Modeling the West African Monsoon Using a Superparameterized GCM and a High-resolution Cloud Resolving Model

Preliminary Examination Prospectus

Rachel Rose McCrary
Department of Atmospheric Science
Colorado State University

Advisor
David A. Randall

Committee
A. Scott Denning
Sue Van Den Heever
Michele Betsill (Political Science)

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1. Introduction/Motivation

The West African Monsoon (WAM) is the term commonly used to describe the seasonal rains that occur in West Africa from May to October. Since rain-fed agriculture is one of the main sources of food and income for the people in West Africa, societies in this region are highly vulnerable to variability in monsoon rains (Baron et al. 2005). Over the past 40 years, sub-Saharan Africa has also been in the throes of a severe drought which has had devastating agricultural, economic and societal consequences for the region (Nicholson et al. 2000). As our planet warms due to increasing greenhouse gas concentrations, it is probable that we can expect changes in the African monsoon circulation, which could further influence water resources in the Sahel. Unfortunately, the global circulation models (GCMs) that are used to make climate projections are currently unable to represent the timing, spatial patterns and magnitude of the monsoon precipitation over West Africa (Yang and Slingo 2001; Dia and Trenberth 2004; Meehl et al. 2006). The inability of these models to capture the observed monsoon system, greatly undermines their ability to represent potential changes to the monsoon in a warmer climate.

The WAM is a complicated system which involves many interactions between the atmosphere, ocean and land surface. The WAM is also influenced by processes that occur over a range of temporal and spatial scales (Hall and Peyrille, 2006). Traditional GCMs have difficulty capturing the monsoon because they are unable to represent the complex multi-scale interactions that are known to be associated with the monsoon (Yang and Slingo 2001). However, it is possible that GCMs that have implemented the multi-scale modeling framework (MMF) may be able to better capture the WAM. MMFs have been uniquely designed to examine the multi-scale interactions between small-scale circulations and large-scale dynamics. While traditional GCMs must parameterize small-scale physical features such as dry and moist convective processes, in MMFs, each GCM grid cell has been embedded with a row of cloud resolving models (CRMs) which allows for explicit simulation of small-scale cloud and boundary-layer processes (Randall et al. 2003). This approach of embedding CRMs within a GCM is sometimes referred to as "superparameterization".

In this study, I propose to examine the ability of the Superparameterised - Community Atmosphere Model (SP-CAM, Khairoutdinov et al., 2005), a MMF, to simulate the West African monsoon. Specifically I will examine the model's ability to represent the dynamics associated with both the seasonal cycle and the diurnal cycle of convection over West Africa. I then propose to use a high-resolution limited-area cloud resolving model (CRM) coupled to a land surface model to look at the influence that land-atmosphere coupling has on the diurnal variability of the WAM. If the SP-CAM is capable of representing the dynamics of the WAM, it is possible that this model could be used to look at potential changes to the monsoon system under global warming conditions.

The remainder of this prospectus is outlined as follows: the basic dynamics of the monsoon is described in Section 2, the three primary research objectives of this study are explained in Section 3, and in Section 4 the models, and observational data sets, experimental design I propose to use in this study are described.

2. Basics of the West African Monsoon

West Africa is typically defined as the westernmost region of the African continent, the segment of the continent that lies north of the Gulf of Guinea (Figure 1, Hall and Peyrille, 2006). From the Guinea coast to the Sahara desert, West Africa is characterized by east-west oriented climate zones (Hall and Peyrille, 2006). These climatic zones can be divided into three main regions, the tropical Guinea Coast, the semi-arid Sahel, and the arid/desert of North Africa (Figure 1). Precipitation over West Africa during the boreal summer is influenced by the position and activity of the inter-tropical convergence zone (ITCZ), which migrates north during the summer, following the annual march of the sun. From Figure 2 we see that during the spring/summer, precipitation migrates from the Guinea coast to the Sahel and back again, resulting in two rainy season per year in the south and one in the north (Sultan and Janicot, 2003).

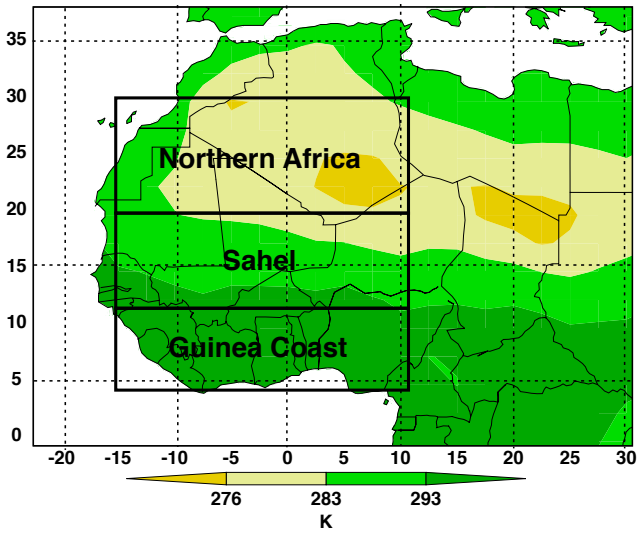


Figure 1. Average wet season dewpoint temperature at the surface over West Africa from ERA-40. Three climatic zones of West Africa are identified.

Differential heating of the ocean and land surface acts to initiate and maintain the low-level southwesterly monsoon flow, which advects relatively cool moist air from the Gulf of Guinea onto the hot dry continent (Figure 2, arrows). These low-level monsoon winds are controlled primarily by the surface pressure gradient force that develops between the Saharan Heat Low (SHL) and the subtropical south Atlantic high. In opposition to the low-level southwesterly monsoon flow, northeasterly advection (Harmattan) of a dry, warm air mass known as the Saharan air layer (SAL) develops in relationship to the SHL. As the SAL extends southward it overruns the cooler moister monsoon layer, providing strong convective inhibition (CIN) in the Sahel (Parker et al. 2005b). The confluence of these two air masses is known as the intertropical front (ITF, black line in Figure 2).

