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Climatology and trend of cold waves over India during 1971-2010

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सार – पिछले 40 वर्षों में सर्दी के मौसम (नवंबर से मार्च) के दौरान भारतीय भू-भाग के 86 स्टेशनों से प्राप्त हुई शीत लहर (CW) की जानकारी का उपयोग करते हुए जलवायु विज्ञान जैसे शीत लहर (CW) और भीषण शीत लहरों (SCW_S) के विभिन्न आंकड़ों के पहलुओ के रूझानों की जांच की गई है। ENSO अवस्थाओं (ला निना और एल निनों) के साथ शीत लहर / भीषण शीत लहर के संबंध की भी जांच की गई है। यह देखा गया है कि भारत के उत्तर, उत्तर पश्चिम, पूर्व और मध्य भारत के स्टेशनों को शीत लहर क्षेत्र / भीषण शीतलहर की आवृति सबसे अधिक रही जिसमें जनवरी के महीनें में सबसे अधिक रही। एल निनों (ला निना) वर्षों के दौरान जलवायविक उनके मानों की अपेक्षा शीत लहर/ भीषण शीत लहर दिन स्थानिक कवरेज और बारम्बारता में उल्लेखनीय कमी (बढ़ोतरी) देखी गई। अधिकांश स्टेशनों के सी डब्ल्यू / एस सी डब्ल्यू दिनों में उल्लेखनीय कमी के रूझान देखे गए है। सी सी जेड के सी डब्ल्यू / एस सी डब्ल्यू दिन प्रतिदशक में हाल ही के 1991-2000 और 2001 से 2010 के दशकों के दौरान सी सी जेड में उल्लेखनीय कमी दिखी है। पूरे विश्व के सबसे गर्म दशकों से यह मेल खाते है। इस शोध पत्र के अध्ययन के कुछ वर्षों के दौरान तीव्र और सतत सी डब्ल्यू / एस सी डब्ल्यू घटनाओं से जुडे मनुष्यों की मार्टेलिटी का पता चलता है।

ABSTRACT. Using Cold Wave (CW) information of 86 stations from Indian main land during the cold weather season (November to March) for the last 40 years (1971-2010), various statistical aspects of cold waves (CWs) and severe cold waves (SCWs) such as climatology and trend were examined. The link of CWs/SCWs with ENSO phases (La Nina & El Nino) was also examined. It was observed that many stations from north, northwest, east and central India together named as core CW zone (CCZ) experienced highest number of CW/SCW waves with relatively higher frequency during January. Noticeable decrease (increase) in the frequency and spatial coverage of CW/SCW days compared to their climatological values were observed during the El Nino (La Nina) years. There were significant decreasing trends in the CW/SCW days over most of the stations from CCZ. The total number of CW/SCW days/per decade over CCZ showed noticeable decrease during the recent decades 1991-2000 and 2001-2010, which coincided with the warmest decades for the country as well as for the globe. Associated with intense and persistent CW/SCW events, large human mortality were reported during some years of the study period.

Key words – Cold waves, Trend, Climatology, ENSO, Cold core zone.

1. Introduction

The globally averaged combined land and ocean surface temperature over the period 1880 to 2012, has shown a warming of 0.85 °C with both averaged maximum and minimum temperatures showing increase since 1950 (IPCC, 2013). As a result, the numbers of cold days and nights have decreased and the number of warm days and nights has increased globally since about 1950. In India, the minimum temperature has steadily increased since 1991 and the rate of its rise is slightly more than maximum temperature during winter season (Attri and Tyagi, 2010; Rathore *et al.*, 2013). The heat and cold waves are one of the less known forms of extreme weather as they are not visible as other forms of severe weather. However, these abnormal temperature events can impose severe physiological stress on the human body, as the body operates best within a fairly normal temperature range. There is a marked relationship between human mortality and thermal stress. During unusually cold/hot episodes, deaths from different causes can rise significantly with the elderly at greater risk than others (WMO/WHO/UNEP, 1996).

