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Extreme droughts and corresponding summer monsoon: A case study of 2009 Indian drought

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सार – निरंतर सतह और वायुमंडलीय ऊष्मा और नमी की कमी के परिणाम स्वरूप सूखा पडता है। सामान्य तौर पर, सूखे का आकलन विभिन्न सूचकांकों (जैसे एसपीआई, एसपीईआई, पीडीएसआई, एसएमआई) के आधार पर किया जाता है। हालांकि, भारतीय ग्रीष्मकालीन मॉनसून (आईएसएम, यानी जून, जुलाई, अगस्त और सितंबर-जेजेएएस) के दौरान सूखा गतिकी की गतिशीलता और संबंधित सतह ऊर्जा को अभी भी बेहतर ढंग से समझने की जरूरत है। लंबे समय तक सतह के गर्म होने से मिट्टी की नमी, सतह/उपसतह अपवाह और वायुमंडलीय नमी में कमी आती है। सकारात्मक सतह ऊर्जा बजट से अत्यधिक सतही ऊष्ण्न हूता है, जिसकी गणना सतही नेट सौर विकिरण (SNSR), सतही नेट तापीय विकिरण (SNTR), सतही संवेद्य ऊष्मा प्रवाह (SSHF), और सतही गुप्त ऊष्मा प्रवाह (SLHF) का उपयोग करके की जाती है। संवहन वातावरण की नमी धारण करने की क्षमता पर भी निर्भर करता है, जो हवा के बढ़ते ऊष्मामान के साथ बढ़ता है। इन प्रक्रियाओं से नमी की मात्रा में कमी आती है और संवहन स्रोतों से नमी के विचलन के कारण वर्षा की कमी होती है। भारत मौसम विज्ञान विभाग (स्टेशन और 0.25° ग्रिडेड) और यूरोपियन-मध्यम अवधि मौसम पूर्वानिमान केंद्र (ECMWF) ERA-अंतरिम पुनर्विश्लेषण (0.25° रेजोल्यूशन) के आँकडों का उपयोग अत्यधिक सूखे की घटनाओं का अध्ययन करने के लिए किया जाता है। मानकीकृत वर्षा सूचकांक (एसपीआई), पामर सूखा गंभीरता सूचकांक (पीडीएसआई), मानकीकृत वर्षा वाष्पीकरण सूचकांक (एसपीईआई), मृदा नमी सूचकांक (एसएमआई) और संवेदनशील ऊष्मा सूचकांक (एसएचआई) जैसे सूखे सूचकांकों का उपयोग किया जाता है। परिणाम बताते हैं कि उपलब्ध सतही मिट्टी की नमी का असामान्य रूप से कम होना और सतह के अनुकूल ऊष्मा प्रवाह में वृद्धि 2009 के आईएसएम के दौरान अत्यधिक सूखे को बढ़ाने का एक संभावित कारण है। संबंधित हैडली संचलन असंगत कमी को दर्शाता है, जिसके कारण दक्षिणी महासागरों से उत्तर की ओर नमी का परिवहन कम हो गया, जिससे नमी की कमी और अधिक हो गई। भारत के अधिकांश भाग सूखे की अवधि के दौरान निम्न से ऊपरी क्षोभमंडल में विशिष्ट आर्द्रता में असामान्य कमी और इससे संबंधित वर्षा की कमी का सामना कर रहे थे। समुद्र/स्थानीय संवहन से नमी विचलन के कारण वातावरण की बढ़ी हुई नमी धारण क्षमता के कारण कमजोर मॉनसून पड जाता है। हालाँकि, अत्यधिक सतही ऊष्मान (SNSR/SNTR के सतह में जम जाने के कारण) के कारण 2009 ISM के दौरान अत्यधिक सूखा पड़ा।

ABSTRACT. Drought is a sustained result of continuous surface and atmospheric heating and moisture deficit. In general, drought assessment is made based on various indices (such as SPI, SPEI, PDSI, SMI). However, drought dynamics and associated surface energetics during Indian Summer Monsoon (ISM, *i.e*., June, July, August and September-JJAS) still needs to be better understood. Prolonged surface heating causes reduction of soil moisture, surface/subsurface runoff and atmospheric moisture. Excess surface heating results from positive surface energy budget, which is computed using, surface net solar radiation (SNSR), surface net thermal radiation (SNTR), surface sensible heat flux (SSHF) and surface latent heat flux (SLHF). The convection also depends on the moisture holding capacity of the atmosphere, which increases with increasing air temperature. These processes lead to moisture content deficit and rainfall suppression due to moisture divergence from the convective sources. India Meteorological Department (IMD) (station and 0.25° gridded) and European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis (0.25° resolution) datasets are used to study the extreme drought events. Drought indices such as Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Standardized Precipitation Evapotranspiration Index (SPEI), Soil Moisture Index (SMI) and Sensible Heat Index (SHI) are used. Results indicate that anomalous lowering of available surface soil moisture and increase of surface sensible heat flux is a possible cause for enhancing extreme drought during the 2009 ISM. The associated Hadley circulation shows anomalous weakening, which led to reduced northward moisture transport from the southern oceans, further exacerbating moisture deficit. Most parts of India suffered from anomalous decrement in specific humidity in the lower to upper troposphere and related precipitation scarcity during drought period. The atmosphere's increased moisture holding capacity sets a weak monsoon due to moisture divergence from ocean/local convection. However, likely, the excessive surface warming (due to SNSR/SNTR trapped into the surface) led to the extreme drought during 2009 ISM.

Key words – Monsoon, Energetics, Drought indices, Moisture, ISM.

1. Introduction

Based on drought's feedback on surface/subsurface runoff, atmosphere, agriculture/vegetation and economy, it is classified as hydrological, meteorological, agricultural and economical drought (Wilhite and Glantz, 1985; Wilhite, 2002; Dai, 2011). In climate change scenarios, the Earth's surface/troposphere gets warmer (*i.e.*, global warming) due to reradiated greenhouse gases (GHGs). Global warming may be responsible for conditions that lead to more intense extremes (Meunier, 2007), which may induce extreme climate events such as drought (Dai *et al*., 2004). The extreme dry/wet areas and surface warming globally have increased by 20% to 38% from post-industrial to recent years (Dai *et al*., 2004). Drought is an outcome of sustained heating of land and near-surface atmosphere as well as a rainfall deficit. The persistence of parched years is a catastrophic threat to society and wildlife. The loss of vegetation in the drier land because of excess heat, deficit precipitation, insufficient surface/subsurface runoff and low soil moisture influences biotic and the abiotic environment. The meteorological drought (excess heat and deficit rainfall) can also cause the subsurface water deficit (*i.e*., hydrological drought). During the 2002 drought, some parts of India, *e.g*., Odisha, suffered from groundwater depletion (Panda *et al*., 2007). Sainath reported that at least 1736 Indian farmers committed suicide as a result of the 2009 drought (P. Sainath, 27 DEC 2010; The Hindu). Drought is reported in terms of drought indices such as Standardized Precipitation Index (SPI) (McKee *et al*., 1993), Palmer Drought Severity Index (PDSI) (Palmer, 1965; Wells *et al*., 2004), Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano *et al*., 2010), Standardized Surface Runoff Index (SRI) (Shukla and Wood, 2008) and Standardized Soil Moisture Index (SMI) (Wang *et al*., 2017). These indices track the dryness/wetness of the surface runoff followed by soil moisture and subsurface water. Zhai *et al*. (2010) has reported a moderately high and statistically significant correlation between the percentage of runoff anomaly (PRA) and the annual average PDSI and SPI. Most of the Indian river basins suffer regular contingency of drought, usually led by weak monsoon/dry spells (Bollasina *et al*., 2011; Shah and Mishra, 2015). The frequency of drought over decades in the Indian subcontinent has increased (Dai, 2011). Some previous studies show an increasing trend in drought severity and frequency from 1970 to 2004 over the Indian region (Mallya *et al*., 2016). Pai *et al*. (2011) also found that SPI shows a negative trend from 1901 to 2003 over the Indian region. Various studies show that the Indian summer monsoon (ISM) precipitation trend also has a high spatial variability (*i.e.*, some parts of India show a dry bias while other show a wet bias) (Guhathakurta and Rajeevan, 2008; Niyogi *et al*., 2010; Roxy *et al*., 2015; Mallya *et al*., 2016). Drought depends on local climatic conditions, although it may also occur in wet and humid regions (*e.g*., because of local feedback and the reduction of evaporation and humidity along with dry soil) (Dai, 2011; Dai *et al*., 2017). The near-real-time drought monitoring over India using various drought indices, *e.g*., SPI, SRI and Variable Infiltration Capacity (VIC), is reported by Shah and Mishra (2015) for a better understanding of drought. Touma *et al*. (2015) discussed the increasing occurrence and duration of future drought-related stress globally from 2010 to 2099 in the Representative Concentration Pathway 8.5 (RCP8.5) scenario (*i.e*., GHGs trajectory). Niyogi *et al*. (2010) reported that human intervention also influences droughts since land use/land cover and cultivation increment induces a change in the surface heat budget through the latent and sensible heat fluxes. Rebetez *et al.* (2009) show that Europe's heat spells and extreme drought during 2003 (JJA) are caused by longer sunshine days and a deficit in precipitation and humidity.

Significant surplus surface heat is one of the prominent causes of increased atmospheric heating, indicating that drought is a surface and atmospheric interaction phenomenon. The paucity of knowledge of drought dynamics, its surface, atmospheric heat and moisture aspect requires more scientific attention. Therefore, the broad aim of the study is to monitor extreme drought events from 1975 to 2014 and employing a specific, extreme drought occurrence of 2009 as a case study, which was also noted by Preethi *et al*. (2011 and 2017; Mishra, 2019) as an exceptional drought year and to investigate the regional surface energetics using several drought indicators. Mishra (2019) has shown that the 2009 drought was prolonged for 9 months from its onset in March 2009 using SRI and SPI. In 2009 India's 338 districts were affected by extreme drought (TOI; Subodh Varma, Oct 3, 2015). This inspires current work to address the knowledge gap concerning the severe drought during ISM.

2. Data and Indices

The SPI time-series is calculated using India Meteorological Department (IMD) precipitation station

TABLE 1

Drought intensity class guideline

Index	Range	Intensity	References
SP1	0 to -0.5	Normal	McKee *et al*., 1993; Bhuiyan *et al*., 2006
	-0.5 to -1	Moderate	
	-1 to -2	Severe	
	-2 >	Extreme	
PDSI	0 to -2	Normal	Palmer, 1965; Wells *et al*., 2004; Hao and Singh, 2015
	-0.5 to -1	Moderate	
	-1 to -2	Severe	
	-2 >	Extreme	
SPEI	0 to -0.5	Normal	Vicente-Serrano *et al*., 2010; Hao and Singh, 2015
	-0.5 to -1	Moderate	
	-1 to -2	Severe	
	-2 >	Extreme	
SMI	0 to -0.5	Normal	Wang *et al*., 2016
	-0.5 to -1	Moderate	
	-1 to -2	Severe	
	-2 >	Extreme	

TABLE 2

The datasets used in the present study

Variables	Period (years)	Sources	References
Standardized Precipitation Index (SPI) (stations and gridded - rainfall)	1975-2015	Indian Metrological Department (IMD)	Pai *et al*., 2014
Palmer Drought Severity Index (PDSI)	1979-2015	UCAR	Dai (2011a, 2011b)
Standardized Precipitation Evapotranspiration Index (SPEI) (*i.e*., 2 meter temperature & total precipitation at surface level)	1979-2015	ECMWF, ERA-Interim	Dee *et al*., 2011
Vertical Integral Moisture Flux Divergence (VIMFD) at surface level	1979-2015	ECMWF, ERA-Interim	Dee *et al*., 2011
Surface Sensible Heat Flux (SSHF) and Surface Latent Heat Flux (SSHF) at surface level	1979-2015	ECMWF, ERA-Interim	Dee *et al*., 2011
Skin Temperature, Surface Net Solar Radiation (SNSR) and Surface Net Thermal Radiation (SNTR) at surface level	1979-2015	ECMWF, ERA-Interim	Dee *et al*., 2011
Temperature, Relative Humidity, Specific Humidity and Vertical Velocity at pressure level	1979-2015	ECMWF, ERA-Interim	Dee *et al*., 2011

dataset and spatial distribution by a gridded dataset with a horizontal resolution of 0.25° × 0.25° (Pai *et al*., 2014). The PDSI (self-calibrated) dataset is taken from the Earth System Research Laboratory/National Oceanic and Atmospheric Administration (ESRL/NOAA), having a horizontal resolution of 2.5° × 2.5° (Dai *et al*., 2004). The SPEI, SMI, surface latent heat flux (SLHF), surface sensible heat flux (SSHF), the sensible heat index (SHI), vertical integral moisture flux divergence (VIMFD), surface net thermal radiation (SNTR) and surface net solar radiation (SNSR) is calculated by using ERA-Interim datasets taken from European Centre for Medium-Range Weather Forecasts (ECMWF) having horizontal resolution 0.25° × 0.25° (Dee *et al*., 2011). A brief description of the datasets is discussed in Table 2. Bhuvan Indian Geo-platform authorized by National Natural Resources

