Dynamics or thermodynamics?

Using water isotopes to answer fundamental questions of paleo-hydroclimate evolution

Tyler Kukla
(Stanford University, Department of Geological Sciences)

E-mail: tykukla@stanford.edu
Twitter: @EarthTKukla
Web: https://sites.google.com/view/tykukla/home

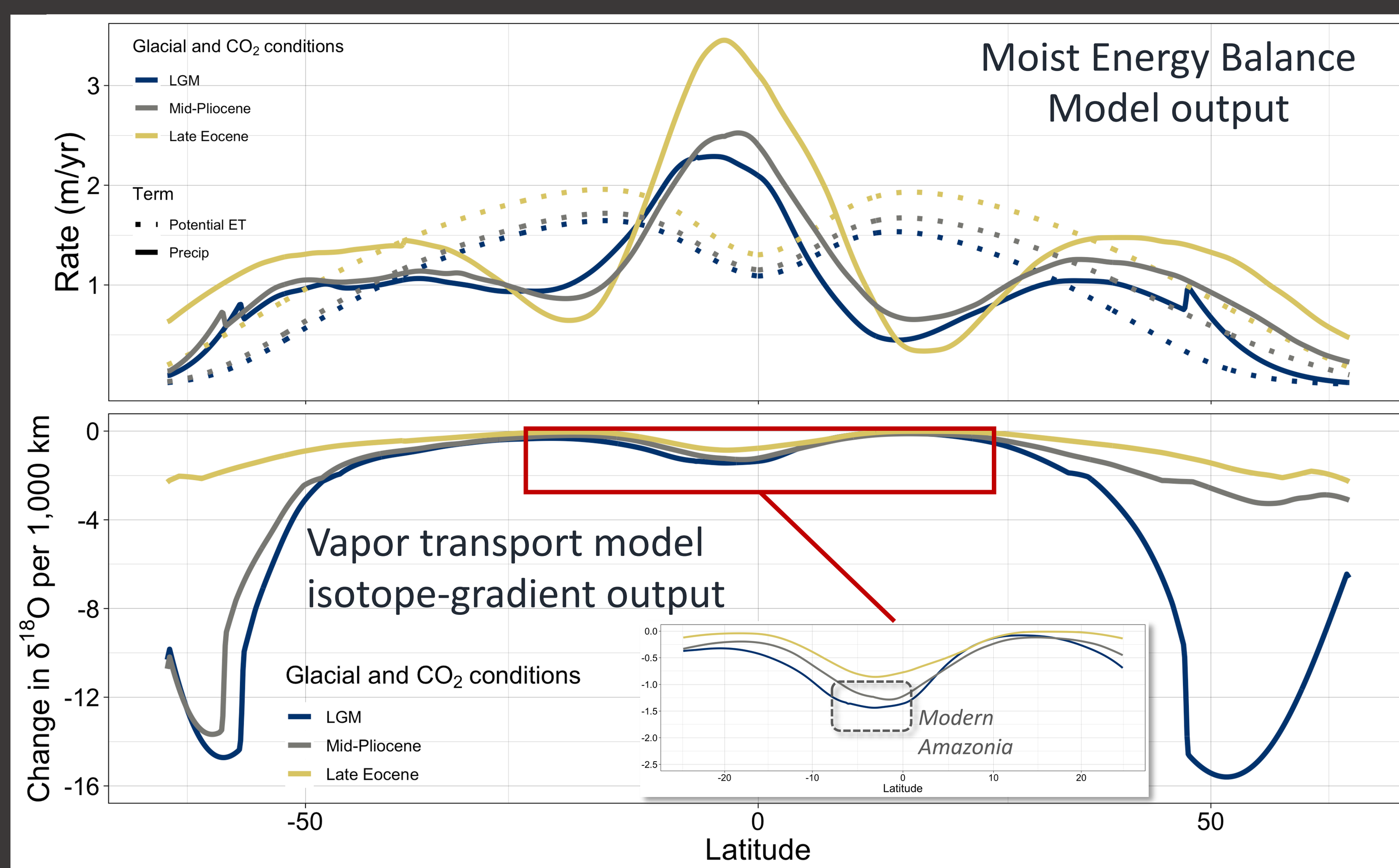
MOTIVATION

- Can we **separate temperature-driven changes in hydroclimate** (*humidity, rainfall, evapotranspiration*) **from those related to atmospheric circulation** using water-isotope data?
- What is the dominant driver of hydroclimate variability at different timescales *(i.e.* thousands-to-millions of years)*?*

