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Research Article

Observational Studies of Monsoonal Droughts and Large Scale Traits

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Abstract

Rainfall variability of the Indian summer (JJAS) monsoon droughts are linked to regional and global parameters. Here, with the use of 30 years of various observational datasets of rainfall, winds, temperature and other major indices, the variability of Indian summer monsoon is explored for drought years. In recent, due to increase in ocean surface temperature, meridional temperature gradient over Indian land and nearby sea is decreased. On the scale of months to season the rainfall and circulation features grow in and out of phase over Indian, Pacific Ocean and African regions. Additionally, droughts over Indian regions are manifestation of the ITCZ's sway in meridional direction influenced by circulation and convective activities over Pacific, Indian and African regions. Ultimately, ENSO, warming in the regional oceans and internal dynamics remain the potential drivers of the ISMR droughts. In recent decades, Indian monsoon is showing favoritism towards drought.

Introduction

The geographical location of Indian subcontinent is unique in terms of, high orography in the north (Himalaya and Tibetan Plateau) and Indian ocean in south, make it a perfect laboratory where monsoon is busy in experimenting droughts and flood events one year to another. It appears that monsoon itself designs its experiments in such a way that no two monsoons are alike [1]. Rainfall variability over Indian region depends on certain regional and global conditions from the previous year and certain conditions from the same year to monsoon season viz. ENSO condition in eastern equatorial Pacific Ocean, heat low over Northern India and adjacent area, Tibetan anticyclone at 200mb, Tropical Easterly Jet (TEJ), intrusion of dry air, Subtropical Westerly Jet (STWJ), lows-depressions-cyclones, previous winter year's Eurasian snow cover and many more [2-6]. Likewise, all Indian monsoonal droughts are related to the above mentioned regional and global parameters [7-10]. In some other years, there are no major roles of the global and regional factor then monsoon is governed by its internal dynamics [11]. Ultimately, ENSO dry air intrusion, warming in the regional oceans, and internal dynamics are the potential drivers of the ISMR droughts.

Indian monsoonal drought in recent years (e.g., 2002, 2009, 2014 and 2015) drew our attention to revisit this problem. Since 1871 Indian region confronted total 25 droughts, while there were as many 32 years, when rainfall was below normal on all India basis [12]. Every summer (June-September) the distribution of rainfall is such that India is bound to faces drought over a smaller or bigger region. The severity of drought may vary amazingly from place to place and time to time. Once a wave of drought is blown out, the life of a common-man and farmers start to experience hardship in their daily activities [13]. Climatologically western part of India is virtually known a drought prone region, and rest of the India experiences wet and dry spells contemporary during June to September. In the literature of Indian monsoon, various drought indices and methods are defined to measure the intensity of monsoon droughts severity. The droughts during the period 1871-1995 are given in [14,12]. Even the hiatus in the summer monsoon rainfall for a large number days over India may lead to drought like conditions [15,16]. Long break of 20-25 days in the month July in 2002, made 2002 as the one of the worst drought years in the Indian history [17].

In last 30 years 6 major India monsoon droughts (1982, 1986, 1987, 2002, 2009 and 2015) were associated with ENSO event [2,18-22,12]. These drought years, were linked with above than normal winter snow cover over Eurasian region [23,24,5,6]. The role of dry air intrusion during monsoonal break also linked with monsoonal droughts [17,25,10]. Thus, internal dynamics, Eurasian snow cover and dry air intrusion are some of the bigger players in producing droughts over the Indian region. The main characteristics of ISMR are 1) Almost no rainfall over central India and heavy rainfall over foothills of Himalaya and east equatorial Indian ocean. 2) High pressure over central India. 3) Shift of monsoonal trough northern region of India.

The motivation of the research is inspired from the recent warming of the Indian Ocean and changes in various large scale circulation patterns related to Indian monsoon. Understanding the large-scale traits of the Indian monsoon droughts is the main goal of the study. In this work, droughts are defined based on rainfall variability only. A drought year is defined when monsoon seasonal rainfall (June-September) is less than 10% of the climatological normal. All such drought years are considered in this study. Authors believe, simply understanding the synoptic and dynamical features of various atmospheric-oceanic systems during a monsoonal drought may help readers immensely. Thus, one of the main issue addressed in this manuscript is the representation of all the large-scale factors those affects ISMR's rainfall. Previous studies and reports considered one

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aspect of large scale features associated with drought, one at time. This observational study raise questions, what are the impact of 1) the weakening of meridional gradient of surface temperature, 2) impact of ENSO on monsoon, 3) role of internal dynamics in the changing climate, on monsoonal droughts?

