Will the best WRF please identify itself?

Choosing the best WRF configuration for precipitation and circulation simulations over West Africa

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NASA Goddard Institute for Space Studies
Program for Environmental Studies at the University of Colorado in Boulder
Goal of Talk

• To introduce the WRF model
• To introduce WRF simulations of daily variability over West Africa
• To discuss this work as a first step towards using WRF as a Regional Climate Model (RCM)
I assess a couple aspects of model performance:

- to reproduce *daily* variability of West African Monsoon (WAM) features
- to determine an optimal set of physics for monthly to intra-seasonal time scales

- by *benchmarking* results to another RCM tuned for this region
Model - The WRF

The National Center For Atmospheric Research (NCAR) Weather Research & Forecasting (WRF) model.

developed primarily as a mesoscale forecast model and data-assimilation system for shorter-range simulations.

a community model with many versions

community - anyone can use it and change it at their will.

approximately 7,000 research users and 22 operational centers in 95 countries

U.S. National Centers for Environmental Prediction (NCEP)

U.S. Air Force.
Model - The WRF

- There are several versions of the WRF model:
  - Research Version:
    - Advanced Research version of WRF (WRF-ARW)
    - Hurricane model (HWRF)
    - Wildfire model (WRF-FIRE)
  - Operational Version used by NCEP and NOAA
    - Nonhydrostatic Mesoscale Model (WRF-NMM)
  - Regional Climate Model version? Answer: not quite black and white
    - in 2009 - a blending of WRF-ARW and the NCAR Community Climate System Model (CCSM)
  - “An ambitious, strategic goal is to combine the WRF and CCSM models into a Nested Regional Climate Model (NRCM) that will allow for fundamental progress on the understanding and prediction of regional climate variability and change.”

* Dr. Jim Hurrel - 2009 “BRIEFING TO THE WESTERN GOVERNORS’ ASSOCIATION”
Setup: West African Domain
Focus: Sahel Region

- Advanced Research version of NCAR’s Weather Research & Forecasting (WRF) model (v3.2.1)
- The picture shows the domain used in model simulations (all of West Africa, central Africa,...)
- 20x20 km² horizontal grid increment
- 30 variably-spaced sigma layers (sfc-100 hPa)
- 2 min time-step; 6-hourly diagnostics
- Initial Conditions (IC) & Lateral Boundary Conditions (LBCs) provided by NCEP-DOE Reanalysis II (NNRP2)
- 9-pt boundary zone (outermost is specified and the adjacent 8 are Newtonianlly relaxed).
- No nudging (conventional or spectral) in the domain interior

My region of interest - the Sahel - is outlined in red.
Why West Africa

- West Africa has a Monsoon climate.
- Rain only comes in the summer.
- Dry season: October – April (Not a drought)

The rainfall animation shows total monthly rainfall in mm as recorded by NASA’s Tropical Rainfall Measuring Mission (TRMM) satellite.

Movie is available at http://earthobservatory.nasa.gov/GlobalMaps/
Variability in the West African Monsoon Matters!
Variability in the WAM impacts the US!

Bonnie (05)

Charlie (05)

Frances (05)

Ivan (05)

Flooding in New Orleans due to Katrina
(courtesy NOAA)

courtesy A. Aiyyer and C. Thorncroft
AFRICAN MONSOON MULTIDISCIPLINARY ANALYSIS
An International Research Project and Field Campaign

by Jean-Luc Redelsperger, Chris D. Thornicroft, Arona Diedhiou, Thierry Lebel, Douglas J. Parker, and Jan Polcher

AMMA strives to improve our understanding of the West African Monsoon system and will facilitate the multidisciplinary analysis needed to improve prediction of its variability and its associated societal impacts.

African Monsoon Multidisciplinary Analysis (AMMA) is an international project to improve our knowledge and understanding of the West African monsoon (WAM) and its variability with an emphasis on daily-to-interannual time scales. AMMA is motivated by an interest in fundamental scientific issues and by the societal need for improved prediction of the WAM and its impacts on West African nations. Vulnerability of West African societies to climate variability is likely to increase in the next decades as demands on resources increase in association with one of the world’s most rapidly growing populations. Vulnerability may be further increased in association with the effects of climate change and other factors linked to the fast-growing population, such as land degradation and water pollution.

Recognizing the societal need to develop strategies that reduce the socioeconomic impacts of the variability of the WAM, AMMA will facilitate the multidisciplinary research required to provide improved predictions of the WAM and its impacts. The international AMMA project has three overarching aims:

1) To improve our understanding of the WAM and its influence on the physical, chemical and biological environment regionally and globally;
2) To provide the underpinning science that relates variability of the WAM to issues of health, water resources, food security and demography for West African nations and defining and implementing relevant monitoring and prediction strategies; and
3) To ensure that the multidisciplinary research carried out in AMMA is effectively integrated with prediction and decision making activity.

