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Executive summary

The aim of this brief note is to summarise what we currently know about present and future climate over the Sahel region. Few other places share the same climate variability that characterises this region. The impact of these large fluctuations has been exacerbated recently by the occurrence of one of the most severe and dramatic droughts of the last hundred years. On an inter-seasonal timescale the precipitation over the Sahel is regulated by three main processes: a flow of moist air from the south associated with the west African monsoon onset, the seasonal movement of the ITCZ and a dry (and aerosol rich) advection from the Sahara.

Despite the skill climate models have in predicting seasonal variability over the Sahel, very little consensus exists on climate change projections with models disagreeing even on the sign of the change. Such a significant disagreement has the potential to make long term model projections nearly impossible for the region as a whole, at least until further advancement is made in the underlying scientific understanding. Projections for temperature tend to be more uniform among climate models and suggest that an increase, especially for summer, is likely to largely exceed the global mean increase. Through an analysis of the most intense droughts of the 20th century three focus areas were identified.

- For west-most Sahel most models agree on a significant decline in annual precipitation.
- For eastern Ethiopia the signal is less clear but most of the models expect an increase in annual precipitation.
- For the area around Lake Chad, at the moment we do not have enough information to evaluate with confidence whether precipitation is more likely to increase or decrease in the future.

Further research is needed to improve climate projections for the Sahel region. The newly released multi-model climate model datasets from the ENSEMBLES project together with extended observational datasets from the AMMA project will allow for more extensive studies and provide new insights on the climate drivers of the region.

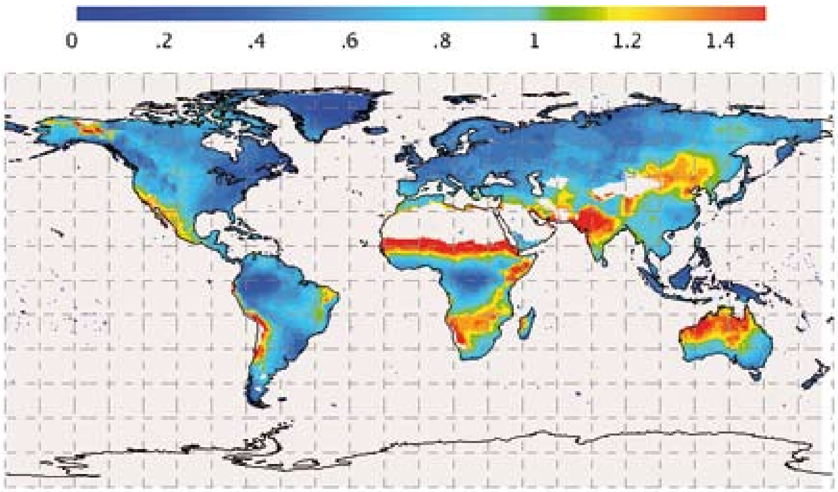

Figure 1

the plot shows the coefficient of variation for annual precipitation (standard deviation normalised by the mean). Sahel sticks out as one of the areas where the variation is most severe. The plot is based on CRU data (Mitchell and Jones, 2005).

1 Introduction

Improving the reliability of climate projections and future precipitation changes is crucial for West Africa and especially the Sahel (12°N–20°N), a semi-arid region on the southern margin of the Sahara desert that is particularly vulnerable to natural variability. The Sahel has experienced an unprecedented and severe long lasting drought from the late 1960s to the late 1980s, with partial recovery through 2003, although the rainfall deficit has not ended (Nicholson et al., 2000; Biasutti and Giannini, 2006; Dai et al., 2004). In addition, West Afica has been identified as a "hot spot" where the land-atmosphere coupling could play an important role, through the recycling of precipitation and the modulation of dry and moist static energy (Douville et al, 2007). There is a growing concern on the future climate of West Africa, as the anthropogenic global warming continues, since the population of the region depends largely on agriculture and climate change may alter the availability of water resources (IPCC, 2007). However, the CMIP3 climate projections produced by a wide range of modeling groups for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change IPCC-AR4 show little consensus over West Africa (IPCC, 2007). This lack of consensus results partly from the inability of climate models to capture the basic features of the present-day climate variability in the region.

The aim of this project is to examine further the issues associated with the producing of reliable climate projections in the Sahel region. Novel datasets from the recent French lead project on African Monsoon Multidisciplinary Analysis (AMMA, Redelsperger et al, 2006), and the European Union funded ENSEMBLES project (van der Linden and Mitchell, 2009) will provide the high quality observational and multi-model climate data needed to carry out the analysis. The study focuses on the following three sub-areas of West Africa where the most severe droughts were recorded: west-most Sahel, eastern Ethiopia and the area centred on Lake Chad. The features of the present-day climate variability of the Sahelian rainfall (section 2) and projection of the future changes (section 3) are discussed.

