Radiative Impacts and Feedback of North African Desert Dust on Sahel Rainfall in GCM Simulations

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From Deserts to Monsoons, Crete, Greece
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A massive sandstorm blowing off the northwest African desert has blanket hundreds of thousands of square miles of eastern Atlantic Ocean with a dense cloud of Saharan dust. The massive nature of this particular storm was first seen in this SeaWiFS image acquired on Saturday, 26 February 2005 when it reached over 1000 miles into the Atlantic. These storms and the rising warm air can lift 15,000 feet or so above the African deserts and out across the Atlantic, many times reaching as far as the Caribbean where they often require the local services to issue air pollution alerts as was recently the case in San Juan, Puerto Rico. Recent studies by U.N. (http://www.un.org/en/esa/landdegradation/desertification/saharadust.html) have linked the decline of the coral reefs in the Caribbean to the increasing frequency and intensity of Saharan dust events. Additionally, other studies suggest that Saharan Dust may play a role in determining the frequency and intensity of hurricanes formed in the eastern Atlantic Ocean.
North Africa

- Largest source of desert dust in the world
- Source regions:
  - The **Sahara** Desert (20-35N)
  - The **Sahel** region (10-20N): the semi-arid transitional zone
The Sahel Climate

- Most of the annual rainfall is associated with the West African Monsoon (WAM)
- The region experienced severe droughts which have caused serious impacts including famines (1970-80s)
- Droughts are exceptionally severe and spatially and temporally coherent:
  - tend to affect the entire region across the continent at the same time
  - tend to continue for many years or even decades;
    Nearly all years in 1970-90s are anomalously dry compared to the 20th century average [Nicholson, 2000]
- Mechanisms to provide positive feedback and/or multi-year memory?
Record of North African desert dust

- A 4-fold increase has been observed in surface concentration in Barbados from 1960s to 80s [Prospero and Nees, 1986, Prospero et al., 1996]
- Negatively correlated with Sahel rainfall

[Mahowald et al. 2002]
Possible causes of the increase of North African dust

- Increased source areas in the Sahel due to drought (through vegetation loss and drying of soils) and land use

- Decreased deposition due to reduced rainfall

- Increased source intensity due to disturbances on soils by vegetation loss and cultivation. However, this kind of sources may not be as important as previously considered
  - 0~25% of total dust emissions from North Africa, as contrasted to previous estimate of ~50% [Yoshioka et al., 2005].

This effect is not included in this study.
Possible mechanisms controlling Sahel rainfall

- Large scale SST patterns
  Folland et al., 1986; Lamb and Peppler, 1992; Rowell et al., 1995; Bader and Latif, 2003; Giannini et al., 2003; Hoerling et al., submitted
  - Contrast in N and S Atlantic Ocean SSTs
  - Indian Ocean SST (debated)

- Land-surface atmosphere interactions
  Xue and Shukla, 1993; Xue, 1997; Clark et al., 2001; Taylor et al., 2002; Xue et al., 2004
  - Surface hydrology and vegetation dynamics could provide a multi-year memory and positive feedback

- GHG warming

- Dust
  - can affect SSTs through radiative forcing
  - may provide the positive feedback and multi-year memory since it is controlled by surface hydrology and vegetation dynamics [Nicholson, 2000; Prospero and Lamb, 2003]
  - Reduced rainfall in North Africa has been obtained when dust radiative forcing is included in GCM simulations [Miller and Tegen, 1998; Miller et al., 2004]
**Model – basics**

- National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM3) at T42 (2.8x2.8 degrees) resolution and 26 vertical levels

- Coupled with Community Land Model (CLM3)

- Either coupled with the Slab Ocean Model (SOM runs) or forced by observed SSTs (AMIP runs)

- Dust Entrainment And Deposition model (DEAD) [Zender et al. 2003]

- Preferential sources for topographic depression

- Dust shortwave and longwave effects and feedback are included (longwave scattering is not included)
Dust particle size distribution
- 4 size bins with a log-normal sub-bin distribution
- Less small particles and more large particles compared to many other studies [e.g., Miller et al., 2004] based on recent observations [Grini and Zender, 2004; Hand et al., 2004]

Dust optical property
- Less absorbing than many other studies [e.g., Miller et al., 2004] based on recent observations [Sinyuk et al., 2003]

