Evaluating the assumption of equilibrium between precipitation and vapor during evaporation using data and models

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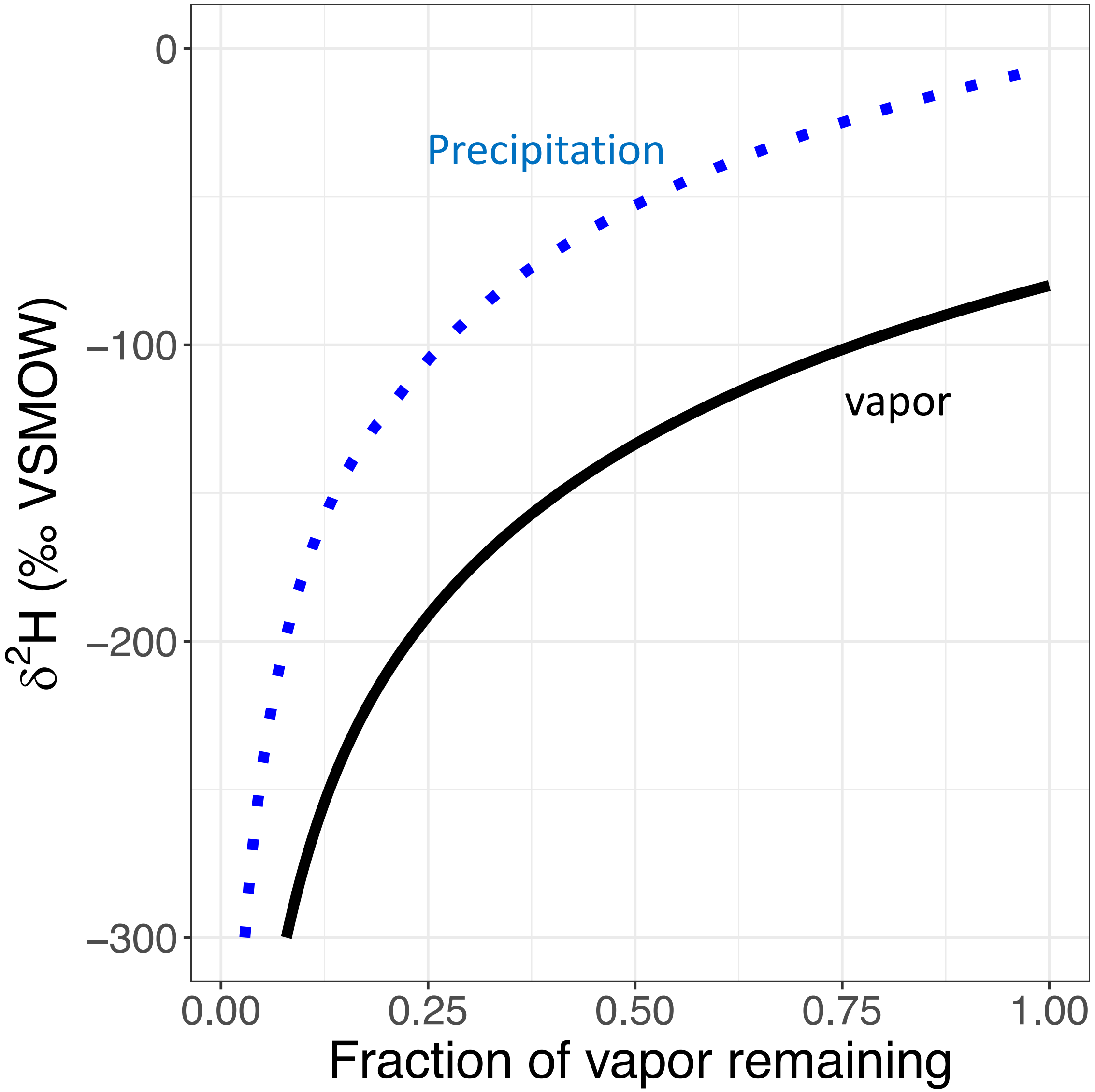
Linking Land and Atmosphere: Craig-Gordon Evaporation Model

$$R_E = \frac{\alpha_K \left(\frac{R_L}{\alpha_{eq}} - hR_A \right)}{1 - h}$$

$$R_E = \frac{\alpha_K \left(\frac{R_L}{\alpha_{eq}} - \frac{hR_P}{\alpha_{eq}} \right)}{1 - h}$$

[Craig and Gordon, 1965]

Why assume vapor/precipitation equilibrium?

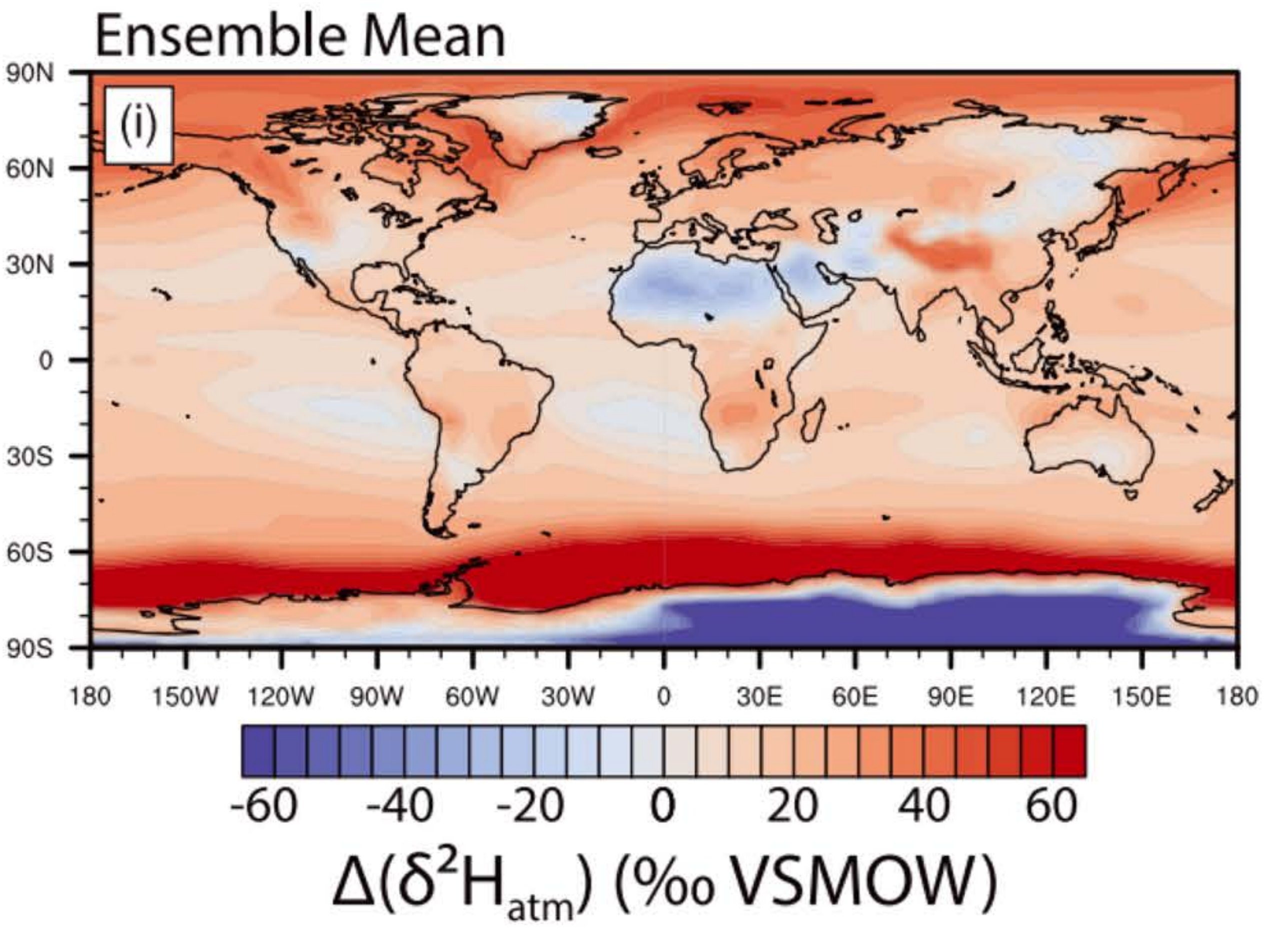


- If we live in a Rayleigh world (e.g., Gat 2000), vapor and precipitation should be in equilibrium
- But what about between events? (Lee et al. 2006; Welp et al. 2008)
- Where/when does this assumption of equilibrium hold?

