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Executive Summary

In northern sub-Saharan Africa and South Asia, large amounts of the population are predominantly rural and depend on rain-fed agriculture. Ecosystem and socio-economic welfare are vulnerable to a warmer climate and may be even more susceptible to regional variations of the global warming. In this report we analyse the sensitivity of the Sahel and of South Asia to variations in the SST in the tropical Atlantic and/or Indian oceans in a generally warmer climate.

In the Sahel, the primary finding is that response of the Sahel precipitation is not only controlled by the sign of tropical ocean SST anomaly but also by the relative difference between the Atlantic and Indian Ocean SST anomaly. If by the end of the 21st century the warming over the Indian Ocean exceeds the global mean we can expect a drier Sahel, while a stronger warming over the Atlantic Ocean would lead to a wetter Sahel.

In South Asia, both inter-annual variability and magnitude of oceanic forcing play a critical role on the South Asian monsoon (SAM). A robust drying response over the Indian subcontinent is caused by a stronger Atlantic and /or Indian Ocean warming. Under a weaker ocean forcing condition, a wetter SAM response is found which is associated with a strengthening/weakening of the land-sea thermal contrast. The response of extreme precipitation events to oceanic forcing are studied with an analysis of wet and dry spells during the SAM period. Compared to the historical period, all experiments tend to produce more enhanced wet/dry extreme events over the central Indian subcontinent. The prolonged dry spells in the future climate are more robust with warm tropical SST anomalies.

Documentation of the impact of regional tropical SST changes at high-end SWLs on Sahel climate and the Indian monsoon

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1. Introduction

The Sahel region of West Africa is a semiarid region along the southern edge of Sahara desert. Rainfall inter-annual and multi-decadal variability associated with the West African Monsoon (WAM) is one of the most important factors for social-economic activities in this vulnerable region. The West African Sahel has been suffered from a prolonged severe drought during the 1970s and 1980s. After the 1980s, a partial recovery of Sahel rainfall is observed (Hagos et al, 2008). Understanding the key factors for Sahel rainfall variability is of fundamental importance.

Earlier studies on the causes of Sahel rainfall variability are motivated by land-sea thermal contrast between Africa and surrounding oceans (e.g. Hagos et al., 2008; Martin et al., 2014). Sea Surface Temperature (SST) is one of the most important factors connecting with air-sea interaction. Over tropical ocean, warm SST changes generally tend to cause deep convection, which further excites large-scale dynamical response and strong surface wind signals (Xie, 2004). This robust relation is critical in understanding certain phenomena, e.g. Sahel drought, Western African and South Asian Monsoons. In addition to the SST impact, anthropogenic greenhouse-gas (GHG) (Dong and Sutton, 2015) and aerosol forcing (Ackerley et al, 2011) are also identified as the most important drivers associated with Sahel rainfall. In this report we try to shed light on the changes of Sahel rainfall variability combing the impacts of SST warming and greenhouse-gas forcing under the RCP8.5 scenario.

The South Asia Monsoon (SAM) is one of the most important components of the global climate system. The SAM is characterized as a system of moisture-carrying winds driven by the land–ocean thermal contrast that develops as the land heats up faster than the ocean in the summer (e.g. Singh, 2016). Krishnan et al. (2015) point out that GHG emissions and the rapid warming signal of the equatorial Indian Ocean are responsible for the observed monsoon weakening changes in rainfall patterns that are expected to continue to the end of twenty-first century. The slowly varying lower boundary condition (e.g. SST) plays a critical role on the predictability of seasonal monsoon rainfall (Charney and Shukla, 1981; Shukla, 1998). The interaction between the thermal wind-driven and moisture-driven effects govern the overall response of the monsoon rainfall to changes in GHG concentrations (Singh, 2016; Krishnan et al., 2015). It is crucial to understand the relationship between SST warming and changes in precipitation/heating that are associated with ocean-to-atmosphere interaction processes (Wu et al., 2008). Here we will investigate the impact on the SAM of a warmer/colder SST anomaly in the tropical ocean on top of the general warmer climate at the end of this century.

A description of the design of the sensitivity experiments is given in the next section. The purpose of this report is to find out the potential answers for the following questions:

1. How will the Sahel rainfall vary in the future if a warming in the tropical Atlantic Ocean and/or Indian Ocean continues under RCP8.5 scenario?
2. What's the impact of magnitude of SST warming under RCP8.5 scenario?
3. What's the influence of oceanic forcing on Sahel rainfall on inter-annual and decadal variability?
4. What's the role of a different warming in the tropical ocean basins, their individual and their combined effects on the forcing of Sahel rainfall and SAM?
5. What's the response of the SAM intensity and associated extreme events to the SST anomalies in the Atlantic and/or Indian Ocean?

The answers to these questions will help us to better understand the role of the tropical ocean SST in a warmer climate.

2. Experiment design

The strength and range of future African and South-Asian Monsoons show large variability among different model simulations which is reflected in the rainfall trends and magnitudes (Figure 1). This variability is to some extent controlled by the heating in the Atlantic and Indian Ocean basins.

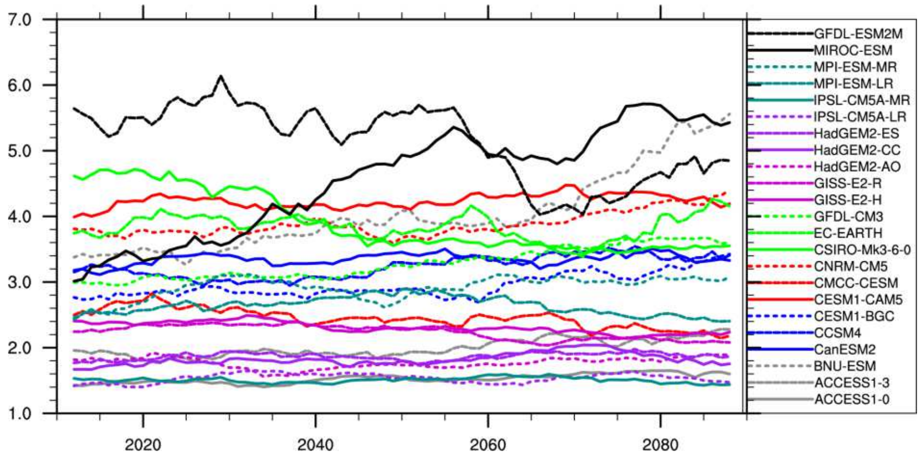

Figure 1. Mean JAS Sahel rainfall (10°W-30°E,10°-20°N) during twenty-first century from CMIP5 models (unit: mm/day).

In order to assess the role of the different ocean basins for the Sahel rainfall and Indian monsoon in a warmer climate, we run the EC-Earth 3.1 model in atmosphere-only mode (AMIP) with T255 spectral truncation (~80 km) and 91 vertical levels. A brief description of the model is given in the supplementary material of Alfieri et al (2017) yet we emphasize that here we use the same model with coarser horizontal resolution.

The control experiment is done with the SST and sea-ice forcing from the EC-Earth CMIP5 experiment. We then replace the SST anomaly relative to 1980-2000 in the tropical Atlantic and/or the Indian Ocean by the SST anomalies from a warm and from a cold CMIP5 model in a series of sensitivity experiments (Figure 2).

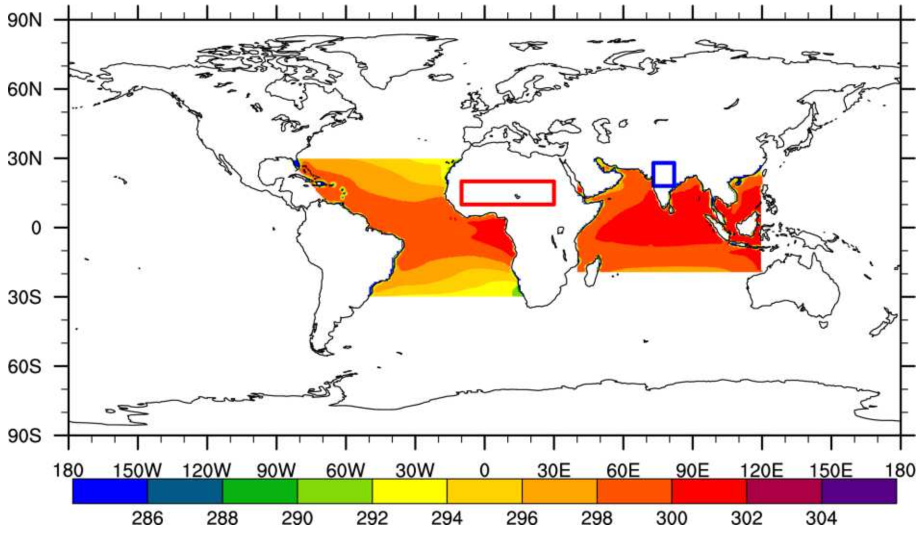

Figure 2. Annual mean SST from EC-Earth between 1980-2000 showing the region in the tropical Atlantic Ocean and Indian Ocean where SST anomalies are added. The red square region denotes the Sahel region (10°W-30°E, 10°-20°N).The blue square region denotes the central Indian subcontinent (8°N-28°N, 68°E-88°E).

The warm SST forcing is taken from the IPSL-CM5A-LR model that has the largest climate sensitivity among CMIP5 models, while for the cold SST forcing we use the GFDL-ESM2M model that has the smallest climate sensitivity in the

RCP8.5 scenario (Figure 3). The anomalies for each forcing model are computed with respect to the 1980-2000 climatology of the same model and then added to the EC-Earth climatology in the tropical Atlantic and/or Indian Ocean. A smooth weight is applied in a transition zone at the edges of the sensitivity region to avoid discontinuities in the SST field.

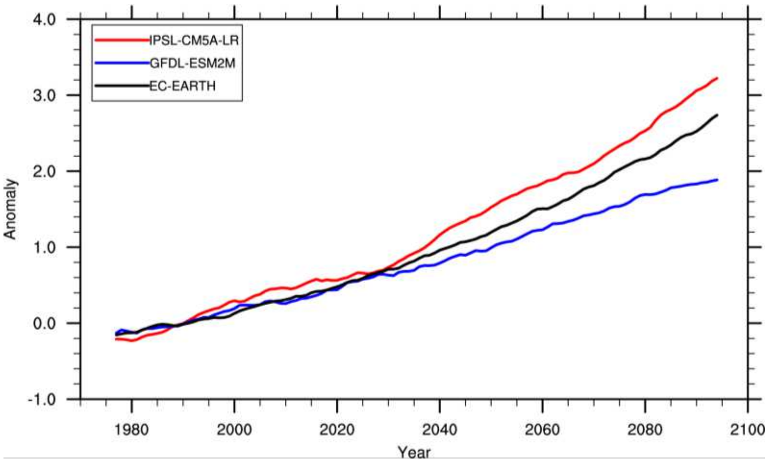

Figure 3. The annual mean anomalies in the tropical Atlantic Ocean from IPSL-CM5A-LR, GFDL-ESM2M and EC-Earth models (unit: K)

In order to estimate the role of the different and combined ocean basin forcing, six sensitivity experiments have been performed (see Table 1). In the table, “Warm Atlantic Ocean” and Warm Indian Ocean” refers to the SST anomalies from the IPSL-CM5A-LR model, while “Cold Atlantic Ocean” and “Cold Indian Ocean” denotes the SST anomalies from GFDL-ESM2M model. All simulations are carried out from 1970 to 2100.

