Risk assessment of extreme Indian summer monsoon precipitation on agro-ecosystem of northern and central-east India

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सार – इस शोध पत्र में भारतीय मैदानी गांगेय क्षेत्र (आई जी पी) और मध्य पूर्वी भारत के क्षेत्रों के कृषि परिस्थितिक तंत्र पर भारतीय ग्रीष्मकालीन मॉनसून (आई एस एम) में अत्यधिक वर्षा के कारण पड़ने वाले जोखिम का आकलन किया गया है। मासिक वर्षा के ग्रिडयुक्त डेटा का उपयोग करके मानक - वर्षा इंडेक्स (एस पी आई) की गणना की गई है जो मानक जोखिम संगणना का एक खरतनाक अवयव है। भारतीय ग्रीष्मकालीन मॉनसून मे अत्यधिक वर्षा की विसंगति के कारण भारतीय गांगेय मैदानी क्षेत्र के कृषि पारिस्थितिक तंत्र को मध्य-पूर्वी भारत से अधिक जोखिम भरा बतायागया है। आई जी पी के सिंचित क्षेत्र होने और मध्य-पूर्वी भारत से अधिक जोखिम भरा बताया गया है। आई जी पी के सिंचित क्षेत्र होने और मध्य पूवी भारत सूखा क्षेत्र होने के कारण दोनो क्षेत्र कम वर्षा होने की स्थितियों(अर्थात सूख संकट् में वृद्धि होने पर अलग अलग प्रकार से प्रभावित होंगे। कुल मिलाकार जाखिम के ऑंकड़े और प्रचलित कृषि कार्य दर्शाते हैं कि मध्य पठारी एवं पर्वतीय भाग के सूखाग्रस्त भाग तथा सिंचित भाग में गंगा का ऊपरी मैदानी क्षेत्र अधिकांश सूखा संभावित कृषि जलवायविक जोन में आते हैं। सूखा जोखिम परिमाण्न के एक्सीडेन्स प्रोबेबिलीटी (ई पी) कर्व और रिटर्न पिरियड (आर पी) कर्व से पता चला है कि आई जी पी के ऊपरी गांगेय मैदानी क्षेत्र अन्य क्षेत्र के विपरीत विशिष्ट रूप से अधिक सूखाग्रस्त क्षेत्र में प्रकट हुए हैं। ऊपरी गांगेय क्षेत्र में सूखे के संकट में वृद्धि और मेघावरण में वृद्धि दोनों साथ साथ हो रहे हैं। सतही पवन, तापमान अथवा इस जोन से निकलने वाली दीर्घ तरंग विकिरण इस संकट की पूरी तरह से जानकारी देते है। औसत एरोसोल इंडेक्स की मौजूदगी की तरफ संकेत करते हैं और जोन में वर्षा नहीं करने वाले बादलों की बढ़ोतरी का यह एक बडा कारण हो सकता है। इस प्रकार मेघावरण वृद्धि की यह प्रवृत्ति सूखा संकट को बढ़ाने में योगदान दे रही है।

ABSTRACT. Risk of extreme precipitation anomaly of Indian summer monsoon (ISM) on agro-ecosystems of Indo-Gangetic Plain (IGP) and central-east India regions has been assessed in the present study. Using monthly gridded precipitation data, standardized precipitation index (SPI) has been computed as the hazard component of the standard risk computation. The agro-ecosystems of IGP are exposed to higher risk due to extreme ISM precipitation anomaly than that of the central-east India. IGP being an irrigated region and central-east India being a rainfed region would be affected differentially due to the increasing negative anomaly in precipitation (*i.e.*, drought risk) in the two regions. Overall the risk score and the prevalent agricultural practice suggest that the Central plateau and hill region in the rainfed region and the Upper Gangetic plain in the irrigated region are the most drought risk pone agroclimatic zones. Exceedance probability (EP) curve and the return period (RP) curve of drought risk quantification revealed that the Upper Gangetic plain of the IGP is conspicuously exposed to a higher drought risk unlike any other region. Increasing drought risk is coupled with increasing cloud cover in Upper Gangetic plain. Surface wind, temperature or the outgoing longwave radiation of this zone could not completely explain the cause of this risk. Changing role of average aerosol index (AAI) hinted to the presence of aerosol altered cloud micro-system in Upper Gangetic plain and may be one of the major reasons for increasing non-precipitating cloud in this zone and thus contributing to the drought risk even with increasing cloud cover trend.

Key words – Standardized precipitation index, Agroclimatic zone, Exceedance probability, Return period, Risk assessment, Monsoon, Extreme weather.

1. Introduction

Indian subcontinent is home to more than 1.1 billion people, which needs assured food supply through sustainable agricultural system. However, the agricultural output is influenced by several variables and most importantly by the anomaly (both positive and negative) of Indian summer monsoon (ISM) precipitation. There are 14 mainland agro-climatic zones (ACZs) of India based on multiple homogeneity factors which represent the
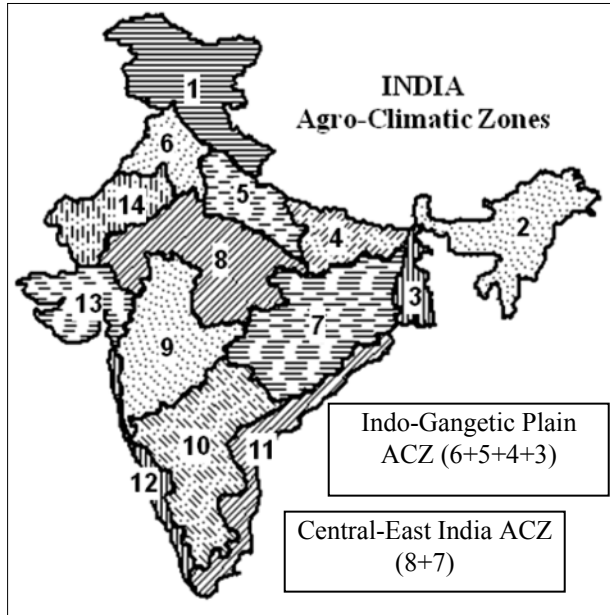
Fig. 1. Fourteen mainland agroclimatic zones (ACZs) of India

