Modeling the West African Monsoon

Rachel R. McCrary and David A. Randall
Center for Multi-Scale Modeling of Atmospheric Processes
Department of Atmospheric Science, Colorado State University

Introduction

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 vulnerable to variability in monsoon rains (Baron et al. 2005). Over the past 40 years, sub-Saharan Africa has 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 cloud resolving model (CRM) which allows for explicit simulation of small-scale cloud and boundary-layer processes (Randall et al. 2003).

In this research we hope to answer the following questions:

1. Does the SP-CAM simulate the seasonal cycle of the WAM?
2. Does the SP-CAM simulate the diurnal cycle of convection in the Sahel during the monsoon season?
3. How does land-surface heterogeneity influence the diurnal cycle of convection over the Sahel?

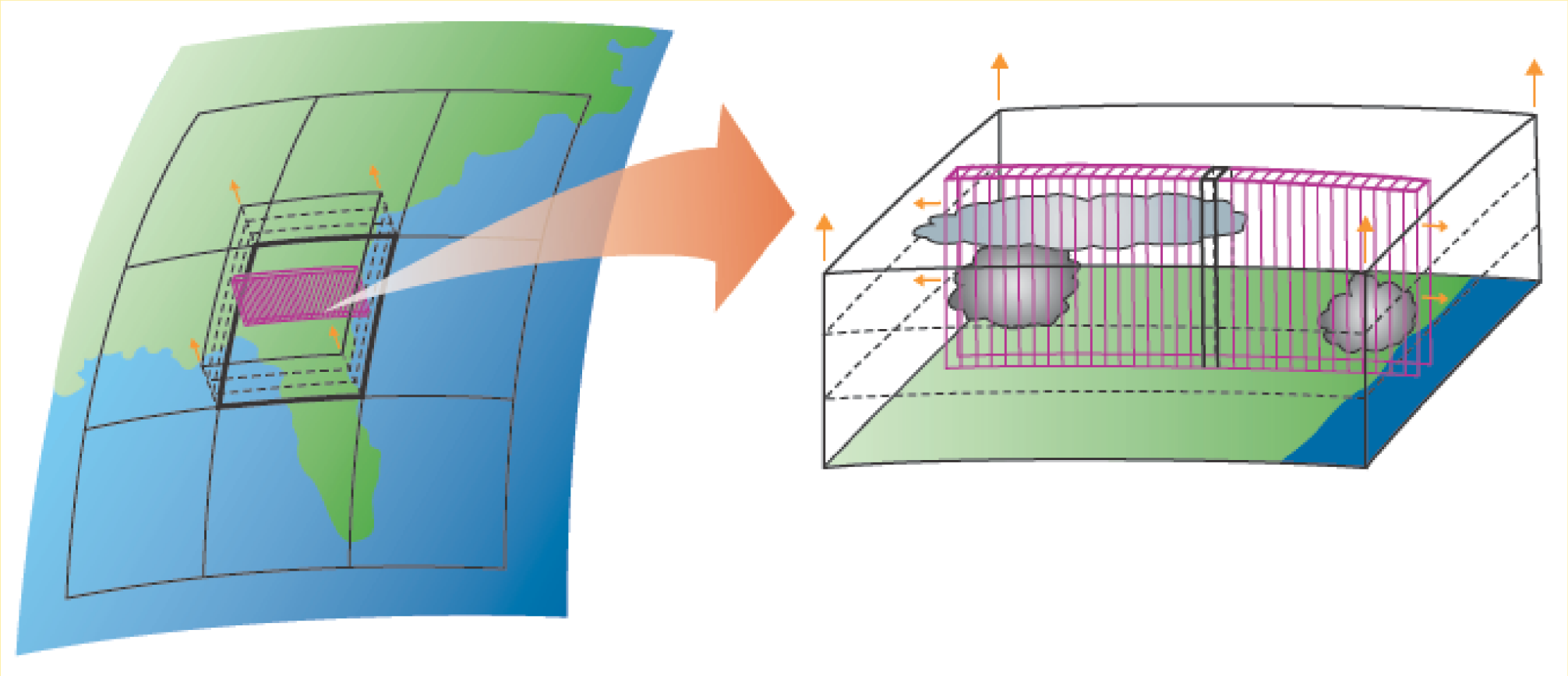

Figure 1. Schematic representing the SP-CAM. From Dave Randall CMMAP presentation.

