Historical climate analysis of the Third Pole Region between 1979-2018

September 2019

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FutureWater Internship Report

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Summary

The high mountain regions of Asia including the Hindu Kush Himalayas (HKH) and the Tibetan Plateau (TP) are referred to as the "Third Pole". It regulates the climate of the region and is the major source of water for over 1.4 billion people across several countries. In this study, we analysed temperature and precipitation data obtained from ECMWF ERA-5 reanalysis dataset for this region between 1979-2018. Along with this, extreme indices for temperature and precipitations as proxies for droughts/floods were analysed. Theil-Sen's slope estimate along with Mann-Kendall's significance ($p<=0.05$) were used to estimate the trend for every index on annual and seasonal scales. We found statistically significant indications of increased temperatures in all basins except in the highly irrigated regions of Indus and Ganges. This is in line with earlier findings that report the role of climate regulation by irrigated areas. In the TP, a statistically significant increasing trend for precipitation and temperature a wetter and warmer TP. In contrast, the Helmand, Amu and Syr Darya basins have become warmer with a small decrease in precipitation. Similarly, we found a decreasing trend for precipitation in the generally wet eastern Brahmaputra and Northern Irrawaddy. This can have implications for the development proposed under the Silk road project given the projected climate change. The careful consideration of these changes will help ensure the development of sustainable and climate proof infrastructure and trade in this region.

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1 Introduction

1.1 Background

Outside the polar regions, the high-altitude regions of the Asian continent, including the Hindu Kush-Himalayan (HKH) ranges, form the largest reservoir of freshwater in the form of snow and glacial ice. This has led them to be referred to as the “Third Pole” or as the “Asian Water Towers” (Immerzeel, Van Beek and Bierkens, 2010). Over 1.4 billion people depend on this source of water across various countries including China, Pakistan, Nepal, India, Bangladesh alone. Furthermore, the HKH along with the Tibetan Plateau (TP) forms an important barrier for the southwestern monsoon winds that bring rain over large parts of the Indian sub-continent during the months of July-September. It is also home to large variety of flora and fauna that are unique to such an alpine ecosystem further highlighting the importance of the region.

In the light of climate change, this region has started seeing impacts in the form of increased extreme warm events and decreased extreme cold events, increase in precipitation in some regions such as the TP and the Karakoram range but decrease in other regions of the HKH (Krishnan *et al.*, 2019). An average region-wide +2°C rise in temperature, under the Representative Concentration Pathway (RCP) 4.5 scenario, by 2036 has been estimated (Immerzeel, Pellicciotti and Bierkens, 2013). Further, the region is prone to elevation dependent warming implying higher changes in temperatures at the higher altitudes for the same amount of forcing (Pepin *et al.*, 2015; You *et al.*, 2017; Krishnan *et al.*, 2019). This can impact the glacial sources that can in turn, have implications for the large, dependent population. Under the RCP8.5 scenario, which is closer to the business as usual/current development trends, this warming will be enhanced and precipitation will likely change. Hence, there is a need to recognize and analyse the possible impacts of enhanced warming in the Third Pole.

The Chinese Government has launched the Silk Road Economic Belt (SREB) initiative under the larger Belt and Road Initiative in the Third Pole region. The SREB is an attempt to foster trade, infrastructural development and cultural exchange primarily between the central Asian countries, Pakistan and China. As a part of this, they have founded the Pan-Third Pole Environment (Pan-TPE) program to assess the impact of climate change on the overall region and its water resources under the umbrella of the Chinese Academy of Sciences (Yao *et al.*, 2012). Consequently, they aim to propose new models of green growth along the SREB.

Under the Pan-TPE project, Utrecht University and FutureWater, are involved in quantifying the impacts of climate change on the Asian Water Towers and the Green Silk Road on the region. They will conduct this research under the following four topics -

- Observed and projected Pan-TPE climate change
- Impacts on the present and future Water Tower of Asia
- The Green Silk Road and changes in water demand
- Adaptation for green development

This study is a contribution to the first topic and looks into historical climate data for the region. We analyse temperature and precipitation data for trends between 1979-2018 on annual and seasonal scales, using a state-of-the-art reanalysis product ((C3S), 2017). Further, we use four climate indices developed by the Expert Team on Climate Change Detection and Indices

(ETCCDI)[1] assess changes in extreme climatic events (extreme precipitation, drought, heat). We also interpret the changes in these indices as proxies for the occurrence of droughts and floods.

1.2 Objectives

The main objectives of this study are:

1) To calculate and analyse long term trends in temperature and precipitation
2) To estimate the trends in climatic extremes using climate indices
3) To estimate trends in droughts and floods using the indices as proxies

1.3 Structure of the Report

The report has the following chapters. In Chapter 2, we discuss the methodology used in this study along with a general description of the study region. Chapter 3 deals with the results of our analysis and a discussion of general trends seen in specific region and implications for droughts and floods. Lastly, we end with conclusion in Chapter 4.

[1] http://etccdi.pacificclimate.org/list_27_indices.shtml

2 Methodology

2.1 Study Area

The Third Pole Region, consisting of the Tibetan Plateau and its surrounding high mountain ranges along with the 18 downstream river basins were considered for this study (see Figure 1). Within this region, the Hindu Kush Himalaya range along with the TP alone covers an area of over 5 million km^2 with an average elevation of ~4000 m (Yao *et al.*, 2012). It stretches from Pamir and Hindu Kush in the west to the Hengduan Mountains in the east. The areal extent considered in this study is 57° E-113° E and 22° N- 47° N. Given the large extent of study area, the overall climate is variable. For example, on the east, Helmand, Amu Darya and Syr Darya have a dry continental climate characterized by cold winters and hot summers (Chen *et al.*, 2011), while in the west, Yangtze experiences sub-tropical climate with maximum rain during the months of April and October (Gu *et al.*, 2018). The TP experiences cold winters and dry summers, with maximum precipitation received during the months of July and August. Additionally, spatial variation is enhanced due to climatic differences within the higher and lower altitudes of each basin (You *et al.*, 2017; Krishnan *et al.*, 2019).

Temperature ranges are highly variable across the region. For example, the southern foothills of the Himalayas experience average temperatures of about 30° C in summers and 18 ºC in the winters while the middle valleys experience summer temperatures between 15-25 ºC and extreme winters (Krishnan *et al.*, 2019). In Central Asian basins of Amu Darya, Syr Darya, Lake Balkash, Junggar and Tarim the average temperature has been reported to be 6.65° C with large spatial variation (M. Luo *et al.*, 2019).

The major part of the precipitation in the south-eastern basins is received from the south-western Indian monsoon between the months of June, July, August and September. Winter monsoon brings rain to the north-western part of the HKH (Krishnan *et al.*, 2019). At the higher altitudes, this is mainly received in the form of frozen precipitation such as snow while at the lower altitudes it is received in the form of rain. The Central Asian basins receive an annual precipitation of ~211mm, ranging from less than <50 mm in the desert areas and greater than 2000 mm on the windward slopes (Deng and Chen, 2017).

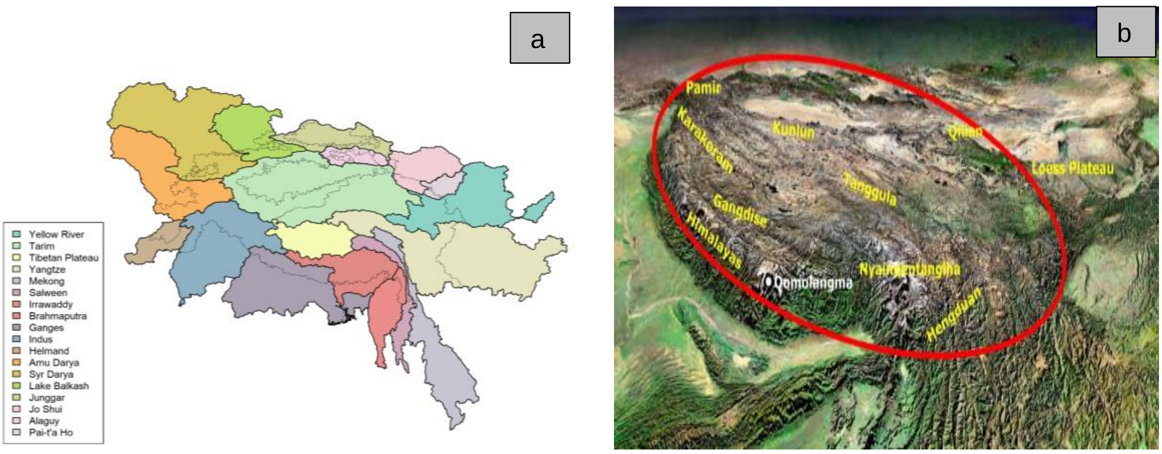

Figure 1 a) River Basins of the Third Pole. Dotted lines represent the upstream region of each basin b) Mountain ranges in the Third Pole Region

2.2 Data Source and Processing

The input data for the climate analysis was sourced from the European Centre for Medium-Range Weather Forecasts ERA-5 dataset between the years 1979-2018 for the selected region. The dataset is the latest product from ECMWF at 30km grid resolution[1]. The variables extracted were:

1) Daily sum of precipitation
2) Daily mean temperature
3) Daily minimum temperature
4) Daily maximum temperature

We used the programming software R and Climate Data Operators (CDO) (Schulzweida, 2019). In CDO, the climate indices developed by Expert Team on Climate Change Detection and Indices (ETCCDI) are inbuilt. The CDO processing of the net CDF was automated in R. The main extreme indices used are described in Table 1.

Table 1 Climate indices used for analysis as defined by Climate Data Operators Manual

Index	Definition	Unit	Proxy for
Consecutive Dry Days (CDD)	Largest number of consecutive days the daily precipitation is lesser than 1mm (default threshold)	days	Drought
Heat Wave Duration Index (HWDI)	Number of days, in intervals of at least 6 consecutive days, when the maximum temperature is greater than TXnorm*+ 5	days	Drought
RX5	Highest five-day precipitation amount	mm	Floods
R95P	Percentage of wet days (precipitation >1 mm) with daily precipitation greater than 95th percentile of all wet days of a given climate reference period (RRn95), here, 1981-2010	%	Floods
R95PTOT	Ratio of precipitation sum at wet days with daily precipitation greater > RRn95 to the total precipitation	-	Floods

*TXnorm is the mean of maximum temperatures of a five day window centred on each calendar day of a given climate reference period, here, 1981-2010.

The magnitude of the trend for each index was calculated using Thiel-Sen's slope estimate and the significance at 5% ($p < 0.05$) was determined using non-parametric Mann-Kendall's

[1] https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

significance. It is preferred over other parametric test mainly because data doesn't need to have a normal distribution or homogeneity and the effect of outliers is reduced as it is based on median values rather than means (Gilbert, 1987). This is a two-step procedure:

The slope is calculated for each data point –

$$Q = \frac{x_i' - x_i}{i' - i} \tag{1}$$

$$\text{Thiel-Sen's slope} = \text{median of Q} \tag{2}$$

Where Q = slope, x_i' and x_i are data values at times i' and i, respectively and where $i' > i$.

It is carried out using the raster.kendall package in R for this study.

Prior to the trend analysis, the data was checked for autocorrelation and corrected based on Yue and Wang (2002). Further, for an in-depth insight into the climate of the higherelevation of each basin, we calculated the upstream basin average for each climate index.

Each index was analysed on an annual scale and seasonal scale, namely –

1) Winter – December, January and February
2) Pre-monsoon/Summer – March, April and May
3) Monsoon – June, July, August and September
4) Post-Monsoon – October, November and December

3 Results and Discussions

3.1 Temperature indices

First, we will present the results of the temperature indices, that is, temperature, CDD and HWDI.

3.1.1 Temperature

The average of daily mean temperature over 40 years in the region, as expected, shows a distinct difference between the higher and colder mountain regions and warmer plains (Figure 2). The highest temperatures are seen in the downstream regions of the Ganges, Indus, Irrawaddy and Salween basin, that are known to experience warm summers with extreme heat events and cold winters (Im, Pal and Eltahir, 2017).

