The impacts of the approaching western disturbances (WDs) on the surface meteorological variables over the north-west Himalaya (NWH), India

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Eastward-moving upper air troughs in the subtropical westerlies, commonly known as the western disturbances (WDs) in the Asian subcontinent, are primary sources of precipitation over the north-west Himalayan (NWH) region and the northern plains of India during winter. Many simulation case studies with the help of numerical weather prediction models and a few observational case studies have been conducted to understand the spatial structure, dynamics, energy and weather associated with the WDs over the NWH in the past. However, studies using in situ observations on the impacts of the approaching WDs on various surface meteorological variables at a local scale in the high-altitude mountainous regions of the NWH are lacking. The objectives of this study are to examine the impacts of the approaching WDs on various surface meteorological variables for 11 stations in the NWH and the associated precipitation amount in a 24-hr time interval. Changes (departures) in the values of various meteorological variables are examined on the first precipitation day of the occurrence of active WDs to study the impacts of the approaching WDs and the associated precipitation amount in the 24-hr time interval which are found to depend on the altitude and geographic location of a station. The mean drop in the maximum and ambient air temperatures are found to be 2.0° and 0.7°C, respectively, while the mean rise in the minimum air temperature was found to be 0.8°C. A mean drop in the surface atmospheric pressure and a mean increase in the relative humidity are found to be 0.9 hPa and 19.5%, respectively, in a 24-hr time interval. The mean precipitation amount and mean maximum precipitation amount associated with the active WDs in the 24-hr time interval are found to be 8.9 and 68.8 mm, respectively. The results are briefly discussed in the paper. The findings of this study can be useful for operational weather forecasting and a selection of precursor variables for developing a real-time local scale weather forecast model(s) for remote areas of the NWH for the winter season.

Keywords. Weather forecasting; Western disturbance; north-west Himalaya.

1. Introduction

Primary sources of precipitation over the north-west Himalayan (NWH) region and the plains

of northern India during winter are the eastward-moving upper air troughs in the subtropical westerlies, commonly known as the western disturbances (WDs) in the Asian subcontinent

(Venkiteshwaran 1938; Pisharoty and Desai 1956; Mooley 1957; Rao and Srinivasan 1969; Hatwar *et al.* 2005; Chand and Singh 2015; Dimri *et al.* 2015; Kumar *et al.* 2015 and references herein). WDs yield winter precipitation, primarily, in solid form i.e., snow, over the NWH and rainfall in the plains of northern India (Venkiteshwaran 1938; Lang and Barros 2004; Dimri 2006; Hatwar *et al.* 2005; Bhutiyani *et al.* 2008; Dimri and Das 2011; Kumar *et al.* 2015; Singh *et al.* 2015). Winter precipitation over northern India and the NWH plays a very important role in many sectors of the economy such as agriculture, horticulture, water resources, hydroelectricity and the daily water needs of millions of people dependent on the rivers originating from the Himalaya (Singh and Arora 2007; Maharana and Dimri 2014; Chand and Singh 2015; Kumar *et al.* 2015; Dimri *et al.* 2016). Snowfall during winter feeds glaciers and it builds extensive seasonal snow cover over the NWH which contributes to the preservation of the ecosystem, serves as a source of fresh water and plays a dominant role in shaping the Indian summer monsoon rainfall (ISMR), and the regional-scale and global-scale weather and climate (Dey *et al.* 1985; Beniston *et al.* 1997; Beniston 2003; Wu and Qian 2003; Archer and Fowler 2004; Bollasina and Benedict 2004; Fowler and Archer 2005; Bhutiyani *et al.* 2008; Rechid *et al.* 2009; Thayyen and Gergan 2009). However, heavy snowfall during winter over the NWH also leads to a loss of life and damage to property due to weather-generated natural hazards such as severe cold temperatures, interruptions in necessary supplies and services, communication and electricity failures, avalanches and landslides, etc. (Rangachary and Bandyopadhyay 1987; Das 2005; Hatwar *et al.* 2005; Singh and Ganju 2008; Singh *et al.* 2008; Srinivasan *et al.* 2005). Hence, weather forecasting in the high-altitude mountainous regions of the NWH during winter plays a key role in planning day-to-day activities and the mitigation of weather-generated natural hazards as mentioned earlier.

Large spatial and temporal variability in the various surface weather elements over the NWH demand local-scale weather forecasts. Local-scale weather forecasts, particularly, precipitation forecasts, largely depend on the interactions of the approaching WDs with the local topography of the NWH. Such interactions modulate local-scale surface weather variables and manifest themselves as impacts of the approaching WDs on various surface meteorological variables. This is because

the interactions of the approaching WDs largely depend on local topography, land surface characteristics, altitude and geographic position, etc. (Dimri 2004, 2009; Dimri and Mohanty 2009; Dimri *et al.* 2015). Hence, gaining some insight into, and an understanding of, the impacts of the approaching WDs on the local-scale surface meteorological variables is extremely important over the NWH. Many simulation case studies with the help of numerical weather prediction models (NWP models) and a few observational case studies have been conducted in the past to understand and gain some insight into the structure, dynamics and energy of the WDs and the surface- and upper-air meteorological variables associated with the WDs over the NWH (Pisharoty and Desai 1956; Mooley 1957; Singh 1963; Datta and Gupta 1967; Rangachary and Bandyopadhyay 1987; Mohanty *et al.* 1999; Dimri 2004, 2006, 2008; Hatwar *et al.* 2005; Roy and Bhowmik 2005; Semwal and Giri 2007; Dimri and Mohanty 2009; Dimri and Chevuturi 2013; Chand and Singh 2015; Kumar *et al.* 2015; Dimri *et al.* 2016). However, most of these studies have been conducted as case studies on the WDs and a comprehensive study on the impacts of the approaching WDs on local-scale surface meteorological variables in the high-altitude mountainous regions of the NWH using in situ observations is lacking. This study was undertaken to provide an insight into, and an understanding of, the impacts of the approaching WDs on various surface meteorological variables at a local scale in the high-altitude mountainous regions of the NWH. The findings of this study can be useful for operational weather forecasting and the selection of precursor variables for developing real-time local-scale weather forecast model(s) in the remote areas of the NWH.

