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ORIGINAL PAPER

Cold waves in Terai region of Nepal and farmer's perception of the effect of fog events and cold waves on agriculture

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Abstract

Cold waves are considered one of the important extreme weather events affecting winter crop production in the Indo-Gangetic Plain (IGP). In spite of media coverage of extreme cold events in the Terai area of Nepal (Nepal section of IGP) in recent years, few studies on this topic were found. This study investigates cold waves and their impact on agriculture during winter in the Terai region of Nepal. Historical daily maximum and minimum temperature data from six stations in the Terai (Dhangadhi, Nepalgunj, Bhairahawa, Simara, Janakpur, and Biratnagar) during 1971–2015 were analyzed to study the occurrence of cold days, cold nights, extreme cold days, extreme cold nights, cold wave days, and extreme cold wave days in the Terai. The average number of cold days per annum ranges from 15.6 to 17.9 days and the extreme cold days per annum ranges from 3.2 to 3.6 days in the Terai. Except for Nepalgunj, all the Terai stations show statistically significant increasing trends in the frequency of cold days and extreme cold days over the last four decades. Similarly, the average number of cold wave days varies from 9.2 to 13.8 per annum and the average number of extreme cold wave days varies from 1.4 to 3.8 days in the Terai region of Nepal. By comparing the co-occurrence of foggy days and cold and extreme cold wave days at Biratnagar, Simara, Bhairahawa, and Nepalgunj airport, it is also observed that most of the cold and extreme cold wave days are also foggy days. The perception of farmers regarding the effect of fog and cold wave events was explored through focus group discussions at Dhanusha and Sunsari districts of Nepal and found that the fog and cold events have significantly affected their winter crops, livestock, and their day-to-day life.

1 Introduction

Large areas of south Asia, extending west from Pakistan to Bangladesh, including the Indo-Gangetic Plain (IGP), are usually covered by a thick blanket of fog during winter (Syed et al. 2012). Similarly, cold wave and severe cold wave conditions are regularly experienced in north India, northwest India, and central India during winter (Bhan 2016). In north India, these extreme weather events are due to "western disturbances" during winter (Dimri and Chevuturi 2016). Significant impacts on agriculture due to these extreme events (cold wave and fog) are reported in several studies in India (Samra et al. 2003; Singh and Singh 2010; Mahdi et al. 2015). In spite of being part of the IGP, only limited information is reported on the agricultural impact of cold wave and fog events in the Terai area of Nepal. In this context, this paper aims to study cold wave events through analysis of historical daily temperature data from stations in the Terai region of Nepal and investigate any relationship between temperature and fog events during winter. In addition, the impact of cold wave and fog events on agriculture in the Terai region of Nepal, along with farmer's perception of these impacts, will also be explored.

Cold waves are a regular episode during winter in the northern part of the Indian sub-continent. After analysis of historical daily temperature data from 103 stations in India during 1961–2010, Pai et al. (2017) concluded that cold waves are a regular phenomenon of most areas of India, except the southern Peninsula and north-east India. Pai et al. (2004) studied cold wave events for the meteorological sub-divisions of India from 1971 to 2000 and indicated a significant increase in the frequency, persistence, and spatial coverage of cold wave events in the decade 1991–2000 compared to the previous two decades. Bhatla et al. (2016) studied the cold wave in the six stations of eastern Uttar Pradesh, India (Allahabad, Varanasi, Gorakhpur, Lucknow, Baharaich, and Khiri) and found that in all the stations

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except Varanasi, the cold wave days during winter increased in the decade 2001–2010 compared to the previous decade. However, Revadekar et al. (2012) studied Indian weather extremes during 1970–2003, at 121 stations, and found that 75% of stations showed a declining trend in the number of cold events. Similarly, Jaswal et al. (2013) studied extreme events at Indian stations using daily maximum and minimum temperature during 1969–2012. Their trend analysis of cold, very cold, and extremely cold nights indicated a significant decreasing trend of cold events in December, a mixed trend in January, while in February there was a significant decreasing trend in North India.

The entire IGP area of Punjab, Haryana, Delhi, Uttar Pradesh, Bihar, and West Bengal area can be engulfed by dense fog during winter (Badarinath et al. 2009; Syed et al. 2012; Jenamani 2012; Sathiyamoorthy et al. 2016). Syed et al. (2012) suggested that moisture available from western disturbances and from vast irrigated agricultural land in the western IGP region could be the reason behind high fog frequency in the region. In addition, their study also found an increasing occurrence of fog events in the foothills of the Himalaya, with a trend of more than 8% increase per decade in mean frequency of fog occurrence during winter. By analyzing Indian weather satellite, INSAT-3D fog data, International Satellite Cloud Climatology Project (ISCCP) cloud data, and Clouds and the Earths Radiant Energy System (CERES) cloud radiative forcing data, Sathiyamoorthy et al. (2016) showed that a foggy winter is colder than a non-foggy winter in the IGP and cooling of the entire IGP occurs at a rate of -0.6 °C for every 10-W m^{-2} decrease in radiative forcing due to fog. Following a western disturbance, fog is normally observed, due to nocturnal cooling, which blocks solar radiation and further reduces the temperature to make the cold wave more intense (Bedekar et al. 1974). Similarly, Gautam (2014) explained that cold waves, in combination with moist air and atmospheric aerosols, help the formation of fog and dense fog, which reduces solar insolation and results in lower temperatures, which provides a positive feedback to the persistence of foggy and cold conditions. During foggy days in winter, the maximum temperature is below normal, which results in prolonged cold periods (Samra et al. 2003). However, the Indian Meteorological Department (IMD) definition of cold wave only considers the minimum temperature (which occurs during the night) and does not consider the reduction in maximum temperature (which occurs during day time). Even though people's health is affected by both prolonged series of cold nights (low minimum temperature) and cold days (low maximum temperature) (Hassi 2005), it is expected that people are more exposed to outdoor temperature in the day time compared to night due to their increased daytime activities. So, in contrast to the absolute threshold of minimum daily temperature used by IMD, Radinović and Ćurić (2012) used a statistical threshold of daily temperature to define cold and hot waves. Labajo et al. (2014) defined the occurrence of a cold wave event when the daily maximum and minimum temperatures are both less than the 10th percentile value for more than 2 days. Similarly, if the daily maximum temperature and minimum temperature are both less than the 5th percentile value for 2 days, it is called an extreme cold wave event. A similar definition, but based on three consecutive days, was adopted by Capozzi and Budillon (2017) during analysis of cold waves in Montevergine during 1984–2015. Similarly, Spinoni et al. (2015) used 10th percentile maximum temperature and minimum temperature for five consecutive days for cold wave days and cold wave nights, respectively, in the Carpathian region from 1961 to 2010.

The Terai region of Nepal in the foothills of the Himalaya is also reported to be severely affected by cold wave during winter, but there is a lack of systematic study of cold waves and their effect in this region. Some cold wave–related studies for the Terai region of Nepal are discussed below.

Baidya et al. (2008) studied temperature extremes during 1971–2006 for Nepal and found an increasing trend in minimum temperature, decreasing trend in maximum temperature, and decreasing trend in daily temperature range in the Terai region during winter. Similarly, Shrestha et al. (2016) analyzed daily temperature data from the Koshi basin between 1975 and 2010, and found an increasing trend of daily maximum and minimum temperatures. Their study also found in the IGP area that maximum temperature in winter and the pre-monsoon season was decreasing (statistically significant) and the number of cold days in winter was increasing.

The cold wave is reported to be a comparatively new weather phenomena in the Terai and well covered in local media in recent years, and it has become a major health hazard to the people of this region (WHO 2016). Cold waves have not only resulted in the death of 797 people during 2000–2013, but also damaged 22,000 ha of crops and caused the death of 732 cattle in Nepal (DesInventor 2015). Manandhar (2006) analyzed the 1997/1998 and 2002/2003 winter fog episodes in the Terai and suggested that the maximum temperature dropped close to the minimum temperature due to the thick and continuous foggy weather, which resulted in cold wave events in the region. Manandhar et al. (2011) reported that the frequency of cold wave days increased at Bhairahawa (Western Terai in Nepal) during 1992–2005 and the combination of a cold wave event with dense fog had adverse effects on agriculture in the Terai region.

