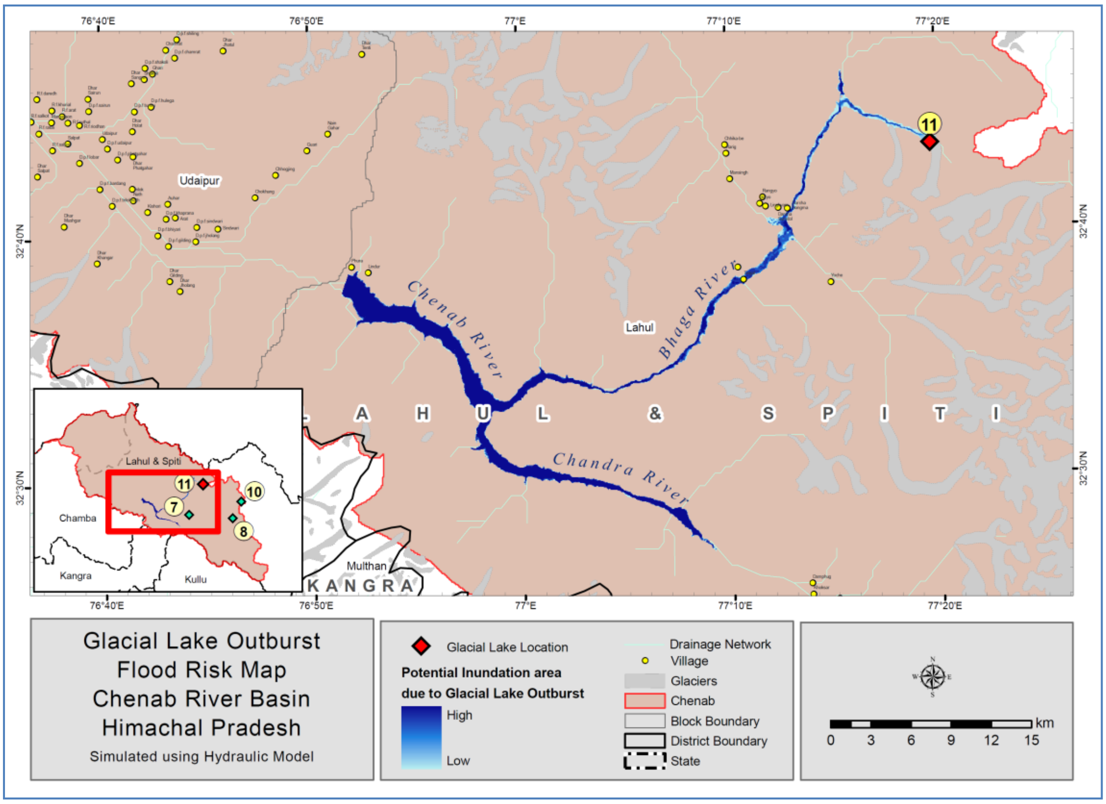
Lake 8 in Chenab Basin



Lake 10 in Chenab Basin



Lake 11 in Chenab Basin



Source: INRM analysis

48, 71, 5 and 7 villages in Ravi basin come under potential risk zone due to GLOF of Lake 7, Lake 8, Lake 10 and Lake 11 respectively.

2.7.2 The GLOF Risk in Himachal Pradesh

The present study illustrates that modelling of GLOFs remain a challenge. The simulation carried out in this study illustrates that, given the present state of knowledge; it is not possible to predict even approximate dates of occurrence or magnitude of risk posed by glacial lakes in Himachal Pradesh.

The study took a step-wise approach to ensure that coverage to be as comprehensive as possible. At the same time careful selection of most critical lakes were taken for study with the help of field experts of the region. Thus 11 (eleven) such existing lakes were selected for study.

Although the eleven lakes considered for study were evaluated as relatively stable, the possibility for a GLOF to occur sometime in the future cannot be dismissed, particularly in view of continued atmospheric warming and the associated increase in volume of glacial lakes. Furthermore, expansion of infrastructure in the vulnerable sectors downstream means that the actual risk associated with an individual event is increasing. As with earthquakes, the difficulty lies not in predicting that such an event is likely to take place, rather the problem is that in the current situation it is impossible with any certainty to predict where such an event will occur, and whether this year, next year, or in the remote future. However, because such an event could be imminent, it is vital that steps be taken to mitigate against severe loss of life and property.

