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Assessing operative natural and anthropogenic forcing factors from long-term climate time series of Uttarakhand (India) in the backdrop of recurring extreme rainfall events over northwest Himalaya

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Abstract

The entire Indo-Himalayan region from northwest (Kashmir) to northeast (Assam) is facing prevalence of floods and landslides in recent years causing massive loss of property, human and animal lives, infrastructure, and eventually threatening tourist activities substantially. Extremely intense rainfall event of A.D. 2013 (between 15 and 17 June) kicked off mammoth flash floods in the Kedarnath area of Uttarakhand state, resulting in huge socioeconomic losses to the state and country. Uttarakhand is an important hilly region attracting thousands of tourists every year owing to numerous shrines and forested mountainous tourist spots. Though recent studies indicate a plausible weakening of Indian summer monsoon rainfall overall, recurrent anomalous high rainfall events over northwest Himalaya (e.g. -2010, 2013, and 2016) point out the need for a thorough reassessment of long-term time series data of regional rainfall and ambient temperatures in order to trace signatures of a shifting pattern in regional meteorology, if any. Accordingly, here we investigate ~100-year-long monthly rainfall and air temperature time series data for a selected grid (28.5°N, 31.25°N; 78.75°E, 81.25°E) covering most parts of Uttarakhand state. We also examined temporal variance in interrelationships among regional meteorological data (temperature and precipitation) and key global climate variability indices using advance statistical methods. Major findings are (i) significant increase in pre-monsoon air temperature over Uttarakhand after 1997, (ii) increasing upward trend in June-July rainfall and its relationship with regional May temperatures (iii) monsoonal rainfall (June, July, August, and September; JJAS) showing covariance with interannual variability in Eurasian snow cover (ESC) extent during the month of March, and (iv) enhancing tendency of anomalous high rainfall events during negative phases of Arctic Oscillation. Obtained results indicate that under warming scenario, JJ rainfall (over AS) may further increase with occasional extreme rainfall spells when AO index (March) is negative.

Keywords: Himalayas; flash floods; Arctic Oscillation; extreme rainfall events

1. Introduction

The Indo-Himalayan region from northwest to northeast (Kashmir to Assam) acts as a barrier for ascending moisture-laden clouds that are advecting northward with the seasonal northward movement of Intertropical Convergence Zone (ITCZ) during boreal summer. This brings summer monsoon precipitation over all mountainous, Himalayan foothills and plain regions of India, Pakistan, Nepal, Bangladesh, and Myanmar. In Northwest Himalayan region Kashmir, Himachal Pradesh, and Uttarakhand (UKS) are three major hilly regions that are characterised by several mountain peaks, valleys, glaciers, rivers, and thick forest cover supporting a large biodiversity. Among the three northwest Himalayan states, UKS has special importance for having several sacred shrines and tourist spots that are visited by a number of pilgrims / tourists every year during summer. The period of famous holy pilgrimage (the Char dham yatra) overlaps with the early summer monsoon period as typically summer monsoon rainfall may arrive over UKS from second to third week of June, gripping the entire state by mid of July. The source of moisture during summer monsoon precipitation is mainly from the Bay of Bengal but in certain cases moisture from the Arabian Sea can also contribute (Sengupta and Sarkar, 2006).

The entire Indo-Himalayan region appears to be experiencing extreme rainfall events more frequently, and several of them have led massive flash floods and landslides (Mishra and Srinivasan, 2013; Chevuturi and Dimri, 2015; Dobhal et al., 2013; Dimri et al., 2016). Flood events occurring in parts of Pakistan, Leh-Laddakh, Kashmir, Himachal Pradesh and UKS during 2010, 2013, 2014, and 2016 support the aforesaid developing scenario (Bharti et al., 2015). Among the three northwest Himalayan states (Kashmir, Himachal Pradesh, and UKS), UKS appears to receive relatively higher frequency of extreme rainfall events compared to others. The extraordinary intense three day long rainfall event of 2013 (between 15 - 17 June) was extensive on spatial and temporal scales covering a vast region compared to other cloudburst events (e.g. over Leh in 2010). In terms of human casualities, the 2013 extreme rainfall of UKS ranks fifth among all the natural calamities that have occurred between 1990 and 2016 (http:www.embat.be). In addition, Manali (Himachal Pradesh) and Rudrarayag (UKS) also witnessed localized cloudburst events during July 2011 and September 2012 (Chevuturi and Dimri, 2015). Socioeconomic impact of 2013 Kedarnath event is summarized in Ziegler et al. (2014). This single event was responsible for excess rainfall ~137% for northwest India and ~402% for the UKS region (source: IMD press release, 20 June 2013).

Chevuturi and Dimri (2015) reported the contribution of voluminous moisture from Arabian Sea that travelled via Bay of Bengal and reached UKS during intense rainfall episode of 15-17 June 2013, using backward wind trajectories and satellite imagery of clouds. The aforementioned scenario is in contrast with monsoonal studies conducted for India indicating a plausible weakening of Indian summer monsoon rainfall in general (Dash et al., 2009; Roxy et al., 2015) amidst the concurrent global warming scenario. For the core monsoon region, Goswami et al. (2006) reported an increase in extreme rain fall events in concurrent warming scenario and De et al. (2005) presented a review of extreme weather events in India in the last 100 years. Dash et al. (2007) reported a decreasing tendency in the summer monsoon rainfall over Indian landmass but also an increasing trend in rainfall during pre- and post-monsoon periods. Hence, how summer monsoon in general (as well as at specific locales like UKS) would behave in a changing climate scenario is an intensely debated research topic that emerged in context of global change (Kitoh et al., 2013). Earlier for the northwest Himalaya region also, Basistha et al. (2009) reported a declining trend in monsoonal rainfall from 1965 to 1980.

Nonetheless, the recurrence of anomalously high rainfall events over the entire northwest Himalayas, specifically over UKS in recent years has attracted monsoon meteorologists/ climate researchers to investigate causal mechanism(s) leading to development of such events through numerical simulation and modelling (*e.g.* Dube et al., 2014; Chevuturi and Dimri, 2015; Joseph et al., 2015; Dimri et al., 2016;; Cho et al., 2016). In the wake of the concurrent anthropogenic climate change debate a deeper understanding of mechanistic links, causal mechanisms, and alignment of different forcing factors are desired to gauge the vulnerability of mountainous regions of northwestern Himalayas against global warming (Bharti et al., 2016). Apparently UKS seems to be a very sensitive region where rising temperatures, changing monsoonal conditions, glacier melting and regional geomorphology appear to be interacting at a rapid pace (IPCC, 2012). Paleostudies (Srivastava et al., 2013) have reported formation and growth of several glacial lakes, which may burst in an anomalously high rainfall event during the warmer and wetter phase of monsoonal climate. Probability of any such future event in the UKS region will depend on alignment of various forcing factors that eventually lead to higher surface runoff. In addition to meteorological variables, rapidly changing surface features such as land use/ land cover pattern, orography, forest cover, etc., make the region more vulnerable for natural disasters (O'Gorman, 2015; Cho et al., 2016; Dimri et al., 2016). India as a whole is experiencing ascendance in warming trend since 1990s (Attri and Tyagi, 2010). How this warming will impact regional precipitation patterns is a major question being debated among policy makers, stake holders, and the scientific community to make the general public aware (Yaduvanshi and Ranade, 2015). In addition, land use and land cover (LU/LC) changes, rapid urbanization, and unplanned settlement specifically over river floodplains of famous holy rivers of UKS have been recognized as important factors for making this hilly terrain much more vulnerable against rainfall event of even mild intensity (Dobhal et al., 2013; Uniyal, 2013; Ziegler et al., 2014).