Yang et al. (2014) found that, contrary to people's perception of decreasing cold wave frequency in the hills and mountains, the farmers of the Terai region of the Koshi basin experienced increasing cold wave frequency, which resulted in loss of crops and adverse effects on both human and animal health. Ojha et al. (2014) studied the perception of the farmers regarding climate change in the IGP covering Nepal, Bangladesh, and the Indian state of Punjab and found that 78% of the respondents felt that summer days are getting hotter and 66% agreed that winter is getting colder. Similarly, Haque et al. (2012) studied people's perception of climate change and subsequent human risks in Bangladesh and found that almost all participants perceived that cold wave and dense fog events increased in recent years compared to the previous 5 to 10 years, and the impact of those events on Boro rice, beetle leaf, potato, and mango crops was negative. Samra et al. (2003) documented the effect of cold waves on agriculture during 2002–2003 in North India and found that winter crops, vegetables, and fruits were seriously affected.

Although cold waves are important weather events in the Terai, very few studies have been conducted. In this paper, we seek to understand cold wave events in the Terai region of Nepal and their effect on agriculture. To do this, we analyzed historical daily temperature data to investigate cold wave occurrence in the Terai region of Nepal via trend analysis of annual cold wave days and extreme cold wave days. We also investigated farmer's perception of the effect of fog and cold wave events on agriculture in the eastern Terai.

2 Materials and methods

2.1 Study area

The Terai region is a flat plain in southern Nepal with elevation ranging from 60 to 200 m (Fig. 1). Compared to hilly and mountainous regions of the country, the Terai only occupies 17% of the land area of Nepal. However, this region is very important as it accommodates 50.27% of the population of the country (CBS 2016). The population of the Terai has increased due to recent migration of people from the mountainous and hilly regions of Nepal (CBS 2014a). Due to the availability of agricultural land and irrigation facilities in the Terai, most of the country's crop production of paddy rice, maize, wheat, lentil, sugarcane, vegetable, etc. comes from the Terai, which is considered the food basket of the country. Based on the Köppen climatic classification (Peel et al. 2007), the Terai region of Nepal has a humid subtropical climate (Cwa) with distinctly dry winters (CBS/GON 2016).

To investigate cold wave events in the Terai region, historical daily temperature data from six stations listed in Table 1 were analyzed. The six selected stations are evenly spread across the Terai region (see Fig. 1), which stretches ~ 885 km from east to west and is 26 to 32 km wide (CBS 2016), and they are considered to be representative of the region.

The Sunsari and Dhanusha districts are representative of the eastern Terai, and these two districts were selected to explore farmer's perceptions of the effect of fog and cold wave on agriculture. In both districts, diverse and mixed ethnic groups are found due to internal migration of people from the hill and mountain districts (Fig. 1). Based on 2011 census data, the four major ethnic groups in Dhanusha are Yadav, Koiri, Musalman, and Teli and in Sunsari are Tharu, Musalman, Chettri, and Bramin (Hill) (CBS 2016). The farmer's perception study was conducted in five randomly selected villages, listed in Table 2, from the Sunsari and Dhanusha districts.

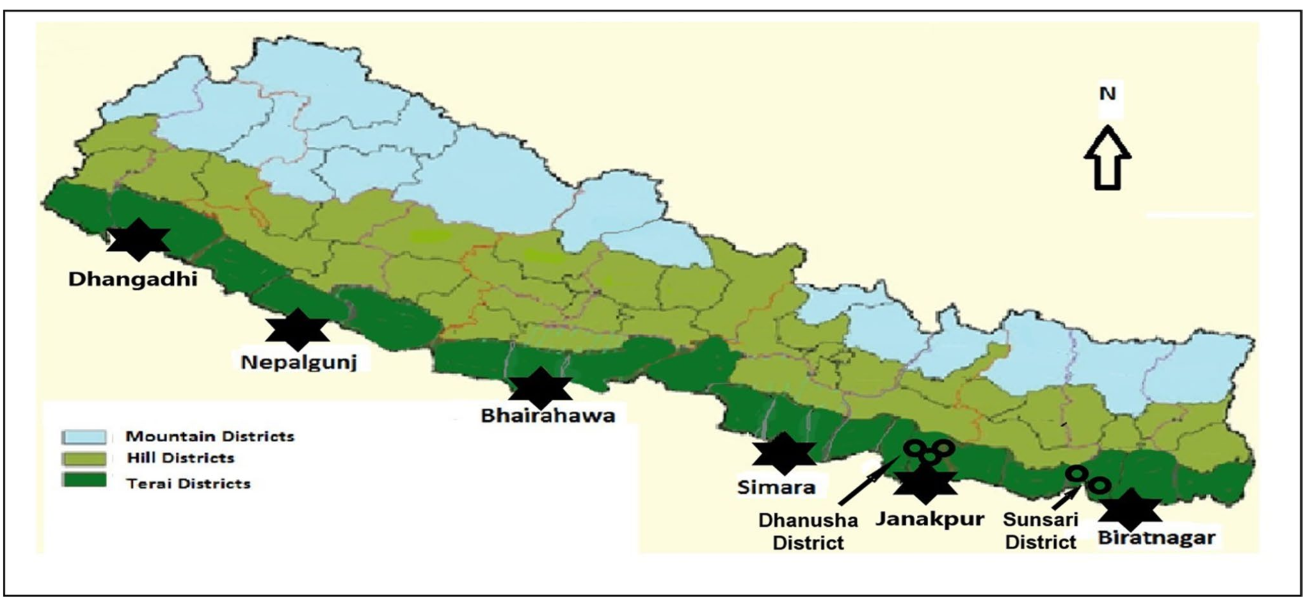


Fig. 1 Study area—Terai region of Nepal (dark green–colored area) and studied stations (stars) and focus group discussion locations (circles). Adapted from Shrestha et al. (2018)

Table 1 Details of studied temperature stations

SN	Station	Index no	District	Latitude (° North)	Longitude (° East)	Elevation (m)
1	Dhangadhi	209	Kailali	28.800	80.550	187
2	Nepalgunj Airport	420	Banke	28.100	81.667	165
3	Bhairahawa Airport	705	Rupandehi	27.517	83.433	109
4	Simara Airport	909	Bara	27.167	84.983	130
5	Janakpur Airport	1111	Dhanusha	26.717	85.967	90
6	Biratnagar Airport	1319	Morang	26.483	87.267	72

Table 2 Villages included in farmer's perception of the effect of fog/cold wave on agriculture

SN	Study village	District	Location	Major feature
1	Batteswor	Dhanusha	26.883°N 85.925°E 120 m elevation	Village with mixed Terai communities and farmers are involved in both cereal and vegetable cultivation
2	Naktajhijh, Mithila	Dhanusha	26.880°N 85.960°E 150 m elevation	Village with major ethnic group Koiri (Mahato) and farmers are mainly involved in vegetable cultivation
3	Sinnorjoda	Dhanusha	26.780°N 85.925°E 80 m elevation	Village with major ethnic group Yadav and mainly cereal crop is cultivated
4	Saalbandi	Sunsari	26.715°N 87.107°E 95 m elevation	Village with mainly migrated communities from the hills and farmers are involved in both cereal and vegetable cultivation
5	Simariya	Sunsari	26.576°N 87.237°E 85 m elevation	Village with indigenous Tharu (Chaudhari) community and farmers are involved in both vegetable and cereal cultivation

2.2 Methods

The methods adopted in this study are discussed in following subsections.

2.2.1 Cold day, cold night, and cold wave analysis

In this study, quality control of the daily maximum and minimum temperature data obtained from the Department of Hydrology and Meteorology (DHM) was performed by removing the outliers and error values (e.g., maximum and minimum temperature greater than 70 °C, minimum temperature greater than maximum temperature, etc.). Time-series plots and histogram were also compared with neighboring stations, and validation against external sources was performed to ensure the quality of the data. In addition, we also tested the homogeneity of daily maximum and minimum temperature data at each study site using the RHtestsV4 software package (Wang and Feng 2013), which is based on the algorithms described by Wang (2008a) and Wang (2008b), to identify any non-climatic variability within each time series.

In this study, we used percentile threshold values of daily maximum temperature and minimum temperature, as suggested by the Expert Team on Climate Change Detection and Indices (ETCCDI) (ETCCDI n.d.), Fang et al. (2016), and Acar et al. (2018), to define cold day and cold night, respectively. The cold day and extreme cold day are defined as a day in which the daily maximum temperature is equal to or less than the 5th and 1st percentiles, respectively. Similarly, cold night and extreme cold night is declared when the minimum temperature is equal or less than the 5th and 1st percentiles, respectively. The number of cold days, extreme cold days, cold nights, and extreme cold nights per annum is used to analyze extreme cold scenario in the six Terai stations of Nepal. In this study, cold wave and extreme cold wave is defined as when both the maximum and minimum temperatures are less than the 10th and 5th percentiles, respectively, for two or more consecutive days.