2.8 Conclusion

The present study illustrates that modelling of GLOFs remain a challenge. Given the present state of knowledge; it is not possible to predict exact time of occurrence or magnitude of risk posed by glacial lakes in Himachal Pradesh. The study took a step-wise approach to ensure that coverage to be as comprehensive as possible. At the same time careful selection of most critical lakes were taken for study with the help of field experts of the region. Thus 11 (eleven) such existing lakes were selected for study.

Inundation map of glacier lake outburst of selected 11 (eleven) lake shows vulnerable villages and area. It is evident from inundation maps that out of 11 (eleven) glacier lakes, few glacier lake in each basin are more vulnerable. According to modelling output and inundation maps of Chenab Basin, area falling under vulnerable zone of Lake 8 and lake 7 are at utmost risk. In Ravi basin area falling under vulnerable zone of Lake 5 and lake 6 are at maximum threat. Volume and area wise Glacier lakes in Sutlej basin are not so vulnerable, when compared to glacier lakes of Chenab and Ravi basins. But number of villages falling within the inundated vulnerable zones are quite high in Sutlej basin.

Although the eleven lakes considered for study have been evaluated as relatively stable, the possibility for a GLOF to occur sometime in the future cannot be dismissed, particularly in view of continued atmospheric warming and the associated increase in volume of glacial lakes. Furthermore, expansion of infrastructure in the vulnerable sectors downstream means that the actual risk associated with an individual event is increasing. As with earthquakes, the difficulty lies not in predicting that such an event is likely to take place, rather the problem is that in the current situation it is impossible with any certainty to predict where such an event will occur, and whether this year, next year, or in the remote future. However, because such an event could be imminent, it is vital that steps be taken to mitigate against severe loss of life and property.

- Sutlej basin - area affected by flooding and inundation caused due to Glacier Lake Outburst
  - three glacial lakes were considered of sizes, 0.07, 0.21 and 0.06 MCM respectively
  - about 49 villages in flood risk zone of Lake 2
  - about 51 villages in flood risk zone of Lake 4
  - about 10 villages in flood risk zone of Lake 9
- Chenab basin - area affected by flooding and inundation caused due to Glacier Lake Outburst
  - four glacial lakes were considered of sizes, 18.36, 44.21, 0.55 and 1.16 MCM respectively
  - about 48 villages in flood risk zone of Lake 7
  - about 71 villages in flood hazard region of Lake 8
  - about 5 villages in flood risk zone of Lake 10
  - about 7 villages in flood risk zone of Lake 11
- Ravi basin - area affected by flooding and inundation caused due to Glacier Lake Outburst
  - four glacial lakes were considered of sizes, 0.06 , .13, 0.28 and 0.88 MCM respectively
  - about 39 villages in flood risk zone of Lake 1
  - about 64 villages in flood risk zone of Lake 3
  - about 59 villages in flood risk zone of Lake 5
  - about 65 villages in flood risk zone of Lake 6

Chapter 3: Impact Assessment: Riverine Flood

3.1 Riverine Flooding

Flood is a temporary inundation of large area/ region as a result of an increase in reservoir or of rivers flooding their banks because of heavy rains or snow melting or dam bursts. In other words flood is defined as “a relatively high flow or stage in a river, markedly higher than usual and thus inundating lowland. It is a body of water, rising, swelling and over flowing land, not usually thus covered”.

The state of Himachal Pradesh has a complex physiography comprising hills and mountains with deep gorges that is cut in between these mountains by the majestic rivers. The altitude ranges between less than 300 meters to more than 6000 metres. Owing to the varying altitudes, the state has variety of climates. There are five main river catchments i.e. the Sutlej, the Beas, the Ravi, the Yamuna and the Chenab.

The occurrence of water related natural disasters especially floods and flash floods are common in most of the hilly states including Himachal Pradesh. The flood can be of various origins, but in a hilly area like Himachal they are the result of some typical reasons. They include intense and prolonged rainfall, the downstream blocking of river channels by landslides or avalanches or the sudden breach or burst of artificial /natural lakes, cloudburst in the catchment region. In Himachal, the riverine flooding is mostly associated with the rivers having snow fed origin because in summer the snowmelt coupled with heavy rain often triggers a flood. The river Sutlej and river Beas, which are being flooded almost every year, are of this type.

