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Impact of El-Niño-Southern Oscillation (ENSO) on extreme temperature events over India

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सार – **इस शोध पत्र में हमने भारत में** 1961-2020 **की अवधि के लिए ग्रीष्म ऋतु (अप्रैल-जून या एएमजे) के दौरान** 103 **स्टेशनों के दैनिक चरम तापमान का उपयोग करके और** 1971-2020 **की अवधि के लिए शीत ऋतु (दिसंबर-फरवरी या डीजेएफ) के दौरान** 86 **स्टेशनों के दैनिक न्यूनतम तापमान का उपयोग करके शीत लहरों (सीडब्ल्यू) की गणना करते हुए ऊष्ण लहरों (**HWs**) की आवृत्ति, अवधि, परिमाण और स्थानिक व्याप्ति पर अल-नीनो-दक्षिणी दोलन (**ENSO**) के चरम चरणों (अल-नीनो और ला-नीना) के प्रभाव की जांच करी है। ऊष्ण लहरों को आमतौर पर मई के दौरान उच्चतम आवृत्ति के साथ उत्तर, उत्तर-पश्चिम, मध्य, पूर्वी भारत और उत्तर-पूर्व प्रायद्वीप [जिसे एक साथ कोर एचडब्ल्यू जोन (सीएचजेड) कहा जाता है] में अनुभव किया जाता है। जबकि, शीत लहरों को आम तौर पर कोर कोल्ड वेव ज़ोन (सीसीजेड) में प्रेक्षित किया जाता है। लगभग सीएचजेड के समान हैइसमें जम्मू और कश्मीर शामिल है लेकिन तटीय आंध्र प्रदेश को शामिल नहीं किया जाता है। इस अध्ययन ने देश भर में दोनों एचडब्ल्यू/एसएचडब्ल्यू और सीडब्ल्यू/एससीडब्ल्यू के दिनों में आवृत्ति, स्थानिक व्याप्ति और अधिकतम आवृत्ति के क्षेत्र में उल्लेखनीय दशकीय भिन्नता देखी। यह भी देखा गया कि अल-नीनो (ला-नीना) घटनाओं के दौरान एचडब्ल्यू दिनों की संख्या में उल्लेखनीय वृद्धि (कमी) हुई है। अल-नीनो वर्षों में चरम ऊष्ण लहरें अधिक सुस्पष्ट (सबसे लंबी और सबसे गर्म) थी। सीडब्ल्यू दिनों के मामले में ठीक विपरीत स्थिति देखी गई। अल-नीनो घटना अधिकतर भारत में सीडब्ल्यू गतिविधियों को रोकती है। सीएचजेड (सीसीजेड) के कई स्टेशनों में एचडब्ल्यू (सीडब्ल्यू) दिनों में महत्वपूर्ण वृद्धि (घटती) की प्रवृत्तियां देखी गईं, जो दुनिया के विभिन्न हिस्सों में देखी गई समान प्रवृत्तियों के अनुरूप है। अल-नीनो / ला-नीना के साथ देश भर में तापमान की इन चरम घटनाओं की प्रेक्षित संभावित भौतिक प्रणाली पर भी इस शोध पत्र में चर्चा की गई है।**

ABSTRACT. In this paper, the impact of extreme phases (El-Niño and La-Niña) of El-Nino- Southern Oscillation (ENSO) on the frequency, duration, magnitude and spatial coverage of Heat waves (HWs) computed using daily maximum temperature of 103 stations during the hot weather season (April-June or AMJ) for the period 1961-2020 and Cold waves (CWs) computed using daily minimum temperature of 86 stations during the cold weather season (December-February or DJF) for the period 1971-2020 from India. HWs are generally experienced over the north, north-west, central, east India and north-east Peninsula [together called core HW zone (CHZ)] with highest frequency during May. Whereas, the CWs are generally observed in the Core Cold Wave Zone (CCZ) which is nearly the same as CHZ but includes Jammu and Kashmir and excludes coastal Andhra Pradesh.The study observed noticeable decadal variation in the frequency, spatial coverage and area of maximum frequency both in the HW/SHW and CW/SCW days over the country. It was also observed that there is an appreciable increase (decrease) in the number of HW days during El-Niño (La-Niña) events. Severe Heat waves were more prominent (longest and hottest) in El-Niño years. Exactly opposite association was observed in case of CW days. El-Niño event mostly inhibits the CW activities in India. Significant increasing (decreasing) trends in the HW (CW) days were observed in many stations from CHZ (CCZ), which is in tune with similar trends observed over various other parts of the world. The possible physical mechanisms for the observed linkage of these temperature extreme events over the country with the El-Nino/ La-Nina are also discussed in the paper.

Key words – ENSO, CHZ, CCZ, Heat waves, Cold waves.