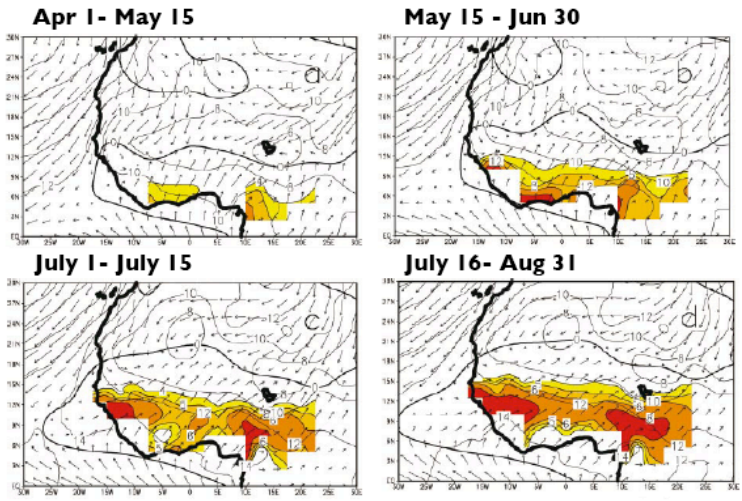


Figure 2. Seasonal progression of monsoon precipitation (color contours) from rain guage data and 925 hPa winds from ERA-40. The 0 contour of the zonal wind component delineates the monsoon winds (black contour). Figures from Sultan and Janicot, 2003.

The WAM is also intimately related to the African Easterly Jet (AEJ), a mid-tropospheric flow centered around 600-700 hPa at a latitude of around 15ºN (e.g. Burpee 1972, Parker et al. 2005a,

Cook 1999, Thorncroft and Blackburn, 1999). The AEJ has been shown to be important for the formation of African easterly waves (e.g. Thorncroft and Hoskins 1994) and for the development of mesoscale convective systems (MCSs, e.g. Houze and Betts 1981, Mohr and Thorncroft, 2006). MCSs are an important component of precipitation over West Africa and have been shown to produce about 90% of the annual regional rainfall in the Sahel (Laurent *et al.* 1998; Mathon *et al.* 2002). The AEJ forms as a result of the positive surface temperature gradient that occurs over West Africa. A number of studies have found that the exact position and intensity of the AEJ is linked to land-atmosphere interactions and large scale gradients in vegetation and soil moisture (Wu et al., 2009).

Previous research regarding the WAM has primarily focused on two areas: large-scale dynamics such as interannual and decadal variability in the monsoon (Rowell 2001, Janicot et al., 2001) and finer scales interactions such as the formation of AEW and MCSs (Diedhiou et al. 1999 and Mathon and Laurent 2001). Until recently, the diurnal variability of the WAM has been largely overlooked, due in part to the paucity of high-frequency observations in the area. The African Monsoon Multidisciplinary Analysis (AMMA, Redelsperger et al., 2006) observational field campaign, which occurred during 2006, has greatly increased the temporal and spatial resolution of observations available over West Africa. Some of the AMMA observation stations are highlighted on Figure 3. These new observation will finally allow us to examine the dynamic, thermodynamic and mesoscale processes that control the diurnal cycle of convection in the WAM.

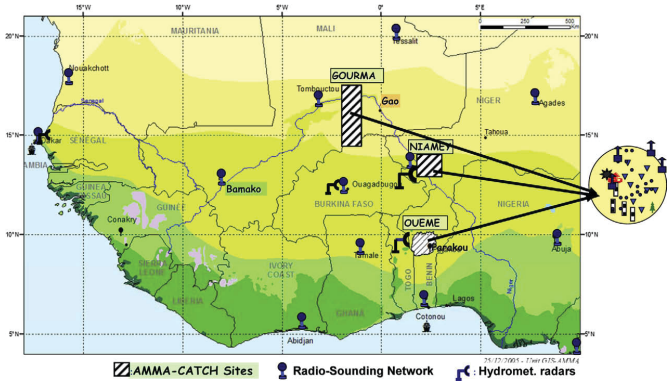


Figure 3. A selection of observation locations from AMMA. Includes some radiosonde stations and AMMA-CATCH long-term monitoring sites. Figure from Lebel et al. (2009).

In tropical West Africa (near the Guinea Coast) deep convection in the boreal summer has been found to develop in late afternoon and reaches a maximum in the evening. In this part of West Africa, the diurnal cycle of convection has been shown to correspond with boundary layer destabilization caused by daytime insolation and surface energy fluxes (Yang and Slingo, 2001). In the semi-arid regions of the Sahel however, convection has been found to initiate in the evening, with peak precipitation rates occurring in the early morning (Nesbitt and Zipser, 2003. Mohr, 2004). The diurnal cycle of convection in the Sahel has in large part been explained by the westward propagation of MCSs throughout the region. In West Africa, MCSs are often triggered by elevated daytime heating and orography (Rowell and Milford 1993). These storms typically propagate westward away from their source regions, such that the timing of peak precipitation occurs later and later as the MCS moves farther and farther away from its source region (Hodges and Thorncroft, 1997).

The generation of convection over West Africa is dependent on the moisture transported onto the continent by the monsoon winds. As discussed in Parker et al. (2005b), the dynamics of the low-level monsoon winds can be explained using a diurnal time frame. Their study (as well

as others) emphasize the importance of the formation of a nocturnal low-level jet (NLLJ) for the intrusion of moist air into West Africa (Lothon et al. 2008). The NLLJ is driven by the land sea pressure gradient that develops during the WAM season. During the day turbulent mixing increases the frictional force at the surface causing a reduction in the low-level winds. After sunset, turbulent mixing drops thereby greatly reducing the frictional force at the surface. This allows the low-level winds to accelerate throughout the night where they reach a maximum in the early morning (Persson 2002, Blackadar 1957). During the night the NLLJ advects cool humid air into the Sahel, then during the day turbulent mixing redistributes these quantities in the vertical (Parker et al. 2005b). Using a 2D model, Peyrille and Lafore (2007) showed that the nocturnal advection of moisture via the NLLJ and the subsequent daytime turbulent mixing are critical for sustaining deep convection in the Sahel during the wet season.

This was only a brief description of the complex dynamic and thermodynamic features that are associated with the WAM. In order to accurately represent the WAM, climate models must be able to represent the multiscale processes (such as interactions between MCSs and the AEJ) that characterize the monsoon. The background information provided here is intended to help motivate the three primary objectives of this study.