On the other hand, another type of flood which is most common in the state is flash-flood. The flash floods are extreme events that are sudden, severe and short lived. The duration of this phenomenon is short but can cause extensive damage. Flash flood is a sudden and often destructive surge of water down a narrow channel or sloping ground, usually caused by heavy rainfall.

The flood problem in the state is mainly during the months of June to August when the south west monsoon is in progress and snow is melting in the higher reaches.

Floods are one of the worst disasters of the state. Almost all rivers of the state carry heavy discharge during the monsoon when their catchments receive intense and heavy rainfall. The problem of flood varies from one basin to another and the magnitude of flood also varies. The most flood prone area in the state are in the Sutlej and Beas rivers. Yamuna River also faces flood problems.

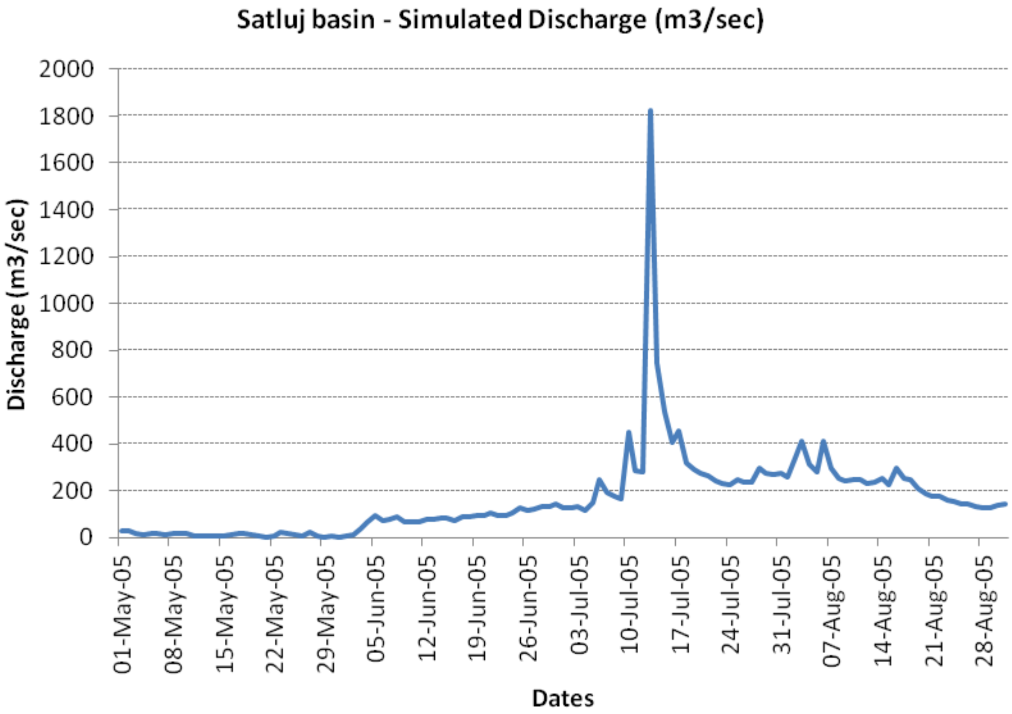
3.1.1 Data Used

- Sutlej and Beas River cross-sections extracted using public domain ASTER digital elevation model.
- Sutlej river: Required boundary condition, flow / stage / rating curve at starting of river and at confluence of river - SWAT hydrological model simulated flow of

Sutlej. This flow was enhanced by 50% to represent order of magnitude of June 2005 flood.

Simulated flow used for modelling is shown in Figure 41.

Figure 41 : Simulated Discharge of Sutlej used for modelling



- Beas River - Probable maximum flood discharge for Gharopa Hydro-electric Project[26] was used as proxy for modeling purpose.