SPI Range	Moisture category
Greater than or equal to 2.0	Extreme wet
1.5 to 1.9	Severe wet
1 to 1.49	Moderate wet
-0.99 to 0.99	Near normal
-1 to -1.49	Moderate drought
-1.5 to -1.9	Severe drought
Less than or equal to -2.0	Extreme drought

broad agro-ecosystem of India formulated by the Planning Commission of India. Indo-Gangetic plain (IGP) and the central-east India are two distinguished regions of India. The former is covered in four ACZs (ACZ 3, 4, 5 and 6) and the latter in two ACZs (ACZ7 and ACZ8), respectively (Fig. 1). These two regions are home to the highest population of low income group in India. IGP primarily follows irrigated agriculture whereas the central-east India is traditionally a rainfed agricultural region. Variability of ISM affects the viability of these two regions differently. Assured aquifer recharge through sufficient ISM precipitation determines the sustainable source of water for agriculture in the irrigated region of IGP, whereas the water harvested during ISM rainfall is the primary source of water for the agriculture of rainfed region of central-east India. Uncertainties associated with the onset and intra-seasonal oscillation of the ISM often leads to drought like situations, leading to a large loss in crop productivity in these ACZs. Total loss due to drought and flood in India has touched the figure of more than 9,00,000 ('000 US$) and 160,00,000 ('000 US$), respectively, in recent times (*Source* : CRED, http://www.emdat.be/databse). Changing climate scenario with complex interaction of many other atmospheric factors like aerosol, cloud microphysics and chemical interaction has increased the uncertainty factor of this impact during the recent decades. Agricultural sustainability of the ACZs of IGP and the central-east India due to extreme precipitation risk of ISM is going to be a future concern for the millions. There is a dearth of studies which address the above issue. Therefore, present study was undertaken to assess the risk of extreme precipitation during ISM on the agro-ecosystems of IGP and the central-east India. This study aimed to identify the most vulnerable agro-ecosystem due to summer monsoon precipitation anomaly and to get a quantitative risk score of extreme precipitation risk of ACZs of the regions. Besides, the study demonstrates a novel approach of risk assessment of agro-ecosystem to ISM anomaly. The study also explored the reasons for differential risk across ACZs.

2.   Methodology

In general, IUCN Red List protocol based on five criteria is followed for risk assessment of an ecosystem. This protocol has been used to investigate the risk assessment of ecosystem of Australia (Keith, 2015; English and Keith, 2015). It is a good procedure for assessing holistic risk of an ecosystem. On the contrary, it becomes very complex to filter out the risk of any particular factor, like precipitation in any particular ecosystem or agro-ecosystem. Therefore, standard conceptual equation (Alexander, 1993; Alexander, 2000) was followed for extreme precipitation risk assessment of the agro-ecosystem of IGP and central-east India during the ISM in the present study. The data used and methodology followed are discussed in the following sub-sections.

2.1.   Data

CRU TS 3.0 gridded monthly (0.5° × 0.5° resolution) observed precipitation dataset prepared by Climate Research Unit of University of East Anglia (http://badc.nerc.ac.uk/data/cru/) for the period 1951-2006 was used in this study. Daily gridded (0.5° × 0.5° resolution) India Meteorological Department (IMD) precipitation dataset (http://www.imd.gov.in/doc/nccraindata.pdf) for the period from 1971-2005 was also

TABLE 2

Comparison metric of Climate Research Unit (CRU) and India Meteorological Department (IMD) Precipitation Data for the Indian Summer Monsoon Season (JJAS) for the period from 1971 to 2005 (Sample Size (N) = 35) for different ACZs

Agroclimatic Zone (ACZs)	IMD Data Linear Regression with time	CRU Data Linear Regression with time	IMD Data Coefficient of Determination (R^2)	CRU Data Coefficient of Determination (R^2)	Volatility of IMD Rainfall Data	Volatility of CRU Rainfall Data	Correlation (IMD and CRU Rainfall)
ACZ1	$y = 0.124x + 13.50$	$y = -0.144x + 32.66$	$R^2 = 0.072$	$R^2 = 0.024$	30%	31%	0.50
ACZ2	$y = 0.042x + 54.61$	$y = 0.135x + 141.4$	$R^2 = 0.004$	$R^2 = 0.008$	12%	11%	0.80
ACZ3	$y = -0.004x + 42.05$	$y = -0.450x + 127.3$	$R^2 = 7E-05$	$R^2 = 0.071$	14%	14%	0.69
ACZ4	$y = -0.004x + 32.55$	$y = -0.723x + 114.3$	$R^2 = 0.0001$	$R^2 = 0.294$	15%	13%	0.55
ACZ5	$y = 0.020x + 27.42$	$y = -0.064x + 9.475$	$R^2 = 0.001$	$R^2 = 0.156$	19%	20%	0.63
ACZ6	$y = -0.017x + 15.31$	$y = -0.335x + 55.02$	$R^2 = 0.001$	$R^2 = 0.052$	31%	31%	0.71
ACZ7	$y = 0.011x + 34.5$	$y = -0.405x + 102.4$	$R^2 = 0.0001$	$R^2 = 0.115$	13%	13%	0.67
ACZ8	$y = -0.102x + 23.2$	$y = -0.222x + 70.14$	$R^2 = 0.047$	$R^2 = 0.02$	23%	24%	0.89
ACZ9	$y = 0.033x + 28.69$	$y = 0.073x + 81.11$	$R^2 = 0.004$	$R^2 = 0.002$	17%	19%	0.90
ACZ10	$y = 0.127x + 23.30$	$y = 0.11x + 46.62$	$R^2 = 0.025$	$R^2 = 0.010$	32%	23%	0.46
ACZ13	$y = 0.023x + 23.73$	$y = 0.174x + 62.02$	$R^2 = 0.001$	$R^2 = 0.008$	32%	31%	0.90
ACZ14	$y = -0.062x + 13.62$	$y = -0.376x + 45.47$	$R^2 = 0.019$	$R^2 = 0.066$	36%	39%	0.85

used to crosscheck the volatility and consistency of CRU TS 3.0 precipitation dataset. High resolution (0.25° × 0.25°) ISLSCP II IGBP DISCover Landuse Land cover dataset (Loveland *et al*., 2009) (http://daac.ornl.gov/ISLSCP_II/guides/edc_landcover_xdeg.html) was used in computing crop land exposure statistics. The NASA GSFC TOMS EPTOMS monthly Aerosol Index data for the available 1997 to 2003 period was downloaded from the IRI data library, (http://iridl.ldeo.columbia.edu/SOURCES/.NASA/.GSFC/.TOMS/.EPTOMS/.monthly/.aai/). Summer monsoon seasonal mean (JJAS) surface air temperature, surface scalar wind speed and outgoing longwave radiation (OLR) data used in this study were downloaded from ESRL-NOAA site (http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl).