Table 1. Descriptions of sensitivity experiments

Experiments name	**Prescription of SST**
ATL_W	Warm Atlantic Ocean
ATL_C	Cold Atlantic Ocean
IND_W	Warm Indian Ocean
IND_C	Cold Indian Ocean
ATLIND_W	Warm Atlantic + warm Indian Ocean
ATLIND_C	Cold Atlantic + cold Indian Ocean

3. Impact of tropical SST on Sahel climate

In West Africa, the local environment, particularly agriculture over the Sahel is vulnerable to climate change due to strong climate forcing, with variability in precipitation being the key parameter. Extreme conditions always lead to dire consequences for African society. Figure 4 shows the mean JAS Sahel rainfall (10°W-30°E, 10°-20°N) from 1971 to 2100 in all experiments, revealing a strong multi-decadal variability. During the historical period, the average SST in the Atlantic and Indian Ocean is equal in the control and in all sensitivity experiments by design, yet the inter-annual variability is different in the different experiments which leads to a variability in the simulated rainfall even during the historical period. Both ATL_C and ATL_W experiments lead to a slightly wetter Sahel while both IND_C and IND_W lead to reduced precipitation over the Sahel region (Figure 4). These results indicate that not only the time averaged regional SST warming matters for the precipitation response over the Sahel, but also the inter-annual variability of the warming.

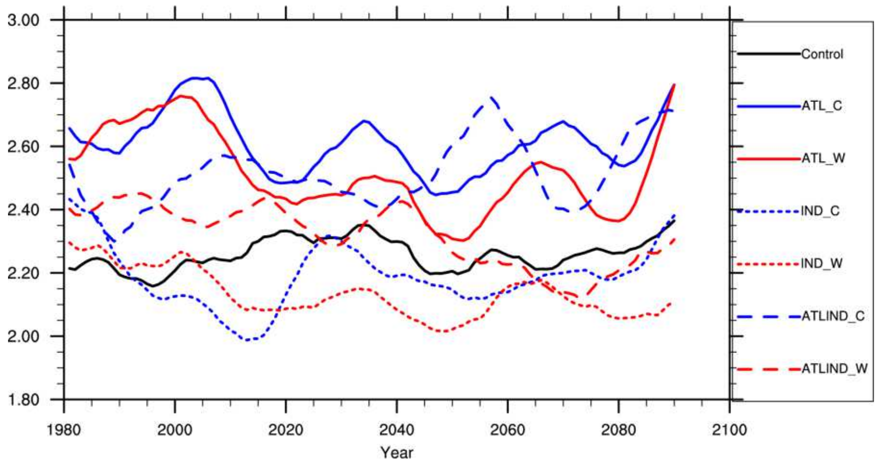

Figure 4. Mean JAS rainfall over the Sahel (10°W-30°E, 10°-20°N) from all sensitivity experiments (unit: mm/day)

With increasing global warming levels towards the end of the 21st century, the response of the precipitation over the Sahel is split into two groups: wetter when the Atlantic SST is warmer or colder than in the control run, and drier when the Indian SST is warmer or colder than in the control run. This result again suggests that the response of the Sahel precipitation is not only controlled by the general warming but also by the variability of the SST. An interesting response is found for the ATLIND_W and ATLIND_C experiments: ATLIND_C leads to more precipitation in the Sahel while ATLIND_W leads to reduced precipitation. If SST in both Atlantic and Indian Ocean are colder than the response in Sahel precipitation follows closer the response from only a colder Atlantic SST, while with warmer SST in both basins the response in the Sahel is similar to that from only a warmer Indian Ocean. Thus we find that the response of the Sahel precipitation can be governed by either the tropical Atlantic or Indian Ocean, depending on the magnitude of the warming and their relative difference in the two ocean basins. Previous studies have recognized the tropical Atlantic Ocean to be the main cause of the partial recovery of the precipitation after the 1990s over the Sahel (Hagos et al., 2008).

The cluster of experiments that leads to a wetter Sahel by the end of the 21st century shows more inter-decadal variability than the other cluster with experiments that yield a drier Sahel. Apart from the large inter-decadal variability, the “wetter” cluster shows only a positive weak trend during the 21st century towards more precipitation, while the “drier” cluster has less inter-decadal variability but a stronger negative trend towards drier conditions over the Sahel. However, none of the trends in either of the clusters is particularly strong. The CMIP5 simulations in Figure 1 also show quite large variability yet most of them show non-significant trends in future Sahel rainfall projections. Our experiments also show considerable variability (Figure 4) yet the magnitude and relative difference between Atlantic and Indian Ocean reveal a stronger and distinct influence on the Sahel rainfall. If by the end of the 21st century the warming over the Indian Ocean is larger than the global mean we can expect a drier Sahel, while a pronounced warming over the Atlantic Ocean would lead to a wetter Sahel.

To study the impact of the SST forcing on the seasonal rainfall distribution we look at the differences in the Sahel rainfall pattern between future projections and the historic period. Figure 5 shows mean annual rainfall cycle averaged between 20°W-10°E during 1971-2000 (contours) and the difference between 2070-2099 and 1971-2000 (shaded). This time-latitude diagram illustrates the North-South propagation of the precipitation band during the West Africa Monsoon (WAM) season. The tropical Atlantic Ocean forcing displays strikingly different impacts south of the Equator: a warm Atlantic Ocean leads to less precipitation over the Gulf of Guinea during winter and spring at the end of the 21st century, while a cold Atlantic increases the precipitation. Over the Sahel, a warmer Atlantic Ocean (ATL_W experiment) tends to intensify the precipitation during the WAM in a generally warmer climate. The wet response over the Sahel is weaker if the Atlantic SST is colder (ATL_C), and in particular it doesn't reach as far North as during the present-day period which reveals the non-linear complexity of atmospheric response to oceanic forcing. Both IND_C and IND_W experiments lead to increased precipitation in the Sahel during the WAM yet the response is stronger with a warmer Indian Ocean. Over the Gulf of Guinea and adjacent coastal areas, IND_C leads to more precipitation at the end of the 21st century in February and March, while IND_W leads to less precipitation in the same region during April and May. In the combined sensitivity experiments with both Atlantic and Indian SST higher (lower) than normal, we find a similar yet weaker response as in the case with only the Atlantic forcing. Interestingly, the precipitation response in the Sahel and in the Gulf of Guinea to warmer (colder) SST over either Atlantic or Indian Ocean is stronger than if the warmer conditions would be found in both ocean basins simultaneously. This again demonstrates the complex non-linear response of the Sahel precipitation to the SST forcing in different regions.

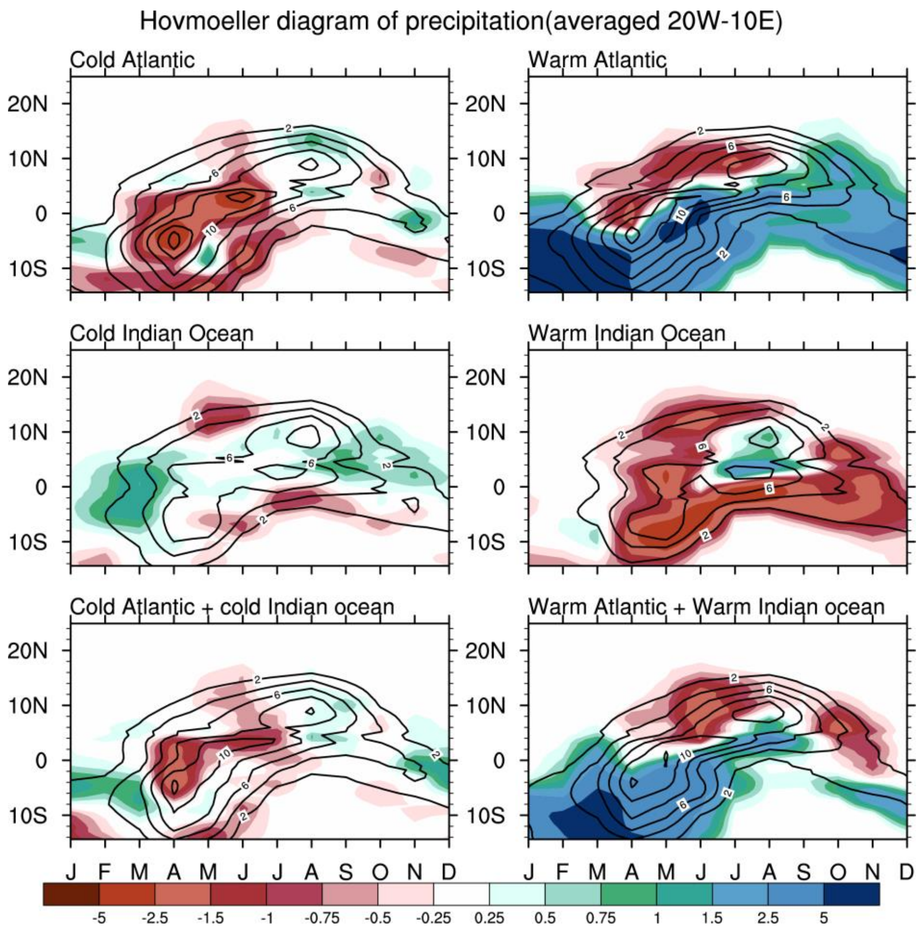

Figure 5. Mean annual rainfall cycle averaged between 20°W-10°E (contour: average between 1971-2000; shaded colours: differences between 2070-2099 and 1971-2000) (unit: mm/day)

To further analyse the regional response of the precipitation we look at the difference between the precipitation in the periods 2070-2099 and 1971-2000 (Figures 6 and 7). Here we focus on the WAM season and show only the plots for April-June (AMJ, WAM onset) and July-September (JAS, WAM peak). The largest differences in precipitation over land between future climate and present-day are found if the Atlantic and/or Indian Ocean SST are warm, with a warm Indian Ocean leading to the largest differences. During the onset of the WAM season (Figure 6), a warm Indian Ocean yields less precipitation at the end of the 21st century over the entire sub-Sahara with little latitudinal variation. On the other hand, a warm Atlantic Ocean would yield less precipitation in the western part, but more precipitation in the eastern part of the sub-Saharan region. In the peak phase of the WAM season (Figure 7) we find a less pronounced response in the regional precipitation change pattern to different SST forcing, the largest differences are found in the precipitation over the Gulf of Guinea. Over land areas in sub-Saharan Africa, the response to a warm Atlantic or Indian Ocean is always a slight increase of precipitation, in particular over the central parts of Sahel, while the response in Western Africa is either weakly positive or neutral. As noticed earlier the response in seasonal precipitation to a warm SST forcing in the Atlantic and/or Indian Ocean is not linear: the response to a combined warm SST Atlantic and Indian Ocean forcing is weaker (more neutral) than with any of the individual forcing. Under a warmer oceanic forcing condition, the pattern of the precipitation change response of the combined Atlantic and Indian Ocean SST forcing resembles strongly the response to the Atlantic only SST forcing, yet the response is weaker. Thus we may conclude, in agreement with other studies (Hagos et al. 2004) that a warmer Atlantic SST forcing plays a dominant role for the precipitation over sub-Saharan Africa (Held et al., 2005; Held et al., 2006). Similarly, the influence of the Indian Ocean on the Sahel precipitation is on a primary role associated with colder oceanic forcing.

