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Consistency of projected drought over the Sahel with changes in the monsoon circulation and extremes in a regional climate model projections

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[1] As a step toward an increased understanding of climate change over West Africa, in this paper we analyze the relationship between rainfall changes and monsoon dynamics in high-resolution regional climate model experiments performed using the Regional Climate Model (RegCM3). Multidecadal simulations are carried out for present-day and future climate conditions under increased greenhouse gas forcing driven by the global climate model European Center/Hamburg 5 (ECHAM5). Compared to the present day, the future scenario simulation produces drier conditions over the Sahel and wetter conditions over orographic areas. The Sahel drying is accompanied by a weaker monsoon flow, a southward migration and strengthening of the African Easterly Jet, a weakening of the Tropical Easterly Jet, a decrease of the deep core of ascent between the jets, and reduced African Easterly Wave activity. These circulation changes are characteristics of dry periods over the Sahel and are similar to the conditions found in the late twentieth century observed drought over the region. Changes in extreme events suggest that the drier conditions over the Sahel are associated with more frequent occurrences of drought periods. The projected drought over the Sahel is thus physically consistent with changes in the monsoon circulation and the extreme indices (maximum dry spell length and 5 day precipitation).

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1. Introduction

[2] Since the late 1960s, West Africa has experienced multidecadal episodes of below normal rainfall, prompting numerous investigations of the possible causes [*Lamb and Peppler*, 1992; *Nicholson*, 2000; *Dai et al.*, 2004; *Lu and Delworth*, 2005]. West African rainfall variability has been linked to such factors as ocean sea surface temperature anomalies [*Giannini et al.*, 2003; *Hoerling et al.*, 2006], continental surface conditions [*Semazzi and Sun*, 1997; *Wang and Eltahir*, 2000], or atmospheric circulation anomalies [*Nicholson and Grist*, 2001; *Jenkins et al.*, 2005; *Nicholson*, 2008]. In addition to the present-day variability, climate change resulting from anthropogenic emissions of greenhouse gases (GHGs) will likely impact human societies and natural ecosystems over West Africa [*Christensen et al.*, 2007]. Therefore, understanding the physical mechanisms underlying projections of future change over the region is of critical importance.

[3] To date, Atmospheric-Ocean Global Coupled Models (AOGCMs) have been used to simulate and analyze climate change over West Africa [*Kamga et al.*, 2005; *Biasutti and Giannini*, 2006; *Hoerling et al.*, 2006]. However, owing to their relatively coarse spatial resolution (order of a few hundred kilometers), these models are often not suitable for simulating detailed regional weather and climate patterns [*Giorgi and Mearns*, 1999; *Jenkins et al.*, 2002; *Sylla et al.*, 2009a]. Regional Climate Models (RCMs) can be used to dynamically downscale AOGCM future scenarios down to scales closer to those required for impact and adaptation studies [*Giorgi and Mearns*, 1999]. While numerous RCM-based climate change scenarios have been carried for the midlatitudes [e.g., *Giorgi et al.*, 1994; *Mearns et al.*, 1995; *Leung et al.*, 2004; *McGregor and Walsh*, 1994; *Christensen et al.*, 1998; *Déqué et al.*, 2005, 2007], few RCM studies have investigated the West African region [*Paeth and Thamm*, 2007].

[4] In addition, the spread of AR4-GCMs over West Africa is quite large, and the response of precipitation to anthro-

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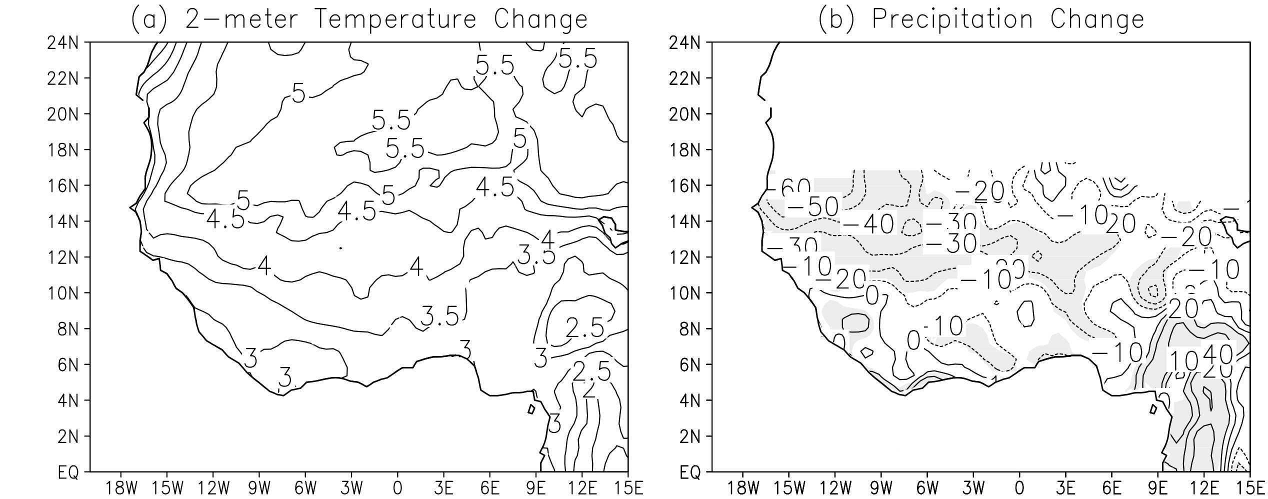

