Chapter 7
Climate Variability and Extreme Weather in High Mountain Asia: Observation and Modelling

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Abstract The hydrological cycle in High Mountain Asia is of critical importance for water security, agriculture and power generation for one of the most densely populated regions in the world. Glaciers over the central Himalaya have retreated at particularly rapid rates in recent decades, while glacier mass in the Karakoram appears stable. This chapter focuses on the climate of recent decades and discusses how the unique orography and complex terrain of this area of the planet influence weather patterns and the climate of the region and implications of these interactions for the future of high-elevation freshwater reservoirs.

7.1 High Mountain Asia Climate

High Mountain Asia (HMA) is the definition of the area that extends from the Hindu Kush and Tien Shan in the west to the Eastern Himalaya in the east. The Lesser Himalayas (average height 1200–3000 m) and the Great Himalayas (snow-covered mountains having an average height of 3000–7000 m above Mean Sea Level) are also part of HMA (Joshi 2004).

The regional climate of the HMA is influenced by two predominant systems: the Indian Summer Monsoon that extends approximately from June to September and winter western disturbances (WWD) from December to March. The interaction between these systems results in two distinct climatic regimes with different precipitation and water storage characteristics (Bookhagen and Burbank 2010; Cannon

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et al. 2016). Consequently, there is an east-west gradient in monsoonal influence across the HMA (Fig. 7.1) with the Central Himalaya (CH) receiving up to 80% of its annual precipitation during the monsoon months. In contrast, the Karakoram-Hidu Kush region (KH) receives more than 50% of its precipitation during the winter months by fewer than ten WWD (Lang and Barros 2004). This chapter discusses the influence of both systems and their variability in the hydrology of HMA and ends showing recent climatic trends affecting the region.

Synoptic scale systems associated with significant snowstorms in the Himalaya and KH during winter have been associated with the propagation of midlatitude wave trains and respective extratropical cyclones that disturb circulation in the lower and upper atmosphere (Singh et al. 1995; Lang and Barros 2004; Barlow et al. 2005; Dimri et al. 2015). These systems affect weather in the KH and adjacent regions (Ridley et al. 2013; Cannon et al. 2015) and although they are more common during winter (December–February) they are often observed during Spring (March–April) (Cannon et al. 2015, 2016; Norris et al. 2015). When cyclones associated with WWD are terrain-locked, they often result in extreme precipitation and snowfall caused by topographic uplift (Dimri 2006; Norris et al. 2015). Snowfall generated by WWD maintains regional snowpack and glaciers (Anders et al. 2006; Tahir et al. 2011; Ridley et al. 2013; Cannon et al. 2015), and is essential to water resources for hundreds of millions of people (Hewitt 2005; Immerzeel and Bierkens 2010; Miller et al. 2012). Nonetheless, while precipitation is primarily orographically forced during intense WWD with strong cross-barrier winds (Braun et al. 1997; Medina et al. 2005; Norris et al. 2017), weaker WWD with similar precipitation totals may occur when enhanced instability and high moisture content are observed at low levels in late winter and spring (Cannon et al. 2016).

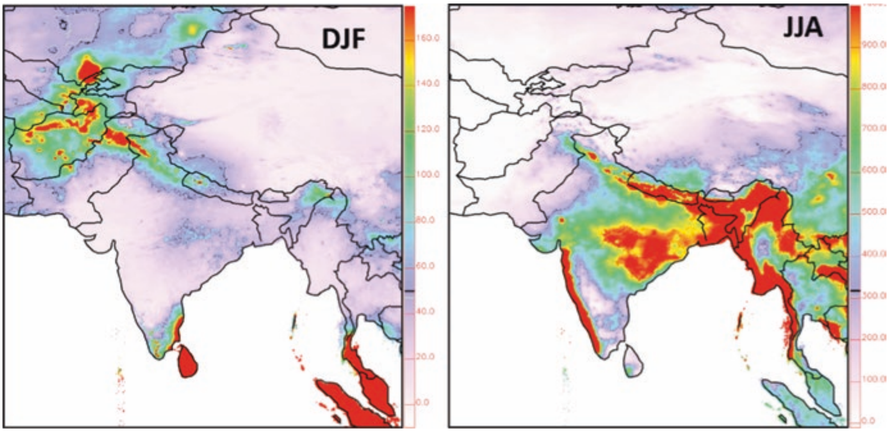

Fig. 7.1 Total seasonal mean precipitation over HMA, Subcontinental India, Southwestern China, Pakistan, Afghanistan, Kyrgyzstan, Uzbekistan, Kazakhstan, Burma, Thailand and Malaysia during December-to-February (left) and July-August (right). Note the difference in scale ranges**.** Data source: CHIRPS. (Funk et al. 2015)