"Wet period (1950-60s) vegetation"
- Dynamic vegetation model didn’t work well coupled with CAM (due to the bias in the hydrology)
- Prescribed by shifting the present (dry period) Sahel vegetation by 2 degrees northward into Sahara
- This is estimated based on the observed vegetation response to rainfall [Tucker and Nicholson, 1999] and observed rainfall record [Nicholson, 1995]
Simulations – AMIP

Forced by observed SST (1951-1993 unless otherwise stated)

- **AMIP.ND**: No dust radiative forcing. Dry period vegetation (based on early 1990s).
- **AMIP.NDV**: Same as AMIP.ND but with wet period vegetation (1951-1970).
- **AMIP.S**: Dust SW radiative forcing and feedback. Dry veg.
- **AMIP.SL**: Dust SW+LW radiative forcing and feedback. Dry veg.
- **AMIP.SLV**: As AMIP.SL but with wet period vegetation for 1951-70. Identical to AMIP.SL in 1971-93.
- **AMIP.SLVH**: Same as AMIP.SLV but dust in the wet period (1951-70) reduced by a half.
- **AMIP.F**: Forced by historical SST only. All other forcings are fixed at 1990s levels. Climatological dust is prescribed. (5 ensemble members.)
- **AMIP.H**: Forced by historical SST, GHG, aerosols and solar forcings. Climatological dust is prescribed. (5 ensemble members.)
Simulations – SOM

Coupled with the Slab Ocean Model (30 years unless otherwise stated)

- **SOM.ND:** No dust radiative forcing.
- **SOM.S:** Dust SW radiative forcing and feedback.
- **SOM.SL:** Dust SW+LW radiative forcing and feedback.
- **SOM.SLV:** Same as SOM.SL but with wet period vegetation.
- **SOM.SP:** Prescribed dust SW radiative forcing and response. (Default version of CAM)
- **SOM.SP2:** Same to SOM.SP but with doubled CO$_2$. Used to see the effects of increased greenhouse gases. 9 years.
Simulated dust distribution

Dust optical depth (annual mean)

Dust optical depth (670 um: SOM.SP, ANNL, global average = 0.0381)

Dust optical depth (JJAS)

Dust optical depth (670 um: SOM.SP, JJAS, global average = 0.0362)
Radiative forcing compared with other studies

Global & annual means

This study

TOA: -0.92, 0.31
ATM: -0.81, 0.67
SFC: -1.59, 1.13

Miller et al. [2004]

TOA: -0.33, 0.15
ATM: -0.03, 1.49
SFC: -1.82, 0.18

Woodward [2001]

TOA: -0.16, 0.23
ATM: -0.17, 1.06
SFC: -1.22, 0.40

Miller et al. [2005]

TOA: -0.62, 0.22
ATM: -0.23, 0.67
SFC: -1.29, 0.45
Annual mean SW forcing

TOA

ATM

SFC

Dust SW TOA forcing [W/m²] (+downward): allsky, annual mean, SOM.SP, global average = −0.92

Dust SW ATM forcing [W/m²] (+inward): allsky, annual mean, SOM.SP, global average = +0.67

Dust SW SFC forcing [W/m²] (+downward): allsky, annual mean, SOM.SP, global average = −1.59
Annual mean LW forcing

TOA

ATM

SFC
Annual mean Net forcing

TOA

ATM

Miller et al., 2004
Precipitation responses to simulated dust radiative forcing

AMIP.SL – AMIP.ND (1951-93; annual mean)

Precipitation [mm/day]: AMIP.SL–AMIP.ND, 1951–93, annual, global average = −0.00118.

SOM.SL – SOM.ND (30 years; annual mean)

Precipitation [mm/day]: SOM.SL–SOM.ND, 30 years, annual, global average = −0.0238.
Summary of precipitation responses to simulated dust radiative forcing

- In SOM simulations (interactive SSTs) precipitation is decreased over global ITCZ and increased to the south of ITCZ. This response is consistent and statistically robust.

- In AMIP simulations (prescribed SSTs) precipitation response is limited over very dusty continental regions.

- However, over the North Africa, the response in SOM simulations is not very different from that in the AMIP simulations

- With SW forcing only (AMIP.S and SOM.S; not shown), the response is stronger but qualitatively the same EVEN THOUGH THE SIGNS OF SURFACE AND ATMOSPHERIC FORCINGS ARE THE OPPOSITE!!!
Annual mean SW forcing

TOA

Dust SW TOA forcing [W/m²] (+downward): allsky, annual mean, SOM.SP, global average = −0.92

ATM

Dust SW ATM forcing [W/m²] (+inward): allsky, annual mean, SOM.SP, global average = +0.67

SFC

Dust SW SFC forcing [W/m²] (+downward): allsky, annual mean, SOM.SP, global average = −1.59
**Summary of precipitation responses to simulated dust radiative forcing**

- In SOM simulations (interactive SSTs) precipitation is decreased over global ITCZ and increased to the south of ITCZ. This response is consistent and statistically robust.