1. Introduction

The latest Intergovernmental Panel for Climate Change report (IPCC, 2021) has observed that each of the last four decades (during 1981 to 2020) has been successively warmer than any decade that preceded it since 1850 and that the Global annual surface temperatures in the recent decade (2011-2020) was 1.09 °C higher than 1850-1900. The report also observed that heatwaves (HWs) have become more frequent and more intense across most land regions since the 1950s, while cold waves (CWs) have become less frequent and less severe. Extreme weather and climate events have received increased attention in the last few years, mainly due to the direct effect it has on the quality of human life and the ever-increasing costs associated with them (Parmesan *et al*., 2000). In consistent with the global warming, the annual mean surface temperatures averaged over India during the period 1901-2020 has also shown significant warming trend of 0.62 °C/100 years (IMD, 2021) with the average surface temperatures in the recent decade (2011- 2020) being 0.34 °C higher than that for the period 1981-2010.

There have been several studies in India (Raghavan, 1966, 1967; Rai Sircar and Datar, 1963; Natarajan, 1964; Bedi and Parthasarathy, 1967; Bedekar *et al*., 1974; Subbaramayya and Surya Rao, 1976; Chaudhury *et al*., 2000; De, 2001; De *et al*., 2005; Pai *et al*., 2004, 2013, Smitha *et al*., 2017) that examined various aspects of the extreme temperature events over the country associated with the observed warming trends, including their impact on human mortality. Recently, in the summer of 2019, India experienced one of the longest heat waves in recent history sweeping the country causing deaths of at least 36 people.

As a major source of climate variability at both global and regional scales, ENSO pose significant impacts on hot extremes in many regions such as the Australian, European, Indian and American sectors (Della-Marta *et al*., 2007; Arblaster and Alexander, 2012; Murari *et al*., 2016; Sun *et al*., 2016; Pai *et al*., 2013). Pai *et al*. (2013) using HW information of 103 stations from Indian main land for the period of 50 years (1961-2010) observed noticeable increase in the HW/SHW days over the country during the decade 2001-2010 compared to previous four decades, which was also the warmest decade for the country during the data period. Significant long-term increasing trends in HW days was also observed during the analysis period. The study had also observed above (below) average frequency, persistency and area coverage of the HWs during El-Nino (La Nina) years. Compared to Pai *et al*. (2013), the present study examines the impact of extreme phases (El-Niño and La-Niña) of El-Nino-Southern Oscillation (ENSO) on the frequency, duration, magnitude and spatial coverage of HWs during the hot weather season (April to June or AMJ) season by including HW information over the country for one more decade (2011-2020), which is also the warmest decade both at the global as well as all India scales. In addition, the study also examines association of extreme ENSO events on the CWs during the coldest weather season (December to February or DJF) using CW information over the country for the period 1971-2020. The possible physical mechanisms linking these extreme temperature events with the El-Nino / La-Nina phases are also discussed at the end of the paper.

2. Data and methodology

The information on heat waves used in this study was prepared from the daily maximum temperature of 103 stations uniformly distributed over Indian main land for the AMJ season for the period 1961-2020. Similarly, cold wave information derived from the daily minimum temperature of 86 stations uniformly distributed over Indian main land for the DJF season for the period 1971-2020 was also used. For this study, climatological normal of maximum and minimum temperatures for the period 1971-2000 was calculated for each station. Both the above data sets were obtained from the archive of the National Data Center (NDC) of the Office of Climate Research and Services (CRS), IMD, Pune.

The Oceanic Niño Index (ONI) [3-month running means of ERSST.v3b Sea surface temperature (SST) anomalies in the Nino 3.4 region (5° N-5° S, 120° W-170° W)] with a threshold of ±0.5 °C is the most commonly used index to define El- Niño and La-Niña events by Climate Prediction Centre (CPC), USA. The events are declared when the threshold is met for a minimum of 5 consecutive overlapping 3-month seasons. A reference year is classified as an El-Nino/La-Nina year, for HW (CW) case when any of the three 3-month seasons of March to May, April to June and May to July (November of previous year to January of reference year, December of previous year to February of reference year and January to March of reference year) is part of the 5 consecutive overlapping seasons. According to the above definition, for HWs during the period 1961-2020, 17 years (1963, 1965, 1966, 1969, 1972, 1982, 1983, 1987, 1991, 1992, 1997, 1998, 2002, 2010, 2015, 2016 and 2019) satisfied the El-Nino criteria and 13 years (1964, 1971, 1973, 1974, 1975, 1976, 1985, 1988, 1989, 1999, 2000, 2008 and 2011) satisfied the La-Nina criteria. Similarly, for the CWs case, during 1971-2020, 18 years (1973, 1977, 1978, 1980, 1983, 1987, 1988, 1992, 1995, 1998, 2003, 2005, 2007, 2010, 2015, 2016, 2019, 2020) satisfied El-Nino criteria and 19 years (1971, 1972, 1974, 1975, 1976, 1984, 1985, 1989, 1996, 1999, 2000, 2001, 2006, 2008, 2009, 2011, 2012, 2017 and 2018) satisfied the La-Nina criteria. To examine the differences in the spatial distribution of HWs/CWs associated with the El-Nino and La-Nina events, composite spatial maps of frequency of HWs/CWs for the respective El- Nino/La-Nina years were prepared. The nonparametric Mann-Kendall test (Gilbert, 1987) was employed to test the increasing or decreasing trends in the frequency and total number and maximum duration of the HWs/CWs and is indicated as per decade.