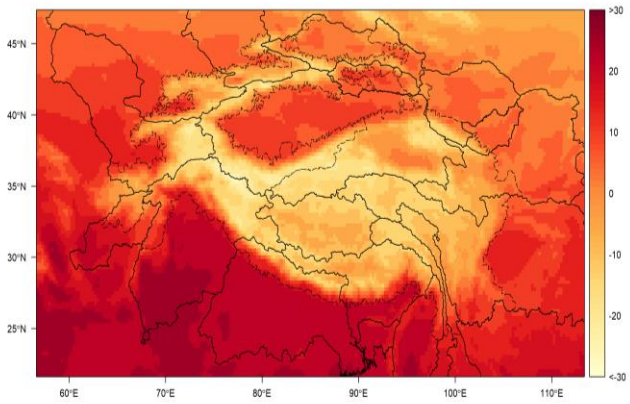

Figure 2 Average of Daily Mean Temperature between 1979-2018 (℃)

This is also observed in Figure 3, which shows the annual trend over 1979-2018 for the region. Nearly over the entire region, the trend is statistically significant. However, we observe less increase over irrigated areas of the Indus basin and the Ganges, although not statistically significant. This is in line with the findings that an increase in irrigated areas can lower the magnitude of change in climate (Zhang, Wang and Teng, 2017).

The basin averaged trend shows an increase in temperature in all the basins with the highest trend observed in Pai-t'a Ho and Jo Shui. The smallest increase in trend is observed in Lake Balkash, Junngar, Alaguy and Irrawaddy. The observed mean temperature trend is higher than previously reported trends of 0.195 ℃ per decade between 1951-2014, resulting in 1.17 degree increase (Ren *et al.*, 2017; Krishnan *et al.*, 2019). However, they use observed station data and calculate the linear trend which can account for some of the differences between the results. ERA5 can have a bias compared to station observations. On the other hand, station data is often not complete and the least square regression analysis is used to calculate the linear trend.

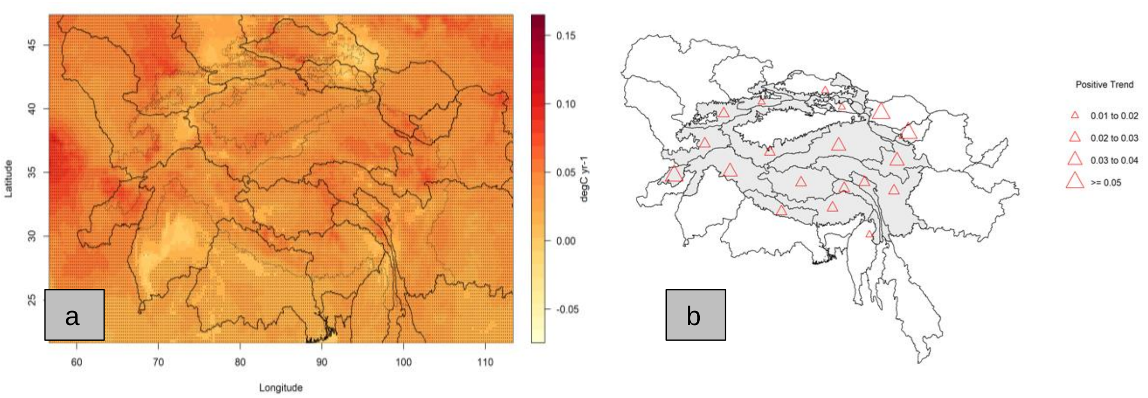

Figure 3 a) Annual trend for daily mean temperature estimated using Sen's Slope (˚C / year), Black dots represent areas with Kendall's significance at p<0.05., b) Annual upper basin averaged daily mean temperature trend (˚C/year)

The seasonal trend shows that the increase is most apparent in the headwaters of the Ganges, Brahmaputra and TP in the winter (DJF), i.e., ~0.08-0.1℃ per year (Figure 4a). This results in a 3.2-4.0℃ increase over the 40-year time period. The warming trend is stronger in the eastern TP for which a winter warming trend of 0.61℃ per decade, resulting in ~2.44℃ increase over 1961-2006, has previously been reported (Liu *et al.*, 2009). The warming trend in TP has been attributed to warmer conditions in the past decade and during the global warming hiatus period (Kosaka and Xie, 2013; You, Min and Kang, 2016; Krishnan *et al.*, 2019). During the summer months, higher values, ~0.10-0.15℃ per year, are seen in the Central Asia region such as Helmand, Amu Darya, Syr Darya and Tarim West (Figure 4b). A trend of 0.30℃ per decade between 1961-2005 has been previously reported by Peng *et al.*,(2019) and 0.37℃ per decade by Luo *et al.*,(2019). However, they also reported these trends based on observations and least squares linear regression method. These are predominantly dry regions and warmer temperatures could increase the occurrence of heat waves and droughts in these areas (Aich *et al.*, 2017).

The upstream basin averaged shows a consistent increase over all the basins (Figure 4c, d). In the winter, the largest change of ~0.05℃ per year is seen in Helmand, the TP, Brahmaputra, Mekong, Salween and Yangtze, which results in a 2℃ increase over the regions which is comparable to the 2.2℃ increase for the higher elevations reported by Krishnan *et al*., (2019). In summer, the basin average trend is large in the Central Asia and northern basins as also observed in Figure 4c.

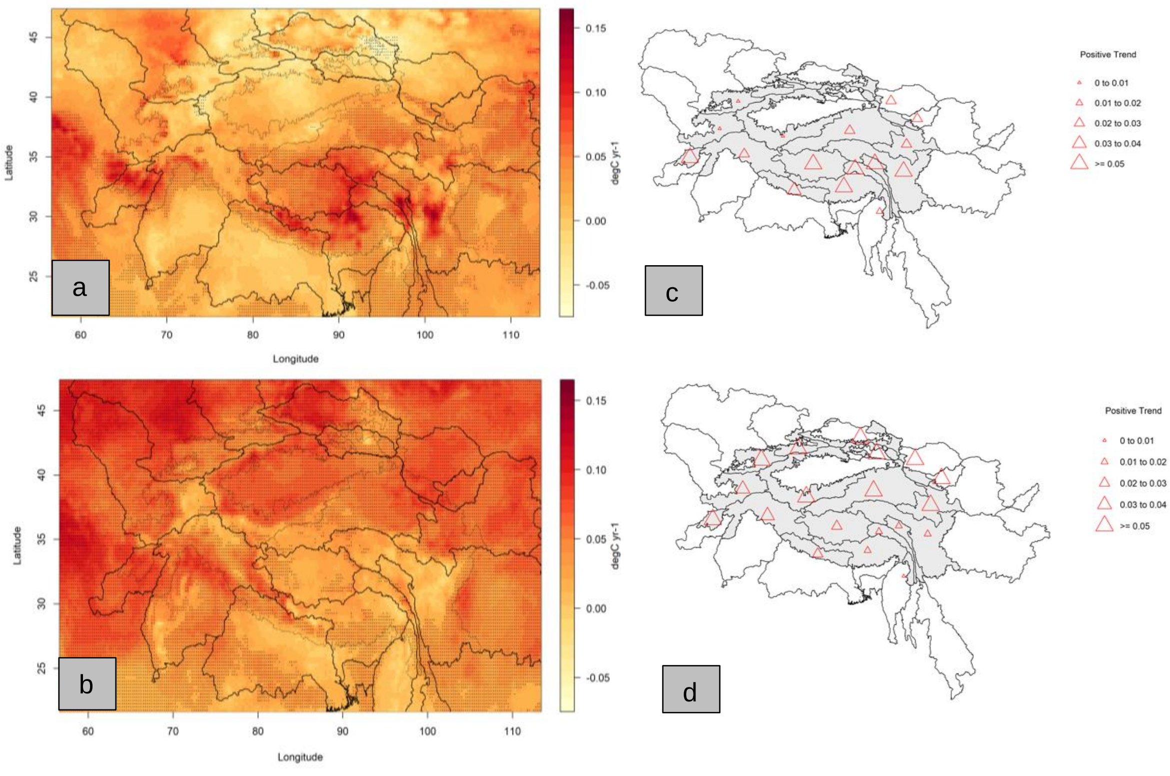

Figure 4 a) Winter trend of daily mean temperature estimated using Sen's Slope (℃/year), b) Summer trend of daily mean temperature estimated using Sen's Slope (℃/year), c) Winter upper basin averaged daily mean temperature trend (℃/year), d) Summer upper basin averaged daily mean temperature trend (℃ /year).Black dots represent areas with Kendall's significance at p<0.05.

3.1.2 Consecutive Dry Days (CDD)

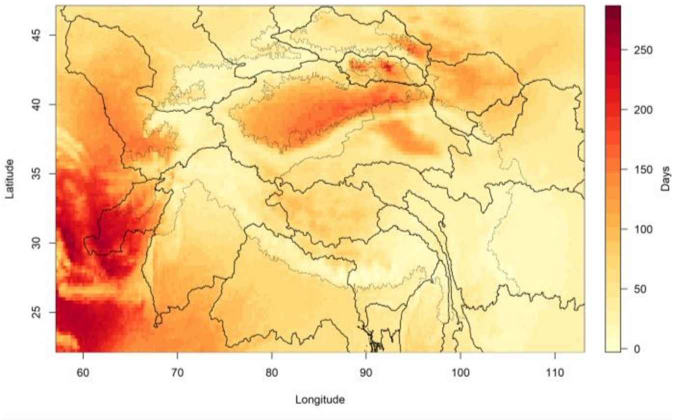

Figure 5 Average number of Annual CDD between 1979-2018 (days)

On an annual scale, the average number of CDD is highest in the Helmand basin, ~250 days, followed by Tarim which is 150~200 days. Similar values for Tarim have also been reported by (Shi *et al.*, 2018). There is a clear distinction in the observed values between the upper basin (marked by light grey border) and the lower basins. Further, low values, 0-10 days, are also seen over large parts of the Yangtze basins.

The annual trend over the examined period, shows an increase of ~1.5-2 days/year in the inner Tarim basin, which is already an arid region (see Figure 6a). Lower Amu Darya and Helmand also show a similar increase. Furthermore, we see an increase of 0.5-1.0 days/year in the Indus and Gangetic plains indicating a drying trend which could have had significant impact on the heavy agriculture-based livelihoods of these regions. Sigdel and Ma (2017) reported a trend of 4.2 days per decade for the southern slope of Central Himalayan region of Nepal which is comparable to our findings of 0.5-1.0 days/year. However, they reported a much smaller but significant trend for of 0.9 days per decade for the northern slope of Central Himalayas in Tibet. Furthermore, in contrast to our findings of statistically significant zero trend in the middle region of the Yangtse basin, a trend of -2 to 2 days per decade has been reported between 1951-2014 using observed data (Shi *et al.*, 2018) .

In Figure 6b, upper basin averaged annual CDD trend, shows an increasing trend for the regions discussed above along with Irrawaddy, Salween and Mekong. This indicates ~4 days increase over the 40-year period. However, a noteworthy observation is the decreasing trend in the TP which is in coherence with the increased precipitation trend in the TP (Krishnan *et al.*, 2019) and is also seen in our results in the following section that discusses the flood indicators.

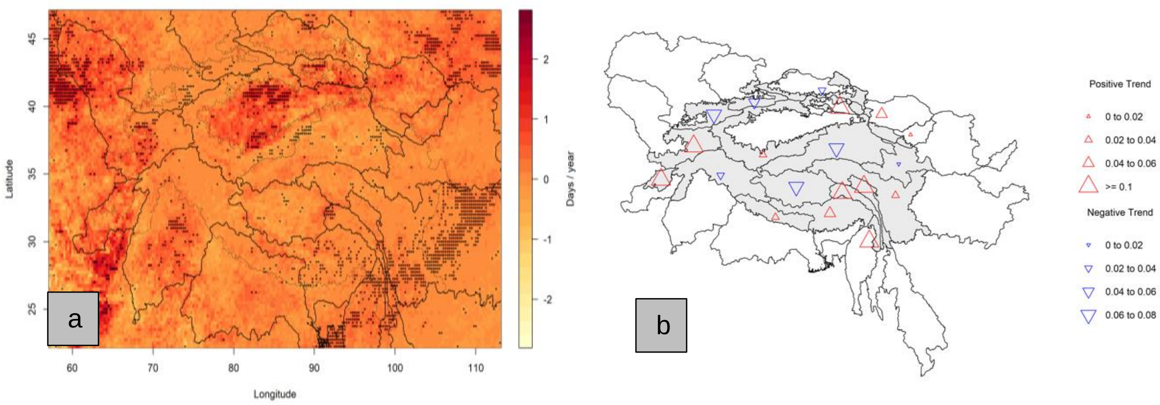

Figure 6 a) Annual trend for CDD estimated using Sen's Slope (days year^{-1}). Black dots represent areas with Kendall's significance at p<0.05. b) Annual upper basin averaged CDD trend (days year^{-1})