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- However, over the North Africa, the response in SOM simulations is not very different from that in the AMIP simulations.

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Responses in tropospheric temperature

15W~15E; JJAS

AMIP.SL – AMIP.ND

Responses are stronger but essentially the same without LW effects (AMIP.S and SOM.S)
Responses in atmospheric circulation

15W~15E; JJAS

No Dust (AMIP.ND)

Change due to Dust SL effects (AMIP.SL – AMIP.ND)
Both SOM and AMIP simulations with dust SW+LW radiative forcing show:

- weaker WAM (West African Monsoon) circulation
- southward displacement of AEJ (African Easterly Jet)
- weaker vertical shear over the Sahel
- weaker TEJ (Tropical Easterly Jet)

These are common in the simulations with SW forcing only.

All of these are features observed in dry years over the Sahel [Grist and Nicholson, 2001].
Sahel precipitation trend from wet (1951-70) to dry (1971-93) periods

Ten-year running mean precipitation

[Graph showing precipitation trends over time]
Increase of North African desert dust

Simulated
50% increase

Forced 200% increase

[Mahowald et al. 2002]
Sahel precipitation trend from wet (1951-70) to dry (1971-93) periods

Ten-year running mean precipitation
Summary of rainfall reductions from wet to dry periods

- SST change (no dust radiative forcing) [AMIP.ND]
- SST change (fixed dust SW forcing) [AMIP.F]
- Vegetation change only [AMIP.NDV (wet)–AMIP.ND (wet)]
- SST change + GHG warming (fixed dust SW forcing + fixed vegetation) [AMIP.H]
- SST change + dust SW+LW forcing and feedback [AMIP.SL]
- SST change + vegetation change + dust SW+LW forcing & feedback (50% increase of dust) [AMIP.SLV]
- SST change + vegetation change + dust SW+LW forcing (forced 200% increase of dust) [AMIP.SLVH]

Rainfall reductions [mm/day]
Summary of contributions of different factors

- SST change explains ~40(±25)% of the observed rainfall reduction.
- Vegetation change explains ~10(±15)% (statistically insig).
- GHG warming appears to increase Sahel precipitation – opposite direction to the observed change (~−12±7 %).
- Direct radiative (SW+LW) forcing and feedback of dust can explain ~30(±10)%.
- The remaining difference (~30%) must be due to other factors such as biomass burning aerosols, aerosol indirect effects, and other long-term variability.
- The dust radiative impact on Sahel rainfall mainly comes through tropospheric cooling over North Africa due to the TOA forcing, and not through the surface forcing on Atlantic Ocean or the North African Continent.
- These numbers are likely model dependent, but they suggest the importance of the role direct radiative forcing and feedback of dust played in the observed change in Sahel rainfall.
Conclusions (1/2)

- Our model predicts less SW absorption and larger LW forcing than other simulation studies, due to the optical properties and the particle size distribution we used, which are based on the recent observations. The results are consistent with recent measurements.

- Precipitation response in AMIP simulations (SST forced) is limited to the regions of high dust loading.

- In SOM simulations (interactive SSTs), dust radiative forcing acts to reduce precipitation over the global ITCZ and increase precipitation to the south of the ITCZ. This suggests the importance of the role of dust through SST changes.

- However, over the Sahel, the difference between SOM and AMIP simulations are small.
Conclusions (2/2)

- A large part of the rainfall impact of dust over the Sahel is thought to be
  » associated with the changes in atmospheric circulation
  » resulted from the tropospheric cooling over North Africa and the reduced meridional temperature contrast,
  » which are in turn due to the TOA forcing of dust.

- The radiative forcing by the observed increase of dust from wet to dry periods appears to have had an impact on Sahel rainfall, which is more important than the impact of vegetation change and comparable to that of SST change.

- Our LW forcing is larger than many other studies. Our vegetation change may be smaller than it should be. Our model predicts smaller change in dust from wet to dry period compare to the observation. Therefore the impact of dust radiative forcing on the Sahel rainfall could be even larger.
vegetation changes and GHG warming,


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