2. Study area and data

This study was conducted at 11 stations spread across different mountain ranges over the NWH and covers a wide area of the NWH in the states of Himachal Pradesh (HP) and Jammu and Kashmir (J&K) (figure 1 and table 1). Snow and Avalanche Study Establishment (SASE), India, has set up a surface meteorological observational network in the high-altitude mountainous regions of the NWH to collect snow and meteorological data (Bhutiyani *et al.* 2009; Dimri and Das 2011; Singh

Figure 1. Stations with their altitudes at which the study was conducted in the NWH, India.

Table 1. Statistics (mean, standard deviation (SD)) of MX, MN, PT and SSH for the stations falling under different mountain ranges over the NWH.

Mountain range	Station	Altitude (m m.s.l.)	Winter period (no. of winters)	MX		MN		PPT		SSH	
				μ	Ω	μ	Ω	μ	Ω	μ	Ω
PP (JK)	A	3200	1995–2016 (21)	4.4	5.7	−2.6	4.1	14.6	16.6	5.1	3.5
PP(HP)	B	2192	1979–2016 (37)	16.1	5.4	2.4	3.5	13.1	14.8	4.4	2.8
PP(HP)	C	3050	1989–2016 (27)	8.1	4.8	−1.4	3.9	23.3	26.1	4.6	3.1
GT(JK)	D	3250	1995–2016 (21)	2.9	6.0	−12.0	7.7	7.2	8.0	5.1	3.4
PP(HP)	E	2800	1995–2016 (21)	5.5	4.8	13.4	−4.9	4.5	15.8	4.4	3.4
PP(JK)	F	3080	1995–2016 (21)	4.1	4.4	−5.4	4.8	14.6	15.9	3.5	3.4
GT(JK)	G	2440	1995–2016 (21)	6.5	5.3	−5.8	5.3	15.1	14.8	4.0	3.2
GT(HP)	H	3800	1983–2016 (30)	2.3	4.8	−11.8	5.4	7.0	8.1	5.2	3.6
SR(JK)	I	2960	1995–2016 (21)	4.9	4.9	−3.5	4.3	15.5	15.9	4.6	3.5
SR(JK)	J	2650	1991–2016 (25)	6.3	5.0	−2.6	4.3	16.8	17.2	4.1	3.3
SR(JK)	K	3192	1995–2016 (21)	2.0	4.7	−5.6	4.5	14.3	14.8	4.6	3.7

PP = the Pir Panjal range, SR = the Shamsawari range, GT= the great Himalaya range, JK = Jammu and Kashmir, HP = Himachal Pradesh, MX= maximum air temperature, MN = minimum air temperature, PT = precipitation amount, SSH = sun shine duration, μ = mean, Ω = SD.

et al. 2015). Data on maximum air temperature (MX), minimum air temperature (MN), ambient air temperature (AM), surface atmospheric pressure (P), relative humidity (RH), average wind speed (AVG), sun shine hour/duration (SSH), snowfall amount (SF), rainfall amount (RF) and precipitation amount (PT) were extracted from the data archive of SASE to conduct this study.

Surface weather data over the NWH are spatially and temporally inhomogeneous and partially incomplete (Singh and Ganju 2008; Singh *et al.* 2015; Dimri and Das 2011). Hence data for

which most of the variables were available were taken to conduct this study (Barros and Lang 2003; Dimri and Das 2011; Singh *et al.* 2015). Extracted data are subjected to the various quality control procedures and suspicious data are removed from analysis (under communication). A large variability in temperatures (MX, MN), precipitation amount in the 24-hr interval and sun shine duration was observed at different stations over the NWH (table 1). This shows that this study covers a variety of meteorological and/or climatological situations (table 1). Daily records

of surface meteorological variables at 00 UTC and 03:00 UTC were obtained for the study.

3. Method of data analysis

The WDs while interacting with the steep topography of the NWH cause cloudiness and wide spread precipitation over the NWH depending on the characteristics of the WDs such as regions of origin, spatio-temporal extent, travel path followed, moisture content and moisture feedback, and speed and direction of motion, etc. (Pisharoty and Desai 1956; Mooley 1957; Rao and Srinivasan 1969; Hatwar *et al.* 2005; Dimri 2006, 2008; Kumar *et al.* 2015). Hence few WDs cause only cloudiness without yielding any precipitation over the NWH and such WDs are not included in this study (Malurkar 1947). Only active WDs are considered for this study and active WDs in the past data are identified using the following expression:

$$WD_j = \begin{pmatrix} 1, PT > 0.0 \\ 0, PT = 0.0 \end{pmatrix}, \quad (1)$$

where WD_j is the occurrence of WD at a station ($j = 1$ to 11) and PT is the precipitation amount observed in the 24-hr time interval at a station j . 1(0) represents the occurrence of active (inactive) WD at a station j .

Data for active WDs on MX, MN, AM, RH, AVG, P , SSH and PT are extracted for the first day of occurrence for each active WD and its previous day from the past data for each station. Extracted past data on active WDs at each station are utilised to study the impacts of the approaching WDs on various surface meteorological variables and the associated precipitation amount with the active WDs in the 24-hr time interval. The impacts of the approaching WDs on MX, MN, AM, RH, AVG, P and SSH are computed as the changes (departures) in the values of these variables on the first precipitation day of active WDs from their previous day values using the following expression:

$$\Delta X_{j,k,t} = X_{j,k,t-1} - X_{j,k,t}, \quad (2)$$

where $\Delta X_{j,k,t}$ is the change (departure) in the value of variable X_k ($k = 1$ to 7, number of surface meteorological variables) at station j ($j = 1$ to 11, number of stations). T and $t - 1$ are first day of occurrence of active WD and its previous day occurrence, respectively.