Model Simulation (in progress)

To accomplish the first two objectives I am currently running a 28-year atmospheric model intercomparison project (AMIP: Fiorino, 2000) style run using the superparameterized community atmosphere model version 3.5 (SP-CAM 3.5; Khairoutdinov et al. 2005). During this run the SP-CAM is being forced with observed sea surface temperatures (SSTs) for the years 1981-2008. This run should be long enough for us to generate a reasonable representation of the annual cycle of convection in the SP-CAM. Also, we can investigate the atmospheric response to interannual variability in SST forcing such as ENSO.

In this version of the SP-CAM, CAM 3.5.32 serves as the host GCM. The host GCM is being run with the finite volume dynamical core with horizontal resolution of 1.9°x2.5°, 30 levels and a time step of 15 min. The large-scale atmospheric model is coupled to the community land model version 3.5.8 (CLM 3.5.8). The CRM used in the SP-CAM is a 2D version of the system for Atmospheric Modeling (SAM; Khairoutdinov and Randall 2003). version 6.7.5. The embedded CRM is made up of 32 grid columns each with 4-km horizontal resolution, 30 levels and a time step of 20s. The "curtains" of CRMs within each grid cell are periodic and position in the north-south direction.

Observational Data Sets

Source	Field	Domain/Location	Time Sampling
TRMM -3B42	precipitation	50°S-50°N and all longitudes 0.25° x 0.25° resolution	1997 - present 3-hourly, daily
ERA - Interim	u, v, geopotential height, moisture fields	Global coverage at 1.5° x 1.5° resolution and 37 levels	1989-present 4 times daily
ERA - AMMA	u, v, geopotential height, moisture fields	100°W - 47°E, 47°N-25°S with 0.5°x0.5° resolution	May - September 2006 4 times daily
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	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

Table 1. List of observation based data sets that will be used to evaluate the SP-CAM

A number of different observation based data sets will be used to evaluate the SP-CAM. To evaluate the climatology of the WAM I will use a number of gridded data sets, as described in Table 1. To evaluate the diurnal cycle I will primarily use data that has been provided by the AMMA 2006 field campaign (Redelsperger et al. 2006).