In this study, our focus is only on cold waves (CWs), which signify certain amount of fall of temperature at a station with respect to normal climatological value. In India, cold wave (CW) conditions are generally experienced during the period from November to March in association with the incursion of cold winds into northwest and central India as a result of passage of western disturbances (WDs) over the region. WDs are transient disturbances in the mid latitude westerlies and are followed by occurrence of cold waves mostly over the areas north of 20º N and rarely in areas south of this latitude. There have been many earlier studies that examined different climatological features of CWs in India (Bedekar *et al.*, 1974; Subbaramayya and Surya Rao, 1976; Chaudhury *et al.*, 2000; De and Sinha Ray, 2000; De *et al.*, 2005; Pai *et al.*, 2004). Most of these studies have used threshold criteria based on minimum temperature anomalies to define the CWs. Pai *et al.* (2004) using daily sub-division scale CW information over all the meteorological sub-divisions of India (country was divided into 35 meteorological sub-divisions by IMD at that time) for the period 1971-2000 derived based on the departure in the minimum temperature, examined the decadal changes in the various characteristics of sub-division wise CWs over the country.

In the present study, the main objective was to use station wise CW information from a network of uniformly distributed stations to examine the climatology and trends of various features such as the frequency, persistency and spatial coverage of CWs over India. In addition, decadal variation of CW features and human mortality associated with the CW events have also been examined. As the ENSO phenomena in the Pacific is known to impact weather and climate over various parts of the world, the changes in the observed frequencies in CWs associated with both the ENSO phases (El Nino and La Nina) have also been examined.

2. Data used and methodology

The CW/SCW information was derived using the daily minimum temperature data from 86 stations uniformly distributed over the country for the cold weather season (November previous year to March of reference year) for the 30 years period of 1971-2010, *i.e.*, a cold weather season of a reference year (say 1971) implies period from November 1970 to March 1971. Fig. 1 shows the locations of these stations on the India map along with sub-division boundaries.

Out of the total 86 stations, 80 stations had daily minimum temperature data available for at least 90 percentage of the total number of days during the period. Adequate care has been taken in ensuring the homogeneity of the data. Any outliers in the data were identified as those daily minimum temperature values

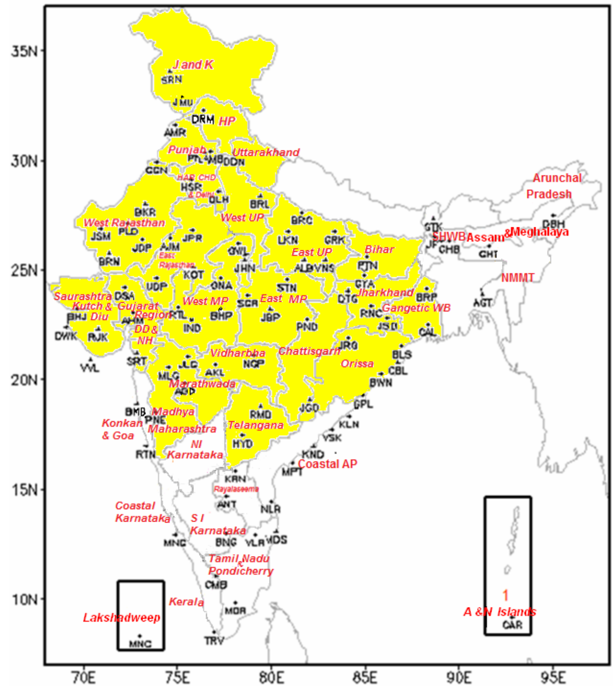


Fig. 1. Locations of 86 stations used in this study. Boundaries of the 36 meteorological sub-divisions of the country are shown in the map along with the sub-division names. The yellow shaded portion represents the core cold wave zone (CCZ)

TABLE 1

Definition for CW used in this study.