KEY FINDINGS

- **Thermodynamic scaling** of hydroclimate **has a small effect** on net continental distillation ($\Delta\delta^{18}O$) because terms nearly cancel out (***Figs. 1, 2***).
- **Atmospheric dynamics** *dominate Amazon hydroclimate since the Last Glacial Maximum* but **may play a small role on Cenozoic timescales** where many $\delta^{18}O$ records and composites lack resolvable trends.

Temperature-driven changes in isotopic distillation



Paleoclimate simulations

Fig. 1 *Predicting continental distillation (and $\Delta\delta^{18}O$) with thermodynamic scaling*
(LGM-to-Late Eocene)

TOP-MEBM output for precip (solid) and potential ET (dashed) for LGM (dark blue) mid-Pliocene (gray) and Late Eocene (yellow) glacial and pCO_2 conditions. (MEBM after: North & Coakley, 1979; Flannery, 1984; Frierson et al., 2006; Roe et al., 2015; Siler et al., 2018)

BOTTOM-Vapor transport model-predicted continental isotope gradients (assumes no orography). (Model: Kukla et al., 2019; *inspired by*: Hendricks et al., 2000; Chamberlain et al., 2014; Winnick et al., 2014) **NOTE: X-axes are equal-area*

TAKE AWAY

Changes in continental isotope gradients are small in low-to-mid-latitudes despite large changes in water-cycle fluxes.

