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West African Monsoon in State-of-the-Science Regional Climate Models

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1. Introduction

The western Sahel (e.g. rectangle in Figure 1) climate is dominated by the West African Monsoon (WAM), a large-scale circulation characterized by reversal in direction of winds in the lower levels of the atmosphere from the Atlantic Ocean transporting moisture into land. Although it occurs only during a small portion of the annual cycle between May and September, the WAM is a climatological feature of major social importance to local populations over West Africa whose economy relies primarily on agriculture. In response to several decades of below normal rainfall experienced since the late 1960s, numerous studies have identified various factors that control the monsoon variability. Among them are the variability of ocean Sea Surface Temperatures (SSTs) (e.g. Fontaine et al. 1998), continental land surface conditions (e.g. Wang and Eltahir 2000) and atmospheric circulation (e.g. Nicholson and Grist 2001; Jenkins et al. 2005).

Within the atmospheric circulation pattern, are embedded a number of rainfall producing systems (e.g. Figure 2). One of the most prominent features is the African Easterly Jet (AEJ), a mid-tropospheric (600–700 mb) core of strong zonal winds (up to ~10 m s^{-1}) that travels from East to West Africa. The disturbances around this zonal circulation, the African Easterly Waves (AEWs), have been identified as key driver of convection and rainfall patterns (Diedhiou et al. 1998). Most of the convective rainfall follows the south-north-south displacement of the Intertropical Convergence Zone (ITCZ) with a mean upward motion that reaches 200 mb. At this level, the Tropical Easterly Jet (TEJ), associated with the Asian monsoon outflow, circulates across West Africa during the boreal summer season. These features form the well-defined meridional structure of WAM circulation related to the mean summer monsoon rainfall (e.g. Figure 3).
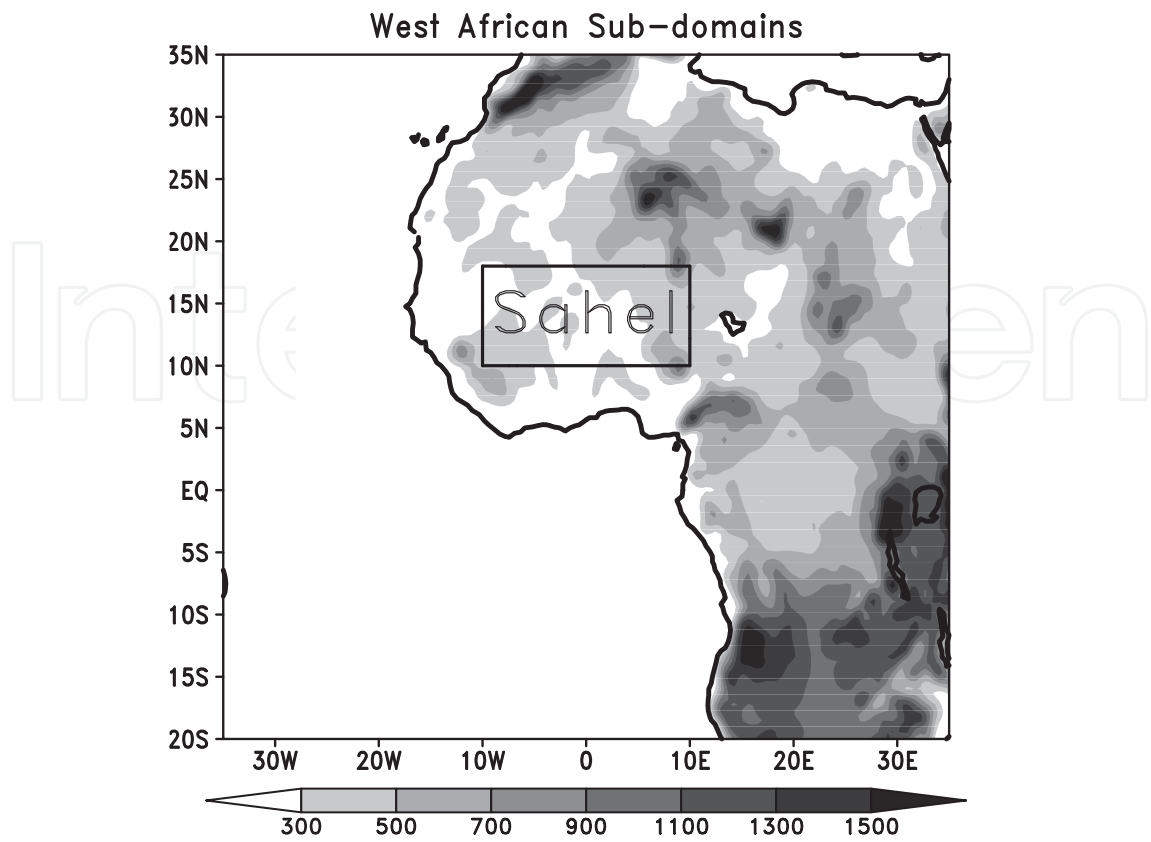
Figure 1. West Africa AMMA domain and topography highlighting the Western Sahel region.
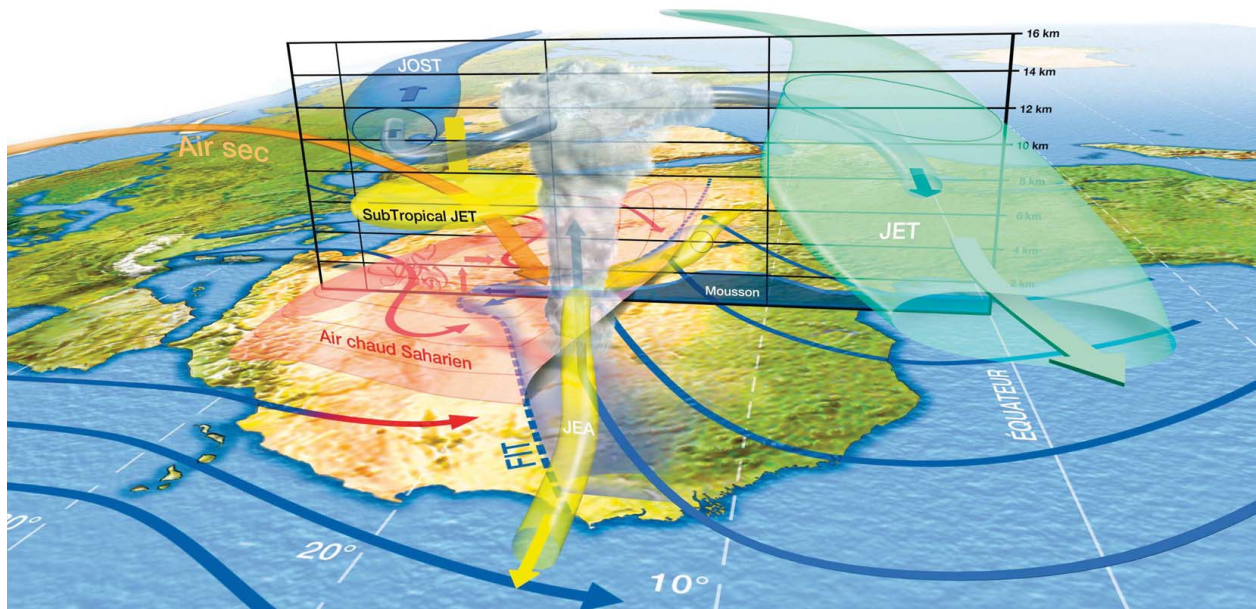

Figure 2. schematic view of the West African Monsoon System adopted from Lafore et al. (2010). FIT stands for ITD (InterTropical Discontinuity), "Air chaud Saharien" stands for 'Warm Saharian Air", JEA stands for AEJ (African Easterly Jet), JET stands for TEJ (Tropical Easterly Jet), "Air sec" stands for "Dry Air".
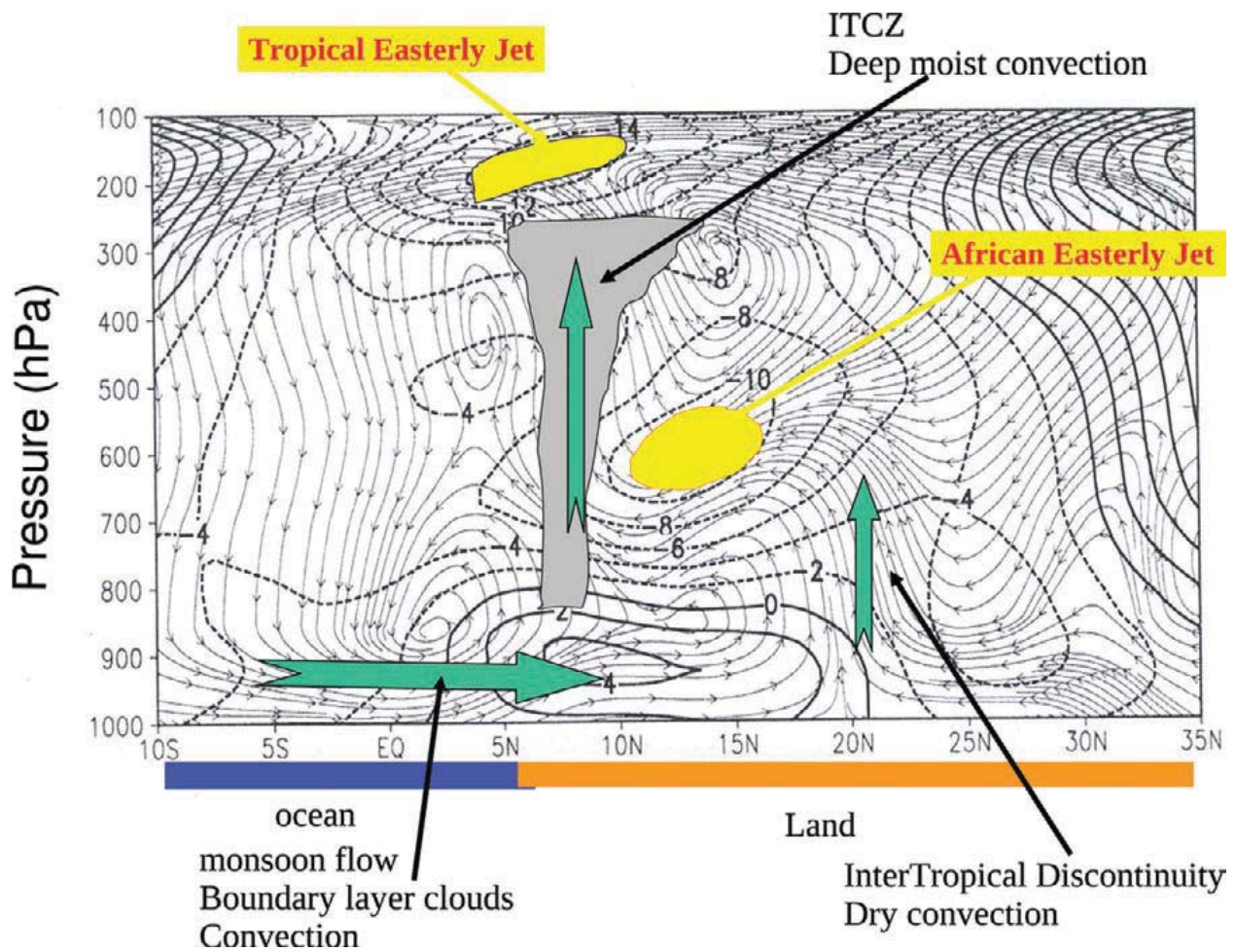
Figure 3. Mean Meridional Circulation (stream lines) and associated mean Zonal Wind (m/s in contours) over West Africa during the summer season adopted from Hourdin et al. (2010).

