7 Synoptic Scale Systems

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Key Messages

- While the frequency of summer monsoon lows has significantly increased, the frequency of monsoon depressions has declined during 1951–2015 (high confidence)
- A significant rising trend in the amplitude of wintertime western disturbances is observed during 1951–2015 (medium confidence).
- Climate models project a decline in the frequency of monsoon low-pressure systems (LPS) by the end of twenty-first century (medium confidence).
- Climate models also project a poleward shift in monsoon LPS activity by the end of the twenty-first century which is likely to enhance heavy rainfall occurrences over northern India (medium confidence).

7.1 Introduction

The weather over the Indian subcontinent is distinctly influenced by various synoptic-scale weather systems, viz., monsoon lows, monsoon depressions, mid-tropospheric cyclones, tropical cyclones and western disturbances (Sikka 2006). These synoptic-scale weather systems have horizontal dimensions varying from 100 to 2000 km and temporal dimensions ranging from a few to several days (Wallace and Hobbs 2006; Ding and Sikka 2006). They bring floods, snowstorms, and avalanches to Indian landmass, subsequently modulating the annual mean Indian rainfall (Ajayamohan et al. 2010; Revadekar et al. 2016; Sikka 2006; Hunt et al. 2016a, b). Since Indian agriculture depends on seasonal rains, the inter-annual variability in the synoptic-scale weather systems plays an instrumental role in the socio-economic fabric of the country (e.g. Ajayamohan et al. 2010; Hunt et al. 2016a, b). This chapter provides an assessment of observed and future changes in synoptic weather systems during boreal summer (i.e., monsoon lows and depressions) and winter to spring season (i.e., western disturbances).

7.1.1 Monsoon Low-Pressure Systems

The synoptic-scale weather systems formed during the Indian summer monsoon season (June to September, JJAS) have varying intensities, collectively referred as the low-pressure systems (LPS; Mooley 1973; Sikka 1977; Saha et al. 1981; Mooley and Shukla 1989; Krishnamurthy and Ajayamohan 2010; Praveen et al. 2015). The India Meteorological Department (IMD) classifies the LPS based on their intensity and their characterization is described viz., (i) Low, a weaker system with wind speed less than 8.75 m s^{-1} and a closed isobar in the surface pressure chart in the radius of 3° from the center, (ii) Monsoon Depressions having wind speeds between 8.75 and 17 m s^{-1} and more than two closed isobars with an interval of 2 hPa in the radius of 3° from the center, and (iii) Cyclonic storms having wind speed more than 17 m s^{-1} and more than four closed isobars at 2 hPa interval on the surface pressure chart (see the summary in Table 7.1).

Summer monsoon LPS mostly comprises lows and depressions, with a very few cyclonic storms. The majority of LPS originate from the head of the Bay of Bengal (BoB, 76%) (Godbole 1977; Sikka 1977, 2006; Saha et al. 1981) and move northwestward and/or westward towards the Indian subcontinent with an average speed of 1.4–2.8 m s^{-1} (Sikka 1980). A few systems also form over the Indian landmass (15%) and the Arabian Sea (9%) and move towards the Indian subcontinent (Sikka 2006). Most of the LPS forming within the Indian monsoon trough region are generally cyclonic systems with weaker intensity as compared to tropical cyclones (Mooley 1973; Godbole 1977; Sikka 1977).

The most efficient rain-producing systems are the LPS forming over BoB and moving along the monsoon trough region in northwesterly/westerly direction and they also regulate the seasonal monsoon rains over the Indian landmass (Raghavan 1967; Krishnamurti et al. 1975; Saha et al. 1981; Yoon and Chen 2005; Sikka 2006; Vishnu et al. 2016). Among the various LPS, monsoon depressions are usually associated with widespread to heavy rainfall over the central part of India and their contribution to seasonal rainfall is as high as 45% (Krishnamurti et al. 1975; Saha et al. 1981; Yoon and Chen 2005; Pai et al. 2014, 2015). The west coast of India also receives a significant amount of rainfall during the occurrence of depressions over the BoB (Krishnamurthy and Ajayamohan 2010; Vishnu et al. 2016). In contrast, observations indicate rainfall reduction over the northeast part of India and the southern Peninsula during the passage of monsoon depression (Raghavan 1967). Monsoon lows, unlike depressions, are not often associated with

Table 7.1 Classification of monsoon LPS following IMD

LPS	Closed isobars	Wind speeds
Low	1	<8.75 m s^{-1}
Monsoon depression	>2	8.75–17 m s^{-1}
Cyclonic storms	>4	>17 m s^{-1}

extreme rainfall events. But they can bring substantial rains to the Indian landmass, and monsoon lows contribute to about 40% of monsoon seasonal rains over the central Indian landmass (Hurley and Boos 2015).

