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Temperature Extremes over India and their Relationship with El Niño-Southern Oscillation

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1. INTRODUCTION

The climate of a place represents the average weather in that place over more than thirty years' time period. While the weather can change in just a few hours, climate changes over longer time frames. Climate change is the variation in the Earth's global climate or in regional climates over time. It involves the variability or average state of the atmosphere over durations ranging from decades to millions of years. These changes can be caused by dynamic processes on the earth, external forces and human activities. Detection of change in climate against its variability is a key issue in climate research. Climate change is often expressed simply in terms of changes in the mean climate. However, regional climatic change in terms of extremes could have more significant socio-economic consequences than the changes in mean climate conditions as they may not show an appreciable change but may be characterized by a variety of extreme situations. There is a general agreement within the climate community that changes in the frequency as well as the intensity of extreme climate events would have profound impacts on natural and social systems. They can have serious and detrimental effects on human society and infrastructure as well as on ecosystems and wildlife. In general, the relationship between climate, extreme events and the extent of damage is extremely complex. The extreme events such as heat waves, floods, storms and dangerous avalanches have caused repeated concern in recent years. Our present knowledge of meteorological processes suggests that frequency and intensity of certain extreme events— for example, number of hot days and nights, heat waves, heavy precipitation and flood situations—will increase with the change in climate. However it remains uncertain whether or not to expect changes in some other extremes. The information based on current meteorological processes and model simulations must be taken into account in risk assessment, planning of precautionary measures and in development processes.

With the growing concerns of the regional manifestations of global warming worldwide, the most important aspects of temperature and precipitation variability are the occurrence of extremes. There have been some significant increases and decreases in extremes over time in some regions. Clear trend to fewer extremely low minimum temperatures in several areas is observed in recent decades, e.g., Australia, United States of America, Russia and China. Widespread extended periods of extremely high temperatures are also expected to become more frequent. Higher temperatures lead to higher rates of evaporation and capacity of atmosphere to hold the moisture also increases with increase in temperature. Therefore, we expect more precipitation as the earth warms and it is also expected to fall over shorter intervals of time leading to increase in frequency of heavy precipitation. Due to more rapid evaporations from soil, lakes, etc., some areas are expected to have frequent and prolonged drought conditions also. Therefore, extreme climate and weather events are increasingly being recognized as key aspects of climate change and they

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adversely affect the biosphere and have serious socio-economic implications (Bijlsma, 1996; Turner et al., 1998; Wheeler et al., 2000; Bugmann and Pfister, 2000; Tol, 2002). For example, decline in the rate of national economic growth leads to increase of import and high prices of food. Other commodities may lead to civil strife, loss of traditional export markets, reduced earnings from tourism, loss of biodiversity, and shortage of energy sources. Many of the assessments also emphasized effects of climate change acting on coastal systems that already are under stress. Temperature extremes constitute an integral component of climate variability and change on the regional scale (Revadekar et al., 2009). Extremes in the temperatures are characterized by daily temperature level exceeding tolerable limits, and their frequency and spell duration are of great interest in terms of human impacts. Extremes of heat and cold have a broad and far-reaching set of impacts on the nation. These include significant loss of life and illness, economic costs in transportation, agriculture, production, energy and infrastructure (Kilbourne, 1997; Hassi, 2005).

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) concluded that global mean surface temperatures have risen by 0.74°C ± 0.18°C as estimated by a linear trend over the recent 100-year period 1906-2005. The rate of warming over the last 50 years in this period is almost double that over the entire 100 years, i.e., 0.13°C ± 0.03°C versus 0.07°C ± 0.02°C per decade (IPCC, 2007).

Most of Europe has experienced an increase in surface air temperature during the 20th century that averaged across the continent amounts to 0.8 °C in annual temperature (Beniston et al., 1998). This warming has been stronger in winter than in summer (Maugeri and Nanni, 1998; Domonkos and Tar, 2003; Feidas et al., 2004). Over Mediterranean region, the warming rate appears to be slightly lower, i.e., between 0.2 and 0.4 °C per 100 years (e.g., Kutiel and Maheras, 1998; Hasanean, 2001). In several regions of the world, indications of changes in various types of extreme climate events have also been noticed. The IPCC report on climate change (IPCC, 2007) indicated significant changes in various types of climate extreme events in several regions across the globe. The number of drought affected regions has been found to be increased as precipitation over land has marginally decreased while evaporation has increased due to warmer conditions. This report summarizes the various studies on extreme climate from different parts of the globe that there has been a significant decrease in the annual occurrence of cold nights and a significant increase in the annual occurrence of warm nights. Decreases in the occurrence of cold days and increases in hot days are generally less marked. The report also pointed out that the cold extremes have warmed more than the warm extremes over the last 50 years. Many regional studies worldwide have attempted the analysis of the changes in frequencies of cold and hot events and have generally indicated that cold extremes are decreasing and warm extremes are increasing (Karl et al., 1996; Plummer et al., 1999; Easterling et al., 2000; Hyun et al., 2002).

