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Improving representations of hydrological processes in coupled models with water isotope ratios

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Talk Outline

1. Brief introduction to water isotope ratios as tracers
2. Natural metric for “unit and regression” testing of the water cycle
3. Urban signatures on water vapor isotope ratios
4. Extensions to generalized ”process-oriented” tracers and DOE missions

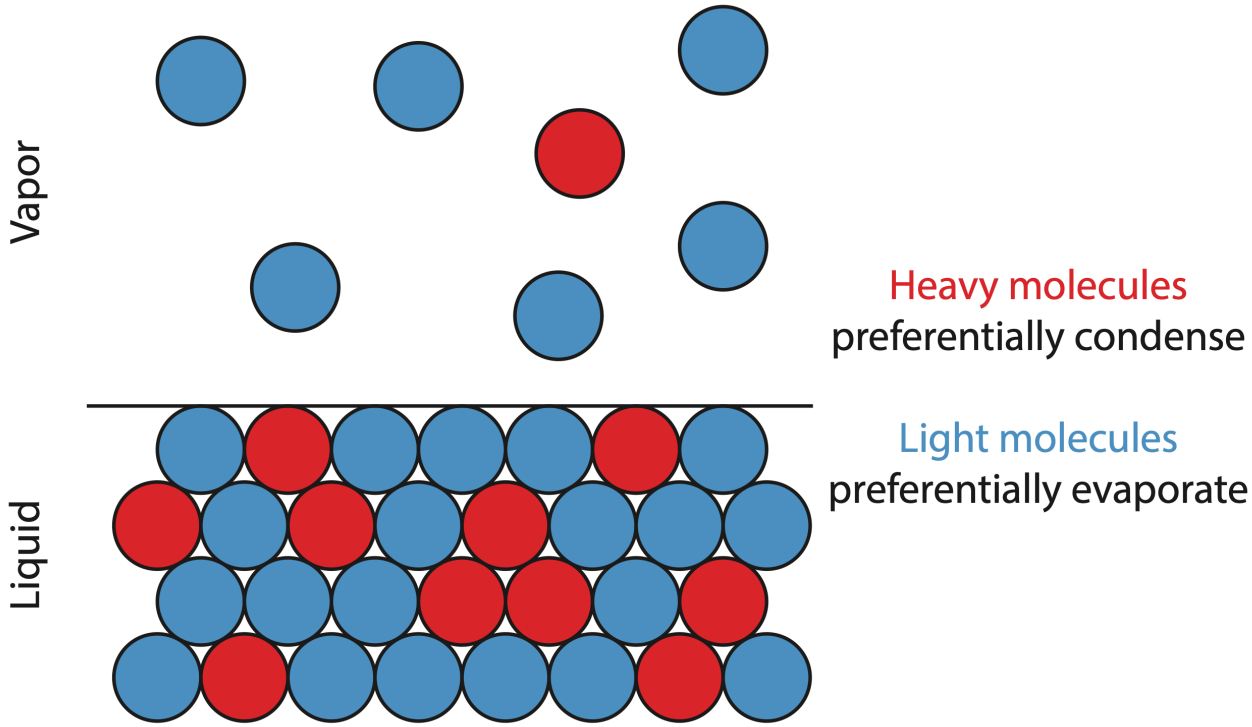
Isotope Fractionation

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

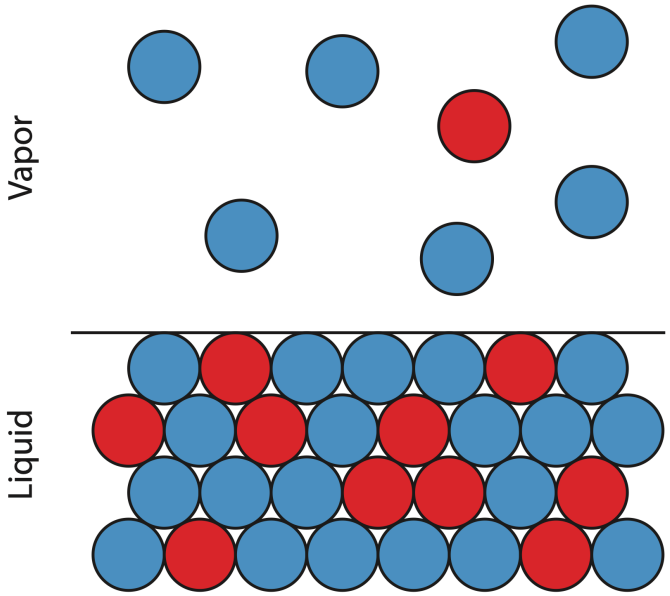
Hydrogen: 99.99% ^{1}H, 0.01% ^{2}H

Water isotopologues:

- $^{1}H_2{}^{16}O$ - 99.74%
- $^{1}H_2{}^{18}O$ - 0.20%
- $^{1}H^{2}H^{16}O$ - 0.01%
- Others - 0.05%