Criteria*		Condition is declared as
When normal minimum temperature is	Departure from normal	
≥ 10 ºC	-5 ºC to -6 ºC	Cold wave (CW)
	≤ -7 ºC	Severe cold wave (SCW)
< 10 ºC	-4 ºC to -5 ºC	Cold wave (CW)
	≤ -5 ºC	Severe cold wave (SCW)

* For Coastal stations whenever minimum temperature reaches 10 ºC or less "Cold wave" may be declared

which are greater/less than its mean by ± 3 times the standard deviation of the corresponding day. Abnormally large difference in the minimum temperature between two consecutive days in the data set were scrutinized by taking current weather into consideration and were accordingly assimilated into the data. The daily station temperature data for the period 1971-2010 which is readily available in the electronic format were obtained from the National Data Center (NDC) of IMD, Pune.

The criteria used in this study for defining CW are given in Table 1. It is seen in Table 1 that the CW/SCW conditions signify certain amount of rise of daily minimum temperature at a station with respect to respective normal climatological value. As seen from Table 1, relatively more intense CW is classified as severe CW or SCW. In order to derive the station wise CW/SCW information, at first, daily normals of minimum temperature for all of the stations were computed for all the days of the cold weather season using all the data available for the period 1971-2000. Using these daily normal minimum temperature data, daily anomalies were computed and using the criteria given in Table 1, days that satisfied the CW/SCW conditions for each station were identified. This formed the basic information for examining various climatological features and trends in the CW/SCW conditions over India in this study. The climatological features of CW/SCW days were examined by preparing monthly and seasonal (November-March) maps of mean number of CW/SCW days. For this purpose, data for the entire data period (1971-2010) were used. The climatological features of the duration of station wise longest CW/SCW days /spell were also examined.

To examine the link between El Nino/La Nina and spatial distribution of the CWs over India, composite spatial maps of mean number of CW (including SCW) days during the cold weather season (November -March) were prepared for El Nino and La Nina years. In this study, El Nino / La Nina years were defined using criteria similar to that used by Climate Prediction Center (CPC), NOAA, USA (http://www.cpc.noaa.gov). For defining El Nino/ La Nina, CPC uses a threshold of +/- 0.5 ºC for the Oceanic Nino Index (ONI) [3 month running mean of ERSST.v3b Sea surface temperature (SST) anomalies in the Nino 3.4 region (5° N - 5° S, 120° - 170° W)] and the event is declared when the threshold is met for a minimum of 5 consecutive over-lapping 3 month seasons. However in this study, a reference year was classified as an El Nino/La Nina year, when at least 2 of the 3 overlapping seasons during the period November of previous year to March of reference year is part of the 5 consecutive overlapping seasons mentioned earlier. Accordingly, during the period 1971-2010, there were 13 El Nino years (1973, 1977, 1978, 1983, 1987, 1988, 1992, 1995, 1998, 2003, 2005, 2007 & 2010) and 13 La Nina years (1971, 1974, 1975, 1976, 1985, 1989, 1996, 1999, 2000, 2001, 2006, 2008 & 2009).

For examining trends in the station wise CW/SCW days, at first the presence of a monotonic increasing or decreasing trend was tested with the nonparametric Mann-Kendall test and secondly the slope of a linear trend was estimated with the nonparametric Sen's method (Gilbert, 1987). These methods are used here in their basic forms; the Mann-Kendall test is suitable for cases where the trend may be assumed to be monotonic and thus no seasonal or other cycle is present in the data. The Sen's method uses a linear model to estimate the slope of the trend and the variance of the residuals should be constant in time. These methods offer many advantages that have made them useful in analyzing atmospheric data.

As will be seen at the end of this study, among all stations, stations from the combined region [hereafter called core CW zone (CCZ)] of north, northwest, east and central India are most prone for CW/SCW events. The CCZ consists of 22 Met. Sub-divisions (shown as yellow shaded in Fig. 1) and includes 63 stations used in this study. This study has also examined the year to year variation and trends in the total number of CW/SCW days/ season over CCZ. The average number of CW/SCWs experienced by all the 63 stations from CCZ region was computed. The trend and the year to year changes in the number of stations from CCZ, which are affected by CW/SCW events was examined to study the changes in the area coverage of CW/SCW events.

The data regarding human mortality related to the CW/SCW events used in this study were collected from reports of Disastrous weather events published by the India Meteorological Department and various media reports.

