Past and Future Trends in Frequency of Heavy Rainfall Events over Pakistan

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Abstract

The South Asian summer monsoon directly affects the lives of almost one-half of the world's population, with substantial variability in the monsoon season such as fluctuating between wet (heavy precipitation) and dry spells. This study presents the changes in temperature and precipitation over Pakistan under two different RCP scenarios of a statistically downscaled CMIP5 Coupled General Circulation Model. The analyses are extended to seasonal scale with a focus on the Summer Monsoon season and heavy precipitation events. There is a positive change in mean temperature of 2.7°C under RCP 4.5 scenario and 8.3 °C under RCP 8.5 scenario till the end of this century. The seasonal cycle shows that the winters are warming more than summers with an increase in temperature of 6 to 8°C in the 21st century with respect to baseline (1975-2005). The spatial analysis of both RCPs shows a much sharper increase in mean temperature of the northern areas with respect to the southern areas of Pakistan. Whereas, the precipitation maxima in the century show an overall increase of 3 to 4 mm/day at annual time scale. Both scenarios show a shift in the monsoon region towards the northeast along with a dipole like a pattern over the region (increase in JJAS mean precipitation over monsoon belt with a coexisting decreasing trend of up to 2 mm/day over Punjab, some areas of Sindh and Balochistan). Summer mean temperature shows more warming after mid-century in lower areas of Pakistan including Punjab, southern parts of KPK and upper areas of Balochistan. Two indices have been defined for the summer season. First is the frequency of extreme precipitation events based on the thresholds of daily precipitation as 50 mm/day, 100 mm/day and the second are for dry days as < 1 mm/day. Results show a significant increase in a number of dry days over the selected area of Pakistan, 130/year under RCP4.5 scenario and 420/year over under RCP 8.5 Scenario. Spatial analysis of dry days show an increasing trend and their decadal variability in future projections under both RCP scenarios show that frequent dry days extend towards the north. Heavy rainfall events analysis show intense rainfall events over Pakistan being confined to only the key monsoon region and coastal area of Sindh having return periods of 1 to 2 years. The temporal variability of heavy rainfall frequency indicate decreasing trend with an increase in the intensity of rainfall under both RCP scenarios.

Key Words: RCP scenario, Dipole, Extreme precipitation events and dry days, frequency

Introduction

The term "climate change" refers to a persistent, and sometimes irreversible shift in the long-term statistics of climate variables in a specific region or the entire globe. The increase in the atmospheric concentrations of greenhouse gases appears to be the predominant cause of recent climate change. The CO_2 induced climate change, which has already started to impact different sectors around the globe, is expected to become more evident in future decades with long term impact in many sectors. Therefore, assessments of climate change impact, both global and regional, are drawing attentions from different groups of researchers and stakeholders (IPCC, AR4). The South Asian summer monsoon rainfall during June to September plays an important role in providing food for almost one-half of the world population (Gadgil, S. & Rupa Kumar, 2006). The variability of the South Asian Summer Monsoon makes the region one of the most susceptible areas around the world to the impacts of climate related natural disasters such as droughts and floods. It has two main features; it's regular prevalence every year from June to September and the irregular interannual as well as intraseasonal variability in terms of precipitation amount both spatially and temporally. This variability exists even on interdecadal time scales along with other global climate variables having a substantial socio-economic impact in the field of agriculture as well as health (Krishnamurthy et al., 2002).

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By comparing simulated dynamical features of the summer monsoon with reanalysis data and observations, Ashfaq et al 2009, found that enhanced greenhouse forcing induced an overall suppression of summer precipitation with an increase in dry spells. The frequency of extreme precipitation events investigated for the period of 1965 to 2009 by Maida et al, 2011, showed evident increase in all the regions of Pakistan. The significant increase in extreme precipitation episodes has been observed in Azad Jammu & Kashmir, Sindh , Northern Areas and Balochistan at all thresholds, However, events at the 98th percentile were not found in Northern Areas and Balochistan. Their study also showed that the southern half of the country is experiencing more wet spells in the recent years under the influence of changing the climate and global warming.

Mathew et al, 2015, analysed multiple observed datasets and long term coupled model simulations which demonstrated a significant weakening trend in summer rainfall during 1901–2012 over the central-east and northern regions of India, including the Himalayan foothills. In their study, they showed a decrease in land-sea thermal gradient over South Asia due to rapid warming in the Indian Ocean and a relatively weak warming over the subcontinent. Thereby dampening the summer monsoon Hadley circulation and reducing the rainfall over parts of South Asia. IPCC AR4 projections show warming of drier subtropical regions at a faster rate than the tropics with warming likely to be above the global mean in South Asia. The temperature projections for South Asia for the twenty-first century suggest a significant acceleration of warming over that observed in the twentieth century. Recent modelling experiments indicate that the warming would be significant in Himalayan Highlands including the Tibetan Plateau and arid regions of Asia. (M.V.K. Sivakumar and R. Stefanski, 2011)

Syed et al, 2013 have recommended that there is warming over all the regions of South-Asia associated with increasing greenhouse gas concentrations. The increase in summer mean surface air temperature by the end of the century ranges from 2.5°C to 5°C, with maximum warming over northwestern parts of the domain and 30 % increase in rainfall over northeastern India, Bangladesh and Myanmar. Y.Y. Loo et al, (2015) found frequent changes and a shift westward of the Indian summer monsoon. Precipitation is observed to be 70 % below normal levels, in some areas the intensity of rainfall is affected by the topography.

Climate extremes take in both extreme weather, with durations of minutes to days (the synoptic time scale), and extreme climate events with durations of months, in the case of periods of wet/stormy weather, or years, in the case of drought (McGregor et al. 2005). In all cases, the frequency of extreme events may be affected by seasonal to inter-annual fluctuations of large-scale climate variations such as El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Schwierz et al. 2006). A distinct spatial pattern in the ongoing directional trends between the northern and southwestern parts of Pakistan during 1950 to 2010 was identified by Mian Sabir Hussain and Seungho Lee 2013. They analysed daily precipitation data set from 15 weather stations in Pakistan. Seven indices defined as: total precipitation from events ≥ 90th, 95th, and 99th percentiles, the number of days with precipitation ≥ 90th, 95th, and 99th percentiles of daily precipitation amounts, and annual dry days were used in all seasons, increasing trends in extreme precipitation dominated in northeastern Pakistan, whereas a reducing tendency towards extreme precipitation the southwestern part of the country were identified. Model simulations in a study by R. Rajbhandari et al, 2014 suggest an overall non-homogenous change in precipitation. Upper Indus basin shows an increase in precipitation; decrease over the lower Indus basin. Projections indicate a higher rate of warming in the upper Indus basin with winters warming more than other seasons. Their analysis also suggests a decrease in the number of rainy days accompanied by an increase in rainfall intensity in the border area of the two basins i.e the monsoon belt region.

Elevation Dependent Warming

Diaz and Bradley (1997) used observations from more than 100 sites between 30°N to 70°N and found that mean temperature warming rates were enhanced at many higher elevation sites between 1951 and 1989. Furthermore, they found that most of the increase was associated with increases in minimum temperatures. The trends in maximum temperatures were, however, small. Pepin and Lundquist (2008) analysis indicated that the warming rates are strongest near the annual 0°C isotherm. This implies a role of the snow/ice albedo feedback mechanism causing enhanced warming at these elevations. Using meteorological and hydrological data in combination with remote sensing data from various sources, Rasul et al 2008 evaluated isothermic dynamics of heat in upslope direction on pentad basis. It revealed that 30ºC isotherm has crept upward by 725m higher elevation than 28 years before. High mountain temperature anomalies were found warmer than the national average (0.93ºC) by additional 0.4ºC. This rise was determined to be 75 % more than what was projected for Pakistan during the decade 2001-2010. (Rasul et al, 2011). Tibetan Plateau has experienced large warming rates in winter (0.32°C/decade) about twice as large as the annual mean warming rates. However, significant seasonal variations in warming rates exist (Liu and Chen (2000), Chen et al. 2006b; Liu et al. 2006; You et al. 2010; Rangwala et al. 2010). Autumn has the next highest warming rate (0.17°C/decade), while summer and spring have only recently (since the 1990s) experienced significant increases in warming (Liu et al. 2006; Rangwala et al. 2010). High elevation regions will remain sensitive to the projected warming during the 21st century (Rangwala, I. and Miller, J.R., 2012).

Data and Methodology

Data

The Asian Precipitation Highly Resolved Observational Data Integration Toward Evaluation of Water Resources APHRODITE, has long term daily gridded precipitation and temperature datasets for Asia available from 1951 and onwards at 0.25°x0.25° resolution; using a dense network of stations which is higher than any other observation dataset available, Yasutomi N, et al. (2012). In this study, the time period of APHRODITE used for baseline analysis is from 1975-2005. The Community Climate System Model 4.0 (CCSM4) CGCM (Coupled General Circulation Model) data was obtained from Coupled Models Intercomparison Project Phase-5 (CMIP5). The model is available at 1.25°x0.94° resolution. Future projections of CCSM4 CGCM analyzed are under two Representative Concentration Pathways (RCPs) defined as RCP4.5 and RCP8.5. Based on specific emissions trajectory, energy use, population, air pollutants, land use, the consequent radiative forcing and temperature anomalies by the year 2100 compared to that in the year 1750, RCP4.5 represents a radiative forcing of 4.5 W/m^2 due to Green House Gas (GHG) concentration of 670 ppm and 8.5 Wm^2 radiative forcing due to GHG concentration of 936ppm in RCP8.5 (IPCC, AR5).

