Chapter 2
The Himalaya

अस्त्युत्तरस्यां दिशि देवतात्मा हिमालयो नाम नगाधिराजः।
पूर्वापरौ तोयनिधी विगाह्य स्थितः पृथिव्या इव मानदण्डः॥

[In the north, there stands Himalaya the King of the Mountains, having a divine soul. It exists like a measuring rod of the earth, having reached the eastern and western seas]
Kalidasa—Kumarsambhava 1.1

2.1 Evolution of Himalaya and Present Geographical Setting

The earth as a planet of the solar system is estimated to have formed about 4.6 billion years ago. It has gone through many evolutionary geological and biological changes and formations during the course of its journey to the present day lively

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planet. One of the most important geological events in the history of the earth during the last 100 million years is the formation of the Himalaya. German meteorologist and geophysicist Alfred Lothar Wegener (1880-1930 AD) proposed the theory of continental drift based on the principle of plate tectonics in 1912 AD to explain the mechanism of changes in the surface layers of the earth. This theory postulates that the upper crest of the earth consists of a combination of solid drifting plates which glide over or may even collide with each other. Accordingly, the geologists suggest that around 125 million years before present (mybp) the earth's crust with drifting land masses was constituted of two major continents, Laurasia and Gondwanaland separated by Tethys Sea. The Gondwanaland comprised peninsular India, Australia, Madagaskar, Africa, and South America (all of which can be seen to fit together into one mass, like the pieces of a jigsaw puzzle).

Gigantic earth movements and volcanic eruptions separated the continents from the Gondwanaland. Northward journey of Indian plate relative to Australia and Antarctica is estimated to have started around 120 mybp. It is estimated that by about 55 mybp the Indian subcontinent was close to its present position as a breakaway piece from the giant Gondwanaland. The mighty Himalayan ranges emerged due to the impact of the Indian land mass with the Asian land mass to its north, followed by a phased uplift between 50 and 40 mybp. This uplift was a result of the continuous upward push of the Indian land mass in phased manner. The most recent phase which occurred about a million years ago gave the mountain ranges its present geomorphic form. The fault lines along the impact regions are fragile and contain the belts of volcanic and seismic activity. An example of this is what was witnessed during the recent devastating earthquake across central Himalaya with its center over Nepal followed by an equally strong earthquake in the north-west Himalaya in the year 2015.

The Himalaya which literally means abode of snow is the greatest east-west oriented mountain range of the world constituting of the youngest mountain system on the Earth, still rising in its height and drifting northward at a slow pace of about a meter per century. These mountain ranges are extensively spread from west to east in a total length of about 2500 Km all along the northern boundary of the Indian subcontinent from Pakistan in the west to frontiers of Myanmar in east and have an average north-south extent of about 200 km. the geographical map of south Asia depicting Himalaya is given by Fig. 2.1. The term Himalaya includes the snow-covered mountain peaks, extensive mountain ranges rising from northern plains of the Indian subcontinent up to the Tibetan Plateau. It is characterized by vast biomass reserve, highly fragile ecosystem with many earthquake and landslide prone zones, large biodiversity, and a chain of glaciers linked to extensive network of rivers with perennial source of freshwater.

The northern most ranges of Himalaya are well known for their scenic beauty with lofty snow-covered mountain peaks garlanded by rivers and glaciers. Out of the mountain peaks of varying altitudes about a dozen of them rising up to 8000 meters above mean sea level (asl) or higher lead by the world's highest peak, the Mount Everest. The glaciers of Himalaya account for about 70% of the nonpolar-glaciated regions of the earth. The great south Asian rivers, the Indus with tributaries, and the Yamuna, Ganga, and Brahmaputra originate from the glaciers and mountain

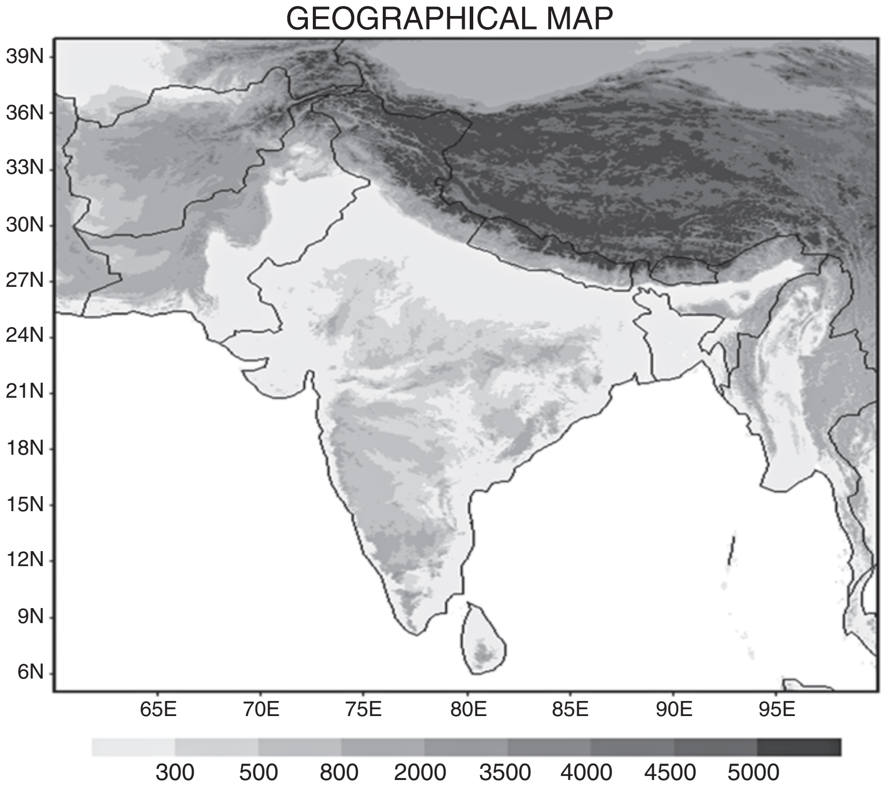

Fig. 2.1 Topographical map of the South Asian region depicting the Himalaya, the shades indicate altitude in meter

lakes of western and central Himalaya, while many tributaries of river Ganga arise from Nepal Himalaya. The river Brahmaputra traverses a long distance almost parallel to Himalayan ranges along its journey from central regions of Tibet to the Bay of Bengal through the mountains of north-east India.

Three major geological fold axes which constitute the Himalaya, Himadri (greater Himalaya), Himachal (lesser Himalaya), and Shiwalik (outer Himalaya), extend almost uninterrupted throughout its length. Geographically, the Himalaya generally described as an east-west mountain range has north-west to south-east orientation and the arc-like structure with enhanced southward slope to the east makes the eastern edges of Himalaya extending into eastern India and Myanmar. The western margins are located in Karakoram at about 37°N while the eastern ranges of Arunachal Pradesh are located around 27°N. Along its length the Himalaya can be divided into three sections: Western Himalaya (Hindukush Mountains, Jammu and Kashmir, Northern Punjab, and the Western Himachal Pradesh), Central Himalaya (Eastern Himachal Pradesh, Uttarakhand, and Western Nepal), Eastern Himalaya (Eastern Nepal, North-East India, Bhutan, and Myanmar). The enhanced southward slope to the east makes the eastern edges of Himalaya more close to the tropical weather under the influence of the dominating monsoons; whereas, the western most parts are away from the tropical influences and enjoy contrastingly different weather of middle latitudes.