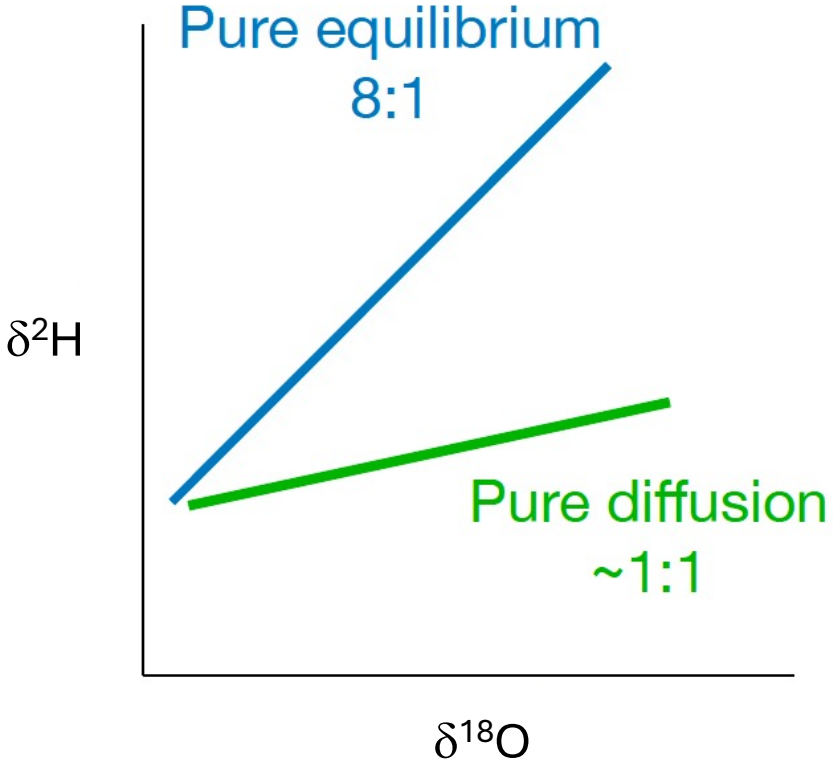


Isotopic Fractionation



Heavy molecules
preferentially condense

Light molecules
preferentially evaporate



Atmospheric dynamics captured in a bottle

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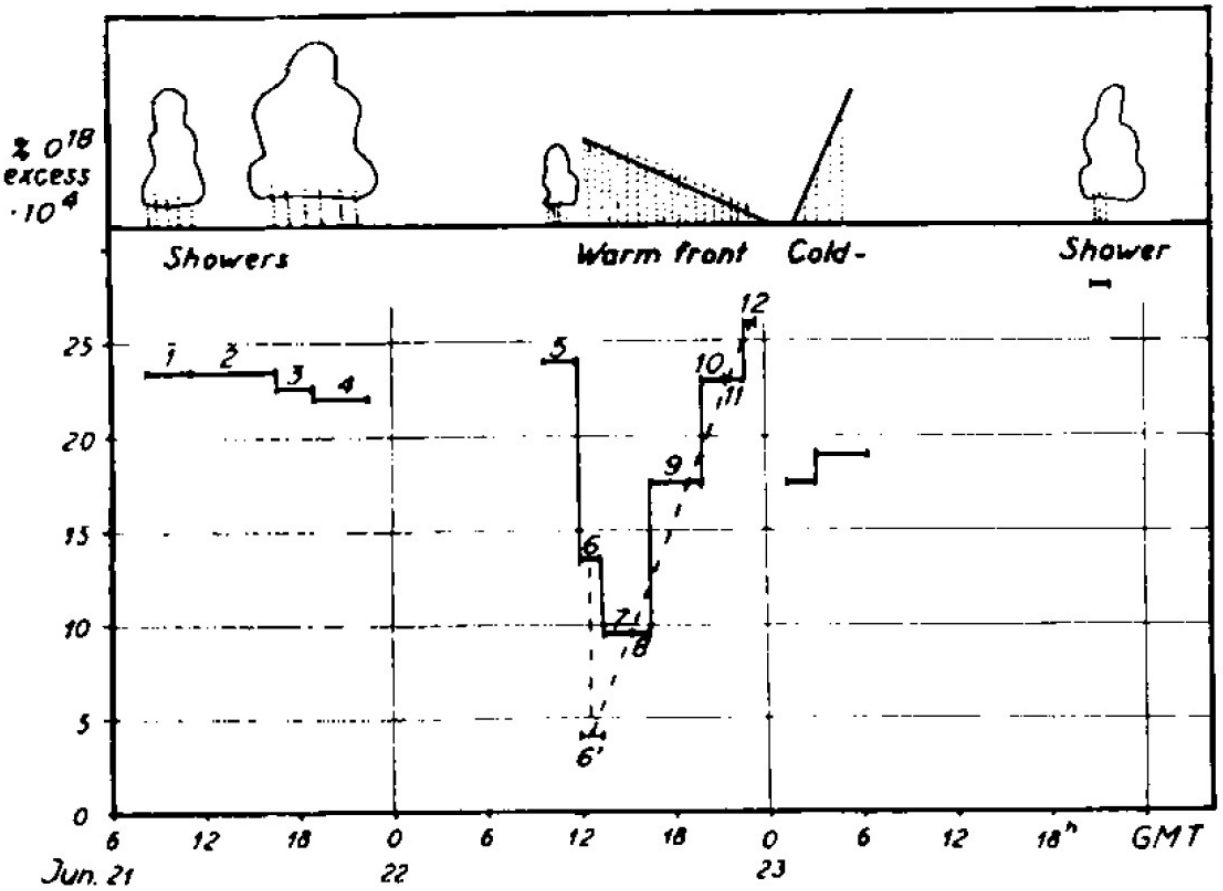
[Dansgaard 1953]



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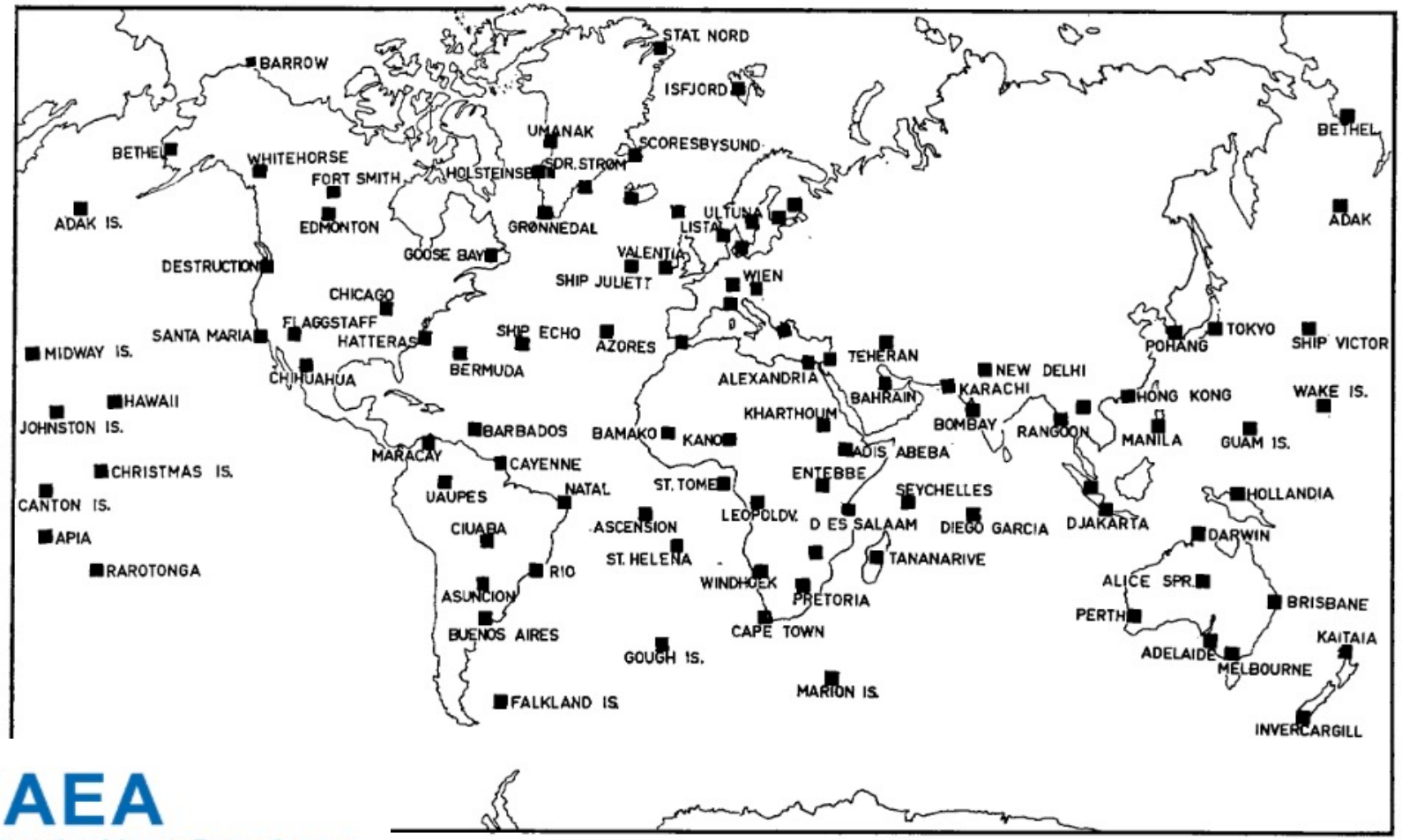


FIG. 7. The I.A.E.A.-W.M.O. precipitation network.

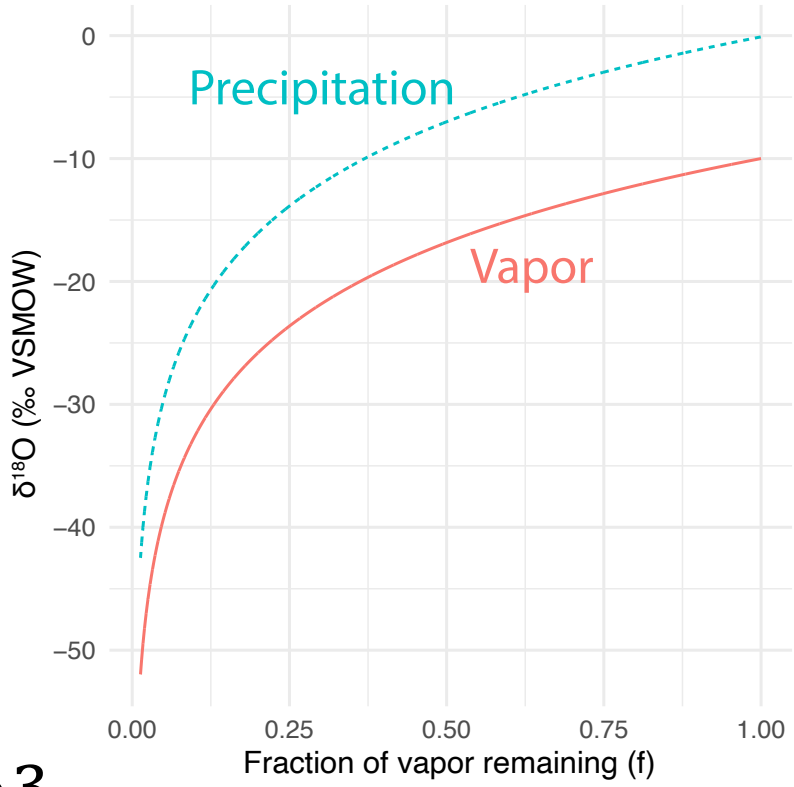
[Dansgaard 1964]