Downscaling Technique:

The downscaling technique employed for this study along with model uncertainties are discussed in detail by Burhan et al, 2015. Therefore, a brief description is provided here. Linear Interpolation and Bias Correction Method (LIBC) is a combination of the two methods used by Wood et al (2004) and Immerzeel et al (2012). APHRODITE datasets for temperature and precipitation were taken for baseline period 1975–2005. Mean and standard deviation of monthly climatology was calculated and the dataset was re-gridded to a horizontal resolution of 0.25°x0.25° for the complete baseline period 1975–2005. Similar procedure was adopted for historical CCSM4 CGCM data (1975-2005). A correction factor was determined from the baseline data by the division of climatological values of APHRODITE to the climatological values of CCSM4 CGCM. Similarly, signal to noise ratio was obtained by dividing the square root of the variance of the monthly observed dataset with the square root of the variance of the monthly GCM reference. The revised climate parameters are computed by multiplying signal to noise ratio of the corresponding month with the deviation between future GCM month and climatology of that month. Subsequently, the element is added to the product of adjusted factor and the respective climatology of that particular month. The Same procedure is repeated for every month of GCMs future data to obtain revised monthly GCM values for both temperature and precipitation parameters. The spatially interpolated grid obtained is temporally disaggregated to daily sequences since diurnal variations in the projected data series is important if it is to be used to commute hydrological or ecological models. This technique is an extension of the one used by Wood et al (2004) where daily sequences are retrieved by employing monthly means of daily time series. For temperature, the methodology is same except that the adjustment factors are added. The diurnal variation bound from that month is imposed upon all grids of the downscaled monthly values while holding the downscaled monthly mean intact. (Burhan et al, 2015)

Extreme Climate Indices

This study presents, spatiotemporal analysis of two extreme indices. The first index is defined for extreme precipitation events. Using the thresholds defined by Maida and G. Rasul, (2011) as 98^{th} percentiles (50 mm/day and 100 mm/day), The frequency of events equal to or greater than these two thresholds have been calculated for both observation i.e baseline period of 1975-2005 and for the future scenarios (RCP4.5 and RCP 8.5) of the statistically downscaled CCSM4 model for the time period of 2011 to 2100. The second index is defined as the number of dry days with <1 mm/day precipitation. If not mentioned extensively, using the same methodology of K.F. Ahmed et al (2013) all the projected changes have been calculated with respect to the APHRODITE as a baseline for both parameters. Student's T-Test has been applied for checking the significance level at $\alpha \leq 0.1$.

Results and Discussion

The CCSM4 statistically downscaled scenarios analysis are presented in this section. There are obviously many factors contributing to the climate change at regional scale. Here we discuss the trends in two most important and widely studied meteorological parameters indicating the effect of climate change i.e. temperature and precipitation. Considering the stabilisation scenario first, the RCP 4.5, there is a significant positive trend in annual mean temperature of 3°C to 3.5°C for the period 2011-2100 along with a decreasing trend in annual precipitation. Under the RCP8.5 scenario, the increase in annual mean temperature is 8.3°C with an increasing trend in precipitation as well (fig 1a and b). The summer mean temperature also show a significant increase of up to 3°C under RCP4.5 scenario and up to 7.5°C under RCP 8.5 scenario. However, there is a significant decrease in precipitation trend of -0.54 mm/day under RCP 4.5 scenario for the time period 2011 to 2100. During the first half of the 21^{st} century (2011-2050) both scenarios show a significant trend in annual mean temperature ranging from 3.5°C and 6.5°C respectively. Whereas, during the next half (2051-2100) the rise in temperature under RCP 4.5 scenario reduces to 2.25°C. The increase in temperature during this half, under RCP 8.5, increases up to 8.9°C. It is worth noting that the precipitation trend is negative during both halves of the 21^{st} century under RCP 4.5 scenario. Under RCP 8.5 scenario, there is a significant increase in precipitation of up to 0.9 mm/day during the first half of the 21^{st} century (also depicted in the spatial patterns discussed later) and a negative trend during the next half which is not statistically significant. The summer temperature trends during the first half of the 21^{st} century show a significant trend of 5.5°C and 6.5°C under both RCP scenarios respectively. During the next half of the century the under RCP 4.5 the trend has reduced to +0.63°C (not statistically significant) leading to stabilisation. However, under RCP8.5 scenario the trend significantly increases up to 7.2°C.

The summer precipitation show an overall decreasing trend with a significant decrease of up to -1.8 mm/day from 2051-2100 under RCP4.5 scenario whereas, RCP 8.5 show an increasing trend of 1.3 mm/day during the first half and a decreasing trend of -0.7 mm/day during the second half of the century. Hence, both scenarios agree in the later half of the century with is also depicted in the spatial plots shown later. Considering the geographical location of Pakistan, these decreasing trends in precipitation are consistent with the IPCC AR4 and AR5, concluding a *likely* decrease in most subtropical land regions, continuing observed patterns in recent trends in observations.

Before we proceed to our next results, some key points are mentioned here about the need to present the decadal analysis. In addition to forced natural variations, internal variability also exists on decadal time scales. Observations and models indicate that, because of the relatively small heat capacity of the atmosphere, in a warming climate there can be a decade of decreasing or even no change in surface temperature. Most of the climate simulations suggest that such periods are associated with a transfer of heat

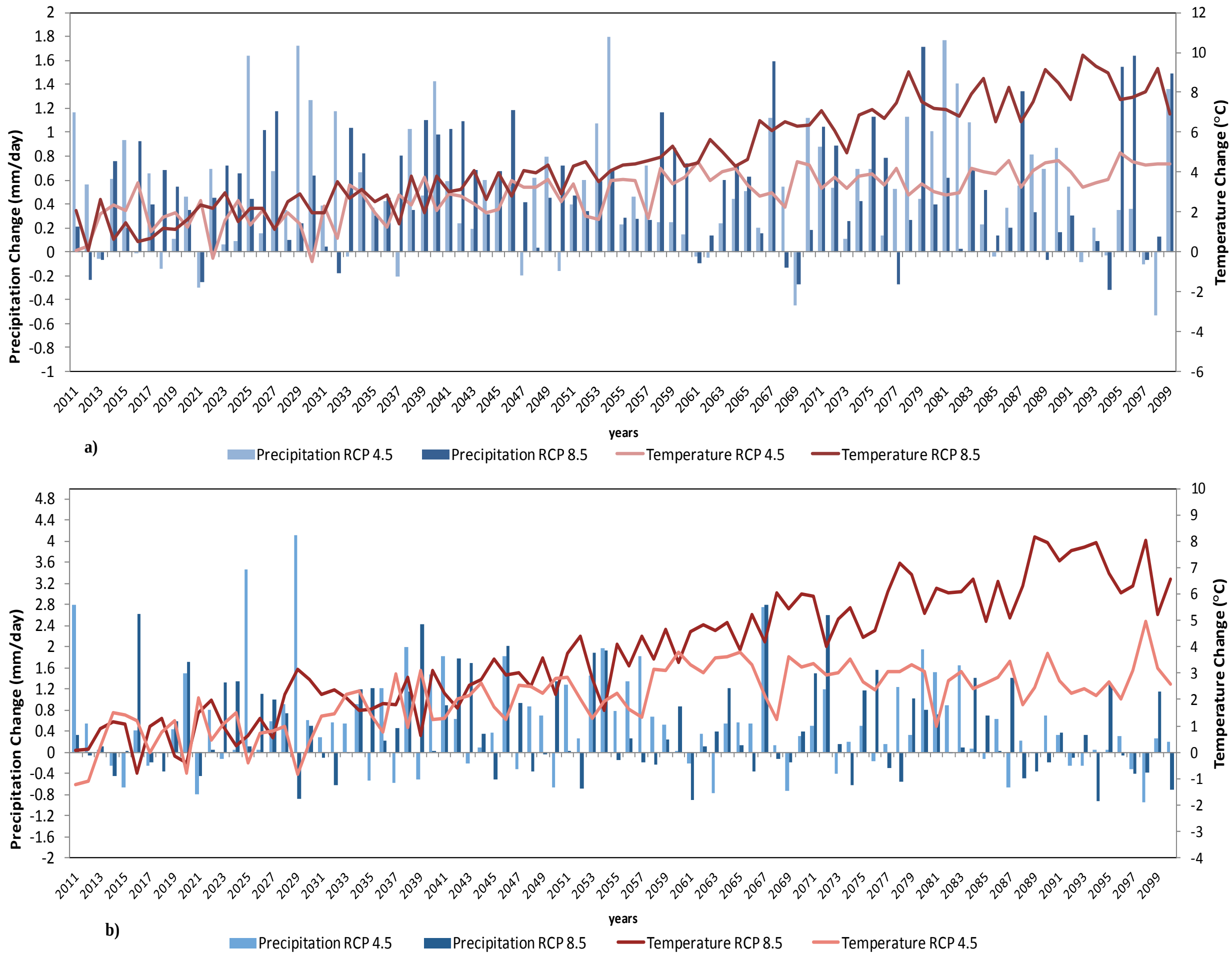


Figure 1: Temperature and Precipitation Anomalies, **(a)** Annual, **(b)** JJAS

from the upper to the deeper ocean since oceans are the biggest heat sinks in the earth system. However, compared to natural variability, the anthropogenic forcing of the Earth's energy budget is significantly larger especially on decadal to multi-decadal timescales. (IPCC AR5, 2013). Near term future projections are sensitive to short-lived aerosols and methane. Long term projections are more sensitive to long-lived GHG emissions. These scenario-dependent uncertainties in the role of aerosols are the dominant sources of uncertainty in long-term projections of the climate Some aspects of observed changes have been attributed to naturally occurring decadal variability (Goldenberg et al. 2001; McCabe et al. 2004; Zhang and Delworth 2006; Meehl et al. 2009a). Anthropogenically-forced climate change, intrinsic climate variability, and natural external forcings (e.g., major volcanic eruptions or possibly the solar cycle) act together to produce the time-evolving climate. Due to the fact that our understanding on natural external forcings is limited, time-evolving climate change and climate variability are of key importance to climate shifts in the future several decades as impacts resulting from these conditions such as droughts, floods and heat waves, have significant socio-economic as well as environmental implications. This time evolution of climate and climate shifts in the near term (10 to 30 years' known as decadal time scale) have become a concern for policy and decision makers (Meehl et al, 2016). According to IPCC AR5, 2013, Warming will continue to exhibit interannual to decadal variability and will not be regionally uniform. Therefore, in this study, we also present the decadal variations of the changes in temperature and precipitation. The Projected changes in annual mean temperature over the domain of study under the two RCP scenarios are presented in figure 2 and 3. RCP 4.5 show an overall effect of higher warming ranging 3°C to 4°C over the northern areas including GB, Kashmir and Northern part of KPK as compared to southern parts of the country. The southern parts show warming of 2°C to 3°C with a slightly higher rate over Balochistan.

