Chapter 5
Western Disturbances – Impacts and Climate Change

Abstract The significance of a weather system is usually measured on the basis its impacts. Impacts related to the western disturbances (WDs) have been mentioned briefly in a preceding chapter. Without detailing the impacts of the WDs, one cannot justify the significance of studying the topic. In this chapter, we will discuss in detail the various positive (on the cryosphere and hydrology of the region) and negative (severe weather and natural hazards) impacts of the WDs and how these influence India as a whole. Discussion of the evolution of WDs in the changing climate is also included in the chapter, along with speculation on how a warming climate might affect changes in the direct and indirect impacts of WDs.

Impacts related to the WDs have been mentioned briefly before in a preceding chapter. In this chapter we detail the importance and justify the significance of WDs as measured in form of their impact. This book is focused on the WDs in an Indian parlance as WDs have significant impact on India. Various positive and negative impacts will be discussed in the sub-sections below. Discussion of the evolution of WDs in the changing climate is also included in the chapter, along with speculation on how a warming climate might affect the changes in the direct and indirect impacts of WDs.

5.1 Winter Precipitation and Its Impacts

The winter precipitation is one of the major impacts of the WDs, and the Indian winter monsoon has been discussed in great detail in the previous chapter. So in this chapter dealing with the impacts of WDs, we will not be repeating this impacts of the weather system. Rather we discuss the effects of the winter precipitation due to WDs. Winter season WDs contribute up to 15 % of the precipitation over the north-western region. This precipitation reduces in frequency and intensity southwards and eastwards (Yadav et al. 2012). As mentioned in the first chapter, precipitation can be a resource for life in moderation or be disastrous in extreme cases. In this section, we discuss both the positive as well as the negative consequences related to the WD-related winter precipitation.

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Precipitation over a region has a high ecological and environmental impact. These rainfall events render ecological services and help in the maintenance of the regional flora and fauna. Natural ecology is acclimatized to this climatological feature and requires the winter precipitation for its preservation. The economic equivalent of the environmental services performed by the precipitation is unquantifiable. This is not only important in the catchment area but also along the downstream flow. Precipitation is also very important for the agriculture sector. This is especially so in a country like India where the irrigation network is not well developed and the farmers are dependent on natural sources for irrigating their fields. Even in the case of the current irrigational infrastructure, the precipitation always supplements the irrigational requirements. Winter precipitation as rainfall is important for 'rabi' crops or winter crops. In Arabic the term rabi refers to spring, which is when the rabi crop is harvested, but it actually grows in the winter season. Examples of rabi crops are wheat, barley, peas, gram and mustard, which are sown in November and harvested in April (Yadav et al. 2012). The WD-related winter precipitation and the cold and dry winds from the northern side at the rear of WDs maintain the moisture and low -temperature conditions required for the development of these crops, specifically wheat. For the sustenance of the region with high food requirements for the growing population, the winter precipitation is very important for the high yield of these staple crops. Winter rainfall also supplements the land-based water bodies, i.e. the lakes, aquifers and rivers of the region. Thus the precipitation is of utmost important for the ecological health and socio-economic requirements of the Himalayan and Gangetic regions.

Winter precipitation over the region might also occur in the form of snow. The snowfall during winters due to WDs is the source for glacier growth over the mountainous regions of the northern India (Benn and Owen 1998). This snowfall is also significant for the ecology of the region. But mainly the glacier mass-balance maintenance is a very important effect of winter snowfall. The snow line of the western Himalayas is as low as 1500 m and for the eastern Himalayas is 3000 m during the winters (Barry 2008). The glaciers are storehouses of fresh water on land, which feeds the watershed hydrology of the region (Thayyen and Gergan 2010). The summer melt of these glaciers (the ablation period) and surface run-off originates and supplements all the major rivers and lakes of the region (Archer and Fowler 2004). So even in cases of summer drought conditions when monsoons might fail, there is a constant source of fresh water over the region. Other than agriculture and power generation, this water supply is essential for domestic, developmental and industrial usage. According to Barros et al. (2006), the storm precipitation over the Himalayas (which also includes winter precipitation) may lead to erosion processes over the mountain range. Also, as already discussed, the snow cover generated during winters has much larger impact than just on the winter-time climate, and impacts the regional climate and large-scale flow patterns.