Rayleigh distillation

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

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

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

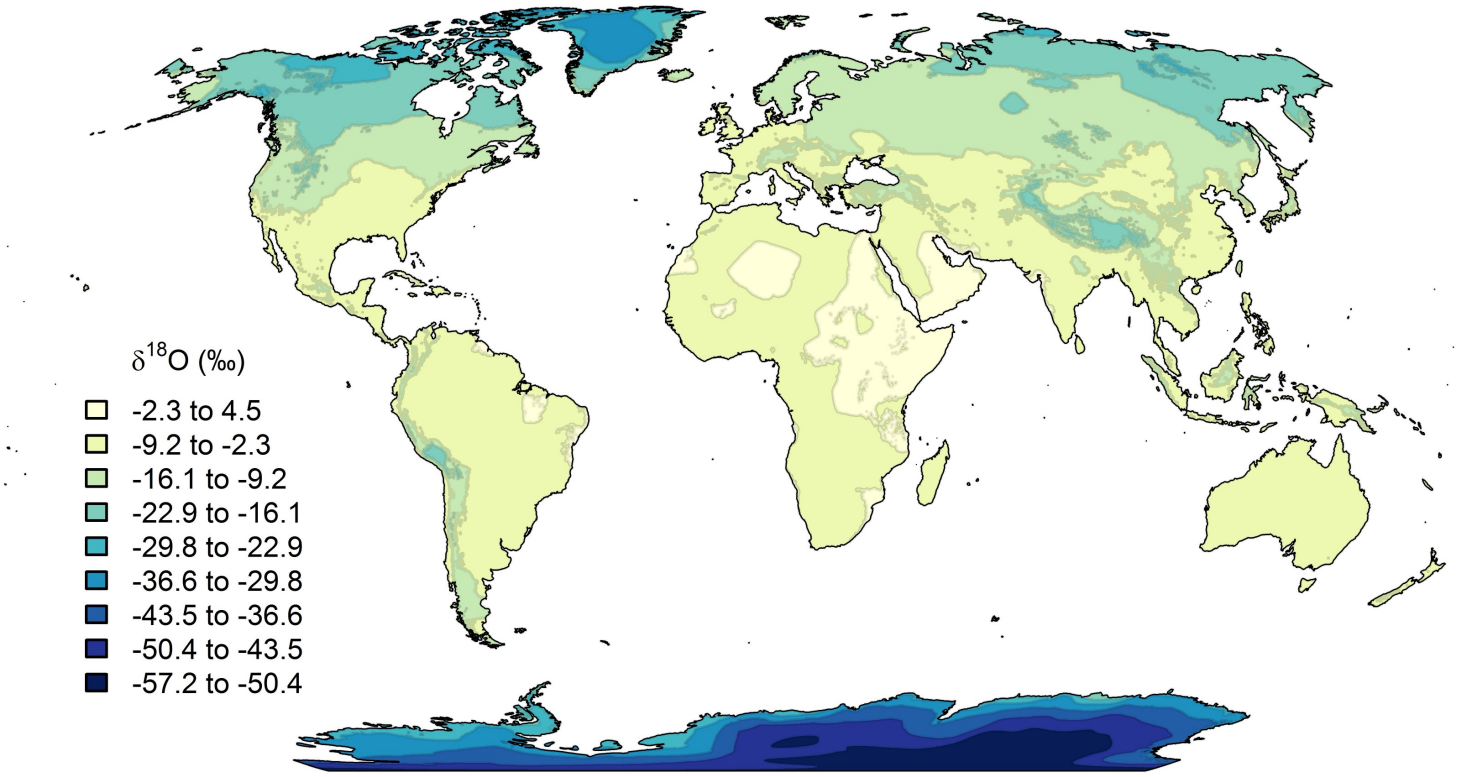


$$f = \frac{q}{q_0}$$

Precipitation isotope ratios match patterns in E, P, transport

δ in long-term mean has strong spatial pattern, low at:

- High latitude
- High altitude
- Continental interiors



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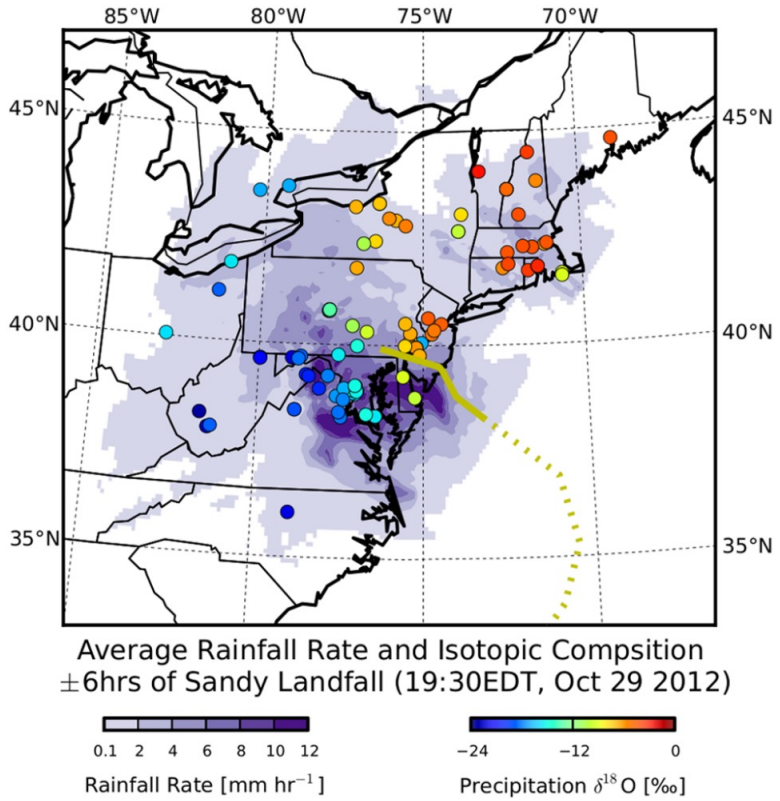
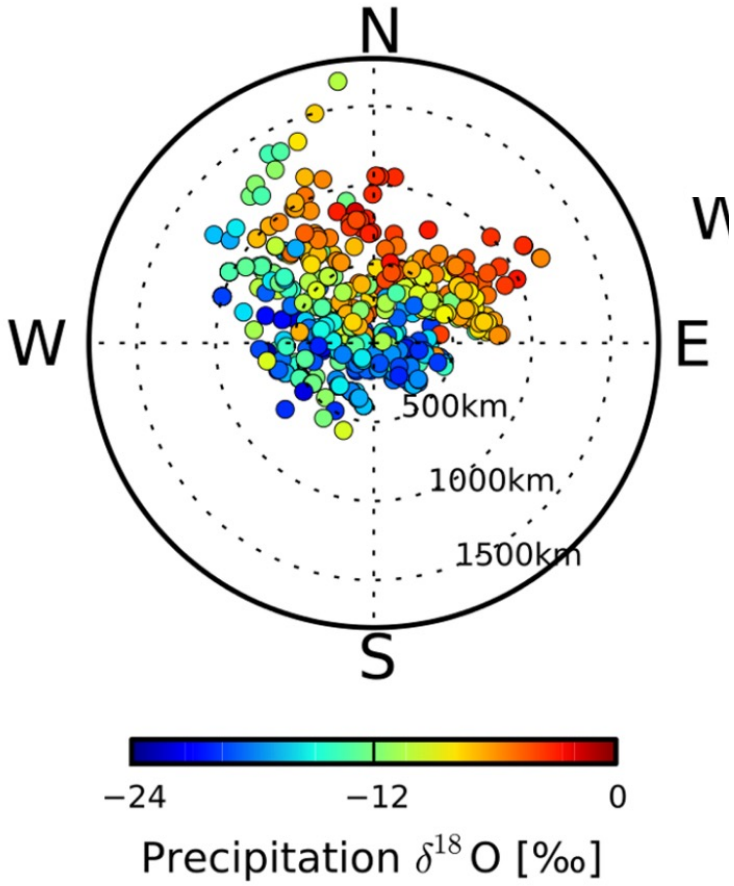
http://waterisotopes.org

