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Impact of Global Warming on Tropical Cyclones and Monsoons

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1. Introduction

Tropical cyclone is one of the most hampered natural hazard in the North Indian Ocean. The North Indian Ocean is divided by the Indian sub continent into two ocean basin one is Bay of Bengal and the other one is Arabian Sea. Bay of Bengal is the most vulnerable to cyclones than Arabian Sea. Recent studies suggest that cyclone activity over the North Indian Ocean (NIO) has changed over the second half of the 20th Century (Mooley, 1980; Rao, 2002; Knutson & Tuleya, 2004; Emanuel, 2005; Landsea, 2005; IPCC, 2007; Muni Krishna, 2009; Yu and Wang, 2009). General features include a poleward shift in strom track location, increased strom intensity, but a decrease in total storm numbers and also the ocean response in the weak of cyclone. Sea surface temperature (SST) is a fuel to tropical cyclones for their genesis and intensification. Global warming heats both the sea surface and the deep water, thus creating ideal conditions for a cyclone to survive and thrive in its long journey from tropical depression to Category Four or Five superstorm.

SST increasing is so fast and high in the equatorial Indian Ocean compared with other the oceans. It has increased 0.6°C over the NIO since 1960, the largest warming among the tropical oceans. Recent increase in frequency of severe tropical cyclones is related to the increase in SST in response to global warming. Higher SSTs are generally accompanied by increased water vapour in the lower troposphere, thus moist static energy that fuels convection. The large scale thermodynamic environment (measured by Convective Available Potential Energy, CAPE) become more favorable for tropical cyclones depends on how changes in atmospheric circulation, especially subsidence, affect the static stability of the atmosphere, and how the wind shear changes (IPCC, 2007).

Despite an increase in SST over the Bay of Bengal (Sikka 2006), observational records indicate for a decline in the number of depressions over the Bay of Bengal since 1976 (Xavier and Joseph 2000), and various factors are attributed to this trend that includes weakening of the low-level westerly flow over the Arabian Sea (Joseph and Simon 2005), decrease in the horizontal and vertical wind shears as well as in moisture and convection over the Bay of Bengal (Mandke & Bhide 2003; Dash et al., 2004).

Vertical wind shear and high static stability has an adverse influence on tropical cyclone formation and on cyclone strength and longevity (Gray, 1968; Hebert, 1978; DeMaria, 1996; Shen et al., 2000; Garner et al., 2009). Joseph & Simon (2005) indicate that low level jet stream associated with Indian summer monsoon over the NIO is weakening in recent years, which reduces the vertical easterly shear and thus it is favorable for the formation of more intense tropical cyclones. In the NIO, vertical wind shear is determined by gradients of SST both locally within the ocean basin and remotely from the Indo-Pacific (Shen et al., 2000). High static stability suppresses deep convection during cyclogenesis and educes the potential intensity (Emanuel, 1986; Holland, 1997) of organized cyclones. The contrast between SST and upper tropospheric air temperature is decide the stability.

Tropical cyclones produce significant changes in the underlying ocean thermodynamic structure, which also involves SST changes. SST may decrease by up to 6°C as a result of strong wind forcing. Vertical turbulent mixing within the upper oceanic layer, accompanied by the mixed layer deepening and entrainment of cooler thermocline water to the warm mixed layer, is the primary mechanism of SST decrease during the tropical cyclone passage. The heat fluxes to the atmosphere account for less than 20% of the total SST decrease.

Surface-air-temperature over the world has been warmed by 0.7°C since last 100 years. This is due to both natural and anthropogenic forcing, which result in year-to-year change of temperatures over the globe and there is a drastic change in shooting up of temperature in the last three and half decades due to abrupt increase of Green House Gases (GHGs), which geared up catastrophic climate change over several parts of the globe. Recently climate experts at a monitoring station in Hawaii reported CO_2 level in the atmosphere have reached a record 387 parts per million, which is 40% higher than before the industrial revolution. Tyndall centre for climate change research, for instance suggests that even global cuts of 3% a year starting in 2020, could leave us with 4°C of warming by the end of the century. The Inter governmental Panel on Climate Change (IPCC) has explained the impact of global warming upon mankind with special reference to developing countries of Africa and Asia and alerted the developed countries to reduce GHGs. Of the developing countries, India with its second highest population in the world is mainly affected by way of vagaries of monsoon in terms of floods, droughts and extreme episodes due to climate change. In the fourth assessment report of the IPCC, it is estimated that there will be 2°C enhancement of temperature in the coming 30-years.

