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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 2013 C.E. (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.

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).

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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., 2016). 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., 2014; Dimri et al., 2016; Cho et al., 2015). 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., 2015; 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 (Basistha 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, 2016; 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