When seasonal trends are considered, most of the regions show very small increase in CDD except parts of Tarim and Helmand in the summer months (Figure 7a). A small decreasing trend is seen in parts of the Ganges and Pai-t’a Ho in this season. In the post monsoon season, there is close to very small/no increase in most basins, except the Alaguy where we see 0.5-0.8 days/year increase which is significant (Figure 7b). In the upper basin averaged CDD, an interesting pattern emerges for the summer and post monsoon months (Figure 7c, d). Out of the 12 basins that experience an increase in CDD in the summer months, 7 show a deceasing trend in the post monsoon season. The summer months are already dry can be indicative of increase in dry days. The increased precipitation in the post-monsoon season in TP is reflective of the annual trend seen in Figure 6b. This increasing trend is also visible in the upper basin average trend for the monsoon season (see Figure 21b in Appendix)

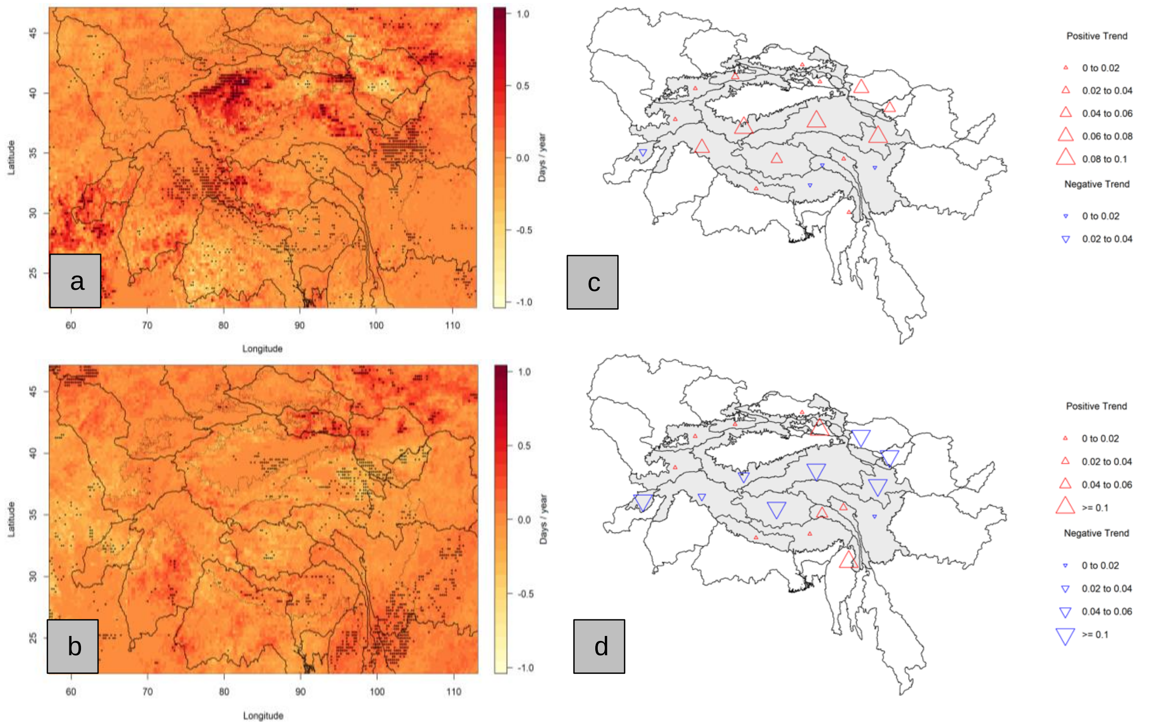

Figure 7 a) Summer trend of CDD estimated using Sen's Slope (days/year), b) Post monsoon trend of CDD estimated using Sen's Slope (days/year), c) Summer upper basin averaged CDD trend (days/year), d) Post monsoon upper basin averaged CDD trend (days/year). Black dots represent areas with Kendall's significance at p<0.05.

3.1.3 Heat Wave Duration Index (HWDI)

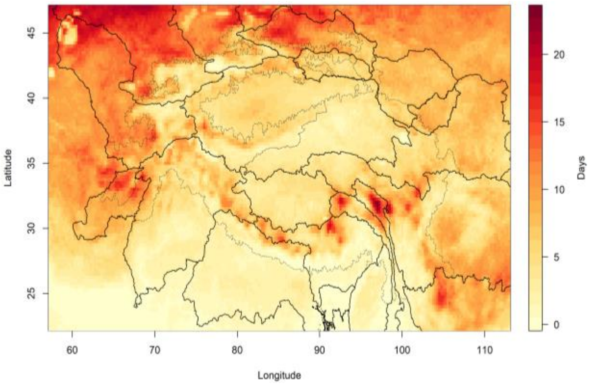

Figure 8 Average number of Annual HWDI between 1979-2018 (days)

As per the definition of HWDI, this is a significantly high threshold as it considers maximum temperature 5 degrees above the norm calculated for the reference period 1981-2010. The annual average HWDI is hence relatively low in the most parts of the study region (Figure 8) . However, the downstream regions in Amu and Syr Darya have 10-20 days when this threshold is crossed. Similar values are noticed at smaller regions in Helmand, Brahmaputra, Ganges, Salween and Mekong. To understand this further we analysed, the annual and seasonal HWDI values per region (see Figure 24a-d in Appendix). An emerging pattern that was clear among all regions except Mekong was that the maximum HWDI was obtained during the El-Nino year of 2016. An El-Nino event is a part of a large-scale circulation pattern observed in the Pacific Ocean called as the El-Nino Southern Oscillation (ENSO) which has been shown to reduce the strength of the southwest monsoon in the region (Pervez and Henebry, 2015). This was one of the strongest El-Nino’s of this century and the predicted increase in amplitude and frequency of such events in the future, can have serious implications for this region (Cai *et al.*, 2018). Trend analysis shows smaller values than CDD but all the highest values are significant. An annual warming trend is seen in Helmand, lower reaches of Amu Darya and Syr Darya as was also seen for CDD (Figure 9a). Smaller increase is noticed in parts of Tarim, Junggar and Yangtze basins. Interestingly, the smaller “hotspots” in Brahmaputra, Irrawaddy, Salween and Mekong don’t show a consistent trend, indicating that the high values are reached due to large scale climate events such as the El-Nino that are known to influence climate of the Indian Sub-continent (Krishnan *et al.*, 2019).

The upper basin averaged annual HWDI, shows very small values with the maximum increase seen in Helmand, 0.2 days/year and for most regions the values range between 0-0.04 days/year (Figure 9a) . The winter trend is very small and for the summer, monsoon and post monsoon seasons, there is no trend over the entire study region (see Figure 23b, c, d in the Appendix). This could be due to high threshold of 5 degrees above the Txnorm which has not yet been reached in most parts of the study region.

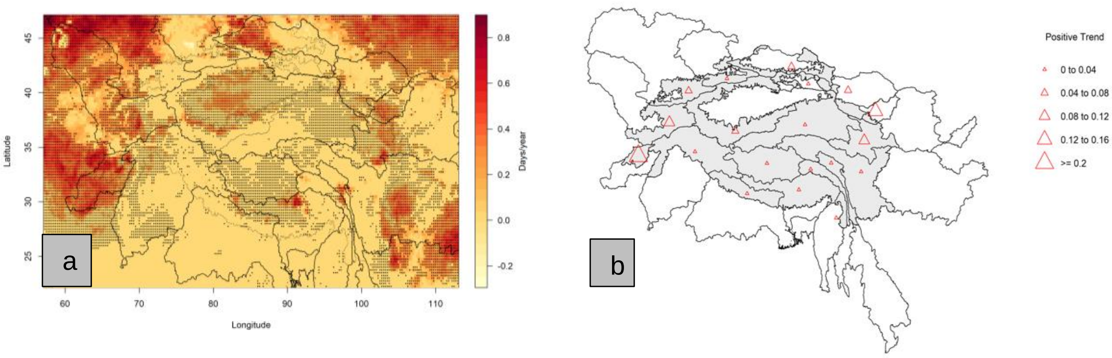

Figure 9 a) Annual trend of HWDI estimated using Sen's Slope (days/year) b) Annual upper basin averaged HWDI trend (days/year)

3.2 Precipitation Indices

In this section, we will present the results the precipitation indices – precipitation, RX5 and R95P.

3.2.1 Precipitation

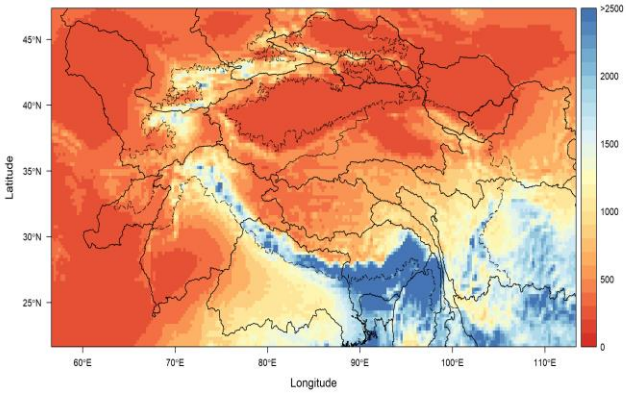

Figure 10 Average of Daily Precipitation 1979-2018

As mentioned in the earlier section, a large part of this region receives its rainfall due to Indian monsoon. This precipitation is mainly received in high quantities in the eastern Himalayas in the Brahmaputra and Irrawaddy basin as is also seen in Figure 10. Additionally, high precipitation amount is also seen in Yangtze and along the upper basin, mountainous region of the Ganges and Indus. The arid regions of Helmand, Amu Darya, Syr Darya, Tarim and adjacent northern basins are evident in the figure. They receive less than <300 mm of rainfall (Deng and Chen, 2017). Further, the eastern TP receives more rainfall than the west.

Between 1979-2018, the annual trend shows an overall near zero/increased precipitation trend in the study region (Figure 10a). The western TP, has seen an increase 5-10 mm/year that are comparable to the findings of (Ren *et al.*, 2017). The highest trend is seen in a small area in the upstream region of the Ganges basin. However, significant decreasing trends are seen in regions that predominantly receive the highest precipitation such as East Brahmaputra and upper Irrawaddy basin. Smaller decreasing trends, -10 to -20 mm/year are seen in the downstream Yangtze basin.

The observed increasing trend in TP and Ganges basin is also reflected in the upstream basin averaged precipitation (Figure 10b). An increase of 3-4 mm/year is seen in both regions. Similarly, the highest decreasing trend is seen in the Irrawaddy basin, >5 mm/year while most other upstream basins have a smaller decreasing trend.

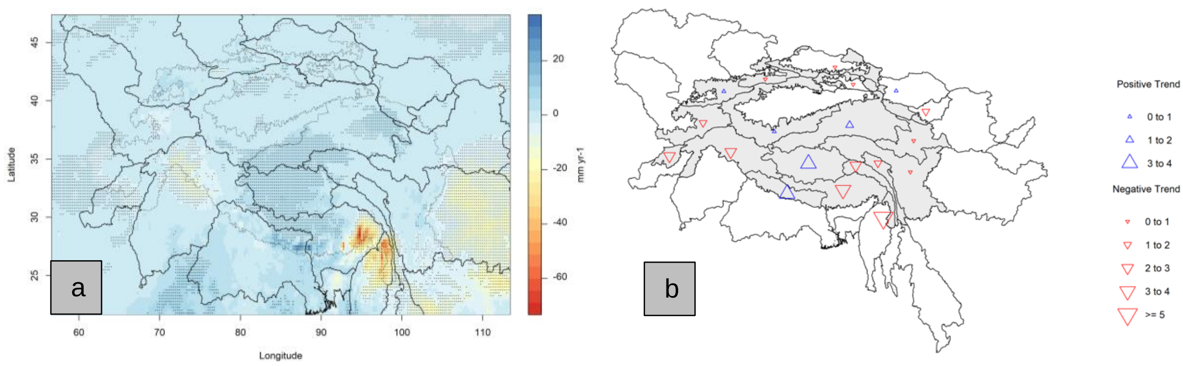

Figure 11 a) Annual trend for daily precipitation estimated using Sen's Slope (mm/year). Black dots represent areas with Kendall's significance at p<=0.05., b) Annual upstream basin averaged daily precipitation trend (mm/year).

In the seasonal trends, the monsoon trend patterns are nearly the same as the annual, indicating the major influence this season on precipitation in this region. Additionally, a decreasing trend of ~-5 mm/year and small areas in Amu Darya and Alaguy. The increasing trend observed in Ganges is also reflected in the upstream basin average of 4-5 mm/year. The trend seen in TP is smaller in comparison. The highest decreasing trend is still seen in Irrawaddy.