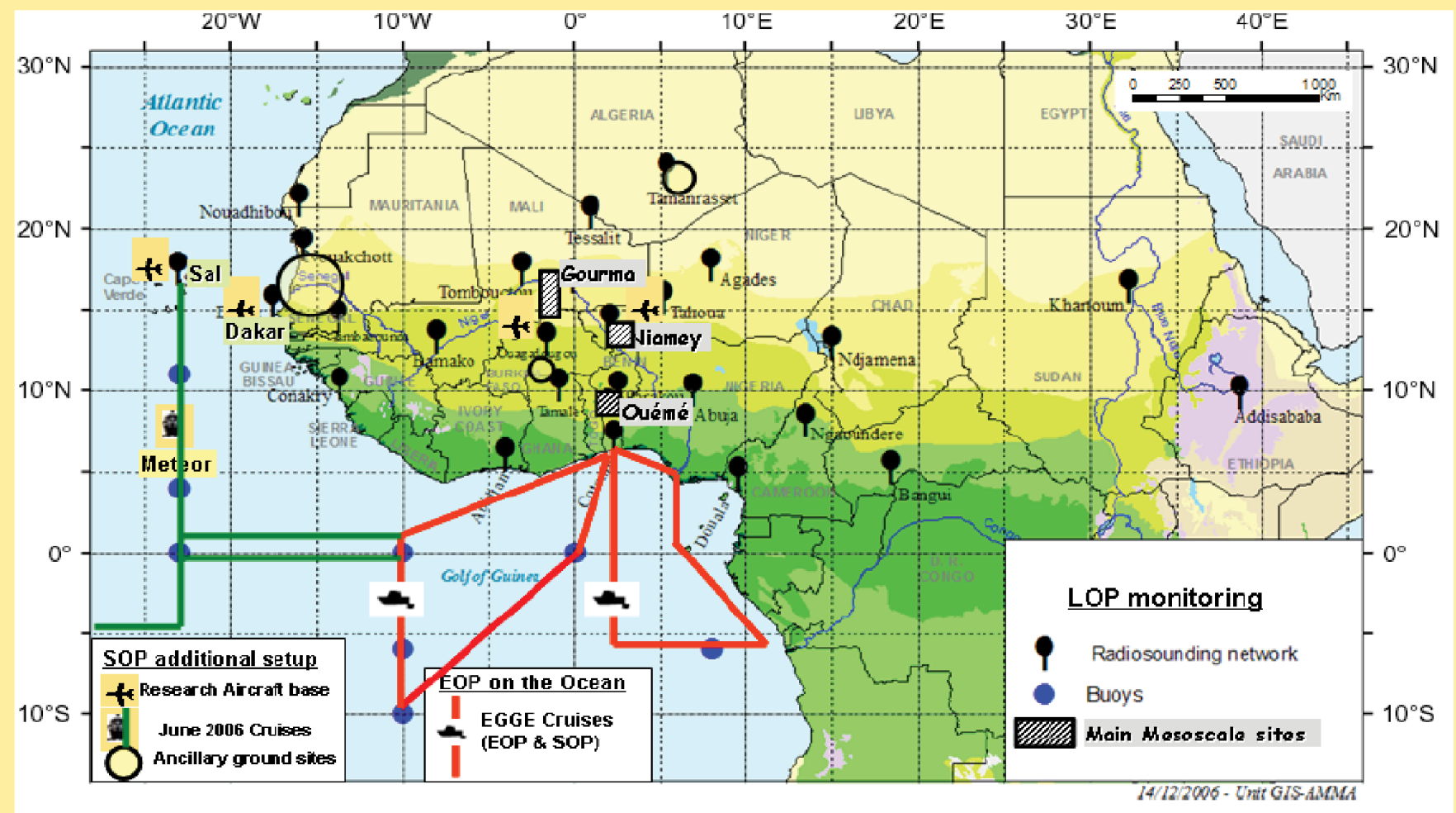

Figure 2. A selection of observation locations from AMMA. Includes some radiosonde stations, buoys over the oceans, mesoscale sites, and aircraft observation locations. From Lebel et al. 2010.

