



# **How numerical tracers and water isotope ratios help us better understand the hydrological cycle and its representation in Earth system models**

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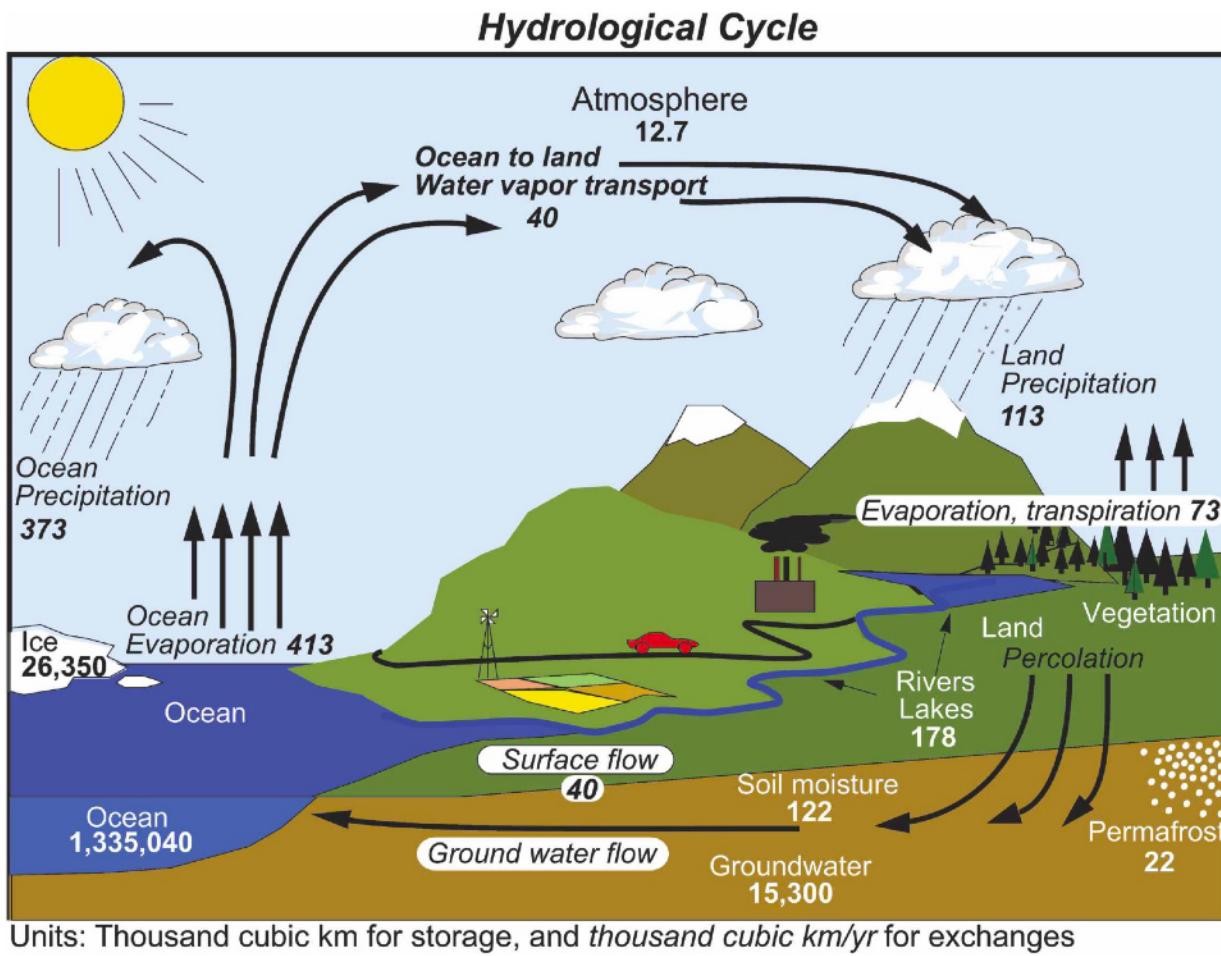
Managed by Triad National Security, LLC, for the U.S. Department of Energy's NNSA.

## About me

- New staff scientist at LANL
- Primary research interests center on understanding the water and carbon cycles using Earth system models and stable isotope ratio observations on a large range of scales
- Have been very involved with development and use of isotope ratio data products from the National Ecological Observatory Network (NEON)