3. Results

3.1. *Spatial distribution of mean CW/SCW days*

Fig. 2 show the spatial variation of mean number (frequency) of CW & SCW days during the cold weather season (NDJFM) over the country expressed as days per season. It is seen (Fig. 2) that most of the areas except Kerala and coastal Andhra Pradesh have experienced on an average 2 CW days or more per season with many areas over Northwest and some parts of Central India experiencing 8 or more number of CW days. At the same time, 1-3 SCW days were mainly experienced over most areas of Rajasthan, Gujarat, Punjab, west Madhya Pradesh, some parts of J & K, Maharashtra, Telangana, Chhattisgarh, Haryana, Jharkhand and southern parts of Uttar Pradesh.

Month wise distribution of CW days [Figs. 3(a-e)] during November shows more than or equal to 2 average CW days were mainly experienced by most parts of Maharashtra and some parts of Rajasthan, Telengana, North Interior Karnataka, Chattisgarh and northern parts of Rayalseema and south Interior Karnataka. During December, 2 CW days or more were mainly experienced by most parts of Rajasthan and some parts of west J & K, west Madhya Pradesh, Punjab and Gujarat. During January, CW days of 2 or more were experienced by

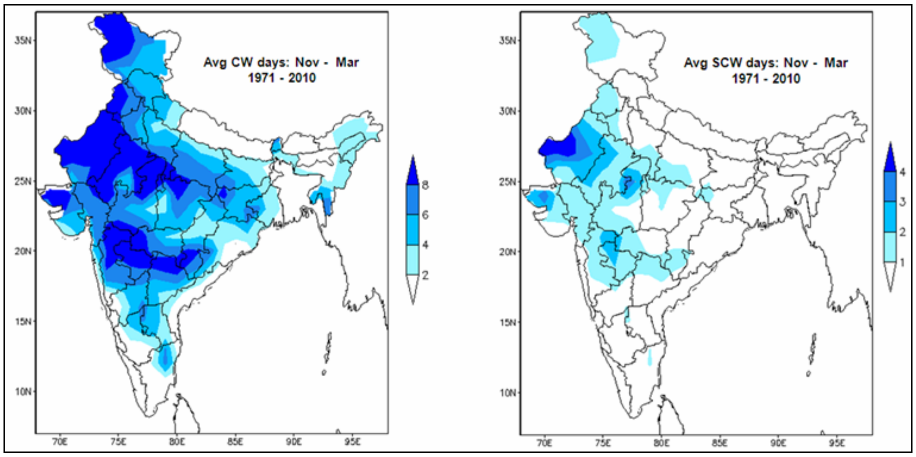
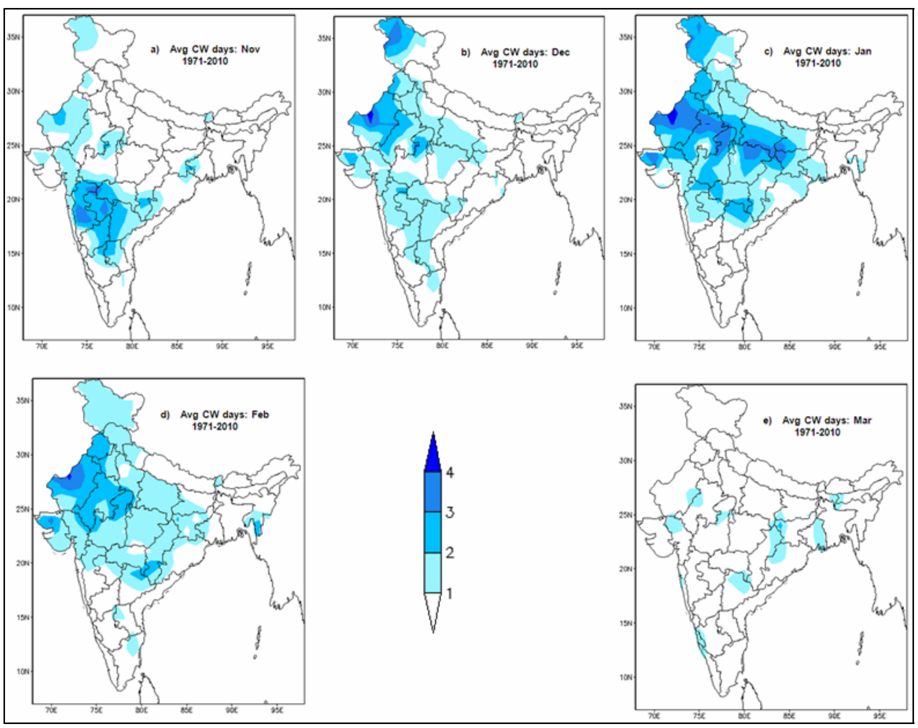


