Model-Proxy Comparison of Precipitation and Hydrogen Stable Isotopes in mid-Holocene Northern Africa with iCESM

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African Humid Periods

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


Photo credit: Wikipedia – Saharan Rock Art

Adapted from Wright (2017)
Hydrogen Isotopic Composition from Leaf Waxes ($\delta D_{\text{wax}}$)

- $\delta D_{\text{wax}}$ from marine and lake sediment cores preserves $^2\text{H}/^1\text{H}$ ratio$^1$

- In northern Africa, 6ka – 0ka depletion in $\delta D_{\text{wax}}$ has been used as evidence for a “Green Sahara”$^2$


Credit: Wikipedia – Plant cuticle
Leaf wax proxy records:

1. Tierney et al. (2017) -15
2. Tierney et al. (2017) -14
3. Tierney et al. (2017) -20
4. Tierney et al. (2017) -16
5. Niedermeyer et al. (2010) -15
7. Collins et al. (2017) -18
8. Costa et al. (2014) -5
9. Tierney et al. (2017)/Tierney et al. (2013) -10/-12
Amount Effect Interpretation

• “Amount Effect”: increases in rainfall rate are accompanied by depletions in isotopic composition of rainfall

• Interpretation for Green Sahara:
  • Depleted $\delta D_{\text{wax}}$ = Increased rainfall
  • $\delta D_{\text{wax}}$ directly interpreted as $\delta D_p$ and mean annual rainfall


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Adapted from Tierney et al. (2017). ScienceAdvances.
Several studies (e.g., Risi, 2008; Konecky et al., 2019) suggest that the relationship between isotopic composition and rainfall in the tropics is more complicated than the simple “Amount Effect”
Research Questions

• Does the “Amount Effect” accurately depict the relationship between stable isotopes and tropical rainfall in northern Africa during the mid-Holocene in iCESM?

• Can the “Amount Effect” be used to interpret mid-Holocene depletions of leaf wax isotopes as increases in northern African rainfall?
iCESM: water isotope-enabled CESM

- Simulates water isotopes, such as $\delta D$
- Fully coupled climate model simulations (atmosphere, ocean, land, etc.)
  - 300 year spin-up
  - 1.9° x 2.5° resolution

Overview of simulations

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Orbital</th>
<th>Sahara Land Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>0ka</td>
<td>Desert</td>
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<tr>
<td>MH</td>
<td>6ka</td>
<td>Vegetated</td>
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- For a vegetated Sahara land surface, the average of land surface variables over the Sahel (10°N zonal region) was calculated and extended north across Africa and the Arabian Peninsula.
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- **MH – PI**
  - Combined effect of orbital and vegetational change
  - Most realistic change
Change in mean annual rainfall

- Proxies appear to match rainfall interpretation

*Stippling indicates 95% confidence interval differences

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Change in $\delta D_p$

- Depleted towards the east $\rightarrow$ continental effect

*Stippling indicates 95% confidence interval differences*
Change in $\delta D_p$

- Depleted towards the east $\rightarrow$ continental effect *Wind patterns
Change in $\delta D_p$

- Enriched in the west

*Stippling indicates 95% confidence interval differences*
Why is $\Delta D_p$ enriched in West Africa in MH?

- Likely due to a stronger Saharan Heat Low

Adapted from Lacour et al. (2017)
Mismatch between changes in rainfall and $\delta D_p$

- Amount Effect does not explain 6ka – 0ka change in West Africa

*Stippling indicates 95% confidence interval differences
Mismatch between changes in rainfall and $\delta D_p$

- Proxies 1-5 do not signify $\delta D_p$ based on model results
How to interpret leaf wax isotopic signal?

• Leaf waxes derive their water from the soil\(^1\)

• Could leaf waxes be demonstrating a soil water isotopic, rather than a precipitation isotope, signal?

1. Sachse et al. (2012)
Soil water increases mainly due to expansion of vegetation

*Stippling indicates 95% confidence interval differences
$\delta D_S$ leads to better agreement with Proxies 1-5
$\delta D_S$ leads to better agreement with Proxies 1-5

- Proxies 1-9 generally agree with the 6ka – 0ka trend of $\delta D_S$

![Map showing δD_S and δp RMSE values](image)

*Stippling indicates 95% confidence interval differences*
Why is $\delta D$ depleted during the mid-Holocene relative to the Preindustrial?