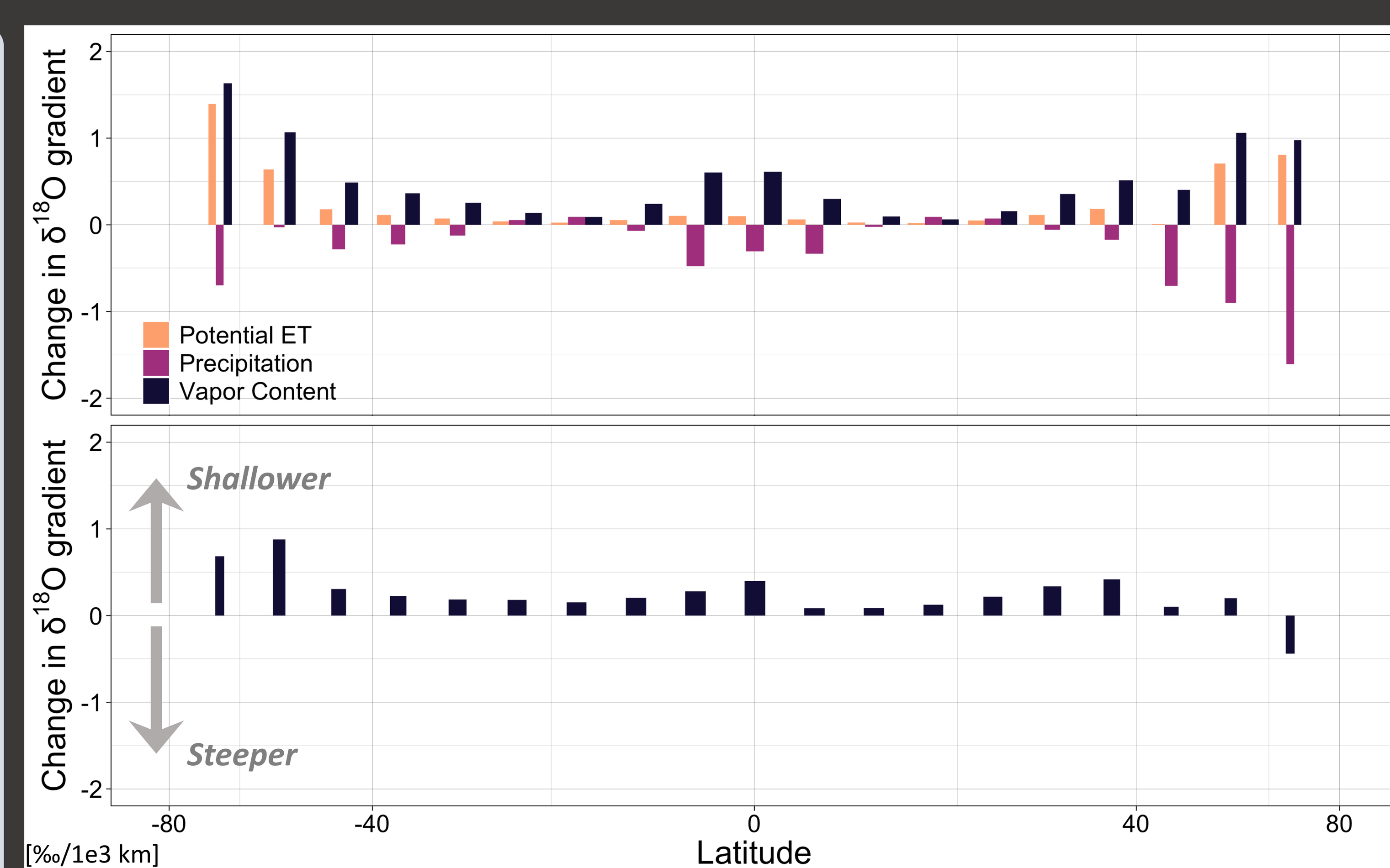
Uniform 5°C warming experiment

Fig. 2 *Thermodynamic scaling drivers of $\Delta\delta^{18}O$ evolution*

TOP-The change in $\Delta\delta^{18}O$ due to just potential ET (salmon), precip (purple) or vapor content (dark purple) with *uniform 5°C warming at each latitude.*
BOTTOM-Total change in the isotope gradient after 5°C warming (assumes no orography).
**NOTE: X-axes are equal-area*