3. Research Objectives

Objective A: Does the SP-CAM simulate the seasonal cycle of the WAM?

The first question that this research will address is, does the SP-CAM capture the broad features of the seasonal cycle of the WAM? Specifically I will compare the seasonal cycle from a 5-yr simulation done with the SP-CAM (described in 4 section) with observations to look at the changes that occur in precipitation, temperature, pressure fields, and horizontal wind fields throughout the seasonal cycle.

To assess the ability of the SP-CAM to represent the seasonal cycle of the WAM I will address the following questions:

1. *When does monsoon precipitation first occur in the model? What is the northern most extent of the monsoon rains, and when does this occur? Is there a wet or dry bias in monsoon rains?*
2. *Does the timing of the onset of precipitation correspond with the onset of the monsoon winds in the SP-CAM? How does the strength of the monsoon winds in the model compare with observations?*
3. *How does the strength of the Harmattan winds compare with observations? Where do the monsoon winds and the harmattan winds converge (ie where does the ITF form)?How does the position of the ITF change throughout the monsoon season in the model?*
4. The Saharan Heat Low (SHL) is a major dynamical element for the WAM system. *How does the Saharan heat low vary throughout the annual cycle and how does this compare with what has been observed?*
5. The African Easterly Jet is also a critical component of the monsoon dynamics. *Does the SP-CAM simulate the AEJ? Where is the AEJ located in the SP-CAM? How does the position and intensity of the AEJ change with time?*

Previous studies that have evaluated the performance of the SP-CAM have shown that the geographical patterns of the seasonal cycle of precipitation are well reproduced by the model

(Khairoutdinov et al. 2005, 2008). It is expected that the model will also do a reasonable job representing the seasonal cycle of precipitation over West Africa. However it is important to note that the chosen orientation of the CRMs within the GCM grid cells (i.e. whether they are north-south or east-west oriented), may influence how well the seasonal cycle of the WAM is represented in the SP-CAM. It is also possible that a dry bias, similar to the one found over the central United States (DeMott et al. 2007), may exist over the Sahel. Pritchard and Somerville (2009) have diagnosed that the dry bias over the United States is due in part to the fact that the CRMs embedded in each grid cell have periodic boundary conditions, which inhibits the propagation of organized convection (such as MCSs) across the region. Since MCSs account for a large fraction of the wet season rain fall in the Sahel, it is possible that West Africa will also experience a dry similar bias.

Objective B: Does the SP-CAM simulate the diurnal cycle of convection in the Sahel during the monsoon season?

Traditional GCMs that must parameterize convection are known to produce a diurnal cycle of continental precipitation that is in phase with insolation, while observed precipitation has been shown to peak in the late afternoon or at night (as in the case of the WAM) (Rio et al., 2009). Biases in precipitation at these short time scales indicates that there are disconnects in how convective processes evolve in models compared to the real world. These problems that occur on short time scales most certainly manifest as problems in large scale phenomena such as the WAM.

To evaluate the diurnal variability of convection over the Sahel during the wet season, I will address the following questions:

1. *What time of day does it typically rain over the Sahel in the SP-CAM? How does this correspond with what has been observed?*
2. *Why does it rain when it does over the Sahel in the SP-CAM?*
3. *Does the timing of peak precipitation vary with longitude?*
4. *Is the SP-CAM capable of simulating the propagation of organized convection across Western Africa?*
5. *Does the SP-CAM simulate the diurnal cycle of the NLLJ over West Africa?*

Of course answering the question, “why does it rain when it does” will not be an easy task. This will require examining the preconvective state of the atmosphere where I will look at how surface sensible and latent heat fluxes, moist static energy in the boundary layer, convective available potential energy (CAPE), convective inhibition (CIN) and buoyancy vary throughout the diurnal cycle.

Further more I will need to investigate whether precipitation is controlled by local diurnal forcing, in which surface fluxes of sensible and latent heat act to destabilize the boundary layer throughout the day eventually resulting in convection, or if the diurnal cycle of convection is primarily influenced by the migration of MCSs that propagate from east to west throughout the Sahel.

Previous studies that have examined the diurnal cycle of convection in the SP-CAM have shown that SP-CAM exhibits marked improvement in representing the diurnal cycle of convection over continents (Khairoutdinov et al. 2005, Pritchard and Somerville 2009). Studies have also found that the SP-CAM improves the diurnal variability of stratocumulus clouds

(Khairoutdinov et al. 2008), and an improved diurnal cycle of nondrizzle precipitation over land (Khairoutdinov et al. 2005).

It is possible that the diurnal cycle of convection will be similarly improved over the Sahel, however the ability of the SP-CAM to simulate the nigh-time/early morning peak in precipitation over the Sahel will depend on whether or not the SP-CAM is capable of simulating the propagation of MCSs across the Sahel.

Objective C: How might including land-surface heterogeneity at the CRM scale influence the diurnal cycle of convection over the Sahel in the SP-CAM?

It is possible that the SP-CAM will have difficulty representing the diurnal cycle of convection over the Sahel for a number of reasons. One challenge, that I have already mentioned, is that the CRMs embedded in each GCM grid cell have periodic boundary conditions, which has been shown to influence the propagation of MCSs. Another reason why the SP-CAM may have difficulty simulating the diurnal cycle of convection in the WAM is that coupling between the atmosphere and the land surface is not calculated on the CRM scale, but is computed only on the GCM scale. This means that fine-scale gradients in soil moisture and temperature do not exist in the SP-CAM and that localized surface fluxes of heat and momentum are not included in the model. Previous research has indicated that mesoscale gradients in surface fluxes are important for the generation of convection in the Sahel (Taylor et al., 1997). The omission of land-atmosphere coupling at the CRM scale may have important implications on how well the SP-CAM represents the diurnal cycle over West Africa.

The land surface and the atmosphere are coupled to each other via sensible and latent heat fluxes as well as precipitation. The magnitude and partitioning of surface turbulent heat fluxes influences the development of the boundary layer throughout the day. These fluxes have an important effect on the moisture state and stability of the atmosphere and are therefore important for the development of deep convection and precipitation over land. Over the Sahel, mesoscale surface flux variability acts to generate horizontal gradients in moist static energy in the boundary layer (Taylor et al., 1997). These mesoscale gradients in boundary layer stability ultimately influence when and where it will rain the the Sahel (Clark et al., 2003; 2004). Taylor and Lebel (1998) have found that mesoscale precipitation gradients can persist in the Sahel on time scales of a few days to a month. They argue that a positive land-atmosphere feedback between antecedent rainfall and subsequent rainfall events is responsible for these persistent precipitation gradients (Taylor et al., 1997).