Several effects of global warming, including steady sea level rise, increased cyclonic activity and changes in ambient temperature and precipitation patterns are projected in India. Heavy monsoon rains in central India between 1981 and 2000 were more intense and frequent than in the 1950s and 1960s and increased by 10% since the early 1950s and it was attributed to global warming by Goswami et al., 2006. Extreme events like severe drought in the year 2002 and 100cm heavy rainfall on 26^{th} July, 2005 were a few examples during monsoon season. There are some more studies, which indicate that India's long-term monsoon climatic stability is threatened by global warming. Of them, Hingane et al., (1985) studied the long-term trends of surface-air-temperatures of India with a limited data and their analysis showed that the mean annual temperature has increased by 0.4°C during the past century. Later Rupakumar & Hingane (1988) have reported the results of the analysis of long-term trends of surface-air- temperatures of six industrial cities in India. Next, Murthy et al., (2000) estimated costs associated with a low GHG energy strategy in terms of foregone income and welfare of the poor. The impact of climate change on agricultural crop yields in India, GDP and welfare is well studied by Kumar and Parikh (2001a and 2001b) and Rosenzweig and Parry (1994). Lal et al., (2001) concluded that annual mean area-averaged surface warming over the Indian subcontinent to range between 3.5°C and 5.5°C over the region during 2080s, while the DEFRA (2005) suggested that for a warming of 2°C, the yields of both rice and wheat will fall in most places, with the beneficial effect of increased CO_2 being more than offset by the temperature changes over India; similar results have been found for soybean (Mall et al., 2004). Next Battacharya and Narasimha (2005) studied the possible association between Indian monsoon rainfall and solar activity. Ashrit et al., (2005) investigated the impact of anthropogenic climate changes on the Indian summer monsoon and the ENSO-monsoon teleconnection. Later Bhaskaran and Lal (2007) studied the impact of doubling CO_2 concentrations on climate by using UK Met Office models, which is a coupled climate model indicated reasonable simulation of present day climate over the Indian region. In a pilot study, Bhanu Kumar et al., (2007 and 2008) thoroughly investigated increase of surface-air-temperature trends over two states of India namely Rajasthan and Andhra Pradesh with a limited data and they concluded that there is a significant warming trend. In view of the above studies, an attempt has been made in the present study to investigate the relation between weather disturbances and sea surface temperature, vertical wind shear and temperature gradient over the North Indian Ocean and also examined the impact of warming due to GHGs over the changing monsoon climate of India.

2. Data and methodology

For the present study, the authors used monthly wind and air temperature data from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset (Kalnay et al. 1996). The source of data of tropical cyclone frequency in the North Indian Ocean for the period 1877-2009 is an India Meteorological Department (1979 and 1996). The data for 1986 – 2009 have been obtained from different volumes of the quarterly journal Mausam. GISS mean monthly surface-air-temperature anomalies data for the study of annual and seasonal variations during 1880-2006, which is obtained from the NASA website (http://www.cdc.noaa.gov/cdc/data.gisstemp.html). Analysis of the NASA GISS Surface Temperature (GISTEMP) provides a measure of the changing global surface temperature with monthly time scale since 1880, when reasonably global distributions of meteorological stations were established. Above dataset is available on an equal area grid (1°x1°). In this study, we used the 250 km smoothing data over whole of India for 280 grids. For the study of climate change over India, the mean monthly Indian rainfall data is used for a period of 1871-2006, which is supplied by the Indian Institute of Tropical Meteorology (IITM), Pune (www.tropmet.res.in). The NCEP/NCAR reanalysis wind data is also obtained for the period 1970-2006 for circulation changes (http://www.cdc.noaa.gov).

In methodology, the homogeneity of the temperature and rainfall datasets have been tested by Swed & Eisenhart's test (WMO 1966). The median and the number of runs above and below the median have been obtained and these are given in table 1. Next, Mann-Kendall test is used for long term trends, while Cramer's running mean test is applied to isolate periods of above and below normal temperature and rainfall. Finally correlation and regression analyses are also used to detect relationship between temperature and rainfall.

Tropical vertical wind shear and temperature gradient over the NIO (5° - 20°N and 40° - 100°E) is given by

Wind Shear $(WS)_{200\text{-}850} = U_{200hPa} - U_{850hPa}$, $WS_{200\text{-}925} = U_{200hPa} - U_{925hPa}$ and

$WS_{150\text{-}850} = U_{150hPa} - U_{850hPa}$,

Temperature gradient $= T_{500hPa} - T_{100hPa}$

Details of the statistical tests used in this study are given below.

