Coupling between carbon and water cycles: challenges and opportunities

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and many collaborators, students, postdocs

Outline

1) Future of CO2-H2O coupling in the **model world**

2) (Large) **biases** compared to reality (LegoLand?)

3) Way forward?
Using high-resolution modeling and remote sensing

4) Time's up? Understanding/ prediciton

Supply vs. demand (P-ET)

Actual vs. Potential Evaporation

Penman-Monteith equation

$$ET = \frac{R_n - G + \frac{\rho C_p}{\Delta}\frac{VPD}{r_a}}{1 + \frac{\gamma}{\Delta}\left(1 + \frac{r_s}{r_a}\right)}$$

How this is changing is essential

r_s(VPD, Soil moisture, CO_2, LAI, LULC…)

Explains the difference between E_p and ET

Over the ocean ~ E_p (no r_s)

Over land, surface resistance response to VPD, Soil moisture, CO_2, LAI is key

Decomposing dryness response

•Different dryness indicators:
-**VPD**: physiology
-**Runoff**: hydrology (similar to long term P-ET)
-**ET**: hydrology, agriculture, climate
-**EF=ET/Rn** (0-1): hydrology, agriculture, climate
-**Soil moisture**: water resource manager
-**LAI**: farmers, ecosystem services

•Better define drivers
-Water supply: P
-Radiation demand: R_n (not Ep – see previous reason), T, VPD
-Physiological impact: [CO_2] surface

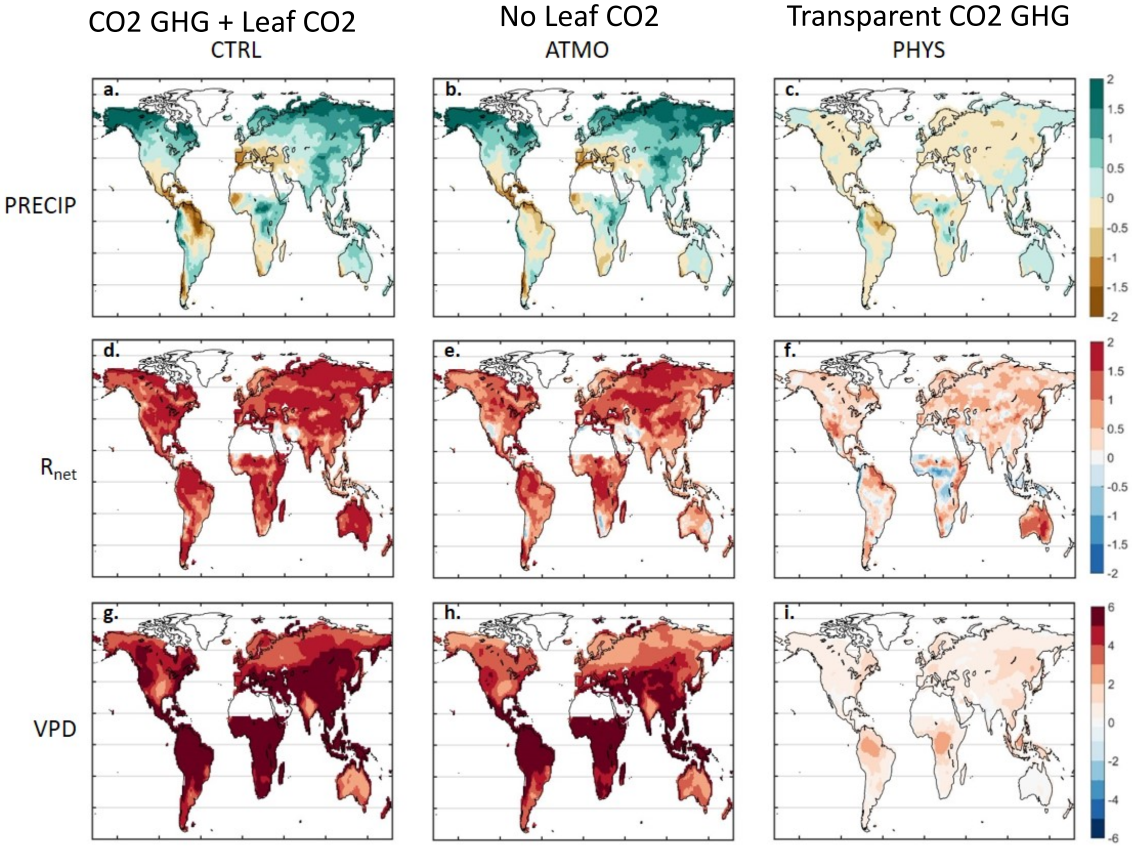
Decomposing model dryness response

-Water supply: P

-Radiation demand: R_n and correlated T, VPD

(not Ep – see previous reason)

-Physiological impact: $[CO_2]$ surface



Lemordant L., … Gentine P., Vegetation physiology dominates future continental water cycle, *PNAS, in press*

Can we go furher?

- Divide radiative runs into Rn and P changes (partial correlations)

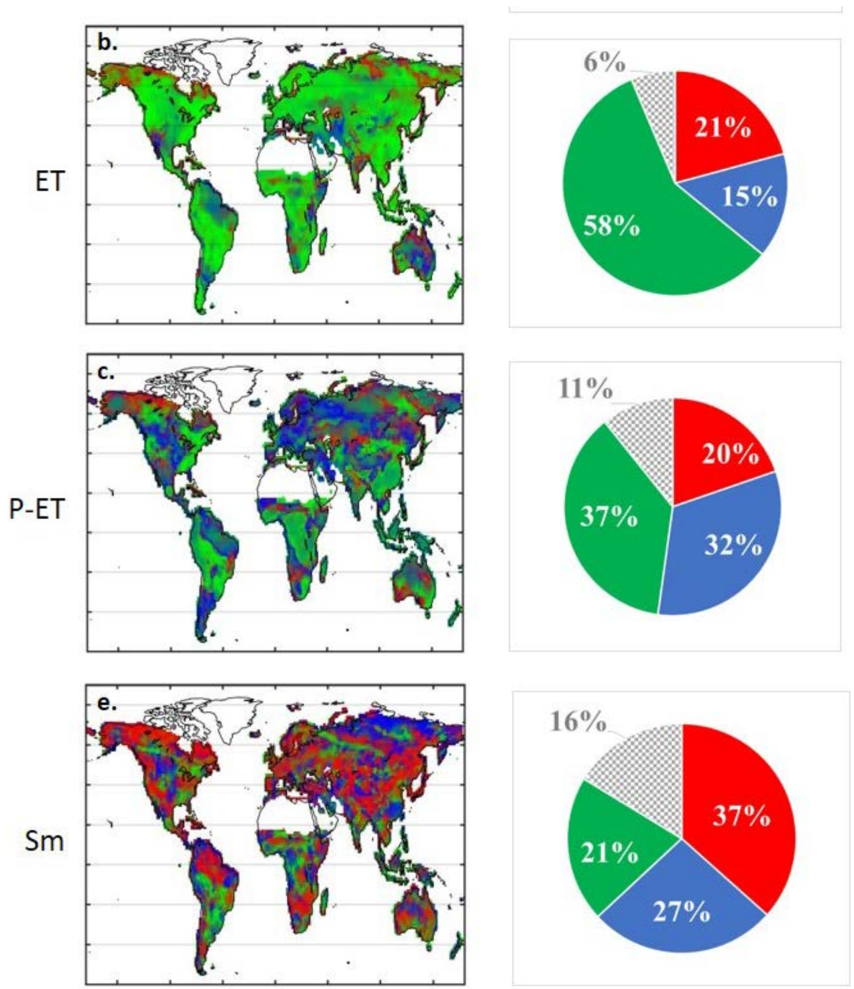
- Explained change under climate change:

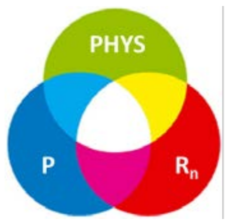
$$dET = \underbrace{\frac{\partial ET}{\partial R_n} dR_n + \frac{\partial ET}{\partial P} dP}_{\text{based on radiative runs}} + \underbrace{\frac{\partial ET}{\partial [CO_2]_{\text{surface}}} d[CO_2]_{\text{surface}}}_{\text{based on physiological runs}}$$

- Report total as a % change

Lemordant L., … Gentine P., Vegetation physiology dominates future continental water cycle, *PNAS, in press*

Decomposing dryness





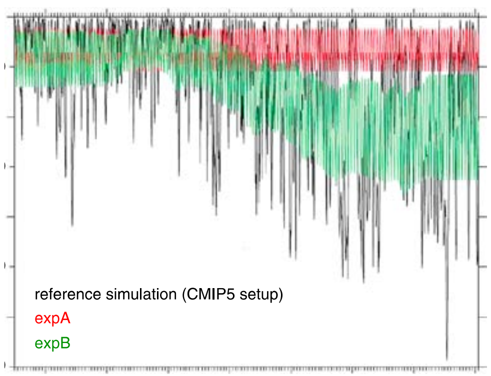
$$\Delta X = \left[\frac{\partial X}{\partial Rn}.\Delta Rn\right]_{ATMO} + \left[\frac{\partial X}{\partial P}.\Delta P\right]_{ATMO} + [\Delta X]_{PHYS}$$

Mostly impacted by CO_2 effects except at cold northern latitudes

Vegetation (and CO2 cycle) dominates future continental water stress

Lemordant L., … Gentine P., Vegetation physiology dominates future continental water cycle, *PNAS, in press*

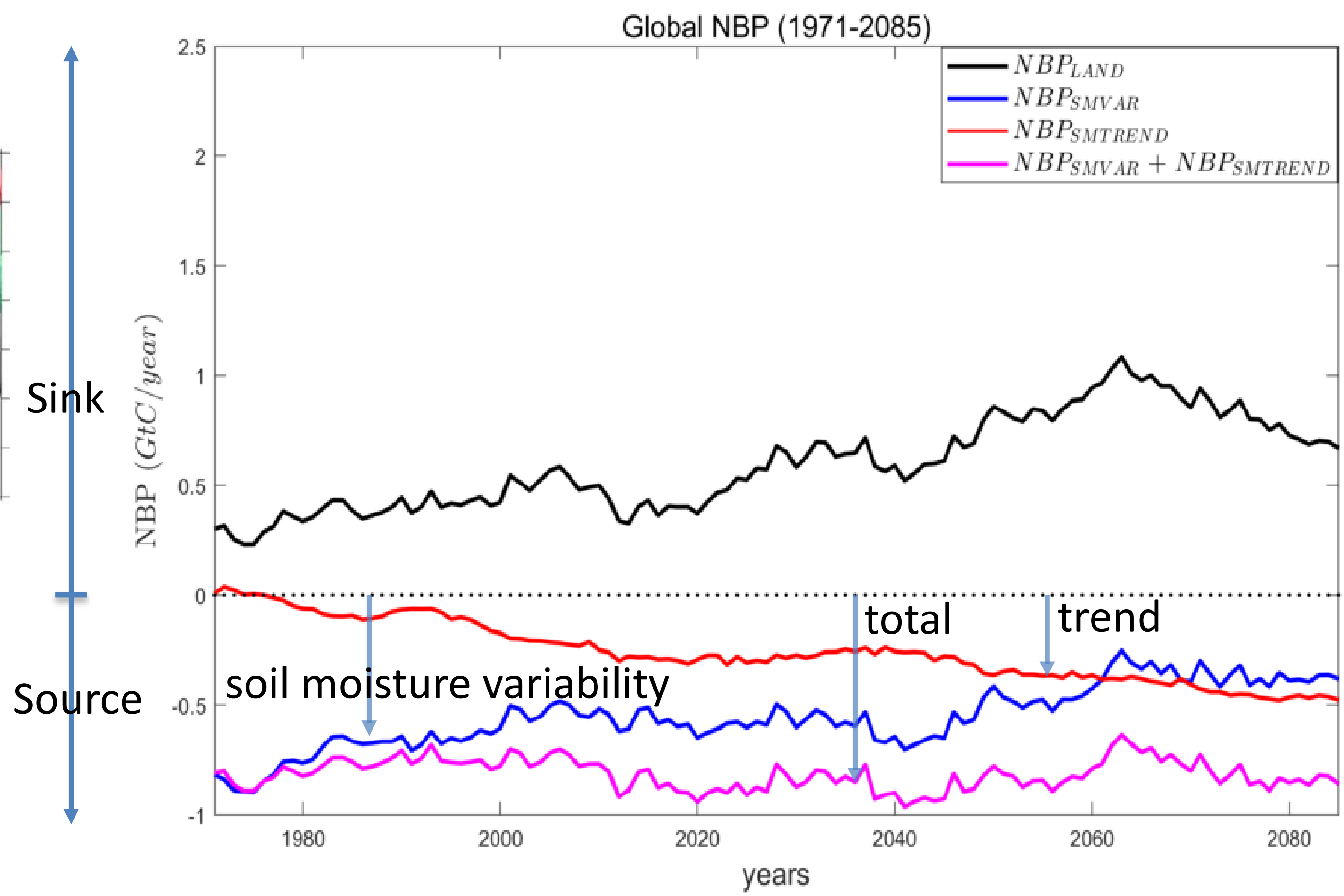
Land CO_2 uptake: role of soil moisture



Based on ESMs with/without interactive soil moisture GLACE-CMIP5

Seneviratne et al. *GRL*, 2013

Soil moisture controls land CO_2 uptake



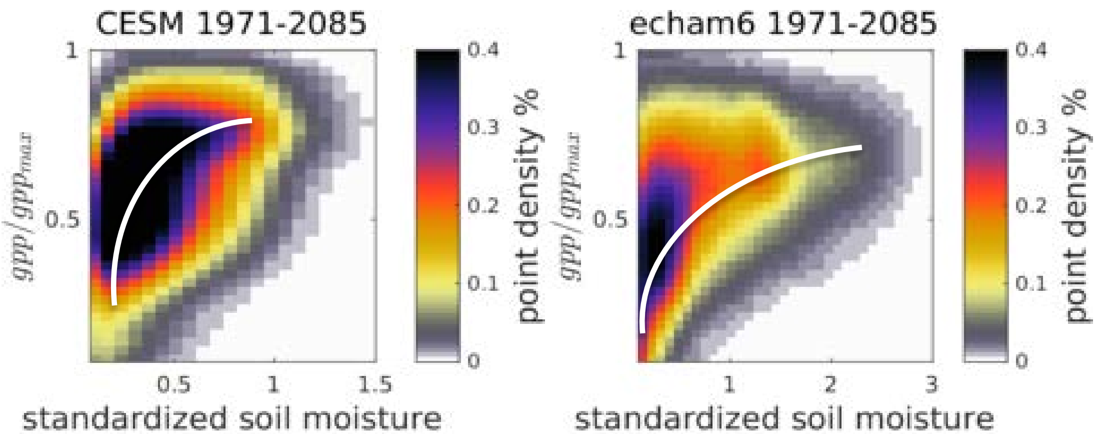
Green et al. submitted

Land CO2 uptake: role of soil moisture

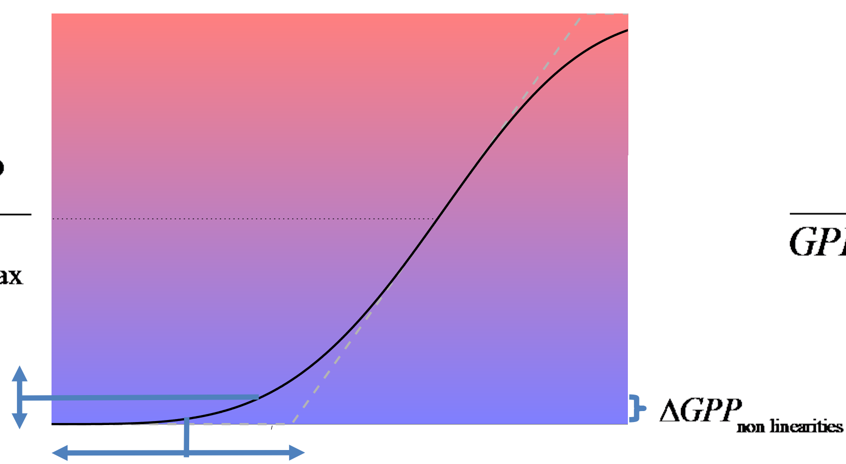
Why is soil moisture so important?

1) Nonlinear water stress response: **Soil moisture variability is not a zero-sum game**

$$\frac{GPP}{GPP_{\max}}$$



$$\frac{GPP}{GPP_{\max}}$$



Soil moisture

Nonlinear stress

$$\overline{GPP(\text{soil moisture})} \neq GPP\left(\overline{\text{soil moisture}}\right)$$

Green et al. submitted

Land CO2 uptake: role of soil moisture

Why is soil moisture so important?