The Mann–Kendall test, as described by Gilbert (1987), is used to determine whether statistical trends in annual cold days, extreme cold days, cold nights, extreme cold nights, cold wave days, and extreme cold wave days exist at the six Terai stations. Standard normal z values are used to test the trend significance at significance levels, $\alpha = 0.001$, 0.01, 0.05, and 0.1. To estimate the slope of any trend in the annual number of cold days, extreme cold days, cold nights, and extreme cold nights at each station, Sen's slope non-parametric method is adopted (Sen 1968). In this method, the trend is assumed to be linear and the equation is given by

$$f(t) = Qt + B \tag{1}$$

where Q is the slope and B is constant.

To investigate fog events and cold wave, visibility observation data from Meteorological Terminal Air

Report (METAR) visibility observations at four Terai airports, Biratnagar, Simara, Bhairahawa, and Nepalgunj, during 1994–2015 were used. A foggy day is defined to occur when the visibility is less than 1000 m in that day (WMO 1975).

2.2.2 Field work

To explore the perception of the farmers on the effect of fog and cold wave on agriculture, the methodologies adopted in this study were key informant survey, transect walk, field observations, and focus group discussion (FGD). For each village, a key informant survey was conducted to acquire general information about the village, agricultural scenario, and potential participants based on the study criteria for the focus group discussion. Potential participants were representative farmers of the selected village who were directly involved in farming with 20 years of experience. Key informants for a village were either a local agricultural technician, social worker, or teacher, etc. A transect walk, along with the key informants and participating farmers, was also performed to observe the crops cultivated, visually observe the effect of fog and cold wave on agriculture, and observe the adaptive measures adopted by the farmers to minimize the effect of fog and cold wave on agriculture and their livelihood. This study was conducted in the study area during the foggy season of December 2017.

Since FGD is considered an appropriate methodology for exploratory qualitative research (Stewart et al. 2007), it was adopted in this study to explore farmers' perceptions of the effect of fog on agriculture and their livelihood in the Terai region of Nepal. In this study, it was planned to conduct a FGD in each of the randomly selected five villages in Sunsari and Dhanusha districts. About six to eight experienced farmers were included in each FGD, which aligns with the advice of Guest et al. (2017). The aim in selecting participants for the FGD was to include representative farmers cultivating major crops in that area as well as farmers from different ethnic groups and gender to capture a diverse perspective on the effect of fog on agriculture and adopted adaptation measures. In Dhanusha, it was noticed that women members of the FGD did not actively participate in the discussion with the male participants. In this case, a separate FGD for only women participants was conducted in Naktajhijh, Mithila in Dhanusha to capture women's perspective on the issue. An open check list was used by the moderator to run the FGD and the methodology adopted to moderate the FGDs in this study was as described and suggested by Morgan (1996), Stewart et al. (2007), and Gill et al. (2008).

3 Results and discussion

The results and discussion of this study are described in three sections. The first section deals with farmers' perception of cold wave and fog at Dhanush and Sunsari districts of the eastern Terai region of Nepal. The second section explains the results of analysis of the daily temperature in relation to cold wave and fog events during winter in the Terai region of Nepal. The third section describes the farmers' perceptions of the effect of cold waves and fog events on agriculture and the livelihood of people of Dhanusha and Sunsari districts.

3.1 Farmers' perception of fog events and cold waves

The perception of the farmers on the effect of fog events and cold waves on agriculture was assessed during field study through FGDs conducted at Dhanusha and Sunsari districts of the Terai region of Nepal, and the results are described in this section.

3.1.1 Characteristics of farmers who participated in FGD

The characteristics of the participants of the six FGDs conducted in the villages of Dhanusha and Sunsari are described in Table S1 (supplementary information). In general, the average age of the participants is above 46 years, except that of the women's FGD at Naktajhijh, Mithila, which is the lowest at 39.3 years. The oldest participant of age 70 participated at Naktajhijh, Mithila (male) FGD. Regarding land ownership of the FGD participants, the average land holding of the participants at Batteswor, Dhanusha is the lowest (0.53 ha), whereas the participants at Simariya Sunsari had the highest (1.67 ha). The average land holding in the Terai region is 0.75 ha (CBS 2014b) and the average land holding of the participants of FGDs are found to be near to this figure.

3.1.2 Perceptions of fog and cold wave occurrence

The major findings of the FGDs conducted in the study area are presented in Table S2 (Supplementary Information). In all FGDs conducted in this study, the participants unanimously agreed that fog events are regular events that occur almost every year in their area. The participants all also agreed that the fog starts in the month of "Mangshir" (the eighth month in "Bikram Sambat" (official calendar of Nepal)), which coincides with mid-November to mid-December of the Gregorian calendar, during winter in their area. As almost all participants of FGDs recalled and agreed that the fog starts around the "Bibaha Panchami" festival which occurs on the fifth day of "Mangshir Shukla" month.

In summary, it can be said from the FGD findings that the fog event generally starts in mid-November. Similarly, the participants agreed that the fog events generally end after the end of "Magh" (10th month of Bikram Sambat) or beginning of "Phalgun" (11th month of Bikram Sambat). Hence, FGD results clearly indicated that fog events generally end by the second week of February. The farmers also indicated that generally they experience 30 foggy days during winter every year (Table S2).

The participants of all the FGDs conducted in Sunsari and Dhanusha agreed that continuous and dense fog events bring a cold wave. According to the farmers, a cold wave starts when the Terai area is engulfed by a blanket of thick fog for several days during winter. The cold wave could be due to the blockage of solar radiation reaching the ground surface by fog, which results in a significant reduction in temperature as described by Bedekar et al. (1974). The participants also mentioned that due to a lack of solar radiation, it is very cold even during the day time, like "*Mutu Samaune Jando*" (very cold catching the heart) in the Terai. Regarding the cold, the FGD at Saalbani (migrated communities from hills) explained a local proverb "*Pahad ko jando lato, Madhesh ko jando tikho*" (the cold at the hills is mild whereas the cold in the Terai is intense). They explained that people and animals in the hills can face more cold than those of the plain area because of their body structure and preparedness. In addition, they explained that during winter in the hills, it is cold at night and morning but in the day time it is warm due to sunny day. In the Terai, during a cold day in winter, it remains cold throughout the day because they will not be able to see the sun for several days due to dense fog.

Regarding recent extreme fog events, the FGD at Mithila (male) recalled the fog event 6 years ago that was continuously foggy for more than a week. Similarly, the FGD at Batteswor, Dhanusha recalled an extreme fog event that occurred 6 years ago (2011 AD) in which 13 people from Batteswor and Kalipur village died due to the cold wave during that period. Similarly, the FGD of Sinorjoda, Dhanusha recalled an extreme fog event in the Terai 6 years before, in which eight villagers died due to cold and they could not see the sun for about 1 month during that winter. The extreme cold event mentioned by the farmers aligns with the cold wave death reported in the DesInventer database, which reports that in 2010, 59 people died due to cold wave in the Terai region of Nepal and 150 died in 2011 (DesInventor 2015). Similarly, the extreme cold wave events of 2010/2011 also align with the extreme cold wave events observed in daily maximum and minimum temperatures at Biratnagar and Janakpur airport, where three and two extreme cold wave events were identified respectively in the year 2011.

During field study, it was noticed that all FGDs (five out of six), except the women FGD at Mithila, Dhanusha, unanimously agreed that there is an increasing trend in fog compared to the past. Among those five FGDs, four FGDs agreed that fog events are increasing over the past 15 to 20 years. To support this statement, most FGDs explained that only in the last 15–20 years have people in their area started using clothes "*Jhul*"/ "*Chaddi*" on their animals to prevent animals from cold during fog events. The participants from Saalbani FGD said that their relatives in the hill areas used to descend to the Terai during winter to escape from cold weather in the hills, but they feel that some of their old people are going to the hills to avoid cold wave in the Terai in recent years. Similarly, the participants from Simariya and Batteswor said that it is warmer in the nearby hilly area (Dhankuta and Sindhuli, respectively) than their area (Terai) during winter. However, the women's FGD at Mithila, Dhanusha were not sure about the definitive trend of fog events in Terai because they feel that fog events are erratic.

Regarding the reason behind the increasing trend of fog events in the Terai, FGD Batteswor, Dhanusha suggested that it could be due to increasing population. Similarly, the FGD at Sinorjoda suggested that it could be due to deforestation, and the FGD at Saalbani, Sunsari suggested it could be due to increasing industrialization, air pollution, and increased irrigation area.