IPCC (2007) concluded that changes in extremes of temperature are consistent with the observed warming of the climate. Over India, Kothawale and Rupa Kumar (2005) reported that although the all-India mean annual temperature has shown a significant warming trend of 0.05ºC/10 years during the period 1901-2003, the recent period 1971-2003 has seen a relatively accelerated warming of 0.22ºC/10 years, which they noted to be largely due to unprecedented warming during the last decade. They also observed that the recent accelerated warming over India was manifest equally in day and night time temperatures. Therefore, information on the changing pattern of climate on global as well as regional scale and the changes in extreme climatic events is very important in the context of socio-economic effects. The vulnerability and adaptation aspects in climate change should be given higher priority to understand the impact of climate change and changing climate extremes on various socio-economic parameters like health, natural ecosystems, agriculture, water sector, forest, coastal zone, etc.

El Niño and La Niña are well known to be associated with significant monthly/seasonal climate anomalies at many places around the globe. It has also been shown that El Niño/La Niña events have a significant relationship with the relative frequency of climatic extremes (e.g., Swolter et al., 1999). Kiladis and Diaz (1989) have shown the relationship between temperature across east Asia and west Pacific with El Niño/Southern Oscillation (ENSO). Regional climate anomalies associated with the major El Niño episode during the 1877-1878 boreal winter were destructive, particularly in the Northern Hemisphere, where starvation due to intense droughts in Asia, Southeast Asia and Africa took the lives of more than 20 million people. At the same time anomalous intense precipitation were reported in other parts of world e.g. coastal areas of southern Ecuador and northern Peru, etc. It may be noted that during the period human influence was negligible to cause greenhouse effect (Aceituno et al., 2009). While there have been several studies on temperature changes over the Indian region (Kothawale and Rupa Kumar, 2005; Klein-Tank et al., 2006; Alexander et al., 2006; Rupa Kumar et al., 2006), and also the impact of ENSO on monsoon rainfall seasonal extremes (Pant and Rupa Kumar, 1997; Krishna Kumar et al., 2006), very little information is available on the role of El Niño/La Niña in temperature extremes over the Indian region.

In view of the above facts, the present study examines the changes in extremes over Indian region using objectively defined indices of observed temperature extremes. An attempt has also been made to examine the relationship between El Niño-Southern Oscillation (ENSO) and the temperature extremes over India in terms of their monthly/seasonal frequencies as well as intensities by computing anomalies in indices of temperature extremes during El Niño and La Niña and also by computing correlation coefficients between temperature extremes over India with NINO3.4 sea surface temperatures.

2. OVERVIEW OF EL NIÑO-SOUTHERN OSCILLATION

2.1 What is ENSO?

The El Niño-Southern Oscillation (ENSO) is a global coupled ocean-atmosphere phenomenon, i.e., an interaction between the ocean and the atmosphere and their combined effect on climate. It is an irregular phenomenon that alternates between its two phases, El Niño and La Niña approximately every 2-7 years. The Pacific Ocean signatures, El Niño (warming) and La Niña (cooling) are important temperature fluctuations in surface of tropical Eastern Pacific Ocean. It is a disruption of the ocean-atmosphere system in the tropical Pacific having important consequences for weather around the globe. Along the equator, western Pacific has some of the world's warmest ocean water, while in the eastern Pacific cool water wells up. After every two to seven years, strong westward flowing trade winds subside. This interrupts the upwelling of cool water at eastern Pacific. Peruvians named this phenomenon as El Niño. Under normal conditions, the atmosphere of the eastern south Pacific is dominated by an eastern center of high pressure. A zone of lower pressure prevails to the west and the resulting pressure difference causes the trade winds to blow east to west; however, trade winds may relax or sometimes even reverse. Since ocean currents are greatly influenced by the winds blowing above them, this ease of the trade winds also affects surface ocean currents. The Southern Oscillation refers to the pressure difference between southeastern tropical Pacific and Australian-Indonesian regions. When the waters of the eastern Pacific warm abnormally, the sea level pressure drops in the eastern Pacific and rises over the west. The combined effect of El Niño and Southern Oscillation (ENSO) affects the local climate and also global impact as well (Bjerknes, 1966,1969; Allan et al., 1996; Glantz, 2001). In contrast, La Niña events cause cooling in tropical Pacific and Indian Oceans that enhances rainfall in eastern Pacific Region (Allan et al., 1996; Joelle and Fowler, 2009).

2.2 Impacts of ENSO

The ENSO is known to be a major force of earth's year-to-year climate variability. ENSO is associated with floods, droughts and other disturbances in a range of locations around the world. These effects of ENSO and the irregularity of the ENSO phenomena make its prediction of high interest. This prominent source of inter-annual variability in climate has 2 to 7 years periodicity. Though not all, many of the countries are severely affected by current as well as Lag-1 ENSO events. Over certain regions, particularly parts of the Tropics, evidence for such relationship is overwhelming (Hastenrath, 1991).

India is largely dependent on the summer monsoon rainfall for agricultural and fishery sectors for food, water, etc. Indian subcontinent is one of the prime locations which is greatly affected by ENSO. Several studies in the past have established the relationship between SSTs over the ENSO region and the climate over India, particularly the ENSO-monsoon teleconnections (Pant and Rupa Kumar, 1997). Association between ENSO and summer monsoon rainfall over India has been rigorously studied (Sikka, 1980; Rasmusson and Carpener, 1983; Parthasarathy and Pant, 1985; Mooley, 1997). Suppression of convection in the El Niño phase and enhancement of convection in the La Niña phase have been observed over the Indian Ocean and land regions (Gadgil et al., 2004). It has been observed that the relationship has been weakening in recent two decades (Shukla, 1995; Kripalani and Kulkarni, 1997; Krishna Kumar et al., 1999; Kinter et al., 2002). Such weakening is possibly a short-lived feature, considering the conflicting results reported by global warming simulations (Ashrit et al., 2001) and some subsequent instances of monsoon failures in association with moderate El Niño situations such as 2002 and 2004.

