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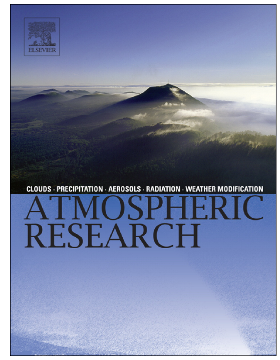

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South Asian perspective on temperature and rainfall extremes: A review

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ABSTRACT

Climate change has pushed the natural limits of our environment, creating extreme weather events that are more frequent and more intense in certain locations around the globe.

There is evidence of increasing trends in temperature extremes in most countries of South Asia, while in a few regions, temperature extremes have been decreasing. Heatwaves have intensified, which has contributed to accelerating drought and extreme flood events in most South Asian countries. Overall changes in rainfall and temperature have led to alterations in water availability in this region. With few exceptions, the general phenomenon in most South Asian countries is that rainfall intensity has increased, but with a reduced number of wet days. Studies that associate rainfall and temperature in the region of South Asia are scarce and rainfall extremes have been studied more extensively than temperature extremes. In fact, temperature trends are spatially less coherent than rainfall trends in most south Asian countries. It is more likely correlated for the teleconnection and South Asian climate for influencing the temperature and rainfall pattern, rather than any other factors. When it comes to trend estimations, statistical slope detection metrics, such as simple linear regression, have been commonly used to detect and quantify mean trends for countries in the regions of South Asia. The application of robust nonparametric statistical tests lacks to quantify temperature and rainfall extremes, particularly in the small countries of South Asia. Statistical downscaling is recommended for better prediction accuracy as well as to find spatial coherence in trends.

Keywords: Climate change, extreme event, heatwave, intense rainfall, teleconnection

1. INTRODUCTION

Weather and climate extremes have begun to receive increasing attention (Easterling, 1997; Fan and Chen, 2016) because the impact of these events strongly felt (IPCC, 2007a) in today's world (Sivakumar and Stefanski, 2011). Climate change, which is defined as statistically significant variability in weather that continues over long periods, portends extremes in weather due to unprecedented environmental change over time. Climate change may become apparent as a change in average weather conditions or in the distribution of weather around the average conditions. In this context, natural variability also plays a crucial role in climate change, which shifts the odds and may cause changes in natural variability, making certain types of extreme weather events more frequent and more intense (Urama and Ozor, 2010; Samo et al., 2017). Seasonal, annual, inter-annual, and decadal variability in an environment within a stationary period is known as climate variability. Climate change, in turn, is a significant lasting change in the statistical distribution of weather patterns over longer periods (Brander, 2007). Recently, the many observed cases of rare weather events show consistent trends that imply a shifting climate.

The inter-annual, monthly, and daily distribution of climate variables (e.g., rainfall, temperature, radiation, wind speed and water vapour pressure in the air) affects a number of physical, chemical, and biological processes that create, sustain, and inform environmental, economic, and social systems (Easterling et al., 1997). With an increasing prevalence of warming trends in the climate, extreme temperatures have become more frequent and severe, leading to extreme heat, intense rainfall, and drought. Heatwaves have become longer and hotter than before (Steffen et al., 2014; Essary and Freedman, 2016), while intense rains and flooding have become more frequent (Lee et al., 2018). Further, humid mid-latitude regions such as the Eastern United States, China, southern Brazil, and Argentina experience annual maximum wet-bulb temperature during summer heat waves comparable to tropics, even though annual mean temperatures are significantly lower (Sherwood and Huber, 2010). Several regions in South Asia are experiencing these changes, which are evidently seen in several significant events including frequent heatwaves in India, recurrent floods in Bangladesh and the northeast states of India, frequent and severe extreme events in Nepal including heavy rainfall events, droughts, heat waves and cold waves, and receding water tables and crop failures in Pakistan and India (IPCC, 2007a). Extreme weather and climate events have caused a rising number of human fatalities and an exponential increase in associated damage (Easterling, 1997; Karl and Knight, 1998; CEJ, 2009; Kan et al., 2011). On a global scale, the intrinsic uncertainty of the climate indicates a shift to newer weather and more intense extreme events, which have become more frequent and severe in the last few decades (Obeysekera et al., 2011; IPCC, 2013; CSIRO, 2014; Steffen et al., 2014).

Among available metrics to analyze climate trends, many researchers have utilized parametric methods for detecting linear trends, which are indeed the simplest available indicators of changes in climate over time. However, it should be noted that such a simple trend analysis may not reliably detect underlying trends in extremes, particularly the indices of relatively rare events (Klein et al., 2009). To tackle this limitation, a few researchers have used other available techniques, such as nonparametric methods (Jung and Chang, 2011; Obeysekera et al., 2011; Gebremichael et al., 2014). Utilizing reliable methodologies together with other techniques such as non-linear methods in an appropriate manner is essential to analyze extreme weather events and their impact. Regardless, the development of a method to reveal observed climate extremes is lacking.

Over the last few decades, extreme weather events have become more significant in countries in South Asia. South Asia provides a home to over one-fifth of the world's population, including countries such as Afghanistan, Bangladesh, Bhutan, India, the Republic of Maldives, Nepal, Pakistan, and Sri Lanka. India is South Asia's largest country, having the highest population and holding nearly 63% of the total land surface, followed by Pakistan, Afghanistan, Bangladesh, Nepal, Sri Lanka, Bhutan, and the Maldives (CIA, 2016). Being islands surrounded by the Indian Ocean and remote to the mainland of India, Sri Lanka and the Maldives differ from other South Asian countries. Nevertheless, the islands have been powerfully impacted by changes in the regional climate (i.e., South Asia). A broader definition of Asia would also include the Middle Eastern countries in the west to China in the east. Weather patterns on the South Asian continent hang in a delicate balance and are typically prone to disastrous weather extremes such as droughts, floods, and cyclones with the influence of strong seasonal monsoons (Sivakumar and Stefanski, 2011; Senaratne and Rodrigo, 2014).

Although mean trends in climate variability have been analyzed in previous research, the literature on extreme weather trends in South Asia is relatively scant. This paper reviews existing recent trends in global extreme rainfall and temperature in comparison to south Asia to present significant consequences in the region of interest. Further, this review emphasizes the role of teleconnections on extreme events and their implications for water resources management, reviewing historical climatic events in South Asia. This review takes a big-picture perspective to visualize the extreme climatic events occurring in the countries of South Asia.