Hence, in the backdrop of aforementioned extreme rainfall events occurring quite regularly over UKS, we revisit here monthly time series data for ambient temperature and precipitation in tandem with some other key global climate indices. Our study probes monthly series of rainfall and ambient temperature data covering the last century (1901-2013 for rainfall and 1901 to 2010 for ambient temperatures). We also investigate interannual variability of Eurasian snow cover (ESC) extent data and Arctic Oscillation (AO) index. Using advance statistical methods we examine significant changes in the natural course of variability in aforementioned indices, changes in interrelationships among various parameters for probable reasons. Major findings of our study from the UKS region are (i) enhanced ambient temperatures during pre-monsoon (MAM) from 1997 onward, indicating a significant change; (ii) increasing June-July rainfall over that in August-September in recent years; (iii) ambient temperatures during May showing correlating patterns with regional JJ rainfall; and (iv) interannual variability in JJAS rainfall anomalies over UKS shows correlation with ESC extent (during March) and negative AO index (during March). Results of this study could be exploited by climate/monsoon meteorologists for forecasting and now-casting of anomalous rainfall events in the region, which can greatly enhance the preparedness to minimize socioeconomic impacts of such abnormal meteorological events.

2. Study area and climatology of the region

The UKS is characterised by heterogeneous topography and variable land use/ land cover. The region is source of major north Indian rivers, viz. Alaknanda-Mandakini (the original tributaries of the Ganges and the Yamuna) and other major tributaries. At the subregional spatial scale, it is divided into two prominent regimes of Garhwal and Kumaun Himalayas. Rainfall over the region is highly variable because of orographic forcings, interactions among various forcing factors (viz. westerly winds, monsoonal winds originating from Bay of Bengal/ Arabian Sea; Bhutiyani et al., 2010). In addition, remote forcing factors such as snow cover at higher reaches of Himalayas/ Eurasia, El-Niño Southern Oscillation (ENSO), position of intertropical Convergence Zone (ITCZ) along the foothills of the Himalayas, etc., could also play a determining role for the net monsoonal rainfall over UKS (Basishtha et al., 2009). Owing to complex interactions of wind systems over UKS, any subtle change in one (or more) of the forcing factor(s) can significantly change rainfall distribution/ pattern. Local demographic changes owing to increasing development, tourist activities, and warming of the planet earth in general, could potentially alter normal climatology (monsoonal meteorology) of this mountainous region, and hence the region is being carefully monitored periodically using satellite-derived data (*e.g.* Mishra and Choudhary, 2015; Bharti et al., 2016).

3. Data

Much of previous research has attempted to analyse time series of rainfall and ambient temperatures to trace out variability in trends and underlying mechanism(s) responsible for abrupt or extreme rainfall events, but rarely have they included northwest Himalaya. Major reasons for this limitation are (i) paucity of spatially distributed rain gauge network-based long-term meteorological rainfall (at least ~100 years long) and (ii) sparsely located rain gauges and automatic weather stations. Long-term time series data are available for a few locations such as Mukteshwar (29.47°N, 79.64°E). However, utility of location-specific data for obtaining a synoptic picture of variability in trends representing perturbation in a regional climatic system is questionable owing to highly variable orography and heterogeneity in the land use/land cover. Advent of satellites (especially meteorological satellites) has provided a useful tool for remotely sensed rainfall over a larger scale including high elevations of northwest Himalaya (Bharti et al., 2016). Gridded data sets can provide more representative time series data of northwest

Himalayan states such as UKS, if gridded time series data can be calibrated with a point location from where similarly long enough rain gauge/weather station data are available. To evaluate secular changes in air temperature and rainfall over UKS for the last century, we used here gridded data of monthly rainfall for a 2.5° × 2.5° size grid (28.75°N, 31.25°N; 78.75°E, 81.25°E) obtained from Global Precipitation Climatology Project (GPCP; Adler et al., 2003), covering almost the entire UKS region (Fig. 1). Monthly air temperature data time series (at ~2 m height above ground) was obtained for a grid size (28°-32°N and 78°-82°E) from the National Center for Environmental Prediction 20th Century ReanalysisV2 (NCEP; Compo et al., 2011). As these two data sets (temperature and precipitation) are at different resolutions, hence there is slight difference in respective grid locations. Rainfall occurring during May, June, July, August, and September (MJJAS) and ambient air temperatures for March, April and May (MAM) are considered for this study.

The gridded reanalysis monthly data for rainfall and ambient temperatures were validated with the corresponding in situ observations at Mukteshwar obtained from the KNMI Climate Explorer (http://climexp.knmi.nl). We can be see that gridded reanalysis reliably represents subregional scale variations (Fig. 2). Figure 2 reveals correlation between the two data sets is 0.75 ($P < 0.001$) for the period 1901-1996 and 0.68 ($P < 0.001$) for full data span i.e. 1901-2013; hence similar patterns of variability in temporal scale validate the utility of gridded data for investigating variability in trends.

The plausible role of Eurasian snow cover (ESC) extent (during winter/spring) impacting the forthcoming Indian summer monsoonal rainfall is an old debate (Blanford, 1884). In contrast, no significant correlation was found between the Himalayan snow cover and subsequent monsoon rainfall. Blanford's hypothesis was questioned by several monsoon researchers later on and it appeared that the snow pattern association with the Indian monsoon rainfall is not homogeneously distributed on a spatial scale (Peings and Douville, 2009). Using the satellite observations and estimated ESC extent data, several studies reinvestigated aforesaid relationships, indicating a positive (negative) anomaly of snow cover over Eurasia or some parts of Eurasia is followed by an anomalous weak (strong) monsoon in the summer. However, these studies also indicated large heterogeneity in a spatiotemporal scale exists between snow-rainfall relationships. We therefore attempted to probe interrelationship between regional rainfall and temperature over UKS and ESC extent data using their time series datasets. Interannual ESC data (during the month of March) between 1922 and 1997 were collated with data available between 1967 and 2013 (Brown and Robinson et al., 2011). From these, a composite time series of ESC extent for the period 1922–2013 was constructed (Fig. 7A).

Joseph et al. (2014) recently examined the role of extratropical forcing factors' triggering mechanism behind the mid-June extreme rainfall event (2013) and noted role of another global climate variability indicator Arctic Oscillation (AO). During the negative AO anomaly over the Arctic Circle, cold air intrusion is known to trigger wet spells in a humid (moisture laden) atmosphere (Li and Fu, 2006). According to them, cold air intrusion from the top may generate an anticyclonic flow, which in turn may increase the buoyancy of lower troposphere and destabilize its potential to hold the moisture laden clouds. As the negative AO anomaly (sluggish air circulation over the Arctic region that spread cold air waves to mid-latitudes) shows interannual variability, we examined rainfall time series data over UKS in the realm of the time series AO index data (of March) to probe any systematic change in trend ? The monthly AO index data (March) for the period 1950–2014 were obtained from the NOAA repository (Fig. 8A; source:

http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/monthly.ao.index.b50.current.ascii.table).