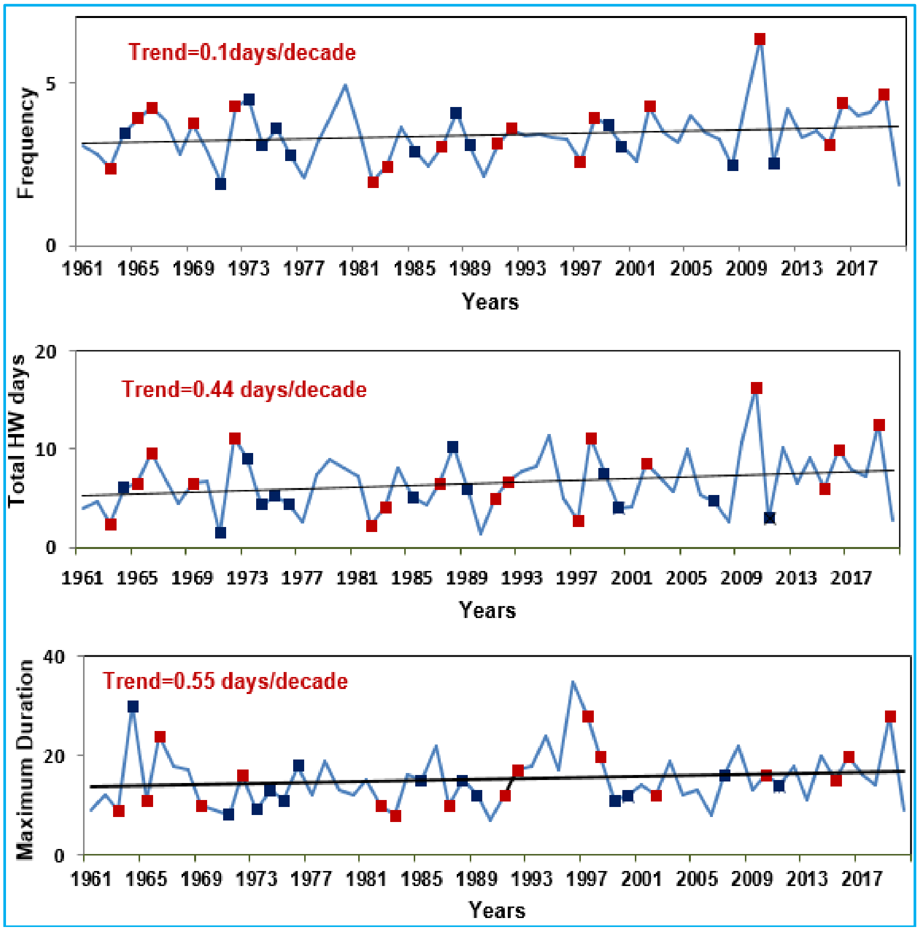


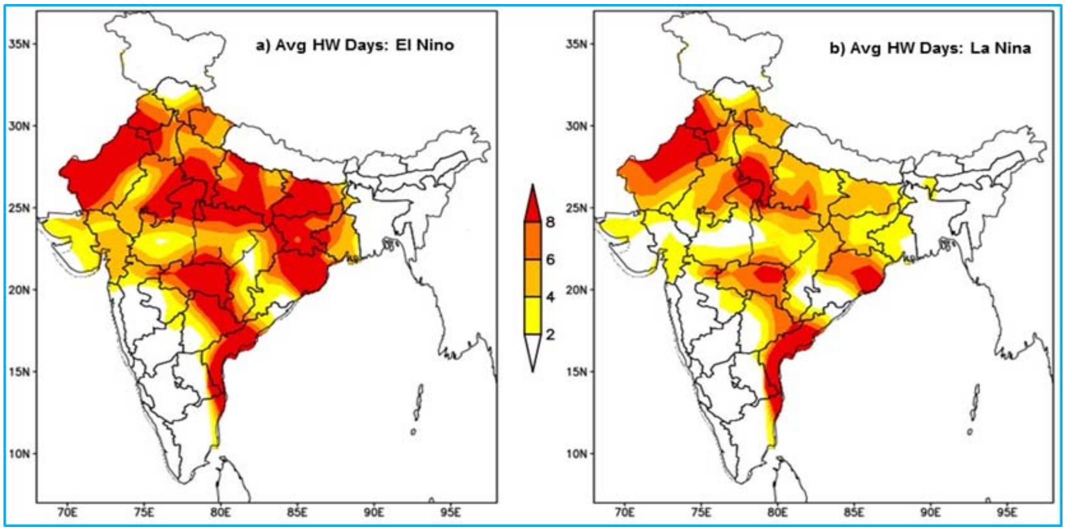
Fig. 1. Time series of (a) frequency (b) Total no of days and (c) maximum duration (days) of heat waves averaged over the CHZ region. The linear trend line is also shown. All the time series show statistically significant trends at 95% confidence level. The magnitude of trends is shown on the upper left corner. In the diagrams, the red/blue markersindicate El-Nino/ La-Nina years