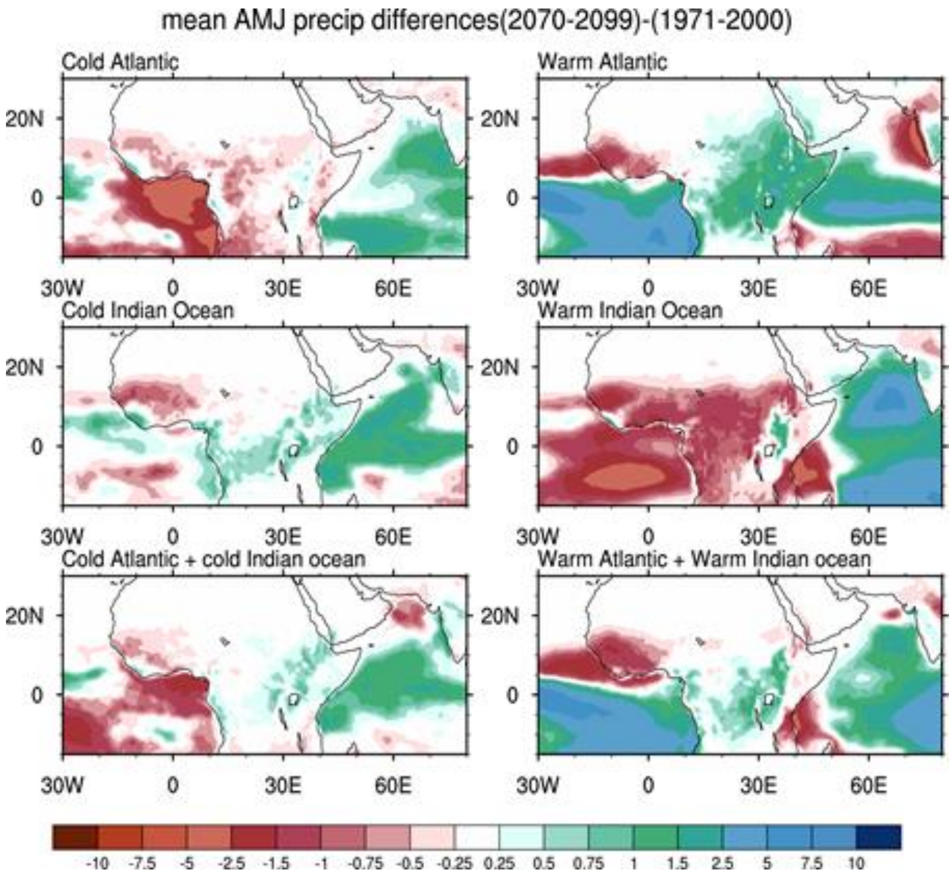

Figure 6. Mean precipitation differences between (2070-2099) and (1971-2000) in AMJ (unit: mm/day)

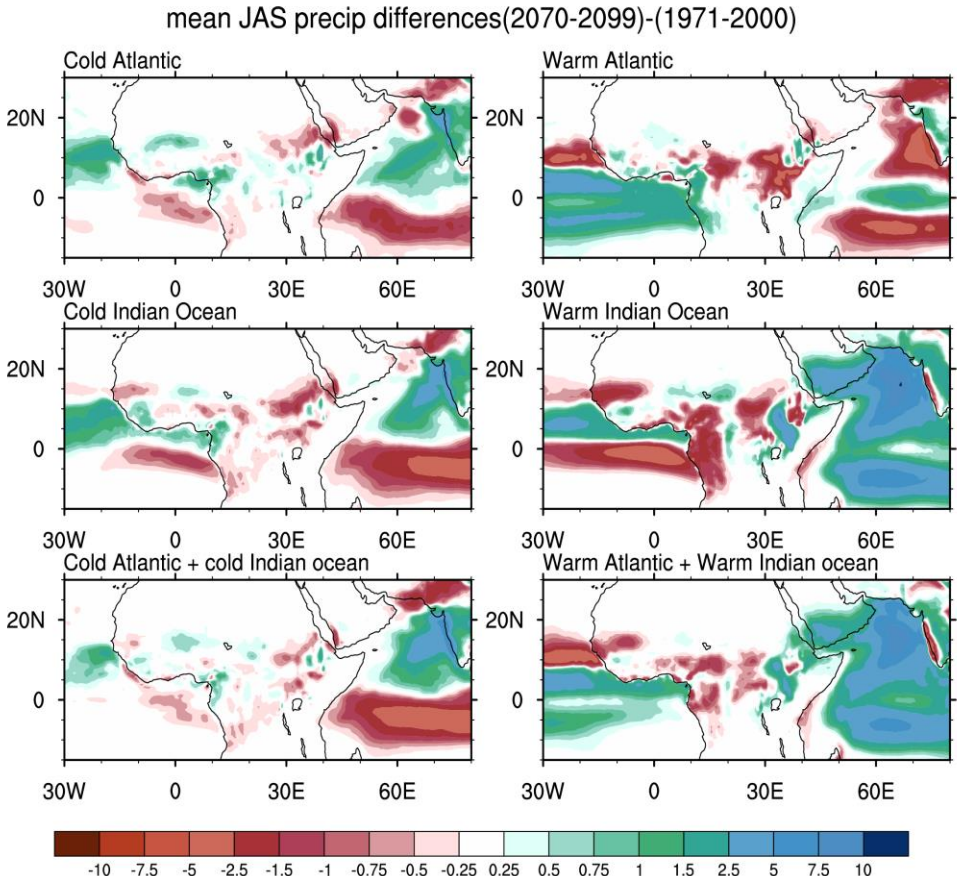

Figure 7. Mean precipitation differences between (2070-2099) and (1971-2000) in JAS (unit: mm/day)

The Gulf of Guinea shows an interesting response to Atlantic and Indian Ocean SST forcing: precipitation decreases (increases) with a warm Indian (Atlantic) Ocean SST forcing, and vice versa for the cold SST forcing. In contrast to the land areas where the response to the precipitation change was independent of the region of the SST forcing (at least over Western Africa).

During WAM peak season, the rainfall variability is associated with the coherent changes of surface temperature. Figure 8 shows the mean JAS T2m changes between 2070-2099 and 1971-2000. All sensitivity experiments show an intense high near surface temperatures anomaly across the Sahara desert which plays a key role in the development of the Sahara Heat Low (SHL) at 25°N. This thermal gradient between cold SSTs in the Gulf of Guinea and the high surface temperature over the Sahara are the primary forcing mechanism for the WAM (Dixon et al. 2017). The distribution of north-south temperature gradient is partly responsible for the dry and wet biases of precipitation along ITCZ. Our results indicate that less warming in the ocean basins will intensify the north-south temperature gradient, which is partly related with the west Sahel drought recovery (Figure 8, ATL_C, IND_C and ATLIND_C experiments). In the strong Indian Ocean forcing experiments (IND_W and ATLIND_W experiments), large T2m warm biases are simulated over almost the whole continent, which tend to weaken the north-south temperature gradient and to favour a weaker SHL.

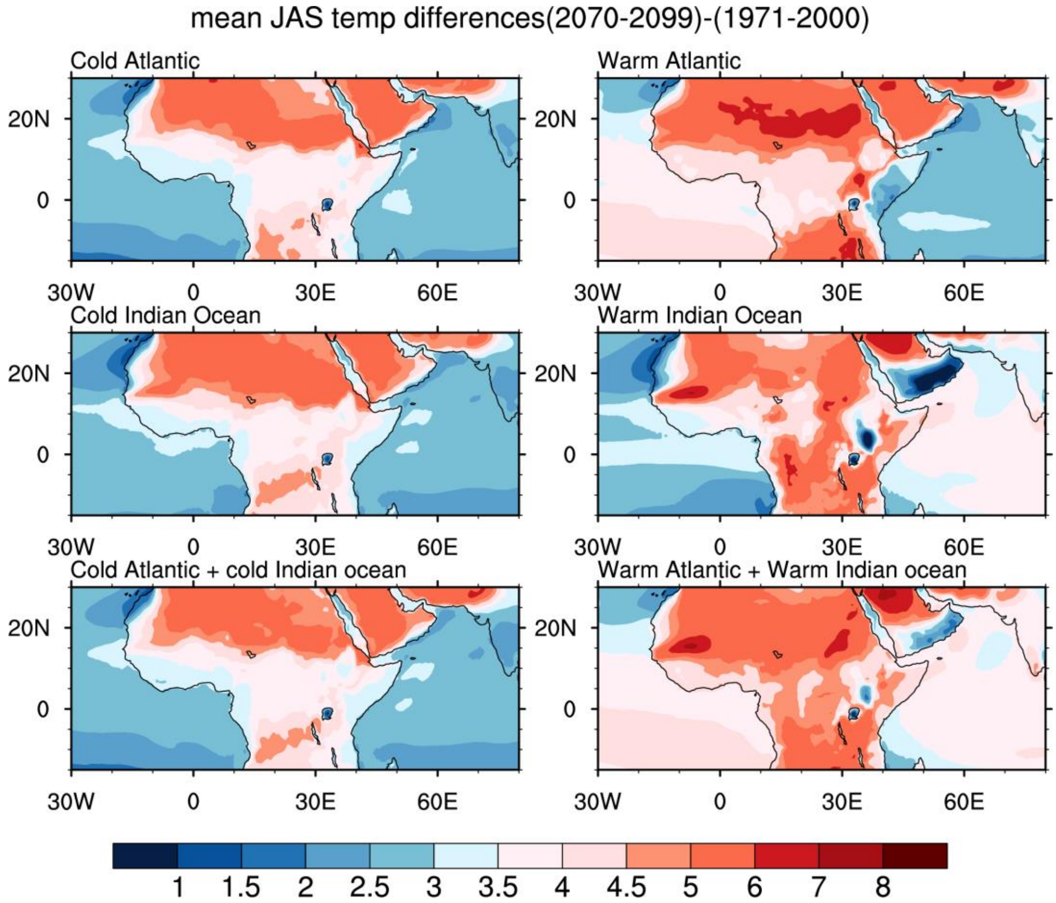

Figure 8. Mean T2m differences between (2070-2099) and (1971-2000) in JAS (unit: K)

The strong surface temperatures gradient between the Sahara desert and its surroundings leads to the formation of the SHL. The variability of SHL has been identified to cause variations in the Sahel rainfall (Biasutti et al. 2009). The low level circulation associated with the SHL brings moisture rich air into the Sahel region to help fuel convection and precipitation across the Sahel during the WAM (Biasutti et al. 2009; Lavaysse et al.2009). The northward propagation of SHL is shown in Figure 9 with contours for the average temperature in the 10W-10E region during the 1971-2000 period, and shaded colours for the difference between 2070-2099 and 1971-2000. In the experiments with cold SST anomalies (Figure 9, left column) the temperature response at the end of the 21st century is restricted to a narrow band throughout the whole year. On the contrary, the warm SST anomalies (Figure 9, right column) lead to a more widespread and stronger warming, mainly from April to September. At the end of the WAM season (September-October), the warming response at the end of the century shows a quick and distinct cooling in the case of warm Indian Ocean SST forcing.

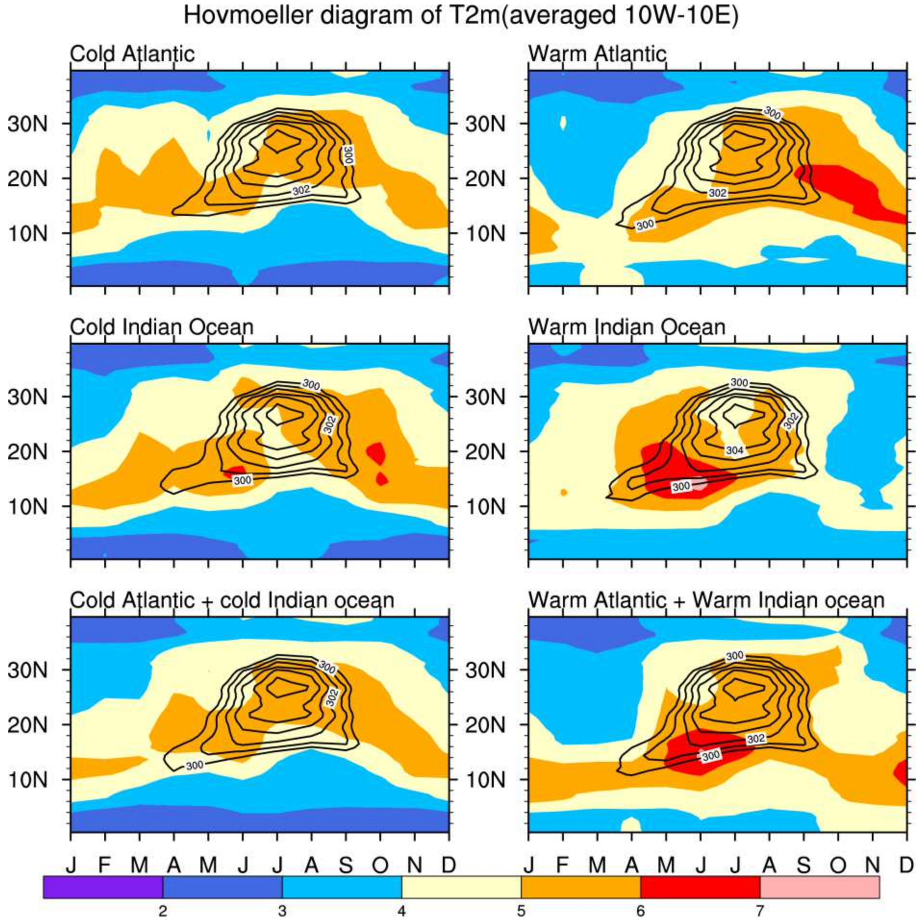

Figure 9. Mean annual cycle of T2m averaged between 10°W-10°E (contour: average between 1971-2000; shaded colours: differences between 2070-2099 and 1971-2000) (unit: K)

In addition to high surface temperature, another key element of SHL is low surface pressure. Figure 10 illustrates the mean JAS sea level pressure (MSLP) differences. Generally a low pressure system forms around 25°N (not shown). Figure 10 shows the MSLP differences between 2070-2099 and 1971-2000. The cold SST anomaly experiments (left column) shift the low pressure to the northern edge of Sahara desert, even further into the Mediterranean Sea. The meridional pressure gradient between the Gulf of Guinea and the northern Sahel is slightly increased, especially in ATL_C experiment that leads to a wetter Sahel (Figure 7). Hastenrath and Polzin (2011) also point out the importance of tropical Atlantic SST in variations of Sahel rainfall through changes in sea-level pressure distribution. A warm SST anomaly doesn't lead to a distinct shift SHL location and strength but instead lead to more widespread changes in pressure perturbations (Figure 10, right column).