Glacialogical and hydrological impacts of the WDs are very significant. On the other hand, extreme precipitating events during the winter time may lead to hazards and are dangerous in nature (Dimri and Chevuturi 2014). During winter, the Himalayan region is prone to severe weather due to large amounts of precipitation produced by WDs. According to Dimri (2006), out of six – seven WDs occurrences per month, two – three WDs can cause severe weather conditions. These events may be realized in the form of heavy rainfall events (Zafar and Rasul 2009). These may be in the form of severe thunderstorms which, if not disastrous, most certainly can disrupt life and damage property. There may be cases of heavy snow storms precipitating high amounts of snow over the north-western Himalayan region during winters (Dimri and Mohanty 1999; De et al. 2005; Dimri 2006). Such blizzards are hazardous for road, rail or air transport, cause agricultural losses, and negatively impact the day-to-day lives of the people. Though uncommon in winters, sometimes hail precipitation also occurs over the northern Indian region under the influences of WDs (Chevuturi et al. 2014). Hailstorms can cause destruction of crops, infrastructure, property and, in extreme cases, may cause injuries to humans (De et al. 2005). Also due to the perception that hailstorms occur only in summer, hailstorms are not expected in the winter months. This may lead to unpreparedness which may increase the devastating consequences.

Extreme precipitating events are quite hazardous in nature, but sometimes these events lead to secondary natural disasters that are even worse. These secondary natural disasters can occur in the form of avalanches, landslides, glacial-lake outburst floods, landslides and flashfloods. The Himalayan region, with pockets of high population density and a migrating tourist population, is very susceptible to natural hazards causing devastating impacts. Also, the precipitating events which are considered as moderate over the plains might have hazardous impacts over the region. On the other hand, heavy precipitation events might not culminate in disasters if the geophysical features of that particular location are not conducive to disasters. For example, heavy precipitation due to WD and MT interaction occurred over the entire Uttarakhand state, but the natural disaster in the form of flashflood struck only the city of Kedarnath.

Avalanches are caused by structural collapse of the snow cover in the mountains. This can be either in the form of loose snow collapsing or a slab of snow and ice falling down the slope of the mountain. Moreover, avalanches can be caused by the internal factors of snow metamorphosis. In this chapter, we focus on the avalanches due to external factors that cause excessive snow loading to the existing snow cover (Srinivasan et al. 2005). For the northern Indian regions, the external factor is snow precipitation during winters caused by WDs. The north-western Himalayan region is under constant threat of avalanches during winter snow storms, as the avalanches in this region are quite frequent. These avalanche incidences can be widespread under the influence of a very intense WD (Rangachary and Bandyopadhyay 1987). These are very hazardous because they sometimes bury whole regions under a huge mass of snow and ice. Tragic human fatalities are a major concern during avalanches and infrastructure destruction is quite high (Ganju and Dimri 2004) Unusually heavy snowfall from 1 to 3 January 1991 triggered a severe avalanche which lead to the tragic demise of many mountain climbers at the base camp (Hara et al. 2004). Landslides are another possible impact of heavy precipitation events during winter or even during summer glacier-melt flow over the Himalayan range (Lang and Barros 2004). The vulnerable geomorphological region of the Himalayan mountains is susceptible to landslides in heavy waterflow conditions. With severe anthropogenic changes to the land use and land cover due to rapid and unplanned developmental activities, the region becomes even more vulnerable. Similar to avalanches, the landslides displace large swaths of land surface down the slope of the mountains. These also have similar devastating impacts on life, property and infrastructure (De et al. 2005).