3. Results and discussion

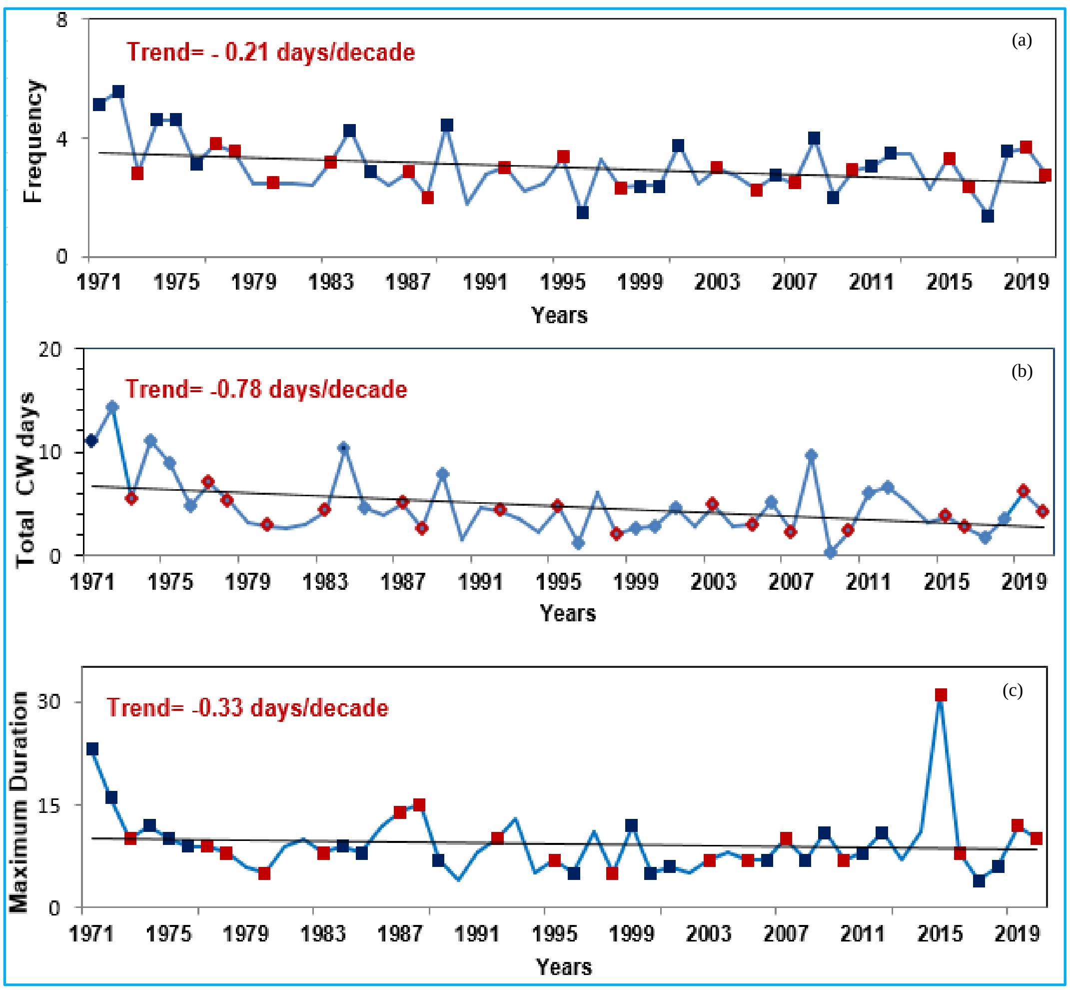
Fig. 1 shows the time series of frequency (total number of spells), total number (total number of days) and maximum duration of heat waves averaged over core heat wave zone (CHZ), which climatologically experiences highest frequency of HWs during the AMJ season. The core HW zone (CHZ) covers states of Punjab, Himachal Pradesh, Uttarakhand, Delhi, Haryana, Rajasthan, Uttar Pradesh, Gujarat, Madhya Pradesh, Chhattisgarh, Bihar, Jharkhand, West Bengal, Orissa and Telangana and met subdivisions of Marathwada, Vidarbha, Madhya Maharashtra and coastal Andhra Pradesh.

It is observed that there is an increasing trend of 0.1days/decade in the frequency of heat waves averaged over the CHZ. Also, it is seen that the total duration of heat waves averaged over the CHZ has shown an increase of 0.44 days per decade with the maximum duration showing an increasing trend of 0.55 days per decade. All the trends are statistically significant. Severe heat waves have also seen an increasing trend in the frequency, total number and maximum duration in the CHZ (figures not shown). These results are in tune with a similar study conducted by Rohini *et al*., 2016 using the daily gridded temperature data set developed by the India Meteorological Department.