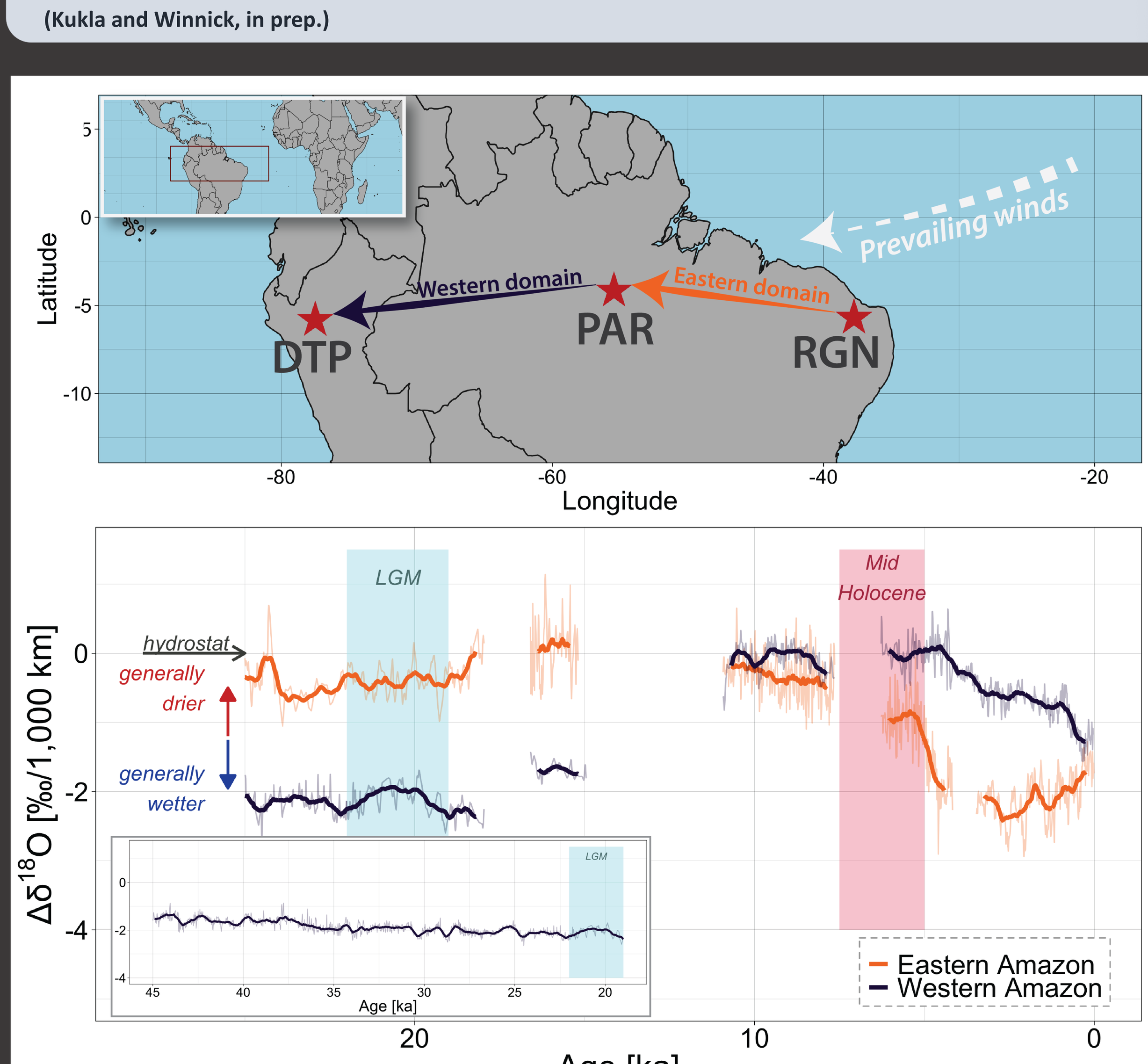
TAKE AWAY

Vapor content (Clausius-Clapeyron) *dominates changes in tropical gradients* while potential ET becomes important in the high-latitudes.



DYNAMIC change in Amazon rainfall (LGM-present)

(Kukla and Winnick, in prep.)



Amazon late-Quaternary isotope gradients

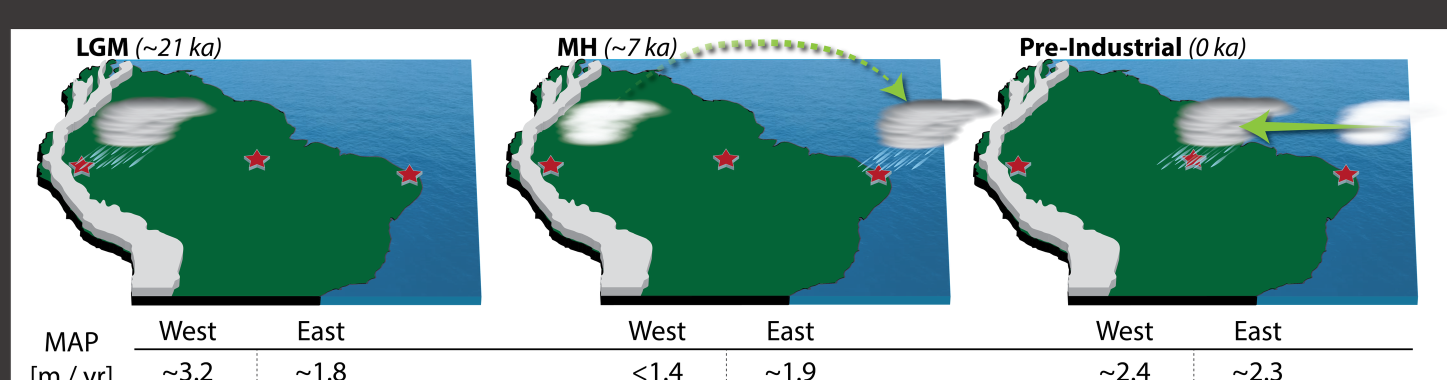
Fig. 3 *Three cave sites and two isotope gradients ($\Delta\delta^{18}O$; ‰/1,000 km)*

TOP-Map of three sites used to reconstruct the paleo-isotope gradients. (RGN; Cruz et al., 2009), (PAR; Wang et al., 2017), (DTP; van Breukelen et al., 2008; Cheng et al., 2013).