In summary, the key perceptions related to fog and cold wave events perceived by the farmers during FGD conducted at Sunsari and Dhanusha in this study are as follows:

- Fog events are regular events during winter and generally start by mid-November and end by mid-February.
- Farmers believe that cold wave conditions are generally brought by continuous dense fog events.
- The farmers experienced an extreme cold wave 6 years before (2010/2011 winter).
- Almost all the participants of all the FGDs, except the women's FGD at Mithila, agreed that fog events and associated cold wave events are increasing over time.

3.2 Temperature and fog data analysis

Temperature and fog data are analyzed in this sub-section to study extreme cold days and cold wave days, and compare fog events with cold wave days.

3.2.1 Maximum and minimum temperature of Terai region

The homogeneity test results indicated that the maximum temperature series at all the stations, except Janakpur, are homogeneous at the 5% level of significance (Table 3). At Janakpur, three change point inhomogeneities within the maximum daily temperature were detected, with step size less than 1 °C (−0.16, 0.5, and 0.14 °C). Compared to the maximum temperature results, more inhomogeneities

Table 3 Key summary statistics of historical daily maximum and minimum temperatures (during winter months) of the Terai stations

	Biratnagar	Janakpur	Simara	Bhairahawa	Nepalgunj	Dhangadhi
Duration	45 years (1971–2015)	45 years (1971–2015)	45 years (1971–2015)	45 years (1971–2015)	20 years (1996–2015)	45 years (1971–2015)
Maximum temperature						
Number of inhomogeneities*	0	3	0	0	0	0
Percentage of missing data (%)	0.89	6.34	3.85	0.00	0.00	10.83
Average (°C)	25.23	24.80	24.51	24.12	22.84	24.01
Minimum (°C)	10.00	10.00	9.00	9.50	9.60	7.50
Maximum (°C)	39.20	38.60	39.20	40.20	39.80	39.00
Standard deviation (°C)	3.54	3.89	4.05	4.44	4.45	4.27
1st percentile (°C)	15.70	13.40	12.50	12.20	11.20	12.31
5th percentile (°C)	19.30	18.00	16.80	15.67	13.80	16.20
10th percentile (°C)	21.00	20.00	19.80	18.70	16.45	19.00
Minimum temperature						
Number of inhomogeneities*	2	7	4	1	2	5
Percentage of missing data (%)	1.67	8.12	4.07	0.11	0.00	15.84
Average (°C)	10.48	10.58	9.10	10.21	9.14	8.78
Minimum (°C)	2.00	0.00	0.60	2.00	−0.30	0.00
Maximum (°C)	24.20	23.00	22.60	22.60	20.50	24.00
Standard deviation (°C)	2.99	3.05	3.11	2.92	2.94	3.26
1st percentile (°C)	4.90	4.00	2.70	4.60	2.80	2.50
5th percentile (°C)	6.20	6.00	4.50	5.90	4.48	3.90
10th percentile (°C)	7.00	7.00	5.40	6.60	5.40	4.80

*For all data

were detected within the minimum temperature series. The number of inhomogeneities within minimum temperature series ranged from 1 step change at Bhairahawa to 7 steps at Janakpur. Since the same instrument (maximum–minimum thermometer) is used to measure maximum and minimum temperature and none of these stations are reported to have shifted, the inhomogeneities in the minimum temperature data could be due to changes in the observer recording the observations and or the surrounding environment. Moreover, the difference in homogeneity results may be due to the change point detection algorithm being more sensitive to changes in minimum temperature than maximum temperature as suggested by Qingxiang and Wenjie (2009). Adopting the step-by-step procedure suggested by Wang and Feng (2013), to assess the homogeneity of maximum and minimum temperature, any section of the time series with a significant step size, beyond the 95% confidence interval, was set to missing. The percentage of total missing data for maximum temperature ranges from 0.44% at Biratnagar to 10.35% at Dhangadhi and that for minimum temperature ranges from 0.69% at Biratnagar to 17.71% at Dhangadhi during the study period (Table 3).

Based upon the homogenized historical daily maximum and minimum temperature of six representative stations during winter months (December, January, and February) in the Terai—Biratnagar, Janakpur, Simara, Bhairahawa, Nepalgunj, and Dhangadhi—the key summary statistics are presented in Table 3. There is little difference in the average daily maximum temperature of the stations in Terai, but the average daily maximum temperature observed in the eastern stations during winter are slightly higher than western stations except Nepalgunj. The standard deviation of maximum temperature in the Terai stations during winter months ranged from 3.54 at Biratnagar to 4.45 at Nepalgunj. Among the six stations, Nepalgunj has the lowest and Biratnagar has the highest 1st, 5th as well as 10th percentile daily maximum temperature. The highest average minimum temperature is recorded at Janakpur, while the lowest average minimum temperature is recorded in far western Dhangadhi during winter.

The distribution of the daily maximum and minimum temperatures at all the stations was tested for normality using the skewness test suggested by D'agostino et al. (1990) and found that the maximum and minimum temperature data at all stations are not normally distributed. Using the Kruskal–Wallis test and Mann–Whitney *U* test (Hollander et al. 2014), it was found that the maximum and minimum temperature data of those six stations are not from the same distribution.

3.2.2 Cold days and cold nights in the Terai

Figure 2 shows the monthly share of average cold days, extreme cold days, cold nights, and extreme cold nights per annum in the studied stations of the Terai. The figure clearly indicates that January, December, and February are the months with cold days and cold nights in a year. On average, the number of cold days per annum ranges from 15.6 days at Dhangadhi to 17.9 days at Nepalgunj. Similarly, the number of extreme cold days per annum ranges from 3.2 days at Dhangadhi to 3.6 days at Biratnagar and Nepalgunj. The average number of cold nights per annum ranges from 13 days at Janakpur to 17.6 days at Bhairahawa. Likewise, average number of extreme cold nights per year varies from 2.6 days at Janakpur to 3.4 days at Nepalgunj and Biratnagar.

The highest median number of cold days per annum is observed at Nepalgunj (21) followed by Biratnagar (17 days), Simara (16 days), Janakpur (16 days), Bhairahawa (14 days), and Dhangadhi (13 days) (Fig. S1). Regarding extreme cold days, Nepalgunj (3 days) and Biratnagar (3 days) have highest median compared to Janakpur (2 days), Simara (2 days), Bhairahawa (2 days), and Dhangadhi (1 day) (Fig. S1). The highest median number of cold nights per annum is observed in Nepalgunj (19 nights), followed by Bhairahawa (18 nights), Simara (17 nights), Biratnagar (17 nights), Janakpur (11 nights), and Dhangadhi (11 nights) (Fig. S2). Regarding extreme cold nights, Biratnagar (2 nights), Bhairahawa (2 nights), and Dhangadhi (2 nights) have the highest median cold nights compared to Nepalgunj (1.5 nights), Simara (1 night), and Janakpur (1 night) (Fig. S2). From the box plots of cold and extreme cold days and nights, it is observed