Glacial lakes are naturally-dammed or moraine-dammed lakes within or at the margin of glaciers which may be left behind when the glaciers retreats. Snow and rain lead to formation of glaciers and supplement the glacial lakes. Sometimes the heavy winter precipitation overwhelms the glacial lakes. Then in summer, when further stress is added from meltwater, there is a possibility of natural moraine breaking. This causes the outburst of water from the glacial lake in the form of the glacial-lake outburst floods (Bajracharya et al. 2007). The structural integrity of the geomorphological features and the drainage of the region changes without warning. Thus, these floods are sudden, showing no prior indication, and thus are very dangerous. Himalayan region is highly prone to the risk of these glacial-lake outburst floods.

The ultimate impact of the winter precipitation events discussed here are the flashfloods. Extreme precipitation or even moderate rainfall events over the Himalayas may collect through multi-channel flow in the catchment area and the natural drainage systems to form flood water (Kala 2014). Due to the steep hill slopes of the region, this collected mass of water gains large momentum and rushes as a flood over a region. An example of flashflood was the Kedarnath disaster of 16 and 17 June 2013. This was the flashflood caused by the heavy precipitation resulting from the interaction of a WD with the MT (Chevuturi and Dimri in review). The flood water dragged along with it eroded surface debris along the steep slope, leading to further devastation throughout the city. Flashfloods in general cause severe damage to the region by causing erosion, destruction to transport and communication lines, and harm to life.

5.2 Severe Weather

A major impact of WDs over the Indian region is the associated precipitation that occurs. Cases of heavy precipitation events leading to natural disasters have been discussed above in detail. But WDs also might lead to other meteorological impacts or weather events which also fall under the category of severe weather conditions. Out of six – seven WDs impacting India during winters, two – three WDs might lead to severe weather conditions (Dimri 2006). There are two types of severe weather that form due to the occurrence of WDs. First is the possibility of severe fog conditions where the visibility over the region drops considerably. And the second severe weather event are the cold waves which reduce the temperature of the region. These two weather events have significant consequences and will be described in this section in detail.

During the winter period, fog is a severe weather hazard impacting the northern Indian region. Though fog is a localized phenomenon, during conditions favorable to its formation, the fog cover may extend over thousands of kilometers and persist for many days. The local occurrence and non-occurrence is dependent on local conditions (Rao and Srinivasan 1969). This blanket of fog usually covers a large area from west to east parallel and south to the Himalayan range over the Gangetic plains, from Pakistan to Bangladesh across the whole of north India (Syed et al. 2012). The formation of fog is usually limited to the lower layers of the atmosphere where the gases and aerosols are in higher concentrations. Fog is a precipitation type with droplets much smaller than rain drops (approximately 100 times smaller). Due to their small size and condensation method, they are suspended in the air and are more concentrated than rain drops (Ali et al. 2004). Fog over the northern Indian region occurs in rare cases during the post-monsoon season (October–November) and is usually seen in the winter season (December–February). The months with peak incidences of fog which is dense and persistent, are December and January.

Of the different types of fog types being formed over the northern India during winters, one is formed due to radiative cooling. A synthesis of the fog formation during winters by Syed et al. (2012) is provided in this paragraph. Radiation fog forms near the surface when an anticyclone occurs over a region of stable conditions. The cause of the radiation fog is, as the name suggests, radiative cooling of the surface and the near -surface cooling due to the loss of energy. Other reasons for the formation of the radiation fog can also be upward heat flux from the soil, dew deposition leading to warming and moisture loss from the atmosphere and turbulent mixing in the stable boundary layer. The capacity of the soil types to hold moisture and its thermal conductivity are important factors that influence the latent heat flux of the surface and determines the capacity of radiative cooling and surface inversions. Conditions of low wind speed, high humidity and low surface temperatures are conducive to the formation of radiation fog. Such conditions lead to the very stable conditions or even inversion conditions that form boundary trapping, since there is limited mixing of air within the troposphere. These conditions lead to condensation of the moisture available into the fog droplets. The presence of gases and particles such as aerosols influence the formation and the composition of the fog particles (Ali et al. 2004). Persistent fog form in regions of high air pollution due to the availability of additional nuclei to generate a larger frequency of smaller fog particles. The physico-chemical interactions between the pollutant gases and particles and the fog droplets allow the formation of the fog in sub-saturated conditions. Some occurrences of advection fog are also observed over this region during the winter season. The advection fog occurs when a warmer air mass moves over a colder surface. But such cases are more common over bodies of water and rare over this region.