BOTTOM-Eastern (orange) and western (purple) isotope gradients. Steeper (more negative) interpreted to reflect greater net moisture distillation. West gradient extends past 25 ka (inset), showing slight shoaling from 45-25 ka (temp-driven change in continental distillation?). *Hydrostat* is the point at which further aridification does not strongly influence $\Delta\delta^{18}O$.

TAKE AWAY

Both gradients change by **more than 2‰/1,000 km**. Analysis in Fig. 1 (inset) shows the change in tropical gradients due to *LGM-to-Eocene thermodynamic scaling is <1 ‰/1,000 km,* suggesting a **possible dynamic driver** of Amazon hydroclimate.



The spatial migration of South American Monsoon convection

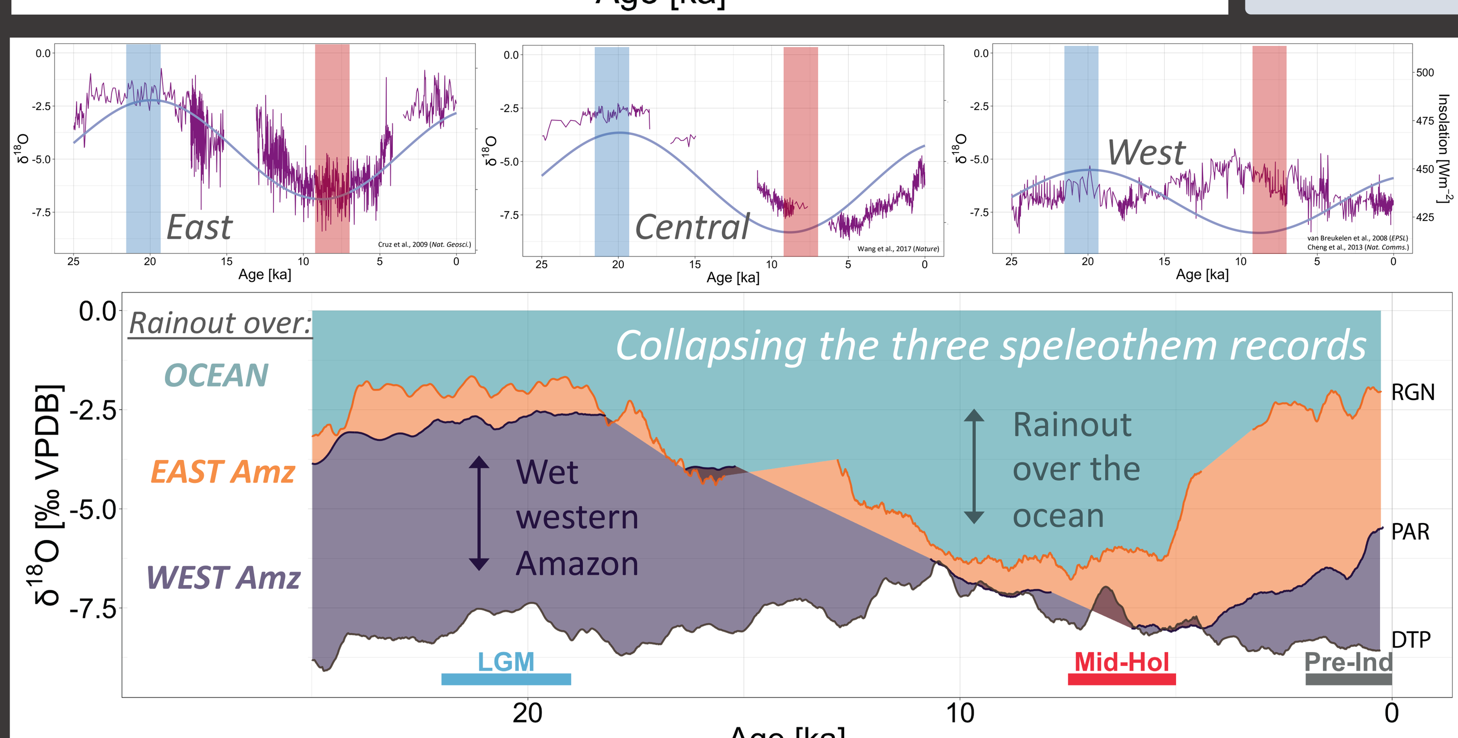
Fig. 5 *Schematic of inferred changes in the climatological location of the convective cell*