2.2. *Computation of standardized precipitation index (SPI)*

SPI is an index of precipitation anomaly (McKee *et al*., 1993) and is computed as the difference of standardized precipitation from its mean for a specified time period divided by the standard deviation, *i.e*., Z variate. SPI is computed as follows:

$$SPI_i^t = \frac{\left(X_i^t - \overline{X_i^t} \right)}{\sigma_i^t}$$

where, SPI stands for standardized precipitation index, *X* for rainfall, and σ for standard deviation of *X* with subscript *i* signifying the location and superscript *t* is the time scale (monthly or seasonal). Overbar on *X* indicates mean climatology. As precipitation is typically not normally distributed for accumulation periods of 12 months or less, SPI overcomes this disadvantage by fitting an incomplete gamma distribution and then transforming it to normal distribution. Negative values of SPI indicate dry atmospheric condition or less rainfall while SPI less than -1 indicates meteorological drought. SPI values and corresponding moisture category are shown in Table 1. Numerous studies have shown that SPI is a well recognized index for meteorological drought monitoring purpose and it rightly indicates the probability of occurrence of normal, deficit or excess rainfall in a region (Khan *et al*., 2008; Loukas *et al*., 2008; Manatsa *et al*., 2008; Patel *et al*., 2007; Shahid, 2009; Dhakar *et al*., 2013). The executable program for computation of SPI was downloaded from the website of University of Nebraska-Lincoln (http://www.drought.unl.edu) to compute the SPI.

The CRU TS 3.0 gridded monthly 0.5° × 0.5° resolution precipitation dataset for the period 1951-2006 was used to compute seasonal JJAS SPI for each year. ArcGIS Geographic Information System (GIS) software was used to digitize the ACZs boundaries of India in geographic coordinated. The ACZ boundary map was

TABLE 3

Probability density function (pdf) of occurrence of SPI of various ranges for the six ACZs of India. Blank cells represent no value of SPI falling within the corresponding ACZ

SPI Category	Range of SPI	SPI Value (Mid of the range)	ACZ3 pdf	ACZ4 pdf	ACZ5 pdf	ACZ6 pdf	ACZ7 pdf	ACZ8 pdf
Extreme drought	-2.5 to -2	-2.25	-	-	0.02	0.02	-	0.02
Severe drought	-1.9 to -1.5	-1.75	-	0.02	0.05	0.02	-	0.02
Moderate drought	-1.49 to -1	-1.25	0.09	0.07	0.05	0.09	0.07	0.02
Normal	-0.99 to -0.5	-0.75	0.18	0.13	0.11	0.18	0.16	0.21
Normal	-0.5 to 0	-0.25	0.27	0.29	0.16	0.25	0.32	0.16
Normal	0 to 0.5	0.25	0.20	0.21	0.30	0.14	0.21	0.32
Normal	0.5 to 0.99	0.75	0.20	0.20	0.23	0.14	0.18	0.16
Moderate wet	1 to 1.49	1.25	0.05	0.07	0.05	0.11	0.02	0.09
Severe wet	1.5 to 1.9	1.75	-	0.02	0.02	0.04	0.02	-
Extreme wet	2 to 2.5	2.25	0.02	-	-	0.02	0.02	-
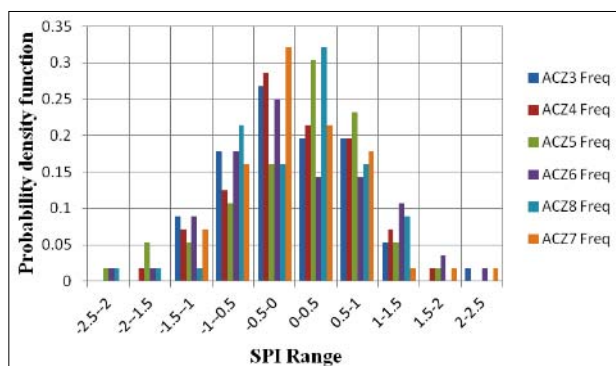
Fig. 2.   Probability density function of occurrence of various SPI ranges in six ACZs of India

Fig. 3.   Exposure (grid wise % of crop area) for all the ACZs of India overlaid with ACZ boundaries

overlaid over the monthly CRU gridded precipitation to compute the average monthly ACZ precipitation. The monthly average ACZ precipitation was used to compute seasonal JJAS precipitation for all the 56 years over the six ACZs. As the coefficient of variation of rainfall is high for a region, so CRU monthly averaged JJAS precipitation was compared with same computed from the IMD daily rainfall gridded dataset for common period of 35 years (1971-2005) for each of the fourteen ACZs. The metrics used for comparison were the linear regression trend with time, its coefficient of determination, volatility [defined as {(Standard Deviation)/Average}] and the correlation of both the time-series with each other and the re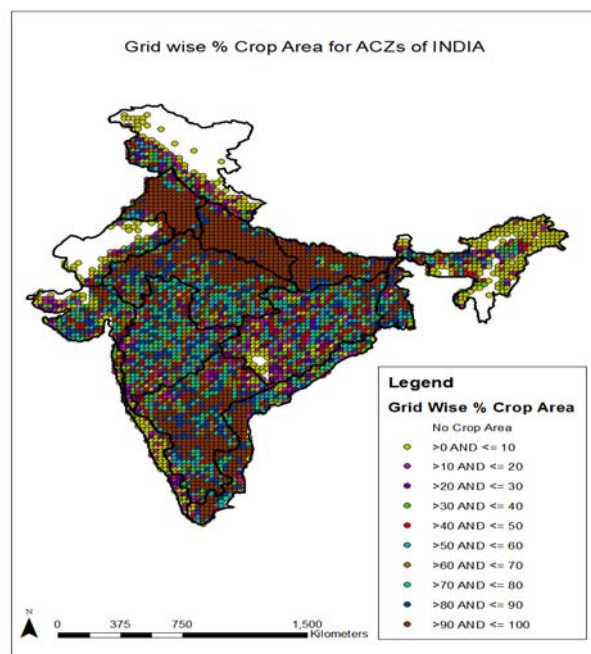sults are given in Table 2. The analysis showed that the two precipitation datasets do not differ significantly. The details of time trend in monthly and seasonal precipitation for different ACZs during 1951 to 2006 period using CRU gridded data are discussed in Jha *et al*. (2013).

