# Chapter 3

## Climatology and long- term trends of Cold Waves

In this chapter, the long-term climatology and long-term trends of cold waves over India are discussed. For this purpose, the results based on the IMD criteria and criteria based on percentile have been used.

Cold waves are predominantly experienced during the period December-February, when minimum temperatures drop to very low levels, especially over the northern parts of India. Fig 3.1 a shows the long-term climatology of minimum temperatures (Tmin) and Fig 3.1 b shows spatial distribution of 10$^{th}$ percentile of Tmin. The long-term climatology was prepared using the daily minimum temperature data of 1971-2000. Daily temperature data developed by Srivastava et al. (2009) have been used for this analysis.

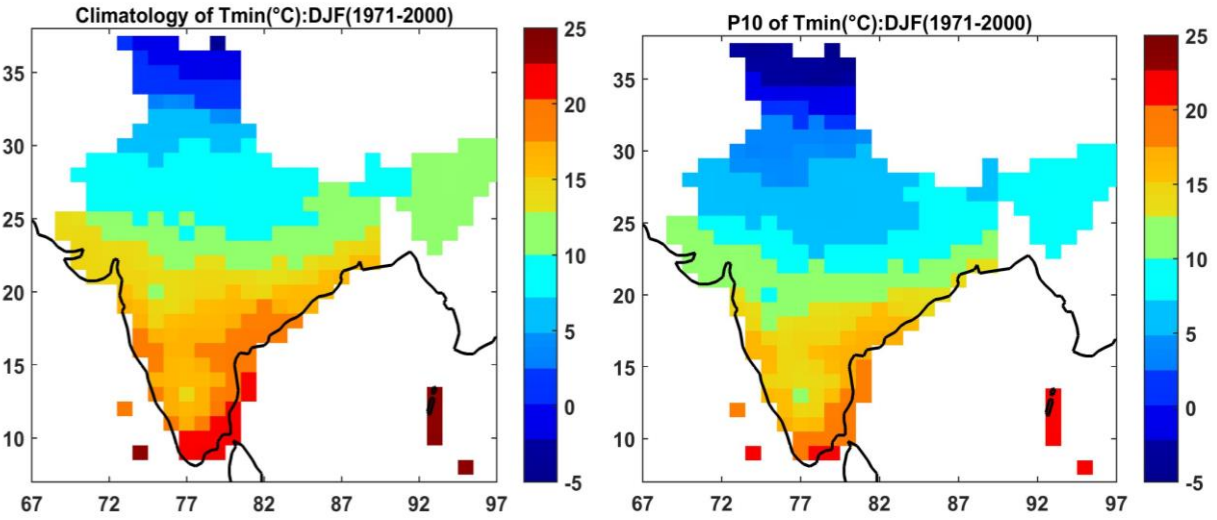



Fig 3.1 a) Climatology of seasonal (Dec-Feb) Tmin ($^{o}$C) (1971-2000) and b) 10$^{th}$ percentile of Tmin ($^{0}$C) during 1971-2000.

Seasonal Tmin values are below 15$^{0}$ C over northern parts of the country, north of 20$^{0}$N. Over parts of Jammu and Kashmir, the Tmin values are even below zero. It is interesting to note that over the northern parts of the country, the isolines of

temperatures run parallel, with a large north-south gradient of over $10^0$ C. North of $25^0$ N, the $10^{th}$ percentile values of Tmin are generally below $7.5^0$C. A large north-south gradient is also observed in this pattern over the northern parts of the country. There is hardly any north-south gradient over the southern peninsula. The coastal regions, especially the east coast, are relatively warmer compared to the inner parts of the southern peninsula, with Tmin values above $20^0$ C.

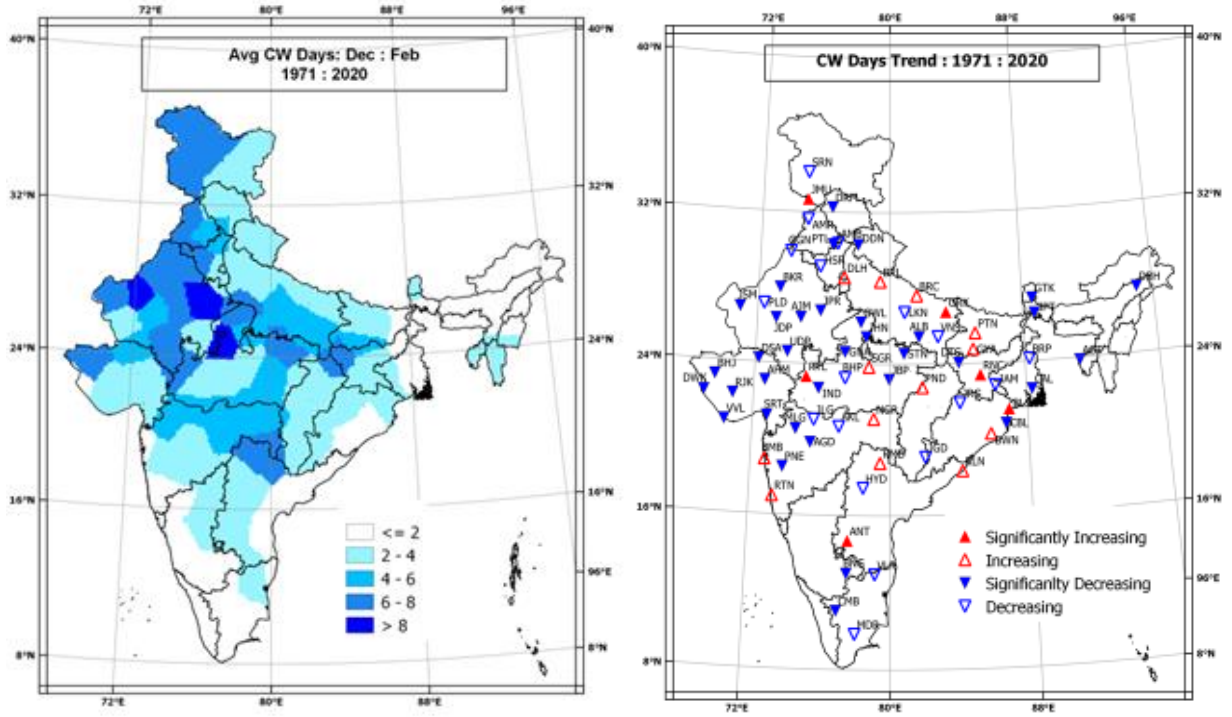
### 3.1 Cold Wave Statistics Based on IMD Criteria

The criteria used by the IMD to define Cold Wave (CW) are listed in Table 2.2. From Table 2.2 it can be seen that CW/SCW conditions imply a certain drop in the daily minimum temperatures at a station compared to the respective normal climatological value. As shown in Table 2.2, a relatively intense CW is classified as severe CW or SCW.