2 Rainfall and droughts in Sahel

2.1 Spatial structure of rainfall and droughts

The Sahel region[1] represents a transition zone between the Saharan desert and the wet climate of tropical Africa. The dominant feature of the climate of this region is the West African Monsoon (WAM) system, which is a recurrent low latitude large-scale circulation pattern arising from the meridional boundary layer gradient of dry and moist static energy between the warm sub-Saharan continent and the tropical Atlantic Ocean. The WAM system develops from April to October, bringing the Inter-Tropical Convergence Zone (ITCZ) and associated rainfall maxima to their northernmost location in August. The analysis of daily rain gauge data performed by Sultan and Janicot (2000) and Le Barbé et al. (2002) reveals that the intraseasonal migration of rainfall maxima is a discontinuous and nonlinear process with three main phases: (i) the preonset or arrival of the intertropical front (ITF) at 15°N in May, bringing enough moisture for isolated convective system to develop over the Sahel; (ii) the onset which occurs at the end of June and corresponds to the abrupt latitudinal shift of the ITCZ from a quasi-stationary location at 5°N in May-June to another quasi-stationary location at 10°N in July-August, and (iii) the retreat of the ITCZ towards the equatorial Atlantic ocean, which occurs in September–October. The intraseasonal variability of the WAM has been linked to various factors, notably the westward traveling monsoon depression (Grodsky and Carton, 2001), interactions with the local orography (Dobrinski et al., 2005), dynamics of the Saharan heat low (Sultan and Janicot, 2003; Sijikumar et al, 2006), and surface albedo (Ramel et al, 2006).

On interannual and decadal time scales, Sahelian rainfall is known to be affected by a variety of regional and global sea surface temperature (SST) anomaly patterns. These include interhemispheric contrasts of SST (Folland et al., 1986; Rowell et al., 1995), anomalies in the tropical Atlantic (Hastenrath, 1990; Vizy and Cook, 2001), the east Pacific (Folland et al., 1991; Janicot et al., 1996; Rowell, 2001), the Indian ocean (Palmer, 1986, Shinoda and Kawamura, 1994; Rowell, 2001), and the Mediterranean (Ward, 1994; Rowell, 2003; Jung et al., 2006).

Rainfall distribution in the Sahel region can be roughly divided into different homogeneous regions: three maxima (one along the west coast at around 8 N, a weaker one around Lake Chad and one over the western Ethiopian plateau)[2] and two minima (one centred around Greenwich meridian and one around 30–35 E) Figure 2.

On an inter-annual timescale one of the most prominent observational features of the area is the dipole structure that associates dry conditions in the Sahel and wet conditions along the Guinean coast (south of 10N) with the presence of warm Gulf of sea surface temperature anomalies (Cook and Vizy, 2006). Figure 2 shows the first empirical orthogonal function for monthly precipitation in August (CRU data 1901–2000; University of East Anglia Climate Research Unit (CRU). CRU Datasets, [Internet]. British Atmospheric Data Centre, 2008, 11-09-2009. Available from http://badc.nerc.ac.uk/data/cru Mitchell et.al 2005). The existence of such a structure indicates that an increase in precipitation over the Sahel is usually associated with a decrease in precipitation along the coast and vice-versa. Such a dipole appears to be linked to the variation in sea surface temperature over the gulf of Guinea. A warm sea surface promotes convection over the sea reducing the penetration of the convergence band over the Sahel.

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[1] In this document the word Sahel is used to refer to the region of Africa laying between 12 and 20 degrees N. Such a definition, slightly more restrictive than others used in the literature, allows us to isolate the area characterized by a single rainy season during the summer

[2] Depending on the observational data-set used a third rainfall maxima may be detected in south west Sudan

