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Drought monitoring over India using multi-scalar standardized precipitation evapotranspiration index

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सार - सूखे का कृषि, पारिस्थितिकी तंत्र और आजीविका पर नकारात्मक प्रभाव पड़ता है। सूखे की तीव्रता की निगरानी और मापने के लिए कई सूचकांक विकसित किए गए हैं। मानकीकृत वर्षा वाष्पोत्सर्जन सूचकांक (एसपीआई) एक नया सूखा सूचकांक है जो सूखे की निगरानी के लिए वर्षा और वाष्पोत्सर्जन पर विचार करता है। पिछले 34 वर्षों (1980-2014) के आंकड़ों का उपयोग भारत में सूखे के अध्ययन के लिए किया गया। भारत मौसम विज्ञान विभाग (IMD) के ग्रिडेड वर्षा और तापमान के आंकड़ों को सूखे की मैपिंग के लिए मानकीकृत वर्षा वाष्पोत्सर्जन सूचकांक (SPEI) की तैयारी के लिए लिया गया है। मानकीकृत वर्षा वाष्पोत्सर्जन सूचकांक (SPEI) की गणना सामान्य (2013) और (1985, 1987, 2002, 2004, 2009 और 2014) सूखे वर्ष के लिए की गई थी। मानकीकृत वर्षा वाष्पोत्सर्जन सूचकांक (SPEI) को अत्यंत शुष्क से अत्यंत वर्षा वाली परिस्थितियों के लिए नौ वर्गों में वर्गीकृत किया गया था। यह स्पष्ट है कि मानकीकृत वर्षा वाष्पोत्सर्जन सूचकांक (SPEI) ने मानकीकृत वर्षा सूचकांक (एसपीआई) को ग्रहण किया है और यह सूखा प्रभावित क्षेत्रों की पहचान कर सकता है। अध्ययन के वर्षों में मानकीकृत वर्षा सूचकांक और मानकीकृत वर्षा वाष्पोत्सर्जन सूचकांक (SPEI) के बीच सहसंबंध गुणांक (आर) 0.63-0.79 तक था। एसपीईआई और वनस्पति स्वास्थ्य सूचकांक (वीएचआई) के बीच स्थानिक तुलना सूखे की निगरानी के लिए एसपीईआई की क्षमता का वर्णन करती है। इससे प्राप्त हुए परिणाम से यह पता चलता है कि मानकीकृत वर्षा वाष्पोत्सर्जन सूचकांक (SPEI) का उपयोग भारत में सूखे की निगरानी और मूल्यांकन करने के लिए एक उन्नत सूचकांक के रूप में किया जा सकता है।

ABSTRACT. Drought has negative impact on agriculture, ecosystem and livelihood. Several indices are developed to monitor and measure the intensity of drought. Standardized Precipitation Evapotranspiration Index (SPEI) is a new drought index that considers the rainfall and evapotranspiration to monitor drought. The data for last 34 years (1980-2014) were utilized in the study to study the drought in India. The gridded precipitation and temperature data from the India Meteorological Department (IMD) were considered for the generation of SPEI for mapping of drought. The SPEI were calculated for normal (2013) and (1985, 1987, 2002, 2004, 2009 and 2014) drought year. The SPEI were classified into nine classes for extremely wet to extremely dry conditions. It is evident that SPEI is in acceptance with Standardized Precipitation Index (SPI) and can identify drought affected areas. The correlation coefficient (r) between SPI and SPEI ranged from 0.63-0.79 for the study years. The spatial comparison between SPEI and Vegetation Health Index (VHI) describes the ability of SPEI for drought monitoring. The finding shows that SPEI can be used as an advanced index for drought monitoring and assessment in India.

Key words – SPEI, Meteorological drought, Agricultural drought, evapotranspiration.