2. EXTREME WEATHER EVENTS

2.1 Temperature

Extreme temperature events depict anomalies in both warm and cold events in terms of frequency and magnitude (Diffenbaugh et al., 2005). Dramatic changes in extreme temperature events in the form of heatwaves are a key risk factor emerging as a major global health concern.

Some studies have shown increases in sea surface temperatures and nighttime marine air temperatures over oceans worldwide. Air temperatures have increased at about almost twice the rate of ocean surface warming, globally (Sivakumar and Stefanski, 2011). Brohan et al. (2006) reported a distinct temperature increase of +0.34 °C in global air temperature measured above the land surface, which marked the twelfth warmest year on record based on historical records (**Figure 1**). In Europe, heatwaves have become more frequent, while low-temperature extremes have become less frequent. The average length of summer heatwaves across Western Europe has doubled and the frequency of warm days has almost tripled in recent weather history (EEA, 2011).

Climate change has certainly intensified heatwaves in the same way it has accelerated other extreme weather events in South Asia. Some South Asian countries show positive trends, while others show negative trends in temperature extremes. Alexander et al. (2006) identified a negative trend in the annual number of summer days and the annual number of consecutive dry days over India although significant decreases occurred in small regions. In particular, increases in nighttime temperatures and warmest daytime temperatures have been observed at most weather stations across Nepal, India, Sri Lanka, and Pakistan (Sheikh et al., 2015). According to Sivakumar and Stefanski (2011) significantly longer durations of heatwaves have prevailed in many South Asian countries. **Table 1** summarises the normal maximum temperatures (i.e., 30-year average) of the past in South Asian countries, together with its trends. It should be noted that temperature increases have been reported in all the countries in South Asia, except for the Maldives, where no records in key temperature changes are kept. The maximum temperature increase was reported for Bangladesh (Badsha et al., 2016) and the minimum increase was reported for Bhutan and Sri Lanka (**Table 1**).

South Asian countries have revealed the warming of both extreme-cold and extreme-warm distributions (Klein et al., 2006). Greater number of warmer months were observed than summer months from 1975 to 2005 has been reported in Pakistan (Ikram et al., 2016). The Panjab province of Pakistan has been shown to have increased numbers of hot days and nights with prolonged summer days (Abbas, 2013). **Table 2** summarizes extreme temperature situations in the countries of South Asia.

Above-normal temperatures have been reported in the recent past by several countries in South Asia. In India, temperatures higher than the 30-year climatological normals have been reported in recent years, with average warming of 0.51 °C (Surinder, 2009; Anil et al., 2015). Also, reports have indicated rising temperature trends over most states of India (APN, 2004; IPCC, 2007b). Annual mean temperature data for Sri Lanka during the period of 1871-1990 show significant warming trends in most districts of the country, indicating an increase of 2 °C in the central highlands (Chandrapala, 1996; Fernando and Chandrapala, 2002). An increasing trend in annual mean air temperatures in Sri Lanka has long been recorded (De Costa, 2010).

In Tibet, in an analysis of monthly and annual temperature changes during 1963-2015 at 112 stations, 87% and 71% of the stations showed positive tendencies in monthly minimum and maximum temperatures, respectively (Ding et al., 2018). Further, 95-96% of the stations showed positive tendencies for annual minimum and maximum, and the trends were largely significant ($p<0.05$). In this study, distinct spatiotemporal patterns of temperature across different time scales were reported.

2.2 Rainfall

Rainfall extremes are defined as abnormally high magnitudes of rainfall within a statistical distribution, which can result in a significant impact to direct runoff or erosion in tropical countries. Landslides and other land-related disasters are a secondary impact of rainfall. Though extreme rainfall events have substantial effects on the environment and humans in the form of high-magnitude disasters, heavy rainfall is considered beneficiary for groundwater recharge in many tropical countries. Rainfall regime highly varies upon space and time, may indicate climate change in the region (Ferdinand et al., 2015). Specifically, in a study by Angeline et al. (2017) rainfall variability also showed a robust change in response to warming.

Even though the number of extreme rainfall events has increased across the continents, global historical trends in various countries have mixed anomalies in terms of rainfall events (IPCC, 2007b). Globally, extreme rainfall events have been observed in a few countries, whereas in many countries, rainfall extremes have been recorded at 70% below normal (Loo et al., 2015). Rainfall extremes have increased in many states in the US (Melillo et al., 2014), although the trend is declining in South Florida (Obeysekera et al., 2011).

In most South Asian countries, except for a few places/regions of high elevation, rainfall occurs in the form of liquid rainfall. South Asian countries mostly receive rainfall via either Northeast or Southwest monsoons. Various trend studies indicated that South Asian monsoon rainfall extremes are becoming relatively frequent (Baidya et al., 2008; Yao et al., 2008; Shrestha et al., 2017). It has been reported for an increased frequency of intense rainfall with an increased likelihood of extreme rainfall in parts of South Asia (Christensen et al., 2007). Despite contrasting trends of decreased rainfall during the period of1976-2005 (Salma et al., 2012), intense rainfall events have been observed in the monsoon regions of Pakistan (Ikram et al., 2016).

Further, heavy rainfall events from 2009 to 2013 in Afghanistan show that spring and winter peaks of precipitation corresponded with large-scale humidity that passes through the Caspian Sea and the Black Sea, which is approaching from north and northwest of Afghanistan (Shokory et al., 2017). Using nonparametric statistical analysis, Nepal has been reported to show an increasing trend of annual mean rainfall, especially during June and July (Shrestha and Sthapit, 2015). Rainfall intensity is largely influenced by topography (i.e., the Tibetan Plateau), more than any other factor, during the Indian summer monsoon (Loo et al., 2015).

Rainfall events in Sri Lanka emphasize that rainfall extreme are mostly concentrated in southwestern parts, especially the Colombo and Ratmalana regions. It has been observed that the Nuwara Eliya district shows decreasing trends in all the extreme indices, including the frequency and intensity of rainfall (Sanjeewani and Manawadu, 2014). Shifts in heavy rainfall based-quarters were found in the Vavuniya district for the year 2013 (Patrick et al., 2015). Also, previous research (Varathan et al., 2010; Mayooran and Laheetharan, 2014) has tested the applicability of appropriate statistical distributions for extreme rainfall in the Colombo district of Sri Lanka.