Composite analysis in mean temperature over India during ENSO events shows negative anomalies in winter and pre-monsoon. However, the winter anomalies are stronger than the pre-monsoon anomalies. In monsoon and post-monsoon anomalies changes are towards the positive side (Kothawale, 2005). Kiladis and Diaz (1989) have shown the relationship of temperature across the east Asia and west Pacific with El Niño/Southern Oscillation (ENSO). Trewin (2001) also observed similar relationship for many parts of the Australian region and suggested that the relationship was strong enough to allow prediction. An effect of the 1997-1998 El Niño on ocean salinity variability has been reported by Maes (2000). The effect of ENSO on Total Ozone Column (TOC) deduced by ground observation and satellite sensors has been studied on a regional scale (Chandra et al., 1998; Langford et al., 1998). It has also been shown that El Niño/La Niña events have a significant relationship with the relative frequency of climatic extremes (Swolter et al., 1999). Han et al. (2001) discussed the ENSO signal in the inter-annual variation of Tibet total ozone based on the analysis of satellite ozone observation and atmospheric circulation data. They have shown that the Tibet ozone increases in El Niño events and decreases in La Niña events. The effect of El Niño in 1997-1998 on TOC has also been discussed by Singh et al. (2002) in light of the prevailing SSTs anomaly over the Indian Ocean and the Arabian Ocean, and concluded that the anomalous TOC is likely due to an El Niño effect which shows a close relation with the observed SSTs over the Indian Ocean and the Arabian Ocean. Sarkar and Singh (2000) also studied the inter-annual variability of total ozone deduced from Global Ozone Monitoring Experiment (GOME) and its relation to the observed El Niño of 1997-1998.

It was also noticed that the El Niño and La Niña events have a significant relationship with the relative frequency of climatic extremes (Swolter et al., 1999). They also have examined the relationship between short-term climate extremes over the continental United States and ENSO. Their results show that the greatest geographical coverage of statistically significant relationship between ENSO and seasonal temperature extremes occur in winter and spring, especially with the SOI leading by one season. For the Indian region, ENSO has been shown a strong relationship with variations in frequencies of extreme precipitation in winter season (Revadekar and Kulkarni, 2008). Jayanthi and Govindachari (1999) observed that Tamil Nadu had received record rainfall in 1997 that happened to be one of strongest El Niño years in which sea surface temperature (SST) anomalies were abnormally high throughout the year over equatorial Pacific. Goswami and Xavier (2005) have shown that ENSO controls the south Asian monsoon through the length of the rainy season with strong negative correlations between the length of rainy season and the ENSO related SSTs. According to Nicholls et al. (2005), the onset of El Niño leads to increased numbers of warm extremes (and fewer cool extremes) in east Asia and western Pacific. While analyzing the annual extremes, they pointed out that further research is necessary to examine seasonal variations in the relationships between climate extremes and ENSO. Deviations in temperature due to warm and cold phases of ENSO are geographically variable (Sittel, 1994).

3. DATA AND METHODOLOGY

3.1 Data Used in the Study

In this study, a good even coverage was sought to ensure that results could be representative of the whole country (India). With the network of fixed number of stations for the entire period, it became possible to perform an in-depth quality control process on data for each site whilst producing results giving a good coverage of India. Daily maximum and minimum temperature data were collected from Indian Daily Weather Report (IDWR), India Meteorological Department (IMD), New Delhi. Both daily maximum and minimum temperatures data of 121 well distributed meteorological stations for the period 1971-2003 were used in the study.

3.2 Quality Control

The data pre-processing is an important part of research. In order to ensure that extremes are not discarded with an over-enthusiastic or a purely automated data cleansing, a well considered pre-processing is crucial to ensure a meaningful analysis (Burn, 2004). An automated statistical system could not have managed the checks performed on the data in this study. Therefore, the following basic manual quality checks were applied to daily temperature data at each station:

- Maximum temperature is less than minimum temperature of the day.
- Same data value is repeated for several consecutive days.
- Same extreme is repeated.
- $\text{Mean} - n \times \text{SD} > x > \text{mean} + n \times \text{SD}$, where '$x$' is data value to be inspected, 'mean' is average for that day of the year, 'SD' is standard deviation of the mean and 'n' is an integer set by the user. All the data values not lying in the range are treated as outliers and are examined relative to the surrounding days and documentary evidences and switched or removed as necessary.

3.3 Calculation of Temperature Extreme Indices

The joint World Meteorological Organization (WMO) Commission for Climatology (CCl)/World Climate Research Program (WCRP) project on Climate Variability and Predictability (CLIVAR), and Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) coordinated the development of a suite of climate change indices which primarily focus on extremes (Peterson et al., 2001). These indices are derived from daily temperature and precipitation data. The definitions of the indices including a user-friendly software package are freely available to the international research community (http://ccma/seos.uvic.ca/ETCCDMI). These indices have been widely used for global and regional analyses of climate extremes (Alexandar et al., 2006; Klein Tank et al., 2006). In the present study, temperature