In this section, we mainly discuss the results obtained by Smitha et al. (2016) on cold waves over India. They had considered 86 IMD stations for the analysis of cold waves over India. Fig. 3.2 a shows the spatial variation of mean number of Cold Wave (CW) days during the cold weather season (DJF) over the country expressed as days per season. Most of the areas except Kerala, coastal Karnataka, Tamil Nadu and coastal Andhra Pradesh experience 2 CW days or more per season. Many areas over northwest and some parts of central India experience 8 or more number of CW days.

Fig. 3.2 b shows the long-term trends in the number of cold wave days (CW) during the cold weather season (DJF) over the period 1971-2020. The blue (red) colour indicates decreasing (increasing) trends. Statistically significant trends (at a 95% significance level) are shown as filled triangles. It can be seen that many stations over the northern parts of India show a decreasing trend in CW days. Only a few stations over the central and eastern parts of the country show increasing trends. Fig. 3.2 c shows the spatial distribution of Severe Cold Wave (SCW) days for the period 1971-2020. It shows that most of the SCW days are observed over the central and north-western India and

they last for more than 2 days. There are hardly any SCW events over the southern peninsula and north-east India.




(a) (b)

Fig 3.2. a) Seasonal climatology map of number of CW days, b) Long term trends in number of cold wave (CW) days during the cold weather season (DJF) during the period 1971-2020. Blue (red) colour shows decreasing (increasing) trends. The trends which are statistically significant at 95% significance level are shown as filled triangles. The climatology was computed by averaging the number of CW days for the period (1971-2010). (After Smitha et al. 2016).

Fig. 3.3 a shows the spatial variation in the mean number of cold wave frequencies during the cold weather period (DJF) over the country during 1971-2020, expressed in numbers. In many areas in the northwest, about 8 cold waves occur during the season. North of $20^0$N, the frequency of CW is more than four. Fig. 3.3 b shows the long- term trends in the number and frequency of CW during the cold weather season (DJF) during the period 1971-2020. The trends which are statistically significant at 95%

significance level are shown as filled triangles. Most stations in northern India show decreasing trends in the frequency of CW during the December-Feb season. A few stations over Punjab, Haryana and Andhra Pradesh show increasing trend but it is not statistically significant. The decreasing trend in the frequency of cold waves could be related to increase in minimum temperatures observed over India during the recent years. The maximum duration of cold wave days (Fig. 3.4 b) shows a decreasing trend in most parts of northern India. Fig. 3.5 clearly shows the decreasing trend in the frequency, duration and maximum duration of cold waves over India during the winter season. The long-term trend in CW frequency, CW days and CW duration is -0.36/decade, -0.62 days/decade and -0.37 days/decade respectively. These trends are statistically significant at 95% significance level.

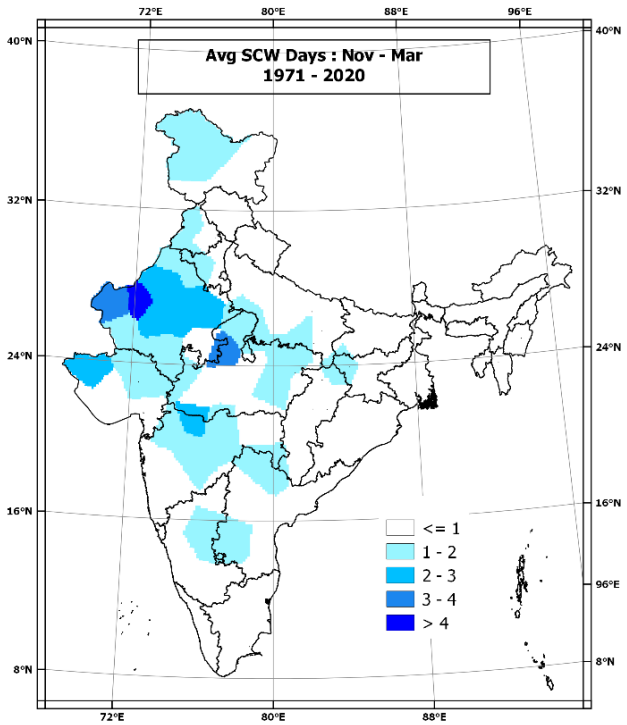



Fig. 3.2. c. Spatial distribution of Severe Cold Wave (SCW) days during November to March (After Smitha et al. 2016)