Generally, the development and intensification of LPS have associations with warm sea surface temperatures (SSTs), and environmental factors, such as the presence of low level (850 hPa) cyclonic vorticity, high mid-tropospheric (500 hPa) humidity and strong vertical wind shear (difference in the zonal winds between 850 and 200 hPa) (Sikka 1977). Further, other large-scale synoptic environments which favor the LPS genesis also includes the following: (i) upper-tropospheric easterly waves, (ii) westward-moving residual low of tropical cyclones from the Western Tropical Pacific–South China Sea (WTP-SCS) region and (iii) slow descent of mid-tropospheric cyclonic circulations (Sikka 2006). While in all other northern hemispheric basins the cyclone activity peaks in July–August, the strong vertical wind shear during summer monsoon season generally restricts the LPS activity over the Arabian Sea and the BoB to further intensify into tropical cyclones (Gray 1968; Sikka 1977; Ding and Sikka 2006; see Chap. 8). Accordingly, intense systems such as Cyclonic Storms and/or Severe Cyclonic Storms (commonly referred hereafter as simply Cyclonic storms throughout the text) very rarely form in the summer monsoon season (e.g. Sikka 2006).

The spatio-temporal variations in monsoon rainfall are often associated with the genesis and movement of the LPS, and the associated rainfall distribution over its domain of influence. According to the pioneering study by Eliot (1884), the heaviest rainfall occurs in the southern quadrant of monsoon depressions over the head BoB in the formative stage, and in the southwest quadrant during its west/west-northwest translation. Monsoon depressions typically produce heavy rainfall amounts of 30–60 cm day^{-1} within the 200–300 km radius located in the southwestern sector of depressions (Sikka 2006).

In addition to LPS, there is another distinct class of summer monsoon (JJAS) synoptic systems known as mid-tropospheric cyclones (MTCs) which are quasi-stationary cold-core systems associated with the strongest cyclonic vorticity between 700 and 500 hPa levels (Miller and Keshavamurthy 1968; Krishnamurti and Hawkins 1970; Carr 1977; Mak 1983; Choudhury et al. 2018). Further, MTCs show strong midlevel convergence, with anomalous temperature field exhibiting cold (warm) signatures below (above) 500 hPa. MTCs seen over the Arabian Sea have received special attention in recent times, as they often produce flood-producing rainfall situations over the western states of India (Maharashtra and Gujarat) during JJAS. Choudhury et al. (2018) showed that some of the heaviest 3-day rain accumulations over the western Indian regions (e.g. south Gujarat and adjoining areas) during 1998–2007 co-occurred with MTC signatures. For example, the MTC occurrence during the 24 June–3 July 2005 period was associated with record 3-day rainfall accumulations of 700 mm at 72.7° E, 20.87° N located just north of Mumbai on 28 June 2005. A few other cases include: the MTC event during 9–20th July 2018 produced heavy rainfall over Saurashtra, Kutch, Gujarat, and interior Maharashtra. The extreme rainfall events over Mumbai that occurred on 29th June, 1st July, and 5th September 2019 (24-h rainfall accumulations exceeding 200 mm, as recorded at the Santa Cruz observatory in Mumbai; Indian Daily Weather Report, IMD) have co-occurred with MTCs seen over north Konkan and adjoining south Gujarat region. Choudhury et al. (2018) also showed that the formation of heavily precipitating MTCs over western India has linkage to stratiform heating structure within the northward propagating organized monsoon convection on sub-seasonal timescales. There are, however, very limited studies on MTCs and ascertaining its association with extreme rainfall events over western India (Miller and Keshavamurthy 1968; Krishnamurti and Hawkins 1970; Carr 1977; Choudhury et al. 2018), and so far no studies have documented the future projections in the MTCs. Hence for JJAS period, we mainly focus on the present and future changes in LPS characteristics.

7.1.2 Western Disturbances

During boreal winter and early spring season (December to April; DJFMA), high-pressure conditions are prevalent over north India and the associated weather is usually clear skies and dry. The conditions of cloudy, dense fog, snow, and light to heavy precipitation also occur intermittently during this season by the eastward passage of synoptic-scale weather disturbances, known as 'western disturbances (WDs)', originating from the Mediterranean (Pisharoty and Desai 1956; Mooley 1957; Singh and Kumar 1977; Kalsi 1980; Kalsi and Halder 1992; De et al. 2005; Schiemann et al. 2009; Madhura et al. 2015; Cannon et al. 2015, 2016; Dimri 2007, 2008, Dimri et al. 2015, Dimri and Chevuturi 2016; Krishnan et al. 2019; Hunt et al. 2018a, b). IMD defined WDs as follows: a cyclonic circulation/trough in the mid and lower tropospheric levels or as a low-pressure area on the surface, which occurs in middle latitude westerlies and originates over the Mediterranean Sea, Caspian Sea, and Black Sea and moves eastwards across north India (http://imd.gov.in/section/nhac/wxfaq.pdf). The WDs are basically synoptic-scale perturbations embedded in subtropical westerly jet stream (STJs) at upper levels, and also latitudinal positioning of these STJs has a greater influence on the frequency of WDs (Hunt et al. 2018a).

The WDs are modulated by the tropical air mass and the Himalayas. Accordingly, the WDs are preceded by warm and moist air mass of tropical origin and succeeded by the cold and dry air mass of extra-tropical character (Mooley 1957). So the interaction between the tropics and mid-latitude systems is manifested in WDs with associated extensive cloudiness in the mid and high levels (Kalsi 1980; Kalsi and Halder 1992; Dimri 2007).