TABLE 4

Probability density function of occurrence of SPI of drought, normal and wet for six ACZs of India

SPI category	ACZ3	ACZ4	ACZ5	ACZ6	ACZ7	ACZ8
Drought	0.09	0.09	0.13	0.13	0.07	0.05
Normal	0.84	0.82	0.80	0.71	0.88	0.86
Wet	0.07	0.09	0.07	0.16	0.05	0.09

Fig. 4. Exceedance Probability curve for ACZs of IGP and central-east India

TABLE 5

Mean value of exposure (%) grid area under cropland) in various ACZs of India

Name of ACZ	Mean Grid Area under Cropland (%)
ACZ3	69
ACZ4	90
ACZ5	93
ACZ6	86
ACZ7	46
ACZ8	76
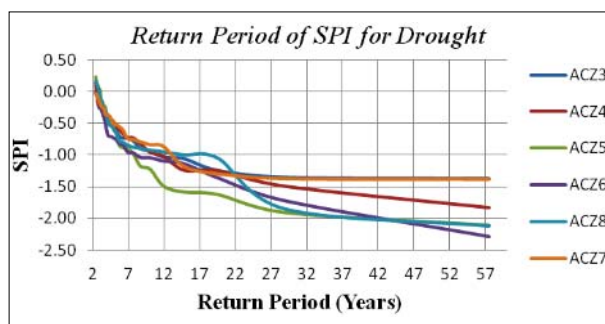
Fig. 5. Return Period curve for ACZs of IGP and central-east India

2.3. *Computation of probability density function of drought/wet/normal year*

Probability density function (pdf) of occurrence of specific range of JJAS SPI for the 56 years (1951-2006) period were computed for all the six ACZs of the two study regions and are given in Table 3 and 4 for various ranges of SPI as well as for drought, normal and wet, respectively. The pdf ranged between 0 and 1. Drought and wet years means SPI range of less than -1 and more than +1, respectively, while SPI between -1 to +1 was taken as normal year as per standard definition of SPI. Fig. 2 shows the pdf of occurrence of various range of SPI as given in Table 3.

2.4. *Development of cropland exposure in ACZs*

High resolution (0.25° × 0.25°) ISLSCP II IGBP DISCover Landuse Land cover dataset was processed to generate the crop land exposure statistics under the six ACZs of India (Fig. 3). To compute the average gridwise cropland area in each ACZ, the IGBP landuse landcover layer was overlaid with ACZ boundary shape file in ArcGIS. The average percent gridwise cropland area calculated for each of the six ACZ is shown in Table 5.
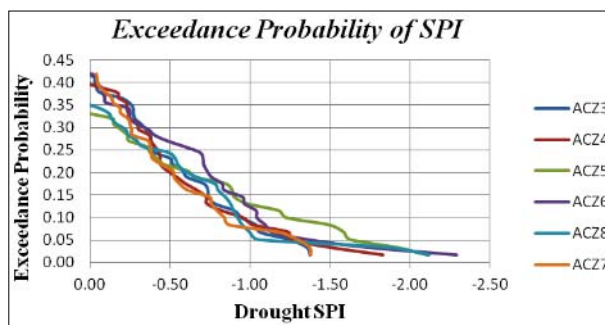
2.5. *Computation of extreme precipitation hazard risk in ACZs*

Extreme precipitation hazard risk (both drought and excess moisture) score was computed as per standard risk computing formula. Risk is generally a probability of threat or damage by any hazard due to external or internal vulnerability of any object under exposure. Risk has been computed through the standard conceptual equation (Alexander, 1993; Alexander, 2000) as below.

$$Risk = (Hazard * Exposure * Vulnerability)$$

The above formula is expanded below as it was used to compute the extreme precipitation risk on the agro-ecosystem of India covering IGP and central-east India.

Extreme Precipitation Risk = [(Quantitative Value of Hazard * Probability of Hazard)* Mean Crop Exposure * Vulnerability}

In this study, quantitative value of SPI and its probability of occurrence under a certain category signified the value of hazard and its probability, respectively. Average gridwise percent cropland data

TABLE 6

Extreme Precipitation Hazard Risk Score for cropland exposure in ACZs under various categories of hazards

Hazard type	ACZ3	ACZ4	ACZ5	ACZ6	ACZ7	ACZ8
Extreme drought	0.0	0.0	4.2	3.9	0.0	3.4
Severe drought	0.0	3.2	8.1	3.0	0.0	2.7
Moderate drought	7.8	7.9	5.8	9.7	4.0	1.9
Moderate wet	4.3	7.9	5.8	11.8	1.2	8.6
Severe wet	0.0	3.2	3.3	6.0	1.6	0.0
Extreme wet	3.1	0.0	0.0	3.9	2.1	0.0

derived from IGBP DISCover Landuse Land cover under an ACZ signified the exposure. Vulnerability of crop exposure towards extreme precipitation event becomes complex due to variation in crop types, agronomic management practices, soil type and technological inputs available. Therefore, vulnerability factor has been assumed a constant value 1 for simplification. Drought and wet range SPI are the hazard here and the mean crop land percent per grid is the crop exposure. Thus, ACZ wise values of SPI and its corresponding probability (Table 3) and crop exposure for six ACZs (Table 5) were used to compute the hazard risk score according to various hazard categories and are given in Table 6. Finally the risk scores of various categories of drought and wet classes were summed up to calculate total drought and wet or excess moisture risk score for crop lands of the six ACZs (Table 7).

2.6. *Drought risk quantification through exceedance probability curve*

Exceedance probability (EP) curve of drought risk was computed for each of the six ACZs using severe most drought SPI (the highest negative SPI value) as the highest rank and standard Weibull distribution formula for the 56 years (1951-2006) study period. Similarly, return period (which is inverse of exceedance probability) of the drought was computed for each of the six ACZs of India. The drought exceedance probability curve and the return period curves for the six ACZs are shown in Figs. 4 and 5, respectively.

