What can we learn about the Amazon water balance from tropospheric deuterium measurements?

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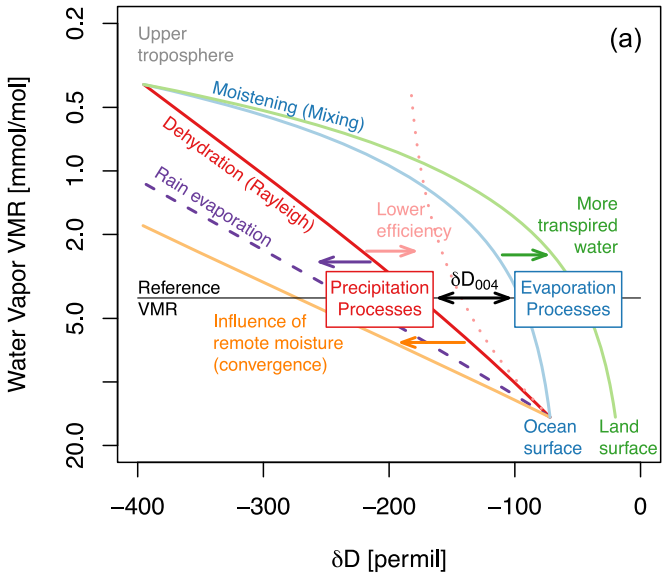

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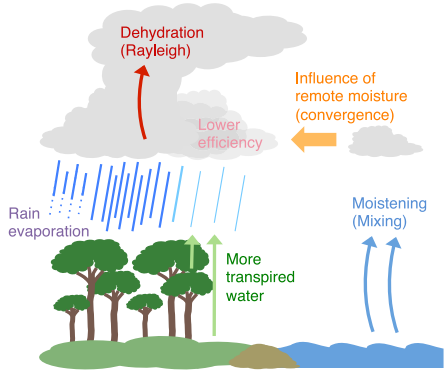
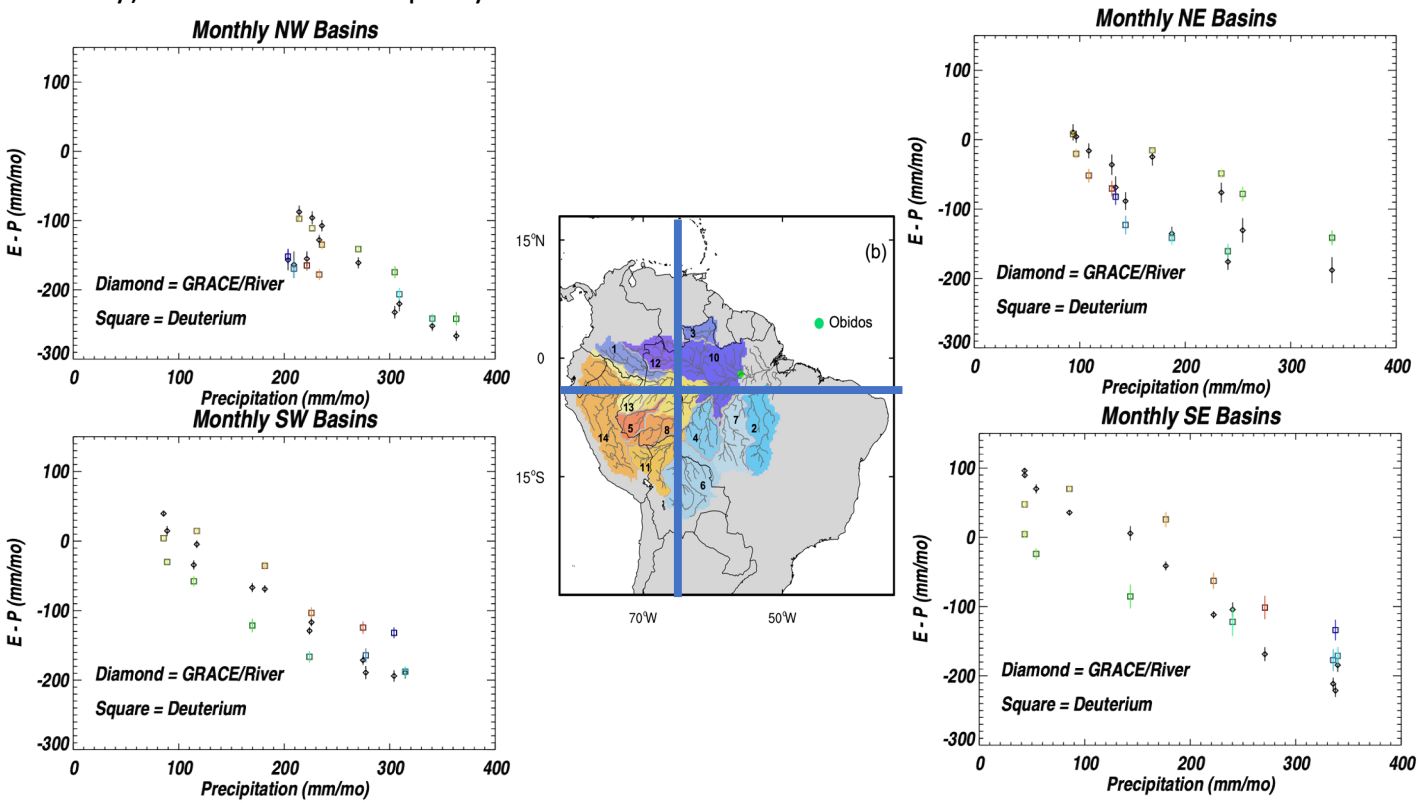


Processes in Figure (b) map to mixing and condensation models in Figure (a)

Satellite based (AIRS) tropospheric observations of the HDO/H2O ratio are sensitive to the net balance of evaporation and condensation plus smaller isotopic effects.

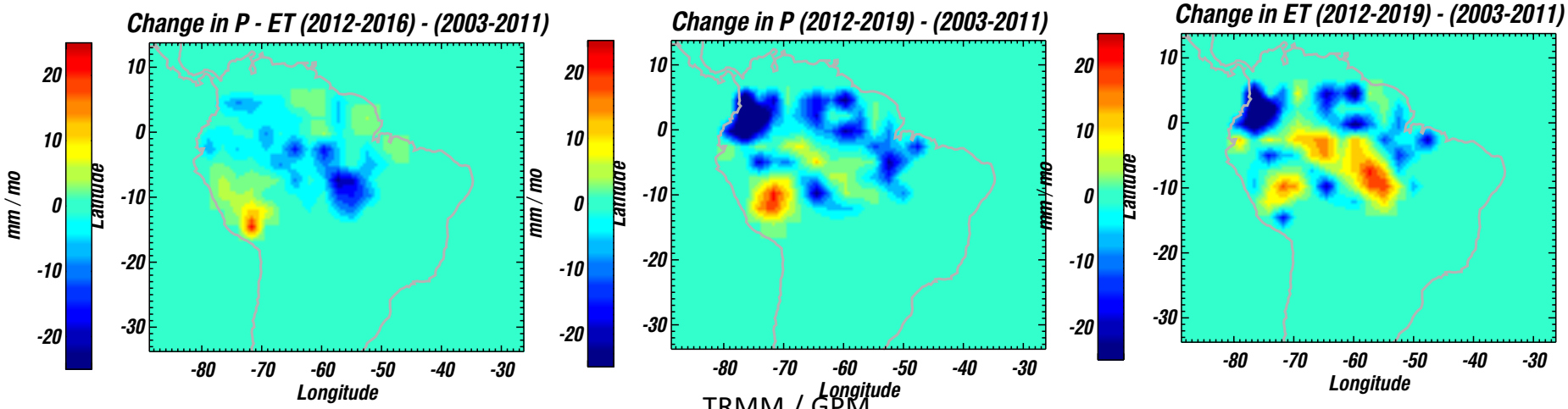
Normalizing this tropospheric value to a specified water amount representative of the total column water creates a proxy that covaries with ET - P

We can use measurements of gravity (NASA GRACE) and river discharge to calibrate the slope and offset (but not variability) of this deuterium proxy



Deuterium water balance proxy co-varies with surface water balance in the North.
However, deuterium water balance proxy depends on local and remote moisture in the South

Is Water Balance in the Amazon changing during the 21rst Century?