In association with WD passages, the Karakoram, Hindu Kush Mountain Ranges and also the northern part of India oftentimes experience extreme winter precipitation and flooding conditions, and the snowfall from WDs is the major precipitation input for the Himalayan Rivers (Pisharoty and Desai 1956; Mooley 1957; Rangachary and Bandyopadhyay 1987; Lang and Barros 2004; Hunt et al. 2018c; Roy and Roy Bhowmik 2005; Kotal et al. 2014; Dimri et al. 2015). The wintertime precipitation from the WDs, a non-monsoonal type of precipitation (Krishnan et al. 2019), contributes significantly by about 30% to the annual mean precipitation over the north Indian region (e.g. Dimri 2013a, Dimri 2013b).

On an average, 4–6 intense WDs are observed during the DJFMA (Pisharoty and Desai 1956; Rao and Srinivasan 1969; Chattopadhyay 1970; Dhar et al. 1984; Rangachary and Bandyopadhyay 1987; Mohanty et al. 1998; Hatwar et al. 2005; Dimri et al. 2015; Cannon et al. 2016; Hunt et al. 2018b). The life cycle of WDs typically ranges between 2 and 4 days, and WDs are relatively rapidly moving weather systems with zonal speeds of about 8–10° longitude/day (about 10–12 m s^{-1}) (Datta and Gupta 1967; Rao and Srinivasan 1969). The periodicity of WDs ranges from 4 to 12 days as noted by various studies (Krishnan et al. 2019; Rao and Rao 1971; Chattopadhyay 1970).

7.2 Observed Variability and Future Projections

7.2.1 Monsoon LPS

LPS plays a significant role in the Indian summer monsoon seasonal total rainfall. Hence, it is of paramount importance to understand their statistics on frequency, duration, etc. Table 7.2 shows the seasonal mean statistics in the frequency of lows, depressions, and LPS for two time periods (1901–2015 and 1951–2015). Note that the statistics is prepared without distinguishing them based on their origin (i.e., irrespective of land or sea). The LPS frequency shown in Table 7.2 includes the total number of summertime synoptic systems (i.e., lows, depressions, and cyclonic storms). The data sources for depressions are from the cyclone eAtlas archived by the IMD (for 1901–2015; http://www.rmcchennaieatlas.tn.nic.in). The data for lows are from published documentations from Mooley and Shukla (1987) for the period 1901–1983, from Sikka (2006) for the period 1984–2002 and from the Journal of Mausam published by Indian Meteorological Society for the latest period (i.e., since 2003).

Consistent with the statistical inferences from previous studies (Godbole 1977; Mooley and Shukla 1987), Table 7.2 also shows that LPS is generally dominated by monsoon lows and depressions as there are only a few intense cyclonic storms during JJAS. The long-term (1901–2015) seasonal mean frequency of monsoon lows is about 7 per season, while it increases to 8 per season during the 1951–2015 period. In contrast, the monsoon depression shows a slight decrease in its frequency during 1951–2015 relative to 1901–2015.

Table 7.2 further shows that the variability in lows and depressions tends to remain the same irrespective of the data period (i.e., for 1901–2015 and 1951–2015, respectively). The mean of LPS days constitutes about 45% of the total number of days in JJAS (i.e., on average, LPS is observed for 59 out of 122 days in the season; as obtained by Krishnamurthy and Ajayamohan 2010, for the period of 1901–2003).

A time series, from 1901 to 2015, of LPS forming (in addition to lows and depressions, frequency of cyclonic storms are also included in the figure) over BoB, Arabian Sea and also on land during JJAS is shown in Fig. 7.1. There is no significant change in trend in the frequency of LPS for

Table 7.2 Statistics of summer monsoon LPS frequency for two time periods (1901–2015 and 1951–2015)

Data period	Lows			Depressions			LPS		
	Mean	Standard deviation	Trend per decade (*p*-value)	Mean	Standard deviation	Trend per decade (*p*-value)	Mean	Standard deviation	Trend per decade (*p*-value)
1901–2015	6.8	3.46	0.38* (0.0001)	4.8	2.37	−0.11 (0.07)	13.0	2.30	0.09 (0.12)
1951–2015	7.7	3.68	1.01* (0.00001)	4.6	2.42	−0.69* (0.00001)	13.3	2.40	0.16 (0.28)

Significant trends at 5% level of significance, as estimated using the *F*-test, are marked with an asterisk (*) and the corresponding *p*-values indicated in parentheses