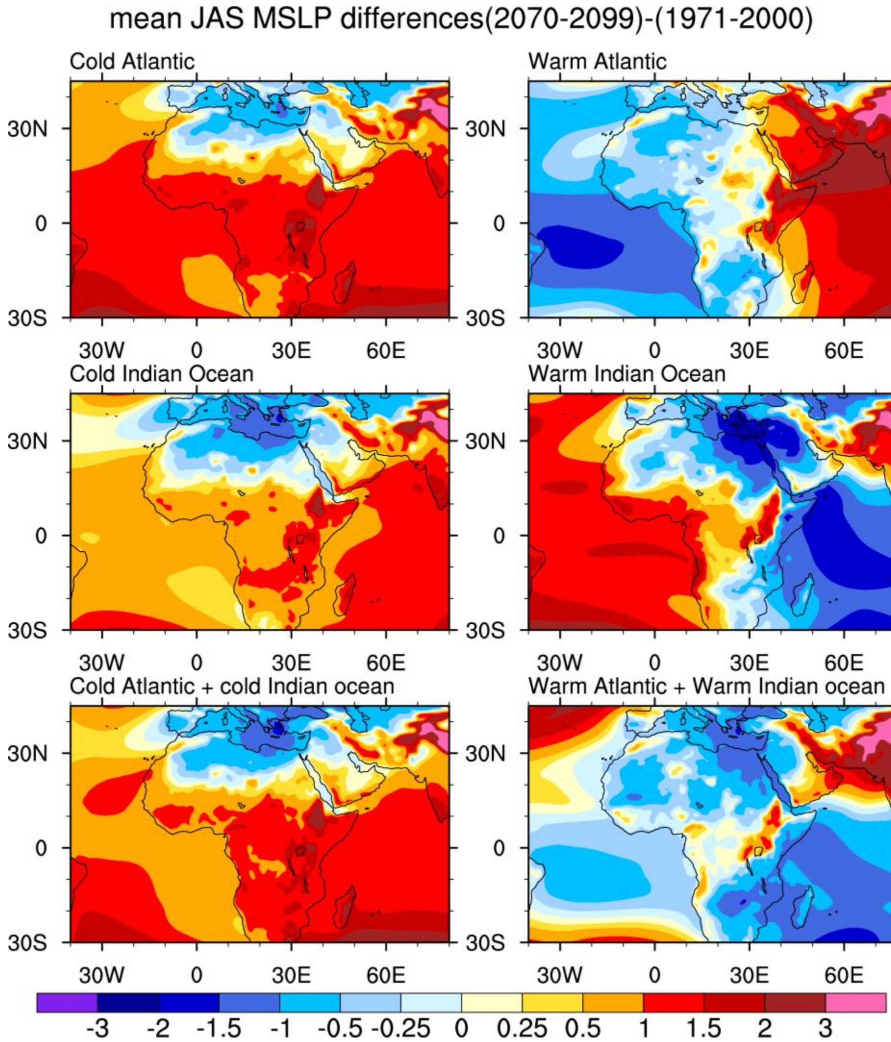

Figure 10. Mean JAS MSLP differences between (2070-2099) and (1971-2000) (unit: hPa)

All the above analyses suggest that a warm Indian Ocean anomaly appears to be the primary forcing in driving the drying in the west Sahel. This agrees with previous studies (e.g. Hagus, et al. 2008; Bader et al., 2003). One thing to be addressed is that our experiments are only SST-driven and the role of air-sea interaction is not considered. The prescribed SST simulations maybe produce excessive SST forcing. The feedbacks of the atmosphere on the ocean also play a critical role on the tropical SST variability and further alter the Sahel rainfall variability. This is beyond the scope of this report and not investigated here. To further investigate the possible causes, Figure 11 illustrates the vertical structure of meridional temperature gradient in JAS. As documented from previous studies, the Sahel rainfall is primarily modulated by a complex interaction between different circulation system, especially the upper-level tropical Easterly Jet (TEJ, ~200hPa), the African Easterly Jet (AEJ) in the middle troposphere (~600 hPa) and the tropical monsoon Westerlies in the lower troposphere that lie beneath the TEJ (e.g. Lu et al., 2005; Wang et al., 2011). Fig. 11 shows the meridional temperature gradient in the 10°-20°N region with contours for the average during 1971-2000 and shaded colours for the difference between 2070-2099 and 1971-2000. With the exception of IND_W and ATLIND_W all sensitivity experiments exhibit a pronounced increase in the meridional temperature gradient across the Sahel region, while the other two experiments reveal a decrease in the meridional temperature gradient. As the SHL is the thermal response of the lower troposphere to surface warming, an intensified south-north temperature gradient will reinforce this feature. Meanwhile, the meridional temperature gradients are associated with the vertical structure of zonal wind shown in Figure 12. In the ATL_C, ATL_W, IND_C and ATLIND_C experiments, the more intense SHL leads to the development of AEJ which is shown in Fig 12 as a negative zonal wind bias the in middle troposphere over the Sahel. Convective systems are frequently initiated or associated with AEJ systems (Reed, 1988) and tend to produce more precipitation during JAS season as we find in all sensitivity experiments except for those that involve a warm Indian Ocean SST anomaly. The IND_W and ATLIND_W experiments lead to a stronger westerly flow in the lower troposphere, weaker AEJ and stronger TEJ. This vertical structure tends to supress the development of convective system, which, at least, can partially explain the Sahel drying.

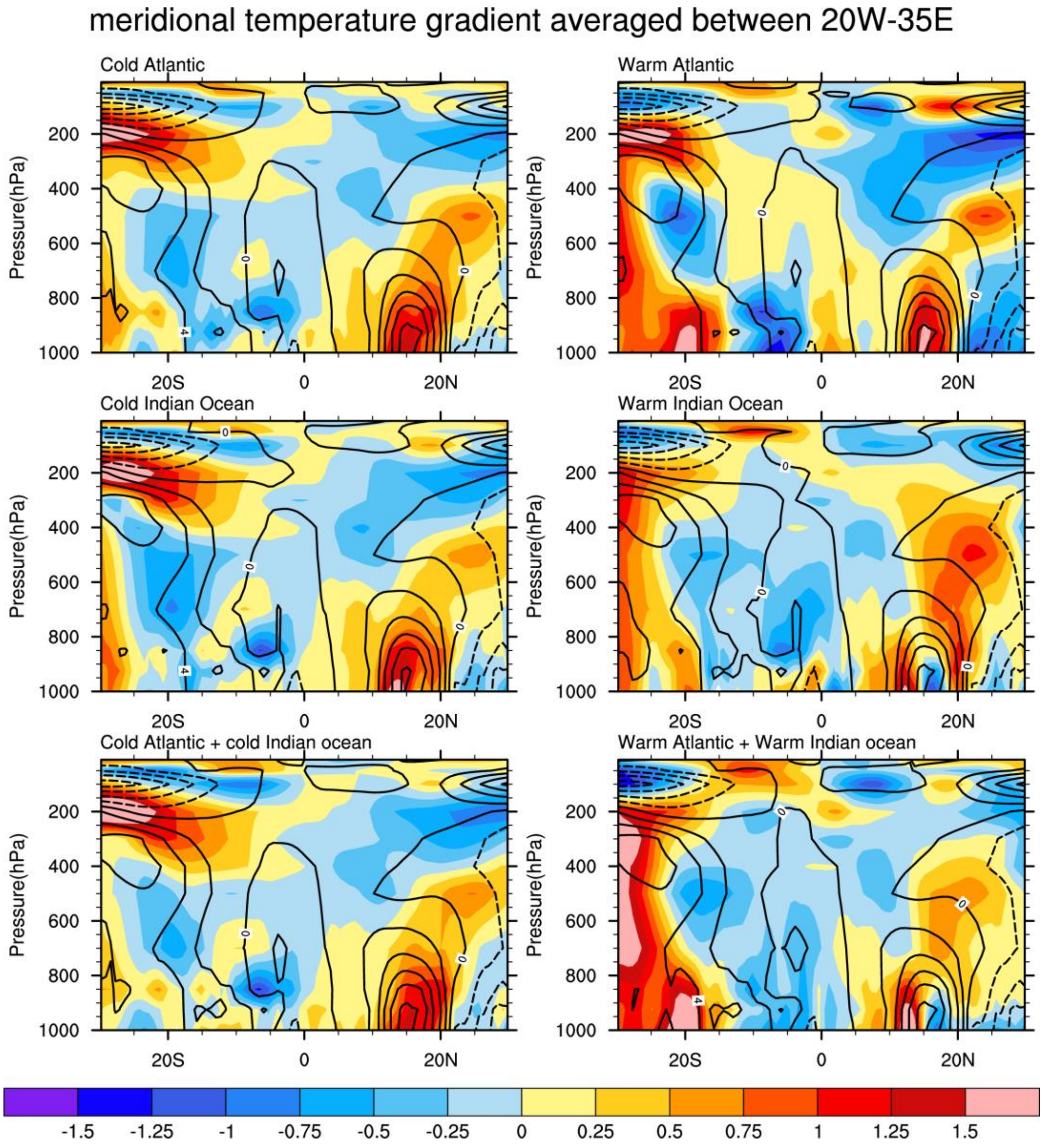

Figure 11. Mean JAS meridional temperature gradient (MTG) between 20°W-35°E (contour: MTG averaged between 1971-2000; shaded colours: MTG differences between 2070-2099 and 1971-2000)(unit: K per 1000km)