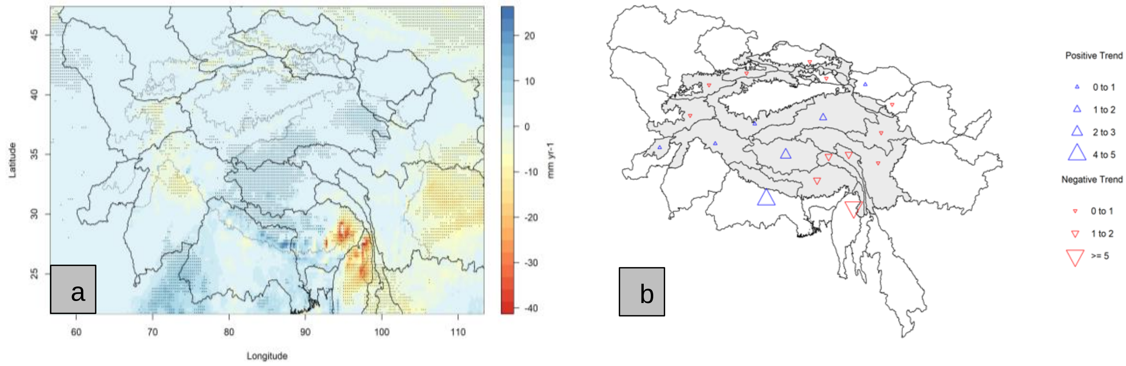

Figure 12 a) Monsoon trend for daily precipitation estimated using Sen's Slope (mm/year) Black dots represent areas with Kendall's significance at p<=0.05., b) Monsoon upstream basin averaged daily precipitation trend (mm/year).

3.2.2 RX5

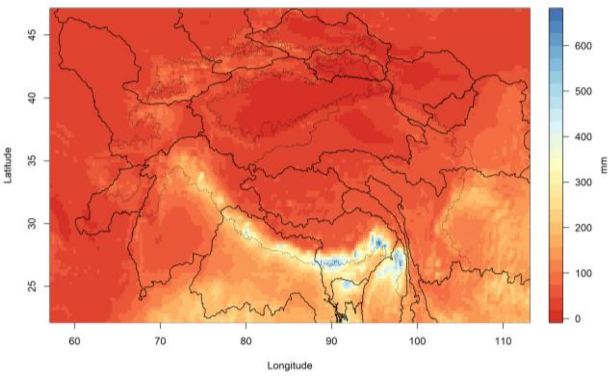

Figure 13 Average of RX5 1979-2018

For this indicator, we again see the highest values in the upstream region of Ganges, Brahmaputra and Irrawaddy (Figure 13). The lower Gangetic, Brahmaputra Yangtze basin receive lower amount of maximum rainfall but it is still higher than other downstream regions. The dry conditions observed in previous indicators in Tarim, Amu Darya, Syr Darya and adjacent northern basins are apparent here with zero mm RX5 at the annual scale.

When the annual trends are considered, it is interesting to note that the regions where we see the highest amount of RX5 show the highest decreasing trend, which is statistically significant. Similarly, the decreasing trend in Yangtze basin is ~-2 mm/year which is also significant. There are small patches of increasing and decreasing trends in the lower Gangetic plains indicating no clear temporal trend for the basin.

In the upper basin averaged RX5, the decreasing trend of greater than >-1.5 mm/year is observed in Irrawaddy. The other increasing trends are too small to draw any concrete conclusions.

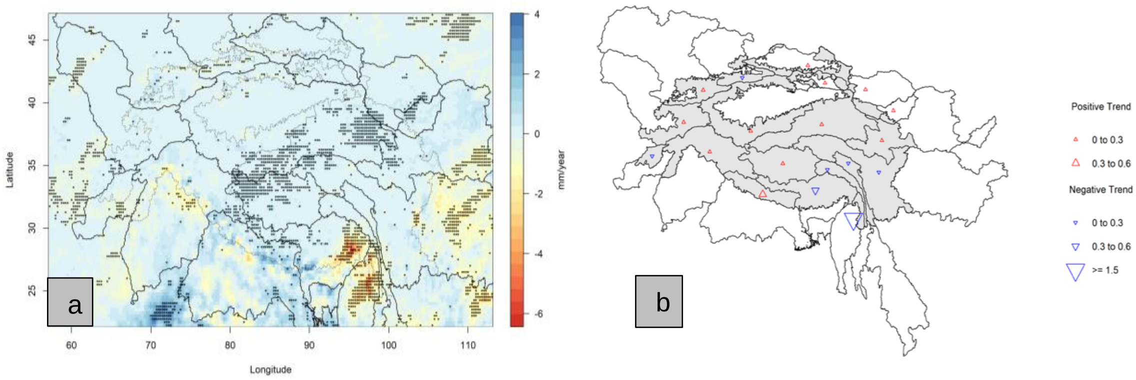

Figure 14 a) Annual trend for RX5 estimated using Sen's Slope (mm/year). Black dots represent areas with Kendall's significance at p<=0.05., b) Annual upstream basin averaged RX5 trend (mm/year)

The monsoon trend, like the other indicators, is very similar to the annual trend. Most basins have no trend. However, we see in Figure 14a more clearly the impact on the Ganges, Brahmaputra and Irrawaddy basin. The erratic increasing and decreasing trend in the Ganges is not statistically significant while the decreasing trend in Irrawaddy and Brahmaputra is significant. Here, we also observe a small increasing trend of about 1 mm/year in small patches of the Yellow River basin and decreasing trends in the downstream Yellow River basin.

The monsoon upstream basin averaged trend is zero/small in all basins except the significant the 1.5 mm/year trend in Irrawaddy, as also seen in the monsoon trend for daily sum precipitation in Figure 12b.

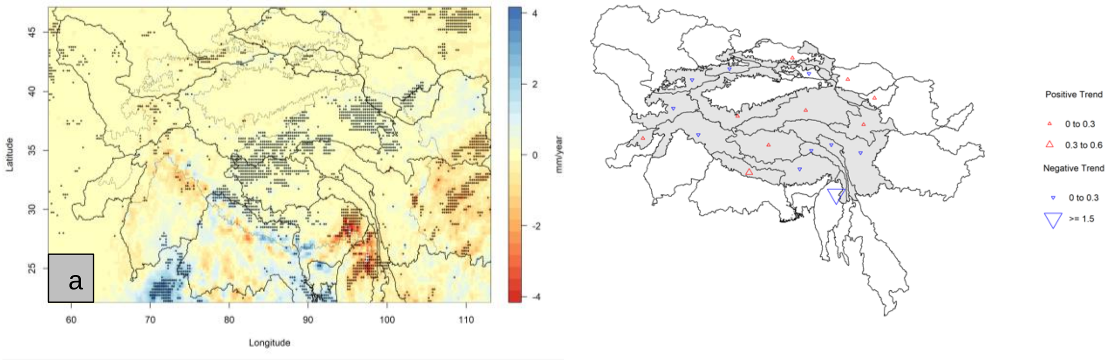

Figure 15 a) Monsoon trend for RX5 estimated using Sen's Slope (mm/year) Black dots represent areas with Kendall's significance at p<=0.05., b) Monsoon upstream basin averaged RX5 trend (mm/year).

3.2.3 R95P

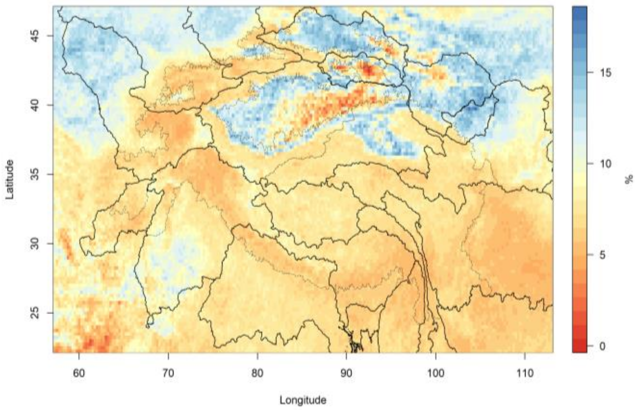

Figure 16 Average of Annual R95P 1979-2018 (%)

For this indicator, the annual trend is striking for Amu Darya, Syr Darya,Tarim, Junggar, Alaguy and adjacent basins, which are primarily arid basins. There is a ~12-15% R95P indicating higher precipitation changes in these regions (Figure 16). This is in contrast to the above findings and to the general pattern seen in this region (Chen *et al.*, 2011). This anomaly could be attributed to the use of reference period within the R95P calculation, thereby resulting in an overestimation.

The annual trend for R95P is close to zero for most parts of the basin (Figure 17a). Again, here in eastern Brahmaputra, Irrawaddy and in some areas of Yangtze we see a declining trend of -0.05-0.1%/year. Indications of a small increasing trend of 0.2-0.4 %/year are seen in the downstream regions of Amu Darya and Indus. In upstream basin averaged trend, we see a small but mainly increasing trend over all the basins except Irrawaddy.

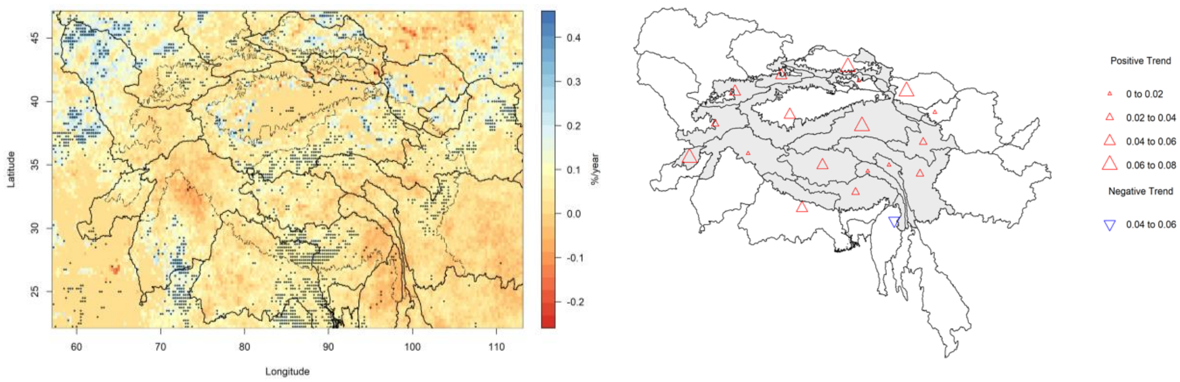

Figure 17 a) Annual trend for R95P estimated using Sen's Slope (mm/year). Black dots represent areas with Kendall's significance at p<=0.05., b) Annual upstream basin averaged R95P trend (mm/year).

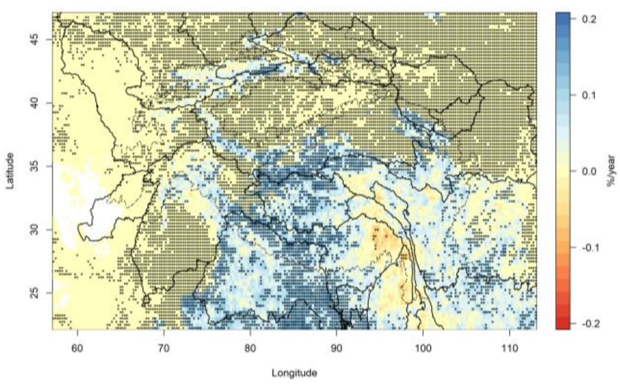

Figure 18 Monsoon trend for R95P estimated using Sen's Slope (mm/year). Black dots represent areas with Kendall's significance at p<=0.05.

In the monsoon season, we see a small increasing trend all over the Ganges, western Brahmaputra, TP and parts of the Yangtze. However, the trend is not statistically significant uniformly. Another important observation is the statistically significant zero trend in the Northern basins excluding Amu Darya and downstream region of Yellow River indicating no significant change in extreme precipitation events.

3.3 Discussion of regional patterns

In light of the results, some clear trends emerge in the region which are in line with findings of previous studies in patterns but not necessarily in magnitude. Here, we combine the results and discuss the major patterns that emerge for three of the regions-

1) **Tibetan plateau**- For this region, we find a warming trend that is predominant in winters. This increase in temperatures has been mainly attributed to elevation dependent warming which has been reported in mountainous regions all over the world (Pepin *et al.*, 2015). Yan and Liu (2014) looked at warming trends over the TP and found a systematic increase in warming with the elevation across different time series of surface temperature. Furthermore, they reported a difference in warming rates with between 1961-1990 and 1990-2012, with higher values for the latter. Over the entire time period they reported a trend of 0.316° C/decade which resulted in a 1.5° C increase which is comparable to our estimate of 1.2° C (Figure 3b). Further, they also reported the highest warming trend in winters. This is also reported in more recent studies (Ren *et al.*, 2017; Krishnan *et al.*, 2019), thereby increasing confidence in the enhanced warming over the TP. However, at altitudes above 5000 m, Gao *et al.*, (2018) did not find any elevation dependent warming trend for the past (1984–2011) and future. Therefore, there is need for further analysis at the higher altitudes. Apart from having impacts on local climate, the warming has also been linked to enhance the precipitation trends in China and Korea (Krishnan *et al.*, 2019).