Cannon et al. (2015) examined variations and changes in the WWD and relationships with extreme precipitation in the KH and central Himalaya (CH) regions from 1979 to 2010 using multiple data sets. They showed that extreme events occurring in these two regions are often independent. Additionally, they used the wavelet-power spectrum of 200 hPa geopotential anomalies on synoptic time-scales as an index for WWD and investigated trends in the amplitude of the signal affecting KH and CH separately. They showed evidence that the frequency and strength of WWD affecting KH have increased, possibly increasing local extreme events. Contrasting trends were observed for the CH domain. Although teleconnections with known modes of climate variability that affect central Asia (e.g., Arctic Oscillation, Eurasian/Polar Pattern, the El Niño Southern Oscillation, and the Siberian High) may influence the interannual variability of WWD, they do not explain the observed trends.

Central Himalaya (CH) is also deeply affected by the Indian Summer Monsoon (Fig. 7.1) (Parthasarathy et al. 1994; Bookhagen and Burbank 2006; Guhathakurta and Rajeevan 2008; Ueno et al. 2008; Mukherjee et al. 2015; Carvalho et al. 2016). In Nepal, the onset of precipitation occurs in the middle of June. Monsoon precipitation generally accounts for 80% of annual precipitation (Ueno et al. 2008), but this amount vary during the season depending on intraseasonal variations of the Indian Summer Monsoon (Carvalho et al. 2016). The El Nino/Southern Oscillation (ENSO) plays a primary role in modulating the interannual variability of precipitation in the CH. Numerous studies have shown that precipitation in the CH exhibits a strong diurnal cycle, with prevalence of daytime precipitation on ridges and night time precipitation in valleys, with the main mechanism being the development of orographic convection (Higuchi 1977; Bhatt and Nakamura 2005). Nonetheless, precipitation patterns are heterogeneous in this region and depend on the steepness and orientation of the slopes relative to the monsoon circulation (Yasunari and Inoue 1978; Lang and Barros 2004).

7.2 Intraseasonal to Interannual Variability

The WWD activity over southwest Asia (25–40°N; 40–80°E) is influenced by global modes of climate variability including the Madden-Julian Oscillation (MJO) (Jones et al. 2004b; Barlow et al. 2005; Dimri 2013b; Hoell et al. 2014), El Niño Southern Oscillation (ENSO) (Syed et al. 2006; Yadav et al. 2010, 2013; Dimri 2013a; Hoell et al. 2013), Arctic Oscillation/North Atlantic Oscillation (NAO) (Gong et al. 2001; Syed et al. 2006; Yadav et al. 2010; Filippi et al. 2014), and the Polar Eurasia Pattern (Lang and Barros 2004).

During the boreal winter, southwest Asia, and particularly the KH, are under influence of upper-level westerlies (Krishnamurti 1961). Variability in the upper-level jet over southwest Asia (i.e, shear, maximum wind speed, and deformation) has a complex relationship with WWD activity (Barlow et al. 2005). Teleconnections with ENSO (Rasmusson and Carpenter 1982) and NAO (Barnston and Livezey

1987) on interannual time-scales and the MJO (Madden and Julian 1971, 1972, 1994; Jones et al. 2004a) on intraseasonal timescales modify circulation in the lower and upper troposphere and the characteristics of the subtropical jet, significantly influencing the frequency and intensity of WWD with implications to the seasonal precipitation totals in HMA (Yadav et al. 2010; Filippi et al. 2014; Dimri et al. 2015). However, Cannon et al. (2015) showed that the characteristics and development of WWD and orographic precipitation affecting KH depend on how these global modes of variability interact and modify the atmospheric dynamic and thermodynamic conditions.