$\Delta X_{j,k,t}$ is computed for all active WDs from the past data of each station and the following statistical measures of $\Delta X_{j,k,t}$ are computed:

$$\Delta X_{j,k,t,ME} = \text{Mean} (\Delta X_{j,k,t}), \quad (3)$$

$$\Delta X_{j,k,t,MD} = \text{Median} (\Delta X_{j,k,t}), \quad (4)$$

$$\Delta X_{j,k,t,SD} = \text{Std} (\Delta X_{j,k,t}), \quad (5)$$

$$\Delta X_{j,k,t,LC} = \text{Low} (\Delta X_{j,k,t}), \quad (6)$$

$$\Delta X_{j,k,t,UC} = \text{Uper} (\Delta X_{j,k,t}), \quad (7)$$

$$\Delta X_{j,k,t,IQR} = \text{Quar} (\Delta X_{j,k,t}), \quad (8)$$

$$\Delta X_{j,k,t,H} = \text{Highest} (\Delta X_{j,k,t}), \quad (9)$$

$$\Delta X_{j,k,t,L} = \text{Lowest} (\Delta X_{j,k,t}), \quad (10)$$

$$X_{j,k,t,SE} = \text{SE} (\text{Mean} (\Delta X_{j,k,t})), \quad (11)$$

where $\Delta X_{j,k,t,ME}$, $\Delta X_{j,k,t,MD}$, $\Delta X_{j,k,t,SD}$, $\Delta X_{j,k,t,LC}$, $\Delta X_{j,k,t,UC}$, $\Delta X_{j,k,t,IQR}$, $\Delta X_{j,k,t,H}$ and $\Delta X_{j,k,t,L}$ are mean (ME), median (MD), standard deviation (SD), lower confidence (LC) level of mean at 95% confidence level, upper confidence (UC) level of mean at 95% confidence level, interquartile range (IQR), highest value (H) and lowest value (L) of $\Delta X_{j,k,t}$, respectively, and mean, median, Std, Low, Uper, Quar, highest and lowest are mathematical operators used to compute ME, MD, SD, LC, UC, IQR, H and L of $\Delta X_{j,k,t}$. $X_{j,k,t,SE}$ represents the standard error (SE) of $\Delta X_{j,k,t,ME}$ and SE is the mathematical operator used to compute SE.

Statistical characteristics of associated snowfall amount, rainfall amount and precipitation amount with active WDs in a 24-hr time interval are computed using expression (3) to expression (10). This is done to gain some insight into the precipitation amount associated with active WDs in the 24-hr time interval for 11 stations over the NWH.

4. Results and discussion

Data on active WDs at each station are analysed and the statistical characteristics of a departure in the values of MX, MN, AM, RH, AVG, P and SSH are computed and analysed. The statistical values (mean, standard deviation (SD)) of MX, MN, AM, RH, AVG, P and SSH on the first precipitation-day of active WDs are computed at each station to study the climatological characteristics on the first precipitation day of active WDs over the NWH. Temperatures (mean maximum air temperature, mean minimum air temperature, mean ambient air temperature) and mean surface atmospheric

Table 2. Statistics (mean, SD) of MX, MN, AM, RH, AVG, P and SSH for the different stations on first precipitation day of the approaching active WDs over the NWH (μ = mean; Ω = SD A–K = stations).

Variable	Statistics	A	B	C	D	E	F	G	H	I	J	K
Maximum air temperature (MX)	μ ($^{\circ}\text{C}$)	1.9	12.0	4.1	−0.8	3.4	1.1	3.4	−0.8	0.6	3.7	−1.0
	Ω ($^{\circ}\text{C}$)	5.2	5.5	3.8	4.5	4.2	3.8	4.2	4.3	3.7	4.3	3.4
Minimum air temperature (MN)	μ ($^{\circ}\text{C}$)	−3.3	2.4	−2.2	−9.7	−3.6	−5.1	−4.0	−10.5	−3.8	−2.6	−5.9
	Ω ($^{\circ}\text{C}$)	3.2	3.4	3.1	6.8	4.3	4.2	4.6	5.0	4.6	3.4	3.9
Ambient air temperature (AM)	μ ($^{\circ}\text{C}$)	−1.4	5.1	0.1	−4.9	−0.3	−2.2	−0.4	−6.5	−1.8	0.0	−3.5
	Ω ($^{\circ}\text{C}$)	3.5	4.0	3.4	5.3	3.9	3.8	3.4	4.0	3.4	3.5	3.5
Relative humidity (RH)	μ (%)	89.3	87.1	90.5	83.7	90.1	89.1	93.0	87.3	88.1	91.2	90.1
	Ω (%)	12.7	11.6	12.6	11.2	8.1	10.1	7.0	10.8	10.7	9.9	7.2
Average wind speed (AVG)	μ (km/hr)	20.0	3.3	3.3	1.6	2.6	4.1	1.1	4.9	3.8	1.5	6.8
	Ω (km/hr)	9.7	2.1	2.5	1.4	2.0	3.3	1.0	3.9	2.9	1.2	3.4
Surface atmospheric pressure (P)	μ (hPa)	721.6	798.5	720.5	700.2	740.1	707.1	760.9	641.9	715.2	745.5	702.1
	Ω (hPa)	3.7	3.3	3.0	7.0	6.3	18.8	6.1	4.1	4.5	3.3	35.9
Sun shine hour/duration (SSH)	μ (hr)	0.3	0.8	0.5	0.2	0.8	0.6	0.4	0.2	0.4	0.5	0.2
	Ω (hr)	1.0	1.3	1.0	0.6	1.3	1.1	0.9	0.7	1.1	1.0	0.6

pressure are found to show large spatial variability on the first precipitation day of active WDs at different stations compared to relative humidity and sun shine duration (table 2). This can be attributed to the geographical positions and altitudes of different stations over the NWH (figure 1). Mean maximum air temperature, mean minimum air temperature and mean ambient air temperature are found to fall in the range (−) 1.0 $^{\circ}\text{C}$ – (+) 4.1 $^{\circ}\text{C}$, (−) 10.5 $^{\circ}\text{C}$ – (−) 2.2 $^{\circ}\text{C}$ and (−) 6.5 $^{\circ}\text{C}$ – (+) 0.1 $^{\circ}\text{C}$, respectively, for all stations except station B on the first precipitation day of the approaching active WDs over the NWH (table 2). High values of mean air temperatures (MX, MN, AM) at station B compared to other stations over the NWH were due to the low altitude of station B and rainfall as major component of winter precipitation at station B (figures 1 and 5b). Mean minimum air temperatures and mean ambient air temperatures were found to be sub-zero at most of the stations over the NWH on first precipitation day of active WDs during winter (table 2). Large variability (SD) in mean air temperatures on the first precipitation day of active WDs at each station can be attributed to the variability of the seasonal snow cover (existence/non-existence) and type of precipitation (snowfall/rainfall) during winter (Namias 1985; Karl *et al.* 1993; Leathers *et al.* 1995). Mean relative humidity, mean surface atmospheric pressure and mean sun shine duration at different stations are found to fall in the range 83.7–93.0%, 641.9–798.5 hPa and 0.2–0.8 hr, respectively, on the first precipitation day of active WDs over the NWH. These findings