The meteorology of high and extensive mountain regions like the Himalaya is a unique example of direct interaction of high altitude mountains with complex terrain and locally originating atmospheric weather patterns as well as the large-scale migratory weather systems. The mountain systems provide highly variable and relatively less predictable weather patterns due to the influence of orography on the large-scale atmospheric flow. This effect gets further complicated by dynamic perturbations caused by the orographic barriers and surface boundary forcings induced at the rough terrains. The mountains in general exert frictional influences on surface winds, create barriers to wind and weather systems and induce vertical ascents and gliding flows across the valley. The mountains interact with the weather systems at different temporal and spatial scales with a capacity to create substantial modifications to the characteristics of these systems. The interactions can be at the level of synoptic scale weather system (fronts and waves), mesoscale mountain valley circulation and gravity waves, forced vertical ascents due to orographic barriers to individual convective cells and the cloud bands. Some of the micrometeorological measurements made over a location (Nainital) in the central Himalayan region providing the information on how the complex and mountainous orography influences the surface winds are discussed in Chap. 3.

2.2 Weather and Climate

Large variation in topography, elevation, soil, rock structure, and vegetation cover result into contrasting climates within short distances in the mountain ranges along their extensive west-east spread. Broadly speaking, the Himalayan climate has prolonged winters and equally long summers, which include the monsoons in its southern periphery. Besides these local variations of weather, the Himalaya in general experiences a weather pattern dictated by the monsoon systems of Asia to its south and the weather patterns of the middle latitudes to its northern parts. The interface between the tropical and extratropical weather at higher altitudes create conditions highly conducive for high intensity extreme weather events. The transition seasons between winter to summer and summer to winter, akin to the spring and fall seasons of the extratropical regions, are not as distinct as experienced over the peninsular India, where they are often referred as pre- and post-monsoon seasons.

Proximity of Eastern Himalaya to Bay of Bengal accounts for the warm humid weather and an extended period of monsoon over the region compared to its western counterpart where generally dry weather prevails during the south-west monsoon, specifically to its western most periphery. The Himalaya functions as a great mountain wall dividing the climates of south and central Asian region. In winter, the great Himalayan ranges serve as effective barriers to the intensely cold continental air blowing southwards to the Indian subcontinent. These winds in the form of the north-east monsoon are blocked by the Himalaya from direct passage towards the south and are diverted further east providing some rain to the east coast of India in winter. This leaves rest of the Indian subcontinent practically free from these wind systems and winter rains. During northern hemispheric summer, the Himalaya forces the moisture bearing monsoon winds up the mountains to deposit most of their moisture over the southern slopes of the mountain ranges.

The Tibetan plateau at the top of the mountains acts as a high level heat source for large-scale monsoon circulation. The plateau with an elevation of about five kilometers is strongly heated by incoming solar radiation and is dominated by Tibetan high pressure belt. These conditions establish an anticyclonic circulation (clockwise) in the upper troposphere over a large area leading to easterlies all over the south Asian subcontinent at these levels. The Tibetan plateau with flat land and high elevation provides source of heat to the atmosphere with maximum in late spring and early summer. The intensity and interannual variability of its strength considerably influences monsoon activity over large parts of South Asia. The role of the Himalaya and Tibetan plateau system in generation and maintenance of South Asian summer monsoon is demonstrated in numerical simulation models by Godbole (1973) and Hahn and Manabe (1975). These simulations have shown that the monsoon circulation becomes practically absent when the mountain influence is removed from the model.

The snow-covered mountain ranges have high Albedo, an expression for whiteness or incident light. The albedo of a surface is defined as the ratio of reflected radiation from the surface to the radiation incident up on it, expressed as a dimensionless quantity. High albedo provides an important feedback to the climate system by providing a highly reflecting snow-covered surface for the incoming solar radiation which absorbs less energy and accelerates the growth of area under snow with extension of higher albedo area. It is generally inferred that the net albedo of the Earth is showing a decreasing trend as the snow and ice on the planet are melting as a result of the global warming.

As the white reflecting snow cover decreases in area, less energy is reflected into space and the warming of the Earth's surface gets enhanced. Over the oceanic regions, the disappearing ice while decreasing albedo triggers a positive feedback by exposing the oceanic surface to sunlight to warm the water. Keeping in mind the importance of the white snow cover in climate change and its numerous impacts on the Earth's surface, some scientists often suggest many impractical suggestions such as the spraying of black carbon shoot over the snow surface to alter the albedo.

Predicting the performance of monsoon rains over India on seasonal scale has been a challenging task for meteorologists, and it is interesting to note that the Himalaya has been the first to provide a predictor parameter to seasonal forecasts of monsoon rains. Henry Francis Blanford (British, 1834–1893 AD), the distinguished geologist and the Imperial Meteorological Reporter in India, appointed in the wake of the devastating cyclone of Bengal in the year 1864 AD was especially assigned the responsibility to develop the seasonal monsoon forecast. He put forth the hypothesis that varying extent and thickness of the Himalayan snow exercises a great and prolonged influence on the climate conditions and weather of the plains of north

India (Blanford 1884). The success of his tentative forecast during 1882–1885 AD for the monsoon season based on the Himalayan snow cover as leading predictor encouraged him to start the operational Long Range Forecast (LRF) of monsoon rainfall covering the then entire region of India and Burma in 1886 AD. The LRF efforts during the periods of severe and prolonged droughts over India in late nineteenth and early twentieth century using simple statistical correlations have unfolded many large-scale features of tropical circulations and the summer monsoon.

His successor Sir Gilbert Thomas Walker (British, 1868–1958 AD) following the severe monsoon failure of 1899 AD extensively studied the data over much of the tropical Oceans with focus on the Indian and Pacific region, the guiding principle being that the monsoon circulation may have large-scale global connections. These global influences subsequently became popular as the teleconnections. These efforts retained the influence of the Himalaya while adding a new parameter of oceanic origin to the LRF equations. This leads to the discovery of a see-saw oscillation of atmospheric pressure between the Indian and Pacific Ocean known as the Southern Oscillation which was later named after him as Walker Circulation (Walker 1918). His statistical analysis incorporating the data from global tropics and the Eurasian region established the foundation of the LRF of monsoon rains over India. Subsequent LRF for the monsoon season prepared by India Meteorological Department (IMD) used three predictors and the first among them remained the Himalayan snow cover for the period October to May. The practice continued till recently when multiparameter statistical models and dynamical general circulation models (GCMs) replaced these original prediction equations. However, the influence of Himalayan climate in the present day statistical and dynamical models of LRF continue to be represented as a manifestation of the tropical–extratropical interaction in some form or the other.

These early attempts during 1880–1920 AD in associating the snow cover over the greater Himalaya and deficient monsoon rainfall over India have distinctly emphasized the role of Himalaya in influencing the monsoon circulation. In the recent years, the availability of reliable and extensive satellite-based estimates of snow cover over Eurasia (Himalaya constituting the major part) have revived interest in the subject (Hahn and Shukla 1976; Dey and Bhanukumar 1983; Dickson 1984; Bhanukumar 1989; Saha et al. 2013) and broadly confirmed the existing concepts. It is highly significant to note that this concept has been under continuous validation for more than one and half a century and it is now accepted that the spatial extent of Himalayan snow cover during winter is an important slowly varying boundary condition for the subsequent development of monsoon circulation over the south Asia. Broadly speaking, an enhanced accumulation and extent of snow during the winter months is most likely to be followed by a weak monsoon (Parthasarathy and Yang 1995; Vernekar et al. 1995).

The parameters representing anomalous behavior of the sea surface temperatures of the southern Oceans more specifically represented by the indices of El-Nino and southern oscillation, a circulation anomaly over the Pacific and Indian Ocean region, now constitute the dominating climate feature on interannual scale. The climatologists commonly refer them as a combined term called ENSO. The ENSO therefore constitute an equally important predictor parameter having a complex but dominating relationship with the South Asian summer monsoon (Pant and Parthasarathy 1981). The other most important effect of the Himalaya on the summer monsoon over South Asia is the location of heat low (a low pressure area caused by the heated land and air over Sindh and adjoining areas prior to full establishment of the summer monsoon) and also the monsoon trough (lower atmospheric pressure belt with extensive convergence of moist winds at lower altitude levels) across north India. These low pressure centers along the convergence zone for moist air have their dynamical and thermodynamical origin. The location of trough axis along foothills of the Himalaya after its formation is influenced by the mountains and hill configuration and the orographic lifting helps in its buildup and sustenance. The mountains in general influence the atmospheric flow as a result of mechanical lifting and also through the heating due to condensation, which in turn is caused by air ascending over the mountain barriers.