These are the mechanisms of typical localized fog formation. The fog formation during winters covering large areas of northern Indian region is associated with the occurrence of the WDs (Rao and Srinivasan 1969). The precipitation related to the WDs causes an inundation of water vapor in the lower levels due to evaporation of the precipitation. And the WDs are the only source of precipitation during the winter season. As discussed before, ahead of the migrating WD trough there is low-level warm air and moisture incursion from the Arabian Sea and the Bay of Bengal that is the source of the high humidity also required for the fog formation. As the WD passes through the region, the rear end of the trough contains a high-pressure (anti-cyclonic) system which develops stable atmospheric conditions. These synoptic conditions, along with low wind speeds, form surface-based inversions with the moisture availability triggers and promotes fog formation (Syed et al. 2012). But these conditions are generated just in the immediate rear vicinity of the WD and thus the fog conditions usually occur immediately after the passing of the WD over a region. Further, as this region is influenced by different aerosols and atmospheric particles in the lower atmosphere, solar radiation further heats up the region (Ali et al. 2004). In cases of large moisture influx, dense and persistent fog may last up to days. In the rare case of advection fog formation, the warm moist air flow in the front of the WD arrives over the cold surface. Another mechanism for advection fog formation is due to an easterly warm wind being drawn towards the region due to the presence of a WD. Such conditions where the fog is formed ahead of the WD by the first method can cause fog over the regions of Orissa and West Bengal. The second mechanism of advection fog formation causes fog occurrences over Bihar and Uttar Pradesh (Rao and Srinivasan 1969).

Changes in land-use and land-cover in the form of urbanization, industrialization, agriculture (leading to crop burning) and road development (increasing transport) lead to the massive increase in the air pollutant load of the region (Syed et al. 2012). Specifically the Gangetic plains are a hub of increased human activity with huge population density. With this region being the focus of the fog formation, there are reports suggesting that these pollutants and emissions are increasing the dense fog incidences over the region (De et al. 2005). On the other hand, the increase in urbanization has lead to an urban heat island effect which is said to help disperse fog much more quickly. But still, according to Syed et al. (2012), the frequency of fog incidences have increased three times in three decades (1976–2010) over India. While the fog incidences over the whole region are a significant impact of the WDs, these fog occurrences have their own impact. One of the major consequences of concentrated fog is the human health hazard. Inhalation within a foggy environment may cause many health issues to humans, for example respiratory distress and disorders. The fog composition may be acidic or alkaline depending on the forming aerosols or emissions which determine the chemistry of the fog (Ali et al 2004). In extreme cases the chemical composition of fog might be a potential hazard to the humans, vegetation, wildlife, cattle and infrastructure due to its corrosiveness. Another impact of fog incidences is the severe reduction of visibility. This reduction in visibility causes obstruction of the transport system. The foggy conditions may lead to transport accidents which may be injurious or fatal to humans (De et al. 2005). These may also cause delays and various other inconveniences specifically in the railway and aviation sector. The fog is a major hazard for aviation which may lead to the necessity of diverting, delaying or grounding aircraft (Jenamani 2012a, b). In these regions of high urbanization and heavy air traffic, the fog occurrences are highly disadvantageous. With the guarantee of increased transport- network density and frequency in the future, these increasing fog events become even more serious. According to De and Dandekar (2001), visibility over northern Indian airports show an increasing trend during winters for more very poor visibility days, due to fog, as compared to the southern airports. Due to all these negative impacts, major economic loses that are comparable to the natural disasters like hurricanes are attributed to the fog events (Syed et al. 2012).