It is seen that during 10 of the 17 El-Nino years, the all-India HW days were above its climatological value. Similarly, during 9 of the 13 La-Nina years, the all-India HW days were below its climatological value. The composite spatial maps of mean HW days over India for the El-Nino and La-Nina cases are given in the Fig. 2. The spatial pattern suggests that there is an appreciable increase in the areas of average number



Figs. 2. Maps showing composite of average number of HW days during the AMJ season for the (a) 17 El-Nino years and (b) 13 La-Nina years



Figs. 3(a-c). Time series of (a) frequency (b) Total no of days and (c) maximum duration (days) of cold waves averaged over the CCZ region. The linear trend line is also shown. All the time series show statistically significant trends at the 95% confidence level. The magnitude of trends is shown on the upper left corner. In the diagram, the red/blue markers indicate El-Nino/La-Nina years

TABLE 1

Maximum duration of heatwave during El-Nino years

Station	Year	Days	Period
Barmer	1963	9	23 Apr to May 01
Dehradun	1965	11	11 May 11 to May 21
Nellore	1966	24	7 May to 30 May
Nellore	1967	18	May 25 to Jun 11
Nellore	1969	10	May 06 to May 11
Berhampur	1972	16	6 May to 21 May
Machilipatnam	1982	10	Apr 28 to May 07
Nellore/Ramagundam	1983	8	Apr 28 to May 05
Agra	1991	17	24 Jun to17 Jul
Phalodi	1992	17	7 Jun to 23 Jun
Nellore	1997	28	16 May to 12 Jun
Phalodi	1998	20	13 May to 1 Jun
Nagpur/Chandbali/Nellore	2002	12	May 03 to May14 /Apr 28 to May 09 / May 20 to May 31
Jhansi	2010	16	13 May to 28 May
Kota	2015	15	18 May to 1 Jun
Chandbali	2016	20	7 Apr to 26 Apr
Nellore	2019	28	02 May to 29 May

of HW days of ≥ 8 during El -Nino years as compared to La-Nina years. It is also seen that during El-Nino years the areas of average number of HW days of ≥ 8 extends slightly both northward along the plains of Himalayas and south ward over northwest and central India. On the other hand, during the La-Nina years, the areas of average number of HW days of ≥ 8 shrink over north and central India.

Fig. 3 shows the time series of frequency (total number of spells), total number (total number of days) and maximum duration of cold waves averaged over the core cold wave zone (CCZ), which climatologically experience highest frequency of CWs during the DJF season. The CCZ is nearly same as CHZ expect that CCZ includes Jammu & Kashmir and excludes coastal Andhra Pradesh. The frequency of cold waves averaged over CCZ showed a decreasing trend of 0.21days per decade. Total duration of cold waves averaged over CCZ has shown a decrease of 0.78 days per decade and maximum duration has shown a decreasing trend of 0.33 days per decade. All the trends are statistically significant. It is observed that the severe cold waves have also seen a decreasing trend in the frequency, total number and maximum duration in the core cold wave zone (figures not shown).

It is also seen that during 11 of the 18 El-Nino years, the all-India CW days were below its climatological value. On the other hand, during 12 of the 19 La-Nina years, the all-India CW days was above its climatological value. This clearly indicates inverse association between ENSO and CW events. The composite spatial maps of mean CW days over India for the El-Nino and La-Nina cases are given in the Fig. 4. The spatial pattern suggests that there is an appreciable increase in the areas of average number of CW ≥ 8 days during La Nina years in the CCZ region as compared to El-Nino years.

Table 1 shows heat wave of the longest duration experienced during an El-Nino year. It can be seen that out of 17 El-Nino years, 11 years had maximum duration of heatwave of ≥ 15 days. Table 2 gives the longest duration of cold wave during a La-Nina year. It is found that out of 19 La-Nina years, 10 years had maximum duration of cold wave of ≥ 10 days.

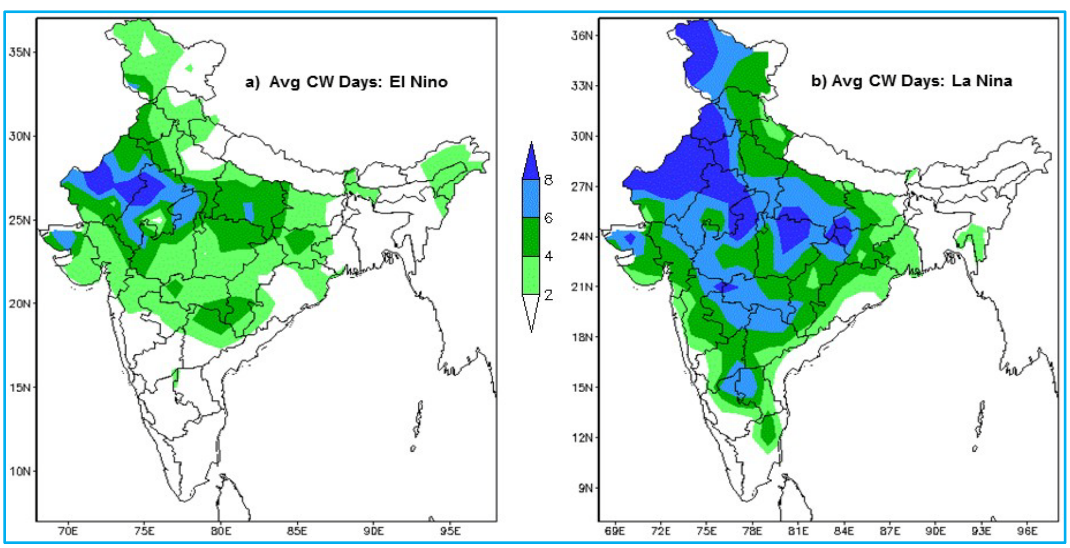
4. Possible mechanisms behind ENSO impact on the extreme temperature events over India