The Himalayan mountain ranges are located in the subtropical high pressure belt where the seasonal north-south migration of pressure and wind systems generally alters the seasonal weather. In winter, the mid-latitude weather systems approaching from the Mediterranean region sweep over the mountain ranges and precipitation is abundant and mostly associated with the troughs and low pressure systems embedded in these circulations known as Western Disturbances (WDs) (Madhura et al. 2015). These winter circulations and disturbances bring in cold winds and precipitation in the form of rain and snow over north India which is the only source of snow to higher mountain ranges of the Himalaya. This influence is most prominent in Western Himalaya than the eastern one. The amount of snow depends on the altitude of the mountains and the intensity and frequency of the weather systems impinging upon them. The annual snow accumulation rate in the mountains of Western Himalaya west of 80°E and north of 34°N is reported to vary between 15 m and 1 m.

The snowfall in Himalaya generally begins in October and continues until April and May, with a maximum in January and February. Even during monsoon months, snowfall can take place over regions of higher elevations far up in the north. In the eastern Himalaya, these weather systems are generally clubbed with pre-monsoon thunderstorm activity due to the availability of higher amount of moist air originating from the Bay of Bengal and large-scale convective activity over the region. The snowfall here is mostly confined to the northern most high altitude mountain ranges with relatively smaller annual accumulation rate. In contrast to the winter season, the south-west monsoon season experiences a sweep of moist winds from the east forming a zone of convergence for the Bay of Bengal and the Arabian Sea branches of the monsoon currents over India. These are more vigorous over the CH and the eastern Himalaya. The rains weaken in strength as the monsoon currents progress towards the west losing most of its moisture before reaching its extreme western margins.

The rains during monsoon months (peak months being July and August) are rather heavy and mostly confined to the lower Himalayan ranges and foothills. Monsoon generally reaches the mountains of the WH in the first part of July though the pre-monsoon convection and orographic rains are also quite common during late summers. Because of direct access to the Bay of Bengal branch of south-west monsoon the eastern Himalaya experiences summer monsoon rains about a month earlier than the WH. The withdrawal of monsoon from the eastern Himalaya is generally a fortnight after it has started withdrawing from the WH in early September. During the peak monsoon months, the southern slopes of Himalayan mountains receive the maximum rain with eastern side exceeding in rain amounts compared to the regions far west. Thus, the difference in monsoon rainfall between the eastern and western portions of Himalaya is opposite to that of rainfall pattern experienced in winter.

There are large variations in monsoon rains on both sides on year-to-year basis, the interannual variability being much higher over the west as compared to the east. It is also observed that the rainfall patterns in the eastern and Western Himalaya are generally in opposite phase. Spatial distribution of rainfall over the country suggest that on many occasions a drought in west peninsular India is a years of excess rainfall and floods in the eastern parts and the vice versa. There are certain occasions when the monsoon reaches the western and central Himalaya much earlier than its normal date of arrival due to the faster than normal advance of the Arabian sea branch of the monsoon across the Indian peninsula. These monsoon currents get coupled with the WDs and local orographic/convective weather systems resulting into enhanced and prolonged rainfall activity. These are the occasions of heavy rain in Himachal Pradesh, Uttarakhand, and Nepal Himalaya resulting in flash floods in the rivers originating from the Himalaya and inundation of flat lands in adjoining plains.

During the situations of weak monsoon activity, when the monsoon trough is nearer to the foothills of Himalaya there is a temporary drought-like situation called break monsoon condition in central parts of Indian peninsula. During the early period of the break monsoon conditions, the lower Himalayan ranges generally get heavy rains resulting into flood in rivers due to channelization of moist monsoon current in a narrow band along the Himalayan foothills. The break monsoon condition may prevail for the duration of many days to few weeks and may also occur on more than one occasion during some years.

Himalaya displays large inhomogeneity in surface temperature distribution as well as in the vertical temperature profiles. In addition to normal vertical temperature lapse rates, latent heat in rain, snow and hail formation, and dissipation processes (evaporation, condensation, and sublimation) along with moist adiabatic processes (moist air being lifted up without losing its heat to the surrounding environment) induced during orographic ascent and descent contribute to these inhomogeneous conditions. At the ground level due to inhomogeneous topography and local weather systems, the temperature varies greatly from place to place and from hour to hour. Low density of air and intense direct solar radiation and variable cloud cover also play an important role in temperature variability across the Himalaya. Mountain areas are unique in the sense that during the daytime one can suffer from sunstroke and at night from acute frostbite on the same day (Mani 1981).

Within the large mountain ranges and valleys of the Himalaya, cool sunny weather turning within hours into unpredictable local shower or thunderstorm with heavy rain or hail is a common sight at many places. Some of the important features at a mountain location such as slope, aspect, local relief, lakes, waterfalls, thick vegetation cover, and such other features may give rise to many peculiar and highly localized weather phenomena with unique experiences. An east-facing mountain slope will have warm mornings with reduced fog and cooler afternoons, whereas the west-facing mountain slopes will experience the opposite effects. During summers, a river valley in between the mountains with lakes and water bodies may experience warm and humid weather with highly localized convective thunderstorms in the afternoon.

Pronounced temperature inversions (normal tendency of temperature decreasing upwards from the ground is reversed due to cold earth's surface with warmer layers of air above) are observed at some locations. Under these conditions, the air cooled by radiation at night flows down the slopes to the bottom of the valleys and settles in hollows or a thick layer of smoke and pollutants trap the heat of the surface air to create an inversion layer. In calm weather, undisturbed by winds, the stagnant air in the hollows is filled with fog when there is enough moisture with ground temperature inversion and creates a common site of valleys filled with white soft cotton-like appearance during the early morning hours. This fog dissipates within hours after the solar radiation evaporates it on clear days and the solar radiation reaching the surface lifts the inversion. Valley fog in mountain areas pose serious aviation hazard for landing and takeoff of airplanes due to drastically reduced horizontal and vertical visibility.

Temperature inversions due to nighttime cooling of the earth's surface also result into fog, mist, and dew over flat terrains. During morning hours with the rising sun, the radiation melts the dew and evaporates the mist and fog to carry the moisture upwards which forms the shallow layers of localized cumulus or stratocumulus clouds which disperses as the day passes. The diurnal range of temperature (difference between daytime maximum and nighttime minimum temperature) is generally higher at the bottom of the valley and lower on convex mountain tops than over the level terrain. The effect of changing climate on Himalayan environment and the contribution of changing Himalayan ecosystem to global climate are complex and least understood. An examination of the rainfall pattern in Himalaya, particularly the central Himalaya, where tropical–extratropical interactions of weather systems are more prominent suggest an increase in the instances of heavy rains and resulting flash floods in recent times usually associated with the WDs and enhanced local convection.

An example of recent happening is the devastating floods in river Mandakini originating from the glaciers at the top of Kedarnath valley in Uttarakhand. This devastating episode occurred due to the combination of meteorological and hydrological factors triggered by the cloudburst and heavy rains on the one side and the glacier lake overflow on the other side (Singh 2013; Dobhal et al. 2013). The monsoons had arrived in the region about a fortnight earlier in 2013 than its normal date of arrival, which was vigorous in nature and got coupled with the active western disturbances at those latitudes during the week of 15–19 June 2013 creating a meteorological condition conducive for very heavy precipitation and resultant floods which induced the glacier lake burst and the disaster which followed.

Due to paucity of surface and upper air observations on meteorological elements, glacier mass balance and snow extent and depth, the exact cause–effect relationships are difficult to establish for such exceptional events. The problem is more complex, as the cryospheric, atmospheric, and land surface processes are equally involved. Besides the permanent snow on the mountain peaks of the upper Himalayan ranges and many perennial glaciers, there is substantial accumulation of snow at lower altitudes and southern slopes of the mountains during winter months which melts in summer and provides large fresh source for groundwater recharge and streamflow. The amount of accumulated snow available as source of freshwater depends on the local climate, altitude of the mountain, and the intensity and frequency of weather systems.