- Isotopic differences between desert vs. vegetated environments
- Evapotranspiration flux dominated by bare ground evaporation or canopy transpiration

Adapted from Wright (2017)
Difference in soil water isotopes during mid-Holocene relative to Preindustrial

Fractionating

Sunlight

\[
\begin{array}{cccc}
\text{Evaporation} & 1^\text{H} \\
\end{array}
\]

\[
\begin{array}{cccc}
\text{Enriched soil water} & ^2\text{H} & 1^\text{H} \\
\end{array}
\]

a) Desert

Preindustrial
Difference in soil water isotopes during mid-Holocene relative to Preindustrial

Non-fractionating

Sunlight

Transpiration

$^2\text{H}$

$^1\text{H}$

Depleted soil water

$^1\text{H}$

$^1\text{H}$

b) Vegetated mid-Holocene
Soil water $\delta D$ signal shows MH-PI difference

- Combination of...
  - Precipitation $\delta D$
  - Modification from the land surface

*Stippling indicates 95% confidence interval differences*
Conclusions

• Re-evaluation of the “Amount Effect”
  • Does not explain mid-Holocene precipitation change in West Africa

• Leaf wax isotopes likely record a signal of soil water rather than precipitation amount

• Northern African leaf wax isotopes contain evidence of expanded vegetation during the mid-Holocene
Thank you!

Questions? Email me at alexjt@umich.edu
Change in $\delta D_p$

- Depleted towards the east $\rightarrow$ continental effect

*Monsoon season rain enhancement
Change in $\delta D_p$

- Enriched in the west

*Monsoon season rain enhancement
Why is $\delta D_p$ enriched in West Africa in $MH_{\text{veg}}$?

- Hypothesis: strengthened Saharan Heat Low
Why is $\delta D_p$ enriched in West Africa in $M_{\text{veg}}$?

- Water vapor $\delta D$ in mid-troposphere is enriched during summer
- Low-level easterly flow brings enriched Harmattan vapor

Adapted from Lacour et al. (2017)
Strengthened Saharan Heat Low
Seasonal cycle of water vapor $\delta D$

West Africa becomes enriched

East Africa becomes depleted

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Seasonal cycle of soil water and isotopes

- Increases in soil water during mid-Holocene are highest during monsoon season
- Soil water $\delta D$ signal is a combination of precipitation $\delta D$ and modification from the land surface
Wong et al. (2017) show that precipitation does not infiltrate as deep into the soil as observations suggest

- Surface soil moisture and isotopes show this an even stronger depletion in West Africa soil moisture isotopes, so this should not impact our conclusions
How well does iCESM simulate present-day African isotopes?

Adapted from Lacour et al. (2017)
How well does iCESM simulate present-day African isotopes?

Fig. 3. Reconstructed precipitation-weighted mean-annual $\delta D_p$ for Africa, based on the interpolated dataset of Bowen and Revenaugh (2003). Sediment cores are numbered (1–9). Major African rivers are marked: Senegal (Se); Niger (Ni); Sanaga (Sa); Nyong (Ny); Ntem (Nt); Congo (Co); Balombo (Ba); Cunene (Cu) and Orange (Or). Hatching marks the approximate source area of each core (Cores 1–4 are joined for clarity; see Table 2 for individual source areas). It should be noted that African GNIP stations are relatively sparsely distributed and therefore the interpolated dataset of Bowen and Revenaugh (2003) may not capture all regional isotopic variability in precipitation.

Adapted from Collins et al. (2013)
How well does iCESM simulate present-day African isotopes?

**Fig. 3.** Reconstructed precipitation-weighted mean-annual δD_p for Africa, based on the interpolated dataset of Bowen and Revenaugh (2003). Sediment cores are numbered (1–9). Major African rivers are marked: Senegal (Se); Niger (Ni); Sanaga (Sa); Nyong (Ny); Ntem (Nt); Congo (Co); Balombo (Ba); Cunene (Cu) and Orange (Or). Hatching marks the approximate source area of each core (Cores 1–4 are joined for clarity: see Table 2 for individual source areas). It should be noted that African GNIP stations are relatively sparsely distributed and therefore the interpolated dataset of Bowen and Revenaugh (2003) may not capture all regional isotopic variability in precipitation.

Adapted from Collins et al. (2013)
MH Precipitation and Soil Water Isotopes

MH Annual $\delta D_p$

MH Surface soil layer 0.366 m depth

Annual $\delta D_S$

Annual $\delta D_S$

Surface soil layer

0.366 m depth

Thompson, CESM Workshop 2019
Soil water increases mainly due to expansion of vegetation
Soil water increases mainly due to expansion of vegetation.
Why is Proxy 8, from Lake Tana, more enriched than iCESM would suggest?

- Evaporation?
- Timing or regionality of physical mechanisms?

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Model-Proxy Comparison
Model-Proxy Comparison

Rainfall RMSE = 17.02‰

Leaf waxes
Rainfall
Soil water

Isotopic Difference MH-PI (%)

Proxy
Model-Proxy Comparison

Rainfall RMSE = 17.02%
Soil water RMSE = 11.34%

Isotopic Difference MH-PI (%) vs. Proxy

Leaf waxes
Rainfall
Soil water