CHAPTER 1
INTRODUCTION

The Earth's climate is mainly maintained by a balance between the energy that reaches the Earth from the sun and that which goes back from the Earth surface to space through atmosphere. The lithosphere, biosphere, hydrosphere, cryosphere and atmosphere all work interactively in regulating this balance, and together form part of the Earth's climate system (IPCC 2001). The climate system consists primarily of land, ocean and ice on the surface of earth, the atmosphere and the radiation from sun that provides energy. All of these constitutes interact, to produce the condition on and around the surface of our planet that we call the ‘climate’ (Dennis 1994). It varies on timescales ranging from millions of years to decades. Now a days the climate change is a concern all over the world; the factors involved in climate change are many and varied. They include things such as changes in the orbit of the earth around the Sun; differences in solar intensity; and changes in the chemical composition of the atmosphere due to volcanic activity and also due to some anthropogenic factors. Several factors within the Earth's climate system may perturb the Earth's energy balance causing a response in climate. For instance, sulphur dioxide (SO$_2$) emissions from volcanic eruptions within the lithosphere (Andres and Kasgnoc 1998) undergo chemical transformation to form sulphate aerosol particles (SO$_4^{2-}$). These particles are highly effective in the backscattering of incoming solar radiation and thereby, affect energy flows within the climate system. Within the biosphere, a change in the earth surface albedo due to deforestation can affect the amount of solar energy absorbed by the ground surface, which may in turn feedback on the local moisture balance and heat fluxes in the atmosphere above (Gondwe and Jury 1997; Jury et al. 1997; D'Abreton et al. 1998; IPCC 2001). Within the hydrosphere, physical oceanographic processes also play an important role in climate relevant radiative and other associated
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processes. The oceans, which cover 70% of the Earth's surface and are in close proximity to most of the lower atmosphere, have an immense capacity to store much more heat in comparison to land and air. Only a small fraction of absorbed incoming solar energy is transferred to the atmosphere through evaporated water (latent heat). Due to its greenhouse properties, water vapour in the atmosphere regulates energy balances almost at all scales i.e. micro, meso and global scales.

Climate is a large-scale phenomenon that emerges from complex interactions among small-scale physical systems. Climate projections made with sophisticated computer codes have informed the world's policymakers about the potential dangers of anthropogenic interference with Earth's climate system. The physics involved in climate models can be divided into three categories. The first includes fundamental principles like conservation of energy, momentum, mass, and processes, which can be calculated from fundamental principles. The second includes the transfer of radiation through the atmosphere and the Navier–Stokes equations of fluid motion. The third category contains empirically known physics such as evaporation as a function of wind speed and humidity.

Out of all the weather and climate parameters, temperature is one of the most important climate variables, which is a measure of the energy contained in the movement of molecules. To understand how temperature is maintained, one must therefore consider the energy balance that is formally stated in the first law of thermodynamics. The basic global energy balance of earth is between energy coming from the sun and energy return to space by earth's radiative emission (Dennis 1994). Solar radiation is also the most important parameter. The intensity and duration of sunshine measures part of the radiation. Cloud cover is the next important parameter because it determines both how much solar radiation reaches the ground and how much is radiated back into the space from the earth. Temperature depending on radiation influence cloud cover and control humidity so it is also important. Wind and pressure are interrelated. The pressure represents the weight of the atmosphere and wind represents the air movement. Humidity indicates the amount of water in vapour form and precipitation measures the amount of water in its liquid or solid phase. Variations in these variables are used as an indicator of climate change. In recent years, there have been many studies dealing with climate changes and their possible
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impact on global and regional water resources (Nemec and Schaaake 1982; Gleick 1986; Beran 1984). Many of the studies have considered hypothetical climate change trends, and their likely impact on catchment resources. A comprehensive approach to the simulation of regional climate change is given by Giorgi and Mearns (1991).

A change in any weather parameter can produce changes in regional climate. For example, if the average regional temperature increases significantly, it can affect the amount of cloudiness as well as the type and amount of precipitation that occur in that place and if these changes occur for long time scale, the average climate values for these parameters will be affected. Climate variability refers to the climatic parameter of a region varying from its long-term mean. Every year in a specific time period, the climate of a location is different. Some years have below average (deficit) rainfall, some have average or above average (excess) rainfall. Also we are not assured of getting every year the same range of temperature or rainfall over a location.

It is now more or less accepted that current warming is due to the combination of natural fluctuations and anthropogenic forcing of the climate. These changes affecting the global climate already have and will continue to have consequences on both oceanic and terrestrial ecosystems and consequently impacts on human activities and settlements. Not all regions will be affected by climate change in the same way. Natural systems and processes in the Himalayas (ecosystems, rivers patterns, erosion processes, etc.) are closely related to temperature and its evolution. Isotherms are crucial for the distribution of species, glacier localisation (trough equilibrium lines), snow cover extent and duration, etc. Slight changes in the mean annual temperature may mask dramatic changes on an hourly, daily or even monthly basis which are the relevant time frames for natural hazard triggering many disasters.

Climate changes can be indicated by the observed differences in the mean values of climatic statistics in successive time periods (Kothyari and Singh 1996). Jones et al. (1986) analyzed near-surface temperature over the land and oceans of both the Southern and Northern Hemispheres for a period of 130 years. Three warmest years have occurred in the 1980's. Studies indicated that in India annual surface air temperature has increased by 0.4°C per 100 years in this century. Increasing trend in mean and diurnal temperature is mainly contributed by the maximum temperature, whereas minimum temperature is trendless during the current century (Rupa Kumar et
al. 1994), but the rate of increase has slowed down in the recent three decades
(Parthsarthy et al. 1993). An analysis of climate data of the last century by the IITM,
Pune shows a decrease in precipitation over 68% area of India (Kumar et al. 2006).
Shrestha et al. (1999) observed warming trend of 0.068 °C to 0.128°C per year (from
1977–1994) in most of the middle Mountain and Himalayan regions.