Material and Methods

The study uses datasets from various sources for the common period of 30 years (1982-2011). All India Summer Monsoon Rainfall (AISMR) (rain-gauge rainfall) datasets were obtained from Indian Institute of Tropical Meteorology (IITM). This dataset is based on fixed set of 306 uniformly distributed rain-gauges over Indian region [26]. Monthly gridded rainfall from CPC Merged Analysis of Precipitation (CMAP), has been used. CMAP dataset is a combined product from ground based rain-gauges and airborne satellite datasets [27]. Monthly means of air temperature, winds and Mean Sea Level Pressure (MSLP) were picked up from ECMWF ERA Interim data set. Outgoing Long wave Radiation (OLR) datasets were downloaded from NCEP/NOAA [28,29]. In addition, Optimum Interpolated Sea Surface Temperatures (OISST) was obtained from NOAA. The OISST uses buoy data, ship data, satellite SST data, and SST's simulated by sea-ice coverage. The satellite data is first adjusted for the biases using the Reynolds method and then only analysis is computed [30].

All the datasets are freely available online on their respective websites for research purposes. Large scale circulation features like Walker and Hadley circulations are calculated based on the zonal and meridional component of the wind field. Rainfall anomalies are calculated based on the 30 years (1981-2010) of rainfall climatology. The study area is limited to the Indian landmass and Indian summer (JJAS) monsoonal droughts for the composite plots years 1982, 1985, 1986, 1987, 2002, 2004 and 2009 are considered throughout the manuscript.

Results

Climatological features of monsoonal droughts over Indian subcontinent

India is the region of varied geographical structures in orography, land characteristics, forests and rivers. All these factors influence the rainfall up to an extent. Rajasthan state, in western India, is a desert region, receives very low rainfall during summer monsoon season. On the other hand, north-eastern part of India is covered with dense forest and windward side mountains, is one of the regions receiving high rainfall every year (more than 11 meters of rainfall, a wettest place) on the planet. Figure 1 shows the inter-annual variations of rainfall anomalies from June to September averaged over the area bounded by longitudes 67˚E to 95˚E and latitudes 8˚N to 35˚N. These rainfall anomalies are the percentage departures of rainfalls based on 30 years (1982-2011) of rainfall climatology taken from Indian Institute of Tropical Meteorology (IITM). CMAP rainfall anomalies are shown in light green color bars while rain gauge datasets from IITM are shown in light blue color bars. Both the rainfall series show decent interannual rainfall variability. The years 1982, 1985, 1986, 1987, 2002, 2004 and 2009 are the drought years for the Indian region. The Indian summer monsoon is defined as deficient if the rainfall deficiency is ≥ 1.0 σ (or ≤-10% in Figure 1)[see Sikka, 1999, where σ= Standard deviation. If all India rainfall is below -10% of the long term climatological normal, then it is called as the drought year. Interestingly CMAP dataset is also able to capture these droughts with correct sign and magnitude. However, the drought intensity in the year 1985 did not attain -10% level (a red dashed line in Figure 1). The bar diagram shows negative rainfall anomalies for 1982, 1985, 1986, 1987, 2002, 2004 and 2009 years while the years 1983, 1988 and 1994 show flood years with positive rainfall variability of 10% and above. Some of main reasons why CMAP rainfall datasets are not showing Indian summer monsoon rainfall variability, as shown by many researchers. In the figure 1, some years show amazingly different CMAP rainfalls than IITM rainfall, because of 1) The coarse resolution of CMAP rainfall datasets 2) Area averaged and coverage over different regions of India 3) The different durations of datasets used for rainfall climatology to calculate rainfall anomalies 4) The number of rain-gauges considered in CMAP data set are not uniform in time.

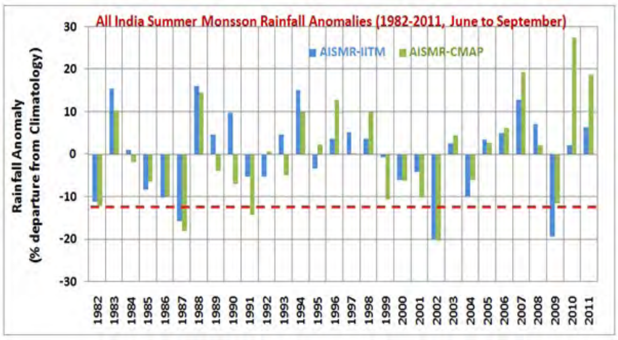

Figure 1: Interannual variability of Indian summer monsoon seasonal (June to September) rainfall anomalies.