Figure 1. Average summer differences (A1B minus reference) for (a) temperature (in degrees Celsius) and (b) precipitation (percent of present-day values). All temperature changes are significant at 99% of confidence level, and all precipitation changes are significant at 90%. Areas shaded in gray in Figure 1b are where precipitation changes are significant at 99% of confidence level. Areas where precipitation is less than 0.5 mm/d have been masked out.

pogenic climate change is uncertain [*Cook and Vizy*, 2006; *Christensen et al.*, 2007; *Joly et al.*, 2007; *Biasutti et al.*, 2008]. Therefore the construction of climate change scenarios for West Africa needs to be approached by using ensembles of RCM simulations driven by different AOGCMs. However, before using an RCM in this ensemble context, it is important to assess the physical consistency of the processes relating changes in precipitation and monsoon dynamics when RCMs are driven by AOGCM fields.

[5] Toward this goal, in this paper we examine multidecadal experiments of late 21st century (2081–2100) changes in West Africa temperature, precipitation, and monsoon dynamics under the midrange IPCC A1B GHG emission scenario [*Nakicenovic et al.*, 2000] as simulated by a nested RCM. The focus of the analysis is on the consistency of precipitation changes over the Sahel with changes in relevant monsoon circulation features and extremes as simulated by the Regional Climate Model (RegCM3). This assessment provides information necessary to evaluate the applicability of the RegCM modeling system for climate change projections over West Africa. We therefore stress that this is a process study and not a study aimed at providing scenarios over the region for application to impact and adaptation work.

2. Model and Experiment

[6] The model used in this study is the latest version of the International Centre for Theoretical Physics (ICTP) Regional Climate Model, RegCM3 [*Giorgi et al.*, 1993a, 1993b; *Pal et al.*, 2007]. The model domain, calibration, and configuration are the same as those used by *Sylla et al.* [2009a], whose selection was based on an analysis of the model performance. The reader is thus refereed to the work of *Sylla et al.* [2009a] for a detailed description of the model's characteristics.

[7] Initial and lateral boundary conditions for the present-day and future scenario simulations are provided by the Max Planck Institute for Meteorology GCM, European Center/Hamburg 5 (ECHAM5) [*Roeckner et al.*, 2003]. ECHAM5 is coupled to the MPIOM ocean model [*Jungclaus et al.*, 2006], which also provides 6-hourly data of present and future sea surface temperature. These are interpolated onto the RegCM grid and used in the corresponding simulations.

[8] RegCM3 is integrated over a West Africa domain (e.g., see Figure 1) for a reference present-day period (1981–2000) and a future period (A1B scenario: 2081–2100) at 40 km horizontal grid spacing with 18 vertical levels. Note that the A1B scenario lies toward the middle of the IPCC emission scenario range, with CO_2 concentrations of ~650 ppm by 2100. We examine changes between the late 20th and 21st century by differencing the RegCM3 simulations of the two time periods (A1B minus reference). As mentioned, the focus of our analysis is on the consistency of RegCM3 projected precipitation changes over the Sahel with changes in key features of the monsoon circulation and how these changes and interconnections compare with those found during the Sahelian drought of the late twentieth century. As a measure of hydroclimatic drought, we consider two quantities: the maximum dry spell length and the maximum 5-day precipitation, which have been used as hydroclimatic indicators by *Christensen and Christensen* [2003], *Pal et al.* [2004], and *Gao et al.* [2006].