1.1 Temperature Trends

1.1.1 Temperature trends in global

Area near the annual 0°C isotherm in the extratropics exhibit the strongest
warming rates. This is resemble to other studies of cryosphere change (Laternser and
Schneebeli 2003; Franssen and Scherrer 2008) which reported rapid change at the
lower margins of current snow/ice cover. Few urban mountains have mean annual
temperature 15°C also show increasing trends. Jones et al. (1986) analyzed near-
surface temperature data over the land and oceans of both the Southern and Northern
Hemispheres for a period of 130 years. According to IPCC fourth assessment report
(2007), warming in the last 100 years has caused about a 0.74°C increase in global
average temperature (IPCC 2007). Over the Indian region the warming will be
restricted to 1.4±0.3°C till 2020’s, 2.5±0.4°C till 2050’s, and 3.8±0.5°C till 2080’s
and the projected increase in precipitation will be limited to 2±1% in the decade
2020’s, 3±1% in the 2050’s, and 7±3% in the 2080’s, respectively. The most important
finding is a warming of the globe since the late nineteenth century of 0.45±0.15°C,
supported by a worldwide recession of mountain glaciers (IPCC 2007). The global
mean surface air temperature has risen about 0.5°C during the 20th century (IPCC
1996). Studies by Cook et al. (2003) in Nepal show late 20th century warming only
during October-February, whereas February-June temperatures show a cooling since
1960.

1.1.2 Temperature trends in India

Singh et al. (2013) studied temperature trends at Dehradun. The annual
maximum, annual minimum and annual mean temperature at Dehradun shows
positive trend. Annual mean temperature increased about 0.47°C during the 41-year
period (1967-2007). Increase in first phase (1967-1987) is 0.12°C but increase in
second phase is 0.54°C. The alarming rise in temperature is due to urbanization,
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industrialization, land use/land cover change, construction of road etc. Diodato et al. (2011) reported that Himalaya and Tibetan plateau region experienced 0.5°C rate of increase over 1971-2005 compared to last century (1901-1960). Kothawale et al. (2010) were assessed seasonal and annual trends in surface air temperature over India and seven homogeneous regions were assessed during 3 periods 1901-2007, 1971-2007 and 1998-2007. Annual mean, maximum and minimum temperature showed increasing trend. However accelerated warming was observed in the recent period 1997-2007 due to intense increase in recent decade 1998-2007. Annual mean, maximum and minimum temperature increased for the period 1971-2007 with sharp increase in minimum temperature than maximum temperature. In recent decade, maximum temperature was significantly higher compared to the long term trend. On seasonal scale, increasing trend in mean temperature was observed in winter and monsoon season and significant influence of El-Nino Southern Oscillation (ENSO) events on temperature anomalies during certain season across India. The composite of maximum and minimum temperature of El-Nino years showed positive anomalies during monsoon, post-monsoon, winter and pre-monsoon, however statistically significant positive anomalies were observed during monsoon and post-monsoon season. Minimum temperature changes were more variable than maximum temperature but not significantly. Kothawale and Rupa Kumar (2005) examined the recent changes in surface temperature trends over India for the period 1901-2003 and reported that all India mean annual temperature has shown significant increasing trend of 0.05°C/10 year during the period 1901-2003, the recent period 1971-2003 has shown a relatively accelerated warming of 0.22°C/10 year, which is use to unprecedented warming during the last decade. A study carried out by Bhutiyani et al. (2007) revealed that there is significant rise of 1.6°C in air temperature in the northwest Himalayan region in last century with fast rate in winter temperature. Maximum and minimum temperature both are increasing. Same as global rate, the study confirms episodes of strong warming and cooling in the northwest Himalaya in the last century and elevated rate of increase was experienced in last two decades. In the last century, surface temperature is increased by 1°C and 1.1°C during winter and post-monsoon months respectively and decrease in the minimum temperature during summer monsoon and increase during post-monsoon months created a large difference in seasonal anomaly. In North India, the minimum temperature shows sharp decrease between 1955 and 1972 and then sharp increase but in south India, the
minimum temperature has continuous increasing trend (Dash et al. 2007). Shrestha et al. (1999) indicate a cooling trend in Nepal from 1935 to 1975 and a warming trend thereafter. They suggest that the middle mountain and high Himalayan ranges are more sensitive to climate change due to their physiographic characteristics.

The Indian climate is mostly controlled by the monsoon and associated processes as it comes periodically covering whole country. Generally two monsoon season prevails one during June-September (the South west monsoon) and other during October-December (the North east monsoon) over Indian sub continent. It is observed that the monsoon variability in turn the annual rainfall pattern and variability is very uncertain causing flood in one year due to excess rainfall and drought in other due to very less rainfall. It is very important therefore to understand the climate of the monsoon system and its effect on multiple spatio temporal scale. In the following section, detailed introductions about the monsoon processes are presented.