The possible underlying physical mechanisms linking the observed HWs and CWs over the country with

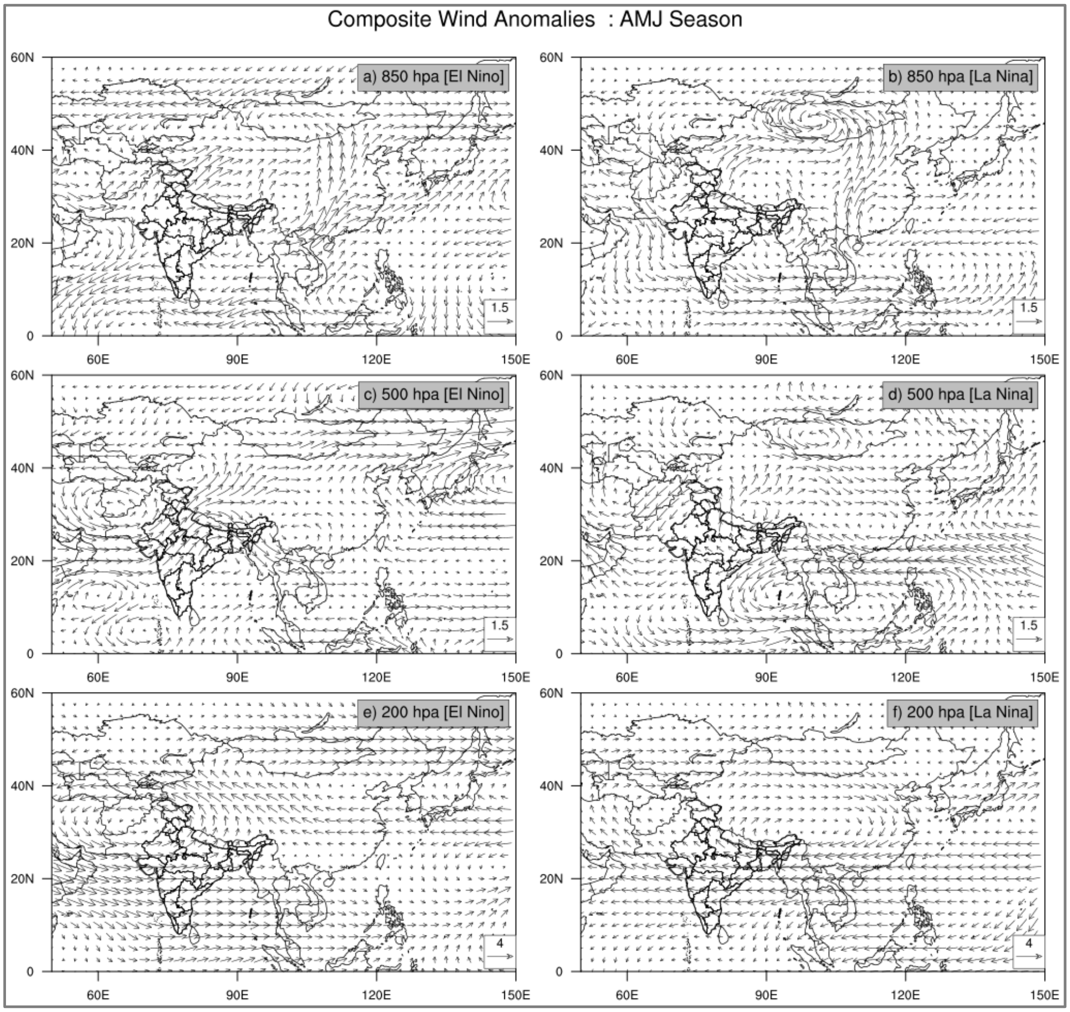
TABLE 2

Maximum duration of cold waves during La-Nina years

Station	Year	Days	Period
Aurangabad	1971	23	1 Dec to 23 Dec 1970
Jhansi	1972	14	8 Feb to 21 Feb
Bikaner	1974	12	4 Feb to 15 Feb
Bikaner	1975	10	14 Feb to 23 Feb
Srinagar/Aurangabad	1976	9	8 Dec to 16 Dec 1975 / 23 Dec to 31 Dec 1975
Udaipur	1984	9	20 Feb to 28 Feb
Gwalior	1985	8	11 Feb to 18 Feb
Vellore	1989	8	02 Feb to 09 Feb
Amritsar/Phalodi/Barmer	1996	5	26 Jan to 30 Jan/1 Dec 1995 to 5 Dec 1995/16 Jan to 20 Jan
Srinagar	1999	12	8 Dec to 19 Dec 1998
Srinagar/Amritsar/Phalodi	2000	5	01 Jan to 5 Jan/23 Feb to 27 Feb/12 Feb to 16 Feb
Vellore	2001	13	6 Dec to 17 Dec 2000