Rainfall anomalies are the percentage departures of rainfalls from the mean. Mean rainfall is based on 30 years of data (1982-2011) from Indian Institute of Tropical Meteorology (IITM). India rainfall is in light blue color, and CMAP rainfall is in light green color. Region for area average is 67E-95E; 8N-35N.

Figure 2, shows climatological characteristics of rainfall distribution over Indian subcontinent region. Here maximum rainfall is usually received by Western Ghats, the Northeastern India, Bangladesh and Myanmar. Furthermore, two extensions of maximum rainfall (ITCZ) are located one over central Africa and another over western Pacific region. One more distinguishable patch of rainfall is seen over east equatorial Indian region, which is known as double ITCZ over Indian region during boreal monsoon. In most of the drought cases northeastern Indian region and western Indian shows opposite rainfall variability. As a matter of fact, during droughts most of the India experiences above normal atmospheric pressures and subsidence of colder and drier air-mass. It is shown that Indian summer monsoon rainfall does not show any trend [26].

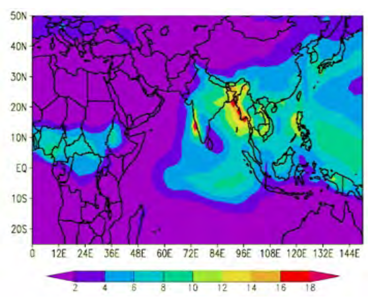

Figure 2: Climatological variations of summer monsoon rainfall over South Asian and African region. The climatology is based 30 years of datasets (1982-2011) from CMAP.

Figure 3a shows the mean sea level pressure climatology for 30 years. The intense solar heating over Indian subcontinent especially over northern India, Pakistan, Iran and Saudi Arabia, produces a low-pressure area. Basically, this low-pressure area prevails over South Asian region from Arabia to China during May to June months and disappears in any of the month, July, August and September. On the other hand, at surface level, two highs remain almost steady, one in the Southern Indian ocean (~70˚E, 30˚S) and another over the Australian region (~140˚E, 30˚S) from June to September. These lows and highs work in tandem to pull and push the Asiatic monsoon, over bigger South Asian countries. Their sway and movement in zonal and meridional directions create variability in Indian summer monsoon rainfall. As a fact, it is known that the meridional temperature gradient across the Indian landmass and Indian Ocean establishes the monsoon over Indian subcontinent (Figure 3b). Hence, the temperature and pressure distributions around the Indian subcontinent launch and maintain the summer monsoon. We are ignoring the circumstances of remote influence on the pressure pattern over Indian sub-continent. Recent, research reveals the weakening of the land sea temperature gradient, attributed to global warming. This is one of the reasons, India may face drought situations more frequent in future [31].

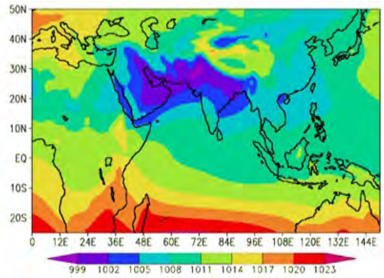

Figure 3a: Climatological MSLP in summer.

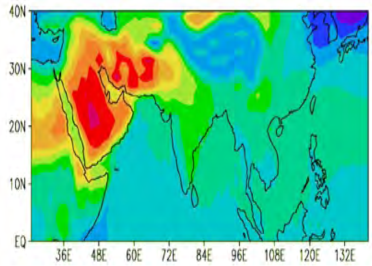

Figure 3b: Climatological temperature at 1000mb. The climatological data are based on 30 years of datasets (1982-2011).

Composite maps several variables for Indian summer monsoon droughts

The composite figures include 7 drought years (1982, 1985, 1986, 1987, 2002, 2004 and 2009) in the period of the study of 30 years (1982-2011). The extensions of these lower and higher MSLP are seen over the eastern side and western side respectively (Figure 4). The obvious features of high pressure are prevailed over western part of India while lower pressure prevails over north-eastern part of India.