TOP-The approximate focus of monsoon convection during three key time-slices. Dashed arrow (MH) reflects the convective cell *does not* pass through the 1-D domain as evidenced by near-constant eastern $\Delta\delta^{18}O$. Solid arrow implies migration through domain (east gradient steepens before west).

BOTTOM (text)-Mean annual rainfall rates for each domain and timeslice calculated by inverting the model of Kukla et al., 2019.

TAKE AWAY

The South American Monsoon is particularly vulnerable to energetically-driven **zonal and meridional** shifts (Liu & Battisti, 2015; Boos & Korty, 2016 their fig. 2b), providing a possible mechanism for changing monsoon dynamics.



Spatial patterns of distillation

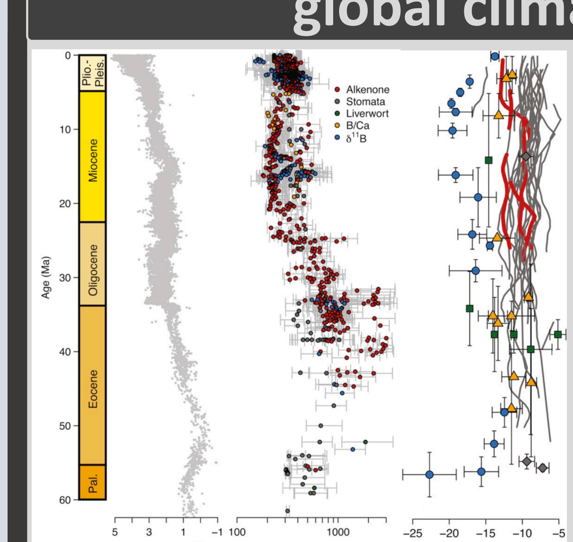
Fig. 4 *Collapsing the three $\delta^{18}O$ records to one time-series*

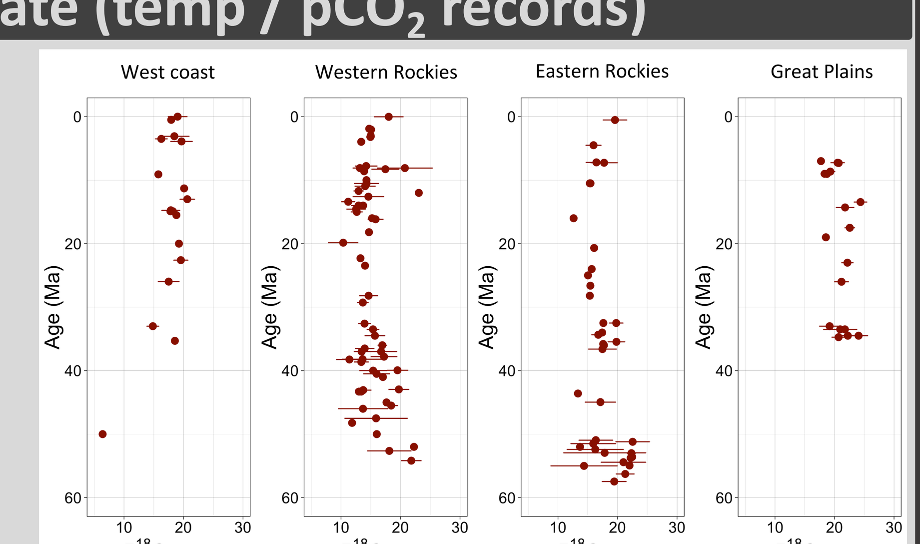
TOP-The three speleothem records.
BOTTOM-Collapsed, records where Y-range of colored polygon reflects relative distillation within the respective domain. East and central $\delta^{18}O$ interpreted as a shift in the focus of monsoon convection (behind-to-in-front of caves; see Cruz et al., 2009) with minimal change in west $\delta^{18}O$ where convection is always upstream.