For this objective, I propose to examine how including land-atmosphere interactions at the CRM scale may influence modeling diurnal variability over the Sahel. To do this I will perform series of idealized high-resolution limited area modeling experiments using the CRM that is embedded in the SP-CAM (the SAM) coupled to a land surface model. With this series of model experiments I will attempt to answer the following questions:

1. *How does introducing land-atmosphere coupling at the CRM level in the 2D version of the SAM influence the diurnal cycle of convection?*
2. *Does the 2D version of SAM-Sib capture the statistics of the diurnal cycle that are found by using the 3D version of SAM-Sib?*
3. How *does the diurnal cycle of convection respond to mesoscale surface flux variability, which is induced by horizontal gradients in soil moisture?*

4. *Does the spatial organization of surface vegetation cover influence where convection occurs over the Sahel?*
5. *Does antecedent rainfall influence where future rainfall will occur over the Sahel?*

The results from these idealized experiments will hopefully help us to determine whether or not we should include land-atmosphere coupling at the CRM scale within the SP-CAM. Ultimately by coupling the SAM to a land-surface model we should be able to represent interactions between surface heterogeneity, clouds and precipitation, which are currently not included in the SP-CAM.

4.Methods (models, observations, experimental design)

In this section I discuss how I plan to accomplish these research objectives.

Objectives A & B: Model

Objectives A and B will use simulated data take from a superparameterized version of the National Centers for Atmospheric Research (NCAR) Community Atmosphere Model (CAM, Collins et al. 2006), or what is commonly referred to as the SP-CAM(Khairoutdinov et al. 2005). The SP-CAM is essentially equivalent to the CAM, except that the conventional parameterizations of moist physics, convection, turbulence, and boundary layer processes have been replaced by embedding a two-dimensional cloud resolving model (CRM) into each GCM grid cell. The CRM used in the SP-CAM is a 2D version of the System for Atmospheric Modeling (SAM; Khairoutdinov and Randall 2003). In the SP-CAM, the large scale model has horizontal resolution of 2.8º x 2.8º (T42 truncation), 30 levels and a time step of either 15 or 30 min. The embedded 2D CRM is made up of 32 grid columns each with 4-km horizontal resolution, 28 levels that are collocated with the 28 lowest CAM levels, and a time step of 20 s. The "curtains" of CRMs within each grid cells are periodic and can be position in either the east-west or north-south direction.

As mentioned previously, the direction in which the curtain of CRMs is oriented in the grid cells (i.e. either north-south or east-west) may influence how well the SP-CAM represents the east-west propagation of organized convection over the Sahel. Ultimately, this could influence both the seasonal and diurnal cycles of convection over West Africa. Sensitivities studies will need to be done to determine whether or not the orientation of the CRMs is important for convection in the WAM.

There is the potential to use simulations that have already been performed as long as the temporal resolution of the model output from both the host GCM and the CRM is three hourly or less, so that diurnal variability can be resolved.

Objectives A & B: Experimental Design

To address the questions posed in objective A I will create composite monthly seasonal cycles of precipitation, temperature, geopotential height, and wind fields in order to look at how well the SP-CAM simulates the seasonal progression of the monsoon. I will then compare the timing of the onset of the monsoon and the seasonal progression of precipitation throughout West Africa with observations. I will focus primarily on the spatial patterns of precipitation associated with the monsoon, and look for regional dry and wet biases. It will also be important to make sure that the model represents the seasonal progression of the low-level monsoon winds, the SHL, and the AEJ. I will use the methods outlined in previous studies to detect and monitor the

seasonal cycles of these monsoon features in the SP-CAM (Sultan and Janicot, 2003; Lavaysse et al. 2009; Parker et al. 2005a).

To address the questions posed in objective B I will focus on SP-CAM output from the West African wet season months (June - September). I will first create composite diurnal cycles of precipitation and latent and sensible heat fluxes. I will use these composite diurnal cycles to determine when it typically rains over the Sahel in the model and how the timing of peak precipitation varies with longitude. I also want to look at the correlation between surface fluxes and the timing of precipitation. I will examine the preconvective state of the atmosphere before precipitation by creating vertical profiles of potential temperature, equivalent potential temperature, water vapor mixing ratio, liquid water content, and moist static energy. I want to try and identify whether local boundary layer destabilization due to solar forcing is what causes convection over the Sahel, or if this area is more heavily influence by the propagation of MCSs.

Finally, to analyze the ability of the SP-CAM to represent the NLLJ, I will look at the composite diurnal cycle of low-level wind fields (~925 hPa) across all of West Africa. The NLLJ has been shown to occur in the lowest kilometer of the atmosphere, and typically peaks around 450m above the ground (Lothon et al., 2008). It is possible that the SP-CAM may have difficulty capturing the NLLJ due to the coarseness its vertical resolution.

Objectives A & B: Observations

I will use a combination of different observation bases data sets to evaluate the SP-CAM. Model simulated precipitation will be compared against the TRMM 3B42 merged satellite precipitation product (Huffman et al. 2007). This data set is a rain gauged-scaled, multi-satellite, gridded 3-hourly, high resolution (0.25ºx0.25º) precipitation product which covers all longitudes and latitudes between 40ºS-40ºN and is available from Jan 1998-present. For the seasonal cycle of temperature, horizontal winds at all levels, and pressure fields I will use the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis-Interim data set (ERA-Interim; Berisford et al. 2009). ERA-Interim data is available at all points of the globe, with a 1.5ºx1.5º horizontal resolution, and 6-hourly data. This data set extends from 1989 - present and is an improvement over its predecessor ERA-40.

To evaluate the diurnal cycle over Africa I will use data that has been provided from the AMMA 2006 field campaign. Primarily I will use the ECMWF reanalysis product which has been rerun specifically for AMMA (ERA-AMMA, http://bddamma.ipsl.polytechnique.fr/ecmwf-amma-re-analysis.html). This reanalysis product was generated using the specific AMMA archive of radiosondes (which were launched 4 times daily from a number of observation stations, Figure 3 and Table 1f). It extends from 100ºW-47ºE, 47ºN-25ºS with 0.5ºx0.5º horizontal resolution, with output 4 times daily and covers the time period from May - September 2006.