Though average trends have been much studied in the countries of South Asia, extreme rainfall trends are scarcely reported in existing literature. **Table 3** summarizes the findings on extreme rainfall trends in South Asian countries. Because the analysis is limited to particular stations due to the nature of rainfall intensity, findings cannot be generalized to countries in their entirety. Depending on the research, parts of countries are reported for extreme rainfall measures. Recent literature on trends in extreme rainfall lacks analysis for the countries of Bhutan, Sri Lanka, the Maldives, and Afghanistan.

Based on the annual rainfall values of two periods (i.e., 1900-1929 and 1964-1993), it has been identified for the expansion of the dry zone in Sri Lanka (i.e., a region with an annual average of 904-1,553 mm of rain) the (Somaratne and Dhanaprala, 1996; Madduma Bandara and Wickramagamage, 2004). Confirmed by the work of Imbulana et al. (2006), a similar conclusion was reached by Sri Lanka National Water Development Report (SLWDR, 2006) based on the mean annual rainfall of two 30-year periods (i.e.,1911-1940 and 1961-1990). According to this study, the most significant expansion was observed in the dry zone of Sri Lanka, while the region measuring annual rainfall above 2,000 mm of rain has also diminished. The decline in rainfall at Nuwara Eliya has been identified by many studies as well (Madduma Bandara and Kuruppuarachchi, 1988; Ranatunge, 1988; Chandrapala, 1996; Domroes, 1996; Kayane et al., 1998; Wickramagamage, 1998; Madduma Bandara and Wickramagamage, 2004; Jayathilaka et al., 2011).

Based on monthly and annual rainfall for the period of 1965-2004, Ampitiyawatta and Guo, (2009) claimed that rainfall observed in the Kalu Ganga basin has declined. Colombo, Puttalam, and Hambantota have recorded increasing trends in Southwest monsoon rainfall, while Nuwara Eliya and Kandy have experienced decreasing trends during a period of analysis from 1871 to 2000 (Kayane et al., 1998; Malmgren et al., 2003; Jayawardene et al., 2005).

Linear regression on the number of rainy days observed for coastal cities during a period of analysis from 1971 to 2011 showed that, except for Ratmalana, stations at Hambantota, Galle, Katunayake, Puttalam, Trincomalee, and Batticaloa had decreasing trends in rainfall, but the trends are not statistically significant (i.e., R-squared values are between 0.29 and 0.51) (Bandara et al., 2013). Further, that research reveals that extreme rainy days (i.e., the number of days with rainfall levels greater than the ninetieth, ninety-fifth, and ninety-ninth percentiles) have increased for the period from 1971 to 2011 in coastal regions of Sri Lanka. One thing to highlight is that only the Ratmalana station had an R-squared value greater than 0.6 for this index (Bandara et al., 2013). Otherwise, the overall number of rainy days has decreased in recent years, except for the Nuwara Eliya region.

Linear regression analysis of annual rainfall over coastal regions in Sri Lanka showed that annual rainfall in the Ratmalana and Batticaloa regions had significant (i.e., R-squared values closer to 0.6) increases during the analysis period from1971 to 2011 (Bandara et al., 2013). Hambantota, Galle, Katunayake, Puttalam, and Trincomalee had decreasing annual rainfall from 1971 to 2011 based on linear regression analysis (Bandara et al., 2013). Chandrasekara et al., 2018 analyzed distributional changes in annual maximum daily rainfall (ADMR) from 1960 to 2015 for coastal regions in Sri Lanka using a quantile regression approach in a Bayesian framework. The study revealed that Colombo, Galle, and Ratmalana stations had a decreasing trend in annual daily maximum rainfall (ADMR) but increasing trend in uppermost quantiles which could indicate a high probability of extremely high rainfall. Further, Hambanthota station showed an increasing trend in both distributional changes in ADMR and lower quantiles. The work of Senadeera et al. (2016) reports the average annual rainfall of the Uma Oya basin (i.e. Narangala and Debedda stations) overlaps with the trends in annual rainfall for the period of 1989 to 2005 based on the linear regression methods. Therefore, it has been concluded that the Uma Oya basin has not been subjected to climate change in recent decades (Senadeera et al., 2016).

Based on linear regression models, coastal regions of Sri Lanka including Ratmalana, Hambantota, Galle, Katunayake, Puttalam, Trincomalee, and Batticaloa have observed increases in Southwest monsoonal rainfall from 1971 to 2011 (Bandara et al., 2013). On the other hand, using Mann-Kendall and Sen's model calculations, many parts of the country experienced increased rainfall during the first intermonsoon, second intermonsoon, and Northeast monsoon seasons. In contrast, during the Southwest monsoon season, trends in seasonal rainfall dropped throughout Sri Lanka (Karunathilaka et al., 2017). For the Uma Oya basin, rainfall trends due to Northeast and Southwest monsoons have increased and decreased, respectively (Senadeera et al., 2016). Therefore, from December to February, the Uma Oya basin stands to experience intense rainfall. On the other hand, from May to September, the region should expect drier months.

Mann-Kendall and Sen's slope methods have been used to identify annual rainfall trends at 32 gauging stations in Sri Lanka (Karunathilaka et al., 2017). Based on Mann-Kendall tests, results revealed significant upward trends for gauges at Anuradhapura (6.31 mm/year), Batticaloa (9.77 mm/year), Mapakadawewa (16.25 mm/year), and Pottuvil (19.89 mm/year) during the period 1966-2015. The rather pronounced increase in precipitation has been observed in the south-eastern region of Sri Lanka where the annual precipitation is relatively low compared to the other regions. Notably, the stations, Mapakadawewa and Pottuvil, showed a significant increasing rainfall trend during the second inter-monsoon season (October-November) which may be the consequence of the enhanced low-pressure systems and cyclones in recent years (Karunathilaka et al., 2017). The increase in annual rainfall and the decrease in the number of rainy days suggest increasing rainfall intensity at these stations (Manawadu et al., 2008). Furthermore, stations at Chilaw, Dandeniya Tank (located in the Matara district), and Iranamadu Tank (located in the Kilinochchi district) showed significant downward trends during the period of analysis from1966 to 2015 (Karunathilaka et al., 2017). Western, northern and southern regions and the central hills of Sri Lanka showed decreasing annual rainfall trends during 1966-2015 (Karunathilaka et al., 2017). Although a significant increasing trend of 3.15 mm/year of annual rainfall was estimated for the Colombo region based onthe130-year period leading up to 1998 (Jayawardene et al., 2005), the work of (Karunathilaka et al., 2017) shows that the observed increase has been only 0.66 mm/year over a recent 50-year period between 1966 and 2015. Furthermore, Jayawardene et al. (2005) found that Kandy and Nuwara Eliya had decreasing trends in rainfall during the 130 years leading up to 1998, while from 1966 to 2015, the rate of decrease diminished (Karunathilaka et al., 2017). These findings suggest an increase in the annual rainfall for the regions of Kandy and Nuwara Eliya.