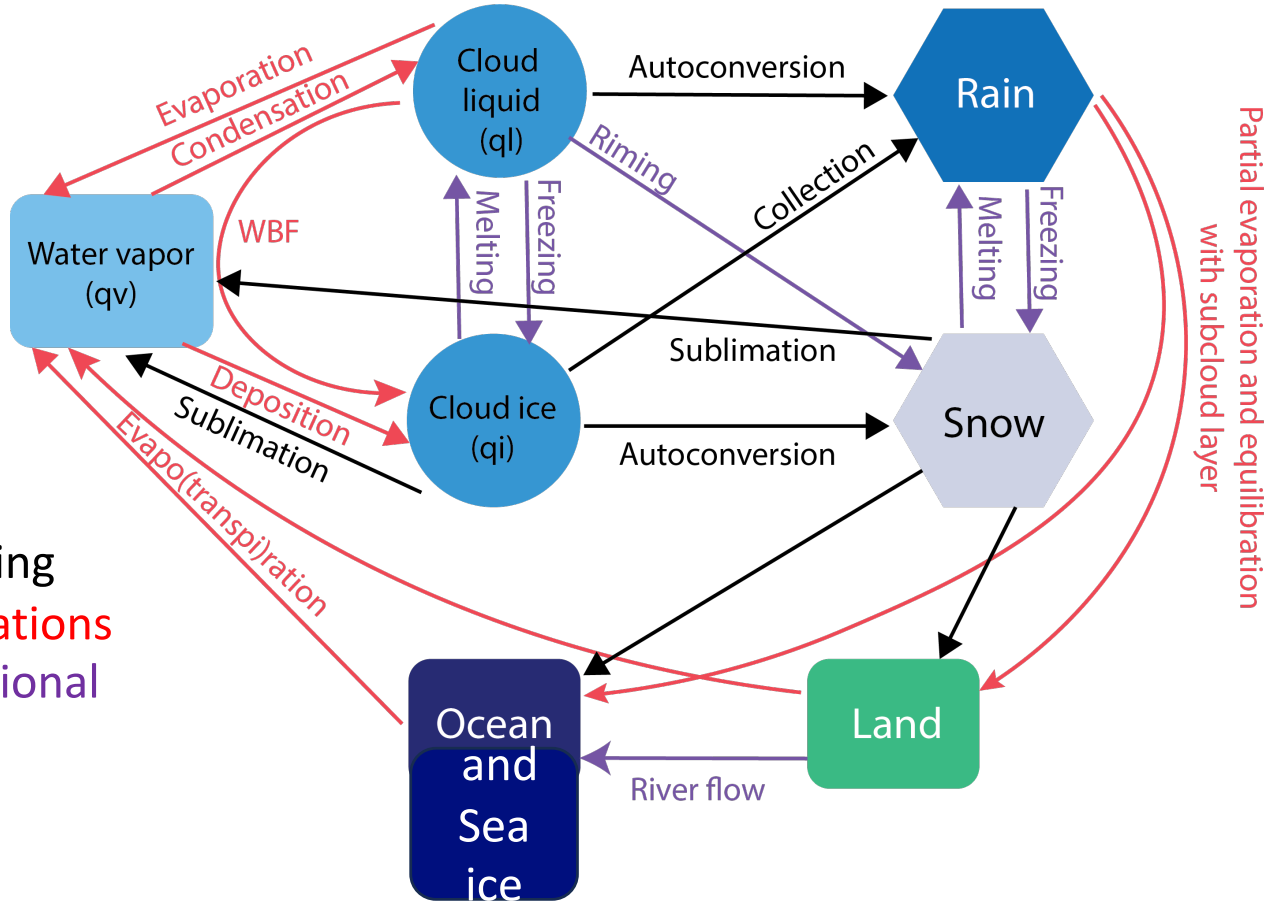
Isotope ratios reflect patterns in E, P, transport across scales





[Good et al. 2015]

Isotope tracers in Earth system models provide natural, observable unit and regression tests