The second severe weather events which are a consequence of WD during winters that we are discussing in this section are the cold waves or cold surges. Conditions in which the minimum temperatures of a region drops well below the normal minimum temperatures are designated as cold wave conditions. Only departures from normal minimum temperatures are used to define cold waves, and no set minimum temperature is set as it may vary for different regions (Bedekar et al. 1974). In such instances, associated reductions in maximum temperatures as well as lowering of moisture conditions are also observed. Strong wind speeds during certain cases of cold waves may add to the wind chill factor. Cold wave conditions are sometimes also associated with ground frost. Ground frost is caused due to the direct deposition of frozen water vapor onto the surface due to freezing temperatures. The cold waves impact mostly northern India during winters, but may also extend their influence southwards and eastwards during severe cases. The frequency of the cold waves reduces drastically southwards and eastwards even within the northern region. This can be explained due to the warming of the cold stream as it descends and moves along the orography. The intensity of the cold waves are generally said to decrease east of 80°E and south of 20°N. These events usually last up to 4–5 days and in extreme cases 7–10 days (Rao and Srinivasan 1969). Due to the migration of the WDs, the cold wave events appear along the track of the WDs.

Cold and dry air from the north is a characteristic feature associated with the rear of the WD. As the WD migrates past a region, cold and dry air from the higher latitudes sweeps over the same region (Yadav et al. 2012). This region is mostly the northern India region as discussed above. Cold waves may form due to active (precipitating) as well as weak (non-precipitating) WD occurrences. In the wake of an active WD, there is a sudden drop in the minimum temperatures due to stronger circulation patterns which draw in cold air quickly from the north. Whereas, if there are already low minimum temperatures associated with weak WD instances, then there is a gradual further fall in minimum temperatures. In certain cases, a low or a disturbance north of India may also generate cold waves from the high at the rear of the disturbance, where the high extends towards the Indian region. From the discussion it can be concluded that cold waves usually are northerly or north-westerly and flow towards southern and eastern directions (Rao and Srinivasan 1969). As the pressure gradient at the back of the WDs can be strong, winds with high speeds might develop along with the cold waves. These winds can be associated with the term wind chill factor which increases the cold impact during such an event and strong wind will also cause the spread of the cold waves over a large spatial extent. Fog conditions may also enhance cold waves as dense fog conditions mute the solar radiation by inhibiting the heating of the ground and causing further cooling (Bedekar et al. 1974). Mooley (1957) stated that to maintain cold wave conditions there should be no successive WD after the first one. This maintains the northerly cold air flow without interruption. A second WD right after the first causes an influx of warm air in the front of the second WD. This warm flow disrupts the cold wave conditions. Thus cold wave conditions are maintained if a intense WD is not followed by another WD or even develop a disturbance in the north of India or an induced low in the south. In fact, continuous and successive WDs over the northern India leads to unusually warm conditions during otherwise colder winter season.

Physiologically, people are acclimatized to a temperature range specifically associated with the region of their long-stay residence. The cold wave events are damaging to the humans due to their sensitivity to extreme lowering of temperatures beyond their acclimatized temperature range (Bedekar et al. 1974). Thus, cold wave events may cause health hazards like frost bite or even claim fatalities in the human population (De et al. 2005). Extremely cold conditions are also not favorable for winter or rabi crops or even wildlife and natural vegetation (Yadav et al. 2012). Frosting conditions are even more harmful for the agriculture sector.