Cannon et al. (2017) examined the influence of ENSO and the MJO on the characteristics and frequency of WWD. They showed that on interannual time-scales, El Niño related changes in tropical diabatic heating induce a Rossby wave response over southwest Asia that enhances the dynamical forcing of WWD and increases available moisture. This combined effect enhances the frequency of extreme orographic precipitation in the KH during El Niño compared to La Niña or neutral conditions. Nonetheless, the Rossby wave response associated with the MJO activity is less spatially uniform over southwest Asia and varies on intraseasonal timescales. Therefore, the relationships between MJO activity and WWD, and how the MJO phases affect KH precipitation, are more complex and depend on numerous factors. For instance, some phases of the MJO favor the dynamical enhancement of WWD and at the same time suppress available moisture over southwest Asia, whereas other phases favor exactly opposite conditions. Because moisture availability and convective instability (thermodynamic factors) and strong cross-barrier winds (dynamical enhancement) may equally influence orographic precipitation (Cannon et al. 2015; Norris et al. 2015), most MJO phases can induce extreme precipitation in the KH as the oscillation evolves. Therefore, understanding and predicting independent and combined effects in tropical forcing by ENSO and MJO must be considered for long-term evaluations of the KH hydrology.

7.3 Recent Climatic Trends Affecting Glaciers in HMA

Most of Earth's Alpine glaciers have generally retreated in recent decades in response to global warming. However, evidence exists that in some areas increasing glacier melt may be offset by regional snowfall and/or temperature trends. This intriguing behavior seems particularly evident in glaciers over HMA (Hewitt 2005; Scherler et al. 2011; Bolch et al. 2012; Kaab et al. 2012). While glaciers in the CH exhibit some of the fastest retreat rates on Earth, many glaciers in the Karakoram appear to be stable or even advancing (Scherler et al. 2011; Bolch et al. 2012; Gardelle et al. 2012). Glaciers are reservoirs of moisture from precipitation for populations and ecosystems. Therefore, understanding how recent changes in atmosphere conditions may have contributed to the observed glacial melting rates in recent decades and whether these changes will remain, cease, or intensify is crucial in predicting the future of freshwater reservoirs for millions of people as the planet warms.

Since precipitation over the CH predominantly occur during summer (Fig. 7.1), the rapid retreat of central Himalayan glaciers has been attributed to increasing summer temperatures at high elevations (Shrestha et al. 1999). Therefore, changes to the Indian summer monsoon (ISM) precipitation are particularly relevant for CH glaciers. In fact, many studies have shown that precipitation associated with the ISM has decreased over the twentieth century because of the weakening of the overturning monsoonal circulation caused by the great warming of the Indian Ocean (Krishnan et al. 2013; Zhao et al. 2014; Roxy et al. 2015). To investigate the influence of these circulations on the CH, Duan et al. (2006) analyzed ice cores from a central-Himalayan glacier and found significant decreases in orographic monsoonal precipitation during the twentieth century. Therefore, there is mounting evidence that increasing temperatures and decreasing precipitation in summer have both contributed to glacier retreat over the CH. Contrastingly, the advance of some glaciers over the KH has been attributed to increasing precipitation in winter and summer (Archer and Fowler 2004), as well as decreasing summer temperature (Fowler and Archer 2006; Forsythe et al. 2017). These observations are consistent with the increase in the frequency and intensity of synoptic-scale activity in the KH together with the decrease of troughs affecting CH in the winter shown in Cannon et al. (2015).

Forsythe et al. (2017) proposed an index to quantify large-scale variations in circulation affecting the Karakoram (Karakoram Zonal Index – KZI). When KZI is positive (negative) there is an anticyclonic (cyclonic) anomaly in the Karakoram. They found a significant negative trend in the KZI over recent decades in summer months correlated with a cooling trend in the upper Indus basin, near the Karakoram. They attributed the negative trend to adiabatic cooling associated with a cyclonic trend, increased cloudiness, and decreased insolation. Contrastingly, they found that CH is under the influence of a vortex over the Indian subcontinent associated with the monsoon that is anomalously anticyclonic when the KZI is anomalously cyclonic. Therefore, these results provide additional evidence that the Karakoram and central Himalayan glaciers appear to have been under the influence of contrasting climatic trends in both winter and summer over the last few decades.

Norris et al. (2018) deciphered some of the regional mechanisms explaining the observed dichotomy between climatic regimes affecting the KH and the CH. They analyzed 36 years (1979–2015) of the Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010) dynamically downscaled with the Weather Research and Forecasting (WRF) model over High Mountain Asia at 6.7 km resolution. They showed that an anticyclonic warming trend is observed over the majority of High Mountain Asia in all seasons, with distinctive differences observed between the CH and KH in winter and summer (Fig. 7.2).