Mann-Kendall test:

In climatological time series, the successive values are not likely to be statistically independent of one another, owing to the presence of persistence, cycles, trends or some other non-random component in the series. In view of this, Mann-Kendall test is applied for trends for surface-air temperatures and rainfall as follows:

$$\tau = 4\sum_{i=1}^{n-1}\frac{n_i}{N(n-1)} - 1 \tag{1}$$

Where n_i is the number of values subsequent to i^{th} value in the series exceeding i^{th} value. The value of τ was tested for the significance by the statistic $(\tau)_t$, which is given by

$$(\tau)_t = t_g\sqrt{\frac{4N+10}{9N(N-1)}} \tag{2}$$

Cramer's test:
The aim is to examine the stability of a long term records in terms of comparison between the overall mean of an entire record and the mean of the certain part of the record (WMO 1966).

$$t_k = \sqrt{\left[\frac{n(N-2)}{N-n(1+r_k^2)}\right]}r_k \tag{3}$$

The statistics t_k is distributed as 'Student's t' with N-2 degress of freedom. This test may be repeated for any desired number and choice of sub periods in the whole record. The time plot of the t-value gives the pictorial representation of variability.
Student's t-test: In order to estimate trends in wind shear, temperature gradient and cyclones, simple linear regression technique was used. These trends have been tested by using Student's *t*-test. The statistic, t is given by:

$$t = b\left[\frac{(N-2)\sum(x-\overline{x})^2}{\sum(y-\widehat{y})^2}\right]^{\frac{1}{2}} \tag{4}$$

Where $b, N, x, \overline{x}, y$ and $\widehat{y}$ represent the slope of the regression, the number of years of data, the year, mean of the years, actual shear and estimated shear respectively. This regression analysis gives an indication of the overall tendency of the wind shear and temperature gradient.

3. Results and discussions

3.1 North Indian ocean warming

A number of features of the tropical climate are relevance to tropical cyclone activity appear to be changing in a trend-like fashion. Based on Hadley Center Sea surface temperature, there is an increasing trend in the recent era (1981-2009) compared with the previous eras (1870-1949 & 1950-1980) over the NIO (Fig 1.). Strong positive SST anomalies (0.8°C) are observed during the period of 1981-2009. This is one of reason for the formation of intense tropical cyclones over the NIO. Strong negative (cc = - 0.26, significant at 99.9 %) relationship is observed between SST anomaly and depressions, cyclones (-0.33, significant 99.9%) and positive (0.05) relation with severe cyclones during 1877-2009. But in 20^{th}

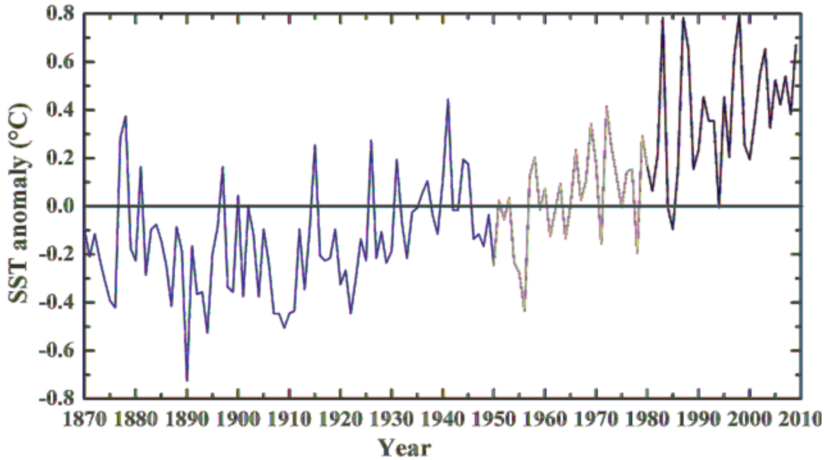

Fig. 1. SST anomaly over the NIO (40°E – 100°E, 5°N – 25°N) during southwest monsoon season. Blue, pink and red colour indicates 1870 – 1949, 1950 – 1980 and 1981 – 2009 respectively.

century 1981-2009) very high negative correlation is noticed between depressions (-0.38, significant at 99%), decrease with cyclone (-0.04) and strong positive correlation with severe cyclones (0.27 significant at 99%). It enlightens that the depressions are decreasing and intense severe cyclones are increasing in the 20th century over the North Indian Ocean. For example, in 2007 category 5 severe cyclone (Gonu) formed in the Arabian Sea after 70 years. The SST increase is a response to the long-term increases in greenhouse gas concentrations. Human induced change in greenhouse gas forcing is the main cause of the rapid increase in SST during 1981-2009 warming. This result is supported by the several other model simulations (Knutson et al., 2006).

3.2 Vertical wind shear

The averaged vertical wind shear for the southwest monsoon season between the upper and lower atmospheric layer over the North Indian ocean is shown in Fig 2. A decrease of 4.2 m/s in easterly shear is observed in a period of 60 years over the NIO. The decrease in the shear is high in 20th century compared with the previous decades. This feature is coinciding with the North Indian Ocean warming. The correlation between shear (in three layers i.e, u(200-925), u(200-850 hPa), u(150-850 hPa) and SST anomaly is -0.5, which is highly significant at 99.9 % level.