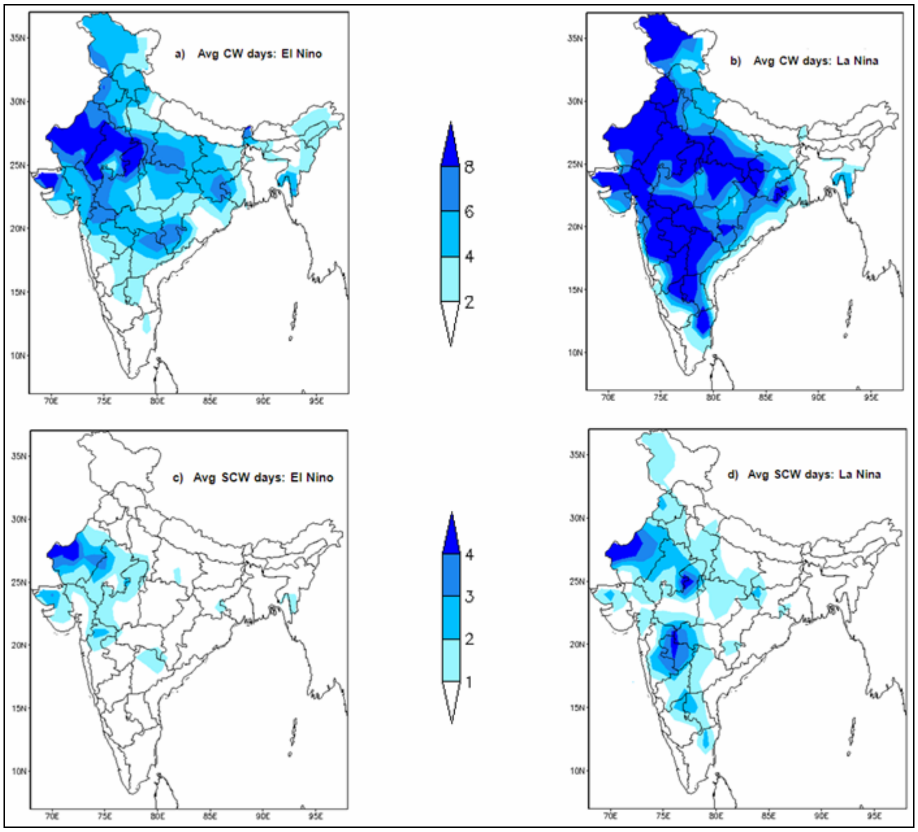
Fig. 2. Seasonal climatology map of number of CW/SCW days during the cold weather season (November-March). The climatology was computed by averaging the number of CW/SCW days for the period (1971-2010)



Figs. 3(a-e). Monthly climatology maps of number of CW days for the 5 months of November to March. The climatology was computed by averaging the number of CW days for the period (1971- 2010)

many parts of Punjab, Rajasthan, Madhya Pradesh, Uttar Pradesh and some parts of J&K, Maharashtra, Jharkhand, Gujarat, Saurashtra & Kutch and Bihar. During February, 2 CW days or more were seen at most places of Punjab and Rajasthan and some places of West MP, Chattisgarh and Nagaland, Manipur, Mizoram and Tripura. In March only some parts of Jharkhand experienced a few days of CW days of more than or equal to 2 days on an average. Among the 5 months of the season, average number of CW days experienced and spatial coverage of CWs were relatively more during the month of January.