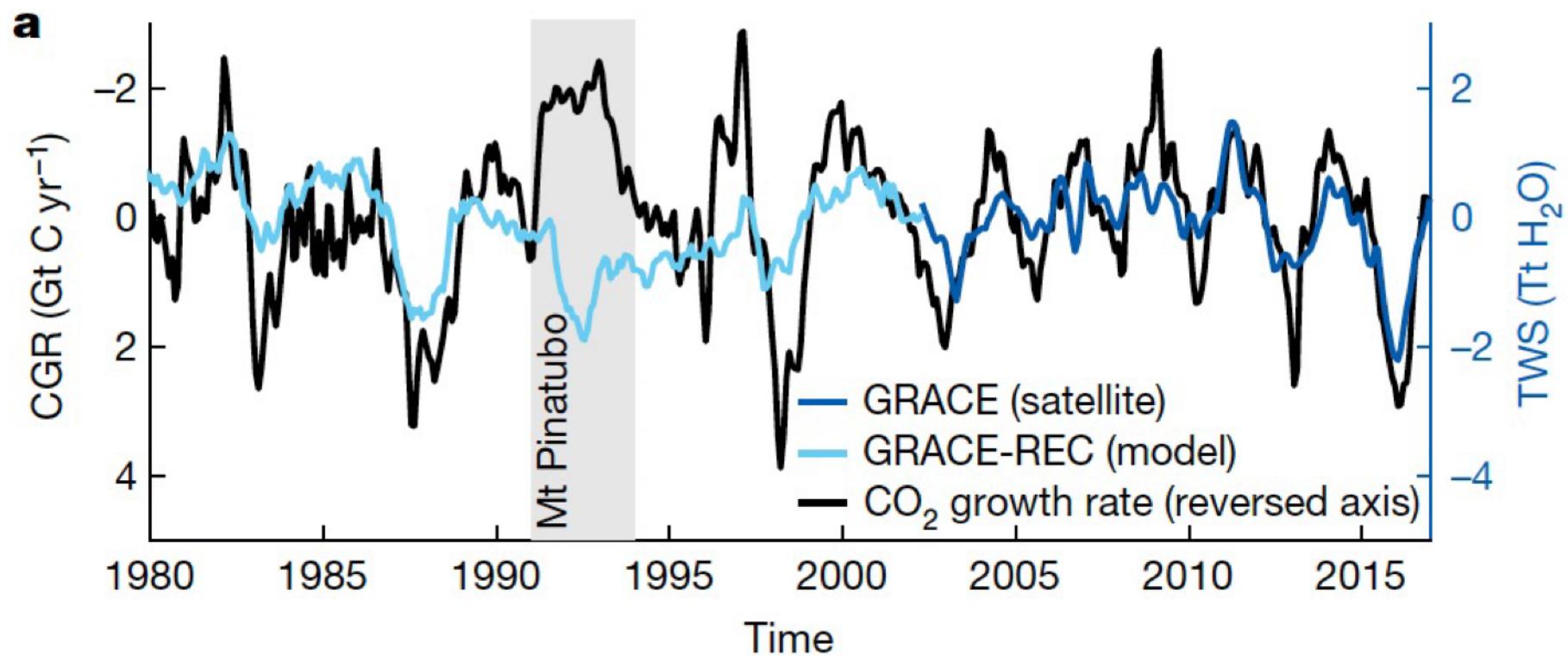


# The importance of land-atmosphere interactions in the terrestrial hydrological cycle

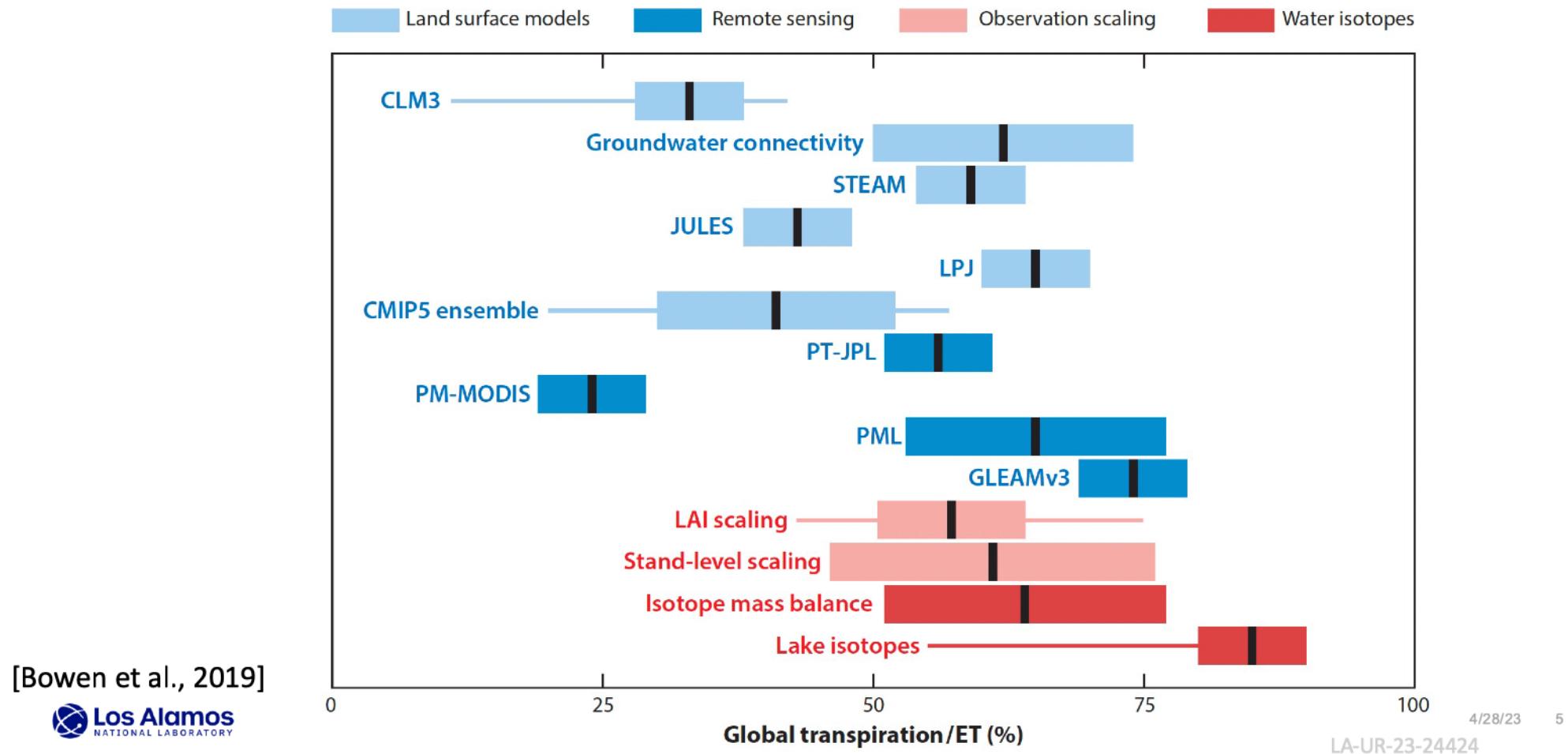


[Trenberth et al. 2007]

## Water and carbon cycles strongly coupled



# How well do we understand terrestrial hydrologic processes?



[Bowen et al., 2019]



# Outline

1. Water isotope ratios and fractionation
2. Isotope tracers in Earth system models
3. Generalized “process-oriented” water tracers in Earth system models
4. Opportunities in E3SM

# Isotope Fractionation

Oxygen: 99.76%  $^{16}\text{O}$ ,  
0.2%  $^{18}\text{O}$ , 0.04%  $^{17}\text{O}$

Hydrogen: 99.99%  $^1\text{H}$ ,  
0.01%  $^2\text{H}$

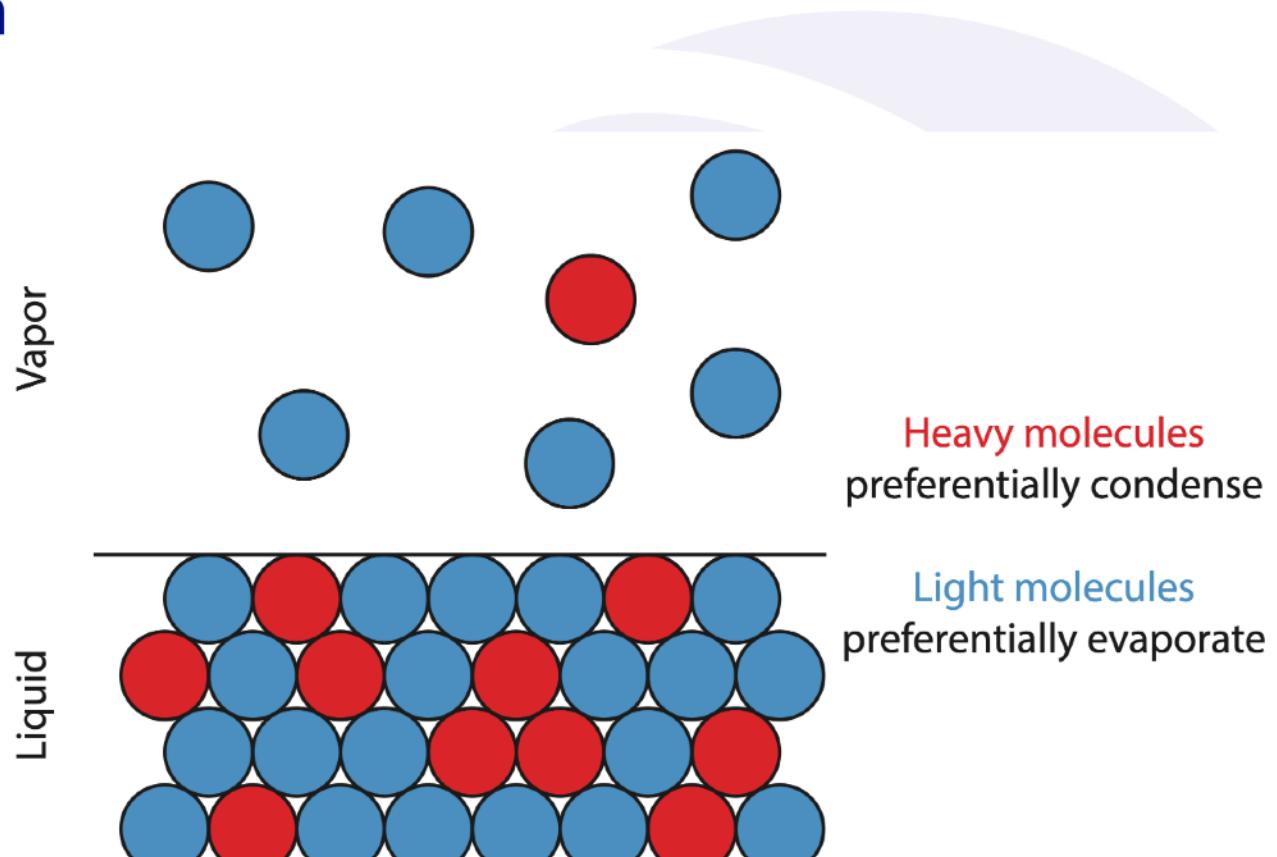
Water isotopologues:

$^1\text{H}_2^{16}\text{O}$  - 99.74%

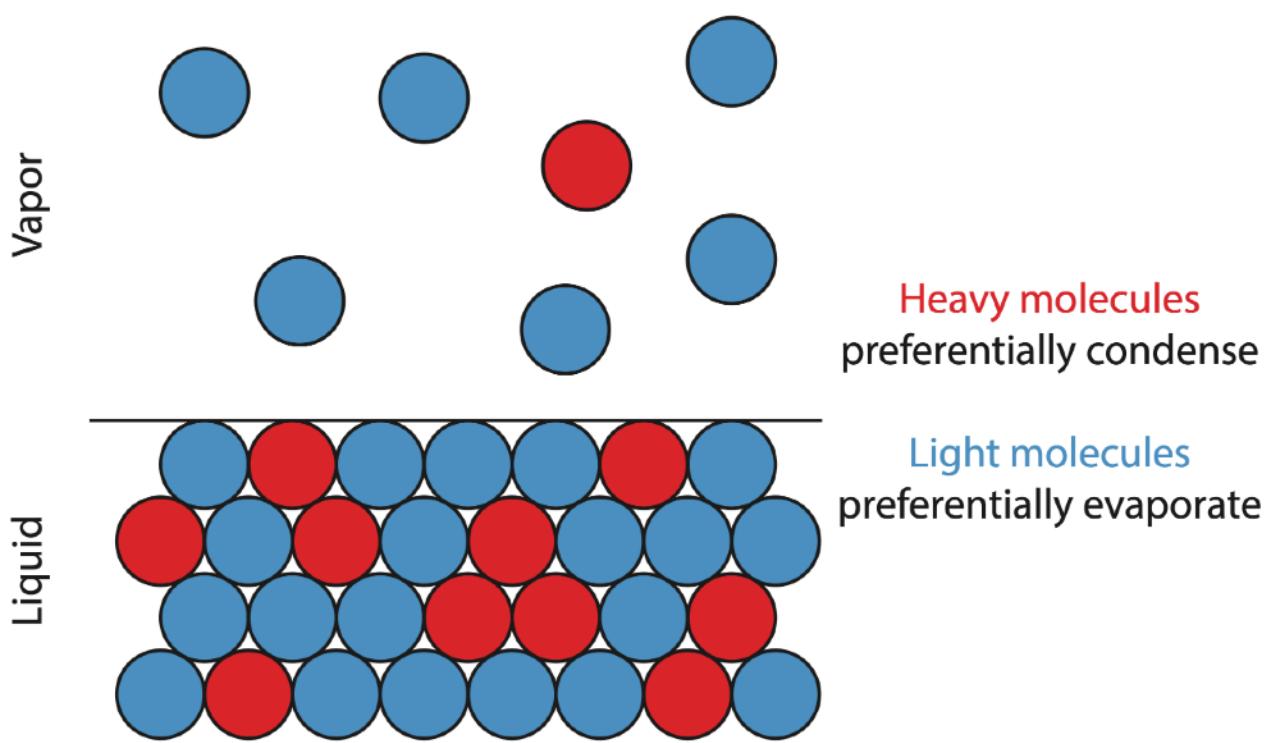
$^1\text{H}_2^{18}\text{O}$  - 0.20%

$^1\text{H}^2\text{H}^{16}\text{O}$  - 0.01%

Others - 0.05%



# Isotopic Fractionation



$$R = \frac{\text{heavy}}{\text{light}}$$

$$\alpha = \frac{R_{\text{liquid}}}{R_{\text{vapor}}}$$

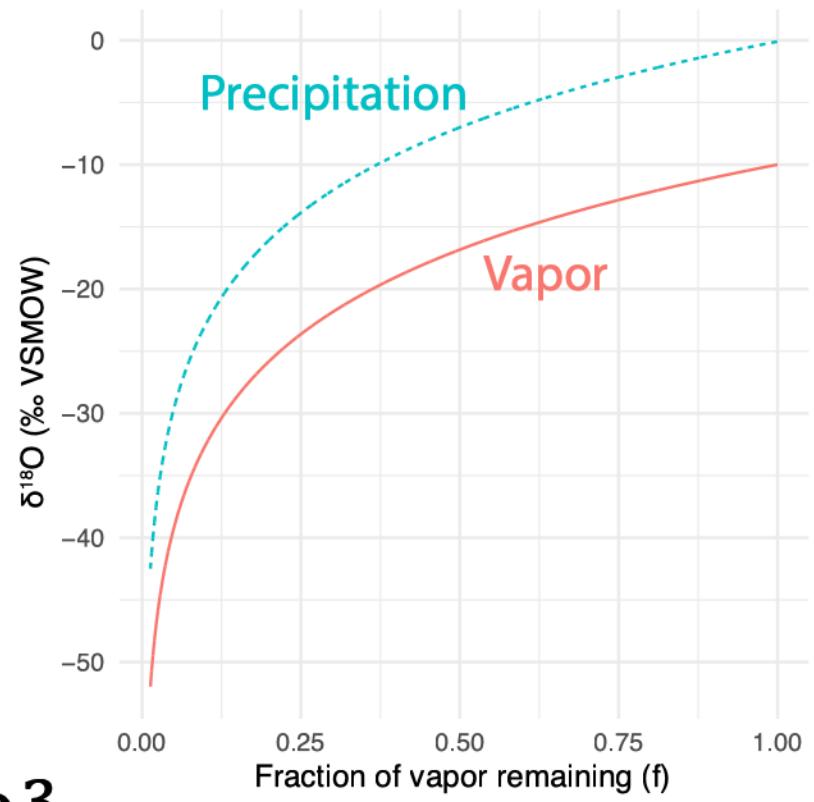
$$\delta = 10^3 \left( \frac{R}{R_{\text{std}}} - 1 \right)$$

## Rayleigh distillation

Dominant model to explain isotope ratio variability in precipitation, based on idealized open-system condensation

