Evaluating the rates of exchange in the tropospheric water budget with isotopes

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Objectives

- Use isotopes to constrain water budget
  (Large scale or at microphysical scale)
- Two observables gives more information than one
  (isotopes tell about the processes)

Specifically

- What processes control moistening and drying the subtopics? (Phenomenology, then budgets)
- Identify sources of water (location and strength)
- Cloud microphysics:
  - Recycling of rainwater (or ice) through re-evaporation
  - Characterize type of condensation (remoistening in region of convection, reversible adiabatic cloud processes, *efficiency with which water is lost from the atmosphere*)

How do isotope help budgets? (quantitatively)

Weknow:

mixing ratio in troposphere q_t= 2 g/kg
mixing ratio near surface q_s = 12 g/kg

You measure an air parcel with q = 7 g/kg

How much from surface?

Conservation gives:

$$q = f\, q_s + (1-f)\, q_t$$

f = 0.5… so half comes from surface

(*2 member mixing model – assuming we know end members*)

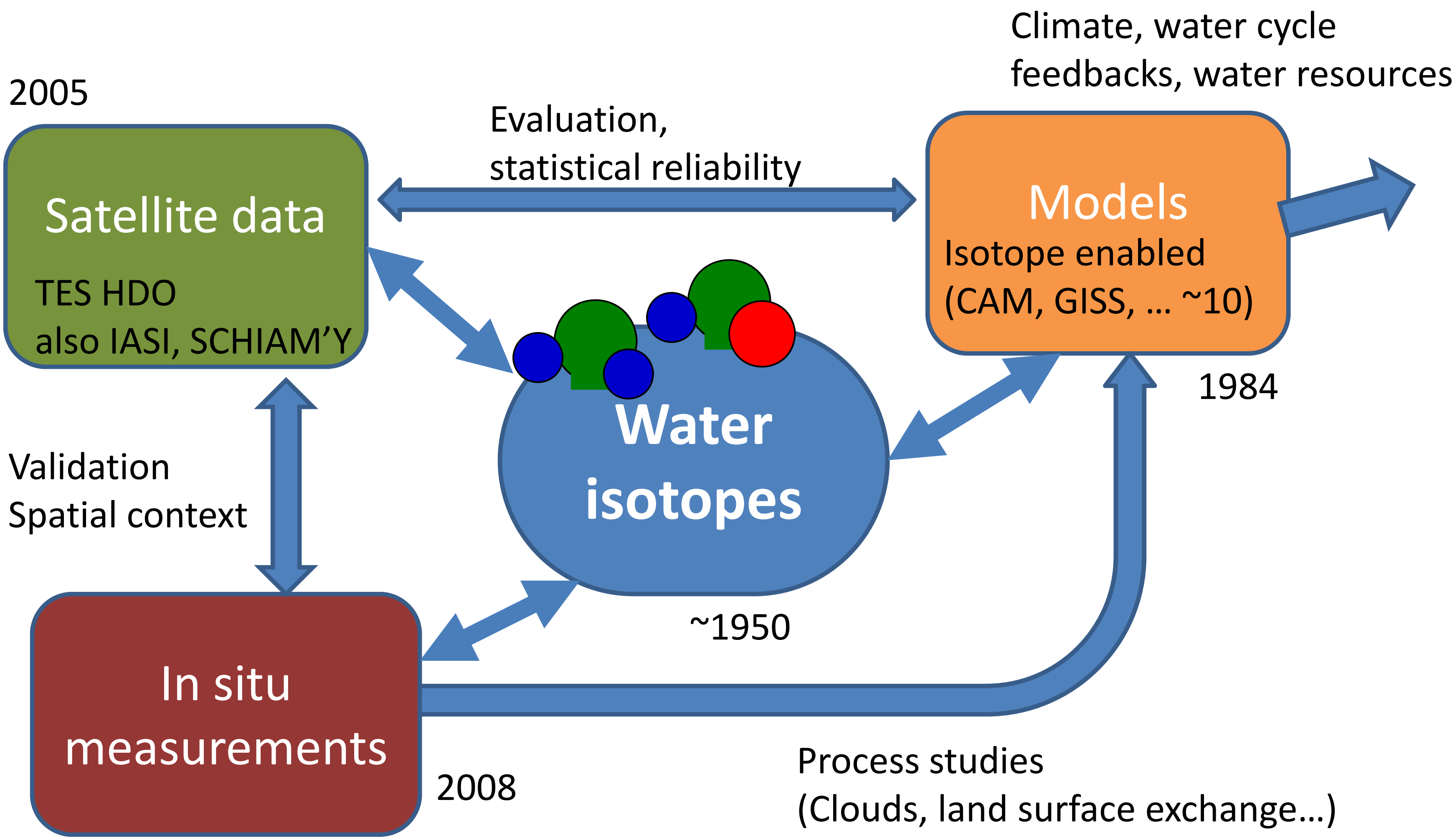
Know half from surface, but T or E?

- Evaporation behaves a simple model for isotopes:
  $R_e = \eta(Rs/\alpha - Rh)/(1-h)$ ~ -110 ‰
- Transpiration is the same as precipitation
  (plants give off water from roots) R_v ~ -50 ‰
- Measure δD: -70 ‰

Restate question: Of the 50% that comes from the surface, what fraction from plants?

- $\delta D = f(q_s\ \delta D_s) + (1-f)(q_t dD_t)$
- $\delta D = f[g\ (q_e \delta D_e) + (1-g)(q_v \delta D_v)] + (1-f)(q_T \delta D_T)$

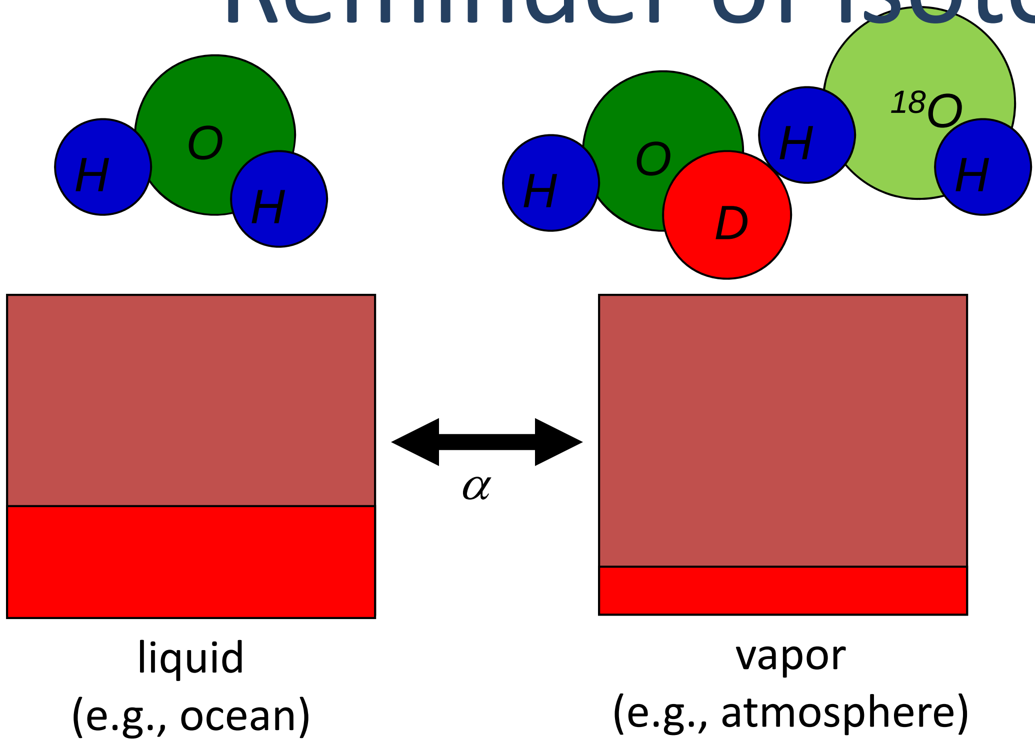
- F = 0.5, as before. Now g = 0.7.
  So 70% of surface flux is transpiration



Traditional sampling (IRMS),
commercial optical analyzers
(LGR, Picarro)

Until recently, problem limited by observations.
(essentially none until TES…)

Reminder of isotope physics



Ratio of HDO to H_2O

Measured as a difference from ocean water.

$$\delta = \frac{R}{R_{ocn}} - 1$$

Two simple isotope models…

Condensation

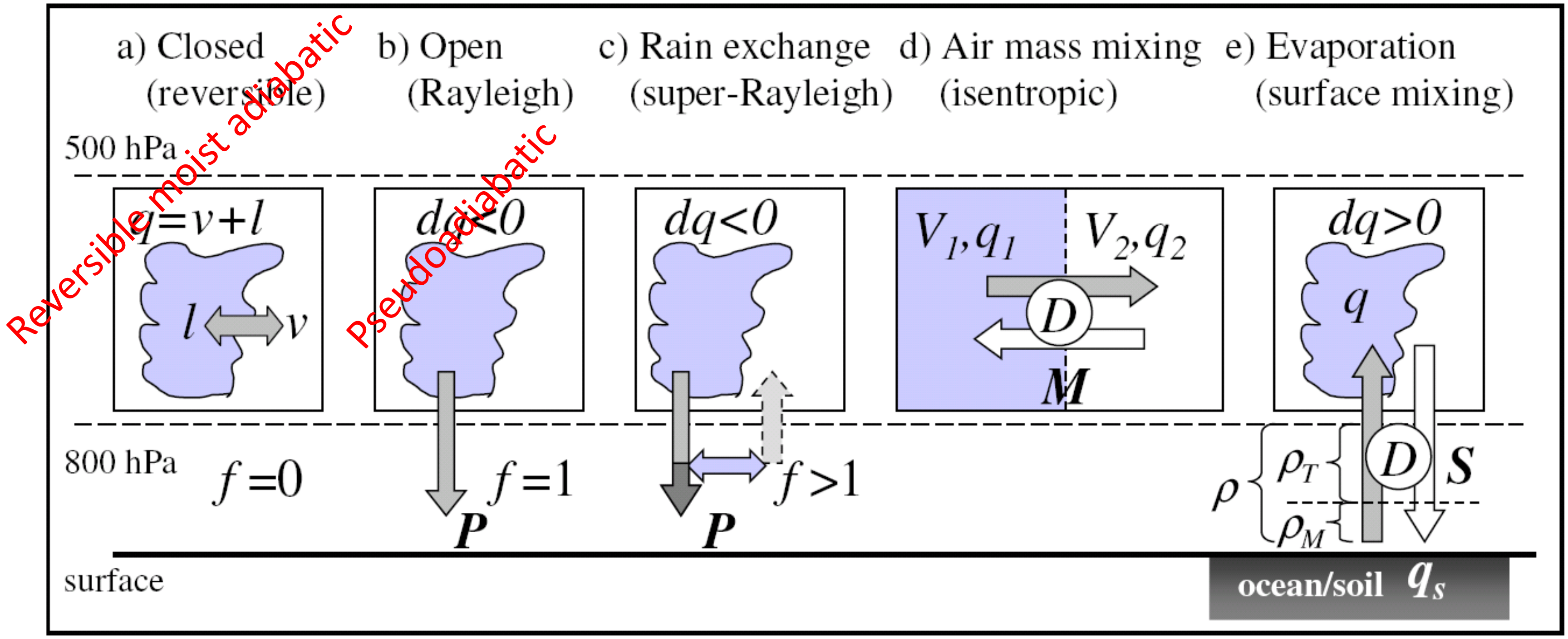
Vapor becomes depleted as heavy removed preferentially

Evaporation

Returns to isotopic composition of the (ocean/land) source.