Testing this assumption in isotopic GCMs

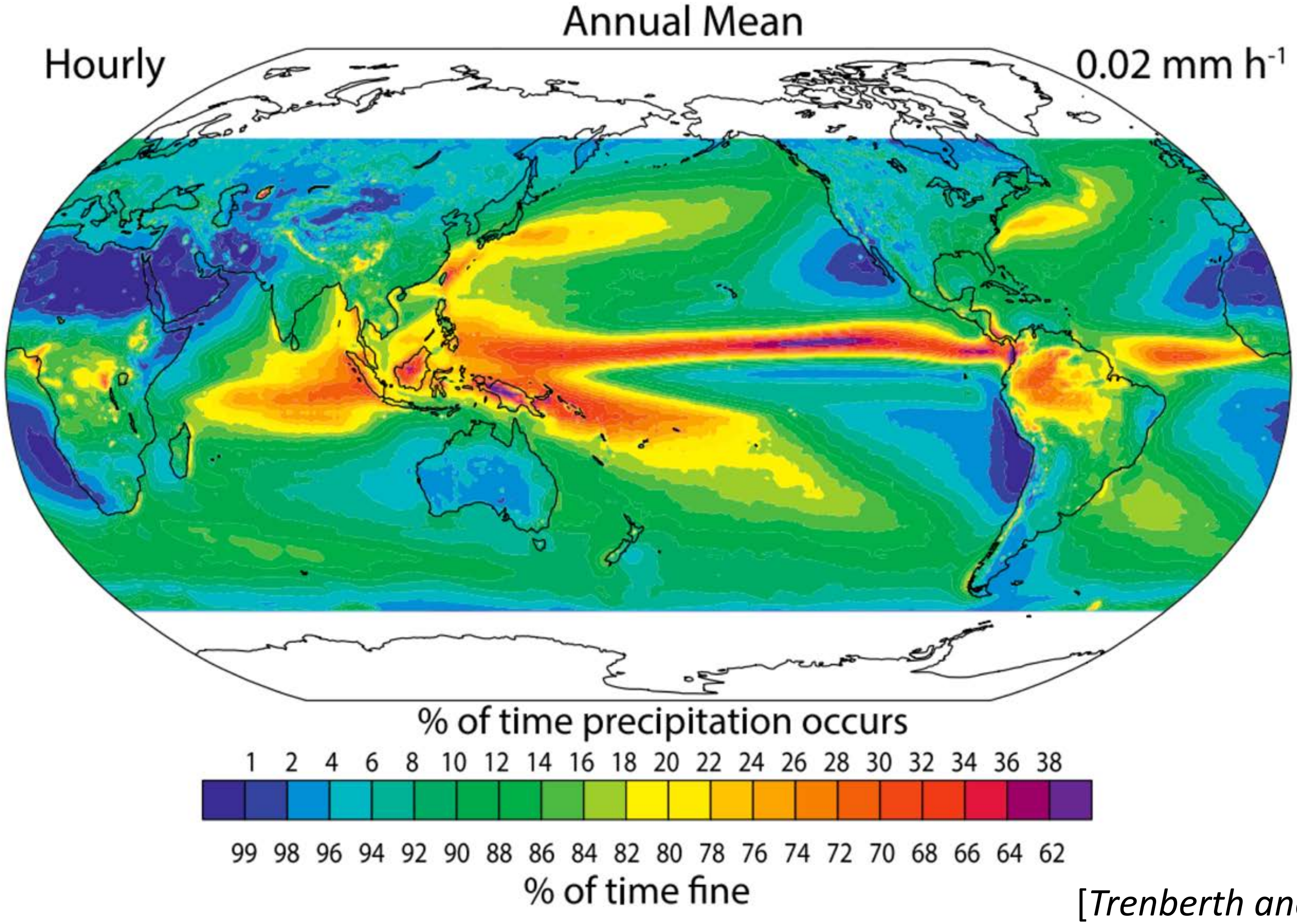
- Constructed an ensemble of 8 GCM simulations with water isotopes, common period of 1980-2000, free-running with forced SSTs
  - 6 of these are from SWING2 [Risi et al., 2012]
  - CAM5 [Nusbaumer et al., 2016]
  - ECHAM5 [Steiger et al., 2017]
- Regridded to a common 2x2° grid in order to generate ensemble mean and variance
- Calculate long-term mean precipitation isotope ratio for each grid cell
- Disequilibrium metric: $\Delta(\delta) = \delta_{v,\,\mathrm{lowest\ level}} - \delta_{v,eqm}$(T)

Is GCM vapor in equilibrium with precipitation?



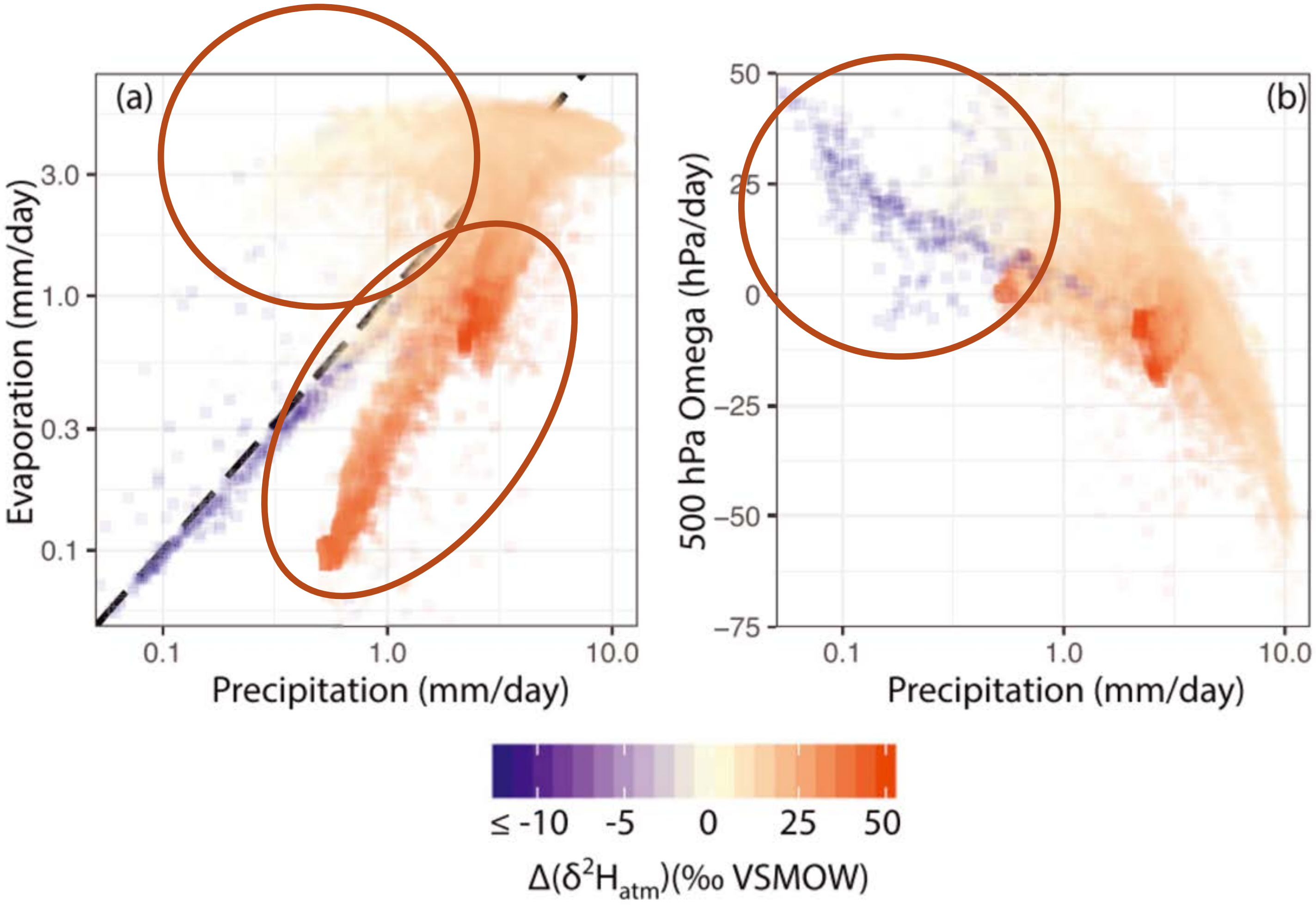
[*Fiorella et al., 2019 HP*]

What drives disequilibrium? 1) Rain is rare

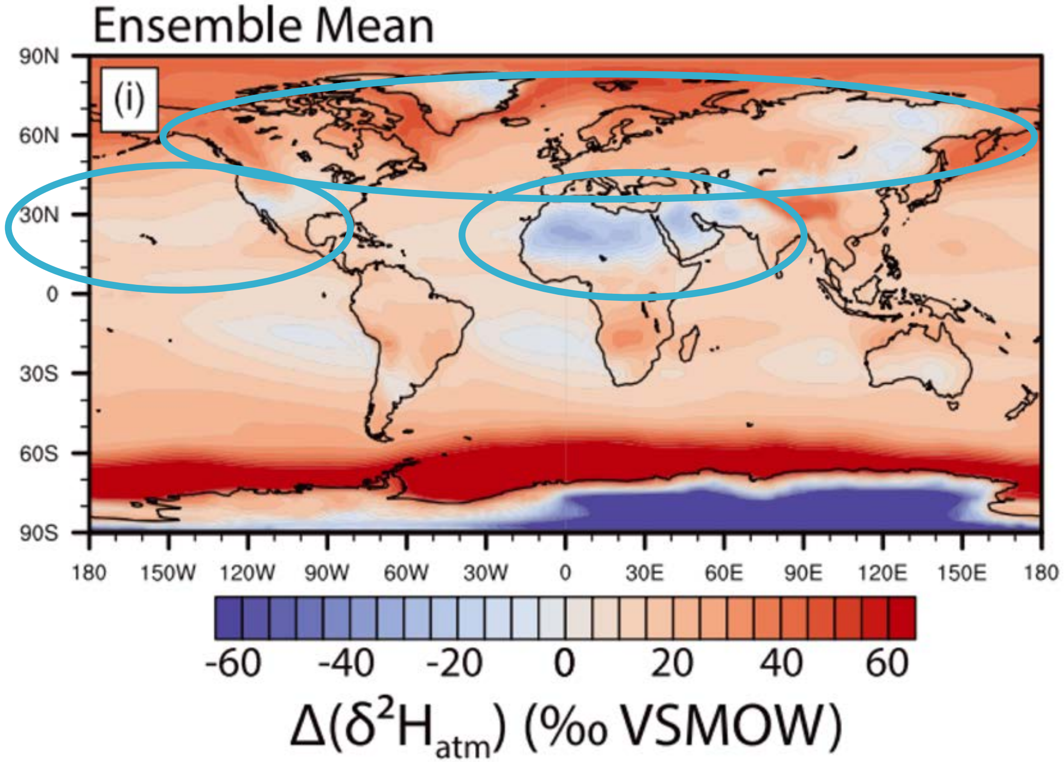


[*Trenberth and Zhang, 2018 BAMS*]