   The second important finding for this region, is the increase in precipitation. Zhong *et al.*, (2019), reported a 0.78 mm/year between 1980-2014 resulting in ~27 mm increase over the period. This is higher than our estimate of 2-3 mm/year resulting in 80-120 mm increase over the 40-year period. However, they also reported a trend of 1.23 mm/year for 1999-2014 which resulted in 18.45 mm over the 15 years. Yang *et al.*, (2011) also reported a wetting trend in TP, however, concluded that the impact on the hydrological cycle of the region is spatially variable across the plateau. Similarly, C. Zhang *et al.*, (2019) reported a significant increasing trend in the Northern TP but a small decreasing trend in the southern TP.

   Therefore, the TP has become warmer and wetter in the past years and it is a trend that has been reported to continue in the future. For example, Krishnan *et al.*, (2019) reported a winter temperature increase of 2.4-2.5ºC (2036-65) and 3.1-3.3ºC (2085-2099) under the RCP 4.5 scenario. Precipitation is also reported to increase between 10-15% (2036-65) and ~30% (2085-2099) relative to 1976-2005. Therefore, it is essential to consider the impacts of such warming and wetting trends on the plateau and consequently on the region.

2) **Central Asia basins** – For these basins, we see a general warming and drying trend that is not consistent across all seasons and indicators. The annual temperature trend shows a warming trend, especially in the downstream regions of all the basins. Limited station data from this region has resulted in fewer studies when compared to other parts of the HKH. Krishnan *et al.*, (2019) reported a small cooling trend of less than 0.1ºC/decade in the Amu Darya region and 0. 2ºC/decade increase in the Helmand region, since 1901. A recent study using the University of East Anglia Climate Research Unit (CRU)'s reanalysis data showed an increase of temperature ~0.11ºC/decade in the Helmand region of Afghanistan (Qutbudin *et al.*, 2019). Further, they reported a decreasing trend of -4.0mm/decade for precipitation in the region. In our results, we see a temperature trend of ~0.05ºC/year and a small/zero decreasing trend for precipitation in this region.

On the other hand, for in the Hindu Kush region of Afghanistan, they reported a cooling and wetting trend. Aich *et al.,* (2017), similarly, reported 0.7-1.2ºC increase in annual mean temperatures between 1980-2010 and 1950-1980 along with 0-10% change in precipitation in the Helmand region. For Amu Darya, Syr Darya, Lake Balkash and Junggar, an increasing trend of 0.032ºC/year for mean temperature has been reported between 1975-2005 (M. Zhang *et al.*, 2019). These consistent warming trends are in line with our findings. For precipitation, they reported an increasing trend of 0.476 mm/year, which is in contrast with the decreasing trend as shown by our results. However, for RX5 they also reported 0.055 mm/year which is line with our findings of 0.3-0.6 mm/year increase in these regions. Furthermore, they reported a decreasing trend in CDD which is also observed in some of the Central Asian basins in our findings. They concluded that the Siberian High and the Tibetan Plateau Index are most likely atmospheric circulation patterns having most effect on the climate of the central Asia.

Given the above findings, it is clear that the Central Asian basins are warming for most parts, but a general increasing or decreasing precipitation trend is harder to establish. With climate change, under the RCP 4.5 scenario, mean annual temperatures have been projected to be 1.5-1.75 ºC higher in 2021-2050 than 1975-2005 and precipitation to be 0 - -5% lower in the Helmand region (Aich *et al.*, 2017). There is a need for more future climate scenarios studies in this region to understand climate change and its impacts (M. Zhang *et al.*, 2019).

3) **Irrawaddy and eastern Brahmaputra –** There is a clear decreasing precipitation trend in this region across all precipitation indices in this region. The impacted eastern Brahmaputra region falls mainly in the Himalayan belt. The decreasing trend observed in the monsoon months is also reported by Immerzeel (2008) with a magnitude of -4% /100 year. Furthermore, they find an inverse relation between precipitation and the temperature between the Tibetan plateau and flood plain region of the basin, indicating that increasing difference in temperatures could lead to reduced precipitation in the flood plains in monsoon season. Our results are in contrast with the literature review findings of Nepal and Shrestha (2015) where they reported a small increasing trend in the monsoon season and no clear overall trend in the basin.

   There are limited studies available on precipitation in the Irrawaddy basin. Roy and Kaur (2000), reported no trend in monsoon precipitation in the basin and did not find any 1:1 relation between El-Nino and monsoon precipitation as well. A recent study, reported a wetting anomaly after 1998 in the period between 1981-2015 (Sein, Chidthaisong and Oo, 2018). However, in the northern part they also reported a trend of -12.88 to -1.93 mm/decade (statistically not significant) which will result in 45.08 to 5.25 mm decrease over the 35-year period which is comparable to our findings. No significant trends for RX5 are reported for the period between 1975-2014 by Ghimire *et al.*, (2019).

   Precipitation in the upper Brahmaputra basin has been reported to change between -2 to 15% above the reference 1483 mm/year (1981-2010) under RCP4.5 scenario between 2071-2100 using downscaled Global Circulation Model data for the region (Wijngaard *et al.*, 2017). More recently in the eastern Brahmaputra basin, Lutz *et al.*, (2019), also reported a 0-5% decrease in monsoon precipitation when compared to reference period of 1981-2010 in a 1.5℃ warmer world. For RX5, on the other hand, they reported a 0-25% increase in the same region. Thereby, indicating a possible increase in extreme precipitation events in the region Further, they also reported a change of -20 to 20 CDD above the reference in the region. For the Irrawaddy region, Ghimire *et al.*, (2019), reported no significant trends in mean annual rainfall for upper part of the basin. In general, however, the ensemble mean of the used Global Climate Models (GCMs) for mean annual rainfall results in a projected increase by 16-20% during the 2040s and 21-28% in the 2080s when compared to baseline of 1975-2014. For RX5, they also reported an increase in the frequencies under both RCP 4.5 and 8.5 scenario and the 2040s and 2080s.

Like the Central Asian basins, more studies are required for Irrawaddy and Salween in order to evaluate the historical trends and also make appropriate projections for the future, in the light of climate change.

3.4 Implications for droughts and floods

We have seen different trends in different areas of the Third Pole for each extreme temperature and precipitation indicator. This can have different implications for floods/droughts in each region.

With respect to CDD, we see an increasing trend over the Helmand, Amu Darya, Brahmaputra and Ganges along with increasing temperature trend which could result in increased magnitude and frequency of droughts in these regions. However, it is also important to consider the role of large-scale circulation patterns such as the ENSO circulation along with the Indian Ocean Dipole (IOD). A positive (negative) phase IOD is characterized by anomalous warming (cooling) of the western Indian Ocean along with strengthened (weakened) easterly wind which results in increased (decreased) precipitation over the sub-continent in the summer monsoon season (Pervez and Henebry, 2015). These patterns either individually or together can influence the amount of precipitation received by basins such as Ganges and Brahmaputra and consequently, the occurrence of droughts or floods in the region. For example, a positive IOD occurring along with an El-Nino event can reduce the precipitation deficit caused due to the latter (Pervez and Henebry, 2015). Hence, while CDD can be used as an indicator, it should be considered along with other weather patterns, local conditions to draw appropriate conclusions for droughts/floods.

In contrast to the above regions, we see a decreasing trend in the number of CDD days in the Tibetan Plateau and eastern Tarim, on the annual scale, as seen in Figure 6b. This decrease is also reported by Liu *et al.*, (2019). They define CDD as the number of consecutive days with precipitation less than 0.01 mm in contrast to the standard 1 mm and still reported a decreasing trend. This could lower the chances of drought in the region, but a consideration of other extreme indices is needed to draw definitive conclusions.

As mentioned before, the HWDI index has a strong threshold which is the likely explanation for the lack of clear trends for this index. However, we still observe small but significant trends in region of Helmand, Amu Darya, Syr Darya, Tarim and Yangtze, on the annual scale. However, under the RCP4.5 and 8.5 scenarios, the TP and North-western Chinese basins of Tarim, Junggar etc are projected to show a marked increase of 5 days/decade and 8 days/decade, respectively, in the HWDI index during the 21st century (Li *et al.*, 2019). As a result of these values, they reported an increased possibility of heatwaves. However, this could also imply increased intensity and frequency of droughts and warrants further consideration. Further, they reported a larger increase in HWDI at higher altitudes which could imply enhanced melting of glaciers/snow peaks (Colucci, Giorgi and Torma, 2017) resulting in floods in the downstream regions, which should also be evaluated (Colucci, Giorgi and Torma, 2017).

For RX5, we see small increasing (almost zero) trend over the entire region except significant decreasing trends in eastern Brahmaputra and Upper Irrawaddy. As discussed in section 3.2.2, this is consistent with the findings of some recent studies, however, it needs to be explored further. These regions face large scale floods in the monsoon season nearly every year and this decreasing trend in RX5 could mean less severe floods. However, future climate change and local conditions such as river depth, socio-economic development could determine if this trend does eventually result in lower floods. Further, there is a possibility of more frequent floods of lower magnitude in a 1.5℃ and 2℃ warmer world which could reduce any potential benefits from reduced extreme precipitation (Uhe *et al.*, 2019).

For R95P, the trends are smaller than RX5. Except Irrawaddy, all the other basins show an increasing trend. These values do not indicate an increased possibility of floods in these regions. However, at higher resolutions, these trends may vary per basin and need to be considered before drawing any conclusions. Wu, Xu and Gao (2017) reported an increasing trend of over 40% in the north-central of the Third Pole region which includes Tarim west, Upper Yangtze basin under the RCP4.5 scenario between the years 2036-2065. Under the RCP 8.5 scenario, they reported ~60% increase over the same region and the northern TP. Thereby, indicating a future increase in precipitation extremes.

3.5 Limitations

This study is one of the first of its kind to evaluate the newly published ECMWF ERA-5 for this region. However, it has limitations such as:

1) Large scale assessment: We have conducted a large-scale assessment that is informative for overall trends in the Third Pole region. Further, it helps to identify hotspots/regions that have been most affected and needed to be investigated further. However, to evaluate trends in each individual basin, more accurate conclusions can be drawn from studies done at higher resolutions, for example - Gu *et al.*,(2018), Ghimire *et al.*, (2019), Dahal *et al.*, (2019) and so on.

2) Utilization of only gridded reanalysis data: The ERA-5 data is the state-of-the-art reanalysis product available today. However, large biases have been reported when compared to observed data stations. Further, ECMWF reanalysis products are known to have a cold bias (Gao *et al.*, 2017; H. Luo *et al.*, 2019). Nevertheless, given the limited precipitation measurement stations available at high altitudes, use of such reanalysis products are the most feasible choice of data (Beck *et al.*, 2019; Bhattacharya, Khare and Arora, 2019).

3) Use of same dataset for reference percentile calculation: Due to the availability of limited historical dataset from 1979-2018, we used a reference period of 1981-2010 for the percentile and Txnorm calculation from within the entire dataset. These thresholds are relevant to the calculation of indices R95P and HWDI, respectively. This could have influenced our findings as we compare the threshold values with themselves. One way to avoid this is to use bootstrapping techniques as recommended by the CDO developers[1] which was not done due to time limitations in this study. Further, the use of a longer dataset that allows for a clear comparison between the reference and analysed period is

[1] http://slides.com/wachsylon/cdoetccdi#/1/11

another possibility. A suitable example for this would be the ECMWF dataset ranging from 1950 to present, which is due to be released by the end of 2019[1]. Nevertheless, the current dataset can be used as a base period for future climate projections.

[1] https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

4 Conclusion

This study is a part of the Pan-TPE project commissioned by the Chinese government under the Silk Road Economic Belt Initiative. In this study, we analysed temperature and precipitation data obtained from ECMWF ERA-5 reanalysis dataset for the Third Pole region between 1979-2018. Along with this, we also used the extreme temperature and precipitation indices developed by ETCCDI as proxies for droughts and floods. For droughts, we considered CDD and HWDI while for floods we considered R95P and RX5. Theil-Sen's slope estimate along with Mann-Kendall's significance ($p<0.05$) were used to estimate the trend for every indicator over the time period on annual and seasonal scales.