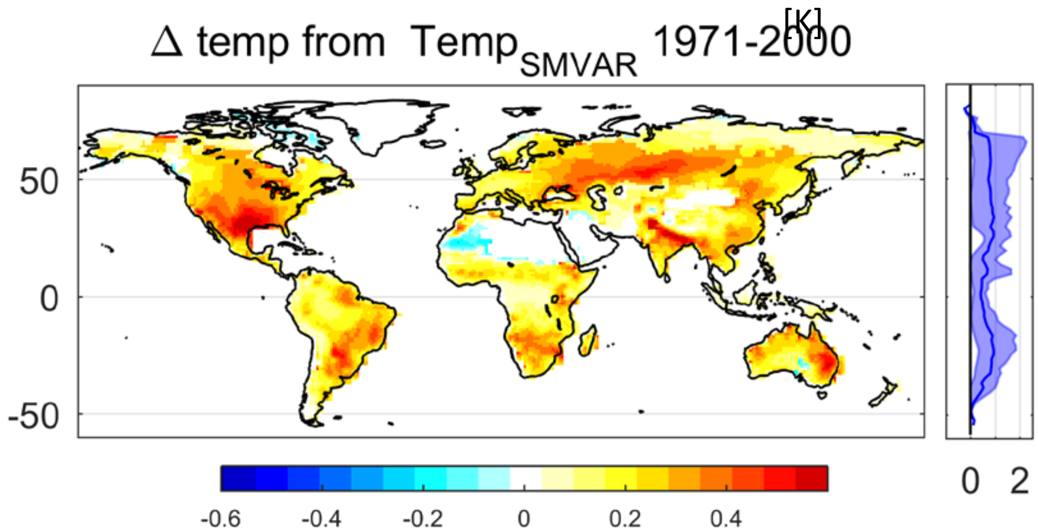
2) **Land-atmosphere interactions**:

Reduced soil moisture

➡ Lower evaporation & Higher sensible heat flux

➡ Higher surface temperature

➡ Increased respiration



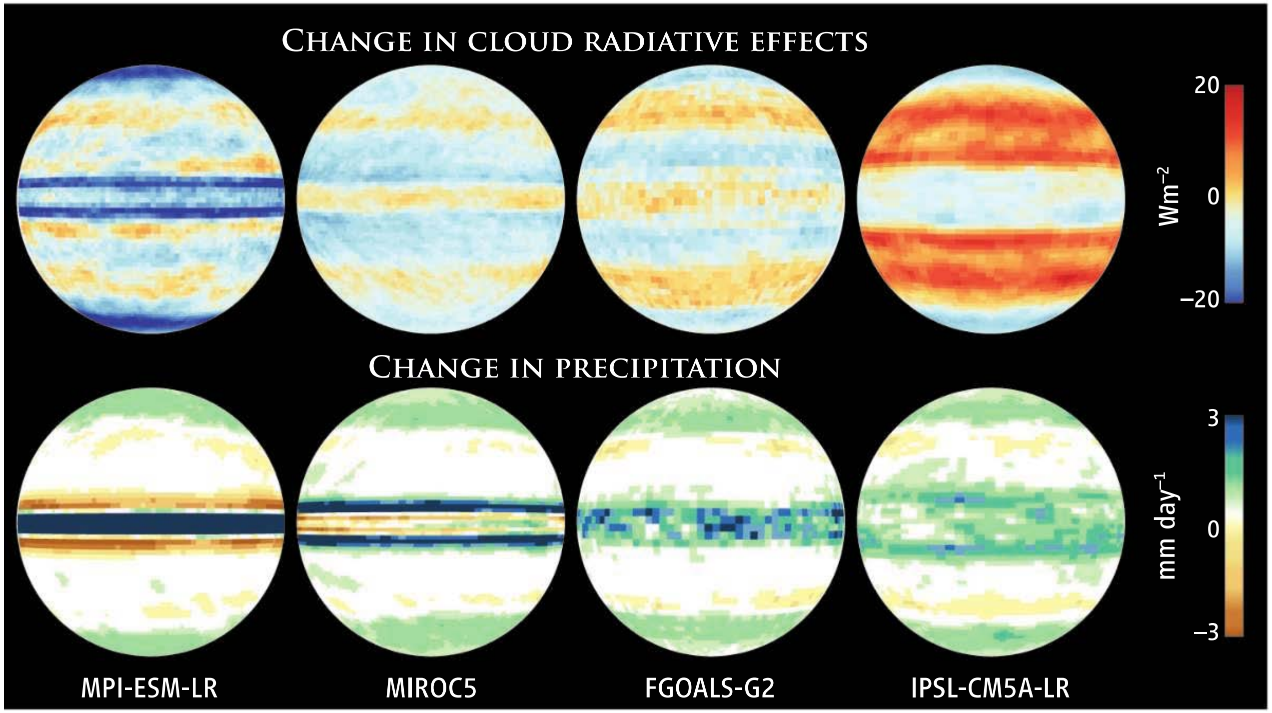
Green et al. submitted

Are we done? Unfortunately not

Bias in precipitation: Water Supply and radiation: Demand

Precipitation poorly represented in models (mean, variability, diurnal cycles)

Even in Aquaplanet: future is completely unclear!



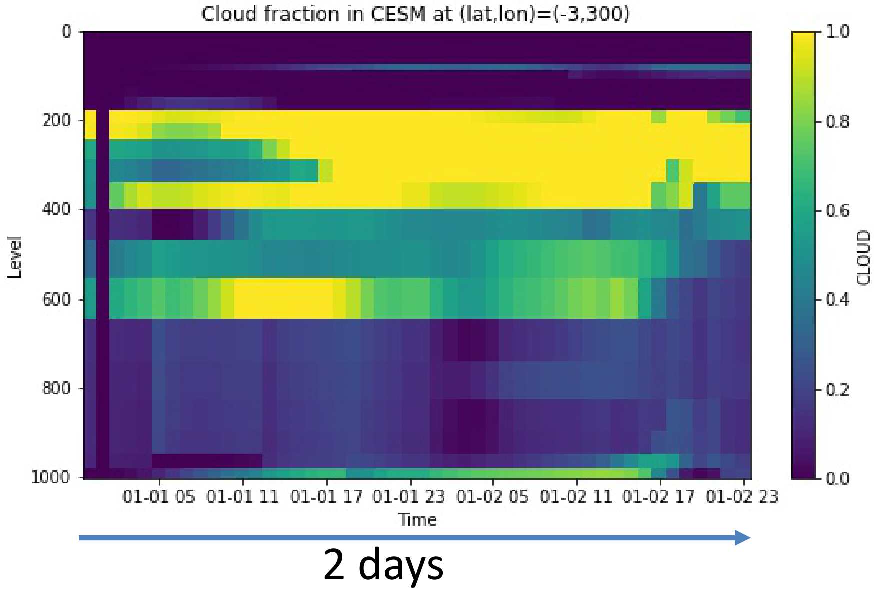
Needs new type of convective/cloud parameterization

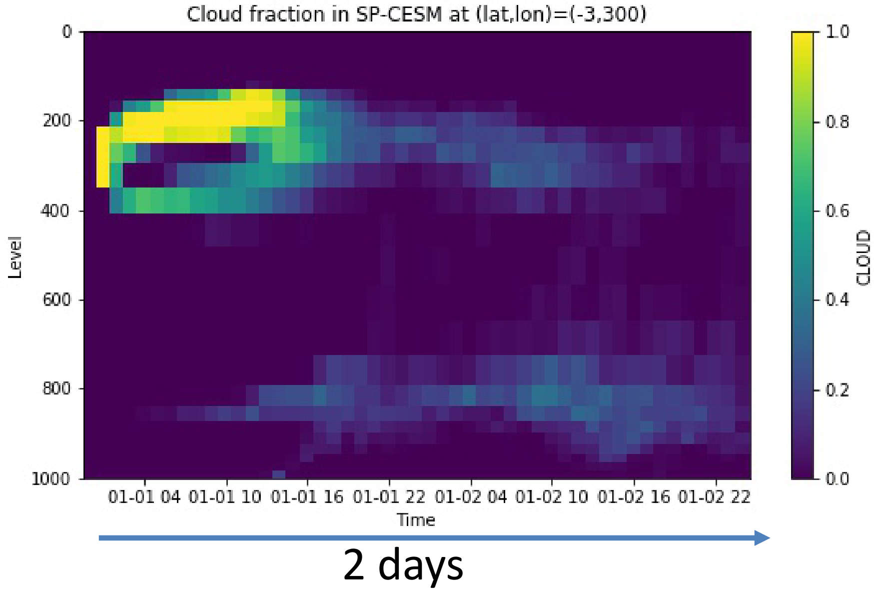
Stevens, B., & Bony, S. (2013). What Are Climate Models Missing? *Science*, *340*(6136), 1053–1054. http://doi.org/10.1126/science.1237554

Are we done? Unfortunately not

Cloud cover and diurnal cycle

Poor continental diurnal cycle





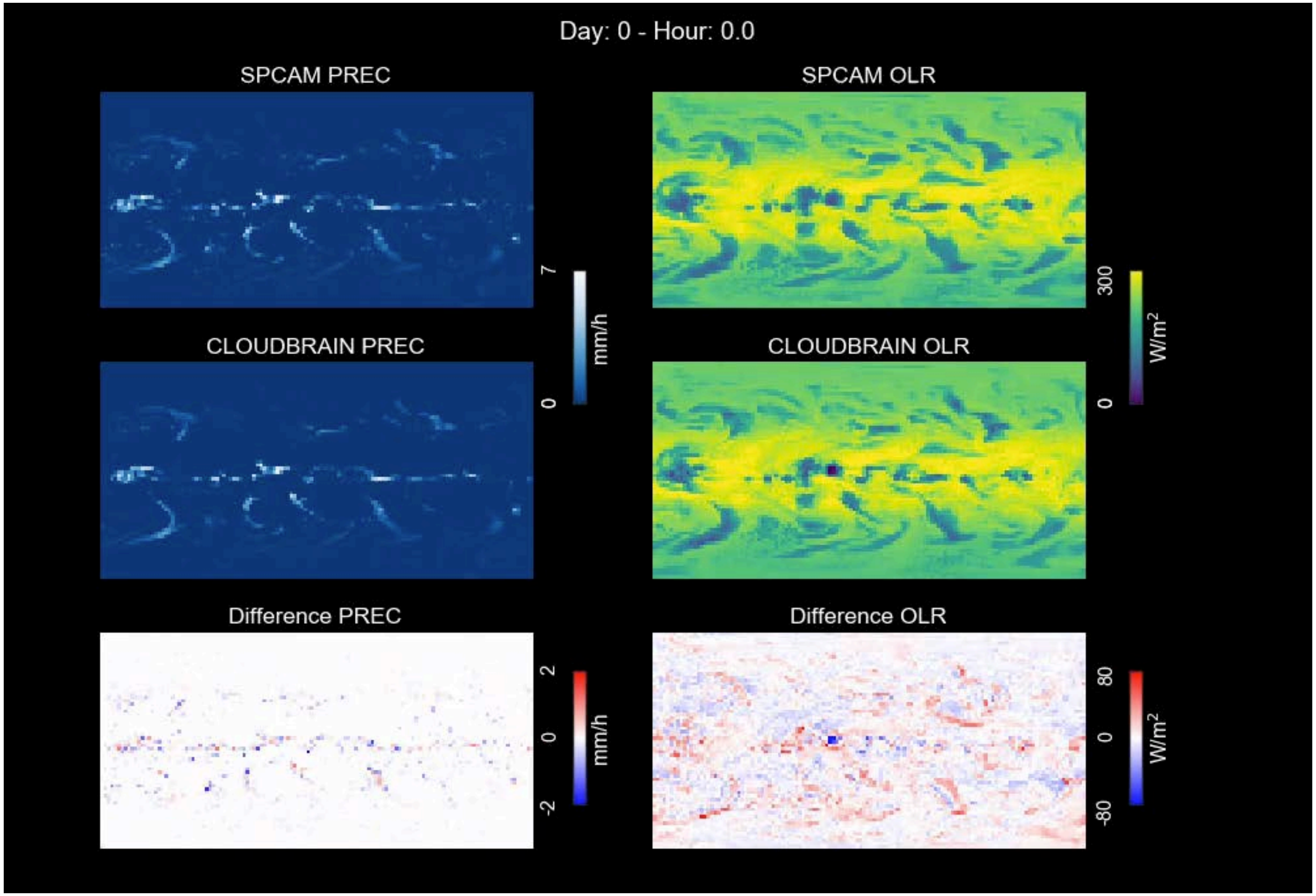
Cloud resolving (2km scale) does a much better job

Needs new type of convective/cloud parameterization

Huang Y., Pritchard M., Gentine P., in preparation

Are we done? Unfortunately not

Way forward: machine learning



Precipitation

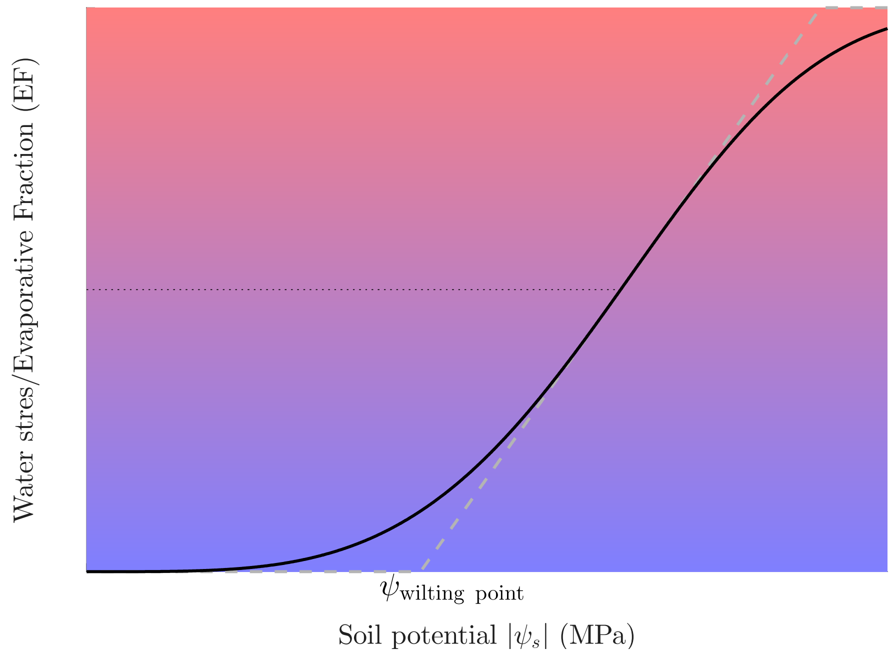
Radiation

Gentine P., Pritchard M., Rasp S., Reinaudi G., Could machine learning break the convection deadlock?, *GRL* (submitted)/EarthXiv

Courtesy Stephan Rasp

Evaporation: vegetation water stress function is essential

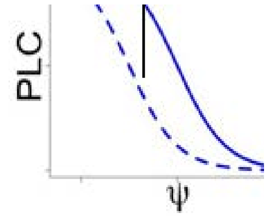
- Built in soil moisture function from wilting point to field capacity

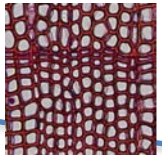


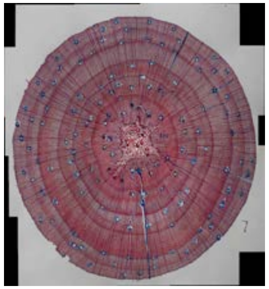
- Reality is more complex and **what about VPD effects (most certain with climate change)**?
- **Not currently in ESMs**

Vegetation water stress

Is **soil moisture** really the main source of vegetation water stress?







Stomatal response to leaf water stress

Xylem cavitation

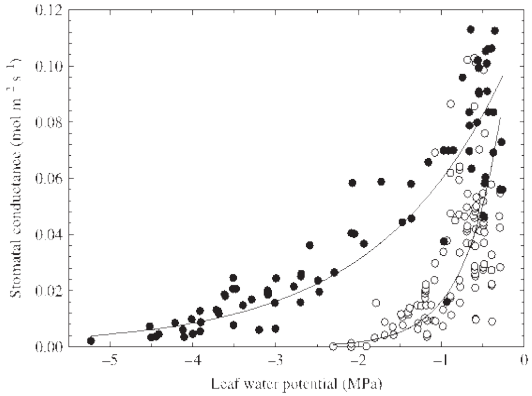


Fig. 8 Stomatal conductance vs leaf water potential for piñon (open circles) and juniper (closed circles) at Mesita del Buey, Los Alamos, New Mexico. Data from Barnes (1986).