What drives disequilibrium? 2) Transport matters

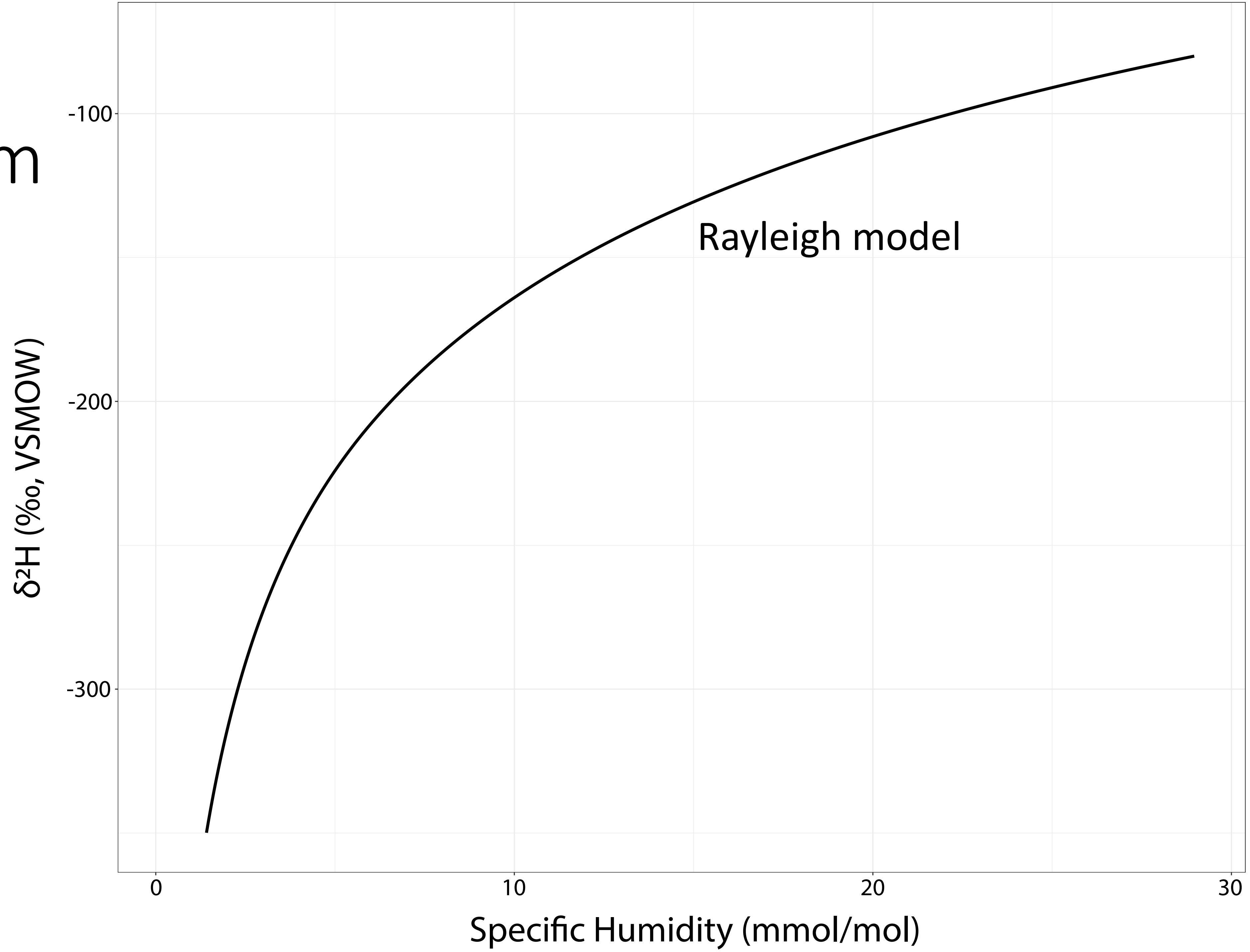


a) Atmospheric subsidence where $\Delta(\delta_{atm}) < 0$
b) Where P-E > 0, $\Delta(\delta_{atm}) > 0$
c) Where P-E < 0, $\Delta(\delta_{atm}) \approx 0$

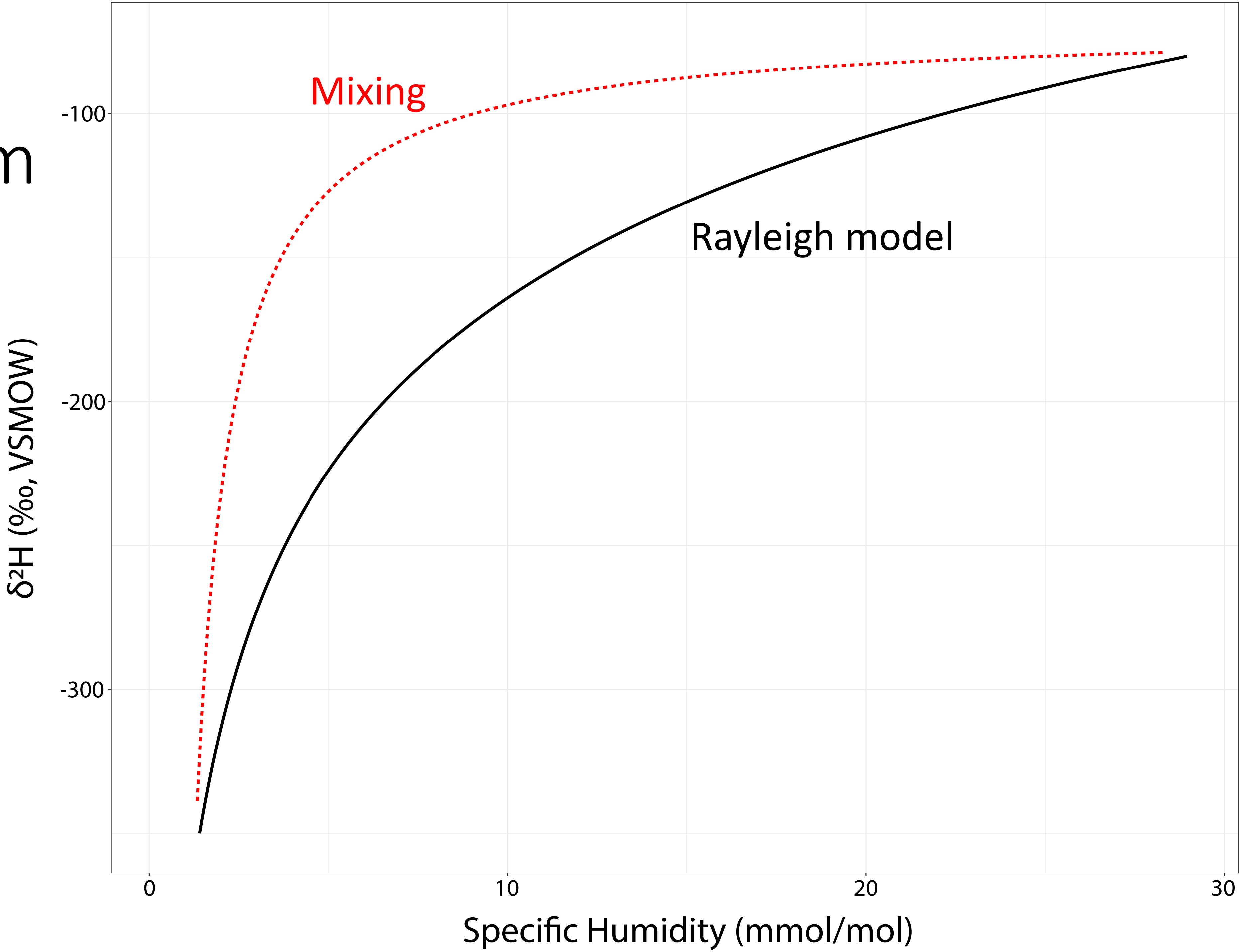


[*Fiorella et al., 2019 HP*]