$$R = R_0 \left( \frac{q}{q_0} \right)^{\alpha-1}$$

$$\delta = (\delta_0 + 10^3) \left( \frac{q}{q_0} \right)^{\alpha-1} - 10^3$$

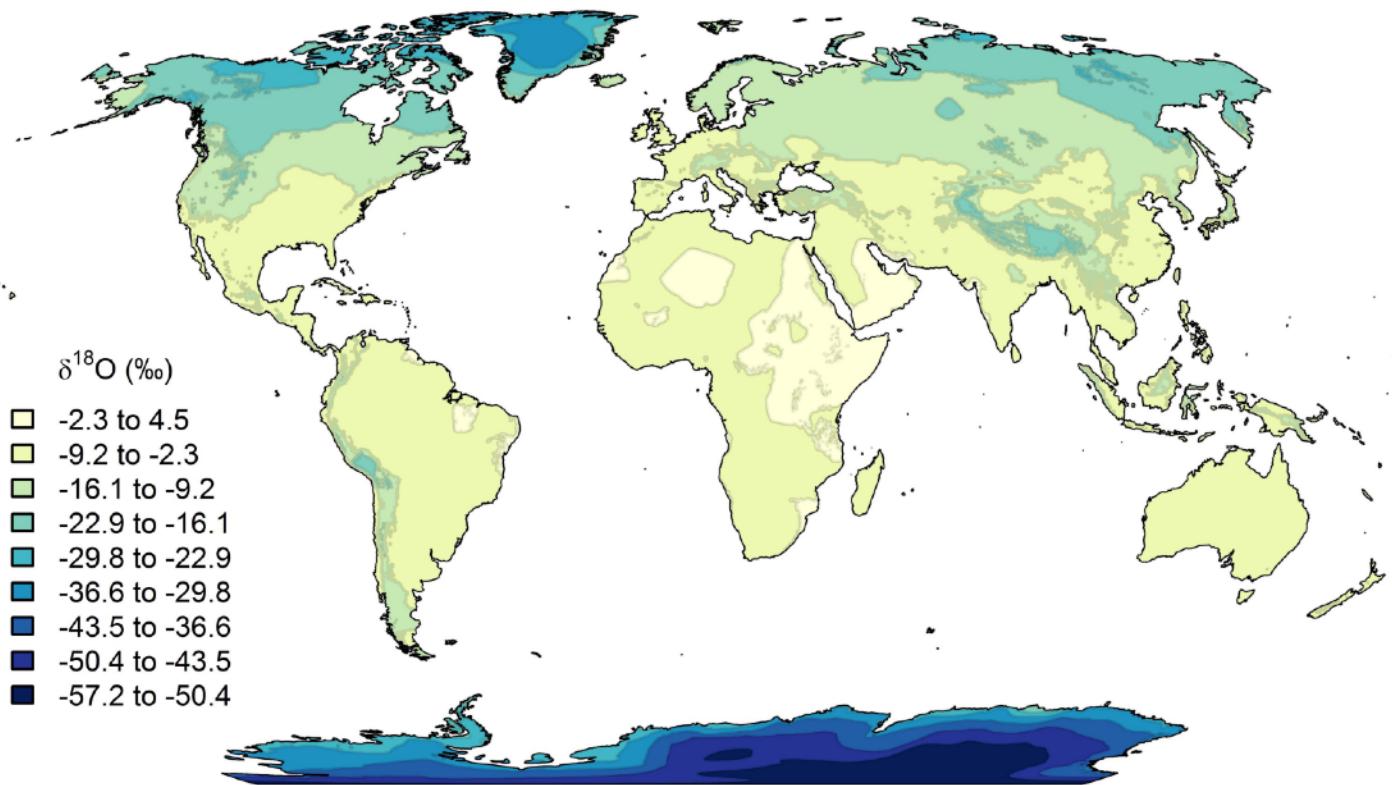


$$f = \frac{q}{q_0}$$

# Dependence of isotope ratios on climate and topography

$\delta$  has strong spatial pattern, low at:

- High latitude
- High altitude
- Continental interiors



<http://waterisotopes.org>

# How well does Rayleigh distillation explain precipitation isotope ratios?

1950s - ~1990s: “simple” applications of the rainout effect: local temperature (ground or cloud), local precipitation amount (“amount effect”), “continentality” (distance from coast).

More data has resulted in more mechanisms:

Lessons learned from oxygen isotopes in modern precipitation applied to interpretation of speleothem records of paleoclimate from eastern Asia

Katherine E. Dayem <sup>a,\*</sup>, Peter Molnar <sup>a</sup>, David S. Battisti <sup>b</sup>, Gerard H. Roe <sup>c</sup>

**Annual variation in event-scale precipitation  $\delta^2\text{H}$  at Barrow, AK, reflects vapor source region**

Annie L. Putman<sup>1,2</sup>, Xiahong Feng<sup>1</sup>, Leslie J. Sonder<sup>1</sup>, and Eric S. Posmentier<sup>1</sup>

**Stable isotopes in global precipitation: A unified interpretation based on atmospheric moisture residence time**

Pradeep K. Aggarwal,<sup>1</sup> Oleg A. Alduchov,<sup>2</sup> Klaus O. Froehlich,<sup>1</sup> Luis J. Araguas-Araguas,<sup>1</sup> Neil C. Sturchio,<sup>3</sup> and Naoyuki Kurita<sup>1,4</sup>

**Patterns of Evaporation and Precipitation Drive Global Isotopic Changes in Atmospheric Moisture**

Adriana Bailey<sup>1,2</sup> , Eric Posmentier<sup>1</sup>, and Xiahong Feng<sup>1</sup> 

**Spatiotemporal variability of modern precipitation  $\delta^{18}\text{O}$  in the central Andes and implications for paleoclimate and paleoaltimetry estimates**

Richard P. Fiorella<sup>1</sup>, Christopher J. Poulsen<sup>1</sup>, Ramiro S. Pilco Zolá<sup>2</sup>, Jason B. Barnes<sup>1,3</sup>, Clay R. Tabor<sup>1</sup>, and Todd A. Ehlers<sup>4</sup>

**Proportions of convective and stratiform precipitation revealed in water isotope ratios**

Pradeep K. Aggarwal<sup>1,\*</sup>, Ulrike Romatschke<sup>1</sup>, Luis Araguas-Araguas<sup>1</sup>, Dagnachew Belachew<sup>1</sup>, Frederick J. Longstaffe<sup>2</sup>, Peter Berg<sup>3</sup>, Courtney Schumacher<sup>4</sup> and Aaron Funk<sup>4</sup>

**A moisture budget perspective of the amount effect**

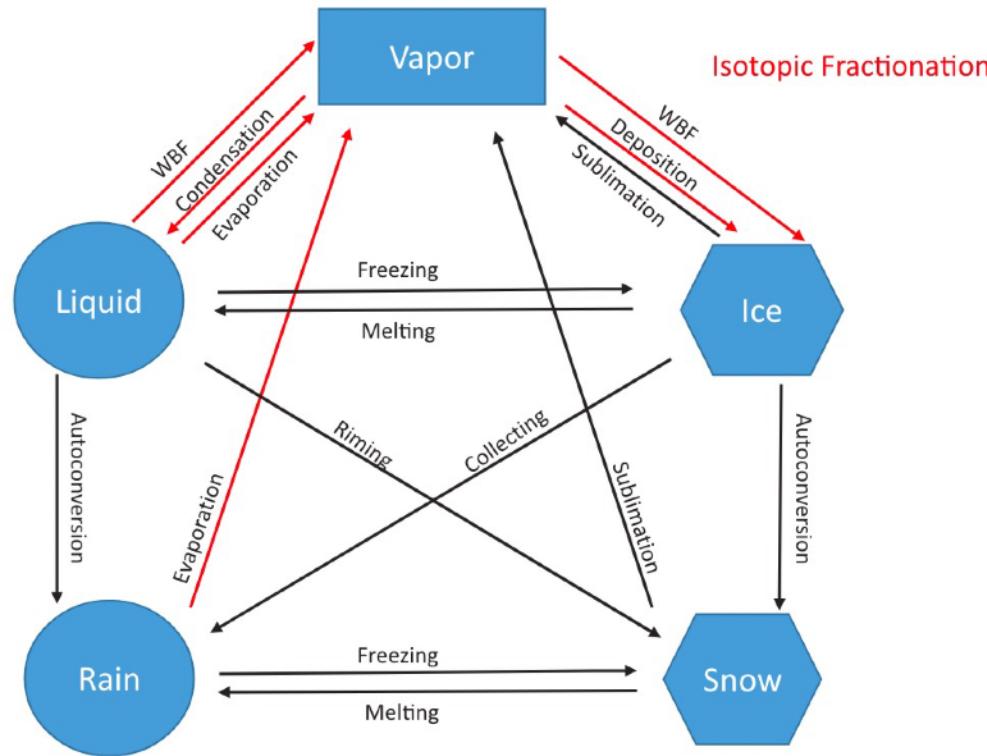
M. Moore<sup>1</sup>, Z. Kuang<sup>1,2</sup>, and P. N. Blossey<sup>3</sup>