The intensity and position of the above features not only influence the amount of rainfall but also its variability, indicating a strong scale interaction between the different elements of the WAM (Redelsperger et al. 2002). For example over the Sahel, a more equatorward position of the AEJ often corresponds with drought conditions (Jenkins et al. 2005; Nicholson 2008) while a stronger than average TEJ often results in wetter climates. It is important to note that not all displacement of the AEJ is associated with wetter/drier Sahel. Precipitation in the region also appears to be strongly related to SSTs (e.g. Giannini et al. 2003; Lu and Delworth 2005; Biasutti et al. 2008). Furthermore, active AEWs are mainly generated by significant occurrence of deep moist and shallow cumulus convection (Hsieh and Cook 2008) and are thus typically expected during wetter periods.

The total seasonal rainfall is the result of successive convective events, which are either local or organized as Mesoscale Convective Systems (MCSs) structured along the AEJ where the interaction between the tropical waves and convection plays the dominant role at both synoptic and intra-seasonal time scales (e.g. Mathon and Laurent 2001; Gaye et al. 2005; Mohr and Thorncroft, 2006). The onset of the rainy season over the Sahel is partly dictated by the

Saharan Heat Low (SHL) (Hagos and Cook 2007; Thorncroft et al. 2011) which plays a significant role in the monsoon jump process, an abrupt shift of the rainbelt characterized by a northward extension of deep convective rainfall from the coast (about 6N) between May-June to about 10-12N in July-August.

Modeling this complex interplay between the monsoon dynamical features is of primary importance for an accurate representation of rainfall over the Sahel and thus paramount for a better understanding of the West African climate response to global warming. Such modeling simulations have often been performed using Global Climate Models (GCMs). However, the GCMs often have problems in representing accurately the main WAM features, presumably due to coarse grid spacing typically used (Hourdin et al. 2010; Sylla et al. 2010a; Xue et al. 2010). Studying the West African climate using Regional Climate Models (RCMs), which are typically applied at a high resolution than GCMs, has therefore become an area of active research in the last decades. The added resolution allows for a better representation of fine-scale forcing and land surface heterogeneity such as vegetation variations, complex topography and coastlines, which are important aspects of the physical response governing the local and regional climate change signal (e.g. Paeth et al. 2005; Rummukainen 2010; Sylla et al. 2012a). The overall aim of this chapter is to assess the extent at which the state-of-the-science RCMs are able to simulate the mean climatology, mean annual cycle and inter-annual variability of rainfall over the western Sahel as well as the relationship of rainfall to the monsoon dynamical structures at different time-scales. This is critical to better assess the key processes associated with the interactions between the atmosphere, land and ocean, as well as between the dynamics and convection. The use of RCMs can contribute to improving our understanding of, and ultimately our ability to predict rainfall variability. Section 2 reviews previous applications of RCMs over West Africa. Section 3 presents our results of mean climatology, annual cycle and inter-annual variability of rainfall over the Sahel along with its interactions with the different WAM features from state-of-the-science RCMs. Section 4 summarizes the conclusions and provides an outlook of future directions of RCMs research over West Africa.

2. Regional climate models applications over West Africa

RCMs use a limited area grid driven at the lateral boundaries from GCM output or reanalysis data. SSTs are generally prescribed, except when an ocean model is enabled. RCMs are employed to add additional detail to GCM simulations or to conduct process studies requiring additional fine-scale detail over what GCMs capture (Giorgi and Mearns 1999). Examples of process studies include investigation of the impacts of land cover change, dust and biomass burning, and climate change.

Over the past 15 years, RCMs have been extensively used as dynamical downscaling tool for different applications over West Africa (e.g. Vizy and Cook 2002; Gallée et al. 2004; Paeth et al. 2005; Afiesimama et al. 2006; Kamga and Buscarlet 2006; Pal et al. 2007; Hagos and Cook 2007; Sylla et al. 2010b; Pohl and Douville 2011; Murthi et al. 2011; Diallo et al. 2012a).In gen-

eral, these studies have shown that RCMs can adequately represent the WAM climatology and its variability.

GCMs, integrated at typical grid spacing (100s km) are unable to represent key features of the WAM such as AEWs, AEJ and TEJ. As mentioned above, one of the primary purposes for using an RCM is to enhance or add-value to individual and multi-model RCM ensembles with respect to their driving GCM or reanalysis field. Generally speaking, RCMs do not correct gross biases in the GCM or reanalysis fields. In other words, garbage in equals garbage out. Sylla et al. (2009), however, concluded that the systematic errors in output from their RCM simulations were driven only to a minor extent from the errors in the driving large-scale GCM fields and thus, were tied to the representation of local/regional processes. In addition, Druyan et al. (2010) found that their individual model errors varied considerably in space and from model to model while Paeth et al. (2011) demonstrated that their multi-model ensemble clearly exhibited added value in WAM rainfall with respect to the European Reanalysis-Interim (ERA-Interim; Dee et al. 2011) driving field. Diallo et al. (2012b) suggested that the multi-model RCM ensembles should be based on different driving GCMs for improved performance.

Recent studies have proposed ways to further validate RCMs dynamics over West Africa using process-based evaluation. Such evaluation examines how well a particular phenomenon, process or feedback is represented in an RCM. Adequate RCM performance in simulating the monsoon dynamical features variability is crucial to reasonably represent rainfall over the Sahel (Diallo et al. 2012c). Performance can also be related to the domain size and location of lateral boundaries (Browne and Sylla 2012). It is important to emphasize that a key feature in this process-based evaluation is to relate the ability of an RCM to represent the process in future climate and a realistic simulation of climate change (e.g. Paeth et al. 2009; Sylla et al. 2010a; Patricola and Cook 2010 Mariotti et al. 2011; Skinner et al. 2012; Abiodun et al. 2012). For example, Sylla et al. (2010c) found that simulations using the International Centre for Theoretical Physics Regional Climate Model (RegCM3; Pal et al. 2007) reproduced the observed relationship between Sahel rainfall and WAM features, such as the AEJ, TEJ and AEWs at both the intra-seasonal and inter-annual time-scales, demonstrating that the model performance was of sufficient quality for climate process and mechanism studies over West Africa.

There is substantial evidence that the representation of the land surface and land-atmosphere coupling is particularly important for the WAM regions (e.g. Patricola and Cook 2008; Steiner et al. 2009, van den Hurk and van Meijgaard 2010). For instance, Abiodun et al. (2010), using RegCM3 conducted land-surface sensitivity experiments and found that deforestation increases the intensity of the AEJ core, thus reducing the northward transport of moisture needed for rainfall over West Africa. Steiner et al. (2009) illustrated that the use of Community Land Model version 3 (CLM3; (Oleson et al. 2004) instead of Biosphere Atmosphere Transfer Scheme (BATS; Dickinson et al. 1993) as land-surface model in RegCM3 induced a weaker temperature gradient which shifted the AEJ southward, in line with observations, and greatly improved the wet model bias. The key role played by vegetation feedbacks in future climate predictions over West Africa has also been highlighted by Wang

and Alo (2012). They found that dynamic vegetation feedback reverses the predicted future trend, leading to a substantial increase of annual rainfall. The response of the WAM to soil moisture anomalies, planetary boundary layer and Southern Sudan bioclimatic zone soil types was reported by Moufouma-Okia and Rowell (2010), Flaounas et al. (2011) and Zaroug et al. (2012) respectively. Their results demonstrated that changes in these surface parameters significantly impact the WAM precipitation.

Of particular interest is the application of RCMs to improve our understanding of the WAM dynamics and features. Using Mesoscale Model version 5 (MM5; Grell et al. 1994), Vizy and Cook (2002) studied the response of the WAM to tropical oceanic heating. Other RCM studies explored the relationship between tropical or Mediterranean SST and the WAM (Messager et al. 2004; Gaetani et al. 2010; Fontaine et al. 2010). They identified the main physical mechanisms connecting the WAM precipitation pattern with Gulf of Guinea, northern Atlantic and Mediterranean SSTs. The dynamics of the observed abrupt latitudinal shift of maximum precipitation from the Guinean coast into the Sahel region around May-June, the so called "monsoon jump", has also been investigated in various studies applying different RCMs (Ramel et al. 2006; Sijikumar et al. 2006; Hagos and Cook 2007; Drobinski et al. 2009; Sylla et al. 2010c). These studies highlight the key role played by SHL, diabatic heating and AEJ in this process. Hsieh and Cook (2005) examined the relationship between the ITCZ, the AEJ and the AEWs and recently, Sylla et al. (2011) addressed the role of the representation of deep convection on key elements of the West African summer monsoon climate using RegCM3. Interestingly, the former found that AEWs develop more readily in a simulation with a weak AEJ and a strong ITCZ pointing out the importance of cumulus convection and the associated release of latent heat while the latter showed that the deep convection scheme is of lesser importance for the genesis and growth of AEWs but is a key factor for the simulation of a more realistic AEJ and for the west coast wave development.

It is evident that RCMs are valuable tools for understanding WAM dynamics and the interactions between its different components. Most of the studies mentioned above, however, are performed using a single RCM, which are known to incorporate unpredictable and large random errors that substantially influence the simulation at shorter time scales (Vanvyve et al. 2008). Therefore, it is not surprising that in the last few years, significant efforts have been employed to establish coordinated frameworks using several RCMs aimed at improving the characterization of the WAM at various time-scales. Such frameworks include the West African Monsoon Modelling and Evaluation (WAMME; Xue et al. 2010; Druyan et al. 2010), African Multidisciplinary Monsoon Analysis (AMMA; Ruti et al. 2010), the Ensemble-based Predictions of Climate Change and their Impacts (ENSEMBLES; Paeth et al. 2011) and recently the Coordinated Regional Downscaling Experiment (CORDEX; Giorgi et al. 2009; Jones et al. 2011).

The AMMA-MIP (AMMA Model Intercomparison Project) has been coordinated to evaluate GCMs and RCMs in terms of their ability to reproduce the mean West African climate and, in particular, the seasonal and intra-seasonal variations of rainfall and associated dynamical structures for two contrasting years: 2000 and 2003 (Hourdin et al. 2010). More recently, multiyear (1989-2007) simulations of the West African climate over the AMMA domain (e.g.

Figure 1) have been completed by eight state-of-the-science RCMs forced by the newly developed ERA-Interim reanalysis at the boundaries for a more robust assessment. To date, this constitutes the most comprehensive database incorporating all the relevant variables for a better characterization of the WAM. Table 1 summarizes the different RCMs and their respective physical schemes and latest references.