The Long term Observing Period (LOP) is concerned with observations of two types:

i. historical observations to study interannual-to-decadal variability of the WAM (including currently unarchived observations) and
ii. additional long term observations (2002-2010) to document and analyse the interannual variability of the WAM.

The Enhanced Observing Period (EOP) is designed to serve as a link between the LOP and the SOP (below). Its main objective is to document over a climatic transect the annual cycle of the surface conditions and atmosphere and to study the surface memory effects at the seasonal scale. The EOP will be 2-3 year duration (2005-2007).

The Special Observing Period (SOP) will focus on detailed observations of specific processes and weather systems at various key stages of the rainy season during three periods in the summer of 2006:

i. the Dry season (Jan-Feb),
ii. Monsoon onset (15 May-30 June),
iii. Peak monsoon (1 July - 14 August) and
iv. Late monsoon (15 August-15 September).

My period of study.
This work is relevant to NASA, too!

US contributions to AMMA field program in 06

- SALEX: NOAA P3 and G-IV
  Targeted Missions and Dropsonde flights with G-IV

- NASA-AMMA
  Targeted Missions with DC-8, + Ground-based obs.
  (N-Pol + TOGA radars, soundings)

- ARM mobile facility (DOE)
- MIT-radar (NASA)
- Surface obs. – malaria studies (NOAA)

- ZEUS lightning detection network

- Drifsonde/THORPEX
  (NCAR/NSF/NOAA + CNES, France)

- Ronald H. Brown Cruises + ship-based obs
  (NOAA), supported by multi-year sustained obs (see next slide)

- US-GCOS: Hydrogen generator at Dakar

Wednesday, February 8, 12
Observational Data Sets

Satellite Rainfall Estimation Products

<table>
<thead>
<tr>
<th>Product</th>
<th>Spatial resolution</th>
<th>Temporal resolution</th>
<th>Data Acquired from:</th>
<th>Available since:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical rainfall Measuring Mission (TRMM) 3B42</td>
<td>0.25°x0.25°</td>
<td>3h</td>
<td>NASA Goddard Space Flight Center</td>
<td>1997</td>
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<tr>
<td>CMORPH (CPC MORPHing technique)</td>
<td>0.25°x0.25°</td>
<td>3h</td>
<td>NOAA Climate Prediction Center</td>
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<tr>
<td>PERSIANN</td>
<td>0.25°x0.25°</td>
<td>6h</td>
<td>University of California Irvine</td>
<td>2000</td>
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</table>

*Not used, but nice to compare with...*
## Observational Data Sets

**Circulation: meridional wind, Relative Vorticity**

<table>
<thead>
<tr>
<th>Product</th>
<th>Spatial resolution</th>
<th>Temporal resolution</th>
<th>Data Acquired from</th>
<th>Available since</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCEP/DOE Reanalysis II (NNRP2)</td>
<td>2.5°</td>
<td>6h</td>
<td>NCEP</td>
<td>1996</td>
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<tr>
<td>Modern Era Retrospective-analysis for Research and Applications (MERRA)</td>
<td>2/3° lon. x 0.5° lat</td>
<td>3h</td>
<td>NASA Goddard</td>
<td>2007</td>
</tr>
</tbody>
</table>
The impact of vertical resolution on regional model simulation of the west African summer monsoon

Leonard M. Druyan,a,b* Matthew Fulakezaa,b and Patrick Lonergana,b

a Center for Climate Systems Research, Earth Institute at Columbia University, 2880 Broadway, New York NY 10025 USA
b The NASA/Goddard Institute for Space Studies, 2880 Broadway, New York NY 10025 USA

ABSTRACT: The RM3 regional climate model is used to simulate the west African summer monsoon for six June–September seasons using NCEP reanalysis data for lateral boundary forcing. The study compares the performance of the previously published 16-level version with a newly tested 28-level version, both running on a horizontal grid with 0.5° spacing, in order to determine what improvements in simulations are achieved by increased vertical resolution. Comparisons between the performances include diagnostics of seasonal mean precipitation rates and circulation, vertical profiles of cumulus heating rates, frequencies of shallow and deep convection and diagnostics related to transient African easterly waves (AEWs). The characteristics of a composite AEW simulated at both vertical resolutions are presented. Results show that the most significant impact of increasing the vertical resolution is stronger circulation, stronger vertical wind shear and higher amplitude AEWs. The simulations with higher vertical resolution also achieve higher peaks of cumulus latent heating rates. Spatial–temporal correlations between simulated daily 700 mb meridional winds versus estimates from the Tropical Rainfall Measuring Mission (TRMM) archive were equally high at both vertical resolutions. Copyright © 2007 Royal Meteorological Society