indicate that the high moisture content on the surface and cloudiness are observed during active WDs over the NWH and support earlier case studies on active WDs and the weather associated with them over the NWH (Hatwar *et al.* 2005; Mohanty *et al.* 1999; Dimri 2006, 2008; Chand and Singh 2015). The large spatio-temporal variability in surface pressure and relative humidity was not found at most of the stations over the NWH on the first precipitation day of active WDs (table 2). Standard deviations in surface pressure at stations F and K are found to be large compared to other stations over the NWH (table 2). This may be due to the wide range of pressure values in the time series of surface pressure at stations F and K in the NWH and it may be due to the lack of proper calibration of pressure sensors and/or faulty pressure sensors for a few early winters in the past data. Mean wind speed falls in the range 1.1–6.8 km/hr on the first precipitation day of active WDs at different stations over the NWH except station A in the NWH (table 2).

Statistical characteristics such as the mean and SD of various surface meteorological variables can provide an idea about prevalent conditions of different surface meteorological variables on the first precipitation day of active WDs for 11 stations over the NWH. However, these do not provide any idea and insight into the impacts of the approaching active WDs on various surface meteorological variables at a local scale over the NWH which can be of enormous help in operational weather forecasting and the selection of precursors for developing

real-time local-scale weather forecast models for remote areas of the NWH. However, departures in the values of MX, MN, AM, RH, AVG, P and SSH in the 24-hr time interval of active WDs can provide an idea and insight into the impacts of the approaching WDs over the NWH. Therefore, the departures in values of MX, MN, AM, RH, AVG, P and SSH in the 24-hr time interval of active WDs are computed and various statistical characteristics such as ME, MD, SD, LC level of mean at 95% confidence level, UC level of mean at 95% confidence level, IQR, highest value (H) and lowest value (L) of departures in the values of each meteorological variable are computed and analysed. The standard error of mean (SE), for each meteorological variable, was computed to obtain the error in the mean of each meteorological variable due to sampling variations. A low value of SE for each meteorological variable indicates that large variations in mean are unlikely due to sampling variations.

Maximum air temperature and ambient air temperature are found to drop while minimum air temperature is found to rise in the 24-hr time interval as the active WDs approach over the NWH (figure 2a–c). A drop in the maximum and ambient air temperatures can be attributed to the cloudiness associated with the WDs which obscures incoming solar radiations and rise in minimum air temperature can be attributed to the cloudiness which prevents outgoing long wave radiations and warm moist air advection in the WDs system (Malurkar 1947; Rao and Srinivasan 1969; Mohanty *et al.* 1999; Dimri 2008; Chand and Singh 2015; Dimri *et al.* 2015). However, departures in air temperatures are found to differ for 11 stations over the NWH (figure 2a–c). Air temperatures (MX, MN, AM) at station D and ambient temperature at station H indicate an increase as the active WDs approach over the NWH (figure 2a–c). However, the largest drop (rise) in air temperatures is found to be 11.0 (13.0)°C over the NWH (figure 2d). A steep drop (rise) in air temperatures can be attributed to the characteristics and strength of the approaching active WDs and the prevalent surface meteorological variables as the active WDs approach over the NWH. Stations located at lower altitudes such as stations B and C are found to show a large drop in the maximum and ambient temperatures compared to other stations over the NWH (figure 2a and c). This is due to the warm air temperatures, early melt of seasonal snow cover and rainfall during early/late winter at stations B and C over the NWH (table 1). Stations at higher

altitudes such as D and H are found to show a large rise in MN compared to other stations over the NWH (figure 2b). The impacts of the approaching active WDs at stations B, C, H and J are derived based on the data of more than 25 winters and departures in air temperatures in the 24-hr time interval of the approaching active WDs are found to differ largely at these stations (table 1 and figure 2a–c). These results indicate that the impacts of the approaching active WDs depend on the altitude and geographic location of different stations over the NWH (figure 2).

Various statistical characteristics such as ME, MD, SD, LC, UC, H and L of departures in air temperatures (MX, MN, AM) for 11 stations over the NWH are shown in figure 2(d). Small values of SE of mean air temperatures indicate that large errors in ME are not expected due to sampling variations (figure 2d). Positive values of ME, MD, IQR, LC and UC for maximum air temperature and ambient air temperature over the NWH show that maximum and ambient air temperatures drop in the 24-hr time interval as active WDs approach over the NWH (figure 2d). Negative values of ME, MD, IQR, LC and UC for minimum air temperature over the NWH show that the minimum air temperature rises in the 24-hr time interval as the active WDs approach over the NWH (figure 2d). The mean drop (positive value) in the maximum and ambient air temperatures are found to fall in the range 1.2–3.4°C and 0.0–2.3°C at most of the stations over the NWH (figure 2a and c). The mean rise (negative value) in the minimum air temperature is found to be in the range 0.0–2.4°C at most of the stations over the NWH (figure 2b). A mean drop in the maximum air temperature, ambient air temperature and a mean rise in the minimum air temperature computed based on the 11 stations are found to be 2.0°C, 0.7°C and 0.8°C, respectively, over the NWH. These results support earlier findings on seasonal scale temperature anomalies associated with precipitation surplus and precipitation deficit winters over the NWH (Dimri 2006). Departures for the maximum air temperature and ambient air temperature are found to show large variability in SD compared to the departures in the minimum temperature in the 24-hr time interval of the approaching active WDs for the 11 stations over the NWH (figure 2d). SDs of departures in the maximum air temperature, the minimum temperature and ambient air temperature fall in the range 2.3–4.0°C, 1.6–2.9°C and 2.0–3.8°C, respectively, for the 11 stations over the NWH (figure 2d).