RCMs	GKSS-CCLM	METNO-HIRHAM	ICTP-REGCM3	KNMI-RACMO2.2b	SMHI-RCA	METO-HC_HadRM3.0	UCLM-PROMES	MPI-M-REMO
Institute	GKSS Forschungsze ntrum Geesthacht GmbH (GKSS), Germany	The Norvegian Meteorologic al Institute, Norway	Abdus Salam Internation al Centre for theoretical Physics, Italy	Koninklijk Nederlands Meteorologis ch Instituut, Netherlands	Swedish Meteorolo gical and hydrologic al institute, Sweden	Met Office-Hadley Centre, UK	Universidad de Castilla La Mancha (UCLM), Spain	Max Planck Institute, Germany
Horizontal	0.44° (50 km)	0.44° (50 km)	50 km	0.44° (50 km)	0.44° (50 km)	0.44° (50 km)	50 km	0.44° (50km)
Convective scheme	Tiedtke (1989)	Tiedtke (1989), Nordeng (1994)	Grell (1993); Fritch and Chappell (1980)	Tiedtke (1989)	Kain and Fritsch (1990)	Gregory and Rowntree (1990), Gregory and Allen (1991)	Kain and Fritsch (1990)	Tiedke (1989)
Radiation scheme	Ritter and Geleyn (1992)	Morcrette (1991), Giorgetta and Wild (1995)	Kiehl et al. (1996)	Fouquart and Bonnel (1980)	Savijarvi (1990), Sass et al. (1994)	Edwards and Slingo (1996)	Anthes et al. (1987), Garand (1983)	Morcrette et al. (1986) Giorgetta and Wild (1995)
Land surface scheme	TERRA3D, BATS, Grasselt et al. (2008)	Dümenil and Todini (1992)	BATSE1E, Dickinson et al. (1993)	TESSEL, Van der Hurk et al. (2000)	RCA land surface model, Samuelsso n et al. (2006)	MOSES2 Essery et al. (2003)	SECHIBA, Ducoudré et al. (1993)	Hangemann (2002) Rechid et al. (2009)
Cloud microphysics scheme	Kessler (1969), Lin et al. (1983), Ritter and Geleyn (1992)	Sundquist (1978)	SUBEX, Pal et al. (2000)	Tiedtke (1993)	Rasch and Kristjànsso n (1998)	Smith (1990), Jones et al. (1995)	Hsie et al. (1984)	Lohmann and Roeckner (1996)
Reference	Rockel et al. (2008)	Christensen et al. (2006)	Pal et al. (2007)	Lendrinck et al. (2003)	Kjellstr¨om et al. 2005	Jones et al. (2004)	Sahchez et al 2004	Jacob et al. (2001)

Table 1. Summary the different Regional Climate Models and their respective main physical schemes and latest references.

3. Evaluation of state-of-the-Science RCMs over West Africa

In this section, we analyse and intercompare the performance of a set of eight (8) RCMs in simulating the mean climatology, annual cycle and interannual variability of rainfall over West Africa during the monsoon season and the related atmospheric features modulating this variability. The models are driven at the lateral boundaries by the ERA-Interim reanalysis, the most recent and improved reanalysis product available. These simulations are performed as part of the AMMA/ENSEMBLES multi-model intercomparison project - Research Theme 3 (RT3).

3.1. Mean summer monsoon climatology

Before evaluating and comparing the mean annual cycle and inter-annual variability of rainfall and its interaction with the main WAM features, it is important to evaluate the mean summer monsoon climatology over West Africa. The temperature field from observations Climate Research Unit (CRU; Mitchell et al. 2004) and University of Delaware (UDEL; Legates and Willmott 1990); Figure 4a, b), the ERA-Interim reanalysis (Figure 4c), the eight RCMs (Figure 4d-k) and their ensemble mean (Figure 4l) depict a zonal pattern with cooler temperatures along the Gulf of Guinea, increasing northward to reach a maximum around the area of the SHL centered at 25N. This area is well-defined by the lower pressure system and higher temperature values observed and simulated there. It is worth noting that the minima are found over the orographic peaks of Guinea Highlands, Jos Plateau and Cameroon Mountains, demonstrating the capability of the RCMs to capture the fine-scale features over regions of steep topography. A cold bias of about 2 degrees Celsius prevails over the Gulf of Guinea and this feature is common for ERA-Interim (the driving fields of the RCMs) and for all the RCMs, except MPI-REMO. However, MPI-REMO, along with METNO-HIRHAM and MET-O-HadRM3P, exhibit a warm bias over the SHL. As a result, the multi-model ensemble fails to outperform individual RCM members and the driving field, highlighting the importance of the individual model in the performance of the ensemble mean. It is difficult to unambiguously determine the causes of the RCMs temperature biases as they depend on a number of factors, including cloudiness, surface albedo, temperature advection and surface water and energy fluxes (Sylla et al. 2012b). It should be emphasized that none of the experiments incorporate aerosol effects and the inclusion of dust radiative forcing would likely reduce the bias and improve the simulation of surface air temperature and resulting effects on the WAM circulation (Konare et al. 2008; Camara et al. 2010; Solmon et al. 2012). Considering these uncertainties, and considering that typical RCM biases for seasonal surface temperature are within the range of 2 degrees Celsius (e.g. Jones et al. 1995; McGregor et al. 1998; Hudson and Jones 2002; Konare et al. 2008; Hernandez-Diaz et al. 2012; Giorgi et al. 2012), these state-of-the-science RCMs bias are in line with other RCMs applications over other regions.

Concerning the summer monsoon rainfall climatology, CRU (Figure 5a), Global Precipitation Climatology Project (GPCP; Adler et al. 2003) (Figure 5b), ERA-Interim (Figure 5c) and the superimposed wind at 850 mb are compared to the corresponding RCM fields (Figure 5d-k) and their ensemble mean (Figure 5l). The main summer rainfall is positioned in a zo-
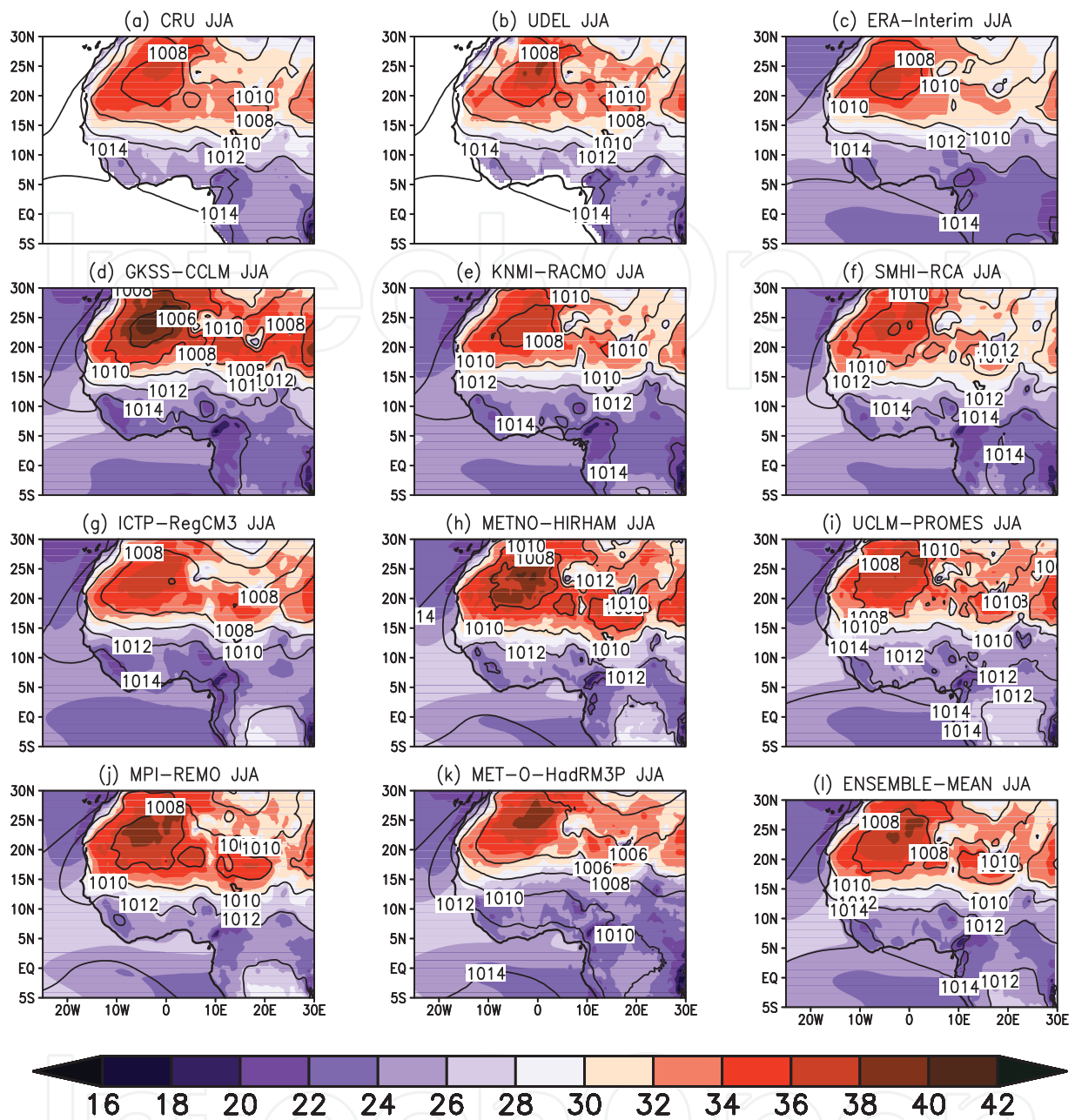
Figure 4. Averaged 1990-2007 JJA 2-meter Temperature (degree Celsius) and superimposed Mean Sea Level Pressure (MSLP, in hPa) in contour from: (a) CRU observation and ERA-Interim MSLP, (b) UDEL observation and ERA-Interim MSLP, (c) ERA-Interim reanalysis, (d) GKSS-CCLM, (e) KNMI-RACMO, (f) SMHI-RCA, (g) ICTP-RegCM3, (h) METNO-HIRHAM, (i) UCLM-PROMES, (j) MPI-REMO, (k) MET-O-HadRM3P and (l) the RCMs ensemble mean.

nal and tilted band between 5N and 15N, with rainfall decreasing to the north and south, as shown in the plots of the observations (CRU and GPCP) and reanalysis (ERA-Interim). Precipitation maxima are, however, located in orographic regions such as Guinea Highlands, Jos plateau, and Cameroon Mountains which also experience the coldest temperatures indicating large evaporative cooling over these areas (e.g. Figure 4). This precipitation pattern is associated with moist southwesterly winds from the Atlantic Ocean, the so-called moisture