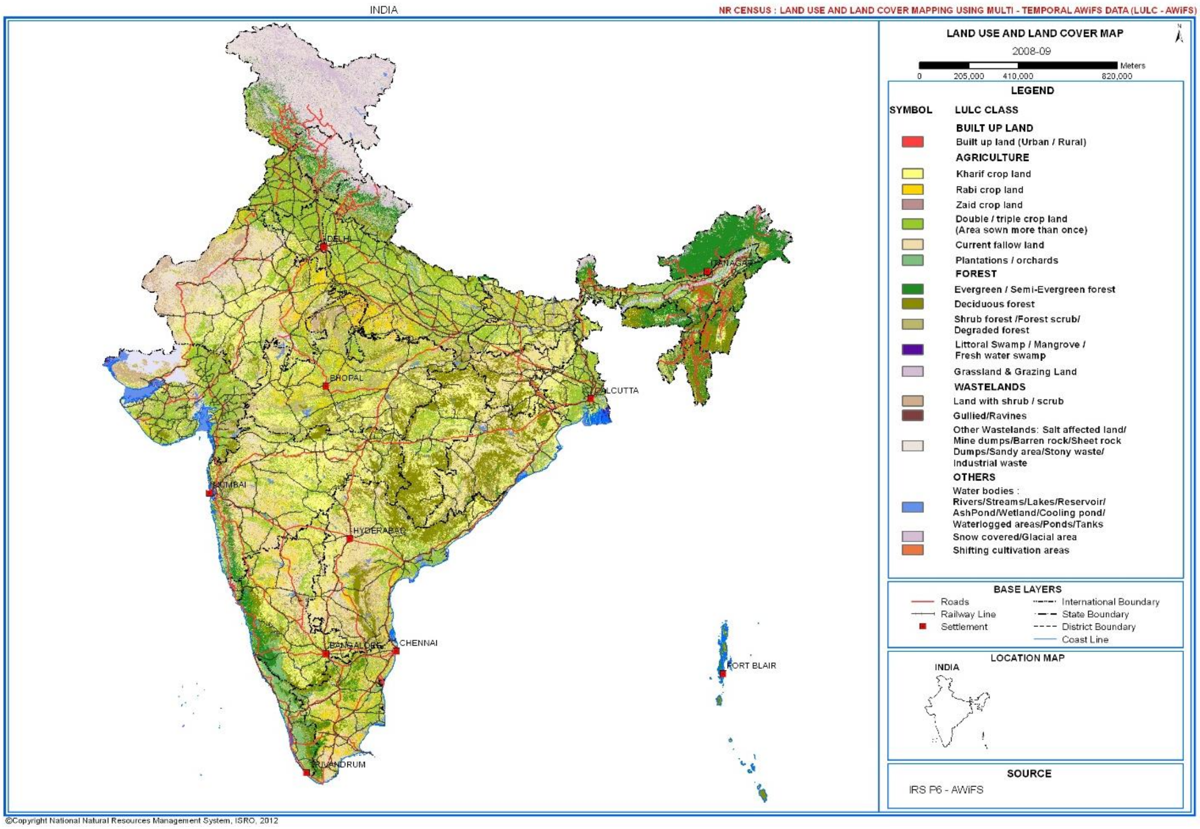


Fig. S1. Land Use Land Cover (LULC) map for the year 2008-2009, multi temporal AWiFS data of resolution 1:250,000 scale mapping is obtained from Bhuvan Indian Geo-platform, Indian Space Research Organisation (ISRO) copyright of National Natural Resources Management System (NNRMS). The figure shows various land features during 2008-09. The discussion is intended for areas with very little soil moisture, such as hard rock, arid, sandy, or wetland environments. Snow cover, water bodies and local convective regions have good convection, evaporation and evapotranspiration. That is clearly illustrated by the green belt and water features

Management System (NNRMS), released the multi-temporal IRS-AWiFS satellite data of resolution 1:250,000 scale mapping is used for the Land Use Land Cover (LULC) for the years 2008-2009. The figure shows various land features during 2008-09 (Fig. S1).

3. Methodology

Various indices such as SPI, PDSI, SPEI and SMI (intensity class of indices are briefly discussed in Table 1) are good tools for Spatio-temporal assessment of extreme drought mechanisms through the surface as well as atmospheric energetics. These can be understood through the following methods.

3.1. *Drought indices*

Standardized Precipitation Index (SPI) time series is the standardized, normalized seasonal precipitation anomaly defined as,

$$\text{SPI} = \frac{\left(X_{ij} - \underline{X}_{ij}\right)}{\sigma} \quad (1)$$

where, X_{ij} is the seasonal rainfall JJAS month sum at the i^{th} grid, j^{th} observation time (month) for JJAS months, $\underline{X}_{ij}$ long term mean for JJAS and σ is the standard deviation (McKee *et al*., 1993; Bhuiyan *et al*., 2006; Trenberth *et al*., 2014).

Palmer Drought Severity Index (PDSI) is based on soil moisture supply and demand of precipitation and temperature. It is used for regional drought condition monitoring in the short-term and long term. It is also used to predict hydrological drought (Palmer, 1965; Wells *et al*., 2004; Dai *et al*., 2004; Hao and Singh, 2015). For a further detailed discussion of PDSI, we refer to Alley (1984); Wells *et al*. (2004) and Dai *et al*. (2004).

Standardized Precipitation Evapotranspiration Index (SPEI) is a multiscale drought index, calculated as the difference of precipitation (P) and potential evapotranspiration (PET) (Vicente-Serrano *et al*., 2010; Hao and Singh, 2015).

$$\text{SPEI} = W - \frac{C_0 + WC_1 + W^2C_2}{1 + Wd_1 + W^2d_2 + W^3d_3} \quad (2)$$

$$D = (P - PET) \quad (2a)$$

$$\text{PET} = 16\left(\frac{10T}{1}\right)^{\alpha}\left(\frac{N}{12}\right)\left(\frac{NDM}{30}\right) \quad (2b)$$

where,

$\alpha = 6.75 \times 10^{-7}I^3 - 7.71 \times 10^{-5}I^2 + 1.79 \times 10^{-2}I + 0.492$

$$I = \left(\frac{T}{5}\right)^{1.514}$$

$W = \sqrt{-2\ln(p)}$ for $p \leq 0.5$, where p is the probability of exceeding value determined as D and $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$ and $d_3 = 0.001308$.

P is precipitation; *N* is the maximum number of sunshine hours (for JJAS over India, it is taken as approx. ~ 12 hrs), NDM is the number of days in the month and *T* is the monthly mean temperature in °K.

Soil Moisture Index (SMI) is standardized, normalized seasonal soil moisture anomaly and represented as :

$$\text{SMI} = \frac{(M - \underline{M})}{\text{std}} \quad (3)$$

where, 'std' is the standard deviation, *M* is volumetric soil water level-1 (0-10 cm) and $\underline{M}$ is the seasonal mean of volumetric soil water (Wang *et al*., 2017).

3.2. *Surface energetic: Heat and moisture dynamics*

The net incident solar energy on the atmosphere and surface is utilized for different natural processes. Some portion of this energy is utilized in atmospheric heating, the other for atmospheric mechanical processes and the rest is utilized in surface heating and surface processes. It is balanced by thermal radiation emitted by Earth following Kirchhoff's law. The surface net solar radiation (SNSR) and surface net thermal radiation (SNTR) is a measure of the total radiation transferred into surface warming in the form of latent heat (LE), sensible heat (H) and ground heat (G). It is a fundamental principle of thermodynamics and the energy is the sum of the phase change of water (LE), surface air temperature change (H) and heat trapped inside the surface (G) (Seller, 1969; Oke, 1987).

$$\text{Q (net energy)} = \text{LE} + \text{H} + \text{G} \quad (4)$$

$$\text{SNSR} = \left(S_{\text{surf}}^{\text{dn}} - S_{\text{surf}}^{\text{up}}\right) \quad (5a)$$

where, S_{surf}, dn and up are surface shortwave, downwelling and upwelling, respectively.

$$\text{SNTR} = \left(L_{\text{surf}}^{\text{dn}} - L_{\text{surf}}^{\text{up}}\right) \quad (5b)$$

where, $L_{\text{surf}}^{\text{dn}}$ and up are surface longwave, downwelling and upwelling, respectively (Hogan, 2015).

However, $Q = (\text{SNSR} - \text{SNTR}) \quad (5c)$

Sensible Heat Index (SHI) is defined as the ratio of sensible heating to total heating (sensible + latent). It is a proportion of total heat energy used to raise the air temperature (Bowen, 1926; Barnes *et al*., 2001).

$$\text{SHI} = \frac{S}{(S+L)} \quad \text{or} \quad \text{SHI} = \frac{B}{(B+1)} \quad (6)$$

where, B is Bowen ratio $\left(B = \frac{S}{L}\right)$, S and L are surface sensible and latent heat energy.

The atmospheric moisture and surface heat (LE and H) are mutually connected. The latent heat released from the surface (as evaporation and moisture convection) is added to the sensible atmospheric heat. This phenomenon can be discussed with the help of vertical integral moisture flux divergence (VIMFD), surface latent heat and sensible heat fluxes (Banacos and Schultz, 2005).

$$\text{VIMFD} = \frac{1}{g}\int_{p=1000\text{hPa}}^{p=100\text{hPa}} q.\nabla.V_h \; dp \; \text{horizontal MFD} + \frac{\partial(q.\omega)}{\partial p} \; \text{vertical MFD} \quad (7)$$

where q, V_h, p, ω and g are specific humidity, horizontal wind, pressure level, omega and acceleration