3. Results and Discussion

[9] For the peak monsoon period (June–August), RegCM3 displays warming (A1B-reference) of 2–6 K over the region (Figure 1a). The smallest temperature increases are found over the orographic zones of Guinea, Cameroun Mountains, and Jos Plateau. Larger warming occurs north of the Gulf of Guinea, with a maximum over the Sahara desert. The temperature changes are significant at the 99% level of confidence. Projected rainfall shows significant changes over orographic areas, with an increase of 10% in the Guinea Highlands and up to 30% around the Cameroun Mountains and Jos Plateau (Figure 1b). Outside the orographic regions,

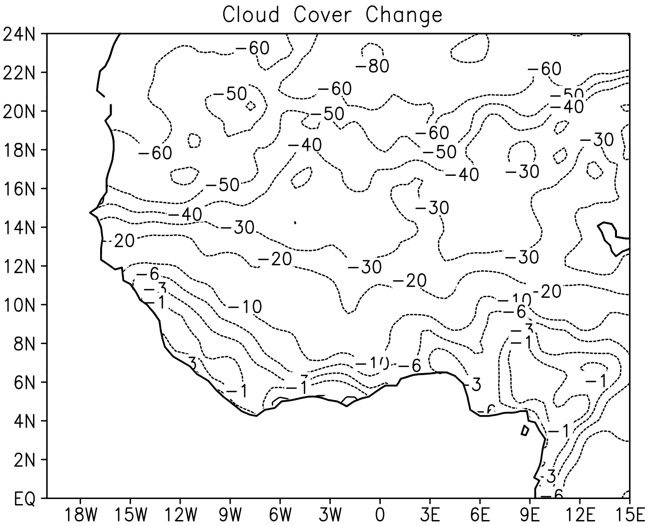

Figure 2. Average summer differences (A1B minus reference) for cloud cover (percent of present-day values). Changes are significant at 99% of confidence level.

RegCM3 indicates drier conditions in the last two decades of the 21st century. The drying is large, over the Sahel, with up to 60% precipitation decrease statistically significant at the 99% of confidence level (Figure 1b, shaded in gray). Note that rainfall increases are found where the smallest warming is located, indicating that the increase in surface evaporative cooling and cloud cover tends to locally counterbalance the greenhouse warming.

[10] Indeed, cloudiness is likely a key factor in modulating the temperature and precipitation changes. Figure 2 presents changes in total cloud cover (in percent of present-day value) between the late 21st century time period and the present day. Total cloud cover is calculated from the individual layer's cloud amounts using the random overlap assumption. Cloud cover is projected to decrease over the entire West Africa region. The smallest changes (~−1% up to −3%) are located around the orographic regions of Guinea, Jos, and Cameroun, where rainfall increases are predicted. Over the Sahel, changes are up to −30% or −40%, consistently, with the drier conditions and large warming (4–5 K) projected over the region. The largest percentage cloud cover reduction is found over the Sahara, where the highest warming occurs; however, the large percentage change there is amplified by the very low present-day cloud amounts. The results of Figure 2 indicate that cloud feedbacks are important in modulating the magnitude of warming.

[11] The physical consistency of the precipitation reduction over the Sahel is diagnosed by investigating changes (A1B minus reference) in key components of the monsoon circulation: the monsoon flow, the convection (pressure velocity), the African Easterly Jet (AEJ), the Tropical Easterly Jet (TEJ), and the African Easterly Waves (AEWs). These features significantly modulate convection and rainfall. In fact, several observational studies have shown that most precipitation events in West Africa are associated with features that are rainfall-generating systems embedded in the AEWs and organized along the AEJ, with the strength of the TEJ strongly contributing to the duration of their lifetime [*D'Amato and Lebel*, 1998; *Mohr and Thorncroft*, 2006; *Diedhiou et al.*, 2001; *Janicot*, 1997]. In addition, the strength and the northward extent of the large core of ascent lying between the AEJ and TEJ significantly affect the rain belt [*Nicholson*, 2008]. Furthermore, it has been shown that a stronger AEJ transports more moisture away from West Africa, leading to drier conditions over the continent [*Paeth and Thamm*, 2007; *Abiodun et al.*, 2008].

[12] Global climate models traditionally have had problems in simulating the strength and location of these circulation features over West Africa. An example illustrating this is shown in Figure 3, which presents the vertical cross section of present-day, averaged summer zonal wind over the Sahel as simulated by six GCMs in the CMIP3 archive [*Meehl et al.*, 2007]. Only CGCM3.1 (Figure 3a) and the UKMO-HadCM3 (Figure 3f) are able to capture a proper vertical profile of the Sahelian atmosphere during the summer season. They both show the monsoon flow (around 4 m/s) in the lower levels, the AEJ (around 10 m/s) in the midlevels, and the TEJ (up to 12 m/s) in the upper levels. CSIRO-MK3.5 (Figure 3b) completely misses the monsoon flow and the TEJ but finds a core of easterly wind around 700 hPa that resembles the AEJ. The IPSL-CM4 GCM (Figure 3c) shows a reasonable monsoon flow, a strong AEJ, and a very weak TEJ. The NCAR models, PCM (Figure 3d) and CCSM (Figure 3e), do not capture well any of the relevant circulation features; however, some widely spread easterly winds can be found in the midlevels. This implies that the spread of the large-scale circulation simulated by different GCMs is quite large. Therefore, in order to study the drought signature in the circulation in climate change projections, the use of good performing models in simulating theses features is critical. In the work of *Sylla et al.* [2009a], it was indeed shown that ECHAM5 produced a reasonable location of the large-scale circulation features during the summer season over West Africa and that RegCM3 was actually able to improve the simulation of these features provided by the global model.