4. Analyses and results

In order to check validity of rainfall time series for the selected grid (Fig. 1), we compared monthly rainfall (MJJAS) and ambient temperature (MAM) time series data with those available for the Mukteshwar town of Uttarakhand (Fig. 2). Statistical significances of observed correlations are mentioned in respective panels. Despite having some discrepancies especially for a higher altitude region (>3000 m) satellite-derived rainfall estimates appear to be more reliable for studying synoptic and secular trends (compare to point-source-based rain gauge data; Bharti et al., 2016). Especially for complete coverage over mountainous regions and sparsely populated areas where rain gauge and automatic weather station maintenance possess logistical issues, satellite-derived rainfall can provide crucial clues for identifying a developing hazard-prone atmospheric pattern originating from mutually competing meteorological processes. We discuss obtained results about recent changes in ambient temperatures during the pre-monsoon period and monthly distribution of summer monsoon rainfall over the UKS in the last ~100-year period in following subsections.

4.1 Ambient surface temperatures over UKS in the recent past

Figure 1 shows the location of the selected grid on the map of India. The selected grid covers most parts of UKS including the Kedarnath area where an extreme rainfall event occurred during mid-June 2013. The location of Mukteshwar town in UKS for which long-term rainfall and temperature data are available for comparison. Frequency of extreme weather events over the northwestern Himalaya have been reported to have increased in recent decades (International

Disaster Database, http://www.emdat.be), most likely owing to increase in intensification of global monsoon in response to the last three decades of general global warming (Wang et al., 2012; Bharti et al., 2016). Extreme rainfall events leading to heavy flash floods (e.g., 2010 and 2013 in the Leh-Ladakh region and over the Kedarnath region, respectively) might have these triggering forcings somewhere in the web of being mutually competing teleconnected climate-forcing factors, but do elevated surface temperatures have a facilitating role in it ? That is the fundamental question being debated. To address this important question we investigated ambient air temperatures during the pre-monsoon period (MAM; Fig.1), which show a conspicuous upward rising trend from the year 1997 onward. Notably, surface temperatures before 1997 (from 1950) show a declining trend during the same pre-monsoon season. The change in annual MAM ambient temperature data was validated through the Sample T statistical test using SPSS software. Data were divided into two groups: group 1 belonging to MAM data from 1997 to 2010, whereas group 2 represents the MAM data from 1901 to 1996. Group 1 and 2 were found to be statistically different using the non-parametric Mann-Whitney test (null hypothesis was rejected because $P < 0.05$).

This anomalous rise in the surface temperature over UKS can be seen in the all India level general warming trend from 1990 onward (Attri and Tyagi, 2010). Notably after achieving separate statehood in 2000, the UKS region has been experiencing faster growth at rural sites and rapid urbanization, tourism, etc., leading to significant changes in land use/land cover with unchecked and unplanned growth. Hence, part of the observed warming in UKS might have been contributed from ongoing anthropogenic activities. Irrespective of the probable causes, this pre-monsoon surface warming can potentially influence the regional rainfall pattern.

4.2 Monthly rainfall distribution and interannual variability

To contemplate rising ambient surface temperature's influence on regional rainfall, we investigated monthly rainfall distribution (MJJAS; Fig. 3) for the selected UKS grid. The vertical (red) line shows data before and after 1997. The June-July rainfall pattern shows an increasing trend compared to rainfall during August–September during a recent warming era of UKS (post-1997). Data sets before and after 1997 were subjected to a non-parametric statistical test using SPSS software. Using the Kendall coefficient of concordance for significance ($P < 0.10$), all monthly time series data and JJ and AS rainfall anomaly data before and after 1997 show significant differences (rejecting null hypothesis). As can be seen from Fig. 3F cumulative monsoonal rainfall (JJAS) shows a significantly increasing trend in the post-1997 warming era. Importantly, the regional rainfall was declining between 1950 to 1980 (Basistha et al., 2009). A steady increase in the September rainfall and possibly its contribution in the cumulative JJAS rainfall over UKS between 1907 and 1926 can be seen (shaded portions in Figs. 3E-F). This observed increase in the early part of 20th century indicate variability in meteorological processes in recent years may not exclusively be attributable to the regional warming trend (Fig. 1) and that causative mechanism(s) governing rainfall distribution might lie in temporally varying teleconnected operative forcing factors also.

However, the recent increasing trend of JJAS rainfall over UKS must be investigated in tandem with possible anthropogenic factors. Several reports suggest that pre-monsoon aerosol loading over the north India/Gangetic-Himalayan region could alter normal distribution of rainfall over four months (JJAS). We anticipate that the emerging scenario JJ rainfall may increase while AS months might get drier (Gautam et al., 2009). The observed increasing rainfall trend in JJ months could also be owing to enhanced temperature contrast between Indian landmass and northern Indian Ocean. Interestingly strengthening of sea surface winds over the western Arabian Sea during the early summer monsoon phase and surface productivity in the western Arabian Sea are reported to have enhanced since 1997 (Goes et al., 2005). Hence, the apparent increase in subseasonality (rainfall distribution between JJ and AS) during 1997 is noteworthy. At the all-India level, it is shown that during extreme rainfall years (above and below normal monsoon) the difference between JJ and AS rainfall increases (Kothawale and Kulkarni, 2015). Higher JJ rainfall over UKS indicates that enhanced SSTs in the northern Indian Ocean could provide enhanced precipitable moisture toward the northwest Himalayas. Boschat et al. (2012) has investigated SST-Indian summer monsoon teleconnections; however, more intrusive ocean-atmospheric research involving satellite-derived lower atmospheric wind and other meteorological parameters can provide more insights for developing scenario.

4.3 Monthly rain-rate distribution

As we focused on extreme rainfall events over UKS and their temporal variability in this study, ideally daily rainfall time series should be analysed to capture these events, as cumulative monthly rainfall time series data may mask effects of some of the abrupt and anomalous (extreme) rainfall events. In the absence of reliable daily rainfall data for a long period (last ~100– years) for the region, rain-rate data analyses could be a good substitute for examining sharp variability. Therefore, in addition to monthly distribution of cumulative rainfall, we also investigated satellite-derived monthly rain-rate ($mm.day^{-1}$) data for the UKS grid available from 1986 to 2015 (Fig. 4). Data source is GPCC (Adler et al., 2003). Rain-rate is radar-based rain probability between no rain and a log-normal distribution for a rain event (Adler et al., 2003). Notably here also, we can see that monthly rain-rate data of June, July and August show significant changes before and after 1997, indicating that concurrent warming over the hilly terrain of UKS appears to be impacting monsoonal strength overall. Daily precipitation rate data show that annual rainfall has actually marginally decreased from 1990 to 2015 (data not shown), but frequency of anomalous rainfall events has increased. Local orographic and regional climate variables, *e.g.,* enhanced ambient surface temperatures, would certainly have their influence; in addition, remote forcing factors (discussed later in detail) appear to collectively contribute intensity of extreme rainfall events. Monthly rain-rate data before and after 1997 fall into two statistically different groups; and it was validated using independent sample null hypothesis testing via SPSS software.