Figure 5a, a composite of 7 rainfall drought years shows a clear cut, how northeastern region and rest of the India are opposite in nature. Interestingly the drought over Indian continent seems to have two limbs one on right side over Indonesian archipelagos and another over western side on and around 10˚N in African continent. An increased rainfall over eastern region of India is stretched up to western and central Pacific Ocean on eastern flank while over African region increased rainfall is observed around 5˚N. During Indian monsoonal droughts, the ITCZ shifts northward over Indian subcontinent and western Pacific Ocean and southwards over African continent [32,25]. The rainfall pattern is well accordance with MSLP pattern in figure 4. Such contrasting, meridional and parallel patterns of decreased and increased rainfall depict the meridional variations of ITCZ during active and break spells during monsoon. Indian region is influenced by western Pacific activities [33,32]. Moreover, equatorial eastern Indian Ocean also experiences a heavy rainfall due to subdued subsidence from local Hadley cell. One of important reasons, being less rainfall over India is the subsidence from the Walker cell. The northward movements of typhoon over western Pacific produce an abnormal subsidence over Indian region and a good rainfall over western Pacific region [32]. Most of the drought years over Indian regions are linked with the warmer than normal Sea Surface Temperature (SST) over Central and Eastern Pacific region termed as El-Niño (Figure 5b). SST is considered as the slowly varying boundary condition, which affect the weather pattern over tropical and subtropical regions and monsoonal rainfall as well. Another parameter which has been studies a lot in the context of Indian summer monsoon rainfall is Indian Ocean Dipole (IOD), which affects rainfall around Indian subcontinent up to some extent [34]. Indian Ocean does not display any IOD nature during drought, showing IOD has less to do with Indian droughts. The Figure 5b shows a tongue of warmer sea surface temperature over central Pacific Ocean for the composite of Indian summer monsoonal drought years. A point to note, that there is a shift of warming from east equatorial Indian Ocean to Central Ocean (specifically known as Modoki El-Niño [35]. Such warming proved to be more vulnerable to produce greater subsidence over Indian region [36].

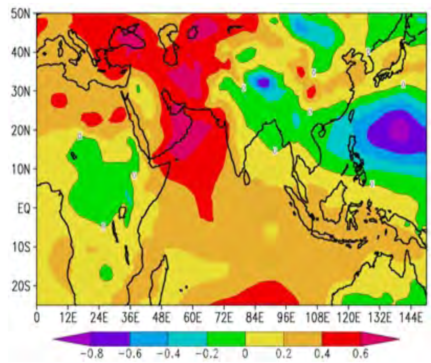

Figure 4: Rainfall anomalies for the composite of drought years.

The understanding of meridional variation of the ITCZ and rainfall in figure 4 & 5a, are well depicted in the OLR anomalies (Figure 6). Negative OLR anomalies over Eastern Indian region are opposite to the rest of India. Positive/negative OLR anomalies are associated with droughts/floods, an absence/presence of cloud cover. These positive OLR anomalies are extended up to central Africa and on other side up to Indonesian archipelago while negative OLR anomalies are prevailed over eastern India and western Pacific Ocean. Meridional migration of ITCZ is well demonstrated by OLR anomalies, which is a proxy for convection (an assessment of cloud cover).

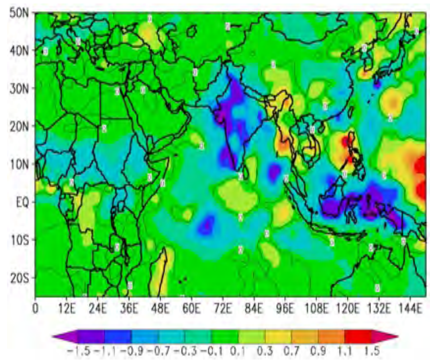

Figure 5a: Rainfall anomalies for the composite of drought years.

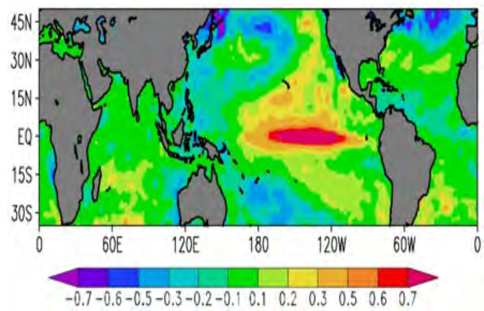

Figure 5b: SST anomalies for the composite of drought years.