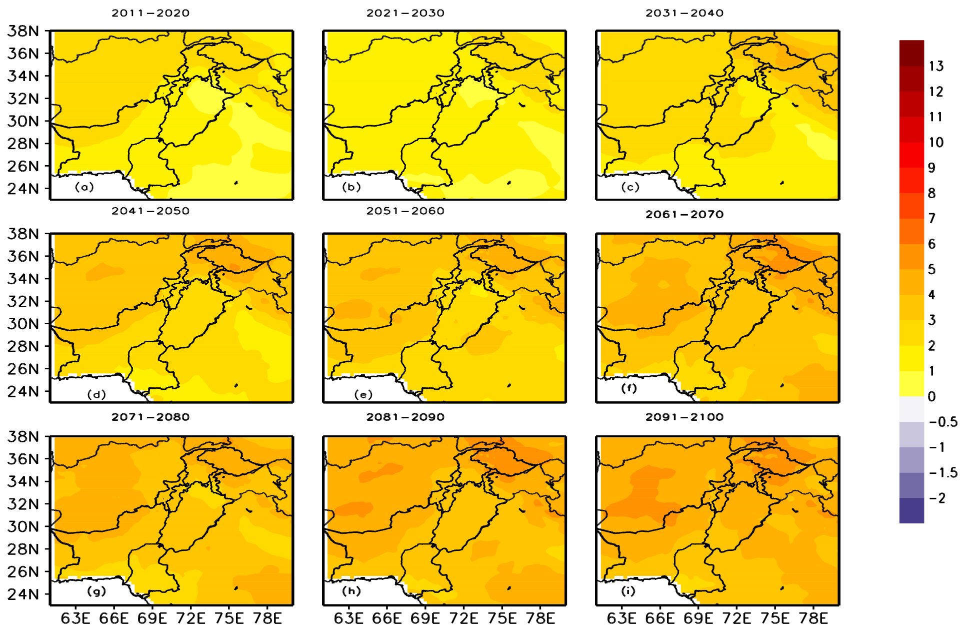


Figure 2: Projected changes in annual mean temperatures (°C) of CCSM4 under the RCP4.5 scenario. (Hatching show changes exceeding 90 % significance level.)

In RCP 8.5 however, the warming effects are more enhanced with an increase of 3°C to 8°C over the northern areas during the first half of the 21st century and up to 11°C by the end of the 21st century. Southern parts of the country also show higher rates of warming under this scenario ranging 5°C to 7°C by the end of the century. Waheed and Maida 2014 have also presented similar and robust magnitude (under 4°C in

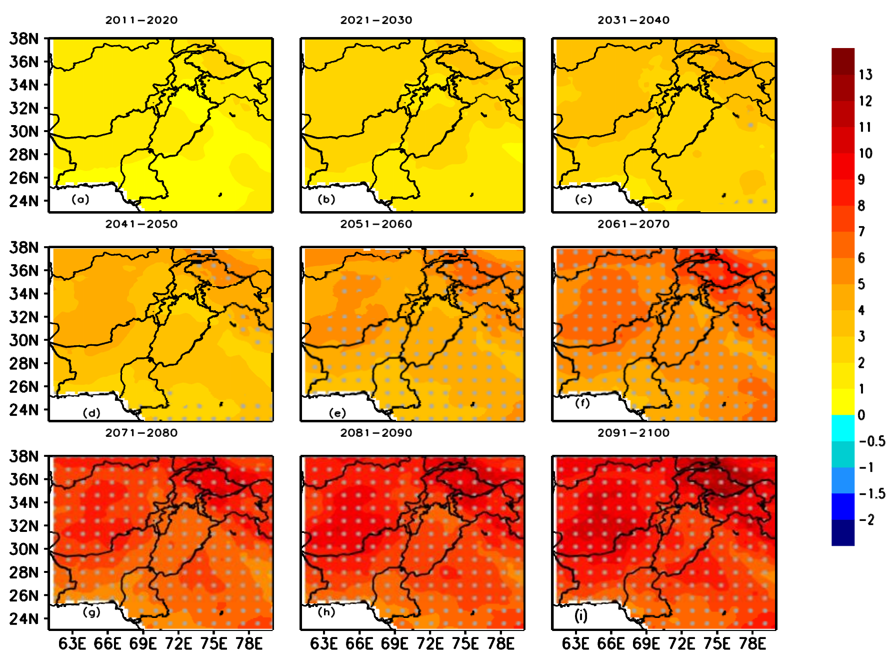


Figure 3: Projected changes in annual mean temperatures (°C) of CCSM4 under the RCP8.5 scenario. (Hatching show changes exceeding 90 % significance level.)

RCP4.5 and above 6°C under RCP 8.5) of change in a CMIP5 multi-model ensemble study. Such warming trends have also been studied on historical time periods e.g Pepin and Seidel (2005) found that surface temperatures at the majority of high elevation stations across the globe are increasing faster than the free air temperature at the same elevation between 1948 and 2002. They also found less discrepancy between surface and free-air temperatures at mountain summits relative to mountain valleys. Their analysis suggesting strongest warming rates near the annual 0°C isotherm implies a role of the snow/ice albedo feedback mechanism causing enhanced warming at these elevations. Under both scenarios, changes in mean annual temperature and precipitation until mid-21st century are not statistically significant above our selected criteria. However, these near-term changes cannot be neglected, since most of the recent studies in the IPCC AR5 suggest an increase in temperature and temperature extremes under both emission scenarios. After mid-21st century, both scenarios show significant warming.

As discussed previously, Rasul et al, 2008 and 2011 also pointed out the upward shift of snow line of about 1km by studying the variation in 30°C during the month of March on pentad basis for a period of 25 years (1981-2008) with 1.3°C rise in the mean temperature of the northern areas. Study of Rangwala et al. (2009), found increased warming rates at higher altitudes in the Tibetan Plateau in the later half of the 20th century. Although the elevation-dependent warming is quite evident in the present study, in order to better understand this elevation-dependent warming and examining this question for mean temperature trends, it may be preferable to assess trends in minimum and maximum daily temperatures separately because they can change at different rates and for different reasons. These parameters are not included here. Studies on the elevation-dependent warming of the glaciated regions of the world in IPCC AR5 show these regions have become most vulnerable to climate change. Several decades are required for glaciers to adjust to changes in climate. The delayed response of some glaciers is larger than they could be in response to the current climate. As the time required for the adjustment increases with the size of the glacier, large glaciers are expected to continue shrinking over the next few decades, even though the temperatures trends toward stabilisation. Smaller glaciers will also continue to shrink, but they will adjust their extent much quickly.

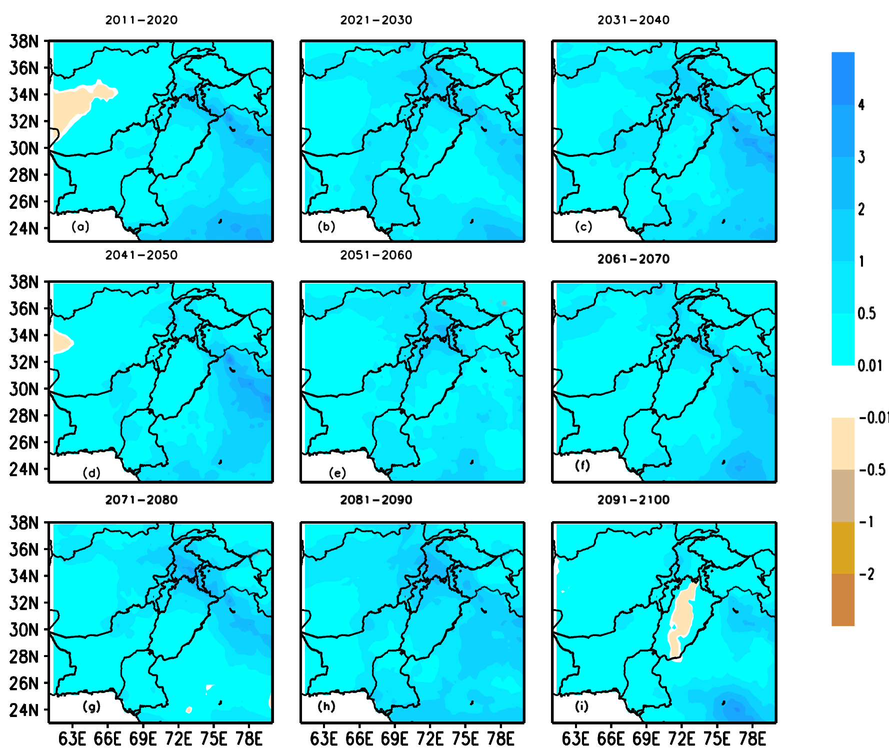


Figure 4: Projected changes in precipitation (mm/day) of CCSM4 under RCP 4.5 scenario.
(Hatching show changes exceeding 90 % significance level.)

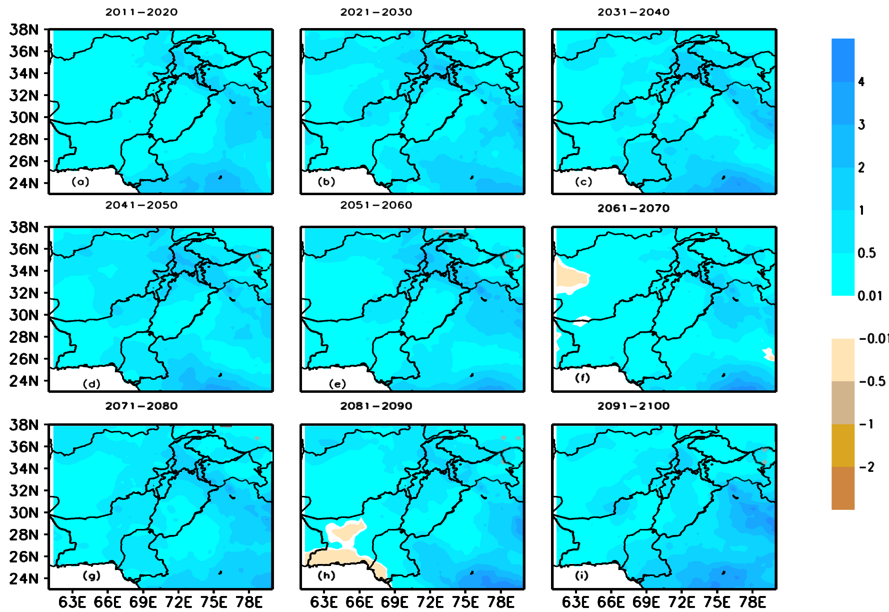


Figure 5: Projected changes in precipitation (mm/day) of CCSM4 under RCP 8.5 scenario. (Hatching show changes exceeding 90 % significance level.)