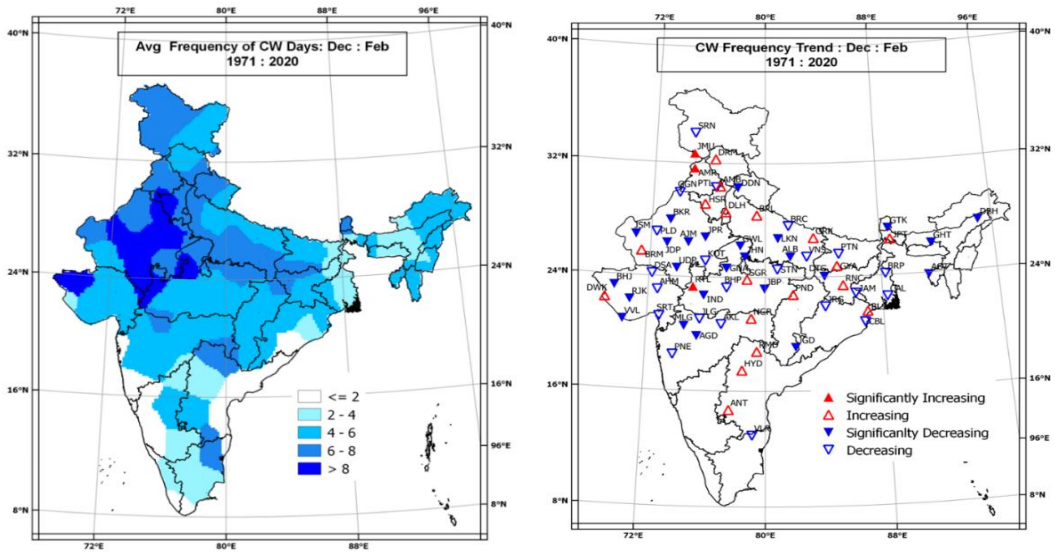



Fig 3.3. a) Seasonal climatology map of frequency of CW events, b) Long term trends in number of cold wave (CW) frequency during the cold weather season (DJF) during the period 1971-2020. Blue (red) colour shows decreasing (increasing) trends. The trends which are statistically significant at 95% significance level are shown as filled triangles (After Smitha et al., 2016)

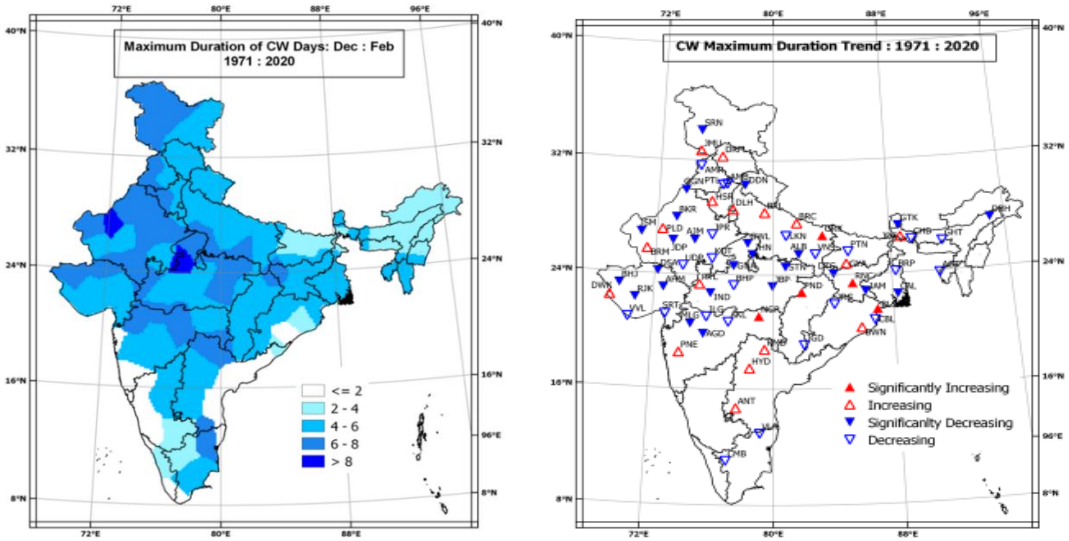
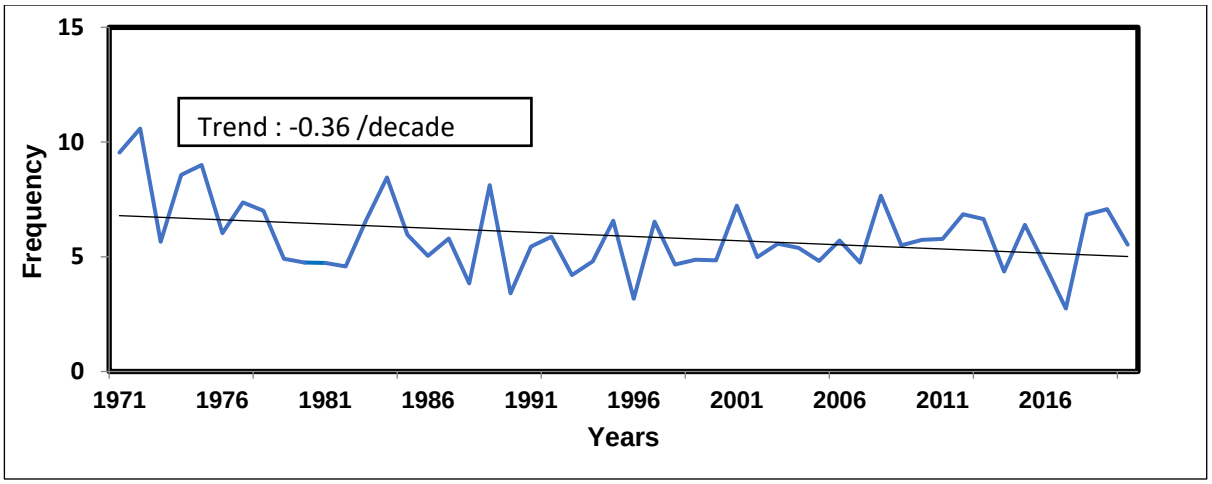
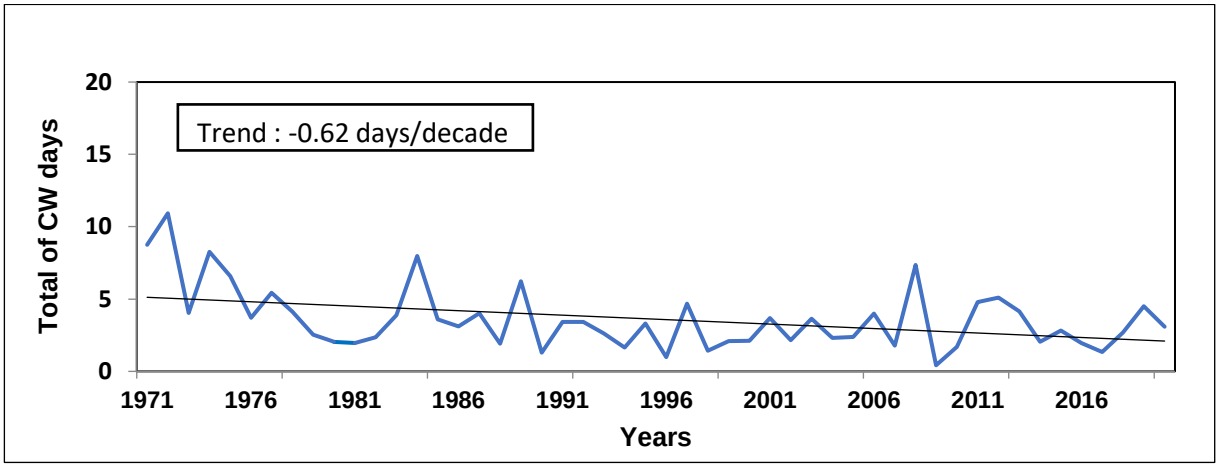