Seasonal Cycle

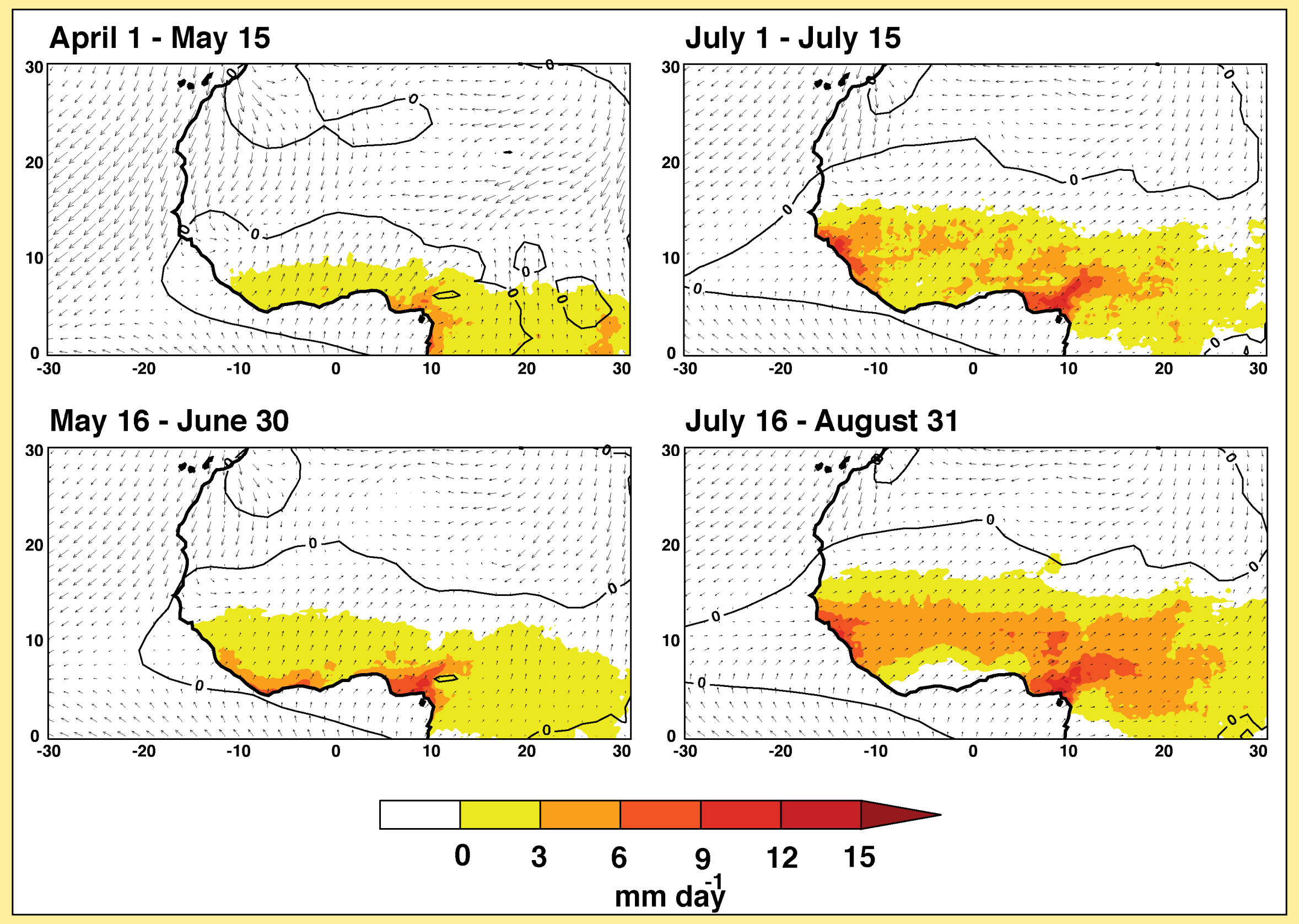

Figure 3. Mean 1998-2009 daily rainfall fields (mm day-1) average from April 1-May 15 (upper right), May 16-June 30 (lower left), July 1-July 15 (upper right) and July 16-August 31 (lower right). Rainfall values are from TRMM. ERA-Interim 925-hPa wind field is expressed in vectors with a scale of m s-1. The black line represents the domain of the monsoon winds.

From the Guinea coast to the Sahara desert, West Africa is characterized by east-west oriented climate zones (Hall and Peyrille, 2006). The goal here is to determine how well the SP-CAM represents these climatic zone. To evaluate the WAM in the SP-CAM we will look at the following features:

1. The seasonal progression of precipitation over west Africa, including the timing of the onset of monsoon precipitation (Figure 3).
2. The timing of the onset of low-level monsoon winds and their penetration on to the continent (Figure 4).
3. The position and intensity of the African Easterly Jet.
4. The seasonal cycle of the Saharan Heat Low.