2.7. *Mann Kendall trend analysis for cloud cover for ACZs of India*

CRU TS 3.0 monthly gridded cloud cover data was processed to derive JJAS seasonal mean monthly time-
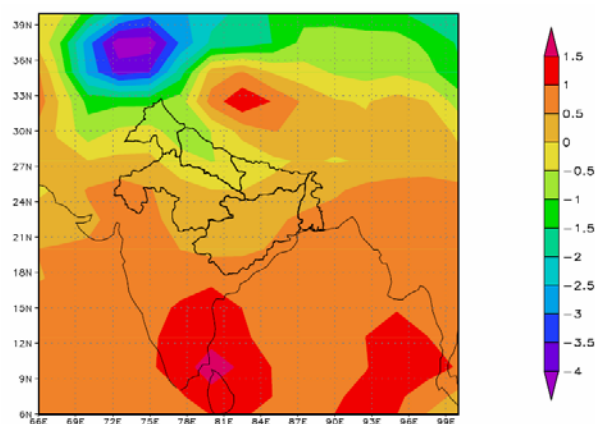

Fig. 6. Surface air temperature (JJAS mean) (Unit: surface air (°C) composite mean) difference {Decade (1991-2000)-(1951-1960)} overlaid with six ACZs
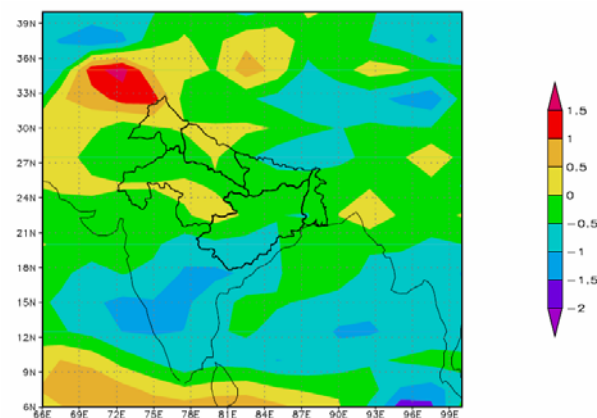

Fig. 7. Surface wind speed (JJAS Mean) [Unit : Surface scalar wind speed (ms⁻¹) composite mean] difference [Decade (1991-2000)-(1951-1960)] overlaid with six ACZs
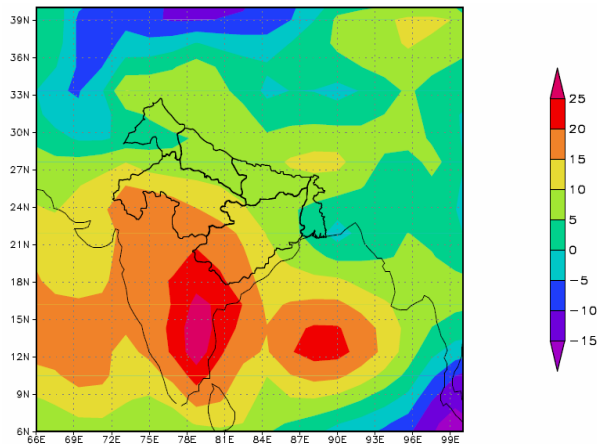
Fig. 8. Outgoing Longwave Radiation (JJAs Mean) [Unit: OLR (W m^{-2}) composite mean] difference [Decade (1991-2000)-(1951-1960)] overlaid with six ACZs
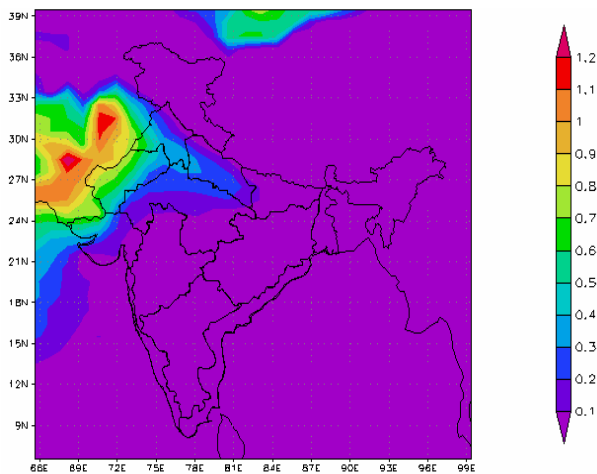

Fig. 9. NASA GSFC TOMS EPTOMS monthly average value of average aerosol index for JJAS season for the period from 1997 to 2003 overlaid with ACZs

series of spatially averaged cloud cover over the 14 mainland ACZs for the 1951 to 2006 period. Non-parametric Mann Kendall trend test was applied to the 56-year time series cloud cover data for each ACZ to analyze the time trend of JJAS (monsoon season) cloud cover in the six ACZs. Finally, the statistically significance of the cloud cover trend was analyzed at two significance levels: highly significant with p ≤ 0.01 and significant with 0.01 < p ≤ 0.05.

2.8. *Seasonal average aerosol index and other meteorological data for ACZs of India*

Summer monsoon seasonal mean (JJAS) surface air temperature, surface scalar wind speed and outgoing

TABLE 7

Extreme Precipitation Hazard Risk Score for cropland exposure for various ACZs of India for Drought and Excess Moisture (Wet)

Hazard Type	ACZ3	ACZ4	ACZ5	ACZ6	ACZ7	ACZ8
Drought	7.8	11.0	18.1	16.6	4.0	8.0
Wet	7.4	11.0	9.1	21.7	4.8	8.6

longwave radiation (OLR) data were downloaded from ESRL-NOAA sites (http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl) and processed to compute composite mean decadal difference between 90s decade (1991-2000) and 50s decade (1951-1960) values. These difference images for JJAS temperature, wind speed, and OLR are shown in Figs. 6, 7 and 8, respectively. The NASA GSFC TOMS EPTOMS monthly Aerosol Index data was downloaded from IRI data library (http://iridl.ldeo.columbia.edu/SOURCES/.NASA/.GSFC/.TOMS/.EPTOMS/.monthly/.ai/) for the available period from 1997 to 2003. Seasonal mean monthly value of Average Aerosol Index (AAI) for JJAS season from 1997 to 2003 period was computed for India and is shown in Fig. 9.

3. Results and discussion

3.1. *Extreme precipitation risk analysis of agro-ecosystem of IGP and central-east India*

