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Short Communication

Evaluation of cold wave events over Indo-Gangetic Plain in India

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Weather extreme events such as thunderstorm, heavy rainfall, heat wave, cold wave, cyclone, flood and drought have large impact on environment and socio-economy of a country like India throughout the year (Pandey *et al.*, 2010). The study of specific category of events separately or all together is necessary aspect to develop any forecasting system. Cold wave can be defined as a prolonged period of excessively cold weather in which a sudden invasion of very cold air over a very large area takes place which leads to unusually large and rapid reduction in temperature over that region of interest (Guha-Sapir *et al.,* 2012). Cold waves occur in India during winter months i.e. from November to February (Ratnam *et al.,* 2016). The cold wave is dangerous to human health as well as affects plants and agricultural activities (Samra *et al.*, 2003; De and Sinha Ray, 2000). The Indo-Gangetic Plain (IGP) region in India is most favourable for the occurrence of cold wave as well as severe cold wave events in winter months from November to March. The main reason behind occurrence of cold wave event isWestern Disturbances from northern latitudes into the north-eastern parts and IGP (Bedekar *et al.,* 1974).The occurrence of cold wave and severe cold wave over the hilly regions and the adjoining plains is mainly due to the mid-latitude westerly winds which often have weak frontal characteristics (De *et al.,* 2005). The minimum temperature over north India has a decreasing trend whereas increase in seasonal mean temperature with 1.1°C per century during the winter season (Sinha and De, 2003; Arora *et al.,* 2005). Dash and Mamgain (2011) found a significant decrease in the frequency and spells of cold nights during 1969-2005 over India and its northern regions excluding western Himalaya. The spatio-temporal distribution of extreme weather events over India during 1967-2006 excluding 1977 shows an increasing trend of cold wave events from about 80 during year 1978 to 460 during the year 2006 with an increasing linear trend (Singh and Patwardhan, 2012). Kumar *et al.* (2013) have studied the effect of regional climate variability on crop production over Hisar region in Haryana, they proposed that the variability of rainfall, temperature and extreme events causes an uncertainty to the growth of crops.

The main objective of the present study is to analyse the trends of the cold wave as well as severe cold wave events in the winter months from November to March during the period of 1951-2013 over Indo-Gangetic Plain (IGP) region. In addition, the frequency of yearly, decadal and tricadal variations are also examined. The gridded minimum temperature data of India Meteorological Department (IMD) at a resolution of 1°x1°over Indo-Gangetic Plain of India (IGP)has been analysedfor the period of 1951-2013. The geographical location of IGP with coordinate has been displayed in Fig.1. The average of minimum temperature for daily basis per year during the months November to February has been taken to calculate the normal minimum temperature and departure of daily minimum temperature from this normal minimum temperature.In the present study, the minimum temperature overIGP during the period 1951-2013 has been used to investigate the frequency of cold wave (CW) and severe cold wave (SCW) as per IMD criteria (http://www.imd.gov.in/doc/termglossary.pdf). For tracking the local climatic conditions over IGP region, the frequency of cold/severe cold wave can be considered. The daily minimum temperature has been used to analyse the occurrence of the frequencies of the CW and SCW events for the months November to February during period 1951-2013 over IGP. Further this study also includes the two Tricadal *viz.* 1951-1980 (T1), 1981-2010 (T2) and six decadal *viz.* 1951-1960 (D1), 1961-1970 (D2), 1971-1980 (D3), 1981-1990 (D4), 1991-2000 (D5), 2001-2010 (D6) variation of cold wave and severe cold wave frequency for the same region.