KEY WORDS west African monsoon; regional climate model; African easterly waves

Received 25 January 2007; Revised 4 September 2007; Accepted 8 September 2007

1. Introduction

This article analyses aspects of the simulated June–September west African monsoon (WAM) climate, with particular attention to the characteristics of African easterly wave disturbances (AEWs). Simulations are made with a regional/limited area model (LAM) on a 0.5° latitude by longitude grid, integrated at two vertical resolutions, at 16 and 28 vertical levels, respectively. The regional model is referred to as RM3 since it has undergone two major improvements (Druyan et al., 2004; Druyan and Fulakeza, 2005) since its first application to WAM studies (Druyan et al., 2000, 2001). The impact of the increased vertical resolution is evaluated by comparing simulations to each other and to empirical evidence in order to better appreciate the relevance of results to the real world. Druyan et al. (2006) previously used lateral boundary conditions from NCEP and land surface (LS) characteristics. Accordingly, downscaled representations of the climate can be quite different from the driving analysis. Druyan et al. (2006) showed that NCPR-driven RM3 simulations produce time-space distributions of WAM precipitation that are highly correlated with Tropical Rainfall Measuring Mission (TRMM) daily estimates in continuous 4-month summer simulations with no perceptible deterioration trend. However, RM3 daily precipitation rates generally had a smaller range than corresponding TRMM data. The simulations achieved too few very high and very low rates.

The summer WAM climate features a northward meridional temperature gradient over west Africa that creates a westward-directed vertical wind shear (thermal wind). Accordingly, near-surface monsoon southwestlies reverse direction with altitude, ultimately creating the mid-tropospheric African easterly jet (AEJ). The AEJ

Figure 1. Cross-sections of zonal winds (m s^{-1}) along 0° longitude, for June–September 1998–2003. (a) RM3-28L, (b) RM3-16L and (c) NCPR (courtesy NOAA/CDC).
Statistical Evaluation

- All precipitation results presented are for daily-accumulation from each model experiment
- All circulation results presented are for 00Z from each model experiment
- I calculate domain-wide statistics for Sahel region only between WRF and observations
- Statistics: Correlation, Standard Deviation, RMSE, Bias
- Variables: precipitation, meridional wind, and relative vorticity
WAM components

- Saharan Air
- Saharan Heat Low
- Harmattan
- African Easterly Jet
- Tropical Easterly Jet
- ITCZ (Inter-Tropical Convergence Zone)
- Oceanic Cold Tongue
- Monsoon Rain-band over land
- African Easterly Jet & African Easterly Waves
- Cyclones
- Convective Systems

MERRA, September 2006

Zonal Wind vs. Height (km)

- Zonal Wind
- 0° Longitude

- Tropical Easterly Jet
- African Easterly Jet
- AEWs (African Easterly Waves)

- Colors indicate wind speed and direction.

Wednesday, February 8, 12
African Easterly Waves over West Africa
Streamlines, MERRA @700 mb, Sept. 02 to Sept. 07, 2006

Direction of Time

Wednesday, February 8, 12
African Easterly Waves over West Africa

Streamlines, 700 mb, MERRA, Sept. 08 to Sept. 13, 2006

AEW2

AEW3

AEW3

AEW4
Closed low moving off the coast is very noticeable at 925 mb.
Hurricane Helene was the 8th named storm of 2006 Atlantic hurricane season.

Category 3 Hurricane - September 17, 2006

Tropical Depression - September 12th 2006, south of the Cape Verde Islands

Time Lapse

NASA image - Earth Observatory, using data provided courtesy of the MODIS Rapid Response team.
95% of the precipitation events are due to convective systems, isolated or organized in AEWs.

Average size of AEWs: 700 km x 300 km
Associated mean rain: 25 mm
Mean traveling speed: 15 m/s
Lifetime: few hours to a few days

There is an easier way to examine the waves.

Use Hovmoller Plots!

Hovmoller Plots are useful for showing wave movement.

All values are averaged between 5°N and 15°N
**Hovmoller Plots** are useful for showing wave movement.

All values are averaged between 5°N and 15°N.

95% of the precipitation events are due to convective systems, isolated or organized in AEWs.