Note that the frequency of LPS includes all summer synoptic systems (i.e., lows, depressions, cyclonic storms, and severe cyclonic storms) originated from BoB, Arabian Sea and land the 1901–2015 period (0.09 decade^{-1}; see Fig. 7.1a and Table 7.2) as well as for the post-1950 period (0.16 decade^{-1}). While the frequency of LPS does not change significantly in the last 100 years, there is a rise in the duration of LPS (Jadhav and Munot 2009). The long-term (1901–2015) trend in the frequency of lows shows a significant increase (+0.38 decade^{-1}, see Fig. 7.1b and Table 7.2), with a pronounced rise (+1.01 decade^{-1}) during the post-1950 period. In contrast, trends in the frequency of depressions during the 1901–2015 period show a decline of −0.11 decade^{-1} (Fig. 7.1c and Table 7.2), which gets prominently significant (−0.69 decade^{-1}) during 1951–2015. This decreasing (increasing) trend in depressions (lows) may also suggest compensating effect as evidenced in the insignificant trends in LPS frequency (Table 7.2). Similar to depressions, the frequency of cyclonic storms (see Fig. 7.1d) also shows a decreasing trend which is significant in both periods, i.e., −0.17 decade^{-1} for 1901–2015 and −0.15 decade^{-1} for 1951–2015. The long-term trends in the LPS frequency has been investigated in several earlier studies (Rajeevan et al. 2000; Patwardhan and Bhalme 2001; Rajendra Kumar and Dash 2001; Mandke and Bhide 2003; Jadhav and Munot 2009; Ajayamohan et al. 2010; Prajeesh et al. 2013; Vishnu et al. 2016; Mohapatra et al. 2017). Though the data periods of these studies are different, major conclusions are, moreover, the same. However, the trends in the frequency of lows and depressions are not significant during the recent three decades (1986–2015).

Also, note that periods associated with frequent lows apparently coincide with periods of fewer depressions which clearly suggest that the frequency of lows and depressions also exhibits significant inter-decadal variations (Fig. 7.1b, c). Earlier studies showed that the frequency of lows and depressions displays an epochal behavior on inter-decadal time scale. For example, Rajendra Kumar and Dash (2001) examined the inter-decadal variations in lows and depressions based on long-term observations (i.e., for 110 years, 1889–1998) and to understand their relationship with the

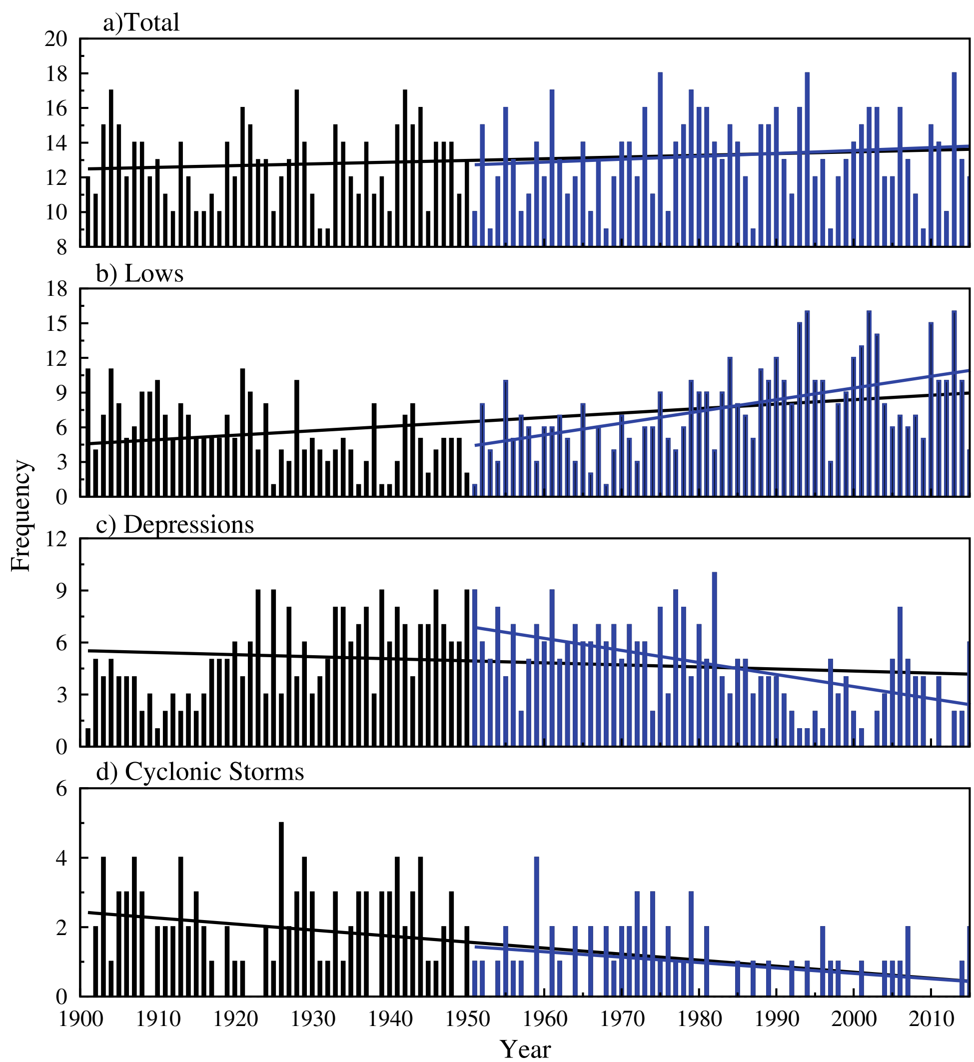

Fig. 7.1 Low-pressure systems (LPS) forming over the Indian region (Bay of Bengal, Arabian Sea, and Indian land) during the Summer monsoon season (JJAS) for the period 1901–2015. The data sources for depressions are from the cyclone eAtlas archived by the IMD (http://www.rmcchennaieatlas.tn.nic.in), and data sources for lows include published documentations (Mooley and Shukla 1987; Sikka 2006) and from the Journal of Mausam published by the Indian Meteorological Society. In **a** LPS, i.e., total frequency of lows, depressions and cyclonic storms, **b** lows, **c** depressions and **d** cyclonic storms (including both cyclonic storms as well as severe cyclonic storms)