Month wise, SCW days were experienced mainly during January and February (about 1-2 days in an average & mostly over northwest India).



Figs. 4(a-d). Composite maps of average number of CW/ SCW days during the cold weather season (November-March) over India for the El Nino case (13 years) and the La Nina case (13 years)

The decade wise spatial distribution and frequency of season average of CW days showed (figures not presented) overall decrease in the average CW days over the country going from 1971-1980 to 1991-2000 with systematic and noticeable decrease over northwest and northeast India. However, during recent decade (2001-2010) there was slight increase in the area of coverage and frequency of CW days compared to the previous decade (1991-2000).

3.2. *ENSO and CW days*

The composite spatial maps of mean CW days over India for the El Nino and La Nina cases are given in Figs. 4(a&b). The composite map for El Nino shows relatively reduced frequency of CW days as compared to the climatology map (Fig. 2). However, the La Nina case shows that most of the areas have experienced significantly more number of CW days than the climatology with large areas of CCZ experiencing more than or equal to 8 CW days. Thus the areas of 8 CW days or more on an average was maximum during La Nina case and minimum during the El Nino case. In the case of SCW also [Figs. 4(c&d)], increase (decrease) in the frequency of the SCW days were observed over central parts of the country during La Nina (El Nino) case.

3.3. *Persistency of CW/SCW events*

For most of the stations, though the duration of the most frequent CW/SCW spells are of about 1-2 days, some individual CW/SCW spells lasted for very long period (10 days or more/5 days or more) over some stations. Fig. 5 shows the duration of the longest CW spell over each of the stations over the country. The CW spells of duration 10 days or more are shown in red. It is seen that stations that experienced longest CW spells of duration 10 days or more , mainly pertains to northwest and central India with Bikaner and Jodhpur from West Rajasthan experiencing the longest CW spell of duration of 16 days. However Gangtok from Sikkim has experienced the longest CW spell of 17 days (10-26 December, 1986).

In case of SCW (figure not given), most of the stations that have experienced the longest SCW spell of duration 5 days or more are from north, northwest and central India.

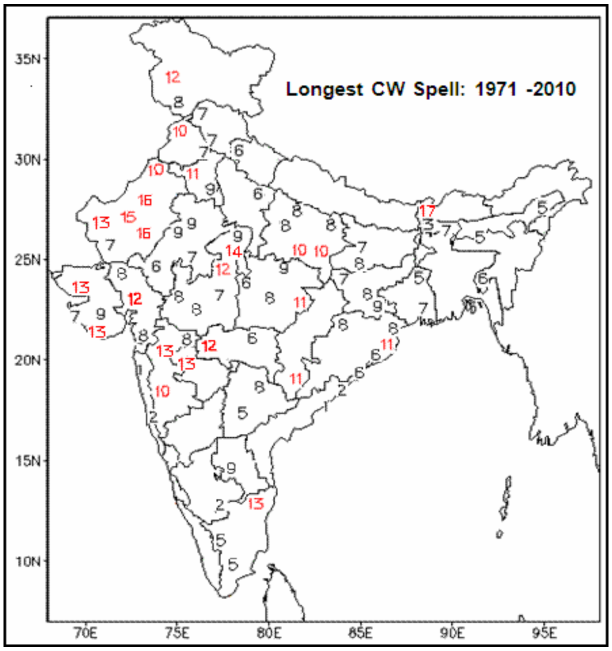
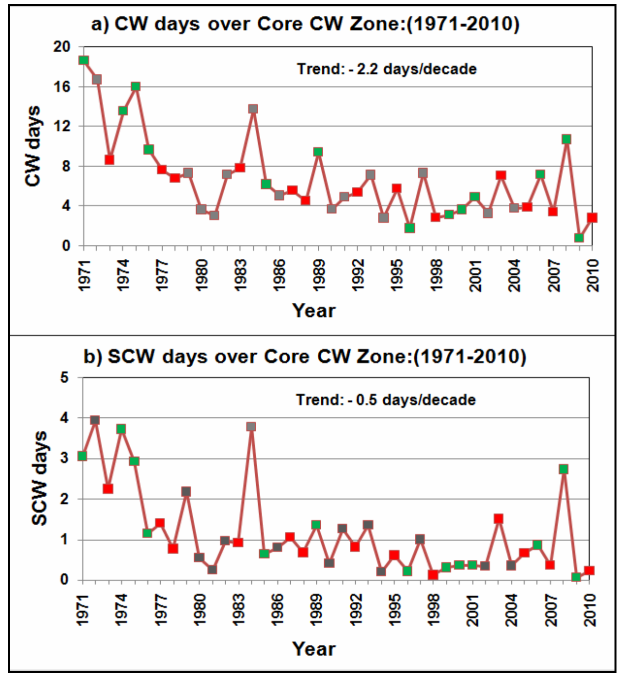