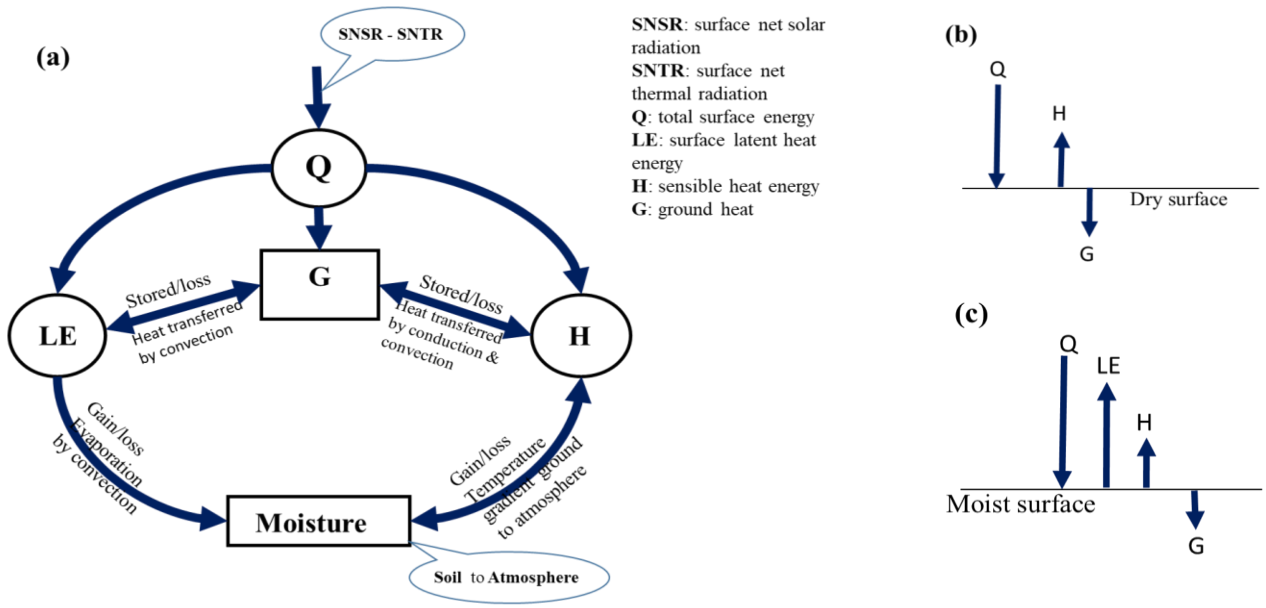
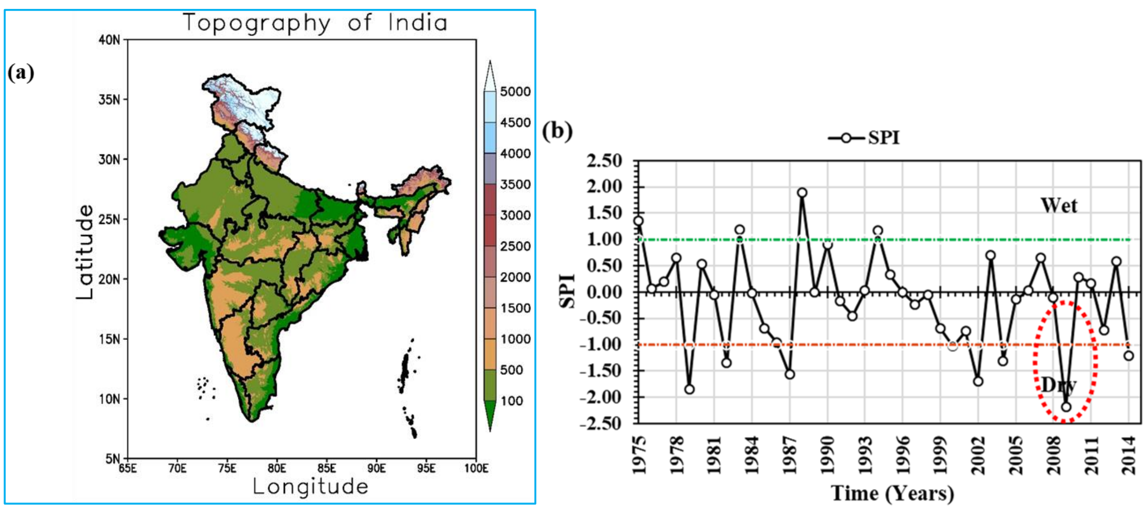


Fig. S2. The schematic demonstrates the many ways in which the total surface energy obtained as a result of solar and thermal net is used for energetics. And another component of the budget that affects both the mesoscale and microscale climate is the way dry and moist surfaces react to sensible and latent heat energy. The interaction of moisture with the surface energy budget (from soil to atmosphere) is vividly shown in this diagram



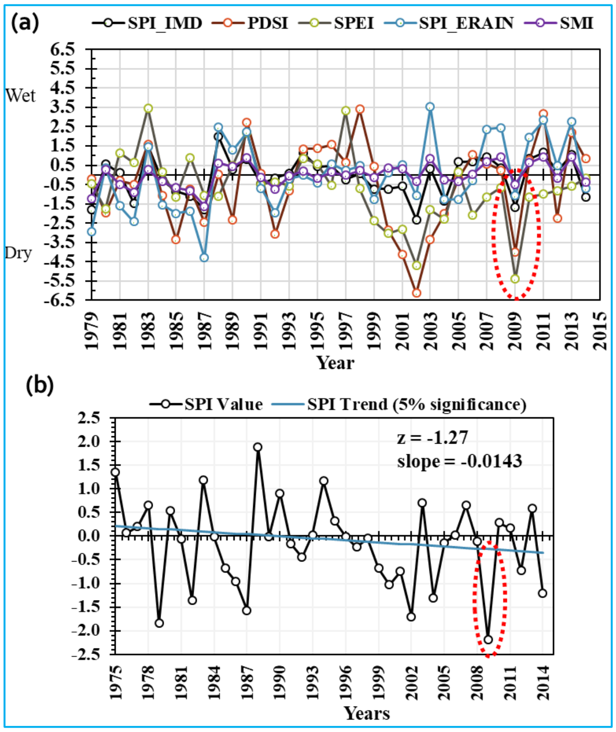
Figs. 1(a&b). (a) The topography (in meter) of the study region, inner lines show the state boundaries and (b) the Standardized Precipitation Index (SPI) (using IMD station data area averaged over India) over the study region. Here values greater than +1 shows extreme wet years, while lesser than -1 shows extreme dry years during Indian Summer Monsoon (ISM)

due to gravity. The interaction of moisture and surface energy budget is shown in schematic Fig. S2.

4. Results and discussion

4.1. *SPI*

The study area, which encompasses the entire Indian landmass, is depicted in Fig. 1(a). Fig. 1(b) shows dry and wet periods during 1975 to 2014 associated with ISM months *i.e.*, June, July, August and September (JJAS) using SPI area-averaged over India (*i.e.*, Indian landmass; Fig. 1(a). Values less than -1 indicate severely dry years, while those greater than +1 indicate severely wet years. In some years (1979, 1982, 1987, 2002, 2004, 2009 and 2014), the SPI value is less than -1, while in others (1975, 1983, 1988 and 1994) it is larger than +1. The corresponding years' drought mechanisms are referenced



Figs. 2(a&b). (a) The different drought indices area averaged over the study region during JJAS; SPI_IMD, SPI_ERAIN and PDSI should be multiplied by 3, (b) Standardized Precipitation Index (SPI IMD station data) trend at 5% significant level; the blue line shows the trend and the black line shows SPI values. In fig. (a) negative value shows dry years and positive value wet years, all indices show dryness during the 2009 (JJAS) Indian Summer Monsoon *i.e*., extreme drought year. In Fig. (b) the negative trend shows that the dry years are getting drier and wet years are also getting drier. Threshold values of each index are given in Table 1

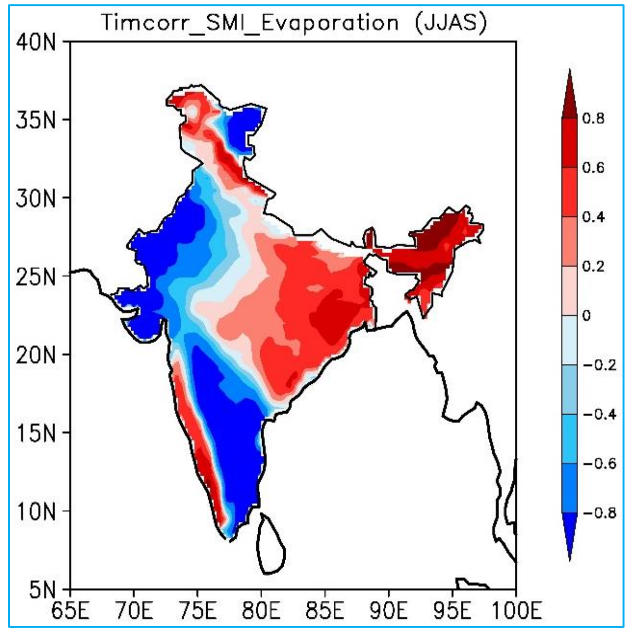
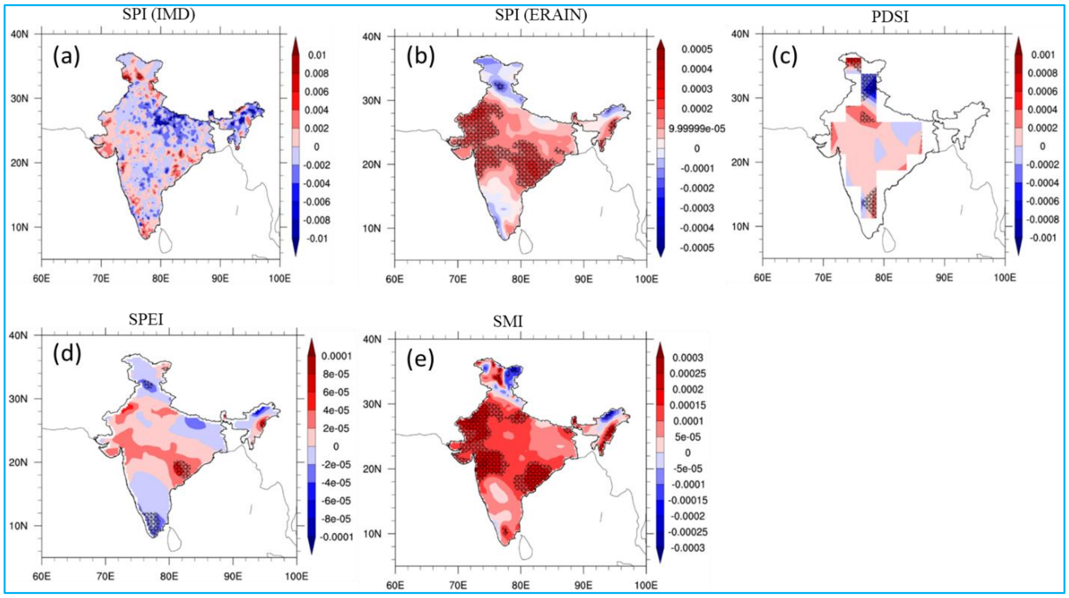


Fig. S3. Correlations between SMI and Evaporation for 1979 to 2015 over study region

in the supplementary materials (Figs. S5 to S16). McKee *et al*. (1993) and Bhuiyan *et al*. (2006) observed that SPI less than -2 indicates an arid year. The same is found over India for the year 2009 ISM. The SPI captures ISM deficit/excess precipitation that is derived by seasonal precipitation. The seasonal deficit precipitation is one of the possible causes of ISM drought. Moreover, the year 2009 shows extreme drought during ISM because of deficit precipitation as seen by SPI [Fig. 1(b)] (Das *et al*., 2009; Neena *et al*., 2011; Pai *et al*., 2011; Varikoden *et al*., 2015). Mishra (2019) reported that the 2009 India drought had its onset in March and continued to persist for 9 months. In addition, it was at its peak during ISM. Additionally, the maximum intensity in the SPI index climbed to -2.16, while the SRI index attained a high of -2.27 (Mishra, 2019). Fig. 2(a) shows that various indices (SPI, PDSI, SPEI and SMI) averaged over the study region similar to SPI calculated from IMD station data [Fig. 1(b)]. These indices are calculated from the gridded dataset and are also shown in Fig. 2(b) and conclude 2009 to be an extreme drought year (Preethi *et al*., 2011 and 2017; Varikoden *et al*., 2015) (Threshold values of each index are briefly discussed in Table 1). Therefore, we focus our study on this extreme drought year, *i.e*., 2009 and discuss associated surface energetics and moisture dynamics. The extreme drought results from deficit soil moisture, reduced surface runoff, induced evapotranspiration (Fig. S3) (*i.e*., shallow convection and moisture transportation) induced by excessive surface heating. In addition, it is reported that the intense droughts in India are highly derived from El Niño/Southern Oscillation (ENSO) events. ENSO has teleconnection with ISM (Mishra, 2019). However, the year 2009 is neutral ENSO or a weak La Niña conditions during January to April of the year 2009. Furthermore, the onset of the 2009 Indian drought is reported as March (Mishra, 2019). However, the various variables and monthly ENSO indices show a weak El Niño during June to September of the year 2009 as well (Varikoden *et al*., 2015; Mishra, 2019). This makes a curious case that even in a weak El Niño year, drought during ISM is proceeding towards the extreme.