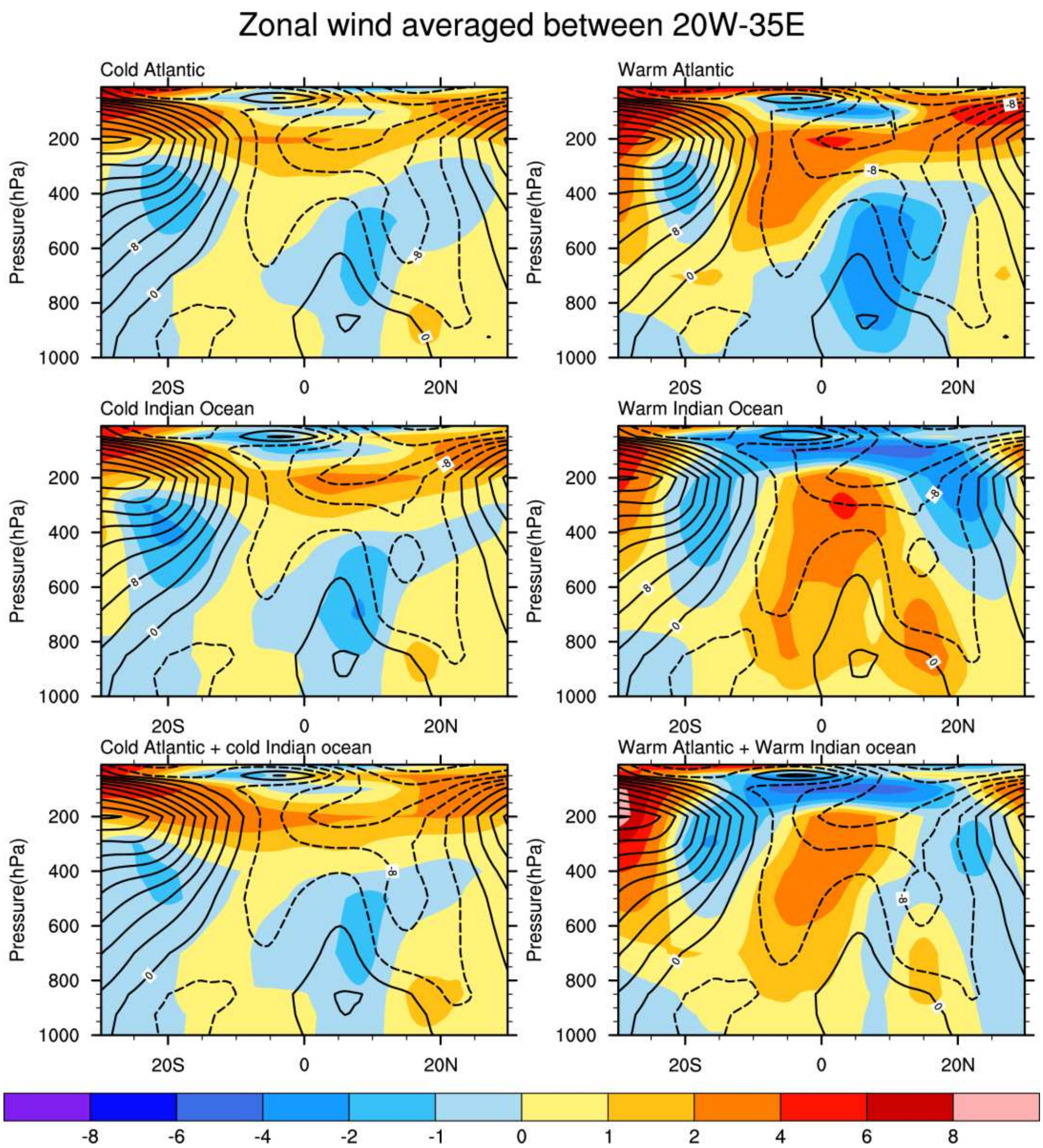

Figure 12. Mean JAS zonal wind between 20°W-35°E (contour: zonal wind averaged between 1971-2000; shaded colours: zonal wind differences between 2070-2099 and 1971-2000) (unit: m/s)

4. Impact of tropical SST on Indian monsoon

In South Asia more than 1/6th of the world population depend on rain-fed agriculture. The monsoon precipitation provides more than 80% of the annual precipitation, which has a strong impact on agriculture and society (e.g. Singh, 2016). The South Asian Monsoon (SAM) is not only a regional and independent phenomenon but it is strongly regulated by the large scale circulation. A large body of literature has contributed to the study of the SAM under increasing CO_2 concentrations (e.g. Turner, 2012; Rajendran, 2012; Syed, 2014).

A key aspect of the SAM is the widespread evaporation from the ocean surface as air is advected towards the land before this accumulated moisture converges onto the Indian subcontinent providing the moisture for the monsoon rains. The increased atmospheric moisture flux into the South Asian region is responsible for the intensified future SAM rainfall under greenhouse warming, particularly the enhancement of moisture over the Indian Ocean source region play an critical role (May et al., 2004; Ueda et al., 2006).

We firstly examine the impact of different oceanic warming on the annual cycle of precipitation over the Indian subcontinent (8°N-28°N, 68°E-88°E). In Figure 13 the annual cycle differences between 2070-2099 and 1970-2000 are shown. In this comparison, only land points are considered. From Jan to May, most experiments show a negligible change in a warmer climate, except for the ATL_W experiment in which a wet bias begins to emerge from March. However, the most striking variations occur during the prevailing monsoon period. In June, both ATL_W and ATLIND_W experiments lead to almost 3 mm/day drier conditions and a somewhat smaller change lasting until the end of the monsoon season (September). During the SAM period, the other experiments show a relatively weak wet impact of ~1mm/day. In October and November, both IND_W and ATLIND_W experiments lead to wetter conditions of almost 2mm/day. This analysis reveals that a warmer Atlantic ocean plays a critical role on the dry response over the Indian subcontinent in agreement with the results of Zhang et al (2006) that found that the Atlantic Multi-decadal Oscillation (AMO) may strengthen the variability of SAM precipitation and the eastward propagation of the wave train originating from the North Atlantic also play an critical role on the precipitation intra-seasonal variability over the northern Indian and Pakistan (Ding and Wang, 2007; Moon et al., 2012).

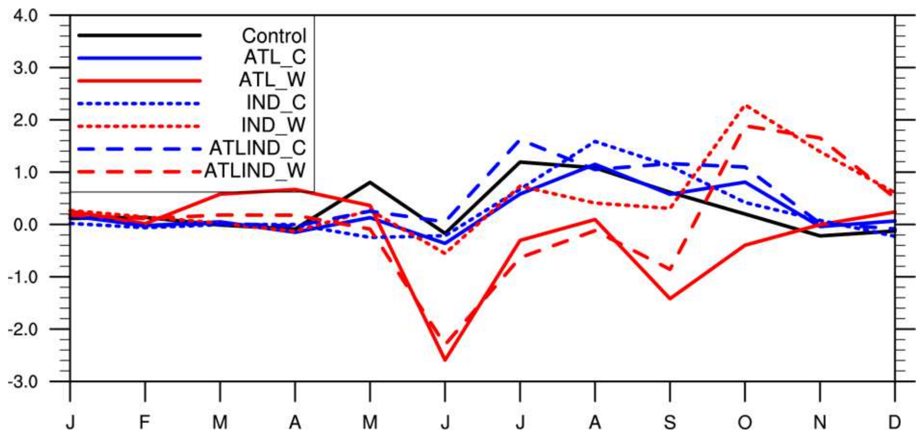

Figure 13. Annual cycle of precipitation difference between 2070-2099 and 1971-2000 over Indian subcontinent(8°N-28°N, 68°E-88°E) (unit: mm/day)

Due to the exponential sensitivity of saturation vapour pressure to air temperature (the Clausius-Claperyon relation; Bohren and Albrecht 1998), surface evaporation is highly sensitive to the magnitude of surface warming, which is strongly modulated by variations in the precipitation. Figure 14 illustrates the annual cycle of T2m change over the Indian subcontinent between 2070-2099 and 1970-2000. The largest change in seasonal variability is seen in the ATL_W experiment where we find a jump from 2.2K in May to 4.8K in June. ATLIND_W experiment also shows a strong variability from June to November. The other sensitivity experiments show all similar changes between present-day and a future warmer climate. The warming is not distributed evenly throughout the year with more warming before and less warming during the SAM period.

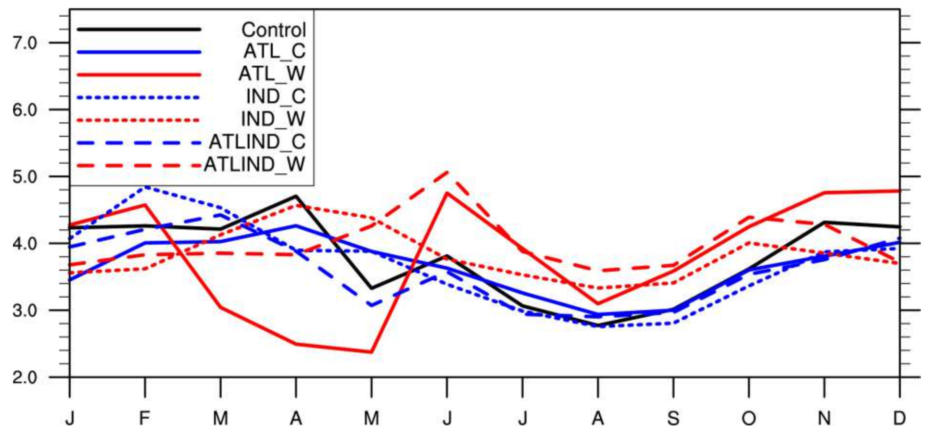

Figure 14. Annual cycle of T2m difference between 2070-2099 and 1971-2000 over Indian subcontinent (8°N-28°E, 68°E-88°E) (unit: K)

To further investigate the decadal variability of precipitation and T2m during monsoon season Figures 15 and 16 show the smoothed JJAS precipitation and T2m over the Indian subcontinent, respectively. The first point to note is the large variability and magnitude spread among all experiments for precipitation. During the historical period, the Atlantic Ocean sensitivity experiments lead to a drier Indian subcontinent (ATL_C and ATL_W), while the Indian ocean sensitivity experiments lead to a wetter Indian subcontinent (IND_C and IND_W). This result suggests that the SST variability play a primary role on the magnitude of precipitation response. The combined ocean basin forcing experiments reveal that both ATLIND_C and ATLIND_W experiments leads to more precipitation, particularly in ATLIND_W experiment. This indicates that the Indian Ocean forcing is more critical for the SAM precipitation. Moreover, with increasing global warming levels towards the end of 21st century, the extra warming imposed on the tropical oceans implies a dryer monsoon season compared to present-day conditions. This trend is especially robust in ATL_W and ATLIND_W experiments. IND_W experiment also shows a slightly drying trend, but it is much weaker. This indicates that the strong Atlantic Ocean warming play a primary role for a drier SAM. When the tropical ocean SST is warming less than (ATL_C, IND_C and ATLIN_C experiments) we observe a weak trend towards a wetter SAM. This variation is associated with a strengthening/weakening of the land-sea thermal contrast. Under a warmer ocean condition, a weakening land-sea thermal contrast will dampen the summer monsoon Hadley circulation and further reduces the SAM precipitation (Roxy, et al. 2015). In Figure 16, both ATL_W and ATLIND_W tend to have faster warming response over the Indian subcontinent by the end of 21st century which tends to favour a weakening land-sea thermal contrast.