TAKE AWAY

East and central $\delta^{18}O$ consistent with dynamic changes in the location of convection (dynamics) while *west may be sensitive to the intensity of upstream monsoon rainout.*

No strong correlation between Cenozoic $\delta^{18}O$ and global climate (temp / pCO_2 records)





Cenozoic $\delta^{18}O$ in Asia

Fig. 5 *Asia carbonate records*
LEFT-Benthic foram $\delta^{18}O$ (Zachos et al., 2001).
CENTRAL-pCO_2 proxy compilation (full list of refs in Caves Rugenstein and Chamberlain, 2018)
RIGHT-Compiled Asia $\delta^{18}O$ data.
Figure from Caves Rugenstein and Chamberlain, 2018)

Cenozoic $\delta^{18}O$ in North America

Fig. 6 *North America carbonate records*

Compiled soil carbonate data along four domains representing different modern topographic and air-mass-mixing regimes.

TAKE AWAY (hypothesis)

Long-term trends may integrate timescales of major dynamic shifts (*i.e.* millennial). Changes due to thermodynamic scaling should largely cancel. Together, this may help explain the poor correlation between Cenozoic $\delta^{18}O$ long-term global climate.

References

Rugenstein, Jeremy K. Caves, and C. Page Chamberlain. "The evolution of hydroclimate in Asia over the Cenozoic: A stable-isotope perspective." *Earth-Science Reviews* 185 (2018): 1129-1156.
Chamberlain, Charles P., et al. "The impact of neogene grassland expansion and aridification on the isotopic composition of continental precipitation." *Global Biogeochemical Cycles* 28.9 (2014): 992-1004.
Cheng, Hai, et al. "Climate change patterns in Amazonia and biodiversity." *Nature communications* 4 (2013): 1411.
Cruz, Francisco W., et al. "Orbitally driven east–west antiphasing of South American precipitation." *Nature Geoscience* 2.3 (2009): 210.
Flannery, Brian P. "Energy balance models incorporating transport of thermal and latent energy." *Journal of the Atmospheric Sciences* 41.3 (1984): 414-421.'
Frierson, Dargan MW, Isaac M. Held, and Pablo Zurita-Gotor. "A gray-radiation aquaplanet moist GCM. Part II: Energy transports in altered climates." *Journal of the atmospheric sciences* 64.5 (2006): 1680-1693.
Hendricks, M. B., D. J. DePaolo, and R. C. Cohen. "Space and time variation of δ18O andδD in precipitation: Can paleotemperature be estimated from ice cores?." *Global Biogeochemical Cycles* 14.3 (2000): 851-861.
Kukla, Tyler, et al. "The Sensitivity of Terrestrial δ18O Gradients to Hydroclimate Evolution." *Journal of Geophysical Research: Atmospheres* 124.2 (2019): 563-582.
North, Gerald R., and James A. Coakley Jr. "Differences between seasonal and mean annual energy balance model calculations of climate and climate sensitivity." *Journal of the Atmospheric Sciences* 36.7 (1979): 1189-1204.
Roe, Gerard H., et al. "The remote impacts of climate feedbacks on regional climate predictability." *Nature Geoscience* 8.2 (2015): 135.
Siler, Nicholas, Gerard H. Roe, and Kyle C. Armour. "Insights into the zonal-mean response of the hydrologic cycle to global warming from a diffusive energy balance model." *Journal of Climate* 31.18 (2018): 7481-7493.
Van Breukelen, M. R., et al. "Fossil dripwater in stalagmites reveals Holocene temperature and rainfall variation in Amazonia." *Earth and Planetary Science Letters* 275.1-2 (2008): 54-60.
Winnick, Matthew J., et al. "Quantifying the isotopic 'continental effect'." *Earth and Planetary Science Letters* 406 (2014): 123-133.