1. Introduction

In last few decades, there have been many attempts to develop new drought indices, or to improve existing ones on the basis of climatological study of precipitation (Gonza´lez and Valde´s, 2006; Keyantash and Dracup, 2004; Wells *et al*., 2004; Morbid *et al*., 2006; Tsakiris *et al*., 2007; Dogan *et al*., 2012; Jain *et al*., 2015). Major studies related to drought analysis have been conducted using Palmer drought severity Index which is based on soil water balance equation. The standardized precipitation index (SPI) also plays a vital role in the development of many drought indices which incorporates both dry and wet conditions on the concept of atmospheric demand and supply of moisture. Many precipitation-based drought indices, including the SPI, which rely only on assumptions: Precipitation variability is much higher than that of other variables, such as temperature and potential evapotranspiration (PET) and the other variables such as temperature, evapotranspiration, wind speed and soil are kept stationary, *i.e.*, they have no temporal change during the time. In this case, the importance of these other variables is negligible and droughts are controlled by the temporal variability in precipitation which gives a wrong conceptualization of drought monitoring. Abramopoulos *et al*. (1988) used a general circulation model experiment to show that evaporation and transpiration can consume up to 80% of rainfall which has empirically shown that temperature rise markedly affects the severity of droughts (Bhuiyan *et al*., 2017). The role of temperature was evident in the devastating central India drought during the summer of 2015. Climate change models predict a marked increase during the twenty-first century over many parts of India. It is obvious that this will have dramatic consequences for drought conditions, with an increase in water demand as a result of evapotranspiration (Sheffield and Wood, 2008). The use of drought indices that include temperature data in their formulation (such as the PDSI) is preferable, especially for applications involving future climate scenarios. Most concerned fact in the study of the drought impacts is the multi-scalar nature of drought, since consequences of the hydrological (river discharge, reservoir, soil moisture, groundwater, storage, etc.) and biological (crops, natural vegetation, etc.) systems to water shortage varies markedly and have different response times. Specially, for the applications involving future climate scenarios there must be use of drought indices which includes temperature data in their formulation. However, scales like SPI and PDSI are with lacuna of detecting the multi scalar character which is essential for assessing drought in relation to different drought type's *viz*., hydrological and agricultural droughts.

Vicente-Serrano *et al*. (2010) formulated a new evapotranspiration based drought index which is Standardized precipitation evapotranspiration index (SPEI) based on calculation of precipitation and PET. The SPEI combines the effect of PET to change in evaporation demand along with the temperature fluctuations and trends to capture the multi temporal nature of the SPI. Literature shows that mathematical difference of annual precipitation and potential evapotranspiration (PET) is less than zero (Hogg, 1994). Therefore, a drought index explicitly based on precipitation data may not be sufficient to monitor droughts for India. Standardized Precipitation Evapotranspiration Index (SPEI) is calculated as similar as SPI only by incorporating moisture stresses to the atmosphere due to evapotranspiration. SPEI is capable of depicting the multi-temporal nature of Hydrological, Meteorological drought and Agricultural drought which consists of computation at various temporal scales based on the probability of precipitation and potential evapotranspiration (P-PET) differences (Vicente-Serrano *et al*., 2010). For the shortest time scales, drought series show a high frequency of drought whereas moist duration of short time. For the climatological scenario, long time scales are related to variations in groundwater and reservoir storage. Long-time scales are useful for monitoring drought conditions in different hydrological subsystems and agricultural use of water resources. Especially, Monsoon of India spreads precipitation widely in terms of total accumulation, seasonal timing and variability in many parts of country. The knowledge of temporal and spatial variability of drought is becoming essential for better mitigation planning and its preparedness. Several studies have been carried out to characterize the drought over Indian region (Bhalme and Mooley, 1980; Parthasarathy *et al***.**, 1987; Sikka, 1999; Vyas *et al*., 2015). The temporal analysis of rainfall and potential evapotranspiration (PET) captured two characteristics, over eastern part of India the increase in drought was attributed due to decreased rainfall over the periods, whereas the decrease in drought occurrence over western arid region was mainly because of decreased PET (Das *et al*., 2016).

Main objective of this study was to accommodate evapotranspiration along with spatial variation of precipitation which gives integral conclusion of atmospheric need of soil moisture for occurrence of precipitation. This will act as a new input for soil moisture content over last week and will be forecasted for agro advisory services to address the farmers under station or AMFU. The study focuses mainly on the use of calculated SPEI using gridded PET and Temperature which may help in better assessment of crop condition and better way of translating the agricultural and hydrological drought across the country.