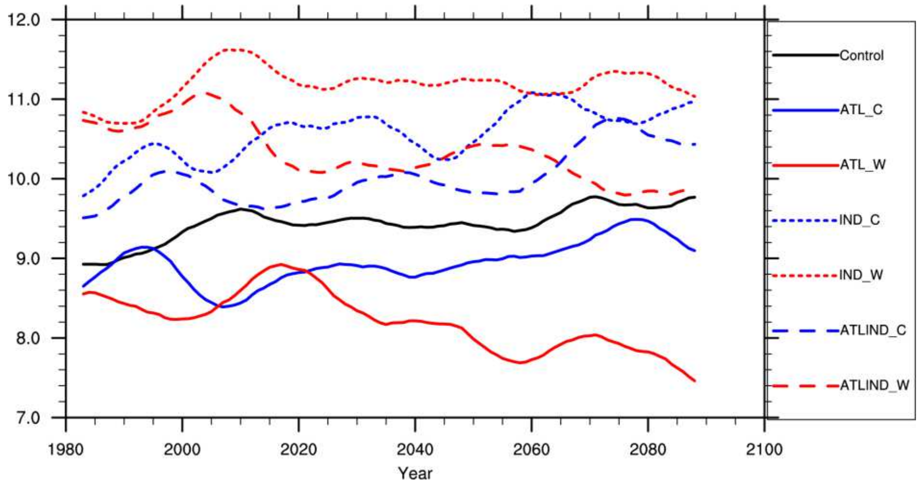

Figure 15. Mean JJAS rainfall over central Indian subcontinent (8°N-28°N, 68°E-88°E) from all sensitivity experiments and control run (unit: mm/day)

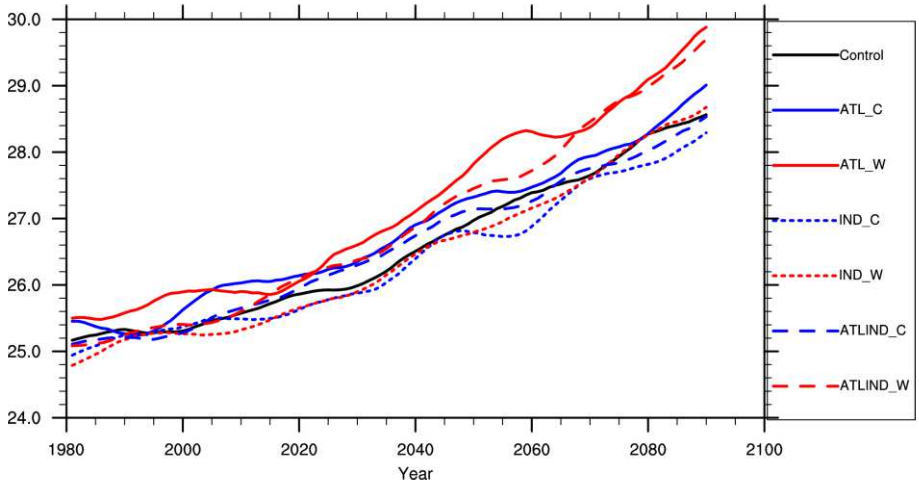

Figure 16. Mean JJAS T2m over central Indian subcontinent (8°N-28°N, 68°E-88°E) from all sensitivity experiments and control run (unit: °C)

To gain detailed regional response information for precipitation, we analysed the precipitation difference between the periods 2070-2099 and 1971-2000 in Figure 17. The precipitation differences from ATL_C and ATL_W experiments show that the sign of the Atlantic Ocean SST anomaly implies a response with a reversed sign in the SAM precipitation. The ATL_C experiment leads to more precipitation in the Arabian Sea, across the Indian subcontinent and in the Bay of Bengal; while the ATL_W experiment leads to less precipitation except for a slightly wetter response found in central India but the northern Indian subcontinent again receives substantial less precipitation. Another notable feature is that both ATL_C and ATL_W experiments lead to less precipitation over the tropical Indian Ocean. This feature is further intensified in the IND_C experiment. In comparison with the IND_C experiment, the IND_W experiment yields significantly increased precipitation covering the whole Indian Ocean and Indian subcontinent, except in a narrow band along the West Ghats and a zone stretching from the foothills of Himalayan to the coast at the Bay of Bengal. Compared with the Indian Ocean sensitivity experiments (IND_C/IND_W), the combined the Atlantic and Indian Ocean sensitivity experiments (ATLIND_C and ATLIND_W) produce similar response although the magnitude is slightly intensified. Again this demonstrates that the Indian Ocean plays a dominant role on the wetter response of the SAM precipitation.

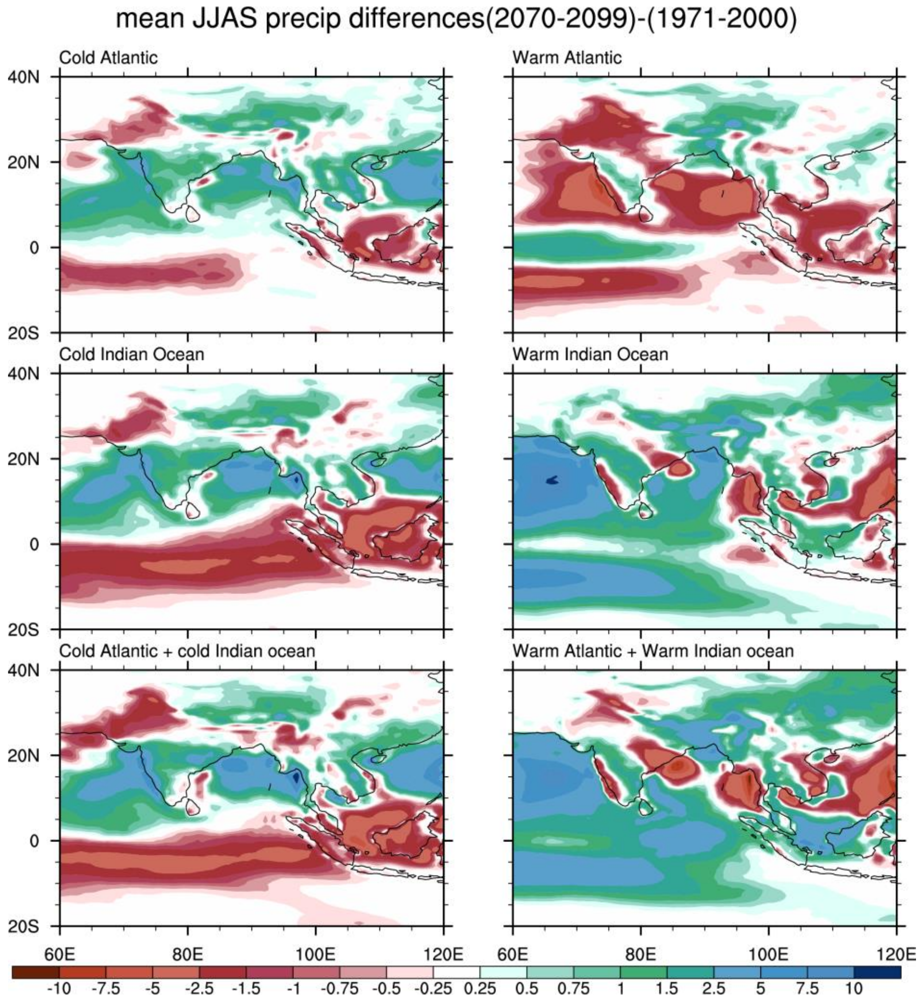

Figure 17. Mean precipitation differences between (2070-2099) and (1971-2000) in JJAS (unit: mm/day)

Previous studies have revealed that the intensified SST anomalies are accompanied with large circulation variation in the lower and upper troposphere due to the altered land-sea thermal contrast (e.g. Dai et al., 2013). To analyse the low-level circulation, Figure 18 shows the mean JJAS 850hPa differences between 2070-2099 and 1971-2000. One of the key aspects of SAM onset is the strong cross-equatorial westerly transport of moisture from the tropical Indian Ocean to Indian sub-continent, further to the Bay of Bengal and the South China Sea. In ATL_C experiment, the easterly flow in the southern tropical Indian Ocean is slightly reduced, while the westerly flow across the Arabian Sea is intensified. Similar patterns are also observed in IND_C and ATLIND_C experiments. In the ATL_W experiment, the difference between the warmer future and today is a strong anticyclonic circulation from the Arabian Sea to the Bay of Bengal which strongly depresses the development of the south-westerly jet and leads to strong drying over the SAM region and neighbouring ocean areas. With a positive SST anomaly over the Indian Ocean, both IND_W and ATLIND_W experiments lead to strongly weakened westerly flow at the end of the next century. This makes the low-level circulation lack the fuel to transport the moisture further inland and retains more precipitation over the Indian Ocean.

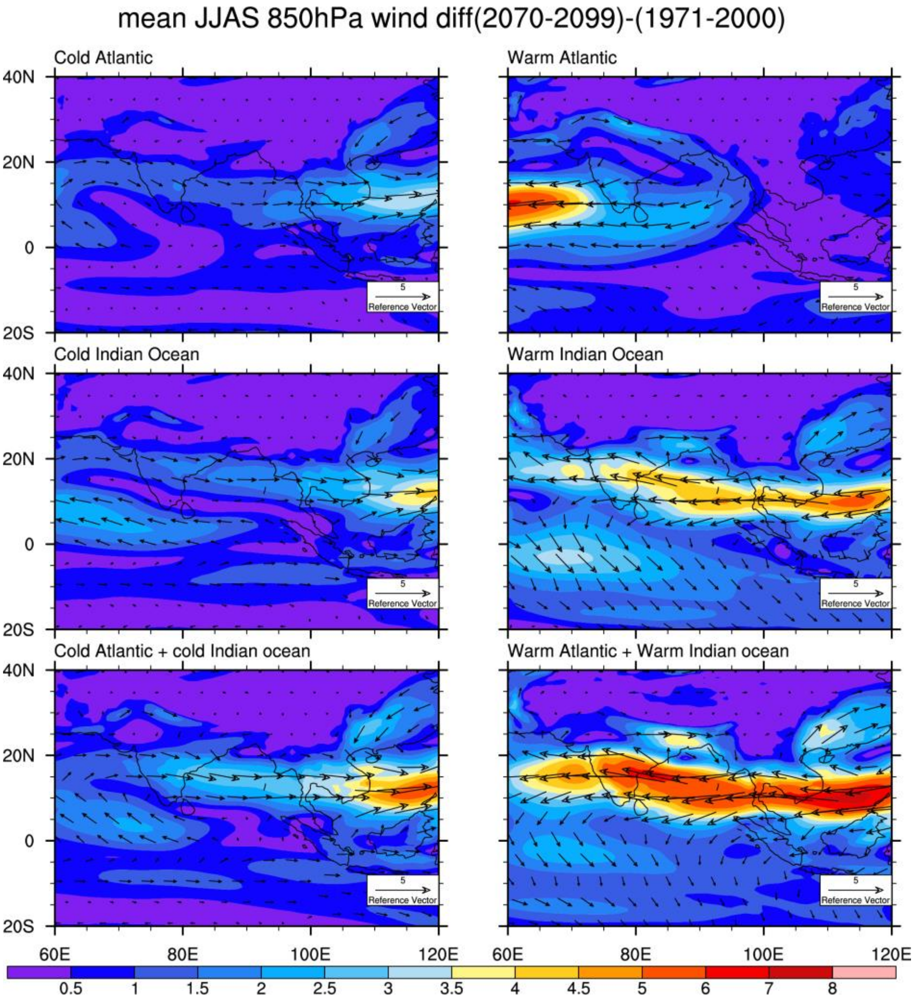

Figure 18. Mean 850hPa wind differences between (2070-2099) and (1971-2000) in JJAS (unit: m/s)

Figure 19 illustrates the mean JJAS 200hPa differences between 2070-2099 and 1971-2000. During the monsoon season, the upper-level wind is characterized by the tropical easterly jet stream (TEJ) with maximum winds along the equatorial region of southern tip of the Indian peninsula and the Tibetan anticyclone is centred on the central Indian landmass. In ATL_C, IND_C and ATLIND_C experiments, compared with historical period, the westerly flow over the northern Indian subcontinent is strengthened. The easterly flow is reduced over the Arabian Sea and enhanced over the Maritime Continent. In ATL_W experiment, the easterly flow is substantially reduced over the western tropical Indian Ocean. In IND_W and ATLIND_W experiments, in addition to strongly intensified westerly flow, a substantial reduced easterly flow is over the Maritime Continent region. All experiments lead to a weakened Tibetan anticyclone, particularly under a strong oceanic warming condition. The weakening TEJ in the upper troposphere is accompanied with decreased meridional temperature gradient which is associated with a rapid warming over the tropical Indian Ocean due to enhanced deep moist convention. This weakening will further lead to a weaker Hadley circulation (discussed in Figure 20) and lower level south-westerly flow (Figure 18).