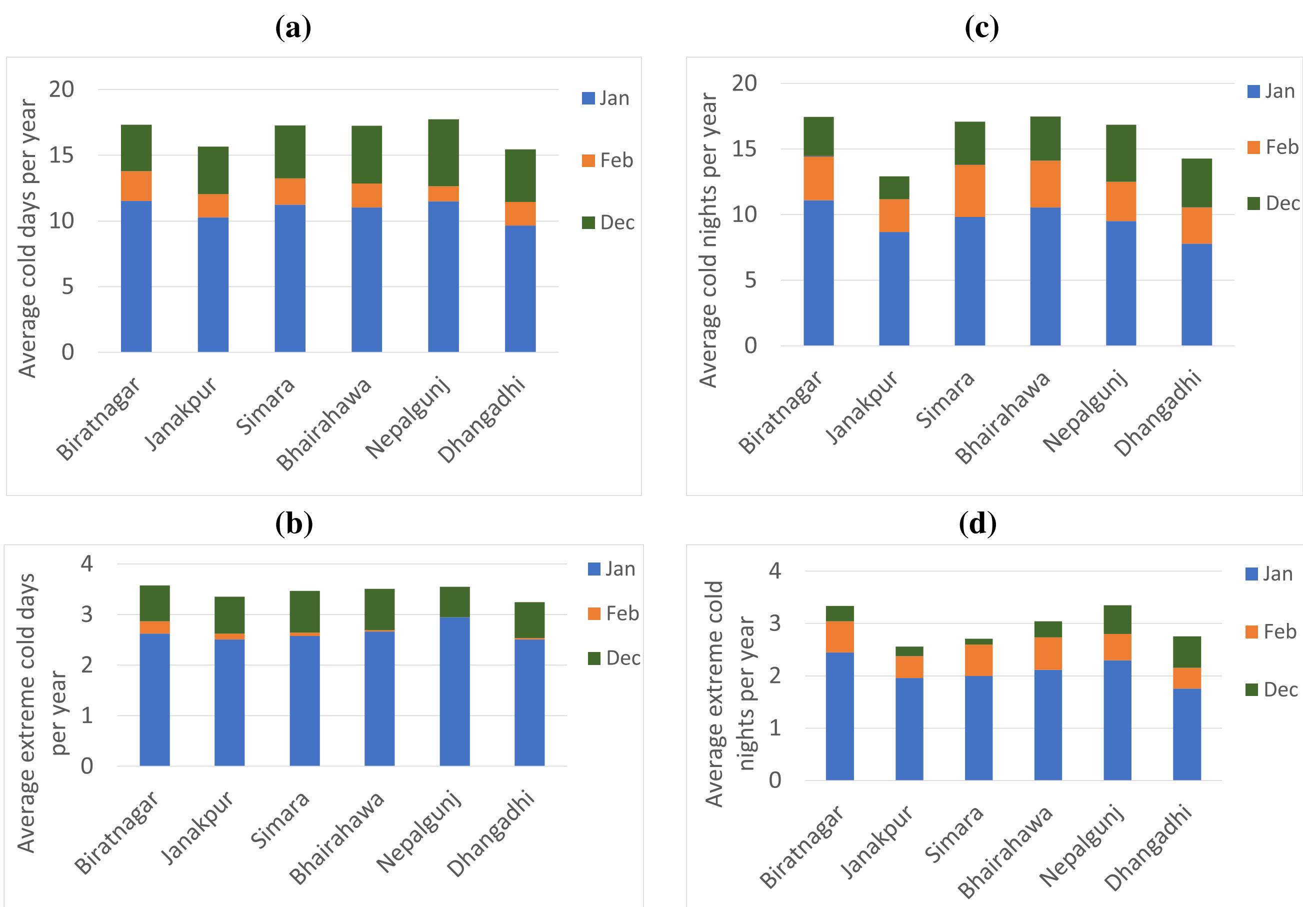


Fig. 2 Monthly share of average number of **a** cold days, **b** extreme cold days, **c** cold nights, and **d** extreme cold nights per annum in the study area

that there are slightly more cold days and extreme cold days compared to cold nights/extreme cold nights in the stations in the Terai region of Nepal.

The presence of annual trends in cold days and extreme cold days during 1971–2015 at the six studied Terai stations is investigated in Fig. S3. From the figure, it is clear that the annual number of cold days and extreme cold days is increasing at all the Terai stations, except Nepalgunj. Compared to the time series of cold days per annum, more variance is observed in the occurrence of extreme cold days in the Terai stations. The Mann–Kendall (MK) test results for trend in annual number of cold days and extreme cold days are presented in Table 4. The results clearly indicate that the annual number of cold days is increasing at all stations, except Nepalgunj, at the statistical significance level of at least 0.05. The rate of increase of annual number of cold days varies from 0.21 days per annum at Biratnagar to 0.46 days per annum at Bhairahawa. The MK test also clearly indicates that the annual number of extreme cold days is increasing at all stations, again except Nepalgunj, at the statistical significance level of 0.001. The increasing trend in annual number of cold days and extreme cold days at all Terai stations, except Nepalgunj, may be due to the increasing trend in fog at Terai stations (Shrestha et al. 2018). The non-significant trend in the annual number of cold and extreme cold days at Nepalgunj may be due to the short data range (20 years) compared to the other stations (45 years). The rate of increase in the annual number of extreme cold days varies from 0.10 day per annum at the eastern station of Biratnagar to 0.15 day per annum at the western stations of Dhangadhi. The analysis of increasing trend in the annual number of cold days and extreme cold days agrees with the perception of the farmers on increasing trend of fog events and cold days in the Dhanusha and Sunsari districts.

The time series of the annual number of cold nights and extreme cold nights at the Terai stations are explored in Fig. S4 (supplementary information). The figure indicates the declining trend on the annual number of cold nights and extreme cold nights at Dhangadhi and no definite trend at all other stations of Terai. The MK test results for trend in the annual number of cold nights and extreme cold nights are presented in Table 5. The results indicate that the majority of stations in Terai have no definite trend in the annual number of cold nights or extreme cold nights over the past 45 years. However, across the south Asian region, the frequencies of cold nights are generally in decreasing trend (Sheikh et al. 2015). At Simara, the number of cold nights is decreasing whereas at Nepalgunj it is increasing at the statistical significance level of 0.1. At Janakpur, the number of extreme cold nights is increasing at the statistical significance level of 0.05. However, at Dhangadhi, both cold nights and extreme cold nights are decreasing at the statistical significance level of 0.05.

Table 4 Results of MK trend test on the annual number of cold and extreme cold days in the Terai stations of Nepal

SN	Stations	First year	Last year	*n*	Cold day			Extreme cold day		
					Test *Z*	*Q*	*B*	Test *Z*	*Q*	*B*
1	Biratnagar	1971	2015	45	2.47*	0.21	12.00	3.31***	0.10	0.81
2	Janakpur	1971	2015	45	4.54***	0.39	5.64	4.75***	0.13	−0.50
3	Simara	1971	2015	45	4.39***	0.44	6.55	4.18***	0.14	−0.11
4	Bhairahawa	1971	2015	45	4.52***	0.46	9.20	4.79***	0.13	−0.67
5	Nepalgunj	1996	2015	20	1.20 ns	0.42	4.42	0.07 ns	0.00	3.00
6	Dhangadhi	1971	2015	45	3.26**	0.39	6.96	4.11***	0.15	−0.58

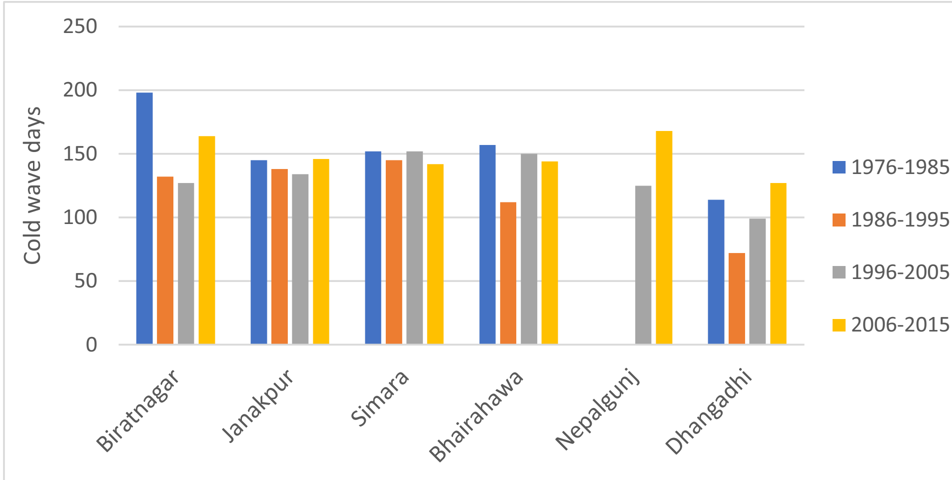
*Significant at 0.05 level, **significant at 0.01 level, ***significant at 0.001 level, ns non-significant

Table 5 Results of MK trend test on the annual number of cold and extreme cold nights in the Terai stations of Nepal

SN	Stations	First year	Last year	*n*	Cold night			Extreme cold night		
					Test *Z*	*Q*	*B*	Test *Z*	*Q*	*B*
1	Biratnagar	1971	2015	45	−0.02 ns	0.00	17.00	0.72 ns	0.00	2.00
2	Janakpur	1971	2015	45	0.52 ns	0.06	10.18	2.03*	0.03	0.18
3	Simara	1971	2015	45	−1.73+	−0.17	20.83	−0.42 ns	0.00	1.00
4	Bhairahawa	1971	2015	45	−1.31 ns	−0.17	21.83	−1.40 ns	0.00	2.00
5	Nepalgunj	1996	2015	20	1.83+	0.67	−6.00	1.73+	0.19	−4.33
6	Dhangadhi	1971	2015	45	−2.09*	−0.22	17.24	−2.09*	−0.04	2.51

+Significant at 0.1 level, *significant at 0.05 level, ns non-significant

Fig. 3 Decadal cold wave days in the Terai region



3.2.3 Cold wave in the Terai

The decadal number of cold wave days is presented in Fig. 3, based on analysis of the daily maximum and minimum temperatures at the six studied Terai stations. The number of cold wave days ranges from 72 to 198 days per decade across the Terai stations. Compared to other stations, less cold wave days are experienced at Dhangadhi. The decade 1986–1995 is the decade with the least cold wave days in the western Terai stations (Bhairahawa and Dhangadhi). In Biratnagar, Janakpur, Nepalgunj, and Dhangadhi, the number of cold wave days has increased in the recent decade (2006–2015) compared to the previous decade (1996–2015) which agrees with the FGD findings. To obtain the annual trend in cold wave events and days at those stations, the MK trend test was performed. No statistically significant trend in annual number of cold wave days was found at those stations during 1971 to 2015 (Table 6).