[13] In the future climate simulation, RegCM3 projects a slight increase in the ascent of air over the land-sea border between the Gulf of Guinea and the land areas (between equator and 5°N) and over the southern Sahara from the lower troposphere to midtroposphere (Figure 4a). At the lower latitudes the increase is likely due to an increase in moist convection as the relative humidity also increases at the same latitudes and up to the same vertical level (Figure 4b). The increase in rising motions over the southern Sahara is related to increased dry convection in association with the summer season thermal low. The most important feature in this region is the deep core of ascent around 10°N, which highly contributes to the location and intensity of the rain belt over the Sahel [*Nicholson*, 2008]. The projections indicate a reduction of its intensity at all levels of the troposphere. Consequently, the relative humidity decreases, particularly in the midlevels (~850–200 hPa).

[14] During the late 21st century, the simulations show that the low-level (925 hPa) horizontal wind field weakens over the West Africa coast and in the Gulf of Guinea (~−0.5 m/s), strengthens over the northern Sahel (0.5–1.5 m/s), and weakens again in the Sahara (−0.5 to −2.0 m/s) (Figure 5). This is related to the local temperature increases that may cause variations in temperature gradients throughout the

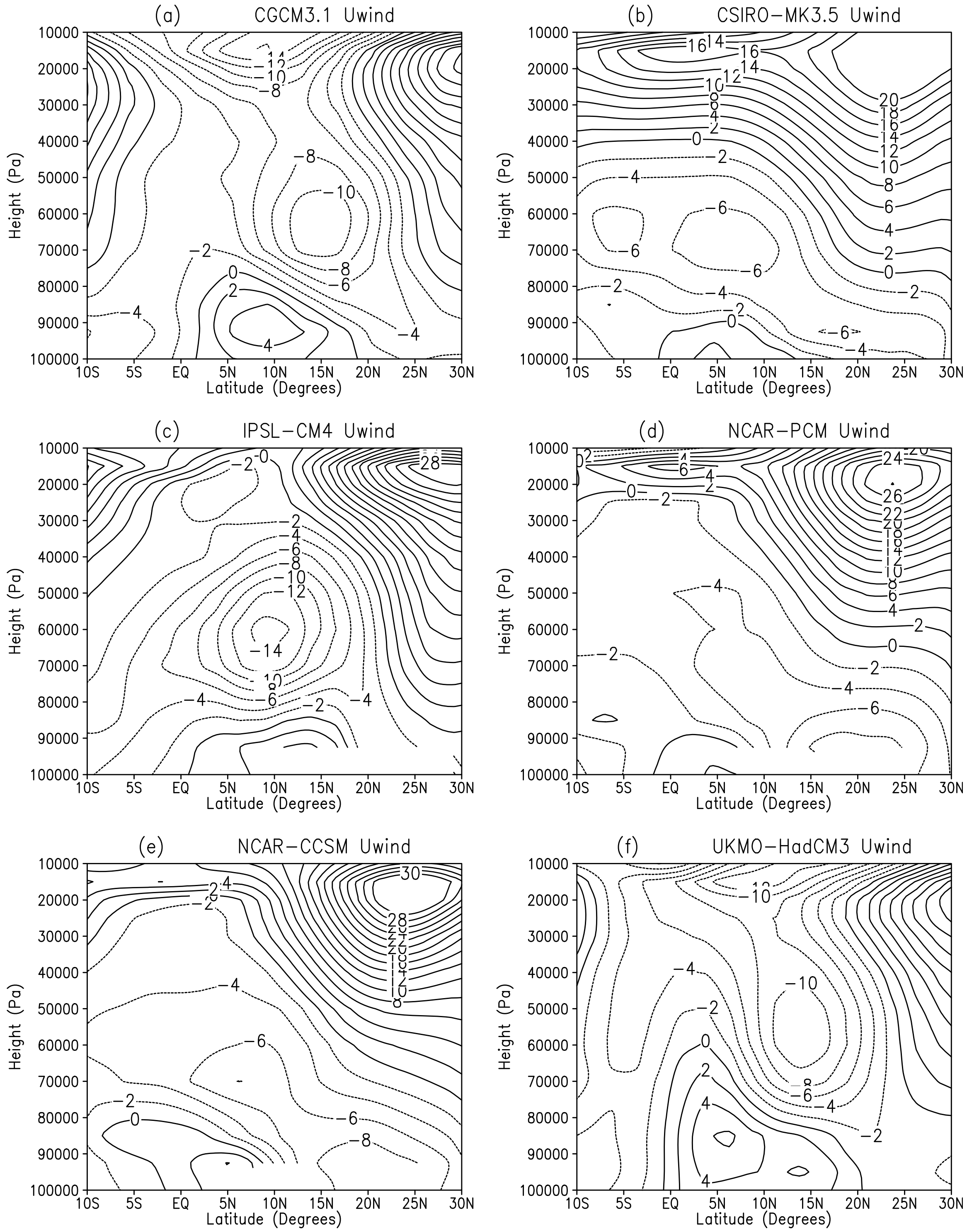

Figure 3. Vertical cross section of present-day (1981–2000) averaged summer zonal wind (in m/s) from some AR4 global models over the Sahel: (a) CGCM3.1, (b) CSIRO-MK3.5, (c) IPSL-CM4, (d) NCAR-PCM, (e) NCAR-CCSM, and (f) UKMO-HadCM3.