Indian summer Monson rainfall over a 30-year time period (i.e., 30-year periodicity of above normal or below normal epochs of the Indian summer monsoon rainfall). This study showed that intense LPS (i.e., except lows) are more (less) seen during the epochs of above (below) normal Indian summer monsoon rainfall. A recent study by Vishnu et al. (2018) examined the inter-decadal aspects of LPS, and they showed that number of monsoon depressions (stronger LPS) over BoB has out-of-phase relationship with the Pacific Decadal Oscillation (PDO). The PDO induced warming in the Western Equatorial Indian Ocean decreases the moisture advection into the BoB, thereby reducing the relative humidity and suppresses the monsoon depression activity. This is in contrast to PDO induced cooling (i.e., over Western Equatorial Indian Ocean) which increases the moisture advection into the BoB, thereby enhancing the monsoon depression activity.

LPS is generally found to be associated with heaviest rain intensities (Sikka 2006). Despite the decreasing trend seen in the occurrence of stronger LPS (monsoon depressions, as noted above), the frequency of monsoon rainfall extremes (i.e., heavy rainfall events, rainfall ≥ 100 mm day^{-1}, and very heavy rainfall events, rainfall ≥ 150 mm day^{-1}; as defined in Goswami et al. 2006; Roxy et al. 2017; Nikumbh et al. 2019) have increased over the central Indian landmass since 1950. An increasing trend observed in monsoon lows during this period (weaker LPS, see Fig. 7.1b and Table 7.2), also implies an in-phase relationship between lows and monsoon rainfall extremes (Ajayamohan et al. 2010). Nikumbh et al. (2019) also noticed that the monsoon LPS, in general, (i.e., without distinguishing between monsoon lows and depressions) is conducive for increasing occurrences of extreme events over the central part of India. For example, the extreme rainfall events which caused large-scale floods over central Indian landmass on 24 July 1989, 18 July 2000 and 7 August 2007, are associated with LPS (Roxy et al. 2017).

The contrasting trends in lows and depressions imply that the intensification from lows to depressions may be rather constrained by certain background atmospheric or oceanic conditions (Mandke and Bhide 2003; Rao et al. 2004; Prajeesh et al. 2013). For example, reduction in the mid-tropospheric relative humidity over BoB is found to be an important factor preventing the intensification of lows into depressions, and thus the reduced frequency of monsoon depressions (Prajeesh et al. 2013; Vishnu et al. 2016). This was also attributed to the weakening of the low-level jet, consistent with the weakening of summer monsoon circulation (Joseph and Simon 2005; Ramesh Kumar et al. 2009).

Though the LPSs significantly contribute to the seasonal total rainfall, it is difficult to designate flood and drought monsoon years in terms of LPS variability (i.e., inter-annual variability of LPS; Sikka 2006) alone. Krishnamurthy and Ajayamohan (2010) have shown that the LPS contribution (to the total seasonal monsoon rainfall) remains invariant during the periods of monsoon floods or droughts, even though LPS frequency is slightly seen higher during flood years. However, they have shown that the track of LPS shows a marked difference between flood and drought years. The LPS reach up to northwest India during the flood years, while they are confined to central India during the drought years.

On the large-scale modes of variability influencing LPS, Hunt et al. (2016a) inferred a significant relationship between El Niño–Southern Oscillation (ENSO) and LPS activities (particularly for monsoon depressions). Their study indicated that there are more monsoon depressions during El Niño years (approximately 16% more) than La Niña years. This study differs from the investigation of Krishnamurthy and Ajayamohan (2010) which suggests that there is no significant relationship. This may be due to the consideration of total LPS in their study, instead of only monsoon depressions. There are few other studies that focused on the association of LPS activity with the Indian Ocean Dipole (IOD). Krishnan et al. (2011) reported that positive IOD is favorable for long-lived LPS. They found an approximate 12% increased lifetime of LPS during the positive IOD as compared to the normal years. Hunt et al. (2016a), however, observed that the state of IOD (i.e., positive and negative IODs) has no significant impact on depressions. Thus far, contrasting results from different studies imply that there is no clear consistency to assert the association of LPS with ENSO/IOD.