3.1.2 Limitation and Uncertainty

In absence of surveyed/observed data model performance has few limitations. They are illustrated below:

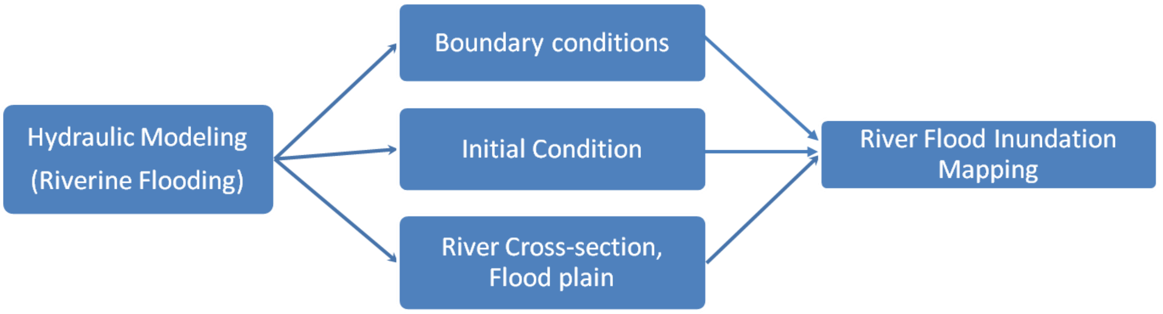
- River Cross section from digital elevation model does not capture accurate river cross-section, which is essential for accurate modeling.
- In absence of observed flow / stage data of flood period
- In Himachal Pradesh cloud burst is major reason for flash flood, such events are not captured and recorded discharge data for these events is unavailable
- In absence of above mentioned data, assumptions based on engineering judgement are made, which may not exactly match with reality.

3.2 Methodology

The steps followed to model and analyse impact of GLOF is shown in the flow chart (Figure 42):

[26] powermin.nic.in/whats_new/PFR/HP/Ghorpa.pdf

Figure 42 : River Flood Modelling Flowchart



3.3 Models Used

A hydraulic model was used to analyze the implication of a flood passing through the river stretches. Flood inundation modeling was done for the identified stretches. HecRas Hydraulic model was used for simulating flood inundation on Sutlej and Beas River.

3.4 Hydrologic Engineering Centre – River Analysis System (HEC-RAS)

HEC-RAS is a one-dimensional steady and unsteady flow hydraulic model developed by the U.S. Army Corps of Engineers (HEC, 2002). The HEC-RAS hydraulic model takes the analysis further by studying the transformation of the flood events as they pass through the upstream to downstream of the river channel. These flood waves cause inundation when the carrying capacity of the channel is exceeded. The output of the model provides the water surface profiles all along the river along with its temporal variation (change in flow depth during the flood period). Effect of storm surge has also been modeled using HECRAS. The model requires high quality of data on channel geometry and terrain to simulate the water surface profiles and the inundation properly. It also needs data on the manmade interventions such as bridges, embankments, etc., so that their effect on the flow can also be simulated. Most of these data required for the modeling were not available and the quality of data obtained from other sources was poor.