- Average size: 700 km × 300 km
- Associated mean rain: 25 mm
- Mean traveling speed: 15 m/s
- Lifetime: few hours to a few days

\[ \zeta = \frac{\partial v_r}{\partial x} - \frac{\partial u_r}{\partial y} \]
Hovmoller Plots of Meridional Wind at 700 mb

MERRA

Units: m/s

NNRP2

Units: m/s

Wednesday, February 8, 12
Hovmoller Plots of Vorticity at 700 mb

\[ \zeta = \frac{\delta v}{\delta x} \text{ (700 mb)} \]

MERA Units: 1/s (scaled)

\[ \zeta = \frac{\delta v}{\delta x} \text{ (700 mb)} \]

NCPR2 Units: 1/s (scaled)

Elapsed Time: SEP 2 to 14, 2006 (00Z)

Longitude

Contour from -10 to 10 by 2
African Easterly Waves over West Africa

Water vapor imagery from Meteosat-7
10 Sept 2006

At any given moment, convection occurs in waves

TRMM Daily Accumulated Precipitation
September 2 to 13, 2006

Orographic forcing
Hovmoller Plots of Daily Accumulated Rain

Statistical scores of the Hovmoller plots
( daily accumulated rain for all 12 days )

<table>
<thead>
<tr>
<th>Model vs. TRMM</th>
<th>R</th>
<th>STD</th>
<th>RMSE</th>
<th>Bias</th>
<th>MAE</th>
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</thead>
<tbody>
<tr>
<td>RM3</td>
<td>0.68</td>
<td>5.23</td>
<td>5.73</td>
<td>2.35</td>
<td>4.76</td>
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<tr>
<td>WRF (Default)</td>
<td>0.05</td>
<td>12.34</td>
<td>16.21</td>
<td>8.34</td>
<td>12.42</td>
</tr>
</tbody>
</table>

What's up with WRF?
Hovmoller Plots of Meridional Wind at 700 mb

Statistical scores of the Hovmoller plots
(700 mb meridional wind for all 12 days)

<table>
<thead>
<tr>
<th>Model vs. MERRA</th>
<th>R</th>
<th>STD</th>
<th>RMSE</th>
<th>Bias</th>
<th>MAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM3</td>
<td>0.79</td>
<td>2.11</td>
<td>2.16</td>
<td>0.09</td>
<td>1.68</td>
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<tr>
<td>WRF (Default)</td>
<td>0.38</td>
<td>4.61</td>
<td>4.61</td>
<td>-0.4</td>
<td>3.53</td>
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</table>
Hovmoller Plots of Meridional Wind at 700 mb

Statistical scores of the Hovmoller plots
(700 mb vorticity for all 12 days)

<table>
<thead>
<tr>
<th>Model vs. MERRA</th>
<th>R</th>
<th>STD</th>
<th>RMSE</th>
<th>Bias</th>
<th>MAE</th>
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</thead>
<tbody>
<tr>
<td>RM3</td>
<td>0.69</td>
<td>4.01</td>
<td>5.82</td>
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<td>4.56</td>
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<td>0.37</td>
<td>13.31</td>
<td>13.13</td>
<td>0.37</td>
<td>9.99</td>
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</table>

What's up with WRF?

Wednesday, February 8, 12
# Alternate configurations in WRF

<table>
<thead>
<tr>
<th>PARAMETERIZATION</th>
<th>SHORT NAME</th>
<th>OPTION</th>
<th>ABBREVIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulus Convection Scheme</td>
<td>CPS</td>
<td>1. Kain-Fritsch cumulus scheme</td>
<td>KF</td>
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<tr>
<td></td>
<td></td>
<td>2. Grell--Devenyi cumulus ensemble scheme</td>
<td>GD</td>
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<tr>
<td>Planetary Boundary Layer</td>
<td>PBL</td>
<td>1. Yonsei University PBL–Eta Similarity Theory</td>
<td>YU</td>
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<tr>
<td></td>
<td></td>
<td>3. Pleim-Based Asymmetrical Convective Model (v.2) PBL</td>
<td>A2</td>
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<tr>
<td></td>
<td></td>
<td>4. Mellor-Yamada-Nakanishi-Nino PBL</td>
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<td>Land Surface Model</td>
<td>LSM</td>
<td>1. 5-Layer Thermal Diffusion Model</td>
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<td></td>
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<td>2. Unified Noah Model</td>
<td>NO</td>
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<tr>
<td></td>
<td></td>
<td>3. Rapid Update Cycle (RUC) Model</td>
<td>RU</td>
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<tr>
<td></td>
<td></td>
<td>4. Pleim-Xiu Model</td>
<td>PX</td>
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<tr>
<td>Long-Wave Radiation Scheme</td>
<td>LWS</td>
<td>1. Rapid Radiation Transfer Scheme for climate models (RRTMG)</td>
<td>Rt</td>
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<tr>
<td></td>
<td></td>
<td>2. Community Atmospheric Model Radiation Transfer Scheme (CAM)</td>
<td>CM</td>
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<tr>
<td>Short-Wave Radiation Scheme</td>
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<td>1. Rapid Radiation Transfer Scheme for climate models (RRTMG)</td>
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<td>2. Community Atmospheric Model Radiation Transfer Scheme (CAM)</td>
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<tr>
<td>Microphysics</td>
<td>MPS</td>
<td>1. WRF-Single-Moment Class 5 scheme (WSM5)</td>
<td>W5</td>
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</tbody>
</table>
Alternative Configurations