The monthly and annual variation of cold wave (CW) and severe cold wave (SCW) frequency over IGP

Month and annual variation of CW and SCW over IGP are presented in the Fig.2a-d and Table 1. It can be seen from the figure that there is no CW and SCW event in November month from 1951-2013. Fig.2a-d observed

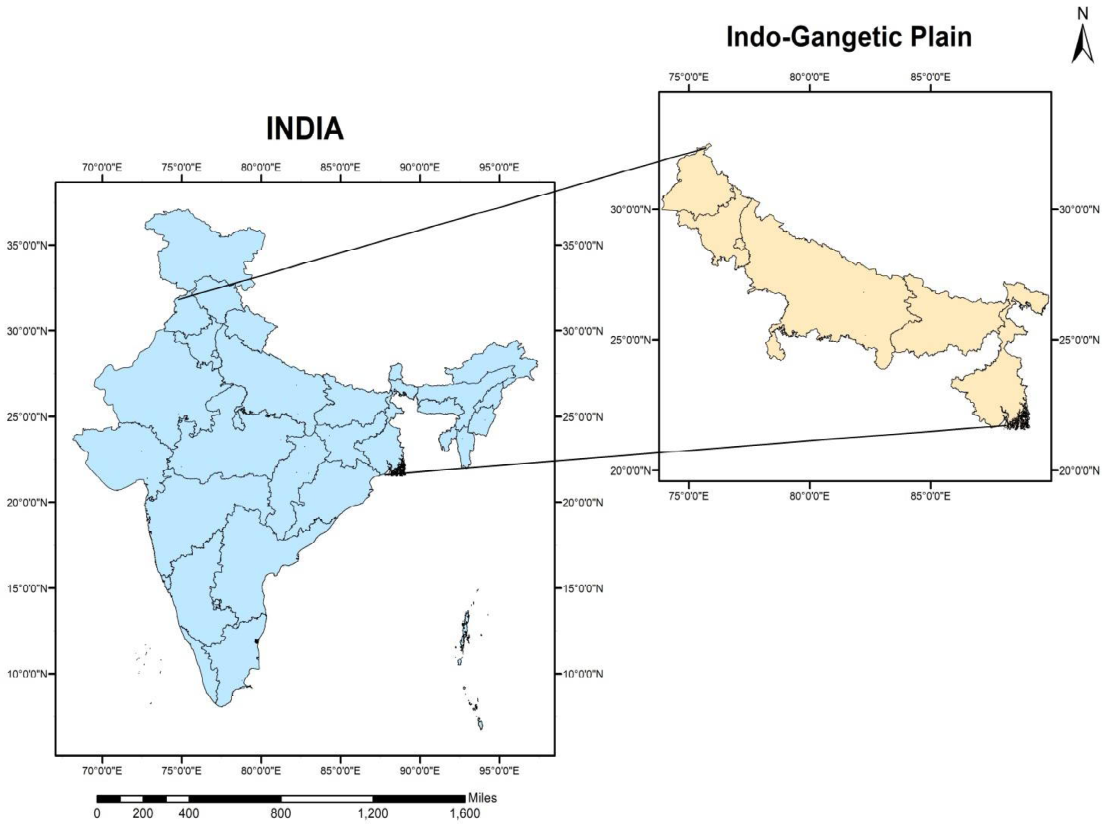

Fig.1: The Indo-Gangetic Plain (IGP) region of India.

variation of CW for the months of December, January, February months. The Fig.2a showed that maximum number of CW is 9 in 2011 year while minimum number exhibited 1 during 1954, 1963, 1971, 1982, 1986, 2007 and 2012 years. Table 1 showed that the maximum number of SCW was 2 during the years 1960 and 1961 besides it the minimum number of SCW is 1 in 1984. The total number of SCW in December during 1951-2013 is 85 and total number of SCW is only 5. In total there are only 3 years of SCW during December from 1951-2013 which are namely1960, 1961 and 1984. Now if we look at 1960 and 1961 there are 2 SCW in each year whereas during 1984 a single event of SCW could be depicted. From Fig.2a we can see that SCW are negligible in comparison to CW during December month.

Fig. 2b shows that for the month of January the maximum number of CW is 5 in the year 1977 while the minimum number of CW is 1 during several years like 1951, 1952, 1958, 1959 and others further, the maximum number of SCW is 5 and the minimum number is 1. In December the total number of CW is 103 and that of SCW is 42. The trend of the CW is increasing by a rate 0.0035 during 1951-2013 in the month of January. Now for the month of February, Fig. 2c shows that the maximum number of CW is 4 in 1972 and 1976 besides it the minimum number of CW is 1 during 1961, 1964, 1979, 1983, and 2004 and the number of CW in February is 36 during 1951-2013. The cold waves are decreasing at the rate of 0.008 during February. Fig.2d shows winter season have the CW with maximum number 11 in 2011 and the minimum number is 1during 1952, 1958, 1963, 1979, 1988, and 2004. The total number of CW is 223 during winter season (DJF) with a decreasing trend at the rate of 0.0095 over IGP.