2.3 Meteorological Observations Over Western Himalaya

Over WH, the network of conventional surface meteorological observations have very limited areal coverage and only few selected hill stations have long period of data. The stations with more than 100 years of continuous record on rainfall and temperature such as Srinagar (Jammu and Kashmir), Shimla (Himachal Pradesh), and Mukteshwar (Uttarakhand) provide highly significant meteorological records of climatic importance. Most of the Himalayan regions of great meteorological significance are located at higher altitudes with difficult terrain and rough weather conditions; hence, they are devoid of very useful long period meteorological records. Lack of data with adequate spatial and temporal coverage is now being recognized as a great deficiency and their augmentation are being taken up with priority using AWSs and satellite remote sensing. At present, it is difficult to document and display long period climatic features and their trends and variations over large spatial and temporal domains for these regions. The compilations of recent data over a period of few decades supplemented by satellite observations would be helpful in drawing definite conclusions regarding the magnitude of global warming over the region. Long period data on climatic elements such as precipitation (rain, snow, hail), pressure, temperature, wind, sunshine, incoming and outgoing radiation along with the level of greenhouse gases (GHGs) concentrations at the surface are required to be routinely measured and records to be safely archived.

In view of intense weather systems being directly related to vertical convection and atmospheric instabilities, vertical profiles of significant parameters are very much required for weather prediction and also to provide a three-dimensional climate picture. In addition to general climatic picture, the information and forecast on weather and climate parameters is essential for agriculture, water resource, tourism, natural disaster management and strategic civilian, and defense aviation services and operations. During the recent decades, multipurpose and multi-institutional efforts are underway to collect and assimilate the weather and climate data over the Himalaya using a combination of automatic and conventional surface observatories and remote sensing data platforms.

Most important among these are the programs initiated by the government departments particularly the India Meteorological Department, Indian Space Research Organization, Ministry of Defense, Ministry of water resources, and the Department of Science and Technology to bridge the data gap in mountain regions. IMD has a large network of various observational facilities across the peninsular India and adjoining coastal regions as explained in Chap. 1 but the Himalayan region still belongs to a very few of them. Meteorological satellites right through the INSAT-series, KALPANA, etc. from India to the most recent state-of-the-art versions around the world and other remote sensing techniques are being used to augment and improve the spatial coverage and quality of information. Remotely sensed data needs advanced retrieval techniques to account for complex orographic features and require validation with high quality ground observations. All diagnostic studies and input for prediction models are invariably using the grid point values of reanalysis data which have proved to be of immense value in analyzing the broad features of the weather systems.

There is an urgent need to enhance the facilities for vertical sounding of atmosphere using ground-based remote sensing tools such as RaDARs of appropriate wavelengths (Wind profilers, Doppler Weather RaDAR, cloud RaDAR) and LiDARs, supplemented with Acoustic Sounders and conventional Radiosonde (Radio signals from the balloon-borne sensors) observations. These observations are very important for the monitoring and forecast of extreme weather events. Special programs of observations in campaign mode need to be carried out in order to investigate and understand specific atmospheric processes. These are essential and of paramount importance to fill the data gaps and improve the quality, in order to support the meteorological operations and atmospheric science research over the region.

In view of cleaner and pristine air of the Himalayan region, observations of atmospheric GHGs, other trace gases and aerosols at high altitude mountain stations will also prove to be the useful benchmark for air quality monitoring. High precision ground observations and tropospheric vertical profiles integrated values for the entire column from the ground to the top of the atmosphere on all relevant parameters are required to be measured. These observations will have to be at many stations evenly located in the region to be recorded at least once a day or at mandatory time intervals as prescribed by World Meteorological Organization (WMO).

2.4 Challenging Scientific Issues

With better quality and coverage of data and improved understanding of weather and climate processes and availability of modern technology the prediction of natural disasters related to weather and climate extremes have improved to the level of reliability and general acceptance. A lot is yet to be done to improve weather and climate services in the mountains as large and diverse as Himalaya. Concerted efforts on part of the scientists, engineers, policy planners, and general public are required to identify the unique weather and climate-related issues of the region and find out appropriate scientific solutions. Following is a preliminary list of important features and challenging subjects of study relating to the Himalayan region, its weather, climate, and other related issues.

1. Study of convective and orographic storms, squall lines, cloudbursts, and other related meteorological phenomena which are associated with the local extreme

weather events often invigorated by the weather systems providing large-scale moisture convergence at ground level.

2. Natural disasters and environmental impacts of hailstorms, heavy snow, lightning, heavy rains, and extreme convective and orographic thunderstorms.
3. Flash floods, landslide, soil erosion, change in river course, loss of topsoil, and biodiversity.
4. Large-scale droughts and floods and their impact on water resources, agriculture, livelihood of the masses, transportation, hydropower generation, and communication. In this context, special efforts are required to model the specific cases of unusual behavior of south-west monsoons and WDs over the region.
5. Role of persistent dry and windy weather in the initiation and spread of forest fire with impact on biodiversity and forests, characteristics of atmospheric aerosols, air quality, and the local climate. Wind measurements and their vertical profiling may also be initiated at some sites with good potential for persistent strong winds for the purpose of wind power generation.
6. Mountain glaciers, snow-covered areas, and extent of seasonal snow and ice, and overall impact of cryospheric variability on local and global climate. Impact of climate change on glaciers and vice versa.
7. Forests, vegetation, human settlements, wildlife, and specifically the role of forests in reducing the global warming by acting as major pool of carbon sink.
8. Artificial channeling of river flow, construction of dams, reservoirs, mining, hydropower projects, and their environmental and hydrological impacts in the background of changing climate.
9. Mountain and valley fog, low clouds, turbulence, and their effect on different modes of aviation and ground transport.
10. Impact of mountain weather on agriculture, horticulture, livestock, tourism and socioeconomic impacts of impending changes under projected climate scenarios on an immediate and long-term perspective.
11. Role of Himalaya in the establishment and maintenance of large-scale circulation systems specifically the monsoons over South Asia.
12. Keeping in mind the long-term impacts of climate change detailed scientific investigations are necessary to map the sources of renewable energy, particularly the hydro, solar, wind, and geothermal energies over the mountain regions.

2.5 Trends and Variability in Climate over Western Himalaya

2.5.1 Altitude Dependency of Surface Climate Change Signal

While studying climate change at high altitudes, the issue of elevation dependency of surface climate change signal is very important primarily due to the following reasons (Giorgi et al. 1997). First, an enhancement in the changes in surface climate at higher elevations would imply greater impact on high altitude hydrology and ecosystem. Second, an amplified response at high elevation could be utilized as an early climate change detection tool. Third, the capacity of reproducing the elevation dependency of climate change signal could provide an important aspect of model verification. Climate change signals in particular the greater rates of warming at higher elevations compared to the low level ground areas have been reported from many parts of the world (Beniston and Rebetez 1996; Giorgi et al. 1997; Fyfe and Flato 1999; Beniston 2003: Pepin and Lundquist 2008; You et al. 2008, 2010; Kang et al. 2010) though there are few contradictory observations from some other parts of the world. Recent studies suggest a more sensitive response to global warming at higher elevations in China compared to other parts in the country (Titan et al. 2006; Yang et al. 2006; Kang et al. 2007).