1.2 Monsoon processes over Indian region

Generally Monsoon is defined as a system of winds characterized by a seasonal reversal of its direction. Winds blowing over the Arabian Sea from northeast for six months and from southwest for another six months are the main feature of the Indian monsoon system. Monsoon is also defined as a tropical and subtropical seasonal reversal in both the surface winds and associated precipitation, caused by differential heating between a continental-scale land mass and the adjacent ocean (IPCC). According to Indian Meteorological Department, Monsoon is defined as the seasonal reversals of the wind direction along the shores of the Indian Ocean, especially in the Arabian Sea, that blows from the southwest during one half of the year and from the northeast during the other half. Monsoon of the Indian subcontinent is among several geographically distributed observations of global monsoon taking place in the Indian subcontinent. Monsoon system is an economically important weather pattern and the most anticipated weather event and unique weather phenomenon over Indian subcontinent. Still it is only partially understood and notoriously difficult to predict. Several theories have been proposed explaining the origin, the process, the strength, the variability, the distribution and the general vagaries of the monsoon of the Indian subcontinent, but understanding of the phenomenon and its predictability are still evolving (Webster et al. 1998, 1999; Wang
et al. 2012; Goswami et al. 2006). The unique geographical features of the subcontinent, surrounded by Ocean in three directions, the great Himalayas on the north, western Ghats in western side and eastern Ghats in the eastern side along with associated atmospheric, oceanic and geophysical components, are extremely influential in ensuring the anticipated behaviour for a monsoon over the Indian subcontinent.

Monsoon is a periodical tropical weather phenomenon. Indian subcontinent, located northwards of the equator up to the Himalayas and Hindukush, primarily in the tropical zone of the Northern Hemisphere. Weather pattern involves winds blowing from the south-west direction (known as South-West Monsoon) from the Indian Ocean onto the Indian landmass during the months of June through September. These are generally rain-bearing winds, blowing from sea to land, and bring rains to most parts of the subcontinent. They split into two branches, the Arabian Sea Branch and the Bay of Bengal Branch near the southernmost end of the Indian Peninsula. They are very important for agricultural and economy.

The Himalayas play role of the orographic barriers for Monsoon. They help in its confinement onto the subcontinent. Without it, the southwest monsoon winds would blow right over the Indian subcontinent into China, Afghanistan and Russia without causing any rain. For Northeast monsoon, the highlands of Eastern Ghats play the role of orographic barrier.

1.3 Rainfall Trends

1.3.1 Rainfall trend in globe

According to IPCC (2007), the global surface warming has been taking place at the rate of 0.74±0.18°C in last 100 years (1906-2005). The increased atmospheric moisture content associated with warming lead to increased global mean precipitation. Global annual land mean precipitation showed a small upward trend of rate 1.1 mm per decade over 1901-2005. During the 20th century, precipitation increased from 30°S to 85°N over land and decreased between 10°S to 30°N in the last 30-40 years. There is 7.5% decrease is recorded in western Africa and southern Asia from 1900-2005 whereas over much of northwest India the period 1901-2005 shows increases of more than 20% per century (IPCC,2007). Several researchers have studied trends in
rainfall on global and regional level. Nicholson (2000) recorded that one of the most important contrasts in rainfall is the multi-decadal persistence of anomalies over northern Africa. Nicholson and Grist (2001) had identified several changes in the general atmospheric circulation that have accompanied the shift to drier conditions in West African Sahel. Rodrigo et al. (2000) studied rainfall variability in southern Spain on decadal to centennial time scales. Rotstayn and Lohmann (2002) showed a prominent feature is the drying of the Sahel in North Africa and suggest that the indirect effects of anthropogenic sulphate have contributed to the Sahelian drying trend. Akinremi et al. (2001) reported that there has been a significant increase in rainfall and rainfall events during the most recent 40-years (1956-1995). Increase in annual rainfall was 16% of the 40-year mean, while the number of rainfall events increased by 29% on the Canadian prairies. Murphy and Timbal (2007) reported that most of the rainfall decrease has occurred in autumn (March-May) in Southeastern Australia. Nicholls and Lavery (2006) reported that summer rainfall over much of eastern Australia increased abruptly around 1950s. In the southwest of the Australia, most of the stations recorded a smoother trend to lower winter rainfall and there is a small area with increased rainfall.

1.3.2 Rainfall trends in India

Many studies are carried out to find the trend in rainfall on country and local level. Many past studies concluded that there is no significant trend in average annual rainfall over the country (Kumar et al. 2010; Lal 2001; Thapliylal and Kulshreshta 1991). With regards to monsoon rainfall, on an all-India scale, it is found to be trend less and stable during the past 150 year (Krishnakumar et al. 2009). However, the rainfall distribution is dominated by large inter-annual variability, and it is also marked by spatial contrasts (Krishnakumar et al. 2009). On the Spatial scale, existence of trends was noticed by Parthasarthy (1984) and Rupa Kumar et al. (1992). Parthasarthy (1984) found that the summer monsoon rainfall for the two subdivisions i.e. sub-Himalayan West Bengal & Sikkim and the Bihar plains are having decreasing trends while for the four sub-divisions i.e. Punjab, Konkan & Goa, West Madhya Pradesh and Telangana are having increasing trends. Parthasarathy and Dhar (1974) examined secular variations of regional rainfall over India for the period 1901-1960. They found positive trend over central India and the adjoining parts of the peninsula and two smaller areas in north-west and north-east India. There is negative trend in
some parts of eastern India. Analysis of long-term rainfall trends in India for 135 year (1871-2005) indicates that there is no significant trend in annual, seasonal and monthly rainfall on all India scale (Kumar et al. 2010). Annual and monsoon rainfall decreased, while pre-monsoon, post-monsoon and winter rainfall increased over the years. Rainfall in June, July and September decreased whereas in August rainfall is showing increasing trend. They divided India in 30 subdivisions. Among 30 subdivisions, half of them have increasing trend but only three stations have significant increasing trend. Out of 15 sub-divisions, which are showing decreasing trend only one sub-division had significant decreasing trend. The five main regions i.e. northeast India, central northeast India, northwest India, west central India and peninsular India showed no significant trend for annual, seasonal and monthly rainfall. Rupa Kumar et al. (1992) analyzed monthly monsoon rainfall data of 306 stations spread over India from 1871-1984 for long term trend. Increasing trend recorded along the west coast, north Andhra Pradesh and north-west India and decreasing trend recorded over east Madhya Pradesh, northeast India and part of Gujrat and Kerala. The sub-seasonal patterns indicate the excess of deficiency of the monsoon rainfall is experienced in the later part of the monsoon season. Kothyari and Singh (1996) observed decreasing trend in monsoon rainfall and rainy days in the Ganga basin and monsoon and annual rainfall over India starting around the second half of the 1960s and elaborated by Singh and Sontakke (2002) to be increasing over western Indo-Gangetic Plains and decreasing (statistically insignificantly), however over the central part. IINCC (2004) recorded a decreasing summer monsoon rainfall trend over the state of Uttarakhand. Guhathakurta and Rajeevan (2006) analyzed monsoon rainfall for the period 1901-2003. Pant and Hingane (1988) found increasing trend in mean annual and southwest monsoon over meteorological sub-division of Punjab, Haryana, west Rajasthan and west Madhya Pradesh during the period 1901-1982. Subraamanya and Naidu (1992) examined spatial and temporal variation of the monsoon rainfall over India. Decreasing trend in the central and western India sub-division during the late 19th century and again in the 1960s was observed. Singh and Sontakke (2002) examined summer monsoon rainfall for the period 1829-1999 over the Indo-Gangetic plains. There is significant increasing trend (170 mm/100 year) over western part of Indo-Gangetic plains, non-significant decreasing trend (5 mm/100 year) over central part of IGP from 1939 and non- significant decreasing trend (50 mm/100 year) during 1900-1984 and non-significant increasing trend (480 mm/100 year) during 1984-1999 over
eastern Indo-Gangetic plains. At all-India scale, the monsoon rainfall it is found to be trend less and stable during the past century and a half (Parthasarathy et al. 1993). However, the rainfall distribution is dominated by large inter-annual variability and also marked by spatial contrast (Kolli et al. 1992).