Table 1. List of temperature extremes used in the present study

	Index with unit	*Description*	*Definition*
(i)	*Frequency with Statistical Thresholds*		
	TN10 (% days)	Cold nights	Number of days in a month or season with minimum temperature below 10th percentile of the daily minimum temperature distribution in the 1971-2000 baseline period.
	TX10 (% days)	Cold days	Number of days in a month/season with maximum temperature below 10th percentile of the daily maximum temperature distribution in the 1971-2000 baseline period.
	TN90 (% days)	Hot nights	Number of days in a month/season with minimum temperature above 90th percentile of the daily minimum temperature distribution in the 1971-2000 baseline period.
	TN90 (% days)	Hot days	Number of days in a month/season with maximum temperature above 90th percentile of the daily maximum temperature distribution in the 1971-2000 baseline period.
(ii)	*Intensities*		
	TNn (°C)	Coldest night	Monthly or seasonal lowest minimum temperature
	TXx (°C)	Hottest day	Monthly or seasonal highest maximum temperature
	TNx (°C)	Hottest night	Monthly or seasonal highest minimum temperature
	TXn (°C)	Coldest day	Monthly or seasonal lowest maximum temperature
(iii)	*Range*		
	DTR (°C)	Diurnal temperature range	Mean monthly difference between maximum and minimum temperature

extreme indices shown in Table 1 were used to examine the role of ENSO on temperature extremes over India. These indices are computed for each of 121 stations over Indian landmass for the period 1971-2003 and are used further for comprehensive analysis.

3.4 Development of ENSO-Extreme Relationships

During the data period, the El Niño, La Niña and normal years were grouped into separate categories to analyze the temperature extremes. The El Niño years categorized for the analysis are: 1972, 1976, 1982, 1987, 1991 and 1997, whereas the La Niña years are: 1970, 1973, 1975, 1988 and 1999 (Halpert and Ropelewski, 1992; Kothawale et al., 2007). For each season, composite anomalies of extreme temperature indices were calculated for El Niño and La Niña with respect to neutral phase to examine their spatial distributions over the Indian region.

Moreover, seasonal composite anomalies of extreme temperature indices for El Niño and La Niña were also calculated for each station and their spatial distributions over the Indian region have been examined. For this purpose, extreme indices computed for each of the 121 stations were gridded onto a 1° × 1° grid. Each seasonal all-India mean index of extreme was correlated with monthly NINO3.4 HadSST values starting from January to December of the previous year (year 1).

4. RESULTS AND DISCUSSION

Until recently, most of the analyses of long-term global climate change using temperature have focused on changes in mean values. For example, Kothawale and Rupa Kumar (2005) have shown that the mean, maximum as well as minimum temperatures have increased by about 0.2 °C per decade during the period 1971-2003, for the country as a whole.

Rupa Kumar et al. (2003) studied the future scenarios of changes in rainfall and temperature in 21st century over the Indian region based on the simulations of various General Circulation Models (GCMs). Their analysis on extreme temperature based on the HadRM2 simulation projected an increase in extreme maximum temperature over the country in the 21st century due to an increase in Green House Gases (GHGs) concentrations. Over the region south of 25° N, this increase will be of order of 2-4°C. In the northern region, the increase in maximum temperature may exceed 4 °C. They also indicated that there will be a general increase in minimum temperature up to 4 °C over the southern peninsula and some parts of north India.

Rupa Kumar et al. (2006) analysed high resolution climate change scenarios of a state-of-art regional climate modeling system, known as PRECIS (Providing Regional Climates for Impacts Studies) developed by the Hadley Centre for Climate Prediction and Research for India. They have shown that PRECIS simulations under scenarios of increasing greenhouse gas concentrations and sulphate aerosols suggest marked increase in temperature towards the end of the 21st century (2071-2100). This study also indicated that extremes in maximum and minimum temperatures are also expected to increase into the future, but the night temperatures are increasing faster than the day temperatures.

However, extreme temperature has important impacts on vital aspects of society including crop yield, power production and consumption and human health. Therefore, detailed analysis on observed temperature extremes using daily station data for well-distributed network of 121 stations for minimum and maximum temperature have been carried out. Results are presented in following sections.

4.1 Changes in Temperature Extremes over India

4.1.1 Summary Statistics for Observed Trends in Temperature Extremes over India

Summary statistics of the stations indicating number of stations with positive/negative and significant trends in seasonal temperature extreme indices over Indian region have been prepared as shown in Table 2. It is clear from this table that all intensity indices of both cold and hot events (TNn, TXn, TNx and TXx) show a widespread increasing trend in temperature. However, more number of stations have an increasing trend for the winter season for all intensity indices. For hot intensities, minimum number of stations have shown an increasing trend during pre-monsoon season, which is the hottest season of India. Whereas for the coldest day temperature, maximum number of stations show an increasing trend during winter season which is the cold season of India.

All frequency indices of hot events (TX90p and TN90p) show a widespread increasing trend and all frequency indices of cold events (TX10p and TN10p) show a widespread decreasing trend (Table 3). For frequency indices also, more number of stations show an increasing trend in hot frequency and a decreasing trend in cold frequency for the winter season.

Considering the changes in both intensity and frequency indices, it is clear that in general higher changes are in post-monsoon season. Out of 121 stations, 94 stations show increasing trend in number of hot days and 97 stations show increasing trend in number of hot nights. Similarly for cold events also, more number of stations (113 for number of cold days and 105 for number of cold nights) show decreasing trends. This indicates the tendency of Indian winter towards the warming. Minimum changes in frequency indices are seen in pre-monsoon season. Analysis in general indicate reduction in seasonality, as hot season is slowly warming while winter show rapid changes.