The average number of cold wave days per month indicates that cold waves occur only in the months of January, February, and December (Fig. S5). At all the stations, January is the month with the highest number of cold wave days. On average, about 68.2%, 19.3%, and 12.5% of the cold wave days occur in the months of January, December, and February, respectively, in the Terai region. The average number of cold wave days per annum ranges from 11.3 days at Dhangadhi to 16.1 days at Biratnagar.

Box plots of the annual number of cold wave days at the Terai stations are presented in Fig. 4. The historical data from 1975 to 2015 are used for the box plots at all stations, except Nepalgunj where data from 1996 to 2015 are used. Even though the median values of annual number of cold wave days at Biratnagar, Janakpur, Simara, Bhairahawa, and Nepalgunj are similar, there is less variation in Nepalgunj compared to other stations (Fig. 4), possibly due to the shorter record length.

3.2.4 Extreme cold wave in the Terai

The number of extreme cold wave days are analyzed based on historical daily maximum and minimum temperature from the six selected Terai stations. The decadal distributions of extreme cold wave days at the studied stations are presented in Fig. 5. The total number of extreme cold wave days per decade varies from 13 to 50 days per decade. The number of extreme cold wave days at Nepalgunj and Dhangadhi is less than the other Terai stations. Regarding any trend in the annual number of extreme cold wave days,

Table 6 Results of MK trend test on the annual number of cold wave days and extreme cold wave days in the Terai stations of Nepal

SN	Stations	First year	Last year	*n*	Cold wave days			Extreme cold wave days		
					Test *Z*	*Q*	*B*	Test *Z*	*Q*	*B*
1	Biratnagar	1971	2015	45	−0.85 ns	−0.11	18.89	0.21 ns	0.00	2.00
2	Janakpur	1971	2015	45	0.14 ns	0.00	14.00	0.35 ns	0.00	2.00
3	Simara	1971	2015	45	−0.29 ns	−0.01	15.33	0.77 ns	0.00	4.00
4	Bhairahawa	1971	2015	45	−1.29 ns	−0.12	17.68	0.05 ns	0.00	2.00
5	Nepalgunj	1996	2015	20	1.49 ns	0.35	2.71	0.99 ns	0.00	1.00
6	Dhangadhi	1971	2015	45	−0.28 ns	−0.01	10.39	−1.40 ns	0.00	0.00

ns Non-significant

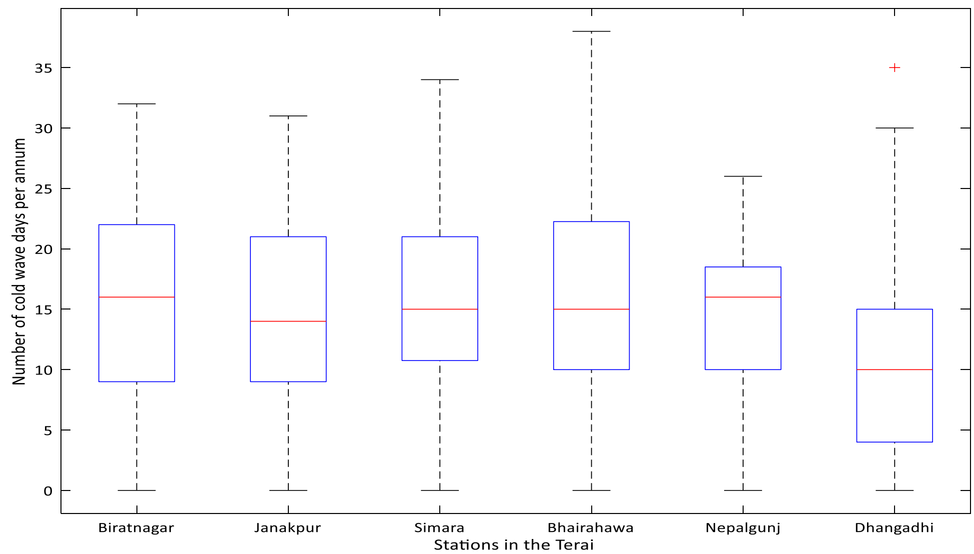


Fig. 4 Box plots of the annual number of cold wave days at the Terai stations. The box plot whiskers extend to the 5th and 95th percentiles

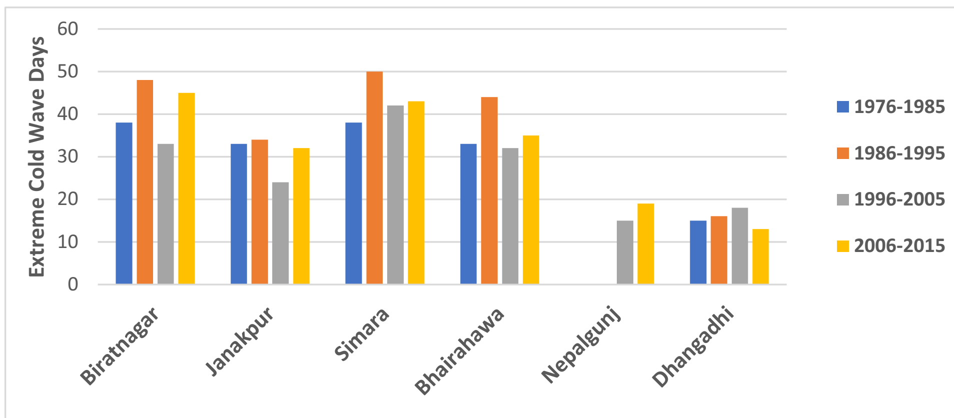


Fig. 5 Decadal extreme cold wave days in the Terai

there is no general trend (statistically significant) across the Terai stations during 1975–2015 (Table 6). However, from Fig. 5, it can be said that at the Terai stations except Dhangadhi, the extreme cold wave days of the recent decade (2006–2015) are increased relative to the previous decade (1996–2005), and this increment is stronger at eastern Terai stations (Biratnagar and Janakpur). This observation agrees with the farmers' perception in the majority of the FGDs. Moreover, it is also aligning with the findings of Oxfam (Gum et al. 2009), which indicated that there are more intense cold waves in the eastern Terai plains in recent years.

The monthly distribution of annual average extreme cold wave days at the Terai stations is shown in Fig. S6. Among the Terai stations, on average the lowest number of extreme cold wave days was observed at Nepalgunj (1.8 days/annum), whereas the highest number of cold wave days was observed at Simara (4.4 days/annum).

To study the distribution of annual extreme cold wave days at the Terai stations during 1976–2015, box plots of extreme cold wave days are presented in Fig. 6. The highest median annual number of extreme cold events was found at Simara (4) and the lowest median at Dhangadhi (0). In spite of the large variation in the distribution of extreme cold wave days over the last four decades at Biratnagar, Janakpur, and Bhairahawa, the median was found to be the same (equal to 2) at these stations.