3.5 Study Area

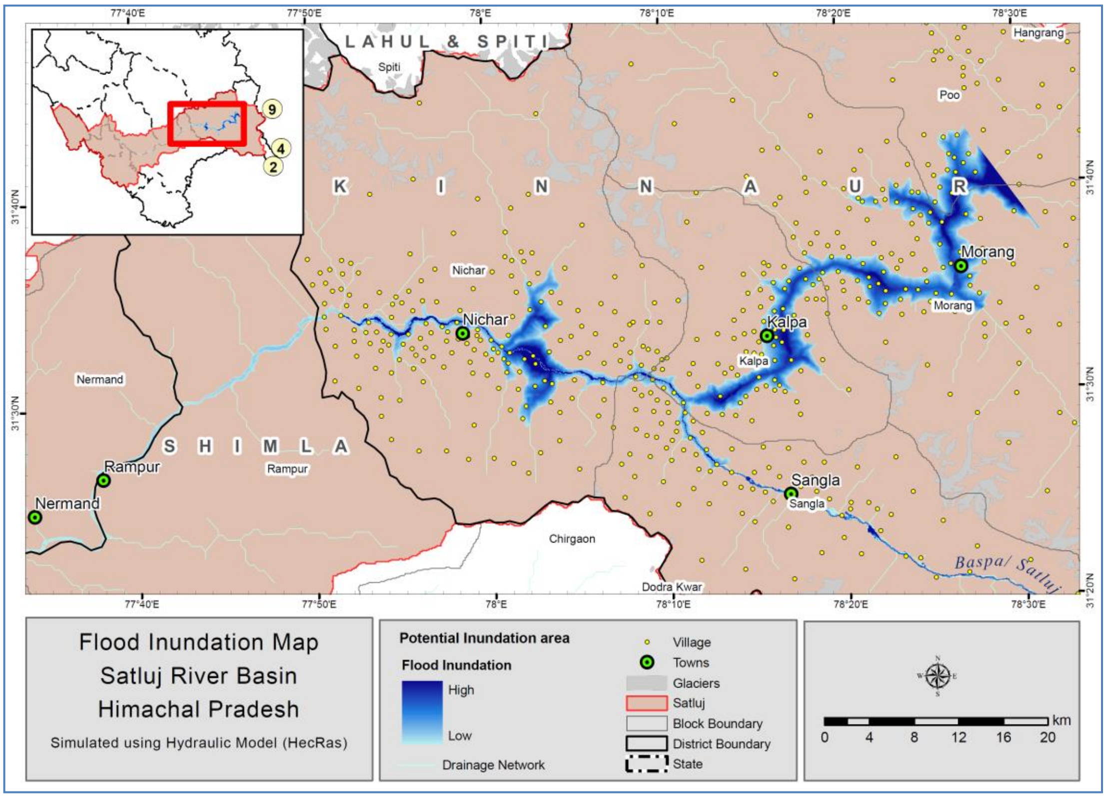
Based on the literature on major floods of Himachal Pradesh, most vulnerable flood prone stretches were identified. Stretches of Sutlej and Beas river were modelled.

3.5.1 Analysis

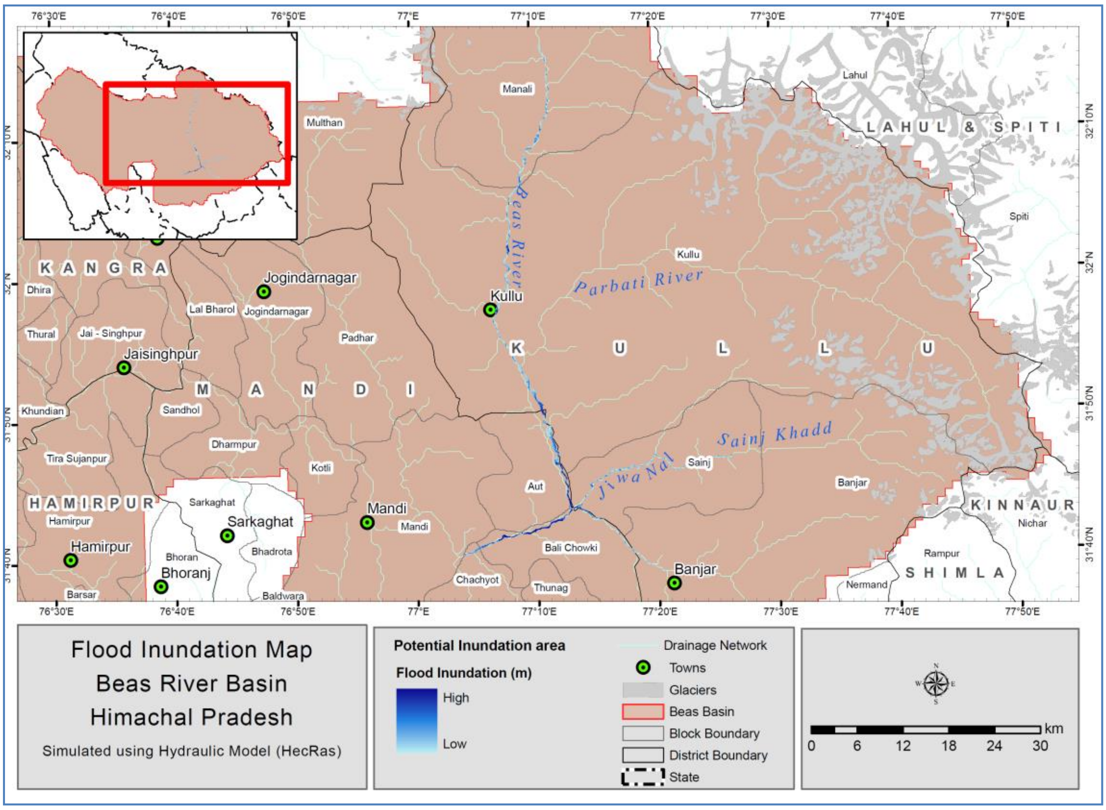
It is seen from the model output that riverine flooding in Beas and Sutlej is within the flood plains. Inundation at a few spots outside the flood plain is seen in the figure. Location of the inundation closely matches with the flood prone location shown in Figure 34.