Slightly more number of stations show decreasing trend in seasonal as well annual Diurnal Temperature Range (DTR) in Table 4. For the winter season, JF number of stations having decreasing

Table 2. Summary statistics of the stations for positive and negative trends in seasonal intensity indices of temperature extremes

Hot events

Intensity	*Hottest day temperature*					*Hottest night temperature*				
Number of Stations with	*JF*	*MAM*	*JJAS*	*OND*	*Ann*	*JF*	*MAM*	*JJAS*	*OND*	*Ann*
+ve trends	97	82	91	103	95	83	75	87	82	70
Significant +ve trends	32	29	27	40	36	27	23	32	23	20
-ve trends	24	39	30	18	26	38	46	34	39	51
Significant -ve trends	2	2	4	0	3	2	12	9	4	3

Cold Events

Intensity	*Coldest day temperature*					*Coldest night temperature*				
Number of Stations with	*JF*	*MAM*	*JJAS*	*OND*	*Ann*	*JF*	*MAM*	*JJAS*	*OND*	*Ann*
+ve trends	100	67	84	94	87	94	73	86	77	81
Significant +ve trends	36	30	23	38	37	36	30	37	19	39
-ve trends	21	54	37	27	34	27	48	35	44	40
Significant -ve trends	2	4	7	1	7	2	9	8	8	14

Table 3. Summary statistics of the stations for positive and negative trends in seasonal frequency indices of temperature extremes

Hot events

Frequency	*Hot days*					*Hot nights*				
Number of Stations with	*JF*	*MAM*	*JJAS*	*OND*	*Ann*	*JF*	*MAM*	*JJAS*	*OND*	*Ann*
+ve trends	72	81	85	94	69	88	90	84	97	86
Significant +ve trends	22	21	25	30	21	37	32	32	46	35
-ve trends	49	40	36	27	52	32	31	37	24	35
Significant -ve trends	5	0	6	1	8	4	5	6	6	8

Cold events

Frequency	*Cold days*					*Cold nights*				
Number of stations with	*JF*	*MAM*	*JJAS*	*OND*	*Ann*	*JF*	*MAM*	*JJAS*	*OND*	*Ann*
+ve trends	34	39	18	8	25	43	35	23	16	18
Significant +ve trends	2	5	4	1	3	6	5	3	6	7
-ve trends	85	82	103	113	96	78	86	98	105	103
Significant -ve trends	25	15	34	38	52	29	32	59	52	67

Table 4. Summary statistics of the stations for positive and negative trends in seasonal Diurnal Temperature Range

Number of stations with	*JF*	*MAM*	*JJAS*	*OND*	*Ann*
+ve trends	46	59	52	53	56
Significant +ve trends	16	22	19	16	24
-ve trends	75	62	69	68	65
Significant -ve trends	25	23	15	14	26

trend is maximum (~62% stations), while it is minimum (~51% stations) for MAM. Also, maximum number of stations shows a significant negative trend for the winter season. Similar to seasonality, daily variation in temperature also has decreasing tendencies.

4.1.2 Trends in All-India Time Series of Temperature Extremes

Simple arithmetic means of extreme indices at all the stations under study are considered to characterize all-India mean temperature extremes. Therefore for all seasons (JF, MAM, JJAS and OND), yearly time series of extreme temperature indices are constructed by taking arithmetic mean of corresponding seasonal index for each of 121 stations. These time series of spatially aggregated extreme indices are tested for the existence of any trends. All the intensity (TXx, TXn, TNx, and TNn) indices show an increasing trend in the all-India time series indicating warmer event towards the recent period. For frequency indices i.e. TX10p, TN10p, TX90p and TN90p, the frequency of hot events (TX90p and TN90p) shows an increasing trend and the frequency of cold events (TX10p an TN10p) shows a decreasing trend indicating that warm events are frequent during the recent period. All these seasonal trend values and their significance are summarized in Table 5.

A rise of 0.02 °C per year in the highest maximum temperature during JF and OND season and in the lowest minimum temperature during JF, MAM and OND are statistically significant and all have the same rate. However, the decrease in cold days/nights in all the seasons is at a higher rate than the increase in hot days/nights. Also, it can be clearly seen from Table 5 that the decrease in frequency of cold nights is at a higher rate than any other seasonal index of temperature extremes of frequency. Thus, it is obvious from the analysis that warming through night temperature (i.e., minimum temperature) is widespread and at a higher rate than that of day time temperature (i.e., maximum temperature). Diurnal Temperature Range (DTR), which is a combination of both these temperatures, shows a decreasing trend in all the seasons except MAM though no trend in DTR is statistically significant.

Table 5. Trends in all-India seasonal time series for indices of temperature extremes

Index	*JF*	*MAM*	*JJAS*	*OND*
TXx	0.02*	0.01	0.01	0.02*
TNn	0.02*	0.02*	0.01	0.02*
TN10p	–0.19*	–0.13*	–0.20*	–0.33*
TN90p	0.13*	0.047	0.13	0.07
TX10p	–0.15*	–0.10	–0.12*	–0.19*
TX90p	0.19*	0.06	0.08	0.13
DTR	–0.004	0.001	–0.003	–0.005

* Significant at 5% level.