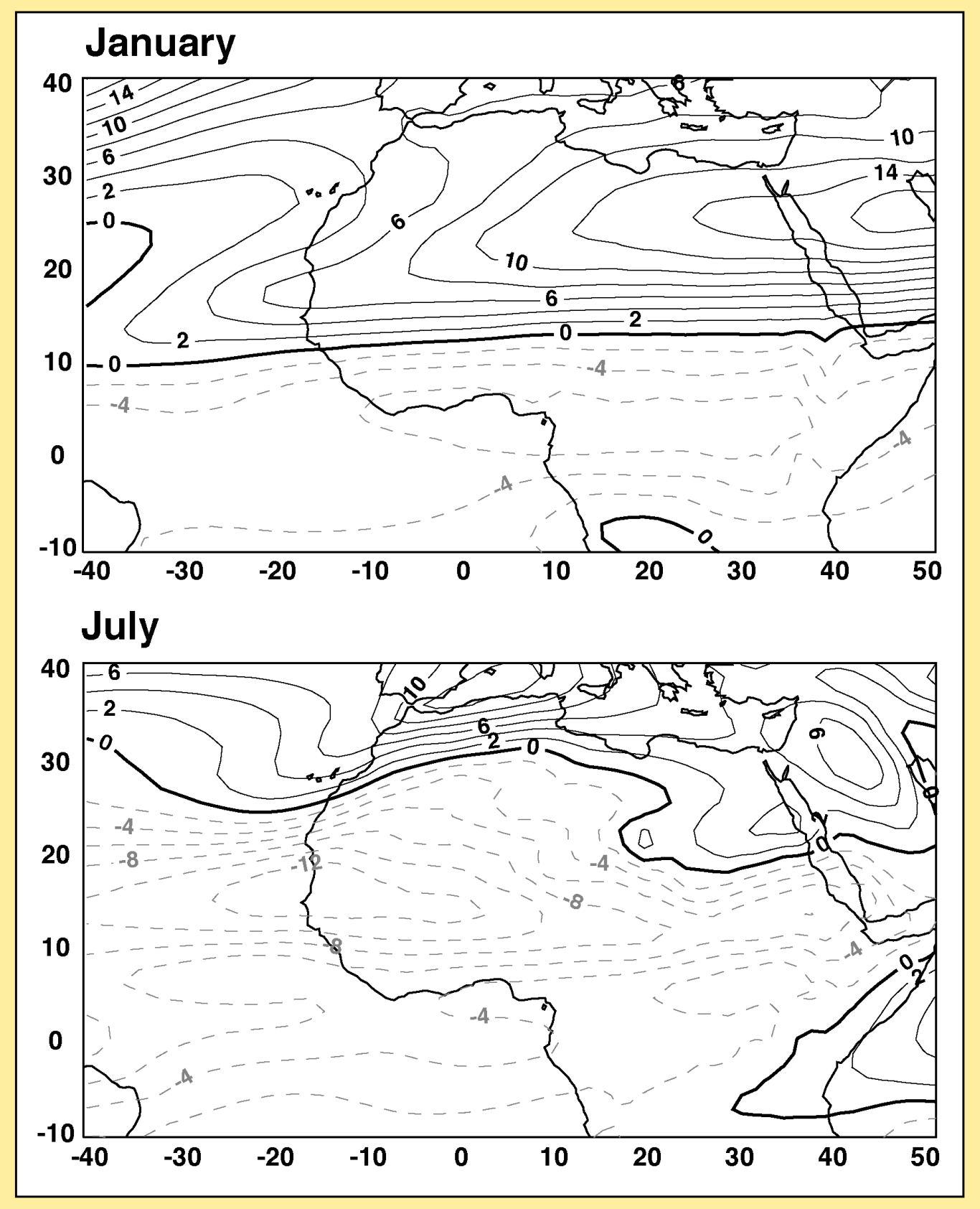

Figure 4. 600 hPa zonal wind contours from ERA-Interim from January and July. Winds are in m s-1 and contours are 2 m s-1 apart. Note the presence of the African Easterly Jet in July.

Land-Atmosphere Coupling

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 gradients ultimately influence when and where it will rain in the Sahel. Mesoscale gradients in surface fluxes typically occur due to heterogeneous vegetation cover and soil moisture content.