Wickramagamage (2016) studied the behavior of mean annual and mean seasonal pentads of rainfall over Sri Lanka from 1981-2010 using least square regression curves and the linear regression method. That study reveals predominant negative trends for the central highlands and northern regions of Sri Lanka, but positive trends for the regions of Colombo and Batticaloa. Further, the study shows that during the first intermonsoon season, rainfall declines mostly on the western side of the central highlands of Sri Lanka, whereas during the second intermonsoon season, the decline is on the eastern side of Sri Lanka. In the period preceding these seasons, the entire island experiences a reduction in rainfall during the Southwest monsoons.

Although general patterns in rainfall reported by different studies appear to be largely consistent, some contradictions remain. The nature of trends seems to be related to the period of analysis. Naidu et al. (2015) designated the period of 1976 to 2004 as a "global warming" period, and this warming signal is detected in weather patterns in South Asia as well. The work of Klein et al. (2006) asserts that comparison of recent hydrological trends (i.e., rainfall and temperature changes during 1961-2000) with changes over the longer period of 1901-2000 reveals that linear trends need to be interpreted with caution insofar as they may not be a good representation of actual changes in climate variability. Further, that research suggests the use of more advanced statistical estimates of trends and their significance, which may see the changes in the magnitude of the trends.

Varathan et al. (2010) performed statistical modeling of extreme daily rainfall over 110 years in Colombo, Sri Lanka, using extreme value distributions under two sampling techniques. Even though the original series of annual maximum daily rainfall data fits the Frechet distribution, the distribution converges to the Gumbel distribution and the predicted values for different return periods and their confidence levels decreased following the removal of the single outlier identified using Grubb's test. Further analysis has revealed that Gumbel and exponential distributions are suitable models for extreme daily rainfall by considering the annual maximums of daily rainfall and daily rainfalls greater than 100 mm.

Klein et al. (2009) calculated 12 indices of temperature and rainfall extremes using the RClimDex software package developed at the Meteorological Services of Canada (available from http://cccma.seos.uvic.ca/ETCCDMI/index.shtml). In that study, trends in the indices of temperature and rainfall extremes are calculated by ordinary least square fits, and statistical significance was tested using a Student's t-test. Further, Sheikh et al. (2015) expanded the study by Klein et al. (2006) using 22 extreme climate indices and focusing on individual regions including Sri Lanka, Nepal, Northern Pakistan, and the Thar Desert. Furthermore, Mann-Kendall tests at a 5% level of significance were used to determine trends. Shahid (2011) used the Mann–Kendall trend test for the trend analysis of rainfall indices and the Sen's slope method to estimate the magnitude of change in rainfall extremes in the pre-monsoon season in Bangladesh.

Lakshmi and Satyanarayana (2019) conducted quantitative analysis of occurrence of heavy rainfall events using integrated horizontal water vapor transport (IVT) algorithm revealed the persistent of atmospheric rivers of more than 18 hours resulted in extreme rainfall over Chennai, India (i.e., Climatological statistically significant correlation of 90% confidence level between IVT during persistent ARs with HPEs was established.

Gao et al. (2018) analyzed the relationship between precipitation extremes and temperature. They found a positive spatial correlation between precipitation extremes and temperature at hourly to daily scales. The results were close to the Clausius-Clapeyron relationship, which states that specific humidity increases with temperature at an approximate rate of 6-7% (Wang et al. 2017; Gao et al., 2018).

3 TELECONNECTIONS

The American Meteorological Society (AMS) has defined teleconnection as "a linkage between weather changes occurring in widely separated regions of the globe." Further, according to the AMS, even if the field is fluctuating, it is possible to correlate negative or positive relationships to the existence of teleconnection. Such teleconnections exist on inter-annual time scales between the El Niño Southern Oscillation (ENSO) phenomenon and the Asian monsoon system, climatologically and theoretically linked to changes in the rainfall in the region especially exposed to hydrologic extremes (Kucharski et al., 2010). The ENSO phenomenon is one of the primary modes of seasonal climatic variability, particularly in the tropics (Ropelewski and Halpert, 1987; Dettingter and Diaz, 2000; Prasanna, 2016), exerting significant influence on the seasonal monsoons in South Asia (SASCOF-8, 2016). The ENSO phenomenon is widely known to have a very strong influence on sea surface temperature (SST) patterns throughout the Pacific Ocean (Lau and Wang, 2006).

Several regional climate studies conducted in South Asia have correlated teleconnections with temperature and rainfall. The strength of such connections in Pakistan, in particular, has been demonstrated in several studies (Arif et al., 1994; Chaudhary et al., 1998; Mahmood et al., 2004). The mean temperature of Pakistan was found to correlate with ENSO teleconnection patterns (Rıo et al., 2013). Further, El Niño phenomena suppress monsoon rainfall activity over Pakistan (Chaudhry, 1995). La Niña phenomena have a negative impact on winter rainfall over Pakistan (Azmat et al., 2003). The worst drought in recent history (1998-2001) over Pakistan and most of South Asia is linked with La Niña phenomena (Hoerling and Kumar, 2003; Farooqi et al., 2005). It is well known that summer monsoons in India are adversely affected by ENSO monsoon years (Shukla and Paolino, 1983). All India rainfall (AIR), defined as rainfall over the Indian landmass, and the ENSO were shown to be significantly negatively correlated throughout much of the twentieth century (Rasmusson and Carpenter, 1983; Kumar et al., 1999). Thus, after showing the peak in the mid-twentieth century, the AIR and ENSO correlation has since weakened dramatically. Many studies have revealed the teleconnection of ENSO on rainfall over India (Kawamura et al., 2005; Yadav et al., 2010; Dimri, 2012; Jha et al., 2016; Prasanna, 2016; Roy et al., 2016; Cash et al., 2017; Chanda and Maity, 2018; Sreekala et al., 2018). However, in the case of Nepal, there is a gap in understanding the influence of teleconnection with