Figure 2. Impacts of the approaching active WDs on the surface air temperature in the 24-hr time interval for the different stations over the NWH. (a) Maximum air temperature. (b) Minimum air temperature. (c) Ambient air temperature. (d) Various statistical characteristics of departures in air temperatures in the 24-hr time interval of an approaching active WDs for 11 stations over the NWH (MX, MN, AM = maximum, minimum, ambient air temperatures; ME = mean, MD = median, LC (UC) = lower (upper) confidence level of mean, IQR = interquartile range, H (L) = highest (lowest) value, SE = standard error of mean).

Figure 2. (Continued.)

Surface atmospheric pressure was found to drop in the 24-hr time interval as active WDs approach over the NWH (figure 3a) which can be attributed to the trough in the mid-level westerly winds and the associated development of induced circulations and/or induced low pressure at the sea level

(Pisharoty and Desai 1956; Mooley 1957; Singh 1963, 1979; Rao and Srinivasan 1969). This drop was found to be consistent with the earlier case studies on WDs over the NWH (Rangachary and Bandyopadhyay 1987; Hatwar *et al.* 2005; Dimri 2006, 2008; Chand and Singh 2015; Kumar *et al.*

Figure 3. Impacts of the approaching active WDs on surface atmospheric pressure, average wind speed and sun shine duration in the 24-hr time interval for the different stations over the NWH. **(a)** Surface atmospheric pressure. **(b)** Sun shine duration. **(c)** Average wind speed. **(d)** Various statistical characteristics of departures in surface atmospheric pressure (P), average wind speed (AVG) and sun shine duration (SSH) in the 24-hr time interval of the approaching active WDs for 11 stations over the NWH.

Figure 3. (Continued.)

2015). However, this study is based on lengthy in situ observations and provides the local-scale impacts of the approaching WDs for the 11 stations over the NWH. Stations at higher altitudes show more drop in surface atmospheric pressure

compared to stations at lower altitudes over the NWH (figures 1 and 3a). Stations B and C with lengthy data show less impacts of the approaching active WDs in surface pressure compared to stations falling under similar altitude zones but

Figure 4. Impacts of the approaching active WDs on relative humidity in the 24-hr time interval for 11 stations over the NWH. (a) Relative humidity. (b) Various statistical characteristics of departures in relative humidity in the 24-hr time interval of the approaching active WDs for 11 stations over the NWH.

different geographic areas of the NWH (figures 1 and 3a). These results provide further evidence that the impacts of the approaching active WDs depend on the geographical locations and altitude

Figure 5. Snowfall amount (cm), rainfall amount (mm) and precipitation amount (mm) associated with the approaching active WDs in the 24-hr time interval for 11 stations over the NWH. (a) Snowfall amount (cm). (b) Rainfall amount (mm). (c) Precipitation amount (mm). (d) Statistical characteristics of the snowfall amount (SF), rainfall amount (RF) and precipitation amount (PT) in the 24-hr time interval of the approaching active WDs for 11 stations over the NWH.

of stations over the NWH. This can be attributed to the spatial extent, strength and the dominant path of WDs over the NWH. Statistical

characteristics such as ME, MD, SD, LC, UC, H and L of the drop in surface atmospheric pressure for 11 stations over the NWH are shown in

Figure 5. (Continued.)

figure 3(d). Positive values of ME, MD, IQR, LC and UC of the drop in surface atmospheric pressure over the NWH show that the surface atmospheric pressure drops in the 24-h time interval

as active WDs approach over the NWH and the mean drop in surface atmospheric pressure in the 24-hr time interval are found to fall in the range 0.3–1.8 hPa for 11 stations over the NWH

(figure 3d). However, a large drop (rise) in surface atmospheric pressure due to the approaching active WDs in the 24-hr time interval are found to be in the range 8.0–5.0 hPa (7.0–3.0 hPa) for 11 stations over the NWH (figure 3d). A large variability (SD) of the departure in surface pressure was not found and it fell within the range 1.8–2.5 hPa for the 11 stations over the NWH (figure 3d).

Sun shine duration is found to decrease as active WDs approach over the NWH (figure 3b). This can be attributed to the increase in cloudiness over the NWH due to the raising motion of moist air due to the mid-tropospheric trough and/or the induced low pressure at the surface and orographic lift of warm moist air over the NWH (Mooley 1957; Rao and Moray 1971; Agnihotri and Singh 1982; Kalsi and Halder 1992). The decrease in sun shine duration due to active WDs over the NWH is consistent with the increasing cloudiness over the NWH reported earlier (Singh 1963; Kalsi and Halder 1992; Dimri 2008; Chand and Singh 2015; Kumar *et al.* 2015). Positive values of ME, MD, IQR, LC and UC of the departure in sun shine duration show that sunshine in the 24-hr time interval decreases as active WDs approach over the NWH (figure 3d). The mean decrease in sun shine duration is found to fall in the range 0.7–1.8 hr for 11 stations over the NWH (figure 3d). However, a large decrease (increase) in sun shine duration is found for a few WDs depending on the timings of precipitation on a given day, i.e., whether active WDs yielded precipitation while approaching a station location or passing over the station location. The maximum decrease (increase) in sun shine duration falls in the range 8.1–10.3 hr (10.0–7.2 hr) for 11 stations over the NWH (figure 3d).

Average wind speed is found to increase marginally in the 24-hr time interval as active WDs approach over the NWH (figure 3c). The impacts of the approaching WDs are found to differ for 11 stations over the NWH (figure 3c). This can be attributed to the local topography and surface roughness of different stations (figure 3c). However, stations A, H and J show an increase in average wind speed over the NWH. Station A lies at an altitude of 3250 m m.s.l. on the top of a mountain ridge surrounded by a large open valley, hence wind at station A is least modulated by terrain roughness. Therefore wind speed at a station A is representative of the free air wind in general. Station H lies in an open valley at an altitude of 3800 m m.s.l. An increase in average wind speed at

station A and station J with approaching active WDs support the enhanced westerly flow over the NWH as reported earlier (Dimri 2006). Marginally negative values of ME, MD, IQR, LC and UC suggest that average wind speed over the NWH increases as active WDs approach over the NWH (figure 3d). The departure in average wind speed shows a large variability (SD) at station A compared to other stations over the NWH (figure 3d). This may be because the enhanced westerly flow is least modulated by terrain roughness at station A over the NWH.