I also propose to observational data from the AMMA sounding network (Table 1) as well as the ground observations taken at the Niamey ARM super site (Table 1) to evaluate the diurnal cycle over the Sahel in the SP-CAM.

Objective C: Models

The cloud resolving model (CRM) that I propose to use in this study is the System for Atmospheric Modeling (SAM; Khairoutdinov and Randall 2003). I have chosen to use this model for two reasons. 1) The 2D version of this model is what has been embedded in the GCM

Source	Observations	Location	Time sampling
AMMA - Radiosondes	Air Temperature, Wind Speed/Direction, Air Pressure, Humidity, Geopotential, Dew Point Temperature, mixing ratio	Bangui, Abidjan, Niamey Aero, Cotonou, Parakou, Conakry, Tamale, Abuja, Ngaoundere, Doula Obs, Ouagadougou, Ndjamena, Tambacounda, Bamako/Senou, Dakar/ Yoff, Sal, Khartoum, Tamanrasset, Tombouctou, Nouakchott, Agadez, Tessalit, Kano, Birni, Parakou, Tahoua, Agadez	1,2,4,8 times daily (depending on time of year)
Microwave radiometer profiler	vertical profiles of temperature, humidity, and cloud liquid water content	Niamey ARM super site	5-min intervals
Microwave radiometer	column-integrated water vapor and liquid water	Niamey ARM super site	25 seconds
wind profiler	profiles of u and v wind	Niamey ARM super site	every 6 min
wind profiler, doppler radar	profiles of u and v wind, vertical wind	Ouagadougou, Djougou	every 6 min

Table 1. Direct observations from AMMA that will be used in this study.

grid cells in the SP-CAM and 2) recently Don Dazlich has coupled the SAM to a land surface model, the Simple Biosphere Model (SiB).

SAM is based on a large eddy simulation model and uses the anelastic approximation equations to describe motion. There are three types of prognostic thermodynamic variables in the model: liquid water/ice moist static energy, total nonprecipitating water (vapor, cloud water, cloud ice), and total precipitating water (rain, snow, graupel). Time integration is performed using the Adams-Bashforth scheme. Subgrid-scale fluxes are computed using first-order Smagorinksy-type closure (Smagorinski, 1963). The SAM is currently set up to run with doubly periodic boundary conditions (in both the x and y direction). Sensitivity testing will need to be done in order to determine the appropriate horizontal and vertical resolutions of the model. However, I estimate that I will use a horizontal grid spacing that is between 1-4km. Typically the vertical resolution used in SAM transitions from 50m in the lower layers of the atmosphere, to 100-200m in the middle atmosphere, to something on the order of 500m in the upper atmosphere. More details about SAM can be found in Khairoutdinov and Randall (2003, 2006),

As mentioned previously, SAM has been coupled to the SiB land-surface model. SiB is based on a land-surface parameterization scheme that computes biophysical exchanges with the atmosphere (Sellers et al., 1986) as well as ecosystem metabolism (Sellers et al.,1996a; Denning et al., 1996). The model calculates the transfer of heat, moisture, momentum and CO2 between the canopy air space and the free atmosphere. Incoming precipitation is allocated between canopy interception, ground puddles and ten soil layers. Water can be lost via evaporation, transpiration, sublimation, or exchanged between soil layers. Over-saturation of soils and vertical gravitational drainage both result in runoff, but the SiB hydrology does not account horizontal

exchanges of water between grid cells. Land surface characteristics in SiB are defined by satellite based LAI and FPAR calculations, soil type (clay loam or sand) and one of 12 possible biome types.

Objective C: Experimental design

To answer the questions outlined in Objective C, I propose to do the following experiments using the SAM-Sib.

Experiment #1

The first experiment I propose to run with SAM/Sib will try to replicate the interactions between the large-scale forcing and the CRMs that is found in the SP-CAM. This experiment will use the 2D version of the SAM and will have horizontal domain size of 250 km in the east-west direction. The simulation will be centered over Niamey, Niger (lat/lon) and will be representative of the Sahel and have uniform vegetation cover. As is currently done with the SP-CAM, I will restrict the extent of the coupling between the land surface and the atmosphere such that each CRM column will be forced by the mean state of the land surface of the domain.

To run the model, I will use methods that are similar to previous CRM studies which have looked at the diurnal cycle (e.g. Guichard et al., 2004) or generating organized convection (e.g. Li et al., 2008). To initialize the model, I will create a composite 0000 UTC sounding for June, from the radiosonde data provided for the Niamey site during the AMMA observational campaign (Figure 4). The model must be initialized with vertical profiles of horizontal wind, potential temperature, and water vapor mixing ratio. I will then drive the model using a time-varying large-scale forcing data set that I will create from the ERA-AMMA product. The large-scale advective tendency profiles for temperature, water vapor mixing ratio and horizontal winds will be imposed on the model grid points uniformly in the horizontal domain and linearly interpolated in time from the 6-hourly ERA-AMMA. It is also possible that the mean state of the CRM domain will need to be nudged toward some idealized diurnal cycle. If so, I will use the composite 0006, 0012, 0018 UTC soundings for June from Niamey (Figure 4). I will then ask the following questions:

1. *How does the diurnal cycle of convection in this CRM compare with the SP-CAM and observations?*
2. *Based on the initialization and forcing data sets used, does the CRM generate MCS-like convection? How can I modify the forcing files or nudge the mean state to generate MCSs.*

Experiment #2

This experiment will be almost identical to experiment 1, except that in this case I will couple each individual CRM to the land surface below. Under each CRM, surface temperature, soil moisture, and turbulent heat fluxes will be determined by the conditions of the CRM column above (not the mean state). Using this experimental setup, I will be able to look at the influence that small scale gradients in moisture, temperature and surface fluxes have on the diurnal cycle of convection. I can then ask the following questions:

1. *How does the diurnal cycle of convection vary between experiments 1 and 2?*
2. *How do land surface fluxes change between experiments 1 and 2? And, do these difference appear to influence convection?*
3. *Where does convection generally form relative to gradients in surface moisture and temperature?*