South Asian monsoon phenomena because of the presence of the mountain range of Himayalas, which are the major reason for rainfall over Nepal (Choi et al., 2014). Shrestha et al. (2000) showed a strong relationship between rainfall over Nepal, and the Southern Oscillation Index (SOI) in that less rainfall has been shown to fall over Nepal during ENSO warm phases. Further, stronger El Niño influence was identified on streamflows in comparison to the influence of La Niña. A stronger overall ENSO impact in western Nepal than in eastern Nepal suggests an inverse relationship between El Niño stream flows and monsoon strength and a direct correlation between La Niña flows and monsoon strength (Shrestha and Kostaschuk, 2005). Scientific research in Bangladesh relating to ENSO is just at the beginning stages. In particular, Bangladesh is wet during moderate El Niño years (Chowdhury, 2003) and positive El Niño indices lead to the occurrence of floods and cyclones in Bangladesh (Choudhury, 1994). Being an island, Sri Lanka rainfall patterns have stronger teleconnections with sea surface temperatures in the Pacific Ocean than in the Indian Ocean (Burt and Weerasinghe, 2014). It has been reported that the seasonal rainfall, in Sri Lanka (and more widely over the Indian subcontinent) is predictable with some degree of confidence by the strength of possible teleconnections (Burt and Weerasinghe, 2014). The reason for this predictive accuracy may be that ENSO is the dominant climate driver, widely responsible for the weather in Sri Lanka and the Indian mainland (Rasmusson and Carpenter, 1983; Ropelewski and Halpert, 1987; Allen et al., 1996; Suppiah, 1996, 1997; Kumar et al., 1999; Zubair, 2002, 2003a, 2003b; Zubair and Ropelewski, 2006; Sumathipala, 2014). In particular, variation in both mean rainfall intensity and total rainfall from different monsoon seasons showed high degrees of correlation with the occurrence of ENSO events (Chandrapala, 1996; Malmgren et al., 2003; Ranatunge et al., 2003). The teleconnection between ENSO and rainfall, particularly in Sri Lanka, has been studied and documented by various researchers over time (Rasmusson and Carpenter, 1983; Ropelewski and Halpert, 1987; Suppiah, 1988, 1989; Fernando et al., 1995; Suppiah, 1996, 1997; Kane, 1998; Sumathipala and Punyadeva, 1998; Punyawardena and Cherry, 1999; Malmgren et al., 2003; Chandrasekara et al. 2017). However, there has been no considerable documentation of such teleconnection of ENSO phenomena with direct temperature. Extreme positive rainfall anomalies in Sri Lanka are linked to the evaporative flux of the surrounding ocean (Abeysekera et al., 2015), attributable to teleconnections with the Indian Ocean Dipole (IOD) and ENSO. It is believed that the similarity of IOD to ENSO has an influence on the climate of

Sri Lanka (Suppiah, 1988; Behera et al., 1999; Saji et al., 1999; Zubair, 2002; Saji and Yamagata, 2003; Zubair et al., 2003; Jayawardene et al., 2015). The scientific determination of the magnitude of this influence is still in debate. It is worthwhile to note that, being part of Asia, ENSO phenomena have more influence in the region than any other climatic drivers (Thirumalai et al., 2017).

However, Indian Ocean sea surface temperatures (SST) and sea surface temperature anomalies (SSTAs) have been proposed as other important factors influencing the circulation/rainfall over Indian Ocean rim countries. Indian Ocean Dipole (IOD) events have a strong influence on the summer monsoons in India (Shukla and Paolino, 1983; Ashok et al., 2001; Ashok and Saji, 2007) and in recent decades, the occurrence of IOD phenomena has weakened the relationship between ENSO phenomena and the monsoons (Kumar et al., 1999; Saji et al., 1999; Behera and Yamagata, 2003). It has been found that in Sri Lanka, IOD has a high positive correlation with seasonal rainfall from September to November (Saji and Yamagata, 2003). Moreover, the influences of IOD and ENSO are statistically inter-linked; IOD influence will be highly significant even when there is no ENSO influence, and when the two compete, IOD influence will prevail preponderantly over the influence of ENSO (Zubair et al., 2003).

Asian brown clouds, presently known as atmospheric brown clouds (ABCs), are widespread pollution clouds that can at times span an entire continent or an ocean basin. Atmospheric brown clouds extend vertically from the ground upward to as high as 3 km, and they consist of both aerosols and gases. The dimming effects (i.e., cooling effects) of ABCs reduce the strength of Asian monsoon circulation (Meehl et al., 2008; Ramanathan et al., 2008; Ganguly et al., 2012) and evaporation. Coupled ocean-atmosphere modeling studies of Ramanathan et al. (2008) demonstrate the behavior of Asian monsoon circulation with the presence of ABCs.

In April 2016, the mainland of Southeast Asia recorded the warmest monthly mean temperature in April, resulting in significant losses in agricultural productivity and an increase in energy consumption. Thirumalai et al. (2017) used observation and ensemble of global warming simulations to explore a relationship between the ENSO phenomenon and surface air temperatures over Southeast Asia. It was found that all extreme temperatures in April occurred during El Niño years. Their results indicate that global warming increases the chances of extreme temperatures in April: they estimate that 29% of the 2016 anomaly was caused by global warming and 49% by El Niño. Their modeling results showed that post El Niño Aprils could be potentially anticipated a few months in advance helping societies and authorities to prepare better.

4. IMPACTS OF EXTREME WEATHER EVENTS

Direct impacts of climate change, especially in the case of extreme weather events, consequently trigger a wide variety of secondary effects on water resources, human health and well-being, economy and livelihood, and systems of agriculture and nature (Kumar et al., 2005; Selvaraju et al., 2006; Eriyagama et al., 2010). The occurrence of more intense rainfall over many parts of South Asia leads to severe flooding, landslides, and debris/mudflow with a reduced number of wet days and reduced total rainfall (Mirza, 2002; Lal, 2003). The effects of increased flood frequency during the wet season and prolonged drought during the dry months exaggerate the magnitude of the impact of extreme weather events.