4.4 May temperature and JJ rainfall relationship

We investigated relationships between monthly temperatures (March, April, and May) with JJ rainfall time series. Figure 5 shows the May temperatures correlative pattern with JJ rainfall over UKS. Two time series data sets show a temporally variable covariance, which appears to be weakening in the last one and a half decade (post-1997; Fig. 5A). Overall spring and pre-monsoon (MAM) temperatures of UKS also appear to show a temporally varying relationship with regional JJ rainfall (Fig. 5B), but again with a noteworthy widening gap during the post-1997 warming era. We surmise that enhanced regional warming may influence regional rainfall with a possibility of uneven distribution of summer monsoon (JJAS) rainfall. Rather than computing pre- and post- 1997 linear correlation coefficients, we examined here running correlations and the trends of the correlation coefficients of JJ rainfall with May and MAM temperature time series data. A moving 11-year sliding window was selected to see a statistically significant correlation coefficient (only $r \geq 0.5$ correlations are statistically significant). Figure 5C reveals temporally nonstationary inter-relationship between pre-monsoon temperatures and JJ rainfall. Although statistical significance is weak, we note a deteriorating relationship between ambient temperature and JJ rainfall in the recent one and a half decade period (post-2000) (Fig. 5C). To gain further insights into the temperature-rainfall relationship, we conducted Wavelet coherence analysis (Grinsted et al., 2004) of the JJ rainfall with May temperature that shows temporal changes in the coherency in frequency domain (Fig. 6). Figure 6 shows the two timeseries are coherent at decadal timescales between mid-1930's and 1970, while between 1980 and 2000 they were coherent at decadal and subdecadal time-scales. The linear correlation and the coherencies have become insignificant in the twenty-first century. Taken together, these observations indicate rising regional temperatures especially in the month of May influencing regional JJ rainfall. Warmer air might be lifting up mineral dust aerosols from the valley region to the tropospheric heights, and thus the possible role played by ambient aerosols just before the onset of the summer monsoon over northwest Himalayas cannot be ruled out as one of the plausible causes responsible for more frequent extreme rainfall events in the region.

4.5 Remote forcing factors and monsoonal rainfall over UKS

The weakening relationship between pre-monsoon surface temperatures and monthly rainfall (JJAS) over UKS during recent warming era (post-1997) indicates the possibility that a regional tropospheric wind circulation pattern has started to realign itself, and during this time regional meteorology may become more vulnerable against global climate variables. Regional summer monsoon rainfall especially during its early part (i.e. June-July rainfall) witnessing more frequent extreme rainfall events hint such a plausible scenario. Because of variable altitudinal heights and highly variable regional orography, subtle changes in any of atmospheric processes responsible for monsoonal rainfall can get substantially magnified. To assess the emerging meteorological scenario over UKS and other northern parts of the northwest Himalayas, a closer watch on various wind and cloud parameters by ground-based monitoring systems as well as using satellite observations is necessary to pre-empt extreme rainfall events. This effort can greatly help to manage future rainfall-related natural hazards.

Though several remote factors may be held responsible for aforesaid increasing vulnerability, we focused here on two remote forcing factors: (i) ESC extent and (ii) AO index (Gong et al., 2003; Dash et al., 2004; Joesph et al., 2014). Figure 7A shows monsoonal rainfall (JJAS) over UKS and its relationships with spring time snow cover (i.e. ESC extent over Eurasia during March). Temperature contrast between Indian landmass and the northern Indian Ocean is known to be modulated by ESC extent. Figure 7A shows the persisting relationship between monsoonal rainfall (JJAS) over UKS and ESC extent during March. Temporal varying correlation coefficients (Fig. 7B) indicate a plausible lead-lag relationship between the two time series. Nonetheless, Figure 7A reveals ESC extent (March) could be treated as one of the key forcing factors influencing UKS monsoonal rainfall and notably the relationship does not seem to have been affected after the 1997 warming. Another important point to note here is that JJAS rainfall anomalies over UKS appear to be positively correlated with ESC extent, i.e. positive (negative) ESC extent year witnessing above (below) normal rainfall over UKS. This observation is intriguing as rising global temperatures are supposed to decrease ESC extent and thereby favour below-normal rainfall over UKS. However, apparently regional rainfall appears to be rising, especially during early months. Snow cover extent during spring over a more specific region of Eurasia might serve as a better antecedent for predicting rainfall over UKS.

Several recent studies investigated sequence of atmospheric (meteorological) processes that led to the extreme rainfall event of 15−17 June 2013 (Joseph et al. 2014; Dimri et al., 2016).

Joseph et al. (2014) reported fast advancement of a monsoon front over UKS and interaction between the monsoonal low pressure system and the mid-latitude atmospheric system plausibly originated from the Arctic region (negative AO anomaly) that helped the early advancement of monsoon and the generation of the heavy rainfall event aided by orographic uplift. We pose a question here: ‘do negative and positive AO anomalies over Arctic region have an influence on extreme rainfall events over UKS ?’. In order to check this, we investigated AO index time series data available from 1950 (source: NOAA) in the realm of a JJAS rainfall anomaly over UKS. Figure 8A shows a noticeable concurrence of negative AO anomalies with positive JJAS rainfall anomalies over UKS. The strength of concurrence between the two could be adjudged by computing likelihood of co-occurrence of a negative AO anomaly and above average rainfall over UKS. Analyzing the two anomalies bin wise, apparently the negative AO anomaly over Arctic region (can be checked in month of March probably) will be followed by an above-normal summer monsoon rainfall over UKS, which appears to be increasing in recent years (Fig. 8B). Notably probabilities are ≤ 0.3 (Figure 8b), which essentially means that only ~30% chances are there when negative AO anomaly over Arctic may be followed by anomalous rainfall over UKS. But, as the year 2013 witnessed a negative AO anomaly over the Arctic and an extreme rainfall event in UKS (Joseph et al., 2014), negative AO anomalies must be carefully monitored for their plausible impact over northern landmass (Europe and north America) as well as higher Himalayas. A strong negative AO in 2009 was followed by anomalously higher rainfall over UKS in 2010 and the Leh-Ladhakh cloud burst event.

5 Conclusions

We attempted to present a simple layout to assess changing patterns of regional summer monsoon rainfall (its intensity and distribution) over orographically variable terrain of Uttarakhand. Results obtained in this study could be utilized by climate/monsoon modellers and policy makers for better assessment of rainfall related natural hazards over the hilly states of India. To comprehend with the rapidly changing meteorological and hydrology of UKS, there is a strong need for setting up ground-based instruments capable of monitoring various climate parameters. These observations coupled with satellite observations can greatly help our preparedness to meet future rainfall-related hazards by preempting them well in advance and evacuating tourists and pilgrims by issuance of hazard warnings. We must note that rapidly changing regional geomorphology (in response to anthropogenic activities such as urbanization, tourism, etc.) may enhance impacts of rainfall- and snowfall- related extreme events in terms of human lives and infrastructure loss. Hence, in addition to monitoring atmospheric processes, and satellite-derived monitoring of surface topographical features such as slope, relief, aspect, and geometry of major touristd' spots also should be monitored in order to assess their vulnerability against human and climatic stress. Use of multi-dimensional surface-atmospheric column data could be exploited to build computer-based models to assess potential regions of vulnerability with possibility of predicting an epicentre well in advance to minimize disaster.