2. Materials and method

2.1. *Data used*

The gridded daily rainfall and temperature data with 0.25 × 0.25 resolutions each were used to calculate the SPEI in this study explicitly for monsoon months (June to September) of each year. For the present study rainfall and temperature data archived at the National Data Centre, India Meteorological Department (IMD) Pune were obtained for the period 1980-2014 (34 years). Thornthwaite temperature method was used to calculate the Potential evapotranspiration (PET) from the gridded temperature data. The Standardized Precipitation Index (SPI) developed by Mckee *et al*. (1993) is the most widely used meteorological drought index. In the present study, the SPI calculated using the long-term monthly precipitation data of IMD rain-gauge stations, from 1963 to 2013 were used for validation of SPEI during monsoon period. The Vegetation Health Index (VHI) (Kogan, 2001), used to estimate crop condition and monitor agriculture drought globally was used in the study to validate the calculated SPEI. The 7-day composite of VHI at 4 km spatial resolution was acquired from the National Oceanic and Atmospheric Administration (NOAA) (https://www.star.nesdis.noaa.gov).

3. Methodology

3.1. *Formulation of SPEI*

A simple multi-scale drought index SPEI was calculated which combines precipitation and potential evapotranspiration data. We follow the original SPI calculation procedure for SPEI calculation. SPEI is calculated using monthly (or weekly) precipitation and temperature as the input data. The SPEI should be used in preference to the PDSI and other drought index's, compared to simplicity because lower data requirement for calculation and its multi-scalar properties. Index PDSI explicitly suggests that, under global warming temperature will play a more important role than precipitation in explaining drought conditions. This phenomenon can also be assessed using the SPEI. It accounts for possible expectation of temperature variability and its extremes can go beyond the context of global warming. SPEI need minor additional data relative to the SPI, which is ultimately useful for analysis and monitoring of droughts in any climate region of the world. Since it can be calculated over a wide range of climates, as can the SPI. The SPEI allows comparison of drought severity in reference to the time and space. Different drought types and impacts can be identified by its multi-scalar characteristics which is a crucial advantage of the SPEI over the most widely used drought indices that consider the effect of PET on drought severity.

With F(x) the SPEI can easily be obtained as the standardized values of F(x). Shape and scale parameters of the difference D = P - PET is calculated by inbuilt function of MATLAB. Simultaneously, gamma distribution applied for current year monthly D value. The classical approximation of Abramowitz and Stegun (1965),

$$\mathrm{SPEI} = \mathrm{W} - \frac{\mathrm{C_0} + \mathrm{C_1 W} + \mathrm{C_2 W^2}}{1 + \mathrm{d_1 W} + \mathrm{d_2 W^2} + \mathrm{d_3 W^3}} \tag{1}$$

where, $\mathrm{W} = \sqrt{-2\ln p}$ for P $\leq$ 0.5 and P is the probability of exceeding a determined D value, P = 1 - F(x). If P > 0.5, then P is replaced by 1 - P and the sign of the resultant SPEI is reversed. The constants are 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.

3.2. *Estimation of potential evapotranspiration (PET)*

The Potential Evapotranspiration (PET) is calculated using the Thornthwaite (1948) method; this method is based mainly on temperature with an adjustment made for the number of daylight hours (Thornthwaite, 1948). The PET estimate is obtained for each month, considering a month is 30 days, is given by the following formula:

$$\mathrm{e} = 1.7(10\ \mathrm{Tm/I})^{\alpha} \tag{2}$$

where, Tm is the monthly mean temperature (C), I is the annual which is sum of 2 values of monthly heat indices i and α is an empirical exponent computed using equation 3.

$$\alpha = 0.0000000675{*}\mathrm{I}^3 - 0.000771{*}\mathrm{I}^2 + 0.017992{*}\mathrm{I} + 0.49239 \tag{3}$$

The Monthly Thornthwaite Heat Index (i) is calculated using the equation 4.

$$\mathrm{i} = \sum(\mathrm{Tm}/5)^{1.514} \tag{4}$$

The factor e is an adjusted value based on 12 hour day on 30 day month. It is corrected by actual day length in hours 'h' and days in a month M, to get the adjusted PET.

Given the monthly mean of gridded temperatures, an estimate of the potential evapotranspiration for each month of the year was calculated. This method has been used widely throughout the world. The PET calculated using this method tends to exaggerate the values in the summer seasons where higher temperatures are dominant. Also, studies have shown that this method underestimates PET in the arid areas and over estimates PET in the humid areas (Pereira and De Camargo, 1989).

4. Results and discussion

4.1. *Comparison of SPEI with SPI*

The severity and spatial extent of drought and wet conditions was mapped using SPEI into nine classes for the selected seven years. In the last two decades the years 1985, 1987, 2002, 2004, 2009, 2014 experienced drought in India. The SPEI were able to depict spatial extent of dry and wet situation as reported in India for these drought years. The SPEI was also calculated for a normal year 2013 to test its spatial variation in normal conditions.