4.2. *PDSI and SPEI*

PDSI is a multivariable index that explains surface runoff and soil moisture (Dai *et al*., 2004). The value of PDSI for the year 2009 is less than -3 and it delineates the severe to extreme drought conditions during ISM (Wells



Figs. S4(a-e). The significant trend (at 95%) of deferent drought indices for 1979 to 2015 (JJAS) over the study region; (a) SPI (IMD), (b) SPI (ERAIN), (c) PDSI, (d) SPEI and (e) SMI. The 95% significance is highlighted using cross patterns

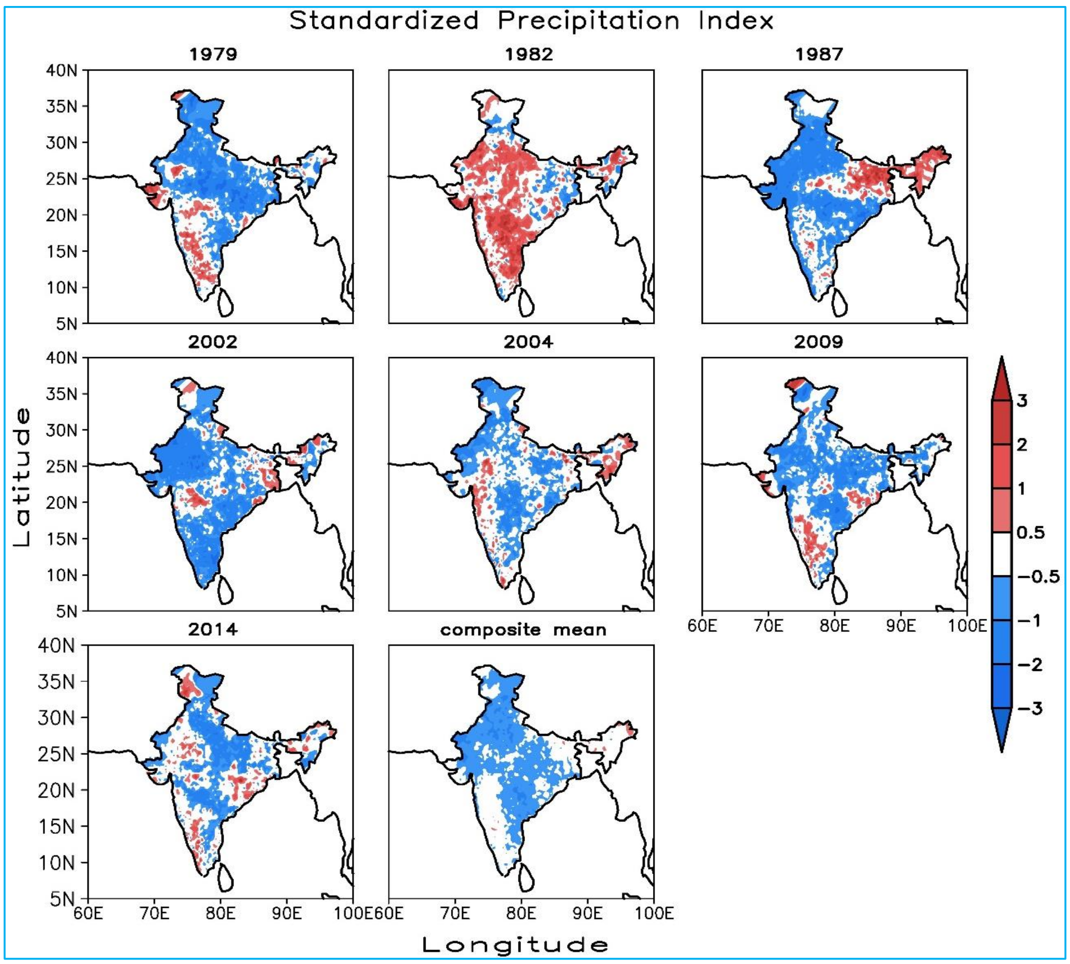


Fig. S5. SPI for the extreme drought years during ISM

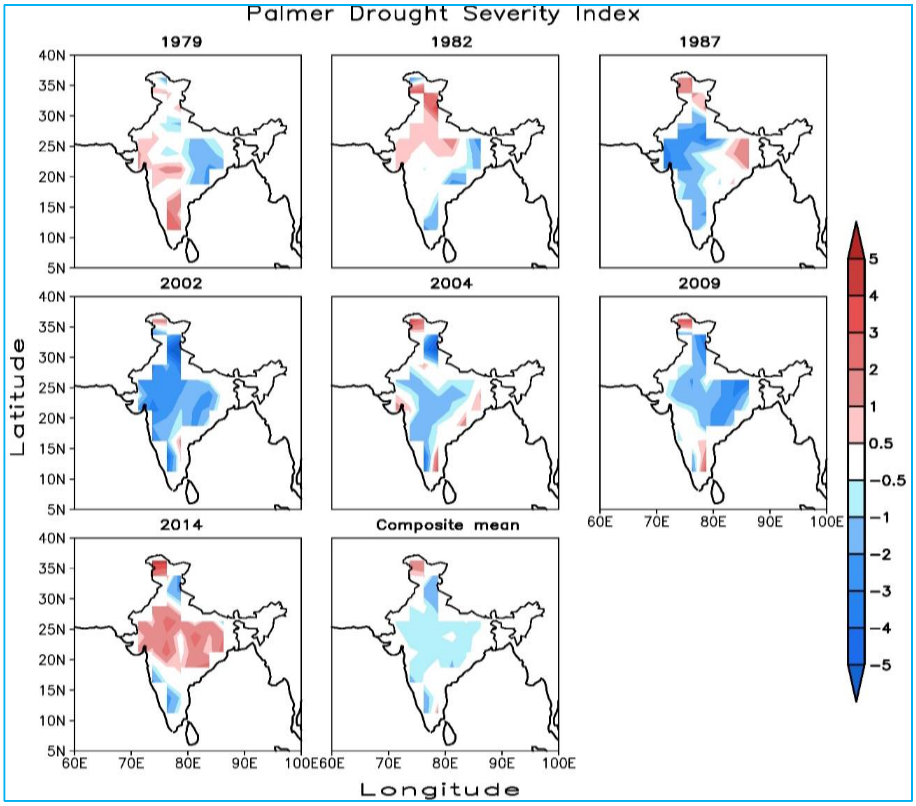


Fig. S6. PDSI for the extreme drought years during ISM

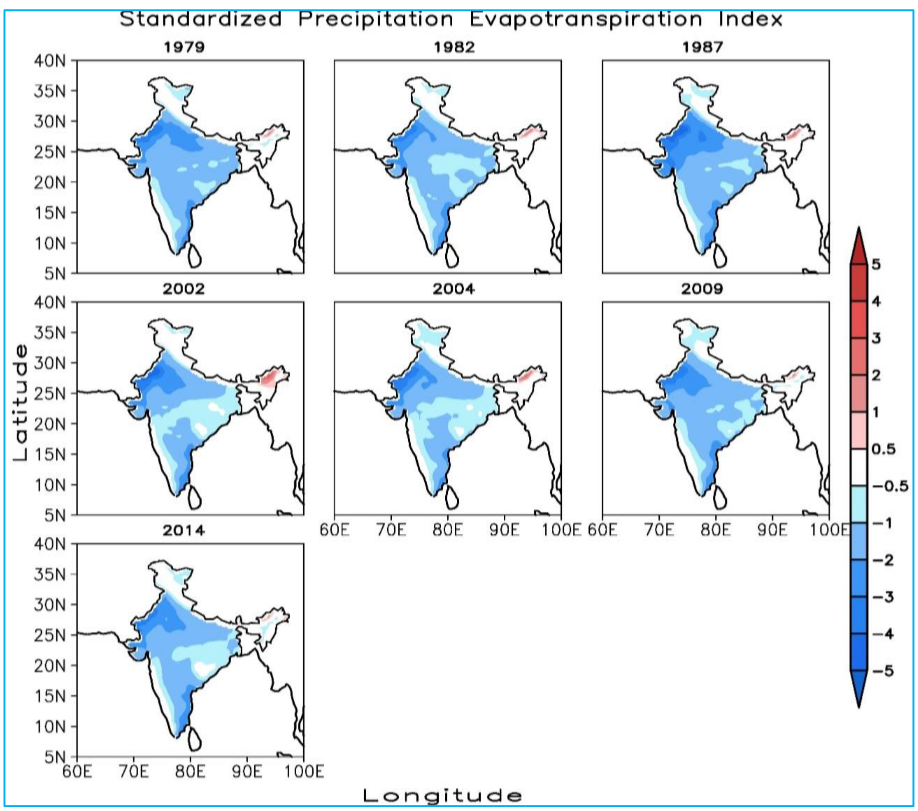


Fig. S7. SPEI for the extreme drought years during ISM