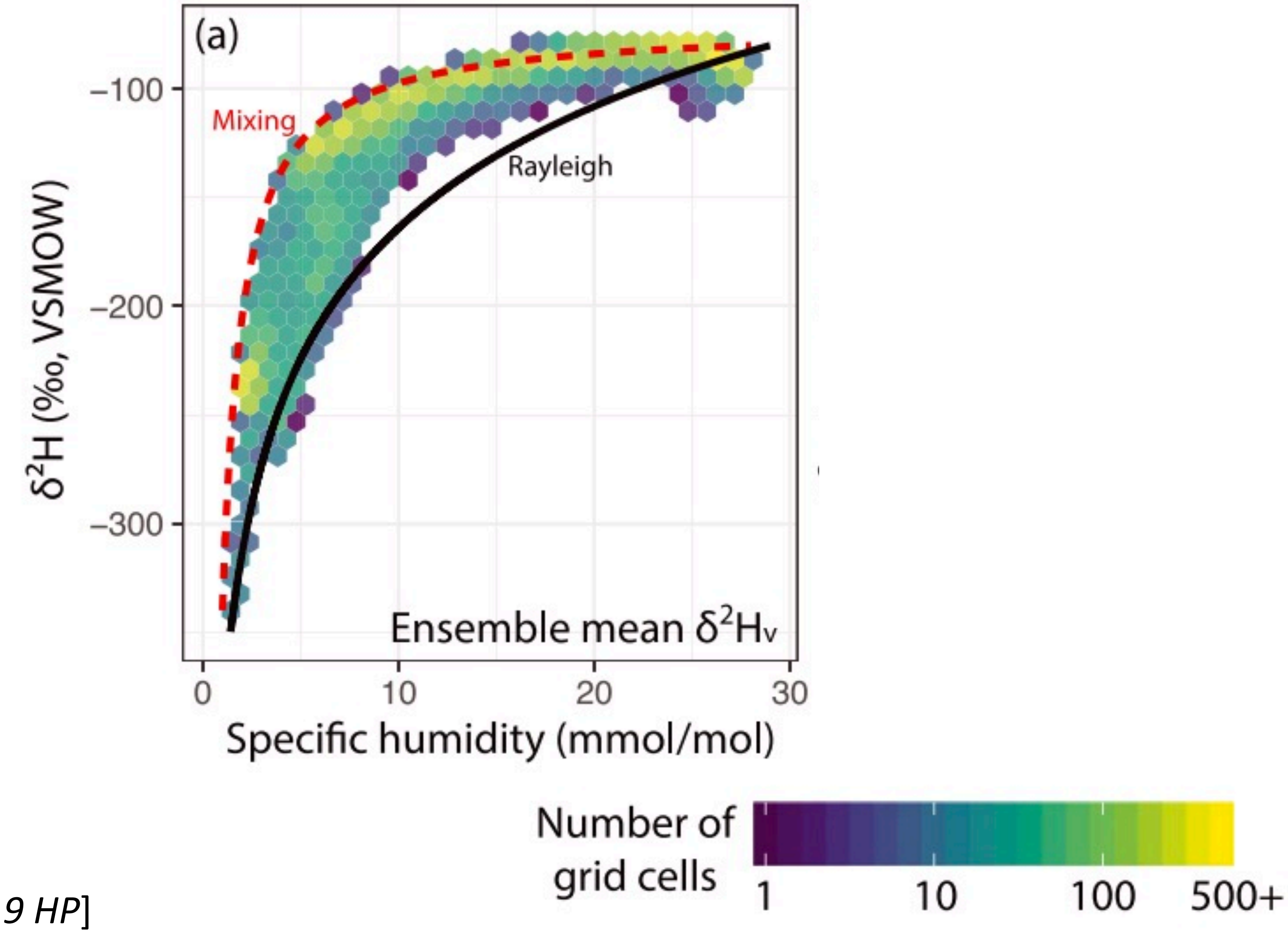
Explaining disequilibrium with simple models



Explaining disequilibrium with simple models



What drives disequilibrium? 3) Precipitation selects for condensation



[*Fiorella et al., 2019 HP*]

Importance for proxies

$$R_{L,1} = \alpha_{eq}\left[\frac{R_E}{\alpha_K}(1-h) + hR_A\right]$$

$$R_{L,2} = \alpha_{eq}\left[\frac{R_E}{\alpha_K}(1-h) + h\left(\frac{R_P}{\alpha_{eq}}\right)\right]$$

$$\Delta R_L = R_{L,1} - R_{L,2} = h[\alpha_{eq}R_A - R_P]$$

[*Fiorella et al., 2019 HP*]

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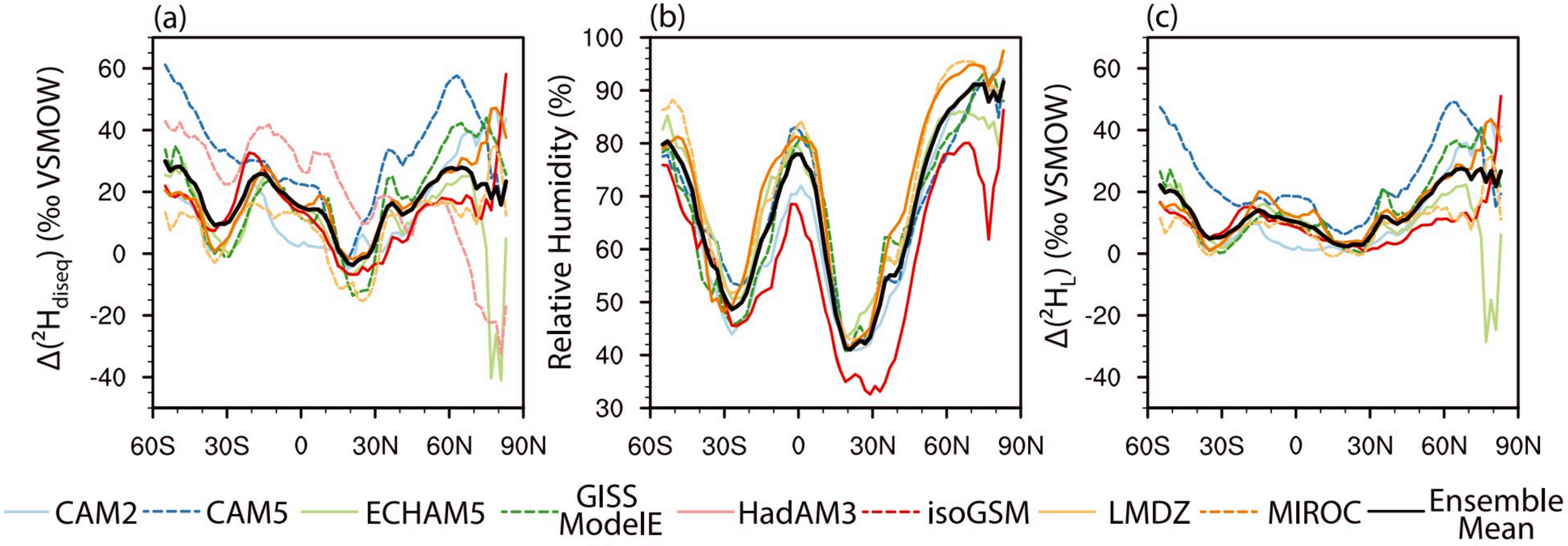
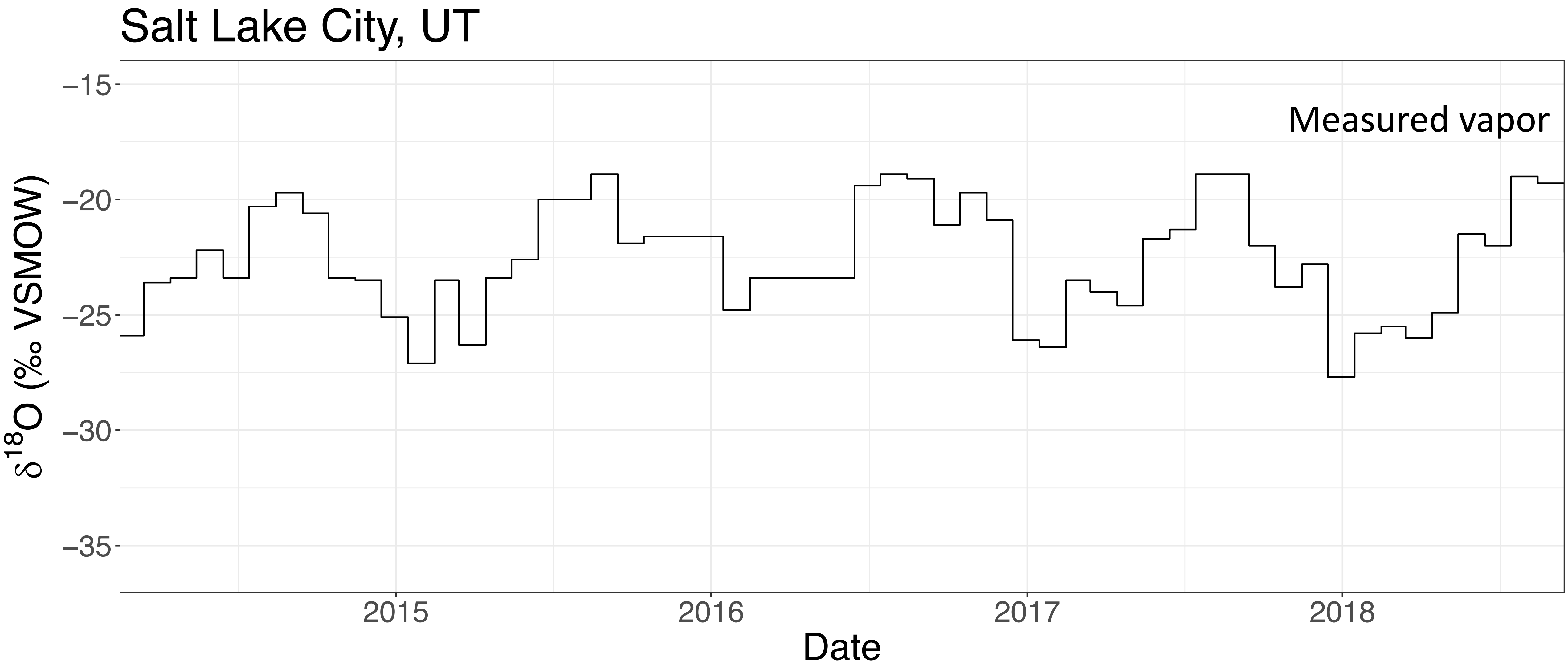


[*Fiorella et al., 2019 HP*]

Are there similar patterns in paired precip/vapor records?



