Ocean-Atmosphere-Land Interactions over West Africa and the Eastern Atlantic

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(1) Components of the Coupled System

- Responses to SSTAs (the forced atmosphere/land surface problem)

- Interactions between the WAM and Atlantic SSTs (coupled atmosphere/ocean)

- Land surface feedback and continental precipitation distributions (coupled atmosphere/land surface/vegetation)

(2) The Fully-Coupled System
(1) Components of the Coupled System

- It’s a Fan!
- It’s a Wall!
- It’s a Spear!
- It’s a Rope!
- It’s a Snake!
- It’s a Tree!
Circulations associated with the proximity of land can influence the atmosphere’s response to SST anomalies:

An old result, presented schematically:


Warm SSTA in Gulf of Guinea

Pcp increase over warm SSTA

warm SSTA
Warm SSTA in Gulf of Guinea

Pcp increase over warm SSTA
Warm SSTA in Gulf of Guinea

Pcp increase over Guinean coast
Warm SSTA in Gulf of Guinea

Pcp increase over Guinean coast

Subsidence over Gulf of Guinea associated with Walker circulation and Congo basin rainfall
Warm SSTA in Gulf of Guinea

Pcp increase over Guinean coast

Drying in the Sahel is a secondary response due to shrinking of absolute vorticity when the southward flow from the Saharan high is extended.
This is a prominent mode of interannual variability that may be relevant to future climate

Reverses with the sign of the SSTA in the Gulf of Guinea

To get this right in a climate model, even with prescribed SSTs, need to correctly simulate the Walker circulation, e.g., Congo basin rainfall location and structure of the Saharan high/thermal low system (soil moisture, African easterly jet, monsoon inflow, etc)

The circulation that is set up because of the proximity of land (the Walker circulation) influences the response to the Gulf of Guinea SSTA.
Remote forcing introduces complications

Dai 2010
Is the primary forcing from the Indian Ocean or the Atlantic on Decadal Time Scales?

Dai 2010
Why were the 1980’s drier than the 1990’s in the Sahel? (physical processes)
Idealized simulations with a regional climate model

1980’s precipitation anomaly

1990’s precipitation anomaly

CRU; mm/day

Idealized simulations with a regional climate model

1990’s minus 1980’s precipitation anomalies

Observed

Modeled: Full SST Forcing
Apply Indian Ocean and Atlantic SST Forcing Individually
Forcing from the Atlantic Ocean
Vertically-integrated irrotational moisture flux

(a) \((qV)_{irr}\) ATL80 - CTL

(c) SST ATL80 - CTL

(b) (qV)_{irr} ATL90 - CTL

(c) SST ATL90 - CTL
Forcing from the Indian Ocean
Vertically-integrated irrotational moisture flux
In transitioning from the dry 1980’s to the relatively wet (normal) 1990’s in the Sahel:

- Forcing from the Indian Ocean and the tropical Atlantic are both important.

- Warming in the Indian Ocean in the 1980’s places subsidence over the Sahel. When the warming intensifies and the horizontal scale increases in the Northern Hemisphere in the 1990’s, the region of subsidence (divergence) moves over the equatorial Atlantic replaced by convergence across the Sahel.

- Forcing from the Atlantic helps: The “meridional dipole” SSTAs of the 1980’s place weak subsidence over the western Sahel. SSTAs of the 1990’s (tripole?) enhances the onshore monsoon flow and moisture convergence in the central Sahel.

- The response to SST forcing is very sensitive to the background distribution of atmospheric moisture (this is the primary nonlinearity identified in the study).
Forcing from the Indian Ocean
Vertically-integrated irrotational moisture flux

(a) $\left(qV\right)_{irr} \text{ IND80 - CTL}$

(b) $\left(qV\right)_{irr} \text{ IND90 - CTL}$
West African Westerly Jet

925 hPa winds and geopotential heights from the ERA 40 reanalysis climatology for 22 July – 5 September

- zonal wind speeds > 4 m/s
- zonal wind speeds > 4 m/s

Embedded in the Atlantic marine ITCZ

Forms when the westward extension of the thermal low and the ITCZ superimpose.

Seasonality, structure and dynamics distinct from the westerly monsoon flow

Associated with (causes) regional-scale warm SSTAs off the west coast

Correlation between the WAWJ strength and Sahel rainfall = 0.691
Correlation between the WAM strength and Sahel rainfall = 0.461


Decadal Time Scales

CRU Sahel rainfall  WAWJ index  WAM index
Anomalous Vertically-Integrated Moisture Transport
African Humid Period (August)

So does variation of the West African westerly jet represent a mechanism by which Atlantic SSTs influence Sahel rainfall?
So does variation of the West African westerly jet represent a mechanism by which Atlantic SSTs influence Sahel rainfall?

No …. the West African westerly jet is insensitive to Atlantic SSTs.

The jet variation is a response to precipitation variations that are forced remotely*. The WAWJ is just the way moisture can be brought into the Sahel - it can’t come across the Guinean coast and reach the western Sahel (conservation of absolute angular momentum).

But the WAWJ is part of the fully coupled system that connects West Africa and the eastern tropical Atlantic.