- 64 Experiments
- Changing the CPS, PBL, LSM & radiation parameterizations one at a time
- Options in Light Blue color were kept constant in all experiments

<table>
<thead>
<tr>
<th>Experiment 1</th>
<th>CPS</th>
<th>PBL</th>
<th>LSM</th>
<th>LWS</th>
<th>SWS</th>
<th>MPS</th>
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<td>Rt</td>
<td>Rt</td>
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<td>Experiment 3</td>
<td>KF YU</td>
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<td>Rt</td>
<td>W5</td>
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<td>KF YU</td>
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<td>Rt</td>
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<td>Rt</td>
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<td>Experiment 9</td>
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<td>Rt</td>
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<td>Rt</td>
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<td>Experiment 13</td>
<td>KF MN</td>
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Wednesday, February 8, 12
Taylor Plot of WRF Hovmollers vs. TRMM
Daily Accumulated Precipitation

This Taylor Plot shows the statistical scores of the Hovmoller plots of daily accumulated rain for all 12 days.

Taylor Plots allow you to show 3 complementary statistics on one plot.

TRMM is the reference field.

(for reference, see Taylor, 2001)
Taylor Plot of WRF Hovmollers vs. TRMM
Daily Accumulated Precipitation

WRF vs. TRMM

WRF vs. CMORPH

Wednesday, February 8, 12
Comparison of Hovmoller scores:
Scores of “first” 24 hours plotted with the “last” 24 hours

The tail of the arrow marks the first set of scores and the head marks the last set of scores.

Wednesday, February 8, 12
Comparison of hovmoller scores:
Scores of “first” days plotted with the “last” 6 days

*Explores the idea of a Spin-up
### Best scores for precipitation

Scores from Hovmoller plots for 12-day period

<table>
<thead>
<tr>
<th>WRF RUN</th>
<th>CPS</th>
<th>PBL</th>
<th>LSM</th>
<th>LWS</th>
<th>SWS</th>
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Scores from Hovmoller plots for 6-day adjustment period

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*There is an improvement in the 2nd set of scores.*
Adjustment period for vorticity?
- doesn’t help...

Scores of vorticity Hovmoller plots of vorticity for day 1 to 6.
Scores of vorticity Hovmoller plots of vorticity for day 7 to 12.
Vorticity winners

Only considering scores from hovmoller plots for 12-day period

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</table>

- Note that top 2 experiments share same physics, except for radiation
- Note that this is the same top set of experiments from the precipitation analysis.
What does this say about WRF

- Over the Sahel region, in this context:
  - the WRF model has difficulty with simulating precipitation.
  - Precipitation simulations can, perhaps, be improved with an adjustment
  - WRF simulates the circulation well in the beginning, but deteriorates with time, which is expected of a forecast model
  - One might expect that if the model lets circulation variables deteriorate, it will not get rainfall in the right place, it miss it altogether.
Streamline comparison: (Top) MERRA V700 (Bottom) WRF #59

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AEW3

AEW4

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Wednesday, February 8, 12
Next Steps

- This paper
  - examine phase shift of modeled waves
  - examine relative sensitivity between parameterizations
  - validate few more variables (T2m, RH, ...)
- Run WRF NMM
- Take top 6 Experiments and start...
  - 6 days earlier - look for adjustment period
  - 15 days earlier - One Month - AMMA Period
- Next Work
  - Seasonal simulations
Oh my, we have AMMA in situ data, ... finally!

- Station data
- Sodar
- Precipitation
- Dropsondes
Compare models with

**Time Series Example**

RM3 vs. Rain Gauges vs. TRMM

Fig. 12 Time series of the mean of 34 daily rain gauge observations (blue) within the area bounded by 13–13.9°N, 1.7–3.1°E (Thornicroft et al. 2003) versus RM3 daily values (red) for 15 co-located grid elements and TRMM daily estimates (green) for four co-located 1° squares, July–September 2000
Finished.
Questions please.