Droughts and monsoonal rainfall are very well influenced by the wind circulation features in lower and upper tropospheric levels (Figures 7a & 7b). Figure 7a shows well marked anti-cyclonic circulations over Indian region and cyclonic circulation anomalies over Western Pacific Ocean (Figure 7a). Wind circulation features are quite strong on Arabian Sea and Bay of Bengal than over Indian landmass. For the prediction point of view argue about the surface level wind stress in May over some pockets of Indian Ocean are well correlated with ISMR [37]. It is to be noted that western Pacific region shows a bigger cyclonic circulation anomaly, coinciding with heavy rainfall and enhanced typhoon activity [32]. Another aspect of these winds is the reversal of the trade winds over western equatorial Indian region. On talking about climatologically upper level circulations (200mb), most of the Indian region experiences easterly winds. But during droughts, the upper troposphere winds (200mb) show an elongated cyclonic circulation extending from north India to Mediterranean Ocean (Figure 7b), which transports cold and dry air from desert region into Indian region [38,17]. This cyclonic circulation stays from few days to couple of weeks and is bolstered by a cyclonic circulation over Korea and Japan region. In other words, the upper tropospheric atmosphere is locked in westerlies. Intrusion of the cold and dry air inhibits the rainfall activities over Indian region by mixing into moist and warm monsoonal air mass from Indian Ocean.

One of the fundamental reasons of the existence of monsoonal flow is the meridional gradient of lower tropospheric temperature (Ocean vs Land). How, this temperature gradient swings from pre-monsoon month of May to monsoonal summer months is very exciting (Figures 8a & 8b). There is barely any warming in the total column of atmosphere, which can pull the monsoon over Indian landmass in May (Figure 8a). Contrasting to the old fact of surface temperature gradient across Indian subcontinent and Indian Ocean, which drives the monsoon, latter on heating of the lower tropospheric column found an important factor for monsoon [39]. In figure 8b, the vertical gradient of the temperature in the lower tropospheric column changes a lot than figure 8a. If this warming is extended up to 600-500mb level, then it is expected that the monsoon may perform better over Indian region.

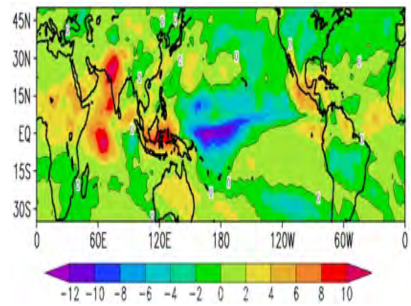

Figure 6: OLR anomalies for the composite of drought years.

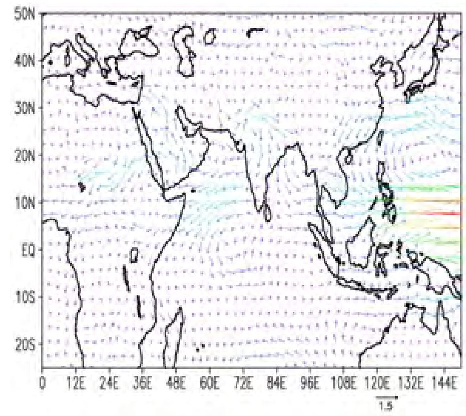

Figure 7a: Wind anomalies at 850mb for the composite of drought years.

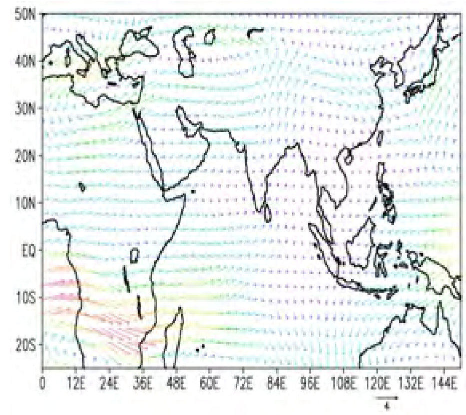

Figure 7b: Wind anomalies at 200mb for the composite of drought years.