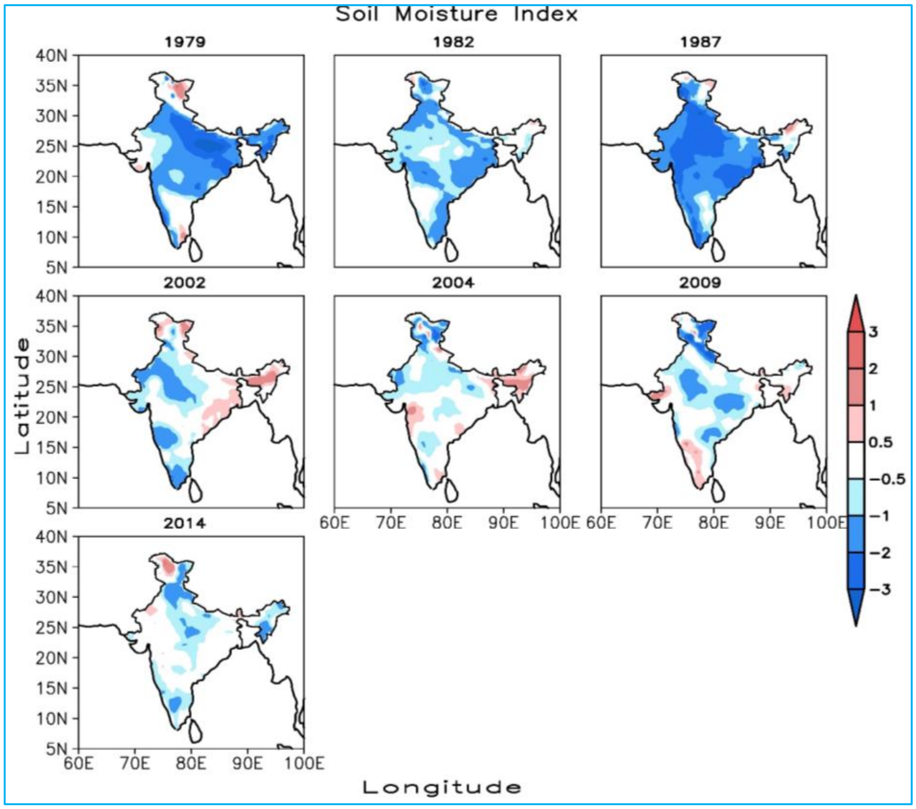


Fig. S8. SMI for the extreme drought years during ISM

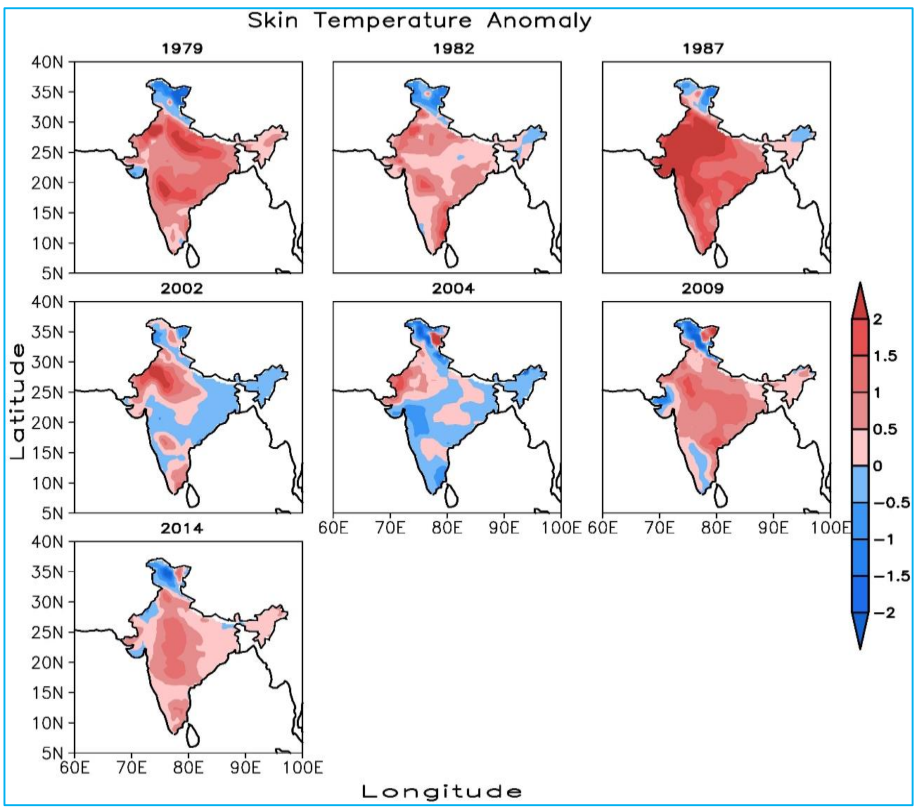


Fig. S9. Skin temperature anomaly for the extreme drought years during ISM

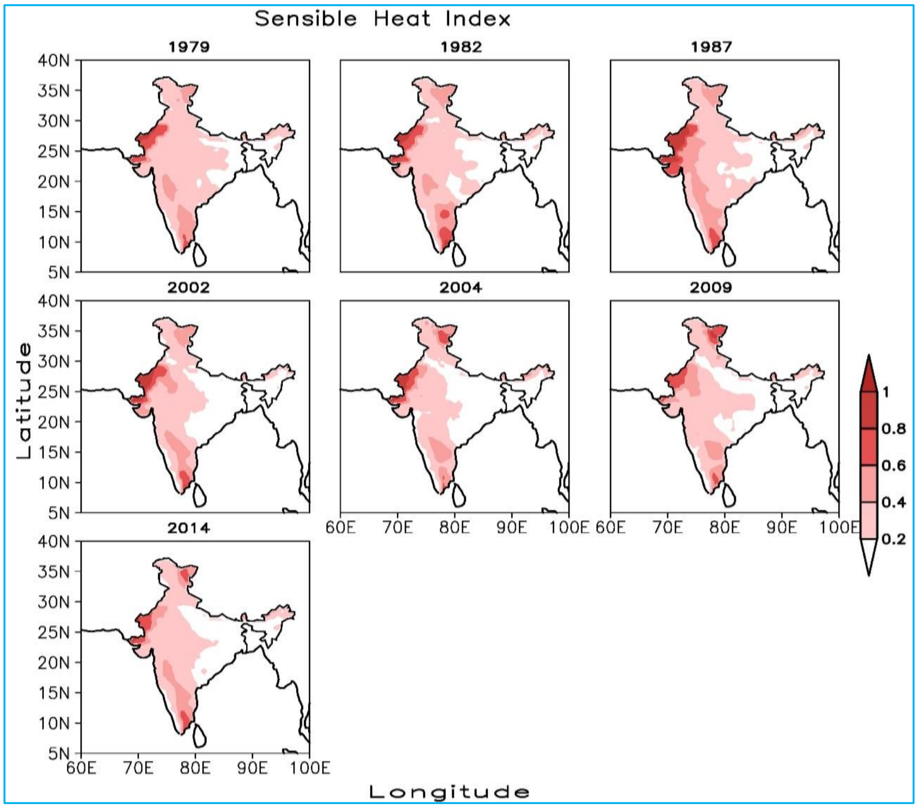


Fig. S10. Sensible heat index for the extreme drought years during ISM

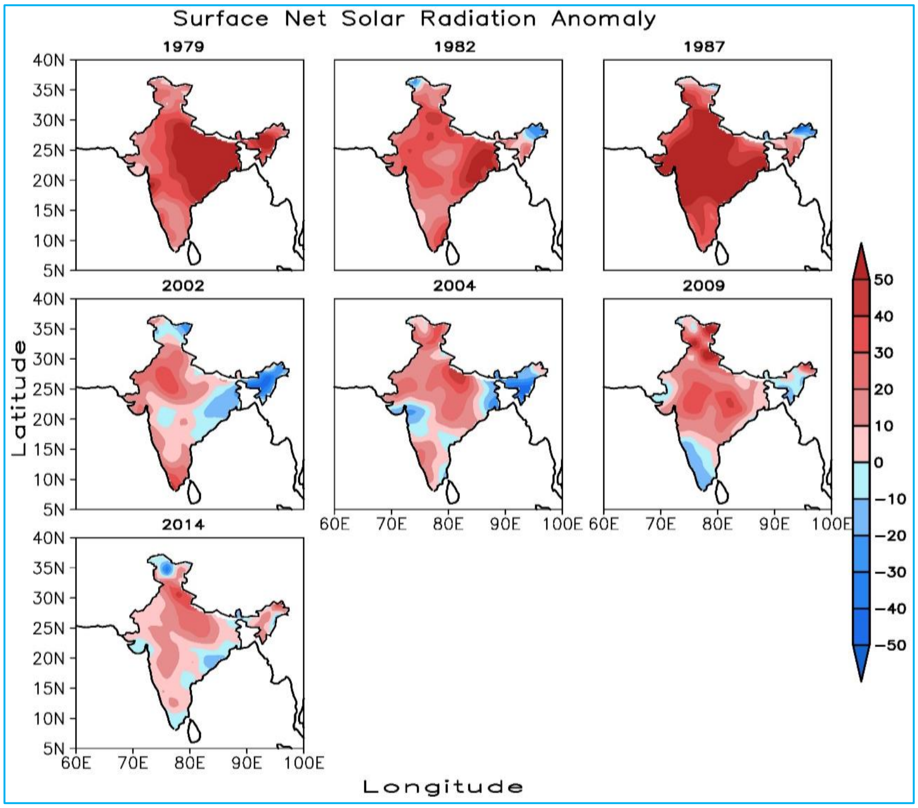


Fig. S11. Anomalous surface net solar radiation on earth for the extreme drought years during ISM

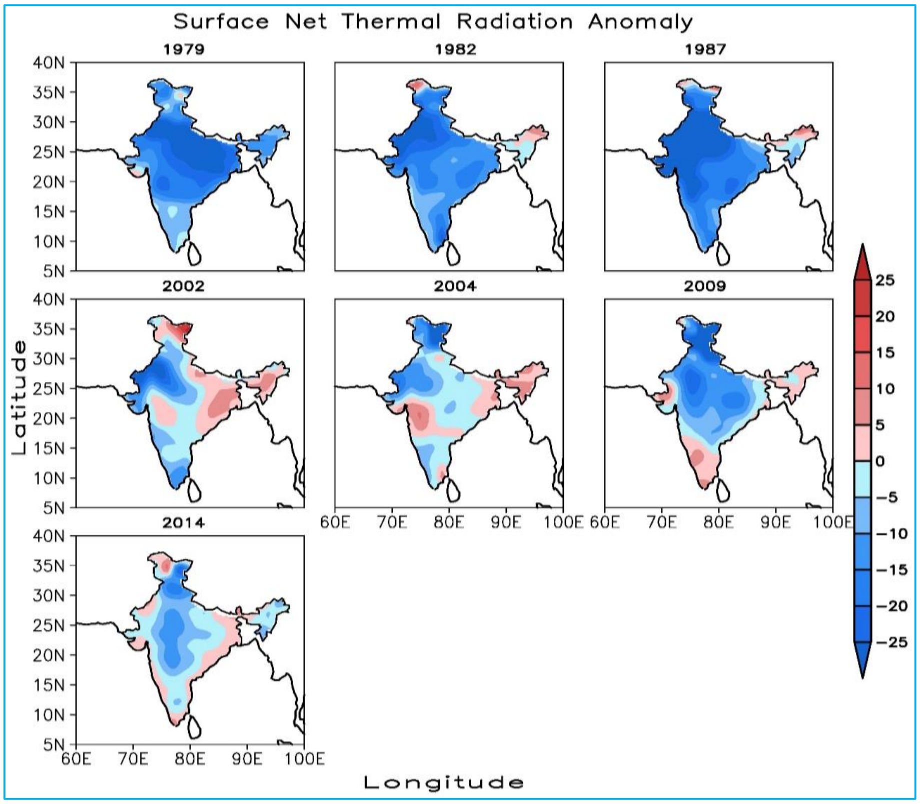


Fig. S12. Anomalous surface net thermal radiation on earth for the extreme drought years during ISM

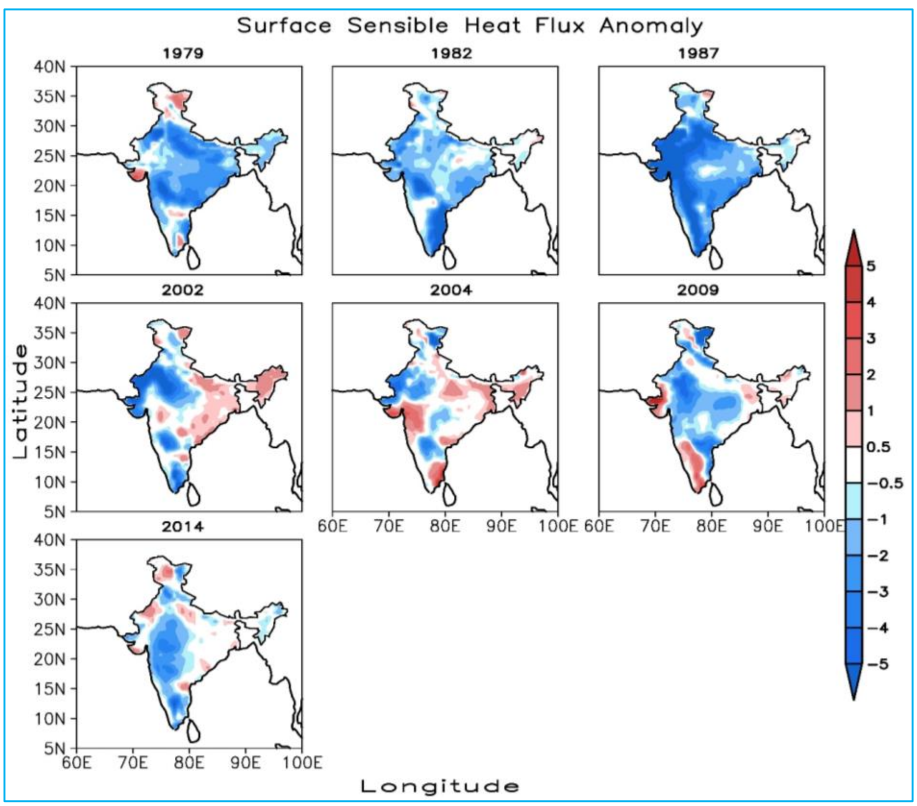


Fig. S13. Anomalous surface sensible heat flux on earth for the extreme drought years during ISM