4.2 Monthly Composite Anomalies in Temperature Extremes during El Niño and La Niña

It is known that all-India mean temperature start to increase from February and attain a peak value in month of May. Thereafter, the temperatures start decreasing and attain a secondary maximum in the month of October (Kothawale, 2004). In case of annual cycle of temperature extremes also, the all-India mean highest maximum temperature and lowest minimum temperature, both start to increase from January and attain their respective peak values in the month of May. Thereafter, the highest maximum temperature decreases sharply with the onset of the summer monsoon and attains secondary maximum in October and then decreases rapidly. However, lowest minimum temperature remains elevated at constant level throughout summer monsoon season (JJAS) and gradually decreases thereafter (Revadekar, 2009). So it is quite interesting to know whether variation in monthly temperature extremes are modulated by variation NINO3.4 SSTs or not. Therefore, this section presents monthly composite anomalies in various temperature extremes for India as a whole during El Niño and La Niña years with respect to neutral phase. The composite all-India monthly anomalies for the two categories of El Niño and La Niña with respect to normal years, for the frequencies (TX90p, TN90p, TX10p and TN10p) and intensities (TXx, TNx, TXn and TNn) of temperature extremes are as shown in Tables 6 and 7, respectively. These tables clearly indicate an association between monthly temperature extremes over the Indian region with El Niño/La Niña events in terms of frequencies as well as for intensities. The frequencies of hot days and hot nights (TX90p and TN90p respectively) presented in Table 6 show negative anomalies in winter (DJF) and pre-monsoon months (MAM), and positive anomalies during monsoon (JJAS) and post-monsoon (ON). Opposite features can be seen in La Niña events which show positive anomalies in winter and pre-monsoon months and negative anomalies during monsoon and post-monsoon months. Similarly, frequencies of cold days and cold nights (TX10p and TN10p respectively) also show a conspicuous association with El Niño/La Niña events with opposite patterns to that of hot events. All the intensity indices of hottest and coldest temperatures show negative anomalies during winter and pre-monsoon months and thereafter they reverse its sign in El Niño years (Table 7). However, opposite features can be seen during La Niña years.

Table 6. Composite anomalies in frequencies of hot day/night and cold day/night during El Niño and La Niña years

Month	*TX90p*		*TN90p*		*TX10p*		*TN10p*	
	El Niño	*La Niña*	*El Niño*	*La Niña*	*El Niño*	*La Niña*	*El Niña*	*La Niña*
January	–3.8	0.4	–1.8	–1.1	0.0	–1.8	–0.2	0.6
February	–2.1	2.5	–3.0	2.3	1.3	–5.3	2.6	–5.6
March	–4.1	–0.8	–2.7	1.6	–2.0	–3.6	–2.0	–0.9
April	–6.0	8.0	–4.5	5.9	4.2	–5.6	2.7	–3.8
May	–2.9	3.3	–4.3	4.2	0.2	–1.4	1.9	–3.3
June	4.2	–4.8	0.9	–2.7	–2.2	0.9	–0.0	0.1
July	7.9	–4.1	3.8	–3.6	–3.3	–0.5	–2.1	0.1
August	2.4	–4.0	–0.2	–2.9	–1.4	0.7	–0.4	–1.1
September	2.9	–4.9	–0.3	–0.9	–3.7	4.6	0.3	–2.7
October	4.1	–5.4	–2.6	–0.9	–1.9	1.3	–0.2	–2.8
November	–1.0	–4.0	3.8	–6.1	1.9	0.0	–4.3	7.1
December	1.2	–3.6	5.1	–6.3	2.8	–0.9	–3.9	6.7

Table 7. Composite anomalies in hottest day/night temperature and coldest day/night temperature during El Niño and La Niña years

Month	*TXx*		*TNx*		*TXn*		*TNn*	
	El Niño	*La Niña*	*El Niño*	*La Niña*	*El Niño*	*La Niña*	*El Niña*	*La Niña*
January	–0.07	0.03	–0.07	–0.01	0.09	0.68	–0.07	0.03
February	–0.01	0.42	–0.30	0.63	–0.07	0.77	–0.09	0.58
March	–0.10	0.39	0.08	0.03	0.15	0.29	–0.06	0.23
April	–0.54	0.41	–0.49	0.41	–0.58	1.37	–0.29	0.35
May	–0.22	0.44	–0.24	0.45	–0.16	0.15	–0.35	0.42
June	0.30	–0.50	0.11	–0.18	0.68	–0.17	–0.13	–0.10
July	0.98	–0.26	0.39	–0.13	0.44	–0.07	0.03	0.00
August	0.33	–0.16	0.09	–0.02	0.12	–0.23	–0.11	–0.05
September	0.34	–0.57	0.06	–0.04	0.40	–0.52	–0.43	0.28
October	0.39	–0.54	–0.35	0.08	–0.04	–0.08	0.09	0.47
November	0.14	0.22	0.39	0.01	–0.62	0.51	0.64	–0.72
December	0.06	–0.23	0.65	–1.06	–0.56	0.41	0.29	–0.27

4.3 Seasonal Spatial Patterns of Temperature Extremes during El Niño and La Niña

As mentioned in the earlier section the composite all-India mean monthly anomalies in temperature extremes have an association with El Niño/La Niña events. It should also be noted that all the months of each season show similar pattern of relationship with El Niño/La Niña, with characteristic change in the ENSO-associated extremes with the onset of the summer monsoon in June. Pre-monsoon season (MAM) is the hottest part of the year during which country faces extreme temperatures and heat wave conditions (Kothawale, 2004). It is well known that the Indian monsoon is one of the most dominant circulations of the atmosphere through its transport of heat and moisture from the tropics (Rajendran and Kotoh, 2008). Therefore, the indices of temperature extremes were analyzed to explore spatial coherence during pre-monsoon (MAM) and monsoon (JJAS). Figures 1(a, b) show MAM and JJAS seasonal spatial distribution of composite anomalies of frequencies of hot days and hot nights during El Niño and La Niña years.