Relative humidity in the 24-hr time interval of the approaching active WDs is found to increase for all stations over the NWH (figure 4a). This can be attributed to the sources of origin of WDs, i.e., the Mediterranean Sea and the Caspian Sea, and moisture feedback from the Atlantic Ocean and from the Arabian Sea while the WDs are in the vicinity of the NWH (Rangachary and Bandyopadhyay 1987; Mohanty *et al.* 1999; Hatwar *et al.* 2005; Dimri 2008; Dimri *et al.* 2015). The stations at higher altitudes show less increase in relative humidity compared to stations at lower altitudes over the NWH (figure 4a). An increase in relative humidity in the 24-hr time interval of the approaching WDs support earlier findings on the enhancement of moisture content over the NWH due to the approaching and/or existing WDs over the NWH (Rangachary and Bandyopadhyay 1987; Mohanty *et al.* 1999; Roy and Bhowmik 2005; Hatwar *et al.* 2005; Dimri 2006, 2008; Chand and Singh 2015). Large negative values of ME, MD, LC and UC and positive values of IQR show that relative humidity increases over the NWH in the 24-hr time interval of the approach of active WDs (figure 4b). The mean increase and maximum increase in humidity in the 24-hr time interval of the approaching active WDs are found to fall in the range 11.1–27.0% and 43.0–62.0% for 11 stations over the NWH (figure 4b). The large variability (SD) of departure in relative humidity in the 24-hr time interval of the approaching active WDs at different stations can be attributed to the regions of origin of WDs, moisture feedback mechanism, path travelled by the WDs, geographic positions and altitudes of different stations over the NWH.

The departures in the values of various surface meteorological variables in the 24-hr time interval provide an insight into, and an understanding on, how approaching WDs impact them at a local scale over the NWH. However, it does not provide any

Table 3. Percentage proportion of precipitation events in the 24-hr time interval falling within the departure range $ME \pm SD$ of each meteorological variable for 11 stations over the NWH.

Station	MX (PC) (%)	MN (PC) (%)	AM (PC) (%)	RH (PC) (%)	AVG (PC) (%)	P (PC) (%)	SSH (PC) (%)	PC (C) (%)
A	80.9	78.5	82.4	71.9	78.6	66.5	84.8	17.1
B	72.0	76.3	71.1	29.2	81.3	71.2	79.9	21.2
C	32.0	78.6	42.8	22.6	78.7	75.2	78.9	25.0
D	81.1	65.9	76.8	72.4	75.2	73.5	78.5	21.6
E	73.3	71.4	82.8	38.5	74.5	74.0	81.6	26.9
F	74.2	72.4	81.8	23.3	77.0	79.7	83.0	26.1
G	73.1	79.1	86.7	29.4	93.5	61.7	85.9	32.2
H	71.9	72.3	79.1	33.1	76.5	68.4	75.5	19.7
I	71.6	78.3	77.2	22.1	79.4	58.1	81.5	27.1
J	69.9	77.4	79.4	24.0	80.7	69.1	82.7	28.8
K	75.7	77.4	83.0	34.1	74.9	77.6	82.4	29.2

ME = mean; SD = standard deviation; MX (PC) = percentage proportion of precipitation events falling within the $ME \pm SD$ range of departure in the maximum air temperature in the 24-hr time interval; PC (C) = percentage proportion of precipitation events.

idea of snowfall amount, rainfall amount and precipitation amount (cumulative rainfall plus snow water equivalent) in the 24-hr time interval associated with active WDs over the NWH. Snowfall amount is found to differ among the 11 stations in the 24-hr time interval of the approaching WDs over the NWH (figure 5a). This is due to the geographic positions of different stations and movement of WDs over the NWH (figure 5a). Snowfall is found to be the highest at station C in the 24-hr time interval of the approaching WDs compared to other stations over the NWH (figure 5a). Early/late winter rainfall is found to be maximum at station B and rainfall does not occur at station H during winter over the NWH (figure 5b). This may be due to the altitude of these stations. The maximum precipitation amount is found at station C in the 24-hr time interval of the approaching WDs over the NWH (figure 5c). Less precipitation is found at station D and at station H in the NWH in the 24-hr time interval of the approaching WDs over the NWH (figure 5c). Statistical characteristics of snowfall amount, rainfall amount and precipitation amount for 11 stations are shown in figure 5(d). Mean snowfall amount, rainfall amount and precipitation amount fall in the range 4.8–14.3 cm, 2.0–7.6 mm and 5.0–13.4 mm, respectively, for 11 stations over the NWH (figure 5d). These results are consistent with the earlier case studies on short-lived active WDs over the NWH (Hatwar *et al.* 2005; Dimri 2006, 2008). ME, MD and IQR of the snowfall amount higher than ME, MD and IQR of the rainfall amount for 11 stations over

the NWH indicate the dominance of snowfall during winter over the NWH (figure 5d). However, the maximum snowfall amount, rainfall amount and precipitation amount in the 24-hr time interval of the approaching active WDs are found to fall in the range 46.0–130.0 cm, 2.0–84.2 mm and 46.0–130.0 mm for the different stations over the NWH (figure 5d). This shows that few WDs yield heavy snowfall within the 24-hr time interval of their approach over the NWH (figure 5d). A large variability in snowfall amount, rainfall amount and precipitation amount of the 24-hr time interval of the approaching active WDs is found for 11 stations over the NWH (figure 5d). This can be attributed to the characteristics and strengths of the active WDs approaching over the NWH.