domain. The weakening of the horizontal wind magnitude along the West African coast indicates a reduction of the monsoon fluxes that results in less moisture entering West Africa from the Atlantic Ocean, thereby inhibiting rainfall.

[15] The zonal wind at the level of the AEJ decreases slightly (up to 1 m/s) north of 16°N and increases south of that latitude by up to 4 m/s around 6°N (Figure 6). This implies a southward displacement and a strengthening of the AEJ during the late 21st century period, which has been observed during 20th century dry periods [*Jenkins et al.*, 2005]. Although the frequency and strength of ENSO events could eventually vary from the 20th and 21st centuries and

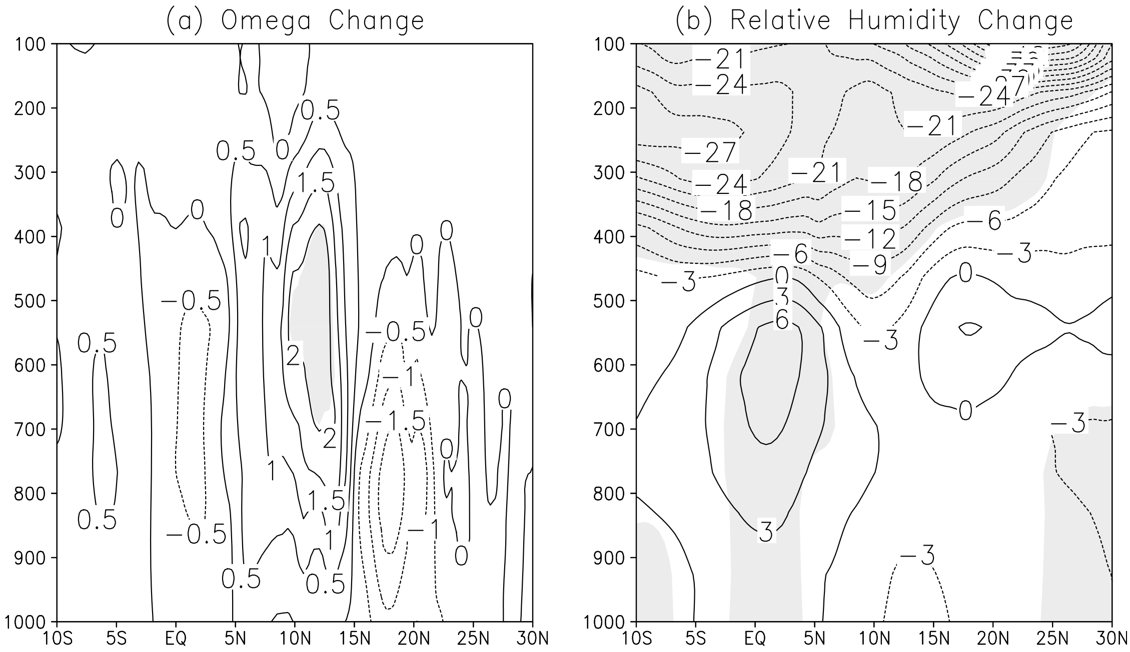

Figure 4. Cross section of average summer differences (A1B minus reference) for (a) Omega (10^{-3} Pa/s) and (b) relative humidity (ratio in percent). All changes are significant at 90% of confidence level. Areas shaded in gray are where changes are significant at 99% of confidence level.

could affect the position and strength of this jet [*Janicot*, 1997], GHG-induced warming may impact changes of the AEJ by setting a stronger temperature gradient between the Sahara and the Gulf of Guinea [*Cook*, 1999; *Thorncroft and Blackburn*, 1999]. In this regard, Figure 7 shows the meridional cross section of temperature for the present-day and future periods as simulated by RegCM3. Although temperatures are higher for all latitudes during the late 21st century than during the present day, the warming is greater north of 15°N than it is south of it. This implies a strengthening of the temperature gradient between the Sahara and the Gulf of Guinea, which should impact the position and the strength of the AEJ [*Cook*, 1999; *Thorncroft and Blackburn*, 1999; *Steiner et al.*, 2009].