Fig. 1 show SPEI calculated for the monsoon months (June, July, August and September - JJAS) of the drought

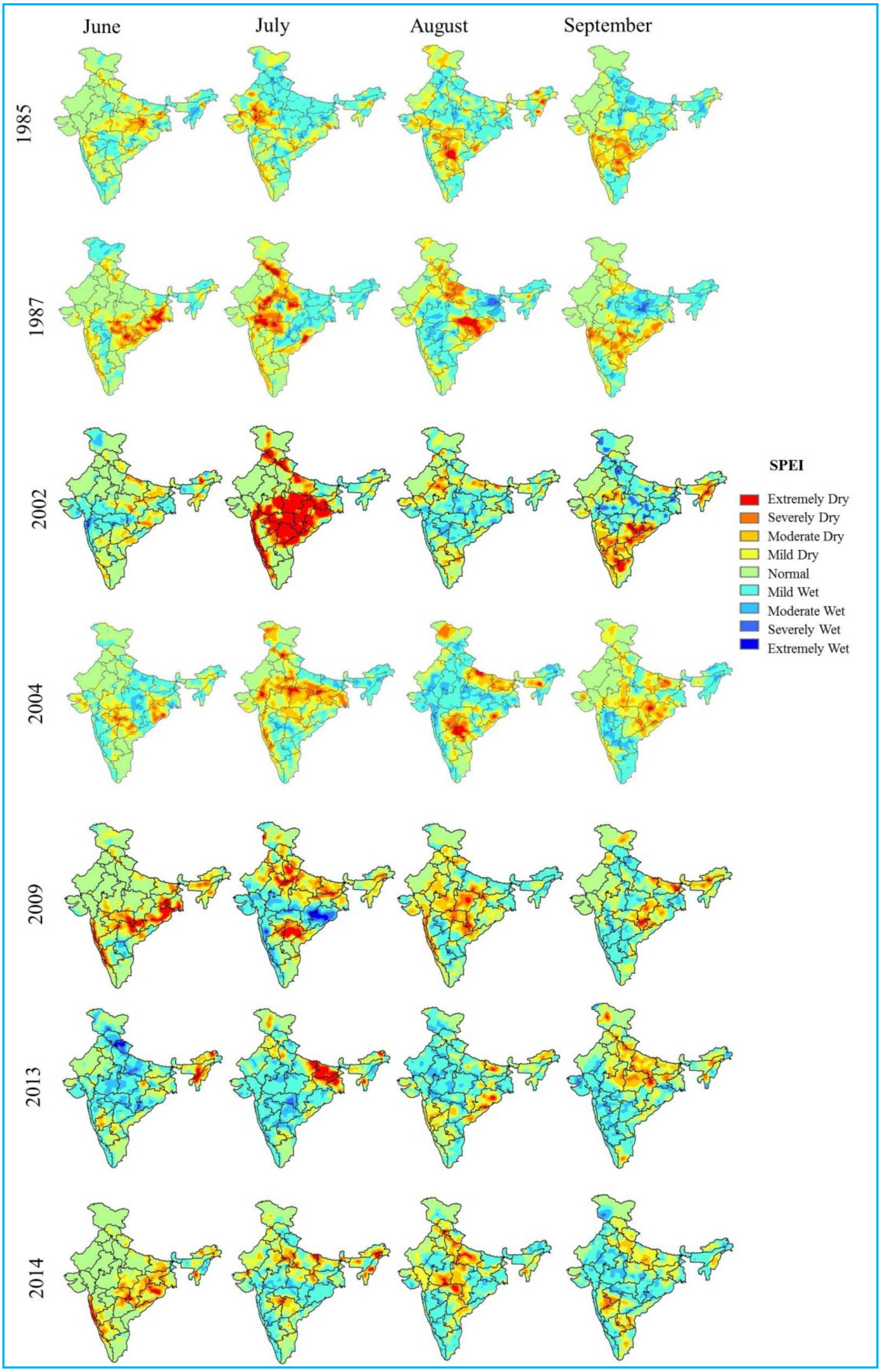

Fig. 1. Spatial distribution of SPEI

TABLE 1

Year wise correlation between the SPI and the SPEI

	SPI - SPEI [correlation coefficient (*r*)]						
Year	1985	1987	2002	2004	2009	2013	2014
SPI - SPEI (*r*)	0.71	0.79	0.74	0.69	0.72	0.63	0.66