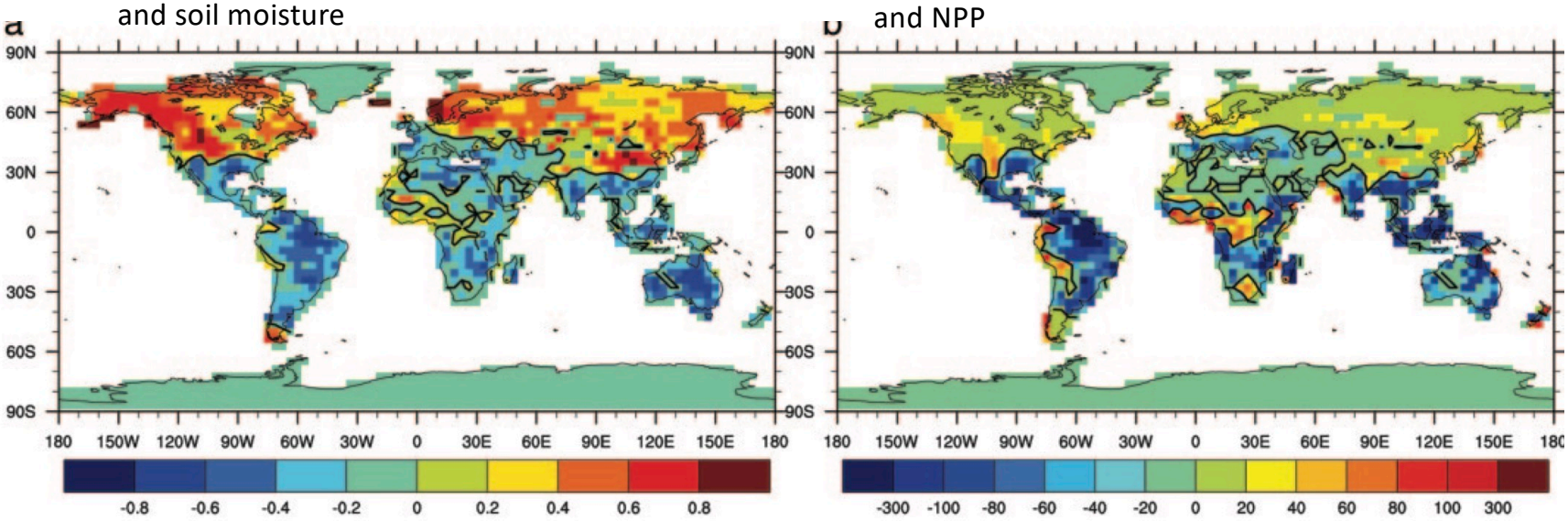
TRMM / GPM

21rst century changes in Water balance are smaller than observed precipitation changes indicating substantial role of ET in controlling Amazon water balance during the 21rst century

Models predict a reduction in Tropical NPP for future climate scenarios because increasing temperature increases soil moisture drying by increasing Evapotranspiration and reducing Precipitation or water balance or E – P. (Fung et al. PNAS 2005)

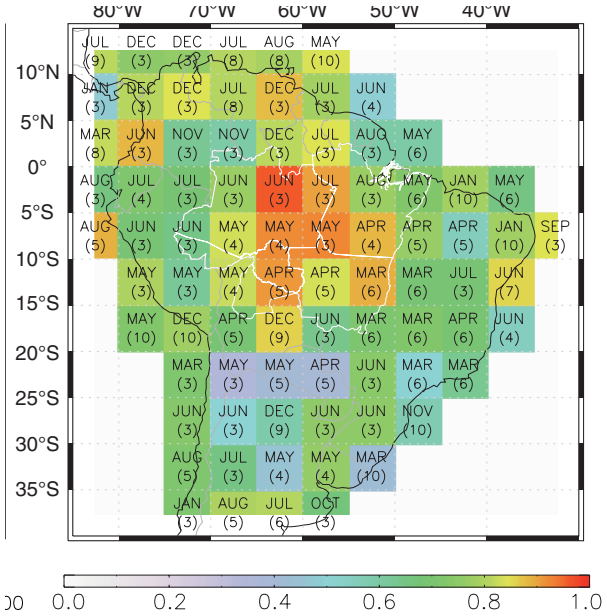
Correlation between change in temperature and soil moisture

Correlation between change in temperature and NPP



Humphrey et al. Nature 2021 demonstrates that feedbacks between soil moisture and Vapor Pressure Deficit (VPD) are a dominant driver of this effect, primarily through VPD impact on photosynthesis

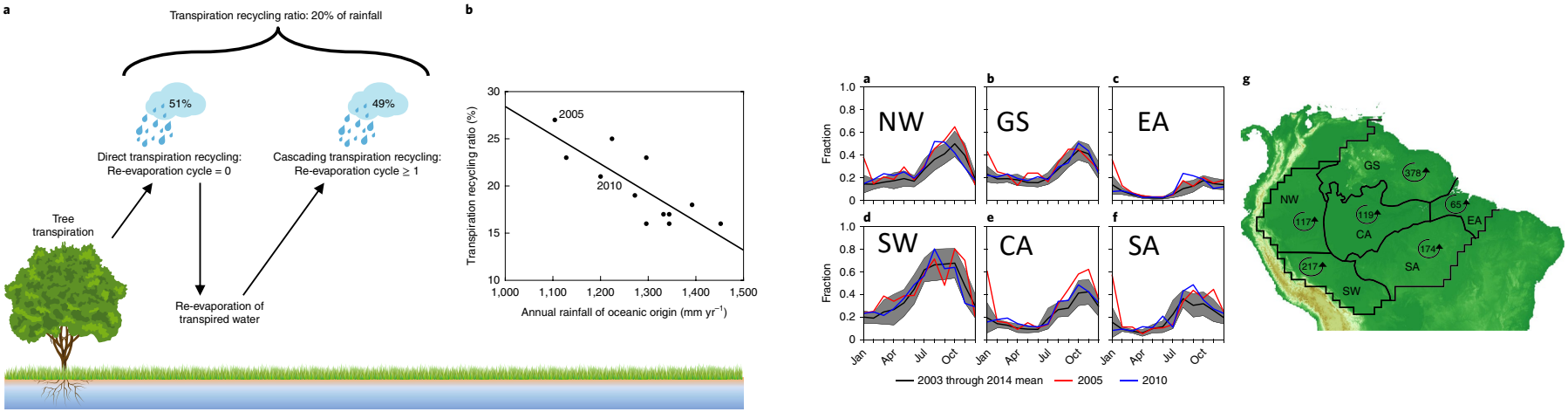
What are the factors modulating Evapotranspiration and Precipitation in the Amazon?



Chen et al. (Science 2011) demonstrates a strong relationship between rainy season Atlantic ocean SST and dry season fire severity.

ENSO related changes to Atlantic sea surface temperatures modulate Amazon rainfall which in turn affects dry season fire severity

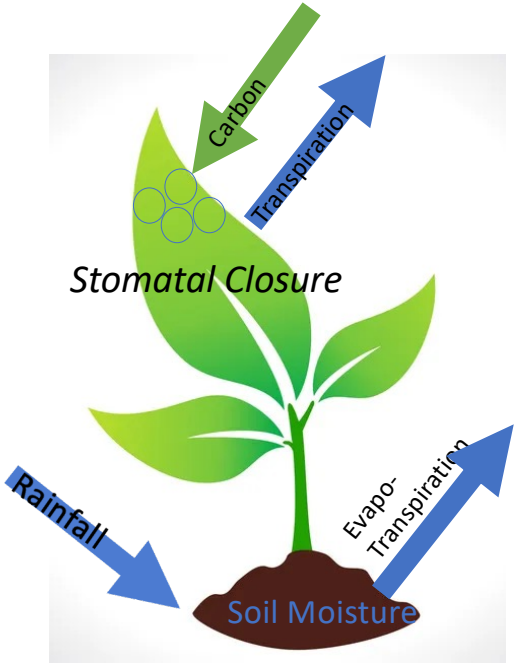
The Amazon (like most tropical forests) have strong feedbacks between ET and P



Staal et al. (Nat Clim Change, 2018) uses simple atmospheric and surface models, with Lagrangian back trajectories to show:

Transpiration contributes up to 30 to 50% to rainfall in Amazon with larger relative contributions during years with less rainfall

Complex, confounding mechanisms affect Amazon water balance and its changes



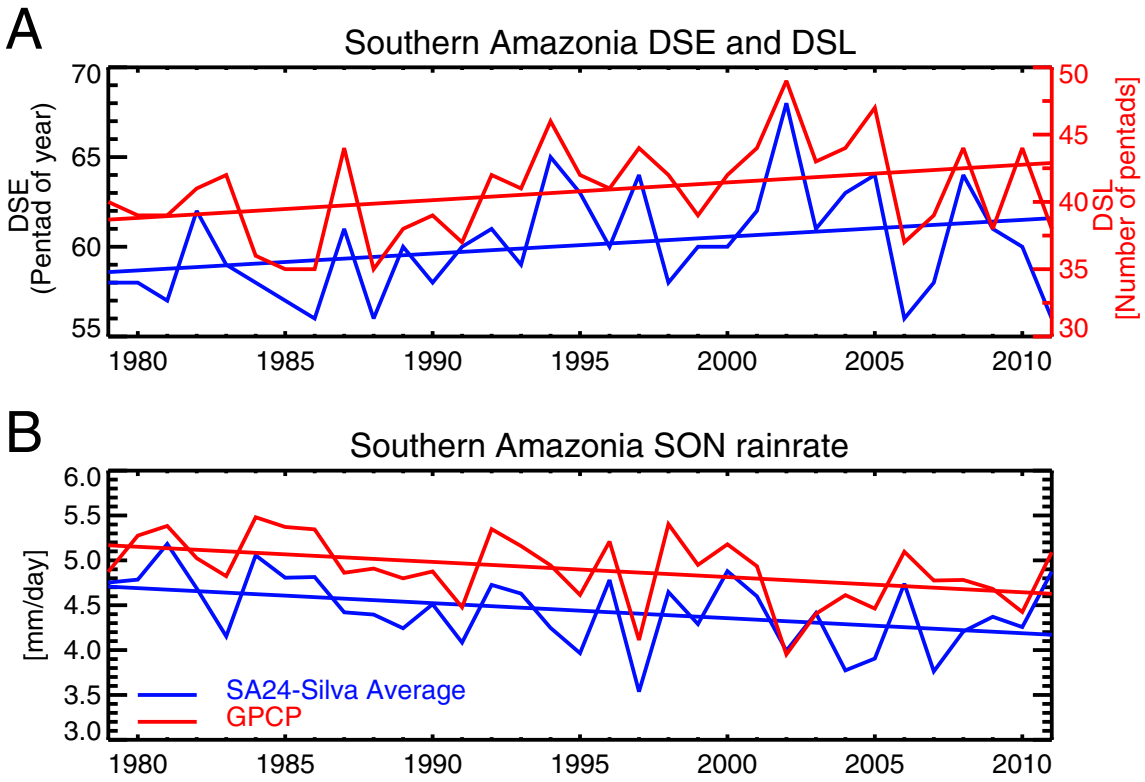
Dry air (i.e. vapor pressure deficit) can either 1) Increase evapotranspiration through demand or 2) force stomata to close, decreasing evapotranspiration (Gentine et al. 2019)

Soil Moisture: Stomata closes if soil moisture becomes too dry . Less soil moisture means less water supply for evapotranspiration which in turn increases VPD (Humphrey et al. Nature 2021)

Increasing CO_2 can also increase water use efficiency (van der Sleen Nat Geo 2015, Walker et al. New Phyt 2020)

→Atmospheric CO2 has increased by ~10% in last 20 years. Has water use efficiency also increased by 10% (decreasing transpiration)? Or have increased temperatures and drying increased transpiration?