Ganaganagar/Dessa	2006	10	11 Dec to 20 Dec 2005/18 Dec to 27 Dec 2005
Amritsar/Phalodi/Barmer	2008	10	20 Jan to 29 Jan
Jalgaon/Anantpur	2009	5	28 Dec 2008 to 1 Jan 2009/12 Feb to 16 Feb
Pendra/Phalodi	2011	11	2 Jan to 12 Jan/5 Feb to 14 Feb
Ratlam/Nagpur/Akola	2012	7	09 Jan to 15 Jan/10 Jan to 16 Jan/10 Jan to 16 Jan
Bahriach	2018	12	05 Jan to 16 Jan



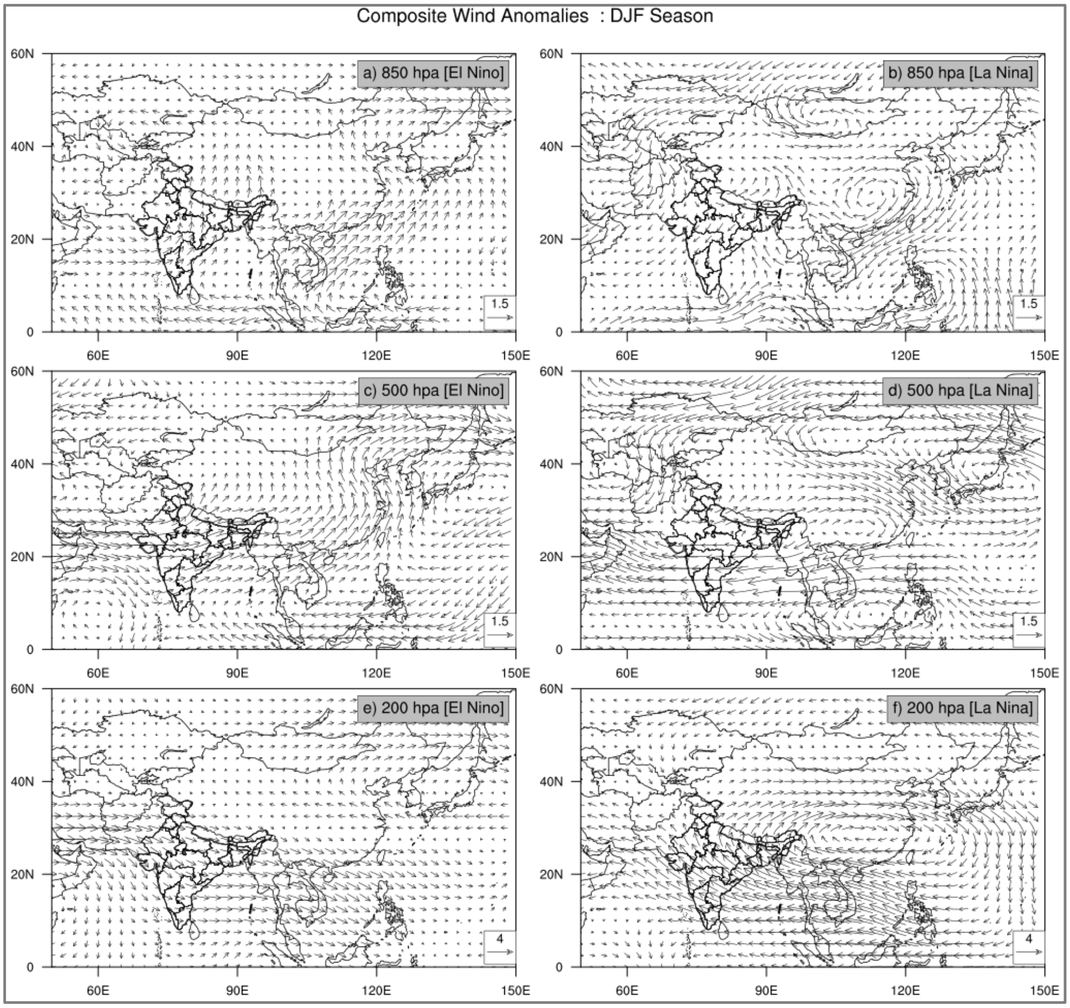
Figs. 4(a&b). Maps showing composite of average number of CW days during the DJF season for the (a) 18El-Nino years and (b) 19 La-Nina years



Figs. 5(a-f). Composite vector wind anomalies at 850, 500 and 200-hPa during AMJ season in respect of El-Nino and La-Nina years during the period 1961-2020

the El-Nino/La-Nina phases are discussed briefly in the next two paragraphs.