1.4 Weather and climate study in Himalaya

The main reason for the limited number of studies found on the Indian Himalayan region is the lack of information available on precipitation especially at higher altitudes (Singh et al. 1995; Borgaonkar and Pant 2001). Borgaonkar and Pant (2001) found no trend over the Indian Himalayas, particularly western Himalayas. Pant et al. (1999) indicate an increasing trend in post-monsoon rainfall of Dehradun, Pithoragarh and other western Himalayan stations contrasting a decrease in winter. Kumar et al. (2005) found an increasing trend in annual rainfall but decreasing trend in monsoon rainfall over Himachal Pradesh.

Borgaonkar et al. (1998) discussed climate variability over high altitude regions of western Himalaya based on instrumental records and tree-ring data. Daily rainfall and monthly rainfall data of 20 stations over the region do not show any significant long-term trend since last more than hundred years but daily as well as monthly temperature analysis indicates increasing trend since last five decades. Sharma et al. (2012) experienced signals of climate change from monthly rainfall and temperature data of Uttarakhand. Results of the trend analysis and extreme events suggest that the rainfall is highly variable in inter-annual scale but there is no significant long term trend in rainfall. However the temperature has significant increasing trends in maximum, minimum and temperature range, particularly in winters. A quantitative winter severity index for the stations Dehradun and Mukteshwar representing mountain peak and valley topography with data of more than a century and their comparison also throw some light on the orographic interception of western disturbances in winter season resulting into local heavy snowfalls and consequent changes in overall temperatures. Borgaonker et al. (1998) have studied the seasonal patterns and climatological inputs to the hydrology of western Himalaya. Their study concludes that seasonal and yearly rainfall does not show any significant increasing or decreasing trend for last 100 years while post monsoon and winter temperature of western Himalaya experience increasing trend.
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Sen Roy and Balling (2004) analyzed daily rainfall from 1910-2000 for 129 stations and found generally increasing trend in a neighbour region extending from the northwestern Himalaya and decreasing value in the eastern part of the Gangetic plains and parts of Uttarakhand. Basistha et al. (2009) examined change in rainfall pattern in Uttarakhand region using 80-years data from 30 rain gauge stations. The results show that the most probable year of change in annual and monsoon rainfall is 1964. There was increasing trend in rainfall from 1901-1964 and decreasing trend between 1965 and 1980.