laden monsoon flow. Key differences across the observations are that CRU shows a discontinuity in the band of maximum rainfall over West Africa and much lower intensities over Jos Plateau and that GPCP has lower rainfall amounts along the coastlines of Cameroon/Nigeria highlands. Uncertainty in rainfall observations are a key factor preventing a rigorous and unambiguous evaluation of RCMs over the region (Sylla et al. 2012c). The use of multiple observed rainfall products can, however, help quantify the uncertainty.
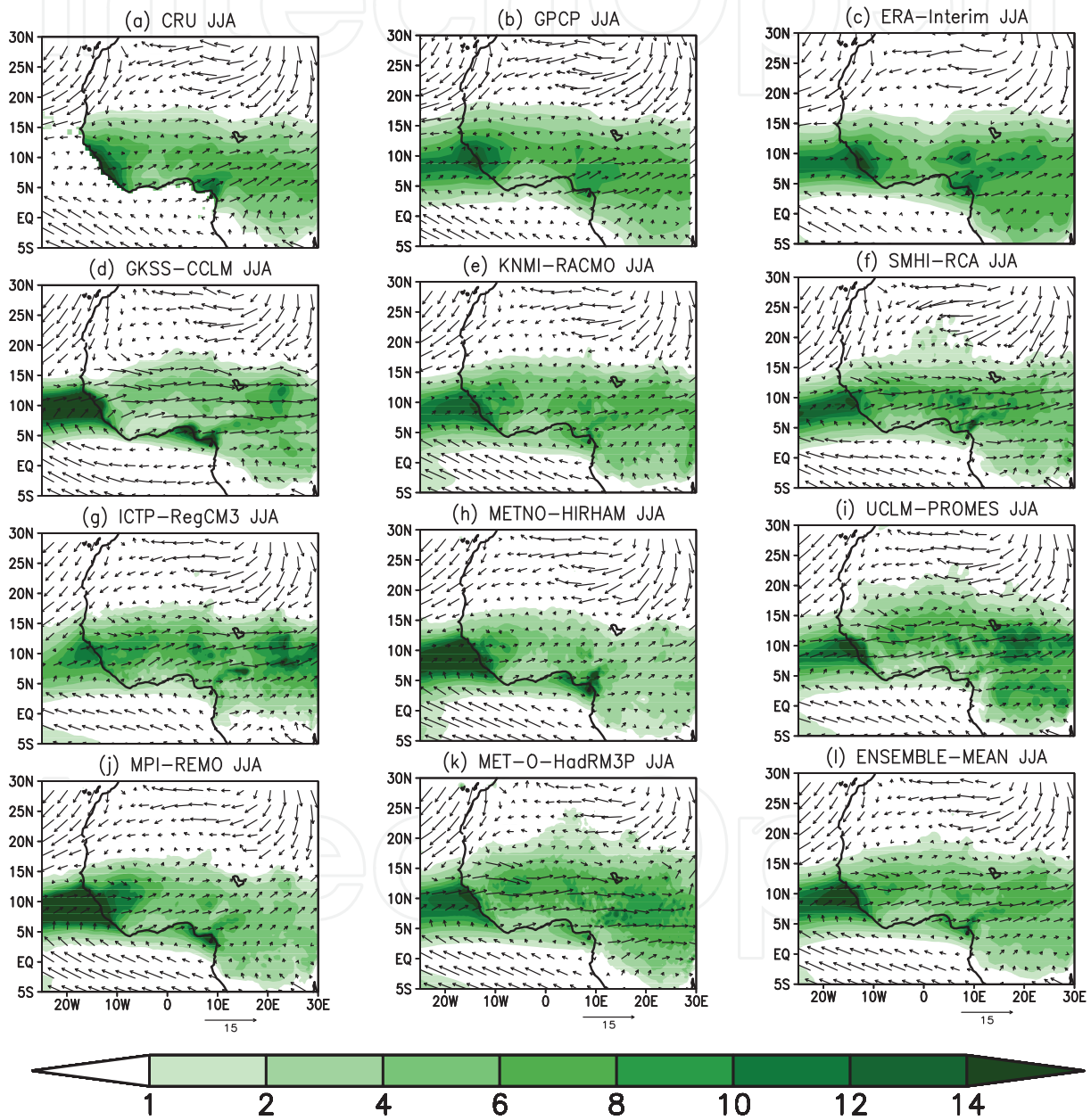

Figure 5. Averaged 1990-2007 JJA Precipitation (mm/day) and superimposed Wind Arrows from: (a) CRU observation and ERA-Interim Wind, (b) GPCP observation and ERA-Interim Wind, (c) ERA-Interim reanalysis, (d) GKSS-CCLM, (e) KNMI-RACMO, (f) SMHI-RCA, (g) ICTP-RegCM3, (h) METNO-HIRHAM, (i) UCLM-PROMES, (j) MPI-REMO, (k) MET-O-HadRM3P and (l) the RCMs ensemble mean.

The RCMs display a similar spatial pattern in both rainfall and low-level winds compared to the observations and the ERA-Interim reanalysis but exhibit different bias magnitudes suggesting that the differences between the RCMs mainly arise from their internal dynamics and physics. Contrary to surface temperature, the ensemble mean of precipitation generally outperforms the the individual RCMs and the driving ERA-Interim data, illustrating the advantages of multi-model assessments of the WAM rainfall (Paeth et al. 2011, Nikulin et al. 2012; Diallo et al. 2012a). Most of the discrepancies occur along the ITCZ indicating that the RCMs substantially differ in their ability to simulate the interactions between the WAM elements and the deep convection.

To better understand this issue, an assessment of how well the RCMs reproduce the mean annual cycle, inter-annual rainfall variability and their relationship with the different dynamical features (AEJ, TEJ, AEWs and SHL) is performed in the next section. It should be noted that the various RCMs well capture their mean position with different magnitudes compared to the ERA-Interim driving field (not shown for brevity).

3.2. Mean annual cycle

The mean annual cycle of the WAM rainfall is presented in Figure 6 through a time-latitude Hovmoller diagram. It corresponds to a south-north-south displacement of the ITCZ, which is characterized by successive active and break phases of the convective activity. This meridional cross-section analysis averaged from 10W to 10E provides a good framework to assess RCM skill in simulating mean annual cycle and intra-seasonal variations of the WAM and associated mechanisms responsible for the rainfall variability (Hourdin et al. 2010).

CRU and GPCP observations as well as ERA-Interim reanalysis clearly identify the three distinct phases of the annual cycle: the initiation or onset phase (March-May), the high rain period (June-August), and the southward retreat of the rainbelt (September-October) as documented by Le Barbe et al. (2002). The onset period is characterized by a northward extension of the rainbelt from the coast to about 4N. An abrupt shift, the monsoon jump (Sultan and Janicot 2003), occurs at the beginning of June in both observation datasets and reanalysis, when the rain core moves rapidly northward to about 10N. This is the beginning of the high rain season in Sahel region and the sudden termination of heavy precipitation along the Guinea Coast. In September, a sharp southward retreat of the rainfall belt occurs, corresponding to the last phase of the WAM season. The AEJ corresponds closely to the rainfall variations and undergoes a poleward migration that peaks in August over northern Sahel around 13N, as depicted by the ERA-Interim reanalysis (Figure 6c). An interesting feature is that the rainfall core is located below the AEJ, suggesting that the easterly shear tends to favor deep convection south of the jet axis in line with previous studies (Thorncroft and Blackburn 1999; Diongue et al. 2002; Mohr and Thorncroft 2006; Fontaine et al. 2010). Unlike the AEJ, the TEJ appears only during the boreal summer season (June-September) with its core located around 5N. The TEJ promotes mid-level convergence by establishing upper-level divergence, indicating that the ITCZ oscillations during the annual cycle occur in association with the deep convective ascent bounded by the jets axes and levels (Nicholson et al. 2008; Sylla et al. 2010b).
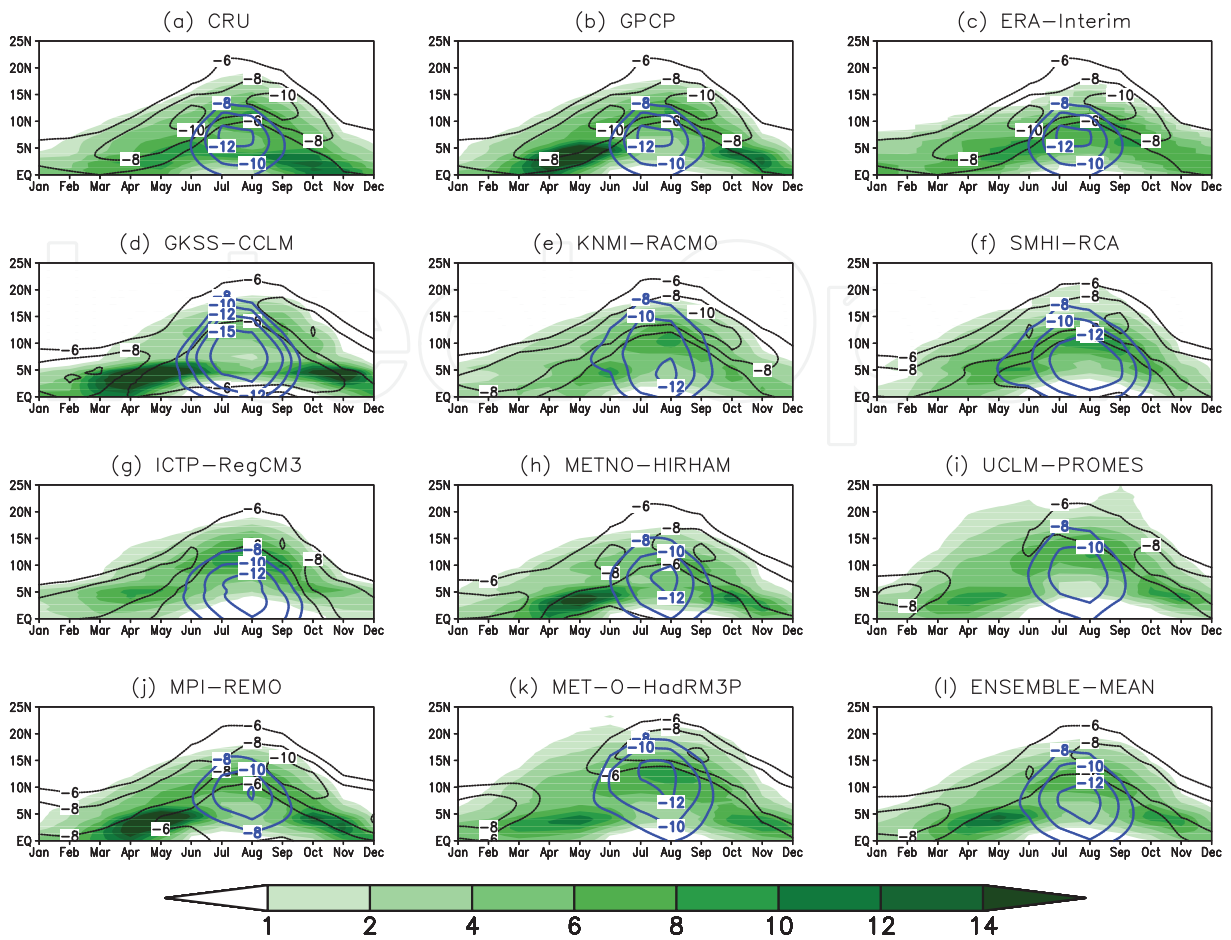
Figure 6. Time-Latitudes Hovmoller diagram of averaged 1990-2007 monthly Precipitation (mm/day) and superimposed 700 hPa (black contours) and 200 hPa (blue contours) Zonal Wind (m/s) from: (a) CRU observation and ERA-Interim Wind, (b) GPCP observation and ERA-Interim Wind, (c) ERA-Interim reanalysis, (d) GKSS-CCLM, (e) KNMI-RACMO, (f) SMHI-RCA, (g) ICTP-RegCM3, (h) METNO-HIRHAM, (i) UCLM-PROMES, (j) MPI-REMO, (k) MET-O-HadRM3P and (l) the RCMs ensemble mean.

Moving to the comparison with the RCMs, it is evident that the three distinct phases of the mean annual cycle, i.e. the monsoon jump, the poleward migration of the AEJ and the appearance and strengthening of the TEJ, are well reproduced. A number of differences can be observed among the experiments with regard to the magnitude and spatial extent of the features. For instance, GKSS-CCLM, METNO-HIRHAM and MPI-REMO overestimate the pre-monsoon rainfall, which is likely due to an early appearance of strong easterlies that would favor intense convection to the south of them. It is important to note that the RCMs exhibit different sensitivity in terms of their response to the intensity of the WAM elements. For example, GKSS-CCLM overestimates the TEJ while UCLM-PROMES and MET-O-HadRM3P underestimate the AEJ during the pre-monsoon period. This, once again, points to the importance of the different internal dynamics and physics of the models. Ensemble means can help to compensate for these errors, improve simulation results, and instigate a more clear connection between the WAM rainfall and atmospheric characteristics at the intra-seasonal time-scale (e.g. Figure 6l).