The changes in annual mean precipitation under both RCP scenarios show an overall increase consistent with most of the studies e.g IPCC AR5, 2013. Figures 4 and 5 show an overall increase in precipitation of 2 mm/day to 3 mm/day over the domain especially in the maximum annual precipitation region of Pakistan (32°N-36°N) having the highest variability and a rather consistent pattern of in precipitation changes following the changes in annual mean temperature. Regions showing a greater change in temperature also show an increase in precipitation. This intensification can also be an effect of increase in land-sea thermal contrast thereby increasing moisture flux acting together with the effect of topography. A second argument for the increase in mean precipitation could be increase in a number of dry days, precipitation events being fewer and intense. Further, increases in temperature lead to increase in the moisture holding capacity of the atmosphere at a rate of about 7 % per °C according to the relation between temperature and vapour pressure. However, the global mean precipitation is projected to increase at a slower rate of about 2 % K^{-1} in models

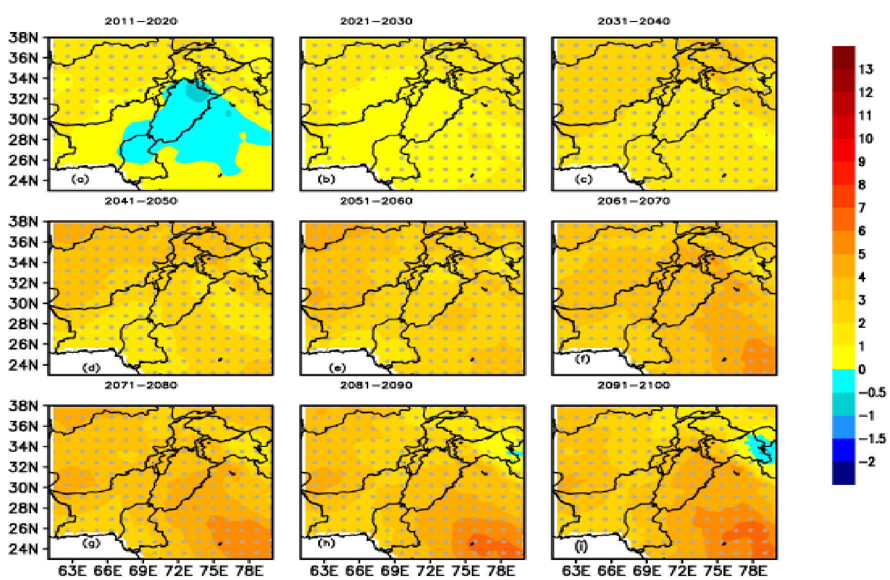


Figure 6: CCSM4 RCP 4.5 JJAS projected temperature change (°C). (Hatching show changes exceeding 90 % significance level.)

(Turner and Annamlai 2012). Combined these responses could lead to increasing intensity of heavy precipitation along with annual mean instead of an increase in the number of precipitation events (Trenberth et al., 2003). Figure 6 (a) JJAS future projections under RCP4.5, cooling of 0.5°C to 1°C is represented over AJK, Punjab and upper areas of Sindh (not statistically significant). This cooling trend disappears from the next decade onwards as the continuous warming signal (2°C to 4°C) is enhanced until the end of 21st century. The last two decades (h and i) show, however, a decrease in the magnitude of the warming signal over eastern part of Kashmir (not statistically significant). One aspect that could induce this cooling trend in the first decade (a) could be the aerosol direct effect parameterized in the model being enhanced at the start of the run. Whereas, the other aspect could be forced natural internal variability (for this we need to analyze more parameters and a bigger domain which are beyond the scope of this study). Figure 7, significant positive 0.5 to 4 mm/day (northwestern KPK, GB, Kashmir, northeastern Punjab, some parts of southwestern Balochistan and coastal area of Sindh) and negative up to 2 mm/day (southern Punjab and KPK, Northern Baluchistan and Sindh) trends coexist in dipole like pattern over Pakistan. The regions associated with an increase in precipitation also show a higher degree positive change in temperature of 3°C to 4 °C (figure 6). As the temperature increases northward, the dipole-like pattern of precipitation also

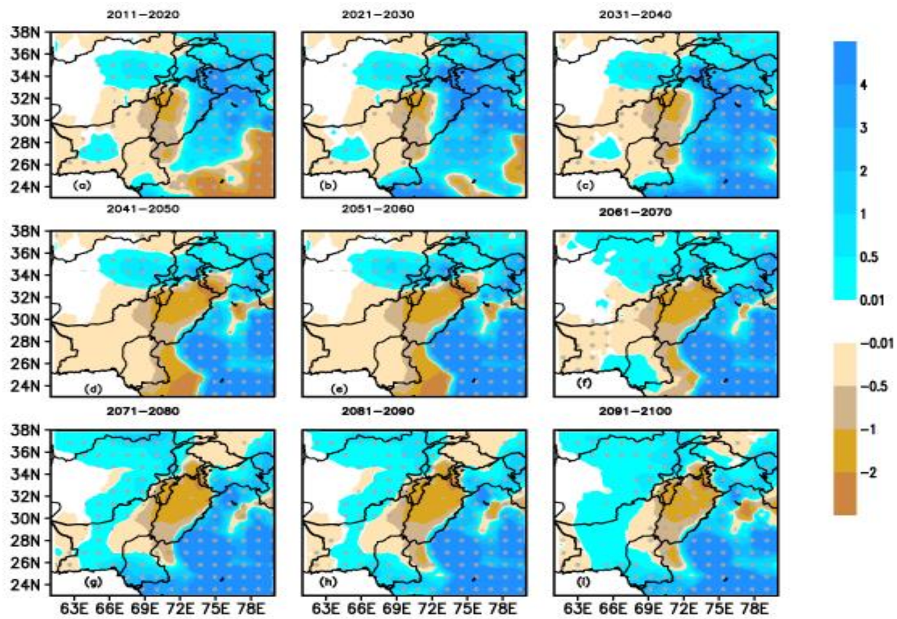


Figure 7: CCSM4 RCP 4.5 JJAS projected precipitation change (mm/day).
(Hatching show changes exceeding 90 % significance level.)

Follows the same shifting pattern. Leading to decreasing trend over most areas of Pakistan. Recent studies exploring direct effect of aerosol forcing on the Indian monsoon with GCMs considering absorbing aerosols (black carbon) only e.g Meehl et al. (2008) found an increase in pre-monsoonal precipitation, but a decrease in summer monsoon precipitation over parts of South Asia. The Same argument is present in IPCC AR4, the convergence of increased water vapour leads to more intense precipitation, but reduces the duration and/or frequency. Therefore the mean does not change much.

RCP 8.5 scenario show a similar cooling pattern in figure 8a but confined over a smaller area. Consistent with the previous result. The increased warming is due to increased forcing of anthropogenic emission but the cooling over some areas of enhanced topography could mean a higher concentration of aerosols is confined there leading to decrease in temperature due to direct effect. Increase in temperature under RCP 8.5 show a somewhat similar pattern to that in figure 6 with a higher magnitude of 4°C to 8°C over monsoon belt region along with eastern parts of the country and western India with an extending pattern towards the north (figure 8). The precipitation projections (figure 9) under this scenario show an overall positive change until late 21st century (2011-2060). The enhanced precipitation under a higher amount of anthropogenic forcing can be considered as a direct consequence (Aerosol direct feedback). As the enhanced GHGs and black carbon, aerosols tend to warm the atmosphere. More warming leads to increase in surface evaporation and water vapour hence increasing the mean. The dipole like pattern in precipitation is only confined to small region over northwestern part of Pakistan including KPK, GB (not statistically significant over

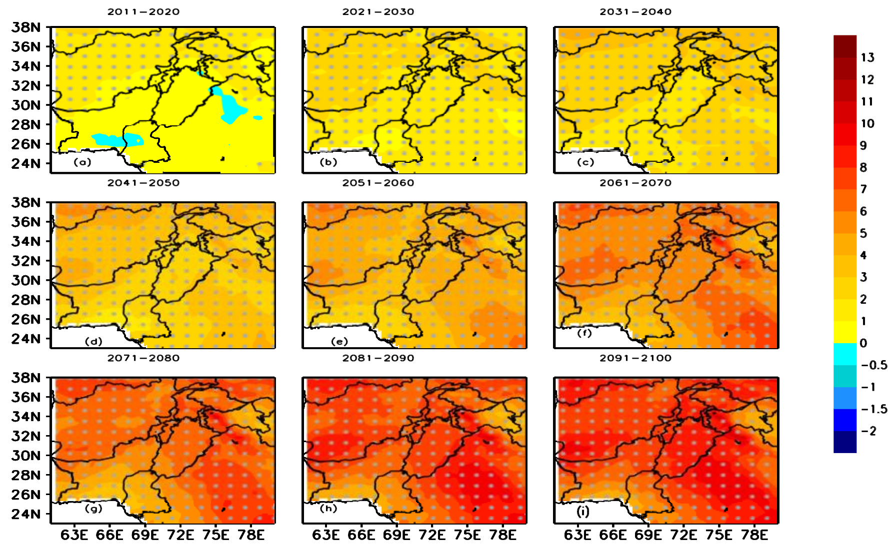


Figure 8: CCSM4 RCP 8.5 JJAS projected temperature change (°C). (Hatching show changes exceeding 90 % significance level.)