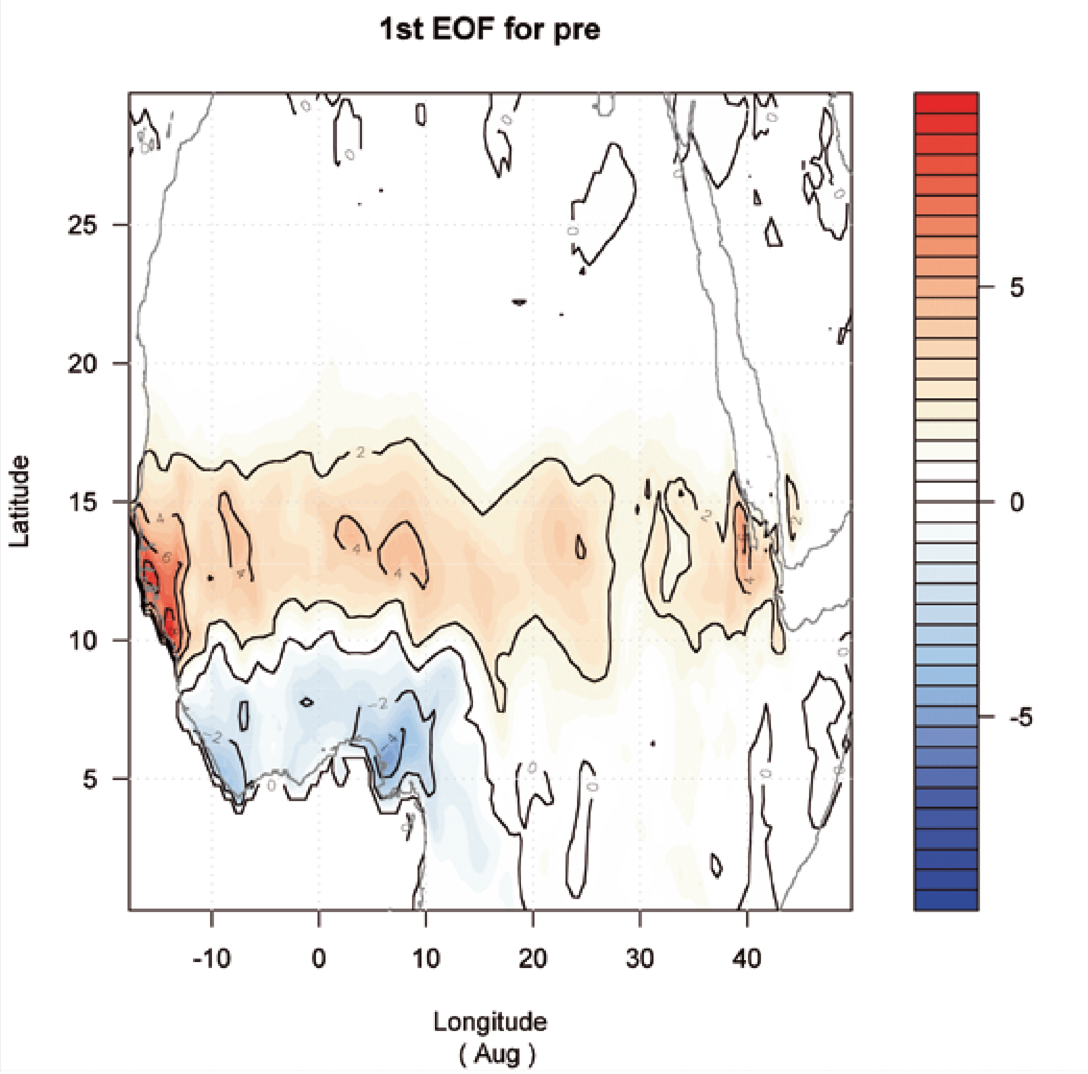

Figure 2

first empirical orthogonal function of the observed precipitation over the area (CRU dataset for 1901–2000)

2.2 Climate variability

Despite the large effort put into establishing the cause of the observed trend, a full consensus on the origin of the drought has not been reached in the scientific community. There is no evidence green-house gasses played a role in driving or exacerbating the drought (Christensen, et al. 2007]. Sahel rainfall variability is likely to be driven by complex interactions between several processes and no process in isolation appears able to explain all the observed variability. A few papers support the idea that a significant part of the recent drying over the region can be attributed to the differential in aerosol loading between northern and southern hemisphere (Baines and Folland, 2007].

Modelling studies have stressed the important role of sea surface temperature in regulating precipitation in the Sahel. More than a third of the observed rainfall variability can be explained by the variability in the ocean surface's temperature. Rainfall in Sahel appears to be negatively correlated with the Tropical Indo-Pacific SST and positively correlated with the Atlantic meridian SST gradient (Folland et al 1986, Giannini et al. 2003].

Such a correlation can be used to provide skilful seasonal and decadal climate predictions. Whether or not the same physical processes are controlling the rainfall variability over longer time-scale is still debated. Some authors believed that coupled processes driving the inter-annual rainfall variability are unable to provide a useful guide on centennial changes suggesting that another mechanism may be operating on those time-scales (Biasutti et al 2006). At least two others processes are likely to influence the rainfall variability in the regions: land surface feedback (Charney et al 1974 and 1975) and aerosol (Biasutti and Giannini 2006 and Christensen et al 2008). The effect of these processes on the climate projections, tends to be model dependent (Scaife et al 2009).

2.3 Observational analysis

Due to time limitation only a simple analysis of the observational datasets has been carried out within this project. This analysis was based on using the CRU 3.0 dataset produced by the University of East Anglia (Mitchell et. al 2005). It is among the most reliable sources of historical information for the region.

Our definition of the Sahel region, corresponds to an area characterised by a single rainy season per year with an annual maximum precipitation occurring in August. Such a circumstance allowed a simplification in the analysis: by analysing only precipitation occurring during the wet season seasonal cycle is automatically removed

One of the first features emerging from the analysis of rainfall is that the dry anomaly associated with the drought of the 80s appears to be mainly associated with a lack of precipitation during the month of August rather than during the other three months of the wet season. Such a result fits nicely with the notion that the drought was associated with a southward shift of the inter-tropical convergence zone.

To visualise the impact of the drought on the spatial structure of precipitation the precipitation for the month of August has been plotted as a function of longitude (or latitude) and time. These plots (fig. 3 and 4), called Hovmuller diagrams in meteorology, allow the user to follow how an anomaly propagates spatially with time.