[16] At 200 hPa, RegCM3 shows an overall decrease of the zonal wind throughout the domain and, in particular, between the equator and 10°N, the tracking region of the TEJ over West Africa (Figure 8). This indicates a weakening

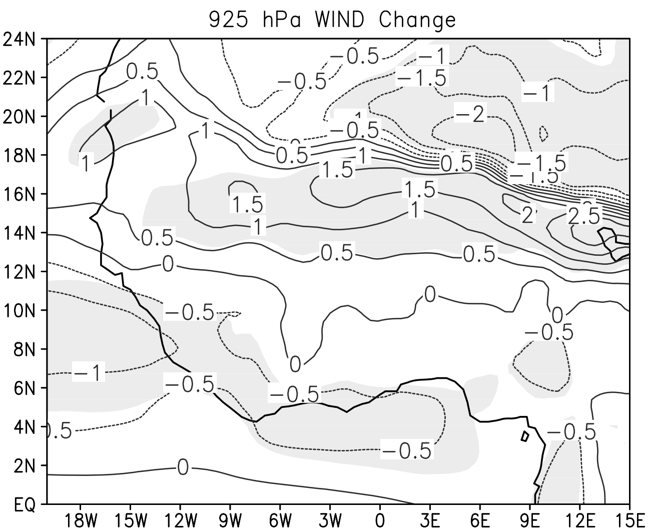

Figure 5. Average summer differences (A1B minus reference) for the wind field at 925 hPa. Units are m/s, and shaded areas are where changes are significant at 99% of confidence level.

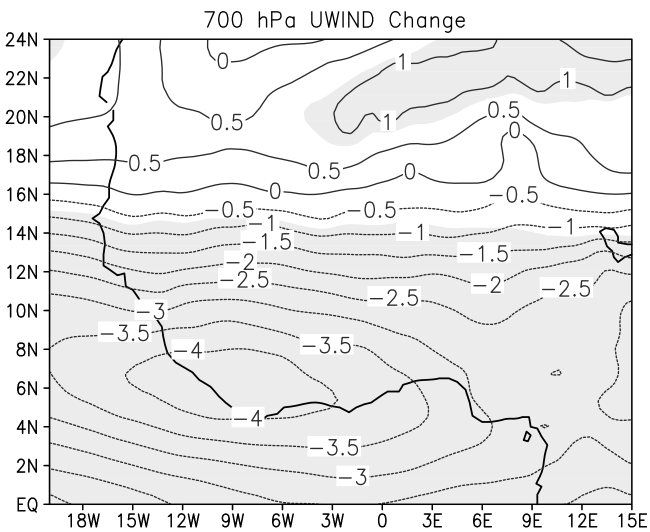

Figure 6. Average summer differences (A1B minus reference) for the zonal wind at 700 hPa. Units are m/s, and shaded areas are where changes are significant at 99% of confidence level.

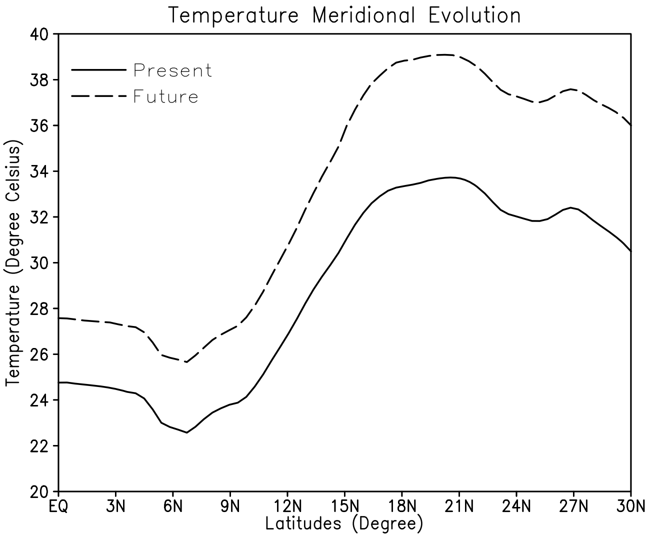

Figure 7. Meridional cross section of summer temperature (A1B and reference) averaged between 10°E and 10°W. Units are degrees Celsius.