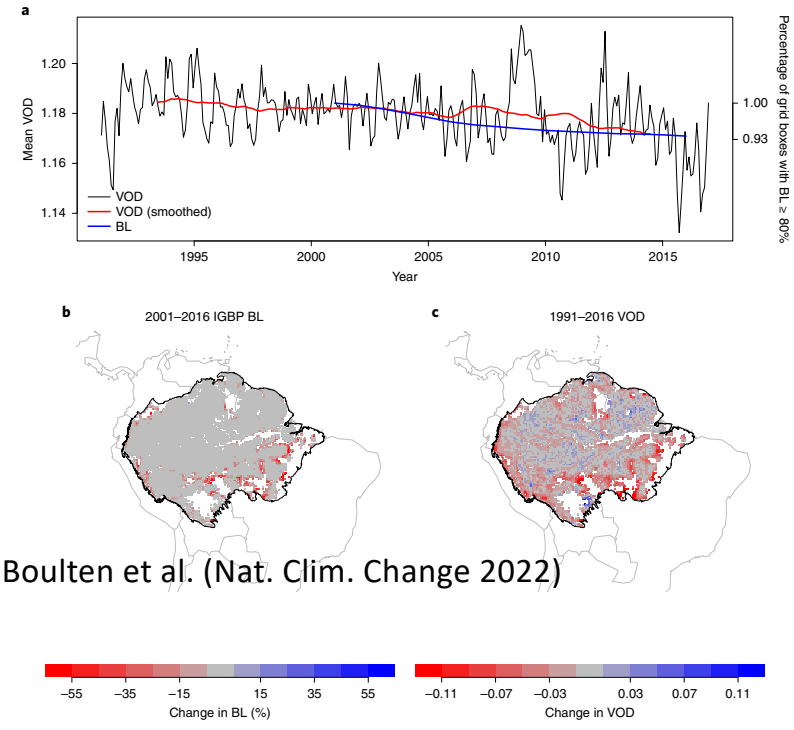
Are there indications of temporal changes in E-P or NPP in the Amazon?



Fu et al. (PNAS 2011) demonstrates a decline in rainfall from 1980 to 2010, associated with a delay in the rainy season onset

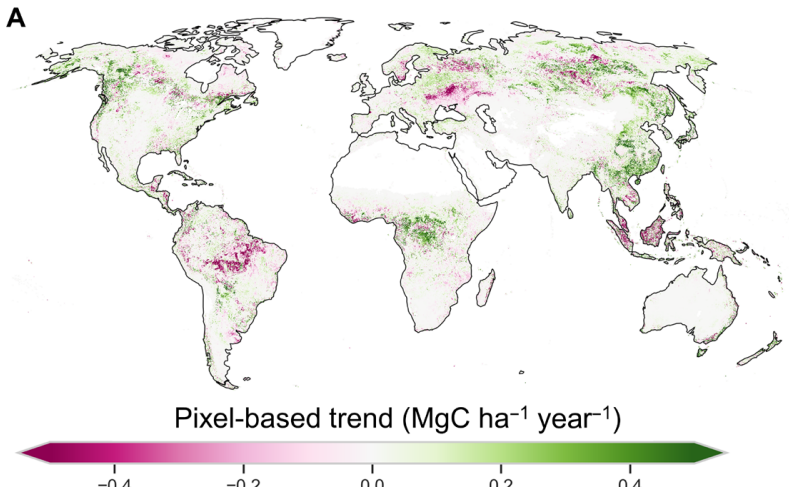
Are there indications of changes in E-P or NPP in the Amazon?

Large Changes since 2000 in MODIS “Broadleaf” (BL) and Vegetation Optical Depth generally coincide with regional declines in above ground biomass



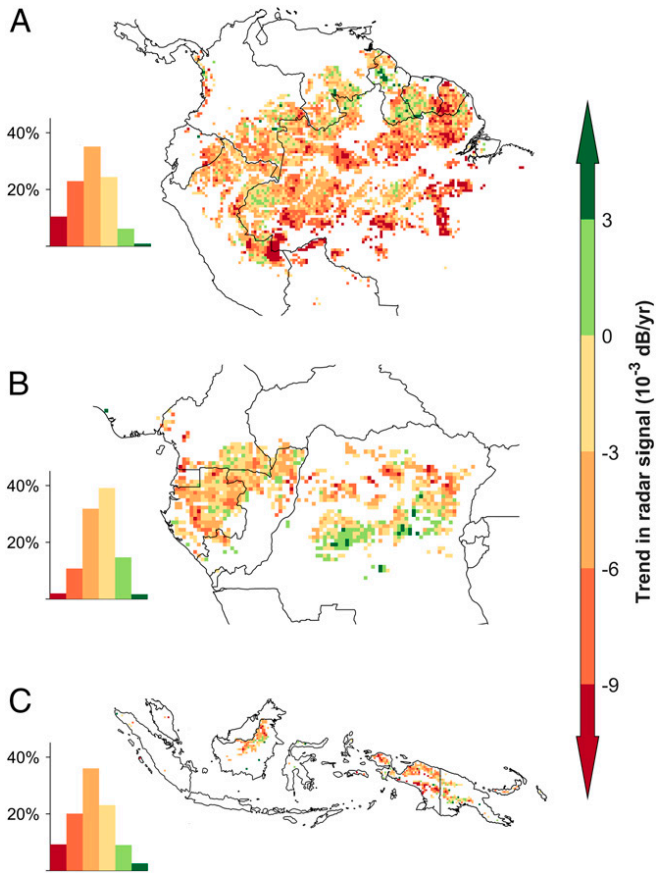
Boulten et al. (Nat. Clim. Change 2022)

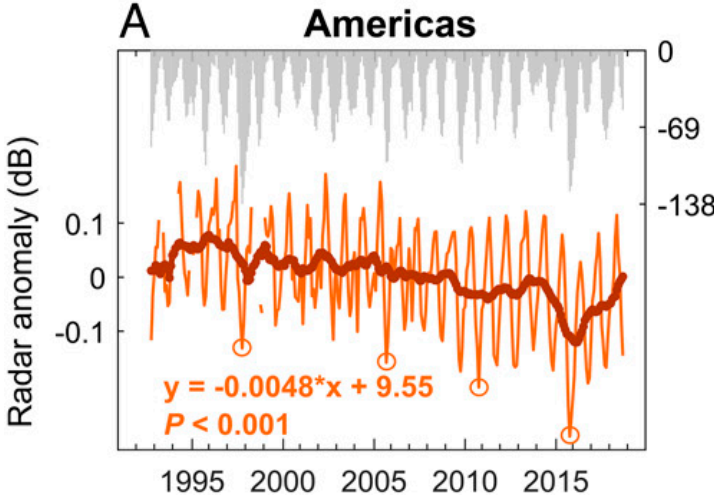
Changes in above ground biomass in the Amazon are mostly along the arc-of-deforestation but to some extent in the Central Amazon



Xu et al. Sci Adv (2021)

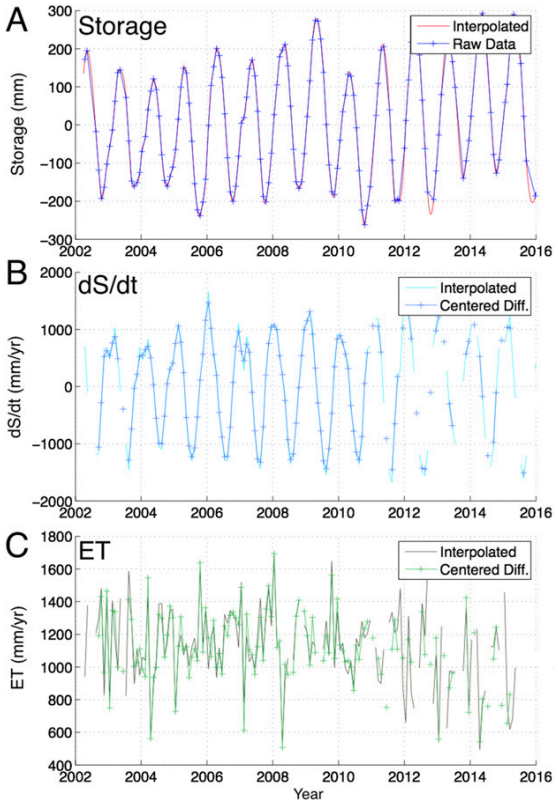
Are there indications of changes in E-P or NPP in the Amazon?