Looking at the plots in fig. 3 and in fig. 4 it is possible to notice that the big drought of the 80s represents the single most dramatic event on record. During this dry period not only was the rain lower then usual but the geographical extent of the humid region moved significantly south (e.g. 1984).

Another important aspect to notice is that, in contrast to other events on record, the drought of the 80s has affected the whole of the Sahel at once. This is particularly evident in figure 4. The same plot seems to suggest a westward movement of the dry anomaly which first hits the region close to 30 E and then “propagates” westward to affect the other part of the Sahel. Such a conclusion at this stage should be considered as a conjecture rather than as observational evidence due to the lack of both data and of a reliable physical explanation.

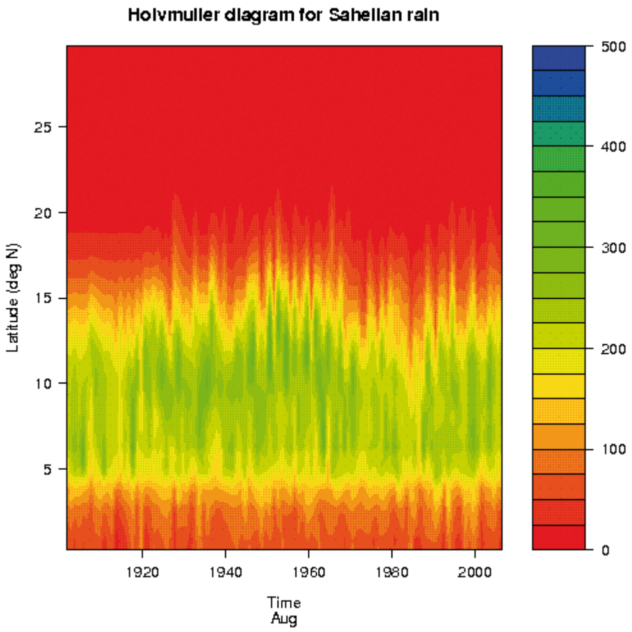

Figure 3

Latitude-time plot of precipitation (Hovmuller diagram) for the month of August for the entire Sahelian region. The drought of the 80s appears both as a reduction in the mean value of precipitation and as a southward displacement of the northern edge of the wet area. Plot based on CRU observation (Mitchell and Jones, 2005).

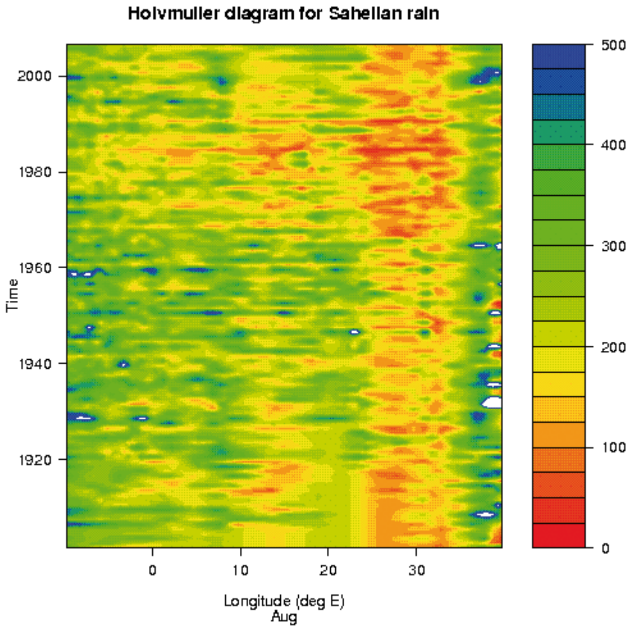

Figure 4

Time-longitude distribution of Sahelian rainfall, at the 12°N. The uniformity of the values at the beginning of the record reflects a significant lack of data there. Plot based on CRU observation (Mitchell and Jones, 2005).

A more conventional representation of the drought is presented in figures 5 and 6. Here the average precipitation for the month of August over the period 1901–2000 can be compared with the same field during the drought period. The latter was obtained by averaging August precipitation for the 15 years between 1975 and 1990 (Figure 5). The difference between the two fields indicates a general reduction of precipitation over Sahel and a little increase along the coast of Guinea. Such a dipole structure maps perfectly onto the first mode of variability described at the beginning (fig. 2) and provides additional evidence to the link between Sahelian rainfall and the position of the ITCZ monsoon front. Such a dipole structure is directly linked to the sea surface temperature in the gulf of Guinea where a warm anomaly can promote convection over the sea inhibiting the propagation of the monsoon front on shore.