3.2.5 Fog events and cold wave

Shrestha et al. (2018) studied winter fog events in the Terai region of Nepal using visibility data from four Terai stations and found that fog events start in November, reach their peak in December/January, and end in February. This finding exactly matched with the farmer's FGD findings in this study. Moreover, Shrestha et al. (2018) findings of an increasing trend in the number of foggy days per annum, at statistically significant levels, in the studied Terai stations also agree with the FGD findings at Sunsari and Janakpur. The increased fog events reduce solar insolation and provide

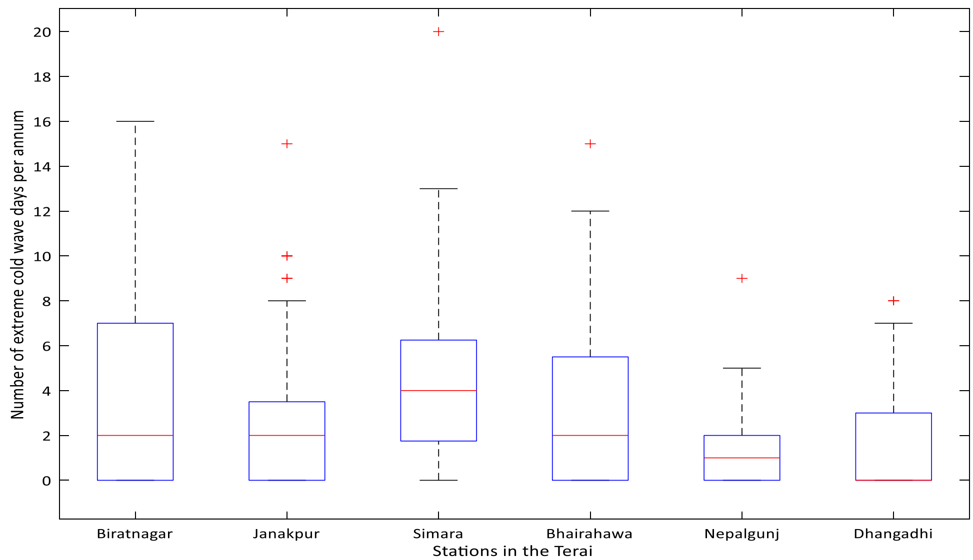


Fig. 6 Box plots of annual number of extreme cold wave days in the Terai. The box plot whiskers extend to the 5th and 95th percentiles

Table 7 Comparison of cold event and fog events at Biratnagar, Simara, Bhairahawa, and Nepalgunj

SN	Conditions	Biratnagar	Simara	Bhairahawa	Nepalgunj
1	Percentage of cold wave day with same day foggy day	77.97	48.46	79.17	58.67
2	Percentage of cold wave day with same day or 1 day after foggy day	87.57	60.77	86.11	70.24
3	Percentage of cold wave day with same day or 1 or 2 days after foggy day	91.53	67.69	93.06	75.20
4	Percentage of extreme cold wave day with same day foggy day	77.78	76.92	96.55	75.00
5	Percentage of extreme cold wave day with same day or 1 day after foggy day	91.67	79.49	100.00	75.00
6	Percentage of extreme cold wave day with same day or 1 or 2 days after foggy day	97.22	82.05	100.00	75.00

a positive feedback for the persistence of foggy and cold conditions during winter (Gautam 2014).

The cold wave events and fog events at four Terai stations during 1994–2015 were compared and presented in Table 7. From the table, it is observed that most (more than three quarters) of the cold wave days and extreme cold wave days co-occur with foggy days at Biratnagar and Bhairahawa. In comparison, at Simara and Nepalgunj, about half of the cold wave days co-occur with foggy days. Similarly, more than 86% of cold wave days co-occur with foggy days on the same day or the previous day at Biratnagar and Bhairahawa, whereas at Simara and Nepalgunj, this condition occurs more than 60% of the cold days. For the condition of a cold wave day preceded by a foggy day anywhere within the previous 2 days, more than 90% of the cold wave days at Biratnagar and Bhairahawa experience this condition, whereas only two-thirds of cold wave days at Nepalgunj and Simara experience this condition. Generally, the percentage of extreme cold wave days associated with a co-occurring, or preceding, foggy day is higher than the percentage for cold wave days. Hence, from the table, it is evident that the majority of cold wave days and extreme cold wave days occur close to foggy days. This is mainly due to the obstruction of solar radiation by the fog during the day time, which reduces the temperature (mainly maximum temperature) (Bedekar et al. 1974; Gautam 2014). It also supports the farmers' perception regarding cold wave events, that they are closely related with fog events.

3.3 Effect of fog and cold waves and adaptations

The results of the FGDs on the effects of fog and cold wave on agriculture are discussed in four subsections. In the first subsection, the effect on crop production is elaborated and in the second subsection the effect on livestock is discussed. Similarly, in the third subsection, other effects are explained, and in the fourth subsection, the adaptation measures adopted by the farmers are discussed.

3.3.1 Effect of fog on crop production

The major crops affected by fog identified by the FGDs conducted during this study are presented in Table S2. All FGDs conducted in this study identified potato and vegetables (including tomato, brinjal, beans, and chili) as the number one and number two crops affected by fog in prioritized order, respectively. Regarding the third most affected crop due to fog, this varied across FGD locations. Wheat was identified as the third most important crop affected by fog by all the FGDs, except that of Saalbani, Sunsari where kidney bean was considered to be the third most important crop affected. Along with wheat, pigeon pea and lentil crops were also considered the third most important crop affected by fog by the FGDs at Batteswor and Sinorjoda, respectively.

According to the FGDs in Dhanusha and Sunsari, fog events bring a conducive environment (humid and cool without sunlight) for late blight disease for potato. This agrees with the findings of Samra et al. (2003) and Bhat et al. (2010), who noted that total crop failure is experienced when timely spraying is not performed. According to the farmers, the effect of fog on potato also depends on the potato planting date. November-planted potato is more damaged due to late blight than October-planted potato. In general, late blight reduces potato production by about 50%. In extreme foggy condition, 100% damage is also observed. A farmer at Simariya, Sunsari experienced total failure of her potato crop by late blight during the foggy season 4 years ago. To minimize damage due to late blight, various chemicals are used, viz., Endophyl, Clear axyel, and Dythenium 45. On average, potato is sprayed 6.33 times (minimum 5 and maximum 8 times across all FGD locations) to minimize damage due to late blight during the foggy season. On average, the spraying against late blight increases the cost of cultivation of potato by about 473 AUD (Rs. 37,887) per hectare in the study area (equivalent to 18% of the production cost) (Table S2). For potato, more than 95% of agricultural pesticides used are fungicides, which indicates that farmers are trying to reduce the severity of late blight in Nepal (PRMS 2014).

Vegetable crops (tomato, brinjal, onion, chili, leafy vegetables, green beans, etc.) are identified as the second most important crop affected by fog during FGDs in the study area. In all the FGDs, the farmers unanimously agreed that infestation of fungal disease increases in these crops during fog events. In addition, the farmers also observed increased infestation of aphids on vegetables (especially on beans, pigeon pea, mustard, etc.) during the foggy season, which is similar to the findings of Samra et al. (2003) and Ali and Rijvi (2008) for mustard crop. A farmer at Simariya FGD noticed that increased fungal infestation in cauliflower is observed in the foggy season, resulting in black spots on the cauliflower curd, which significantly reduced the market value of the cauliflower. To get rid of fungal attack and aphid infestation, farmers are spraying chemicals which has increased the cost of cultivation.

Wheat is also considered to be an important crop affected by fog events in the Terai (Table S2). If there is early fog during November, the harvested paddy left in the field does not dry and it delays wheat cultivation (Table S2). Since there is a linear decline of wheat productivity at the rate of 1 to 1.5% per day at Ludhiana (agro-ecology similar to the Terai region of Nepal) due to delay in planting after the end of November (Ortiz-Monasterio R et al. 1994), the resultant delay due to fog may also cause reduction in wheat yield in the Terai.

According to the farmers, the fog period lies in the vegetative growth period of wheat and its vegetative growth rate is reduced during foggy period. Moreover, all FGD participants agreed that delay in maturity of wheat makes it more susceptible to being affected by dry western wind, which may significantly reduce the wheat yield due to shriveled grain (Table S2). The effect of dry western wind and shriveled wheat grains in the Terai explained by the farmers exactly matches with the shriveled grain scenario due to dry wind during maturity of wheat in the Punjab explained by Luthra and Chima (1941).

The participating FGD farmers at Saalbani described increased infestation of fungal attack on kidney bean during the foggy season. Similarly, the participating farmers at Sinorjoda described increased blight infestation of their lentil crop during fog events. The farmers' observations match with the findings of Subedi et al. (2015) regarding favorable conditions for the occurrence of *Stemphylium* blight in lentil as high humidity and low solar radiation (similar to foggy day condition). To address the blight and fungal attack on lentil and kidney bean, the farmers are spraying pesticides (mainly fungicides).

Pesticide consumption is reported to be increasing in the Terai area and the accessible hilly areas of Nepal (Joshi et al. 2012). The share of agricultural pesticide use in the Terai area is reported to be 59% of the total use in Nepal. Similarly, vegetable crops are the main consumer of agricultural pesticides, with about 79% share on total agricultural pesticides used in Nepal. Among the vegetable crops, brinjal, tomato, potato, and cole crops are the major consumers of agricultural pesticides in Nepal (PRMS 2014).