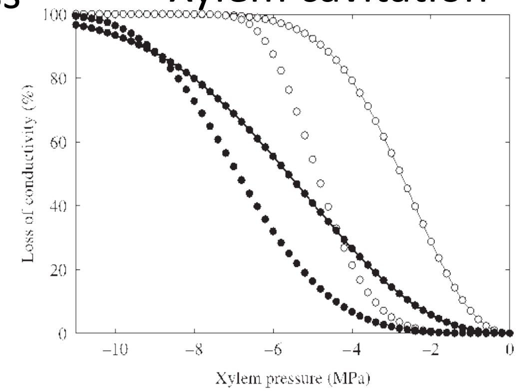
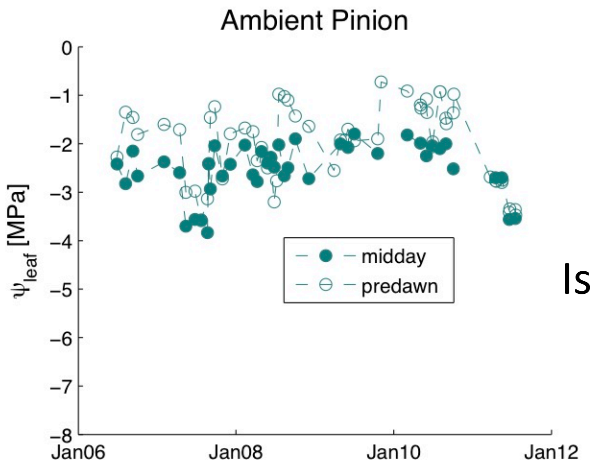


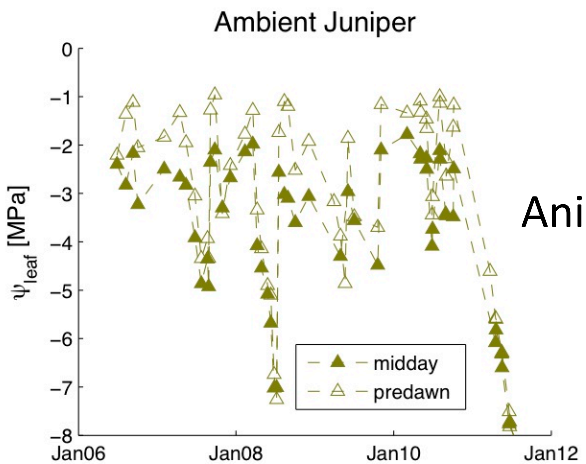
Fig. 4 The percentage loss of conductivity of excised root (connected circles) and stem (unconnected circles) segments of piñon (open circles) and juniper (closed circles) as a function of xylem pressure. These 'vulnerability curves' were obtained by the air-injection method (Linton *et al.*, 1998).

Water stress: Isohydric vs. Anisohydric species

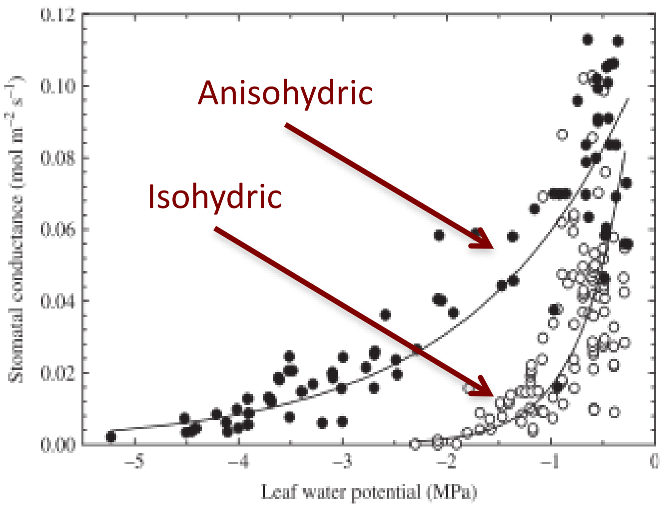


Near-constant Leaf water potential

Isohydric



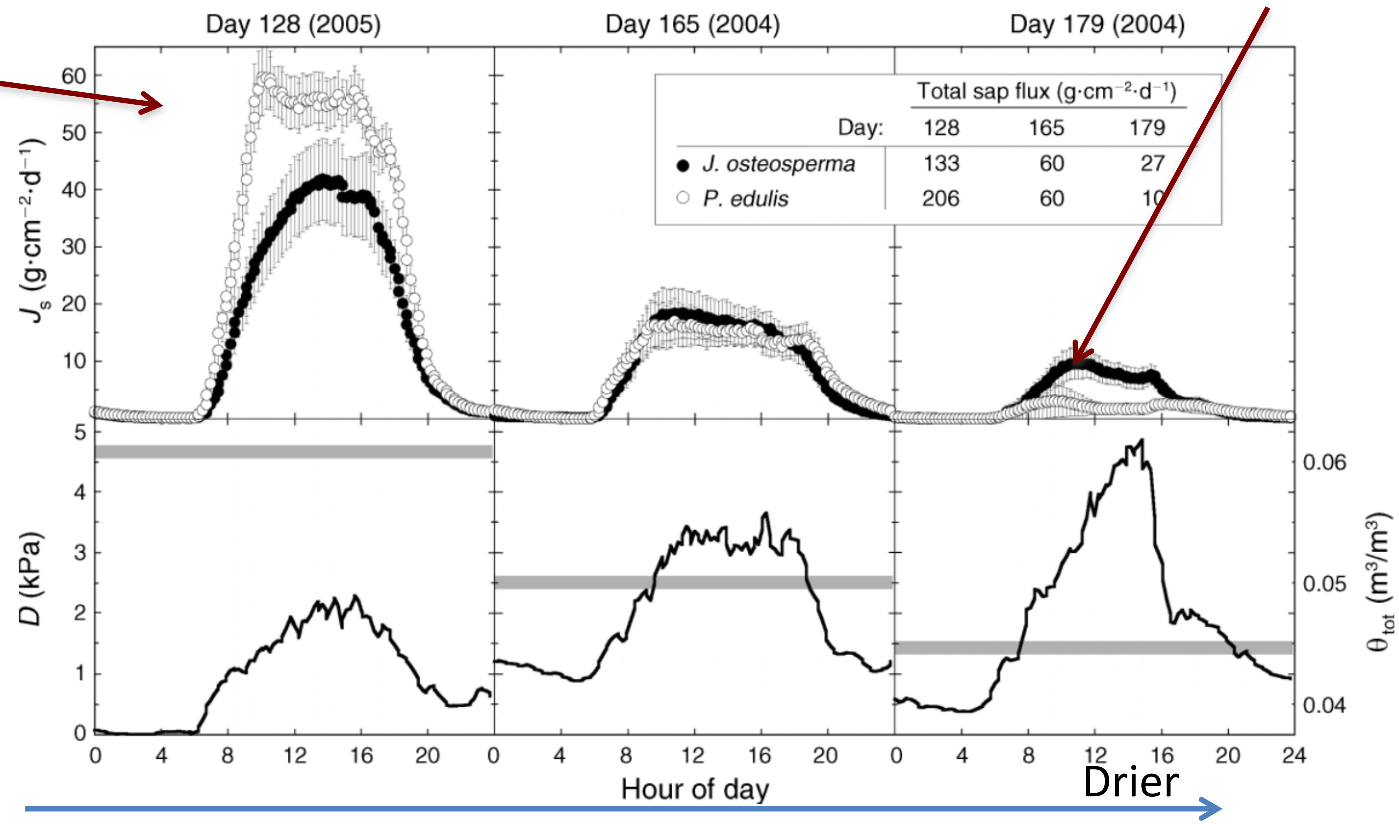
Anisohydric



Isohydric vs. Anisohydric species

Isohydric
Strong
stomata
regulation

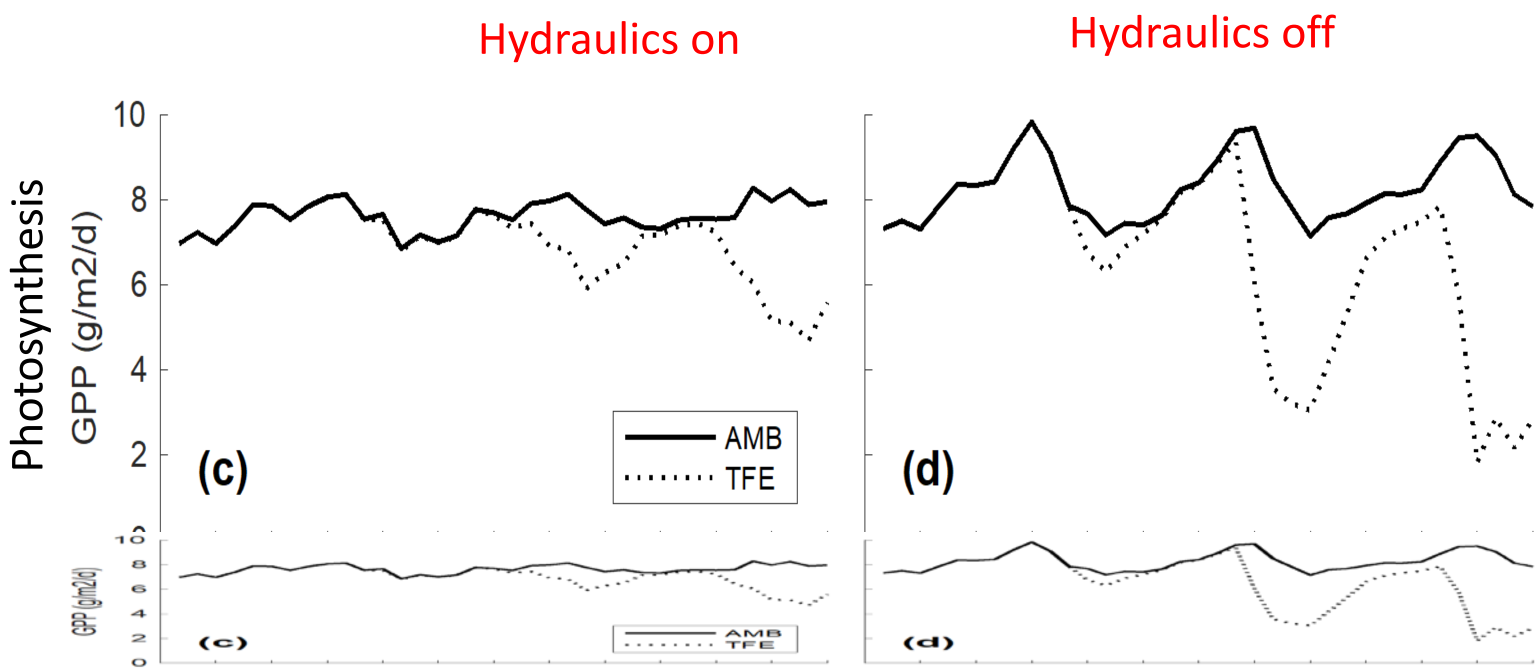
Anisohydric - Xylem control



Isohydry modifies transpiration/GPP time scales drought response
➔ would want to include this in surface models

Model implementation

Improves resistance to droughts (a known bias)



TFE: throughfall exclusion

Reduced impact of droughts with plant hydraulics
(hydraulic redistribution, VPD dependence of stress)

Kennedy D, ..., Gentine P., Including plant hydraulics in the CLM model, JAMES, in prep.

Constraints: Observational opportunities

- What we want:

  - Observations of dryness response of GPP
    GPP and ET = f(Soil moisture, VPD)

  - Interannual variability – to observe drought response

  - Flux towers might see limited drought conditions – **go global**

  - Need to **observe vegetation water content** (gives an idea of plants' strategies)

How can we get GPP/ET?

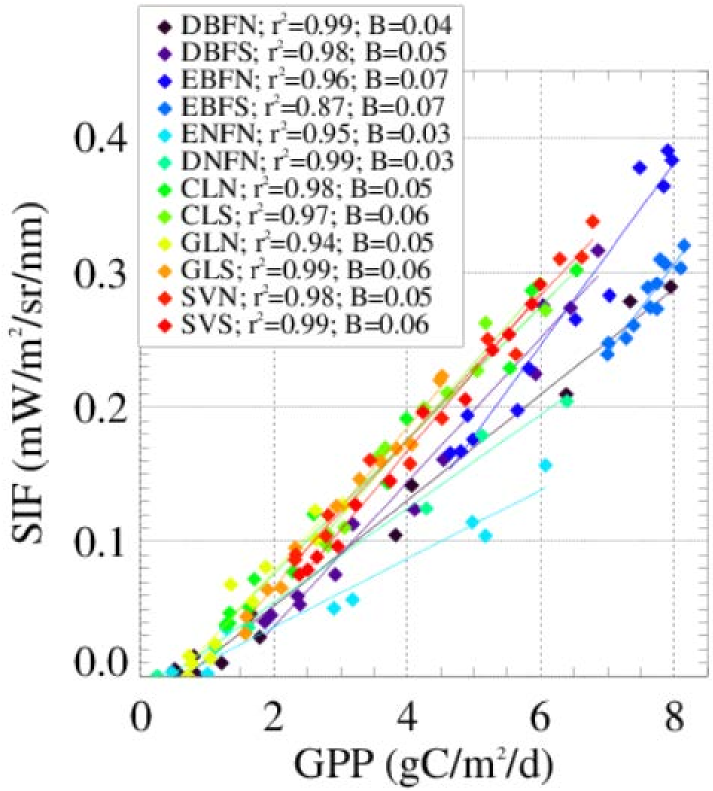
- **Solar-Induced Fluorescence (SIF)**

During photosynthesis a plant absorbs energy through its chlorophyll

- % used for ecosystem gross primary production (GPP)
- % lost as heat
- % re-emitted (SIF: **byproduct**)

Relationship between GPP and SIF is ~ linear

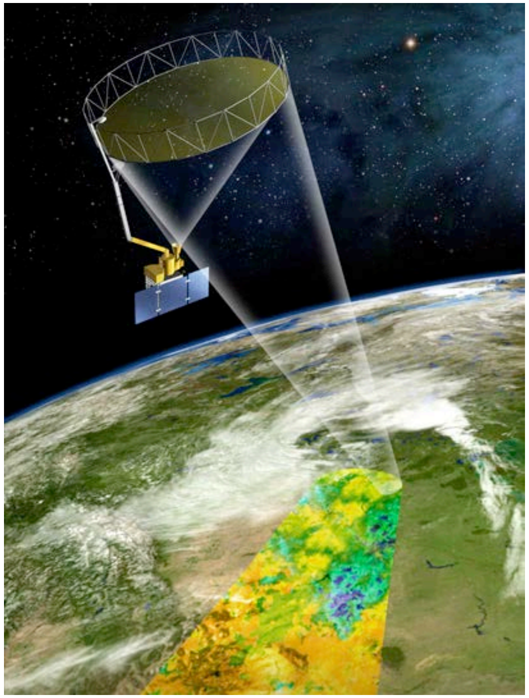
Responds to stressors (water, light, T)



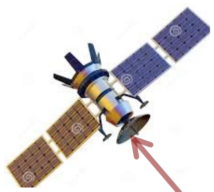
Guanter, L., et al. 2013

Global ecophysiology: how can we assess stress strategy globally?