Fig. 5. Map showing the duration of the longest CW spell over each of the stations used in the study during the analysis period of 1971-2010. The duration of CW spells of 10 days or more are shown using red colour



Figs. 6(a&b). The year to year variation of core cold wave zone (averaged over all the stations) (a) CW days and (b) SCW days for the period 1971-2010. The red (green) markers correspond to El Nino (La Nina) years

3.4. *CW/SCW features of CCZ*

Figs. 6(a&b) show the year to year variation of the average CW days and SCW days over CCZ for the cold weather season (November - March) for the period 1971-2010. Red (green) markers are used for the El Nino (La Nina) years. The CCZ CW (SCW) days in a season was computed as the average of the CW (SCW) days experienced in all the stations in that season. The mean number of CW (SCW) days in CCZ for the period 1971-2010 is 421 (73) days. As seen in Figs. 6(a&b), time series of both CW and SCW days show significant (at ≥5%) decreasing trend. It may be mentioned, on analyzing the trends in the station wise CW and SCW days, it was found that 57 stations out of 63 stations from the region showed negative trends with trends of 39 stations being statistically significant at ≥5%. In the case of SCW days, 47 stations showed negative trend out of which 18 were statistically significant at ≥5% level. It may also be added that significant increasing trends were also observed in the station wise season averaged minimum temperature in majority of the stations from the region (57 out of 63 stations). This clearly indicates that the decreasing trend in the CW/SCW days in the region was caused by the increasing trends in the minimum temperature.

Analyzing the year to year variation of the number of stations from CCZ affected by the CW (SCW) during the season for the period 1971-2010 (figures not shown) showed that on an average around 48(20) out of 63 stations used in the study got affected by CW (SCW). Highest (63) number of stations affected by CWs was in 2003 and lowest (14) number of stations affected by CWs were in 2009. Highest (47) and lowest (2) number of stations affected by SCWs were during the years 1984 and 2009 respectively. A significant decreasing trend was seen in the number of stations affected by the CWs & SCWs.

It was also seen that during 9 (10) of the 13 El Nino years, the number of CW (SCW) days over CCZ were below its climatological value. On the other hand during 7 (5) of the 13 La Nina years, the number of CW (SCW) days over CCZ were above its climatological value. This clearly indicates inverse association between CW events and ENSO phases. This inverse association is further visible in Fig. 7 which shows the annual variation of the Correlation Coefficient between monthly NINO3.4 SST anomaly and CW days over CCZ during the cold weather season for the period 1971-2010. Fig. 7 also shows the Correlation Coefficient between monthly NINO3.4 SST anomaly and station minimum temperatures averaged over CCZ. As seen there is positive association between the minimum temperatures averaged over CCZ and NINO3.4 SST anomaly indicating that the increase (decrease) in the CW days of CCZ during La Nina (El Nino) years were

