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

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1. Introduction

- During the mid-Holocene (6,000 years before present), northern Africa experienced higher rainfall amounts, expanded vegetation cover, and reduced dust aerosol emissions[1,2]
- However, climate models underestimate the rainfall enhancement shown by the proxy record[3]
- Previous studies show that dust's *direct aerosol effects* improve model-proxy agreement[4,5]
- The impact of *indirect aerosol effects* on this region and time period has not been investigated
- *Direct aerosol effects*: changes to the energy balance when dust scatters or absorbs radiation[6]
- *Indirect aerosol effects*: aerosol-cloud interactions that alter cloud optical properties and precipitation efficiency[6]

2. Methods

- Simulations using earth system model CESM CAM5-chem
  - Includes direct and indirect aerosol effects in model physics
  - Indirect aerosol effects are included for stratiform cloud microphysics only
- Suite of model simulations were performed to investigate the respective roles of dust and other climate and land feedbacks
- Land surface was modified to reflect mid-Holocene northern Africa, in terms of vegetation, soil albedo, and dust emissions

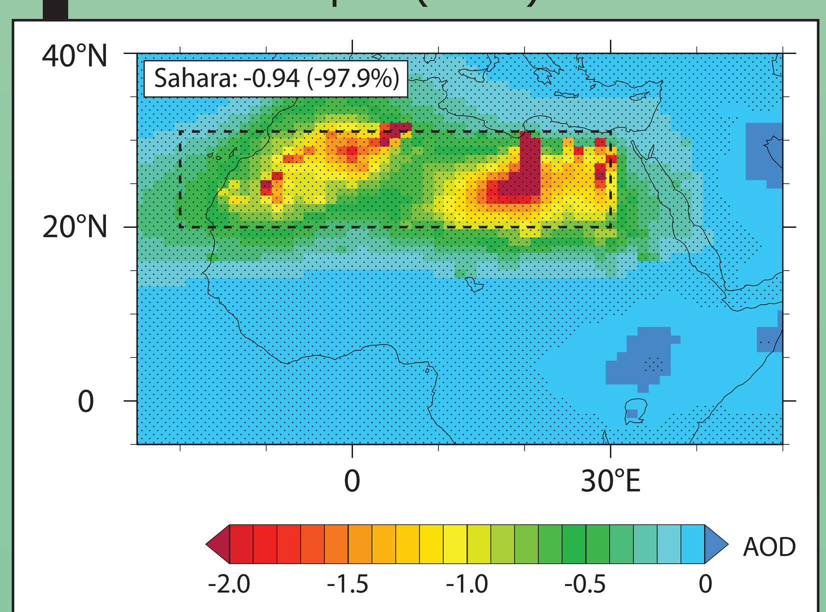
Simulation	Orbital Forcing	Vegetation	Soil Albedo	Mobilizes dust?
PI Control	PI	PI	PI	Yes
MH Control	MH	MH	MH	No
MH HighDust	MH	MH	MH	Yes
MH DesertVeg	MH	PI	MH	No
MH DesertSoil	MH	MH	PI	No
MH Orbital	MH	PI	PI	Yes

Table 1: List of simulations and their respective boundary conditions
PI=Preindustrial, MH=mid-Holocene