Microwave: penetrates through atmosphere and clouds
Sensitive to moisture in plants and soil
(Lower frequencies penetrate deeper though canopy
e.g. new SMAP satellite for **soil moisture)**



Vegetation Optical Depth (VOD)

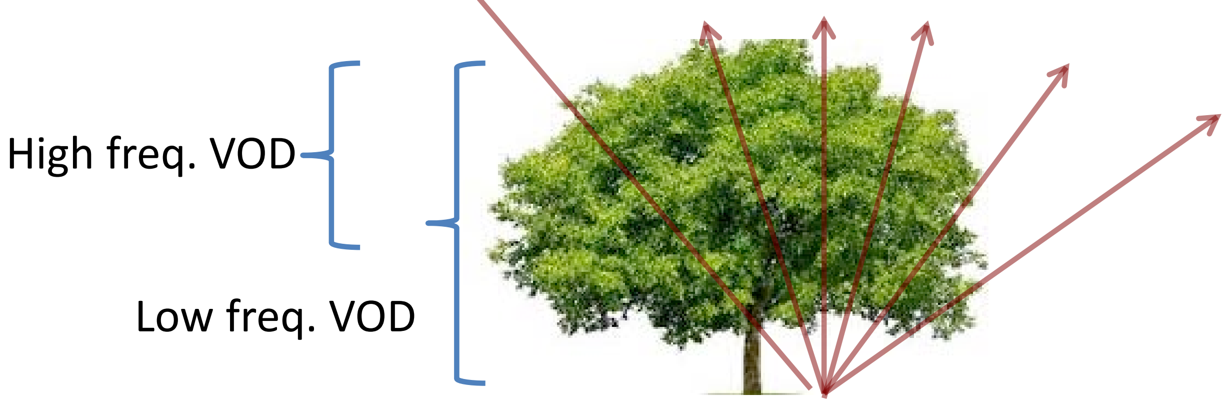


A **byproduct** of the soil moisture retrieval (shading)

Vegetation Optical Depth (VOD)

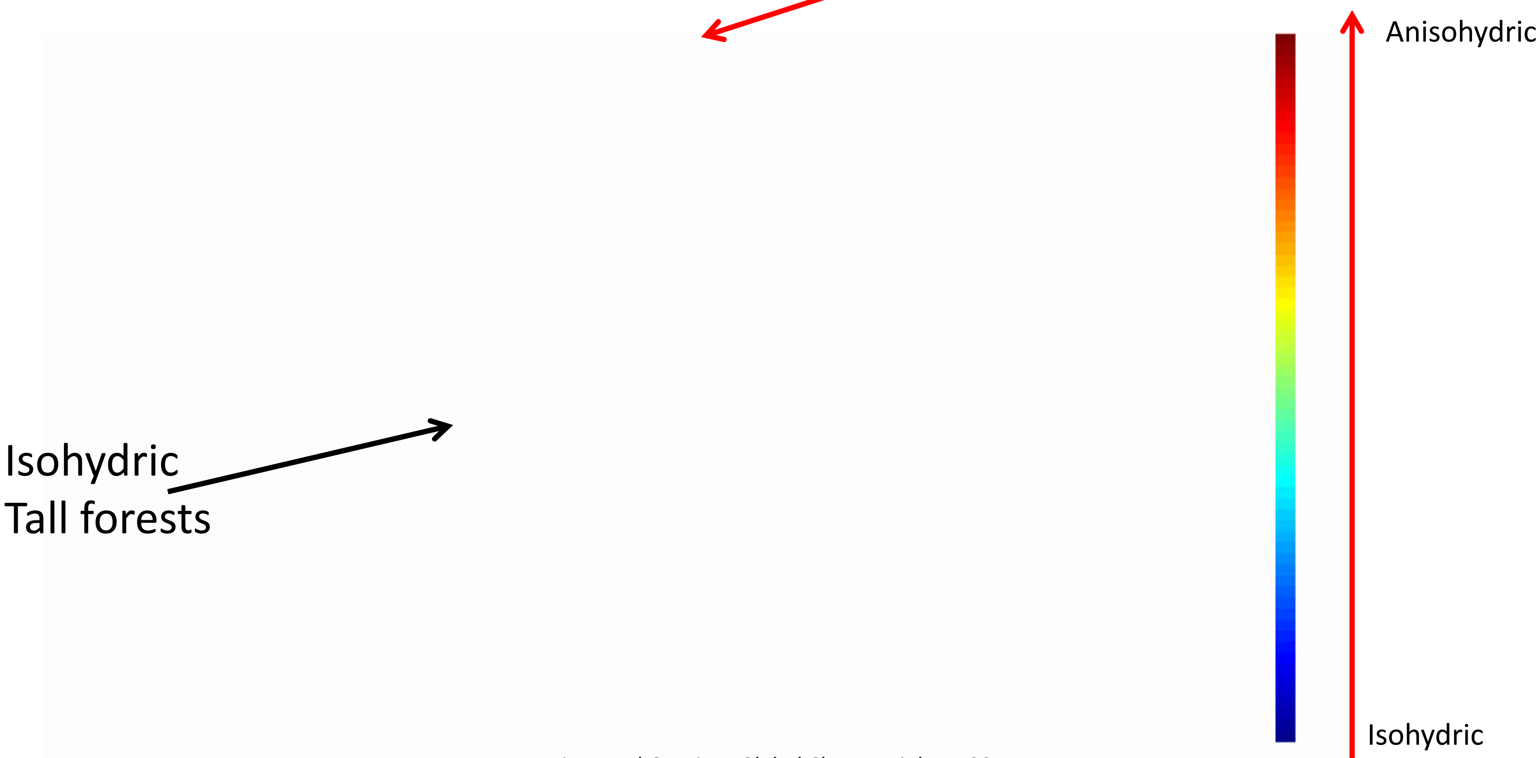
~ vegetation density . vegetation water content

Different frequencies sense different canopy layers



$$\psi_l = \psi_s - \frac{LAI\ VPD\ g_{\mathrm{sto,max}}\ f_{\mathrm{sto}}(\psi_s)}{A_s k_{\mathrm{s,max}}\ f_x(\psi_s)} \approx \psi_s - \Gamma - \Delta\psi_s$$

Vegetation water content variations

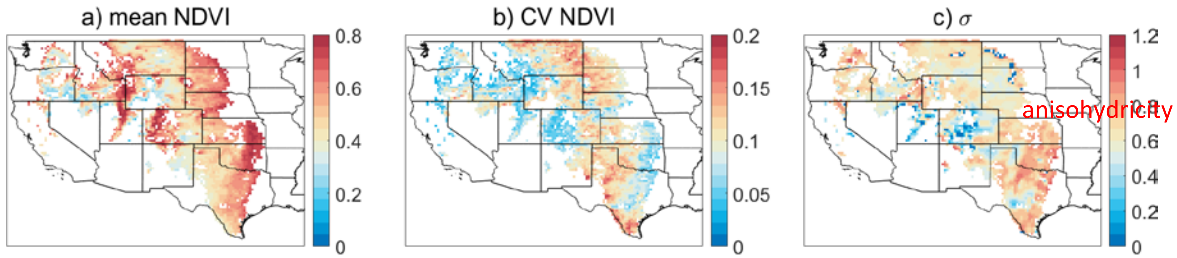


Konings and Gentine, *Global Change Biology*, 2017

Can be used to constrain plant hydraulic parameterization at global scale

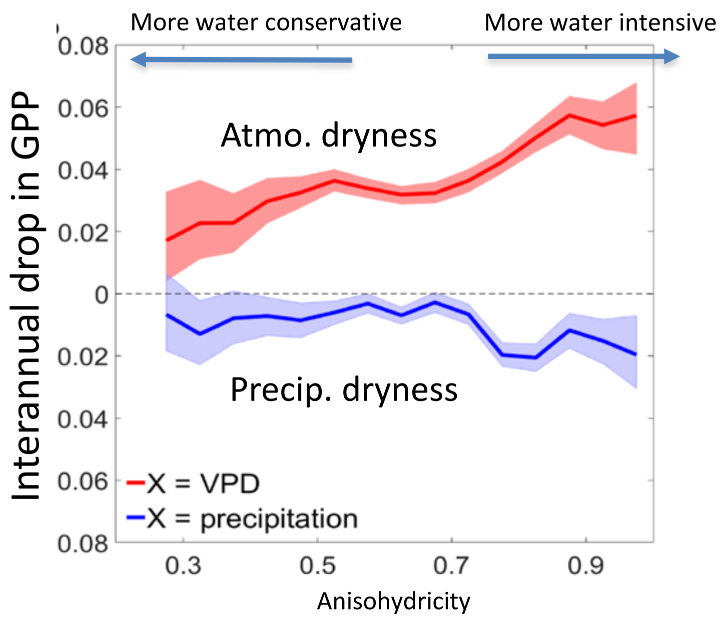
GPP=f(water stress): Example of US grasslands

Isohydricity regulates water stress response

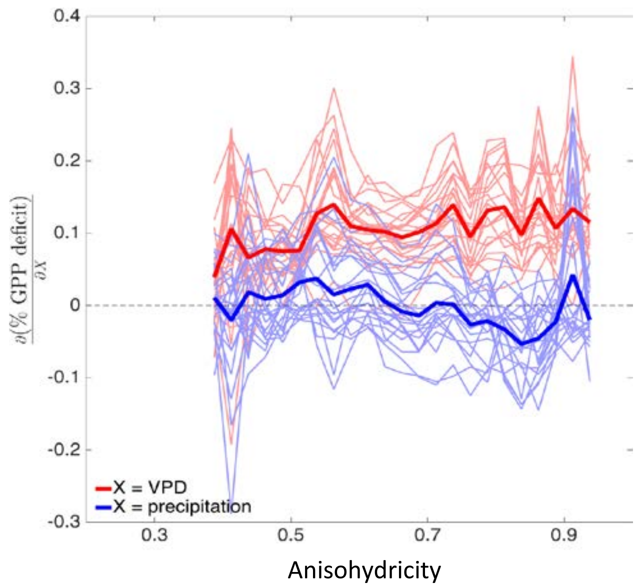


Many isohydricities per NDVI – not a single value per PFT!

Observations



Models

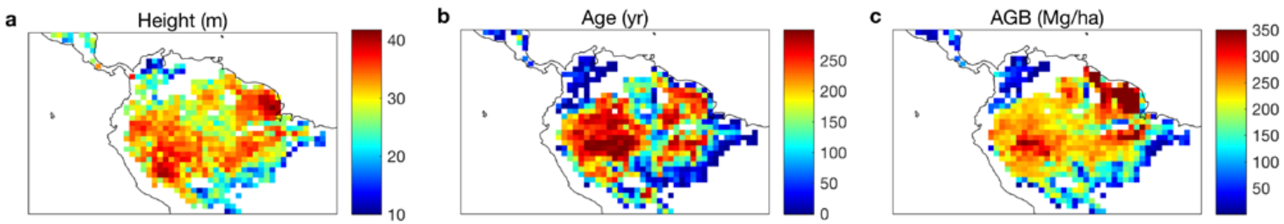


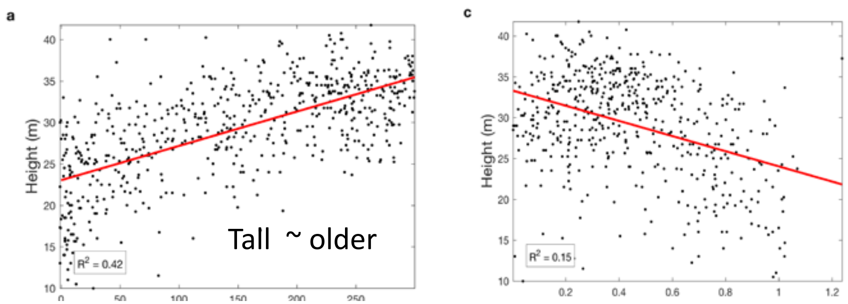
•Konings, A. G., A. P. Williams, and P. Gentine (2017), Sensitivity of grassland productivity to aridity controlled by stomatal and xylem regulation, *Nat Geosci*, *7*, 2193–7.

GPP=f(water stress): 2) Tropical forests

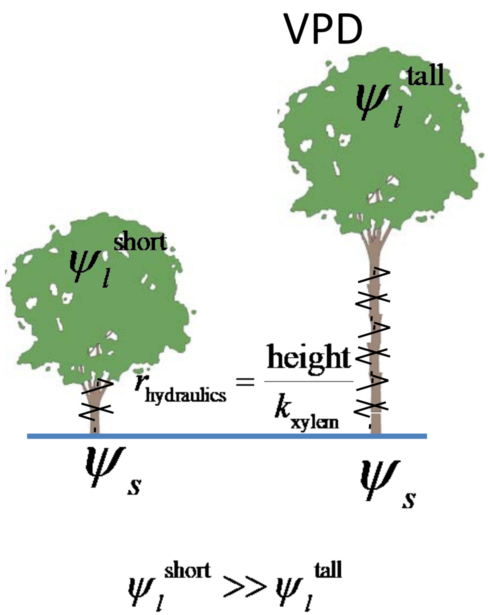
Tall forests less sensitive to water supply

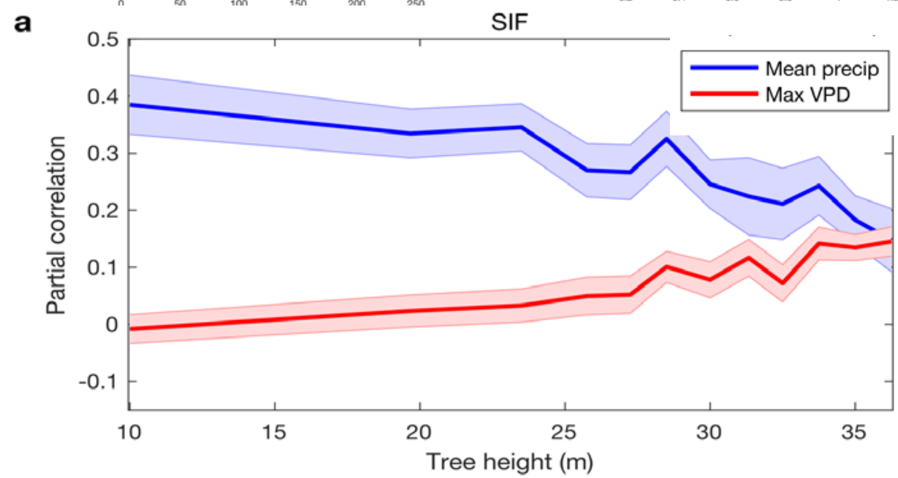
Tree height/age/isohydricity regulate water stress response





Tall ~ more isohydric



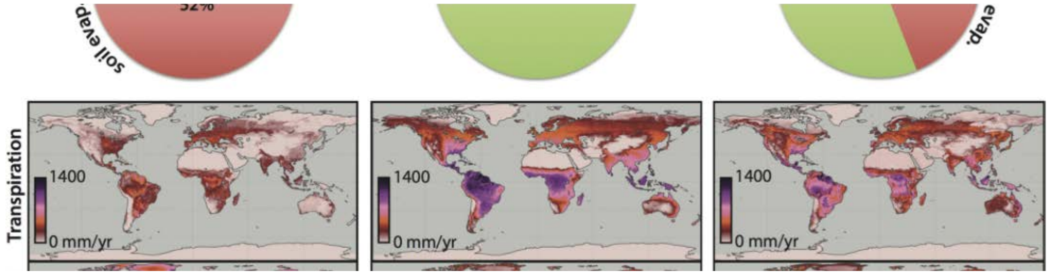


Tall forests less sensitive to rainfall but more to VPD

Giardina F., …, Gentine P., Tall Amazonian forests are more resistant to precipitation variability , *Nat Geo*, in revision

Soil texture effect on resistance to bare soil evaporation

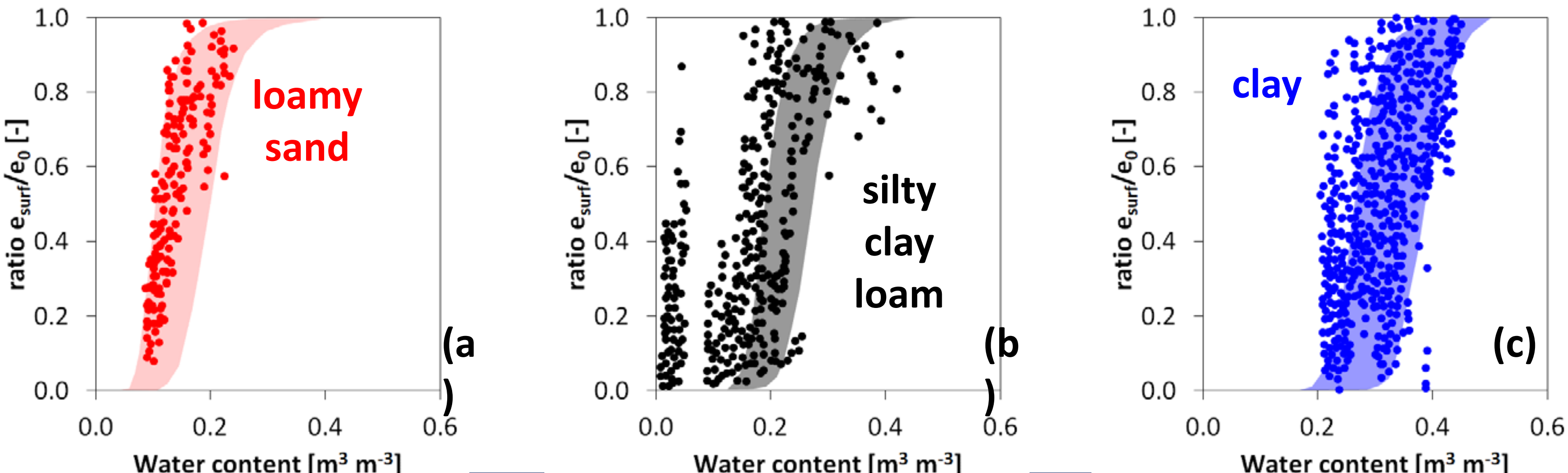
Huge uncertainties in E:ET estimates



- Simulating the surface evaporation e_{surf} as a function of surface water (Haghighi et al. 2013) θ_{surf}

$$e_{surf} = \frac{e_0 \cdot 4K(\theta_{surf}) \cdot \nabla}{e_0 + 4K(\theta_{surf}) \cdot \nabla}$$

- The gradient ∇ driving water supply is a soil intrinsic property defined by the characteristic length for capillary flow



Courtesy Lehmann and Or

Conclusions

- H_2O-CO_2-climate are strongly coupled **in models**

- Future carbon and water states cannot be fully comprehended in isolation

- Representation of processes need improvement

- Vegetation water stress and land-atmosphere interactions are key
  Need better representation in models

Is SIF holding its promises?