Conditions under which condensation occurs is different from the conditions when evaporation occurs

Theoretical guidance: box budgets



Condensation

$$(\delta-\delta_0)=(\alpha-1)\ln\left(\frac{q}{q_0}\right)$$

$$\alpha=\frac{\alpha_e}{\alpha_e(1-f)+f}$$

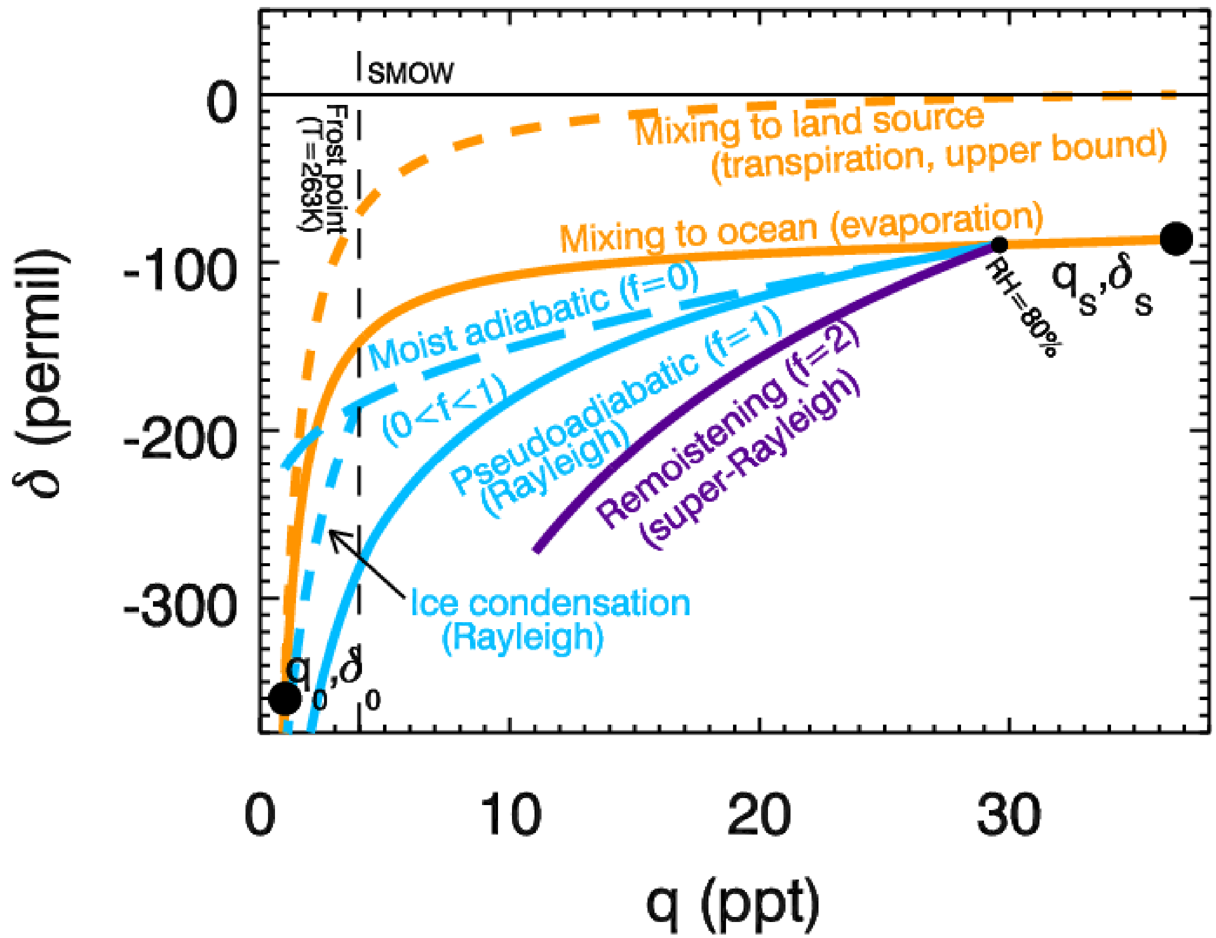
Mixing/hydration

$$\delta\approx\frac{R}{R_s}-1=-\left[\hat{q}\left(\hat{\delta}-(1-H)\right)\right]\frac{1}{q}-(1-H)$$

$$H=\left(\hat{q}_i-q_{i,0}\right)\left[\hat{q}-q_0\right]^{-\eta}$$

Noone, J, Climate, in review

Framework for interpreting HDO



(Noone, in review)

"6 easy pieces"

Very powerful analytic tool since constrains *balance and bulk microphysics*

Two things to worry about:

1) What is source composition? (end members, balance of sources)

2) What is *slope*? (rainfall efficiency, type of cloud)

HAVAIKI 2008

Hawaii Atmospheric Vapor Isotope “Knowledge” Intercomparison

PIs: David Noone (U. Colorado) and Joe Galewsky (U. New Mexico)

Objectives

1. Test optical analysers
   JPL, Picarro, Los Gatos Research
2. Provide validation opportunity for TES and IASI HDO
3. Science objectives
   Understand hydrology of dry zones

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NOAA Mauna Loa Obs
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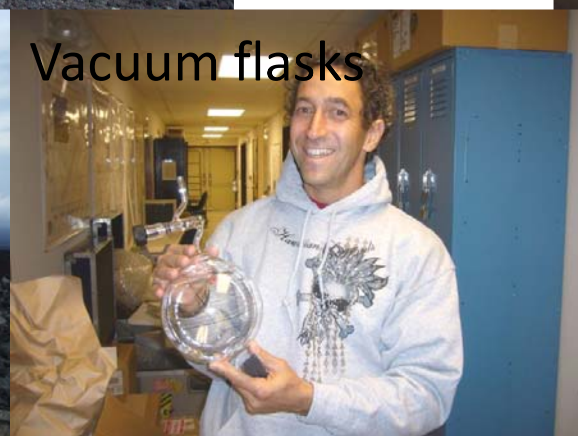
Doug Baer
Manish Gupta