TABLE 2

Year wise correlation between SPI - VHI and SPEI – VHI

	correlation coefficient (*r*)				
Year	2002	2004	2009	2013	2014
SPI - VHI	0.54	0.53	0.49	0.51	0.50
SPEI - VHI	0.56	0.60	0.54	0.63	0.61

years of 1985, 1987, 2002, 2004, 2009, 2014 and normal year of 2013 using 0.25 × 0.25 mean temperatures and rainfall of IMD network by program in MATLAB. The IMD rainfall for 2013 over some sub-divisions of the central region *viz*., West Madhya Pradesh, Vidarbha and Gujarat state as a whole received its respective normal rainfall in excess that was captured using SPEI of JJAS months (IMD, 2013).

In the year 1985 the western and the southern part of the country experienced drought conditions. In the year 1987 the eastern and northern part of the country experience drought in the first half on the monsoon season, whereas the southern part experience drought in the end of the monsoon season. In the year 2002 extreme drought conditions were experienced in the western central and eastern part of the country, SPEI recorded severely dry conditions in these regions, by the end of monsoon the southern peninsular India also experienced drought. In the year 2004 drought conditions were observed in the central and northern regions of India. SPEI represented moderate wet conditions in the month of July in the western, eastern and central region, however by the end of the monsoon season SPEI confirmed drought conditions in the central region and few pockets in the eastern region of India. In the year 2009 drought conditions were experience throughout India in the month of June. The drought conditions prevailed throughout the monsoon season, except in the month of August were mild wet conditions of SPEI were observed over central and north western states of India. Extremely dry conditions are shown in SPEI for the state of Bihar, Jharkhand and West Bengal along with parts of Utter Pradesh, Maharashtra, NE states and Orissa.

The seasonal rainfall over the country as a whole was deficient due to large deficiency in rainfall during June and first half of July 2014 and created stress over the major parts of country (IMD, 2014). The SPEI for 2014 correctly observed same mild dry conditions across India for June and mild wet conditions in parts for July 2014 (Fig. 1). During September 2014, the rainfall activity over many parts of the country showed significant increase and 23 subdivisions received excess or normal rainfall. However, 13 subdivisions mainly from north India along the plains of Himalayan region and north peninsula received deficient rainfall (IMD, 2014), which is also captured by mild dry conditions compared to 9 sub divisions in SPEI.

In conclusion SPEI measured actual demand of the soil with reference to temperature change. While in peninsular states of India, *viz*., Maharashtra, Telangana Andhra Pradesh and parts of Karnataka SPEI shows mild wet condition. The Monsoon of 2014 over Jammu & Kashmir is known for the severe flooding at many parts of the state (IMD, 2014) which, was well captured by the SPEI index. However, the severe wet spell captured by SPI during normal year 2013 and few events in 2014 were reported with less severity by SPEI. The authors suggest the use of SPEI is quite useful and easy instead of numerical weather prediction to forecast drought years in advance for preparation of agro advisories.

4.2. *Comparison of SPEI with SPI*

SPI and SPEI were compared using simple correlation analysis by computing the Pearson correlation coefficient (*r*). The correlation was observed for the acceptance of SPEI as an alternative and better index for