Walker Circulation for 7 drought years shows subsidence over Indian region (Figure 9a), and enhanced convection over central Pacific Ocean. Furthermore, it is also comprehended from other supporting figures of the OLR and Rainfall anomalies as well. Local Hadley cell (Figure 9b) shows heavy subsidence all over the Indian landmass. Basically, the event of ENSO sways the Indian summer monsoon through anomalous East-West Walker circulation and regional Hadley circulation [8,9,40,36]. These are the two large scale circulation features of the global climate those influence monsoonal a lot. A typical example of the composite of 24 droughts (years 1973, 1877, 1899, 1901, 1904, 1905, 1911, 1918, 1920, 1928, 1941, 1951, 1965, 1966, 1968, 1972, 1974, 1979, 1982, 1985, 1986, 1987, 2002, 2004) pattern over Indian region is delineated in (Figure 10). Virtually, all parts of the India are under the shadow of drought.

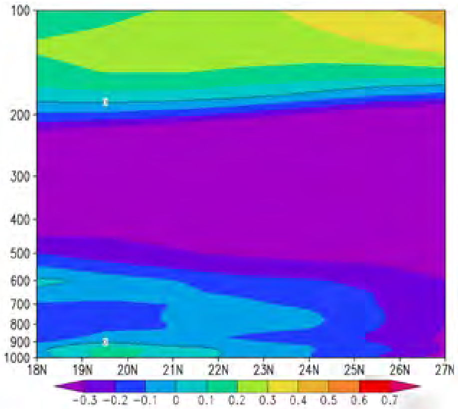

Figure 8a: Vertical profile of temperature averaged over lon=72 to lon=85 for May.

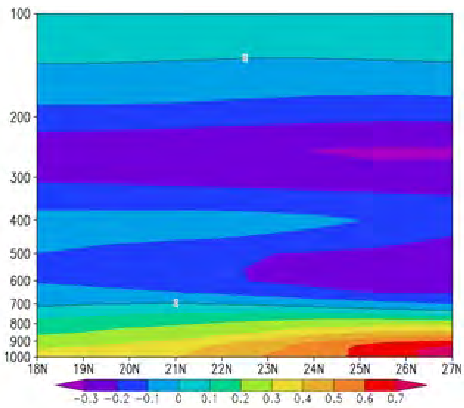

Figure 8b: Vertical profile of temperature averaged over lon=72 to lon=85 for Summer Season (JJAS).

Knowing the fact, ENSO is the lone player in influencing the Indian monsoon, Southern Oscillation Index (SOI) is shown for a longer period from 1982-2014. It shows, how SOI becoming positive (also increasing trend) in recent years, which means its relationship with IMSR is fading (Figure 11). In noting the spatial variability of the rainfall anomalies from one drought-year to another, it is also realized that the severity of monsoon droughts in most of the cases has dominated the northwest and central parts of the country. Somehow the ISMR and ENSO relationship is weakening in recent years. In fact [41], this feature is consistently reflected in the composite map of the rainfall anomaly based on the 24 drought cases (Figure 11).

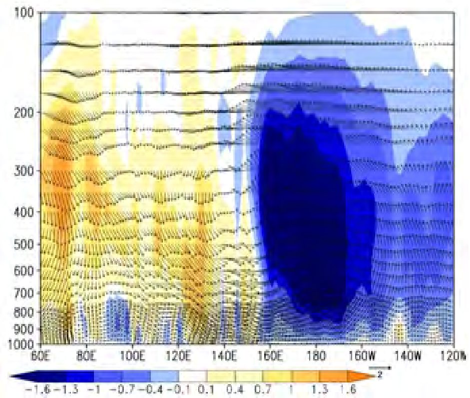

Figure 9a: Zonal Walker circulation (averaged over lat=-10 to lat=20).

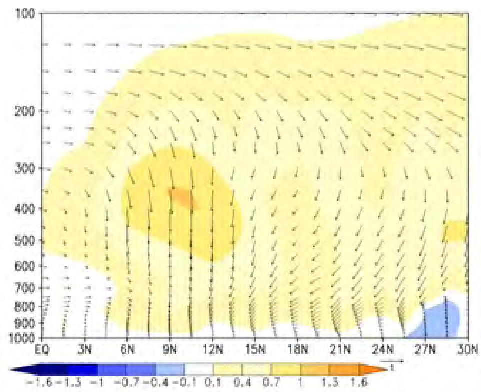

Figure 9b: Meridional local Hadley cell (averaged over lon=70 to lon=95) for the composite of drought years.