Given the prominent dependency of the Indian summer monsoon seasonal rainfall on LPS, it is important to understand the potential impact of climate change on LPS; yet there are only few studies in this direction. Patwardhan et al. (2012), with a focus on stronger LPS, showed that the frequency (intensity) of LPS may reduce (increase) by about 9% (11%) towards the end of the twenty-first century (under SRES-A2 scenario). They focused mainly on stronger LPS, except lows. Although observational evidence portray significantly increasing long-term trends (Fig. 7.1b and Table 7.2), there are no studies to diagnose the potential future changes in monsoon lows so far. Sandeep et al. (2018) reported that there would be about 45% reduction (significant at 5% level) in the LPS activity during the late twenty-first century (2071–2095) following RCP8.5 scenario (i.e., stronger warming climate scenario) from the High-Resolution Atmospheric Model (HiRAM) simulations, and the simulations from the fifth phase of Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2011) also indicated weakening of LPS activity (over central India) in the RCP8.5 simulation. They used a combined measure of frequency, intensity, and duration of LPS to determine the LPS activity. The HiRAM projections also showed a

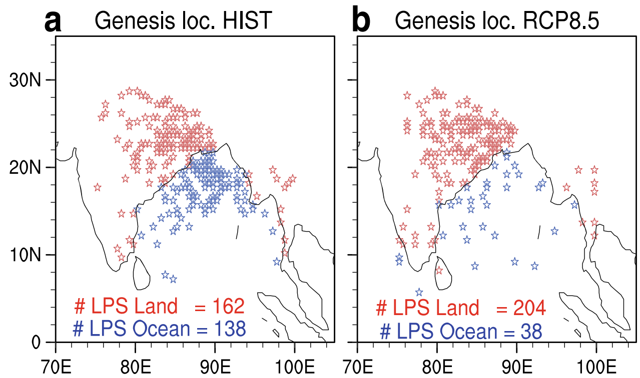

Fig. 7.2 Genesis locations of LPS formed during the monsoon season (June–September) from **a** HIST and **b** RCP8.5 simulations from High-Resolution Atmospheric Model (HiRAM). The HIST refers to historical simulation which includes both natural and anthropogenic forcing. The RCP8.5 is the simulation following the Representative Concentration Pathway 8.5 (RCP8.5) scenario. The red (blue) color indicates the genesis location overland (ocean). Adapted by permission from Sandeep et al. (2018)

poleward shift in the distribution of LPS genesis with a reduction by about 60% from the oceanic regions, and a rise by about 10% over the continental regions (see Fig. 7.2 for more details). The poleward shift in LPS activity is further stated to have wider implications and societal impacts, as it may possibly dry up central India as well as increase the frequency of extreme rainfall events over northern India. On the other hand, the future projection results from another recent study using CMIP5 models do not suggest a significant change in frequency and trajectory of the monsoon depressions during the twenty-first century (using RCP8.5 scenario, Rastogi et al. 2018). The contrasting inferences from different model projections may be attributed to the differences in experimental designs and methods of analysis.

Though climate models show a decline in LPS activity under the global warming scenario, there is medium confidence in the projected changes in LPS frequency. In this context, it is noteworthy to mention here that there is a big challenge in detecting the LPS from the model simulations, as LPS has weaker structure compared to other tropical storms (e.g. Cohen and Boos 2014; Hurley and Boos 2015; Praveen et al. 2015). Praveen et al. (2015) showed that only a very few CMIP5 models capture the observed characteristic of LPS. Moreover, the CMIP5 models usually being coarser in resolution show poor representation of LPS structure raising concerns on the reliability of future projections in LPS (Sandeep et al. 2018). The aforesaid clearly suggest an inherent uncertainty of GCMs to simulate and represent the observed and future characteristics of LPS (such as frequency, track, variability, trends, etc.). This clearly warrants careful evaluation of the model's ability to capture the observed LPS activity and its characteristics, along with continued efforts to find better modeling and identification strategies for LPS.

7.2.2 WDs

Observational studies have reported a significant warming trend in the winter and annual temperatures over the WH (Kothawale and Rupa Kumar 2005; Bhutiyani et al. 2007), and there is, however, less spatially coherent trend in the non-monsoon precipitation observed over this region (Madhura et al. 2015). The estimates from contemporary studies of Cannon et al. (2015) and Madhura et al. (2015) show a rising trend (significant at 95% confidence level) in the frequency of WD activity and in the associated localized heavy precipitation over the WH region. Madhura et al. (2015) further attributed it to anomalous warming of the Tibetan Plateau and associated mid-to-upper-level meridional temperature gradients over the sub-tropics and mid-latitudes, i.e., pronounced mid-tropospheric warming in recent decades over the west-central Asia increases the baroclinic instability of the mean westerly winds. These changes tend to favor increased variability of WDs (Puranik and Karekar 2009; Raju et al. 2011) and also increase the tendency of extreme precipitation events over WH. Krishnan et al. (2019) also highlighted the significant rising trend of WD activity and precipitation extremes over the WH through the use of daily filtered geopotential height anomalies at 200 hPa averaged over the WH region (Fig. 7.3; see also Fig. 11.8b). The reader is referred to Fig. 11.8b for the corresponding changes in precipitation over the WH region. Using a global variable-grid climate model simulations (with telescopic zooming over the South Asian region; see Fig. 7.4 for more details) for the period 1900–2005, they further attributed that wintertime regional changes over WH come from human activity.