To investigate the relationships between a heterogeneous land surface and the overlying organization of clouds and convection, we will perform a series of idealized high-resolution limited area cloud resolving model (CRM) experiments where the CRM has been coupled to a land surface model. These simulations will cover a relatively large area (10° x 10°) with 2km resolution and 64 levels centered over the ARM super-site over Niamey, Niger (Figure 5).

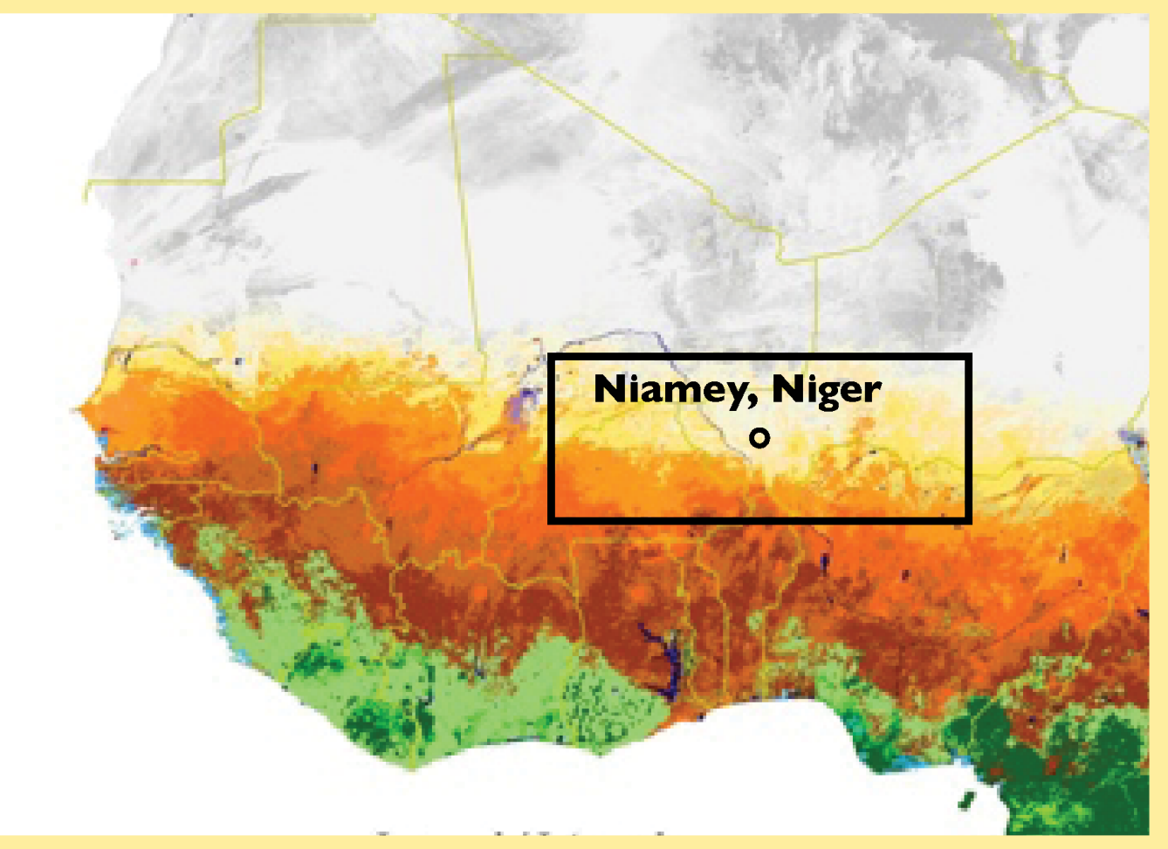

Figure 5. 10°x10° domain centered over Niamey, Niger selected for the SAM-Sib runs.

This simulation will use realistic vegetation and biome type information based on satellite data. The lateral boundary conditions will be nudged to observations and the central domain will be forced by large scale winds, temperature and moisture from the ERA-AMMA reanalysis data set (Figure 6).