**The Influence of Competing Hydroclimate Processes on Stable Isotope Ratios in Tropical Rainfall**

B. L. Konecky<sup>1,2</sup> , D. C. Noone<sup>3</sup> , and K. M. Cobb<sup>4</sup> 

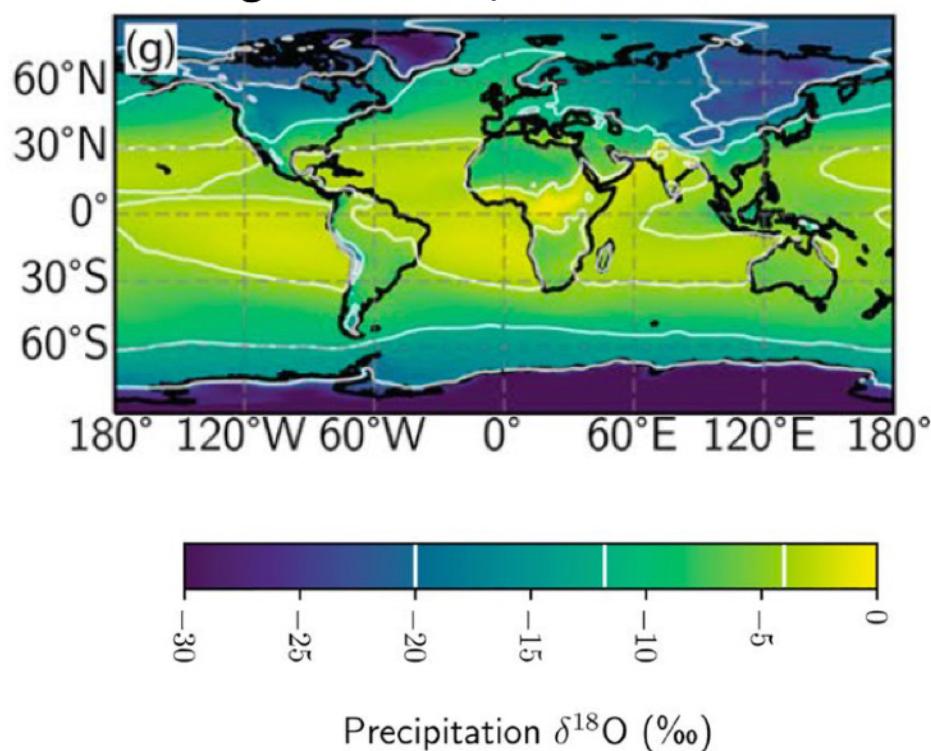
# Isotope tracers in Earth system models

Nusbaumer et al. 2017



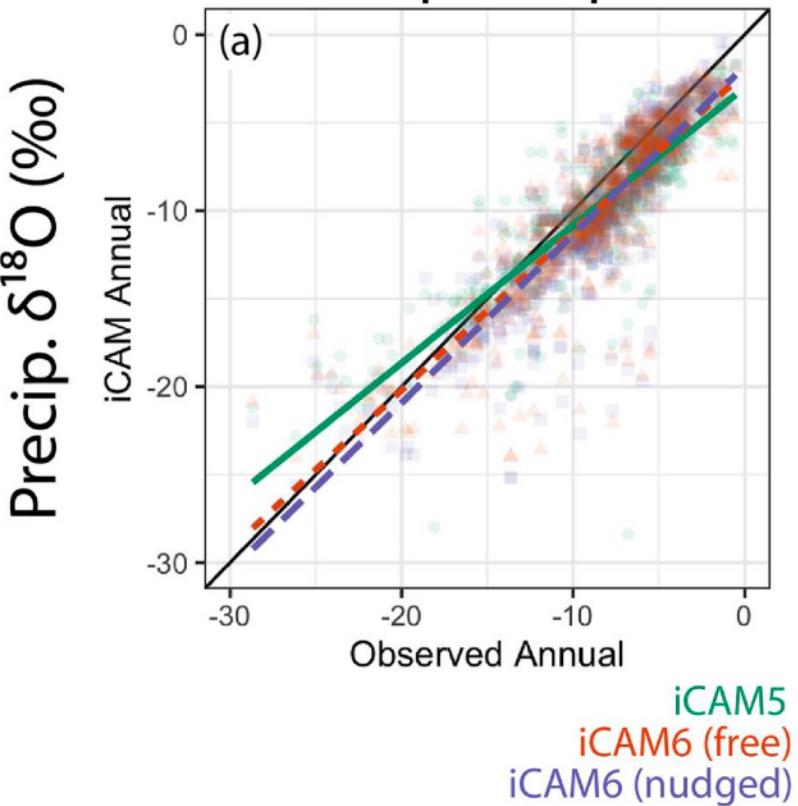
# Isotope tracers in Earth system models

CAM6, F compset (atm+Ind), 0.9x1.25°FV,  
nudged to ERA5, 1980-2004 mean

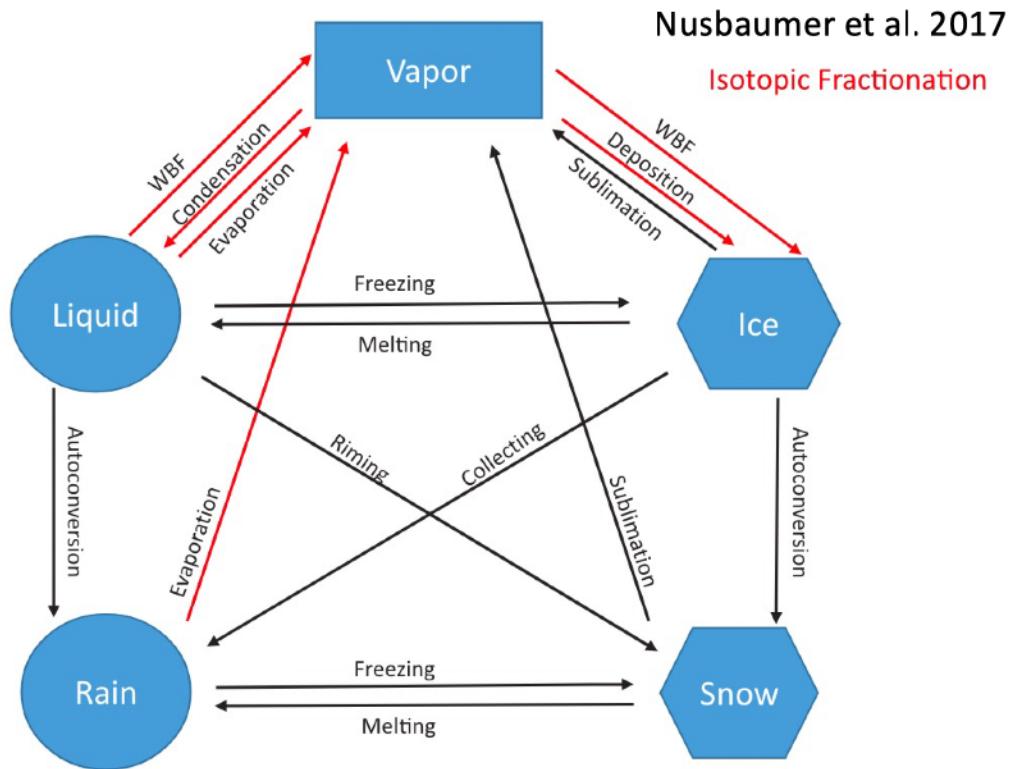


[Fiorella et al. 2021]