Substantial area in Sutlej basin gets inundated with 2005 derived flow. The map also shows flood spread area super imposed with the village boundaries and towns. Modelling is done for 268 Km stretch of Sutlej downstream of Spiti confluence. Extent of inundation is approximately 2 km to 4 km in Kinnaur districts and 50 m in Shimla district along Sutlej River. Approximately 280 villages lie in flood plain are potential risk areas for river flood inundation.

Figure 43 : Sutlej River Flood Inundated Area



Beas River Flood Inundated Area



Flooding in Beas River is comparatively lower. Total of 87 km stretch of Beas from origin is modeled. Pārbati River, which is tributary of Beas, which joins Beas has also been considered while modelling. Extent of inundation is approximately 10 m to 600 km on Beas and approximately 10 m to 278 km on Parbati. Approximately 59 villages along both banks of Beas and its tributary Pārbati lie in flood plain and are in potential risk area.

3.6 Conclusion

Riverine flooding or river floods is caused when a river reaches its flood stage. Water can rise and spill over the banks of the river. The amount of flooding is a function of the amount of precipitation in an area, the amount of time it takes for rainfall to accumulate, previous saturation of local soils, and the terrain around the river system.

Floods are natural phenomena, which can have severe economic, social and environmental consequences. An increased number of people and economic assets are located in riverine flood plain areas. The rising water level may be caused by heavy snowmelt or high-intensity rainfall creating soil saturation and high runoff either directly or in upstream catchment areas.

Locally, rising groundwater after prolonged natural recharge may contribute to severity of the flooding. Dam and embankment failures are important causes for flooding. In Himachal Pradesh, flash flood due to cloud burst is common phenomena.

Himachal Pradesh experiences riverine flooding of varied magnitude almost every year and Sutlej and Beas are most vulnerable rivers. All the villages and property inside the flood plain and near close vicinity are in vulnerable zone.

In the current study hydraulic modelling was carried out for stretches of Sutlej and Beas rivers to simulate the extent of inundation. Probable maximum flood discharge was used to route the flood wave to map the potential risk areas.

The study shows that about 59 villages in Beas basin and 280 villages in Sutlej basin are potentially at risk due to inundation caused by river flooding.

Annexure

Some of the devastating Floods, which caused heavy damage to Private as well as Public Property in Himachal Pradesh, are:

ANNEXURE – A: Major Flash Floods in Himachal Pradesh

Prominent Flash Floods	History of Damage Occurred
8 July 1973	Lake formed by the blockage of Satluj river due to Nathpa rock fall damaged Sanjay power house, loss of about Rs. 45 million estimated.
19 Jan. 1975	In Satluj basin two blockages were observed in Spiti valley. One on Parechu River between Sumdo and Kaurik due to landslide created by 19 Jan. 1975 earthquake, which occurred along the Sumdo-Kaurik fault. Blockage was 60m in height and 150m in length created temporary lake. In march this lake burst causing flash floods in Spiti valley
On 29 Sept 1988 (2.30 a.m.) a flash flood occurred due to cloud burst in SoldangKhad.	Caused heavy loss of life and property in the Soldng village. • Washed away the Bhabanagar water works. • Washed away 2 Km of NH-22 across SoldanKhad. • Created landslides along the eastern slopes of SoldanKhad and damaged road to Ponda. • Lake was formed on the Satluj river near conference. • Block stopped the flow of Satluj river for about 30 minutes and created a temporary lake having dimensions roughly about 6000 m long. 200-250 m wide and 25-30 m deep extending up to Wangtoo Bridge. • Lake water entered Sanjay VidutPariyojna and damaged the Power House.
31 July and 2 August 1991	Cloudburst and flash flood along SoldanKhad in Satluj valley killed 32 people, 15 houses, 35 bigha agriculture land, 600 apple trees, 2Km of road of NH 22 and 20 m bridge on SoldanKhad washed away. Agriculture land along Leo village situated downstream.
24 Feb 1993	Flood washed away 15 houses, 35 bigha of agriculture land and about 600 apple trees in Soldang village.
4th and 5th September	Satluj river blocked twice due to major landslide and rock fall near Jhakri and Nathpa, damaging NH-22. Another flash flood occurred in two phases along DulingKhad on 4th and 5th September causing extensive damage in Tapri, district Kinnaur.
First flash flood occurred on 4Sept 1995 at 2 p.m. After cloudbursts in the	• 32 people and 35 cattle lost their lives. • Huge debris formed a fan along Satluj and formed a take partially blocking the Satluj