Present study analyzed the comparative drought and excess moisture or wetness risk for cropland in the two major food producing zones of India *viz.*, Indo-Gangetic plain (IGP) and the central-east region. The analysis was undertaken for six corresponding component units of Agro-Climatic Zones (ACZs) covering the above two regions. Results showed that ACZ5 (Upper Gangetic plain) and ACZ6 (Trans Gangetic plain) have maximum probability of occurrence of drought among all the ACZs of IGP and central-east India (Table 4). The ACZ6 has least probability of occurrence of a normal year among the ACZs of IGP and Central and Eastern India (Tables 3 and 4). The ACZ5 has highest 5% probability of occurrence of severe drought (SPI range -1.5 to -1.9); ACZ6 and ACZ3 both have 9% probability of occurrence of moderate drought (SPI range of -1 to -1.5). Probability density function of occurrence of various SPI ranges (Fig. 2) showed that ACZ5 has high probability of occurrence of intense drought (severely dry) year than any other region. Probability density function of SPI reveals that all the ACZs of IGP have lower probability of normal year than the ACZs of central-eastern Indian regions (Table 4). Risk Score metric given in Table 6 shows that
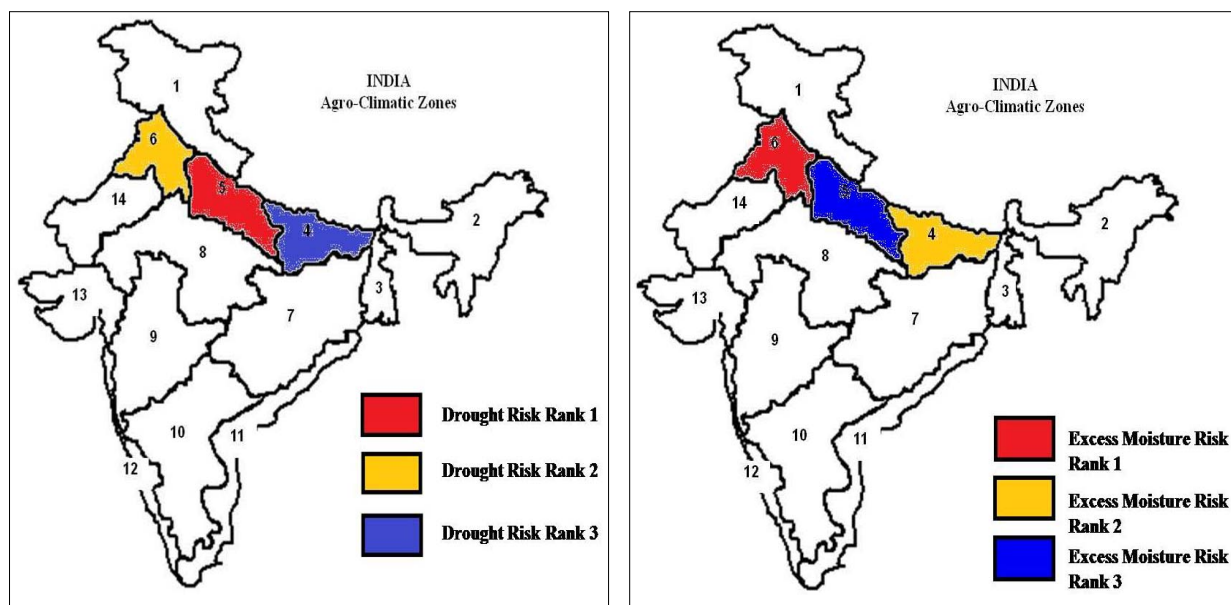
Fig. 10. Top three ranked drought and excess moisture risk score ACZs during Indian summer monsoon

ACZ5, ACZ6 of IGP and ACZ8 of the central-east India have comparatively high risk of both extreme and severe droughts than other ACZs. ACZ5 has the highest drought risk for all categories followed by ACZ6 and ACZ4 (Table 7). ACZ8 has the highest drought risk in central-east Indian region. ACZ6 also has the highest excess moisture (wet) risk in the category of severe wet among all ACZs of the region (Table 6). ACZ6 followed by ACZ4 and ACZ5, respectively has the highest excess moisture for all categories (Table 6). Fig. 10 shows the three highest drought and excess moisture risk prone ACZs of IGP and central-east India. Thus Upper Gangetic plain (ACZ5), Trans Gangetic plain (ACZ6) and Middle Gangetic plain (ACZ4) are the primary regions of high drought and excess moisture risk prone ACZs, whereas the western part of the IGP, *i.e.*, ACZ6 is experiencing extreme wetness hazard risk. Significantly increasing wetness during the June month in ACZ6 and significantly increasing deficiency of the summer monsoon season for ACZ5 and ACZ4 may be the potential reason of the above enhanced risk in the western part of IGP (Jha *et al*., 2013). Pai *et al*. (2010) also reported that district wise long-term linear trend in SPI has an increasing trend sparsely distributed in India including parts of western ghats and northwest part of India. Dash *et al*. (2011) reported that all India, West and Central India and Northwest India homogenous zones have significantly increasing heavy rainfall events during the whole summer monsoon season. Similarly, this study indicated that the Central Plateau and Hill region (ACZ8) has nearly double the risk of drought and excess moisture than the Eastern Plateau and Hill

region (ACZ7) (Table 7). Pai *et al*. (2010) reported a significant decreasing trend of SPI in Middle Gangetic plain and Eastern Plateau and Hill regions of India which is in agreement with the findings of this study. Pal and Al-Tabbaa (2009) reported that magnitude of extreme monsoon rainfall deficiency has an increasing trend in India except in northwest and peninsular India. Short spell rain events with high intensity are an increasing trend over India whereas long spell rain with moderate and low intensities shows a decreasing trend (Dash *et al*., 2011). Thus, present study shows a similar region experiencing decreasing precipitation, in agreement with Dash *et al*. (2011).

In case of excess moisture, the surplus moisture in the IGP (primarily irrigated region) or central-east region (primarily rainfed region) shall results in good crop productivity due to lower requirement of irrigation water in the former and availability of good soil moisture in the latter case. Nature of drought vulnerability in terms of probability of occurrence of drought year is conspicuously different for ACZ5 than any other ACZs. In any year, the probability of exceeding moderate drought (SPI range -1 to -1.5) lies between 8 to 12% for ACZ5, whereas for all other ACZs it is around 5% (Fig. 4). Fig. 5 shows the abrupt change of gradient of ACZ5 return period from 8 year to 12 year for the moderate drought range of SPI (-1 to -1.5). For rest of the ACZs, a return period ranging between 12 and 32 year was observed (Fig. 5). Thus, exceedance probability curve and the return period curve of the drought risk quantification of ACZs of IGP and
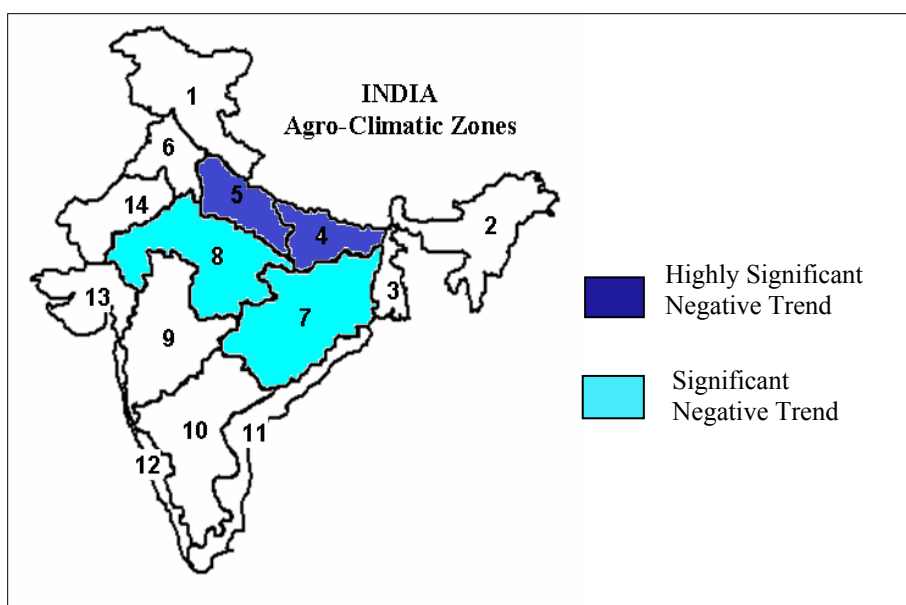
Fig. 11.   ACZs of India which showed highly significant (p ≤ 0.01) and significant (0.01 < p ≤0.05) negative SPI time trend (Mann Kendall test) during JJAS for 1951 to 2006 period