Pakistan) some parts of India. The dipole pattern as in RCP4.5 also appears in the future projection of RCP 8.5 after 2070 extending towards the north with a further shift of monsoon towards east (figure 9). Increasing mean along with extreme precipitation events being confined in the foothills of mountains suggest the higher amount of aerosols in that region, hence, acting as condensation nuclei (CCN) with a significant amount of moisture available under a warming climate. However, a decrease in mean precipitation over plainer areas along with increasing anthropogenic forcing suggest the availability of higher amount CCN than moisture, therefore, increased the formation of smaller sized droplets without causing precipitation (Aerosol indirect effect). The CCM4.0 is a coupled model. The atmospheric

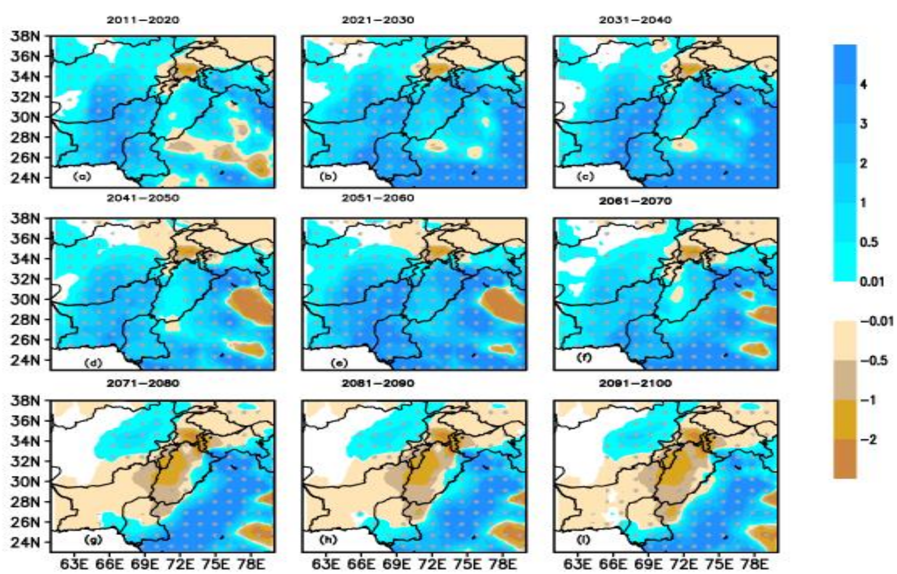


Figure 9: CCSM4 RCP 8.5 JJAS projected precipitation change (mm/day). (Hatching show changes exceeding 90 % significance level.)

component is Community Atmosphere Model (CAM4.0) is a global atmospheric general circulation model which incorporates the aerosol direct and semi-direct effects only, excluding the aerosol indirect effect. Therefore, this dipole like pattern could be more related to increased evaporation due to increased warming but also depend on the soil moisture. The significant positive trend in the JJAS (June, July, August, and September) precipitation is also discussed by Latif et al 2016. They have identified a dipole like a pattern in precipitation over Pakistan's key monsoon region (+ve) and Central India (-ve) associated with strengthening and weakening of moisture transport from the Arabian Sea.

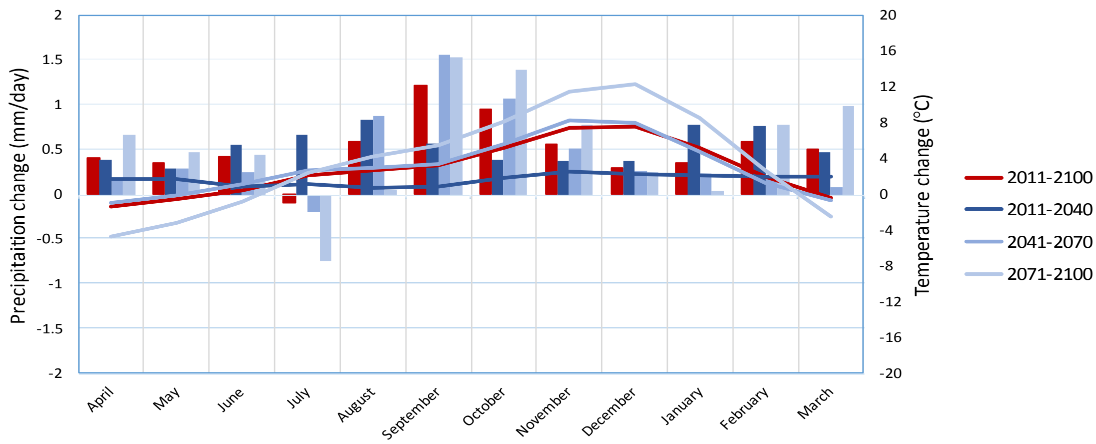


Figure 10: Change in projected Seasonal Cycle CCSM4 RCP4.5.

The change in seasonal cycle shows that the winters are warming more than summers with an increase in temperature of 8°C to 10°C in the 21st century with respect to baseline (1975-2005) (Figure 10 and 11.). The month of July in both RCPs show a decrease in precipitation from 2041 onwards (0.1 mm/day to 0.3 mm/day) with a much sharper decrease (0.7 mm/day to 1 mm/day) in last thirty year's time period 2071-2100. The seasonal cycle during this time period also represents a higher degree of change in temperatures

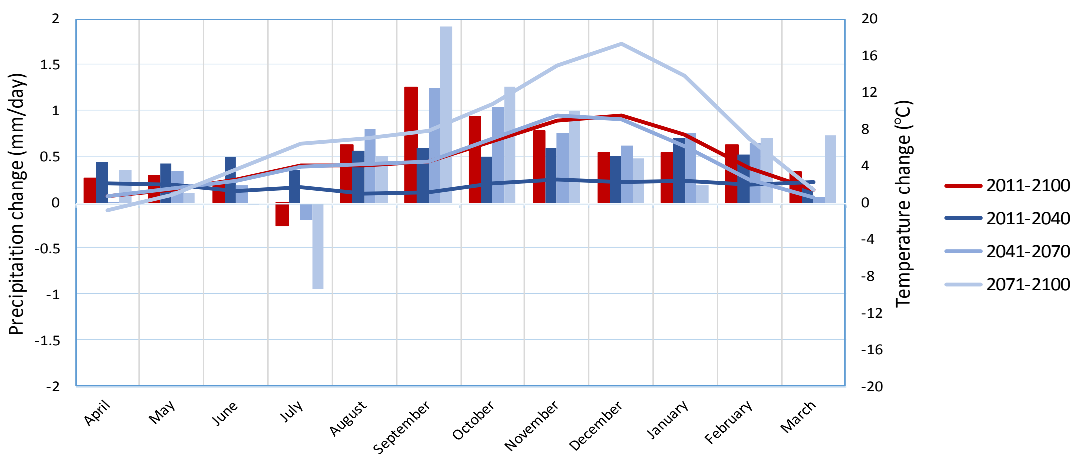


Figure 11: Change in projected Seasonal Cycle CCSM4 RCP8.5.

for summer and winter season. While the months of August and September show largest positive deviation in precipitation, highest magnitude of warming is projected in winters, specifically in the months of October, November, December and January (12°C to 16°C). The projected changes in precipitation and temperature are somewhat consistent with IPCC AR5, suggesting projections have reduced mean summer precipitation in the regions on the poleward edges of the subtropics with a clear increase in temperature, especially in winter.

Figure 12 and 13 represent the temporal variation of frequencies which are greater than or equal to 50 mm/day and 100 mm/day threshold of daily precipitation. The frequency count represents the sum of these events over Pakistan during each year. It is interesting to note that years having a higher frequency of events (>100counts/year) over 50mm/day threshold also have a higher frequency of events over 100mm/day. Since these frequencies and thresholds have been calculated over Pakistan, some areas might have thresholds for

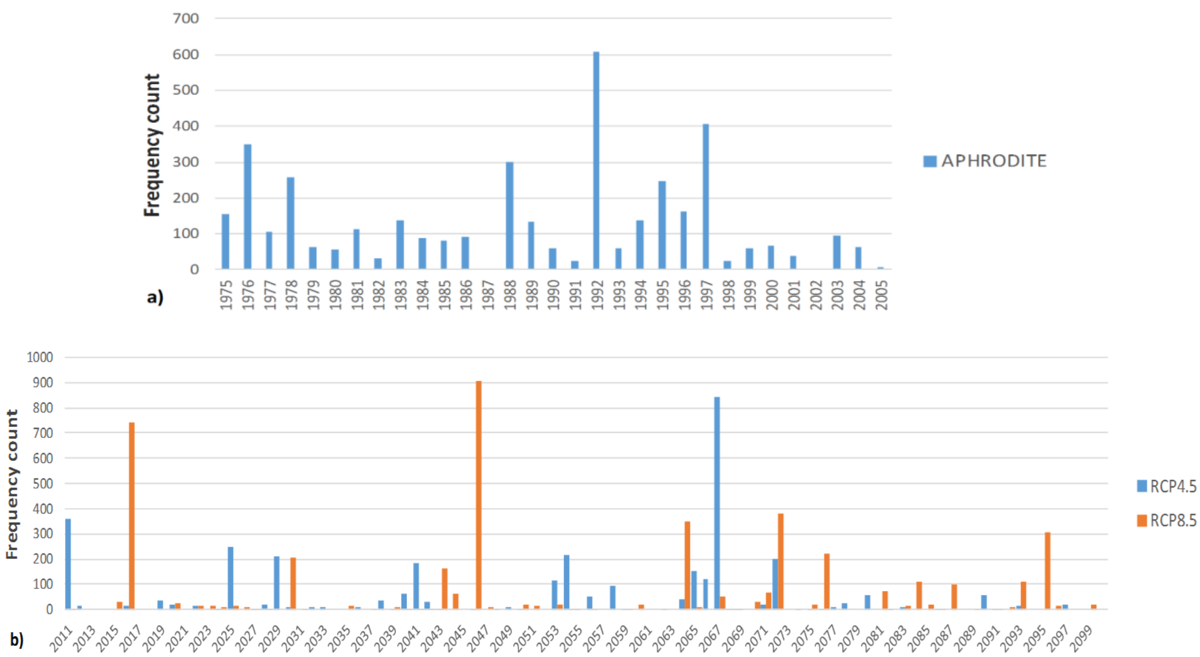


Figure 12: (a) frequencies ≥50 mm/day calculated over Pakistan for the base period of 1975-2005 and **(b)** for CCSM4 future scenarios.

extreme rainfall well below our defined values. Therefore, the contribution from such regions is not present in the calculated indices. As most of the extreme events over Pakistan mainly occur in the monsoon season and the key regions of monsoon such as coastal areas of Sindh and monsoon belt, precipitation received in these areas is well above our defined threshold of 50 mm/day.