Numerous arguments are put forth by the scientists to logically explain their finding on the elevation dependency of changes in surface climate. Beniston and Rebetez (1996) attribute it to the fact that high-elevation stations are more directly in contact with the free troposphere than the one at the low elevations; therefore, they are relatively less affected by ameliorating anthropogenic factors, such as urbanization and pollution. The snow-albedo feedback to climate system can also provide a strong elevation-dependent forcing. As snow is depleted at high altitudes under warming conditions, the surface albedo decreases, so that more solar radiation is absorbed at the surface and the surface warming is enhanced at the higher altitude thus providing a positive feedback (Meehl 1994). It is also important to note that the cooling history of the Himalayan ranges in longer time frame of geological periods are complex and largely a function of mountain uplift and erosion in addition to climate factors (Zeitler 1985). An overlap between geological and climatic influences may complicate the detection of global warming effect of very long timescales and its altitude dependency particularly in the systems in which the geomorphic features are continuing the process of formation, like in the Himalaya.

There are many ways of looking at the issue of climate change and its altitude dependency. In addition to changes in temperature, it is also possible to examine the influence on temperature extremes in relation to altitude as well as the slope and aspect of the mountain ranges. Analysis of data from some high-elevation stations on the Tibetan Plateau for the period 1961–2005 showed no significant correlations between elevation and trends and magnitudes of temperature extremes, except for coldest day temperature (You et al. 2008). In South America, lower elevations to the west of the Andes have experienced the greatest warming, while warming at higher elevations to the east is less marked (Vuille et al. 2003). An analysis of 1084 stations from the Global Historical Climate Network (GHCN) and data of the Climate Research Unit, University of East Anglia, Uttarakhand, by Pepin and Seidel, (Pepin and Seidel 2005) did not yield systematic relationships between temperature trends and the elevation.

Higher elevation sites over the south Asian region with monsoon dominated climate exert significant influence on climate by way of a permanent orographic barrier to the prevailing moist monsoon currents. This creates a steep precipitation gradient along the mountain slope as well as contrasting rainfall regimes along the windward and leeward sides of the mountain ranges as seen along the west coast of India during the peak south-west monsoon months. Higher monsoon rainfall at the mountain peaks may moderate the temperature profiles thus making it more complex problem to detect the effect of climate change on mountain temperatures. It is, therefore, concluded that the warming over these regions is more likely to be influenced by local factors and, hence, the changes in temperatures or their extremes may become less detectable and predictable (Revadekar et al. 2012).

An analysis of data over Nepal (Shrestha et al. 1999) suggests a relatively higher rate of warming over the country compared to the global mean which is attributed to contribution by higher rates of warming in high-elevation areas of the Nepal Himalayas and Middle mountain regions. Similar warming trends are also observed in the Tibetan plateau where the warming is more pronounced in higher altitude stations than in the lower ones (Liu et al. 2002). It is suggested that the reduction of snow and glacier cover in the Himalayas as a result of global warming may also be contributing to higher rates of warming observed in the higher elevation regions (Kadota and Ageta 1992; Yamada et al. 1992; Fujita et al. 1997; Jin et al. 2005). However, with limited available data it is not possible to arrive at a conclusion suggesting uniform elevation-dependent trend in mean temperatures or the extremes of temperature. Preliminary studies indicate that the Himalaya seems to be warming more than the global average rate and the temperature increases are greater during winter and the autumn seasons than during summers which are also larger at higher altitudes (Liu and Chen 2000; Shrestha et al. 1999).

The trends of change in rainfall over the Indian subcontinent have large spatial variability with patches of increasing and decreasing trends almost in balance resulting into a stable long-term monsoon rainfall regime. Model simulations of precipitation over the Western Himalaya in general indicate small but statistically insignificant increasing trend which is also detectable in the data for few stations with long series of available data over the region (Kumar et al. 2006; Agarwal 2009). There are trend analyses for the mean annual temperatures of few stations over the Himalaya with limited continuous data period. For example, Kumar et al. (2008) infer that the mean annual temperature in the Alaknanda valley (Western Himalaya) has increased by 0.15 °C between the years 1960 and 2000 and Sinha (2007) found that the average temperature of Kashmir valley has gone up by 1.45 °C over the last two decades.

Aerosol Optical Depth (AOD), a measure of the opaqueness of the atmosphere in a vertical column from the earth's surface with reference to specific part of the solar spectrum due to presence of aerosols, is taken as an index of change in regional climate. The AOD measurements are being done in situ at a few selected stations in many mountain regions with detection of climate change signals in mind. Recently, scientists have been using many satellite-based instruments to quantify the aerosol generated radiative forcing to the climate system. In Himachal Pradesh, at Kullu, a valley station the AOD obtained through Multi-wavelength Radiometer (MWR) has shown highest ever AOD at 500 nm wavelength as in May 2009 which was 104% more than mean AOD value from April 2006 to December 2009 (Kuniyal et al. 2009).

The value of AOD was found to be much smaller at Nainital, a hill station in Uttarakhand at higher altitude (Pant et al. 2006) thus suggesting a sharp regional variability in AOD and also in an important component of the radiative forcing to the climate. Temperature rise due to radiative forcing from aerosols in the atmosphere based on per unit AOD increase at Mohal-Kullu (Himachal Pradesh) was calculated as high as 0.95°K/day during summer (April-July) and as low as 0.51°K/day during winter season (December, January-March) (Guleria et al. 2011). There are meteorological observations over high altitude stations and glaciers in many part of the WH for selected seasons over a part of the year with discontinuities in the data due to many dates with missing observations. In view of their limited spatial coverage and discontinuities in time series, this information is of little climatic significance.

2.5.2 Temperature Changes Over Western Himalaya Since 1901

The region of Western Himalaya for the analysis carried out in the present study is a latitude-longitude domain. In view of the epochal behavior of the monsoon rainfall over India and also considering a period of 30 years as a representative time period in climatology, a detailed analysis of temperature over the Western Himalaya is done for 30 year subperiods using a homogeneous data for the period 1901–2007. The time series for maximum temperature during the months of January and February over the period from 1901 to 2007, along with the 31 sliding trend over the Western Himalayan region is given in Fig. 2.2. The monthly maximum and minimum temperature are analyzed for trends and variability for the following subperiods: (1) 1901–1930, (2) 1931–1960, (3) 1961–1990, and (4) 1991–2007 (Figs. 2.3, 2.4, and 2.5). For the above-mentioned periods, the annual cycles in the maximum and minimum temperatures are examined and compared to detect the signal of global warming (Figs. 2.6, 2.7, and 2.8). Basic characteristics of the annual cycles, the persistent increase from January to June and then decrease till the end of the year remains practically the same for all epochs. However, the most recent epoch of 27 years (1991–2007) shows substantial increase in both maximum and minimum temperatures.

In general, it can be inferred that the warming have been occurring prominently during the winter season and changes are smallest during the summer monsoon season (JJAS). The warming trend shows a clear increase for each epoch starting from the beginning of the twentieth century. Epochal trend analysis for monthly maximum temperature clearly shows a negative trend in maximum temperature during period 1931–1960 indicating cooling during the epoch (Fig. 2.2). The epochal trends in minimum temperature, on the other hand displays a negative trend during the period 1901–1930 (Fig. 2.3). The time series of both the maximum and the minimum temperatures show a positive trend during the recent period throughout the year from January to December. Higher trends are seen in all winter months compared to the rest of the months in a calendar year.