Prominent Flash Floods	History of Damage Occurred
upper catchments of Duling and damaged the PWD rest house. Another flood came at 6 a.m. and 9 a.m. on 5th Sept. 1995 bursting the lake formed during the previous cloudbursts.	• Flash flood caused heavy damage due to change in course of Satluj from left to right bank increased the tow and lateral erosion at Tapri. • Washed away 19 houses, HRTC workshop along with 3 buses. • Change in course is still causing tow erosion to NH-22.
4th and 5th Sept. 1995 flash flood in Kullu valley	Flash flood in Kullu valley occurred which cause damage to the tune of Rs.759.8 million.
Feb-93	500 m road section of NH-22 washed away by Jakhri slide. Rs. 10 million loss to road and forest land, a village upper slope was in danger.
4-5 and 12 Sept. 1995	Flood and landslide along Bas river in Kullu valley killed 65 people. NH damaged at numerous places, loss to government and private property, road and bridges estimated US$ 182 million.
4-5 Sept. 1995	Flash flood along PanwiKhad in Satluj valley washed away 19 houses, 3 buses, HRTC workshop and damaged HPPWD rest house at Tapri.
11-Aug-97	Flash flood and landslide along Andhra khad in Pabbar valley killed 124 people, 456 cattle, washed away government and private buildings, 200 m road section and damaged Andhra power house at Chirgaon. Loss was estimated Rs. 10.63 million.
Aug-97	Cloudburst and flash flood along Satluj river killed 19 people, 464 cattle, 105 houses damaged, 10 cattle sheds and 39-hectare agriculture land. Total loss was estimated Rs.672.9 million.
Flash floods in the night of 31st July and 1st August 2000 in Satluj valley.	Flash floods in the Satluj valley resulting in the increase in water level of Satluj an up to 60 feet above the normal level. The flash flood was termed as the one that occurs once in 61,000 years. Widespread damage in the valley right from its confluence with Spiti river near Khab to downstream areas. Extensive damage to 200 Km of NH-22, washed away 20 bridges, 22 Jhulas and badly damaged 12 bridges. About 1000 irrigation, sewerage, flood protection and water supply schemes were badly damaged. Expensive damage to hydel projects including NJPC. 135 people and 1673 cattle lost their lives. The total estimated loss was to the tune of Rs. 1466.26 crore.
Flash floods on the night of 23rd July 2001 in Sainj valley in District Kullu.	Cloudbursts in the upper reaches of Sainj valley caused flash floods in two nallahs namely, Sainj and Jeeba, affecting about 40 families 2 bridges on Sainj and Jeebanallahs and plenty of fertile land were washed away. Connecting road to Slund and Sainj was also washed away at a number of places. Two persons were washed away and