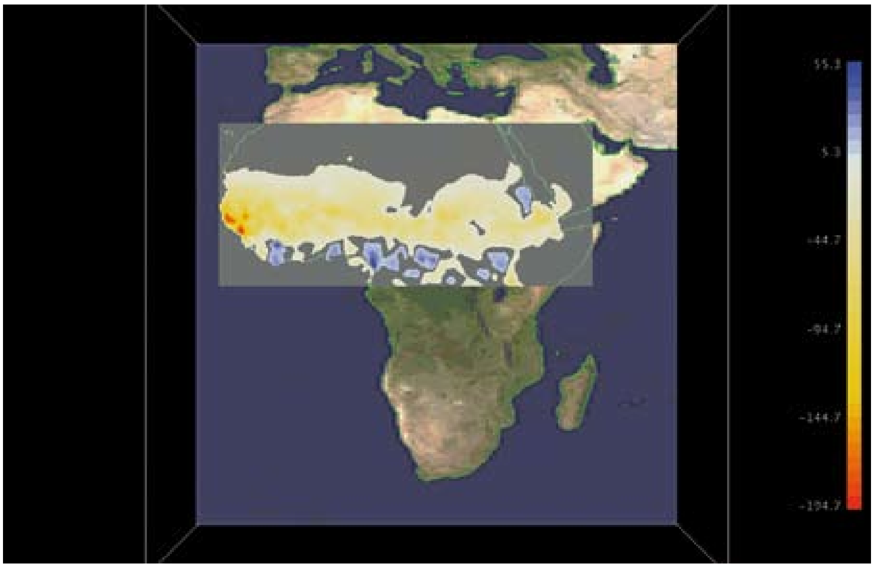

Figure 5

average august precipitation anomaly [mm/month] for the period 1975–1990 with respect to the mean of the 20th century. Plot based on CRU observation (Mitchell and Jones, 2005).

We have performed a sensitivity analysis based on historical observations to identify the regions where in the past, droughts have caused the largest amplitude in rainfall anomalies. We limited the analysis to the region where annual precipitation exceeds 77mm because below this threshold human activities are very marginal. The analysis, shown in figure 6 suggests the presence of at least three particularly sensitive regions. One lays along the west-most part of the region (Senegal and Mauritania), the second stretches between Mali and Niger and the third sits along the eastern fringe of Ethiopia and extends northward up to Sudan. For some of these areas, such as eastern Sudan/Eritrea, the average reduction of rainfall during the 10 most severe droughts of the 20th century has reached almost 100%. Of the 10 worst droughts on record, only 4 (1984, 1972, 1986, 1990) were simultaneously among the worst 10 for eastern and western Sahel (arbitrarily separated at 20 E) separately. For this reason the analysis has been conducted for the two sub-regions separately and rejoined into a common plot (fig. 6) at a later stage.

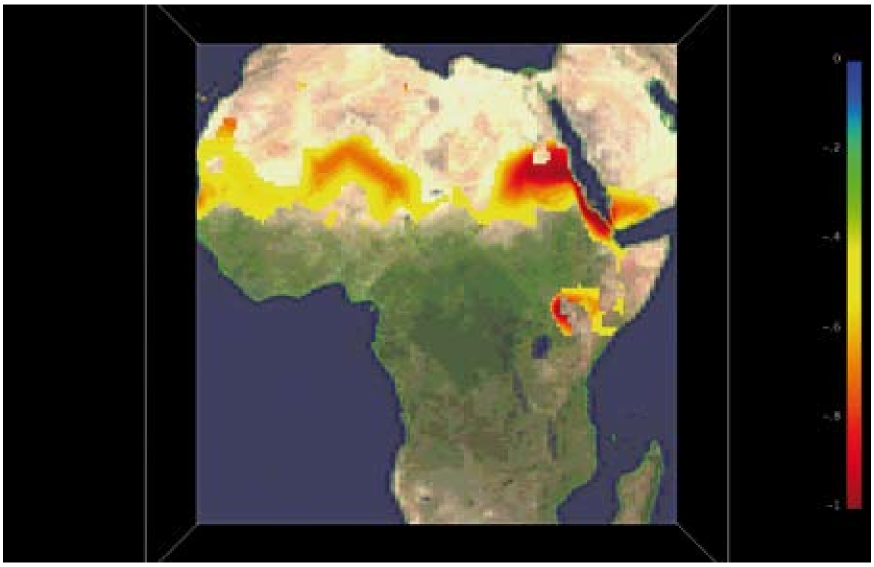

Figure 6

Number of wet days in August during the 10 worst droughts of the 20th century expressed as a fraction of the climatogical value over the 20th century. Only the area with at least 77 mm/month is shown in the plot. Three hotspots can be identified: one along the west coast (Senegal Mauritania, one between Mali and Niger and the third on Sudan-Eritrea and eastern Ethiopia. Plot based on CRU observation (Mitchell and Jones, 2005).

2.4 Time series analysis

Summer monthly precipitation over the Sahel is not normally distributed (Fig. 7). This is not particularly surprising since monthly mean rainfall rarely shows a perfectly normal distribution. What is more interesting is that in the case of the Sahel the largest deviation occurs on the dry tail. This means that precipitation can be significantly less than would be expected in a normally distributed process.