Not fractionating

Large fractionations

Small or situational fractionation

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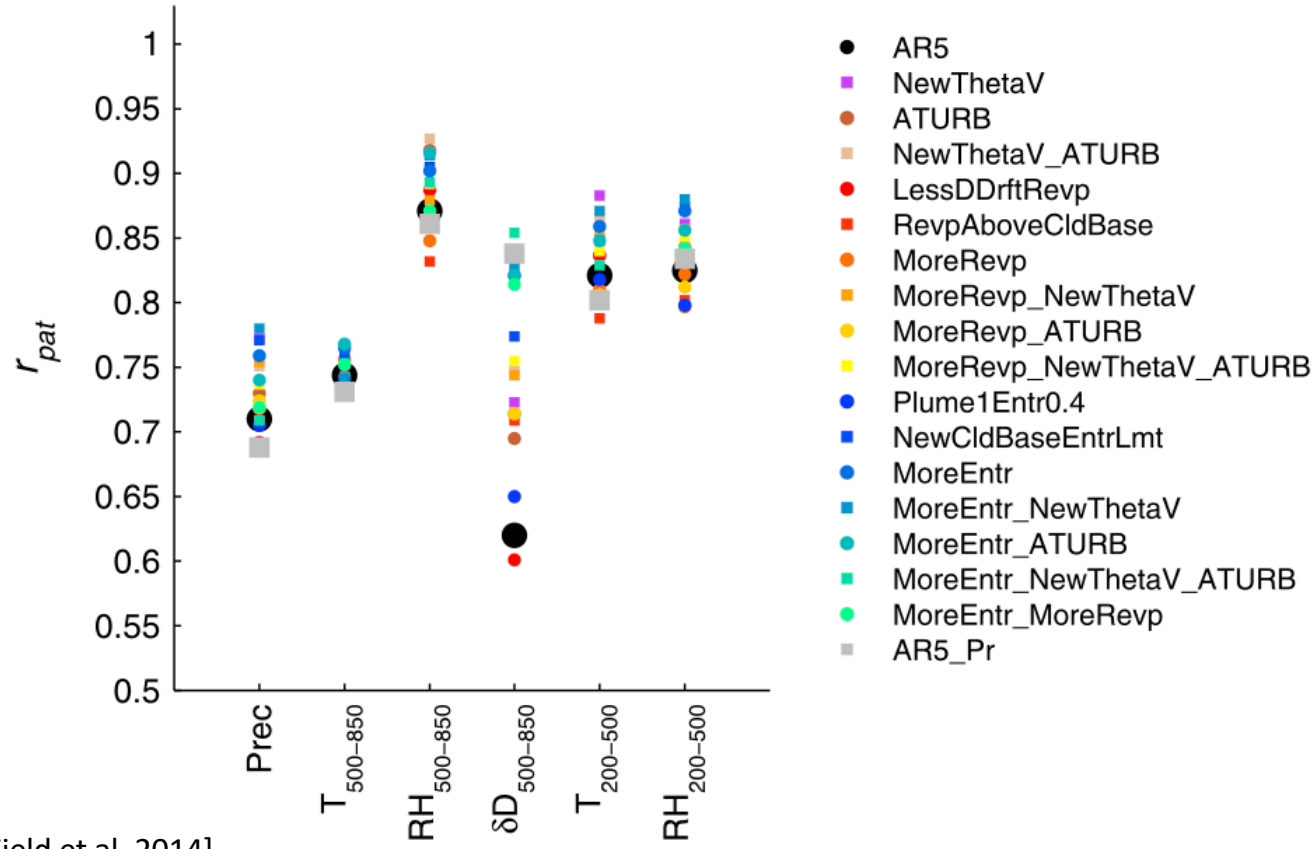
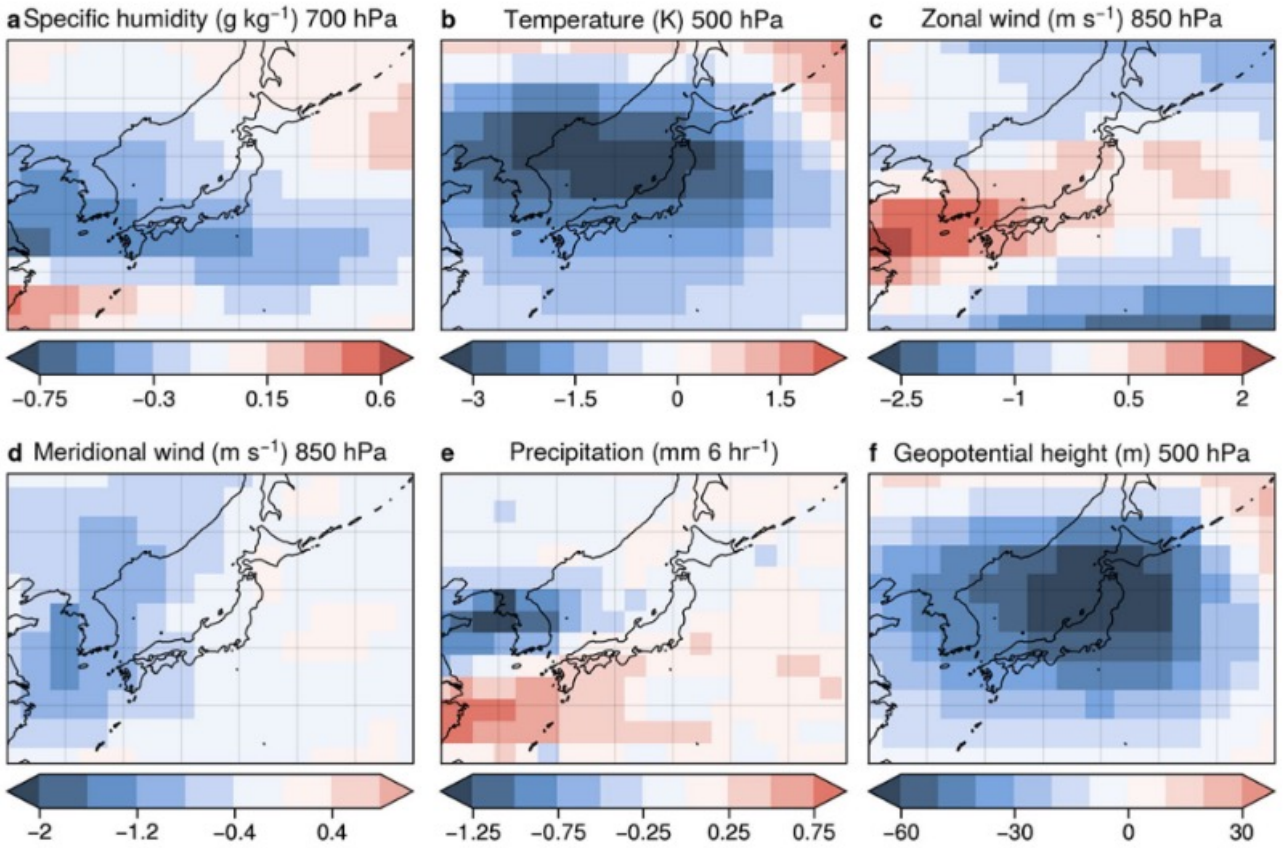
Water isotope ratios can advance model development, evaluation, and improvement



[Field et al. 2014]

Assimilation of water isotope ratios improves forecasts



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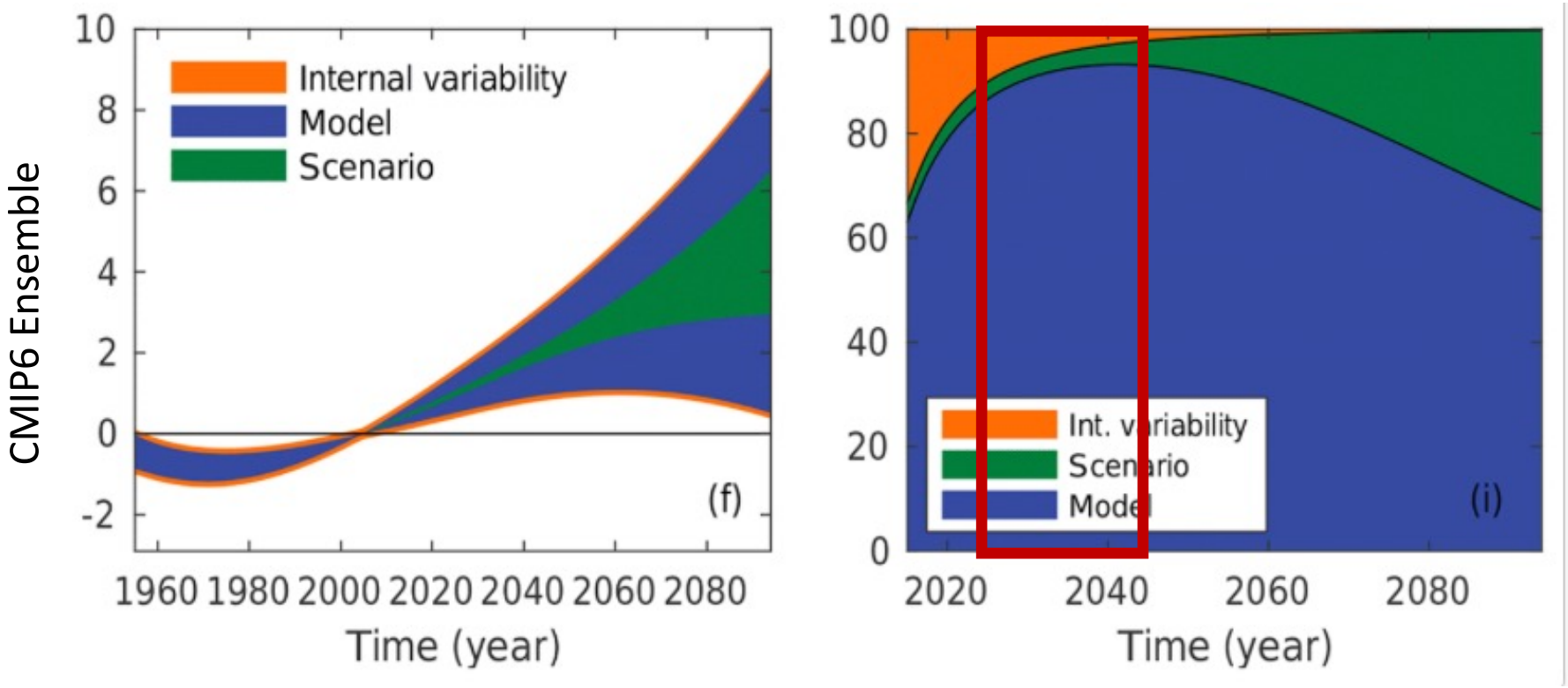
[Tada et al. 2021]