Prominent Flash Floods	History of Damage Occurred
	5 cattle perished. Some other areas in Kullu district were also affected due to excessive rains in July and the population of 6355 was adversely affected.
17th and 19th July 2001 floods in Mandi district.	Excessive rains caused damage to 160 houses in Mandi district and destroyed 11 cattle and one human life.
Flash floods in the night of 29th and 30th July 2001 in ChhotaBhangal and Baijnath Sub Division of Kangra District.	Caused widespread damage in the area. 12 deaths occurred due to flash floods and loss of 150 cattle was reported from the area. Bridge connecting Deol and Baijnath was also washed away. Total estimated loss was to the tune of Rs. 18.27 crores.
Flash floods in the night of 9th August and 10th August 2001 on Moral-Danda peak in the Rohru sub Division in Shimla District.	Flash floods occurred along two streams, one along the Devidhar area and another along Darkali in Rampur Sub Division. Damage to infrastructure like roads, bridges, water supply schemes, forest wealth, agriculture land, horticulture land, footbridges, village paths, residential houses and water mills and loss of 3 lives and 39 cattle and destruction of private property. Total loss in both the Sub Divisions was 145.15 lacs. In Rohru Sub Division 7 bridges, 8 village paths, 8 water supply schemes, and I power house were damaged besides 16 houses, whereas in Rampur Sub Division, 10 bridges, 8 village paths, 1 water supply scheme, I soil conservation plant, 7 residential houses and 16 water mills were damaged.
Flash floods in the night of 21st and 22nd August 2001, cloudburst in Ani Sub Division of Kullu district occurred.	Due to flash flood in village Badhali 2 houses in which a couple was buried alive and their two children injured. In village sarli 7 people lost their lives, 15 houses were washed away besides the loss of 12 cows, 18 oxen and 40 sheep and about 115 bighas of agriculture and horticulture land was washed away.
Flash floods in Sihuntaara and Tissa areas of Chamba district in the night of 12th and 13th August 2001.	Washed away 9 hectare of fertile land, 2 small bridges causing a total loss to property of some Rs. 2 Crore.
Flash floods due to cloudbursts in Gharsa valley on 16th July 2003 in Kulludistrict.	Due to these flash floods 21 people lost their lives, 21 people suffered major injuries and 9 are still missing.
Flash floods in Kangninalla near Solang in Kullu district on 7th August 2003.	30 people lost their lives and 19 people were injured and 9 people are missing, 2 people lost their lives due to landslide in Bhang nalla.
Flash flood in Satluj river due to breach in the Parachoo lake in Tibetan catchment on 26th June 2005	Extensive damage as a result of risen water level of Satluj river due to breach in Parachoo lake formed in Tibet catchments. Washed away the NH-22 at a number of places, 10 bridges, 11 ropeways washed away, 15 motor able bridges and 8 jeep able and footbridges damaged/affected, 10 Km stretch of NH-22 between Wangtoo and Samdo was washed away, and various link roads were damaged. Total

Prominent Flash Floods	History of Damage Occurred
	loss estimated to the government as well as public property was some Rs. 610 crore.
Flash floods during July 2005.	Flash floods in Pabbar river in Rohru Sub Division resulted in heavy losses to roads, bridges, public buildings, residential houses, cowsheds, private land. Dhirgaon block was totally cut off. On July 7th, 2005, flash flood in Baspa river took place causing the loss of 6 bridges and 600 mt link road to Sangla. More than 3000 cattle perished in different parts of the state leading a total loss of some of Rs. 55980.76 lacs.
15th August 2007, Bhavi Village, Ghanvi, Shimla	58 persons died; All roads leading to village cut off
7th August 2009, Dharampur, Mandi	2 persons died
12th September 2010, Kharahal Valley	Washed away several roads and bridges

Source: Bhandari, 1988; Sah et al, 1996[27]; Sah and Mazari 1998[28]; Sah and Bist, 1998[29]; Paul et al, 2000[30], Revenue Department, Govt. of Himachal Pradesh.

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[27]SAH, M.P., VIRDI, N. S. & BARTARYA, S. K., 1996.The Malling slide of Kinnaur, causes, consequences and its control on channel blocking and flash floods in the Lower Spiti Valley, Himachal Pradesh.In : Proc. Int. Conference on Disasters and Mitigation, Anna. University, Madras, 1(A-4). 102-106

[28]SAH, M.P. & MAZARI, R.K., 1998.Anthropogenically accelerated mass movement, Kulu Valley Himachal Pradesh, India. Geomorphology, 26,123-138

[29]BIST, K.S. & SAH, M.P. 1998.The devastating landslide of August 1998 in Okhimath area, Rudraprayag district, Garhwal Himalaya. Current Science, 76(4), 481-484

[30]Paul, S. K., Bartarya, S. K. ,Rautela, P. and Mahajan, A. K . , Cat a strophic mass movement of 1998 monsoons at Malpa in Kali Valley, Kumaun Himalaya (India) . Geomorphology , 2000, 35 , 169 – 180

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