With the aim of understanding present-day rainfall trends and fluctuations, an analysis of the observational time series has been performed. This was structured in two distinct parts: first we calculated the Hurst exponent [Hurst 1951] from the monthly observations of August rainfall. This parameter provides an estimation of the probability of large deviations from the mean. It can be shown that an Hurst exponent of 0.5 represent a perfect random walk. This means that at any instant the probability for the time series to re-converge toward the mean is equal to the probability for the time series to step away from the mean. Hurst exponent between 0 and 0.5 are indicative of processes which tend to reconvene rapidly toward the mean while values in between 0.5 and 1 indicate the probability of persistent and large fluctuations. For Sahelian monthly mean precipitation we calculated the Hurst exponent using several different algorithms. We obtained values ranging between 0.56 and 0.9. These values, obtained from a de-trended and normalised time series, all lay well above the threshold value of 0.5. This indicates that rainfall in this area is a long-memory process where large clustering deviations are to be expected. Although this doesn't come as a surprise to a climate scientist with experience in the area it is interesting how this complex behaviour can be detected by such a simple analysis.

As a further investigation of the properties of the observed time series we performed a quantile regression. This technique allows us to analyse separately the trend of different parts of the distribution. For this purpose the total amount of monthly rainfall was divided into 4 quantiles (0.25, 0.5, 0.75, and 0.9). For each quantile group a linear fit was then performed. The results indicate that for west Sahel the decrease in precipitation has been quite homogeneous across the distribution while for east Sahel the upper tail has shown a larger decrease than the mean. Considering the limited size of the sample the results should be taken with caution.

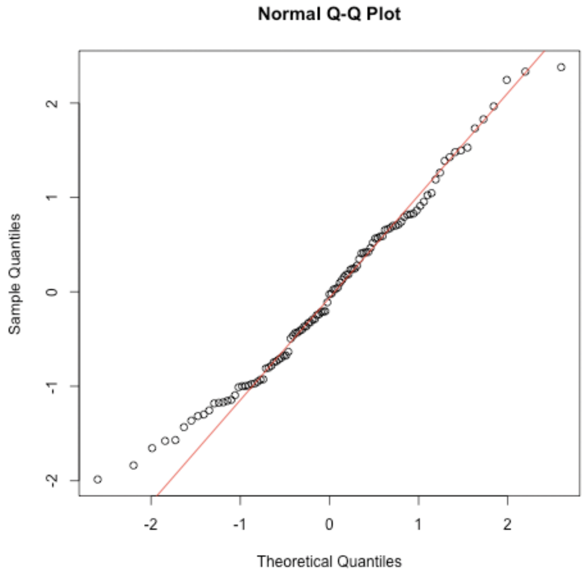

Figure 7

Quintile-Quintile plot for observed August rainfall (CRU data). The red line indicate the theoretical behaviour of a normal process. The plot emphasise the presence of a long dry tail in the observations.

3 Climate projections for the Sahel

Climate projections over the Sahel are particularly challenging for two reasons. On the one hand the large climate variability observed over the 20th century makes it more difficult to extract a sign attributable to climate change above the background noise on the other hand climate models are in significant disagreement over this region. This is particularly true for precipitation where models disagree even on the sign of the change. In this section we have discussed separately the projection for temperature, which is more certain, than those of precipitation. The difference in model skill between these two parameters has motivated some authors (PNAS Nov 2009) to analyse the implication of climate variability on security only looking at temperature variation. Although such an approach appears interesting there is enough evidence to suggest that the direct impact of climate variability on water resources still represents the dominating factor in the region.