1.5 Extreme rainfall events

Studies carried out by various researchers show that, the frequency of more intense rainfall events in India, Bangladesh, Nepal and other part of Asia has increased while number of rainy days and total annual precipitation has decreased (Dash et al. 2007; Goswami et al. 2006; Sinharay et al. 1999, Min et al. 2003; Khan et al. 2000; Lal 2003; Shrestha et al. 2000; Mirza 2002). The global sea level will rise between 0.09 to 0.88 m in the period 1990 to 2100 and the frequency of extreme events like excessive rainfall, flash flood, droughts, cyclones and forest fires are likely to increase (IPCC 2001). The combined effect of climate change and increase in extreme events is expected to lead to significant impacts on various systems. A high-resolution daily 1° x 1° gridded data set has been constructed by Rajeevan et al. (2006) for the period 1951–2004 based on 1803 stations distributed all over the country. This data set was used by Goswami et al. (2006) to demonstrate that both the frequency of occurrence and intensity of extreme rainfall events over the central India show a significant increasing trend, while low and moderate events show a significant decreasing trend over the past 50 years. The results of this study were contradicted for some places when analysis was performed at finer resolution by Ghosh et al. (2009). Rakhecha and Soman (1994) analyzed extreme events from 1 to 3 days duration for 316 stations across India for 80 years (1901-1980) rainfall and found that the annual extreme rainfall records of most stations are trend less. However, the extreme rainfall series at stations over the west coast north of 12°N and at some stations to the east of the Western Ghats over the central parts of the Peninsula showed a significant increasing trend at 95% level of confidence. Stations over the southern Peninsula and over the lower Ganga valley have been found to exhibit a decreasing trend at the same
level of significance. Pal and Tabba (2009) recorded that the magnitude of the regional differences are very high and a negative tendency leading to increasing frequency and magnitude of monsoon rainfall deficit and decreasing frequency and magnitude of monsoon rainfall excess. Variability of extreme rainfall events over India during southwest monsoon season for 1951-2005 was studied by Pattanaik and Rajeevan (2009). The average frequency of extreme rainfall events along with the contribution of extreme rainfall events to the seasonal rainfall shows a significant increasing trend (above the 98% confidence interval) over India during JJAS as well as in June and July. Increasing trend of contribution from extreme rainfall events during monsoon is balanced by decreasing in low rainfall events. Using 104 year of high resolution daily gridded rainfall data, Rajeevan et al. (2008) examined variability and long term trends of extreme rainfall events over central India. They found that increasing trend of extreme rainfall events in the last five decade are associated with the increasing trend of sea surface temperature and surface latent heat flux over the Tropical Indian Ocean. Trends in precipitation extremes over India for the period 1901-2000 were examined for 100 stations by Joshi and Rajeevan (2006). Results of the study show that most of the extreme indices have shown significant positive trends over the west coast and north-western parts of Peninsula whereas two hilly stations i.e. Shimla and Mahabaleshwar have shown decreasing trend in some extreme rainfall indices. Sen Roy and Balling (2004) analyzed daily rainfall data of 129 stations for the period 1910-2000 and found increasing trend in a contiguous region extending from the north western Himalayas in Kashmir through most of the Decan Plateau in the south and decreasing values in the eastern part of the Gangetic plain and parts of Uttarakhand.

1.6 Precipitable Water Vapour

Water vapour is the engine of the weather. Due to large latent energy associated with it, phase changes of water significantly affects the vertical stability, structure and the energy balance of the atmosphere. Jade et al. (2005) have analyzed the integrated water vapour (IWV) estimates from GPS data of Bangalore, Kodaikanal, Hanle and Shillong over a period of 3-years (2001-2003). Prasad et al. (2007) have given that water vapour estimates obtained from GPS data and MODIS is found to be highly variable over Indo-Gangtic plain which is agriculturally very
productive. Kumar et al. (2009) examined the variability of GPS derived water vapour and MODIS water vapour over the northern Indian plains (IIT Kanpur and BHU Varanasi). Water vapour over these two regions show characteristic changes associated with meteorological parameters showing a close relationship with the dynamics of monsoon. The study carried out by Kurekar and Kuraishi (2012) at IIT Bombay indicates that GPS technology can be effectively used for the determination of PWV in near real time. Musa et al. (2011) have investigated that the potential of applying GPS meteorology in the peninsular Malaysia. They compared GPS derived IWV with radiosonde derived IWV and indicated that RMS value of range difference is in between 3.447 to 4.253 kg/m² and linear co-relation coefficient ranges from 0.797 to 0.877. Most of these studies focus on plain areas without any topographic barriers. There is a lack of understanding of the weather system that is important for winter and monsoon precipitation in the central Himalaya.

Joshi et al. (2013) calculate Precipitable Water Vapour (PWV) values using GPS geodesy and observed meteorological data. PWV shows a large increment in values with the monsoon initiation (later June and early July) and with the phase of monsoon (July to September) in all three years (2009-2011). Moderate Resolution Imaging Spectroradiometer near-infrared (MODIS NIR) clear column water vapour product shows a higher correlation with GPS derived precipitable water vapour on annual scale as compared to the seasonal scale. The seasonal dependency is reflected in terms of bias and RMSE differences between PWV$_{GPS}$ and PWV$_{MOD}$, which shows the effect of cloud and wet atmospheric condition. The MODIS NIR clear column water vapour product show overestimation compared to GPS estimation in all season. The PWV$_{GPS}$ values drop after the rainfall event. PWV$_{GPS}$ depends on surface temperature, monsoon onset and rainfall pattern. PWV$_{GPS}$ value increases in the afternoon to evening then the PWV$_{GPS}$ value again decreases in both the seasons. These results suggest that diurnal variation of water vapour is caused by the transport of water vapour by thermally induced local circulation.

1.7 Wind speed

Variation in long term wind speed during different decades in Arabian Sea and Bay of Bengal is examined by Kumar and Philip (2010). Study shows the inter-decadal variability of extreme winds in three selected locations i.e. Off Goa,
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Vishakhapatnam and Machilipatnam in north Indian Ocean. There is no significant increasing trend in extreme wind speeds in any of the locations. At Off Goa, a gradual decrease, a slight increase in Machilipatnam and for Vishakhapatnam neither decreasing nor increasing trend was found. A study on prospects and challenges of decentralized wind applications in the Himalayan terrain is carried out by Ramchandra and Krishnadas (2012). Wind speed in the range of 1-3.25 m/s were seen during monsoon season, 0.75-2.25 m/s during post-monsoon and winter season and 1.25-3 m/s during summer and pre-monsoon season. High elevation zone i.e. Lahaul Spiti, Kinnaur, Kullu and Shimla districts showed wind speed above 2 m/s for all seasons and identified as suitable candidates for further wind exploration. Wind potential in Himachal Pradesh is observed to be suitable for small-scale wind applications i.e. low wind speed turbines, agricultural water-pumps, wind-solar hybrids, battery charging etc.