Major outcomes of our study can be summarized as follows:

- Abrupt increase in pre-monsoon air temperatures after 1997.
- Statistically significant upward trends in June-July rainfall compared to rainfall in August–September.
- Temporal varying relationship between ambient air temperatures (spring to pre-monsoon) and JJ rainfall over UKS.

- ESC extent (March) and AO index (March) appear to influence JJAS rainfall over UKS; however, their quantitative impacts are yet to be estimated.

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Figure Captions-

Figure 1: *Monthly rainfall data for the shown grid (2.5°× 2.5°) covering most parts of Uttarakhand (including Kedarnath area) were retrieved from GPCC (source:*http://www.esrl.noaa.gov/psd/*). Lower panel shows inter-annual variability MAM temperatures (steeply increasing trend after 1997 is noteworthy). Right panel shows political boundaries of Uttarakhand state.*

Figure 2: *Monthly rainfall distribution for the selected UKS grid. June- July rainfall show distinct upward change while August-September rainfalls do not show any significant change*

before and after 1997. Shaded portions of panels (e and f) demonstrate steady increasing trends in JJAS rainfall owing increasing September rainfall between ~1905-1926.

Figure 3: *Comparison of monthly rainfall (MJJAS) and ambient temperature data (MAM) time series with available time series data for the Mukteshwar town of Uttarakhand. Statistical significances of observed correlations are mentioned in respective panels.*

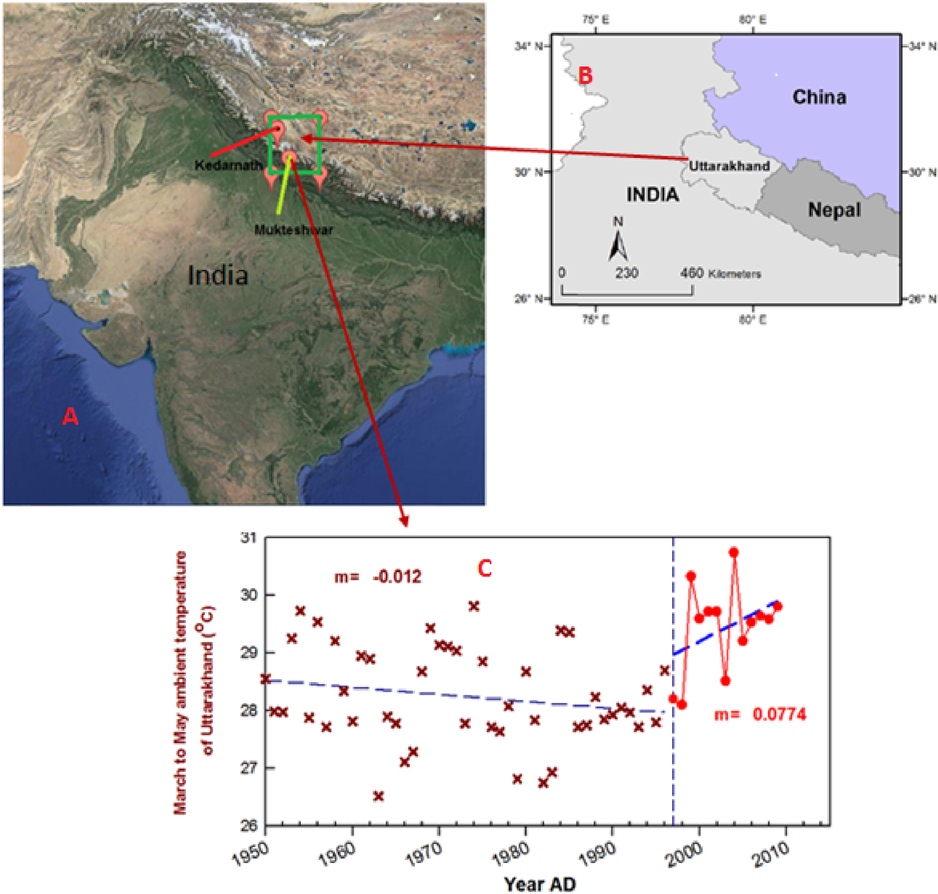
Figure 4: *Monthly rain rate (mm.day^{-1}) for UKS grid since 1986 June-July rain rates show significant increasing trends compared to August and September month. Rain rate in May shows an abrupt shift pre- and post- 1997 (shown by red vertical line).*

Figure 5: *Monsoonal rainfall (JJ) over UKS and its relationship with (A) May and (B) MAM temperature time series. (C) 11-year moving linear correlation coefficients of May and MAM temperatures with JJ rainfall. The dashed lines represent the 90% significance limits of the correlation coefficients. Recent deteriorating correlative patterns are noteworthy.*

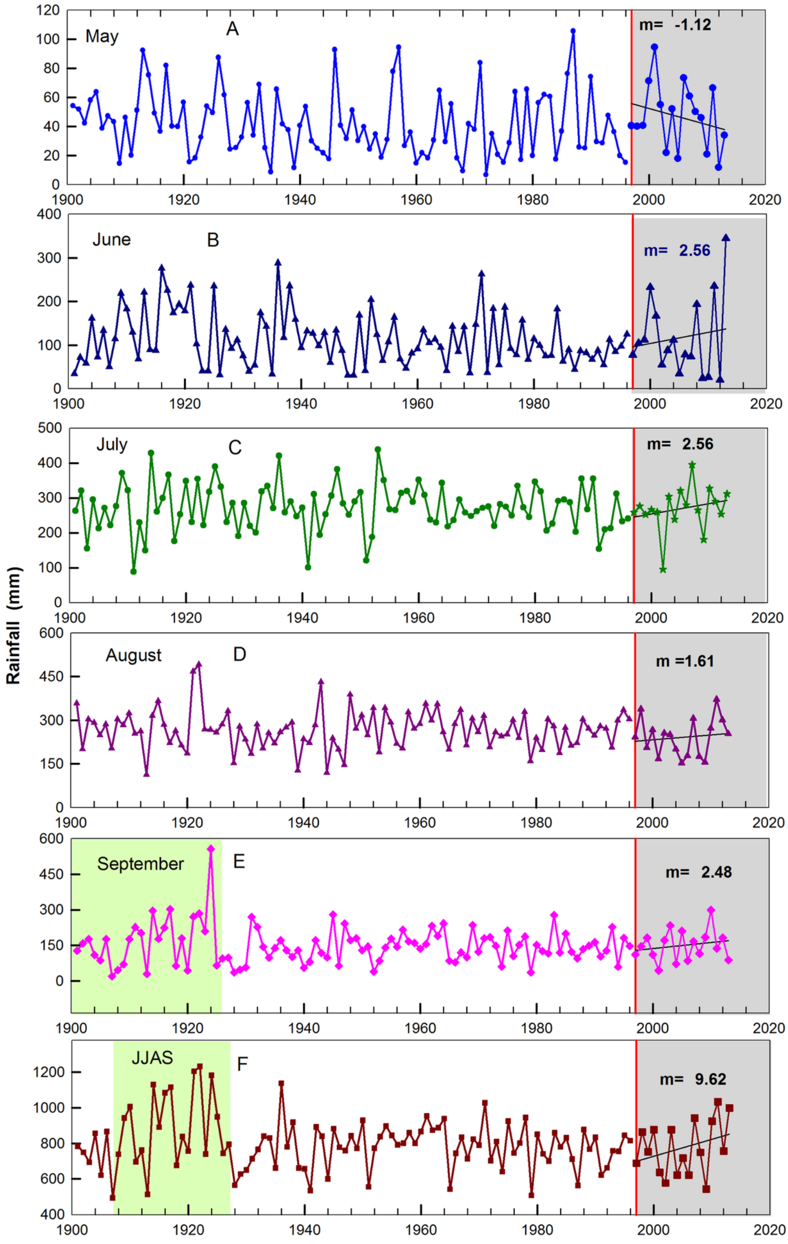
Figure 6: *Wavelet coherence of UKS May temperature and June-July rainfall. The yellow shaded regions indicate coherencies that are significant above 95% level, while the orientation of the arrows indicate the phase lag. The results show temporally varying coherencies with identified forcing factors.*