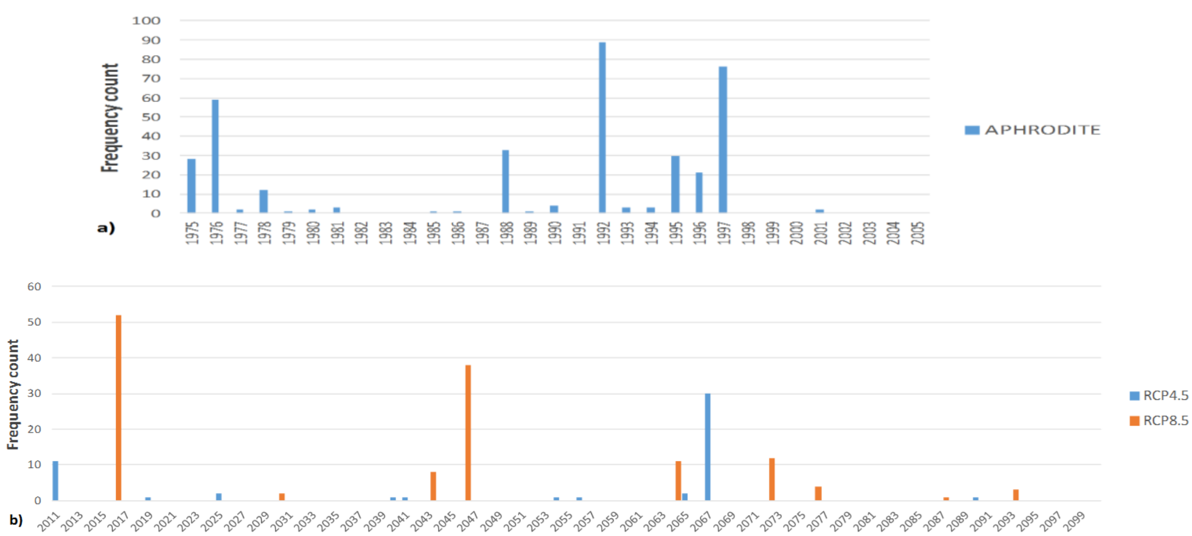


Figure 13: (a) frequencies ≥100mm/day calculated over Pakistan for the base period of 1975-2005 and **(b)** for CCSM4 future scenarios.

The decreasing trends in the frequency of heavy rainfall events indicate increasing number of dry days in the season (figure 16 b). Consistent with changes in summer mean precipitation, the decreasing trends over most areas of Pakistan, the frequency count summed over the domain show the fewer number of events as compared to a baseline which is also represented in the spatial analysis of these events in the figures later. Kitoh et al 2013 found a 10 to 25 % increase in SDII (Simple precipitation Daily Intensity Index) along with 10 to 25 % increase in consecutive dry days as well under RCP 8.5 scenario. Hsu et al 2013 suggested ENSO (El Niño Southern Oscillation) as a potential predictor of global monsoon precipitation under a warming climate. As the relation between the two strengthens it reinforcesthe intensity of rainfall variability. Their study suggested increase in Global Monsoon Precipitation (GMP) and Global Monsoon Intensity (GMI) by 3.2 % and 1.3 % respectively per 1 K of surface warming under the RCP4.5 scenario.

Decline in a number of events greater than 50 mm/day is significant in the last decade of the baseline period. A similar trend is noticeable in the future scenarios. However, future scenarios show mixed trends in the decadal variability, e.g RCP 4.5 scenario show a significant decreasing trend in frequency until mid of 21st century. This is consistent with finding of Yen Yi Loo et al 2015, suggesting intensification of active-break cycles with an increase of CO_2 in the atmosphere. Semenov, V. A. & Bengtsson, L, 2002, Turner, A. G. & Slingo, J. M, 2009, Tebaldi et al , 2006 also suggested a consistent decrease in a number of wet days with increased intensity of South Asian monsoon rainfall in the models (Precipitation summed over the number of wet days). Decadal trends for events greater than or equal to 50 mm/day are mentioned in table 1.

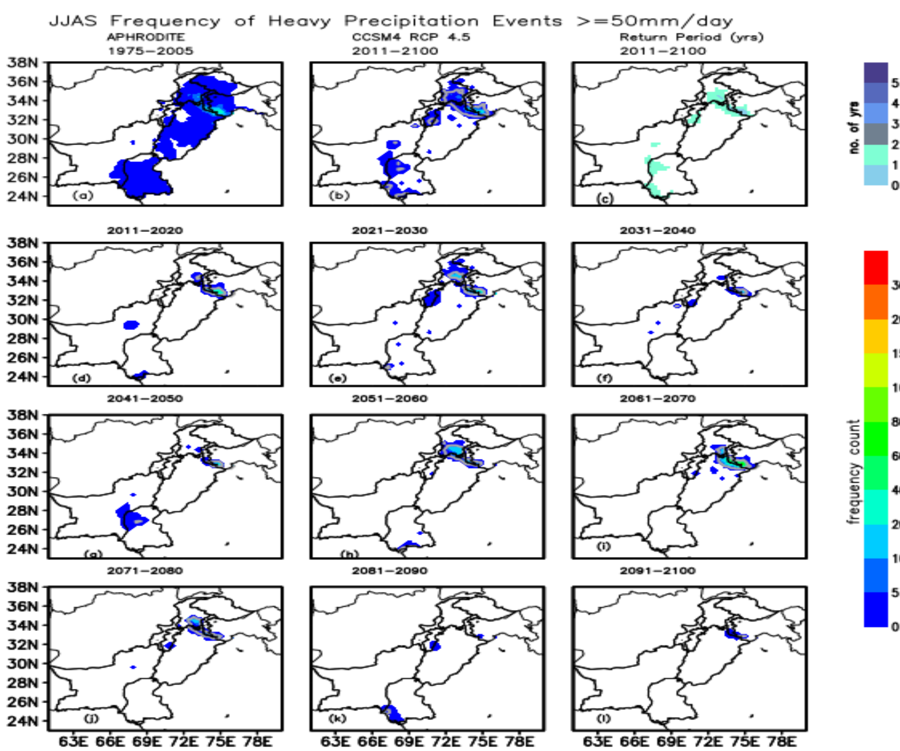
Table 1: Trend and probabilities heavy precipitation frequencies (≥ 50 mm/day)

APHRODITE	**Trend**	
1975-1985	-15.7	
1986-1995	15.5	
1996-2005	-22.34	
1975-2005	-2.47	
CCSM4 RCP4.5	**Trend**	**Probability %**
2011-2020	-17.7	84
2021-2030	7.86	60
2031-2040	3.76	92
2041-2050	-10.89	92
2051-2060	-4.2	38
2061-2070	14.45	36
2071-2080	-5.8	58
2081-2090	2.7	83
2091-2100	0.32	30
2011-2100	-0.2	50
CCSM4 RCP8.5		
2011-2020	5.56	16
2021-2030	9.9	85
2031-2040	0.63	69
2041-2050	0.62	2
2051-2060	0.13	11
2061-2070	-3.69	23
2071-2080	-18.5	80
2081-2090	-4.69	64
2091-2100	-4.8	33
2011-2100	0.12	18

The spatial distribution and decadal variation in the trends of heavy precipitation events under the two scenarios are presented in figure 14 and 15. The distribution of frequencies for both thresholds over space and time are consistent with changes in mean summer precipitation and distribution of dry days over space and time (figure 7, 9, 16, and 17 respectively). This coupling pattern (increasing dry days and decreasing wet days) was also diagnosed by B. Wang et al, 2012, Turner et al 2009. They found that the enhanced summer monsoon directly induces a ‘‘wet-gets-wetter’’ trend pattern besides enhancing the annual cycle and indirectly induce a ‘‘dry-gets-drier’’ trend pattern through monsoon desert coupling with the drying trend in Arid regions due to descending motion of air produced by increased monsoonal heating and convection.

The monsoon precipitation decreases over time and along with it, the frequency of heavy precipitation events also decreases. The spatial variation of heavy precipitation events is also consistent with the change in the mean summer precipitation patterns i.e shift of the summer monsoon further towards the northeast. Higher frequency heavy precipitation events (≥50 mm/day and ≥100 mm/day) are concentrated in the northeast in both observation and model. Here we see a consistent pattern with the time series that the events ≥100 mm/day are only confined in the region representing ≥100 frequency count of ≥50 mm/day events over each decade under both RCP scenarios and baseline. There is also a consistent pattern of higher frequency heavy precipitation events being confined in the northeast. Time series analysis of dry days under RCP 8.5 scenario show high confidence in the overall increase at the rate of 420 events per year in a 21st century. RCP 4.5 also show an increase in a number of dry days at the rate of 130 events per year (Table 2 and figure 16), consistent with the previous results. The declining trends in heavy precipitation events with more frequent dry days are also suggested by Kulkarni, 2012. Figure 7, 9 and 16 are consistent with results of (Dash et al., 2009) suggesting increasing monsoon breaks over India with an overall decrease in seasonal mean rainfall and decrease in light rain events during summer monsoon (Goswami et al., 2006). Return periods of events above 50 mm/day thresholds under both RCP scenarios are presented in figures 14.1 c and 15.1 c respectively. The key areas of heavy rainfall events show return periods of two years including coastal areas of Sindh, some parts of KPK and monsoon belt. Some regions within the monsoon belt indicate return periods of one year as well. Therefore representing that the key areas of monsoon belt likely to receive heavy rainfall every year, however, the coastal areas of Sindh along with topographically prominent areas of Balochistan, Sindh and Southern KPK are likely to receive heavy precipitation every two years.