## Annual spatial pattern



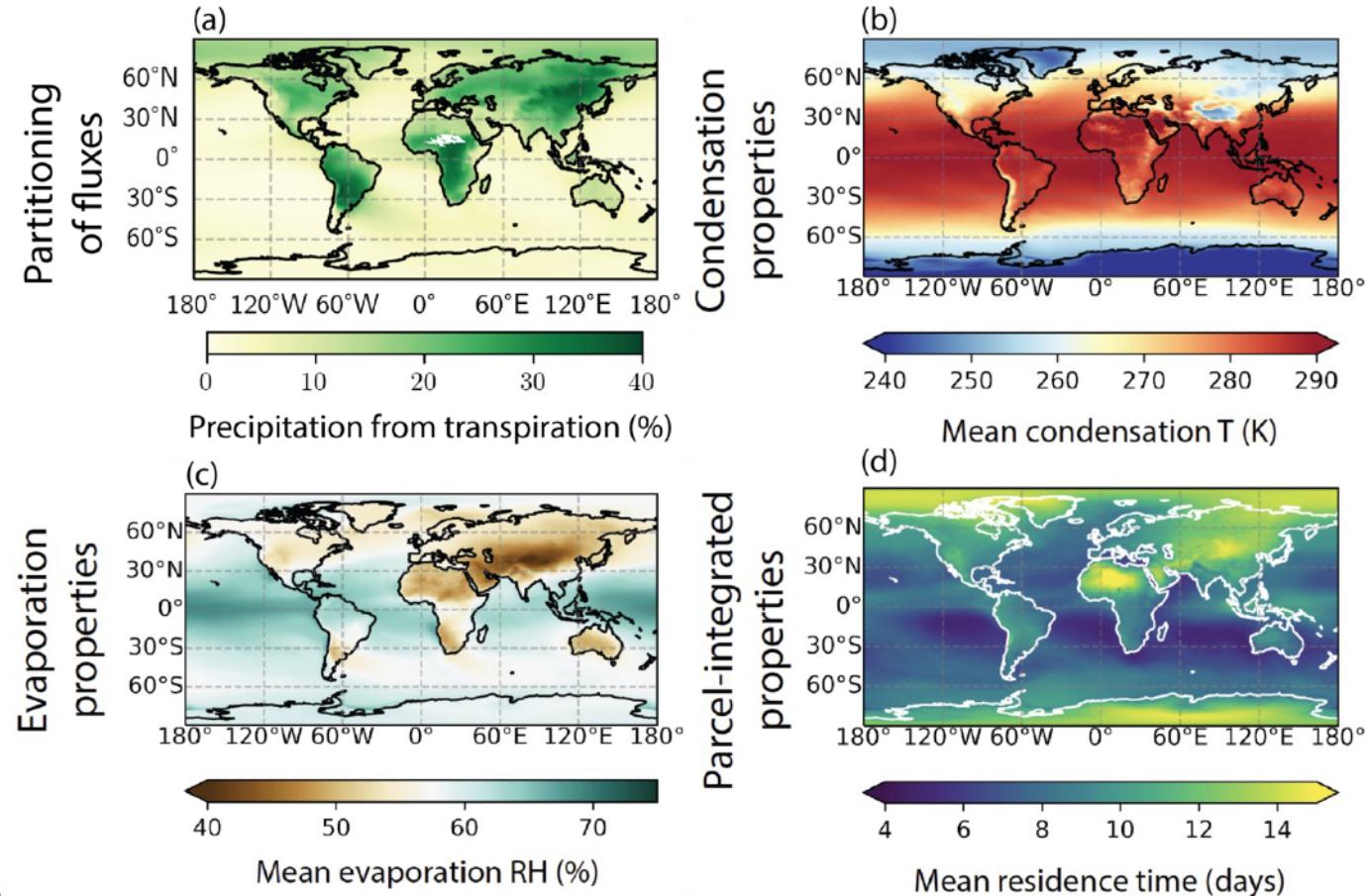
# Process tracers in Earth system models



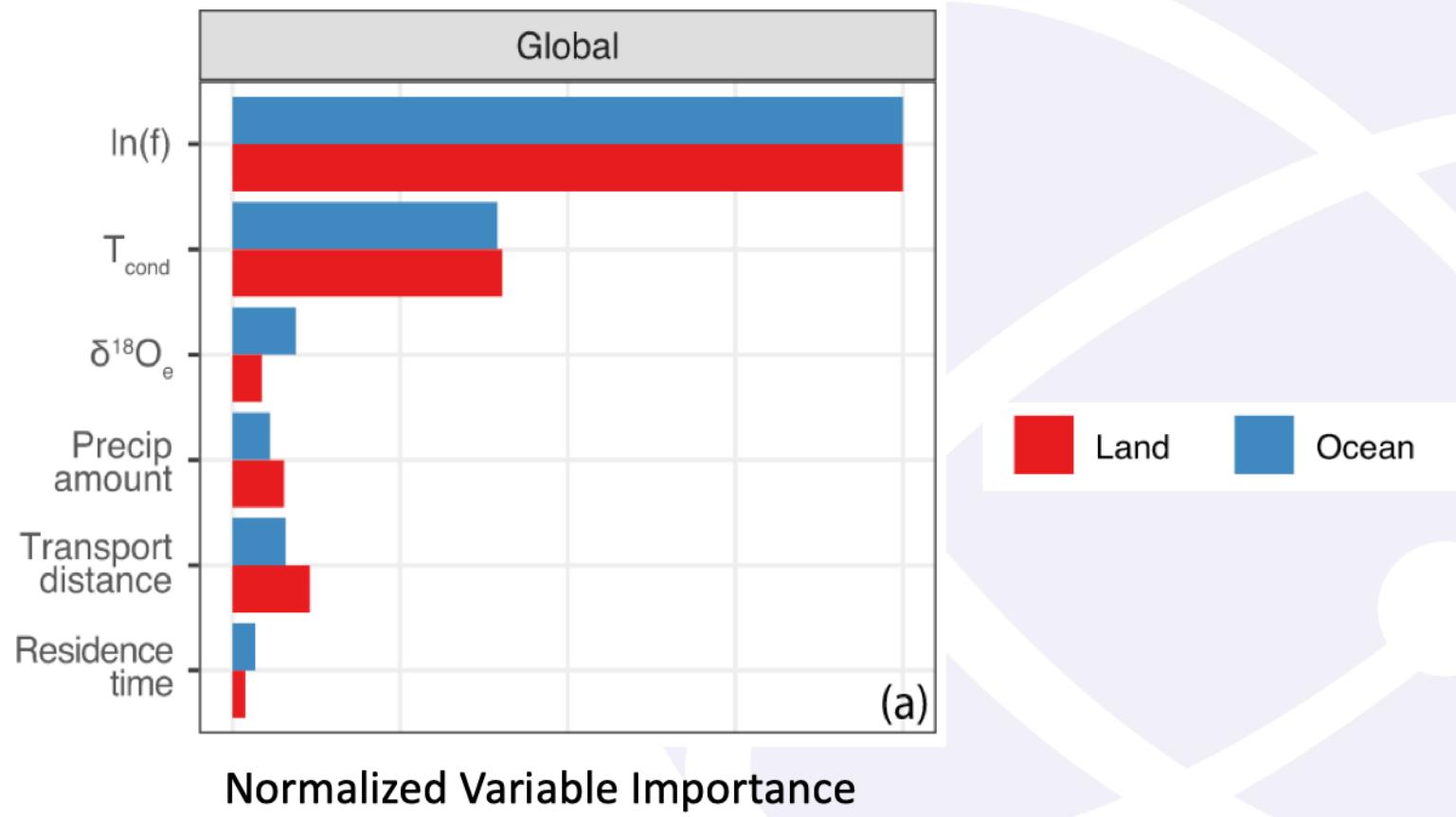
We can change fractionation factors + flux weighting to preserve any property of evaporation, condensation or transport!

# Enhanced hypothesis testing and model metrics

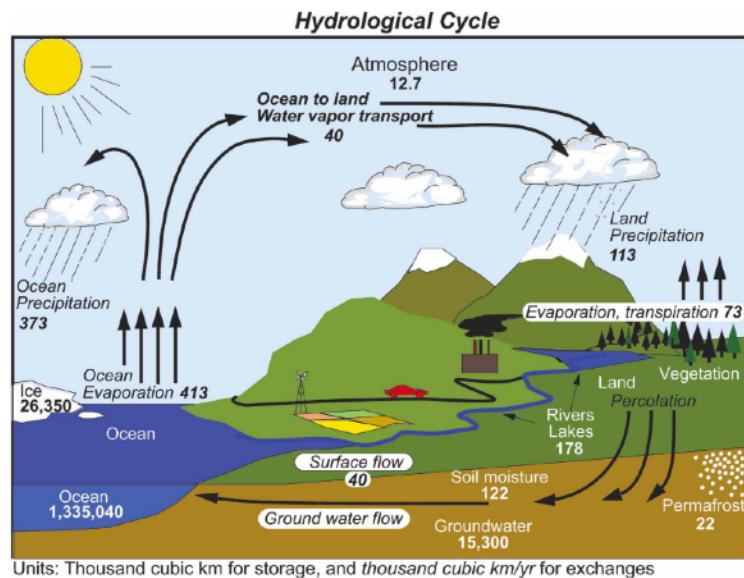
Extracting more information on hydrological processes using “process” tracers



# New variables for regression/machine learning: how important are different drivers of precipitation $\delta^{18}\text{O}$ ?