The occurrence of hot days has a strong association with El Niño and La Niña events and a marked spatial coherence. Frequencies of hot days show a strong association as compared to hot nights. Also, for MAM, strong association has been observed over central and northern parts of India. Inconsistent with known association of ENSO with the Indian summer monsoon activity (Pant and Rupa Kumar, 1997), overall increase in hot frequencies has been noticed during El Niño events. Figures 2(a, b) show a weak but opposite association of frequencies in cold days and cold nights with El Niño or La Niña events. For the frequency of cold events also, day time frequencies have a strong association with ENSO; however, night time frequencies have a weak association. The spatial distribution of composite anomalies can also be seen for intensity indices, viz., highest maximum temperature and lowest minimum temperature [Figs. 3(a, b)]. El Niño leads to an increase in extreme highest temperature during monsoon. It is worth mentioning that the cloudy and humid conditions during the summer monsoon season are primarily responsible for the elevated temperature. Both the highest maximum temperature and the lowest minimum temperature show a decrease in temperature during pre-monsoon season. However, the lowest minimum temperatures do not show negative anomalies during monsoon, especially over northwest India.

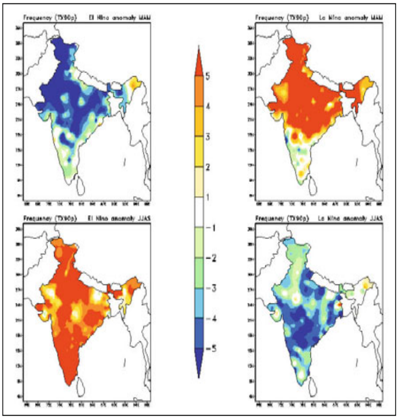

Fig. 1(a) Composite anomalies of frequencies of hot days (TX90p) during El Niño (left) and La Niña events (right). Top panel is for the pre-monsoon season (MAM) and bottom panel is for the monsoon season (JJAS).

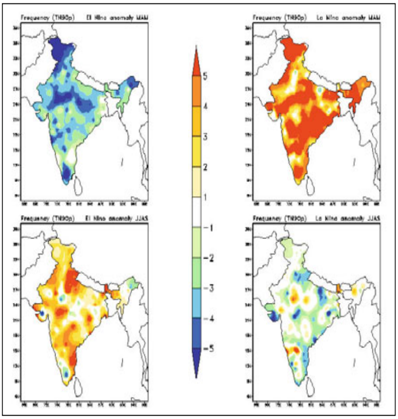

Fig. 1(b) Composite anomalies of frequencies of hot nights (TN90p) during El Niño (left) and La Niña events (right). Top panel is for the pre-monsoon season (MAM) and bottom panel is for the monsoon season (JJAS).

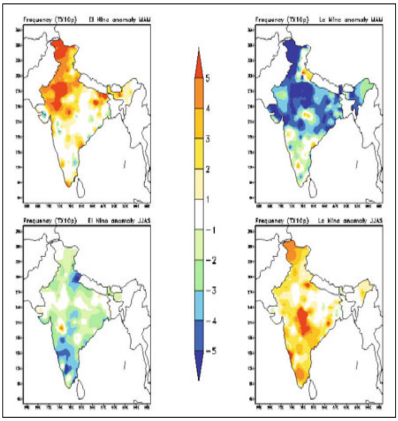

Fig. 2(a) Composite anomalies of frequencies of cold days (TX10p) during El Niño (left) and La Niña events (right). Top panel is for the pre-monsoon season (MAM) and bottom panel is for the monsoon season (JJAS).

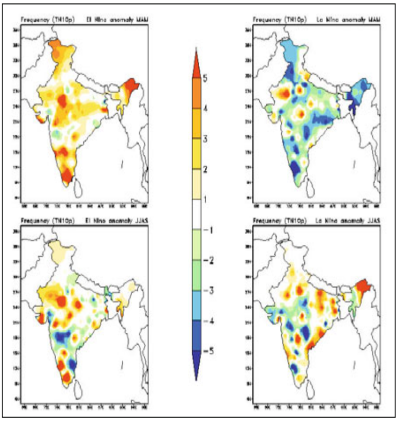

Fig. 2(b) Composite anomalies of frequencies of cold nights (TN10p) during El Niño (left) and La Niña events (right). Top panel is for the pre-monsoon season (MAM) and bottom panel is for the monsoon season (JJAS).

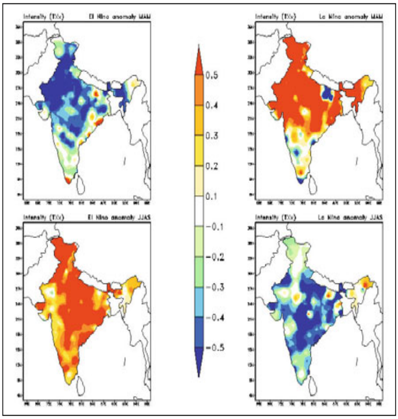

Fig. 3(a) Composite anomalies of hottest day temperature (TXx) during El Niño (left) and La Niña events (right). Top panel is for the pre-monsoon season (MAM) and bottom panel is for the monsoon season (JJAS).