The relation between the vertical wind shear over different atmospheric layers and frequency of weather disturbances over the North Indian Ocean is given in Table 1. The relationship between depression and vertical wind shear in all the atmospheric layers shows negative in both before (1950-1980) and in the global warming era (1981-2009). This relation is also statistically significant at 95 % and 99% level. It means that higher easterly wind shear generates more depressions. Fascinatingly the relationship between wind shear and severe cyclonic storm is opposite (positive) i.e. lower shear is more flattering for the formation of more number of severe cyclonic storm. Gray (1968) was suggested that the tropical cyclones of hurricane intensity over several basins including North Indian Ocean basin occur only when the vertical wind shear is small (around 10 m/s between 850-200 hPa). Recently formed sever cyclonic storm (Phet, during 31 May 2010 - 7 June 2010) over the Arabian Sea supporting the impact of global warming on the intensity of severe cyclonic storm. It is the second strongest severe cyclonic storm (first one is Gonu in 2007) to hit the Arabian Peninsula since record keeping began more than 60 years ago.

Layer	Depressions	Cyclones	Severe Cyclones	SST anomaly
200-925 hPa	-0.23 (-0.31)	0.01 (0.13)	0.44*** (0.15)	0.50***
200-850 hPa	-0.28* (-0.27)	-0.05 (0.08)	0.42*** (0.11)	0.50***
150-850 hPa	-0.46** (-0.36)	-0.15 (0.07)	0.33** (0.07)	0.50***

Table 1. Relationship between the weather disturbances and vertical wind shear, SST anomaly over the North Indian Ocean during 1950-2009. Brackets represents for the period of 1981-2009. (*, ** and *** indicate the levels of significance, 95%, 99% and 99.9% respectively).

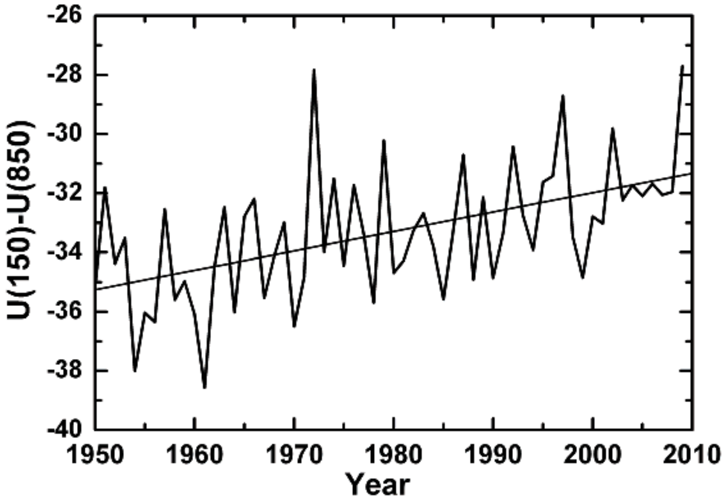

Fig. 2. Vertical wind shear (m/s) of zonal wind during southwest monsoon season over the North Indian Ocean.

3.3 Air temperature gradient

The air temperature difference between lower and upper atmosphere shows an increasing trend (Fig 3) during the southwest monsoon season over the North Indian Ocean. The increasing linear trend is 0.5°C in 60 years which is also significant at 99.9 % level. It shows a strong environmental warming in the layers of the atmosphere over the North Indian Ocean. The increase trend in air temperature and SST anomaly in 20^{th} century over the tropical NIO, capitulates reduced wind shear.

3.4 Mid tropospheric humidity

Mid tropospheric (relative humidity difference between 700 hPa and 500 hPa) is one of favorable condition for the formation and intensification of tropical cyclone in the North Indian Ocean (Fig 4). In 20^{th} century the mid tropospheric humidity (MTH) trend is increasing (~ 6 %). Along with the increase SST anomaly, decrease in wind shear and increasing trend in

MTH is also give an indication of increase intense tropical cyclone over the North Indian Ocean. The correlation between severe cyclones and MTH is 0.23. A strong relation is observed with vertical wind shear (0.24, 0.30 and 0.51 with the layers 200-925, 200-850 and 150-850 respectively). The relation is strong with the upper layers (150-850 hPa) of the atmosphere (which is the most important wind shear for the formation of intense cyclones). SST anomaly is also shows good correlation with MTH (0.61, significant at 99.9 % level).

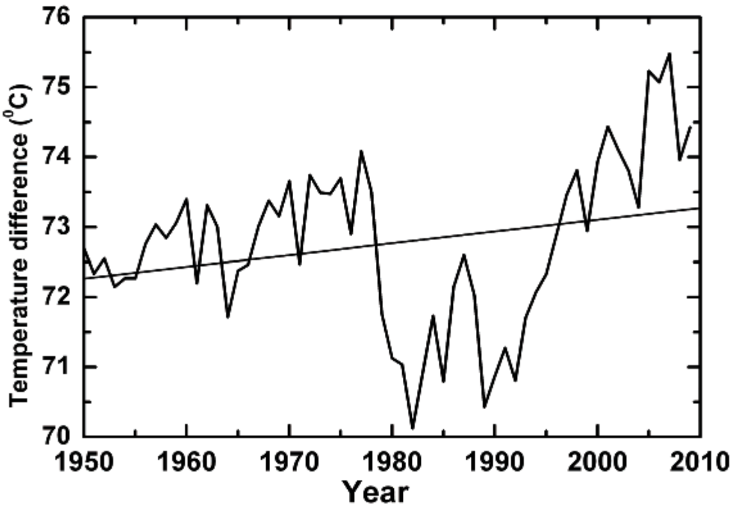

Fig. 3. Air temperature difference between lower (500 hPa) and upper (100 hPa) atmosphere during southwest monsoon over the North Indian Ocean.