A characteristic feature distinctly seen in all epochs is the smallest value of trend as well as variability in maximum and minimum temperatures during the monsoon season. Though the most active period of monsoons in the Western Himalaya is during the months of July and August, the influence of local moisture with cloudy

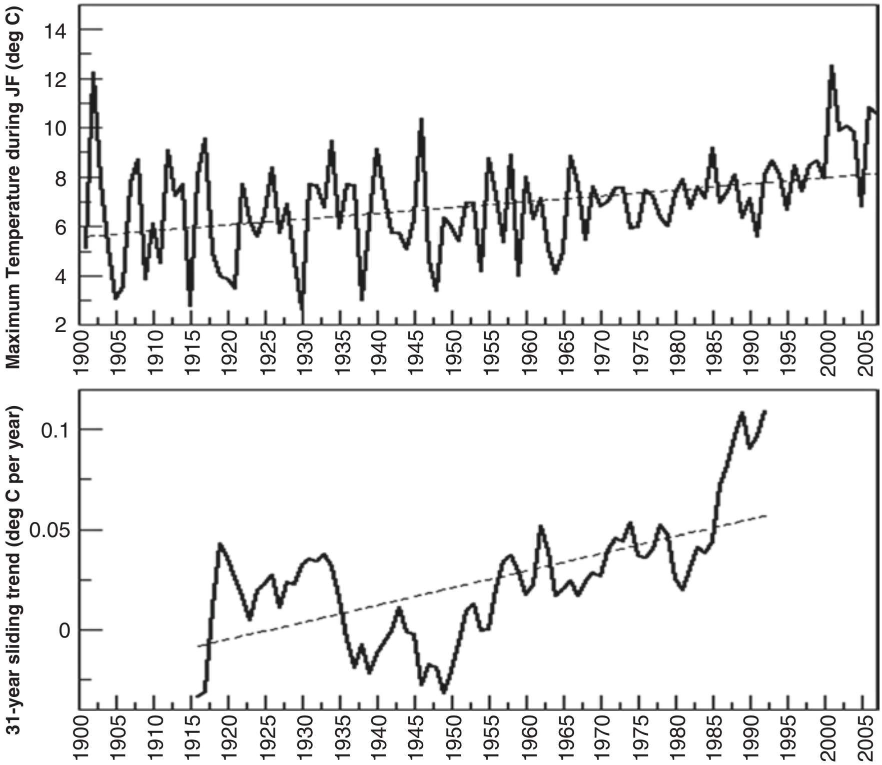

Fig. 2.2 Maximum temperature during January-February (*top*) and 31-year sliding trend (*bottom*) over Western Himalayan region, for the period 1901–2007

nights and strong summer convection coupled with orography perhaps moderates the rising summer temperatures throughout the monsoon season. During the summer months as the surface temperatures continue to increase, there is an increase in the intensity and frequency of organized convective activity particularly over Shiwalik and the southern slopes of the middle mountain ranges. The indications of the stabilizing effect of pre-monsoon convective activity and heavy monsoon rains on the hotter parts of the Western Himalaya are reflected in the moderating influence on monsoon surface temperatures.

Time series of seasonal temperatures constructed for Western Himalaya for the period 1901–2007 shows an increasing trend during all seasons, namely, January-February (JF), March-April-May (MAM), June-July-August-September (JJAS), and October-November-December (OND) for maximum temperature (Fig. 2.9) and for minimum temperature (Fig. 2.10). A summary of the results of the above analysis are presented in Table 2.1 for comparison at a glance. The details presented in

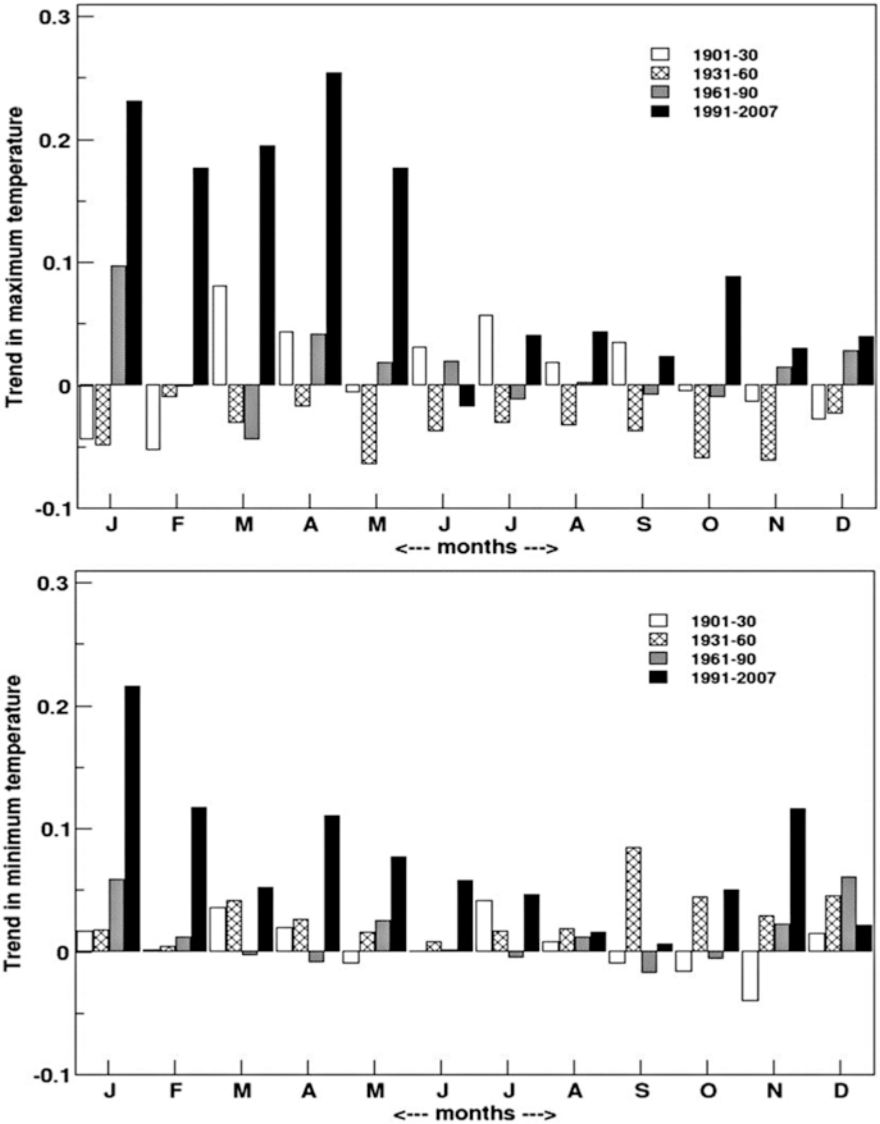

Fig. 2.3 Monthly trend values of mean maximum (*upper panel*) and minimum (*lower panel*) temperature over Western Himalaya for successive 30 year periods since 1901 (recent period ends at 2007)