Issue: SIF is VERY noisy (small signal)

$GPP=LUE.fPAR_{green}.PAR$

$SIF=E_{SIF\text{-}yield}.\ fPAR_{green}.PAR$

If most of the signal we are seeing is

$APAR_{green}=fPAR_{green}.PAR$

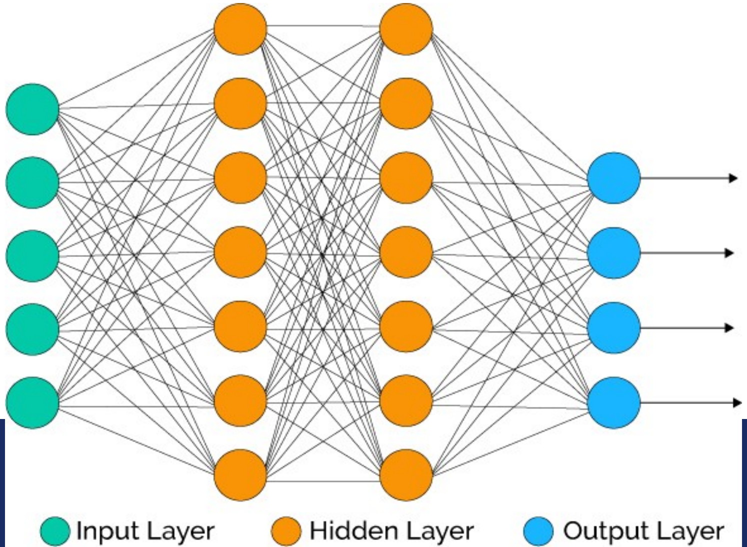
(i.e., vegetation structure + light)

then maybe old generation sensors are "good enough" (MODIS)

+ less noisy + longer record

Solution: Use machine learning

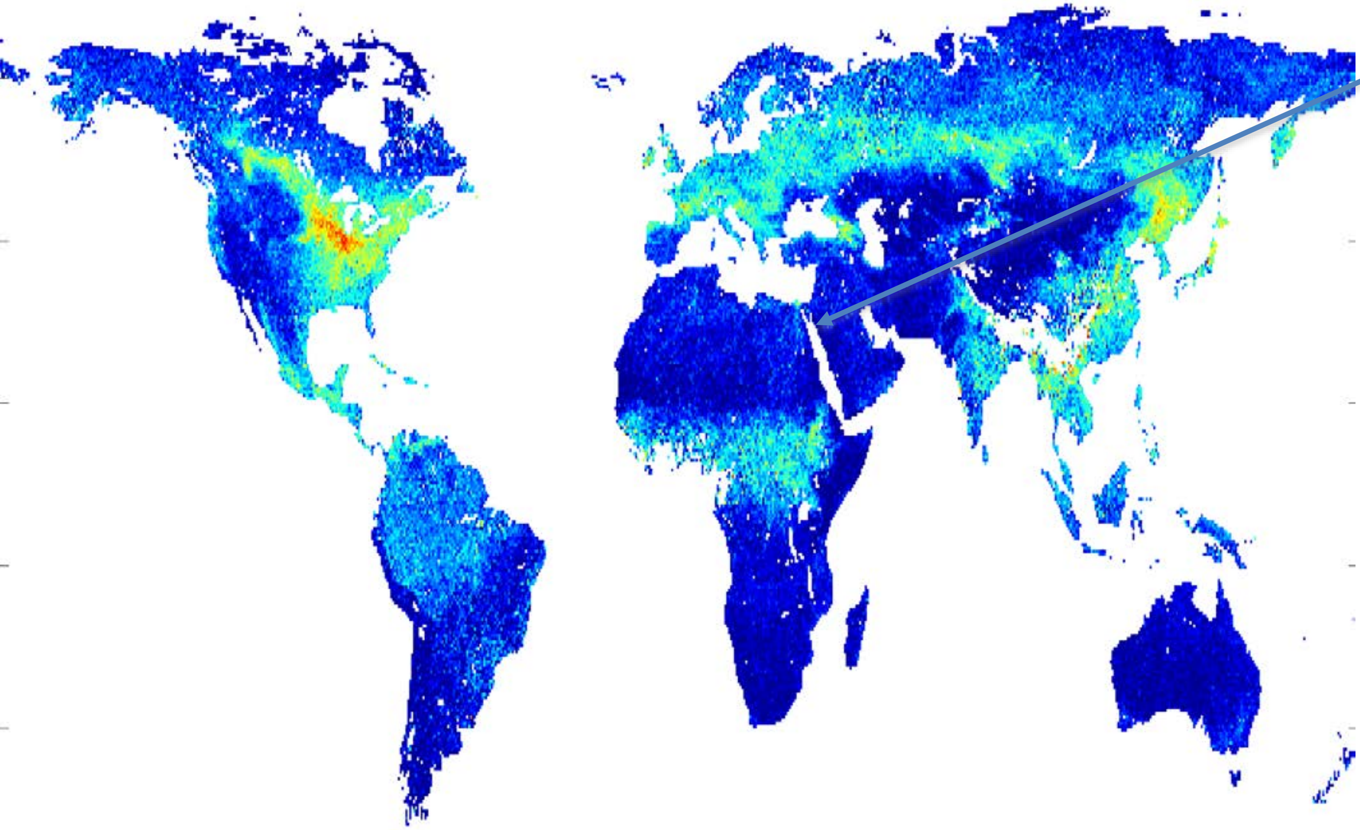
MODIS channels

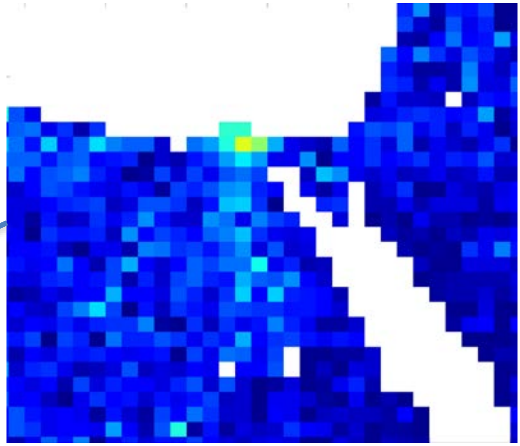


Reconstructed SIF (RSIF)

Is SIF holding its promises?

SIF is VERY noisy (small signal)



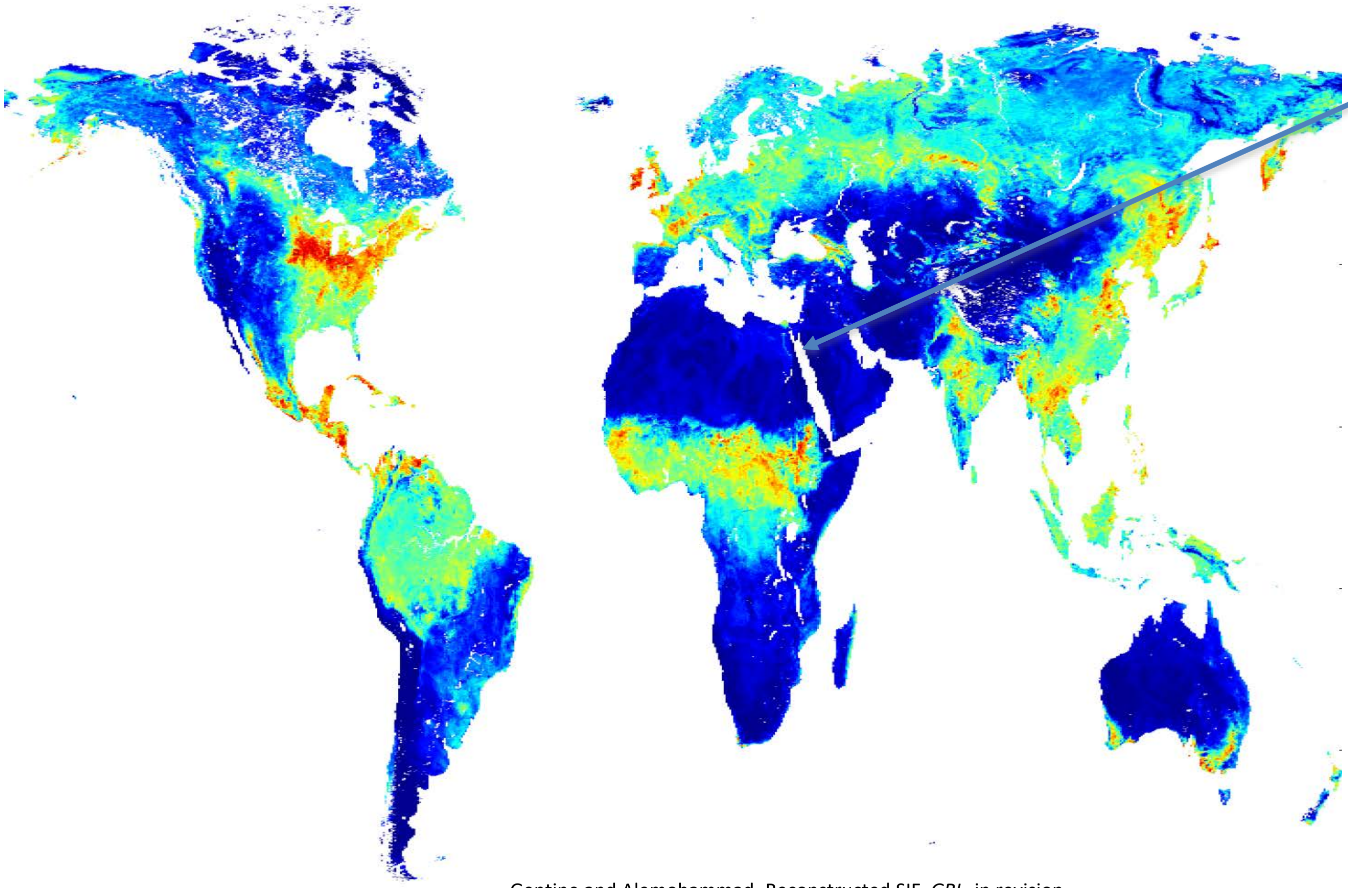


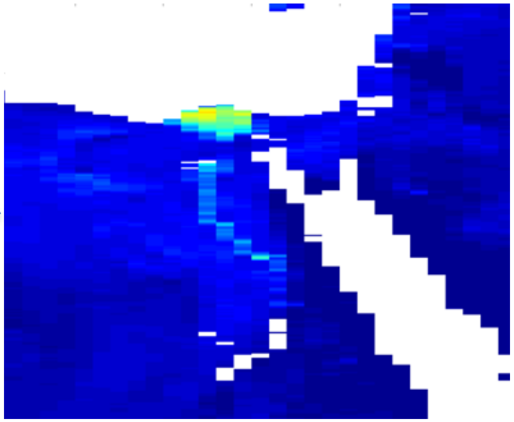
Nile

Gentine and Alemohammad, Reconstructed SIF, *GRL*, in revision

Is SIF holding its promises?

RSIF strongly reduces noise



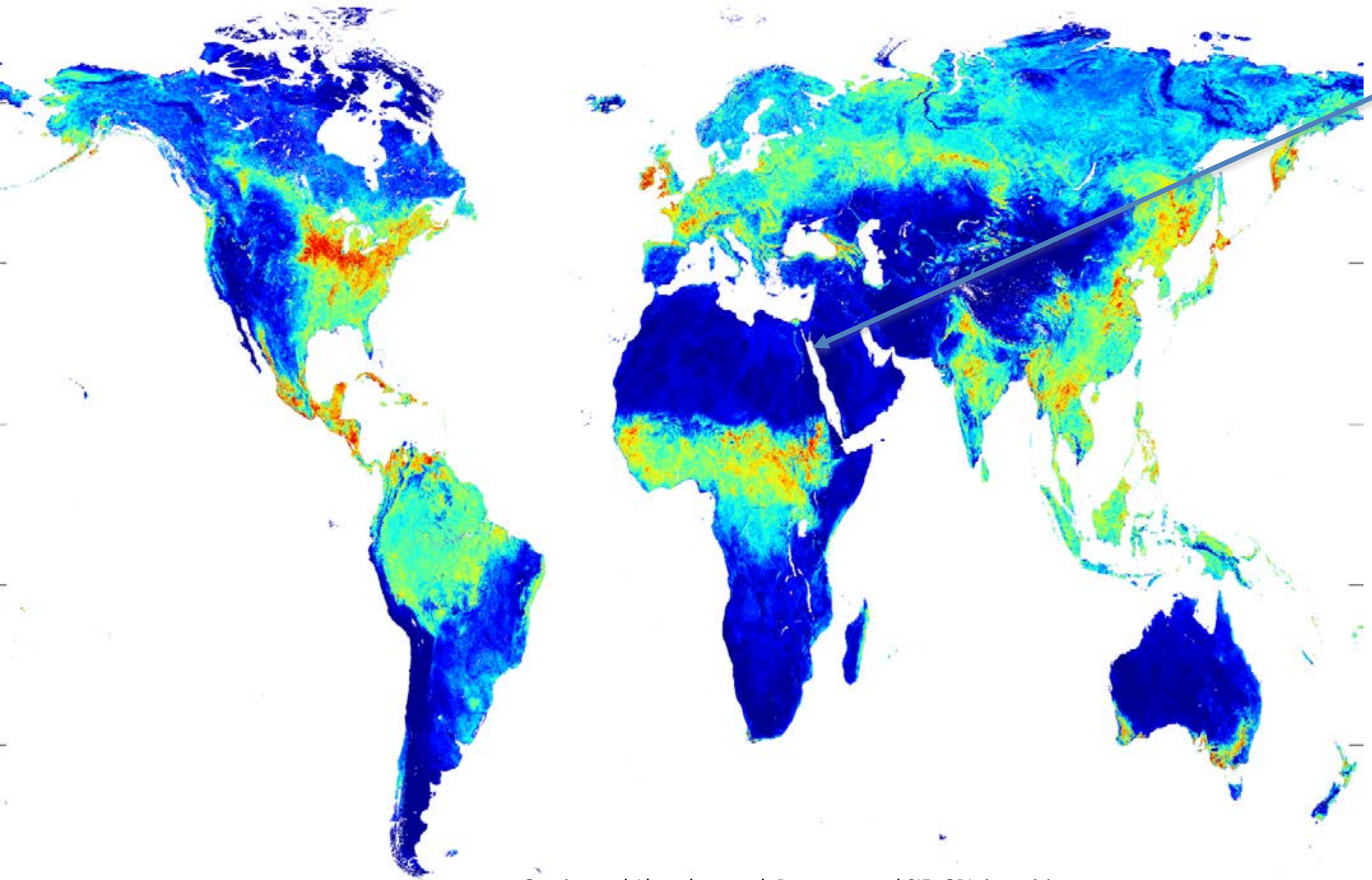


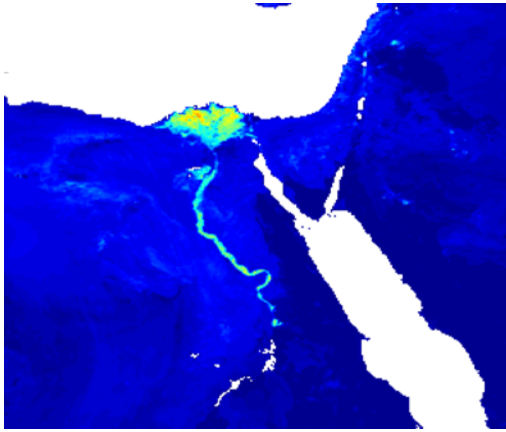
Nile

Gentine and Alemohammad, Reconstructed SIF, *GRL*, in revision

Is SIF holding its promises?