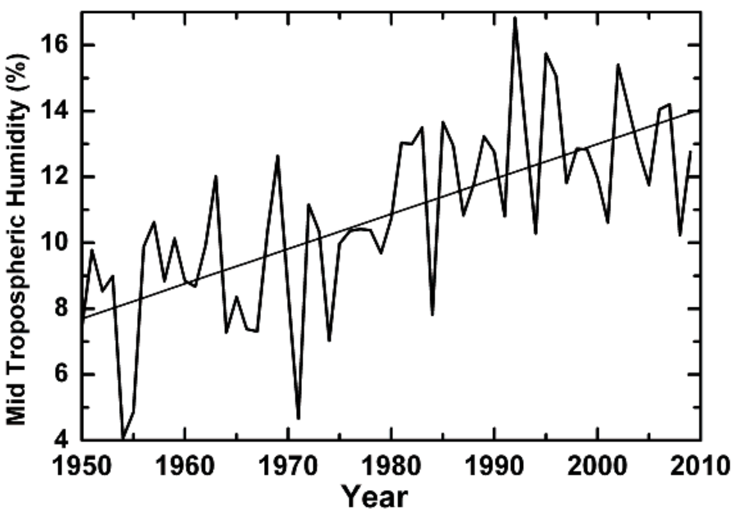

Fig. 4. Mid tropospheric humidity (700-500 hPa) during southwest monsoon over the North Indian Ocean

3.5 Trends of surface-air-temperatures and rainfall over India

The earth's climate is dynamical and always changing. The climate of a place is the average weather that it experiences over a period of time. The factors generally determining the climate of a region are temperature and rain in this study. For temperature and rainfall series, values of statistics for Mann-Kendall rank statistic test have been calculated and the results are given in table 2. The test statistic for N=127 significant at 5% is ±0.1167 and significant at 1% level is ±0.1552. On examination of the table, there is no suggestion of non randomness in the series and that for the purpose of our statistical analysis, these series could be taken as random.

Analysis of mean monthly surface-air-temperature for 280 grids over India is averaged from January through December for annual, SW monsoon (June, July, August and September; JJAS) and NE monsoon (October, November and December; OND) seasons. Fig. 2a indicates year-to-year variations of annual surface-air-temperatures over India for the study period and it clearly indicates that there are 10 hot episodes (based on ±0.5 anomaly; 1910, 1938, 1955, 1984,1985, 1994,1995,2000,2003 and 2006) over the study region. Of them, 7 episodes were recorded during 1970-2006. Trends are also evaluated for the whole of the study period and recent three and half decades separately, which amount to 0.57 and 0.68 (significant at 5% level) respectively. This trend line clearly indicates that global warming is significantly increased during 1970-2006. This is due to a reason that GHGs emissions have grown since pre-industrial time (1970-2006) with an increase up to 70%. Along with the CO_2, the production of CH_4 is also a maximum extent over India and both may lead to climate variability.

Season	Median	No. of runs above and below the median	Mann-Kendall rank statistic test
Annual	-0.097 (1094.3)	46 (60)	6.5 (-0.21)
Southwest	0.001 (860.0)	53 (70)	6.0 (-1.12)
Northeast	0.153 (124.4)	39 (64)	6.5 (0.72)

Table 2. Median, Swed & Heisenhart and Mann-Kendall rank statistic tests for Surface-air temperatures and rainfall (in brackets).

Coming to monsoon season (Fig. 5b), the aberrations of the temperatures are reduced drastically due to the influence of monsoon. There are 8 warm episodes and figure indicates that the many of the warm episodes were noticed during 1970-2006 as similar to annual. The trend values are very close to 0.54, which is significant at 5% level for above specified periods. For the NE monsoon season (Fig. 5c), the surface-air-temperatures are relatively higher for the last three and half decades (1970-2006), but at the beginning i.e. from 1880 onwards up to 1970 the anomalies of the surface-air-temperatures were negative. The trend value for the NE monsoon is same (0.57) for both periods. Similarly an attempt is also made to find out trend values for rainfall series during the study period and recent three and half decades. Those are not at all significant (not shown here).