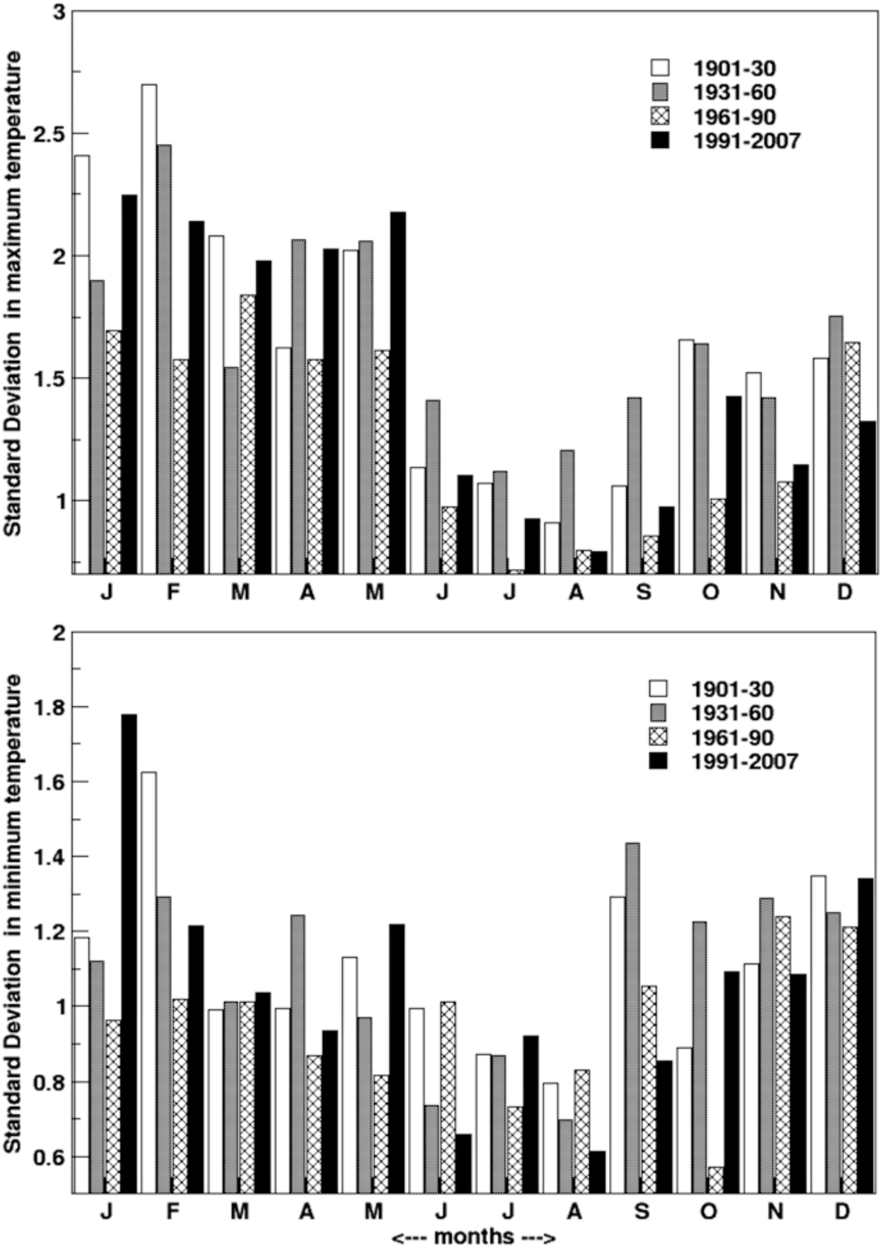

Fig. 2.4 Monthly values of the standard deviation of maximum (*upper panel*) and minimum (*lower panel*) temperature over Western Himalaya for successive 30 year periods since 1901 (recent period ends at 2007)

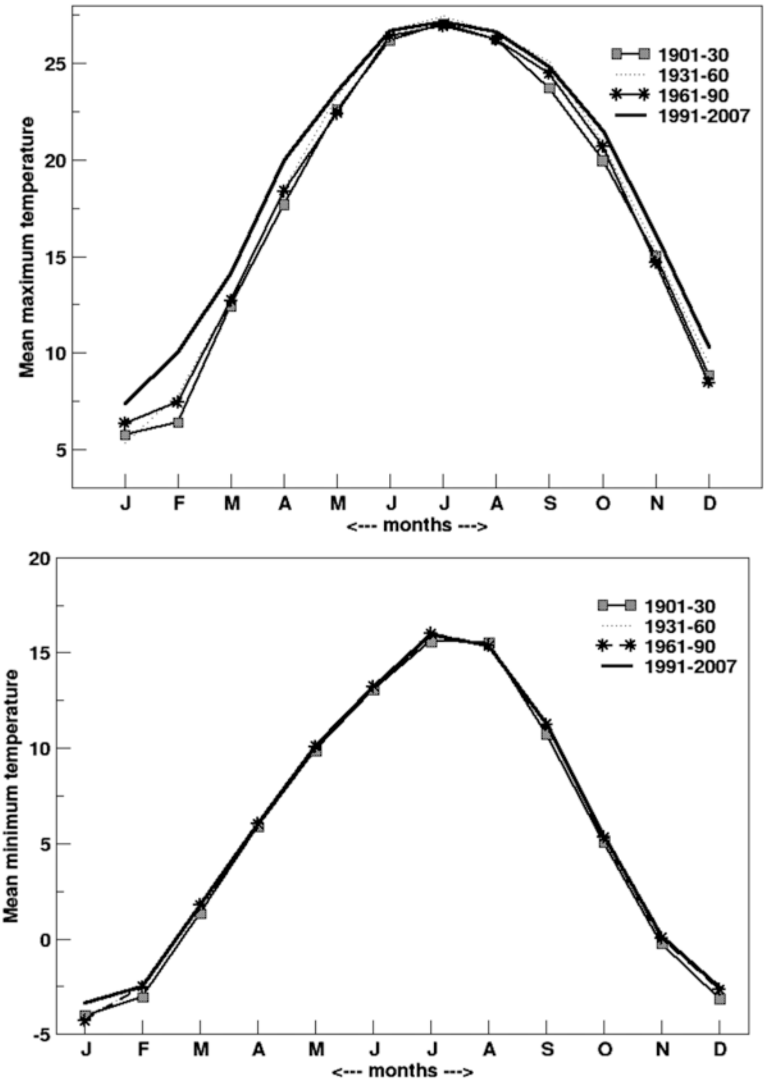

Fig. 2.5 Successive increase in monthly mean maximum temperature for 30 year periods 1991–2007

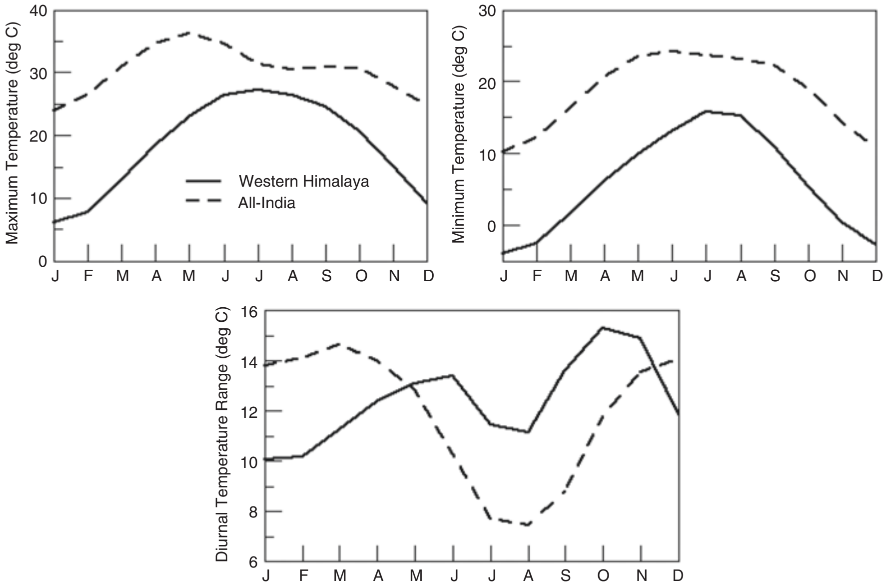

Fig. 2.6 Annual cycle of Maximum temperature, Minimum temperature, and Diurnal temperature range (max-min) for Western Himalaya (*solid*) in comparison to All-India value (*dash*)

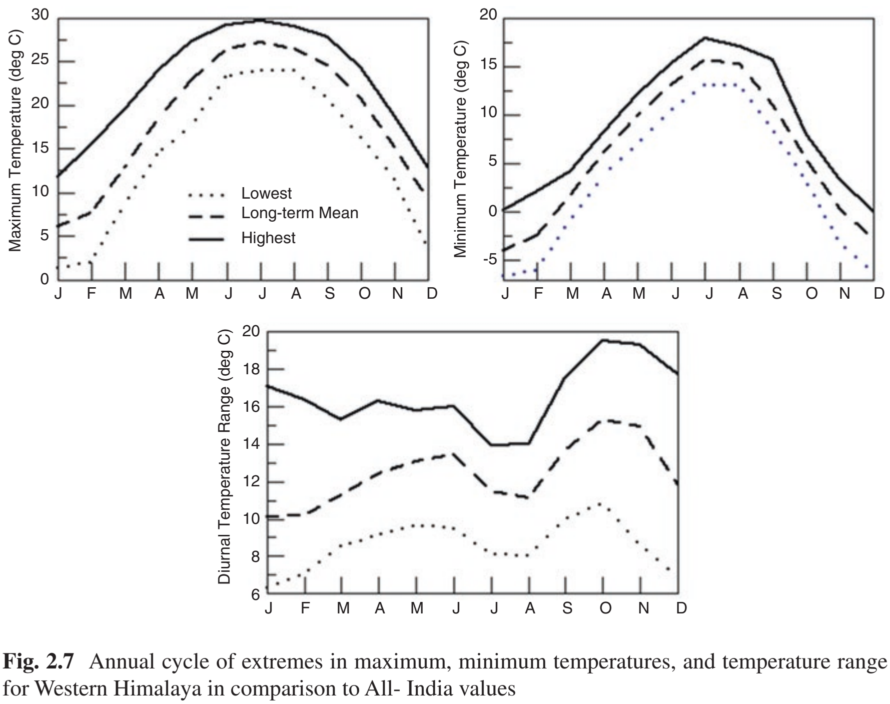

Fig. 2.7 Annual cycle of extremes in maximum, minimum temperatures, and temperature range for Western Himalaya in comparison to All- India values