Fig 3.4 a. Seasonal climatology map of maximum duration of CW days during the cold weather season (December-February) b) Long term trends in maximum duration of CW days during the cold weather season (DJF) during the period 1971-2020. Blue (red) colour shows decreasing (increasing) trends. The trends which are statistically significant at 95% significance level are shown as filled triangles (After Smitha et al., 2016).



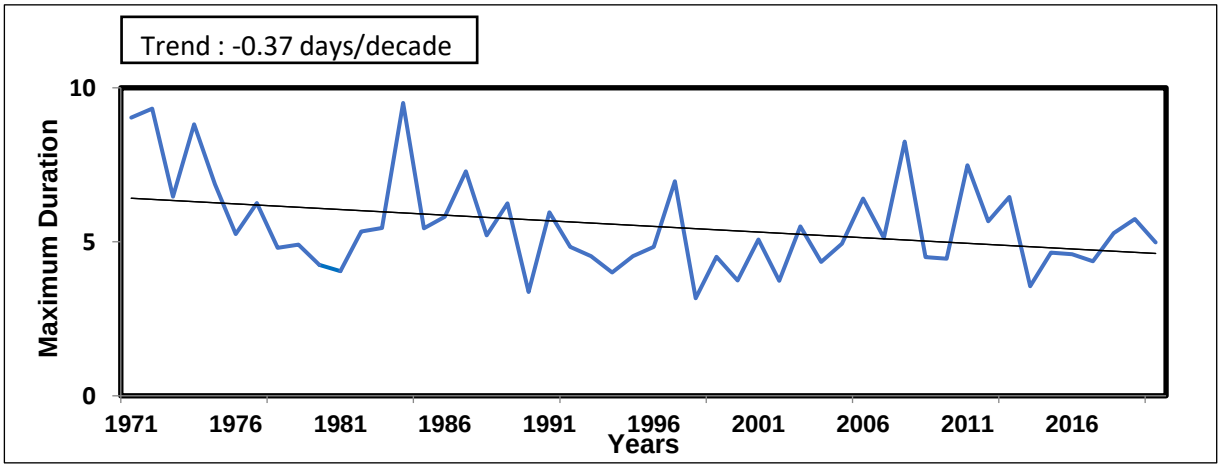
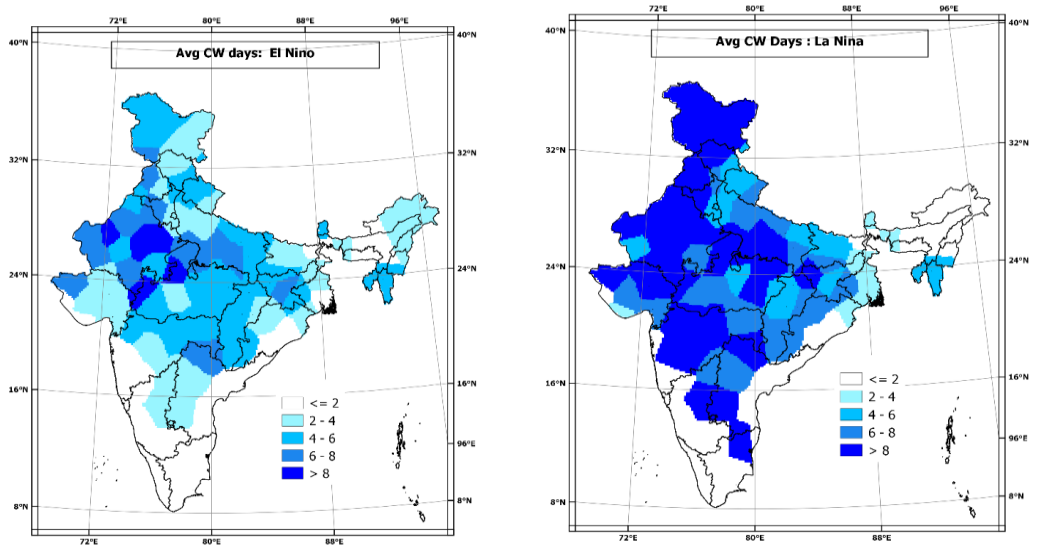