3.6 Decadal variability of surface-air-temperature and rainfall over India

To have a broader outlook of smoothed temperature and rainfall variations, decadal variability is also evaluated with Cramer's t-statistic test (Fig.6). Fig 6a shows values of Cramer's t-statistic for the 31-year running means of surface-air-temperatures (line format) and all India annual rainfall (bar format). The most striking features are the epochs of above and below normal temperatures and rainfall. It throws light that the temperatures were running above normal during the decades 1930-2006, while there appears to be an inherent internal epochal variability in the rainfall series. The period 1915-50 (1880-1915 and 1950-76) are characterized by above (below) normal rainfall with a very few (frequent) droughts. The turning points are noted around 1915 and 1950. The transition from one state of above (below) normal is an interesting sinusoidal feature. The fall from an extreme state of below normal occurs in a short span of about a decade (1940-1950). However, the rise above normal state is gradual and may take about four decades (1910-50).

The Cramer's t-statistic test for surface-air-temperatures of SW monsoon season shows that there is a turning point around 1900 and the above normal temperatures are continuing till 2006 (Fig.6b). The 31-year sliding Cramer's t-statistic test for all India monsoon rainfall (Fig.6b) shows that the most striking feature is the presence of multi-decadal epochs of

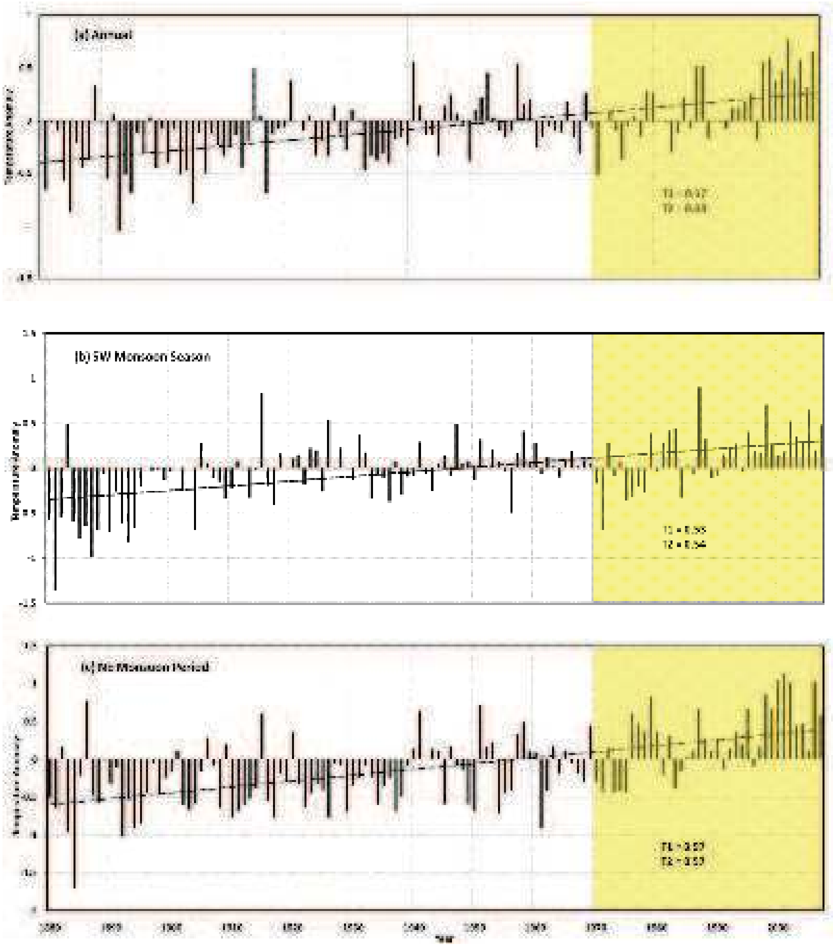

Fig. 5. Variation of all India surface-air-temperature (Dashed line is trend; T1-trend for 1880-2006, T2-trend for 1970-2006).

above and below normal rainfall. The rainfall shows major turning points around 1915 and 1955. The transition from one state of above or below normal monsoon rainfall is an interesting sinusoidal feature like annual rainfall series above. The monsoon rainfall series is free from any sub-period (31-year) trend since nowhere the Cramer's test for 31-year running mean is statistically significant. Thus there is a lot of similarity in the trend and variability of rainfall in both annual and monsoon seasonal rainfall. Similarly for NE monsoon period, temperatures attained increasing tendency since 1960, while rainfall shows major turning points during 1910, 1960 and 1970 (Fig.6c). In general it has been observed that variability is below during the epochs of above normal rainfall.