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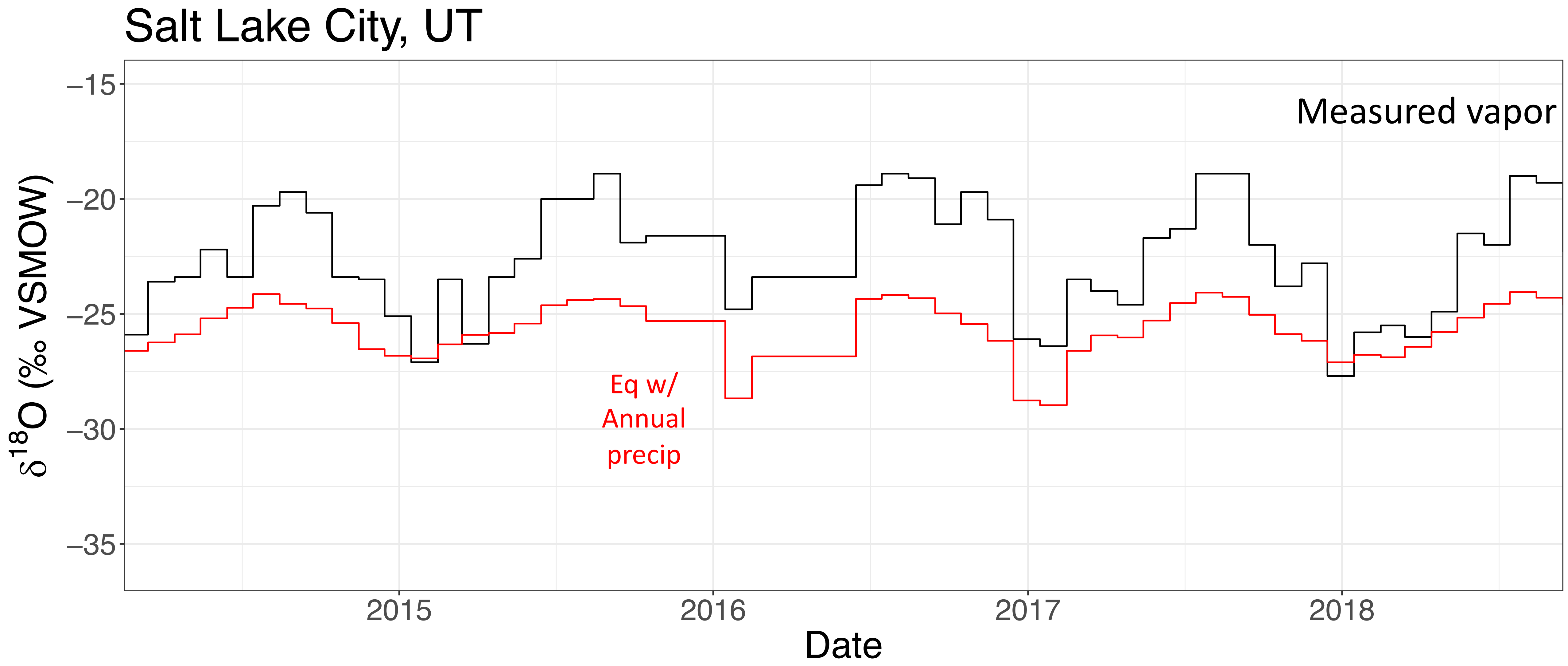

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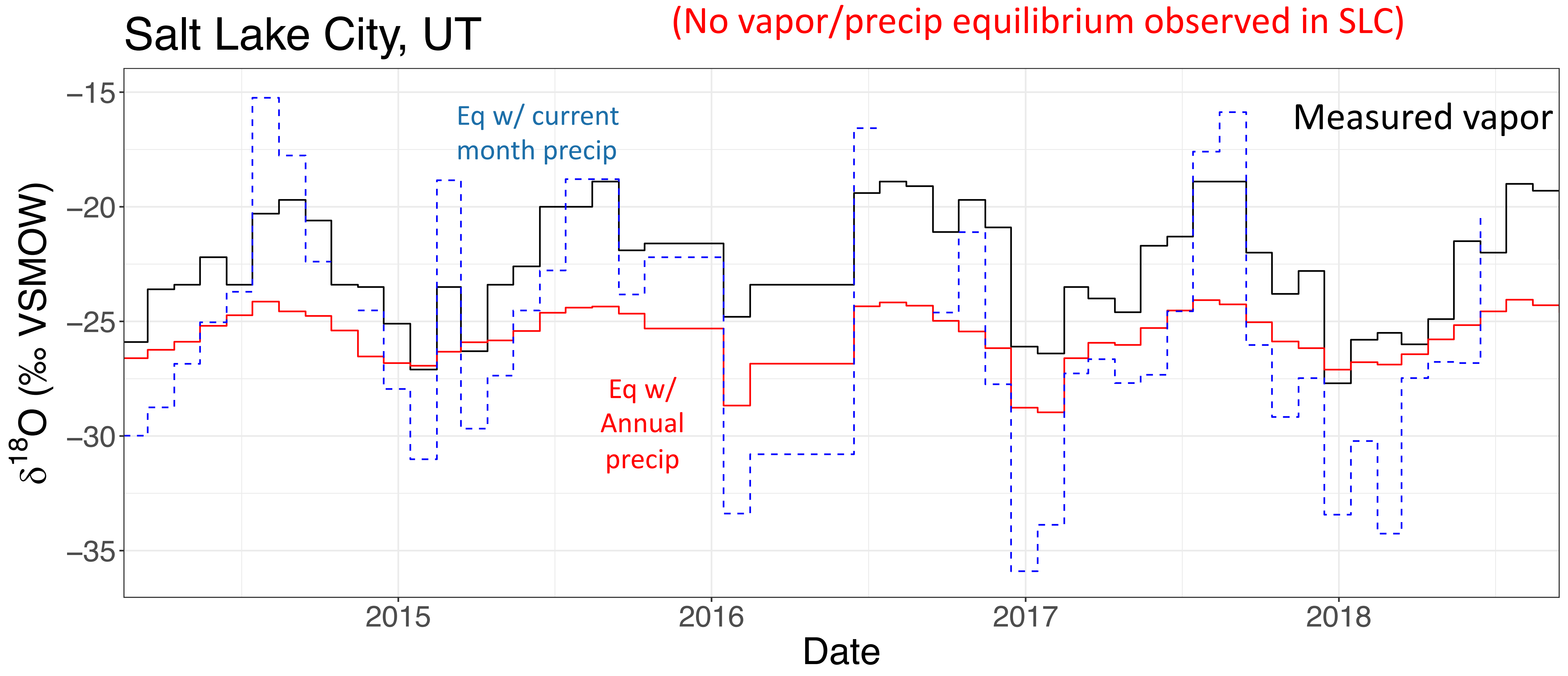