India and Pakistan have had high death tolls due to heatwaves during the last three decades (Zahid and Rasul, 2010). The area's higher heat index is due to the low-level air pressure together with the high humidity. It has been suggested that consistent increases in temperature and humidity, even for a short time for a certain period over a region, is recognized as a significant weather hazard (Zahid and Rasul, 2010).

Several studies correlate primary disease incidence mostly with temperature-associated factors rather than rainfall, which causes secondary outbreaks of disease. An association between increased rates of diarrhea with high temperatures has been confirmed (Hashizume et al., 2007; Chou et al., 2010). Cholera outbreaks in coastal countries in South Asia have been associated with high temperatures and algal blooms (Huq et al., 2005).

A pervasive natural hazard, extremely warm weather that lasts for several days with no relief is often referred to as a "heatwave"(WMO-WHO, 2015). The term heatwave has no universally accepted definition (Robinson, 2001; Perkins and Alexander, 2013), but heatwaves are commonly understood as periods of unusually warm or dry/warm or humid weather conditions. Heatwave-related medical conditions include heat rash, heat edema, heat syncope, heat cramps, heat exhaustion, and life-threatening heatstroke, which have been observed to have considerable effects on levels of mortality and morbidity(WMO-WHO, 2015). Heatwaves and their impacts have become more frequent than ever before in South Asia (Sivakumar and Stefanski, 2011). Heatwaves lead to severe drought in India, influencing crops and livestock, whereas, in parts of Indian states, groundwater reservoirs (major sources of water other than rivers, lakes, and dams) have dried up due to prolonged drought conditions. This scenario has worsened conditions in the states of Maharashtra and Gujarat (WMO-WHO, 2015). **Table 4** lists the impacts of extreme weather events on the South Asian continent as reported in various literature.

Additional to increasing drought events, other impactful extreme weather events reported in South Asian countries include rainfall of high intensity within a short period, causing flash floods, landslides, soil erosion and sedimentation in mountainous regions (PANO, 2009). The impacts of extreme weather events in South Asian countries are on par with other natural disasters worldwide.

Although the changes in climate extremes of temperature and precipitation may vary in time, their concurrent occurrence can cause severe damage to agriculture. Lu et al. (2018) investigated the compound risk associated with extremely high temperature and low precipitation during the crop growing seasons for wheat and maize in China (i.e., North China Plain, Northwest China and part of Southwest China) from 1980-2015. They found an upward trend in the compounded hot and dry extremes, which were different from the climate experienced during the wheat and maize growing seasons, suggesting the need for targeted strategies focusing on specific crop seasons. They further found that projections, based on regional climate downscaling experiments, for future temperature and precipitation are expected to increase by over 160% (relative to 1980-2015 period) for wheat and maize growing seasons. They conclude that these concurrent climate extremes would have a more severe impact on food security compared to extremely hot and dry days considered individually.

5. FUTURE PROJECTIONS

The substantial advantages of climate prediction are beneficial to many parts of the world for risk management and adaptation. Therefore, reliable climate prediction is considered useful. Further, climate prediction helps policymakers and the general public to understand the range of possible future events to evaluate potential responses.

Recent reports from the IPCCpredictthe increased occurrence of extreme weather events in South Asia within this century, including heatwaves and intense rainfall events (IPCC, 2007b). The frequency of extreme wet events is likely to increase by about four-fold in India and Sri Lanka during a period of the forecast from 2071-2100 compared to the period from 1971-2000 (Ahmed et al., 2009). Rainfall maxima at 1-3 day durations anda100 -year return period is projected to increase significantly under the projected future climate in the majority of urban areas in India. Further, the number of urban areas with significant increases in rainfall maxima under the projected future climate is far larger than the number of areas that experienced significant changes in historical climate data on record (1901–2010) (Ali and Mishra, 2014). Strengthening variability in amounts of extreme rainfall, an increase in warm extremes, and a decrease in cold extremes are projected for Asian regions (Xu et al., 2017).

An average temperature increase of 3.3°C was projected for South Asia, which is more than the increase in global mean temperature (IPCC, 2007a), indicating that average annual temperatures could rise by more than 2 °C over land in most South Asian countries by the mid-twenty-first century and may exceed an increase of 3 °C under high emission scenarios (IPCC, 2013).South Asia experiencing a modest warming range of 1.5-2 °C is significantly hazardous to development (Vinke et al., 2016).

Apart from regional-scale predictions, rainfall and temperature projections for Sri Lanka are lacking, especially in terms of extreme weather events. National-level modeling, undertaken by the Climate Change Research Centre in Sri Lanka, suggests that climate changes in Sri Lanka broadly (but not wholly) follow regional expectations (Practical Action, 2016). By 2100, temperatures during the Southwest monsoon season (May to September) are anticipated to reflect an increase of 2.5 °C, while the Northeast monsoon season (December to February) is expected to produce a temperature increase of 2.9 °C. Increases in rainfall levels are anticipated in both seasons. However, changes in rainfall are expected to be greater during the Southwest monsoons (May to September) than during the Northeast monsoons (December to February). In both seasons, rainfall and temperatures are projected to increase incrementally with time from 2025 to 2050 to 2100. Rainfall changes are also predicted to be uneven across Sri Lanka—much greater increases are expected on the windward side of the central hills. Even though droughts are not projected during a period of the forecast from 2020-2049, increased frequency and intensity of droughts are anticipated during the period from 2040-2059 (USAID, 2015; Practical Action, 2016).

In terms of extremes, Bangladesh is predicted to have high-intensity rainfall with a reduced number of rainy days under the SRES A1B scenario (Islam and Hasan, 2012; Hasan et al., 2013). Although rainfall and temperature averages are sufficiently projected, predictions for extreme climatic events lack for many countries in South Asia.

General climate projections indicate a significant warming trend in the daytime and nighttime temperatures all over the South Asian countries. More intense, frequent, and prolonged heatwaves are the possible consequences that can be probable events in the future. It is highly likely that the future temperature increase will severely affect the current agriculture practices in many of the countries in South Asia. The anomalous and extreme rainfall with the high likelihood flood events will be the common phenomenon in future South Asia mostly driven by the teleconnections in the region (Farooqi et al., 2005). It has been anticipated for reliable trend detection and projection methods that explicitly quantify the future trends of rainfall and temperature. Such quantification may help to formulate specific policies that allow adapting to the situation to manage the future calamities due to extreme temperature and rainfall events in South Asia.