The SHL and its relationship to the rainfall annual cycle is presented as a time-latitude Hovmoller diagram of surface air temperature for CRU, UDEL, ERA-Interim and the superimposed mean sea level pressure, the different RCMs and their ensemble mean (Figure 7a-l). The SHL appears as the area of very low pressure and higher temperature. The RCMs show good agreement in reproducing the intensification and northward migration of the SHL from the northern Sahel in March-April to the Sahara in July-August. This drives a progressive increase of lower-level temperature gradient between the Gulf of Guinea and the Sahara, strengthening and shifting toward the north of the AEJ, which ultimately favors intense convection in the latitudes below. Notable overestimations of about 2 to 4 degrees Celsius appear during the pre-monsoon and the monsoon periods in GKSS-CCLM, METNO-HIRHAM and MPI-REMO consistent with the early appearance and stronger easterlies discussed previously. Unexpectedly this warm bias in the Sahara during the peak monsoon period does not trigger a stronger and more poleward AEJ, nor a wider rainfall band indicating that the land surface-atmosphere coupling may be less responsive in some RCMs.
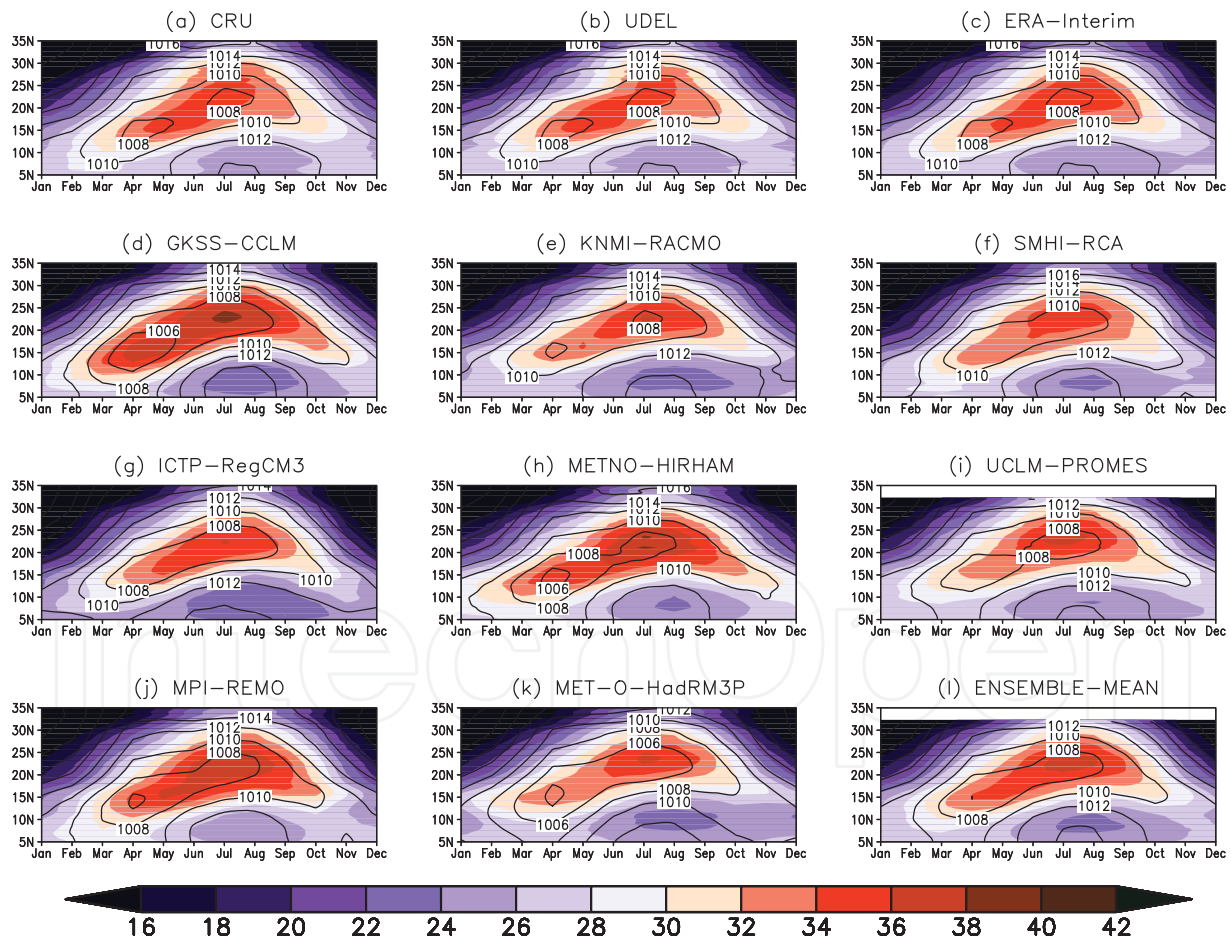

Figure 7. Time-Latitudes Hovmoller diagram of averaged 1990-2007 monthly Temperature (mm/day) and superimposed Mean Sea Level Pressure (MSLP, in hPa) in contour from: (a) CRU observation and ERA-Interim Wind, (b) UDEL observation and ERA-Interim Wind, (c) ERA-Interim reanalysis, (d) GKSS-CCLM, (e) KNMI-RACMO, (f) SMHI-RCA, (g) ICTP-RegCM3, (h) METNO-HIRHAM, (i) UCLM-PROMES, (j) MPI-REMO, (k) MET-O-HadRM3P and (l) the RCMs ensemble mean.

3.3. Inter-annual variability

Figure 8 shows observed and simulated mean June, July, and August (JJA) rainfall anomalies over the Sahel (e.g. see outlined box in Figure1). As a reference, we use the CRU data, which exhibits similar variability to the UDEL and GPCP data with a significant (at 95%) Pearson's correlation coefficient of more than 0.9 (Figure 8a and b). The anomalies are calculated with respect to the precipitation mean derived from the full 18-year period 1990–2007. The area averages of precipitation anomalies are normalized by the standard deviation derived from the 1990–2007 time series. The first interesting aspect to note is that all the RCMs outperform the ERA-Interim reanalysis in terms of the coefficient of correlation. This suggests that all of the RCMs produce a clear added value to the driving ERA-Interim data. This also implies that the inter-annual rainfall variability across the Sahel is less dependent on the large-scale boundary conditions and that the regional forcing, such as higher resolution land–surface interactions with synoptic processes may play important role. Another aspect is among the models, only GKSS-CCLM and MET-O-HadRM3P fail to capture the interannual variation. The ensemble mean of the RCMs not only reproduces the overall variability but also most of
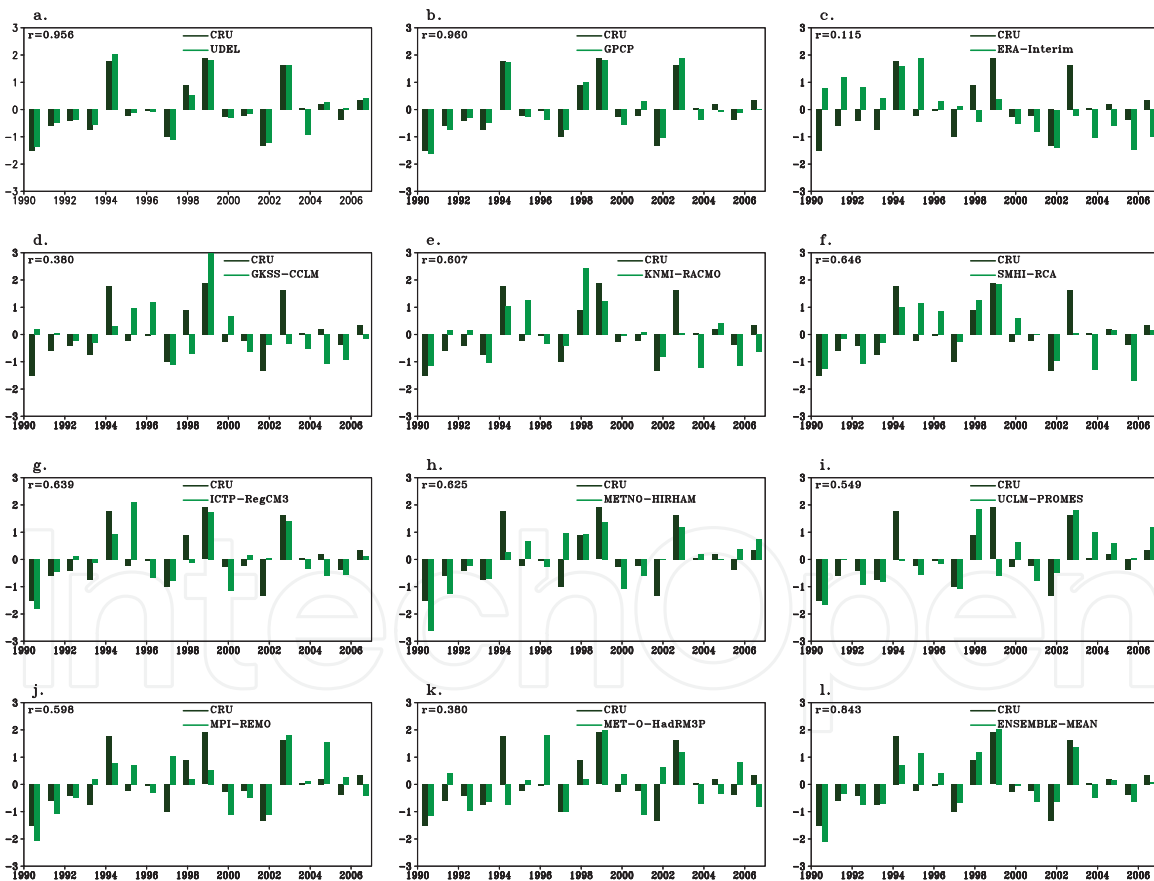

Figure 8. Interannual Variability of Standardized Seasonal (JJA) Precipitation Anomalies from 1990 to 2007 for: (a) CRU and UDEL observations, (b) CRU and GPCP observations (c) ERA-Interim reanalysis and CRU, (d) GKSS-CCLM and CRU, (e) KNMI-RACMO and CRU, (f) SMHI-RCA and CRU, (g) ICTP-RegCM3 and CRU, (h) METNO-HIRHAM and CRU, (i) UCLM-PROMES and CRU, (j) MPI-REMO and CRU, (k) MET-O-HadRM3P and CRU, and (l) the RCMs ensemble mean of the anomalies and CRU.

the direction and magnitude of the individual anomalies with by far the highest correlation coefficient of 0.84 (significant at 95%). This supports the use of RCMs and their multi-model ensembles to explore drivers of inter-annual variability over the Sahel.