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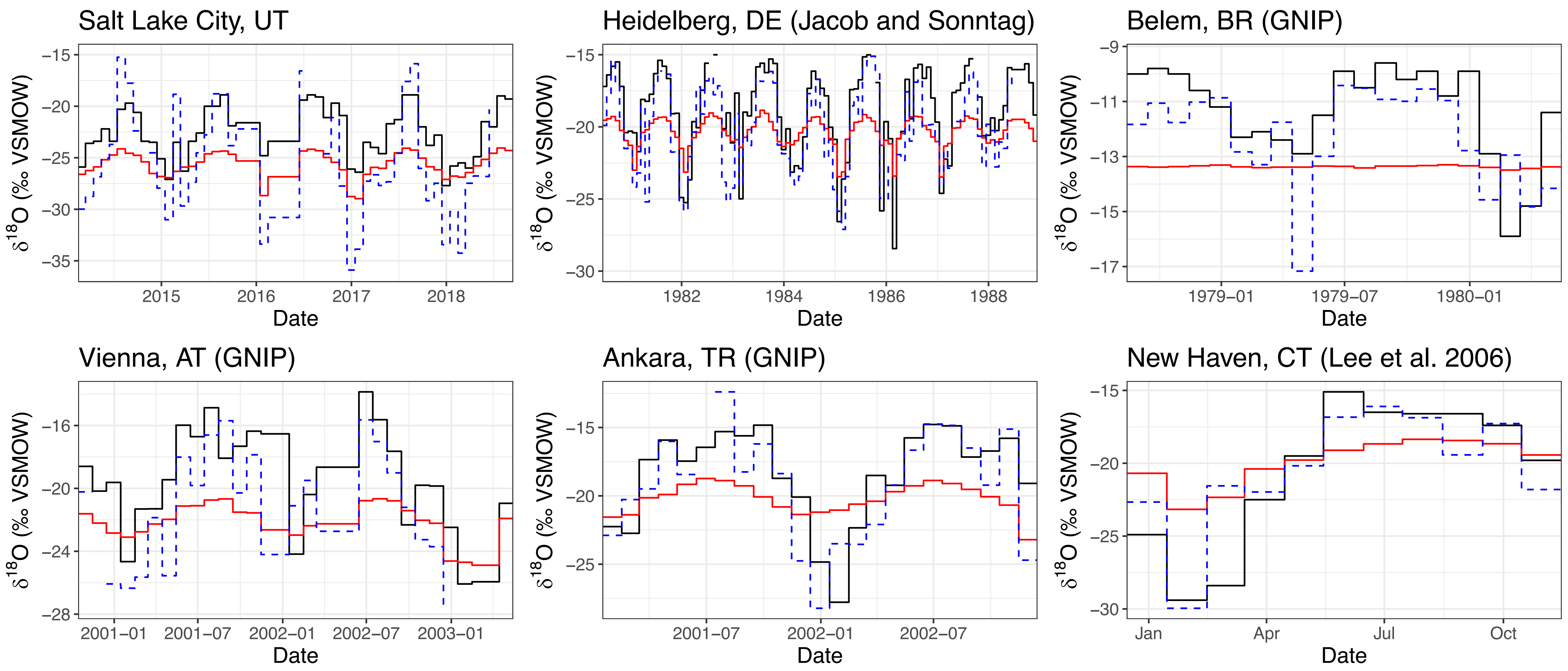

Black = measured vapor, red = vapor in eqm. w/ annual precipitation, blue = vapor in eqm. w/ monthly precipitation

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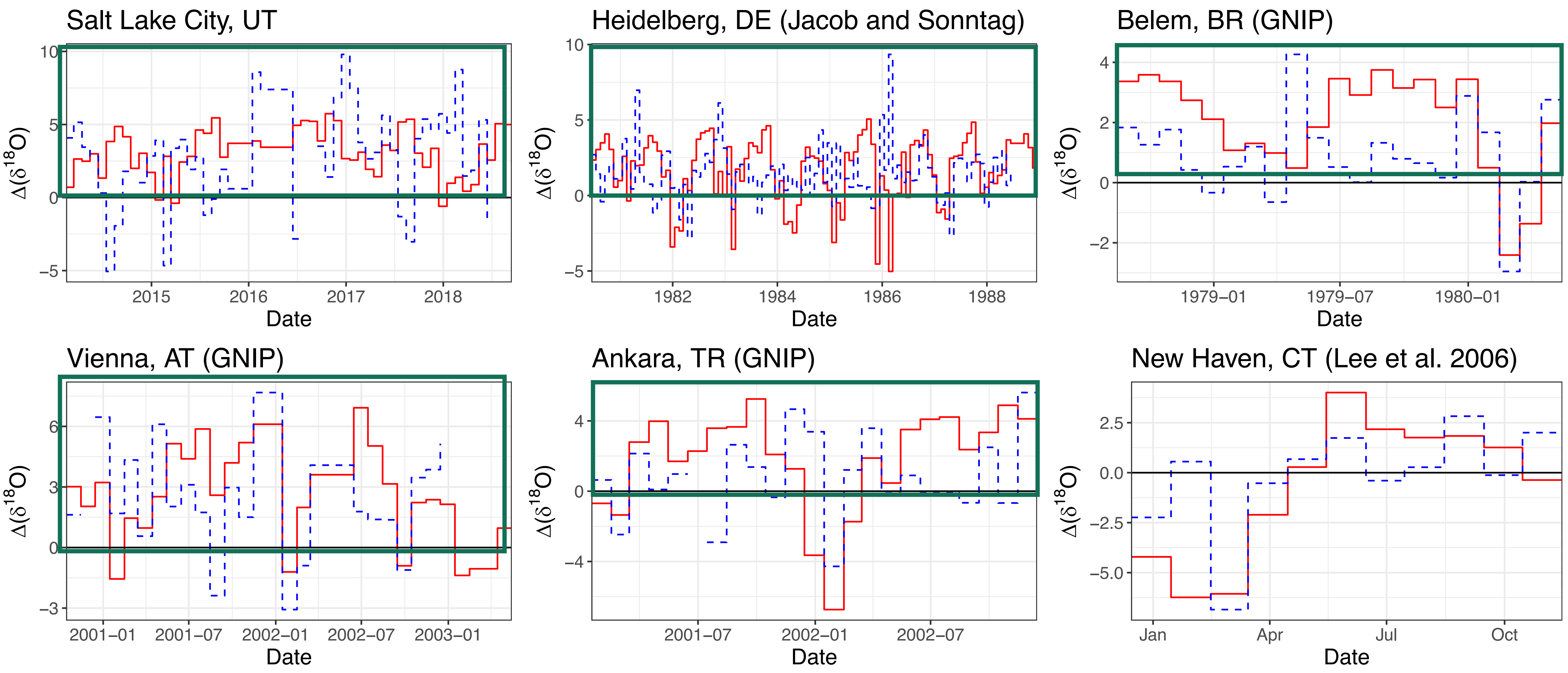
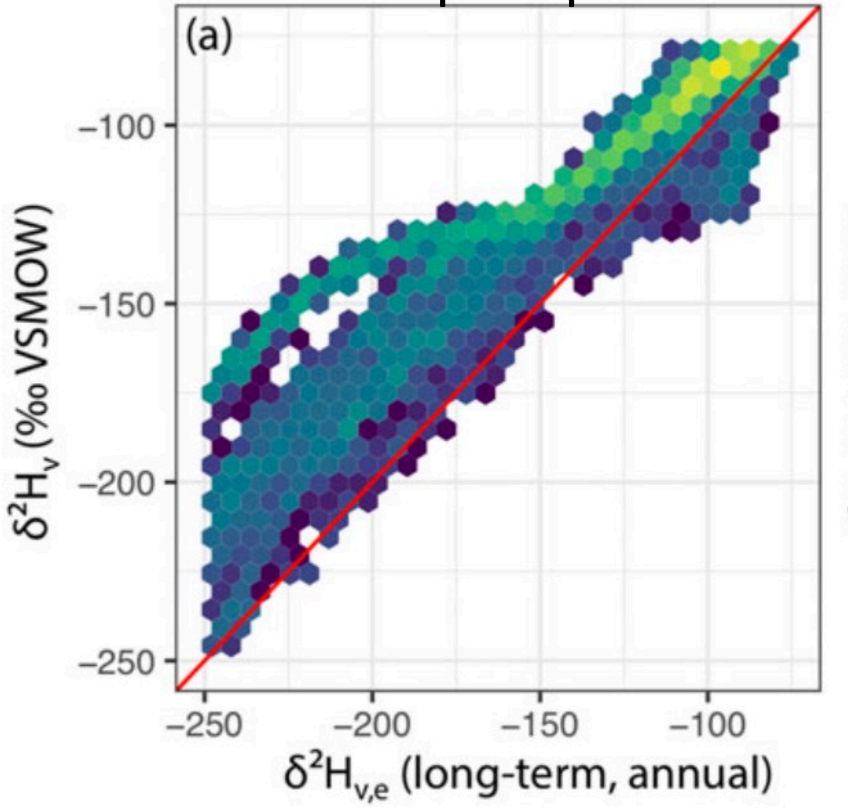


red = measured vapor - vapor in eqm. w/ annual precipitation, blue = measured vapor - vapor in eqm. w/ monthly precipitation