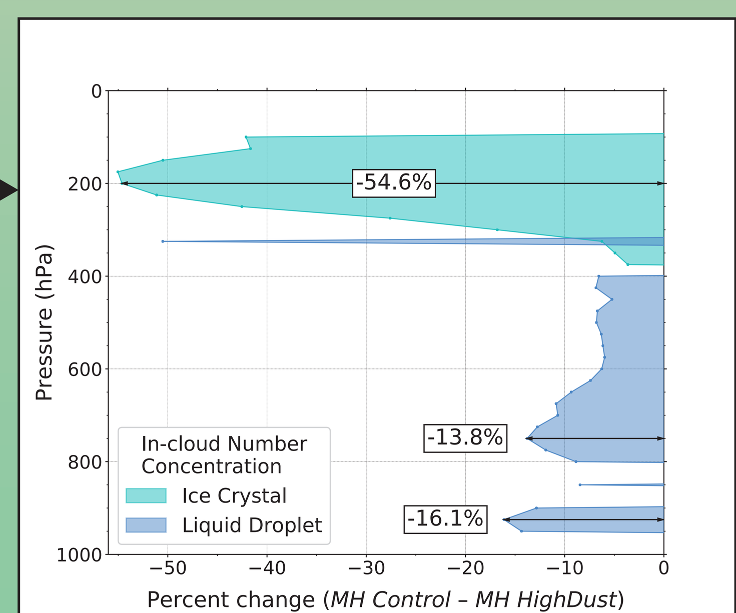
3. Results

Indirect Aerosol Effects Pathway

Reduced dust aerosol optical depth (AOD)



Reduced in-cloud ice crystal and liquid droplet number concentration



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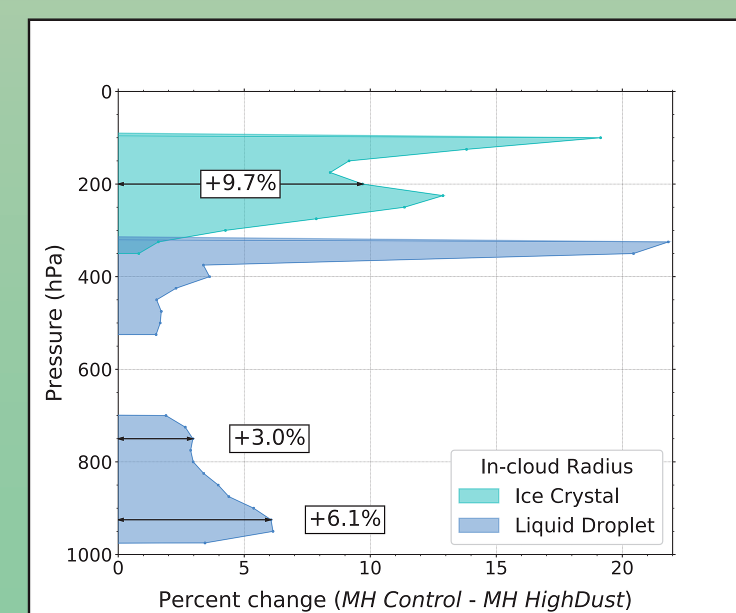
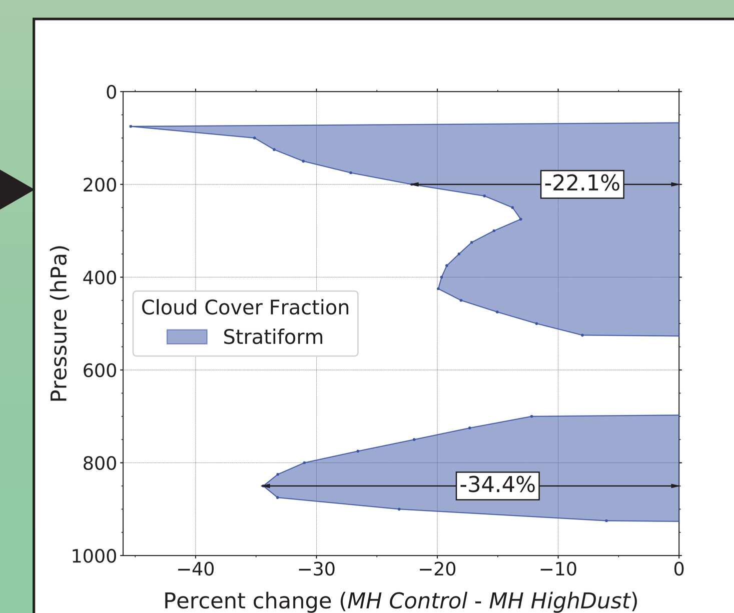
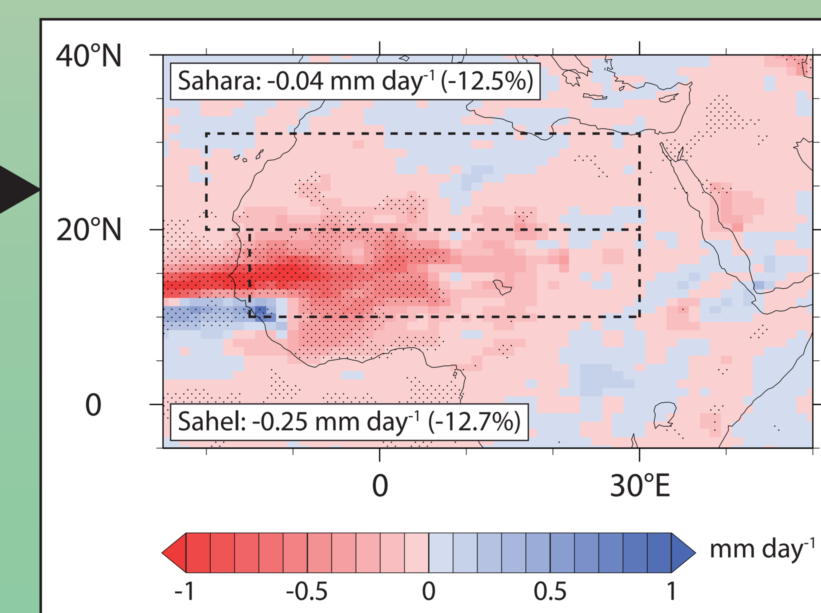
Increased in-cloud ice crystal and liquid droplet radius