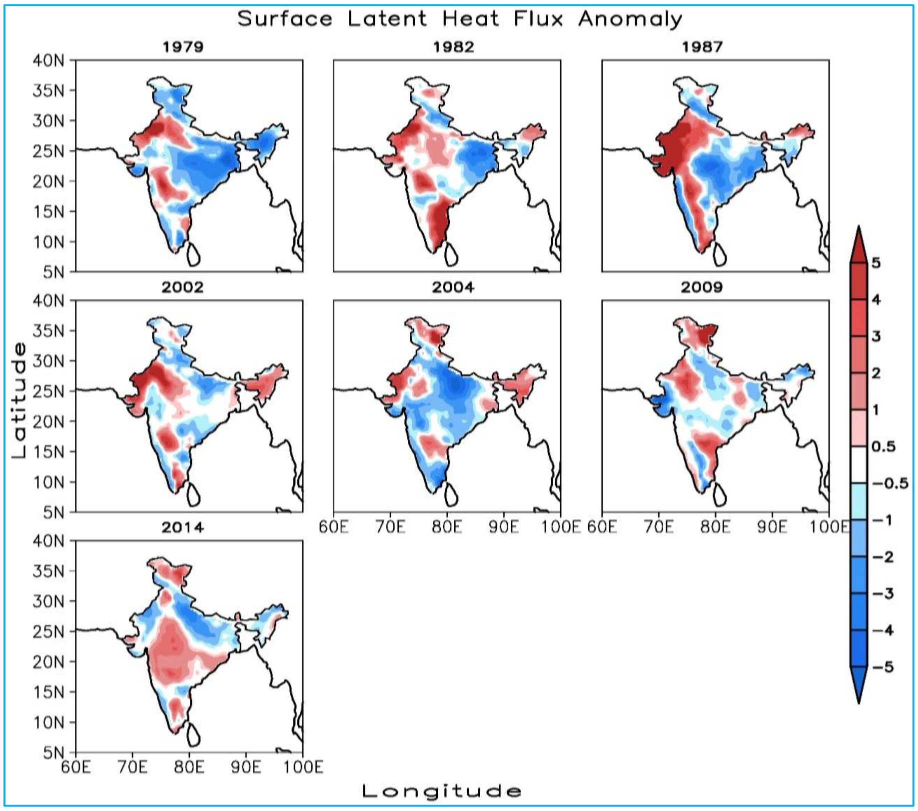
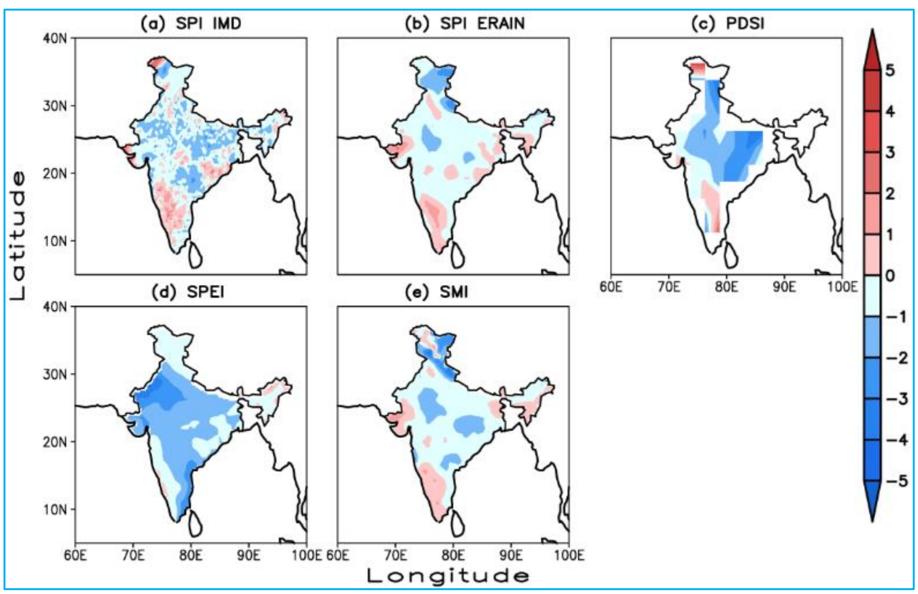


Fig. S14. Anomalous surface latent heat flux on earth for the extreme drought years during ISM



Figs. 3(a-e). The spatial distribution of different drought indices for 2009 (JJAS) over the study region; (a) SPI_IMD, (b) SPI_ERAIN, (c) PDSI, (d) SPEI and (e) SMI. Each index shows extreme drought over the major part of the India during 2009 monsoon season All indices show most part of India is dry. The Fig. (a and b) show precipitation condition *i.e.*, most part of India is dry, while some apart from this are extremely dry. In Fig. (c and d) show the almost whole region is extremely dry (*i.e.*, excessive evapotranspiration from the surface and low surface runoff). Fig. (e) shows the moisture availability in the soil (upper level) that also shows the water condition as well as vegetation condition. Threshold values of each index are given in Table 1

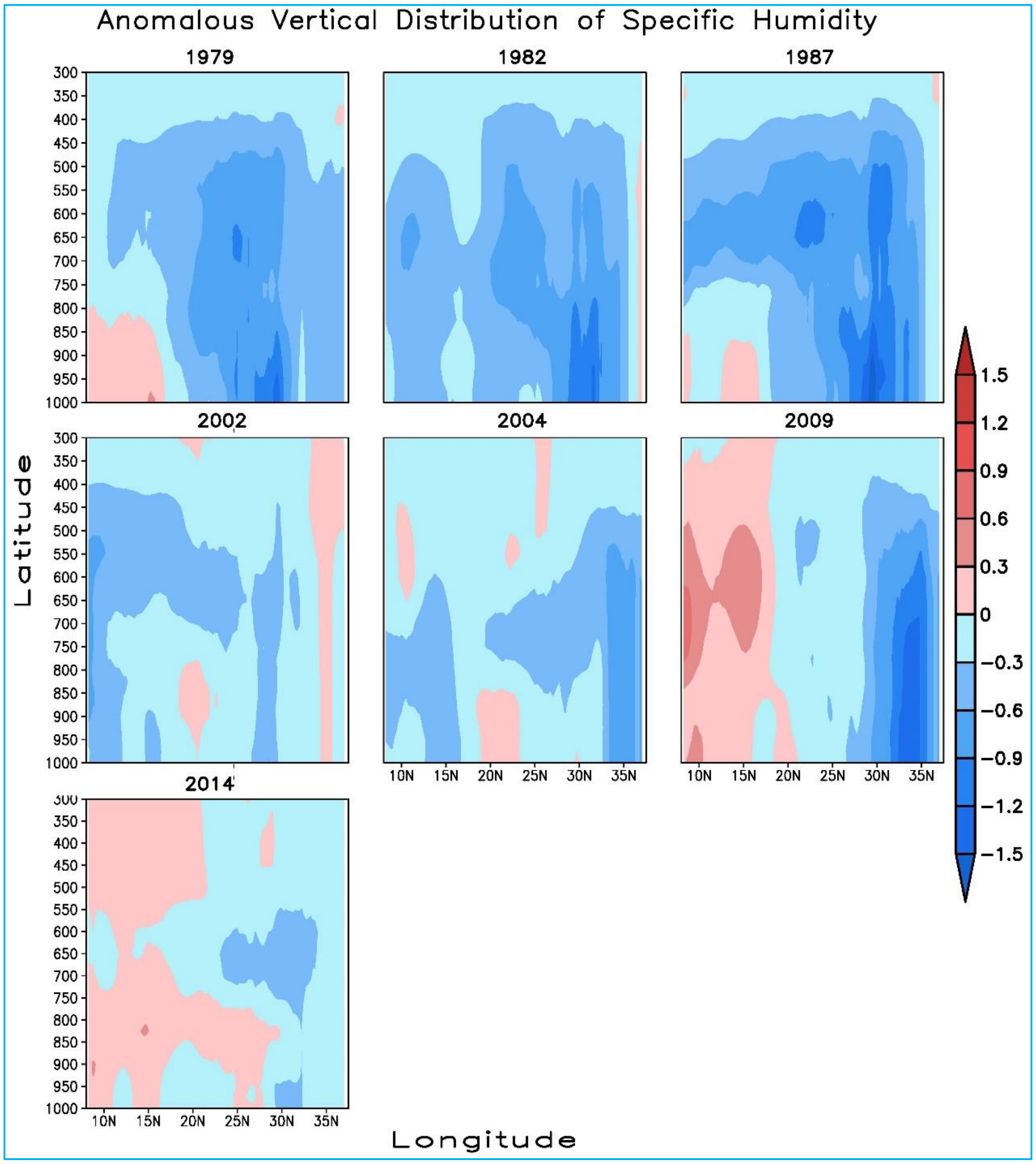


Fig. S15. Anomalous vertical distribution of specific humidity for the extreme drought years during ISM

et al., 2004). The value of SPEI for this year is also less than -3 in some places (Rajasthan, Gujrat, Tamil Nadu and Orissa), which justifies the extreme drought. Apart from this, the rest of the places SPEI values vary from 0 to -3. However, SPEI is a good index for explaining greater evapotranspiration than precipitation (Vicente-Serrano *et al.*, 2010; Hao and Singh, 2015). The availability of soil moisture governs evapotranspiration. The unavailability of soil moisture can be a possible cause for the loss of vegetation's/crops during ISM. The value of SMI Fig. 2(a), is also negative, indicating the soil moisture scarcity (*i.e.*, dry soil). Fig. 2(b) presents the trend of SPI at 95% significance [The significant trend of different drought indices for 1979 to 2015 (JJAS) over the study region is referred to Fig. S4]. It shows that both the dry and wet years are getting drier during the ISM. This could be due to climate change and induced variability, changes in precipitation seasonality and enhanced climatic extreme events, *e.g.*, drought, heatwaves, floods etc. (Feng *et al.*, 2013). Figs. 3(a-e) shows the spatial distribution of various drought indices over India during 2009 ISM. Each index shows extreme drought over significant parts of India (Threshold values of each index are briefly discussed in Table 1). In Figs. 3(a&b), SPI over most parts of India

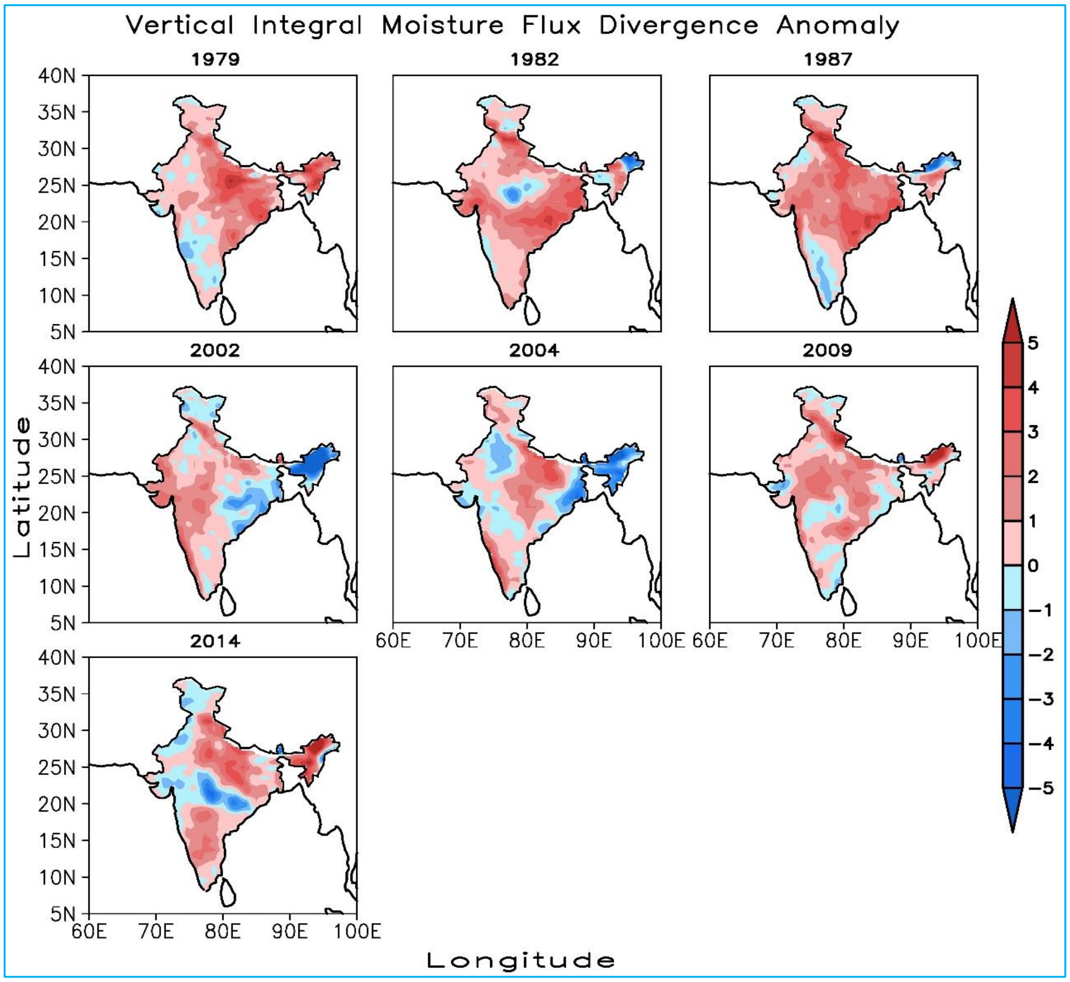


Fig. S16. Anomalous vertical integral moisture flux divergence for the extreme drought years during ISM