RSIF available at higher resolution – 500m



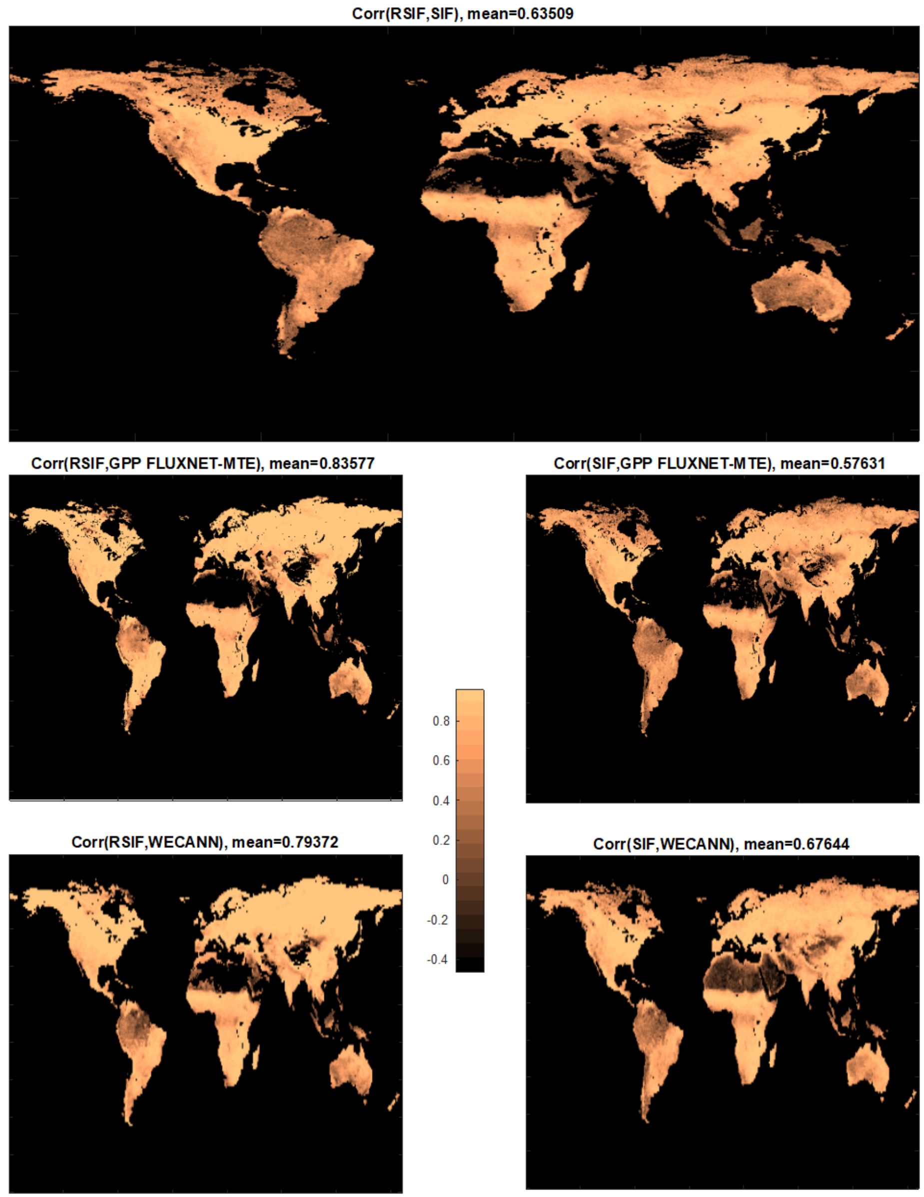


Nile

Gentine and Alemohammad, Reconstructed SIF, *GRL*, in revision

RSIF: Reconstructed SIF

Machine learning using MODIS raw channels to reproduce SIF



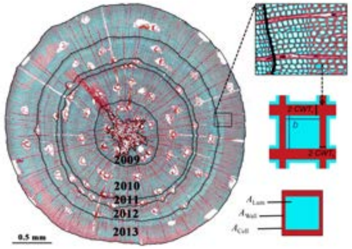
Next steps

- **Overall objective: Improving prediction of water cycle**

Tools:

- **1) surface observations**

flux towers, soil moisture, hydraulics, radiation, local fluorescence, wood anatomy

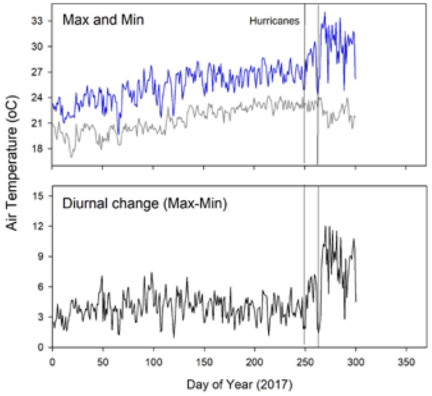


Guerin et al. submitted

2) **Remote sensing and atmospheric observations**

Microwave, solar-induced fluorescence, atmospheric inversion (temperature, DTR, VPD, xCO_2, isotopes (T:ET), OCS)

→ to develop **long-term and consistent observations** (trends)



Next steps

3) **High resolution models**

- Turbulence: DNS, LES, CRM, observations – key for tropics and cold regions
- Physically based hydrological physiological models

4) Theory

Turbulence, land-atmosphere interactions, stomatal response to water stress

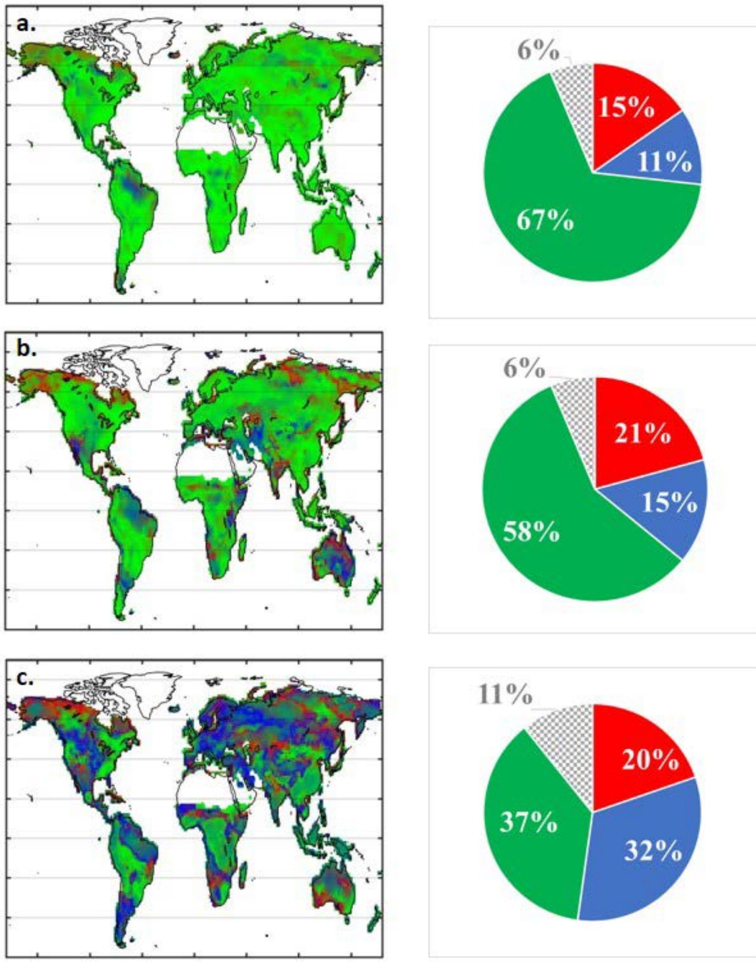
Use these to improve model physics across scales (time and space)

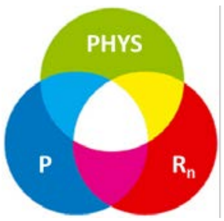
- Precipitation
- Surface fluxes
- Soil moisture
- Turbulence and atmospheric boundary layer

So we can be more confident and reduce the spread in our climate predictions of the water cycle and coupled carbon cycle


Is this our future? ☺
Thank you

Decomposing dryness





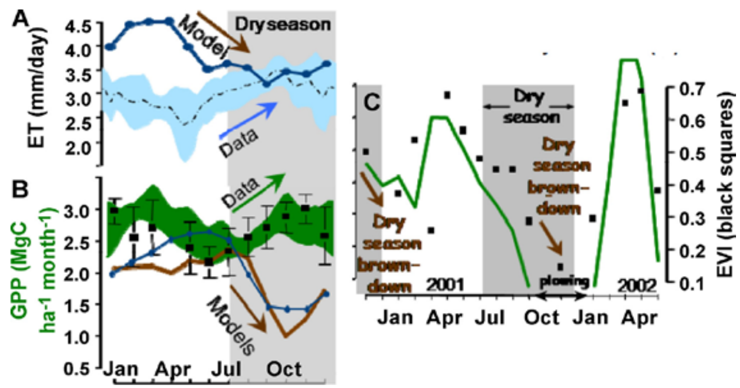
$$\Delta X = \left[\frac{\partial X}{\partial Rn}.\Delta Rn\right]_{ATMO} + \left[\frac{\partial X}{\partial P}.\Delta P\right]_{ATMO} + [\Delta X]_{PHYS}$$

Mostly impacted by CO_2 effects except at cold northern latitudes

Lemordant et al., submitted

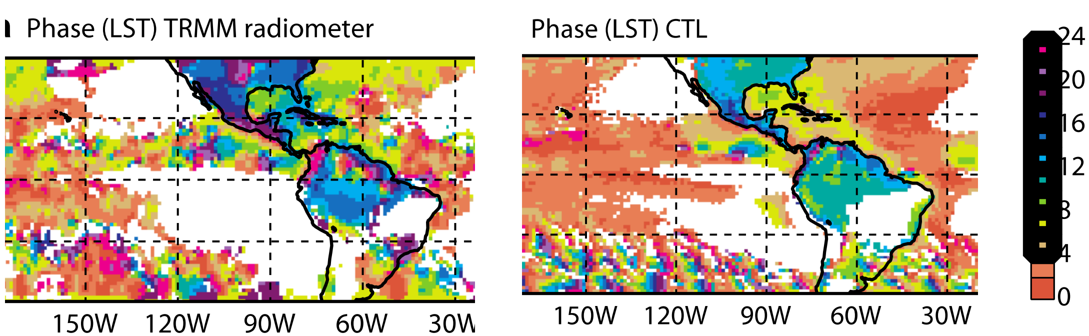
Important **GCMs biases**

- Incorrect **surface flux seasonality** in tropical forests (e.g. Amazon)

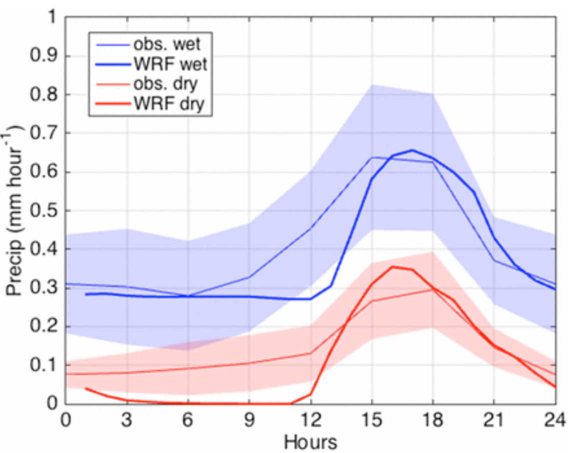


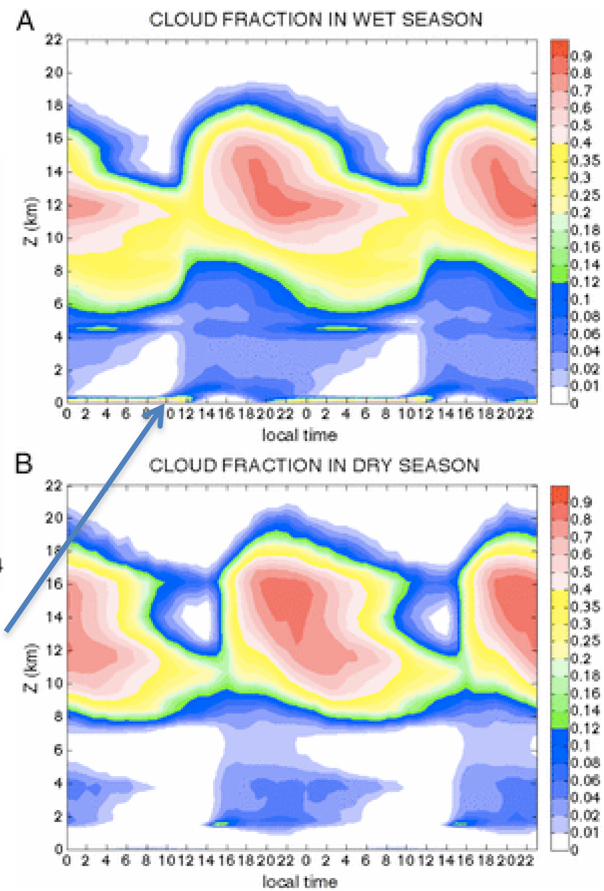
- Incorrect **diurnal** cycle of precipitation and (less appreciated) **of cloud cover**!

Bechtold et al. (2014)

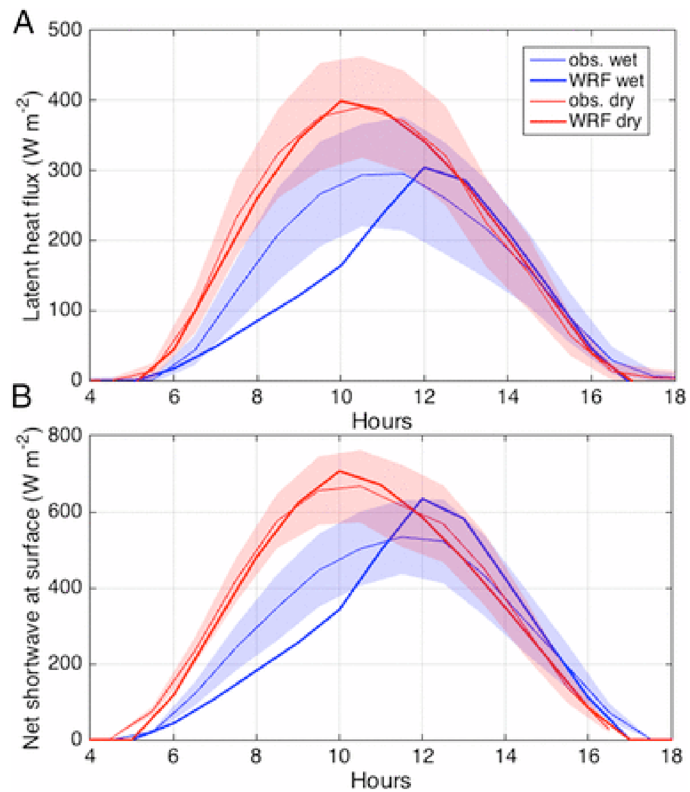


- Example in the Amazon: **Biases are absent** using Cloud-Resolving model with **explicit convection** and **Weak Temperature Gradient** (for large-scale circulation feedback)





Fog

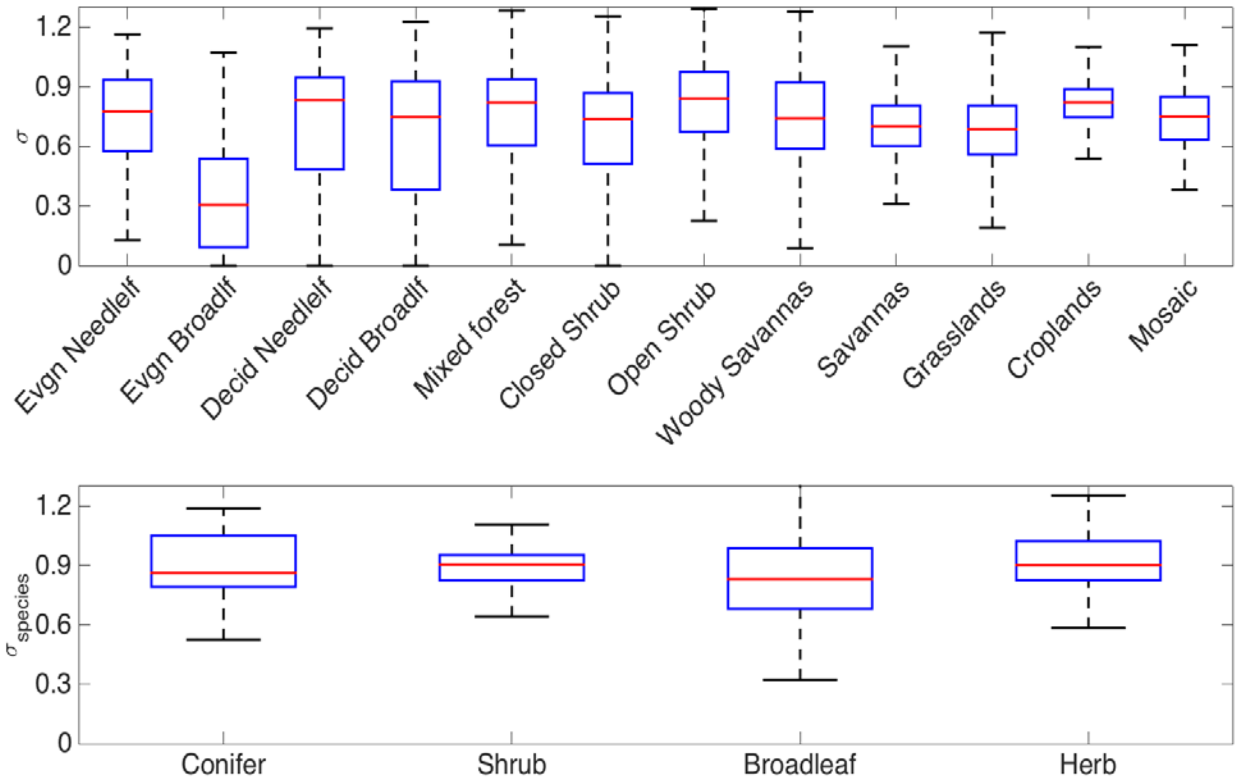


43

Anber et al. (2015) Fog and Rain in the Amazon PNAS (poster in the afternoon)