Radar signal related to upper canopy also declining since the early 2000 due to repeated droughts in the Amazon (Tao et al. PNAS 2022)

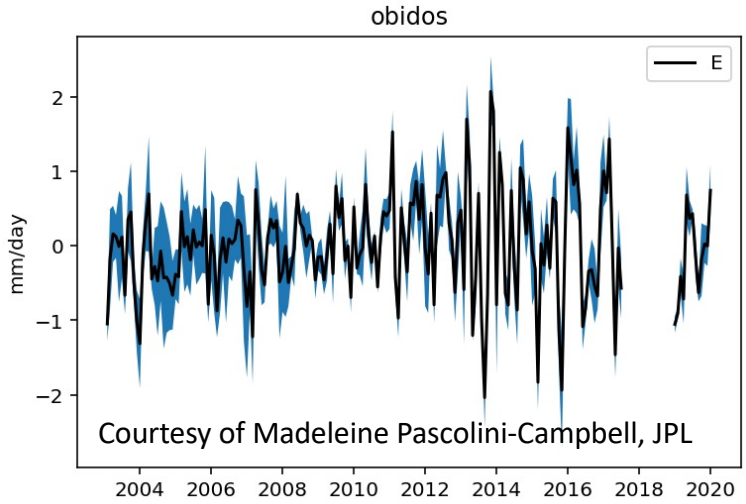
Water balance arguments suggest decline in ET in Amazon basin starting 2012
Increasing temperature not yet affecting ET?
Increasing CO2 affecting water use efficiency?



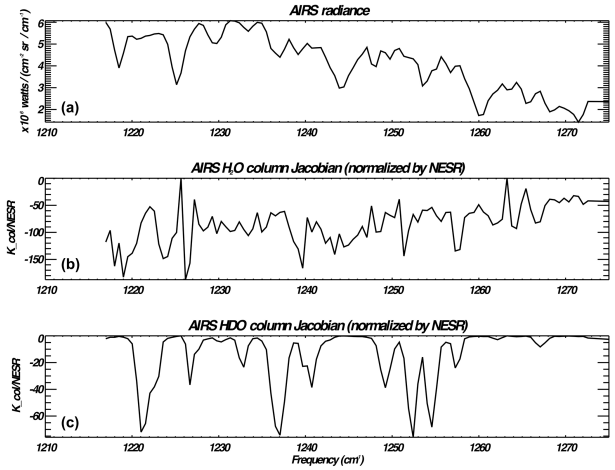
$$\mathrm{ET}_{\mathrm{GRACE}} = P - Q - dS/dt\,,$$

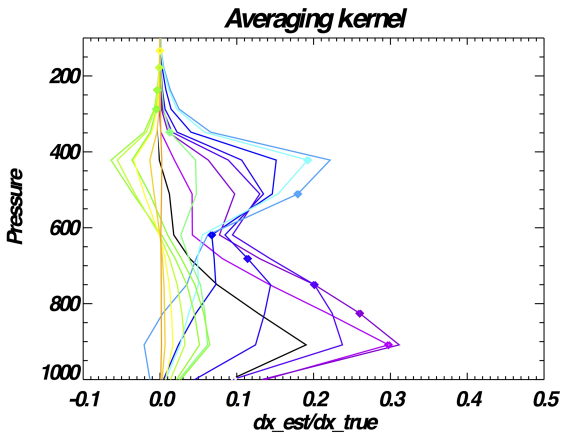
Uses data from GRACE and river discharge to quantify ET (Swann and Koven 2017)

Or maybe not? (More on this in subsequent slides)



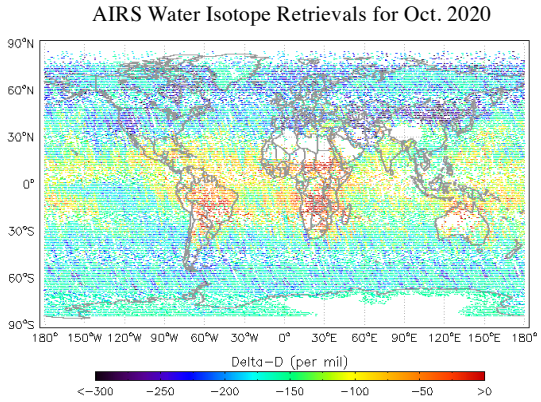
What do Tropospheric Deuterium Measurements say about S. American Tropical Water Balance during the 21rst century? (first a primer on TES and AIRS measurements of the HDO/H2O ratio)





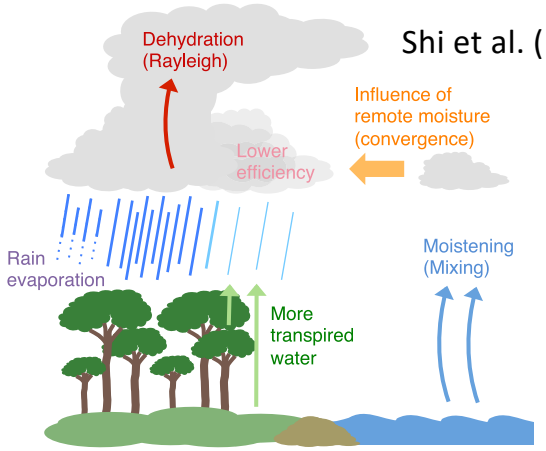
- We convert NASA Aqua AIRS observed spectrally resolved radiances to tropospheric profiles of HDO/H2O using an optimal estimation approach (Worden et al. AMT 2019)
- These data are sensitive to ~2 pieces of information in the tropics ***and cannot resolve the near-surface layer***
- ***AIRS provides a well-characterized record of tropospheric deuterium content (HDO/H2O) for 2003 to the present with no observable changes in calibration affecting this record***

What do Tropospheric Deuterium Measurements say about S. American Tropical Water Balance during the 21rst century?



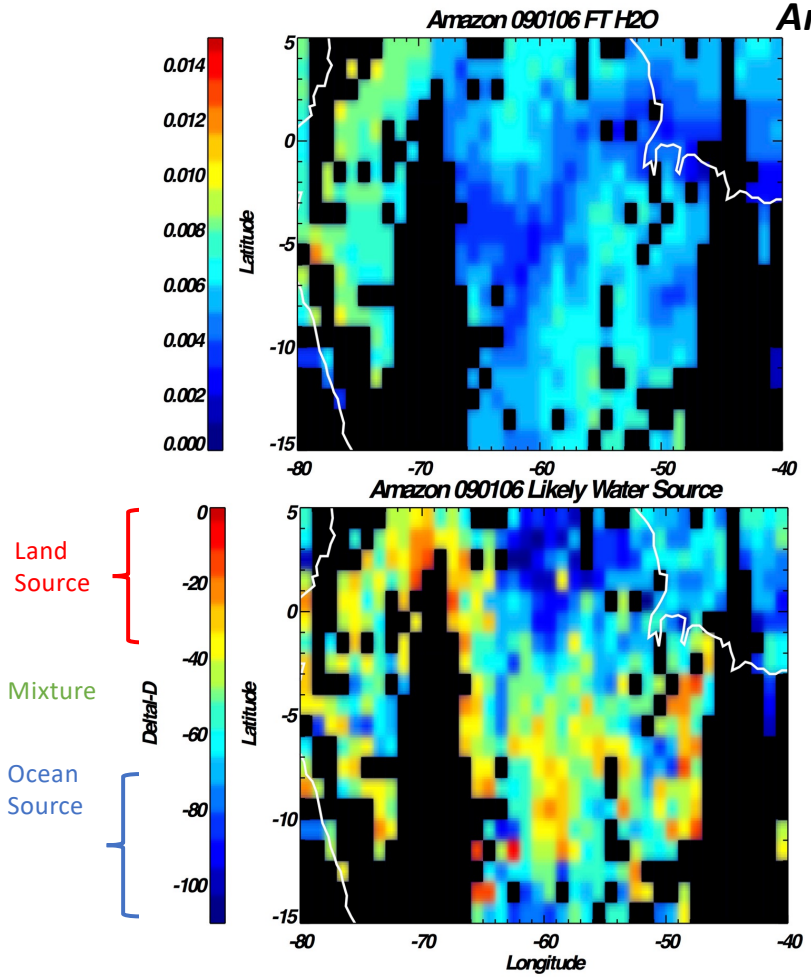
(b)

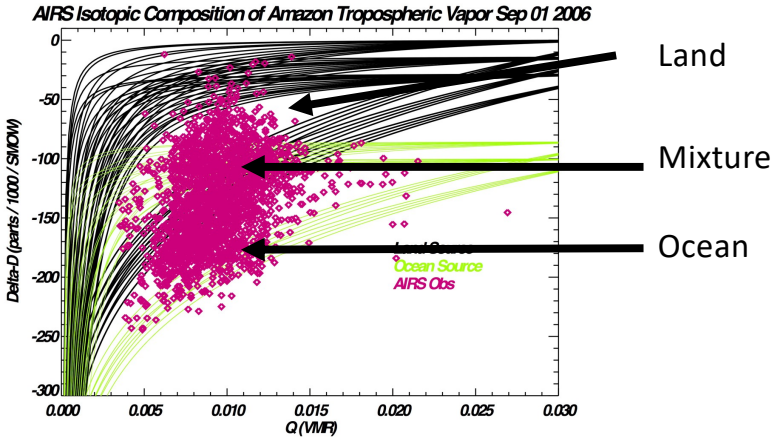
Shi et al. (Nat. Com 2022)



- Lighter Isotopes Preferentially Evaporate : Heavier Isotopes Preferentially Condense: No net isotopic fractionation for transpiration
- Deuterium content given by parts per thousand relative to ocean water content → δ-D = 0 means deuterium content is same as ocean water; δ-D = -1000 means there is no HDO.
- Largest deuterium content in the tropics less at the poles as gradual rainout during transport depletes the isotopic composition
- Global observations show enhanced deuterium content over tropical forests in the dry season, consistent with increased contribution from transpiration

Where does the water in the free-troposphere during dry-to-wet Season Transition over the Amazon originate?