1.8 Relative Humidity

Dai (2006) found statistically significant increasing trend in global and northern Hemisphere average specific humidity since 1970, while trends in relative humidity were small. These trends in humidity corresponds to the observed changes in temperature in a quantitatively similar way to that which would be expected due to the Clausius–Clapeyron relationship. Seasonal and inter-annual variations and linear trends are analyzed in relation to observed surface temperature changes and simulated changes by a coupled climate model (Parallel Climate Model (PCM)) with realistic forcing. Spatial patterns of long-term mean of specific humidity are largely controlled by climatological surface temperature, with the largest specific humidity of 17–19 g kg⁻¹ in the Tropics and large seasonal variations over northern mid and high-latitude land. Surface RH has relatively small spatial and inter-annual variations, with a mean value of 75%–80% over most oceans in all seasons and 70%–80% over most land areas except for deserts and high terrain, where RH is 30%–60%. Night time mean RH is 2%–15% higher than daytime RH over most land areas because of large diurnal temperature variations. The leading EOFs in both specific humidity and relative humidity depict long-term trends, while the second EOF of specific humidity is related to the El Niño–Southern Oscillation (ENSO). During 1976–2004, global changes in surface RH are small (within 0.6% for absolute values), although
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decreasing trends of $-0.11\% - 0.22\%$ decade$^{-1}$ for global oceans are statistically significant. Large RH increases (0.5%-2.0% decade$^{-1}$) occurred over the central and eastern United States, India, and western China, resulting from large specific humidity increases coupled with moderate warming and increases in low clouds over these regions during 1976–2004. Relative humidity over Chota Sigri glacier was found to vary between 12-99 %. The half hourly variation in relative humidity was also observed. The maximum relative humidity was observed during night while minimum was observed between 12:00 noon to 1:00 pm. Trend analysis of weather variables in Sagar Island Bengal, India a long term perspective (1982-2010) by Mandal et al. (2013) found that rising trend in long period average (LPA) maximum and average temperature and because of its strategic selling in the delta region surrounded by coastal lines all water vapours are continuously flushing to the atmosphere of Sagar Island. This may be one of the reasons for increasing trend in relative humidity of the land. Relative humidity increases by 7% with every 1K increase in surface temperature. Ahmed et al. (2007) examined recent changes in relative humidity in Jordan. The analysis indicates an increasing trend in relative humidity at different stations. At Amman Airport Meteorological (AAM) station, significant increasing trend with rate 0.13% per year is recorded. These increasing trends are statistically significant during summer and autumn season. A major change point in relative humidity occurred in 1979 at AAM station.

1.9 Motivation

Weather and climate study is important for making the present sense of our world and plan for the future. Climate information guided us to take decision like, crop to grow, size and design of water management plan, advanced planning of weather relate disease spread, disaster mitigation, etc. Weather forecasts help us planning for short period like few hours to few days, but climate information helps us planning for a long period i.e. months to decades. More often the weather and climate system is not similar i.e. the year to year or months to month variation in the weather and climate parameters are very high and the weather system is very non linear and chaotic and sometimes the weather system become unstable resulting various severe or extreme events so more accurate prediction of severe weather can help us to reduce the losses due to the hydro meteorological disaster events. Climate information is very
useful from the hydrological point of view, for efficient and smooth agriculture operations, forest management and also provides some glimpse on human activities causing the changes in the regional environment.

Mountains are among the regions, which are most sensitive to climate change. Mountains play a major role in influencing regional and global climate system. They act as barriers for wind flow, which induce precipitation on the windward side, and reduce precipitation and warmer temperatures on the leeward side causing different weather and climate pattern in the both side of mountains. Changes in atmospheric wind flow patterns may induce large and locally varying precipitation responses in mountain areas, which could be much stronger than average regional climate change (IPCC 2007). During winter, the high Himalayas interact with the strong winds of the upper-level subtropical jet stream (Moore 2004). During summer, moist southerly flows from the Bay of Bengal impact on the Himalayas, with the subsequent release of latent heat playing an important role in amplifying the circulation of the monsoon (Kennett and Toumi 2005). The Himalayas are also the source of three of the world’s largest rivers, the Indus, Ganges and Brahmaputra, which supply water to hundreds of millions of people. Understanding of the interactions between weather systems and the complex Himalayan topography is essential for making accurate predictions of future climate change in the region, However, substantial uncertainty in weather and climate processes in the Himalayas remains, partly due to the lack of meteorological observations in this remote region. For example, there are no radiosonde stations in the central Himalayas (Lang and Barros 2002).

The Himalayan region is an essential part of the global mountains with very rich biological and environmental resources. It serves as the water reservoir and a regulator of climate for the region and the subcontinent. The climate of Indian Himalaya is governed by the extra–tropical weather systems of Asia. The central Himalayan region which covers Uttarakhand state is a hot spot in the global climate system in terms of its unique geographical features. It is also a region of a fragile ecosystem of diverse flora and fauna that are sensitive to the changes in the climate. However, very little is known about the details of weather and climatic variability over this region. At the same time, conclusions derived over other locations, may not be applicable over the Himalayan region. Information about the long term climate is
important to understand the nature of different climatic systems over any region. There are very few studies available about climatic condition of Himalayan region (Pant and Borgaonkar, 1984) however such information is very important for different sectors like the water resources, agriculture operations and resource management, etc. Most of the studies over the region deal with the climatic conditions over the specific locations (Dhar and Farooqui, 1973)

Rainfall studies in the Himalayan region are also limited due to the lack of information on rainfall at high altitudes. Literature reveals that studies related to spatial distribution were carried out in other parts of the Himalayan range; however the spatial variability in this region is still unexplored. Vulnerability and sustainability are primarily local issues; depend on the amount and temporal distribution of rainfall received over a region. Thus, rainfall patterns need to be examined in a local perspective (Goswami and Ramesh 2007). Every year several events of hazards are reported from all parts of Indian Himalayan Region (IHR) and causing loss of lives (human and animal) along with their property (Kumar and Satyal 1999). In this context, the knowledge of the space-time distribution of rainfall as well as extreme rain events in the region is critical for disaster preparedness. However, no good documentation of the space-time distribution of extreme rain events exists over the region because of lack of good high-resolution rainfall data and this become a less explored study. Thus, in the Himalayan region, poor availability of climate data has been a major constraint in such studies. In this context, the present study focuses on recent climate trends along different altitudinal transect of central Himalaya based on multi-source observed data and simulation using a variable resolution general circulation model.