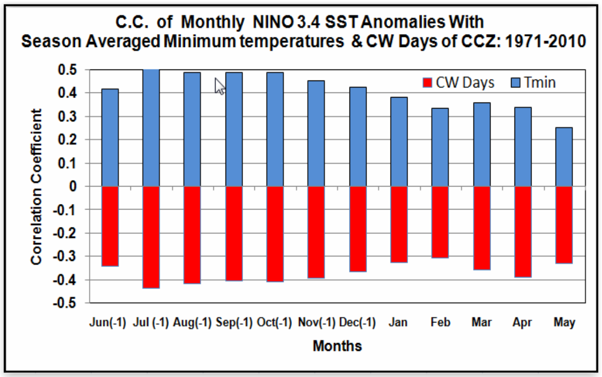


Fig. 7. Correlation coefficient of monthly NINO 3.4 SST anomalies with season averaged minimum temperatures and CW days of CCZ for the period 1971-2010

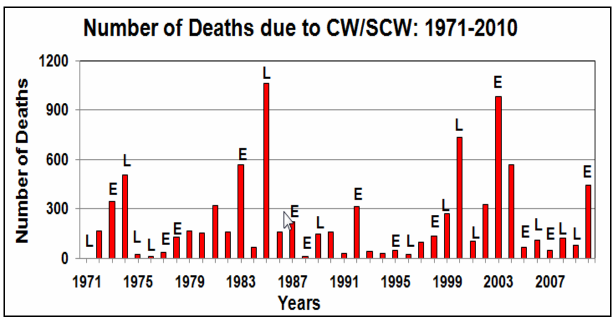


Fig. 8. Number of deaths reported in India annually in association with CW/SCWs for the period 1971-2010. The data was collected from media reports and IMD's reports on annual disaster weather events. The vertical bars corresponding to EL Nino (La Nina) years are labeled as E (L)

due to the decrease (increase) in the station wise minimum temperatures over the region. This result is also in line with the findings of Kothawale *et* al. (2010), who have shown that there is a decrease (increase) in the maximum and minimum temperatures during the winter that coincides with the peaking of La Nina (El Niño) episodes. It may be noticed that in this study the El Nino / La Nina year by definition is the year during which this phenomena peaks.

On examining the composite spatial maps of mean CW days over CCZ for the El Nino and La Nina years (figures not presented) it was seen that during the El Nino case, the areas of average number of eight or more CW days were restricted to northwest India compared to the climatological distribution (Fig. 2). On the other hand, in the La Nina case, the areas of average number of CW days of 8 or more extended southward over parts of north, east and central India compared to the climatological distribution.

3.5. *Human mortality associated with the CW/SCW*

Fig. 8 shows the loss of human lives due to cold waves in India during the period 1971-2010. Highest number (1061) of deaths related to CW was reported in 1985 followed by 2003. As seen in this figure, no noticeable trend is visible in the time series. However, the decade (1981-1990) registered the highest number of deaths due to cold wave events compared to the other 3 decades. In winter the smog and fog caused by heavy vehicular and factory emissions, block the sunlight and lower the day time temperature, thus aggravating the discomfort from cold waves.

4. Conclusions

From the examination of various features of the CW (SCW) events from 86 stations uniformly distributed over the country for the last four decades (1971-2010) we can make the following conclusions.

(*i*) During the cold weather season (November to March) many stations from north, northwest, east and central India together named as Core CW Zone (CCZ) experienced highest number of CW/SCW waves with relatively higher frequency during January. Noticeable decadal variation was observed in the frequency, spatial coverage, and persistency of the CW/SCWs days. A decrease in the frequency, spatial coverage and persistency of the CW/SCW days were observed during recent 2 decades (1991-2000 and 2001-2010) compared to previous two decades.

(*ii*) An association between the occurrence of the extreme temperature events (CW/SCW) and ENSO phases was observed. Noticeable decrease (increase) in the frequency and spatial coverage of CW/SCW days compared to their climatological values were observed during the El Nino (La Nina) years over the regions that generally experience these extreme events.

(*iii*) Significant decreasing trends were observed in the frequency and spatial coverage of the CW/SCW days over CCZ. This was caused by the significant decreasing trends in the CW/SCW days of majority of the stations from the region which in turn was caused by the significant increasing trends in the season averaged minimum temperatures of these stations.

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