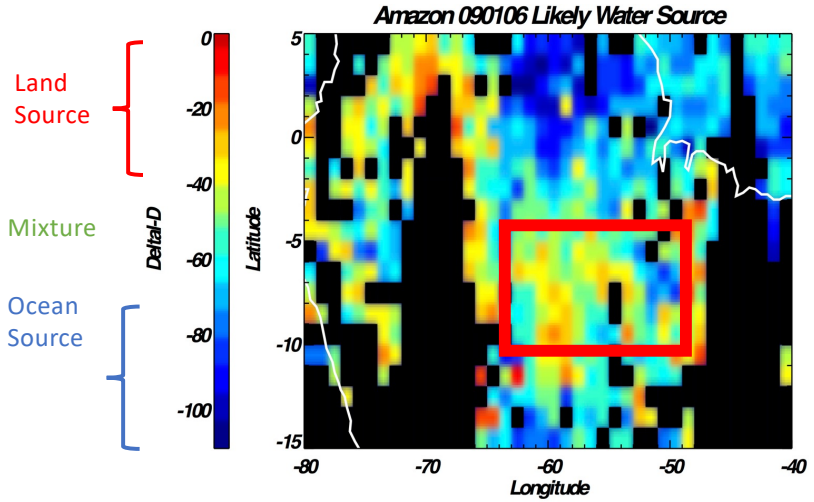


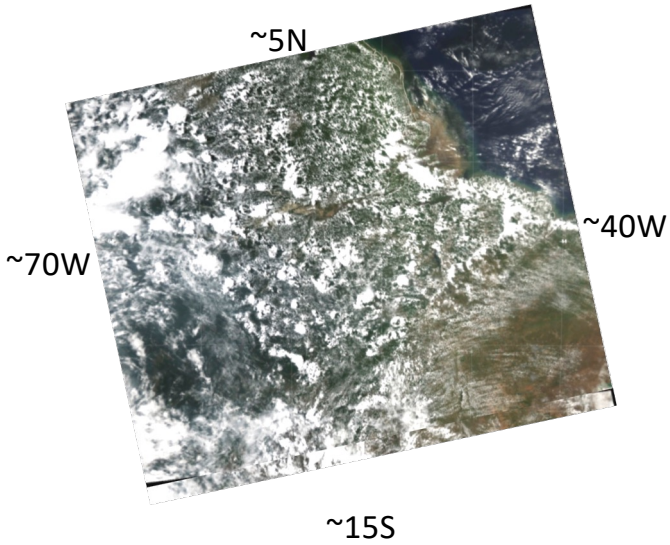
(Top Left) Map of AIRS H_2O vertically integrated between 825 and 400 hPa

(Top Right) AIRS Delta-D and H2O observations overlayed on simple mixing / rainfall, or Rayleigh, models for air-parcels from land (black curves) and ocean (green curves)

(Bottom Left) Difference between Observed Delta-D and Rayleigh model of Delta-D over land indicates if air-parcel is from transpiration

Where does the water in the free-troposphere during dry-to-wet Season Transition over the Amazon originate?





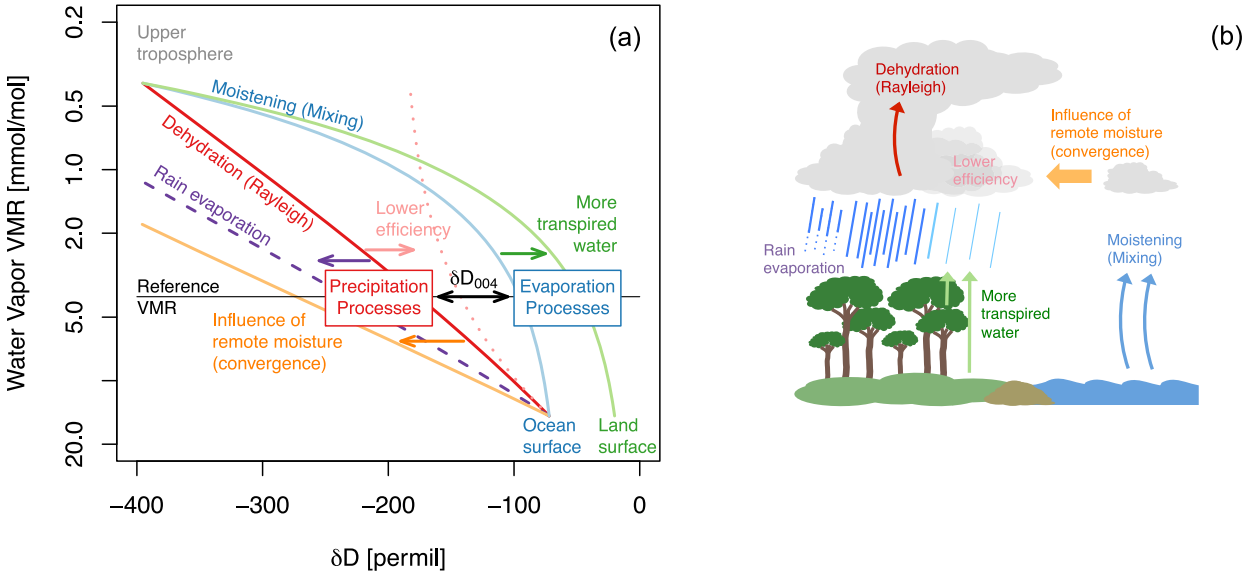
Comparison of AIRS Delta-D difference figure and MODIS indicates enhanced deuterium content in Southern Amazon is associated with shallow convection across the Amazon

This priming of the lower-troposphere with deuterium enriched transpiration was called the “Shallow Convection Moisture Pump” in Wright et al. (2017) as a mechanism explaining why the S. Amazon monsoon starts ~6 weeks before arrival of heavy rainfall associated with the ITCZ

What do Tropospheric Deuterium Measurements say about S. American Tropical Water Balance during the 21rst century?

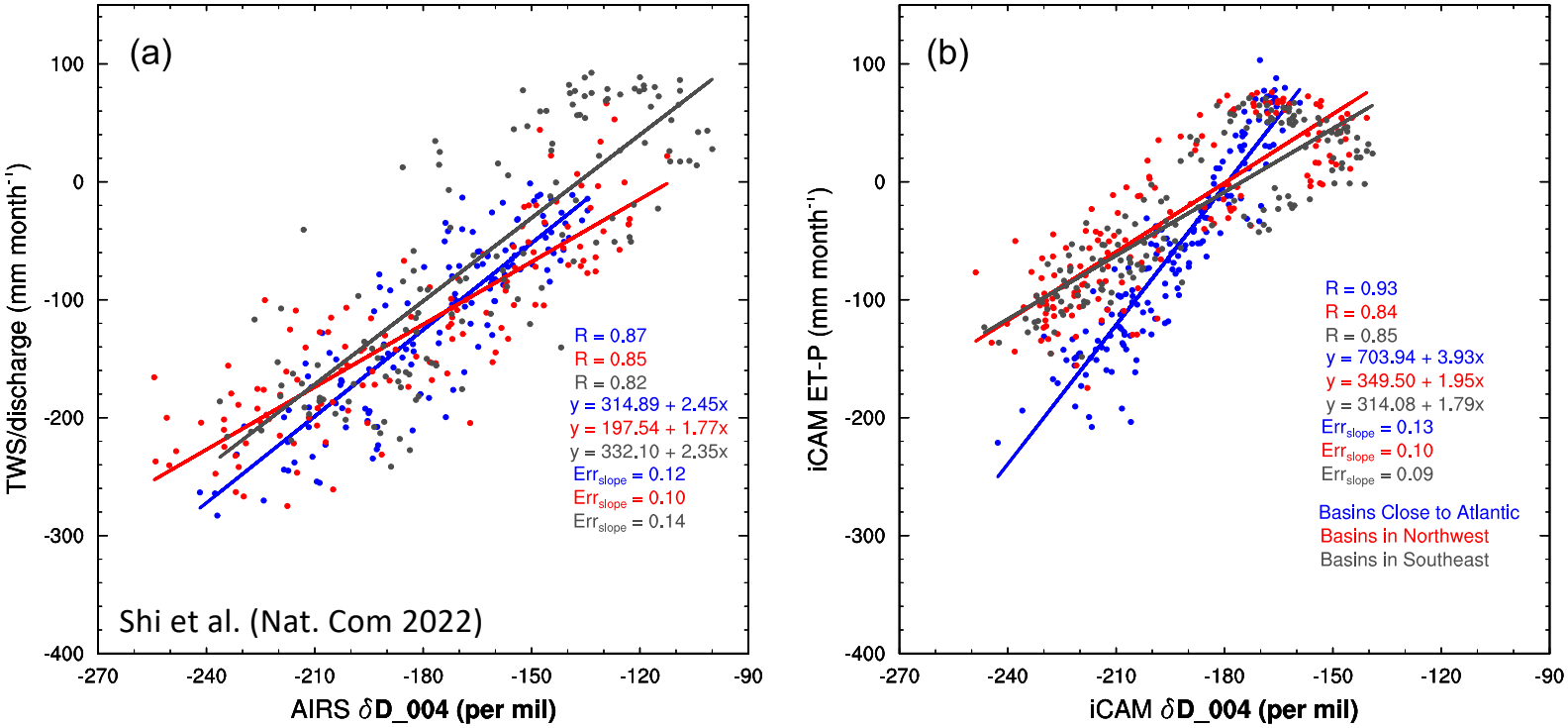
Normalizing tropospheric deuterium observations to a single tropospheric “water” value will allow the deuterium to reflect variations in water balance (ET – P) as it removes variations in q, the dominant factor affecting deuterium content variability