A sixfold increase in import and formulation of agricultural pesticides in the year 2011/2012 relative to 1997/1998 clearly indicates a rapid increase in consumption of agricultural pesticides in Nepal (Sushma et al. 2015). Among the pesticides used in agriculture, fungicides have a major share of about 60% in the total used in Nepal (PRMS 2014). The increased pesticides use in the Terai could be due to the conducive environment for disease and pests during increasing fog events, as mentioned in FGDs in the study area. During field observations, farmers were not found adopting a safe method of chemical applications by using mask, apron, and gloves. Due to low level of awareness of Nepalese farmers on the safe use of pesticides (Giri et al. 2008), the increasing pesticide consumption trend not only threatens the farmers' health and the consumers' health, but also negatively affected the natural environment (Diwakar et al. 2010). Apart from the negative effect of fog on the crops, a woman farmer in the Simariya FGD observed that in foggy conditions, mushroom grows well, which may be due to high humidity during fog events.

3.3.2 Effect on livestock production

The participating farmers of all the FGDs in the study area unanimously agreed that fog events and resulting cold waves have significantly affected their livestock during winter. Cattle, goat, and buffalo are the major livestock affected by fog in the study area. The FGDs conducted in the study area agreed that milk production from cows and buffalos were significantly reduced. The farmers of Batteswor FGD estimated about 25% reduction in milk production whereas those of Sinorjoda, Naktajhijh, Simariya, and Saalbani estimated about 33% reduction of milk production during fog-induced cold wave. The reduction in milk production reported by the farmers agrees with the findings of Upadhyay et al. (2014), who reported that milk production of bovines was reduced during cold wave at the rate of 10 to 30% in first lactation and 5 to 20% in second and third lactations. Upadhyay et al. (2014) also reported that the cold wave not only has an immediate effect on milk production, but also short- to long-term cumulative effects on milk yield and production in cattle and buffalos that depend on the extent and severity of cold wave. The reduction in milk production estimated by the farmers in the study area was higher than the 20% reduction of milk production due to the 2002–2003 cold wave in Agra reported by Samra et al. (2003).

The FGD farmers also indicated that calves are more susceptible to cold stress than the cows and mature heifers. The reason behind this could be due to larger surface area/body mass ratio of calves than that of more mature animals, resulting in more body heat loss. In addition, it could also be due to less fat availability in calves compared to mature animals (Singh et al. 2015). The farmers also noticed that goats are also affected with respiratory disease during foggy season in winter. Similarly, they also agreed that compared to adult goats, kids are more effected by cold wave in the study area. These farmers' observations align with the findings of Paudyal et al. (2012).

To minimize the effect of fog and cold wave on the animals, it was observed that the farmers of the study area use coats made of jute bag or old cloths to cover their animals. Similarly, the animal sheds were improved with better roof and wall to make it warmer. Even poor farmers are using thatched roof and straw mat to cover the side wall of their animal sheds. On the extreme cold days, it was observed that the farmers are also burning agricultural residue near their animal shed to make it warm. The farmers also mentioned that they also started to provide warm water and cooked feed during winter to increase water intake of their cattle during the winter foggy season.

3.3.3 Other effects

According to the participating FGD farmers, children and old people are more affected by cold, pneumonia, and respiratory disease during the foggy season (Table S2). All the FDG participants agreed that they do not prefer to work in the field due to cold and that farm laborers are not easily available during the foggy season. Moreover, all agreed that farm labor productivity was significantly reduced, even by more than 50% during the foggy season (Table S2). Because of a reduction in labor productivity, the cost of cultivation is increased, and the farm operation is delayed. These farmers' observations are supported by the findingd of CBS (2017), which reported that in the Terai, 23.36% of households are affected due to cold wave and Terai households have missed an average of 4.1 working days due to cold wave in the last 5 years.

The FGD participants at Batteswor and Naktajhijh recalled the death of several villagers during the extreme cold event in 2011. According to them, the old people from poor families died due to a lack of enough clothes to make them warm during those extreme cold events. They also realized that this was due to a lack of preparedness for the cold event. Similarly, the Saalbani FGD agreed that compared to people from migrated hill communities, people from indigenous Terai communities were more affected by the fog and cold wave due to a lack of preparedness and poor economic condition.

During dense foggy days, children cannot go to school and schools are generally closed during those periods. Due to poor visibility during fog events, the road transportation is also affected. Similarly, the participants of the FGD noticed that road accidents increased during fog events. One of the tractor drivers at Naktajhijh died due to a road accident during fog events 4 years ago (Table S2).

3.3.4 Adaptation measures

To minimize the effect of fog and cold wave on crop and livestock production in the study area, the following adaptation measures were found to be successfully adopted by the farmers:

- To minimize the effect of late blight, aphids, and other fungal disease on potato, vegetables, and other crops, farmers are spraying chemicals during the foggy season (Table S2).
- The farmers also realized that early planting of potato (October planting) may escape fog (Table S2).
- To minimize the effect of delay in cultivation of the winter crop and labor unavailability due to fog, farmers are adopting more agricultural mechanization technologies

for timely accomplishment of agricultural operations (Table S2).

- The farmers also realized that groundwater irrigation during winter (foggy season) is beneficial due to water being warmer relative to the colder surface water (Table S2).
- Farmers have improved their animal sheds to minimize the effect of fog and cold wave on their livestock (Field observations).
- Use of coat (made from jute bag/old clothes) for animals to minimize the effect of cold during foggy season (Field observations and Table S2).
- Making the animals and people warm by burning agricultural residue near the animal shed (Field Observations).
- Providing warm water and even cooked feed to increase water intake of animals (Table S2).

4 Summary and conclusions

Historical daily maximum and minimum temperatures were analyzed to investigate the occurrence of cold days, cold nights, extreme cold days, extreme cold nights, cold wave days, and extreme cold wave days in the Terai region of Nepal for the first time. Similarly, the perception of farmers regarding the effect of fog and cold wave events was explored through focus group discussion in Dhanusha and Sunsari districts of the Terai. The major findings of the study are listed below.

January, February, and December are the months when cold/extreme cold days/nights occur in the Terai region of Nepal. The average number of cold days per annum ranges from 15.6 to 17.9 days and the average number of cold nights per annum ranges from 13 to 17.6 days in the Terai region. Similarly, the average number of extreme cold days per annum ranges from 3.2 to 3.6 days and the average number of extreme cold nights per annum ranges from 2.6 to 3.4 days in the Terai. Except for Nepalgunj, all the Terai stations show statistically significant increasing trends in the frequency of cold days and extreme cold days over the last four decades. However, statistically significant trends in the frequency of cold nights and extreme cold nights over the last four decades were not observed in the majority of stations in the Terai.

Cold wave and extreme cold wave days occur during winter in January, February, and December in the Terai region of Nepal. Based on historical data, the average number of cold wave days varies from 9.2 to 13.8 days per annum and the average number of extreme cold wave days varies from 1.4 to 3.8 days in the Terai region of Nepal. By comparing the co-occurrence of foggy days and cold and extreme cold wave days at Biratnagar, Simara, Bhairahawa, and Nepalgunj airports, it is also observed that most of the cold and extreme cold wave days are also foggy days.

Through an exploratory study of the farmers' perception of the effect of fog events and cold wave on agriculture, it was found that there is a significant effect on winter crop cultivation and livestock farming. Potato, tomato, brinjal, wheat, chili, onion, beans, etc. are the major crops affected by fog and cold wave in the Terai. The major effect of cold wave and fog events is to create a conducive environment for fungal infection/late blight and poor vegetative growth. Up to 100% damage of crops, especially potato, tomato, and brinjal, is reported during fog/cold wave events in the Terai due to late blight. All the farmers are spraying more chemicals to prevent late blight during the foggy season. On average, 6.3 times spraying events are done to prevent potato crop from late blight and the increased chemical spraying of fungicide increased the cost of cultivation by about 18%. Livestock are also affected by cold events in the Terai. Milk production is reduced by 25 to 50% due to cold wave. Similarly, goats are affected by respiratory disease and cold during a cold wave. During cold wave days, farmers prefer not to work on the farm and they have noticed that labor productivity is significantly reduced on cold wave days.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration

Ethics approval This research involves focus group discussions (FGDs) of the people in the study area. This study (Ethics ID 1,750,778) was conducted after approval by Engineering Human Ethics Advisory Group, University of Melbourne as a minimum-risk project.

Consent to participate Before conducting the FGD, the participants were well informed about this research and its possible applications. Only after receiving the signed consent form, the FGD was conducted.

Consent for publication All authors have read the manuscript and agreed to publish.

Conflict of interest The authors declare no competing interests.

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