Figure 7: (a) *Monsoonal rainfall (JJAS) over UKS and its relationships with Eurasian Snow Cover extent (March. ESC extent (March) appears to positively correlated with monsoonal rainfall over UKS. (b) 11-year moving linear correlation coefficients of ESC with JJAS rainfall.*

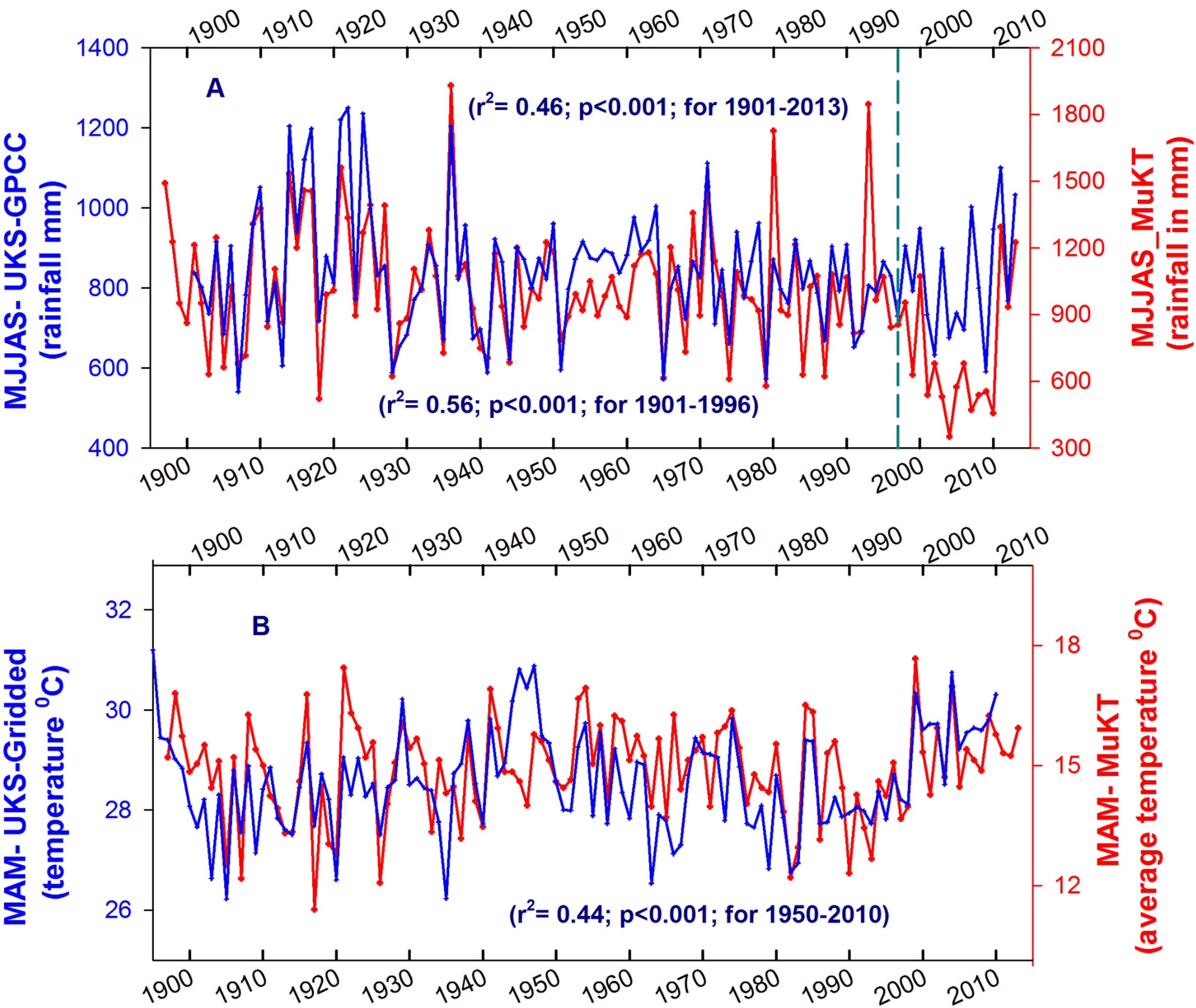
Figure 8: *Monsoonal rainfall anomaly over plotted against Arctic anomaly (AO) index (reverse scale). Negative AO anomalies appear to enforce positive rainfall anomalies over UKS. The tendency of co-occurrence of negative AO anomaly over Arctic and above average rainfall over UKS appears to be increasing in recent years (lower panel).*