Picarro
Eric Crosson
Priya Gupta
Aaron van Pelt

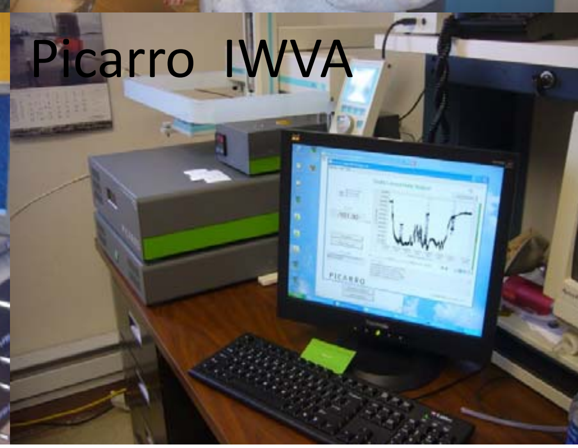
Cryogenic traps



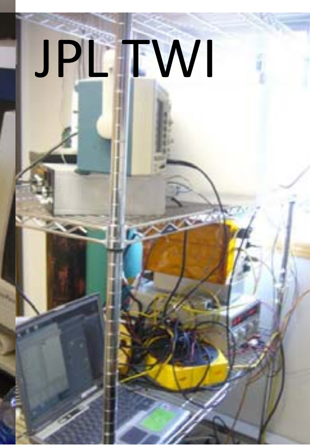
Vacuum flasks

http://cires.colorado.edu/science/features/vapor/

LGR WVIA



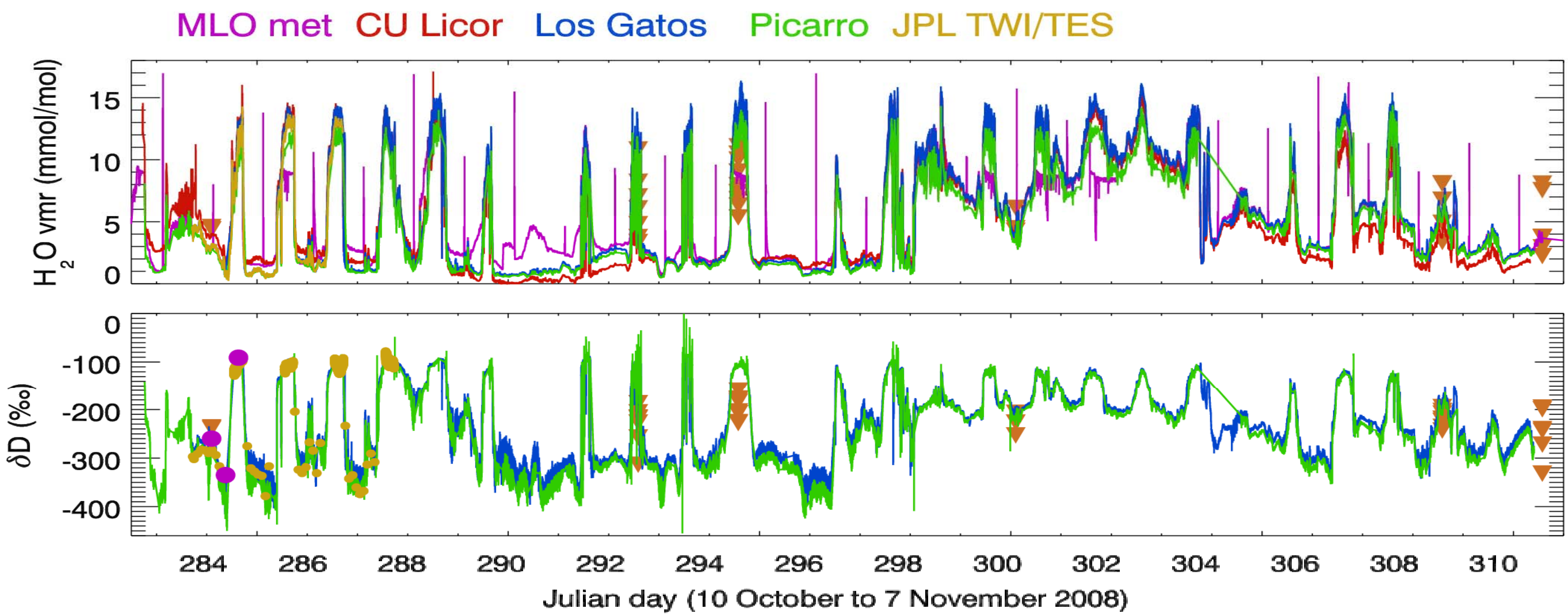
Picarro IWVA



JPL TWI

Inlet

Water and isotopes at Mauna Loa



General agreement between instruments

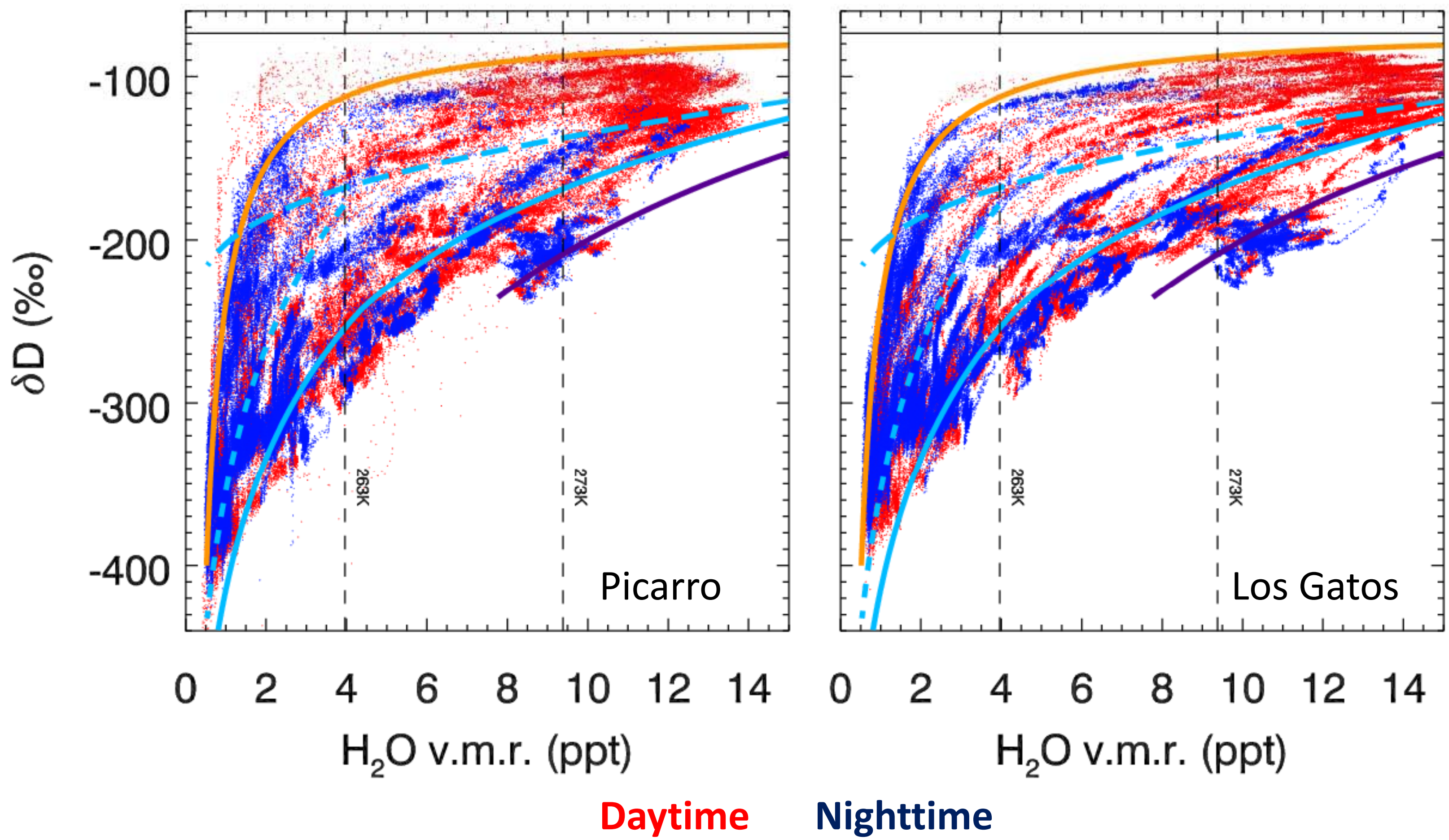
Some differences in details

Dominant diurnal cycle

Very dry night (free troposphere)

Boundary layer during daytime

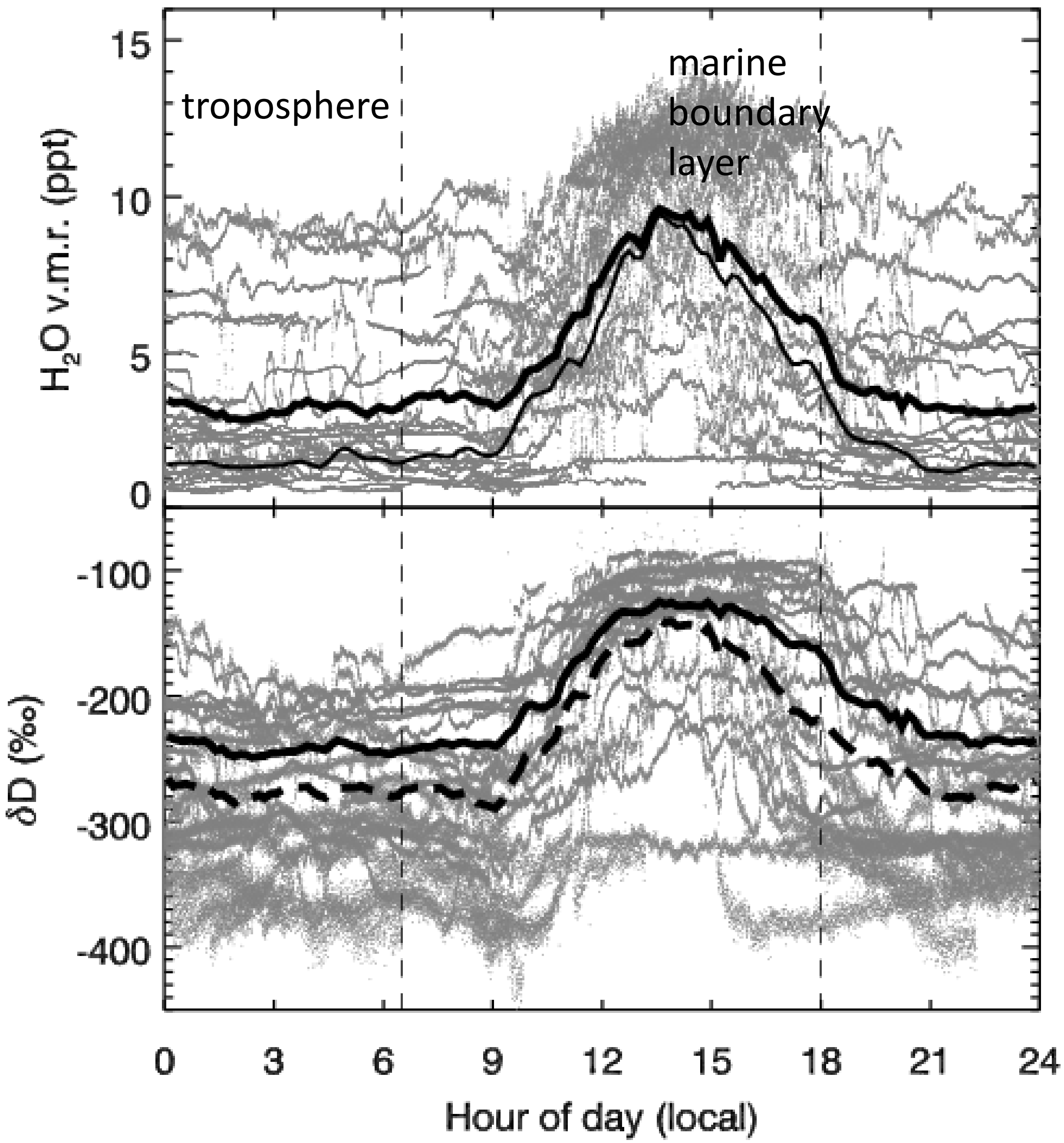
Noone , Galewsky et al., JGR, in prep,



Measurements immediately confirm simple models!

Thus theory can be used to interpret data quantitatively

Key aspect is that it is a ***2 dimensional problem***, to give a cycle.

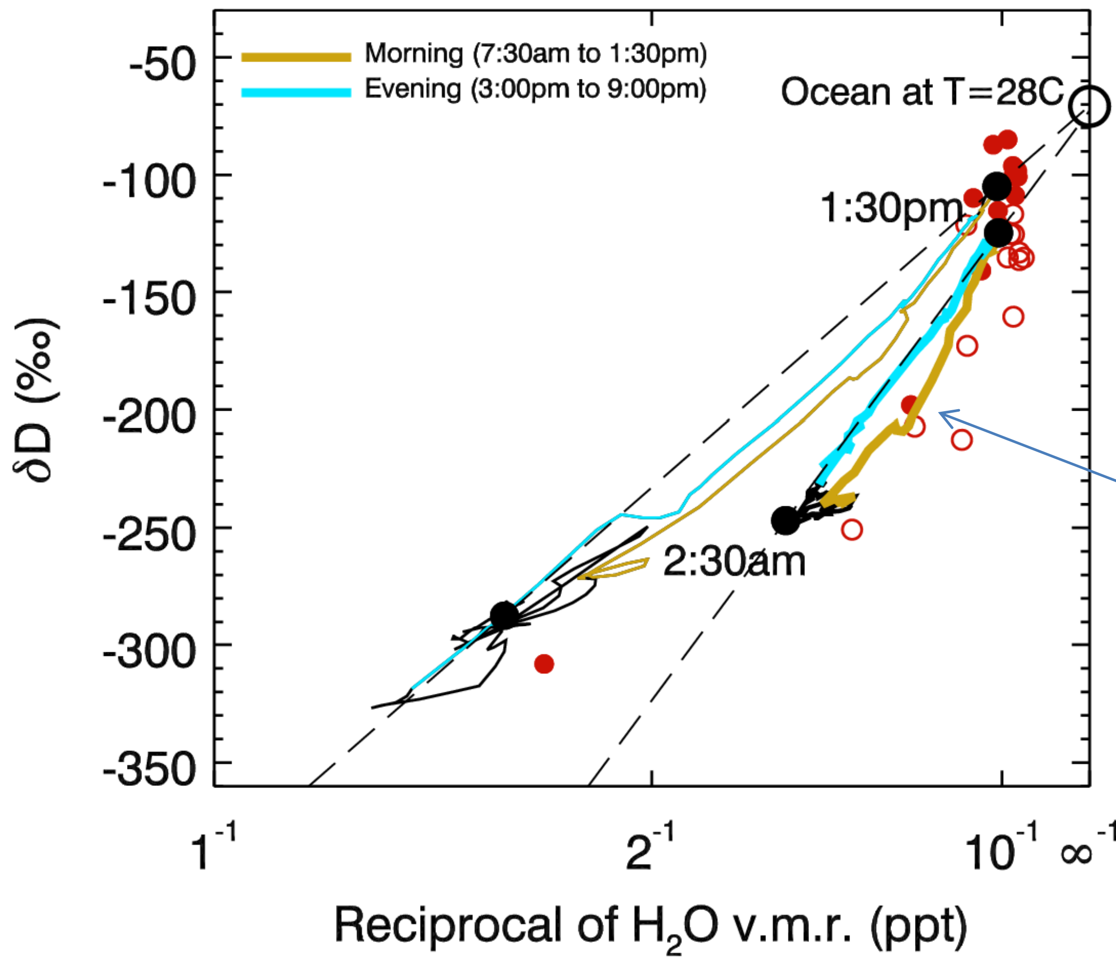


Notice difference in shape:
This is where the information from isotopes resides.