Blue = lower RMSE from assimilating water isotopes

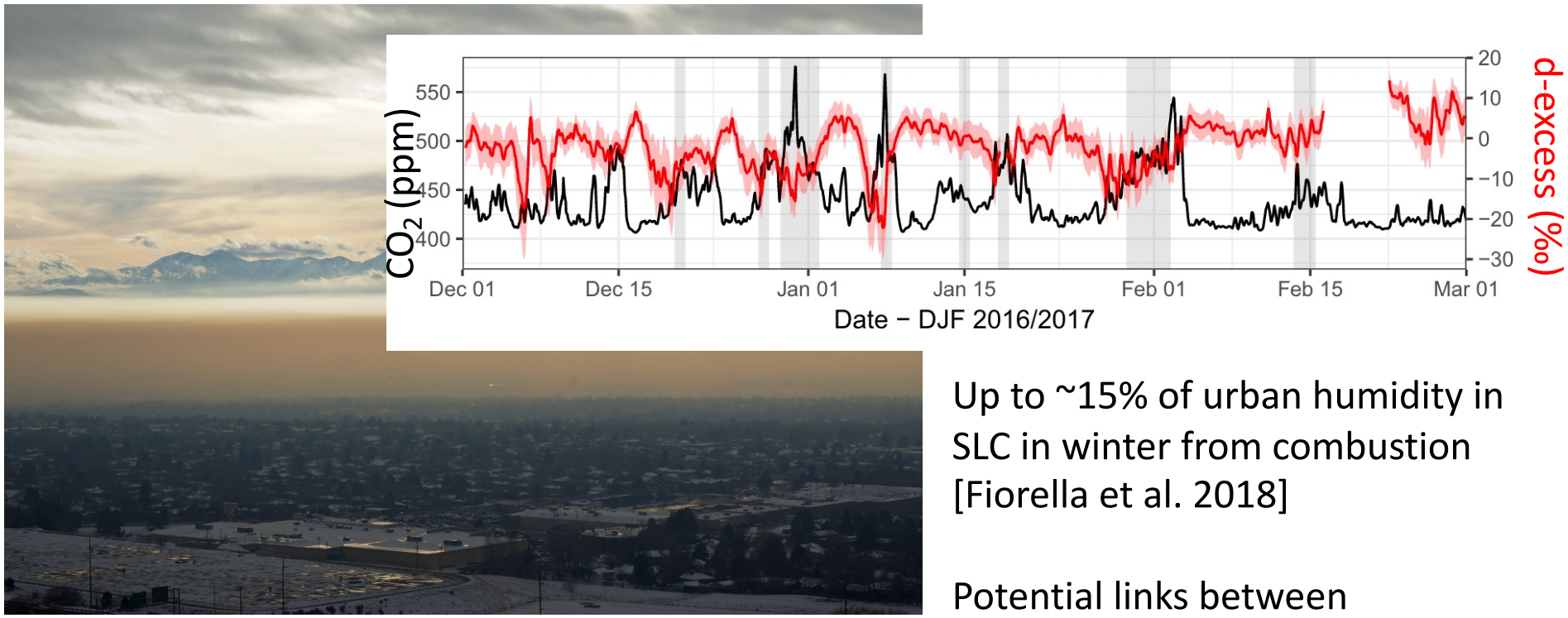
Extra hydrological constraints to reduce model uncertainty in ~decadal predictions



Model uncertainty as a source of projection uncertainty peaks around 1-2 decades

[Lehner et al. 2023]

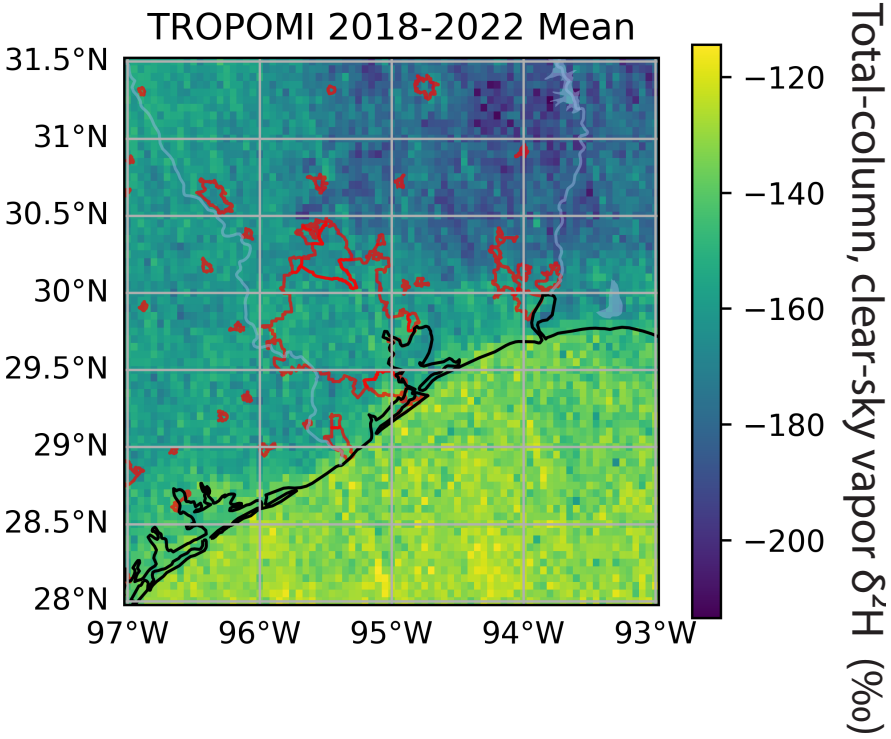
Anthropogenic isotope ratio signatures

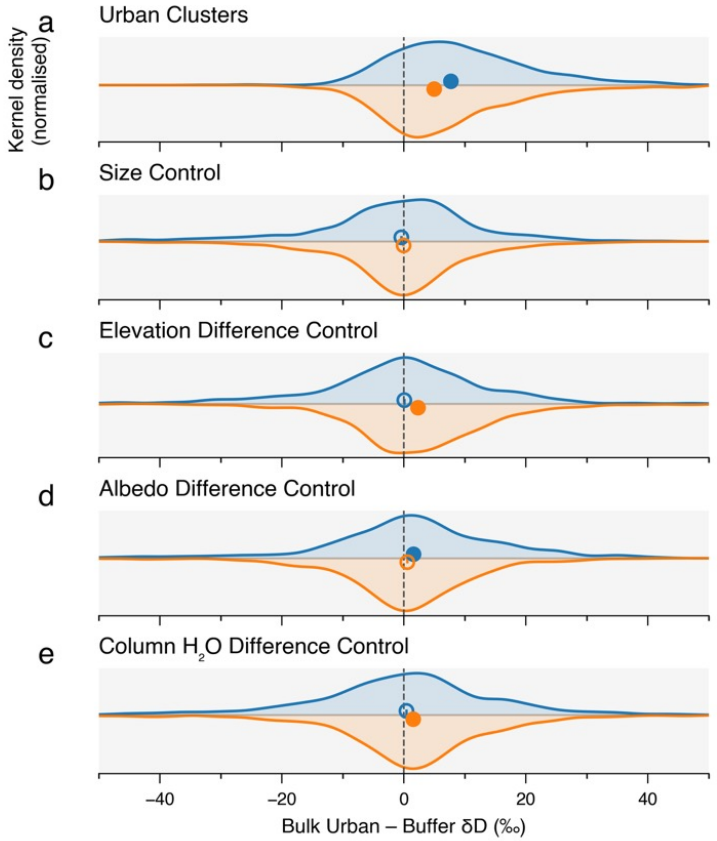


Up to ~15% of urban humidity in SLC in winter from combustion [Fiorella et al. 2018]

Potential links between combustion vapor and air quality [Xing et al. 2021]