There are some observational studies showing either no significant trends or decreasing trends in the frequency of WDs (Das et al. 2002; Shekhar et al. 2010; Kumar et al. 2015). Shekhar et al. (2010) suggested a decreasing amount of snowfall in boreal winter (using data for the period 1984–2008), but with no appreciable and consistent trend in the occurrence of WDs. Kumar et al. (2015) identified (based on the data for the period 1977–2007) a decreasing trend in total precipitation over Himachal Pradesh with significant (at 95% confidence level) reduction in the frequency of WDs. Note that these studies used a shorter period for detecting the trends as compared to studies by Madhura et al. (2015) and Krishnan et al. (2019) which also suggests that the results may be sensitive to the analysis period. In addition to the climate change associated changes in WDs, WD activity can also be modulated by large-scale modes of variability such

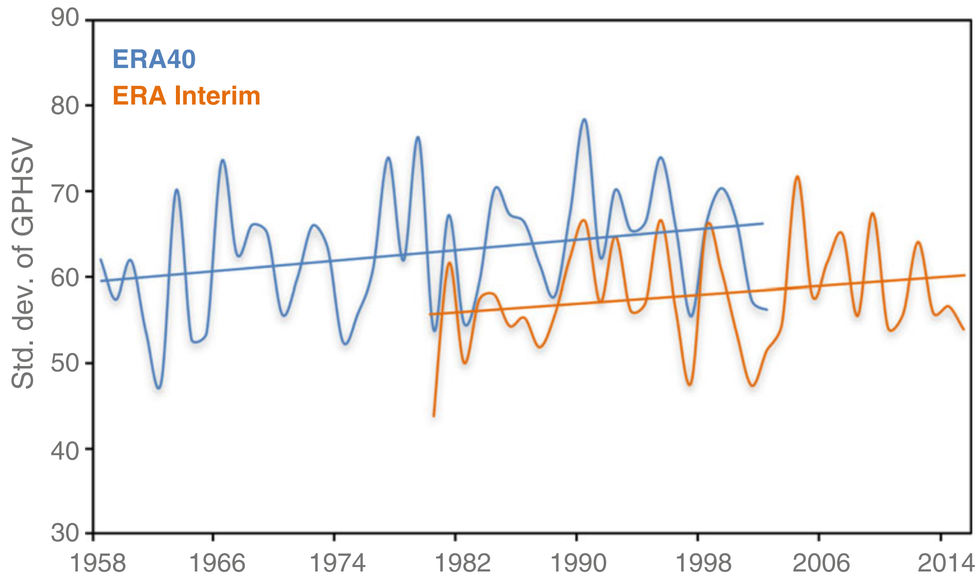

Fig. 7.3 Time-series of standard deviations of daily filtered (4–15 days band-pass) index (in gpm units) computed for every DJFMA season using 200 hPa geopotential anomalies averaged over the region 58° E–62° E and 32° N–36° N, from ERA-40 (1958–2002) and ERA-Interim (1979–2015) datasets. Adapted by permission from Krishnan et al. (2019)

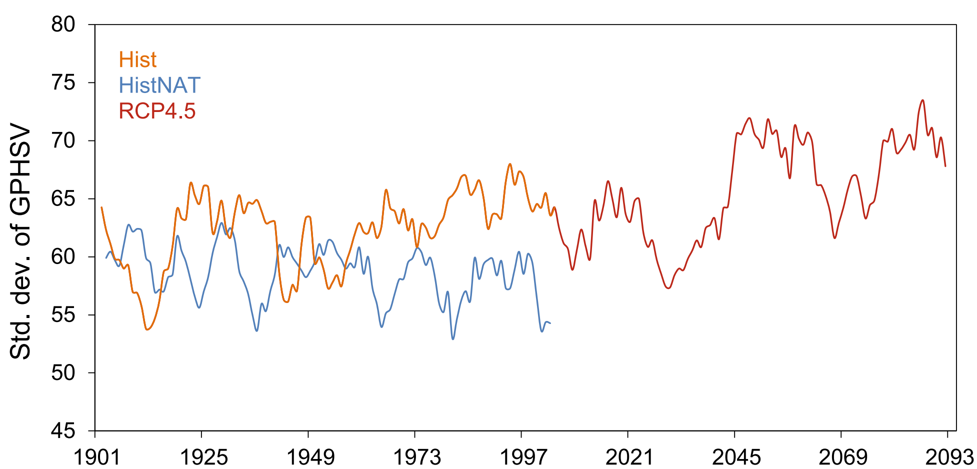

Fig. 7.4 Time-series of standard deviation of daily filtered (4–15 days band-pass) index (in gpm units) computed for every DJFMA season using upper-level geopotential anomalies at 200 hPa averaged over the region bounded by 58° E–62° E and 32° N–36° N, from the HIST (orange), HISTNAT (blue) and RCP4.5 (red) experiments. A 5-year moving average has been applied on the time-series. The first two experiments (HIST and HISTNAT) are for the twentieth-century period 1900–2005. The HIST experiment includes both natural and anthropogenic forcing, whereas the HISTNAT includes only natural forcing. The third experiment is performed in continuation with HIST into the twenty-first century period 2006–2095, following the Representative Concentration Pathway 4.5 (RCP4.5) scenario. Adapted by permission from Krishnan et al. (2019)

as Madden Julian Oscillation, ENSO, Arctic Oscillation, North Atlantic Oscillation and PDO (for more details, see Sect. 11.2).