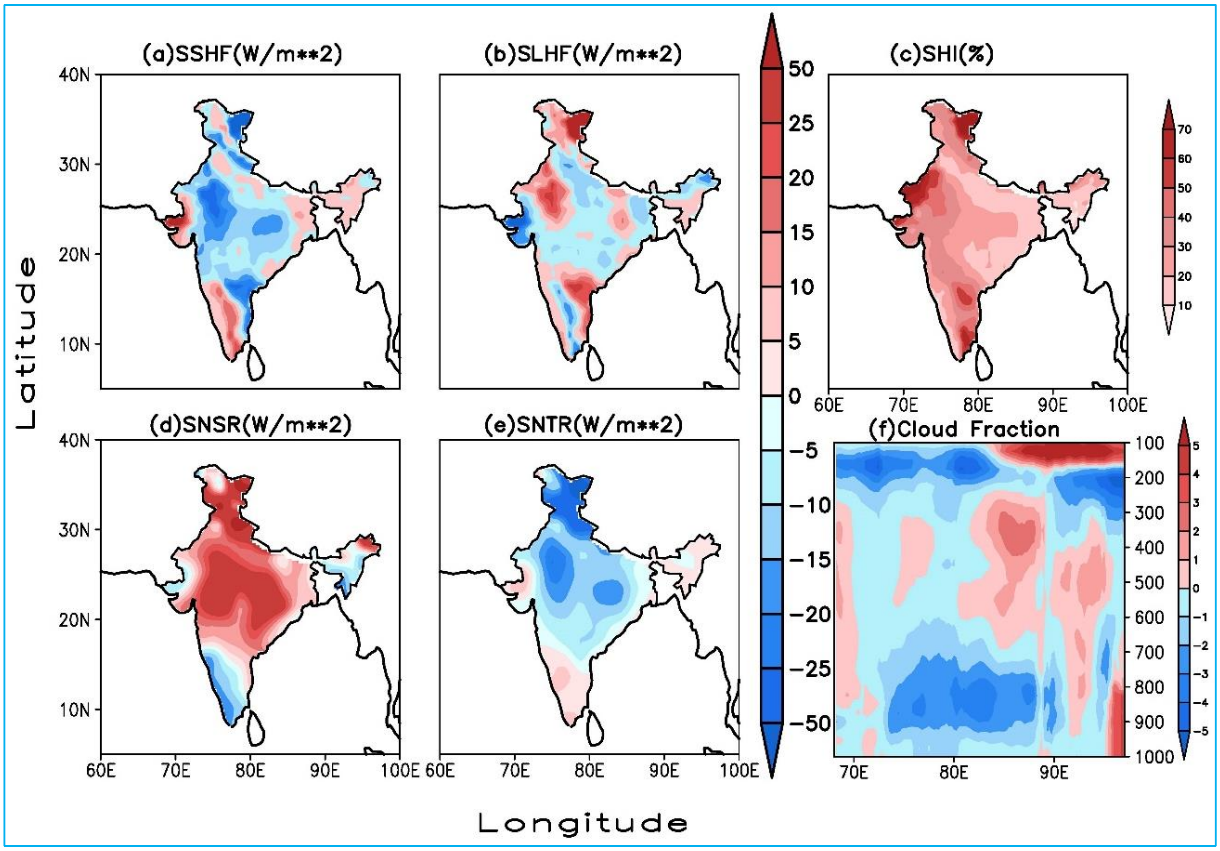
shows severe drought and over some parts as extreme drought. A similar result is observed in all of the remaining indices. SPI is a simple to reckon index that accomplishes better results than detailed hydrological indices (Oladipio, 1985; Pai *et al.*, 2017). SPI is a tool to measure the dryness and wetness of the study region through seasonal precipitation. However, the precipitation deficiency introduces the meteorological drought and SPI is used as a meteorological drought analysis tool (Mishra and Singh, 2010). PDSI is a globally used meteorological drought index, multivariable in computation such as precipitation, evapotranspiration and soil water holding capacity. Hence, this index is suitable for representing excess surface warming situations. PDSI is typically used as a substitute for streamflow and soil moisture (Dai *et al.*, 2004). In Fig. 3(c), the central and north parts of India show extreme drought concerning the negative values of PDSI. SPEI is precipitation and temperature-based multiscale index. It is a measure of precipitation and evapotranspiration. In Fig. 3(d), the area with negative values has more evapotranspiration than precipitation (*i.e.*, dry and warm surface). Hence, the highest negative values are found over Rajasthan and east peninsular regions.

4.3. *SMI*

SMI is a measurement of available soil moisture on the surface's upper layer (10 cm). The soil moisture vaporizes from a hot surface and the surface gets drier and intensifying the ground heat during weak monsoon. The less soil moisture availability is a possible cause for weak local convection during ISM. In Fig. 3(e), some parts of India (central and north) are under extreme stress conditions during the 2009 ISM. SMI shows a similar result as PDSI, a proxy for soil moisture.

4.4. *Surface energetics*

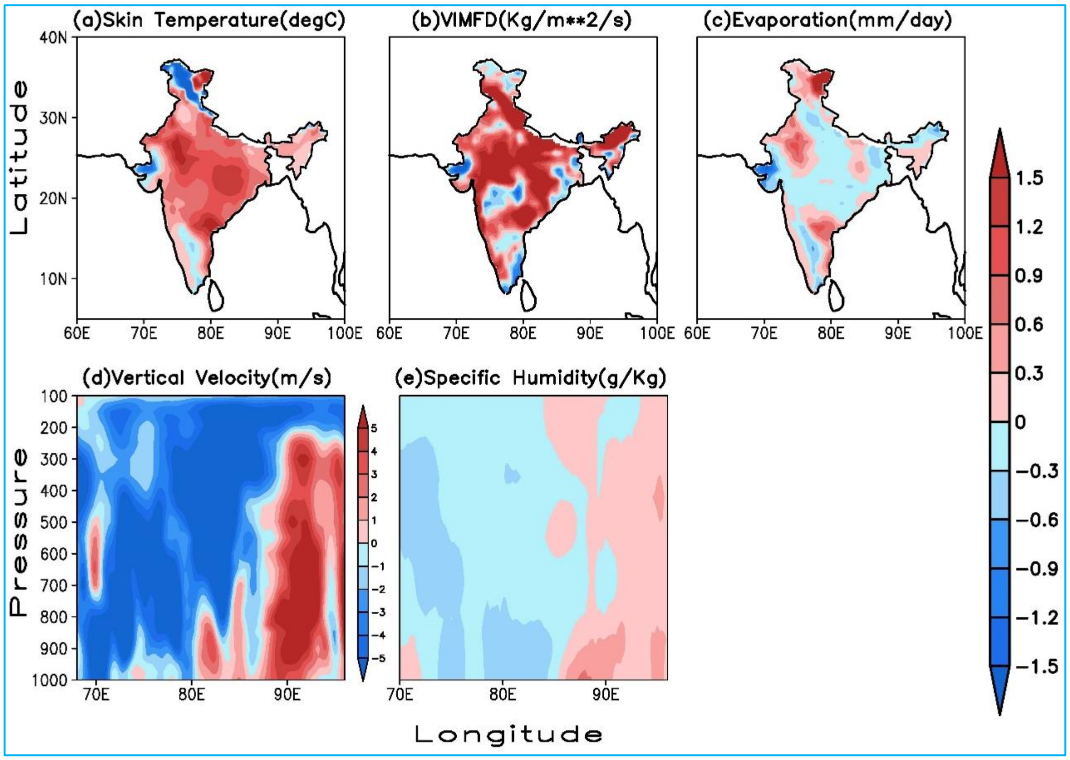
The decrease in soil moisture implies that the surface evaporation has been abnormally reduced. This results in



Figs. 4(a-f). The anomalous behavior of surface energy during 2009 ISM, extreme drought year; (a) SSHF (W/m^2), (b) SLHF (W/m^2), (c) SHI (%) [*i.e.*, sensible heat/(sensible heat + latent heat)], (d) SNSR (W/m^2), (e) SNTR (W/m^2) and (f) Cloud Fraction (latitudinal averaged over Indian land mass only). In Fig. (a) negative anomaly shows to abnormal increment in the sensible heat (*i.e*., going to add into the atmosphere), similarly in (b) negative anomaly shows to abnormal increment in latent heat (*i.e*., released from the surface available soil moisture to the atmosphere), Fig. (c) shows the dryness of the surface, in Fig. (d) positive anomaly shows the abnormal increment of solar radiation remain on the surface (*i.e*., trap of shortwave radiation into the surface), in Fig. (e) negative anomaly shows the abnormal increment of surface thermal radiation remain on the surface (*i.e*., trap of longwave radiation into the surface) and in Fig. (f) the negative anomaly shows the abnormally decrement of cloud cover over Indian landmass vertically

abnormal surface warming and intensification as lesser evaporation leads to lesser cooling. After that, SSHF shows an abnormal increase in sensible surface heating (*i.e*., due to short waves and longwave radiation trapped inside the ground) (Fig. 4). In Fig. 4(a), SSHF shows a negative anomaly over the central and northern parts of India (*i.e*., abnormal heat transfer from the atmosphere to the surface). The air near the surface is warmer; therefore, heat is transferred to the ground. However, local convective regions such as Western Ghats, Gujarat and Northeast India show abnormal sensible heat loss. In Fig. 4(b), negative SLHF reveals that the evaporation process is unable to cool due to the absence of soil moisture. Hence, the SLHF trapped into the ground creates a warmer surface (*i.e*., extreme induced drought during ISM). However, anomalous positive values over snow-covered regions, desert and hard rock show that latent heat is transferred from the surface to the atmosphere. The sensible heat index (SHI) shows a moderately dry surface (SHI = 10-30) over most parts of India Fig. 4(c). SHI values in the 30-50 range show an arid region. The high values (*i.e*., greater than 50) shows no vegetation regions (Barnes *et al*., 2001). The excessive warming is possibly caused by the anomalous solar radiation trapped in the surface. In Fig. 4(d), most parts of India show a positive anomaly of SNSR.

The positive values show the abnormal increment of solar radiation remaining on the surface. The positive values of SNTR show that the longwave radiation transfers from the surface, cooling the Earth's surface. An anomalous decrease in SNTR delineates that the longwave radiation is trapped into the surface, Fig. 4(e). A strong negative anomaly of the cloud cover fraction is observed

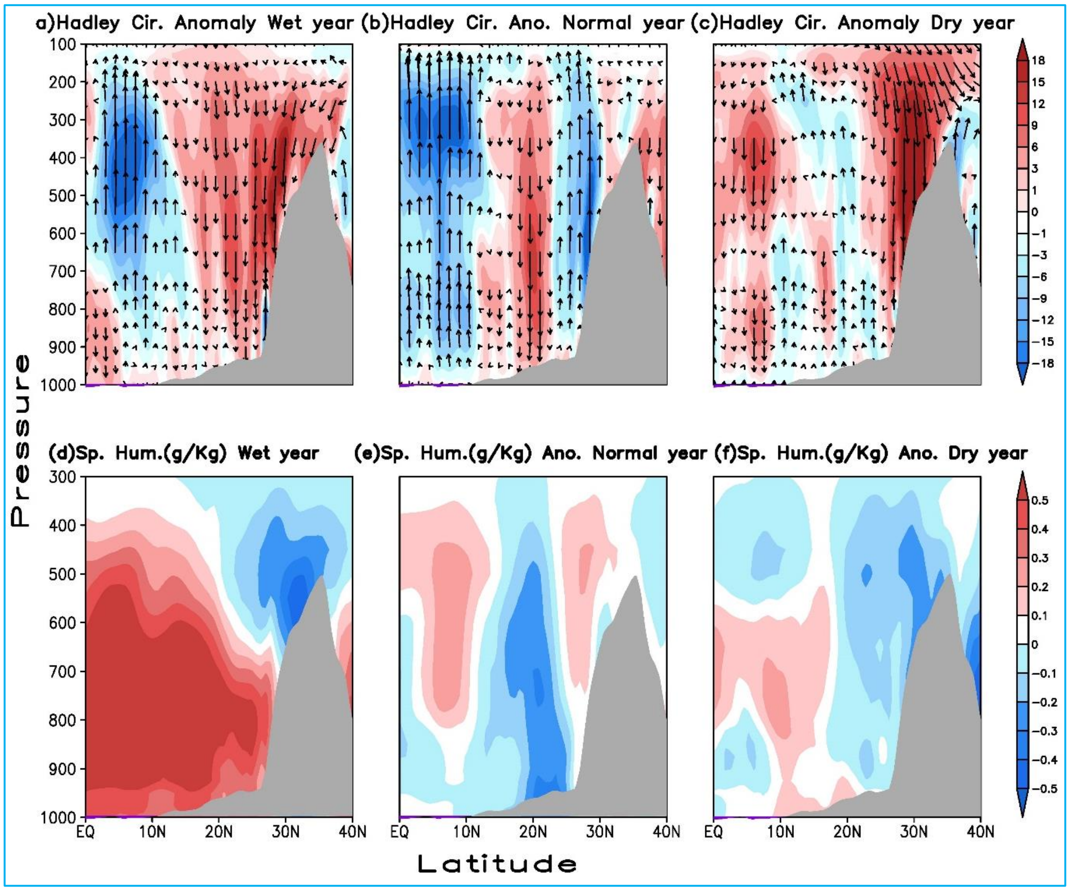


Figs. 5(a-e). The anomalous behavior of heat & moisture from surface to the surrounding atmosphere during 2009 ISM extreme drought year; (a) Skin temperature (deg. C), (b) VIMFD (kg/m^2/s), (c) Evaporation (mm/day), (d) Sectorial mean of vertical velocity (m/s) along latitude (7° N- 38° N, Indian land mass only) and (e) Sectorial mean of specific humidity (g/kg) along latitude (7° N-38° N, Indian land mass only). In Fig. (a) the most part of India is showing positive anomaly (*i.e.*, an abnormal increase in surface temperature or heating), in Fig. (b) a positive value shows the anomalous divergence of vertical integral moisture (*i.e.*, moisture unavailability/ move away), in Fig. (c) the most part of India is showing a negative anomaly of evaporation from the surface (*i.e.*, due to lesser available soil moisture), in Fig. (d) negative values show anomalous sinking motion of the air mass (*i.e.*, suggests low convection) and in Fig. (e) negative value shows the anomalous decrease in specific humidity from the surface to upper troposphere over Indian land mass