1.10 Himalayan Environment and its Ecosystem

Himalaya constitutes one of the greatest and youngest folded mountain systems in the world rising from ~1000 m to more than 8000m above mean sea level. The Indian Himalayan Region (IHR) lying between 21°57’ – 37° 5’N latitudes and 72° 40’ – 97° 25’E longitudes occupies an strategic position & forms the entire northern boundary (North-West to North-East) of the nation and touches as many as seven international borders with India. This great chain of mountains in Indian territory extends all along the northern front of the country, from the eastern border of Pakistan
on the west to the frontiers of Myanmar in the east for about 2,500 km in length with an average width of 240 km. The IHR covers an area of about 5 lakh km$^2$ and contributes about 16.2% of India's total geographical area. Orographically, the Himalayan mountain system is divided into greater Himalaya (Himadri) - area above the main central thrust consisting of snow-clad peaks, glaciers, and ranges of majestic mountains; Lesser Himalaya (Himanchal) - separated from the Himadri by the 'main central thrust' in the north and by the 'main boundary thrust' in the south, consisting of high mountains cut into deep ravines and precipitous defiles; and the Sub-Himalayan tract (Sivalik) - the foot-hill belt of the region - consisting of latest geological formation of loose boulders and soil (Nandy et al., 2006).

The topography of the study area is shown in the following Figure. 1.1. The elevation of the Tibetan Plateau is more than 4000 m asl. One of the characteristics of the topography over the Tibetan Plateau is the large undulation in the north–south direction. The major mountain ranges and valleys are oriented in an east–west direction over the Tibetan Plateau. On the other hand, the Gangetic Plains in India is a low-elevated land in this domain. Smaller mountains also exist around the northern Indian subcontinent. The Himalayas, an approximately SE–NW trending mountain range, are located on the verge of 27.0°–32.0°N, 77.0°–92.0°E, in south Asia. East of 84.0°E, the mountains run roughly E–W, while to the west of 84.0°E the barrier is arranged ESE–WNW. The southern slope of the Himalayas is steep. Most of the river valleys are approximately oriented in the north–south direction and orography has large undulations in this region. The Hindukush Mountains lie to the west of the Himalayas and extend up north of Pakistan. The Himalayan range provides a huge barrier to the flow in this region. The summer monsoon depressions collide with them from the south-southeast direction and undergo strong orographic capture because of the favourable geometry of the Himalayas. Conversely, westerly disturbances encroach them from the west-southwest direction.
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Figure 1.1: Topography of Himalayan Region.

In a north-south sequence, the geo-geographical regions of Central Himalaya, Uttarakhand may be delineated as follows (Joshi 2004):

The Trans Himalaya- It is situated north and north east direction of the Greater Himalaya and extending northwards upto the Indo-Tibetan border. The range of elevation is between 4500-5700 amsl

The Greater Himalaya- It is the zone of perpetual snow characterized by many high peaks with numerous mountains and valley glaciers. This highest zone, with maximum elevations constitutes of the high snow peaks between 6000-7000 amsl while a vast zone adjacent to it is occupied by glaciers and snowfield with altitudes varying between 4000-6000 amsl. Besides this, the southern part of the greater Himalaya is characterized by steep slope areas falling between elevations of 3000 to 4000 amsl.

The region is characterized by a varied relief-consisting of deep river valleys, the ridge and mid-slope areas and the high upland zones. Towards the north, the altitudinal range in the valleys is between 1800-2800 amsl, while to the south, the
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altitudes in the valleys are much lower and the elevations ranges between 800 amsl and 1400 amsl.

The Siwalik range-It is the outermost and the youngest region. These are also the lowest ranges of the Himalaya and the altitude varies between 500 amsl along the deep river valleys to about 1200 amsl at the ridge tops.

The Foothills- This undulating country at the foothills of the Himalaya is made of a variety of detritus brought down by the swift surface flow along the south face of the Shiwalik. According to the situation and slope conditions, this zone may further be divided into two categories:

(a)Bhabhar and The Dun Valleys- This region situated next to the Siwalik and have either an undulating topography or an identical substratum containing river borne detritus. This zone, on an average, has an altitude of 500 amsl.

(b)Tarai and the Plains-Tarai extends further south of the Bhabar and is characterized by a deposit of fine sediments carried by streams flowing down the Bhabar zone, while Bhabar has a porous substratum, the water disappearing in Bhabhar, reappears at surface at the junction of Bhabar and Tarai-rendering the Tarai, a zone of superabundance of water. Further southwards, the end of the Tarai, where form begins the Plains of North India. These are the lowest parts in Uttarakhand with an altitude of 200 amsl or less. There is a general decrease of altitude towards the south.

1.11 Challenges in multi-scale observation and simulation

Both in terms of statistical quantities like mean and standard deviation and in terms of change, the meteorological fields exhibit significant spatio-temporal variability. While the spatial variability is an indicator of inhomogeneity in the local forcing like orography, temporal variability contains effects of various low- frequency quasi-periodic oscillations. Besides, estimates of mean and standard deviation do not necessarily provide accurate information of change (Ramesh and Goswami 2014). Thus multi-scale analyses are important for drawing accurate and reliable conclusions for regional climate change. However, such multi-scale analysis is challenging for both observational and simulation studies. In case of observations, such multi-scale analysis requires sustained, multi-variable observations over different climatically
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diverse locations. Establishment and maintenance of such observation network is a major challenge. In terms of simulations, attaining accuracy at required resolution remains a challenge; on the other hand, coarse resolution simulations and projections do not provide a database suitable for regional analysis.