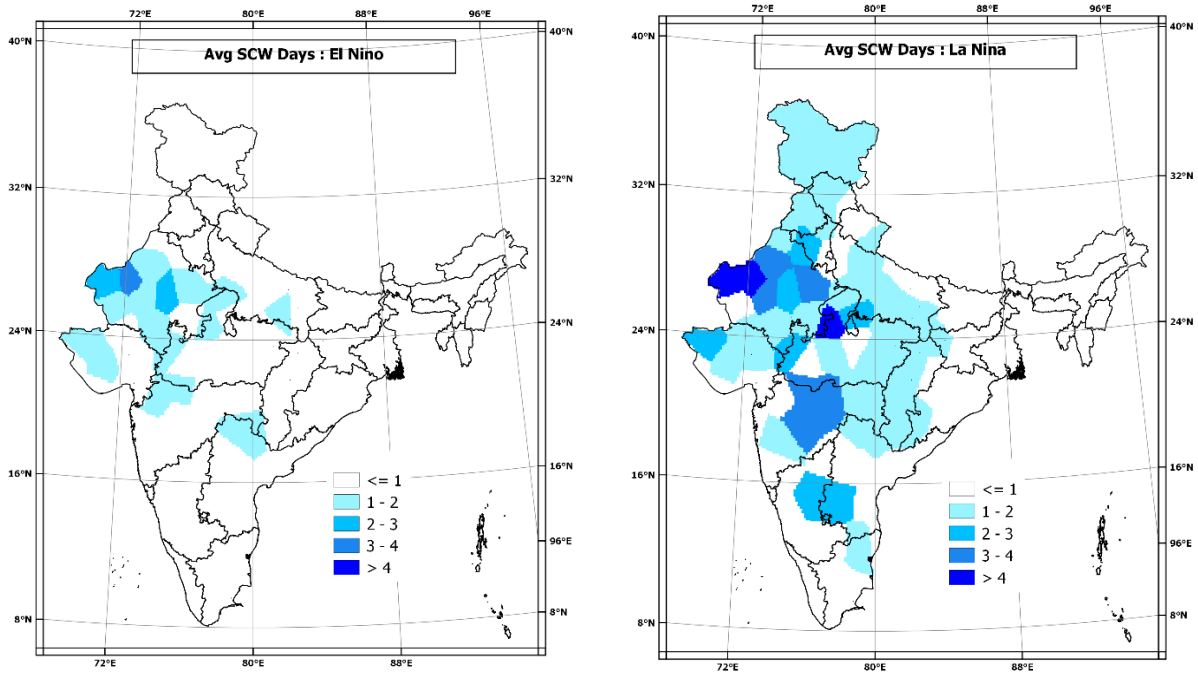

Fig. 3.5. Long term trends of a) frequency b) total of CW days and c) maximum duration averaged over the cold wave core for the period 1971-2020. (After Smitha et al., 2016).

Earlier studies (Pai et al. 2017 and Smitha et al. 2016) showed the relationship of occurrence of cold waves over India with the EL Nino and La Nina phases. To understand the impact of El Nino and La Nina on cold waves over India, composite spatial maps of mean CW days over India for El Nino/La Nina events are constructed. Fig. 3.6 a and b show the composite spatial maps of mean CW days over India for El Nino and La Nina events. These maps were prepared using data from 1971-2010. The composite map for El Nino shows a relatively lower frequency of CW days compared to the climatology map. However, the La Nina case shows that most areas experience significantly more CW days than the climatology, with large areas of the central and northwest India experiencing more than 8 CW days. An increase (decrease) in the frequency of SCW days [Fig. 3.7 a and b] was also observed over central parts of the country during the La Nina (El Nino) fall. Ratnam et al (2016 b) suggested that both ENSO phases (La Nina and El Nino) provide a favourable background for the occurrence of cold waves over India, however, more frequent in La Nina years. This aspect is further discussed later in the monograph.




(a) (b)

Fig 3.6 a) Average CW days during the El Nino years and b) Average CW days during the La Nina years. (After Smitha et al., 2016)




(a) (b)

Fig. 3.7 a) Average SCW days during the El Nino years and b) Average SCW days during the La Nina years (After Smitha et al., 2016)

Fig. 3.8 shows the duration of the longest CW period over each station across the country. The CW cycles with a duration of 10 days or more are shown in red. The stations with the longest CW periods of 10 days or more are in the north-west and central India. The station in Jammu and Kashmir experienced the longest duration of cold wave (18 days). Bikaner and Jodhpur in western Rajasthan experienced the longest CW period with a duration of 16 days. Gangtok in Sikkim experienced the longest CW period with 17 days (December 10 to 26, 1986). Even over Maharashtra, the maximum duration of CW days was more than 8 days. Most of the stations that experienced the longest CW period of 5 days or more are in North, Northwest and Central India. As mentioned earlier, there are no cold waves in the south of peninsular India.

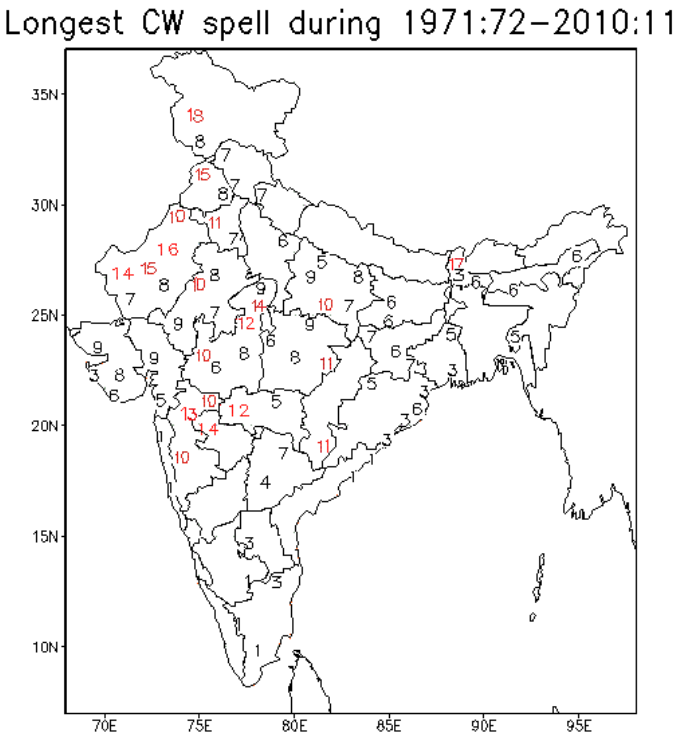



Fig. 3.8. Map showing the duration of the longest CW spell over each of the stations used in the study during the analysis period of 1971-2010. The duration of CW spells of 10 days or more are shown using red colour (After Smitha et al. 2016).

## 3.2 Cold Wave Statistics Based on Temperature Gridded data

In this section, the cold wave statistics based on gridded temperature data (area averaged over $1^0$X $1^0$ grids) is discussed. For this purpose, the IMD daily gridded temperature data (Srivastava et al., 2009) have been used. This analysis will provide us a different perspective about cold waves than the statistics based on IMD station data and IMD criteria.