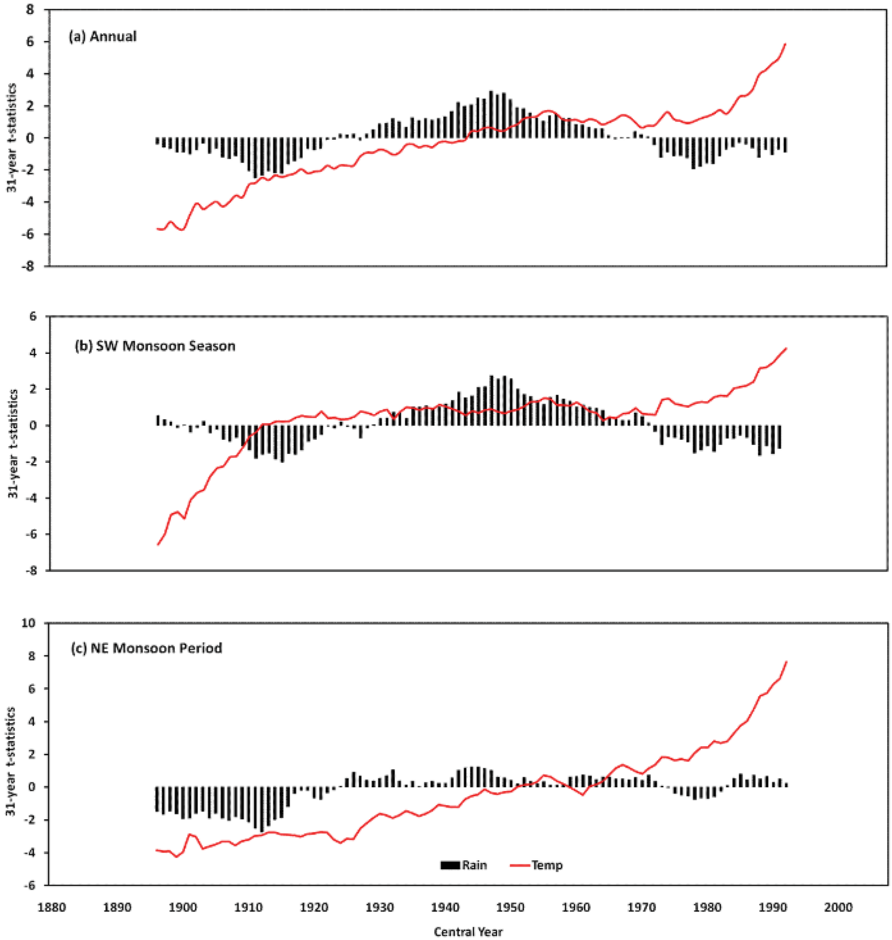

Fig. 6. Values of Cramer's t-statistics for the 31-year running mean depicting climatological variability and epochs of above and below normal rainfall and surface and air temperatures. Values are plotted at the centre of 31-year period.

To further examine the signature of above surface-air-temperatures on rainfall of annual and seasons over India, correlation coefficient is found for 11-year running mean datasets. This study clearly indicates that the impact of temperatures on monsoon rainfall is significant (r = -0.4). Hence the stability of Indian monsoon rainfall is more or less influence to some extent with considerable year-to-year variability in surface-air-temperatures over India.

3.7 Observational evidence of circulation changes during warm/cold temperature episodes

To substantiate above significant inverse relationship between global warming and monsoon rainfall, an attempt is made to investigate contrasting circulation changes in the typical years of clod (1998) and warm (2002) episodes. The chief amounts of monsoon seasonal rainfall were 105% in 1998 and 81% in 2002. Figure 7a shows the anomaly U-wind

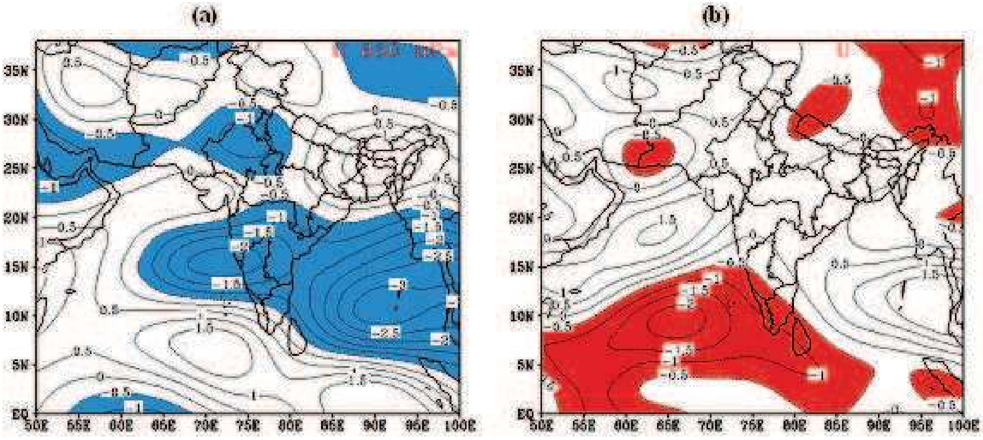

Fig. 7. Anomaly U-wind at 850 hPa level during (a) cold episode-1998 and (b) warm episode-2002.