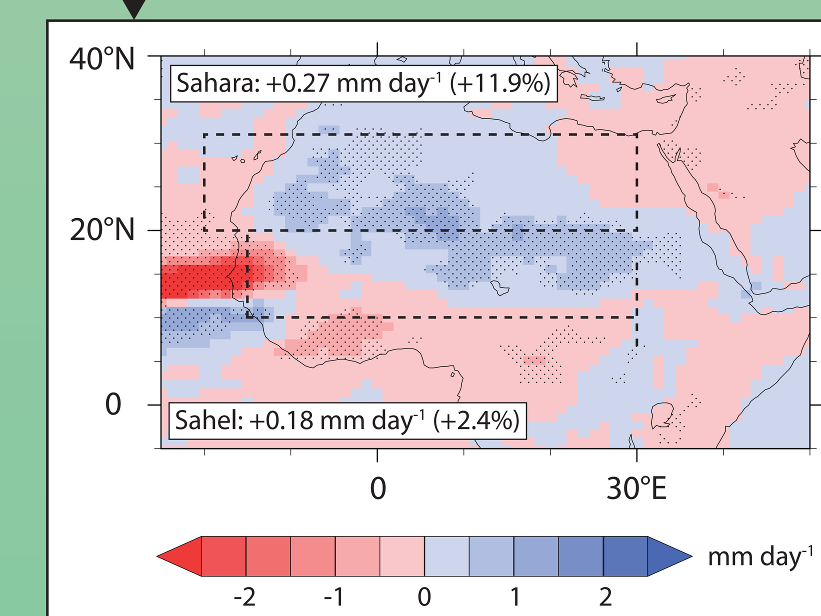
Reduced fraction of stratiform cloud cover