In Southwest Asia, the future temperature is expected to exceed a threshold for human adaptability under the IPCC Representative Concentration Pathway (RCP) scenarios, RCP 4.5 and RCP 8.5 (Pal and Eltahir, 2016). In this study, an ensemble of high-resolution regional climate model simulations was used to assess changes in temperature under climate change in Southwest Asia (or the Middle East), and climate projections reveal that temperature is likely to increase rapidly in the next 30 years.

6. REMARKS

Justified through statistically significant trends in extremes of rainfall and temperature, most of the countries in South Asia has undergone changes concerning various statistical indices. It should be noted, however, that other meteorological parameters, such as relative humidity, also strongly influence the environment. Indeed, relative humidity is essential to calculate heat stress in the form of a heat index. Although changing climatic events, directly and indirectly, impact human health and the environment worldwide, the prevailing warming trends are overly harmful to South Asian countries. Warming trends are observed not only in maximum temperatures but in minimum temperatures as well. Although intense rainfall is hazardous concerning secondary disasters, increases in total rainfall may benefit groundwater recharge phenomena. Considering their unique nature, flood-related damages are acute in comparison to the impacts of heatwaves. As developing nations, South Asian countries stand to benefit enormously from a more proper and efficient disaster risk management mechanisms to tackle the adverse effects of extreme weather events. Although the effects are low, another secondary weather impact faced by most of the countries in South Asia is lightning and thunderstorms. Damages and losses due to lightning events cannot be negligible relative to cases of heat stress.

The teleconnection phenomena that correlates the rainfall and temperature in South Asia also plays a vital role in acquainting departures in the normal climate. Significant warming temperature and anomalous rainfall trends are anticipated in the South Asian countries, is also equally important to predict and manage the future calamities.

Trend detection techniques have analyzed trends in rainfall and temperature using traditional statistical parametric linear regression techniques. Although parametric regression is a simple technique to understand mean trends, it ignores aspects of distribution such as upper and lower tails, which are more valuable than the mean trend in extreme climate studies. To overcome this problem, a statistical technique called quantile regression has been developed, which can provide a complete picture of long-term temporal trends (Tareghian and Rasmussen, 2012). It is a general rule that departs from true linear relationships, which are normally distributed, parametric techniques are more efficient, and if residuals depart from normality, then nonparametric equivalent is more robust (Moberg et al., 2006; Indrani and Abir, 2011; Jung and Chang, 2011; Obeysekera et al., 2011; Tareghian and Rasmussen, 2012; CDMP, 2013). It should be noted that only partial regional studies are available with log area ratio (LAR) tests for South Asia— (Indrani and Abir, 2011) for example—and therefore, it is necessary for country/continent-scale studies to take a big-picture view of actual extreme weather events in South Asia.

It is essential to mention that the lack of available information regarding temperature/rainfall or climate change for some South Asian countries, including the Maldives, Afghanistan, and Bhutan, needs attention. The scarcity of available metrics in existing literature to detect changes in rainfall and temperature averages is acknowledged in this review. In addition to the available metrics, more research employing non-conventional methods may be beneficial to understand and predict climate change, especially when the use of nonparametric techniques stands to reveal precise trends in considered weather parameters in the countries in this region in terms of both historical trends and future predictions.

Finally, Keskinen et al. (2010) and Nuorteva et al. (2010) suggested in their study that an area-based adaptation approach can be used to complement the dominant sector-based approaches. Amalgamating adaptation approaches for all the sectors (i.e., social, environmental, economic, political, hydro-geological, etc.) for a specific climatic vulnerable area would be advantageous.

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Figure 1: Global temperature anomalies from 1850-2010. *Adapted from* Brohan *et al*., (2006).

Table 1. Temperature trends in South Asian countries

South Asian country	**Normal max. temperature**[a]	**Temperature change**	**Source**
Afghanistan, Zaranj	51.0 °C	0.13 °C ↑ per decade	(Matthew, *et al*., 2009)

Bangladesh, Rajshahi	45.1 °C	0.5-1 °C ↑ per year	(Cruz, *et al*., 2007)
Bhutan, Phuentsholing	40.0 °C	0.05 °C ↑ per decade	(Robert, 2016)
India, Pachpadra	50.6 °C	0.68 °C ↑ per century	(Cruz, *et al*., 2007)
Maldives, Male	36.8 °C	N/A	-
Nepal, Manang	46.4 °C	0.12 °C ↑ per year	(DHM, 2017)
Pakistan, Jacobabad	53.0 °C	0.36 °C ↑ per decade	(Rıo, *et al*., 2013)
Sri Lanka, Anuradhapura	39.9 °C	0.01-0.036 °C ↑ per year	(Chandrapala & Fernando, 1995)

N/A: Not available

[a]*Source*: Normal maximum temperatures were extracted from www.meteorologyclimate.com, 2007 for key temperature cities of the countries.

Table 2. Extreme temperatures in South Asian countries

Country	**Temperature measures**	**Reference**
India	Increases in annual warmest day temperatures during 1971-2000, increasing trends in annual coldest night temperatures during 1971-2000, increases in annual summer days (where daily maximum temperatures exceed 25^0C) during 1971-2000	Sheikh, *et al*., 2015
Nepal	Increases in annual warmest day temperatures during 1971-2000, increasing trends in annual coldest night temperatures during 1971-2000, increases in annual summer days (where daily maximum temperatures exceed 25^0C) during 1971-2000	(Sheikh, *et al*., 2015)
Sri Lanka	Increases in annual warmest day temperatures during 1971-2000,	(Sheikh, *et al*., 2015)

	increasing trends in annual coldest night temperatures during 1971-2000, increases in annual summer days (where daily maximum temperatures exceed 25^{0}C) during 1971-2000	
Pakistan	Increasing trends in annual coldest night temperatures and increases in annual warmest night temperatures during 1971-2000, decreases in annual summer days (where daily maximum temperatures exceed 25^{0}C) during 1971-2000	(Sheikh, *et al*., 2015)
	Rise in mean temperatures of 0.6-1^{0}C in arid coastal areas, arid mountains, and hyper-arid plains	(Farooqi, *et al*., 2005)
Bangladesh	Decline in number of cool days and cool nights	(Badsha, *et al*., 2016)
Central and South Asia region	Statistical (5%) decreases in cold nights and increases in warm nights, reflecting general warming in the region during 1961-2000.	(Klein Tank, *et al*., 2006)
	Frequencies of cold nights and cool days decreased during 1971-2000, and the rate of decrease was significant during 1986-2000 in comparison to 1961-1985. Warm nights and warm days increased during 1971-2000. Cold spell duration index decreased and warm spell duration index increased during 1971-2000.	(Sheikh, *et al*., 2015), (Alexander, *et al*., 2006)