(14.1)



(14.2)

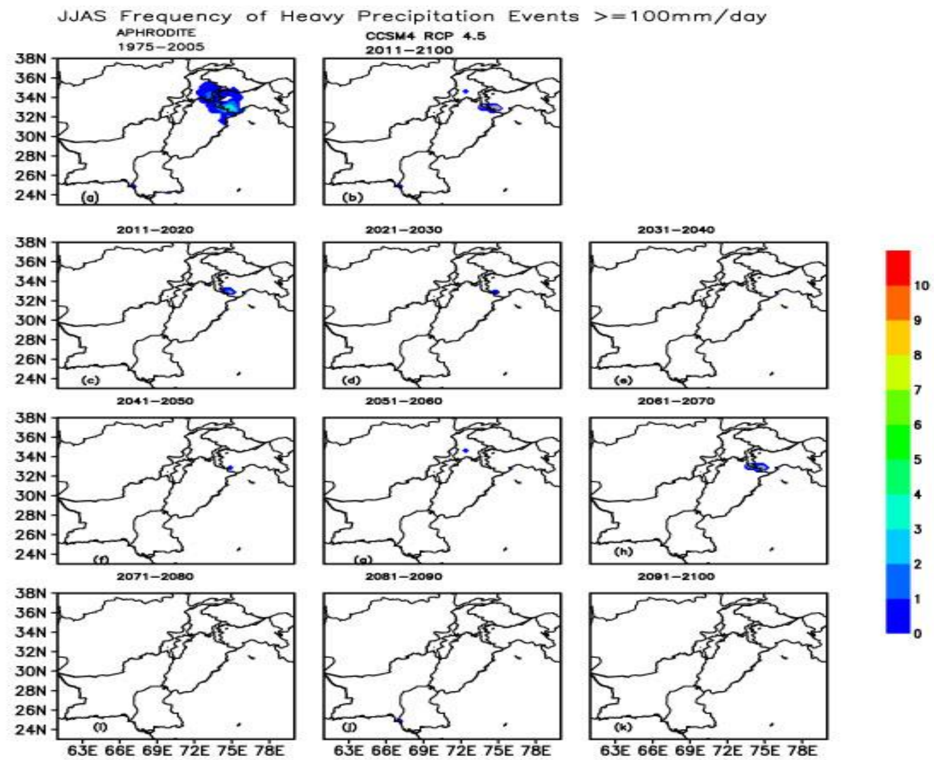
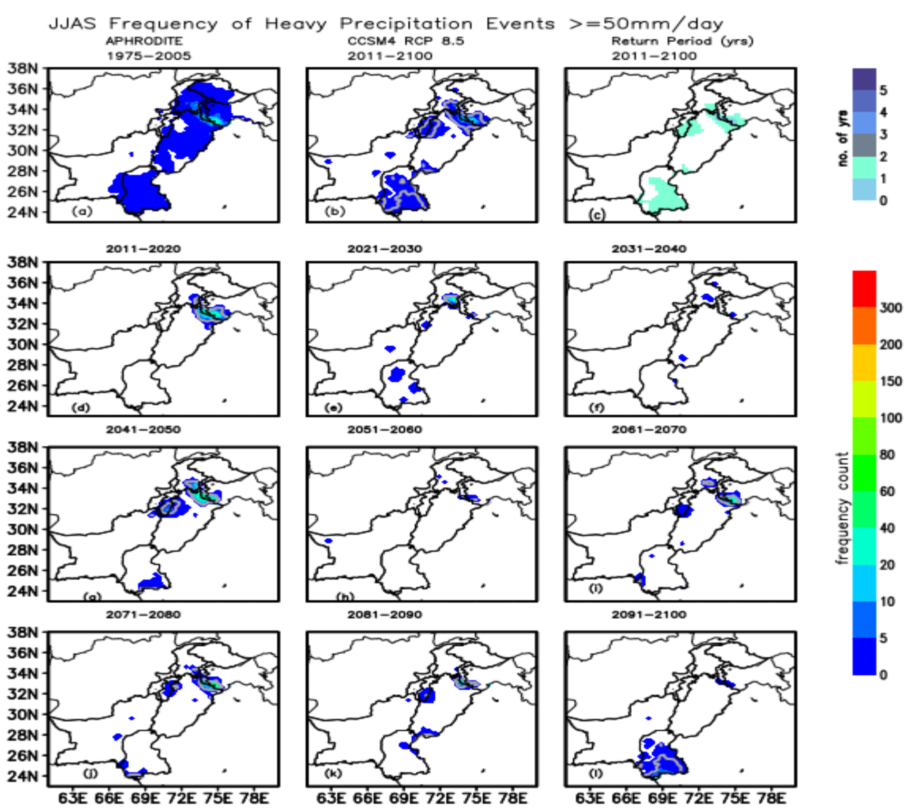


Figure 14: RCP 4.5 Spatial Distribution of heavy precipitation events greater than or equal to 14.1)50 mm/day and 14.2)100 mm/day thresholds. Grey contours show probability ≥ 90 %

(15.1)



(15.2)

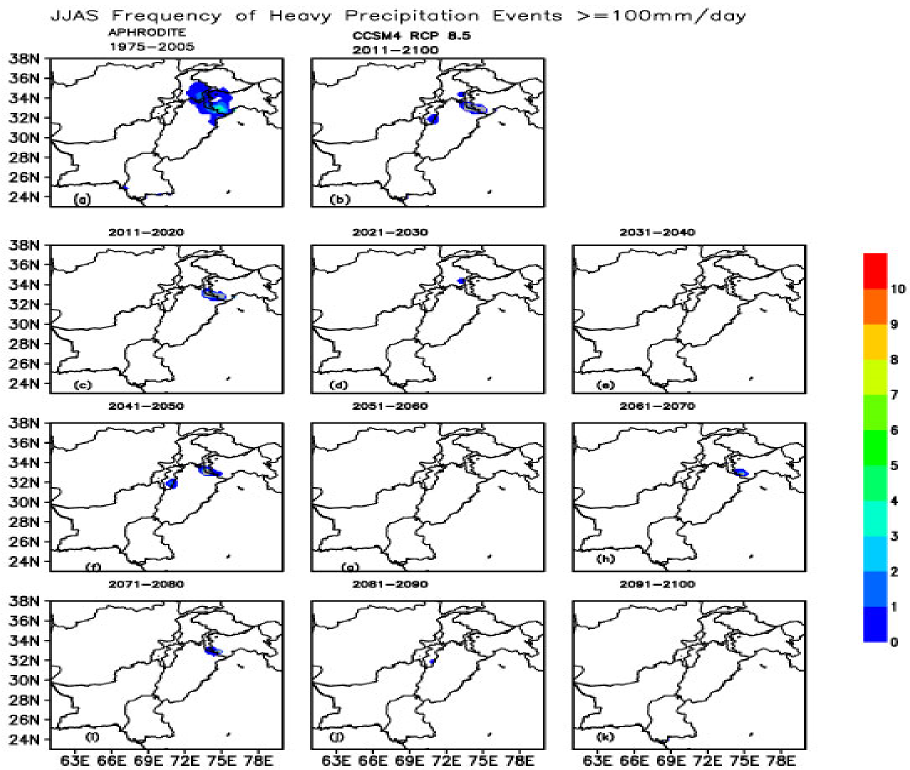


Figure 15: RCP 8.5 Spatial Distribution of heavy precipitation events 15.1) ≥50 mm/day and 15.2) ≥100 mm/day thresholds. Grey contours show probability ≥ 90 %.

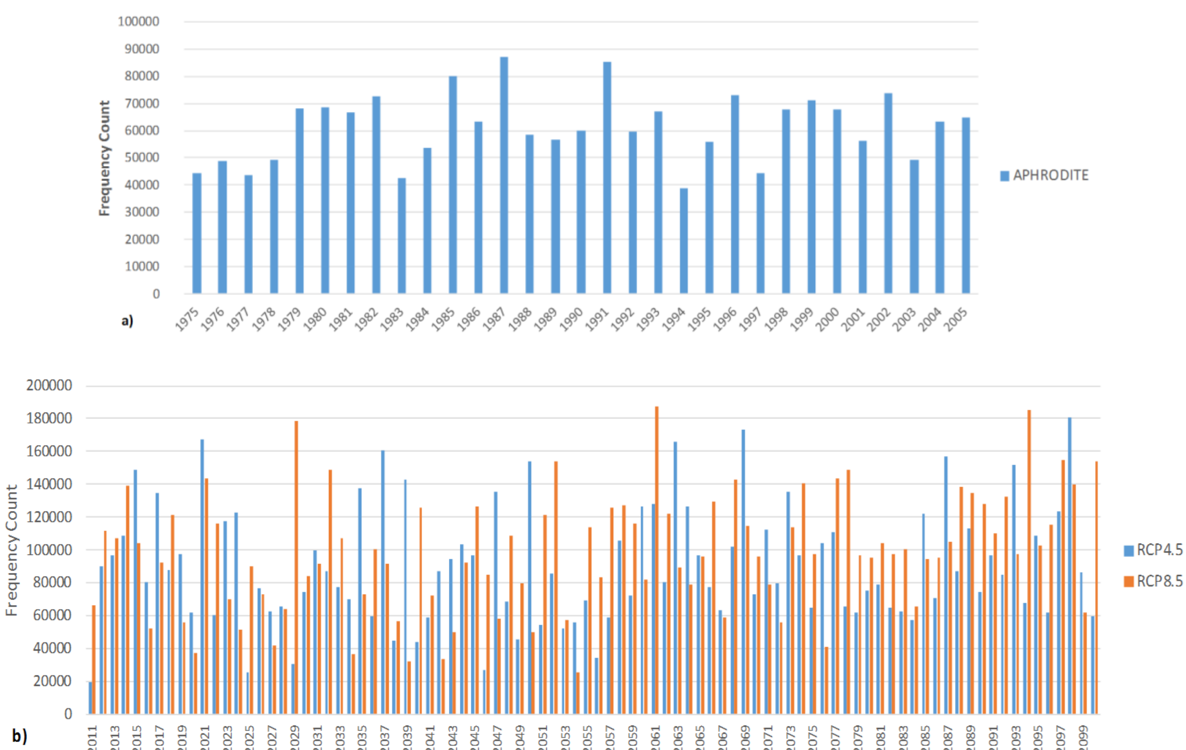
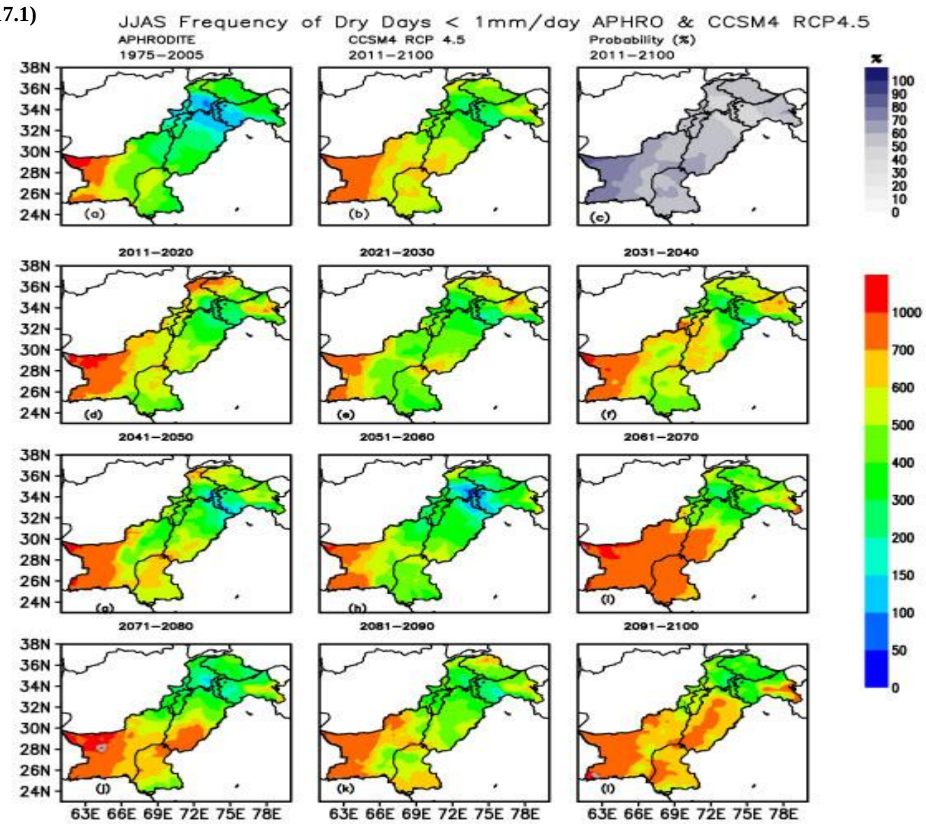