30-year period (Tricadal) variation of cold wave and severe cold wave event during 1951-2013 over IGP

In this section the tricadal variation of CW and SCW has been discussed (Fig.3). Study shows that the maximum number of CW is 47 in the month of December during tricade T1 (1951-1980) whereas the minimum number of CW is 27 during period T2 (1981-2010). During the month of January here the maximum number of CW is 65 in tricade T2, while its minimum number is 47 during T1 tricade. In the month of February, the maximum number of CW is 26 during tricade

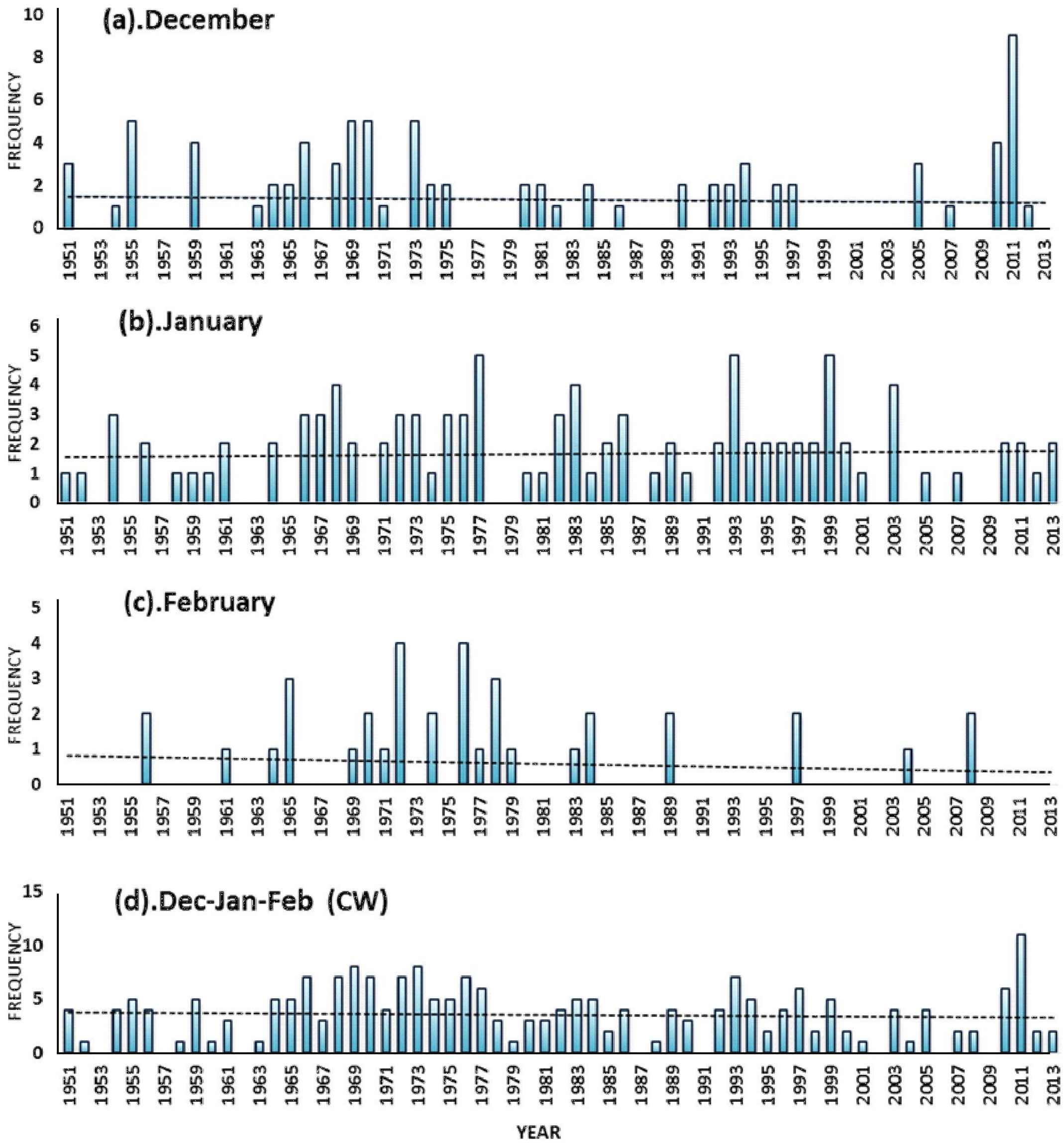

Fig.2: Yearly frequency variation of cold wave events during (a) December (b) January (c) February and for (d) winter season (Dec-Jan-Feb) during 1951-2013 over IGP.

T1 and the minimum number is 5 during the period tricade T2. Now if we look at the winter season the maximum number of CW is 124 during 1981-2013 and the minimum number is 89 during 1981-2010. A periodically increasing trend of cold wave events is observed at the rate of 19.8 and 14.5 for the Tricadal periods T1 (1951- 1980) and T2 (1981-2010), respectively. The