Modulation of mid-Holocene northern African rainfall by direct and indirect dust aerosol effects

Alexander J. Thompson¹, Christopher B. Skinner², Christopher J. Poulsen¹, Jiang Zhu¹

¹Department of Earth and Environmental Sciences, University of Michigan
²Department of Environmental, Earth and Atmospheric Sciences, University of Massachusetts Lowell

Paleoclimate Working Group
Boulder, CO
February 5, 2019
African Humid Periods

- Expanded vegetation cover\(^1\)
- Increased rainfall\(^2\)
- Reduced dust aerosol emissions\(^3\)
- Most recent wet phase: African Humid Period (~14.8 to 5.5 ka BP)\(^3\)

Adapted from Tierney et al. (2017), *Geology*


Wright (2017)
Climate models underestimate rainfall enhancement

- Proxies: 31°N limit of the monsoon
- Orbital forcing alone cannot explain increase in rainfall
- Land surface feedbacks enhance rainfall:
  - Vegetation
  - Dust direct radiative effects
- Model-data discrepancy not solved

Adapted from Pausata et al. (2016)
Indirect Dust Aerosol Effects

- Never been investigated in mid-Holocene (MH, 6 ka) modeling study
- Dust aerosols
  - Efficient ice nuclei
  - Important climatic impacts

Adapted from IPCC WG1 AR5 Chapter 8:

8: DeMott et al. (2003), 9: IPCC WG1 AR5 Ch. 8

Thompson, Paleoclimate Working Group 2019
Research Questions

• How do indirect dust aerosol effects impact MH African rainfall?

• With added indirect dust aerosol effects, does dust solve the model-data discrepancy?
Model Experiments with CESM1.2

- CAM5-chem simulations
- Prescribed vegetation
- Dust properties

- 35 year simulations
- Indirect aerosol effects explicitly treated for stratiform clouds (absent for convective clouds)
Model Experiments with CESM

- CAM5-chem simulations
- Prescribed vegetation
- Dust properties

- Zone 1: shrubland
- Zone 5: savanna
- Other zones: transition

Thompson et al. (2019), in review
Model Experiments with CESM

- CAM5-chem simulations
- Prescribed vegetation
- **Dust properties**

- Modal Aerosol Module: MAM3
- DEAD Model: vegetation cover and wind speed
- Mobilization prevented if LAI+SAI>0.3

Adapted from Thompson et al. (2019), in review

Thompson, Paleoclimate Working Group 2019
## Control Experiments

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Orbital forcing</th>
<th>Vegetation</th>
<th>Soil albedo</th>
<th>Mobilizes Saharan dust?</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI Control</td>
<td>PI</td>
<td>Desert</td>
<td>Lighter</td>
<td>Yes</td>
</tr>
<tr>
<td>MH Control</td>
<td>6 ka</td>
<td>Vegetated</td>
<td>Darker</td>
<td>No</td>
</tr>
</tbody>
</table>

Thompson: Paleoclimate Working Group 2019
Dust Sensitivity Experiment

- Impact of reduced dust emissions
  - *MH Control – MH HighDust*

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Orbital forcing</th>
<th>Vegetation</th>
<th>Soil albedo</th>
<th>Mobilizes Saharan dust?</th>
</tr>
</thead>
<tbody>
<tr>
<td>MH Control</td>
<td>6 ka</td>
<td>Vegetated</td>
<td>Darker</td>
<td>No</td>
</tr>
<tr>
<td>MH HighDust</td>
<td>6 ka</td>
<td>Vegetated</td>
<td>Darker</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Impact of reduced dust emissions

Adapted from Thompson et al. (2019), in review

Thompson, Paleoclimate Working Group 2019
Dust Direct Aerosol Effects

• Net positive surface and TOA radiation

Adapted from Thompson et al. (2019), in review

Thompson, Paleoclimate Working Group 2019
Dust Direct Aerosol Effects

- Warms the Saharan surface and increases convection
Dust Direct Aerosol Effects

• Increased convective rainfall and total rainfall
  • Convective rainfall makes up >70% of total in Saharan region

Adapted from Thompson et al. (2019), in review
Impacts of dust direct aerosol effects: flowchart

Direct Aerosol Effect Pathway

- Reduced dust emissions
- Increased net surface and TOA radiation
- Increased surface temperature
- Increased convective cloud cover
- Increased convective rainfall
- Increased total rainfall

Thompson, Paleoclimate Working Group 2019
Impacts of dust direct aerosol effects: flowchart

Direct Aerosol Effect Pathway

- Reduced dust emissions
- Increased net surface and TOA radiation
- Increased surface temperature
- Increased convective cloud cover
- Increased convective rainfall
- Increased total rainfall

Indirect Aerosol Effect Pathway?
Impact of reduced dust emissions

Adapted from Thompson et al. (2019), in review

Thompson, Paleoclimate Working Group 2019
Dust Indirect Aerosol Effects

- Decreased number concentration of ice crystals and liquid droplets

![Graphs showing decreased number concentrations of ice crystals and liquid droplets with reduced dust emissions and number concentration.](image)
Dust Indirect Aerosol Effects

- Increased size of ice crystals and liquid droplets

Adapted from Thompson et al. (2019), in review

Reduced dust emissions

Reduced droplet number concentration

Increased droplet size

Adapted from Thompson et al. (2019), in review
Dust Indirect Aerosol Effects

• Reduced stratiform cloud cover and stratiform rainfall

Adapted from Thompson et al. (2019), in review
Dust Indirect Aerosol Effects

• Dampens dust-induced increase in total rainfall by 13.1% in the Sahara and 58.6% in the Sahel