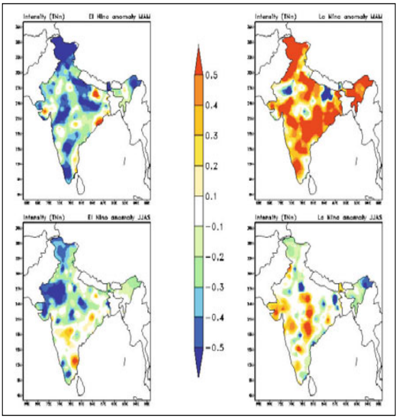

Fig. 3(b) Composite anomalies of coldest day temperature (TNn) during El Niño (left) and La Niña events (right). Top panel is for the pre-monsoon season (MAM) and bottom panel is for the monsoon season (JJAS).

4.4 Lag-Correlation of Extreme Temperature Indices with NINO3.4 SSTs

For the Indian region, pre-monsoon (MAM) is the hottest and winter (JF) is the coldest season of a year. Therefore, the existence of lag-correlation is examined for the indices of temperature extremes occurring during JF and MAM with NINO3.4 sea surface temperature, which would be helpful to have a prior indication of cold or hot events. Table 8 presents lag (–1) correlations of hot events during MAM/cold events during JF with NINO3.4 SSTs. Frequencies of both hot days and nights during MAM have positive correlations with NINO3.4 SSTs for all months from January to December of preceding year. Correlations are weak during the beginning of the year, then start increasing and become strong in May onwards and again decrease towards the end of the year. Similar relationship is seen for the highest maximum temperature also, with positive correlations in all lag-1 months and a significant relationship in mid of the year. However, the relationship is weak compared to the frequencies of hot day and night. For the frequencies of cold day and night occurring during JF, opposite relationship can be seen to that of frequencies of hot day and night occurring during MAM. For these indices, positive but weak relationship was observed at the beginning of previous year. It changes its sign to negative in the month of March and becomes stronger from March onwards. For the cold nights, correlations are strong negative with statistically significant at 1% level towards the end of the previous year. The lowest minimum temperature during JF shows strong positive correlations towards the end of previous year. On the whole, extremes in minimum temperature have strong correlations. The frequencies of hot (cold) nights have a strong correlation than the frequencies of hot (cold) days. Magnitudes of the correlations of hot nights are higher than those of cold nights. Correlations of frequencies in hot and cold events are opposite to each other in sign.

Table 8. Correlations of seasonal temperature extreme indices over India with monthly NINO3.4 SSTs

Month	*JF*			*MAM*		
	TN10p	*TX10p*	*TNn*	*TN90p*	*TX90p*	*TXx*
January	0.06	0.05	–0.09	0.08	0.24	0.25
February	0.01	0.01	–0.04	0.13	0.28	0.26
March	–0.06	–0.07	0.02	0.19	0.34*	0.30
April	–0.17	–0.18	0.13	0.31	0.41*	0.34*
May	–0.26	–0.13	0.24	0.40*	0.44**	0.34*
June	–0.37*	–0.19	0.33	0.45**	0.42*	0.32
July	–0.45**	–0.29	0.43*	0.55**	0.47**	0.39*
August	–0.47**	–0.30	0.45**	0.59**	0.49**	0.38*
September	–0.49**	–0.34*	0.44**	0.53**	0.42*	0.31
October	–0.46**	–0.28	0.43*	0.40*	0.28	0.20
November	–0.47**	–0.27	0.45**	0.38*	0.27	0.19
December	–0.44**	–0.23	0.42*	0.35*	0.26	0.17

* Significant at 5% level; ** Significant at 1% level.

5. CONCLUSIONS

Analysis based on the indices of temperature extremes derived from daily station data for maximum and minimum temperature over the period 1971-2003 for well distributed network of 121 stations suggest tendency of Indian regions toward the warmer climate and also the warm events are frequent during the recent period. An analysis also suggests that the temperature extremes over Indian region have conspicuous association with El Niño and La Niña events. The analysis of this study indicated that the onset of summer monsoon in June shows a characteristic change in ENSO-associated temperature extremes. This is consistent with the known associations of ENSO with summer monsoon rainfall activity. El Niño leads to an increase in the frequencies of hot events and a decrease in the frequencies of cold events. In addition, El Niño is associated with an increase in the temperature of intensity indices, i.e., highest maximum temperature and lowest minimum temperature. Spatial distribution of composite anomalies of various indices of temperature extremes shows a spatial coherence during El Niño and La Niña. Correlation analysis suggests that the frequencies and intensities are modulated by NINO3.4 SSTs. Strong correlations were found in extremes in minimum temperature and in frequencies of hot events. An ENSO is well known to be associated with weakening of Indian summer monsoon and it is also known to be associated with the strengthening of northeast monsoon rainfall activities. Therefore, it causes increase in temperature over the country during summer monsoon and decrease in temperature over northeast monsoon.

Strong relationship of seasonal temperature extremes over Indian region with the ENSO is consistent with other regional studies made by Muller et al. (2000), Rusticucci and Varagas (2002) and Nicholls (2005) for Pampa Humeda region, Argentina and East Asia/west Pacific respectively.

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