Enormous!

Instruments sensitive < 1 permil

Diurnal cycle: 2-box mixing model



Similar to a "Keeling plot" used for $^{13}C/C$

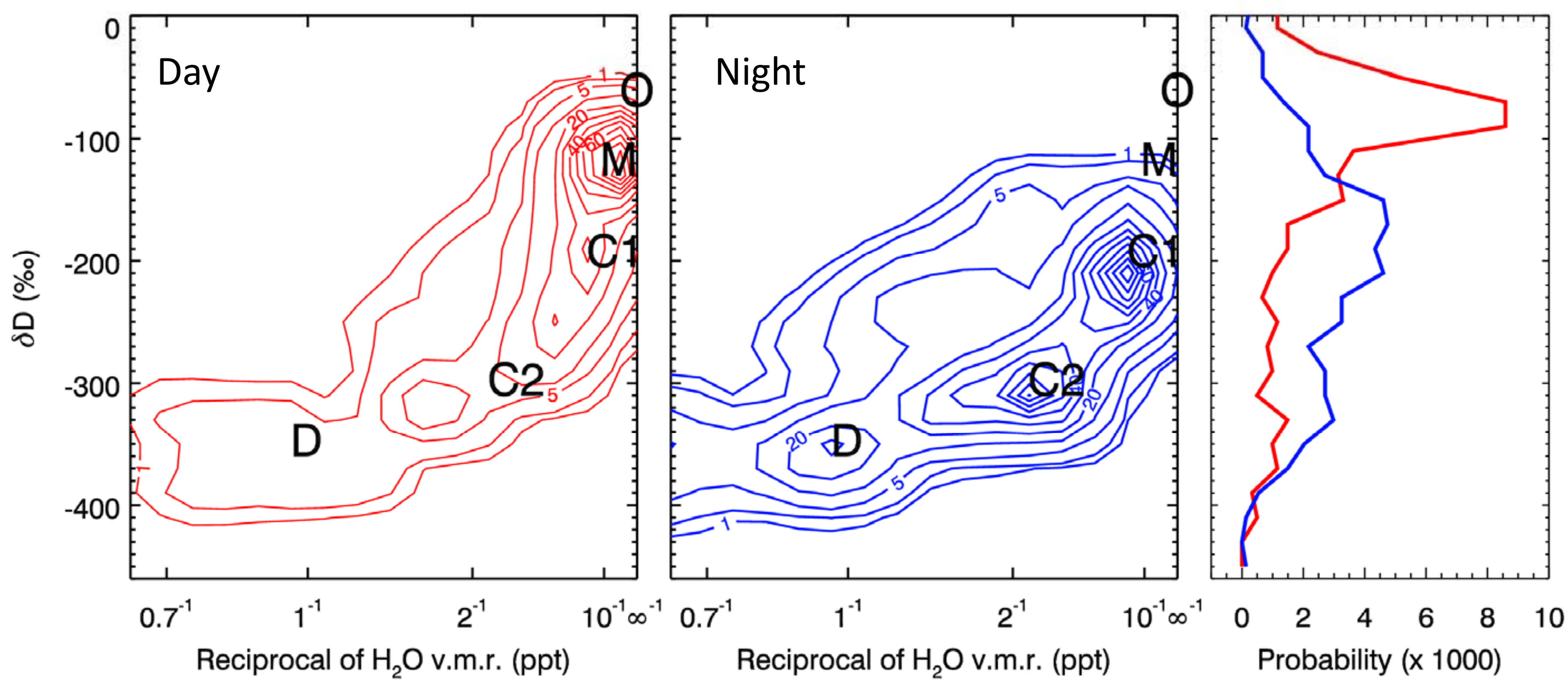
Collapse of the MBL in the evening is simple mixing.

Daytime growth has a "third" reservoir: boundary layer clouds

Source is identified as evaporation of ocean water near 28°C (plus kinetic effects)

Mean source, OK. What about sources for individual days/events?

What is the moisture source?
(end member for mixing)

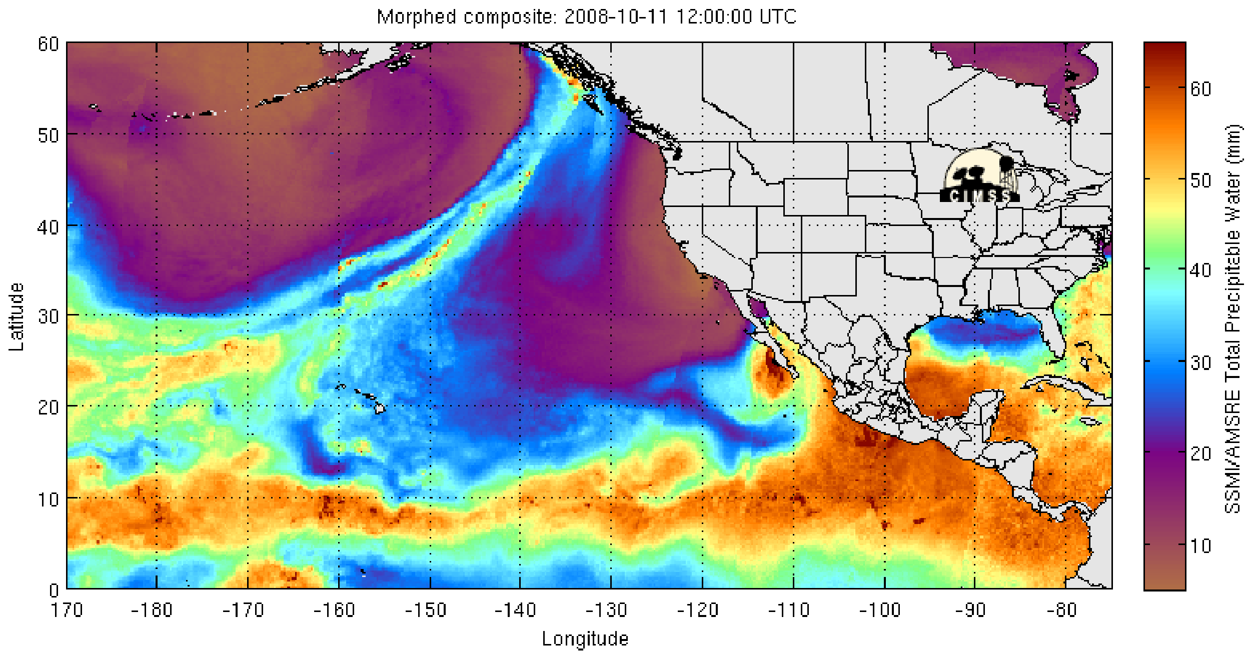


Daytime source – evaporation from the ocean ("O")

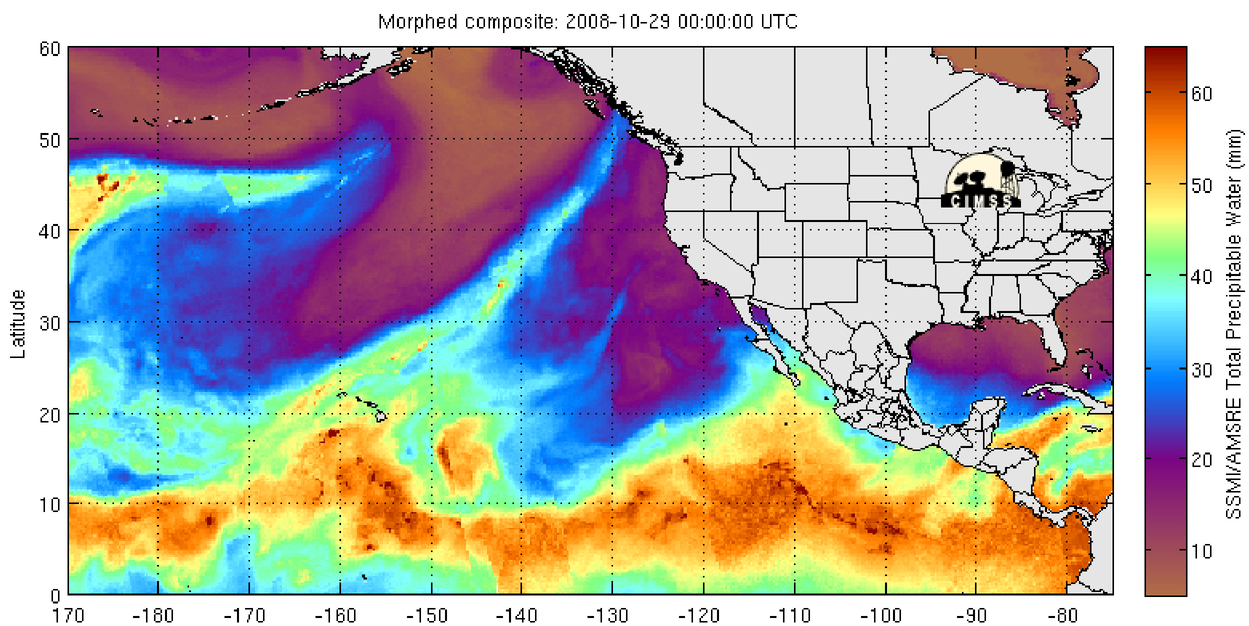
Nighttime – detrainment from shallow convection ("C1", "C2")
(importantly, NOT evaporation)

Probability distributions only possible with high volume of data (satellite and in situ)