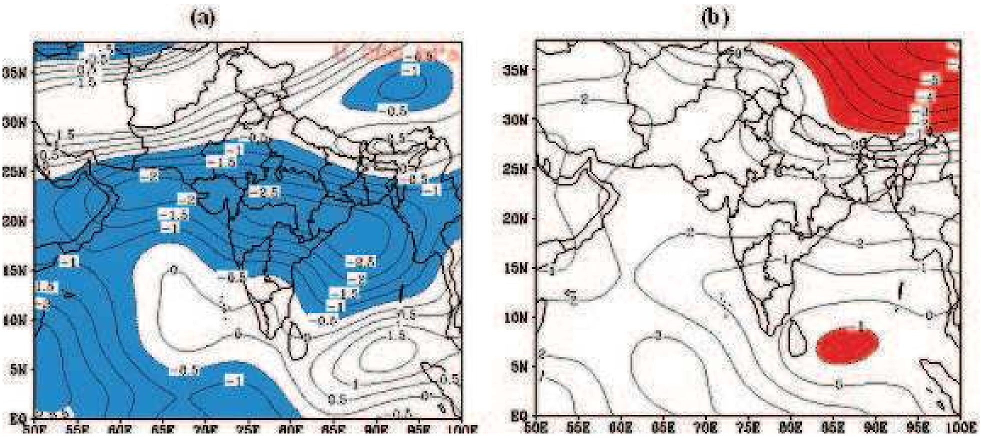

Fig. 8. Same as above except for U-wind at 200 hPa level.

at 850 hPa level for cold episode (1998) and it indicates excess westerly wind (2 m/s) over southern India and parts of Bay of Bengal and Arabian Sea. In warm episode (2002), the anomaly wind pattern is weak (Fig.7b). Similarly the wind filed at 200 hPa during 1998 is negative over parts of Arabian Sea, Bay of Bengal and whole of India except southern tip of India. Anomaly wind speed of -1.5 m/s is observed in the region of tropical easterly jet, while opposite wind appear in 2002 (Fig. 8b). Thus Indian summer is due to a series of feed back mechanisms where in global warming is one important such parameters.

4. Conclusions

The negative anomaly of SSTs over the North Indian ocean is one of the major impacting factor in explaining the lack of major intensification of sever storm during summer monsoon season. The occurrence of intense tropical cyclones in the North Indian Ocean has chronicled increasing trends during southwest monsoon. The increasing trend has been primarily due to increase in SST anomaly, mid tropospheric humidity, temperature difference between lower and upper atmosphere and decrease in the vertical wind shear. In future evolution of North Indian Ocean storm activity will critically depend on the warming of the sea surface waters and also the vertical wind shear. Strong relationship between SST anomaly and vertical wind shear supporting the formation of intense tropical cyclone in the North Indian Ocean. Given the strong correlation between the decreasing easterly wind shear and the increasing number of severe cyclonic storms, decreased TEJ may lead to additional severe tropical storms of hurricane intensity over North Indian Ocean. The catastrophic storms in June 2007 portend disastrous conditions for the large fraction of the global population in the Indian sub-continent and adjacent regions. Other parameters than SST, however, such as the vertical stability of the atmosphere or changes in oceanic mixed layer depth also need to be considered in future projections of cyclonic activity over the North Indian Ocean. There is a growing concern that global warming may be affecting the monsoons and tropical cyclones, their frequency and intensity. The present study shows a good relationship between both ocean and atmospheric variables and severe cyclonic storms. If this trend is continue in future more and more intense cyclonic storms will occur in the North Indian Ocean.

The present study highlights that the increasing trend of temperatures is very similar to that of global warming increasing trend with a little difference of magnitude. The impact of climate change on the Indian monsoons in terms of seasonal rainfall is conspicuous to some extent, but it may be responsible for extreme weather events like Mumbai rainfall on 26th July, 2005 when the warm temperature episode was prevalent. The NCEP circulation changes at 850 and 200 hPa levels in two contrasting episodes show striking contrast in terms of Indian monsoon westerlies and strength of easterly jet stream etc. Climate change may exacerbate water shortage especially during the dry season, as India has 17% of world population with 4% of its water resources. Thus global warming may cut per capita water availability in India in future. This aspect may be further substantiated with global coupled ocean-atmospheric models. Thus more work needed to understand local manifestations of monsoon changes and the possible role of land-surface changes/process.

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Global Warming

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This book is intended to introduce the reader to examples of the range of practical problems posed by "Global Warming". It includes 11 chapters split into 5 sections. Section 1 outlines the recent changes in the Indian Monsoon, the importance of greenhouse gases to life, and the relative importance of changes in solar radiation in causing the changes. Section 2 discusses the changes to natural hazards such as floods, retreating glaciers and potential sea level changes. Section 3 examines planning cities and transportation systems in the light of the changes, while section 4 looks at alternative energy sources. Section 5 estimates the changes to the carbon pool in the alpine meadows of the Qinghai-Tibet Plateau. The 11 authors come from 9 different countries, so the examples are taken from a truly international set of problems.