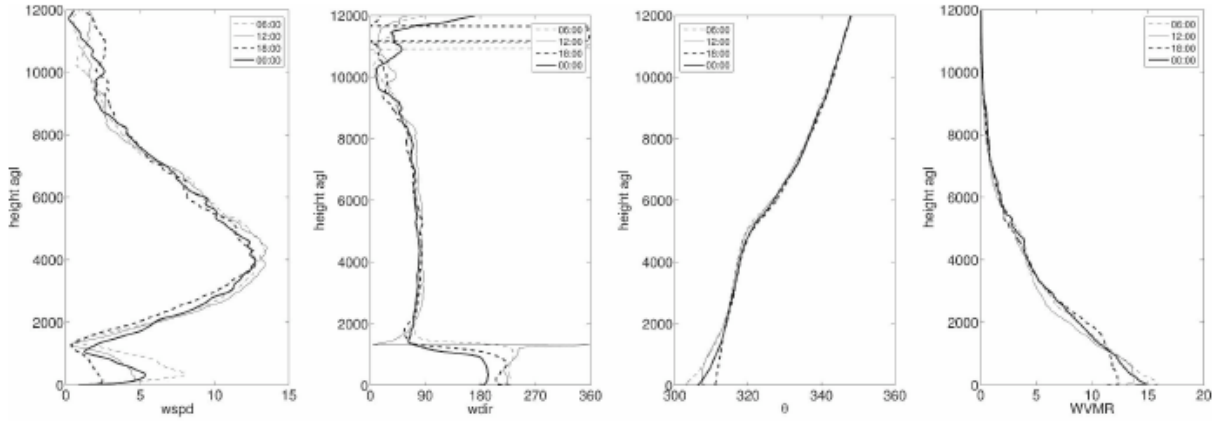


Figure 4. Composite (0000, 0006, 0012, 0018 UTC) soundings of wind speed, wind direction, potential temperature, and water vapor mixing ration from Niamey for June. From Lothon et al. 2008.

Experiment #3

This experiment will also be comparable to experiments 1 and 2, except that I will expand the CRM from its 2D version into the 3D version. The horizontal domain size for this experiment will now be 250 km x 250 km however it will still be set up to be centered over Niamey. I will then use the same initial condition, large-scale forcing, and nudging (if needed) data sets as used in both experiments #1 and #2. As with experiment #2, each CRM will be coupled to the land surface.

With this experiment, I can assess whether or not the 2D model is capable of capturing the statistics of the diurnal cycle of convection that are found when using the 3D model. I can also look at the spatial coherence of precipitation, and look to see if MCS like organization occurs. Furthermore, I can then investigate the influence that fine-scale gradients in moisture and temperature have on when and where convection occurs in the domain.

Experiment #4

The final experiment I propose to do with SAM-SiB, will extend beyond the traditional uses of the SAM. Here I propose to do a relatively large area, high-resolution run (something on the order of 10º longitude x 5º latitude with 2-4km grid spacing) for the Sahel. This way I can look at the importance that meridional gradients in surface vegetation cover, soil moisture and temperature have on convection in the Sahel. I can also look at how changes in surface vegetation cover influence the diurnal cycle of convection. For instance, I can ask, how does switching the vegetation cover over the Sahel from woody grassland, to tropical rain forest influence when it tends to rain in the region. With this large-area run, I also propose to investigate if soil moisture rainfall feedbacks, which cause future rainfall events to occur where previous storms have already passed through, exist in this model.

To initialize this model I will use horizontally varying initial soundings, which can either be interpolated onto the high-resolution grid from ERA-AMMA or from the observational sounding network (Table 1). As shown in Stirling and Petch (2004) horizontally varying initial conditions will have important influence on the diurnal cycle of convection. I will also need to use horizontally varying large scale forcing data, which again can be generated from ERA-AMMA. With this large scale data set, I will want to make sure that the position and the

intensity of the AEJ is well represented. Finally, I will nudge the outer most CRM cells with an idealized diurnal cycle so that I can avoid having to nudge the inner most CRMs.

One challenge I will face with this experiment is how to set up the land surface conditions in SiB (vegetation cover, biome type, soil type) on a high resolution grid in Africa. Hopefully I can use the high resolution MODIS LAI, FPAR and biome type descriptions (citation) and the 5-minute resolution IGBP soil type dataset (Global Soil Data Task 2000). It is also possible that I can use the observational data obtained from the AMMA-CATCH sites (Figure 3; Lebel et al., 2009), which document soil and vegetation type for ecosystem dynamics studies.

5. Summary

The over arching goal of this research is to asses the ability of the SP-CAM to represent the complex multi-scale dynamics associated with the WAM. For this study, I have proposed to examine how well the model represents both the seasonal and diurnal cycles of convection over West Africa. This will involve examining how well the model represents the dynamic and thermodynamics elements of the monsoon that are important on these time scales. Based on the work proposed here, we may also find that land-atmosphere interactions are essential for capturing the diurnal variability associated with the monsoon. If so, we may want to include land-atmosphere coupling at the CRM scale in the model (something that has already been considered, but not implemented). Eventually, if the SP-CAM proves to do a reasonable job representing the WAM, we can use the model to investigation how global warming conditions may influence the intensity of the monsoon. We could also possibly look at the potential impacts that land use change (human or natural) may have on the monsoon system.

List of Acronyms (alphabetical order)

AEJ - African Easterly Jet
AEW - African Easterly Waves
AMMA - African Monsoon Multidisciplinary Analysis
CAM - Community Atmosphere Model
CAPE - Convective Available Potential Energy
CATCH - Couplage de l'Atmosphere Tropicale et du Cycle Hydrologique
CIN - Convective Inhibition
CRM - Cloud Resolving Model
ECMWF - European Center for Medium-range Weather Forecast
FPAR - Fraction of Photosynthetically Active Radiation
GCM - Global Circulation Model
ITCZ - Inter-tropical Convergence Zone
ITF - Inter-tropical Front
LAI - Leaf Area Index
MCS - Mesoscale Convective System
MMF - Multiscale Modeling Framework
NLLJ - Nocturnal Low Level Jet
SAL - Saharan Air Layer
SAM - Simple Atmosphere Modeling
SHL - Saharan Heat Low
SiB - Simple Biosphere Model
SP-CAM - Superparameterized CAM
TRMM - Tropical Rainfall Measuring Mission
WAM - West African Monsoon

References

Baron, C., B. Sultan, M. balme, B. Sarr, T. Lebel, S. Janicot, and M. Dingkuhn, 2005: From GCM grid cell to agricultural plot: Scale issues affecting modeling of climate impact. *Philos. Trans. Roy. Soc. London*, **360B** (1463), 2095-2108.