5.3 Western Disturbances in the Changing Climate

Climate change is the most debated scientific topic of the twenty first century. India, with its large expanse and heterogeneous geography, already has a wide variety of climatic sub-divisions, and any change in the climate has a large temporal and spatial impact. Specifically over India, issues of vulnerability, prevention, mitigation and adaptation are usually associated with climate change. But as it is not in the scope of this book, we will not be getting into this debate of the truth about the climate change over India. Instead this section focuses on the question if there is an impact of climate change on the WDs or even vice versa. And in addition, as there might be very few studies relating the climate change and WDs directly, hence we will also focus on the relation between changing climate and the impacts of WDs (winter precipitation, cold waves or low temperature conditions etc.) that have been discussed previously in this chapter. According to Dash et al. (2007), the general perception is that there has been an increase in the frequency of the extreme events like cold waves, natural disasters etc. But as they suggested, such a perception should be supported by scientifically sound facts. Thus this section provides a review of the different scientific studies on WDs or their impacts on changing climate.

The global hydrological cycle is expected to accelerate with increased CO_2 as the warmer atmosphere can hold more water (Zahn and Allan 2013). Thus regions where the precipitation is strongly dependent on ocean moisture uptake will experience stronger precipitation events (Gimeno et al. 2013). The variability of mid-latitude winter weather is strongly governed by extratropical cyclones, although there is very little evidence that the frequency or wind speed of these cyclones will increase. However, more intense precipitation from the cyclones associated with WDs will have socioeconomic impacts over the western Himalayas. This remains an open question for social scientists to investigate further in line of existing scientific knowledge and understanding. So far there are no observation-based studies concerning the changing nature of WDs with increased CO_2 concentrations. Based on Coupled Model Intercomparison Project Phase 3 (CMIP3) experiments, Meehl et al. (2007) revealed possible increased future storm activity; however, the more recent CMIP5 simulations show a decline in Northern Hemisphere storm activity (Chang et al. 2012). Therefore, extensive investigations in line with various model projections are needed to establish how exactly the trend of these storms will be in future. It is important to note that accurately simulating snow/rain differentiation in models are likely to be significantly limited in their ability to capture this. Of the climate drivers presented within the model environment, snowfall amounts are likely to be more uncertain, as well as how good the regional topography is represented in the coarse resolution global CMIP series of models. In addition, since polar amplification means that the higher latitudes will warm faster than the Northern Hemisphere as a whole, the temperature gradient will decrease (Hall 2004). It can be expected that the total winter snowfall from WDs will increase, but the frequency of such events will remain largely unchanged.

According to Dash et al. (2007) there has been an slight increase in the precipitation during winter over the northern Indian region. This study also reported a warming trend, and an increasing trend in the maximum temperature and fluctuating minimum temperatures during winters in northern India in the recent decades. This warming trend has become more pronounced after 1960s (Bhutiyani et al. 2007). Winter rainfall over the hilly region shows a decreasing trend for moderate rainfall days and increasing trends for heavy rainfall days (Dash et al. 2009). Also the short burst events of precipitation interspersed with longer dry spells show significant increasing trends. Due to the increasing temperatures, the melting of the winter snow cover during summer period has been enhanced (Kripalani et al. 2003). Dash et al. (2009) specifically mentioned that the increase in the short but heavy precipitating events are an indication of increasing frequency of intensified WDs which leads to strong localized storms. Syed et al. (2009) also reported an increase of winter precipitation over central and southwest Asia during the period 1951–2000 which is possibly due to intensification of eastward moving synoptic disturbances from the Mediterranean. According to Fowler and Archer (2006) and Dimri and Dash (2012), there is a warming trend over the western Himalayas during the winter, thus indicating the lowering of the frequency of the cold waves events. Though the trends in the winter precipitation are inconsistent, still the study showed a decreasing trend in the winter precipitation over the western Himalayas (Dimri and Dash 2012). There is a decrease in the heavy precipitation events. The inconsistency is due to the variable orography which leads to highly variable precipitation events over such terrain which might not be detected on the sparse observational station network. On the other hand, variability within the winter precipitation over the north of India shows an increase in the recent decades (Yadav et al. 2012). And the future trend of the precipitation patterns and surface air temperatures show an increase over northwestern India during winters at the end of the twenty-first century (Yadav et al. 2010). Shekhar et al. (2010) also showed a decreasing trend in the winter seasonal snowfall and frequency of snowfall days. As previously discussed, there is a possible teleconnection between the snow cover over the north and the ISM. But after 1970s there has been weakening of this teleconnection which is attributed to the warming trends observed during winters and post-winters which is causing the rapid melt of the snow cover post-winters (Bhutiyani et al. 2007). In fact the study of Kripalani et al. (2003) suggests that the earlier negative correlation between this winter snow cover and ISM in recent decades has turned positive in certain cases as there is higher impact of snow melt on the monsoon circulation. Such rapid melting of snow in the warming climate has also lead to flood situations over the region.