The performance of departures in MX, MN, AM, P, RH, AVG and SSH are evaluated for representing precipitation events at each station over the NWH. The percentage proportion of precipitation events falling within the range $ME \pm SD$ of departure in each parameter is computed and the percentage proportion of precipitation events is also computed at each station. The percentage proportion of precipitation events falling within the range $ME \pm SD$ of departure in MX, MN, AM, P, RH, AVG and SSH is found to fall in the range 32.0–81.1%, 65.9–79.1%, 42.8–86.7%, 22.1–72.4%, 74.5–93.7%, 58.1–79.7% and 75.5–84.8% for 11 stations over the NWH (table 3). Higher values of percentage proportion of precipitation events falling within the $ME \pm SD$ of the departure in each parameter for most of the variables compared to

the climatological frequency of precipitation events indicate that the $ME \pm SD$ range of departure in each parameter covers a reasonably good number of precipitation events for 11 stations over the NWH (table 3). However, the percentage proportion of precipitation events for the departure in RH in the range $ME \pm SD$ is found to be less compared to other meteorological variables over the NWH (table 3). This is due to the less number of observations of RH compared to other meteorological variables at the 11 stations over the NWH (table 3).

Heavy snowfall/precipitation associated with few active WDs within the 24-hr time interval and large spatial variability in the precipitation (snowfall/rainfall) amount highlight the need for a real-time local-scale weather forecast model(s) over the NWH. The approaching active WDs are found to largely impact the surface meteorological variables in the 24-hr time interval at a local scale over the NWH. Hence these variables can be utilised as precursors for developing real-time local-scale weather forecast models over the NWH.

5. Conclusions and limitations

The WDs are primary sources of winter precipitation over the NWH and the plains of northern India. Snowfall over the NWH during winter is extremely important for the livelihood of millions of people dependent on the rivers originating from the NWH for their daily need of water, agriculture, irrigation, hydro-electric power, etc. However, heavy snowfall during winter over the NWH causes a loss of life and damage to property, hence weather forecasts play a key role in planning the day-to-day human activities and the mitigation of weather-generated natural hazards during winter over the NWH. Therefore, an insight into, and an understanding of, the impacts of the approaching WDs on local-scale surface meteorological variables and the associated precipitation amount over the NWH is needed. This study is conducted to examine the impacts of the approaching active WDs on local-scale meteorological variables utilising in situ observations over the NWH. Approaching active WDs are found to cause a drop in maximum air temperature, ambient air temperature, surface atmospheric pressure and sun shine duration whereas a rise in the minimum air temperature and relative humidity in the 24-hr time interval over the NWH. The

impacts of the approaching WDs on various surface meteorological variables are found to depend on the altitudes and geographic locations of the stations over the NWH. Heavy precipitation (snowfall) in the 24-hr time interval of the approaching active WDs are found for a few active WDs. The findings of this study are consistent with earlier case studies on the simulation of a few WDs and observational synoptic studies on the WDs and the associated precipitation over the NWH. Results of this study can be useful for the selection of precursor variables for developing real-time weather forecast models and operational weather forecasting in remote areas of the NWH.

This study provides simple statistical means to examine the impacts of the approaching active WDs on surface meteorological variables over the NWH. The method can be employed for any length of data and a variety of meteorological situations compared to simulation studies conducted as case studies on WDs with the help of NWP models over the NWH. In this study, the impacts of the approaching active WDs on surface meteorological variables and the associated precipitation in the 24-hr time interval at the local scale over the NWH were examined. However, detailed studies on WDs (approach to dissipation) in the future may provide a better insight into, and an understanding of, the impacts of WDs and the associated precipitation at the local scale over the NWH.

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References

- Agnihotri C L and Singh M S 1982 Satellite study of western disturbances; *Mausam* **33** 249–254.
- Archer D R and Fowler H J 2004 Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications; *Hydrol. Earth Syst. Sci.* **8** 47–61.
- Barros A P and Lang T 2003 Monitoring the monsoon in the Himalayas: Observations in central Nepal, June 2001; *Mon. Weather Rev.* **131** 1408–1427.
- Beniston M 2003 Climatic change in mountainous regions: A review of possible impacts; *Clim. Change* **59** 5–31.
- Beniston M, Diaz H F and Bradley R S 1997 Climatic change at high elevation sites: An overview; *Clim. Change* **36** 233–251.