Column precipitable water



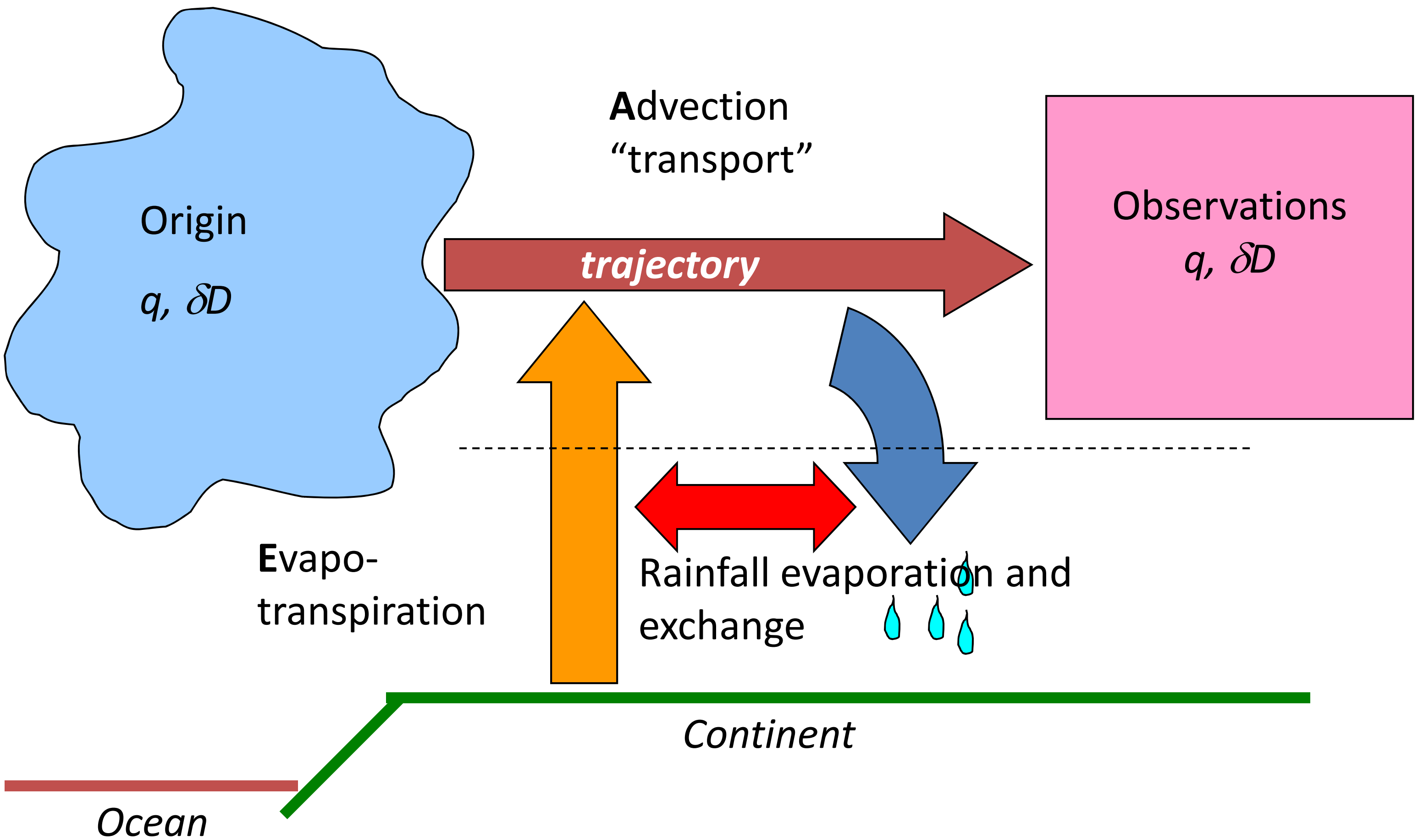
Dry, subtropical nights



Moist, “river” outflow (C2 event)

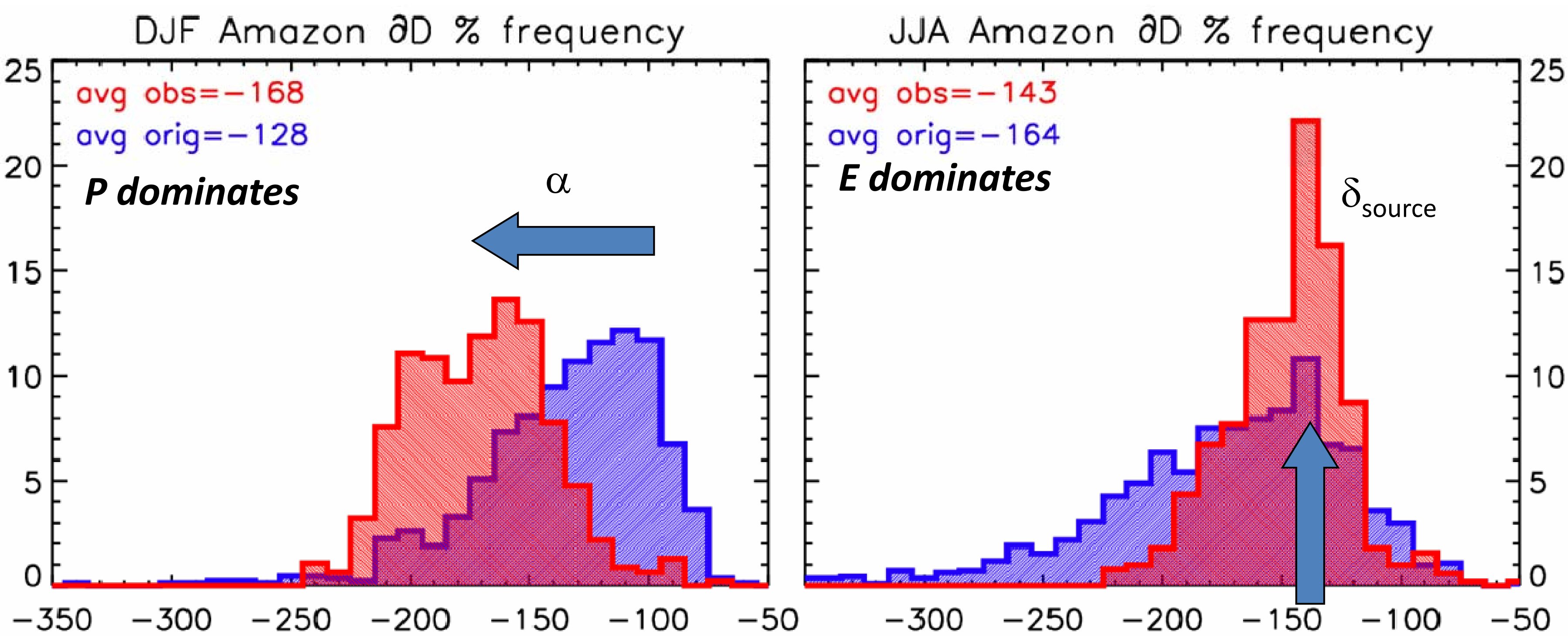
Isotope mass balance (simple boxes)

Dominated by P or be E?



Can be closed by assuming isotope physics (not unambiguous!)

Example: Amazon



Upstream/initial → (*processes along trajectory*) → Downstream/final

Condensation depletes, and shifts distribution by cloud efficiency

Evaporation/source enriches distribution, at value of origin water

(Brown *et al*., JGR, 2008)

Time mean budget: ensemble estimate

Mass balance

$$\frac{dq}{dt} = \kappa(q_s - q) - aq^n$$

$$\frac{d(Rq)}{dt} = \kappa\eta(R_s q_s - Rq) - \alpha a(Rq)^n$$

Integrate:

$$q_{\mathrm{mod}}(t+\Delta t) = \overline{q}_{src}\left(\frac{\tilde{k}}{\tilde{k}+\tilde{a}}\right)\left[1 - e^{-(\tilde{k}+\tilde{a})\Delta t}\right] + q_0 e^{-(\tilde{k}+\tilde{a})\Delta t}$$

$$R_{\mathrm{mod}}(t+\Delta t)q_{\mathrm{mod}}(t+\Delta t) = \overline{Rq}_{src}\left(\frac{\tilde{\eta}\tilde{k}}{\tilde{\eta}\tilde{k}+\tilde{\alpha}\tilde{a}}\right)\left[1 - e^{-(\tilde{\eta}\tilde{k}+\tilde{\alpha}\tilde{a})\Delta t}\right] + R_0 q_0 e^{-(\tilde{\eta}\tilde{k}+\tilde{\alpha}\tilde{a})\Delta t}$$

- Fit 6 ***mean*** parameters $(\tilde{a}, \tilde{k}, \overline{q}_{src}, \overline{R}_{src}, \tilde{\alpha}, \tilde{\eta})$ via minimization of cost function

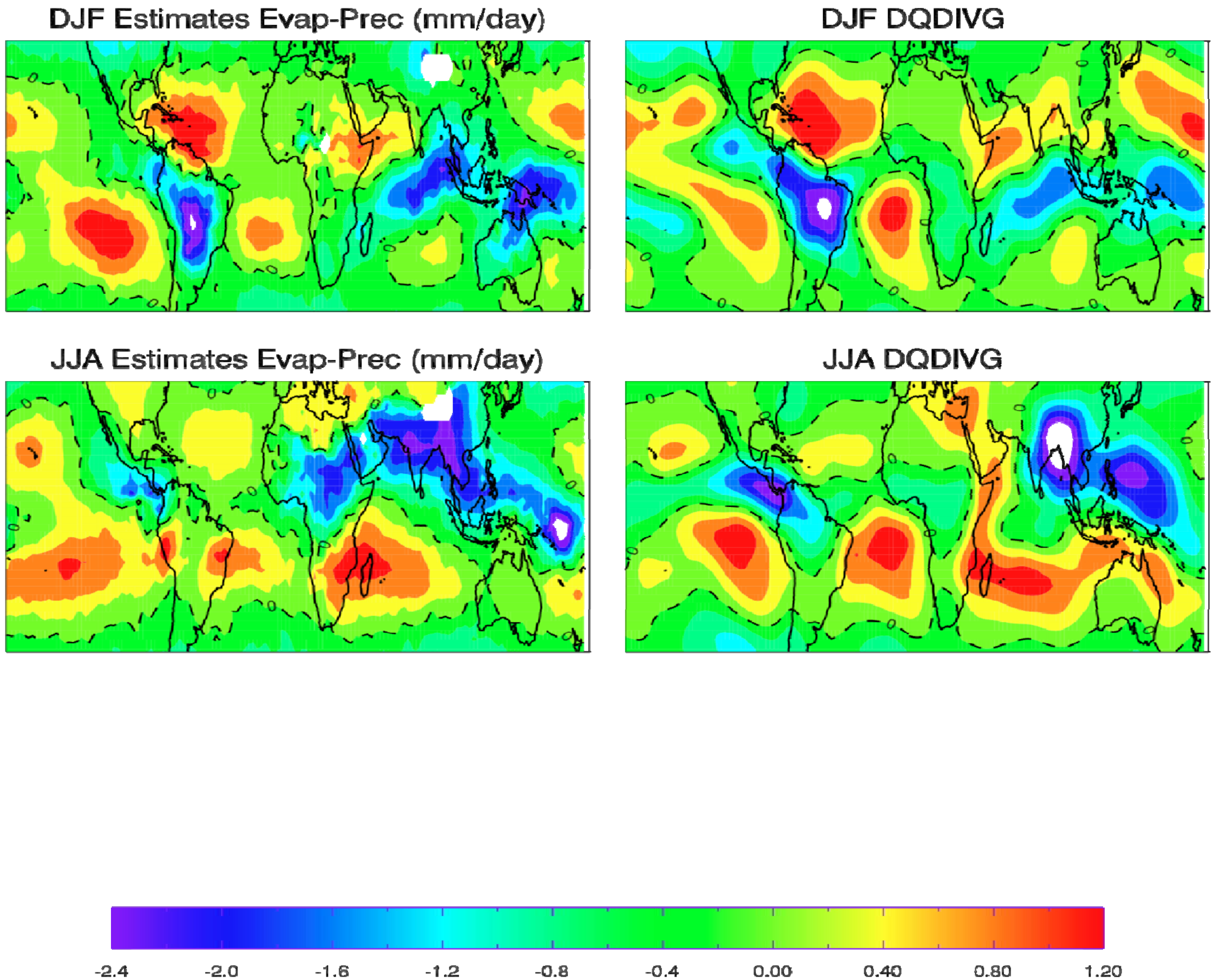
$$J = \sqrt{\frac{1}{\overline{q}}\left[\overline{q\left(\ln\left\{\frac{q_{\mathrm{mod}}}{q_{obs}}\right\}\right)^2} + \overline{q\left(\ln\left\{\frac{R_{\mathrm{mod}}}{R_{obs}}\right\}\right)^2}\right]}$$