tricadal variation of severe cold wave frequency (Table 1) indicates that the number of SCW in the month of December is 4 during the period T1. During the tricadal period T1, the maximum and minimum number of SCW is found to be 26 and 16 respectively whereas for the period T2, these values increases to 43 and 22, respectively.

Decadal variation of cold wave and severe cold wave frequency during 1951-2013 over IGP

The decadal variation of cold wave frequency over IGP during the period 1951-2013 has been shown in Fig.4a-d. The linear Increasing/decreasing trend of CW and SCW has been analysed and tested its statistical significance using Mann-Kendall Rank Statistics at 0.15 significant level. The analysis shows that the maximum number of CW is 22 during the decade D2 while the minimum number is found to be 8 during D4 and D6. In the same way Table 1 shows the maximum number of SCW is 2during D1 and D2 for the months of December and Januarywhile the minimum number

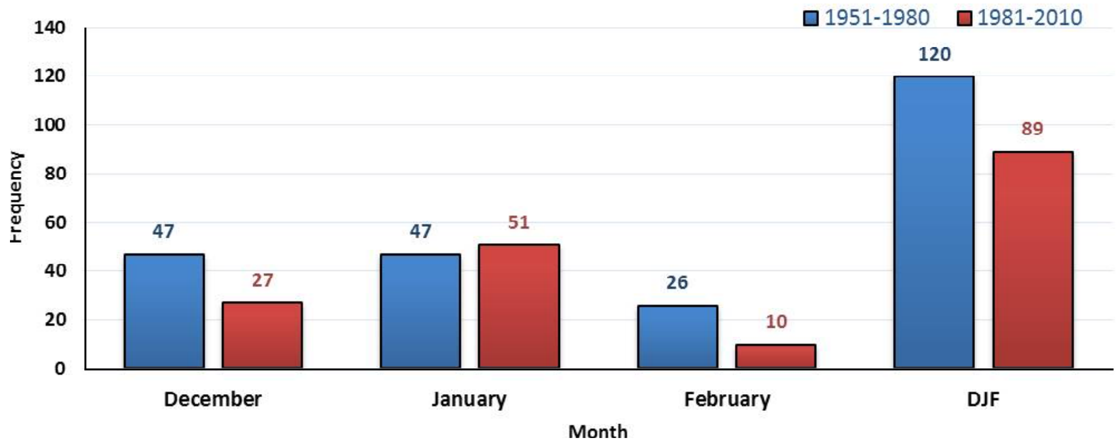

Fig.3: 30-year period (Tricadal) variation of cold wave frequency during 1951-2013 overIGP.