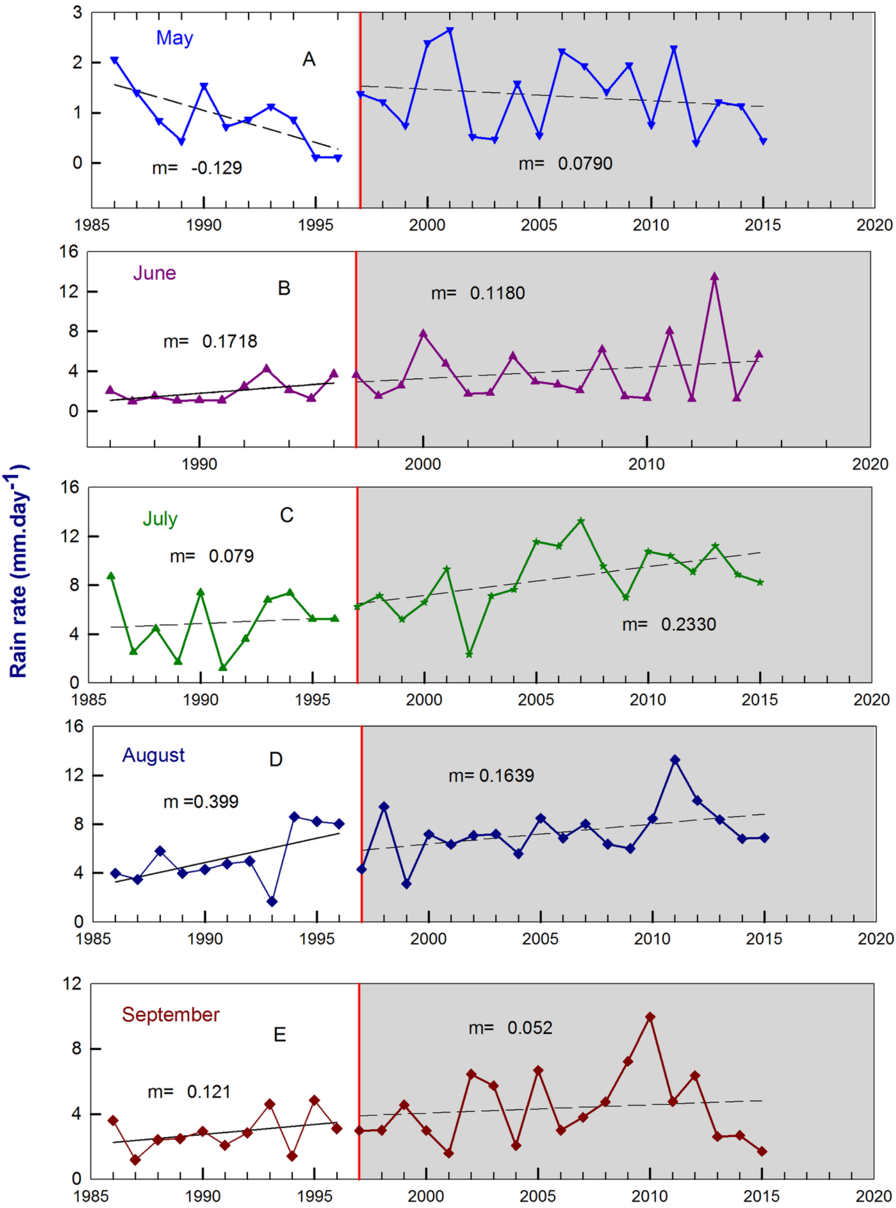


Kedarnath
Mukteshwar
India
A
75° E
80° E
34° N
30° N
26° N
B
China
Uttarakhand
INDIA
Nepal
N
0
230
460 Kilometers
C
m= -0.012
m= 0.0774
March to May ambient temperature of Uttarakhand (°C)
Year AD
1950
1960
1970
1980
1990
2000
2010
26
27
28
29
30
31

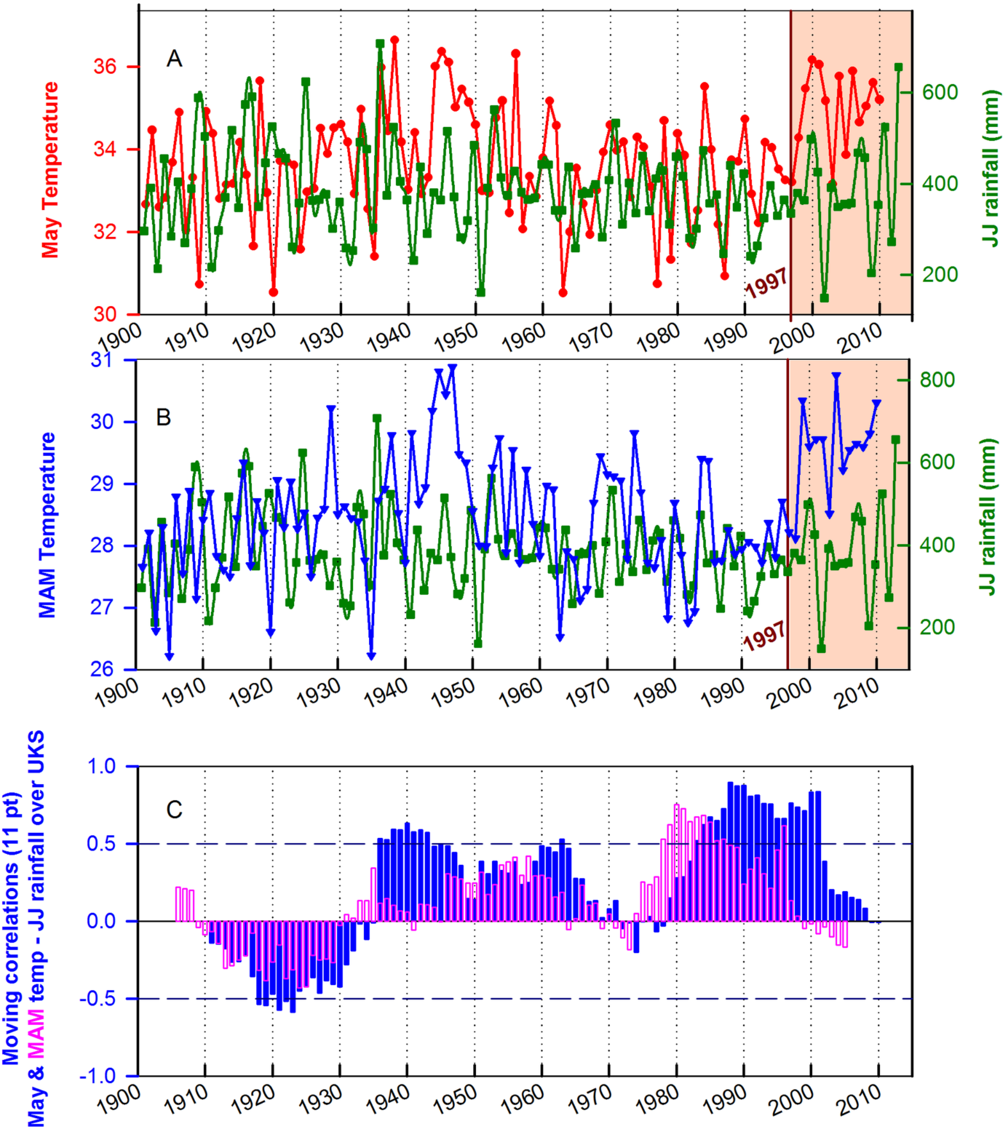


May
A
m= -1.12
June
B
m= 2.56
July
C
m= 2.56
August
D
m =1.61
September
E
m= 2.48
JJAS
F
m= 9.62
Rainfall (mm)

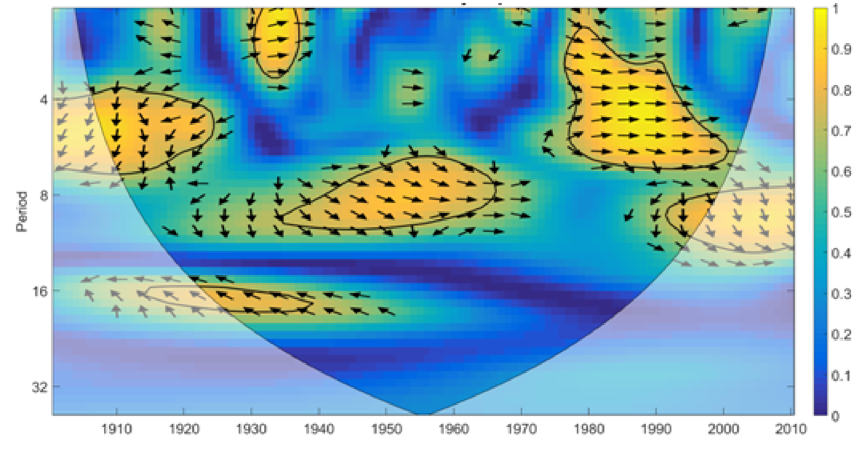

A
(r2= 0.46; p<0.001; for 1901-2013)
(r2= 0.56; p<0.001; for 1901-1996)
MJJAS- UKS-GPCC (rainfall mm)
MJJAS_MuKT (rainfall in mm)
B
(r2= 0.44; p<0.001; for 1950-2010)
MAM- UKS-Gridded (temperature 0C)
MAM- MuKT (average temperature 0C)