R_s gives isotopic composition of source vapor (*source conditions*)

α is “net” fractionation, characterizes cloud physics (*efficiency*)

Simple validation

Comparison of modeled E-P with that from NCEP diagnostic output for the 500-825 hPa layer



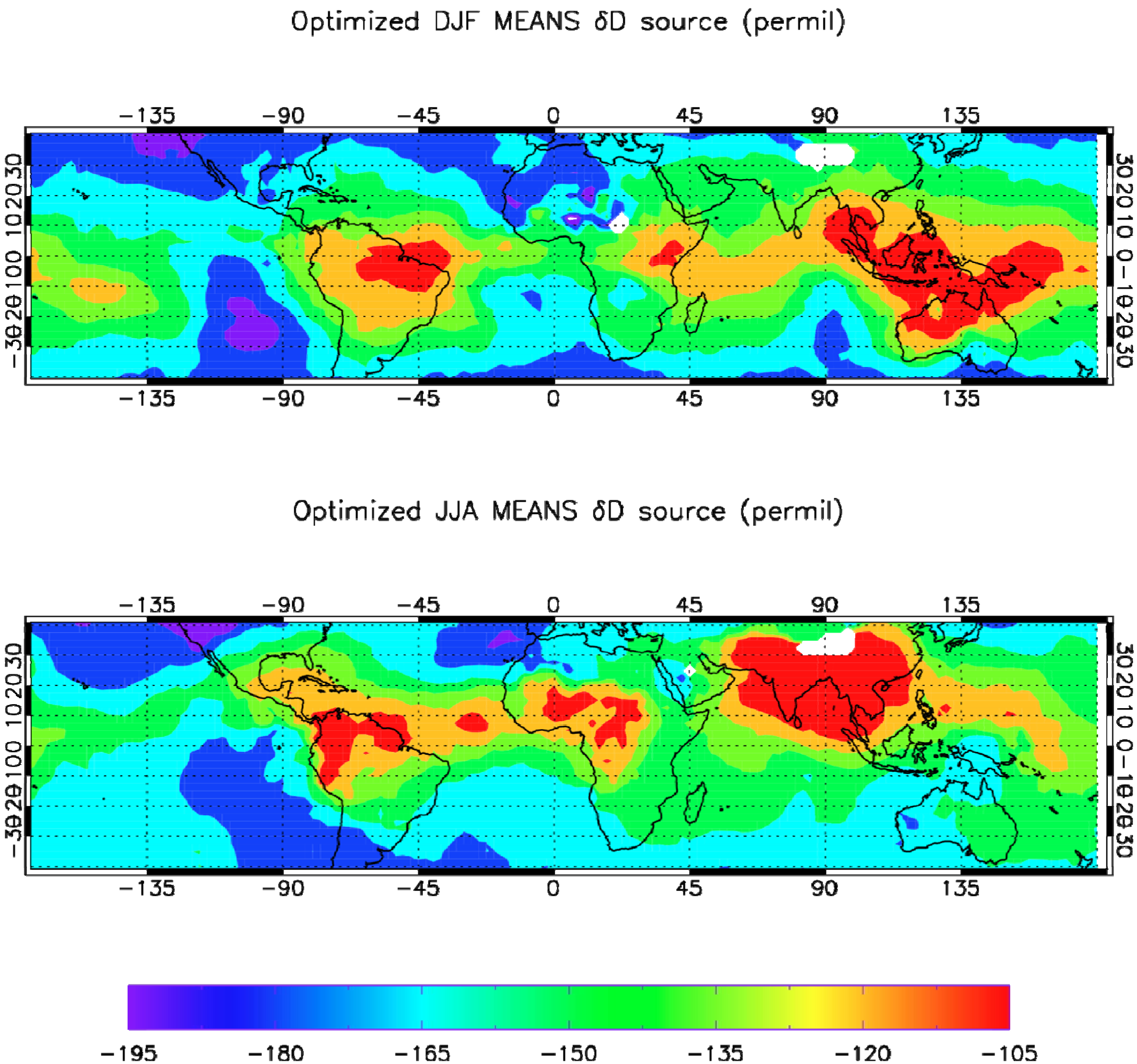
Good general agreement

The isotopic version of the model has 5-15% greater E and P than a moisture only run

Isotopic composition of the source waters:

The δD value of recently evaporated oceanic moisture in the boundary layer ≈ -110‰

Trajectories over the monsoonal regions indicate the "freshest" source waters for turbulent exchange



Isotopic composition of source water

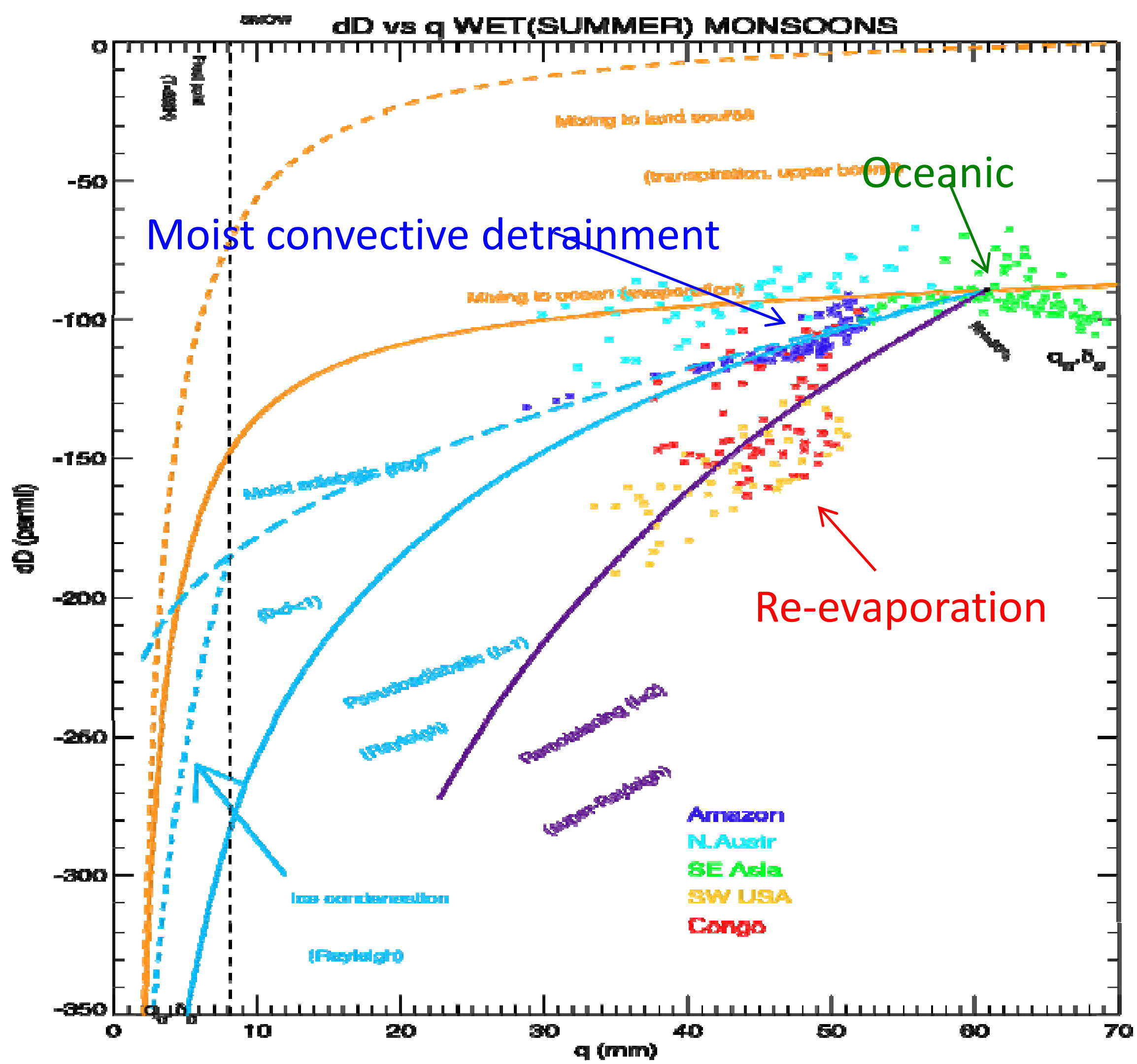
(source of water getting into the troposphere)

Amazon: Moist convective detrainment

N.Austr, convective detrainment of partially transpired water?

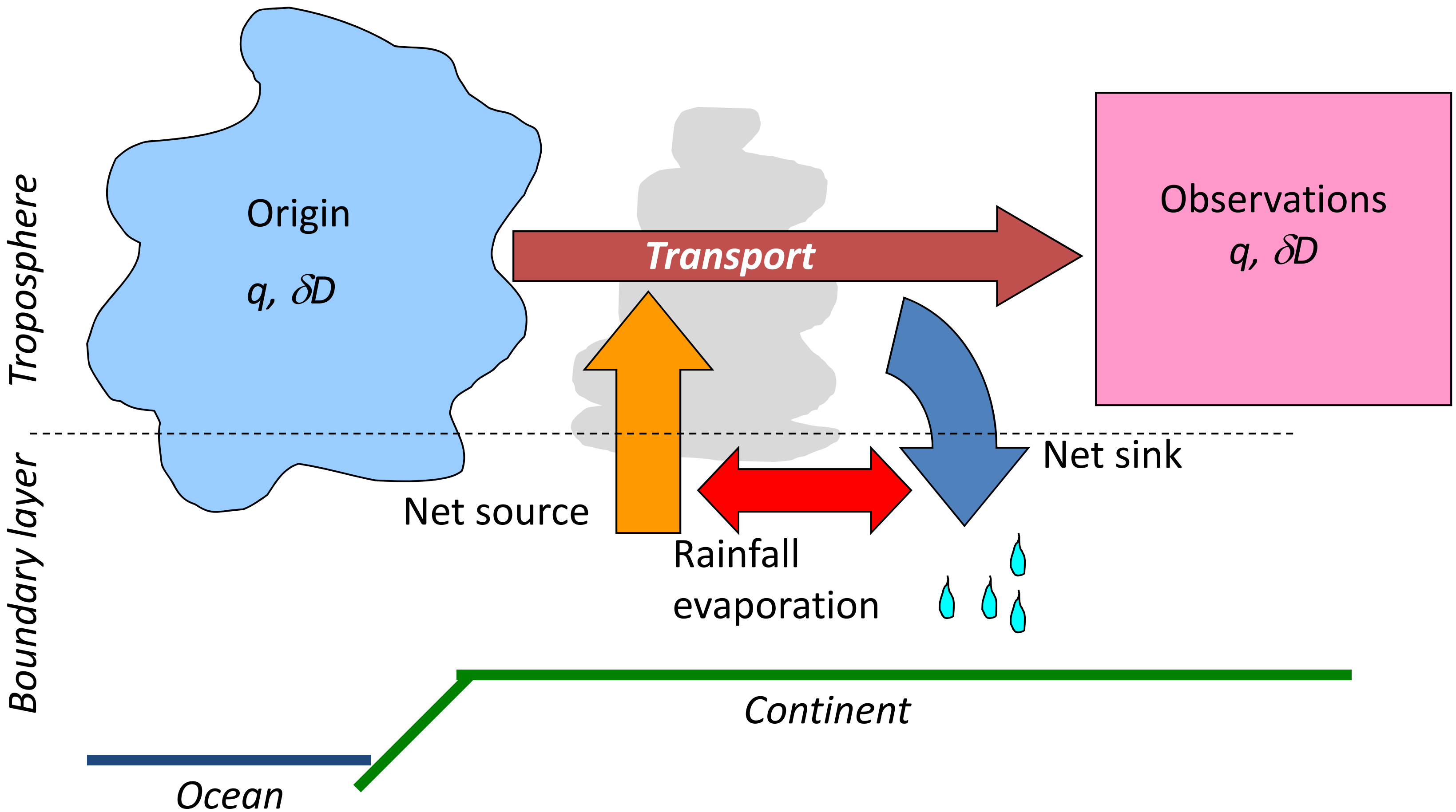
SE Asia: Fresh maritime boundary layer air