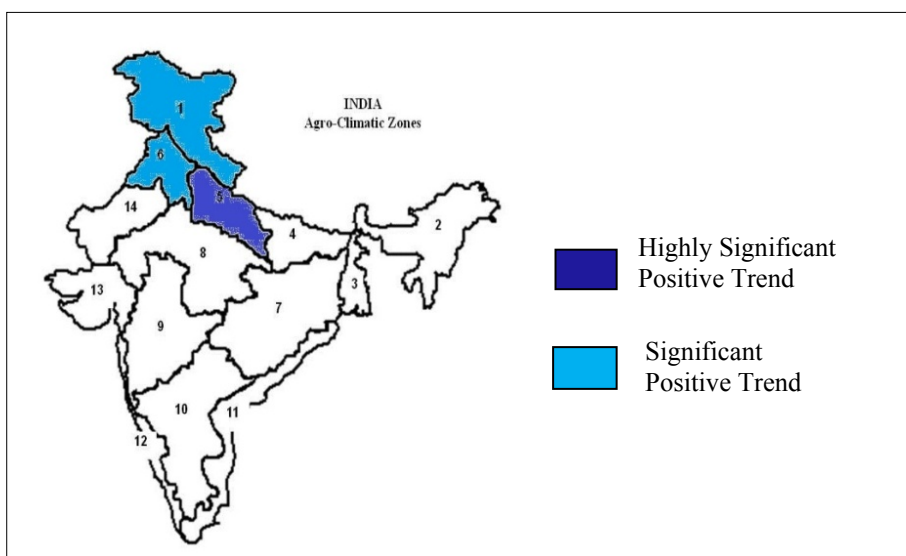**Fig. 12.**   ACZs of India which showed highly significant (p ≤ 0.01) and significant (0.01< p ≤ 0.05) positive trend in cloud cover (Mann Kendall test) during JJAS for the 1951-2006 period

central-east India show the conspicuously different risk prevalence in ACZ5 as compared to other ACZs of the study regions. Fig. 3 and Table 5 also reveal that ACZ5 has the maximum average grid-wise percent cropland (93%) among the six ACZs. Besides, ACZ5 has also revealed its conspicuous nature of high rate of change of gradient of SPI for the drought. Western part of the IGP

and the Central Indian region are the worst hit agro-ecosystem for both the extreme precipitation risks. Increasing wetness risk in ACZ6 and increasing drought risk in ACZ5 of IGP (Fig. 10) are of serious concern as these regions contribute significantly to the food security of the country. Comparatively, the central Indian region comprising of ACZ 7 and ACZ 8 have
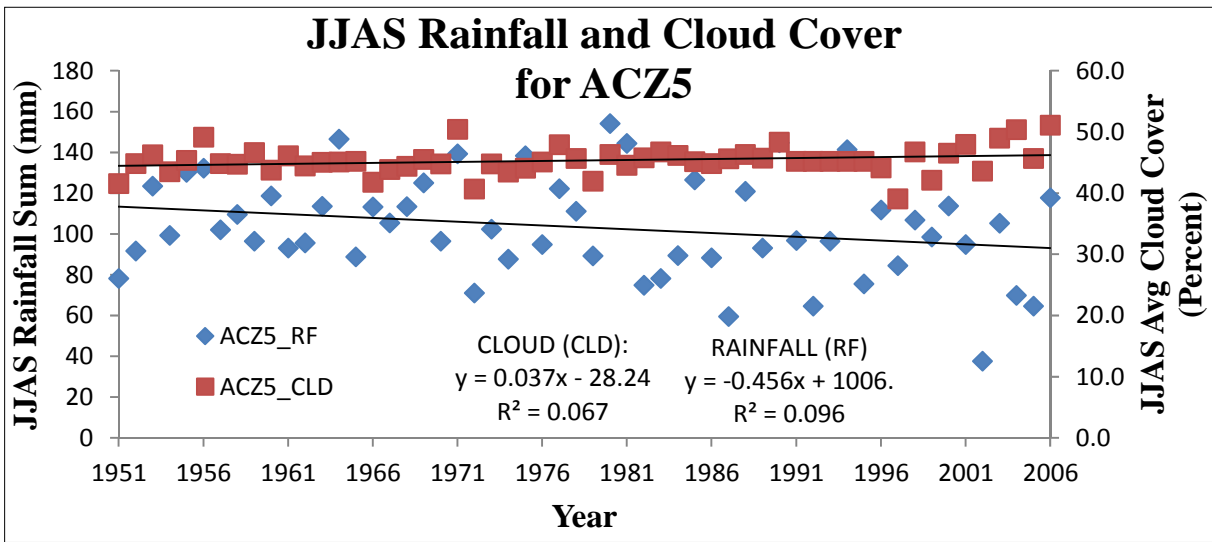
Fig. 13. JJAS rainfall sum (mm) and JJAS cloud cover (per cent) for ACZ 5 for 1951 to 2006 period

lower risk of both wetness and drought, but being rainfed region, the lower risk may have equal or higher adverse impacts on crop production.