There are only a few studies that examined the changes in WD activity (e.g. frequency) in a changing climate. For example, Ridley et al. (2013) have investigated the future projection of WD frequencies and the associated winter snowfall using two simulations of regional climate model, HadRM3 (i.e., HadRM3-H and HadRM3-E). HadRM3-H projected an increased occurrence of WDs and an increase in total winter snowfall by 2100, whereas HadRM3-E did not indicate any significant future change in snowfall or occurrences of WDs, suggesting that their RCM result was sensitive to the boundary forcing from GCM. Krishnan et al. (2019) showed a projected increase in the trend of WDs and precipitation extremes over WH using RCP4.5 scenario (i.e., a warming climate scenario; see Figs. 7.4 and 11.8d for more details) and attributed the rising trend to strong surface warming over eastern Tibetan Plateau compared to that over western side thus creating enhanced zonal gradient across Tibetan Plateau. That is, the warming trend tends to alter the background mean circulation to favor enhancements of the WDs and the orographic precipitation over the WH (see Fig. 11.8d for the precipitation changes). On the contrary, Hunt et al. (2019) found a significant 10% reduction in the annual frequency of WDs at the end of the century in future projections (i.e., in a warming climate scenario, RCP8.5) and attributed the changes in WD frequency to the projected widening and weakening of the STJ. Their study also suggests that as a consequence of this falling WD activity, the winter precipitation in north India will decrease at the end of the century.

7.3 Knowledge Gaps

Most of the studies on climate model projections focused mainly on stronger LPS (monsoon depressions) and not on monsoon lows, which remains a knowledge gap, thus requiring more studies in this direction. Further, there is no clear understanding of the various factors causing changes in LPS characteristics (i.e., both observed and projected changes), thus calling for more process-oriented studies in this direction. Secondly, the monsoon LPS associated rainfall contribution is not well represented in climate models, despite their prominent contribution to the monsoon seasonal rainfall. More studies to fully comprehend the genesis mechanisms (i.e., originating mechanism of LPS) of LPS may help in its improved representation in climate models. Finally, it is a challenge to detect the synoptic systems (i.e., LPS and WDs) from reanalysis and model simulations. Particularly, detecting monsoon LPS, having a weaker structure compared to the other tropical storms, poses a serious problem. Further, the number of synoptic systems detected in the reanalysis dataset, and climate model simulations are quite sensitive to the algorithm used for its detection and tracking. The discrepancies due to the tracking algorithm subsequently generate uncertainty in the climate model projections of synoptic systems. Furthermore, the model constraints to represent the small-scale process associated with synoptic systems (e.g. coarse resolution in CMIP5 models lead to the poor representation of LPS) raises concerns on the reliability of its future projections. In view of this, continued efforts are required to find better modeling and identification strategies for the synoptic systems.

7.4 Summary

This chapter documents a review on the current understanding of observed variability and future changes in synoptic systems that form during boreal summer and winter–spring [i.e., monsoon low-pressure systems (LPS) and western disturbances] seasons. Generally, majority of LPS originates from the head BoB migrates northwestward into the Indian subcontinent producing heavy rainfall (30–50 cm day^{-1}), thereby significantly contributing to the total seasonal (June–September) rainfall in India. On interannual time scales, rainfall contribution from LPS (to the total seasonal monsoon rainfall) remains invariant during flood or drought years, even though the LPS frequency is slightly higher during flood years. The frequency of LPS also shows significant inter-decadal variations with more (less) monsoon depressions in the epochs of above (below) normal Indian summer monsoon rainfall. On the large-scale modes of variability influencing LPS, there is no consistency between the investigations to infer the associations of monsoon LPS with ENSO or IOD. However, studies show an out-of-phase relationship between the monsoon depressions and PDO. There is no detectable long-term trend in the observed frequency of total LPS during both periods of our analysis (1901–2015 and 1951–2015). The observed frequency of monsoon depressions shows a decreasing long-term trend (1901–2015), but the decline is more significant during the 1951–2015 period. In contrast, monsoon lows show a significant increasing trend during the 1901–2015 period. There are only few studies that are currently available to understand the potential impact of climate change on LPS. Climate model projections generally show a weakening of LPS activity and a poleward shift of the genesis locations of LPS at the end of the twenty-first century. The poleward shift in the LPS activity is expected to have profound societal impacts, as it may possibly dry up central India as well as increase the frequency of heavy rainfall events over northern India.

The WDs are the synoptic weather systems that propagate eastward from the Mediterranean region towards south Asia during boreal winter, impacting the northern parts of India and the WH region. There is a significant rise in the observed WD activity during the 1951–2015 period. Yet, there is no clear consensus from the climate model projections for potential changes in the occurrence of WDs under global warming.

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