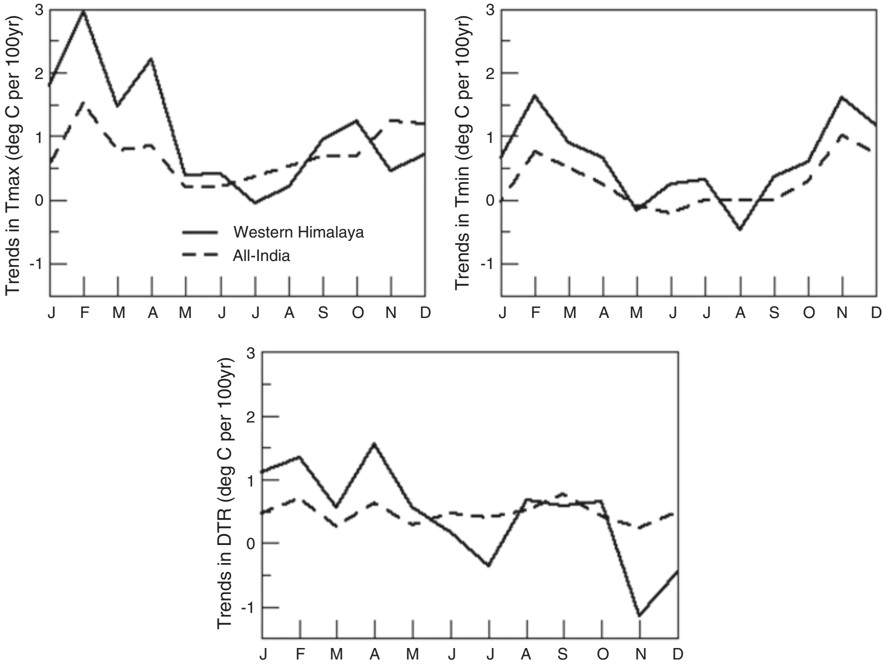

Fig. 2.8 As Tmax over Western Himalaya is showing higher trends during winter, JF time series is plotted (*top*) and 31-year sliding trends are computed (*bottom*). 31-year sliding trend show accelerated warming during recent period. Further analysis is therefore is done to find possible causes behind this warming over Western Himalaya

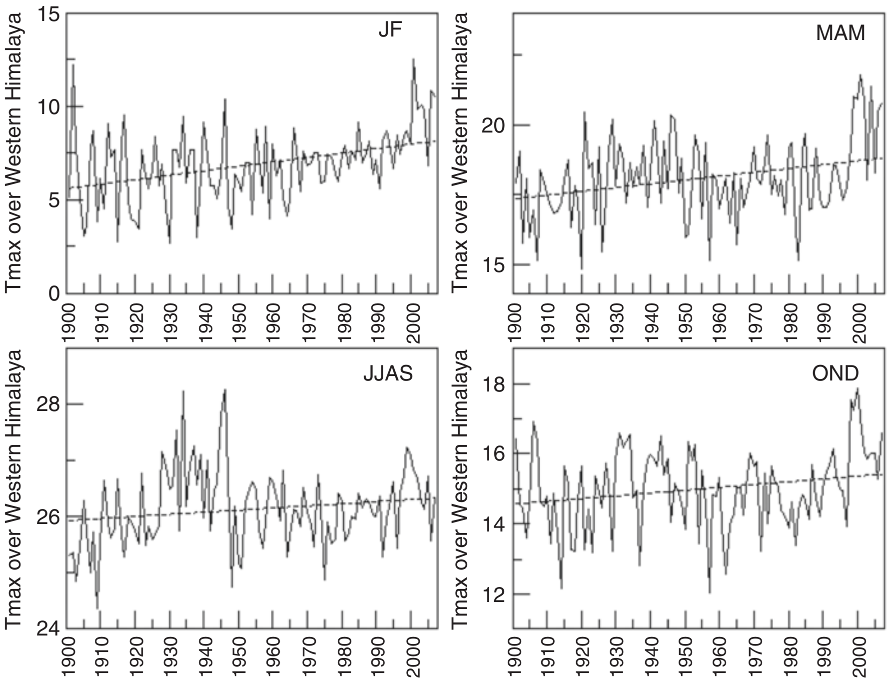

Fig. 2.9 Seasonal trends in maximum temperature over Western Himalaya

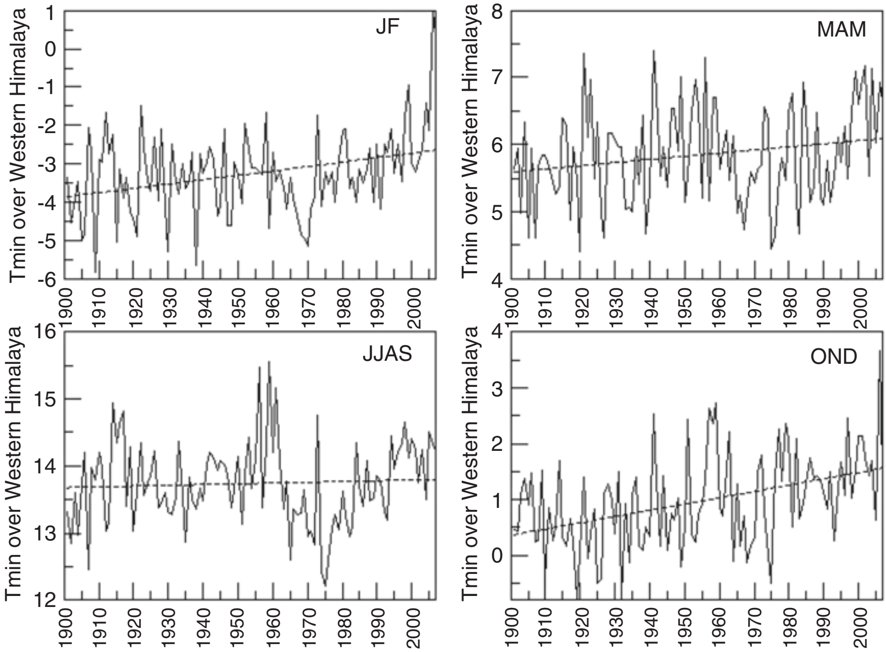

Fig. 2.10 Seasonal trends in minimum temperature in Western Himalaya

Table 2.1 Temperature statistics for Western Himalaya for the period 1901–2007

T_{max}	JF	MAM	JJAS	OND
Mean	6.87	18.09	26.23	14.99
Std. Dev.	1.97	1.43	0.69	1.14
Trend per decade	0.24[a]	0.14[a]	0.04	0.08[a]
T_{min}	**JF**	**MAM**	**JJAS**	**OND**
Mean	−3.26	5.84	13.74	0.97
Std. Dev.	1.12	0.74	0.63	0.84
Trend per decade	0.11[a]	0.05[a]	0.01	0.11[a]

[a]Indicates the statistically significant values at 90% level

the table and the analysis carried out for the monthly trends for maximum and minimum temperatures is based on the average taken over Western Himalayan region.

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