We found statistically significant indications of increased temperatures in all basins except in the highly irrigated regions of Indus and Ganges. This is in line with earlier findings that reported the role of climate regulation by irrigated areas. In the TP, a statistically significant increasing trend for precipitation and temperature indicates towards a wetter and warmer TP. In contrast, the Helmand, Amu and Syr Darya basins have also become warmer with a small (zero) precipitation decrease. Similarly, a decreasing trend for precipitation, RX5 and R95P is seen, in the generally wet eastern Brahmaputra and Northern Irrawaddy.

An overall outlook of the results of this study show that, the occurrence of droughts can increase in the Central Asian basins of Helmand, Amu Darya and Syr Darya due to increasing temperatures (mainly in winter), CDD and HWDI in this region. As for floods, we find decreasing trend in precipitation, RX5 and R95 in the flood-prone eastern Brahmaputra and Northern Irrawaddy. This points towards a drying trend in the region which could have potential benefits but a deeper analysis incorporating more indicators and socio-economic factors is needed to draw concrete conclusions.

This study is one of the first of its kind to analyse the newly released ECMWF dataset for this region. Our results do show higher trends than those previously reported for temperature and precipitation in some parts of the Third Pole. Thereby, highlighting the need to carry out more in-depth analysis and validation using the observations to determine the accuracy of this new dataset. Furthermore, for indicators such as HWDI and R95P, we used values from the reference period (1981-2010) for percentile calculations, which falls within the study period. This could have influenced the results obtained for these parameters. Hence, future studies should involve use of longer datasets, such as the upcoming ECMWF dataset ranging from 1950-2019, to draw better conclusions about these parameters.

In conclusion, we find a warming trend over the entire region, while for precipitation the trend is more spatially variable. This can have implications for the development proposed under the Silk road project given the projected climate change. The careful consideration of these changes will help ensure development of sustainable and climate proof infrastructure and trade in this region. As a next step, hydrological trends are calculated using a hydrological model forced with ERA-5 for the entire region. These hydrological trends will be then combined with climatic trends to assess the effect of climate change in the region.

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6 Appendix 1: Figures

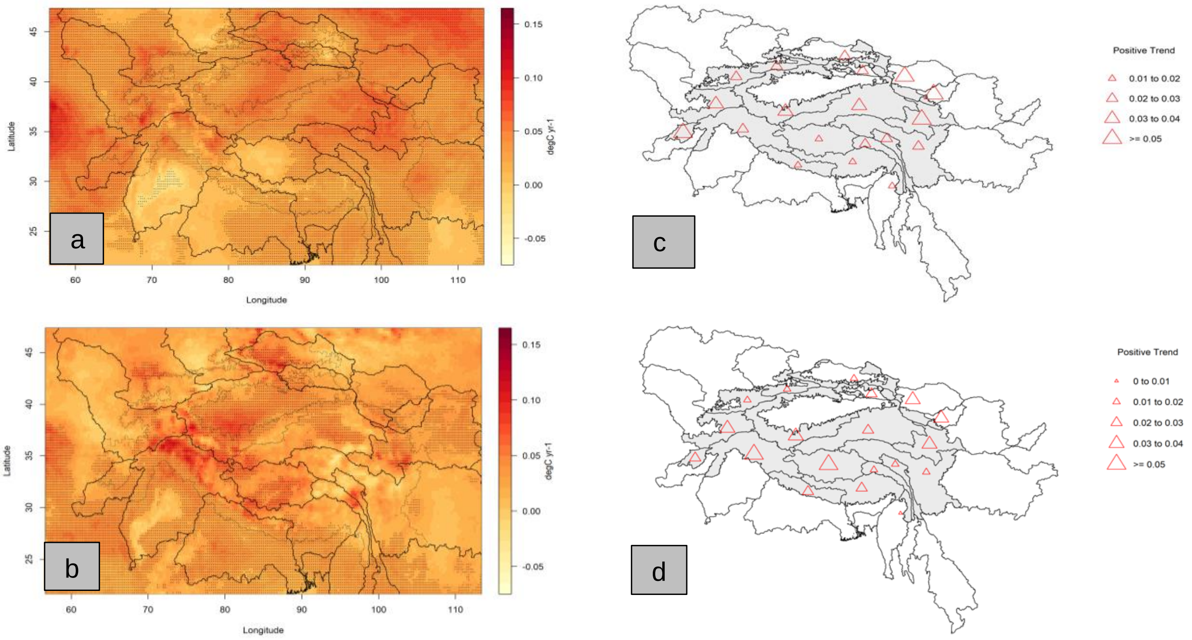

Figure 19 a) Monsoon trend of daily mean temperature estimated using Sen's Slope (℃/year), b) Monsoon trend of daily mean temperature estimated using Sen's Slope (℃/year), c) Post-monsoon upper basin averaged daily mean temperature trend (℃/year), d) Post-monsoon upper basin averaged daily mean temperature trend (℃/year).Black dots represent areas with Kendall's significance at p<0.05.

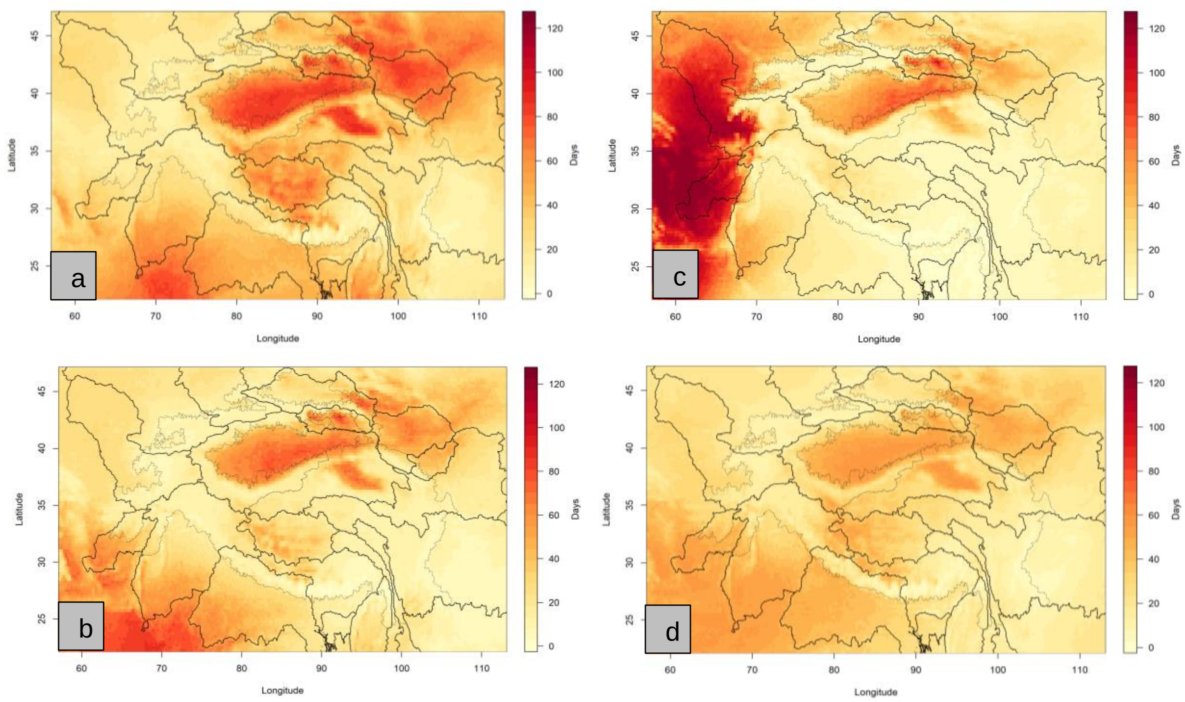

Figure 20 a) Average number of Winter CDD between 1979-2018 (days) b) Average number of Summer CDD between 1979-2018 (days) c) Average number of Monsoon CDD between 1979-2018 (days) d) Average number of Post - Monsoon CDD between 1979-2018 (days)

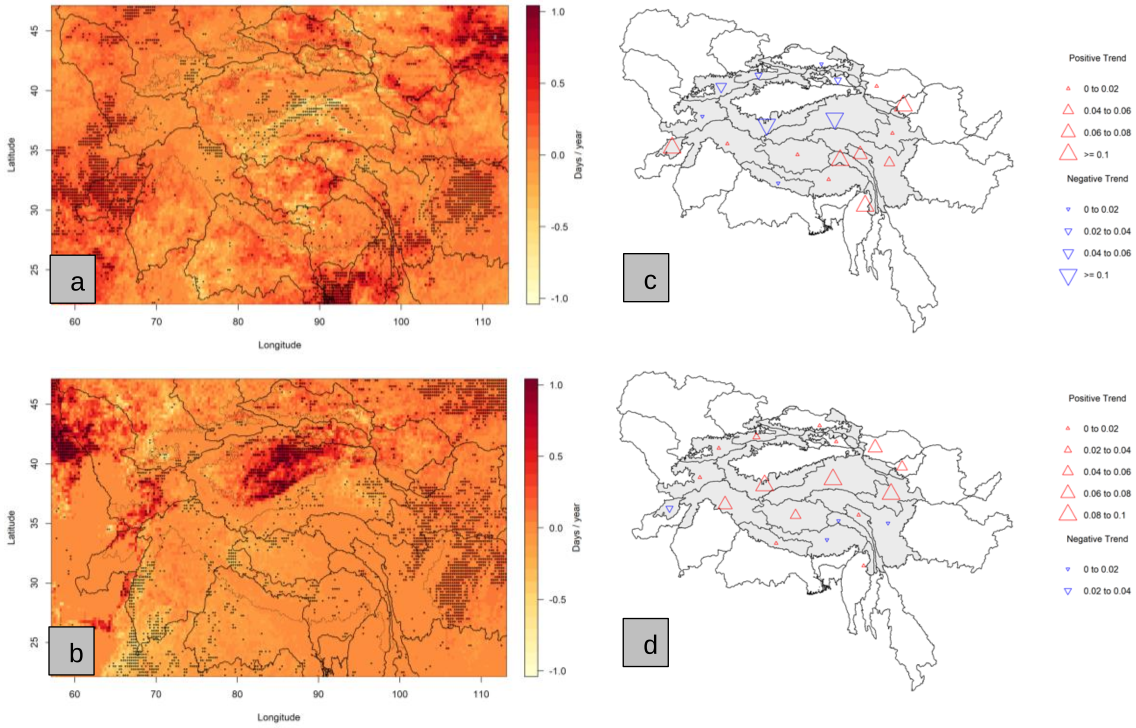

Figure 21 a) Winter trend of CDD estimated using Sen's Slope (days/year), b) Monsoon trend of CDD estimated using Sen's Slope (days/year), c) Winter upper basin averaged CDD trend (days/year), d) Monsoon upper basin averaged CDD trend (days/year). Black dots represent areas with Kendall's significance at p<0.05.