To further investigate this issue, the four wettest years (1994, 1998, 1999, and 2003) and four driest years (1990, 1993, 1997, and 2002) are examined to assess the ability of the RCMs to simulate the characteristic circulation of these contrasting regimes. The difference between the dry and wet years for the 700 and 200 hPa zonal winds are respectively shown in Figures
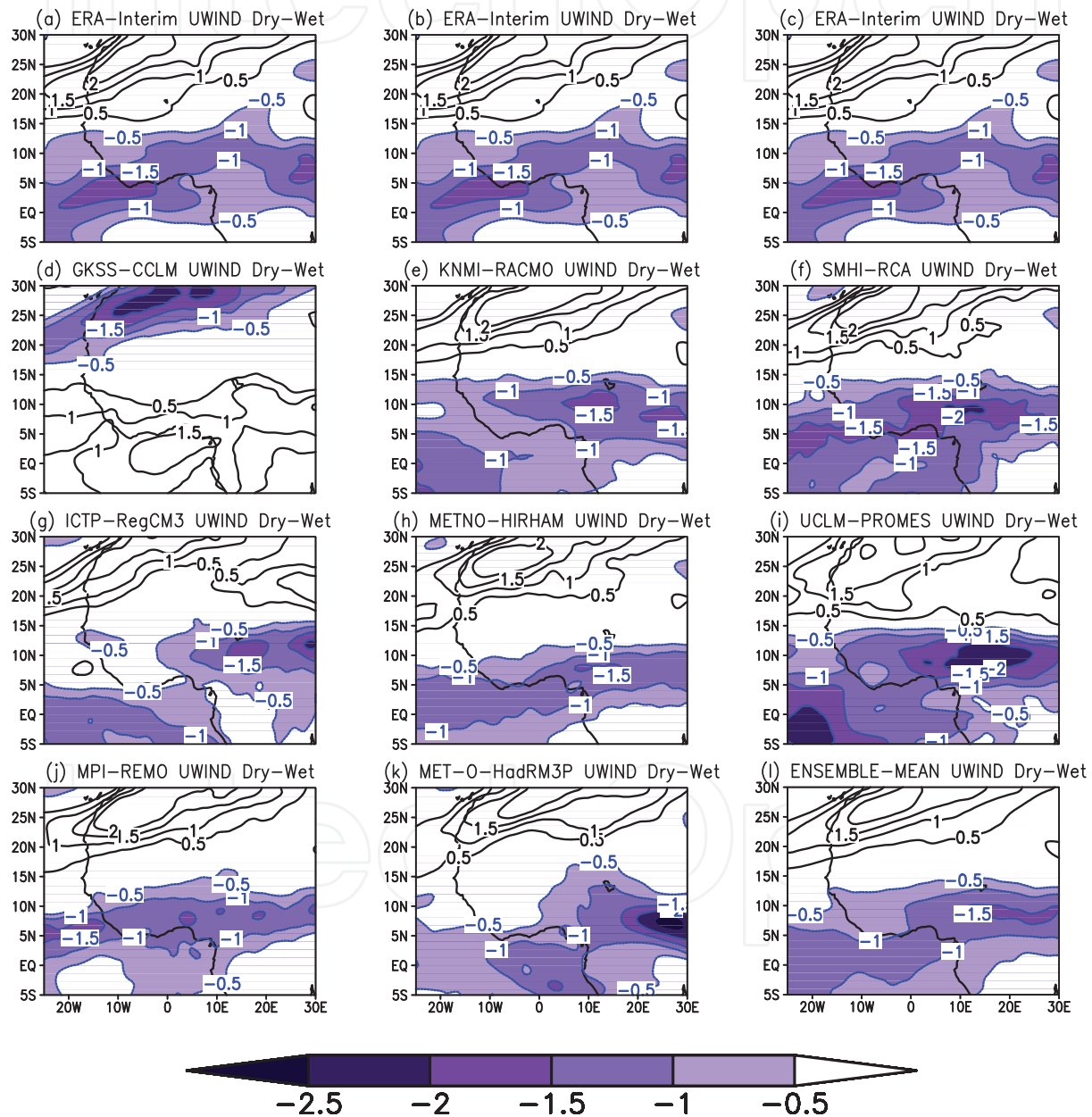

Figure 9. Difference of Dry (1990, 1993, 1997, and 2002) minus Wet Years (1994, 1998, 1999, and 2003) for the JJA 700 hPa Zonal Wind (m/s) for: (a,b,c) ERA-Interim reanalysis, (d) GKSS-CCLM, (e) KNMI-RACMO, (f) SMHI-RCA, (g) ICTP-RegCM3, (h) METNO-HIRHAM, (i) UCLM-PROMES, (j) MPI-REMO, (k) MET-O-HadRM3P and (l) the RCMs ensemble mean.

9 and 10. The ERA-Interim and all the RCMs, except GKSS-CCLM, exhibit an increase (decrease) in the 700 hPa zonal wind speed south (north) of 15°N during dry years. This indicates that the AEJ undergoes a southward displacement and thus shifts the deep convection equatorward, consistent with a drier Sahel. Compared to the individual RCM members, the ensemble mean produces a pattern most similar to that of the ERA-Interim. At the upper levels (200 hPa), only the ICTP-RegCM3 and UCLM-PROMES are able to depict a clear weakening of the TEJ seen in the ERA-Interim data implying a weaker upper-level divergence and hence much less lower-level convergence consistent with the rainfall deficit.
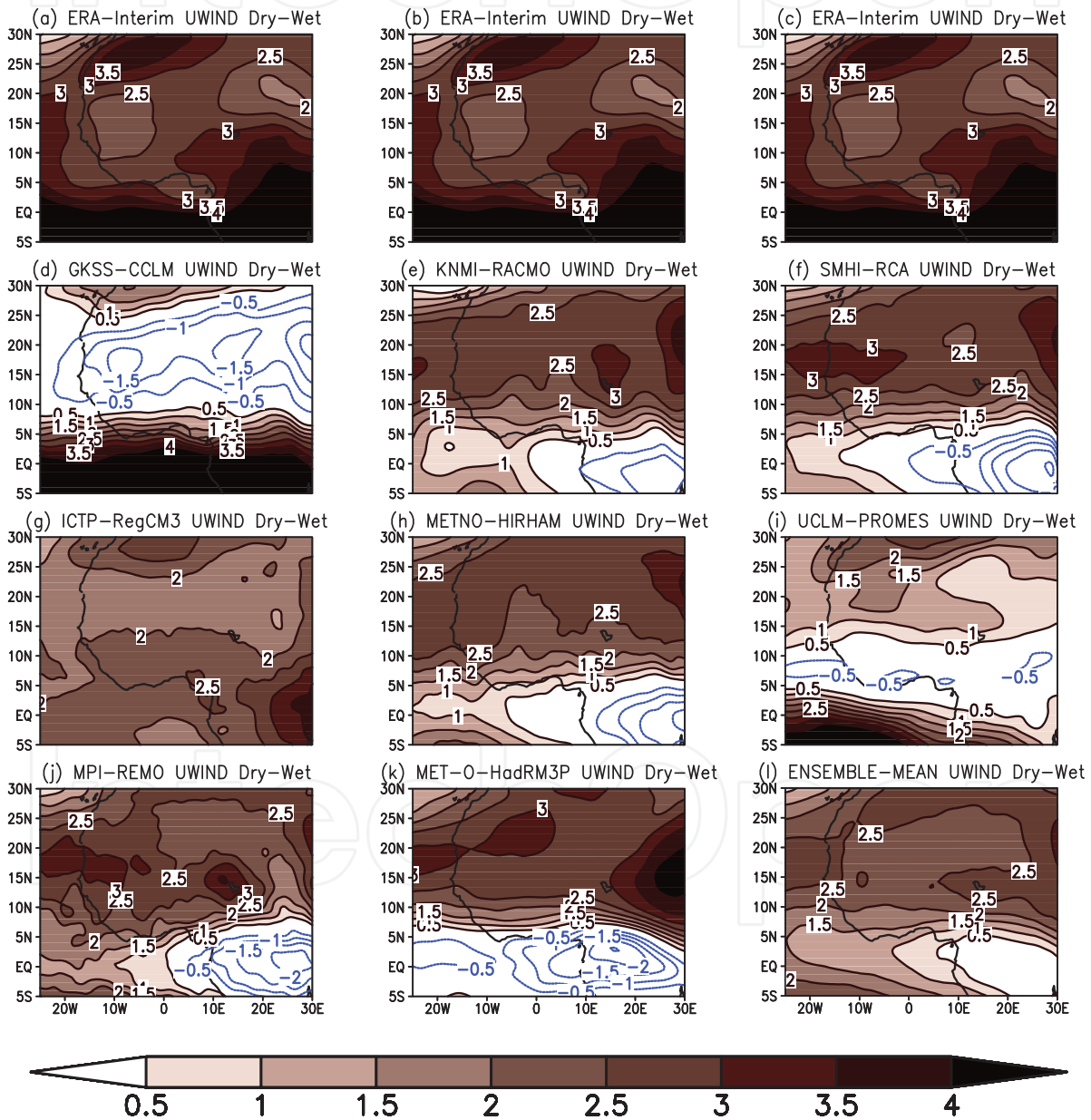

Figure 10. Difference of Dry (1990, 1993, 1997, and 2002) minus Wet Years (1994, 1998, 1999, and 2003) for the JJA 200 hPa Zonal Wind (m/s) for: (a,b,c) ERA-Interim reanalysis, (d) GKSS-CCLM, (e) KNMI-RACMO, (f) SMHI-RCA, (g) ICTP-RegCM3, (h) METNO-HIRHAM, (i) UCLM-PROMES, (j) MPI-REMO, (k) MET-O-HadRM3P and (l) the RCMs ensemble mean.

The corresponding composite for surface air temperature and superimposed mean sea level pressure for observations (CRU and UDEL), the ERA-Interim reanalysis, the RCMs and their ensemble mean are displayed in Figure 11. The observations and the reanalysis portray a dipole pattern with decreased temperature in Western Sahara accompanied by higher mean sea level pressure, and an increase in the Eastern Sahara along with a drop of the mean sea level pressure system. This illustrates a reduction of the SHL intensity and a possible shift of its core to the east during dry years over the Sahel. It is worth noting that the temperature pattern does not show any changes over the Gulf of Guinea with the CRU and UDEL observations. This implies substantial weakening of the meridional temperature gradient between the Gulf of Guinea and the Sahara thus preventing a northward displacement of the AEJ consistent with a drier Sahel. Furthermore, the observations and reanalysis data exhibit elevated temperature values over the Sahel probably due to strong soil moisture - temperature feedback. For the most part, all of the RCMs represent the weakening of the SHL in Western Sahara and the shift of its core to the East. The complete observed pattern, however, is fully replicated by SMHI-RCA and MPI-REMO and to some extent by KNMI-RACMO, UCLM-PROMES, GKSS-CCLM and the ensemble mean. Some of the RCMs, for instance ICTP-RegCM3, METNO-HIRHAM and MET-O-HadRM3P simulate cooler temperatures over some regions of the Sahel indicating weaker soil moisture - temperature feedback.

3.4. African Easterly Waves

AEWs are key drivers of climate variability in West Africa during the monsoon season. They are defined as disturbances around the zonal circulation of the mid-tropospheric AEJ and have been identified as the main mechanism organizing convection and rainfall patterns in this region (Diedhiou et al., 1999). They are triggered by localized finite-amplitude perturbations associated with latent heating upstream of the region of growth (Thorncroft et al. 2008; Leroux and Hall 2009) and maintained by combined baroclinic and barotropic conversions around the AEJ (Hsieh and Cook 2007). Hence the key role of deep convection in initiating the AEWs over the Darfur and Ethiopian highlands, and favoring its subsequent development is a consolidated result (Berry and Thorncroft 2005; Mekonnen et al. 2006; Sylla et al. 2011). Therefore, the existence of different convection schemes in climate models (e.g. Table 1) is likely to drive large uncertainties inherent to the simulation of AEWs (Ruti and Dell'Aquila, 2010). To gain insight into these uncertainties, we evaluate AEW activity simulated by different RCMs with similar and different convection schemes.