In the scenario of the changing climate, we need to understand the alterations in the frequency, intensity and tracks of the WDs. Studies have found a decreasing trend (Das et al. 2002) or no consistent significant trends (Shekhar et al. 2010) in the WD occurrences in the recent decades. Shekhar et al. (2010) suggest that there is decreasing amount of snowfall in winter, but WDs are not reducing in frequency. Though they are suggesting no correlation between WDs and winter snowfall, it can mean that intensity of the WDs is reducing and thus leading to lower precipitation. Observations suggest recent decreasing trends in cyclonic activity over the western Mediterranean, whereas no significant change over the central and eastern Mediterranean (Syed et al. 2006). With specific reference to the frequency of WDs, Ridley et al. (2013) have provided a comprehensive overview of the increase in WD frequencies up to 2100, and associated snowfall is also predicted to increase over the region. Ridley et al. (2013) explained this by changes in circulations using the regional climate model (HadCM3) which simulated increased occurrence of WDs and an associated overall 37 % increase in winter snowfall. In view of this model, the environment produces higher circulation corresponding to the evolution of the WDs and hence higher precipitation. But one of the regional climate models (HadRM3-E) used in the study did not show any significant changes in the frequency of the WDs or the snow precipitation. Madhura et al. (2014) also indicate an increase in the frequency of the WDs due to the mid-tropospheric warming trends in recent decade over the west-central Asia. Such warming enhances the meridional temperature gradient which will in turn increase the baroclinic instability of the mean westerly wind. These changes favor increased variability of the WDs and higher propensity of the associated precipitation. Another important finding for such increase is based on elevation dependency of the climatic signals over the Tibetan Plateau and Himalayan region, which introduces zonally asymmetric changes in the winter circulation through mid- and upper tropospheric temperatures over the Eurasian region.

There exists still no in-depth study on the trends of the intensities of WDs in the changing climate or even future predictions, let alone on the track changes of the WDs. But studies on the typical extra-tropical cyclones in the northern hemisphere show a decreasing trend in the frequency of the extra-tropical cyclones with increasing temperatures (Catto et al. 2011; Mizuta et al. 2011; IPCC 2012). A warming environment is also suggested to increase the intensity of the extreme extra-tropical cyclones (Mizuta et al. 2011) due to changes in the temperature gradients required for the development of these cyclones. Such cases of sporadic but extreme weather events are predicted to produce higher episodic losses increasing the risk of such events even in the face of decreasing frequency of the events (Air Worldwide 2012). Increase in such disasters due to extreme WDs are also possible in the future warming climate. But there is another school of thought that suggests that the warming environment may cause a decrease in the temperature gradient between latitudes and so will reduce the intensity and frequency of these disturbances. Additionally, studies also predict a poleward migration of the tracks of the extra-tropical cyclones in a warming climate (Catto et al. 2011; IPCC 2012). These changes predicted for the typical extra-tropical cyclones might be reflected in the changes in the WDs. Thus, this might even mean a poleward shift of WDs which would result in reduction in the winter precipitation over India. As already discussed, the winter precipitation is a very import part of the Indian ecology and economy and loss of this part of Indian climatology would be disastrous. Thus, there is possibility of a change in WDs in the changing climate, and these changes will have significant direct or indirect impacts on the Indian subcontinent. There is a need to list and quantify these changes in the different scenarios so as to develop mitigation and adaptation strategies.