The questions we hope to answer with these experiments are:

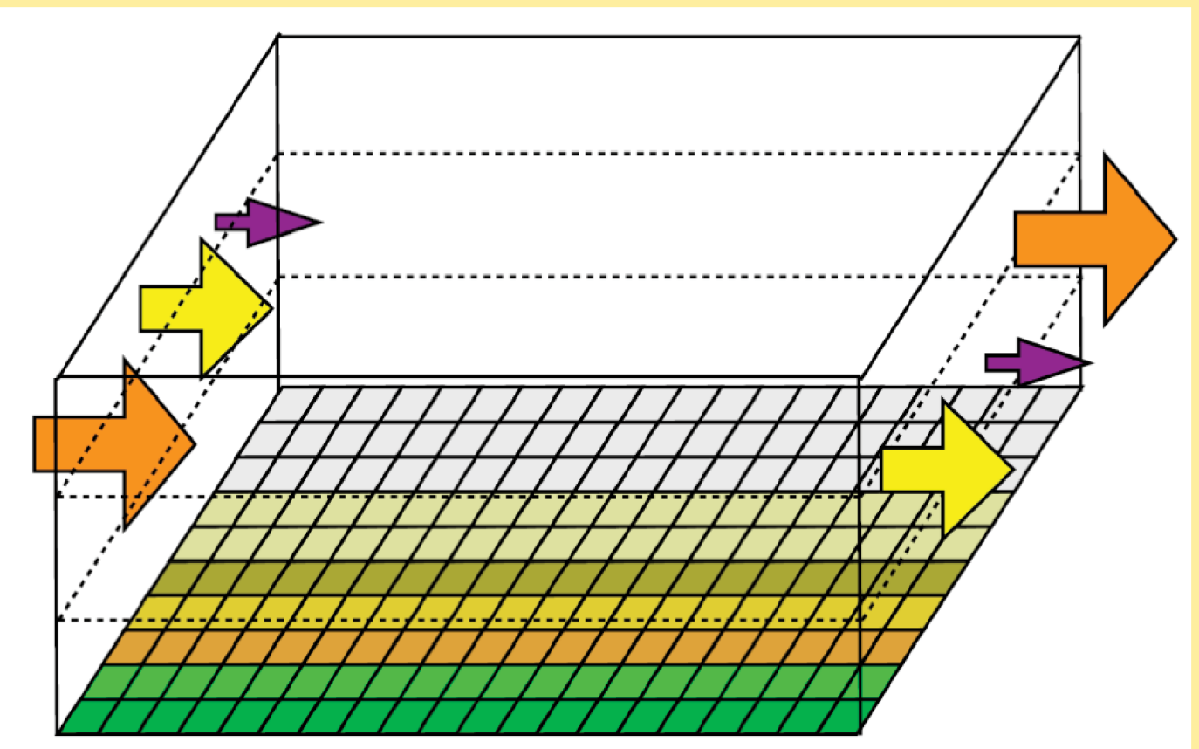

Figure 6. Schematic of domain the SAM-Sib run will cover. Land surface vegetation will be determined by satellite data.

1. How does the diurnal cycle of convection respond to mesoscale surface flux variability induced by horizontal gradients in soil moisture?
2. Does the spatial organization of surface vegetation cover influence where convection occurs over the Sahel?
3. Does antecedent rainfall influence where future rainfall will occur over the Sahel?

Diurnal Cycle

In the semi-arid regions of the Sahel, convection has been found to initiate in the evening, with peak precipitation rates occurring in the early morning (Nesbitt and Zipser, 2003). Over the Sahel, the timing of the diurnal cycle of convection has been shown to be linked to two main features: 1) the influx of moisture into the region by the formation of a nocturnal low-level jet and subsequent turbulent mixing throughout the day (Figure 7) and 2) the westward propagation of mesoscale convective systems (MCSs) throughout the region. Over the Sahel, MCSs are typically triggered by elevated daytime heating and orography (Rowell and Milford 1993). These storms then 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 (Hodges and Thorncroft, 1997).