Importance of timescale

Annual precipitation

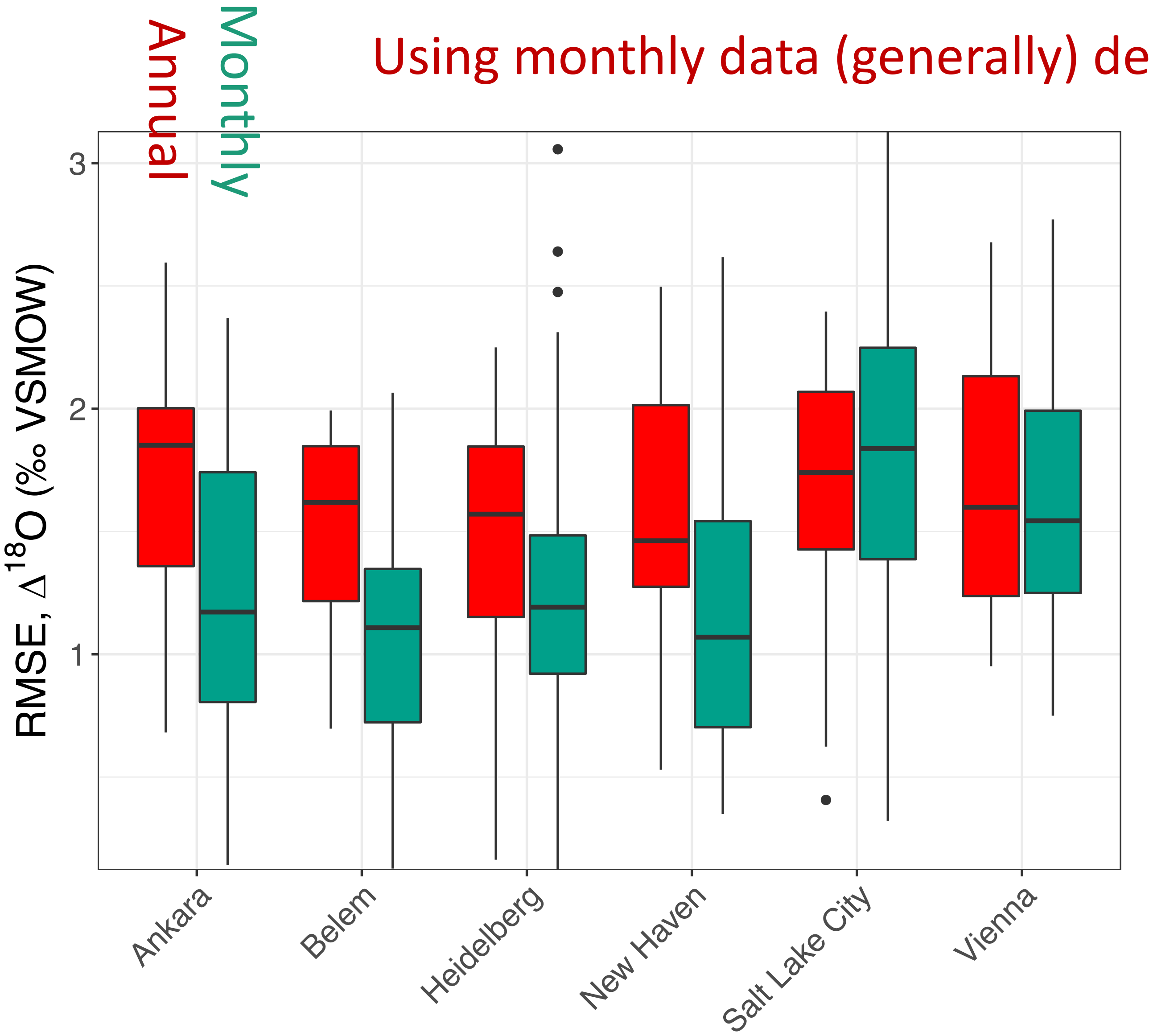


Vapor more enriched in heavy isotopes than anticipated from equilibrium assumption at greater-than-event timescales

[*Fiorella et al., 2019 HP*]

Importance of timescale

Using monthly data (generally) decreases RMSE, distribution of disequilibrium



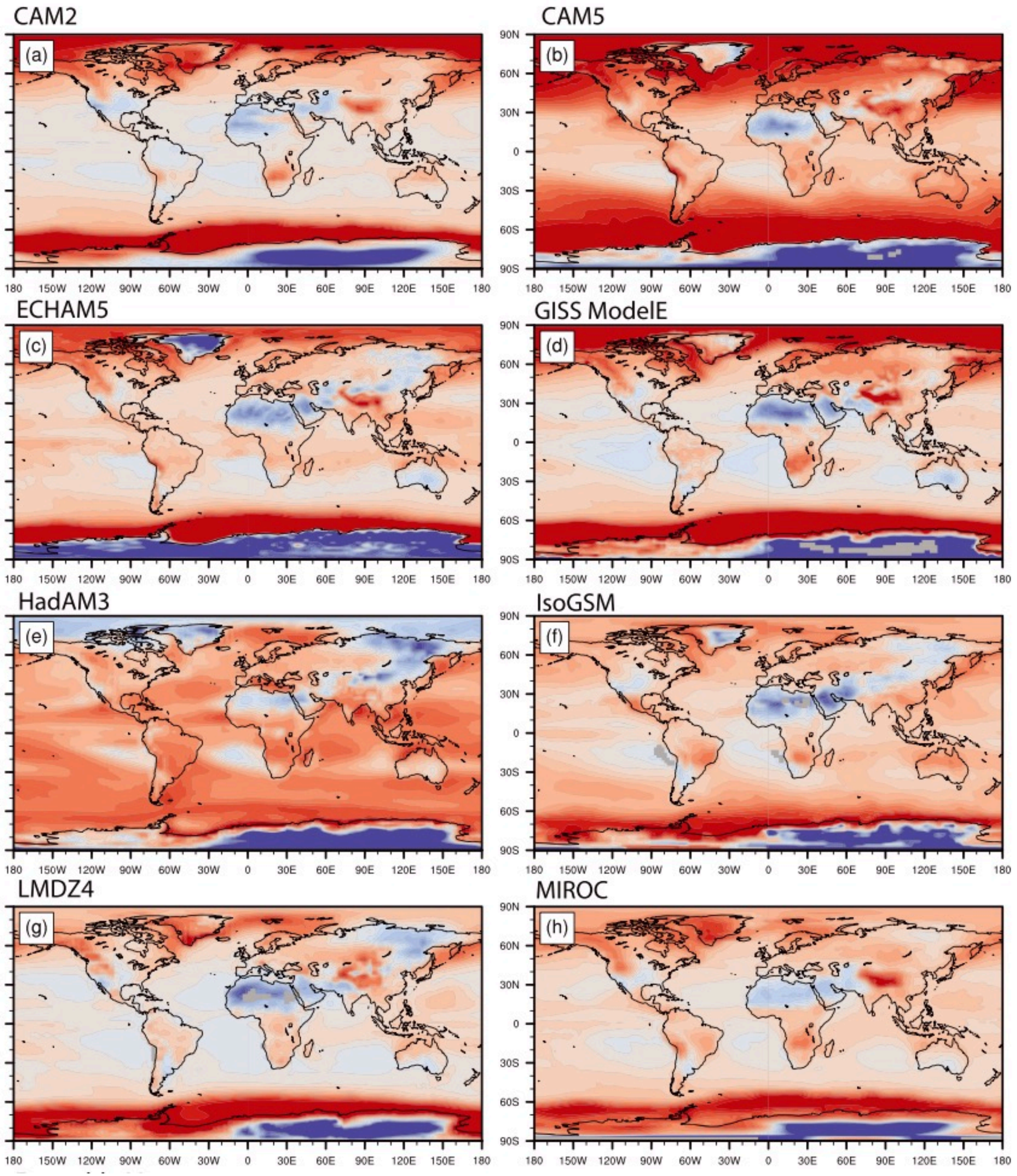
Conclusions and Outlook

- At greater-than-event timescales, equilibrium between precipitation and vapor at a site is rare (both in GCMs and in observations)
- On average, vapor in most locations is isotopically heavier than anticipated from equilibrium assumption, can arise purely from air mass mixing
- “Bias” in assumption is often smaller on monthly compared to annual timescales, but requires higher data resolution
- Models generally agree with observations, but we’re still data poor. (Perhaps new. observational networks (satellites, FTIR, NEON) allow for broader testing)

Acknowledgments

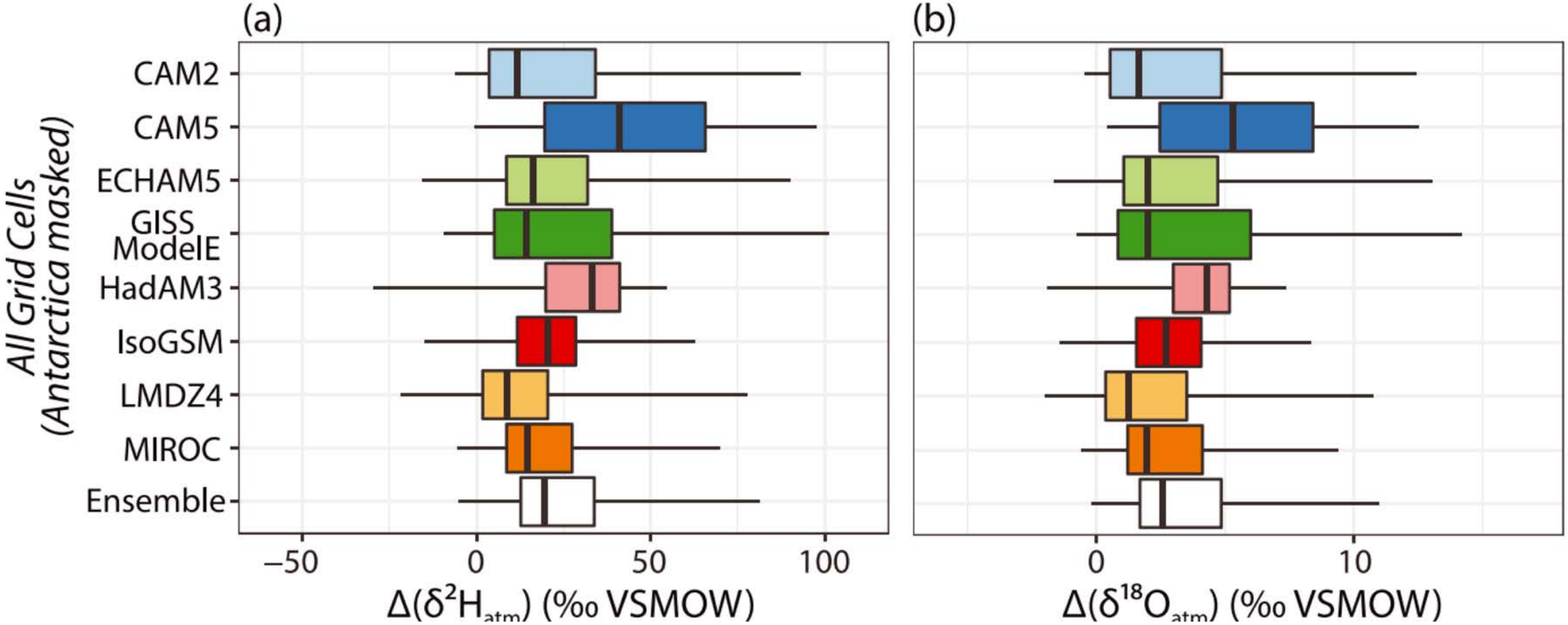
Thanks for making general circulation model and observational data available