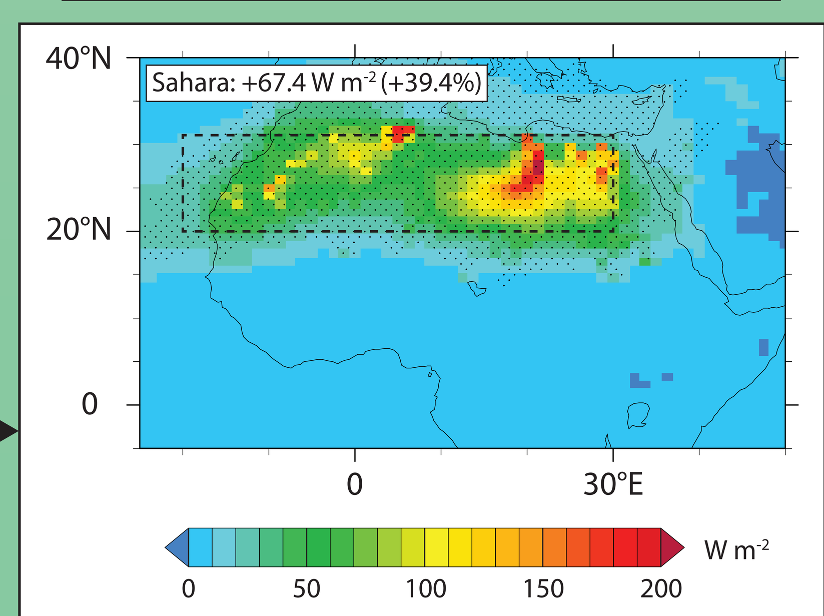
Reduced stratiform precipitation



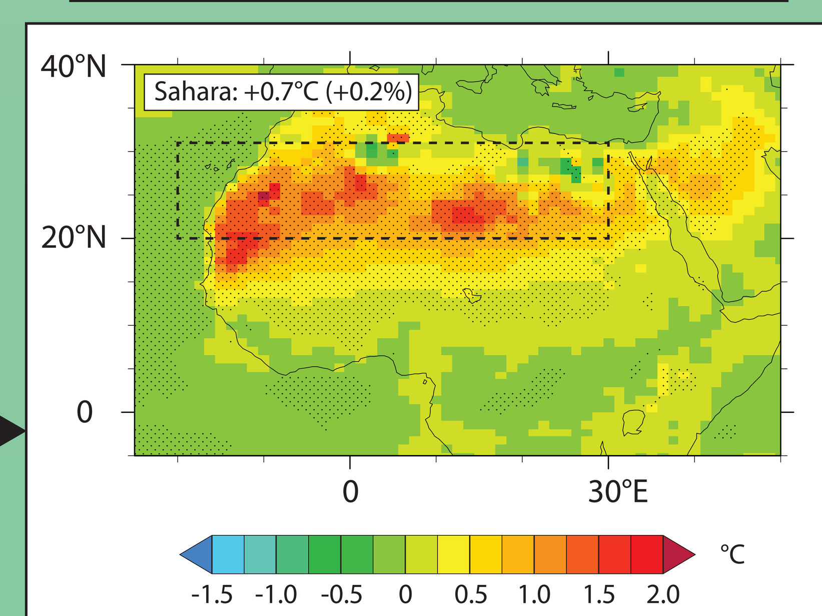
Increased, but *dampened* total precipitation