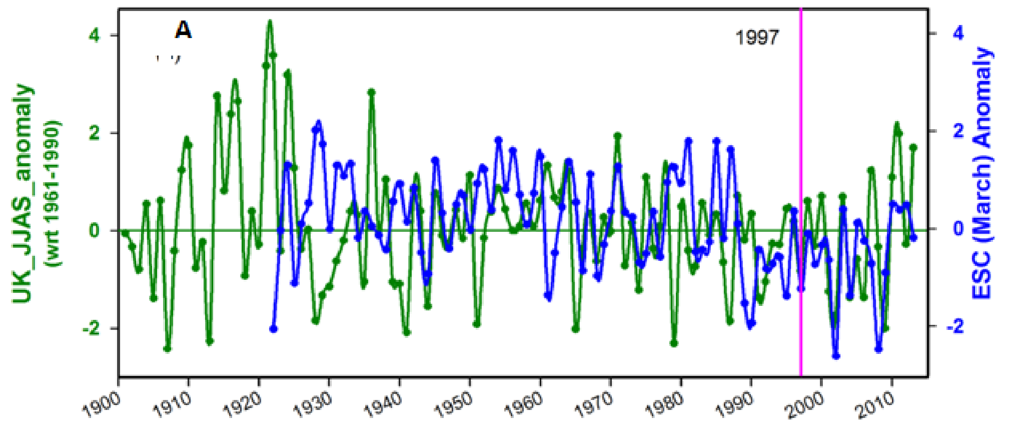
Rain rate (mm.day-1)
May
A
m= -0.129
m= 0.0790
June
B
m= 0.1718
m= 0.1180
July
C
m= 0.079
m= 0.2330
August
D
m =0.399
m= 0.1639
September
E
m= 0.121
m= 0.052
1985
1990
1995
2000
2005
2010
2015
2020

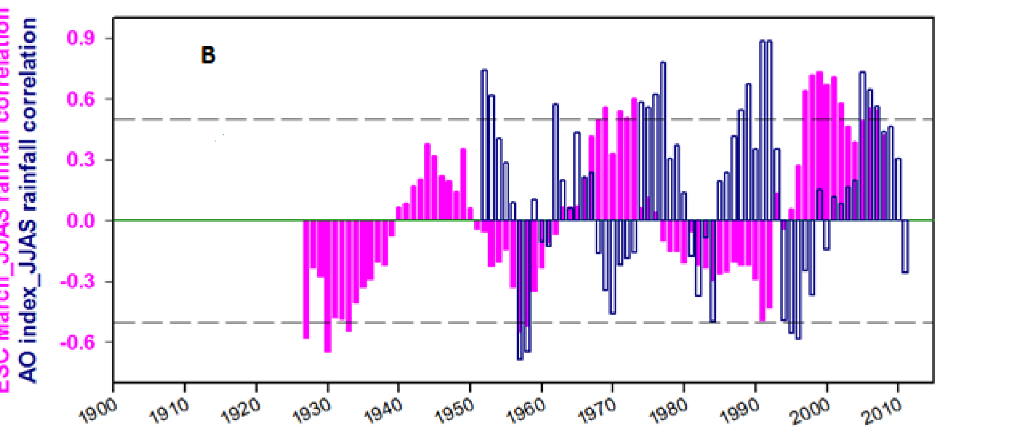


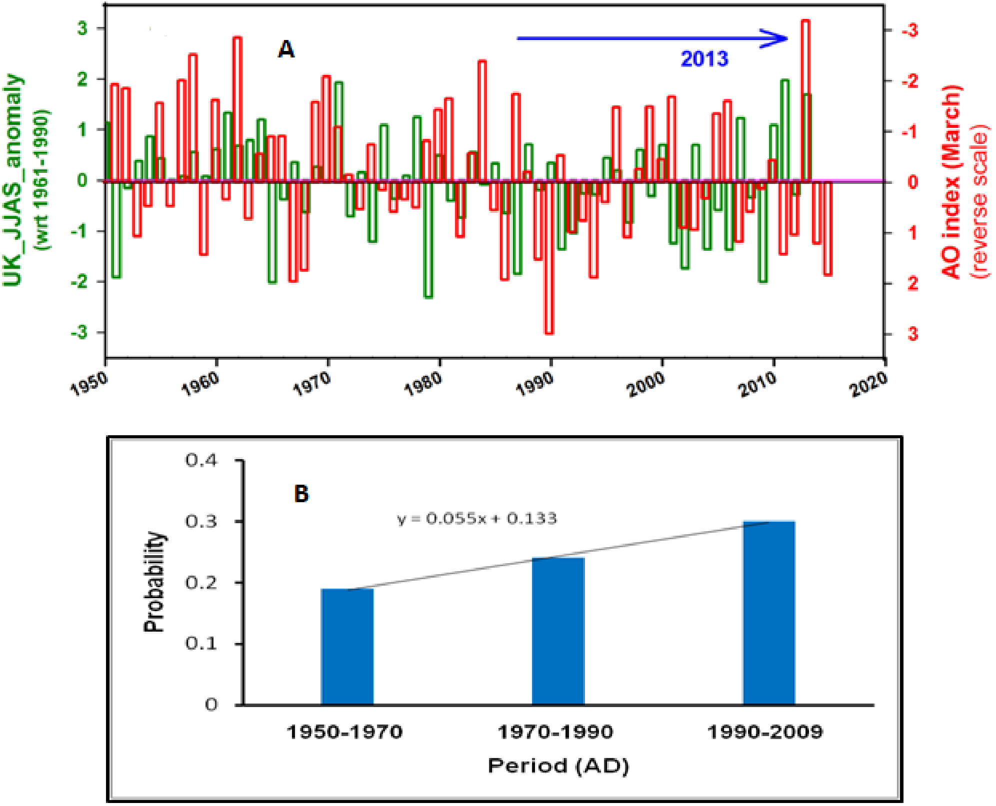
A
May Temperature
JJ rainfall (mm)
1997
B
MAM Temperature
JJ rainfall (mm)
1997
C
Moving correlations (11 pt)
May & MAM temp - JJ rainfall over UKS



Period
4
8
16
32
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0


A
1997
UK_JJAS_anomaly
(wrt 1961-1990)
ESC (March) Anomaly
4
2
0
-2
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010


B
ESC March_JJAS rainfall correlation
AO index_JJAS rainfall correlation
0.9
0.6
0.3
0.0
-0.3
-0.6
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010



A
2013
UK_JJAS_anomaly
(wrt 1961-1990)
AO index (March)
(reverse scale)
3
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2
3
1950
1960
1970
1980
1990
2000
2010
2020
B
y = 0.055x + 0.133
Probability
0.4
0.3
0.2
0.1
0
1950-1970
1970-1990
1990-2009
Period (AD)