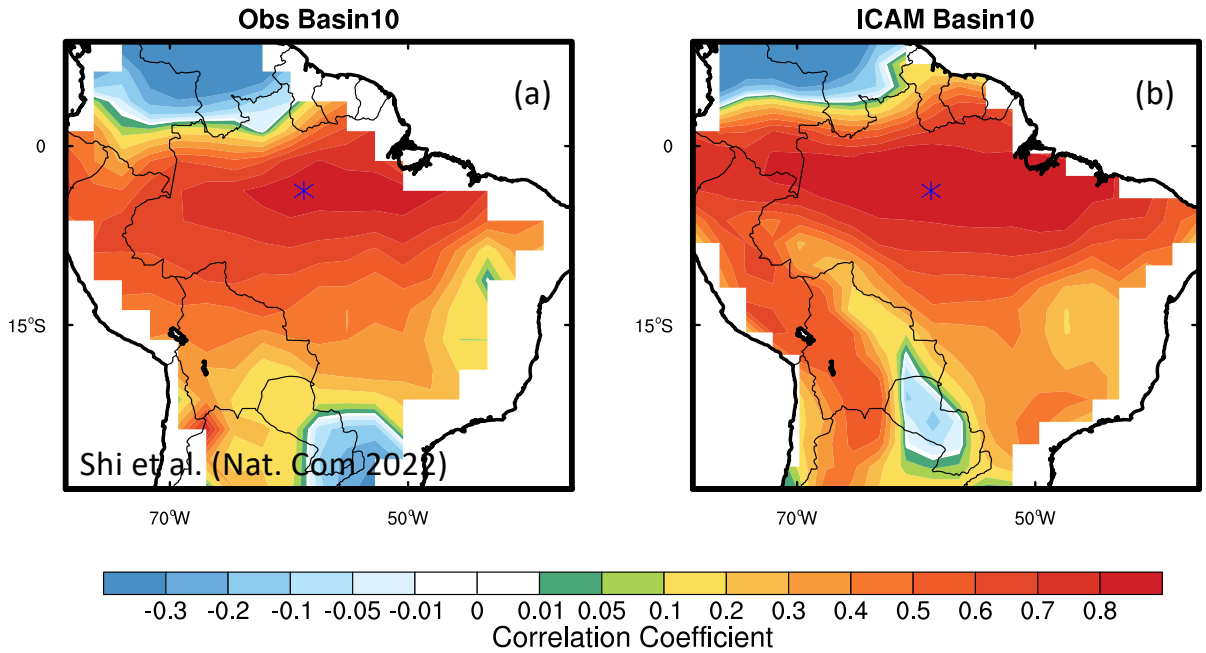
Bailey et al. (JGR 2017) Shi et al. (Nat. Com 2022)



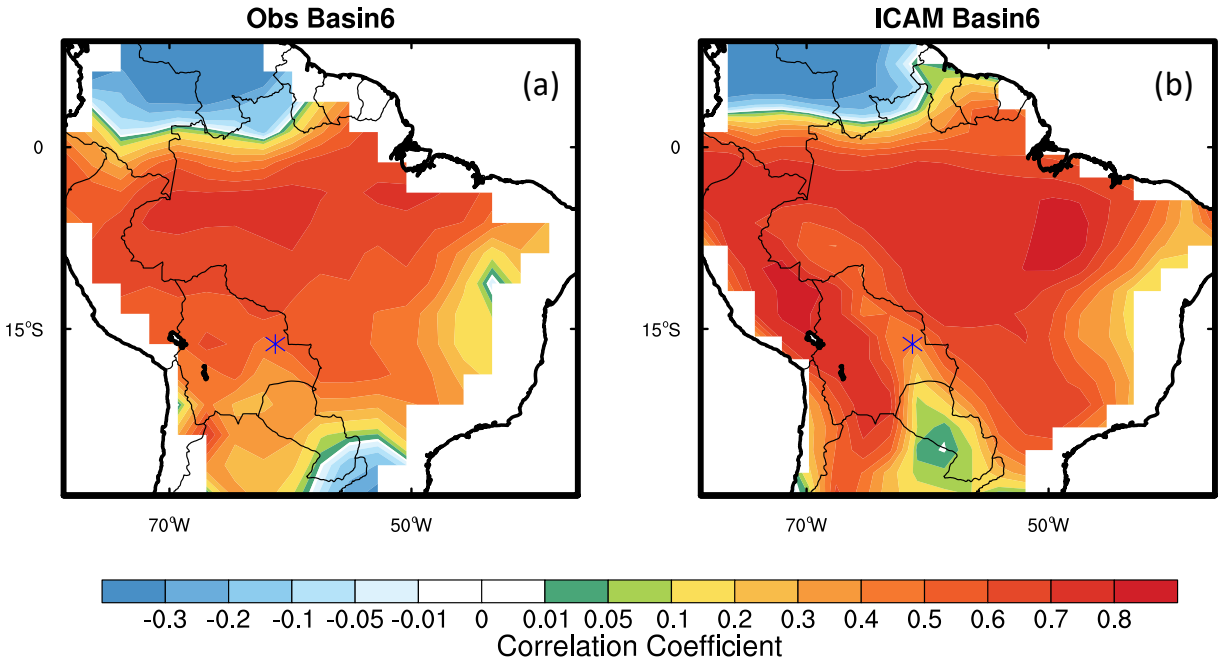
However, other processes and sources (e.g. changes in precipitation efficiency, rainfall recycling and change between oceanic and transpiration source) also affect normalized deuterium proxy

- Linear relationship expected between normalized deuterium (dd_004) and E-P from both model (ICAM) and data (comparison to GRACE and river discharge).
- Evaluation of model shows that change in slope in different location reflects distribution of moisture sources whereas the scatter reflects the seasonal variation in moisture source.



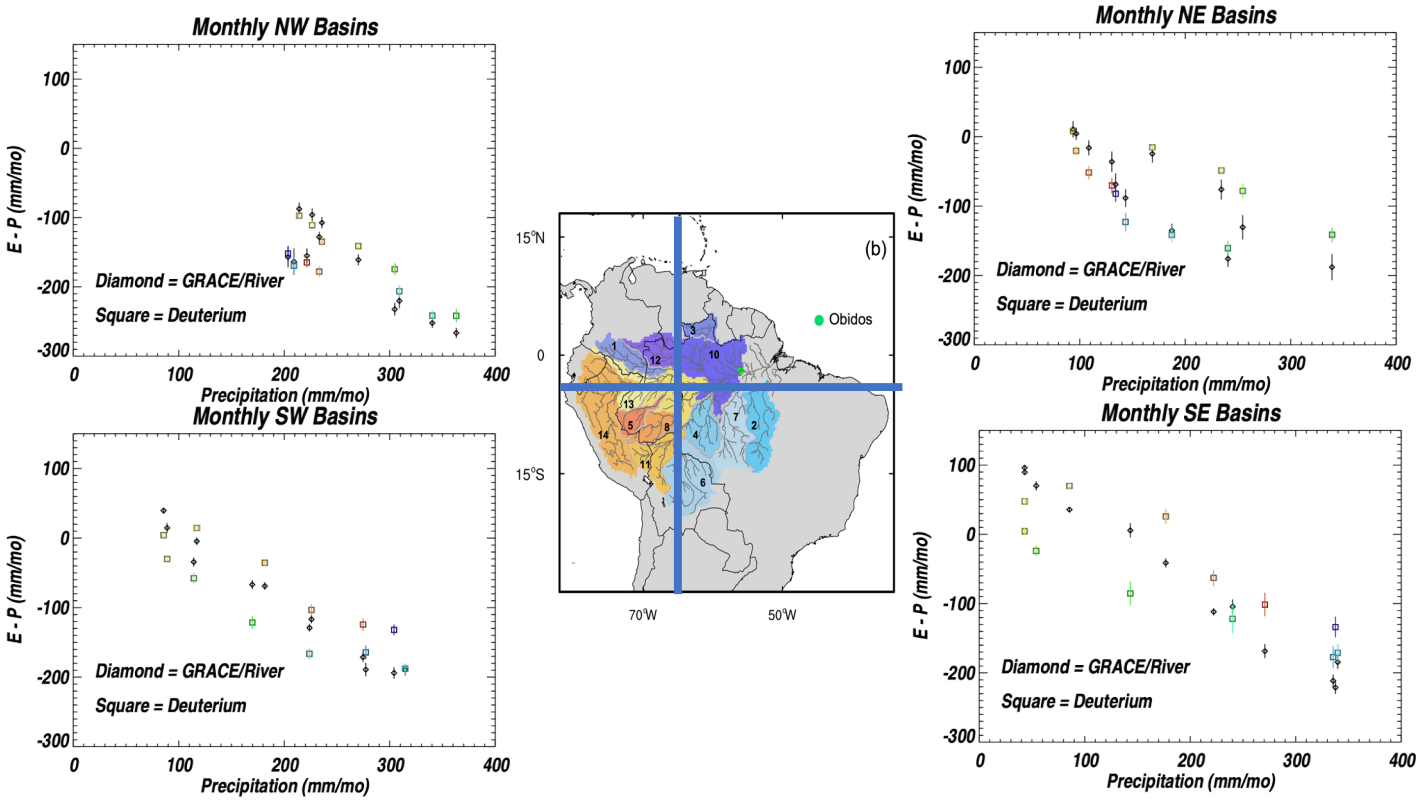


NE. Amazon ET – P Based on Deuterium primarily depends on local ET-P in both the model and by comparing against GPCP and JPL-PT ET