1.12 Simulation study

Based on the various outputs of equilibrium General Circulation Model (GCM) experiments, the Third Assessment Report of IPCC suggest that under the combined influence of GHGs and sulfate aerosols, climate may warm globally by 1.4 to 5.8°C in next 100 years (IPCC 2001). Dimri (2012b) studied winterline land surface characteristics of climatic simulation over the western Himalaya using ICTP-RegCM3.

Simulation and forecasting of the Indian Summer Monsoon (ISM) has remained a major scientific challenge; the challenge is greater at smaller (regional) scale. At the same time, actionable knowledge requires reliable simulation and forecasting at regional scale. This is particularly true for regions like the Himalaya characterized by large orography. The challenges involved in seasonal forecasting of monsoon rainfall are well known; in spite of decades of efforts, even models with increasing complexity fail to provide forecasts of even all-India seasonal rainfall with adequate accuracy sufficiently in advance. However, significant uncertainties still exist regarding the reliability of the projections from the dynamical climate models, especially for regional systems like the Webster et al. (1998), Meehl et al. (2007) and Turner and Annamalai (2012). The global circulation models today generally possess superior skill in seasonal forecasting than statistical models, and can be evaluated in hindcast mode; especially over areas with contribution from natural climate variability, such as the Indian monsoon (DelSole and shukla 2012; Deser et al. 2012; Goswami et al. 2006). In spite of their common basic mechanism, monsoons over different regions are subject to diverse forcings; thus the responses of the various regional monsoons to a changing climate are expected to vary (Meehl et al. 2007; Turner and Annamalai 2012; Kitoh et al. 2013).

Most of the models now simulate the annual cycle of rainfall over India fairly accurately; the spread in the simulations is not unacceptably high (Rajeevan et al.
2006; Wang and Ding 2006). Several studies have examined simulation of ISM using GCM (Ajaymohan 2007; Sabin et al. 2013; Kitoh and Kusunoki 2009). However not many works have examined seasonal forecasts over the Himalayan region.

Several works have investigated application if variable resolution GCM (VR GCM) and an inter-comparison of stretched grid models (SGMIP) was reported (Fox-Rabinovitz et al. 2006). VR GCM have been also used to simulate of East Asian summer monsoon (Zhou and Li 2002), tropical dynamics (Hourdin et al. 2006). Several studies have also examined simulation at smaller regional scale like north India (Tiwari et al 2014), Hindukush region (Kulkarni et al. 2013) and the Western Ghat (Rajendran et al. 2012). However these are essentially simulation studies and do not quantify forecast skill. However an assessment of skill over the Himalayan region has both potential for application as well as further enhancing our knowledge of this system.

1.13 Objectives

The present study is being carried out with the following major objectives:

- Development of a comprehensive, multi-source data set for the Himalayan region by combining archived data, analysis and fresh observations.
- Investigation of the weather and climate of the Himalayan region at different spatial and temporal (decades to days) scale using observation and simulation.
- Identification of long-term trends in the regional climate and investigation of relative roles of various local Vs large-scale processes in the observed trends.
- Performance analysis of General Circulation Model (GCM) in the simulation of weather and climate parameters over Himalayan region.

The present study is being carried out in the following major steps:

- Collection of long term data of climate from different sources.
- Compilation of long-period observations and analysis from different sources.
- Generation and analysis of high-frequency local observations to fill the data gaps and for calibration and validation.
- Compilation of model simulations to create a homogeneous and high-resolution data set.
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- Determination of relative weights of various analyses and model simulations for the region by using local observations
- Comparison and quantification of relative roles of large-scale (such as global circulation, sea surface temperature) and local (such as orography and vegetation) processes in regional weather and climate.
- GPS data archiving, processing and to identify (and if needed modify) the best-fit model for atmospheric correction used by GPS processing software for the study area.

Such a study can provide useful information on regional climate change based on multiple lines of evidence and can allow assessment of vulnerability based on observations, analysis and model simulations.

1.14 Organization of the thesis

The present thesis consists of seven chapters. A brief summary of the work presented in different chapters is described below.

In the present chapter (i.e. Chapter-1) we have presented detailed description about weather and climate parameters i.e. rainfall, temperature, precipitable water vapour, wind speed and relative humidity and their review of literature. We have also discussed temperature and rainfall trend over globe and India, monsoon process over Indian region, and weather and climate study over Uttarakhand. A detailed description about simulation study carried out over India and Himalayan region, Himalayan environment and its ecosystem and challenges in multi-scale observation and simulation has also been presented in this chapter.

The analysis and the results described in this thesis are based on the data set from various instrument, multiscale observation and simulation. For long term data we have used multisource data. Detailed information about these data sources and GCM model configuration are presented in Chapter-2.

In Chapter-3 we have presented detailed analysis of climatology and trends over the central Himalaya. In this chapter we had elaborate spatial and temporal trend of each climate parameter.
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In Chapter-4 we have investigated pattern analysis of the climate parameters and the physical mechanism of the weather and climate variability in the different parameters. In this chapter, we have also discussed teleconnection of the large scale processes with the rainfall over the Himalayan region.

In Chapter-5 we have studied water vapour study over central Himalaya Uttarakhand. In this chapter, we have discussed water vapour study using GPS geodesy and its comparison with MODIS water vapour and NCEP water vapour.

Simulation of rainfall using GCM and performance of GCM over central Himalaya India is presented in Chapter 6. In this chapter, we have elaborated seasonal forecast skill over central Himalaya with an Atmospheric General circulation Model (AGCM)

Finally Chapter-7 summarizes the main conclusions of the present work and gives an outline of the future research plans in this area.