3.2. *Possible factor behind conspicuous nature of drought in upper Gangetic plains*

Jha *et al*. (2013) reported that the most of the ACZs of India (11 out of total 14 ACZs) have a negative SPI trend over the last 56 years (1951-2006) and it was statistically significant in four ACZs of India shown in Fig. 11; drying trend of ACZ4 and ACZ5 are highly significant ($p \leq 0.01$) whereas of ACZ7 and ACZ8 are significant ($0.01 < p \leq 0.05$). They also reported that the significant drying pattern shifts from western to eastern agro-climatic zones with the monthly progression of Indian summer monsoon season (JJAS). Similarly, Mann Kendall Trend for the summer monsoon seasonal (JJAS) cloud cover for the last 56 years (1951-2006) was tested for all 14 mainland ACZs of India in the present study. In general all the 13 ACZs of India except north-eastern region (ACZ2) showed increasing trend in cloud cover. Results showed that three ACZs (ACZ1, ACZ5 and ACZ6) have statistically significantly increasing cloud cover trend. ACZ5 showed highly significant ($p \leq 0.01$) increasing trend whereas ACZ1 and ACZ6 showed significant ($0.01 < p \leq 0.05$) increasing cloud cover trend (Fig. 12). The findings of increasing trend of cloud cover in ACZ5 and ACZ6 is in agreement with the findings of Lal *et al*. (2013). It reveals a conspicuous feature of ACZ5 (upper Gangetic plain) that it is having significant increasing drought risk even though it also has a highly significant increasing cloud cover trend (Figs. 11 and 12).

There is a consistent reverse trend of increasing cloud cover *vis-à-vis* decreasing summer monsoon seasonal rainfall leading to drought and the gap in these two trends is increasing with time for the ACZ5 (Fig. 13).

Decadal difference in summer seasonal surface temperature, surface wind speed and outgoing long wave radiation (OLR) between 90s (1991-2000) and 50s (1951-1960) decade (Figs. 6, 7, 8) showed that there was an increase in surface wind speed, a decrease in surface temperature along with increase in OLR. The increase in OLR suggests lower convective activity even though cloud cover showed an increasing trend in cloud cover for ACZ 5. This contradiction led to exploring the possibility of aerosol nuclei induced increased cloud cover. In the present study, NASA GSFC TOMS EPTOMS monthly average value of Average Aerosol Index for JJAS season for the 1997 to 2003 period (Fig. 9) showed increasing aerosol index towards ACZ 5. The consistent opposite trend of increasing cloud cover *vis-à-vis* decreasing summer monsoon seasonal rainfall in ACZ5 (Figs. 11 and 12) indicate that the Upper Gangetic plain (ACZ5) is the only agroclimatic zone of India where the aerosol altered cloud microphysics plays a critical role in making the zone drought prone by increasing the non-precipitating cloud cover. Other three significantly drying ACZs (ACZ4, ACZ7 and ACZ8) do not show any such aerosol-cloud complex interplay dynamics and thus indicating the increasing drought proneness may be due to the long term changes in summer monsoon dynamics. This study points to the fact that rainfall deficiency due to changing monsoon dynamics is not always the primary reason of drought. Cloud Cover trend, aerosol loading may also

determine the rainfall risk of a region. Cloud cover, rainfall and aerosol dynamics are related in a complex manner and is one of the least investigated area (Eastman and Warren, 2013; Lal *et al*., 2013; Costantino and Breon, 2013; Gryspeerdt *et al*., 2014; Kaufman and Koren, 2006). Lal *et al*. (2013) reported an increasing trend of aerosol index and High Cloud Cover (HCC) and a decreasing trend of low Cloud Cover (LCC) in IGP; the positive correlation of HCC and negative correlation of LCC with the aerosol indicated that aerosol resulted in altering the cloud microphysics by reducing the size of cloud droplet and thus decreasing the precipitating cloud and increasing the life-time of cloud over the region.

ACZ5 (mainly comprising of the Uttar Pradesh province of India) is traditionally the highest sugarcane producing and second highest sugar producing state of India. The increasing cloudy weather and lack of direct solar radiation with increasing drought risk may have impact on the sugarcane quality and disease-pest incidences. Quality degradation and yield reduction of sugarcane in ACZ5 over the last decade is a matter of concern. Vishwakarma *et al*. (2013) has reported that Pokkah Boeng of sugarcane (causal organism: *Fusarium moniliformae*) has become a major threat to sugarcane during the recent decade, showing an increasing trend of disease incidence and making most of the commercial cultivars susceptible. They also reported that the severity of the airborne disease Pokkah Boeng incidence increases manifold under cloudy weather and high humidity up to 70-80% with favourable temperature during the rainy season (JJAS) in ACZ5. Thus, the present study forewarns that the aerosol induced increasing non-precipitating cloud and increasing drought proneness in ACZ5 may have a detrimental impact on the food production of the region and thus affecting the livelihood and food security of a large population.

4. Conclusions

Using CRU TS 3.0 gridded precipitation data for 56 years (1951 - 2006), the study presented a methodology to calculate the extreme precipitation risk (both drought and wetness) during monsoon season (JJAS) for six ACZs of India covering IGP and Central-East Indian regions. The hazard risk score was computed based on the probability distribution function of JJAS SPI and average grid area under cropland landuse signifying the exposure to hazard. The study indicated that the ACZ 6 (Trans Gangetic plain) covering Haryana and Punjab States and ACZ5 (Upper Gangetic plain) covering western Uttar Pradesh State of the IGP have both high drought and excess rainfall risk. In Central India, ACZ8 (Central plateau and hill region) has nearly double the risk than ACZ7 (Eastern plateau and hill

region) for both drought and excess rainfall. The highest excess moisture (wetness) risk among the six ACZs was found for ACZ6. The exceedance probability curve and the return period curve of the drought risk quantification showed conspicuously higher drought risk prevalence in ACZ5 as compared to other ACZs. Even though irrigated agriculture is practiced in ACZ6 and ACZ5, the increasing precipitation risk of drought and wetness may seriously impact the stability of agricultural output and food security of a large population of these zones in times to come.

The study found an increasing trend in percent cloud cover in ACZ5 over the 56 years period, while decreasing trend in SPI conspicuously indicated a higher drought risk. Conspicuous coexistence of increasing cloud cover and increasing drought proneness in Upper Gangetic plain agro-climatic zone (ACZ5) alongwith high aerosol load indicated a possible role of aerosol altered cloud microphysics in this region by increasing the non-precipitating cloud cover. This study concluded that rainfall deficiency due to changing monsoon dynamics is not always the only reason of increasing drought risk. Cloud Cover trend and aerosol loading may also contribute to the drought risk of a region by interacting in a complex manner.

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