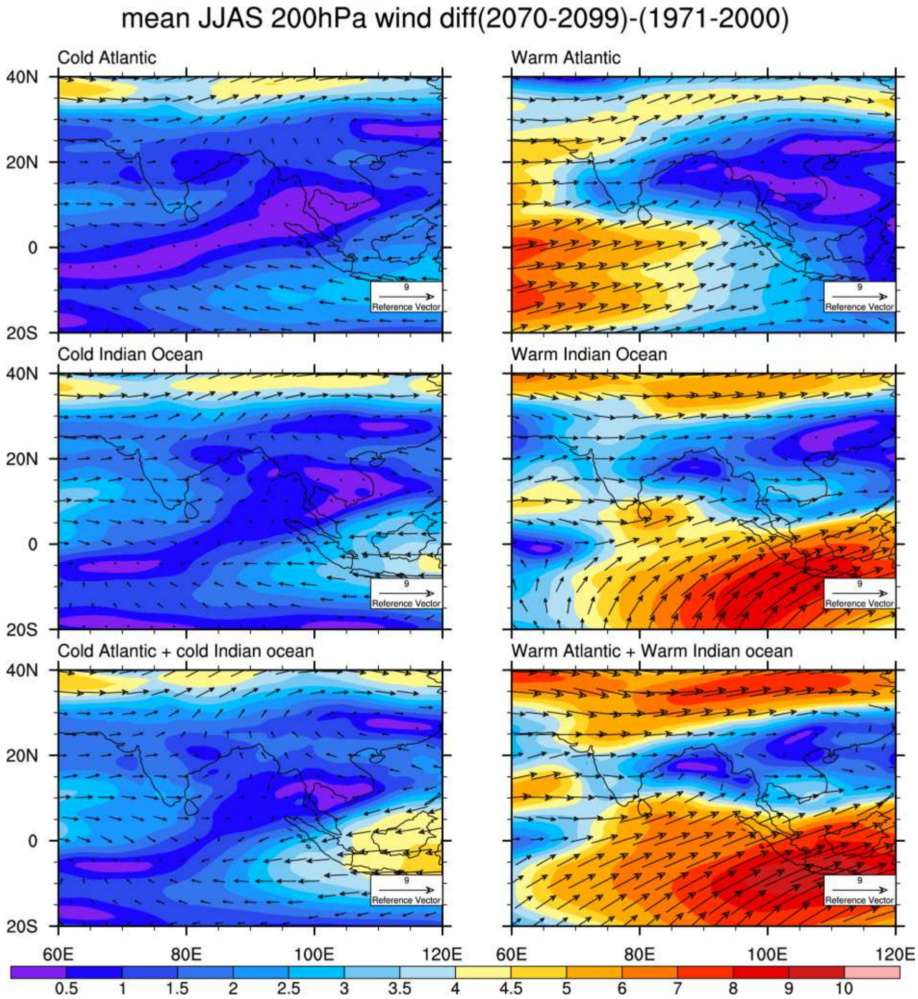

Figure19. Mean 200hPa wind differences between (2070-2099) and (1971-2000) in JJAS for all experiments (unit: m/s)

Precipitation over the Indian subcontinent is strongly influenced by the large-scale monsoon circulation which advects moisture from the tropical Indian Ocean onto the subcontinent. To better understand the response to the SST anomalies over the tropical oceans, we analyse two circulation indices for the SAM, after Goswami (1997) and Webster-Yang (1992). Goswami (1997) suggests the South Asian summer monsoon represents a large-scale heat source around 20ºN associated with the Hadley circulation. The Goswami Monsoon Index (GMI) is based on vertical shear of the meridional wind velocity.

$$GMI = V_{850} - V_{200} \qquad (1)$$

V_{850} and V_{200} are, respectively, averaged over season (June-September) and over monsoon region (10ºN-30ºN, 70ºE-110ºE).

Webster and Yang (1992) defined another monsoon index which reflects the low-frequency baroclinic Rossby-wave response to monsoon heating. The Webster-Yang Monsoon Index (WYMI) is calculated from vertical shear in the zonal wind velocity over the region; 0°N-20°N, 40°E-110°E.

$$WYMI = U_{850} - U_{200} \qquad (2)$$

Figure 20 shows the time evolution of anomaly of the Goswami and Webster-Yang dynamical monsoon indices and corresponding meridional and zonal wind at 850hPa and 200hPa. Comparing the Goswami index, all experiments except IND_W and ATLIND_W show a reduction of the monsoon index. This is primarily caused by opposite responses of the meridional wind at 850hP and 200hPa. At 850 hPa, the meridional wind tends to increase in IND_W and ATLIND_W experiments and decrease for all other experiments. At 200hPa, all experiments yield a decrease the meridional wind. Through modulated meridional Hadley circulation, the intensified Indian Ocean warm pool could enhance the tropical ocean convection and further inducing a dry bias over land (Bollasina, 2013; Roxy et al., 2015). In Webster-Yang index, all experiments show a reduction, which reflect the tendency of weakening the equatorial overturning (Walker) circulation and also partly explaining the reduction in precipitation over the equatorial Indian Ocean. In a general sense the two dynamical indices suggest a decrease in the monsoon circulation strength (except there is a disagreement between these two indices for IND_W and ATLIND_W experiments). This results show that warm SSTs anomalies in the tropics in combination with increased surface evaporation counteract the weakening monsoon circulation strength which still could increase the total convergence of moisture from the Arabian Sea into the central Indian subcontinent.

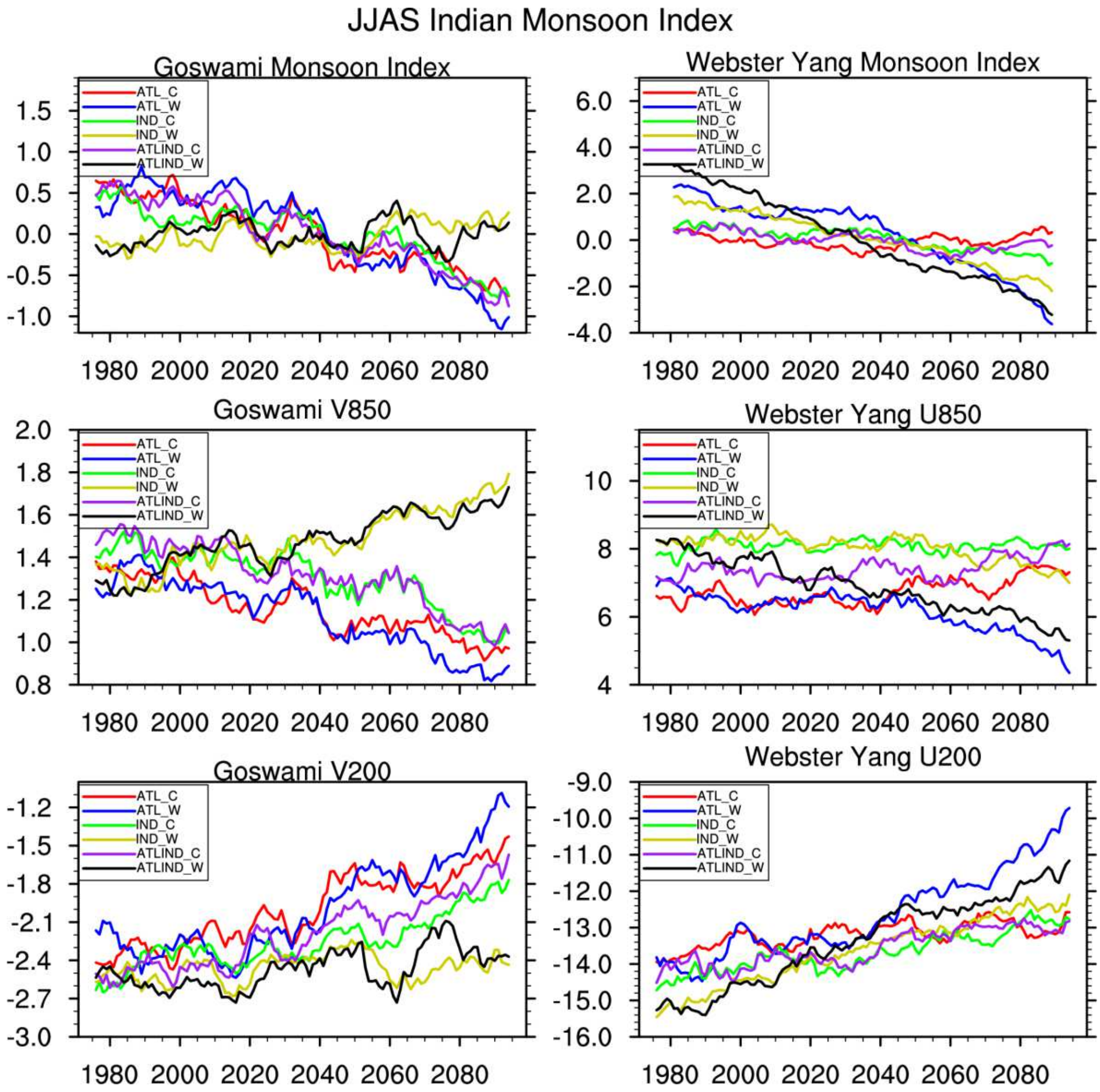

Figure 20. Left column: Time series of Goswami Monsoon Index (based on anomaly of V850 and V200) for JJAS season, meridional wind at 850hPa (V850) and 200hPa (V200) averaged over region (10°N-30°N, 70°E-110°E). Right column: Time series of Webster-Yang Monsoon Index (based on anomaly of U850 and U200) for JJAS season, zonal wind at 850hPa (U850) and 200hPA (U200) averaged over region (0°N-20°N, 40°E-110°E). All the time series are smoothed by a 11-year sliding window.

In South Asia, the rain-fed agriculture is strongly influenced by the monsoon precipitation, particular the monsoon extreme events. To investigate this issue, we calculate the precipitation for the wet and dry spell period. Firstly the daily precipitation is averaged over the box between 18°N-28°N and 73°E-82°E from 1 June to 30 September of each year, and then the time series is normalized by its standard deviation. A wet spell is defined as at least three consecutive days when the standard deviation is bigger than 1mm/day, while a dry spell is defined as at least three consecutive days when the standard deviation is smaller than -1mm/day (Singh et al., 2014). Figures 21 and 22 show the wet and dry spell precipitation differences between periods 2070-2099 and 1971-2000, respectively. Comparing to seasonal mean precipitation (Figure 17), all experiments show a robust increasing for extreme wet spell precipitation over the core Indian region (Figure 21), despite a decrease in mean rainfall is observed in IND_W and ATLIND_W experiments (Figure 17). This indicates that both Atlantic and /or Indian Ocean SST anomalies tend to produce more prolonged wet extreme events, and even the mean seasonal precipitation could decrease. In contrast, an opposite drier bias pattern is produced by all experiments during dry spell period, particularly significant in ATLIND_C, ATL_W, IND_W and ATLIND_W experiments. This reveals that the warm tropical SST anomalies also tend to lead more prolonged drought events in agreement with previous studies (e.g. Singh, et al., 2014). The mean monsoon precipitation decreasing might be caused by large-scale multi-decadal variability and the wet and dry spells are weakly correlated with mean seasonal precipitation. (Krishnamurthy et al., 2007; Wang, et al., 2013; Singh, et al., 2014).