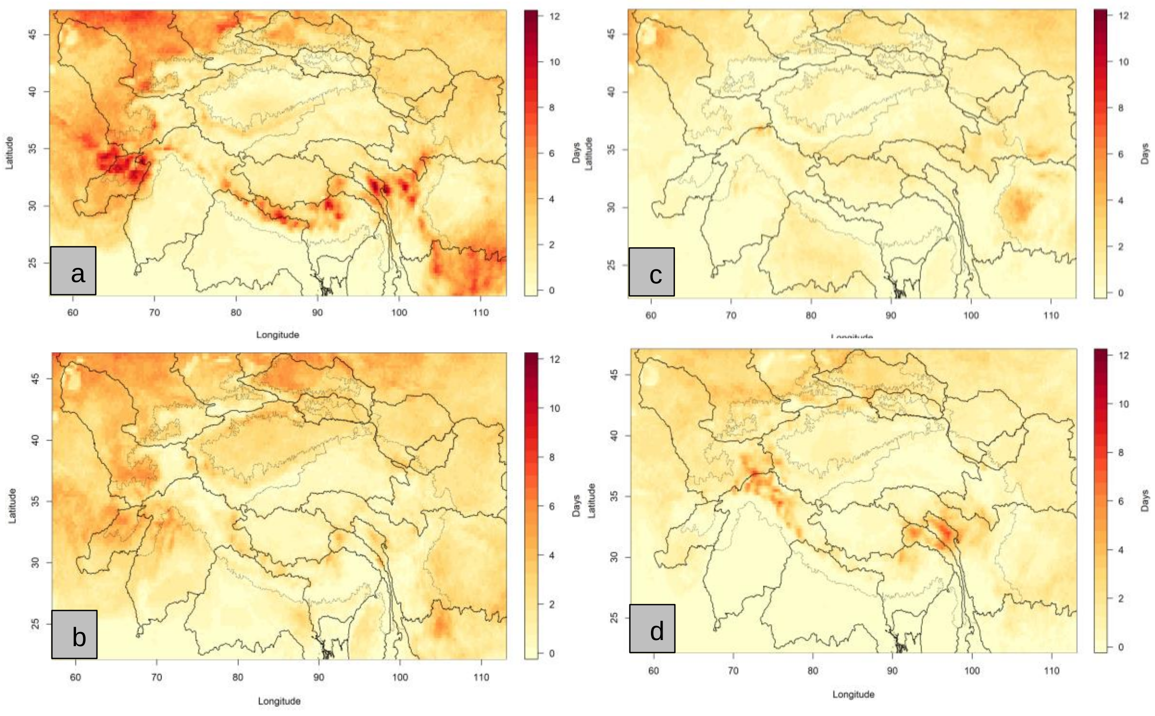

Figure 22 a) Average number of Winter HWDI between 1979-2018 (days) b) Average number of Summer HWDI between 1979-2018 (days) c) Average number of Monsoon HWDI between 1979-2018 (days) d) Average number of Post - Monsoon HWDI between 1979-2018 (days)

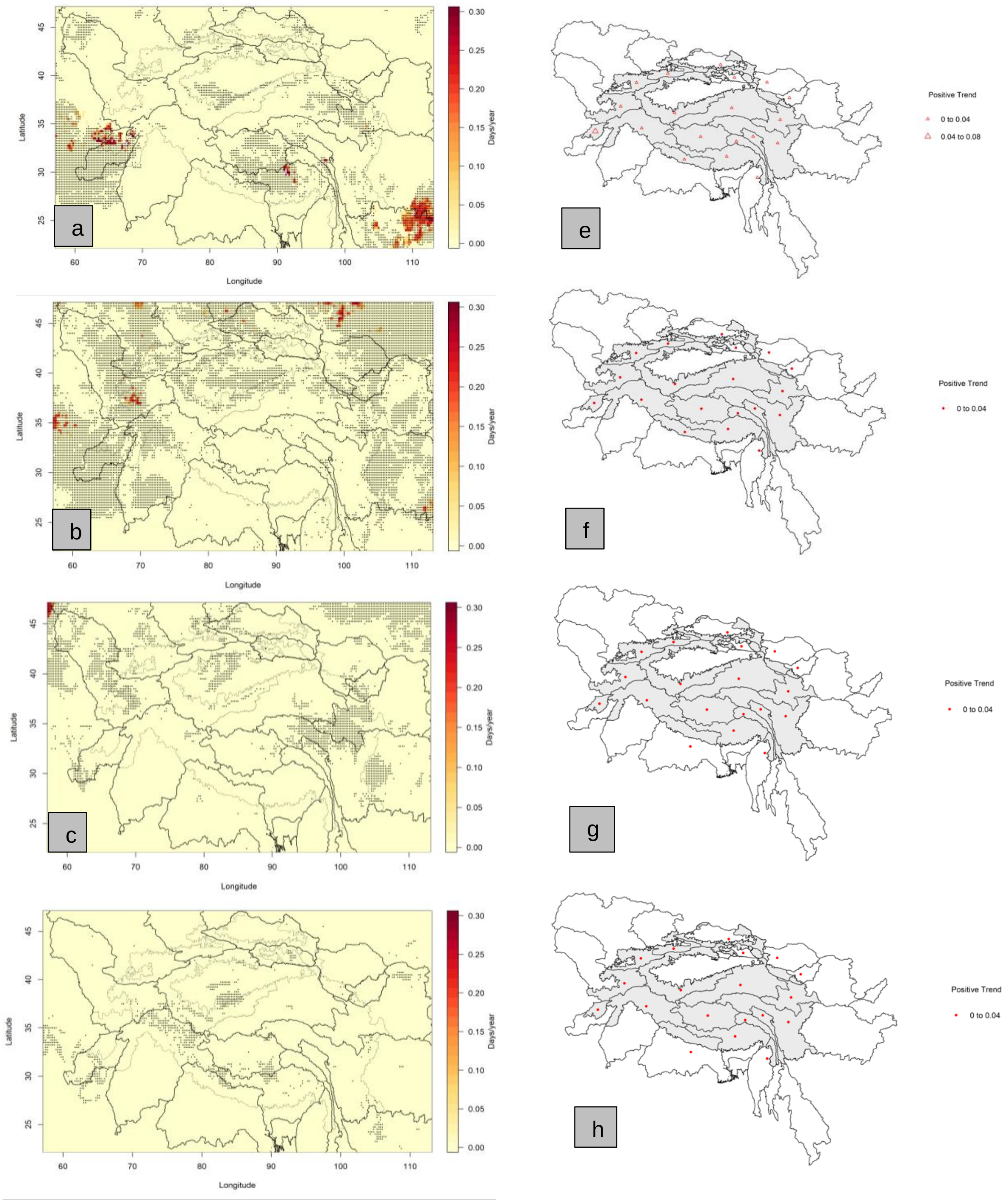

Figure 23 a) Winter trend of HWDI estimated using Sen's Slope (days/year), b) Summer trend of HWDI estimated using Sen's Slope (days/year), c) Monsoon trend of HWDI estimated using Sen's Slope (days/year), d) Post- Monsoon trend of HWDI estimated using Sen's Slope (days/year), e) Winter upper basin averaged CDD trend (days/year), f) Summer upper basin averaged CDD trend (days/year), g) Monsoon upper basin averaged CDD trend (days/year), h) Post- Monsoon upper basin averaged CDD trend (days/year). Black dots represent areas with Kendall's significance at p<0.05. The red circles in f-h, indicate a zero trend.

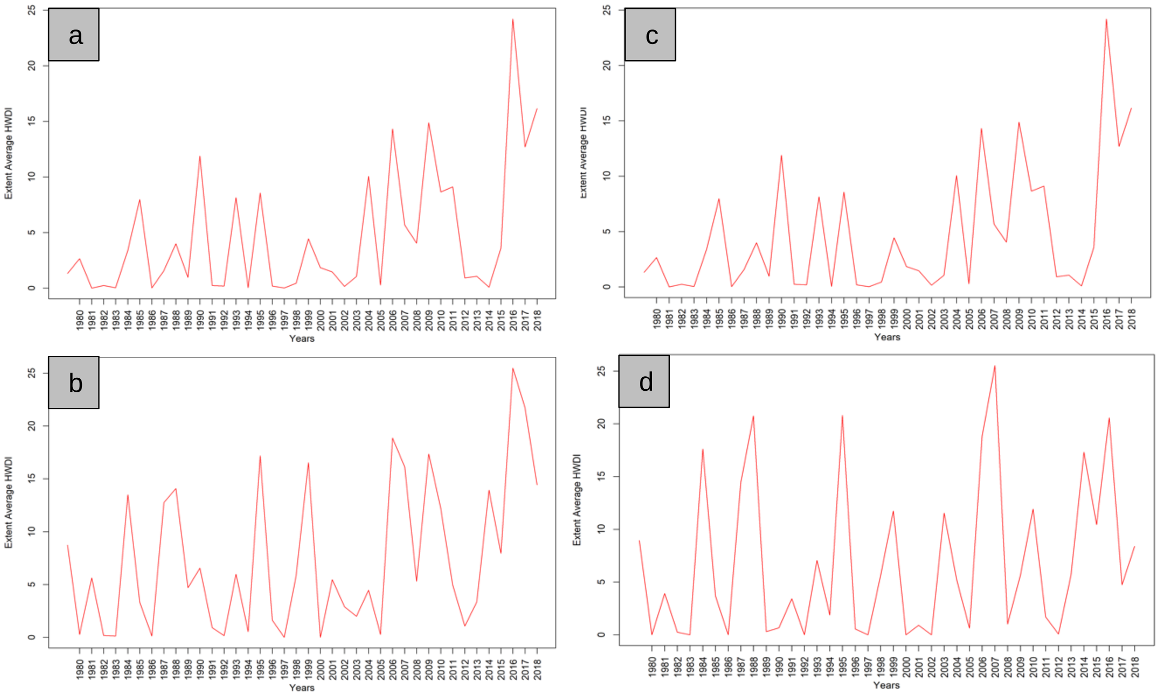

Figure 24 a)Temporal variation of HWDI in Helmand b) Temporal variation of HWDI in Brahmaputra, c) Temporal variation of HWDI in Salween, d) Temporal variation of HWDI in Mekong

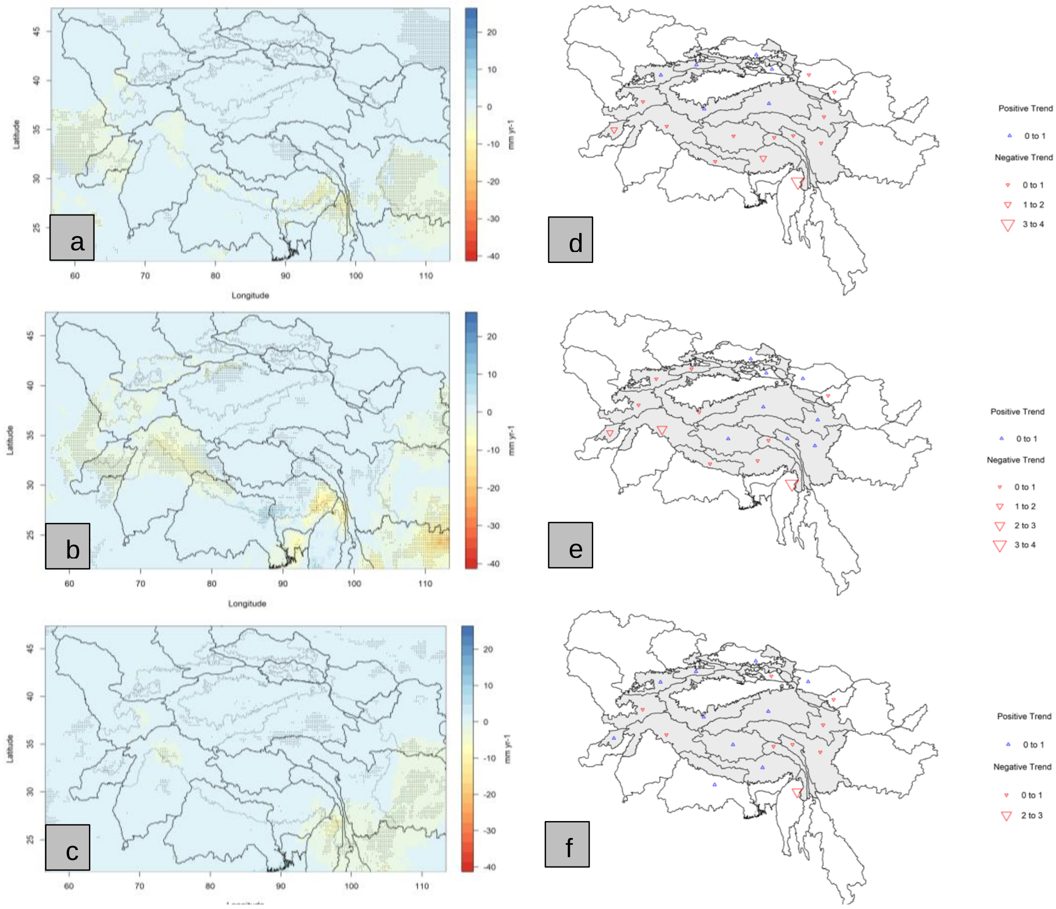

Figure 25 a) Winter trend for daily precipitation estimated using Sen's Slope (mm/year), b) Summer trend for daily precipitation estimated using Sen's Slope (mm/year), c) Post-Monsoon trend for daily precipitation estimated using Sen's Slope (mm/year), d) Winter upstream basin averaged daily precipitation trend (mm/year), e) Summer upstream basin averaged daily precipitation trend (mm/year), f) Post-Monsoon upstream basin averaged daily precipitation trend (mm/year). Black dots represent areas with Kendall's significance at p<=0.05.