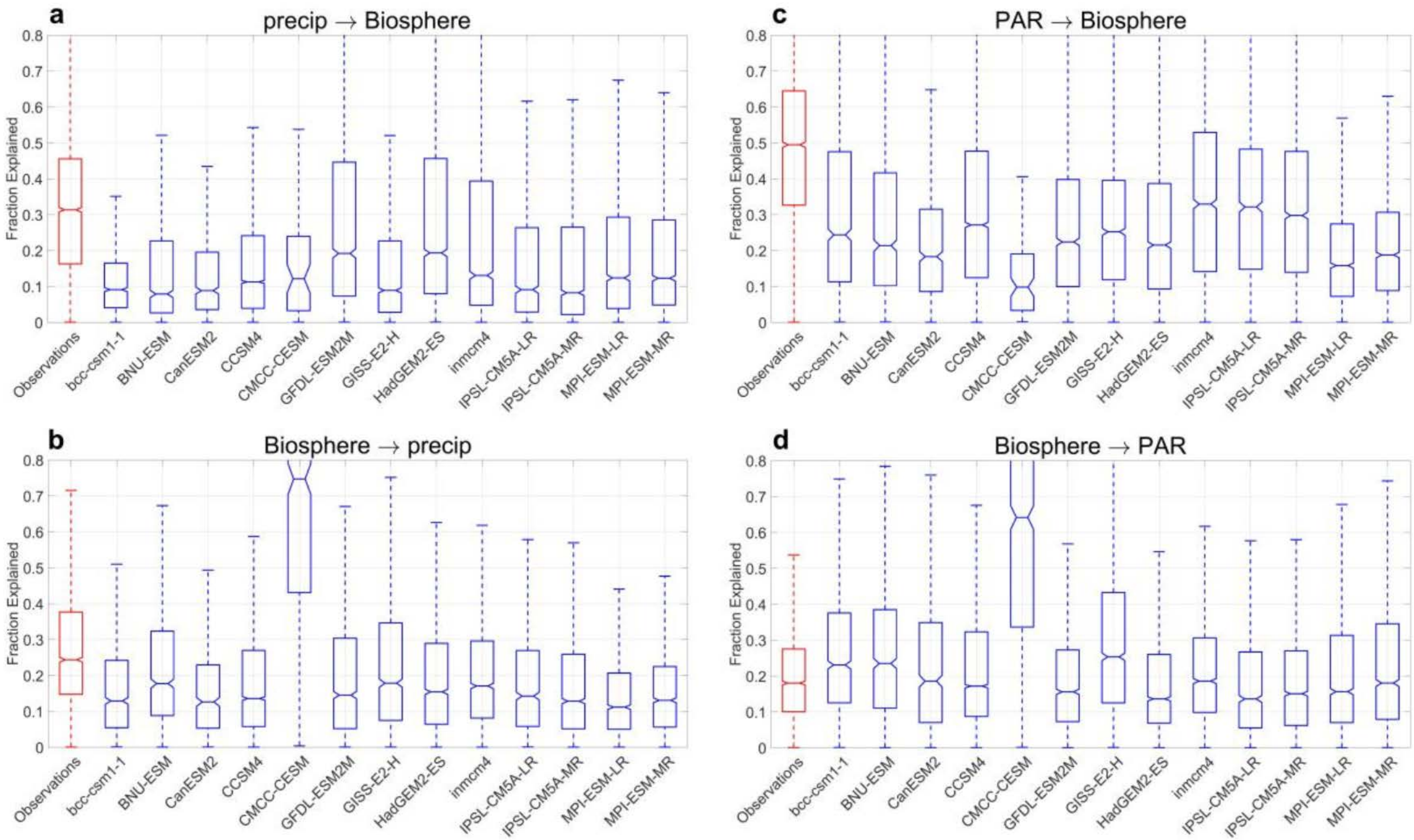
Comparison w/ static indicator: plant functional types

Not related to plant functional types (PFT):
we need to include hydraulic traits in LSMs

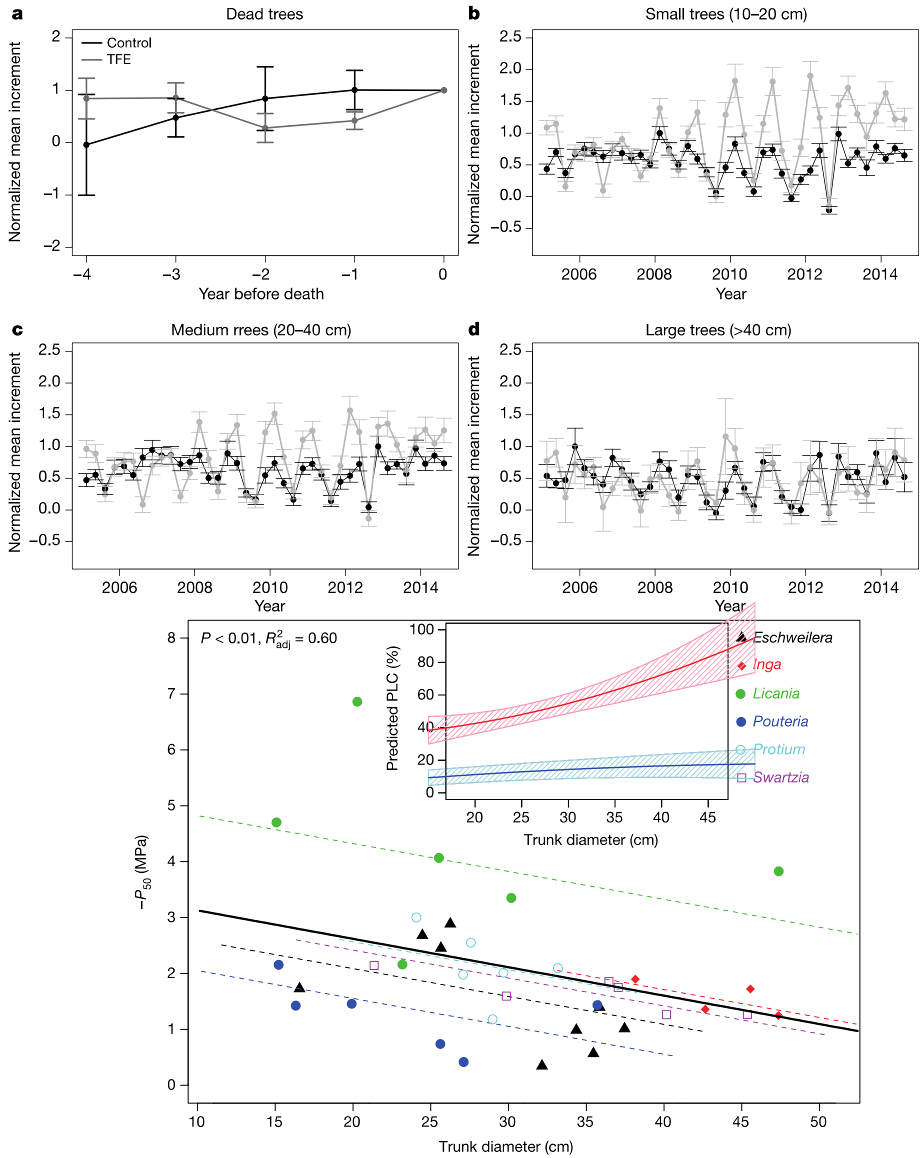


Vegeataion water stress

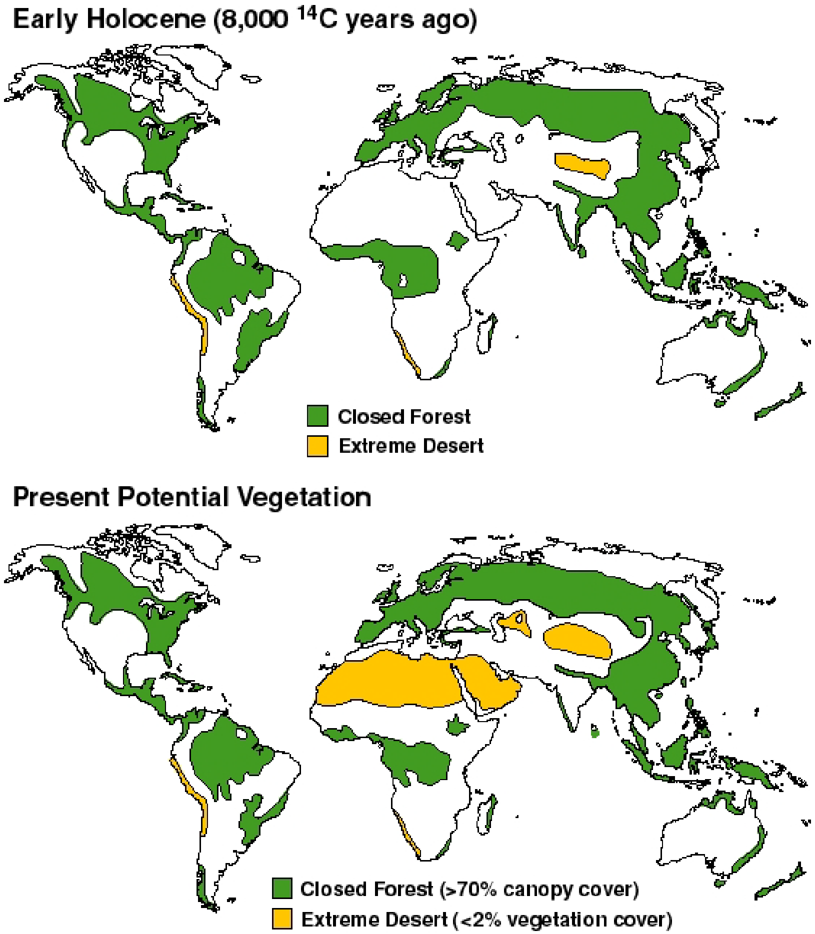
More effect of vegetation water stress



Green et al. Nat Geo 2017

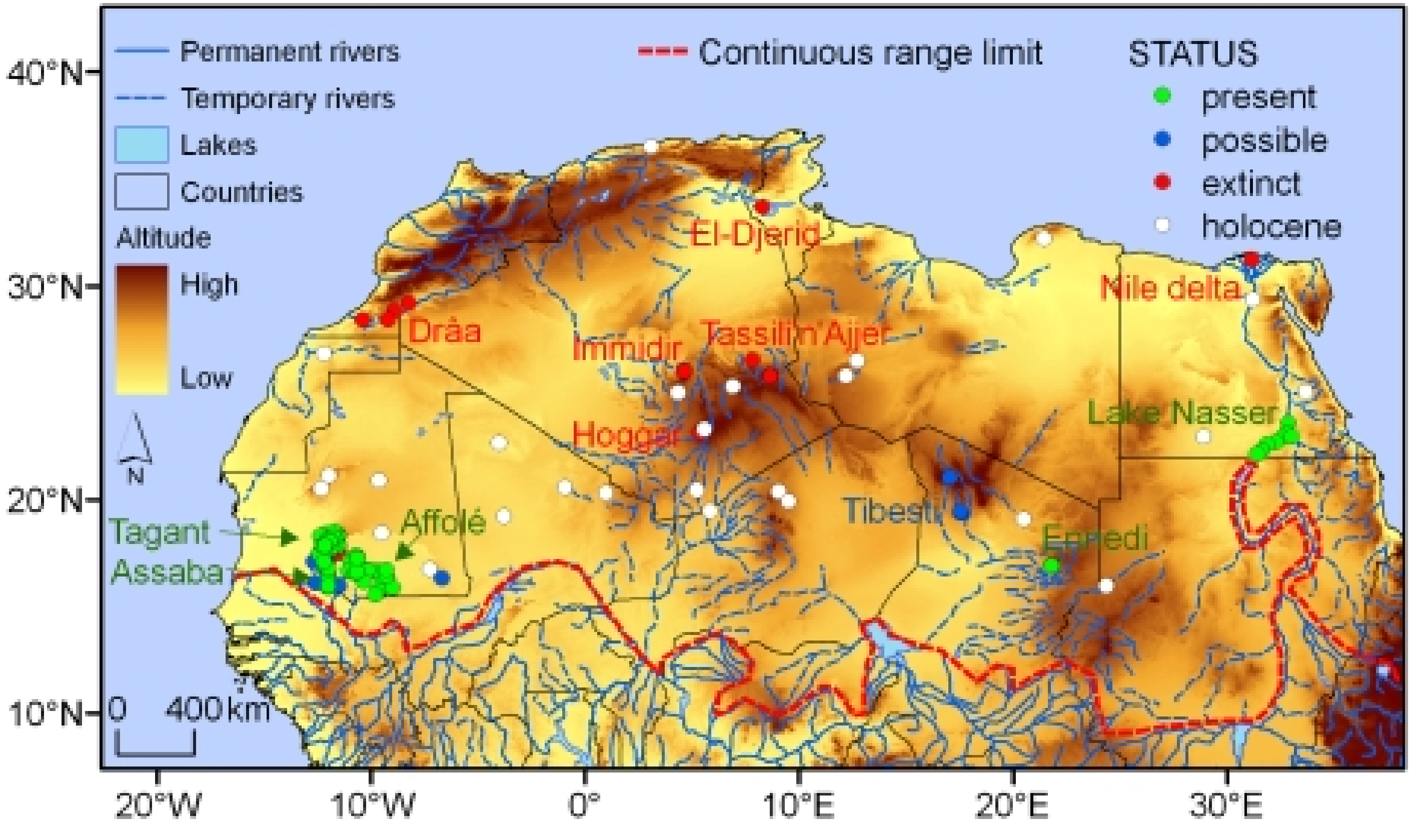

a
Dead trees
Control
TFE
Normalized mean increment
Year before death
b
Small trees (10–20 cm)
Normalized mean increment
Year
c
Medium rrees (20–40 cm)
Normalized mean increment
Year
d
Large trees (>40 cm)
Normalized mean increment
Year
$P < 0.01$, $R^2_{adj} = 0.60$
Eschweilera
Inga
Licania
Pouteria
Protium
Swartzia
Predicted PLC (%)
Trunk diameter (cm)
$-P_{50}$ (MPa)
Trunk diameter (cm)

What about paleoclimate observations:



Very different vegetation, Sahara not an extreme desert

What about paleoclimate results:



Corocodiles (and hippos) in Sahara!

Palmer Drought Severity Index (PDSI)

"PDSI **uses a supply and demand model with readily available temperature and precipitation data** to **estimate relative dryness**. It is a standardized **index that spans -10 (dry) to +10 (wet)**. It has been reasonably successful at quantifying long-term drought. As it uses temperature data and a physical water balance model, it **can capture the basic effect of global warming on drought through changes in potential evapotranspiration**. Monthly PDSI values do not capture droughts on time scales less than about 12 months"

In other words try to **easily represent soil moisture anomalies**

Supply - demand

From NOAA website

What do observations tell us?

Wet gets wetter, dry gets drier?

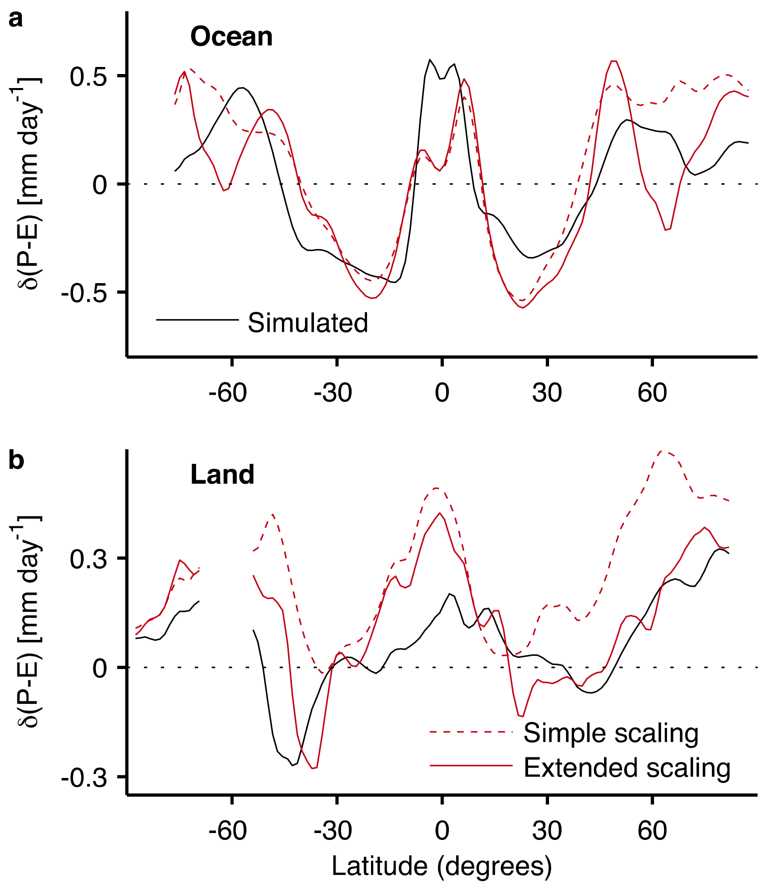
Unclear conclusion

Greve, P., Orlowsky, B., Mueller, B., Sheffield, J., Reichstein, M., & Seneviratne, S. I. (2014). Global assessment of trends in wetting and drying over land. *Nature Geoscience*, *7*(10), 716–721.