For this analysis, December to February season is considered and the data from December 1970 to February 2021 have been used. The criteria considered for the analysis of cold wave and severe cold wave are given below:

A cold wave is considered if minimum temperature (Tmin) is less than $10^{th}$ percentile of daily climatological value and the climatological daily Tmin is less than

15°C. This condition should satisfy consecutively for three days to be considered as one cold wave event. Similarly, severe cold wave (SCW) is considered if daily Tmin is less than 5$^{th}$ percentile of daily climatological value and the climatological daily Tmin is less than 15$^0$C. It should be satisfied for three consecutive days to consider as one cold wave event. The period 1971-2000 was used as a reference period to calculate the climatology. The percentile has been calculated for a 5-day moving window.

Fig 3.9 shows the long term climatology of cold wave frequency, cold wave days (days) and cold wave intensity (°C) for the period 1971-2021, calculated using the above criteria. It is to be mentioned that the above criteria are based on departures from long term normal and not the actual minimum temperatures. To satisfy as a cold wave, the temperature departures should be more than this threshold (10$^{th}$ percentile).

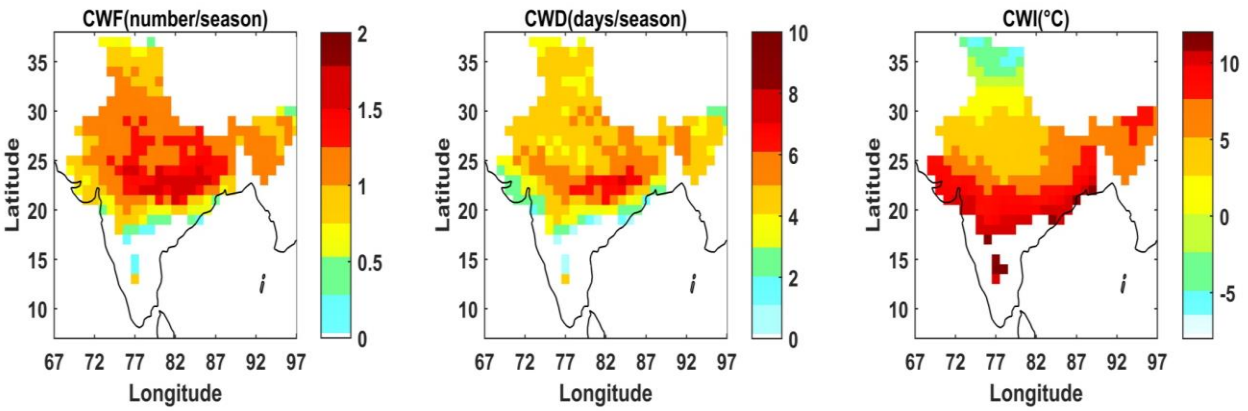



Fig 3.9 Climatology of a) CW frequency b) CW duration and c) CW Intensity based on the data of 1971-2021. The DJF season is considered for the analysis.

The greatest frequency of more than one event is observed over the northern parts of the country, north of 20$^0$N. In this region, more than 6 days of cold wave (CW) occur on an average. In some areas, the average number of CW days is also more than 8. The CW intensity is the lowest temperature measured during a CW event. In the extreme northern parts of the country, CW intensity is close to zero or below zero. With these criteria, no cold wave event is generally observed south of 20$^0$ N.

Fig. 3.10 shows the long-term climatology of severe cold wave frequency, severe cold wave days (days) and severe cold wave intensity ($^0$C) for the period 1971-2021. The maximum frequency of 0.5 SCW events is observed over the central parts of the country north of 20$^0$ N, which means that one event occurs every two years. In this region, an average of about 2 days of severe cold wave occurs. In some areas, the average number of CW days is also more than 8. The SCW intensity is the lowest temperature recorded during the SCW event. In the extreme northern parts of the country, the intensity of the cold wave is close to zero or below zero. With these criteria, no severe cold wave event is generally observed south of 15$^0$N.

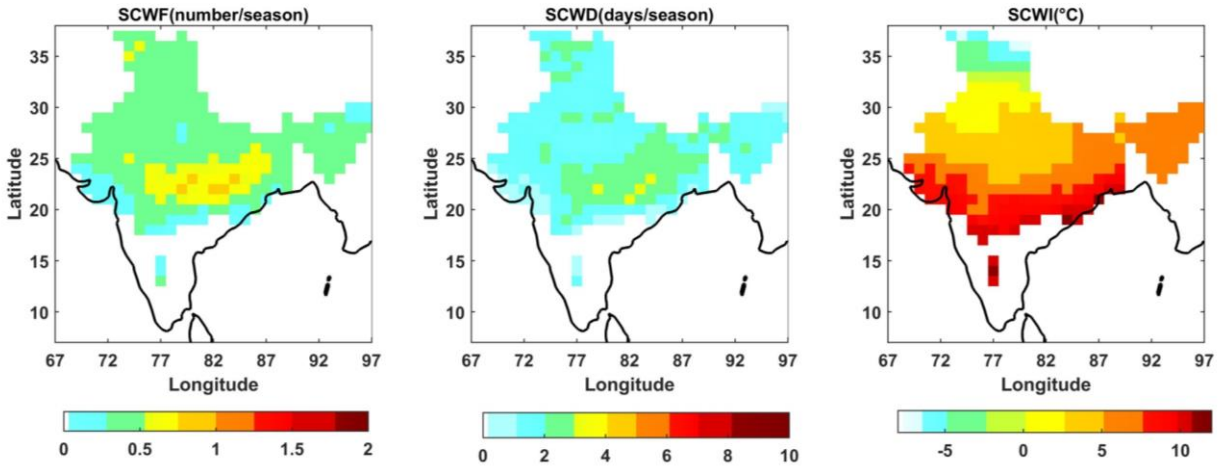



Fig 3.10 Climatology of a) SCW frequency b) SCW duration and c) SCW Intensity based on the data of 1971-2021. The DJF season is considered for the analysis.