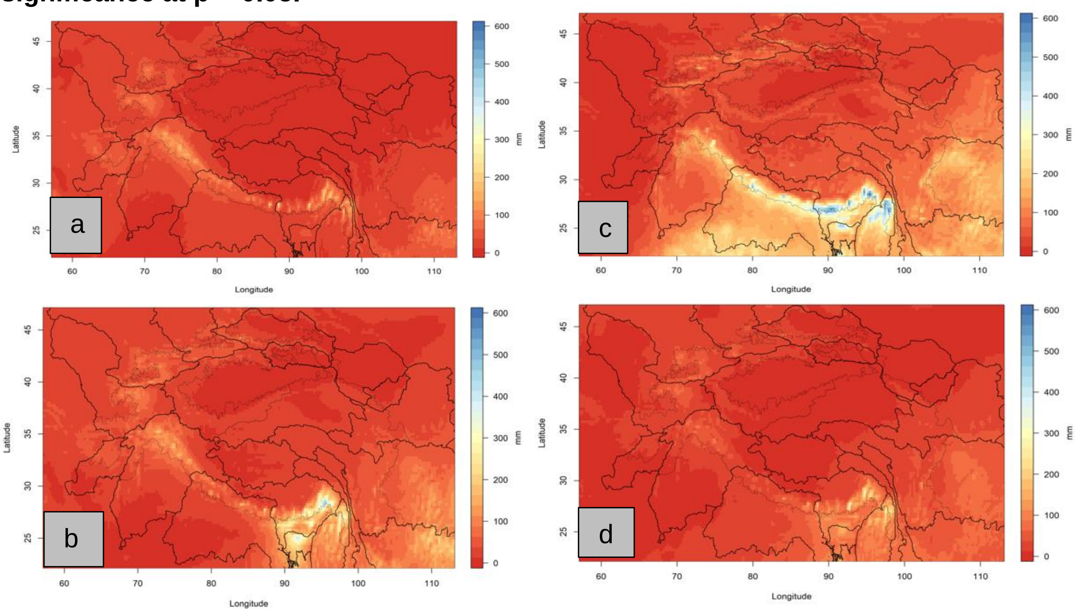

Figure 26 a) Average of Winter RX5 between 1979-2018 (mm) b) Average of Summer RX5 between 1979-2018 (mm) c) Average number of Monsoon RX5 between 1979-2018 (mm) d) Average of Post - Monsoon RX5 between 1979-2018 (mm)

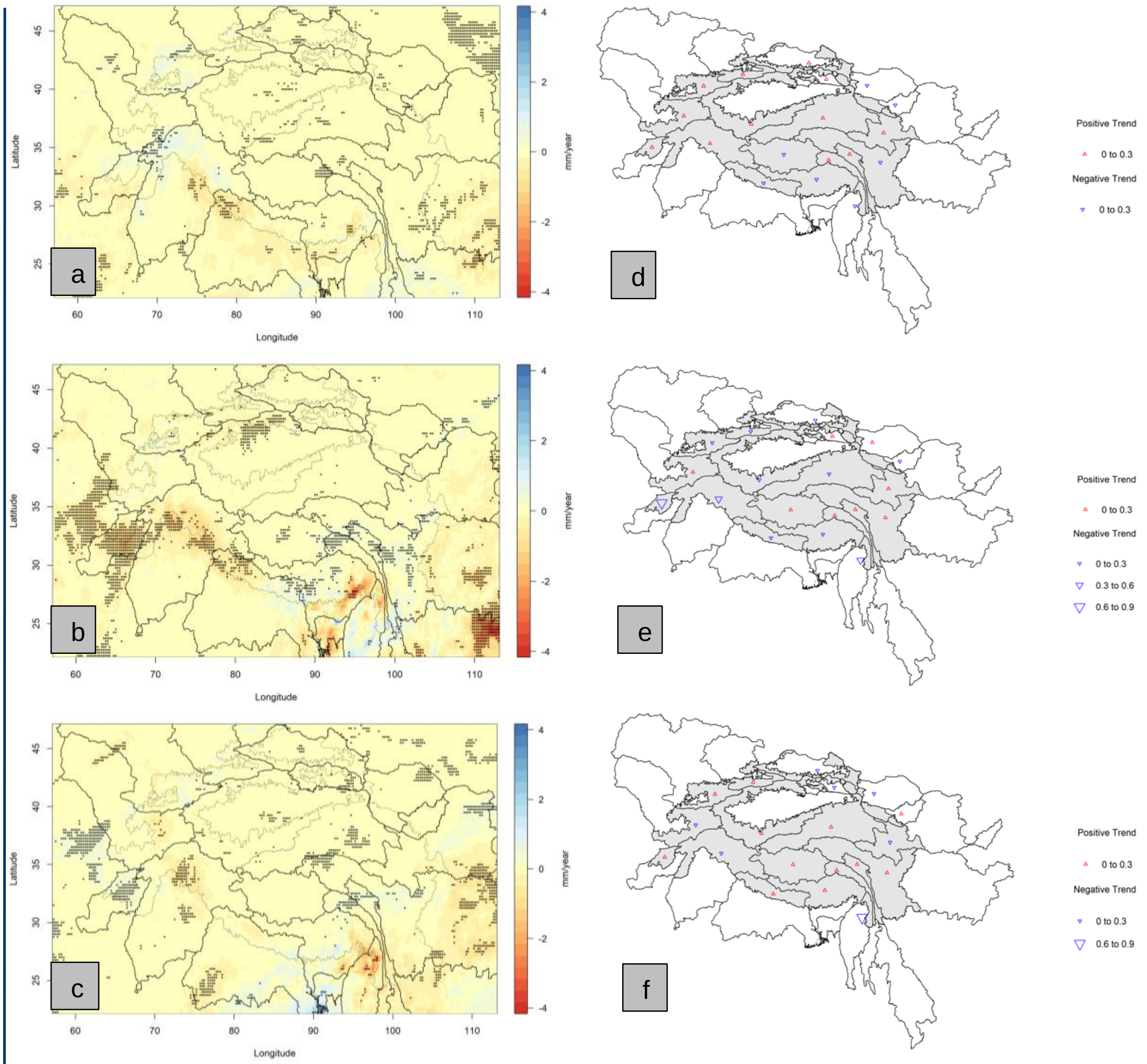

Figure 27 a) Winter trend of RX5 estimated using Sen's Slope (mm/year), b) Summer trend of RX5 estimated using Sen's Slope (mm /year), c) Monsoon trend of RX5 estimated using Sen's Slope (mm /year), d) Post- Monsoon trend of RX5 estimated using Sen's Slope (mm /year), e) Winter upper basin averaged RX5 trend (mm /year), f) Summer upper basin averaged RX5 trend (mm /year), g) Monsoon upper basin averaged RX5 trend (mm /year), h) Post- Monsoon upper basin averaged RX5 trend (mm /year). Black dots represent areas with Kendall's significance at p<0.05.

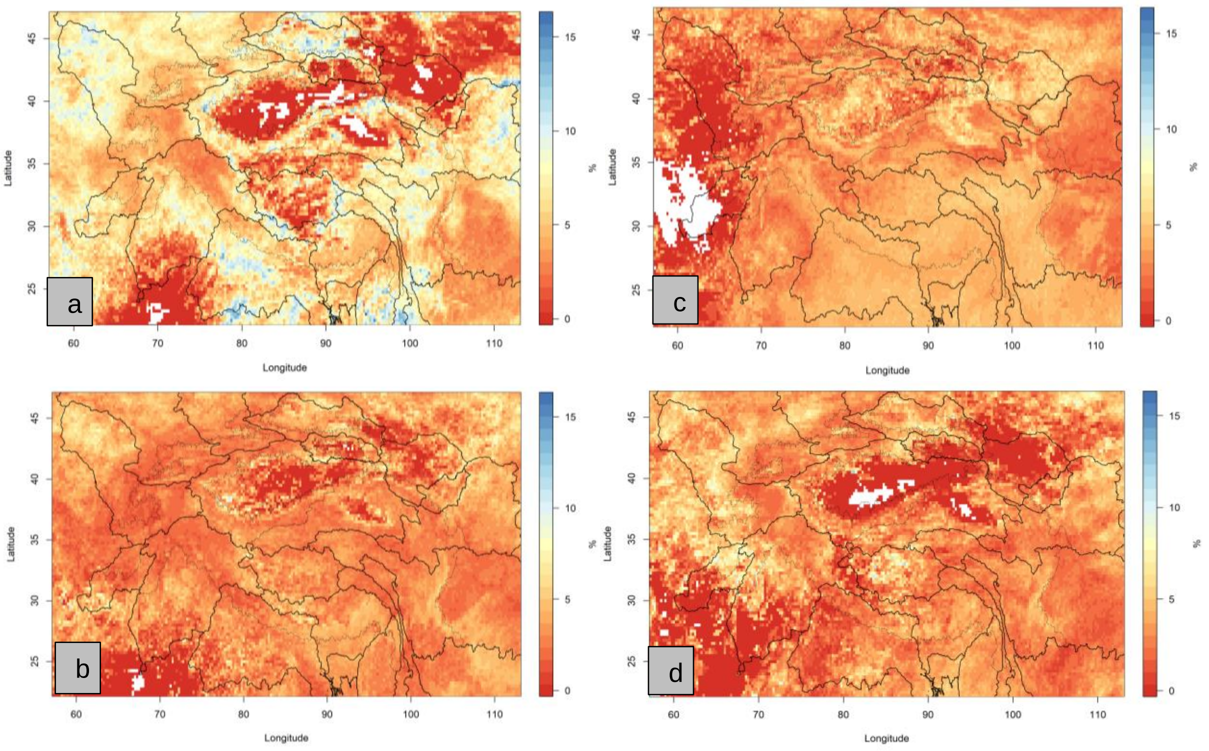

Figure 28 a) Average of Winter R95P between 1979-2018 (%) b) Average of Summer R95P between 1979-2018 (%) c) Average number of Monsoon R95P between 1979-2018 (%) d) Average of Post - Monsoon R95P between 1979-2018 (%)

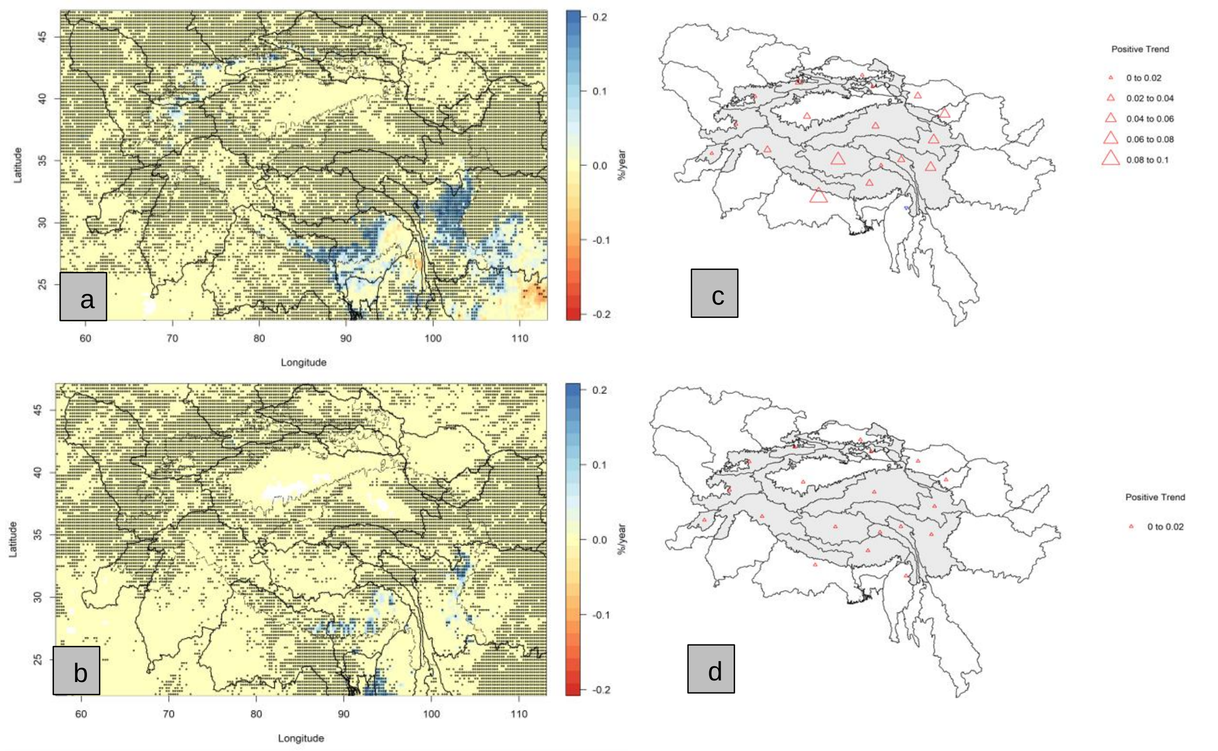

Figure 29 a) a)Summer trend of R95P estimated using Sen's Slope (%/year), b) Post-Monsoon trend of R95P estimated using Sen's Slope (%/year), c) Summer upper basin averaged R95P trend (% /year), d) Post-Monsoon upper basin averaged R95P trend (% /year)