Table 3. Extreme rainfall in South Asian countries

Country	**Rainfall measures**	**Reference**
Central and South Asia region	Increase in very wet days (above the 95^{th} percentile) during 1961-2000	Klein Tank *et al*., 2006
Nepal	Increase in number of rainy days	(DHM, 2017)
	Decrease in number of wet days and prolonged dry spells	(Karki, *et al*., 2017)
	Decrease in number of consecutive dry days (rainfall < 1mm/day)	(APN, 2004) (Sheikh, *et al*., 2015)
Bangladesh	Increase in number of consecutive dry days	(Badsha, *et al*., 2016)

	Increase in number of days of heavy precipitation and decrease in consecutive dry days	(Shahid, 2011)
	Decrease in number of consecutive dry days (rainfall < 1mm/day)	(Sheikh, *et al.*, 2015)
Pakistan	Increase in the number of heavy rainfall days Occurrence of high intensity rainfall with declining number of rainy days	(Sheikh, *et al.*, 2015) (Samo, *et al.*, 2017)
	Decrease in number of consecutive dry days (rainfall < 1mm/day)	(Sheikh, *et al.*, 2015)
	Increase in number of consecutive wet days (rainfall > 1mm/day)	(Sheikh, *et al.*, 2015)
India	10-15% decrease in both winter and summer rainfall in coastal belt and hyper-arid plains, 18-32% increase in monsoon rainfall Increase in the frequency of extreme rainfall events during 1910 to 2000 (i.e., total rainfall, largest 1-day event, largest 5-day total, largest 30-day total, extreme frequencies at 90th, 95th, and 97.5th percentiles)	(Farooqi, *et al.*, 2005) (Roy and Balling, 2004)
	Decreasing monsoon rainfall	(Indrani & Abir, 2011b)
	Decrease in number of rainy days	(Cruz, *et al.*, 2007)
	Decrease in number of consecutive dry days (rainfall < 1mm/day)	(Sheikh, *et al.*, 2015)
	Increase in number of consecutive wet days (rainfall > 1mm/day)	(Sheikh, *et al.*, 2015)
Sri Lanka	Increase in number of heavy rainfall days in northwestern and east coast India, but decrease in number of heavy rainfall days in southern India Increase in number of consecutive dry days (rainfall < 1mm/day) Decrease in number of heavy rainfall days	(Sheikh, *et al.*, 2015)

Table 4. Direct and indirect impacts of extreme weather events in South Asia

Event	Country	Impact	References
Flooding	Afghanistan	Flash floods	(Shokory, *et al.*, 2017)
	Bangladesh	Coastal flooding	(Rahman & Rahman, 2015)
	India	Mosquito proliferation	(Pawar, *et al.*, 2008)

		Exposure to rodent-borne pathogens	(Kawaguchi, *et al*., 2008; Zhou, *et al*., 2011)
		Loss of livelihood	(Nguyen, 2007; Keskinen, *et al*., 2010; Nuorteva, *et al*., 2010; Dun, 2011)
		Post-traumatic stress	(Udomratn, 2008)
	India/Pakistan	Pathogens/toxic compounds	(Sohan, *et al*., 2008; Warraich, *et al*., 2011)
	Pakistan	Superfloods	(Salma, *et al*., 2012)
Heatwaves	India	Mortality	(McMichael, *et al*., 2008)
	South Asia	Heat stress	(Sivakumar & Stefanski, 2011)
Drought	South Asia	Asthmatic conditions, skin and eye irritation	(Griffin, 2007; Hashizume, *et al*., 2010; Kan, *et al*., 2012:)
		Malnutrition	(Kumar, *et al*., 2005)
		Loss of livelihood	(Selvaraju, *et al*., 2006; Harshita, 2013)
Waterborne disease	India/Sri Lanka/Nepal	Diarrhea	(Hashizume, *et al*., 2007; Chou, *et al*., 2010; Dhimal, *et al*., 2017)
	South Asia/Nepal	Cholera	(Huq, *et al*., 2005; Dhimal, *et al*., 2017)
Vector-borne disease	India	Dengue	(Hsieh & Chen, 2009; Shang, *et al*., 2010; Hashizume, *et al*., 2012; Sirisena & Noordeen, 2014)
	Nepal/India	Japanese encephalitis	(Partridge, *et al*., 2007; Bhattachan, *et al*., 2009)
	India/Nepal	Malaria	(Devi & Jauhari, 2006; Dev & Dash, 2007; Dahal, 2008; Laneri, *et al*., 2010)

	Sri Lanka	Leptospirosis	(Ehelapola, et al., 2019)
Reduced crop performance	Pakistan/India	Yield loss	(Sivakumar & Stefanski, 2011)
		Grass yield decline	(Lu & Lu, 2003)

Highlights

- Climate extremes in South Asia are barely studied, using general statistical methods
- Evokes primary literature on climate trends, extremes, teleconnection, and projections
- An immense need of statistical estimation to identify trends in extremes required
- Eminent demand for data collection and analysis of climate extremes for hinterlands
- Obligatory scope for future studies on teleconnection and projection of extremes

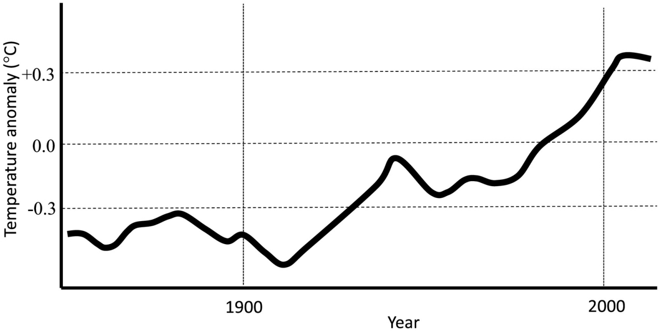

Figure 1