Although the CH has been under the influence of an anticyclonic trend in winter and summer, the WRF simulations show reduced cloud cover in the summer leading to significant warming and reduced snowfall in recent years. Contrastingly, the KH is at the boundary between large-scale cyclonic and anticyclonic trends (Fig. 7.2). WRF downscaling shows that the KH has not experienced significant snowfall or temperature changes in the winter or summer, despite significant positive trends in cloud cover and consequent negative trends in shortwave radiation. The downscaling at 6.7 km resolution did not identify any significant trends over glaciers or in

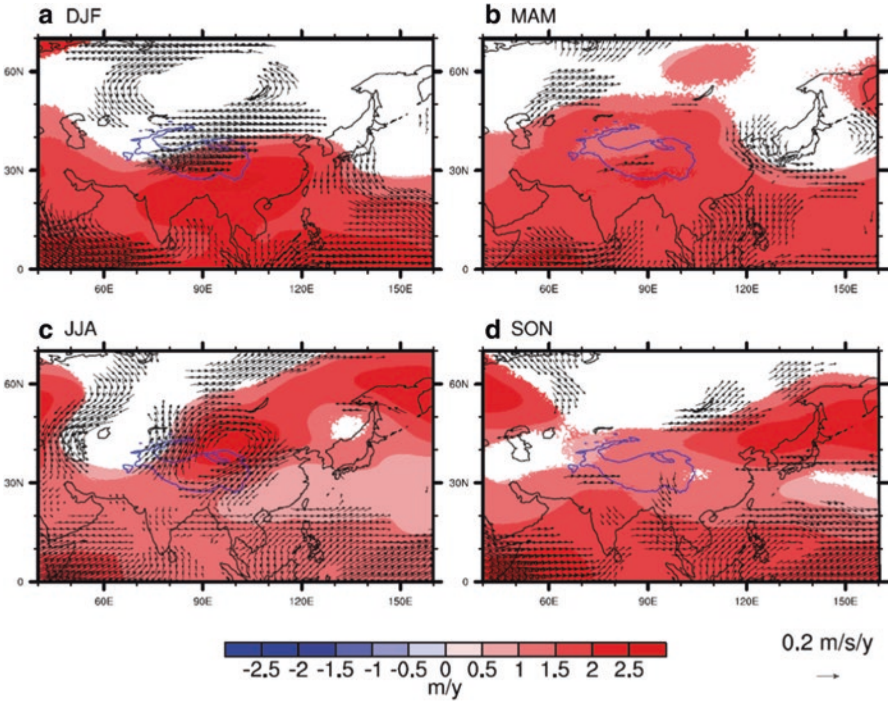

Fig. 7.2 Seasonal trends over Asia (1979/80 to 2014/15) obtained with CFSR of 200 hPa geopotential heights (colours, m/year) and winds (ms^{-1}/year). Only statistically significant trends (at 5% significance level) are plotted. Blue contour indicates the 3-km elevation to locate HMA. Reproduced from Norris et al. (2017)

neighboring regions to the KH or Spiti Lahaul, where glaciers have retreated as over the CH (Gardelle et al. 2012; Kaab et al. 2012). Although the reasons for the KH anomaly and the fast melting rate of the CH cannot be totally explained by atmospheric mechanisms, this study showed the complexity of the problem and the need of assessing variations in local circulations in regions with complex terrain such as HMA under conditions of a changing climate.

7.4 Conclusions

HMA is an important reservoir of fresh water for millions of people in the form of perennial glaciers and snow. The hydrological cycle in HMA is influenced by the Summer Indian Monsoon and the WWD. These two systems distinctly affect circulation and diurnal cycles of precipitation across the steep terrain and complex network of mountains and valleys that characterize HMA. Both the Summer Indian Monsoon and the WWD exhibit variations on multiple time-scales that modulate circulation and precipitation in HMA. These distinct systems and respective driving mechanisms play significant role in glacial growth rates and in the observed dichotomy between glaciers in the western HMA (mostly stable or growing) and central HMA (where glaciers exhibit fast melting rates) in recent decades. This apparent paradox appears to be associated with an anomalous cyclonic trend affecting the upper Indus basin near the Karakoram, whereas an anomalous anticyclonic trend is influencing Central Himalaya. These trends have contributed to variations in cloudiness, temperature, radiation and circulation across HMA that are relevant to the regional hydrological cycle. Additional observational and modeling studies are necessary to investigate the impacts of these trends, how they have contributed to glacial balance in these distinct regions and whether these conditions will persist in the future.

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