Figs. 5(a, c&e) show the composite wind vector anomalies at 850 hPa, 500 hPa & 200 hPa levels during the hot weather (AMJ) season over Asia- Pacific region for the 17 El-Nino cases during the period 1961-2020. Figs. 5(b, d&f) are same as Figs. 5(a, c&e) but for 13 La-Nina cases. It is seen that for the El-Nino composite, there is anomalous anticyclonic circulation over north Bay and neighboring land region at lower and mid tropospheric (850 hPa & 500 hPa) levels [Figs. 5(a&c)] and another anomalous anticyclonic circulation over northwest off India at mid and upper tropospheric (500 hPa & 200 hPa) levels. Associated with these anomalous anticyclonic circulations, an anomalous ridge extending from north Bay of Bengal to northwest India can be seen in the lower and middle tropospheric levels indicating anomalous subsidence motion over the region. Over the Indian main land, the anomalous ridge region closely corresponds to CHZ. In case of La Nina composite, an anomalous trough can be seen at the 850 & 500 hPa [Figs. 5(b&d)] levels across CHZ extending from northwest India to Bay of Bengal. However, the anomalous trough at 500 hPa level extends between two cyclonic circulations; one each over Northwest India and east central Bay of Bengal. Thus, in the La Nina composite case, there is an anomalous rising motion over the anomalous trough region between Northwest India and Central Bay of Bengal. This is exactly opposite to the anomalous subsidence motion observed in the El-Nino Composite. This feature can also be seen in the composite anomaly charts for velocity potential at 200 mb for El-Nino and La-Nina cases (figs not shown) with anomalous convergence (divergence) over the CHZ during El-Nino (La-Nina) years.



Figs. 6(a-f). Composite vector wind anomalies at 850, 500 and 200-hPa during DJF season in respect of El-Nino and La-Nina years during the period 1971-2020

During AMJ season, presence of the sun over the region causes increase in the temperatures over India with maximum over central, northwest and northern parts. The increase in the temperatures is also caused by the advection of warmer air from desert region to these areas due to changes in wind patterns over the region. This leads to formation of climatological heat low pressure area over the region and associated rising motion helps in transfer of the heat from low to upper levels sometimes resulting in strong convective activity. As seen in the Figs. 5(a-f), the anomalous subsidence (rising) motion over CHZ, associated with El-Nino (La-Nina) years result decreased (increased) transfer of heat from surface to upper air causing increased (decreased) surface temperatures. This indicates the existence of deep anomalous warming (cooling) of boundary layer during the El-Nino (La-Nina) years, which in turn is a good indicator of above (below) normal HW events over the region as shown by previous studies (Brugge, 1995; Chang and Wallace, 1987).

During DJF season, as the sun is in the southern Hemisphere, climatologically the temperatures decrease going from equator to pole with temperatures over north, northwest and central parts of India also experiencing cold weather. There are periods, when the temperatures over the region cools further due to the incursion of the dry and cold air from the north into the region associated with the changes in the wind and precipitation patterns particularly during the passage of the transient disturbances (troughs / low pressure systems) in the mid latitude westerlies resulting in CWs. These western disturbances also cause substantial amounts of snow/ rain falls in the hilly areas and adjoining plains of the region.

Figs. 6(a, c&e) show the composite wind vector anomalies at 850 hPa, 500 hPa & 200 hPa levels during the cold weather (DJF) season over Asia- Pacific region for the 18 El-Nino casesduring the period 1971-2020. Figs. 6(b, d&f) are same as Figs. 6(a, c&e) but for 19 La-Nina cases. For the El-Nino (La-Nina) composite, anomalous southerlies (northerlies) in the lower (850 hPa) and mid tropospheric (500 hPa) levels can be seen over CCZ in general and over north and northwest India in particular indicating below (above) normal incursion of dry and cold air from the north. This leads to anomalous warming (cooling) of the boundary layer leading to below (above) normal CWs during El-Nino (La-Nina) phases. It is also seen that for the El-Nino (La-Nina) composite, the upper air wind anomalies (at 200 hPa) are mainly westerlies (easterlies) indicating stronger (weaker) than normal mid latitude upper air westerlies leading to below (above) normal westerly trough activity over north/ northwest India during the El-Nino (La-Nina) phases.

4. Conclusions

(*i*) Significant increasing (decreasing) trends in the HW (CW) days were observed in many stations from CHZ (CCZ), which is in tune with similar trends observed over various other parts of the world.

(*ii*) There is strong influence of extreme phases of ENSO events on the frequency, total number and maximum duration of HWs/CWs over India.

(*iii*) More than normal spatial coverage of HW (CW) days was observed over CHZ (CCZ) during the El-Niño (La-Niña) phase.

(*iv*) During the El-Niño (La-Niña) phase, the increase in the (decrease) in the HW events over CHZ is associated with the deep anomalous warming (cooling) of boundary layer due the anomalous sinking (rising) motion over the region that reduce (increase) climatological transfer heat from low to upper levels of the atmosphere.

(*v*) During the El-Niño (La-Niña) phase, the decrease (increase) in the CW events over CCZ is associated with the deep anomalous warming (cooling) of boundary layer due to the below (above) normal incursion of dry and cold air from north to the region caused by the passage of below (above) normal transient disturbances in the mid-latitude westerlies.

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