- Bhutiyaani M R, Kale V S and Pawar N J 2008 Changing stream flow patterns in the rivers of northwestern Himalaya: Implications of global warming in the 20th century; *Curr. Sci.* **95** 618–626.
- Bhutiyaani M R, Kale V S and Pawar N J 2009 Climate change and the precipitation variations in the northwestern Himalaya: 1866–2006; *Int. J. Clim.* **30** 535–548.
- Bollasina M and Benedict S 2004 The role of the Himalayas and the Tibetan Plateau within the Asian monsoon system; *Bull. Am. Meteor. Soc.* **85** 1001–1004.
- Chand R and Singh C 2015 Movements of western disturbance and associated cloud convection; *J. Ind. Geophys. Union* **19** 62–70.
- Das S 2005 Mountain weather forecasting using MM5 modelling system; *Curr. Sci.* **88** 899–905.
- Datta R K and Gupta M G 1967 Synoptic study of the formation and movements of western depressions; *Indian J. Meteorol. Geophys.* **18** 45–50.
- Dey B, Kathuria S N and Kumar O B 1985 Himalayan summer snow cover and withdrawal of the Indian summer monsoon; *J. Appl. Meteorol.* **24** 865–868.
- Dimri A P 2004 Impact of horizontal model resolution and orography on the simulation of a western disturbance and its associated precipitation; *Meteorol. Appl.* **11** 115–127.
- Dimri A P 2006 Surface and upper air fields during extreme winter precipitation over the western Himalayas; *Pure Appl. Geophys.* **163** 1679–1698.
- Dimri A P 2008 Diagnostic studies of an active western disturbance over western Himalaya; *Mausam* **59** 227–246.
- Dimri A P 2009 Impact of subgrid scale scheme on topography and land use for better regional scale simulation of meteorological variables over the western Himalayas; *Clim. Dyn.* **32** 565–574.
- Dimri A P and Chevuturi A 2013 Model sensitivity analysis study for western disturbances over the Himalayas; <https://doi.org/10.1007/s00703-013-0302-4>.
- Dimri A P and Das S K 2011 Wintertime climatic trends in the western Himalayas; *Clim. Change* **111** 775–800.
- Dimri A P and Mohanty U C 2009 Simulation of mesoscale features associated with intense western disturbances over western Himalayas; *Meteorol. Appl.* **16** 289–308.
- Dimri A P, Niyogi D, Barros A P, Ridley J, Mohanty U C, Yasunari T and Sikka D R 2015 Western disturbances: A review; *Rev. Geophys.* <https://doi.org/10.1002/2014RG000460>.
- Dimri A P, Yasunari T, Kotlia B S, Mohanty U C and Sikka D R 2016 Indian winter monsoon: Present and past; *Earth Sci. Rev.* **163** 297–322.
- Fowler H J, Archer D R 2005 Hydro-climatological variability in the upper Indus basin and implications for water resources; In: Regional hydrological impacts of climate change—Impact assessment and decision making (eds) Wagner T *et al.*, *Proceedings of symposium S6 held during the Seventh IAHS Scientific Assembly at Fozdolguacu*, Vol. **295**, Brazil, IAHS, UK. ISBN: 978–1901502-13-8 pp. 131–138.
- Hatwar H R, Yadav B P and Rama Rao Y V 2005 Prediction of western disturbances and associated weather over Western Himalayas; *Curr. Sci.* **88** 913–920.
- Kalsi S R and Halder S R 1992 Satellite observations of interaction between tropics and mid-latitudes; *Mausam* **43** 59–64.
- Karl T R, Groisman P Y, Knight R W and Heim R R 1993 Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations; *J. Clim.* **6** 1327–1344.
- Kumar N, Yadav B P, Gahlot S and Singh M 2015 Winter frequency of western disturbances and precipitation indices over Himachal Pradesh, India: 1977–2007; *Atmósfera* **28** 63–70.
- Lang T J and Barros A P 2004 Winter storms in central Himalayas; *J. Meteorol. Soc. J.* **82** 829–844.
- Leathers D L, Ellis A W and Robinson D A 1995 Characteristics of temperature depressions associated with snow cover across the northeast United States; *J. Appl. Meteorol.* **34** 381–390.
- Maharana P and Dimri A P 2014 Impact of initial and boundary conditions on regional winter climate over the Western Himalayas: A fixed domain size experiment; *Glob. Plan. Chan.* **114** 1–13.
- Malurkar S L 1947 Abnormally dry and wet western disturbances over north India; *Curr. Sci.* **5** 139–141.
- Mohanty U C, Madan O P, Raju P V S, Bhatla R and Rao P L S 1999 A study on certain dynamic and thermodynamic aspects associated with Western Disturbances over northwest Himalaya; In: *The Himalayan Environment* (eds) Dash S K and Bhadur J, New Age International Pvt. Ltd, New Delhi, pp. 113–122.
- Mooley D A 1957 The role of western disturbances in the production of weather over India during different seasons; *Indian J. Meteorol. Geophys.* **8** 253–260.
- Nimas J 1985 Some empirical evidence for the influence of snow cover on temperature and precipitation; *Mon. Weather Rev.* **113** 1542–1553.
- Pisharoty P R and Desai B N 1956 Western disturbances and Indian weather; *Ind. J. Meteorol. Geophys.* **7** 333–338.
- Rangachary N and Bandyopadhyay B K 1987 An analysis of the synoptic weather pattern associated with extensive avalanching in Western Himalaya. Avalanche formation, movement and effects; In: *Proceedings of the Davos symposium*, Vol. **162**, September 1986, IAHS Publ., pp. 311–316.
- Rao N S B and Moray P E 1971 Cloud systems associated with western disturbances: A preliminary study; *Ind. J. Meteorol. Geophys.* **22** 413–420.
- Rao Y P and Srinivasan V 1969 Discussion of typical synoptic weather situation: Winter western disturbances and their associated features; India Meteorological Department Forecasting Manual Part III, Poona FMU Rep No. III – 1.1
- Rechid D, Hagemann S and Jacob D 2009 Sensitivity of climate models to seasonal variability of snow-free land surface albedo; *Theor. Appl. Climatol.* **95** 197–221.
- Roy S S and Bhowmik S K R 2005 Analysis of thermodynamics of the atmosphere over northwest India during the passage of a western disturbance as revealed by model analysis field; *Curr. Sci.* **88** 947–951.
- Semwal G and Giri R K 2007 Precipitation simulation of synoptic scale systems over western Himalayan region using advanced regional prediction system (APRS) model; *Mausam* **58** 471–480.

- Singh M S 1963 Upper air circulation associated with a western disturbance; *Ind. J. Meteorol. Geophys.* **14** 156–172.
- Singh M S 1979 Westerly upper air troughs and development of western disturbances over India; *Mausam* **30** 405–414.
- Singh P and Arora M 2007 Water resources potential of Himalayas and possible impact of climate change; *Jalvi-gyan Sameeksha* **22** 109–132.
- Singh D and Ganju A 2008 Expert system for prediction of avalanches; *Curr. Sci.* **94** 1076–1081.
- Singh D, Dimri P and Ganju A 2008 An analogue method for simultaneous prediction of surface weather parameters at a specific location in the western Himalaya in India; *Meteorol. Appl.* **15** 491–496.
- Singh D, Sharma V and Juyal V 2015 Observed linear trend in few surface weather elements over the Northwest Himalayas (NWH) during winter season; *J. Earth Syst. Sci.* **124** 553–565.
- Srinivasan K, Ganju A and Sharma S S 2005 Usefulness of meso-scale weather forecast for avalanche forecasting; *Curr. Sci.* **88** 921–926.
- Thayyen R J and Gergan J T 2009 Role of glaciers in watershed hydrology: ‘Himalayan catchment’ perspective; *Cryos. Discuss.* **3** 443–476.
- Venkiteswaran S P 1938 Rainfall due to winter disturbances and the associated upper air temperatures over Agra; *Ind. Met. Dep. Sci. Notes* **7** 117–121.
- Wu T W and Qian Z 2003 The relation between the Tibetan winter snow and the Asian summer monsoon and rainfall: An observational investigation; *J. Climate* **16** 2038–2051.

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