Figure 16: JJAS Dry days <1mm/day frequency count of Observation (a) and future scenarios (b).

The decadal analysis of dry days frequencies shows mixed trends (Table 2). However, there is an overall positive trend over baseline and in future scenarios. Spatial distribution and decadal variation of the dry days during summer season under the two RCP scenarios is presented in figure 17. Under both scenarios, the number of days during the season depict increase. In the monsoon belt region (defined earlier) the trend is 10 dry days per season, however, under RCP 4.5 scenario the number of dry days increases to 30 to 40 days per season and 70 to 80 dry days under the RCP8.5 scenario.

The highest number of dry days (up to 100 days per season) is only confined to south-west Balochistan during the reference period. This trend further extends towards the north of the province in RCP 4.5, towards Sindh and South Punjab in RCP 8.5 scenario for the period of 2011-2100. Decadal trends show a sharp increase in the frequency of dry days over northwestern parts of GB and KPK especially during 2011-2020 under both RCP scenarios. After mid 21st century, the spatial distribution of high-frequency dry days extends to most parts of the country including Kashmir and GB. The probability distribution over space is shown in figures 17.1 c and 17.2 c. The southern parts of Pakistan show higher probability (≥70 %) of increasing dry days especially over Balochistan and Southern Punjab whereas 40 to 50 % probability is represented over the monsoon belt area under both RCP scenarios. Considering the overall trend in a number of dry days summed over Pakistan, RCP 8.5 show a very likely increase in the number of dry days in the 21st century which is consistent with the IPCC AR5, recommending a virtually certain increase in the number of dry days hence increasing the risk of droughts in the coming decades. Several studies have suggested that the majority of models underestimate the sensitivity of extreme precipitation to temperature variability or trends especially in the tropics, including strengthened break in monsoon-related to Madden-Julian Oscillation (MJO) which could result in underestimated projected increase in extreme precipitation in the future (IPCC, AR5). The changes in the mean and extreme precipitation events under both warming scenarios show good agreement between the results presented. Therefore, based on the outcome of this analysis, a higher risk of intense drought prevailing over most parts of the country and fewer but intense precipitation events are suggested.

(17.1)



(17.2)

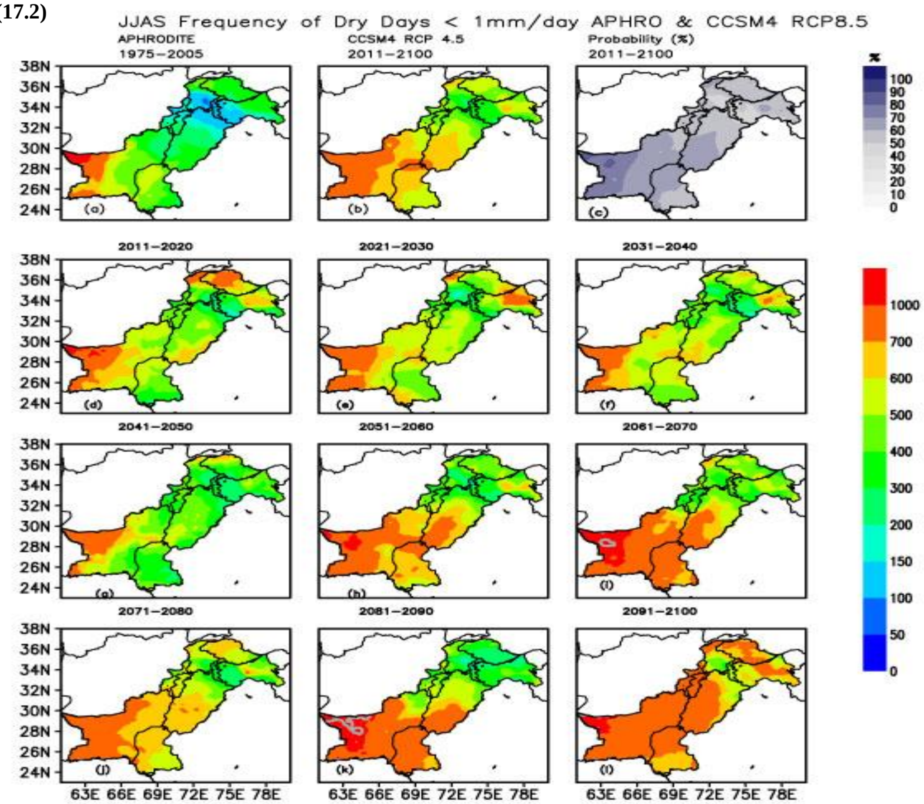


Figure 17: spatial variation of JJAS dry days (< 1 mm/day), 17.1) RCP 4.5 and 17.2) RCP 8.5

Table 2: Trend and probabilities of dry days (< 1 mm/day) frequencies over Pakistan

APHRODITE	**Trend**	
1975-1985	2187	
1986-1995	-2004	
1996-2005	-219	
1975-2005	252	
CCSM4 RCP4.5	**Trend**	**Probability %**
2011-2020	2427	43
2021-2030	-8691	94
2031-2040	-463	8
2041-2050	-2786	46
2051-2060	4809	90
2061-2070	-2254	38
2071-2080	-4387	90
2081-2090	4064	73
2091-2100	-329	6
2011-2100	130	63
CCSM4 RCP8.5		
2011-2020	4641	77

2021-2030	1062	16
2031-2040	3457	57
2041-2050	1639	37
2051-2060	-10.72	0
2061-2070	-3849	63
2071-2080	3420	57
2081-2090	4729	96
2091-2100	234	5
2011-2100	420	100

Conclusion

The uncertain role of aerosols, especially black carbon along with their direct and indirect effects complicates the nature of future projections of monsoon precipitation, particularly in the Asian monsoon, Meehl et al 2007, L. Guo et al 2016. Our findings of dampening of Summer Monsoon are consistent with the studies of IPCC AR4, Meehl et al, 2007, Ashfaq et al, 2009, Mian Sabir Hussain and Seungho Lee, 2009, Turner and Annamalai, 2012, B. Wang et al, 2012, IPCC AR5, 2013 and Roxy et al, 2015).

We have analysed the changing trends of extreme rainfall events under two different anthropogenic forcing scenarios. The results presented are in good agreement with each other. There is annual increase in temperature of 3°C to 4°C under RCP 4.5 and 3°C to 8°C under RCP 8.5 in the northern areas and 2°C to 3°C under RCP 4.5 and 5°C to 7°C under RCP 8.5 in the southern part of the country hence depicting accelerated rate of warming at high elevations. The annual precipitation also show an overall increase of 2 to 3 mm/day and 3 to 4 mm/day under RCP 4.5 and RCP 8.5 respectively. Seasonal cycle shows winters are warming more than summers (4°C difference) with 4°C to 6°C and 6°C to 8°C w.r.t baseline (1975-2005) rise in the 21st-century projections respectively. Spatial analysis of summer season show rise in temperature of the northern area during the first half of 21st century (2°C to 3°C) whereas in the late 21st century, the warming trend increases over the plain areas. There is a significant dipole like pattern in summer precipitation with a northeastward shift in it and interdecadal variability in the magnitude of change. The increase in precipitation over Monsoon belt is up to 4 mm/day whereas, the decrease in precipitation is up to 2 mm/day over southern parts of the country.

This the dry (negative change in precipitation) extends northwards with time due to rising temperatures causing a shift of the monsoon further towards north east and complete drying over Pakistan. This dipole like behaviour could be the result of direct aerosol effect leading to increasing in evaporation from the soil which in turn depends on the soil moisture. There is a high frequency of heavy precipitation events mostly confined in the north east region of the country (Monsoon belt). The frequency of heavy precipitation decreases over time with the higher probability of an increase in a number of dry days during the summer season. This implies that wet days are likely to become less frequent and intense with longer break periods. As a consequence of longer breaks with intense wet days, there is higher risk offlooding because the decrease in wet days along with a decrease in light and moderate rainfall will make the ground drier and harder due to a decrease in soil moisture. This will lead to the inability of the soil to absorb excess water in short time.

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