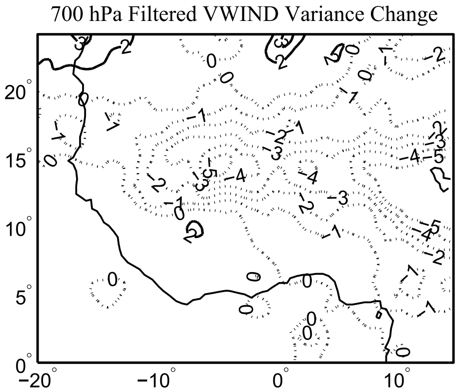

Figure 9. Average summer differences (A1B minus reference) for the 2–10 days band-pass-filtered meridional wind variance at 700 hPa. Units are m/s, and changes are significant at 99% of confidence level.

of the TEJ for the late 21st century period, again consistent with 20th century dry periods [*Jenkins et al.*, 2005].

[17] Figure 9 presents the difference of the variance of the 2–10 days band-pass-filtered 700 hPa meridional wind between the future and the reference period. The primary source of variance is associated with the passage of AEWs during the summer season. The variance generally decreases between 10°N and 20°N from eastern to western West Africa, more markedly in the central Sahel. This suggests that the AEWs' activity in the main tracking region is weakened during the late 21st century.

[18] In summary, overall, the drier conditions projected by RegCM3 over the Sahel during the 21st century are accompanied by a weaker monsoon flow, a southward migration and strengthening of the AEJ, a weakening of TEJ, a decrease of the deep core of ascent between these jets, a decreases of the relative humidity, and reduced AEWs' activity. The behavior of these features is characteristic of a dry period over the Sahel, and their changes are similar to those observed during the late twentieth century drought in the region. In fact, *Fontaine and Janicot* [1992] and *Nicholson and Grist* [2001] showed that during dry years the monsoon flow from the Atlantic Ocean to the continent is reduced. Further, using National Centers for Environmental Prediction (NCEP) reanalysis and RegCM simulations, respectively, *Nicholson* [2008] and *Jenkins et al.* [2005] demonstrated that during the Sahelian drought the AEJ has a more equatorward position, while the strength of the TEJ is weakened. Finally, both *Grist* [2002] (using NCEP reanalysis) and *Sylla et al.* [2009b] (using RegCM3 simulations) found that AEWs are more active in wet years than they are in dry years. These findings show that the precipitation signal projected by RegCM3 is consistent with changes in the main features of the monsoon circulation (i.e., monsoon flow, the ascent, the AEJ, the TEJ, and the AEWs), which are, in turn, internally consistent. Therefore, the projected changes in the monsoon circulation are coherent with the late twentieth century observations during the Sahelian drought.

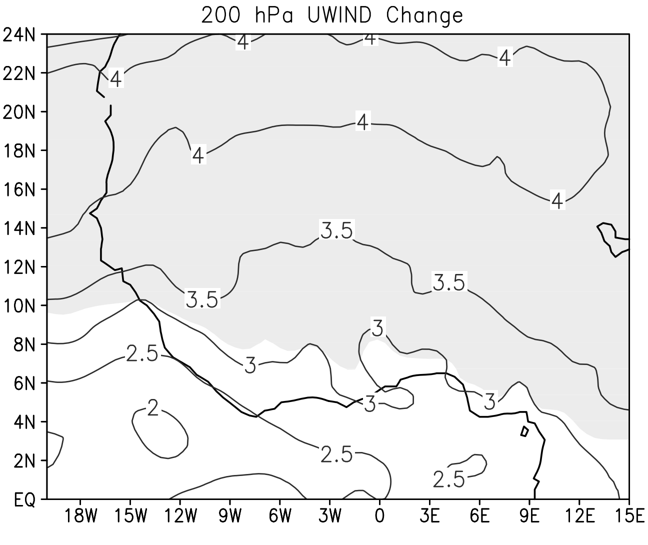

Figure 8. Average summer differences (A1B minus reference) for the zonal wind at 200 hPa. Units are m/s, and shaded areas are where changes are significant at 99% of confidence level.

[19] Although the change in mean rainfall shows a general decreasing trend over most of West Africa (except over orographic regions), it does not indicate how the occurrence of flood and drought conditions might change. On the one hand, higher temperatures and reduced precipitation may increase drying, leading to increased drought conditions. On the other hand, the increased moisture holding capacity of the atmosphere due to the warmer temperatures makes the region more prone to flood events. As mentioned, as a measure of drought conditions, we here take the maximum dry spell length. In general, the changes in maximum dry spell length (Figure 10a) follow the changes in mean precipitation (Figure 1b), suggesting an increase in persistence of drought conditions. Not surprisingly, there is also a decrease in high-intensity precipitation (i.e., maximum 5 day precipitation) (Figure 10b). Conversely, along the Cameroun Mountains and Jos Plateau, where an increase in precipitation is projected, there is a reduction in drought persistence and greater 5 day