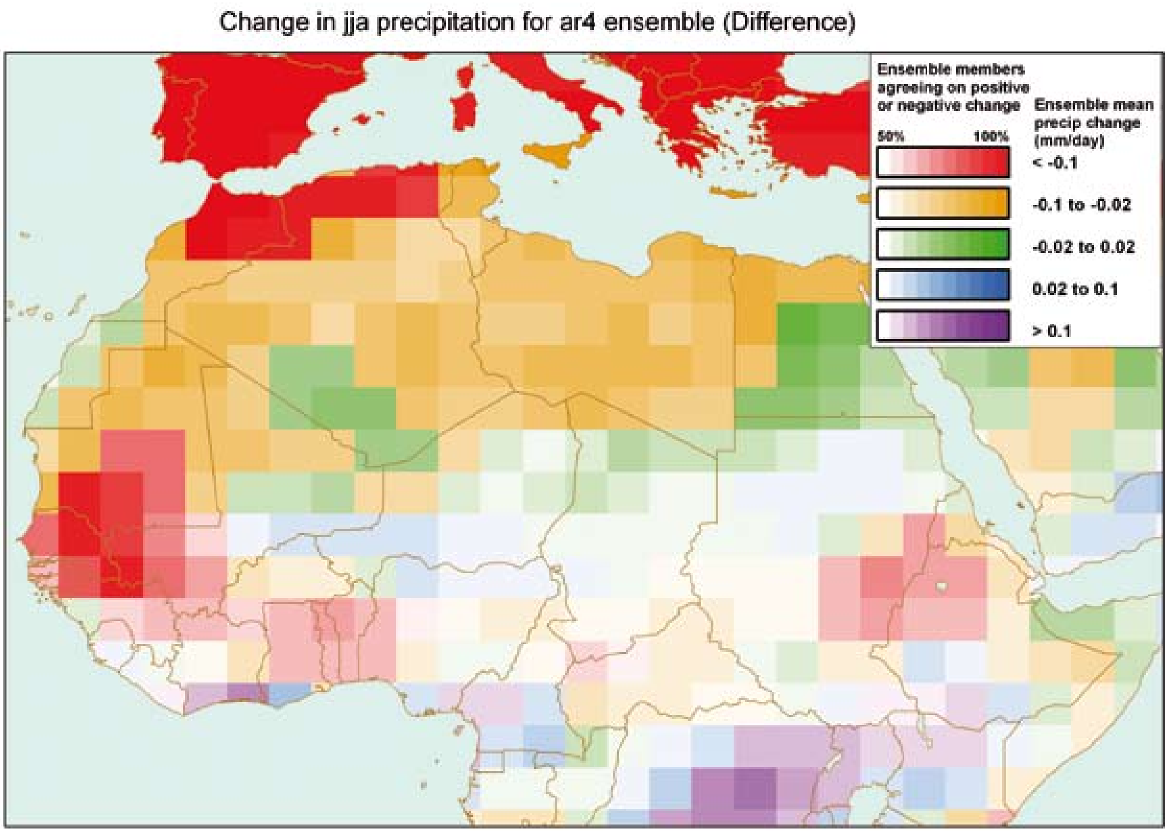

Figure 8

Difference (mm/day) in summer (JJA) precipitation between 2041 – 2070 and 1960 – 1990 across AR4 ensemble. The colour indicates the strength of the signal while the colour-intensity indicates the consistency across the ensemble. For example, deep red colours indicated where nearly 100% of models agree on a precipitation reduction of more than 0.1 mm/day, dark green indicates where nearly 100% of models agree on nearly no change West-most Sahel is the area where both the largest and the most reliable signal can be noticed.

3.1 Rainfall

Very little consensus exists on what the long term climate signal is likely to be for most of the region, under a business as usual future scenario. Model disagreement is surprising considering that most climate models, despite underestimating amplitude and phase of rainfall fluctuations, have some skill in reproducing the recent drying trend when forced by observed SST.

Our limited understanding of the processes governing tropical rainfall doesn't allow us to make any robust climate prediction in the Sahel as a whole. The faster warming of the land with respect to the sea, by increasing the land-sea contrast would intensify the monsoon activity. In contrast a strengthening of the Saharan thermal high may increase the dry advection in the region thus suppressing convection.

We advice against basing the assessments of future climate change in the Sahel on the results from any single model in isolation.

According to IPCC AR4, whose summer projections are presented in Fig. 7, the coastal countries of west Sahel are likely to see a reduction in precipitation while the Ethiopian highlands are likely to receive more rain (DJF, MAM) [Christensen et al. 2007]. Met Office ensemble (fig. 8) depicts a similar picture over west Africa while predicting an increase in precipitation on both central and east most Sahel even during the summer months.

Following the hotspot analysis we presented in the previous section we can see what model projection means for each of the three areas we have identified. For the west-most part of the region a robust decrease in summer precipitation (<-0.1 mm/day which represent a few percents of the annual precipitation) is expected. This clearly appears both in the AR4 ensemble and in the smaller parameter ensemble we have at the Hadley Centre. For the second hotspot, located over the central Sahel the situation is less clear. Model projections are less robust and are different in the two ensembles analysed. This means that for this area it is essential to provide reliable seasonal prediction to promote adaptation in the absence of a clear climate signal. Finally for eastern Sahel (east of 20E) although no consistent message emerges for summer precipitation, an increase in annual precipitation appears to be detected in most of the models.