To evaluate the diurnal cycle over the Sahel in the SP-CAM we will look at the following features:

1. What time of day does it typically rain over the Sahel in the model?
2. Why does it rain when it does over the Sahel in the model?
3. Does the SP-CAM simulate the nocturnal low level jet?
4. Can the SP-CAM simulate the propagation of organized convection over West Africa?

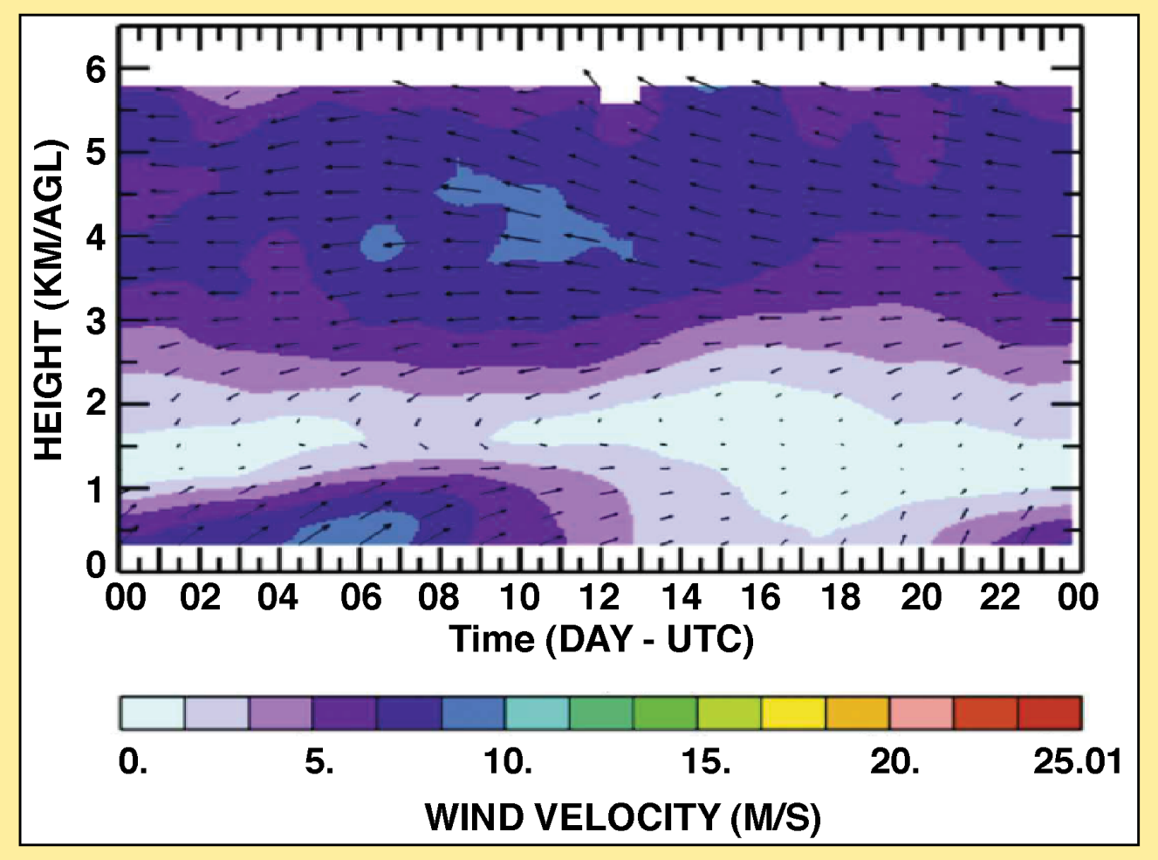

Figure 7. Composite diurnal cycle of winds from Niamey, Niger wind profiler. Notice the nocturnal low level jet in the lower km which peaks at 06Z. Units are m s-1. From Lothon et al. 2008.

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