<table>
<thead>
<tr>
<th>Precipitation Change</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sahara</strong></td>
</tr>
<tr>
<td>Convective only</td>
</tr>
<tr>
<td>Total change</td>
</tr>
<tr>
<td>Dampening by indirect aerosol effects</td>
</tr>
<tr>
<td><strong>Sahel</strong></td>
</tr>
<tr>
<td>Convective only</td>
</tr>
<tr>
<td>Total change</td>
</tr>
<tr>
<td>Dampening by indirect aerosol effects</td>
</tr>
</tbody>
</table>
Impacts of dust: flowchart

Direct Aerosol Effect Pathway

- Reduced dust emissions
  - Increased net surface and TOA radiation
  - Increased surface temperature
  - Increased convective cloud cover
  - Increased convective rainfall
  - Increased but dampened rainfall

Indirect Aerosol Effect Pathway

- Reduced droplet number concentration
  - Increased droplet size
  - Reduced stratiform cloud cover
  - Reduced stratiform rainfall

Thompson, Paleoclimate Working Group 2019
Impacts of dust: flowchart

Direct Aerosol Effect Pathway

Previous studies

Reduced dust emissions

Increased rainfall

Thompson, Paleoclimate Working Group 2019
Impacts of dust: flowchart

Direct Aerosol Effect Pathway

This study

Reduced dust emissions

Increased but dampened rainfall

Indirect Aerosol Effect Pathway

This study
Does dust solve model-data discrepancy?

- No, not with CAM5-chem

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Northern monsoon limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>MH Control</td>
<td>28.7°N</td>
</tr>
<tr>
<td>MH HighDust</td>
<td>27.8°N</td>
</tr>
</tbody>
</table>
Relative contributions

![Bar graph showing relative contributions to precipitation anomaly in millimeters per day. The contributions are as follows: Vegetation 1.19, Dust 0.27, and Orbital Forcing 0.36.]

Thompson, Paleoclimate Working Group 2019
Dust impact on rainfall across models

- Pausata et al. (2016) – used EC-Earth (direct dust aerosol effects only)
- Larger dust-induced rainfall anomaly than CAM5-chem

Adapted from Thompson et al. (2019), in review

Thompson, Paleoclimate Working Group 2019
Summary

• Competing effects from direct and indirect aerosol effects on MH northern African rainfall

• Models that exclude indirect aerosol effects likely overestimate rainfall response to dust

• Rainfall response to dust in CAM5-chem does not solve model-data discrepancy
Thank you!
Supplementary Slides
EC-Earth vs. CAM5-chem

- Possible reasons why rainfall anomaly in EC-Earth is larger than CAM5-chem
  - Exclusion of indirect aerosol effects
  - Prescription of SST vs. dynamical ocean
  - Prognostic vs. diagnostic microphysics scheme
  - Overall model rainfall sensitivity to forcings
Could aerosol absorption account for stratiform cloud decrease?

- May have had a role, but not one greater than indirect dust aerosol effects

Adapted from Thompson et al. (2019), in review
Is surface warming responsible for stratiform cloud reduction?

• No, surface warming actually increases stratiform cloud cover in our simulations

Adapted from Thompson et al. (2019), in review
# Sensitivity Experiments

## Dust

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Orbital forcing</th>
<th>Vegetation</th>
<th>Soil albedo</th>
<th>Mobilizes Saharan dust?</th>
</tr>
</thead>
<tbody>
<tr>
<td>MH Control</td>
<td>MH</td>
<td>MH</td>
<td>MH</td>
<td>No</td>
</tr>
<tr>
<td>MH HighDust</td>
<td>MH</td>
<td>MH</td>
<td>MH</td>
<td>Yes</td>
</tr>
</tbody>
</table>

## Vegetation

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Orbital forcing</th>
<th>Vegetation</th>
<th>Soil albedo</th>
<th>Mobilizes Saharan dust?</th>
</tr>
</thead>
<tbody>
<tr>
<td>MH Control</td>
<td>MH</td>
<td>MH</td>
<td>MH</td>
<td>No</td>
</tr>
<tr>
<td>MH DesertVeg</td>
<td>MH</td>
<td>PI</td>
<td>MH</td>
<td>No</td>
</tr>
</tbody>
</table>

## Orbital forcing

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Orbital forcing</th>
<th>Vegetation</th>
<th>Soil albedo</th>
<th>Mobilizes Saharan dust?</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI Control</td>
<td>PI</td>
<td>PI</td>
<td>PI</td>
<td>Yes</td>
</tr>
<tr>
<td>MH Orbital</td>
<td>MH</td>
<td>PI</td>
<td>PI</td>
<td>Yes</td>
</tr>
</tbody>
</table>

## Soil albedo

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Orbital forcing</th>
<th>Vegetation</th>
<th>Soil albedo</th>
<th>Mobilizes Saharan dust?</th>
</tr>
</thead>
<tbody>
<tr>
<td>MH Control</td>
<td>MH</td>
<td>MH</td>
<td>MH</td>
<td>No</td>
</tr>
<tr>
<td>MH DesertSoil</td>
<td>MH</td>
<td>MH</td>
<td>PI</td>
<td>No</td>
</tr>
</tbody>
</table>

Thompson, Paleoclimate Working Group 2019