S. Amazon ET – P Based on Deuterium depends on local ET-P AND Advected Moisture from N. Amazon

N. Basins show good seasonal agreement between Deuterium/Atmosphere Based Water Balance and Terrestrial Water Balance → Large observed seasonality in ET affects terrestrial and atmosphere water balance

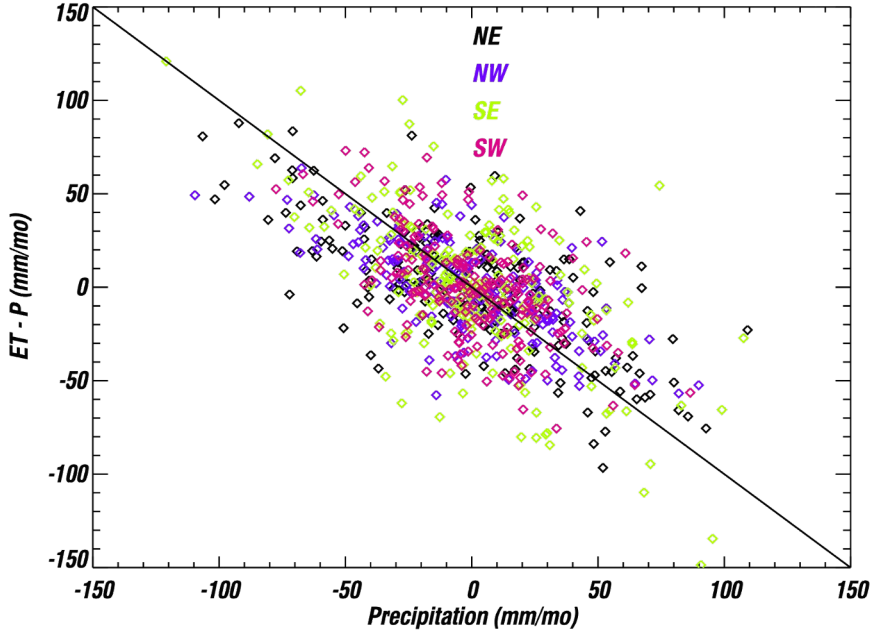


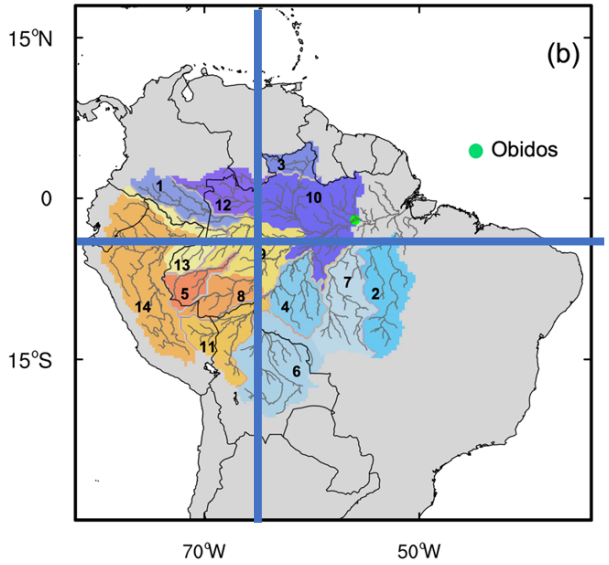
S. Basins seasonal atmosphere water balance strongly depends on transported moisture, consistent with Staal et al. 2018 and Wright et al. 2019

Little seasonality in ET at surface but large contribution of ET to atmospheric based water balance

What controls inter-annual variability of S. American tropical forest water balance?

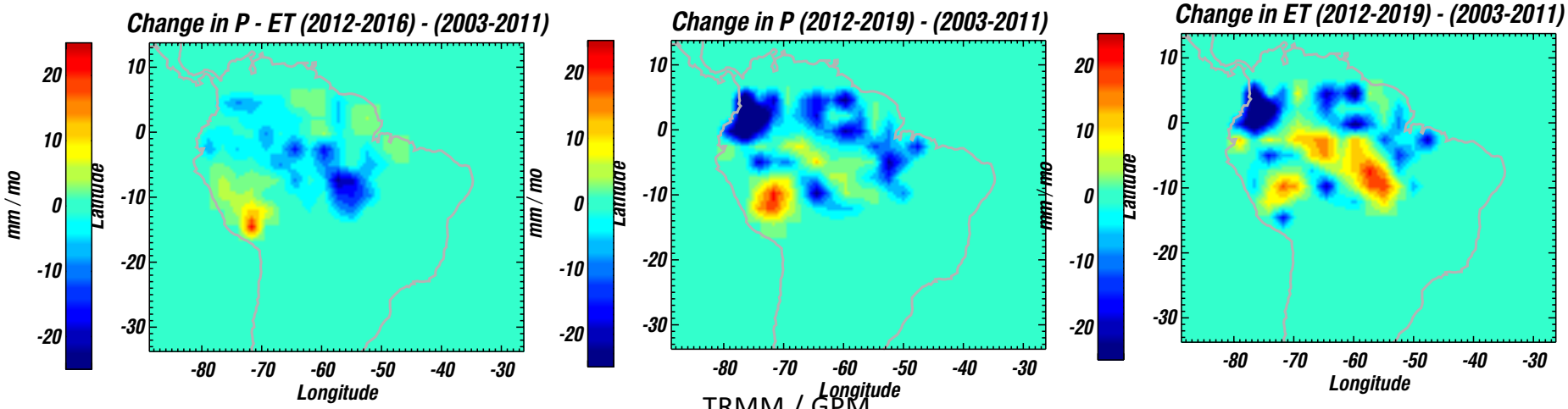
De-Seasonalized Precipitation and Water Balance





Interannual variability of water balance co-varies with precipitation for four quadrants in S. American Tropics (NE, NW, SE, and SW regions)

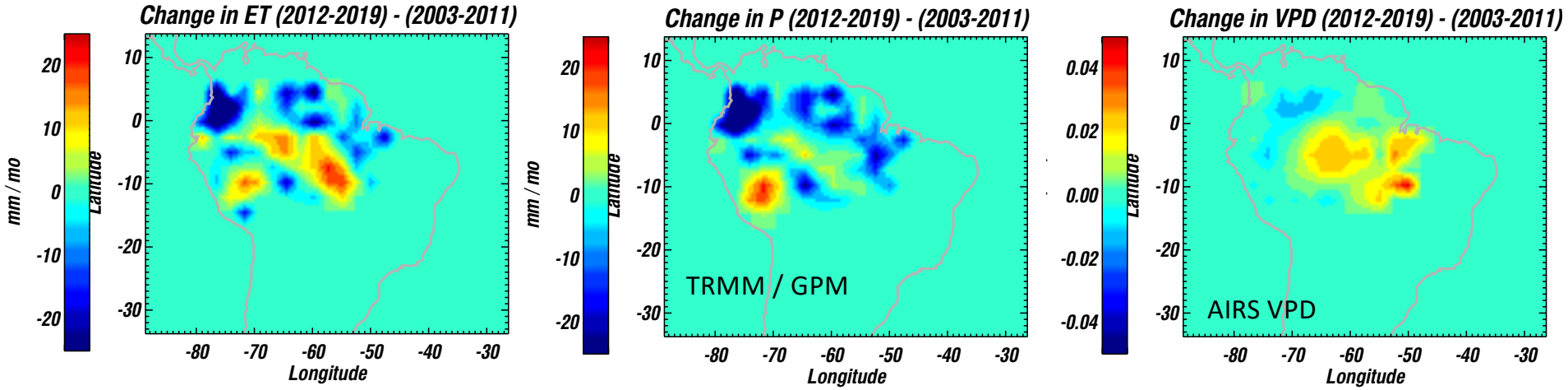
Is Water Balance in the Amazon changing during the 21rst Century?