Table 1: Frequency of Severe cold wave (SCW) over IGP during 1951-2013

	Period	Dec	Jan	Feb	DJF
T1	1951-1980	4	25	14	43
T2	1981-2010	1	16	5	22
D1	1951-1960	2	1	0	3
D2	1961-1970	2	17	1	20
D3	1971-1980	0	7	13	20
D4	1981-1990	1	4	3	8
D5	1991-2000	0	3	2	5
D6	2001-2010	0	9	0	9

is 1 during the decade D4 for the same months.The number of cold wave event is alternatively increased and decreased from decade D1 to D6. Similarly, the number of SCW is 2 which is same during decades D1 and D2 and there is an absence of SCW during D3. Now further, during the last two decades (D5 and D6) there is no any SCW in the month of December and analysis shows that the trend of the cold wave frequency is decreasing at a rate of 1.7714 for the month of December during 1951-2013(Fig.4a). Moving to the month of January Fig.3b shows the decadal variation of cold wave frequency during 1951-2013. The maximum number of the CW is 24 during the decade 1991-2000 (D5) while minimum number is 9 during the decade 2001-2010 (D6). It can be observed that the number of CW shows an increasing trend during the decades D1 (10) to D3 (21) whereas during decade D4 to D6 the number of CW is alternatively decreasing. There is an abrupt increase of CW from decade D1 (1) to D2 (17) during the month of January. An increasing trend of the CW is observed at the rate of 0.0357 for the month of January during the period 1951-2013. In the same way Table 1 represents the variation of severe cold wave frequency for the six decades during 1951-2013 with the maximum number of SCW 17 during the decade 1961-1970 (D2) and minimum number of SCW is 1 during the decade D1. Further number of SCW shows a decreasing trend during the decade D2 (17) to D5 (3) for the month of January over IGP. Now Fig.4c depicts the variation of CW in the month of February during the six decades namely D1, D2, D3, D4, D5, and D6. It can be seen that the maximum number of CW is 16 during the decade 1971-1980 (D3) and the minimum number of cold wave event is 2 which is same during the decades 1951-1960 (D1) and 1991-2000 (D5). The number of CW has an increasing trend during the first three decades D1 (2) to D3 (16) while from D3 (16) to D5 (2) it starts decreasing. Thus, the CW has a decreasing trend at rate of 0.75 during 1951-2013 over IGP. Now Table 1 represents the variation of severe cold wave frequency for the month of February during the decades D1, D2, D3, D4, D5, and D6. The maximum number of SCW is 13 during the decade 1971-1980 (D3) and the minimum number SCW is