Blackadar, A. K., 1957: Boundary layer wind maxima and their significance for the growth of nocturnal inversions. *Bull Amer. Meteor. Soc.*, **38**, 283-290.

Burpee, R. W., 1972: The origin and structure of easterly waves in the lower troposphere of North Africa. *J. Atmos. Sci.*, **29**, 77-90.

Clark, D. B., C. M. Taylor, A. J. Thorpe, R. J. Harding, and M. E. Nicholls, 2003: The influence of spatial variability of boundary layer moisture on tropical continental squall lines. *Quart. J. Roy.* Meteor. Soc., **129,** 1101–1121.

Clark, D. B., C. M. taylor, and A. J. Thorpe, 2004: Feedback between the Land Surface and Rainfall at Convective Length Scales. *J. Hydrometeo.*, 5, 625-639.

Cook, K. H., 1999: Generation of the African Easterly Jet and Its Role is Determining West African Preciptation. *J. Climate*, **12,** 1165-1184.

Dai, A., and K.E. Trenberth, 2004: The diurnal cycle and its depiction in the community climate system model. *J. Climate*, **17**, 930-951.

D'Amato, N. and T. Lebel, 1998: On the characteristics of the rainfall events in the Sahel with a view to the analysis of climatic variability. *Int. J. Clima.*, **18**, 955-974.

DeMott, C. A., D. A. Randall, and M. Khairoutdinov, 2007: Convective Precipitation Variability as a Tool for General Circulation Model Analysis. *J. Climate*, **20**, 91-111.

Denning, A.S., G.J. Collatz, C. Zhang, D.A. Randall, J.A. Berry, P.J. Sellers, G.D. Colello, and D.A. Dazlich (1996), Simulations of Terrestrial Carbon Metabolism and Atmospheric CO_2 in a General Circulation Model. Part I: Surface Carbon Fluxes. *Tellus*, *48B*, 521-542.

Diedhiou, A., S. Janicot, A. Viltard, P. de Felice, H. Laurent, 1999: Easterly weave regimes and associated convection over West Africa and tropical Atlantic: results from NCEP/NCAR and ECMWF reanalysis. *Climate Dyn.*, **15**, 795-822.

Guichard, F., J.C. Petch, J.L. Redelsperger, P. Bechtold, J.P. Chaboureau, S. Cheinet, W. Grabowski, H. Grenier, C.G. Jones, M. Kohler, J. M. Piriou, R. Tailleux, and M. Tomasini, 2004: Modeling the diurnal cycle of deep preciptating convection over land

with cloud-resolving models and single-column models. *Q. J. R. Meteorol. Soc.,* **130**, 3139-3172.

Hall, N. M. J and P. Peyrille, 2006: Dynamics of the West African Monsoon. *J. Phys. IV France*, **139**, 81-99.

Hodges, K. I, and C. C. Thorncroft, 1997: Distribution and statistics of African mesoscale convective weather systems based on the ISCCP Meteosat imagery. *Mon. Wea. Rev.*, **125**, 2821-2837.

Houze, R. A. and A. K. Betts, 1981: Convection in GATE. *Rev. Geophys. Space Phys*., **19**, 541-576.

Huffman, G., R. Adler, D. Bolvin, G. Gu, E. Nelkin, K. Bowman, Y. Hong, E. Stocker, and D. Wolff, 2007: The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. Journal of Hydrometeorology, 8 (1), 38–55.

Janicot, S., S. Trzaska, and I. Poccard, 2001: Summer Sahel-ENSO teleconnection and decadal time scale SST variations. *Climate Dyn.*, **18**, 303-320.

Khairoutdinov, M. F., and D. A. Randall, 2003: Cloud Resolving Modeling of the ARM Summer 1997 IOP: Model Formulation, Results, Uncertainties, and Sensitivities. *J. Atmos. Sci*., **60**, 607-625.

Khairoutdinov, M., D. Randall, and C. DeMott, 2005: Simulations of the Atmospheric General Circulation using a Cloud-Resolving Model as a Superparameterization of Physical Processes. *J. Atmos. Sci.*, **62**, 2136-2154.

Khairoutdinov, M. and D. Randall, 2006: High-Resolution Simulation of Shallow-to-Deep Convection Transition over Land. *J. Atmos. Sci.*, **63**, 3421-3436.

Khairoutdinov, M., C. DeMott, and D. Randall, 2008: Evaluation of the Simulated Interannual and Subseasonal Variability in an AMIP-Style Simulation Using the CSU Multiscale Modeling Framework. *J. Climate*, **21**, 413-431.

Lavaysse, C., C. Flamant, S. Janicot, D. J. Parker, J. P. Lafore, B. Sultan and J. Pelon, 2009: Seasonal evolution of the West African heat low: a climatological perspective. *Clim. Dyn.*, **33**, 313-330.

Lebel, T., B. Cappelaere, S. Galle, N. Hanan, L. Kergoat, S. Levis, B. Vieux, L. Descroix, M. Gosset, E. Mougin, C. Peugeot, and L. Seguis, 2009: AMMA-CATCH studies in the Sahelian region of West-Africa: An overview. *J. Hydrology*, **375**, 3-13.

Li, Y., E. J. Zipser, S. K. Krueger, and M. A. Zulauf, 2008: Cloud-Resolving Modeling of Deep Convection during KWAJEX. Part 1: Comparison to TRMM Satellite and Ground-Based radar Observations. *Mon. Wea. Rev.*, **123**, 2699-2712.

Laurent, H., I. Jobard, and A. Toma, 1998: Validation of satellite and ground-based estimates of precipitation over the Sahel. *Atmospheric Research*, **47-48**, 651-670.