A global urban signal in urban water vapor isotope ratios



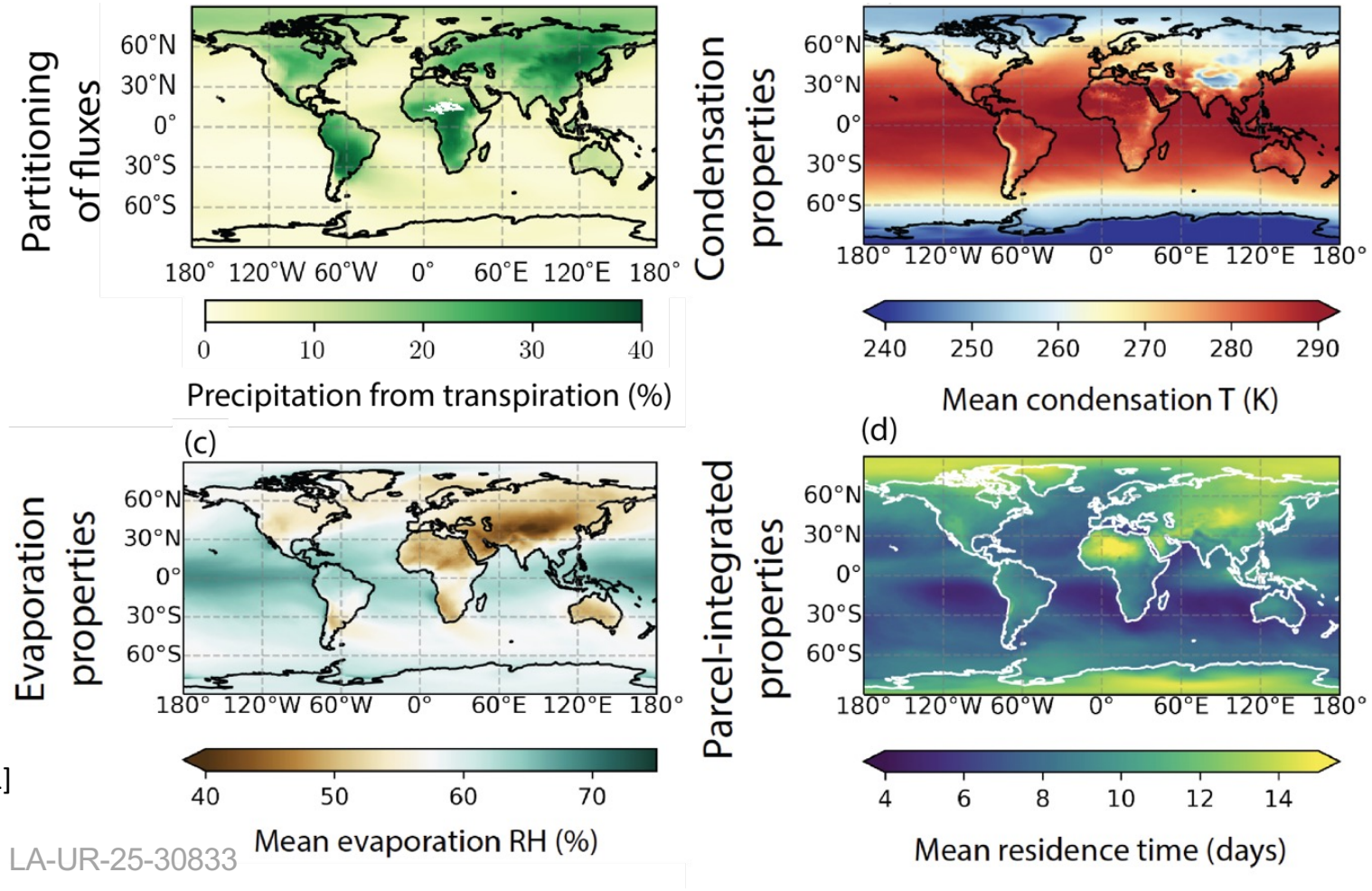


Upper curve = coastal clusters; lower = inland. Shaded areas: KDE (bandwidth 2.5 ‰). Circles mark medians.

[Velez Pardo, Noone, and Fiorella, in prep]

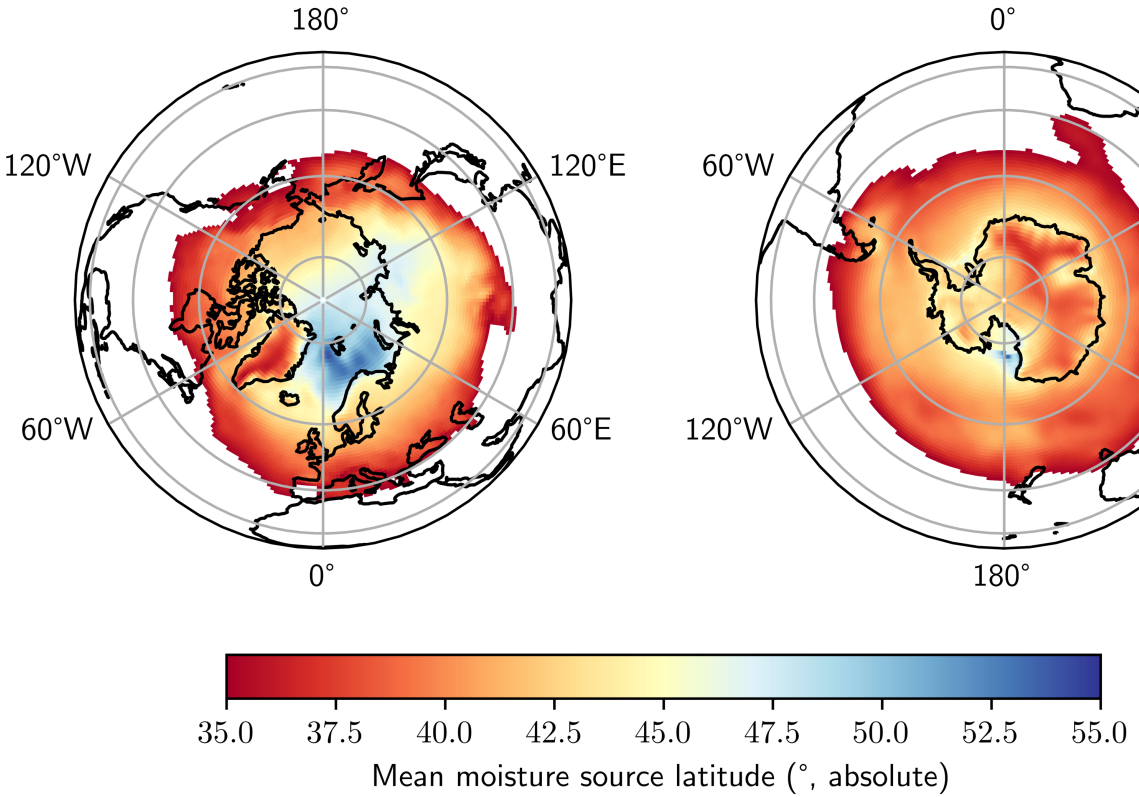
Enhanced hypothesis testing and model metrics

Extracting more information on hydrological processes using “process” tracers



[Fiorella et al. 2021]

Polar isotope ratios and moisture sources

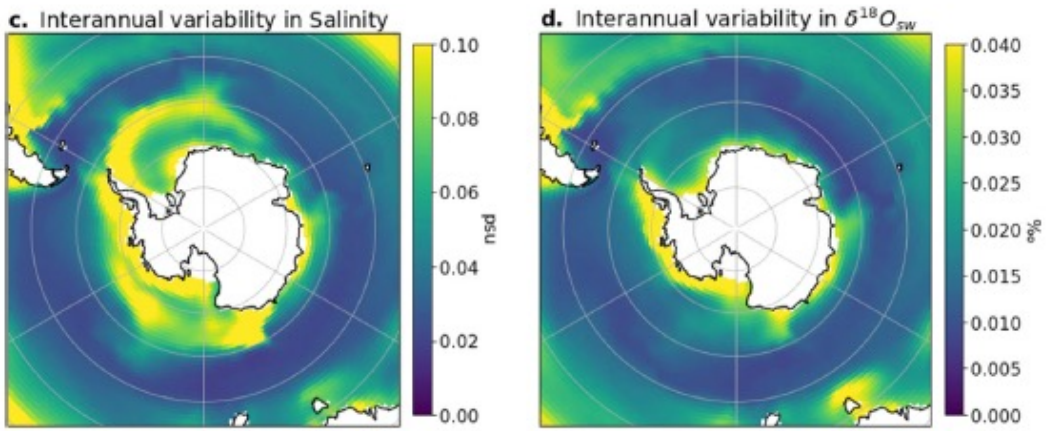


Key features:

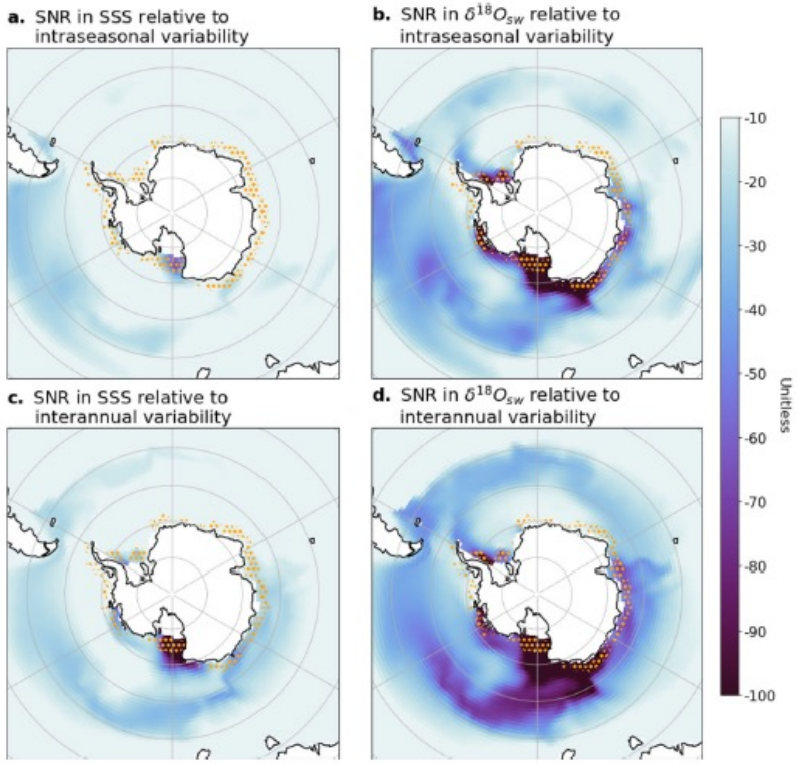
- Mean evaporative sources are far away (35-40° lat), particularly at high elevations
- Lots of asymmetry:
  - Siberian vs. Canadian Arctic
  - Norwegian Sea vs Greenland
  - W. Antarctica 5-10° poleward of E. Antarctica

[Fiorella et al., in prep]

Water isotopes in coupled models

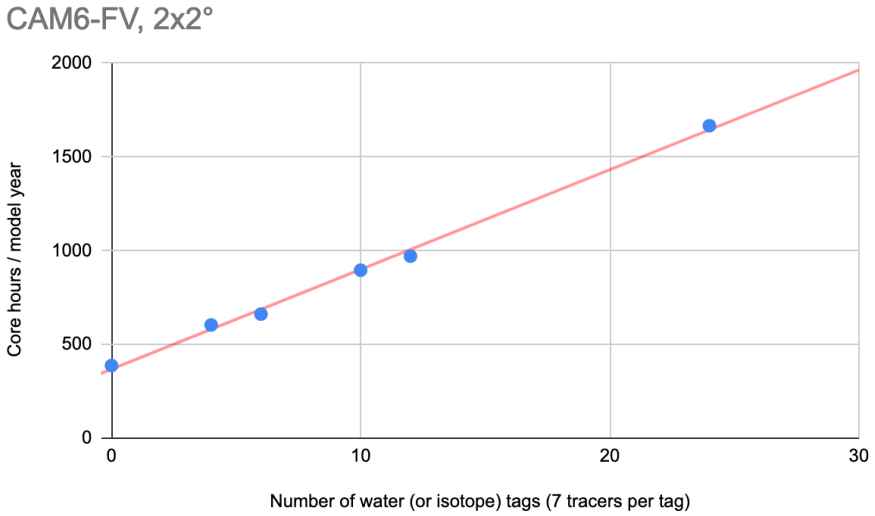


- Terrestrial water $\delta^{18}O$ << $\delta^{18}O$ sea water, particularly at high latitudes
- Sea water salinity and $\delta^{18}O$ are highly correlated due to meltwater impact
- In warming experiment with iCESM, much higher SNR in $\delta^{18}O$, signal emerges decades sooner



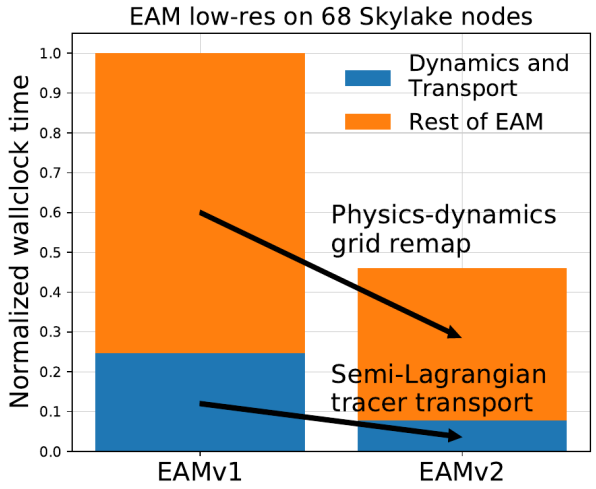
[Kim and Timmerman, 2024]

Why not always include tracers? Tracers can be expensive



For CAM6: Adding isotopes alone increases cost by 50%

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



[Bradley et al. 2021]

Implementation as a "stealth" option allows information on hydrologic processes from short, expensive runs to be applied to longer, less expensive runs and to emulators.

Tracers also open new potential application areas

"DOE model for DOE missions on DOE computers"

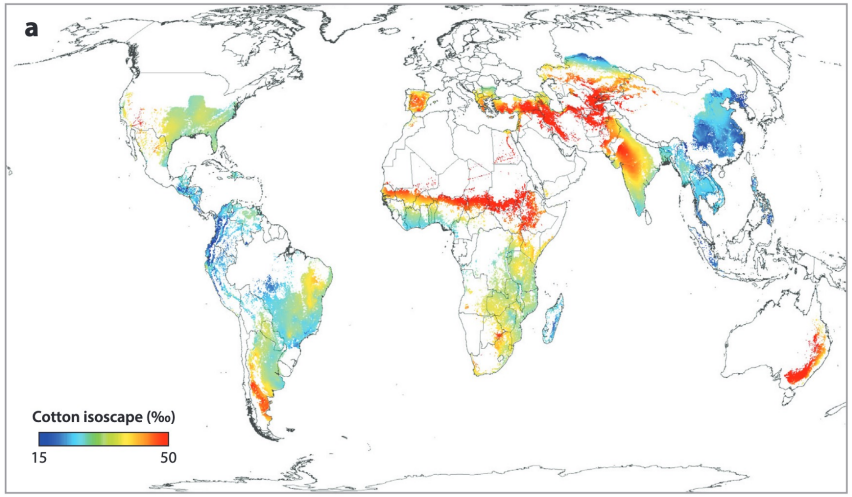
[IEEE Spectrum]

[E&E News]

Environment

Tijuana wastewater chemicals found in coastal aerosols, UCSD study finds

[KPBS]



Material provenance and forensics [Cerling et al. 2016]

Conclusions

- Water isotope ratios are powerful tracers of hydrologic processes throughout the coupled Earth system
- Provide an easily and widely observed metric for hydrologic “unit” and “regression” testing
- Isotope ratios have been shown to improve short-term forecasts when assimilated (testing with emulators/foundation models ongoing)
- Cities impact water vapor isotope ratios independently from humidity changes
- Water isotope ratio tracers do add to model cost, however:
  - integration as an optional feature would add no expense unless requested
  - process constraints from evaluation against isotope ratio observations helps address largest source of uncertainty in ~decadal scale predictions (uncertainty in model physics)
  - natural extensions of capability enable applications to other DOE mission spaces

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