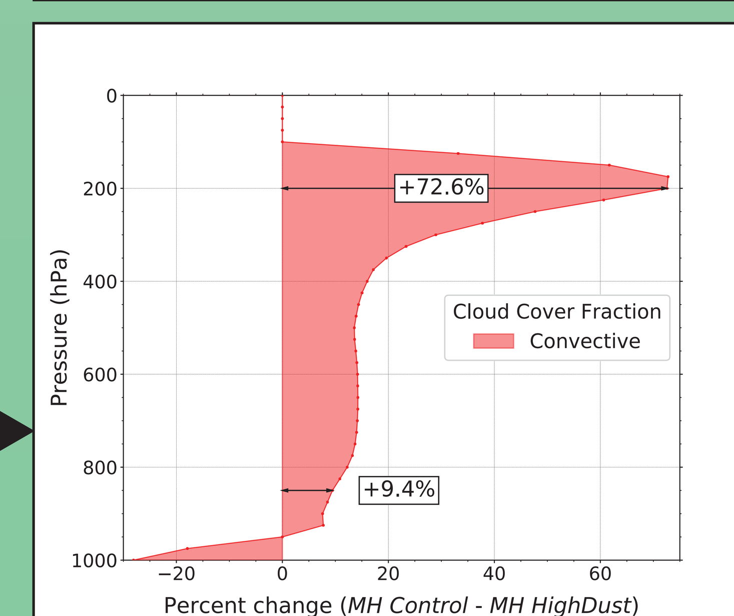
Direct Aerosol Effects Pathway



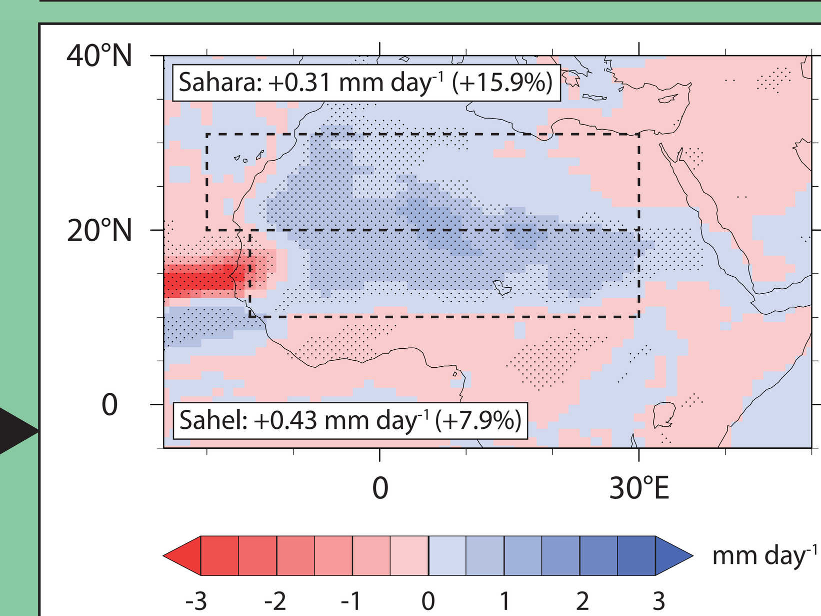
Increased net shortwave radiation at the surface



Increased 2-m air temperature



Increased fraction of convective cloud cover



Increased convective precipitation

Figure 1: Progression of simulated climatic events due to a reduction in Saharan dust loading (*MH Control - MH HighDust*), with events split into direct and indirect aerosol effect pathways and ending with the net effect on Saharan and Sahelian rainfall. Dashed boxes represent the Sahara (upper; 20-31°N, 20°W-30°E) and Sahel (lower; 10-20°N, 15°W-30°E). Stippling on spatial maps represents changes significant at the 95% confidence level. "Percent change" plots show statistically significant average changes over the Sahara region. All plots show average changes and values during monsoon season (Jun., Jul., Aug., and Sept.). "In-cloud" calculated by dividing output variable by the fractional occurrence of ice or liquid.

Figure 2: Impact of indirect aerosol effects on total Saharan and Sahelian precipitation. "Convective only" represents percentage of precipitation change if total precipitation was only determined by convective precipitation. The percent dampened is the percent reduction from "Convective only" to "Total change". Arrows are to scale.