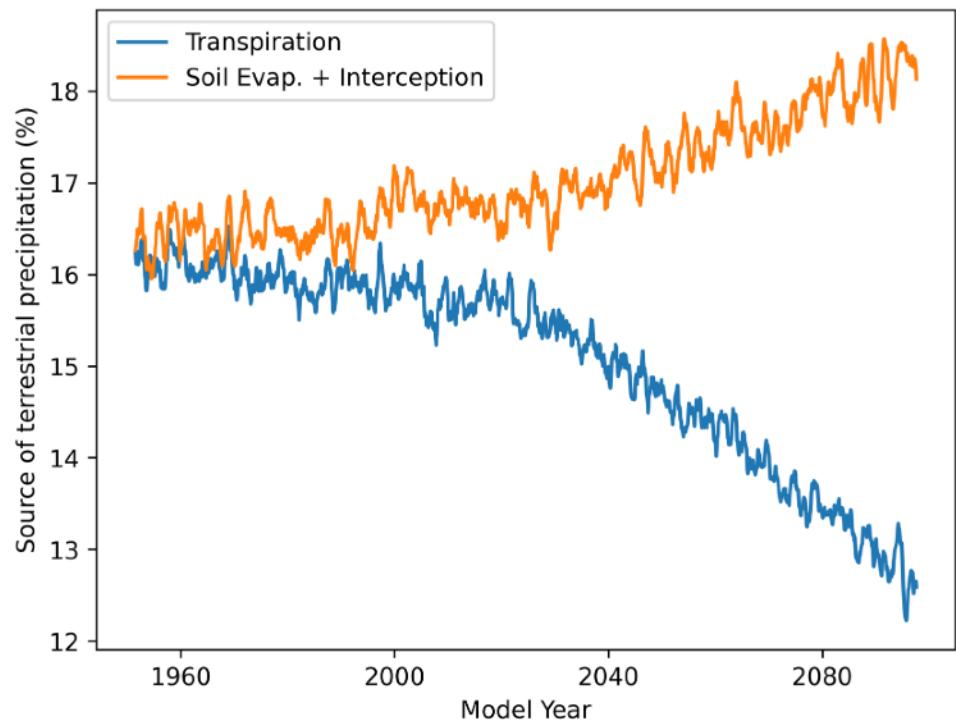
# Changing origins of terrestrial precipitation



[Trenberth et al. 2007]



F compset (atm+Ind), 0.9x1.25° FV, SSP3-7.0



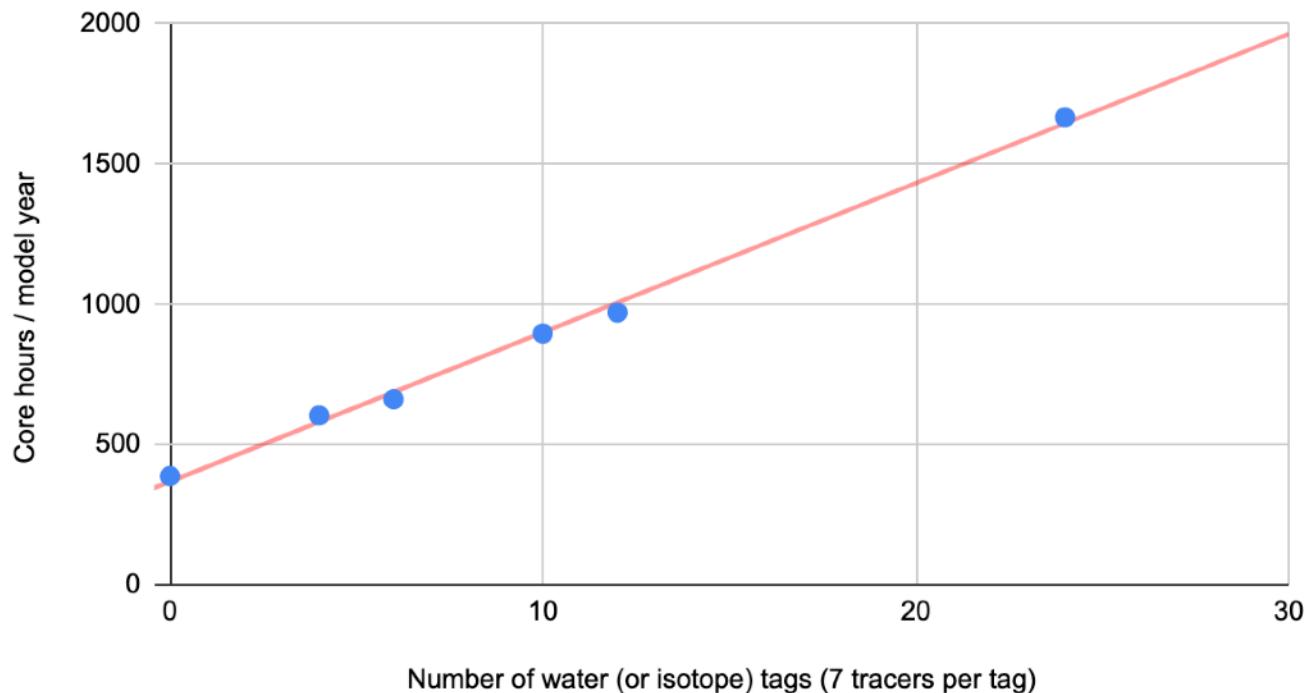
[Fiorella et al., in prep]

# Water isotope ratios and T/ET partitioning



## Why not include tracers? Tracers are expensive

CAM6-FV, 2x2°



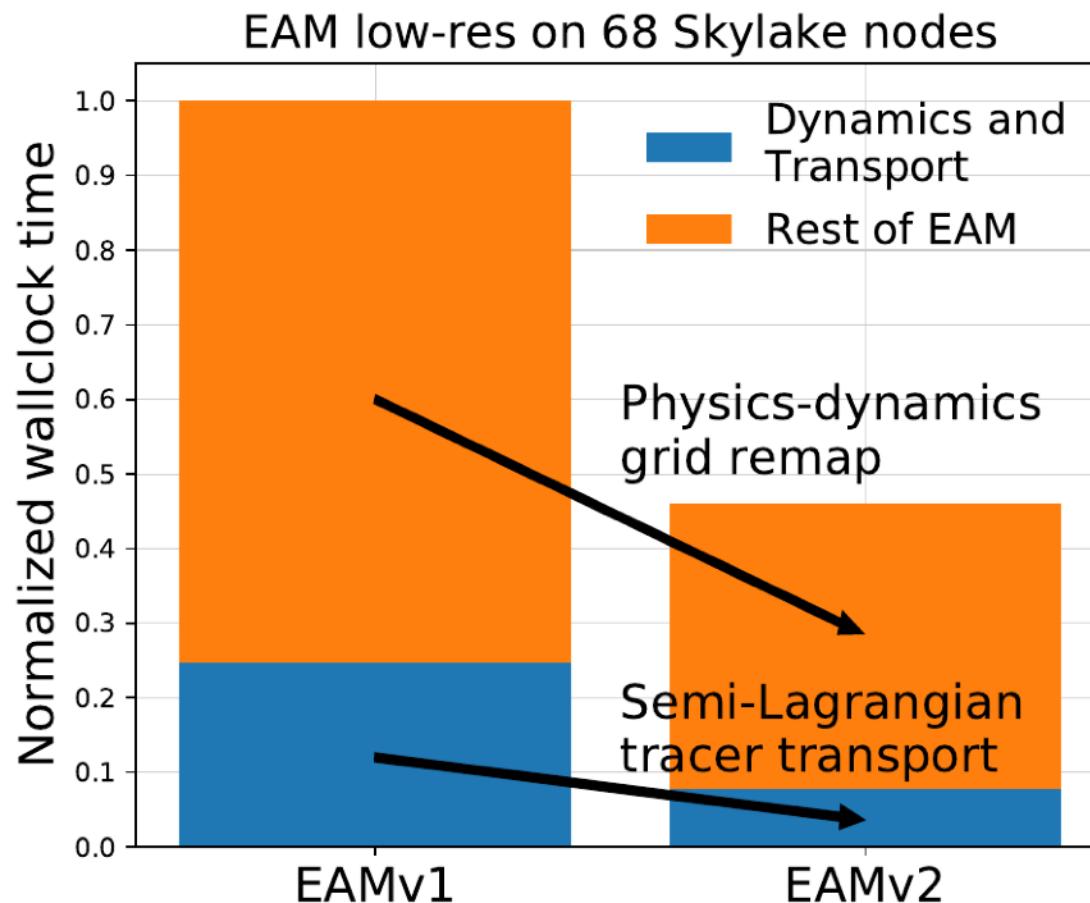
Runs I have described so far:

- CAM6, F compset (atm+Ind) on NCAR Cheyenne
- FV dycore
- Either 1x1 or 2x2 nominal resolution

Adding isotopes alone increases cost by 50%

Cost >4x if we want to trace only 20 locations/properties/processes

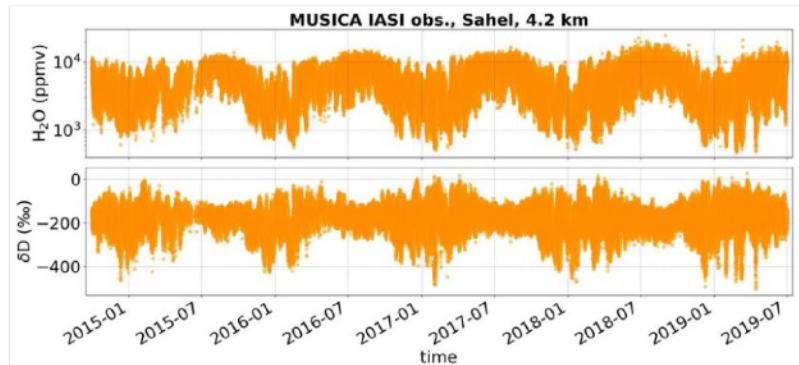
# Developments in E3SM have reduced tracer cost substantially



# Ever expanding range of isotopic datasets for validation, data assimilation, and processes studies

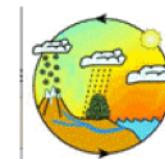
AmeriFlux and the NEON Program  
Join Forces for Eddy Covariance  
Data

June 24, 2020



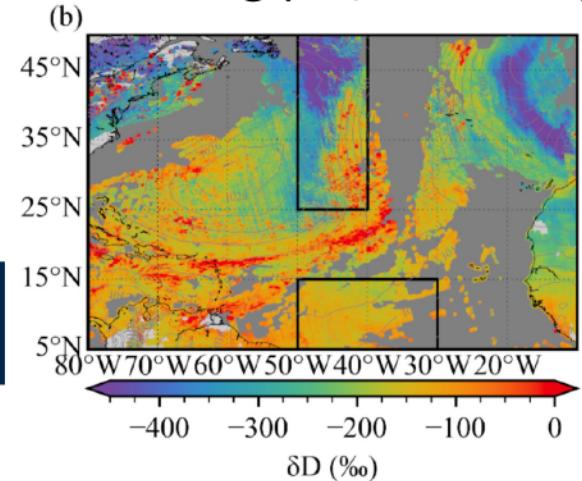
IAEA

International Atomic Energy Agency



Waterisotopes.org

Remote sensing (ex., TROPOMI)



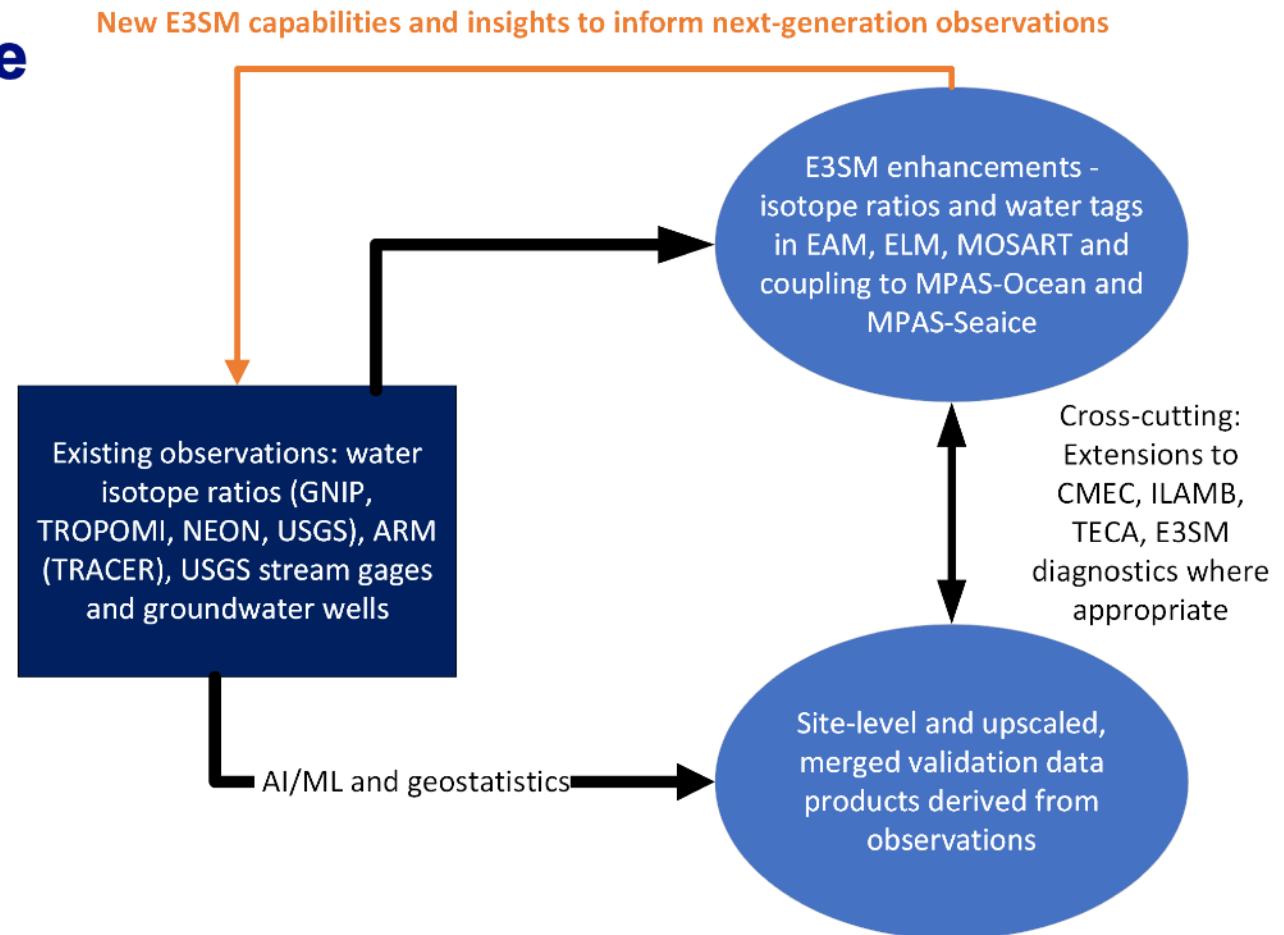
RESTON STABLE ISOTOPE LABORATORY (RSIL)



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# A fully-coupled water tracer infrastructure in E3SM



# Conclusions

1. Water isotope ratios are a powerful tool for understanding hydrological processes across all Earth system model domains
2. “Process-oriented” water tracers, derived from the same code, provide new insight into hydrological processes that can improve interpretation of both observed data and model processes, and help to validate new parameterizations
3. Tracers can be computationally expensive, but the improved performance of tracer transport in E3SM provides a new opportunity
4. Water isotope ratio data are rapidly becoming more available, providing a critical link between models and observations, as well as providing new opportunities to improve process representations (e.g., T/ET partitioning, cloud processes, partitioning of streamflow, coastal or urban impacts on hydrology, etc.)



**Questions?**

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