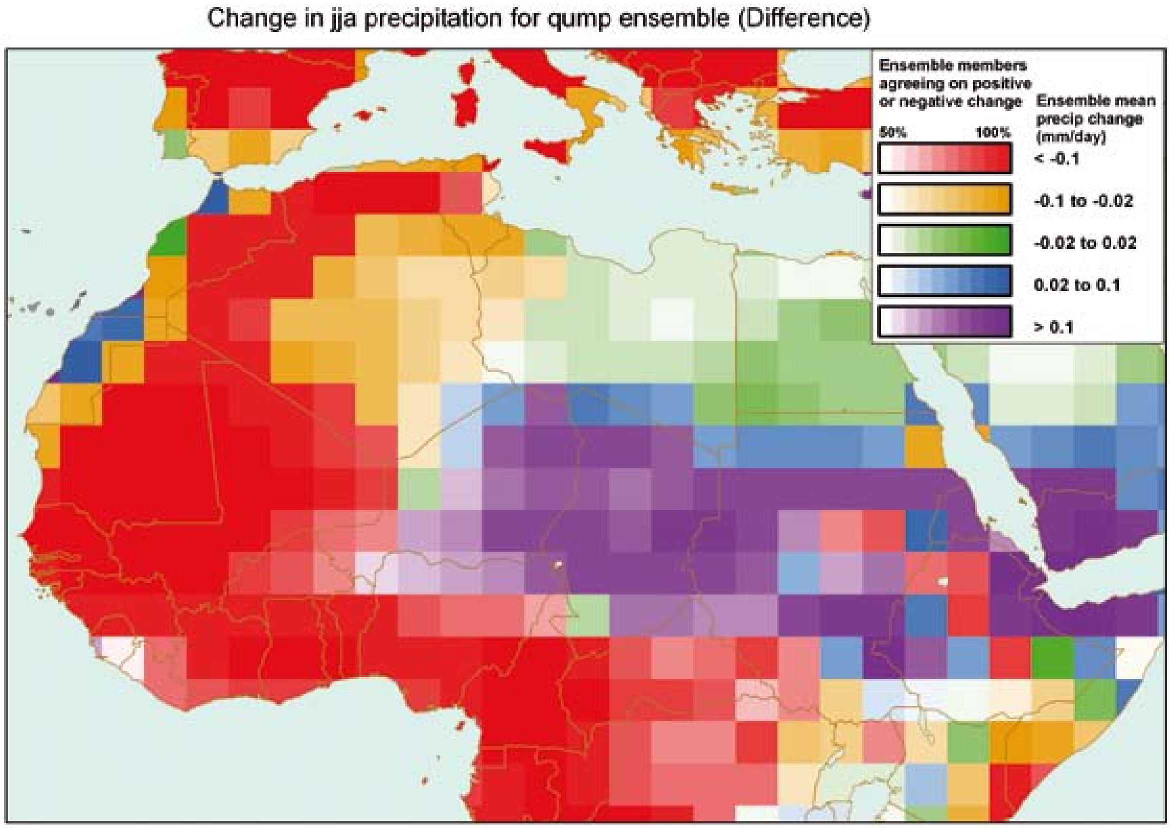

Figure 9

As in figure 8 but for Met Office Hadley Centre ensemble. The signal on west-most Sahel appears to be fairly similar to the one detected by AR4 while significant differences exists over Central and east Sahel where Met Office ensemble seems to suggest a consistent wetting.

3.2 Temperature

The inter-model disagreement is less problematic for temperature where all models are suggesting an increase in surface temperature for business as usual future scenarios. This warming is likely to be higher here than in the global average. This means a temperature increase between 3 and 4 degrees by the end of the century with respect to the last twenty years of the 20th century. Half of the models used in IPCC AR4 predict an increase within 0.5 degrees of this median values [Christensen et al. 2007]. In Africa the signal to noise ratio for temperature is very high. This implies that for most of the locations a 10 years average is sufficient to notice a discernible warming.

Geographically the greatest warming (~4 degrees) occurs over land and in particular in the western side of the Sahel; over the coast and close to the southern edge of the region the increases are expected to be smaller but still substantial (~3 degrees). The strongest warming is expected to occur during the summer months. [Christensen et al. 2007].

At surface level part of the warming can be offset by a local increase in precipitation via evaporative cooling. This can potentially become important in some regions along the southern edge of the Sahara desert.

3.3 Extremes

Very little modelling and observation evidence on trends in extremes exists for the Sahel. Thermodynamic argument suggests a general increase in the intensity of high-rainfall events. There is no consensus among models whether extremely dry or extremely wet seasons are likely to become more common over the area. However it is virtually certain that extremely hot seasons will become more frequent in the future.

4 Conclusion

Clarifying the limit of our current understanding is at least as important as providing a well-defined answer. For west Sahel this is probably the best we can do today. Interactive vegetation, land use, and aerosol-cloud interaction are but a few of the processes believed to be important in regulating the climate of the region. These same processes are only partially addressed by the current generation of climate models which may also miss some important teleconnection patterns.

In order to overcome these difficulties we proceeded with a hotspot analysis. This has allowed us to identify three hot spots where the difference in precipitation between dry and normal years has been greater than in the rest of the region. Three regions have emerged as being particularly sensitive to climate variability. These are: the coastal area of west-most Sahel; the central region between Mali and Niger and the coastal area along the eastern edge of the Ethiopian plateau, Eritrea and Sudan.

Analysing the model projections in these hot areas specifically allowed us to be a bit more specific in the projections. Over western-most Sahel a robust drying appears in most climate models while for the eastern hotspot, at least in annual average, an increase in precipitation appears likely. For the hotspot around 20E, as for most of the Sahel, model projections do not provide a reliable message. This means that while waiting for a new generation of climate models able to better understand the processes regulating the climate of this region, adaptation to climate variability should be promoted. This is an area where seasonal predictions have skill and can provide useful guidance to policymakers.

The time series analysis provided evidence of the drought clustering in the region. From past evidence, once a dry anomaly is detected the system is more likely to evolve toward an exacerbation of the drought than it is to recover. Such statistical information can potentially be used in conjunction with seasonal predictions to improve the usefulness of short-term climate projection over the area.

A new ensemble of high resolution simulations over the region is likely to become available shortly through the project ENSEMBLES. Such a new source of data may potentially help to reduce the uncertainty in model prediction over the region.

Acknowledgment

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