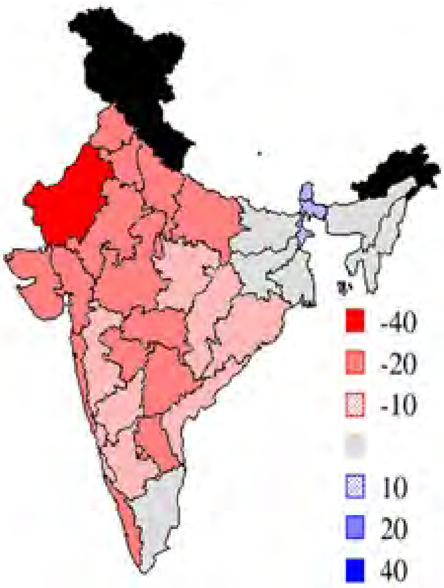

Figure 10: Composite map of the seasonal (June-September) variation of sub divisional rainfall expressed as percentage departure from long-term normal.

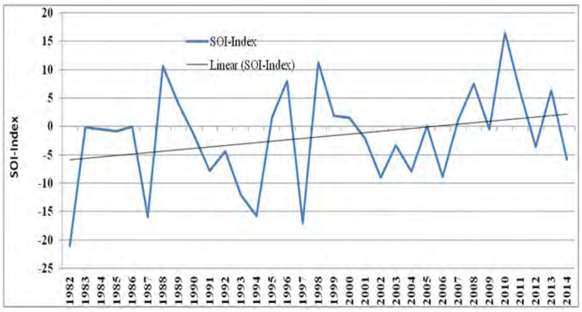

Figure 11: SOI Index averaged from June to September showing its value becoming negative to positive from 1982 to 2014.

Discussion

With the point of discussion Indian monsoon is going through changing phases e.g., the decrease/increase of rainfall in northern/southern India, increasing extreme events, monsoon depressions are decreasing, increase of green-house gas emissions [42-46]. Due to industrialization of the developing country like India the pollution from vehicles is increasing enormously [47]. In the scenario of global warming the decrease of atmospheric circulation, decreasing light rains, aerosol change, change in western disturbance frequency, increase of northern hemisphere temperature, decline of Arctic Ice, increasing pre-monsoon rainfall and change in cloud morphology [48,49,17,50-52]. These studies are possible due to advanced climate modeling and their cloud-aerosol component (known as clod microphysics). Finally, either internal dynamics or climate change the Indian is witnessing droughts time to time.The resolution of data coverage, model components, and parameterization schemes should be improved with the time for the improvements in predictions of monsoon rainfall. Every model needs improvement and the same is true for the data coverage in space and time.

The variability of rainfall brings natural calamities to the society, disaster to the environment, food scarcity, and imbalance to ecology. Among all the possibilities of the advanced forecasts we should facilitate the society to prepare for the natural disasters. We should educate and prepare society for a judicial use of natural resources, manage water problems, landslides, floods and droughts because the oddity of the monsoon is difficult to dodge. Further, there modeling of droughts may verify the weakening of meridional gradient of surface temperature, impact of ENSO on monsoon, role of internal dynamics and for other influences in the changing climate for monsoonal droughts?

Some of the important points as the discussion are raised here in the time of global warming how the monsoon will behave;

a. On the disappearance of Eurasia and Arctic Ice completely

b. On the shift of the warming in the middle of Pacific Ocean than eastern Pacific Ocean during El-Nino years

c. The land and sea temperature gradient across the Indian continent and Indian ocean is decreasing

d. It has been shown that the depressions are decreasing in Bay of Bengal

e. Local circulation e.g., local Hadley cell, over Indian subcontinent are weakening

Conclusion

The rainfall and wind circulation anomalies over Indian region and western Pacific region follow each other. Additionally, presence of the anti-cyclonic circulation over Indian region and enhanced cyclonic circulation anomalies over western Pacific region enhances subsidence over Indian region. OLR anomalies are quite coinciding with rainfall patterns of flood and drought patches over Indian subcontinent, western Pacific Ocean and African region. Total air column up to 200mb and above is colder in the month of May which is an indicator of a drought year. Global warming is one of the well-known aspects of the climate change. Thus, increase in ocean surface temperature and atmospheric temperature, meridional temperature gradient over Indian land and nearby sea is decreased from surface in the total vertical column of the troposphere. Conclusively, the ITCZ over Indian region, thus the rainfall is quite influenced by the convection and circulation features over Pacific region and African region. In recent, it is found that there is a tendency of the Indian monsoon to show favoritism towards drought. Even though SOI is showing weakening relationship between ISMR and ESNO; still ENSO, warming in the regional oceans and internal dynamics are the potential drivers of the ISMR droughts.

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