Fig. 3.11 shows the long-term trends in CW frequency, duration and intensity for the period 1971-2021. These graphs show that the frequency and duration of CW is generally decreasing in most parts of northern India, except in Chhattisgarh, Jharkhand and Bihar, where a slight increase is observed. The declining trend is most pronounced in the north-western parts of the country where the duration of CW decreased by more than 1 day. However, this trend is also reflected in the spatial distribution of CW intensity. In most parts of north-western India, CW intensity is increasing, which means that the minimum temperatures observed during CW events are increasing. In the

north-eastern parts, especially over Bihar, the CW intensity decreases, which means that the lowest minimum temperatures decrease or, in other words, the CW events become harsher.

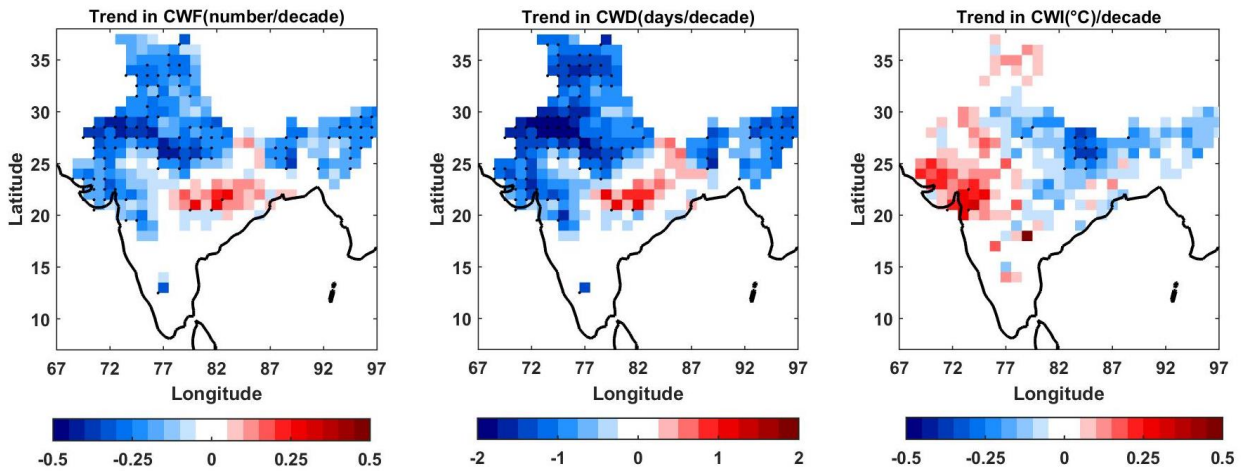



Fig 3.11 Trends of a) CW Frequency b) CW duration and c) CW Intensity. The trends are in decade. The data of 1971-2021 have been used to calculate these trends.

Fig. 3.12 shows the time series of a) frequency of cold waves and b) duration of cold waves over the period 1971-2020. The red line shows the linear trend and the dashed lines on either side of the trend line indicate the 95% confidence levels. The time series is averaged over a larger area: $72.5^0$ E-$87.0^0$ E, $20.5^0$ N-$37.5^0$ N. Both time series show a decreasing trend that is significant at the 95% significance level. The trend in frequency is 0.15 per decade and the trend in duration is 0.81 days per decade. The trend based on the IMD criteria (Fig. 3.5) for frequency is slightly higher than this trend value. However, the trend for duration is lower than the trend obtained from the gridded data. This could be due to the slight differences in the criteria used to define cold waves. While the IMD analysis used station data, the present analysis is based on area-averaged gridded data. However, both data sets show a very clear downward trend in CW frequency, days and duration, suggesting that the recent increase in minimum temperatures is leading to a decrease in the characteristics of cold waves over India.

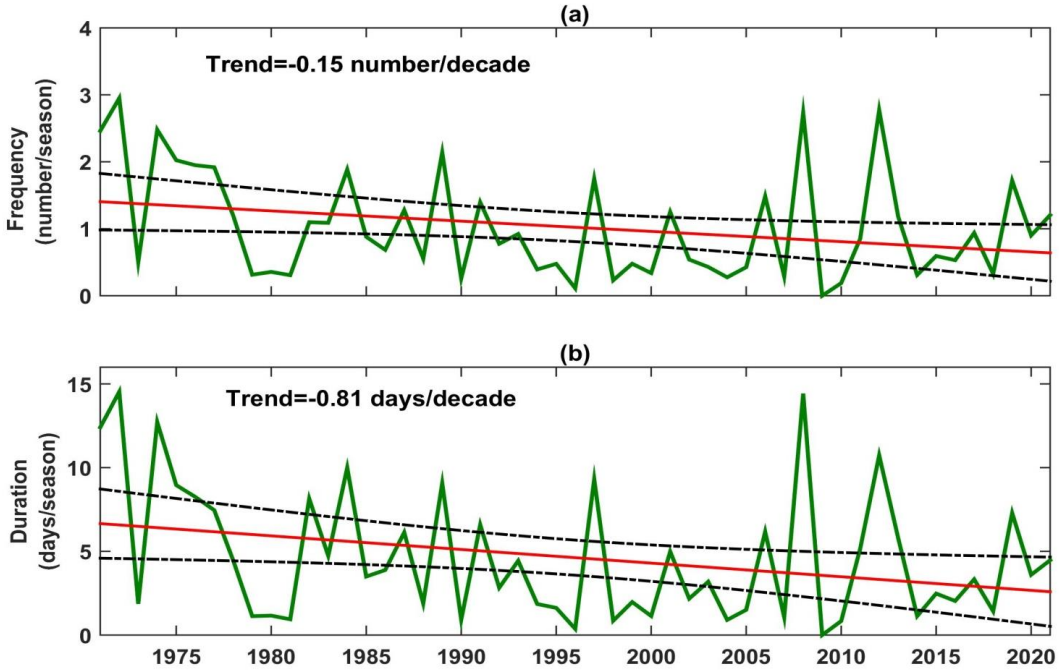



Fig 3.12. Time series of a) Cold Wave frequency and b) CW duration during 1971-2020. The red line shows the linear trend and dotted lines suggest 95% confidence level. The time series is averaged over a larger area $72.5^0$ E-$87.5^0$ E, $20.5^0$ N-$37.5^0$ N**.**