Precipitation Change

Sahara

Convective only	13.7%
Total change	11.9%
Dampening by indirect aerosol effects	13.1%

Sahel

Convective only	5.8%
Total change	2.4%
Dampening by indirect aerosol effects	58.6%

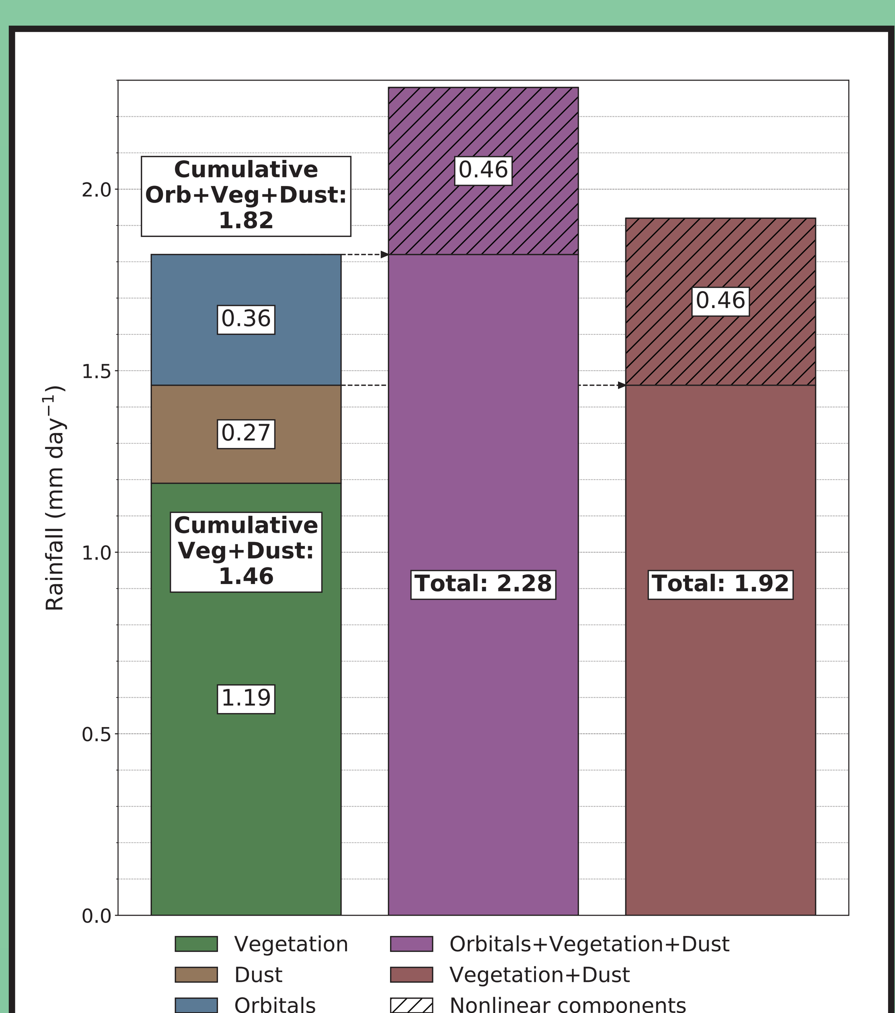


Figure 3: Bar chart of the rainfall contributions from vegetation, dust, orbitals, the combined effect of all three, and of vegetation and dust. These values represent Saharan averages from the monsoon season. Sensitivity experiments are as follows: **Vegetation** (*MH Control - MH DesertVeg*), **Dust** (*MH Control - MH HighDust*), **Orbitals** (*MH Orbital - PI Control*), **Orbitals+Vegetation+Dust** (*MH Control - PI Control*), and **Vegetation+Dust** (*MH Control - MH Orbital*).

4. Key Points

- Reduced mid-Holocene Saharan dust loading, and its associated direct aerosol effects, lead to increased convective, and total, rainfall in northern Africa.
- The indirect aerosol effects from reduced dust loading lead to reduced stratiform rainfall, which weakens the total rainfall increase due to dust.
- The northern African rainfall response to total dust aerosols is substantially weaker than vegetation forcing, but is comparable to orbital forcing.

References
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