SW USA and Congo: Re-evaporation of falling rain



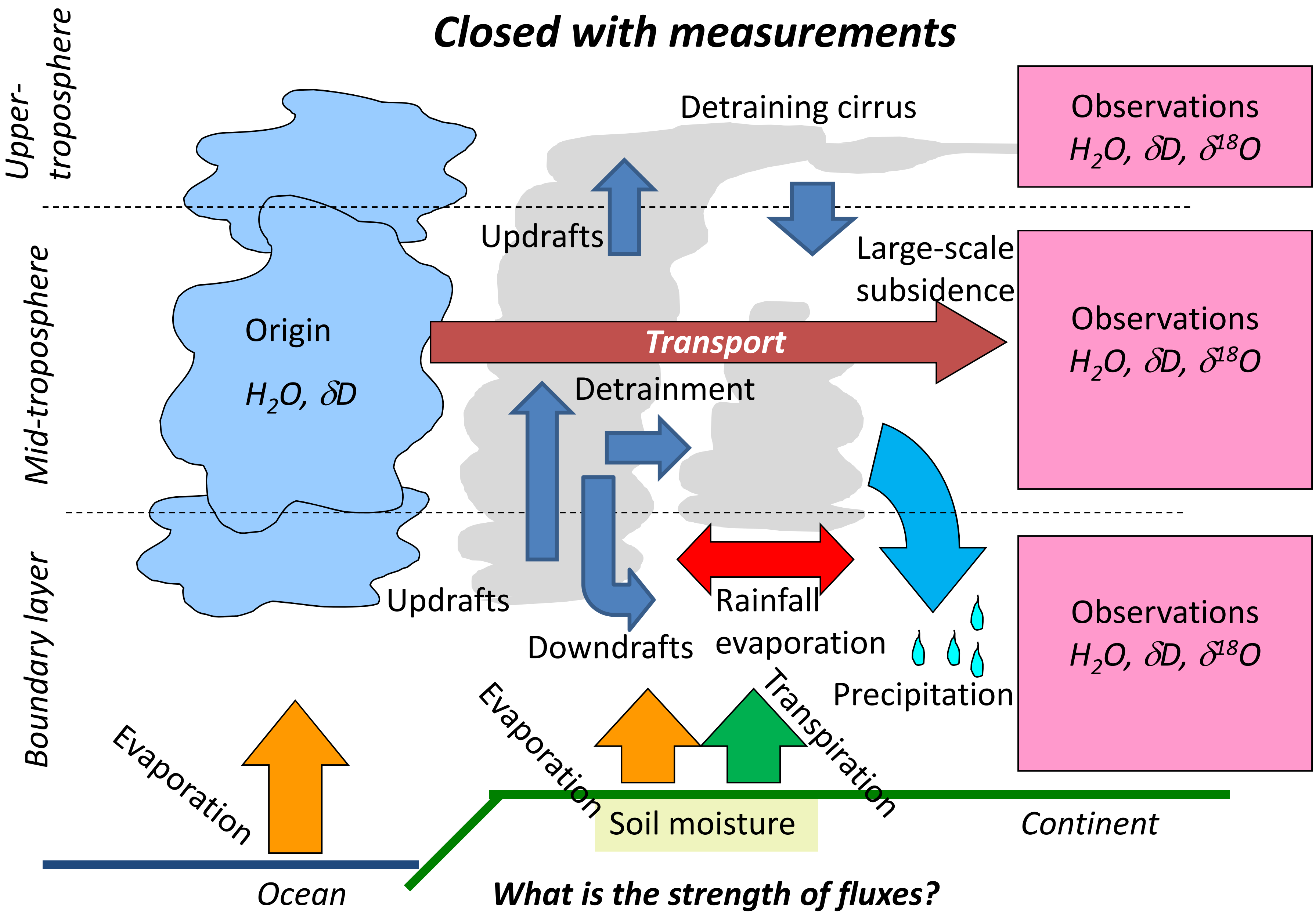
Water mass balance (TES era)

Closed with (simple) physical models



Dominated by Source ("E") or sink ("P")?

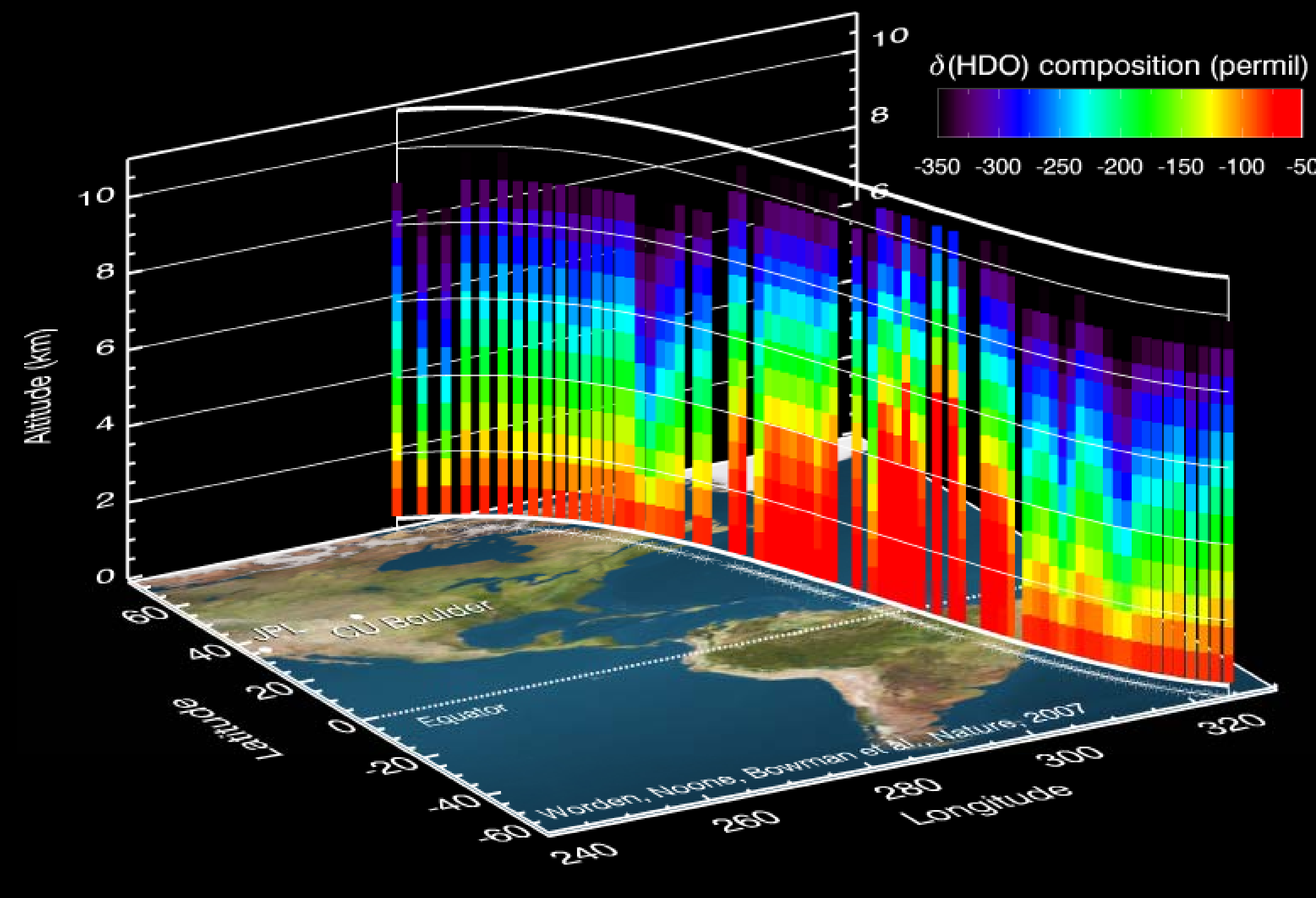
Water mass balance (next generation)