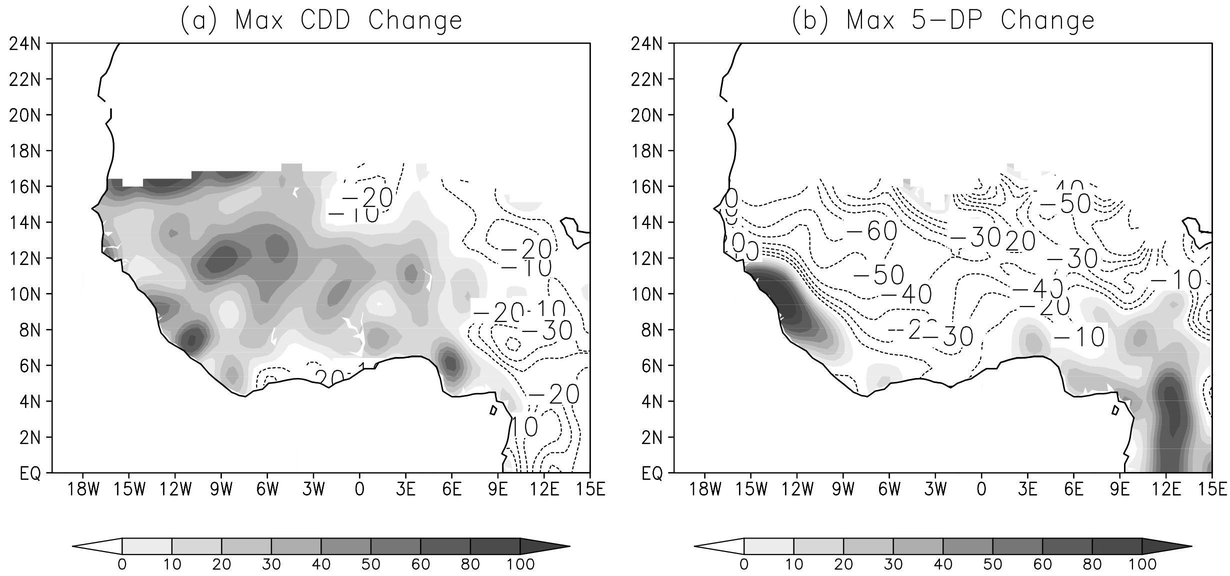

Figure 10. Average summer differences (A1B minus reference) for (a) maximum dry spell length and (b) maximum 5 day precipitation. Units are percent of present-day values. Positive changes are shaded, while contours represent negative changes. All changes are significant at 99% of confidence level. Areas where mean precipitation is less than 0.5 mm/d have been masked out. CDD, consecutive dry days; 5-DP, 5 days precipitation.

intensity precipitation, suggesting increased vulnerability to flood in these regions (Figure 10b). Over the coasts of the Guinea Highlands, both dry spell length and maximum 5 day precipitation are enhanced, while mean precipitation slightly increases. This implies a greater contribution of more frequent, extreme precipitation events than of maximum dry spell length changes.

4. Summary and Conclusion

[20] In our scenario, anthropogenic GHG-induced global warming leads to drier conditions over most of West Africa, and especially over the Sahel. The changes in projected rainfall are consistent with the changes in the main features of the monsoon circulation. More specifically, the moisture-laden monsoon fluxes weaken, the AEJ undergoes a southward migration and intensifies, the TEJ core speed decreases, the AEWs' activity lessens, and the deep core of ascent lying between the AEJ and the TEJ weakens. These simulated changes in the circulation are consistent with drier conditions over the Sahel, as similar changes in the behavior of the AEJ, the TEJ, the AEWs, and the ascent have been observed during the dry period of the late twentieth century in the region.

[21] Our results also indicate significant changes in the occurrence of dry spell length and 5 day precipitation intensity over West Africa that are generally consistent with the changes in mean precipitation. In regions of increased simulated drying, drought persistence (i.e., the maximum dry spell length) increases, while the maximum 5 day precipitation decreases. In the regions of complex topography where rainfall is projected to increase, drought persistence decreases, and 5 day precipitation intensity increases. The main exception to this is along the coast of the Guinea Highlands, where both flood and drought intensity are projected to increase.

[22] This work provides evidence that projected rainfall changes from RegCM3 are consistent with changes in the monsoon circulation. This provides robust indications toward the use of the RegCM3 modeling system to simulate climate change conditions over West Africa. As mentioned, because of the large uncertainty in climate change projections over West Africa [*Christensen et al.*, 2007], a multimodel ensemble approach where RCMs are driven by different GCMs needs to be used in order to provide information that is useful for impact and adaptation study. Toward this goal, we plan to use the RegCM model for the production of a new generation of climate change scenarios for the whole of Africa under the Regional Climate Change Hyper-Matrix Framework [*Giorgi et al.*, 2008] and the Coordinated Regional Climate Downscaling Experiment (CORDEX) [*Giorgi et al.*, 2009].

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