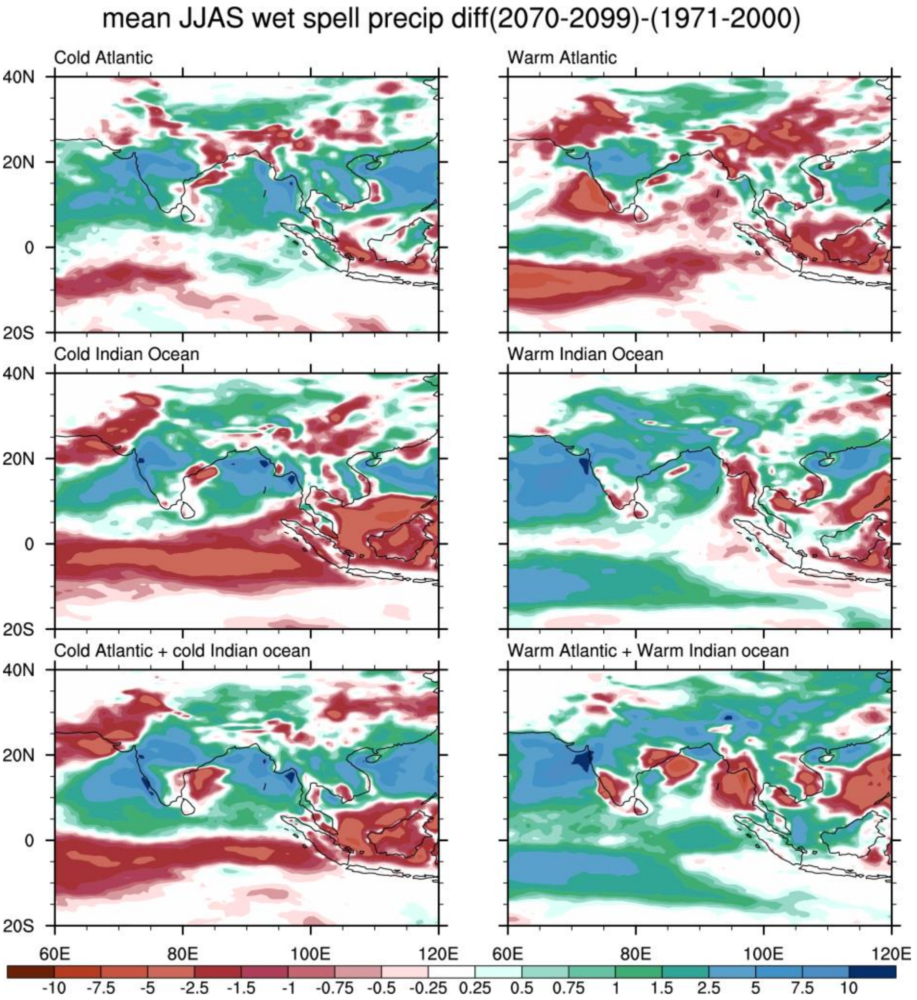

Figure 21. Mean JJAS wet spell precipitation differences between (2070-2099) and (1971-2000) (unit: mm/day)

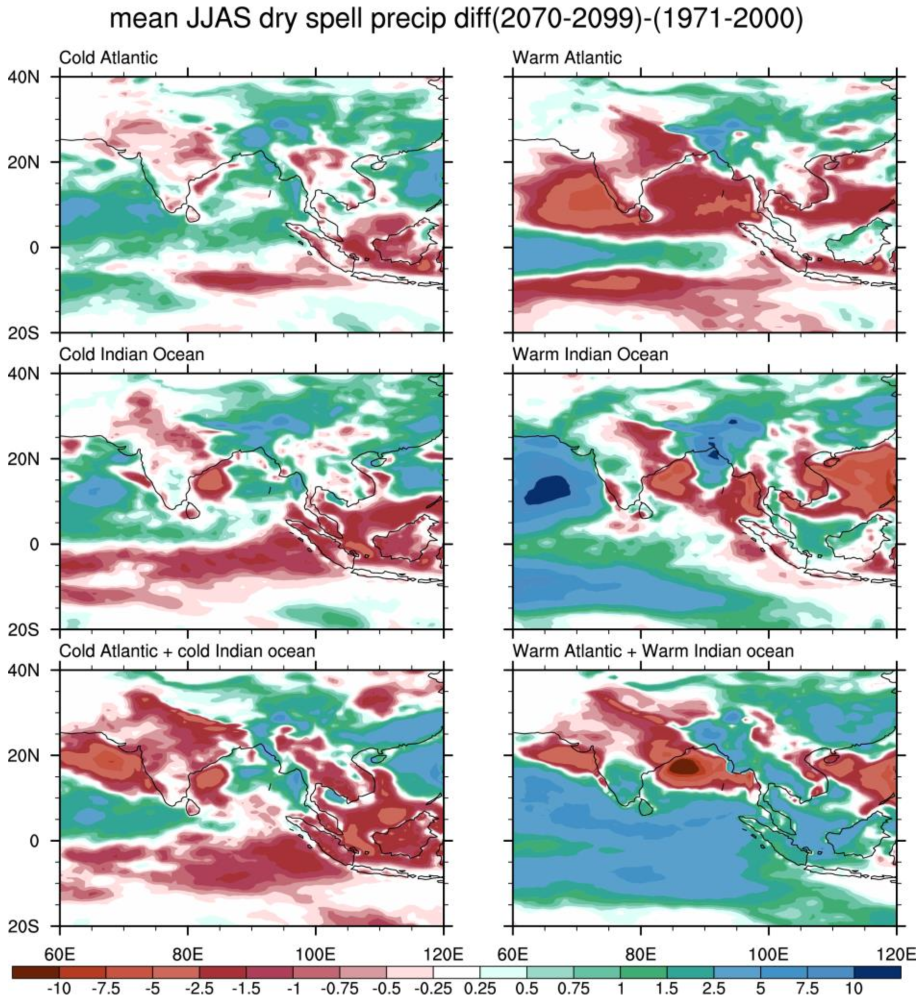

Figure 22. Mean JJAS dry spell precipitation differences between (2070-2099) and (1971-2000) (unit: mm/day)

To investigate the precipitation variation during the monsoon period, we define the onset and demise timing of the SAM using following methods. Wang et al. (2009) defined the onset based on the 850hPa zonal wind averaged over 5°N-15°N, 40°E-80°E. The onset date is defined as the first day of six consecutive days when the index exceeds 6.2 ms-1. Considering rapid transitions of atmospheric conditions when the SAM retreats, a daily circulation index is defined as the difference of averaged 850 hPa zonal winds between a southern region (5°N-15°N, 50°E-80°E) and a northern region (20ºN-30ºN, 60ºE-90ºE) and the demise date is defined as the first day of seven consecutive day when this index is negative (Syroka and Toumi, 2004). Figure 23 shows the mean precipitation difference averaged over entire SAM period between periods 2070-2099 and 1971-2000. Compared with seasonal mean precipitation distribution (Figure 17), all experiments show no significant changes on the wet response pattern, except in the ATL_W experiment. A robust wet response is observed over central Indian in ATL_W experiment. Although the spatial distribution is similar to JJAS mean precipitation differences distribution (Figure 17), but the magnitude is slightly weaker except ATL_W experiment. This indicates that the precipitation may be more intense during the JJAS period which is centred within the overall monsoon onset and demise dates.

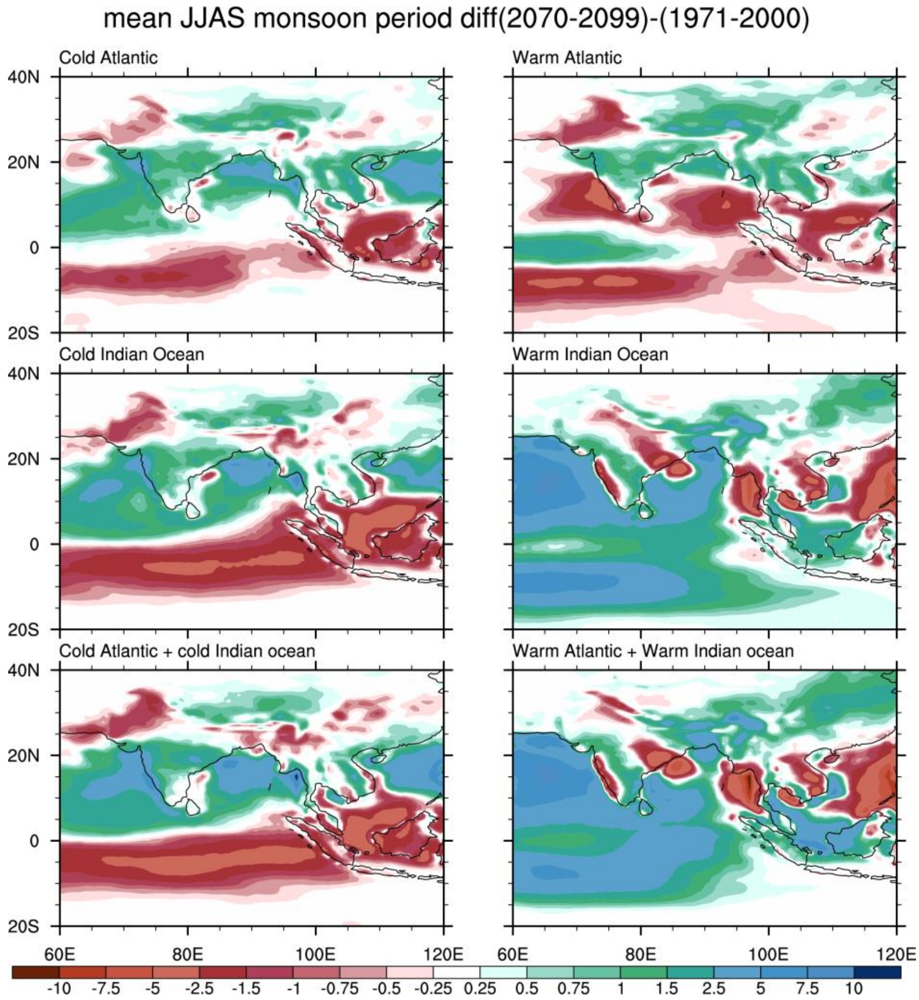

Figure 23. Mean precipitation differences between (2070-2099) and (1971-2000) during SAM period (unit: mm/day)

5. Summary

The main objective of this report is to analyse the atmospheric response over the Sahel and South Asia to tropical SST anomalies in the Atlantic and/or Indian oceans in a generally warmer world, e.g. at the end of this century

In the Sahel, the primary finding is that response of the Sahel precipitation is not only controlled by the magnitude of oceanic forcing but also by the variability of the SST. The Sahel rainfall is governed by either the tropical Atlantic or Indian Oceans, depending on the magnitude of the warming and the relative difference in the two ocean basins. If by the end of the 21st century the warming over the Indian Ocean is larger than the global mean we can expect a drier Sahel, while a pronounced warming over the Atlantic Ocean would lead to a wetter Sahel. The detailed response is strongly seasonal and geographical regions dependent.

The Sahel rainfall variability is associated with the coherent changes of surface temperature. The large uncertainty in future Sahel rainfall projections are amplified by altered land-sea thermal contrast. A warmer Atlantic Ocean produces stronger meridional temperature gradient over the Sahel, which lead to an intensified SHL, while a warmer tropical Indian ocean tend to have weaker meridional temperature gradient. The more intense SHL leads to the development of convective system and further to produce more precipitation over the Sahel. These changes are also accompanied with altered large-scale circulation patterns.

In the South Asia, both inter-annual variability and magnitude of oceanic forcing play a critical role on the SAM. A robust drying response over the Indian subcontinent is due to a stronger Atlantic and /or Indian Ocean warming. Under a colder ocean condition, a wetter SAM response is observed. This variation is associated with a strengthening/weakening of the land-sea thermal contrast. Under a warmer ocean condition, a weaker land-sea thermal contrast will dampen the summer monsoon Hadley circulation and further reduce the SAM precipitation. This will depress the development of the south-westerly jet and further lead to robust drying over the SAM region. The weakened westerly flow makes low-level circulation lacks the fuel to bring the moisture to further into East Asian, which induces more precipitation over the Indian Ocean.

The impact of the SST variability on the occurrence of extreme events are analysed by studying the changes in the wet and dry spell during monsoon period. Both Atlantic and /or Indian oceans anomalies tend to produce more prolonged wet extreme events, despite the mean seasonal precipitation decreased in part of the subcontinent. At the same time, a dry response pattern is produced by all experiments during dry spell period, especially pronounced under individual or combined warmer ocean basin conditions. The precipitation during monsoon period is further analysed. The spatial distribution of SAM precipitation is similar to the mean JJAS precipitation; however, the magnitude is slightly weaker except under an extreme warmer Atlantic Ocean condition, which the monsoon precipitation is substantially enhanced over the central of Indian subcontinent. This indicates that a warmer Atlantic ocean is primarily responsible for the enhanced heavy precipitation events during monsoon period.

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