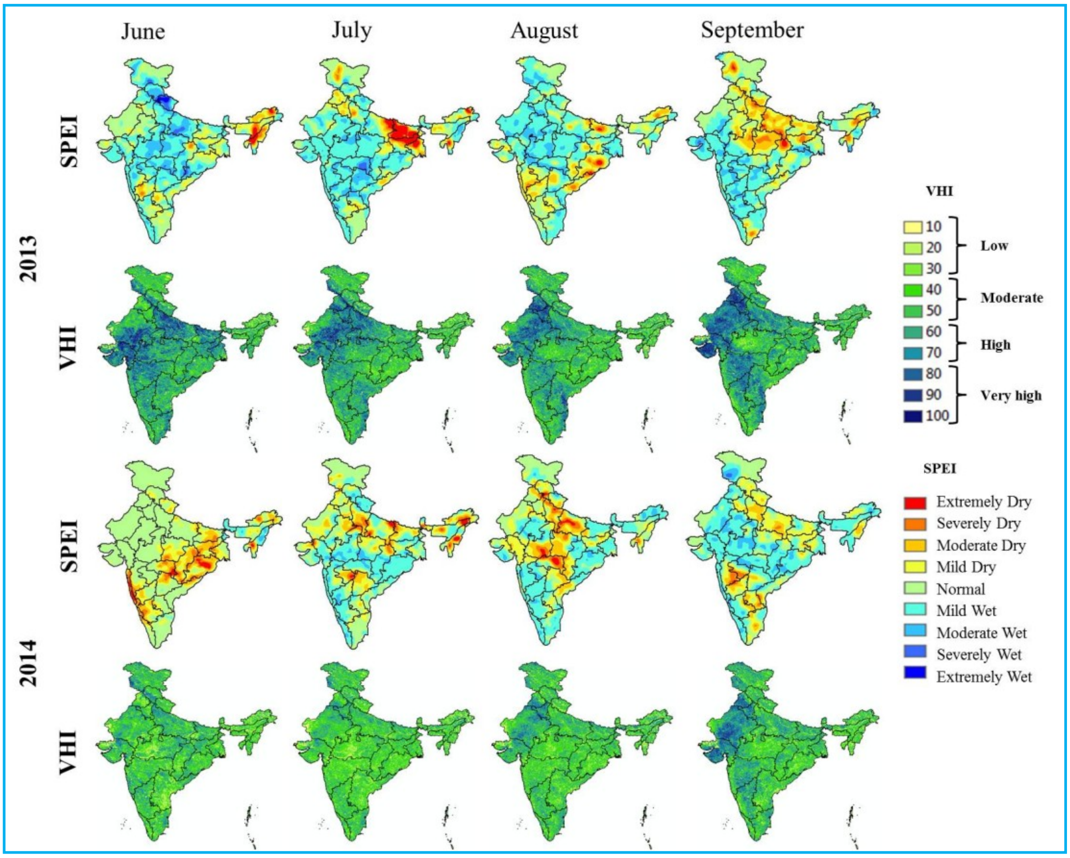

Fig. 2. Distribution of vegetation using Vegetation Health Index (VHI) for the year 2013-2014

drought stress assessment. The results comparison between SPI and SPEI were significantly correlated with a correlation coefficient ranging from 0.63- 0.79 (Table 1).

The correlation was relatively weaker but positive at the coastal and hilly region. The results show a little difference between the droughts depicted by SPI and SPEI primarily because of the variability of the temperature accounted by SPEI.

4.3. *Comparison of SPEI and SPI with VHI*

SPI and SPEI were further compared using simple correlation analysis with Vegetation health index (VHI) (Table 2).

The results of the comparative analysis between VHI and the two indices indicate that the SPEI were significantly correlated with a correlation coefficient ranging from 0.54 - 0.63 with VHI. The correlation was relatively weaker 0.49 - 0.54 between SPI and VHI. SPI and SPEI in general show high correlation indicating that either of the indices is good for drought monitoring. However, the correlation between SPEI and VHI indicate that the SPEI depicts droughts better than SPI. Fig. 2 shows a spatial comparison between the SPEI and the VHI for the drought year 2014 and non-drought (normal) year 2013.

The present study will be further extended at different timescales (3-, 6- and 9-months) to study the influence of temperature and to depict the severe and longer duration droughts. With the changing climate variability and climate change, monitoring of agriculture will be challenging, where SPEI can be used to solve the problem of drought monitoring.

5. Conclusions

This study investigated the drought assessment using long-term temperature and precipitation data over India. The 0.25° resolution gridded SPEI maps seemed to be suitable for the drought detection, monitoring and assessment at the regional scale. The drought characterisation based on the gridded SPEI provides comprehensive results on the complexity of drought phenomena. The SPEI was able to capture the impacts of increased temperature and drought stress in the drought years of 1985, 1987, 2002, 2004, 2009 and 2014. Under low temporal variability in temperature climatic conditions, the SPEI is superior to the SPI, since it identifies different drought types because of its multi-scalar character. Both indices have the capacity to identify an intensification of drought severity related to reduce precipitation in a climatic change scenario. The SPI cannot account for the influence of temperature variability and the role of heat waves to detect drought. SPEI on the other hand considers the effects of temperature variability and temperature extremes beyond the context of global warming for drought detection. Therefore, the former can preferable used for the identification, analysis and monitoring of droughts in any climate region. With precipitation and additional evapotranspiration information SPEI is more useful for climate change studies, monitor agricultural droughts and show better results than precipitation-based SPI. The multi-scalar characteristic of SPEI that consider the effect of PET on drought severity, captures crucial advantage over the other most widely used drought indices for drought monitoring.

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