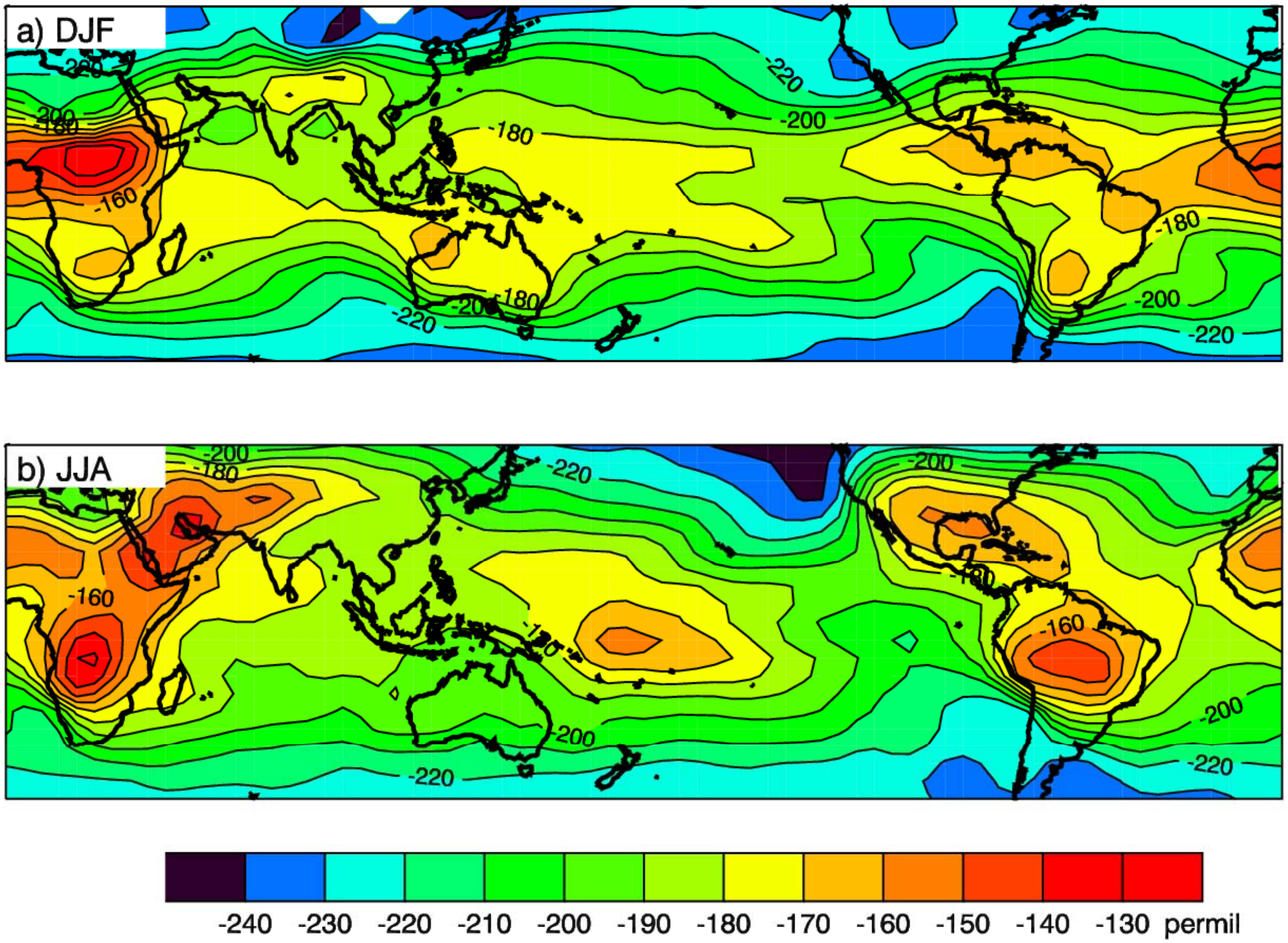
Conclusions

- With data, can move from phenomenology to quantification of (budgets)
  - Source of moisture to the subtropics is detrainment from shallow (warm) convection
  - Dehydration is by mixing with dry air (cloud be detrained from convection, could be at higher latitudes… it's the latter but can't tell without dynamics)
- Budgets constrained – how the water moves.
- But learn ***NEW INSIGHT*** from "isotope only" quantities. Specifically fractionation efficiency (bulk measure of microphysics) and isotopic composition of source water (conditions at/of source)
- Joint PDFs are the key. Normalize out the common conservative advection.

TES
Tropospheric Emission Spectrometer

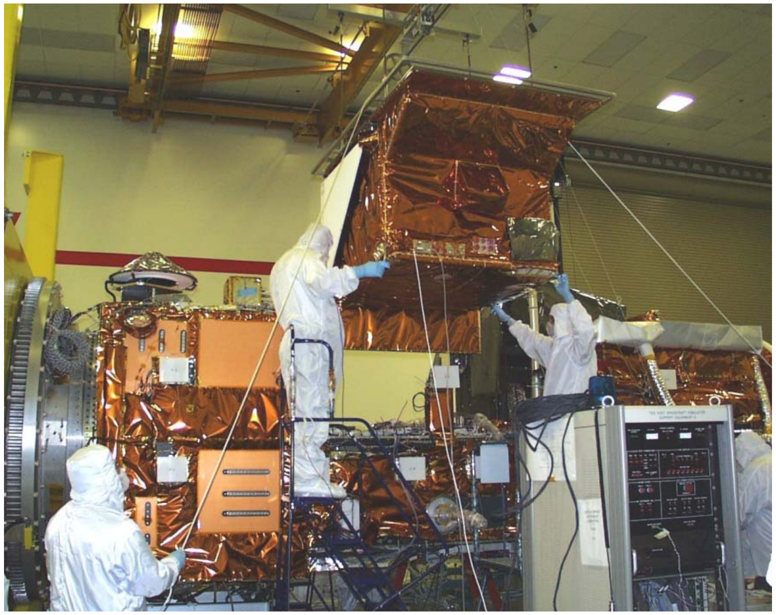


TES δD climatology (850-500 hPa)

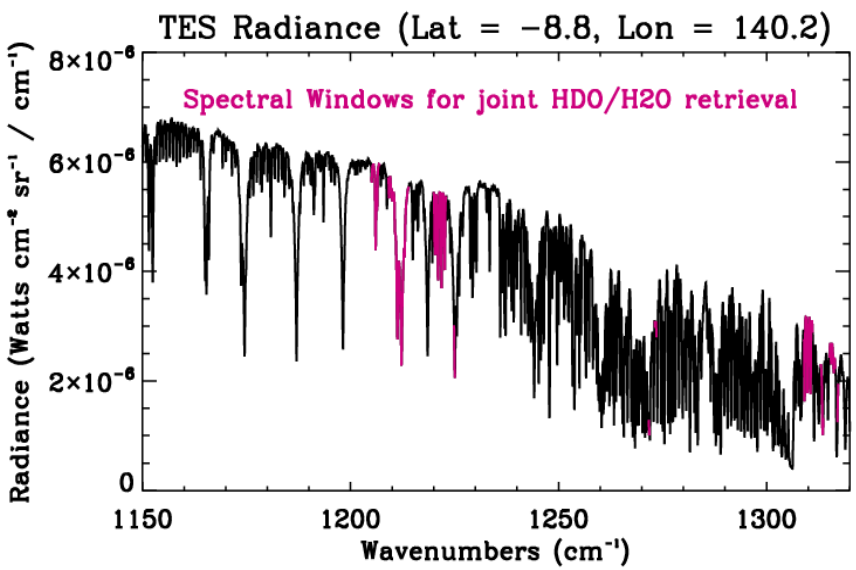


December 2004 – March 2008

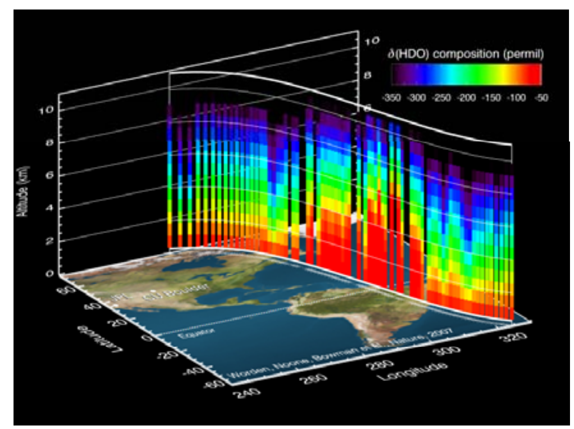
Brown et al., in prep, Helliker and Noone in press, Noone, et al., in prep., Brown et al., 2008, Worden et al., 2007, Worden et al., 2006



- Fourier transform spectrometer
- Thermal infra-red (650 – 3050 cm^{-1})
- Individual lines resolved (0.06 cm^{-1})
- Primary mission O_3, CO, CH_4
- Micro-window contains H_2O, CO_2, HDO and $H_2^{18}O$ lines.
- Retrieval minimizes error in covariance HDO/H_2O to precise isotope *ratio*



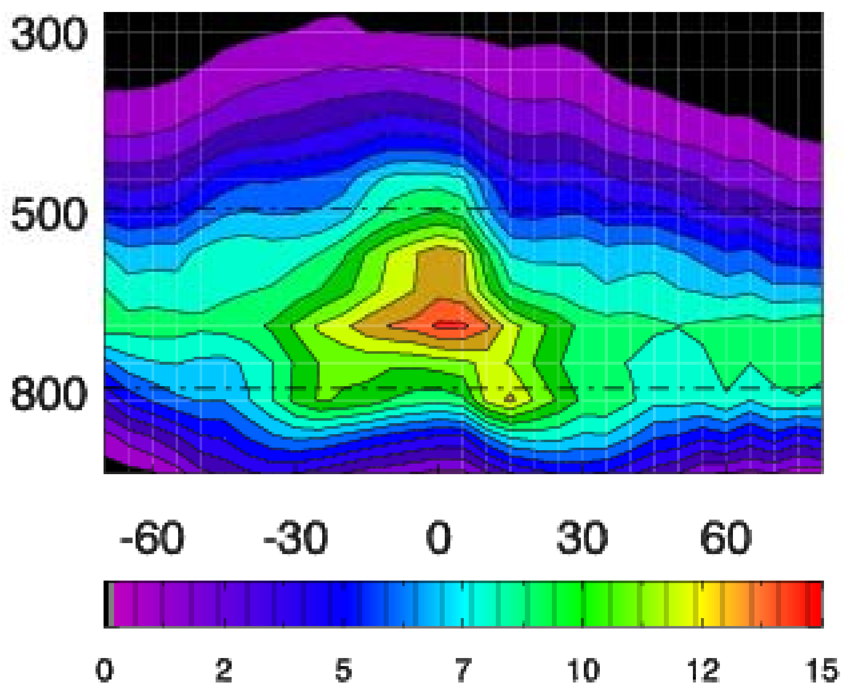
~10 km hoz. resolution,
~200 km sampling,
~ 1 d.o.f. in vertical



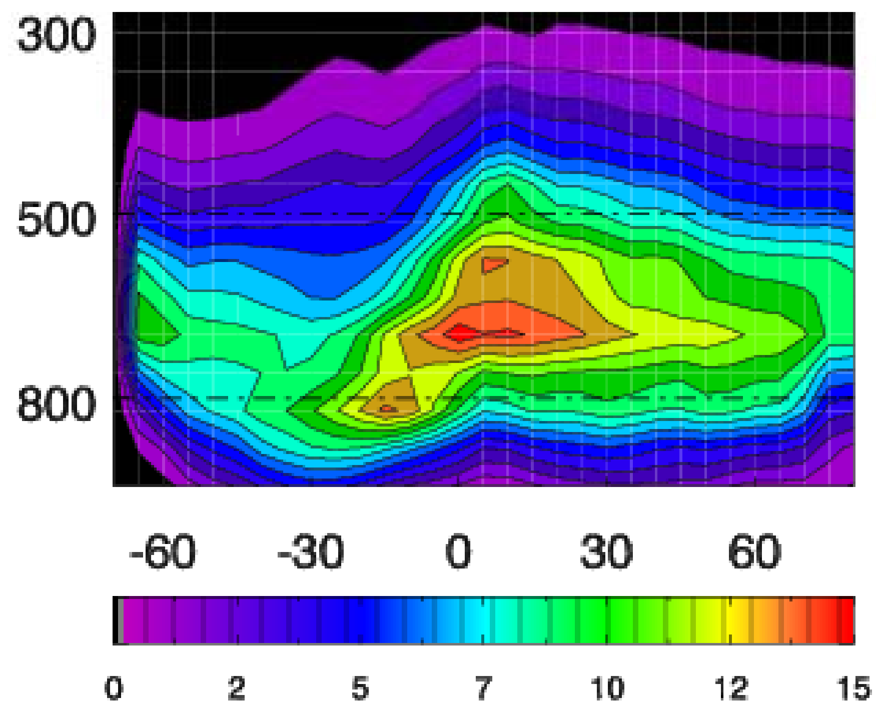
Worden, Bowman, Noone, et al. (2006)

Averaging kernel diagonal

December-January-February



June-July-August



800-500 hPa layer has adequate sensitivity. (DOFs 0.5 – 1.2)

Unwise to look in upper troposphere/boundary layer

Tropics/subtropics most reliable