For this, we adopt two different bandpass filters in the 700 hPa daily meridional winds to separate the 3- to 5-day and the 6- to 9-day wave regimes as observed by Diedhiou et al. (1998) and Hsieh and Cook (2005). The wave activity is then obtained by averaging the seasonal mean variance of the filtered 700 hPa daily meridional winds for the period 1990-2008. This is shown for ERA-Interim (that drives the RCMs), National Center for Environmental Prediction (NCEP; Kalnay et al. 1996), and each of the RCMs and their ensemble mean respectively in Figure 12 The daily meridional winds are not available for KNMI-RACMO and UCLM-PROMES, and thus are not analyzed in this section.
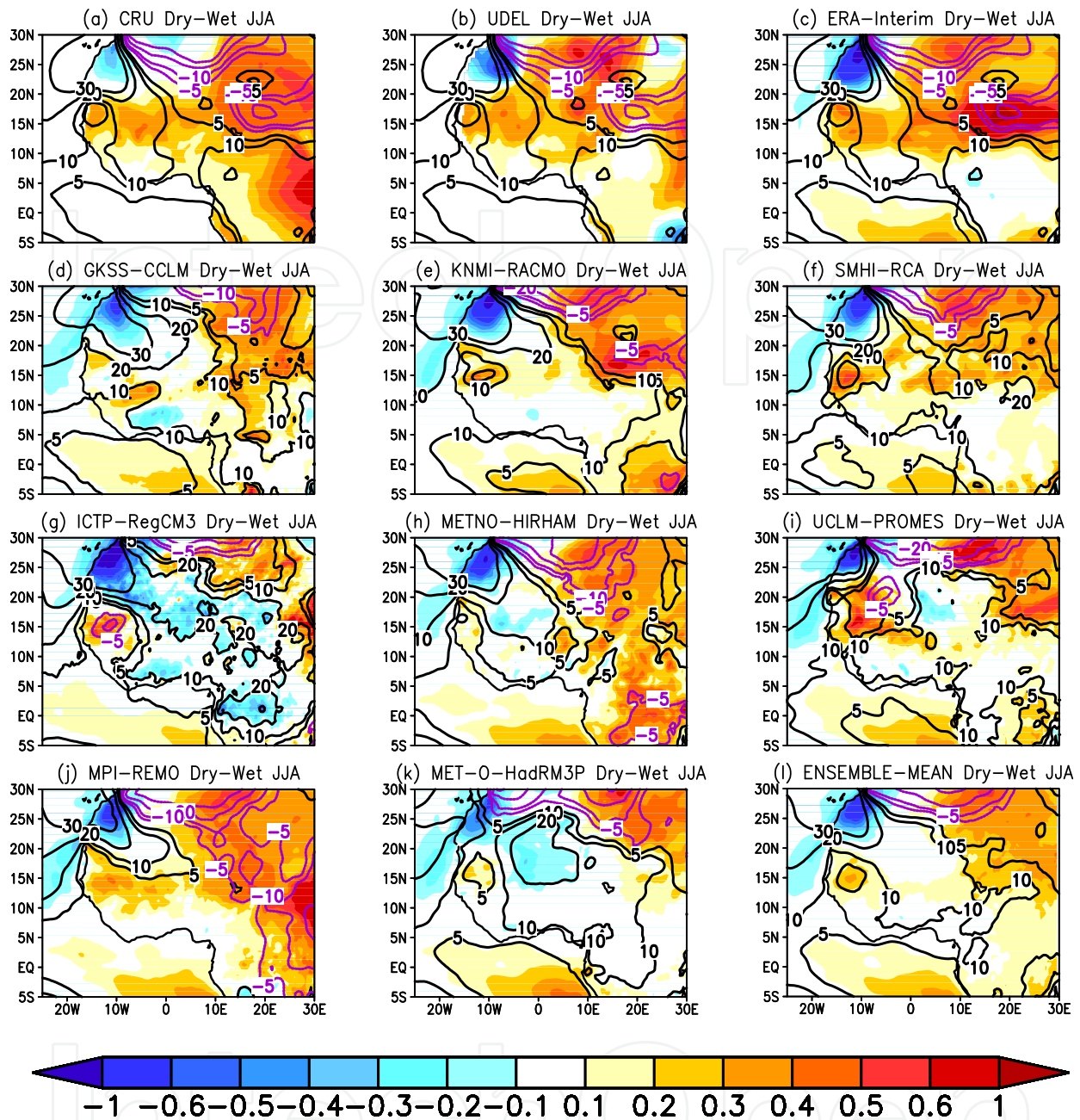
Figure 11. Difference of Dry (1990, 1993, 1997, and 2002) minus Wet Years (1994, 1998, 1999, and 2003) for the JJA 2-meter Temperature (degree Celsius) and superimposed Mean Sea Level Pressure (MSLP, in hPa) for: (a) CRU observation and ERA-Interim Wind, (b) UDEL observation and ERA-Interim Wind, (c) ERA-Interim reanalysis, (d) GKSS-CCLM, (e) KNMI-RACMO, (f) SMHI-RCA, (g) ICTP-RegCM3, (h) METNO-HIRHAM, (i) UCLM-PROMES, (j) MPI-REMO, (k) MET-O-HadRM3P and (l) the RCMs ensemble mean.

Striking differences are observed between the reanalysis. The ERA-Interim reanalysis depicts the higher 3- to 5-day wave activity slightly north of the ITCZ (around 15N) and off the west coast between 5N and 25N, and some weaker activity around the Gulf of Guinea and southern Sudan bioclimatic zone while NCEP reanalysis shifts the inland wave activity further north (around 20N). These differences between reanalysis products in terms of the rep-
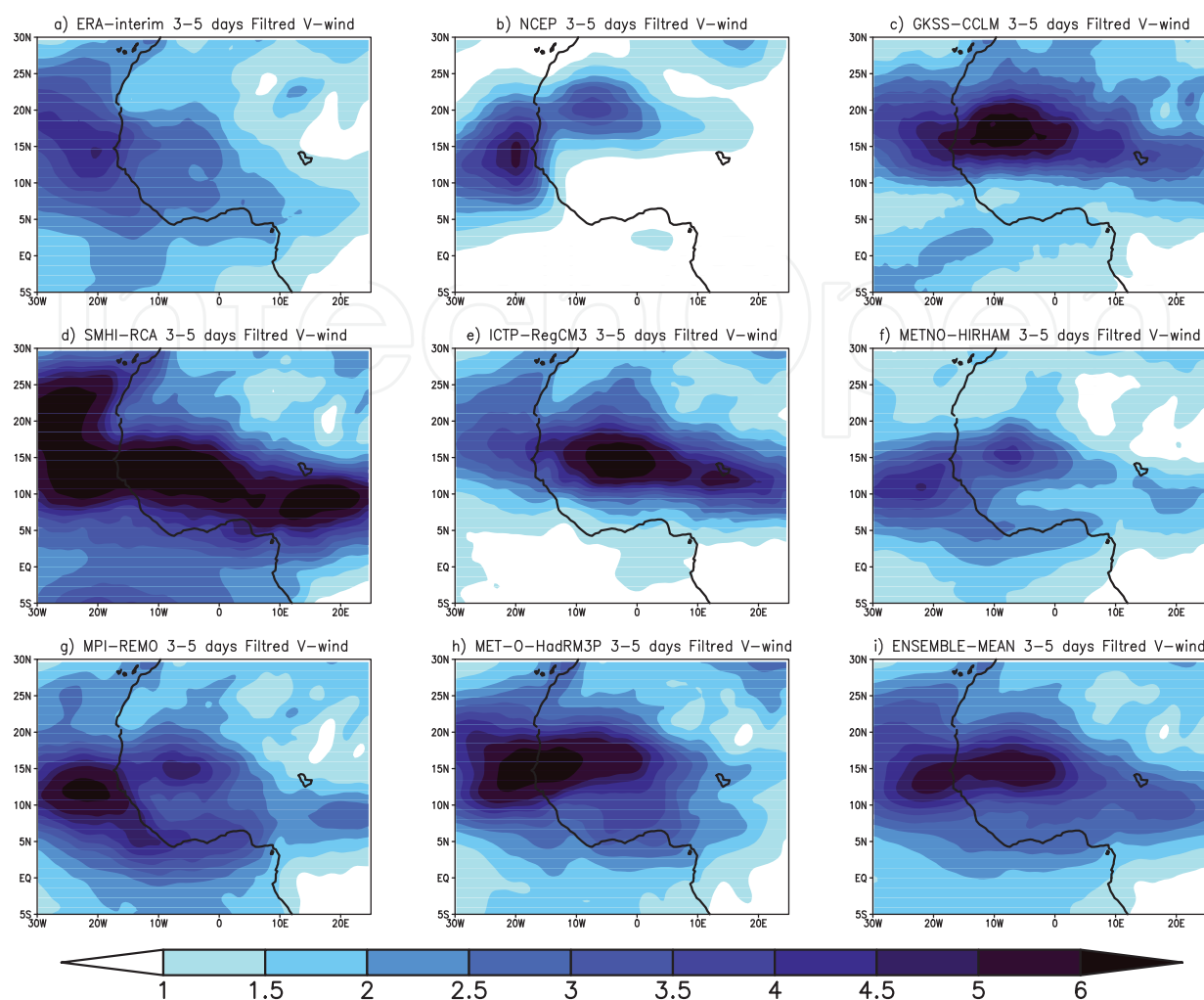
Figure 12. Mean (1990-2007) Variance of the 3- to 5-day filtered JJA 700 hPa Meridional Wind from (a) ERA-Interim reanalysis, (b) NCEP reanalysis (c) GKSS-CCLM, (d) SMHI-RCA, (e) ICTP-RegCM3, (f) METNO-HIRHAM, (g) MPI-REMO, (h) MET-O-HadRM3P and (i) the RCMs ensemble mean.

resentation of AEW activity have been identified and analyzed in detail by Ruti and Dell'Aquila (2010). The RCMs and their ensemble simulate a similar pattern to ERA-Interim but considerably overestimate the 3- to 5-day wave activity over the Sahel. This implies that these overestimates originate internally within the RCMs although some precursors of AEWs may enter the domain through the boundary forcing.

Compared to the 3- to 5-day, the core of the 6- to 9-day wave activity (Figure 13a-i) is generally weaker, probably due to their intermittent nature (Diedhiou et al. 1998; Hsieh and Cook 2007; Sylla et al. 2011), and located further north in both reanalysis datasets and all of the RCMs. Some of the largest model overestimates in both wave regimes, for instance SMHI-RCA and ICTP-RegCM3, are associated with excessive rainfall along the ITCZ, highlighting the key role of convection in triggering and maintaining the AEWs in these models. It is worth noting that GKSS-CCLM also exhibits stronger activity for both wave regimes but lower rainfall amounts implying the existence of dry convection fueling the AEWs. Contrary