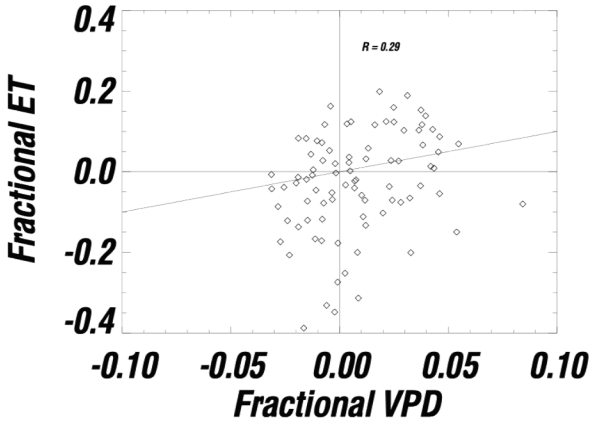
TRMM / GPM

Decadal Changes in Water balance are smaller than observed precipitation indicating substantial role of ET in controlling changes in Amazon water balance during the 21rst century

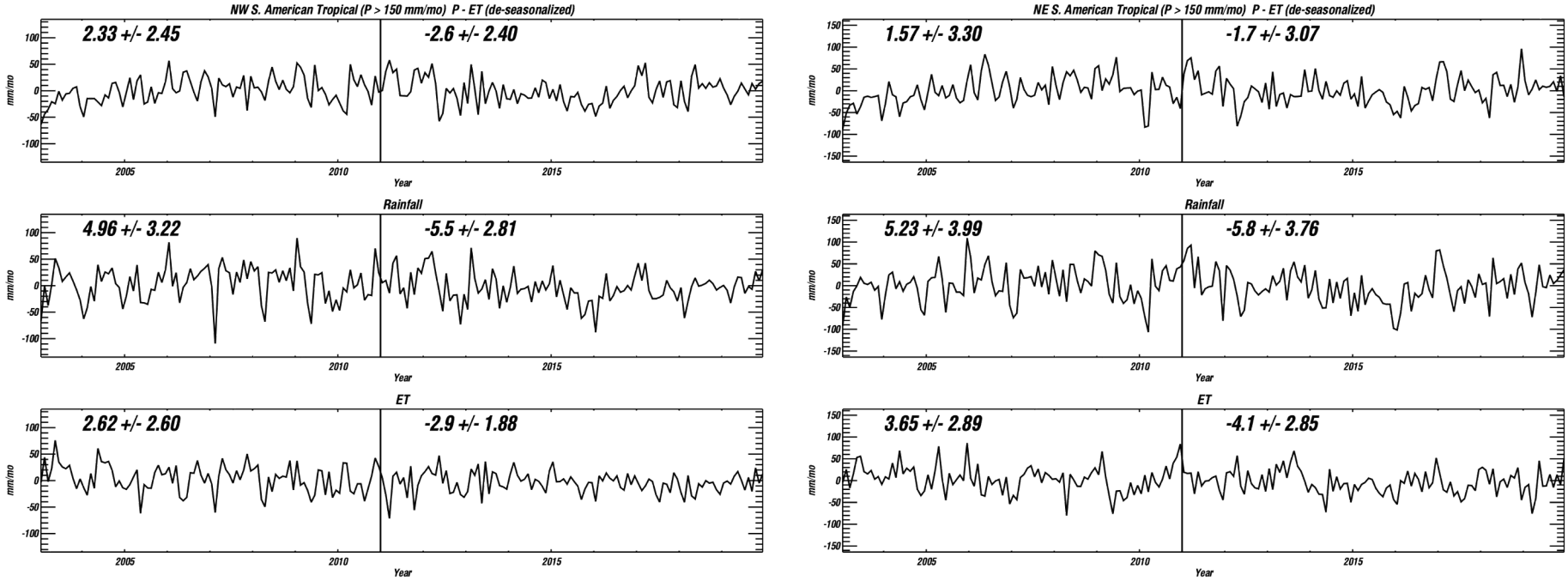
ET may be responding to both changes in P (supply) in N. Tropics and changes in VPD (demand) in S. Tropics



S. Amazon VPD is increasing → Increased ET?
But we might expect WUE to increase during same time period → Decreased ET?

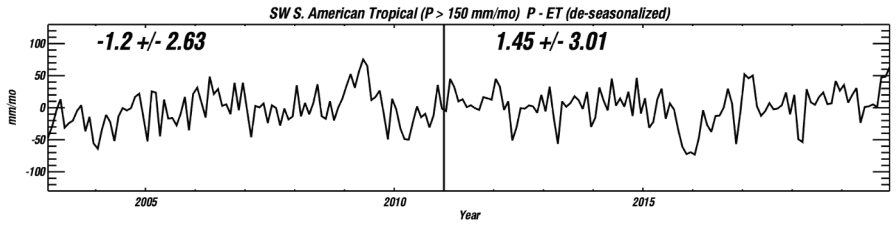


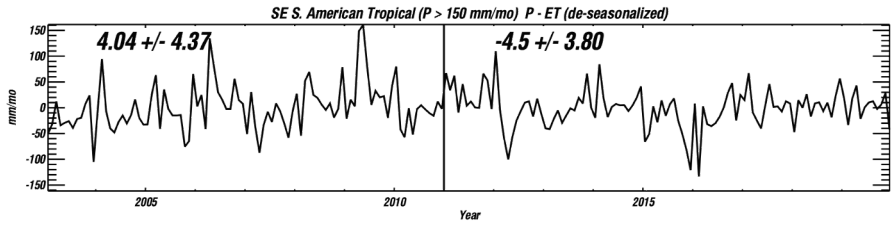
Decline in N. Amazon rainfall primarily driven by 2015 ENSO.
ET is less variable and showing decline primarily related to change in water balance in 2003 and 2004

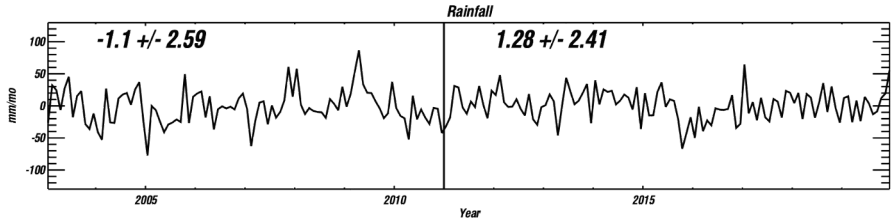


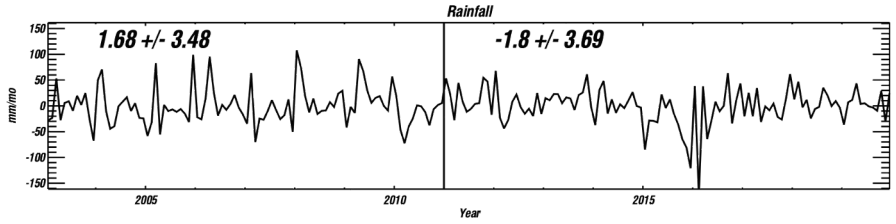
Decline in ET is ~7.1 +/- 4.0 mm/mo and 5.5 +/- 3.2 mm/mo in NE and NW basins respectively corresponding to decline in rainfall

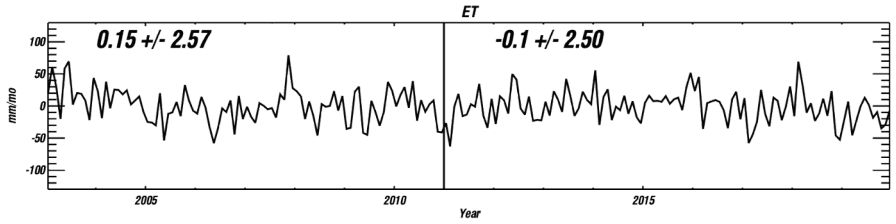
Larger than expected decline in water balance from both declining rainfall and increasing ET in SE Amazon
No observed changes in water balance or its components in SW Amazon

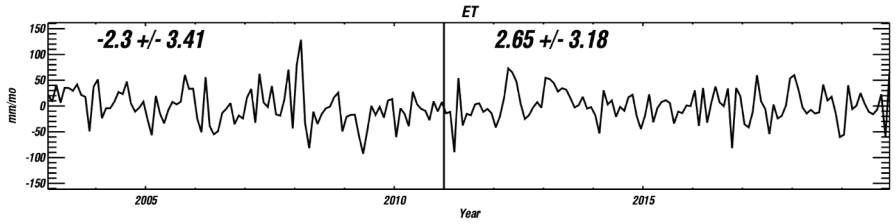












Increase in (SE) ET is ~4.95 +/- 4.3 mm/mo
Decrease in (SE) Rainfall is 3.48 +/- 5.0
Expected increase in ET from VPD alone is between 1 to 5 mm/mo depending on model but confounding factors include change in WUE and P and dependency of SE atmospheric water balance to advected moisture

Summary / Conclusions / Questions

We use Satellite-based Tropospheric deuterium measurements to estimate Spatio-temporal distribution of Amazon Water Balance

N. Amazon atmospheric (deuterium based) water balance consistent with surface based water balance

S. Amazon atmospheric water balance depends on local + advected moisture

What controls interannual to decadal changes in Amazon water balance?

1) Precipitation is the dominant control on water balance inter-annual and decadal variability across the basin
2) Decadal changes in Water Balance likely (~1 sigma) different than that of Precipitation across the Amazon

3) Decline in ET in N. Amazon corresponding to rainfall decline
4) Slight increase in ET in SE Amazon possibly related to increases in VPD
5) We cannot obviously resolve different effects of changing Temperature, VPD and WUE on Amazon water balance

Need →

There does not appear to be good literature (or prior knowledge) on the distribution of processes controlling water balance and ET in the Amazon, any suggestions on how to frame these results on water balance?

Many of the river discharge results cutoff in 2014 / 2016 → challenging to compare to basin scale changes during these time periods → any expectations river discharge measurements will resume?