- SWING2 archive: https://data.giss.nasa.gov/swing2/
- CAM5 data: Jesse Nusbaumer/David Noone
- ECHAM5 data: Nathan Steiger
- GNIP/IAEA
- Lee et al. (2006) and Jacob and Sonntag (1991)



CAM2
(a)
CAM5
(b)
ECHAM5
(c)
GISS ModelE
(d)
HadAM3
(e)
IsoGSM
(f)
LMDZ4
(g)
MIROC
(h)
90N
60N
30N
0
30S
60S
90S
180
150W
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
180

Similar patterns for oxygen and hydrogen in GCMs



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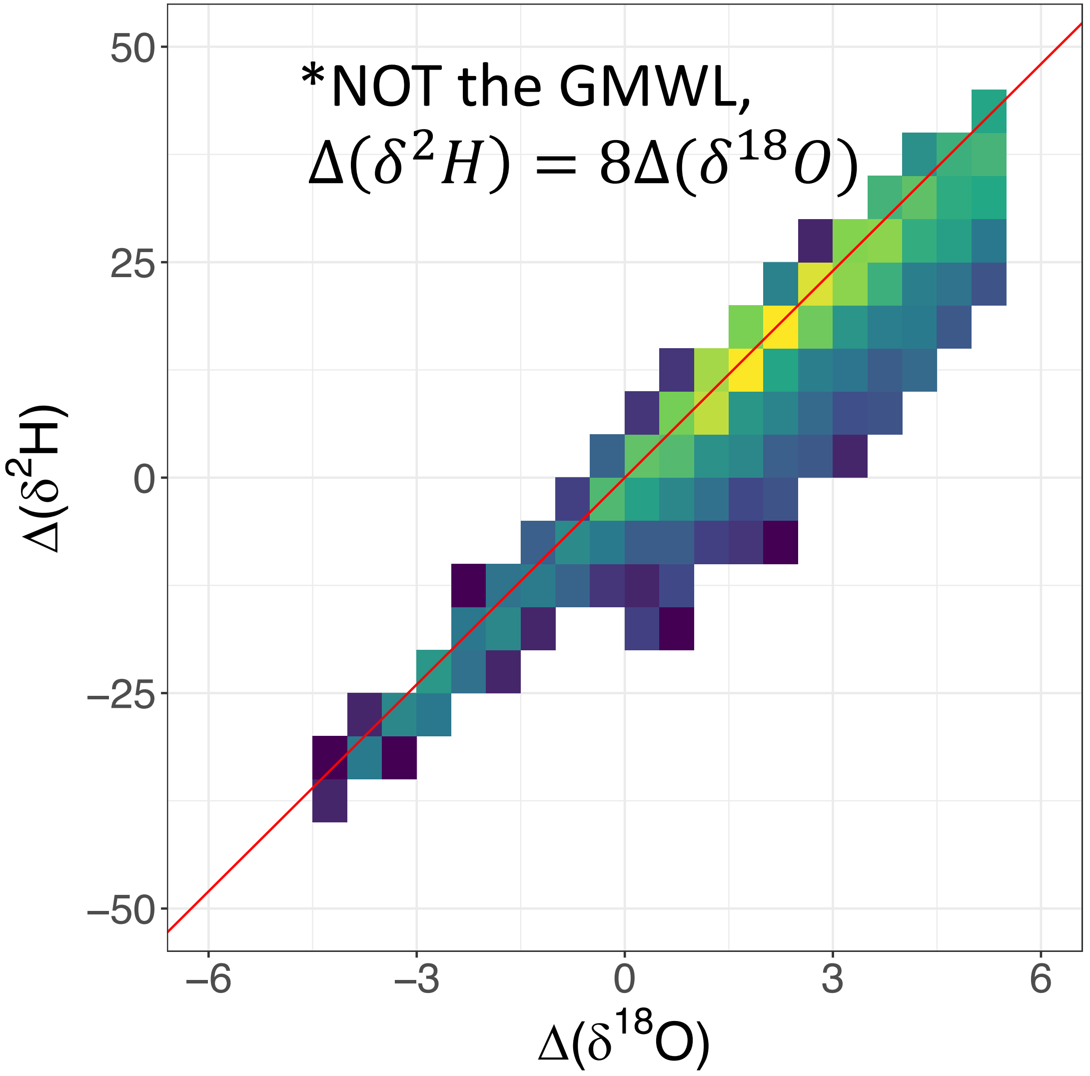
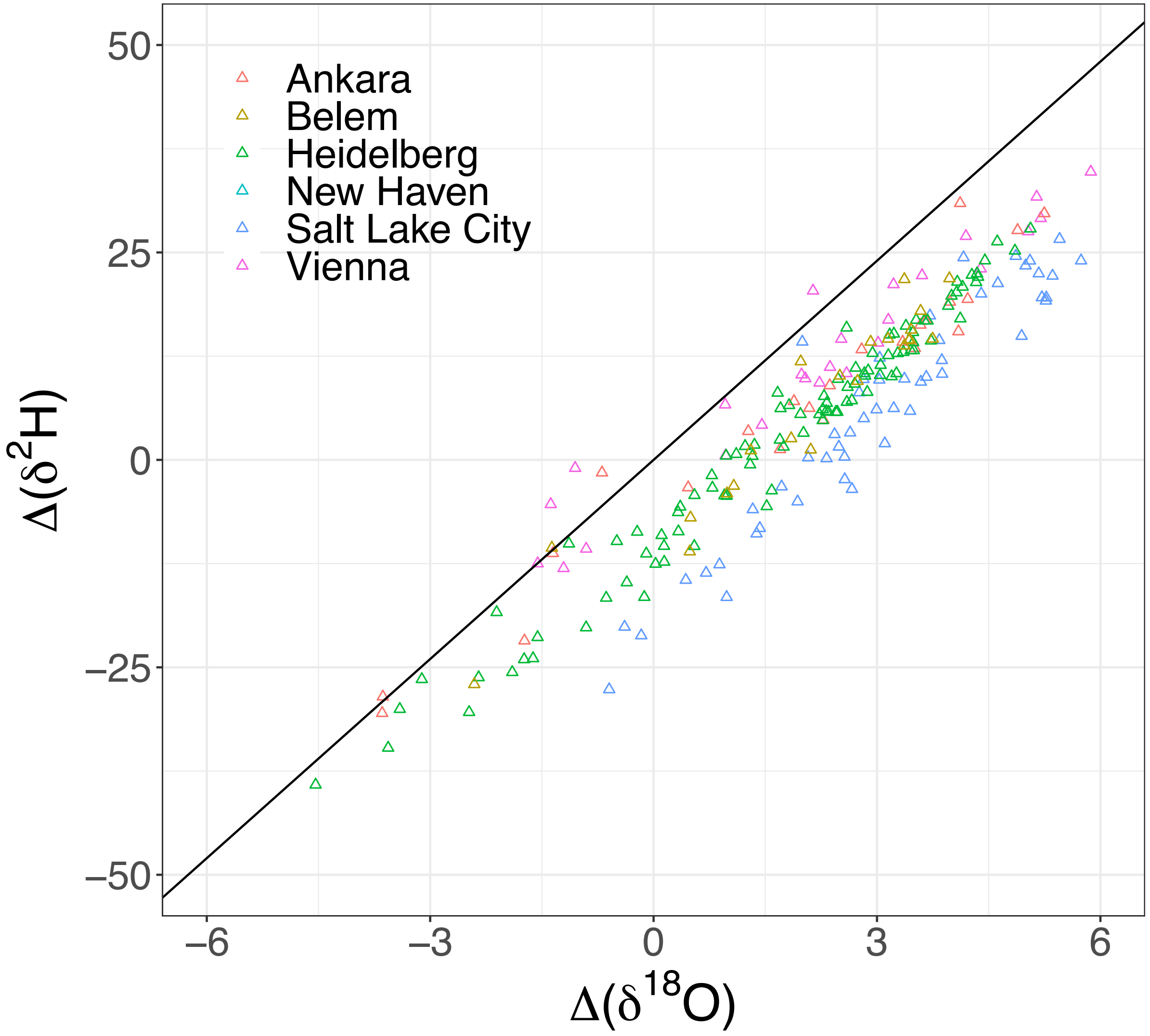
Similar scaling between data and models





Models seem to do fairly well – but only 6 locations represented!

Another way to $\Delta(\delta) > 0$

- Gat 2000 notes snow/convection produce precipitation with lighter-than-Rayleigh isotope ratios
- Net decreased fractionation between vapor and precipitation
- If we use this precipitation to estimate vapor using equilibrium assumption, we estimate a vapor that's too light (e.g., $\Delta(\delta) > 0$)
- But, same pattern can arise from vapor mixing alone – vapor often deviates from the Rayleigh line!