to the 3- to 5-day wave regime, the ensemble mean of the 6- to 9-day activity substantially improves the individual RCM members; however, much of this improvement results from cancellation of errors of opposite signs.
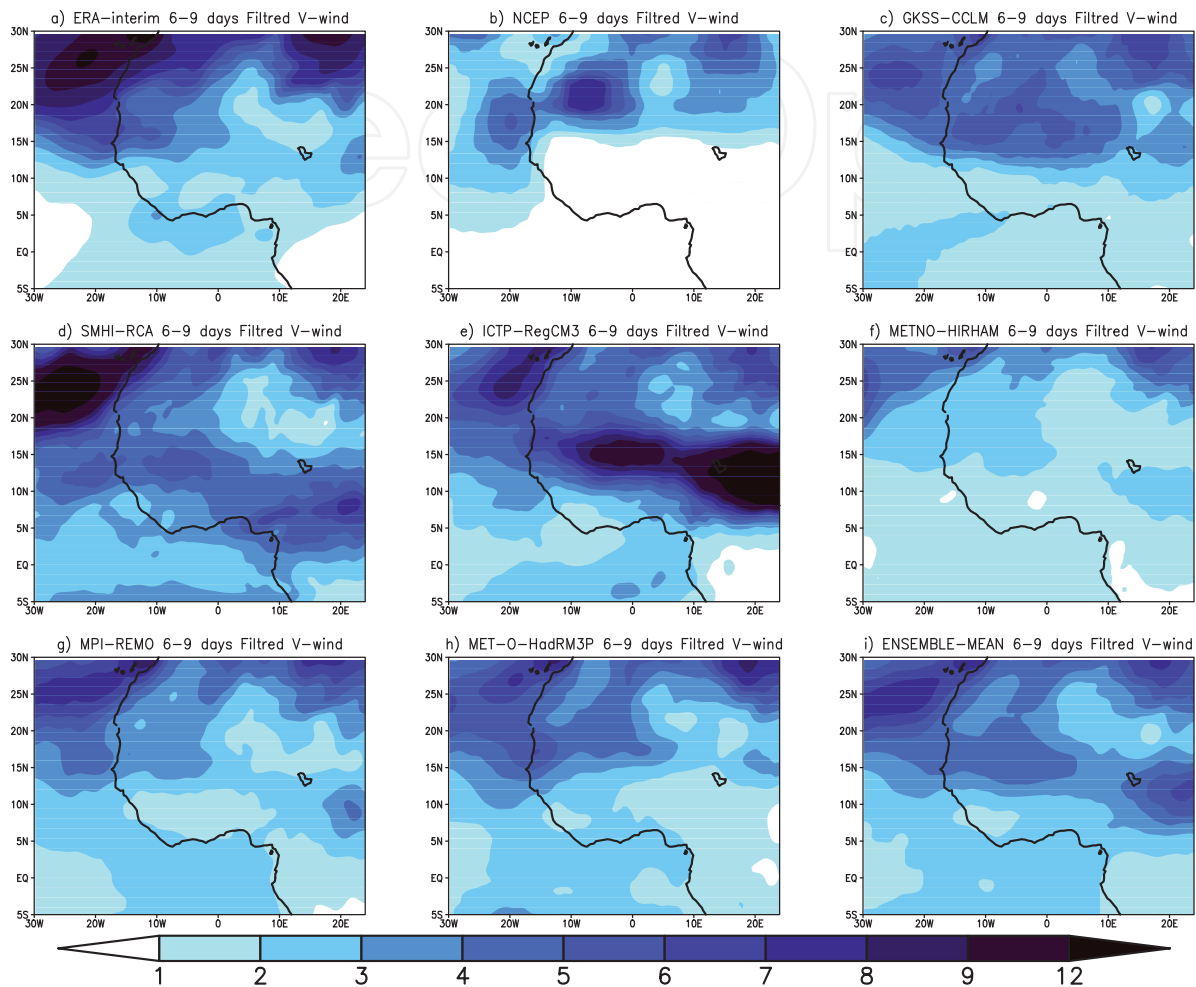

Figure 13. Mean (1990-2007) Variance of the 6- to 9-day filtered JJA 700 hPa Meridional Wind from (a) ERA-Interim reanalysis, (b) NCEP reanalysis (c) GKSS-CCLM, (d) SMHI-RCA, (e) ICTP-RegCM3, (f) METNO-HIRHAM, (g) MPI-REMO, (h) MET-O-HadRM3P and (i) the RCMs ensemble mean.

It is thus evident that the different RCMs, incorporating different convection schemes, produce quite different representation of AEWs regimes. Whether this is going to affect their dynamics during contrasting (wet and dry) years needs to be explored. We consider the same previous set of wet and dry years and examine the ability of the RCMs to reproduce the AEW composite pattern (Figure 14). The ERA-Interim data exhibit a reduction of the 3- to 5-day wave activity along a tilted zonal band extending from Cameroon Mountains to the Atlantic Ocean and encompassing the Gulf of Guinea and the Sahel region south of 15N (Figure 14a). This is consistent with less frequent convection events and thus a drier Sahel. The lower activity off the west coast is a robust result as is also observed in the NCEP data (Figure 14b). This pattern portrayed by ERA-Interim is well replicated by the ensemble

mean, MPI-REMO and MET-O-HadRM3P (although they overestimate the magnitude of the difference) and to some extent by ICTP-RegCM3. The 6- to 9-day wave regime composite does not show any significant change over the Sahel (not shown).
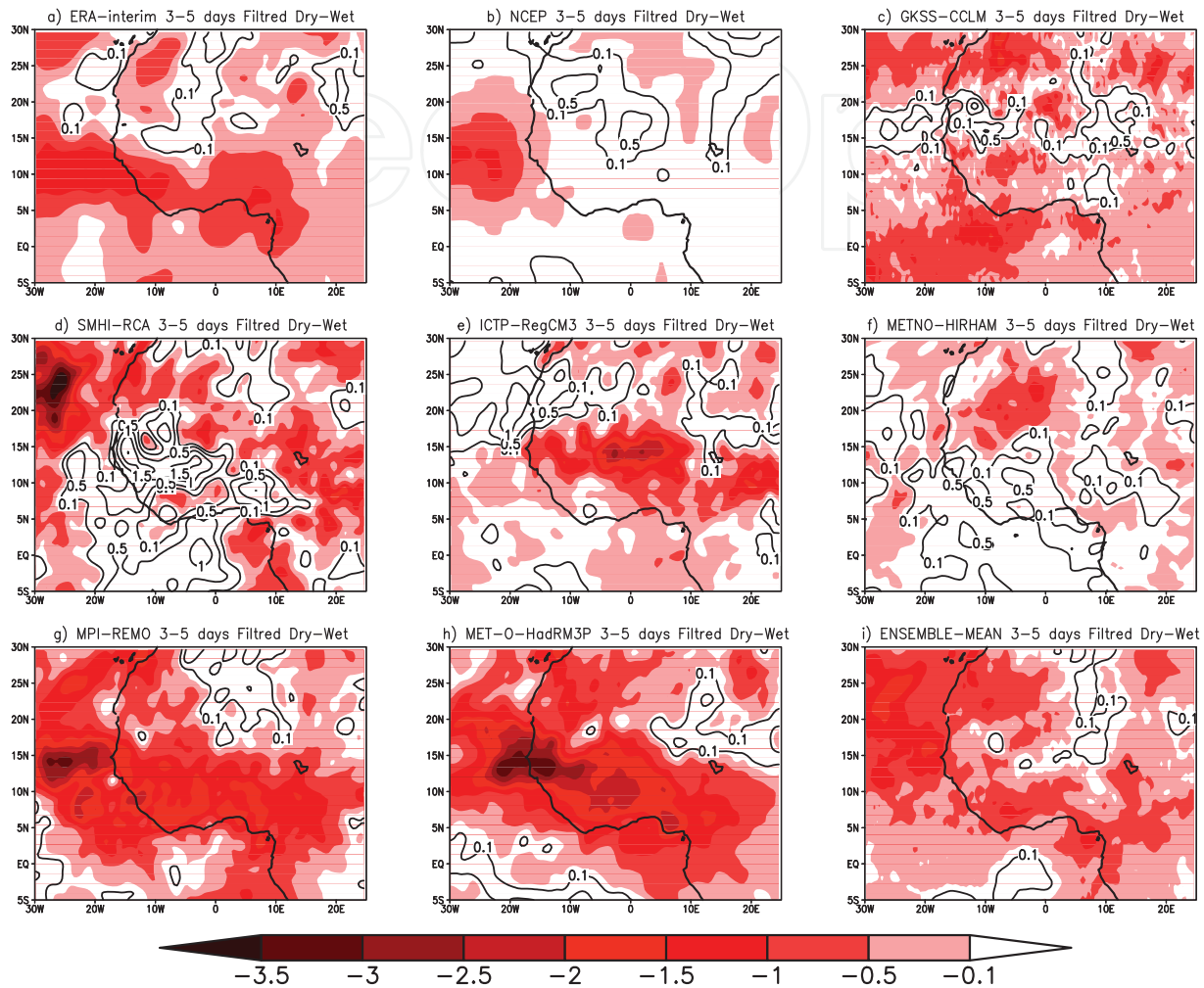

Figure 14. Difference of Dry (1990, 1993, 1997, and 2002) minus Wet Years (1994, 1998, 1999, and 2003) for the Mean Variance of the 3- to 5-day filtered JJA 700 hPa Meridional Wind from (a) ERA-Interim reanalysis, (b) NCEP reanalysis (c) GKSS-CCLM, (d) SMHI-RCA, (e) ICTP-RegCM3, (f) METNO-HIRHAM, (g) MPI-REMO, (h) MET-O-HadRM3P and (i) the RCMs ensemble mean.

A number of considerations can be highlighted based on the results of interannual variability along with the differences between the dry and wet years pertaining to the WAM circulation features. First, the monsoon circulation represented by the ERA-Interim data is not related to the inter-annual rainfall variability. This may be understandable as rainfall in this product is mostly simulated (Dee et al. 2011). Second, GKSS-CCLM fails to reproduce the inter-annual variability partly because of its inability to capture the circulation change characteristics of dry/wet periods over the Sahel (mostly AEJ and AEWs). Third, the interannual variability is more consistent with the change in AEJ and AEWs rather than in the TEJ for the majority of the models, suggesting that these rainfall variations are less sensitive to the

upper-level divergence. Therefore, while almost all RCMs successfully replicate the inter-annual variability of precipitation over the Sahel, only few of them (ICTP-RegCM3, UCLM-PROMES and MPI-REMO) along with the multi-model ensemble mean are able to capture most of the related monsoon circulation patterns during contrasting years.

4. Conclusion and outlook

This chapter provided a review of recent RCMs applications for the WAM and its variability at a wide range of spatial and time scales. These applications illustrate the increased interest in research activities concerning the WAM that have been substantially and consistently developed during the last decade. Such interest has been motivated in large measure by the vulnerability of the West African countries to recurrent drought episodes. The socio-economic repercussions of drought have prompted the scientific community to improve seasonal forecasts to be able to accurately predict onset dates and growing season length among other relevant parameters related to agriculture. Understanding the WAM is thus crucial for developing early warning of imminent drought and mitigation strategies. We highlight the key role played by RCMs in improving our understanding of the nature of the interactions between the WAM rainfall and the features triggering and maintaining it. Much of the progress achieved can be attributable to the AMMA project (Redelsperger et al. 2006) through AMMA/ENSEMBLES, which provided a comprehensive dataset to study the multiple scales interactions, the related processes and the uncertainties that characterize the simulation of the WAM. We then analyze and compare eight state-of-the-science RCMs in simulating these interactions, identify key biases and seek to provide useful information for future modeling work. In particular, we establish that a good representation of the variability of the relevant atmospheric circulation features is paramount for the simulation of the monsoon precipitation pattern at different time-scales. Overall the multi-model ensemble and the majority of the RCMs provide encouraging results in the representation of the WAM rainfall climatology, the mean annual cycle and Sahel interannual variability along with their connection to the different atmospheric features during the summer monsoon season and contrasting wet and dry years. RCMs are thus suitable tools (albeit not perfect) for investigating the dynamics of the main features triggering and maintaining the WAM precipitation.

However, we should emphasize that an important limitation about RCMs is that the model solution depends strongly on boundary conditions provided by reanalyses or GCMs. Thus, the quality of the regional simulations relies on observations supplying the boundary conditions or the GCMs performance. In addition, although RCMs can be run at higher resolution (10s of km), unresolved scales are always present and thus RCMs still depend on parameterization quality. Another deficiency may be related to the domain size and the location of the lateral boundaries, i.e. whether the RCMs simulate or acquire from the boundaries the circulation features influencing precipitation over West Africa. Such shortcomings induce large uncertainties for both present-day and projections of future climate, suggesting merit in performing multi-model ensemble of RCM simulations nested within multiple GCMs.

Since AMMA, a new and broader framework, the Coordinated Downscaling Experiment (CORDEX; Giorgi et al. 2009, Jones et al. 2011) recently established by the World Climate Research Program (WCRP) is underway. CORDEX intends to foster an international coordinated effort to produce improved multi-model RCMs-based high resolution climate change scenarios in such a way that the uncertainty can be minimized, quantified and effectively communicated to the end-users for informed decision making. For West Africa, the program offers an unprecedented opportunity to advance knowledge of the African monsoons response to anthropogenic climate change. However, the datasets generated need to be comprehensive enough to allow a full characterization of key processes in order to provide new insights about the future evolution of the coupled atmosphere-land-ocean monsoon systems.

Acknowledgements

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