Regional model studies suggest an increase in mean annual temperature, averaged over the Ganges basin, in the range of 1–4 °C for the period from 2000 to 2050 (Moors et al. 2011). Projections of precipitation indicate that natural variability dominates the climate change signal, and there is considerable uncertainty concerning changes in regional annual mean precipitation by 2050. Glaciers in headwater tributary basins of the Ganges appear to continue to decline (Bolch et al. 2012), but it is not clear whether meltwater runoff would continue to increase in the future since this depends on the snow accumulation regime. Future changes of monsoon intensity will have an important effect on Himalayan glaciers, but current climate projections do not agree even on the sign of change, thus introducing further uncertainties (Moors et al. 2011). Nevertheless, all models project glacial mass losses in the coming decades that are substantial for most parts of the Himalayas, but consistently fall well short of complete region-wide glacier disappearance even by 2100. Water availability is subject to decadal variability, with much uncertainty in the contribution from climate change (Moors et al. 2011). Meltwater is extremely important in the Indus basin and important for the Brahmaputra basin, but plays only a modest role for the Ganges (Immerzeel et al. 2010). Interannual variability of the monsoon onset alone can have a strong influence on monsoon rainfall totals (20–30 %) and the patterns of accumulation (Lang and Barros 2004; Barros and Lang 2003), which are difficult to predict. The predicted changes in precipitation and temperature will probably not lead to a significant increase in water availability by 2050, but the timing of runoff from snowmelt will likely shift to earlier in the spring and summer.

Although global socioeconomic scenarios show trends to urbanization, locally these trends are less evident and in some districts rural population is increasing. Falling ground-water levels in the Ganges plain may prevent expansion of irrigated areas for food supply (Rodell et al. 2009). Changes in socioeconomic development in combination with projected changes in the timing of runoff outside the monsoon period may increase flash floods associated with more extreme rainfall (Thayyen et al. 2012), and will make choices difficult for water managers. Because of the uncertainty in future water availability trends, decreasing vulnerability by augmenting resilience is the preferred way to adapt to climate change. Adaptive policies are required to increase society's capacity to adapt to both anticipated and unanticipated conditions.

This work on the role of the WDs during the present climate provides motivation to anticipate the impacts on impacts on various socio-economic issues particularly over the northern Indian region. Better understanding and an improved corresponding forecast will provide advantages in cases of adaptation and vulnerability within a changing global context.

5.4 Western Disturbances and Future Research

Despite the all the information reviewed and synthesized in this book about the WDs, there are still gaps in our knowledge on these complex systems, the WDs. With ongoing research, future studies need to be planned for the different focus areas related to WDs. From our understanding, we can classify the some areas of focus for improvements as follows:

1. Dynamical studies
   - These should include more exhaustive research on the origin and tracks of the WDs before they reach the Indian sub-continent.
   - More studies to quantify the impact of surface variability on the WDs in light of urbanization and other increasing anthropogenic activities.
   - Directed studies on the influence of WDs during the non-winter season and the WD linkages with global teleconnections.
2. Impact studies
   - Performing correlation studies to define the various significant impacts of the WDs over the Indian subcontinent.
   - Inter-disciplinary studies to understand the hydrological and geomorphological impacts of the WDs
   - Quantification of the socio-economic losses associated with the disasters linked with the WDs.
3. Climate change studies
   - Understanding the changes in the WDs' intensity, track and frequency due to the changing environment.
   - Listing the possible impacts due to the changes in the WDs and developing possible mitigation and adaptation strategies.
   - Understanding possible impacts of WDs on the regional climate and how these might influence the changing climate.

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