A further analysis is carried out to see the spatial pattern of ocean influence on cold waves. Fig. 3.13 shows the spatial pattern of correlation between cold wave duration and sea surface temperature (SST) using data from 1971-2020. SST data from HADI SST was used for this analysis. The spatial pattern shows very clearly that cold wave duration is negatively correlated with SST over the equatorial Pacific and Indian Oceans, suggesting that the La Nina phase of ENSO and the colder Indian Ocean cause more days of CW duration. The same type of conclusion was drawn by Smitha et al. (2016) using IMD data and IMD cold wave criteria. Ratnam et al. (2016 b) suggests that both La Nina and El Nino phases can cause cold waves. They referred to them as Type 1 and Type 2 events respectively. However, the Type 2 cold wave events that occur during the El Nino years are less frequent and only affect the northern parts of the country.

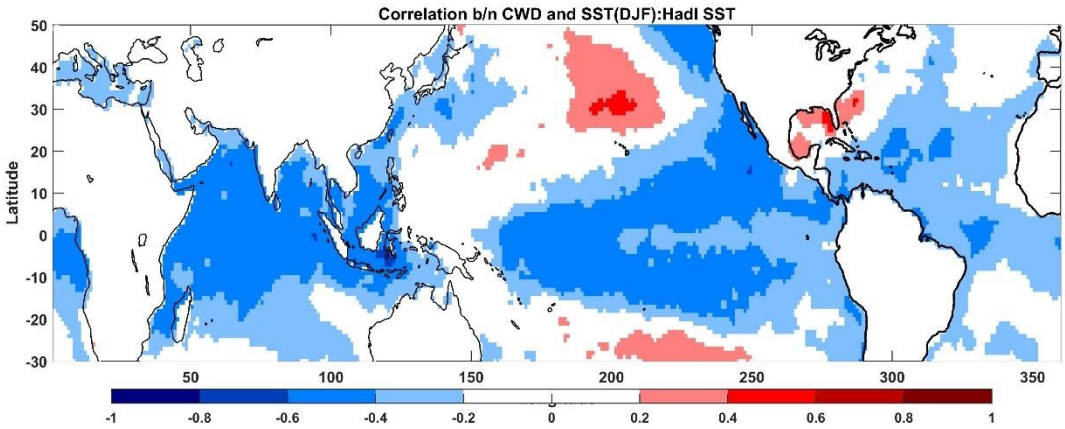



Fig 3.13. Correlation between Cold Wave Duration and Sea Surface Temperature (SST) during the DJF season. Period of data: 1971-2020.

Further, a list of CW events which persisted for more than 5 days is prepared using the 90$^{th}$ percentile criteria. For this purpose, data of 1971-2020 was used. Cold Wave events are calculated using area averaged minimum temperatures over the cold wave core zone (72.5$^0$ -82.5$^0$ E, 20.5$^0$ -35$^0$ N). The criteria for identifying the cold wave events are as follows:

1) Daily Tmin is less than the 10$^{th}$ percentile of daily climatological value and the climatological daily Tmin < 15$^0$C.
2) The cold wave event should persist with minimum duration of 5 days.

Table 3.1 shows such CW events that occurred during the period 1971-2020. The intensity suggests the lowest minimum temperature observed during the event. The longest cold wave event observed was 10 days during 01-10 December 1971. There are many cold wave events with 8 days of duration. The lowest Tmin recorded during the CW events was 0.93$^0$C during February 1974. On average duration of CW is 6 days. Table 3.1 also clearly suggests the cold wave frequency is decreasing during the recent years. During the decade 2011-2020, only six cold wave events were observed.

**Table 3.1**

List of cold wave events during the period 1971-2020

as per the 90th Percentile criteria based on IMD gridded data set

| Year | Date | Intensity (ºC) | Total Duration (Days) |
|---|---|---|---|
| 1971 | 1 Dec-10 Dec | 4.74 | 10 |
| | 29 Jan-02 Feb | 3.43 | 5 |
| 1972 | 6 Jan-12 Jan | 2.97 | 7 |
| | 14 Feb-20 Feb | 2.35 | 7 |
| 1974 | 5 Feb-10 Feb | 0.93 | 6 |
| 1975 | 19 Dec-25 Dec | 3.34 | 7 |
| 1976 | 8 Dec-13 Dec | 3.74 | 6 |
| 1982 | 12 Dec-16 Dec | 4.43 | 5 |
| 1983 | 01 Feb-06 Feb | 3.49 | 6 |
| 1984 | 21 Feb-28 Feb | 3.17 | 8 |
| 1985 | 18 Dec-25 Dec | 3.46 | 8 |
| 1986 | 04 Jan-08 Jan | 2.43 | 5 |
| 1989 | 10 Jan -15 Jan | 2.22 | 5 |
| | 19 Feb-23 Feb | 5.02 | 5 |

| | | | |
|---|---|---|---|
| 1991 | 01Jan-06 Jan | 1.45 | 6 |
| 1993 | 20 Jan-24 Jan | 2.87 | 5 |
| 1994 | 21 Dec-25 Dec | 4.43 | 5 |
| 1997 | 8 Dec-14 Dec | 3.09 | 7 |
| 2006 | 12 Dec-19 Dec | 3.98 | 8 |
| 2008 | 21 Jan-28 Jan | 2.43 | 8 |
| | 09 Feb-15 Feb | 2.48 | 7 |
| 2011 | 18 Dec-22 Dec | 4.48 | 5 |
| | 5 Jan-11 Jan | 2.72 | 7 |
| 2012 | 10 Jan-14 Jan | 2.95 | 5 |
| 2013 | 05 Jan-09 Jan | 1.91 | 5 |
| 2019 | 26 Dec-31 Dec | 2.96 | 6 |
| 2020 | 27 Dec-31 Dec | 2.92 | 5 |