(A red herring)

* e.g., from the Indian Ocean on decadal time scales (Hagos and Cook 2008)
Land surface/atmosphere feedbacks may be important determinants of the large-scale climate over Africa

One example …
Regional Coupled Atmospheric/Vegetation Model

Asynchronous coupling of the RCM with a potential vegetation model

Initial conditions: desert border at 10.0°N
Asynchronous coupling of the RCM with a potential vegetation model

Initial conditions: desert border at 10.0°N

1st iteration
Asynchronous coupling of the RCM with a potential vegetation model

Initial conditions: desert border at 10.0°N
Asynchronous coupling of the RCM with a potential vegetation model

Initial conditions: desert border at 10.0°N
Asynchronous coupling of the RCM with a potential vegetation model

Initial conditions: desert border at 10.0°N

Similar to today’s climate.
Asynchronous coupling of the RCM with a potential vegetation model
Initial conditions: desert border at 20.9°N
Asynchronous coupling of the RCM with a potential vegetation model

Initial conditions: desert border at 20.9°N
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Asynchronous coupling of the RCM with a potential vegetation model

Initial conditions: desert border at 20.9°N

Green Sahara solution
Sahara

Gulf of Guinea

Guinean coast

Sahel

Sahara

African easterly jet

West African Westerly jet

monsoon inflow

Saharan high

5N

15N

25N
Sahara
Gulf of Guinea
Guinean coast
Sahel
Sahara

West African Westerly jet
monsoon inflow

THRESHOLD LATITUDE ~18N
This example reminds us that an accurate simulation of a region’s basic climate dynamics is needed to evaluate and understand the processes of variability and change, including the coupling processes.
The Coupled System

- Observations of the West African monsoon onset: clearly couples land surface, atmosphere and ocean processes

- Our attempts at regional coupled modeling
Daily Rainfall Climatology (1998-2009) from TRMM averaged 12W - 6E; Contour interval is 1 mm/day

10-day smoothing
Daily Rainfall Climatology (1998-2009) from TRMM
9-day smoothing

30W to 20W

5E to 5W

15E to 25E
There is no discontinuity (jump) over the ocean or over the central Sahel.
Daily Rainfall Climatology (1998-2009) from TRMM
9-day smoothing

black contour:
Atlantic marine
ITCZ
12 mm/day
Rainfall lingers along the Guinean coast in the spring.
Surface temperature from ERA Interim with TRMM precip (1998-2010)

West Africa (5W to 5E)

Tropical Atlantic (25W to 15W)
Our efforts at regional coupled modeling

Why take a regional approach?
- Higher resolution for an improved (?) simulation
- Optimize the model (e.g., parameterizations) for an improved simulation
- Focus on processes important to a particular region
- Focus on coupling processes via thermodynamic and dynamic interactions between the atmosphere and ocean mixed layer

E.g.,
- If we have a more accurate, higher-resolution simulation of the surface Winds can we improve the simulation of tropical Atlantic SSTs and currents?
- How does the ocean help control monsoon onset, and what happens in the ocean when the West African monsoon begins?
Model Description

**Atmosphere:** MM5 (Hagos and Cook 2009) and now WRF

**Land:** Noah, RUC, CLM

**Ocean:** Ocean mixed layer with Ekman dynamics, but no large-scale density-driven (thermohaline) circulation

Interactive heat balance (Navarra 1999; Sterl and Hazeleger 2003)

\[ \rho C_p h \frac{\partial T}{\partial t} = -\rho C_p h v_e \cdot \nabla T - \rho C_p w_e (T - T_*) + Q_{rad} - Q_{lat} - Q_{sen} + \kappa \rho C_p h \frac{\partial^2 T}{\partial z^2} \]

Ekman dynamics (Zebiak and Cane 1987)

\[ ru_e - f y = \frac{\tau_x}{\rho h} \quad rv_e + f y = \frac{\tau_y}{\rho h} \quad w_e = \Gamma \left[ \frac{\partial h}{\partial t} + \nabla \cdot (h v_e) \right] \]

Simulated SSTs in the Tropical Atlantic

Simulated SSTs (contours) and bias (shading)
JAS Surface Winds (m/s) and Precipitation (mm/day)

NCEP reanalysis and TRMM

Coupled Regional Model
Seasonality of SSTs in the Tropical Atlantic
The coupled regional model captures the seasonality of SSTs in the eastern Atlantic, but fails to capture sufficient cooling in the Gulf of Guinea in summer and fall (similar to a common problem in CGCMs.)
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Eastern Tropical Atlantic SSTs

Solar cycle
  min SST Mar/Apr
  maximum Sept/Oct

Suppression of evaporation in early summer amplifies the warming SSTs
  ~ Evaporation is suppressed when meridional winds decrease in association with the northward migration of the ITCZ

As a result, the NASH weakens over the eastern Atlantic, favoring the westward expansion of the thermal low, the formation of the WAWJ, and the import of moisture into the Sahel
What’s the problem over the Gulf of Guinea?

One concern: Surface wind stress is underestimated. ~ primarily meridional component
Right processes occur, just not strong enough because the surface wind stress is too weak. Higher resolution??
Current coupled model development:

Coupled to WRF instead of MM5
    Improvement of surface winds and wind stress – but maybe still not
good enough in the northeastern Gulf of Guinea

Tried runs at 30 km resolution instead of 90 km but that didn’t lead to an
improvement in the simulation of the wind stress

Adding a parameterization to account for stress at the base of the mixed
layer within 3 degrees of equator due to the equatorial undercurrent (EUC)
    = improvement in cold tongue formation

… thinking about adding the physics of the EUC to the model
Thank you