Lothon, M, F. Said, F. Lohou, and B. Campistron, 2008: Observation of the Diurnal Cycle in the Low Troposphere of West Africa. *Mon. Wea. Rev.*, **136**, 3477-3500.

Mathon, V., and H. Laurent, 2001: Life cycle of Sahelian mesoscale convective cloud systems: *Quart. J. Roy. Meteor. Soc.*, **127**, 377-406.

Mathon, V., H. Laurent, and T. Lebel, 2002: Mesoscale Convective System Rainfall in the Sahel. *J. App. Meteo.*, **41**, 1081-1092.

Meehl, G. A., J. M. Arblaster, D. M. Lawrence, A. Seth, and D. Min, 2006: Monsoon Regimes in the CCSM3. *J. Climate*, **19**, 2482-2495.

Mohr, K. I, 2004: Interannual, Monthly, and Regional Variability in the Wet Season Diurnal Cycle of Precipitation in Sub-Saharan Africa. *J. Climate*, **17**, 2441-2453.

Mohr, K. J. and C. D. Thorncroft, 2006: Intensive convective systems in West Africa and their relationship to the African easterly jet. *Q. J. R. Meteorol. Soc.,* **132**, 163-176.

Nesbitt, S. W. and E. J. Zipser, 2003: The Diurnal Cycle of Rainfall and Convective Intensity according to Three years of TRMM Measurements. *J. Climate*, **16**, 1456-1475.

Nicholson, S.E., B.Some, and b. Kone, 2000: An analysis of recent rainfall conditions in West Africa including the rainy seasons of 1997 El Nino and the 1998 La Nina years. *J. Climate*, **13**, 2628-2640.

Parker, D. J., C. D. Thorncroft, R. R. Burton, and A. Diongue-Niang, 2005a: Analysis of the African easterly jet, using aircraft observations from the Jet2000 experiment. *Q. J. R. Meteorol. Soc.,***131**, 1461-1482.

Parker, D. J., R. R. Burton, A. Diongue-Niang, R. J. Ellis, M. Felton, C. M. Taylor, C. D. Thorncroft, P. Bessemoulin, and A. M. Tompkins, 2005b: The diurnal cycle of the West African monsoon circulation. *Q. J. R. Meteorol. Soc.,* **131**, 2839-2860.

Persson, A., 2002: The Coriolis force and the nocturnal jet stream. *Weather*, **57**, 28-32.

Peyrille, P. and J-P. Lafore, 2007: An Idealized Two-Dimensional Framework to Study the West African Monsoon. Part II: Large-Scale Advection and the Diurnal Cycle. *J. Atmos. Sci.,* **64***,* 2783-2803.

Pritchard, M. S. and R. C. J. Somerville, 2009: Assessing the Diurnal Cycle of Precipitation in a Multi-Scale Climate Model. *J. Adv. Model. Earth Syst.*, **1** Art No 12, 16 pp.

Randall, D., M. Khairoutdinov, A. Arakawa, and W. Grabowski, 2003: Breaking the Cloud Parameterization Deadlock. *Bull. Amer. Meteor. Soc.*, 1547-1564.

Redelsperger, J-L., C. D. Thorncroft, A. Diedhiou, T. Lebel, D. J. Parker, and J. Polcher, 2006: African Monsoon Multidisciplinary Analysis. *Bull. Amer. Meteor. Soc.*, 1739-1746.

Rio, C., F. Hourdin, J.-Y. Grandpeix, J.-P. Lafore, 2009: Shifting the diurnal cycle of parameterzied deep convection over land. *Geophys Res. Lett*. **36**, doi: 10.1029/2008GL036779

Rowell, D. P., and J. R. Milford, 1993: On the generation of African squall lines. *J. Climate*, **6**, 1181-1193.

Rowell, D.P., 2001: Teleconnections between the Tropical Pacific and the Sahel. *Quart. J. Roy. Meteor. Soc.*, **127**, 1683-1706.

Sellers, P.J., Y. Mintz, Y.C. Sud, and A. Dalcher (1986), A Simple Biosphere Model (SiB) for use within General Circulation Models. *J. Atmos. Sci.*, *43*(6), 505-531.

Sellers, P.J., D.A. Randall, G.J. Collatz, J.A. Berry, C.B. Field, D.A. Dazlich, C. Zhang, G.D. Colello, and L. Bounoua (1996), A Revised Land Surface ParameterizatiAtmospheric GCM's. Part I: Model Formulation. *J. Clim.*, *9*(4), 676-705.

Smagorinski, J., 1963: General circulation experiments with the primitive equations. I: The basic experiments. *Mon. Wea. Rev.*, 91, 99-164.

Stirling, A. J. and J. C. Petch, 2004: The impacts of spatial variability on the development of convection. *Q. J. R. Meteorol. Soc.*, **130**, 3189–3206.

Sultan, B and S. Janicot, 2003: The West African Monsoon Dynamics. Part II: the "Preonset" and "Onset" of the Summer Monsoon. J. Climate, 16, 3407-3427.

Sultan, B., S. Janicot, and P. Drobinski, 2007: Characterization of the Diurnal Cycle of the West African Monsoon around the Monsoon Onset. *J. Climate*, **20**, 4014-4032.

Taylor, C. M., F. Said, and T. Lebel, 1997: Interactions between the Land Surface and Mesoscale Rainfall Variability during HAPEX-Sahel. *Mon. Wea. Rev.*, **125**, 2211-2227.

Taylor, C. M. and T. Lebel, 1998: Observational Evidence of Persistent Convective-Scale Rainfall Patterns. *Mon. Wea. Rev.*, 126, 1597-1607.

Thorncroft, C.D. and Hoskins B.J., 1994: An idealized study of African easterly waves. I: A linear view. *Q. J. R. Meteorol. Soc.*, **120**, 953-982.

Thorncroft, C. D. and M. Blackburn, 1999: Maintenance of the African easterly jet. *Q. J. R. Meteorol. Soc.,***125**, 763-786.

Wu, M. C., O. Reale, S. D. Schubert, M. J. Suarez, R. D. Koster, and P. J. Pegion, 2009: African Easterly Jet: Structure and Maintenance. *J. Climate*, **22**, 4459-4480.

Yang, G. and J. Slingo, 2001: The Diurnal Cycle in the Tropics. *Mon. Wea. Rev.*, **129**, 784-801.