at the lower troposphere, Fig. 4(f). Moreover, a small patch of the positive anomaly is also found in the mid-troposphere over latitudinal averaged from 85° E to 95° E (*i.e.*, orographic cloud cover) and a strong positive anomaly over 100 hPa and beyond. Hence, the lower troposphere (*i.e.*, planetary boundary layer) and upper troposphere show an anomalous decrease in cloud cover at around 80° E. It enhances the shortwave radiation, leading to abnormal surface warming during the 2009 ISM. In addition, it makes the sky clear for the emission of terrestrial radiation that creates a radiative sink of heat against its vicinity (Charney, 1975). Hence, the ground stores some heat, which enhances drought.

Fig. 5(a) shows an anomalous increase in skin temperature that suggests extreme surface warming. Northwest J&K, western Gujarat and a small patch of southern India shows negative anomaly (*i.e.*, an anomalous surface cooling during the ISM). Northwest J&K surface cooling is possibly due to snow melting during warmer atmospheric conditions (Zhang *et al.*, 2004; Barnett *et al.*, 2005; Sharma *et al.*, 2012 and 2013). However, western Gujarat surface cooling is due to evaporation and local convection from the Rann of Kutch. VIMFD of the atmospheric column over most parts of India shows a positive anomaly, Fig. 5(b). It signifies that moisture is moving away from the Indian landmass. It means that the monsoon moisture convergence zone was reversed due to prominent land heating.

The evaporation shows an abnormal decrease in most parts of India, Fig. 5(c). Some minor negative values are observed over the Eastern Ghats, Odisha and western Gujarat (*i.e.*, because of local convection source and evapotranspiration), possibly due to unavailability of soil moisture or constant soil moisture dry surface. While northeastern J&K, Eastern Ghats and Western Ghats have positive evaporation anomalies. The anomalous increased skin temperature causes abnormal evaporation from the



Figs. 6(a-f). The anomalous behavior of Hadley circulation and moisture during ISM (longitudinal averaged over 65º-100° E), (a) Hadley circulation for extreme wet year (1983), (b) Hadley circulation for normal year (1996 taken from Monsoon Monograph volume 2), (c) Hadley circulation for extreme dry year (2009) (Figs. a, b and c : color shading shows anomaly of omega, hPa/s), (d) Specific humidity (g/kg) for extreme wet year (1983), (e) Specific humidity (g/kg) for normal year and (f) Specific humidity (g/kg) for extreme dry year (2009). In Fig. (a) negative anomaly shows to an abnormal strengthening in the Hadley circulation (*i.e*., opposite of the dry year's circulation), similarly (c) shows abnormal weakening the Hadley circulation [*i.e*., opposite and weaker than a wet year's circulation (both deviates from normal)], (d) shows the anomalous increment of moisture (*i.e*., due to high convection during extreme wet ISM) and in (f) negative anomaly shows the abnormal decrement of moisture (*i.e*., the low convection). The gray shading shows longitudinal averaged topography over 65º-100° E (*i.e*., Indian landmass and the Himalayas)

surface to the atmosphere as per the Clausius-Clapeyron equation (Monteith and Unsworth, 2013). It induces atmospheric warming through the latent heat released from the surface to the atmosphere vicinity. Fig. 5(d) shows an anomalous shrank of vertical motion from the upper to lower troposphere, which reveals shallow convection over the Indian landmass.

Nevertheless, a strong positive anomaly of vertical motion is observed over 90° E, which corresponds to northeast India with anomalous favourable specific humidity [Fig. 5(e)]. A negative anomaly of specific humidity justifies less convection, less evaporation and moisture divergence over the Indian landmass, Fig. 5(e). The present study establishes the role of increased surface warming in propelling drought to an extreme event during 2009 ISM.

4.5. *Moisture dynamics*

The moisture transport and wind circulation during ISM also played a crucial part in the precipitation over the Indian landmass. The land-ocean heat contrast drives the Indian monsoon system (Das, 1995) by modulating Hadley circulation. Hence to see the anomalous Hadley circulation variation during ISM months, moisture and wind circulation during an extreme wet year (1983), Normal year (1996) (taken from Monsoon Monograph volume 2; Tyagi *et al*., 2012) and an extremely dry year (2009) are compared in Figs. 6(a-f). However, the wet

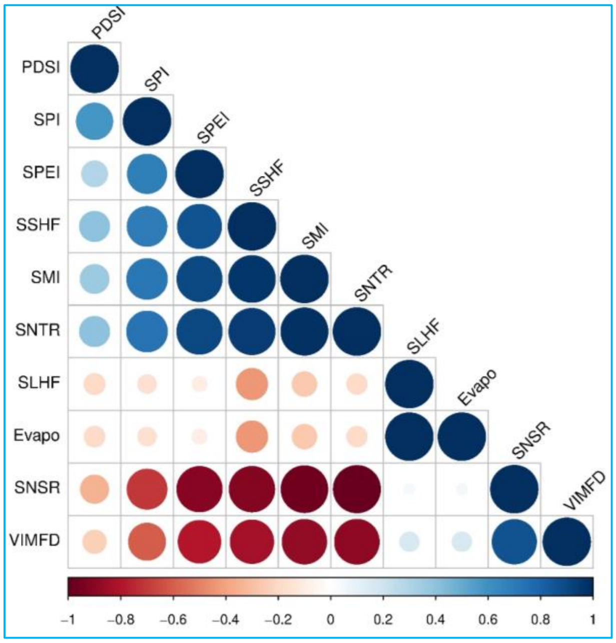


Fig. 7. A correlation matrix of PDSI, SPI, SPEI, SSHF, SMI, SNTR, SLHF, Evaporation, SNSR and VIMFD is shown. This is used to investigate the dependence between all the variables at the same time

year shows an eccentric strengthening in Hadley circulation (Goswami *et al*., 1999; Feddema *et al*., 2005) [Fig. 6(a)]. Similar results are observed for specific humidity anomalies [Fig. 6(d)]. The wet year shows strong rising motion from 850 to 150 hPa over the oceanic region and strong lower-level convection. Sinking motion over the Indian landmass signifies more vigorous Hadley circulation compared to a typical year, Figs. 6(a, b and e). While, the arid year showed that the wind in Hadley circulation gets downward and narrowed over the Himalayas and near Equator (Goswami *et al*., 1999; Feddema *et al*., 2005; Preethi *et al*., 2011) [Fig. 6(c)]. The specific humidity is negative/very low all over the region from lower to upper troposphere, Fig. 6(f). Hence, this insinuates that lower tropospheric Jetstream (the Findlater Jetstream) mass transport from the ocean existed during a drought year. Similar results are found from the evaporation anomaly. Most of the Indian landmass shows anomalously low evaporation [Fig. 5(e)]. The years (1983 and 2009) show completely different strong circulation patterns. The anomalous positive value of specific humidity during the wet year shows more vigorous convection over the ocean and landmass but more strong negative values over the Himalayas. This causes moisture pull-up from the ocean to the Indian landmass, strengthening the Hadley circulation (Das, 1995) [Figs. 6(a-d)]. In contrast, the abnormal Hadley circulation weakens during the arid year (Goswami *et al*., 1999; Feddema *et al*., 2005) [Figs. 6(c&f)]. Fig. 7 shows a correlation between most of the variables used for the analysis. This observed that PDSI has positive correlation with SPI, SPEI, SMI and SHI. SPI has good positive correlation with SPEI, SSHF, SMI, SNTR and the correlation coefficient is higher comparative to PDSI (*i.e.*, because of precipitation dependent index). A strong positive correlation between SLHF and Evaporation indicating latent heat release during the evaporation. SMI has a strong negative correlation with VIMFD, indicating towards convergence of moisture along with high soil-moisture. It is found that PDSI, SPI and SPEI have a good positive correlation with SSHF and SNTR and a good negative correlation with SNSR and VIMFD. This implies that the variables are interdependent and play a significant part in the climate dynamics, which is what the current study is trying to determine.

5. Conclusions

Drought assessment can be explained through various indices in terms of its spatial and temporal extent, magnitude and intensity. However, understanding the dynamics and energetics of drought is equally important to quantify its magnitude and mechanism (or intensity and processes). The various SPI, PDSI, SPEI and SMI show intense dryness during 2009 ISM. It is found that the extreme drought is induced as a result of excessive surface heating (Das, 1995), which in turn give way to deficit soil moisture, reduced precipitation and induced evapotranspiration (*i.e.*, shallow convection and moisture transportation) (Preethi *et al*., 2011) and excessive surface heating. Abnormal increment of SSHF and abnormal decrement of SLHF clearly explain heat transfer from the atmosphere to the surface (*i.e.*, heat is gained and transferred to the ground through SNSR/SNTR). It is also found that an anomalous low cloud cover during 2009 ISM is a possible cause for the high SNSR and excessive warming of the surface that induced the extreme drought. The anomalous negative behaviour of Hadley circulation is associated with the lesser transportation of moisture from the ocean due to the anomalous excessive heating of landmass. This substitutes the moisture convergence to divergence zone, even though the year is neutral ENSO (Preethi *et al*., 2011; Mishra, 2019) due to excessive atmosphere/surface warming, the moisture-holding capacity of the atmosphere increases, which makes moisture coming from the ocean/local convection to diverge and setup a weak monsoon. Hence, excessive surface warming is the prime factor resulting in the extreme drought during 2009 ISM.

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Appendix

ECMWF: European Centre for Medium-Range Weather Forecasts
ESRL/NOAA: Earth System Research Laboratory/National Oceanic and Atmospheric Administration
ENSO: El Niño/Southern Oscillation
ERAIN: Era Intrerim
G: Ground Heat
H: Sensible Heat
ISM: Indian Summer Monsoon
LE: Latent Heat
PDSI: Palmer Drought Severity Index
PRA: Percentage of Runoff Anomaly
SHI: Sensible Heat Index
SLHF: Surface Latent Heat Flux
SMI: Soil Moisture Index
SNSR: Surface Net Solar Radiation
SNTR: Surface Net Thermal Radiation
SPEI: Standardized Precipitation Evapotranspiration Index
SPI: Standardized Precipitation Index
SRI: Standardized Surface Runoff Index
SSHF: Surface Sensible Heat Flux
VIC: Variable Infiltration Capacity
VIMFD: Vertical Integral Moisture Flux Divergence

Footnote
http://bhuvan.nrsc.gov.in/gis/thematic/index.php
http://www.earthonlinemedia.com/ebooks/tpe_3e/energy/energy_balance.html
https://www.ecmwf.int/sites/default/files/radiation_in_mars.pdf
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https://earthobservatory.nasa.gov/features/GlobalWarming/page2.php (Global Warming)