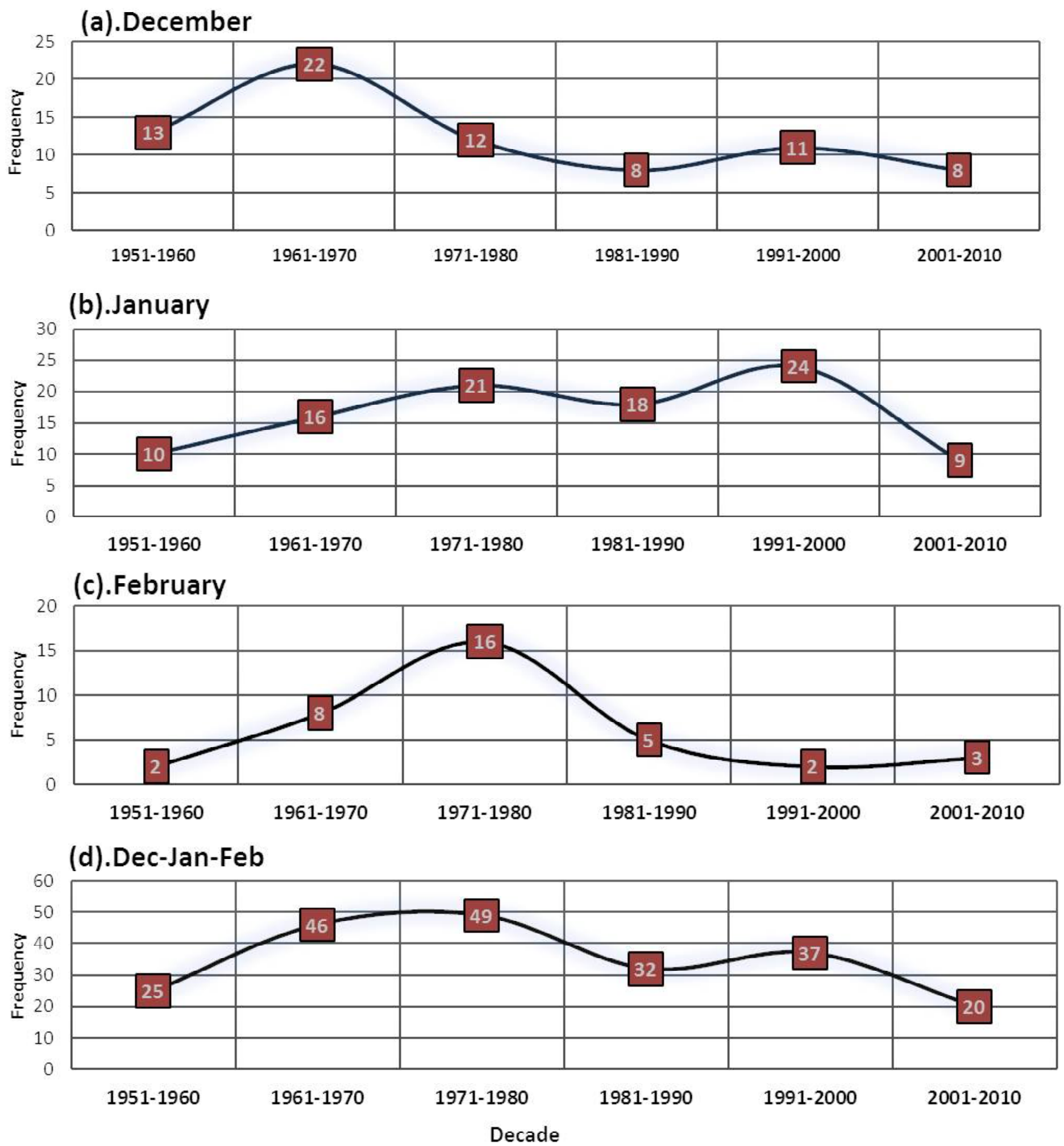

Fig.4: Decadal variation of cold wave frequency in the month of (a) December (b) January (c) February (d) winter season (DJF) during 1951-2013 over IGP.

1 during 1961-1970 (D2). The number of SCW shows a decreasing trend from decade D3 (13) to D5 (2). Now in the Fig. 4d the variation of cold wave frequency is shown here for the winter season during 1951-2013. It is found that the maximum number of CW is 49 during the decade 1971-1980 (D3) while the minimum number of CW is 20 during the decade 2001-2010 (D6). During the winter season CW shows an increasing trend D1 (25) to D3 (49) while during the last four decades the number of CW alternatively increases. The overall trend of the CW is decreasing at a rate of 1.2143 in the winter season during the period 1951-2013 over IGP. Similarly, the variation of severe cold wave frequency can be seen in Table 1. Analysis shows that the maximum number of SCW is 20 during the decade 1971-1980 (D3) while the minimum number of severe cold wave event is only 3 during decade 1951-1960 (D1). The number of SCW has an increasing trend during first two decades D1 (3) to D2 (20) and during second (D2) and third (D3) decade the number of SCW remains same with value 20 in the winter season.

The year to year variability of cold wave and severe cold wave were study over IGP during 1951-2013. Seasonal study of cold wave analysis shows significant increase in the no. of cold wave events during month of January, whereas during February trend were decreasing. In the year 2011 sudden increase in number of cold wave event has been observed which might be explain by combined effect of cold wave/severe cold wave associated with severe La-Nina events. The study of Ratnam *et al.* (2016) stated that the far-reaching association of ENSO events might be the possible cause behind the fluctuating trends of cold wave events over India. The 30-year (tricadal) variation has proved the decrease in cold wave events due to the increase in average temperature of Earth's atmosphere or due to the global warming. The decadal analysis concluded that during the months of December and January high frequency of cold wave and severe cold wave events has been observed. As the cold wave events are very less in February, It can be explained with decreasing winter cold days/nights.

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