What do observations tell us?

Wet gets wetter, dry gets drier does not hold over land

P-ET

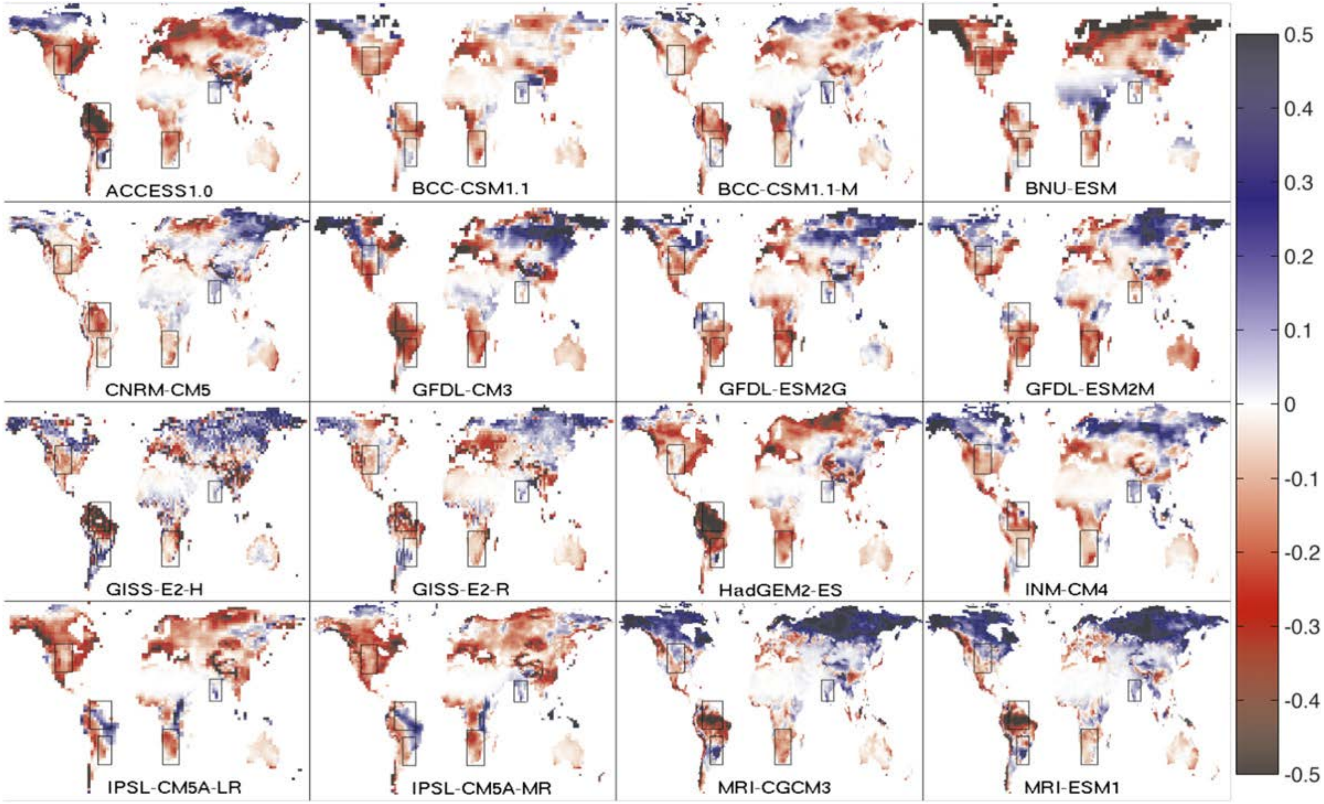


Byrne, M. P., & O'Gorman, P. A. (2015). The Response of Precipitation Minus Evapotranspiration to Climate Warming: Why the "'Wet-Get-Wetter, Dry-Get-Drier'" Scaling Does Not Hold over Land* . *Journal of Climate*. http://doi.org/10.1175/JCLI-D-15-0369.s1

What do observations tell us?

P / Potential ET

Overall drier except in snow/ice regions



1981–99 and 2081–99, for each model.

Scheff, J., & Frierson, D. M. W. (2015). Terrestrial Aridity and Its Response to Greenhouse Warming across CMIP5 Climate Models. *Journal of Climate*, *28*(14), 5583–5600.

What do observations tell us?

EF=ET/(H+ET)

Not that dry, not that clear

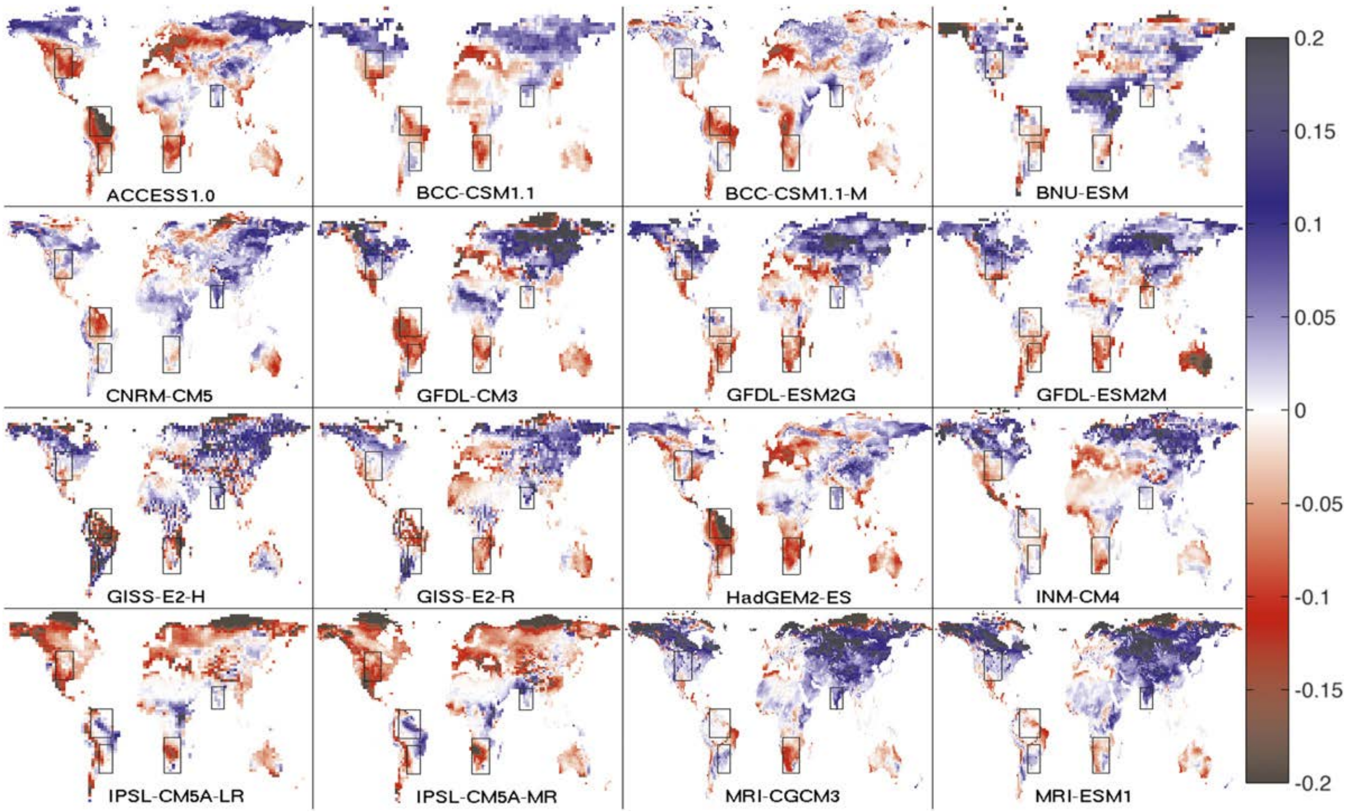
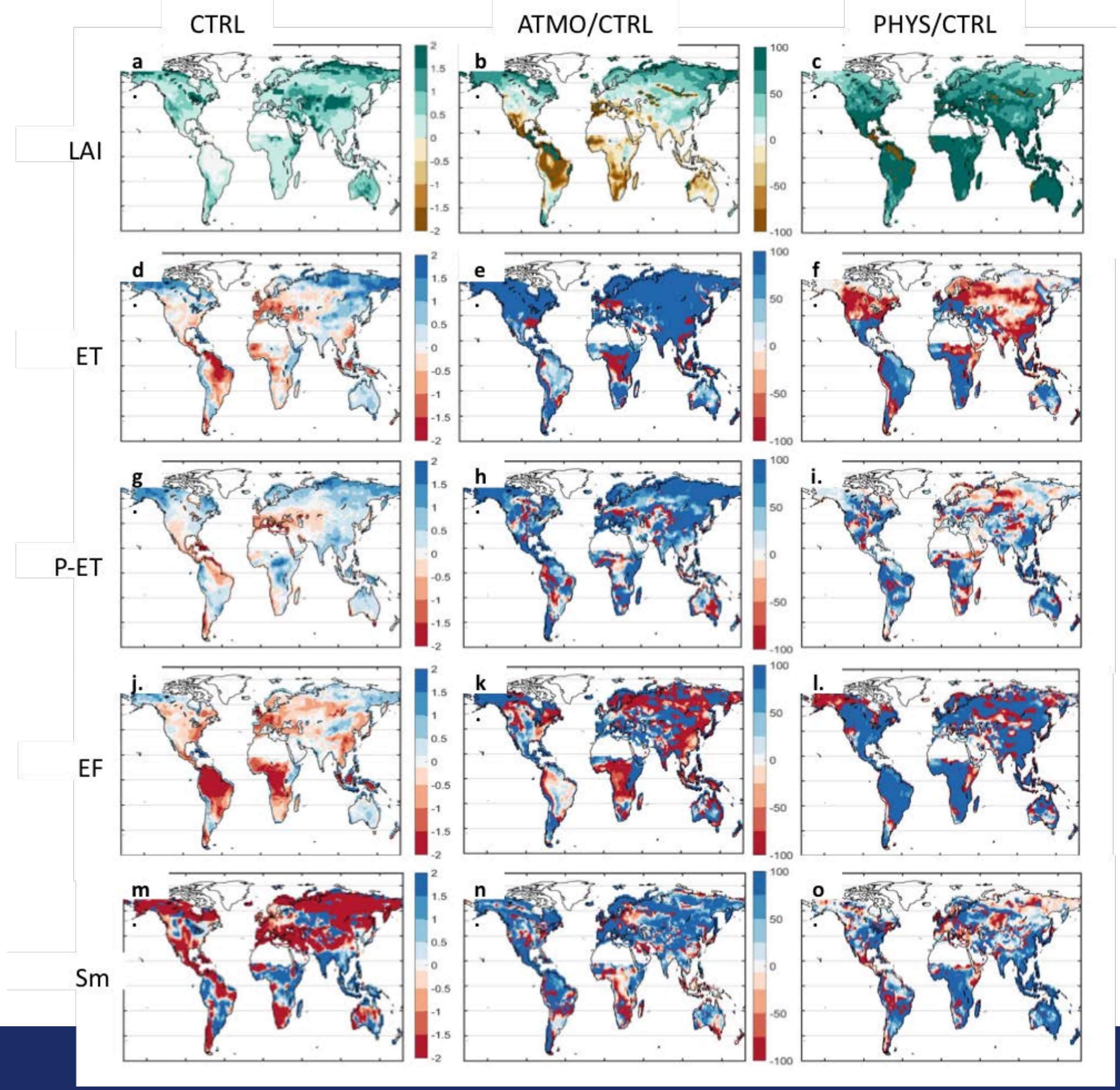


FIG. 15. Changes in evaporative fraction LH/(LH + SH) between 1981–99 and 2081–99, for each model.

Scheff, J., & Frierson, D. M. W. (2015). Terrestrial Aridity and Its Response to Greenhouse Warming across CMIP5 Climate Models. *Journal of Climate*, *28*(14), 5583–5600.

Drying?



Problems

What are the problems of assessing dryness over land using P-ET/P-Ep?

Over the Ocean

- ET=Ep, so directly P-Ep

-Precipitation increases ~ based on Clausius-Clapeyron

(Column water vapor - holding capacity of atmosphere)

$$\boxed{e_s(T) = e_{s0} \exp\left(\frac{L_v}{R_v}\left[\frac{1}{T_0} - \frac{1}{T}\right]\right)}$$

1% T increase -> 7% increase in $e_s(T)$

-Evaporation increases as Sea Surface Temperature (SST) increases, also linked to Clausius-Clapeyron

-Dynamics in addition to that (expansion of Hadley cell for instance)

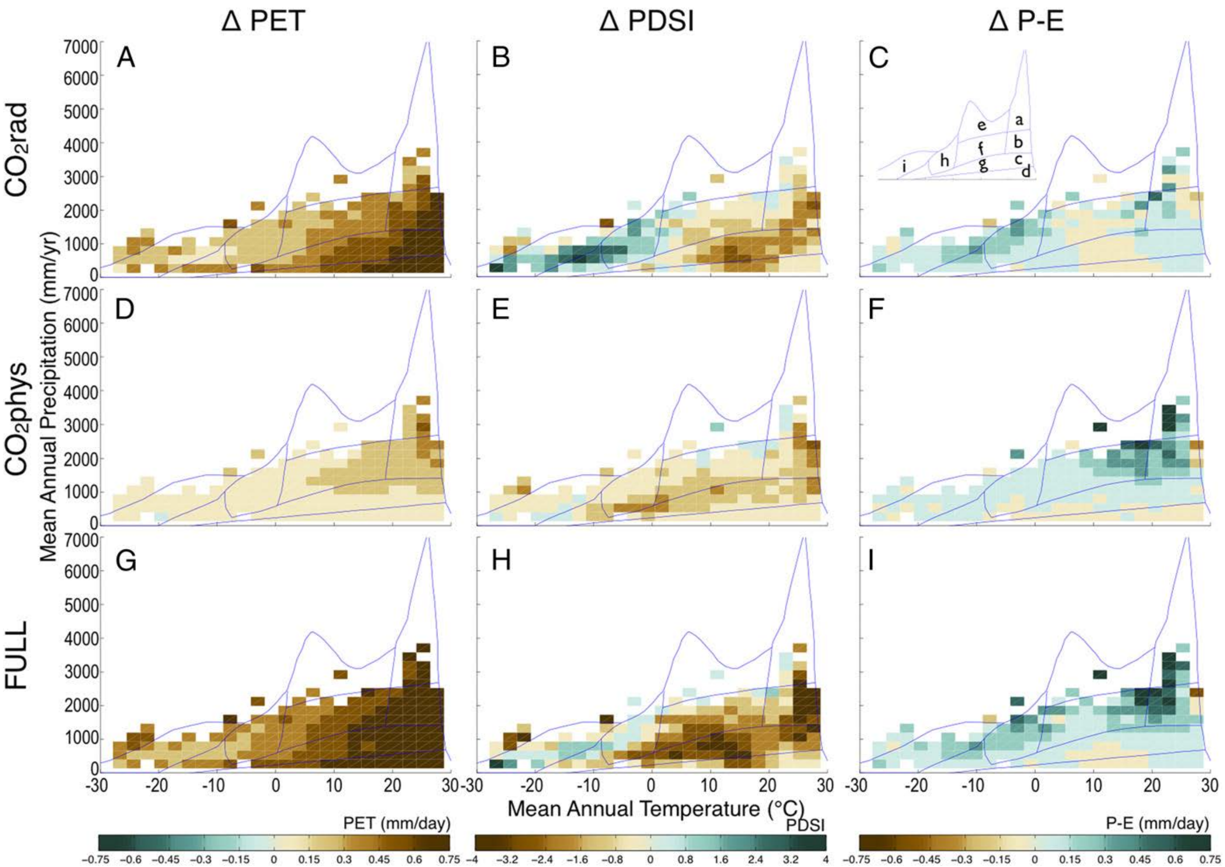
CO_2 effect on ET

- How does CO_2 impact ET and P-ET
- 1000ppm experiment (1000ppm vs. preindustrial)

Atmo. CO_2 only

Plant. CO_2 only

Plant. and Atmo. CO_2



Swann, A. et al. (2016). Plant responses to increasing CO2 reduce estimates of climate impacts on drought severity. *PNAS*, *113*(36), 10019–10024.

How can we assess role of the surface?

- **Climate models:**

  define an experiment to isolate feedback (e.g. GLACE: impose soil moisture)

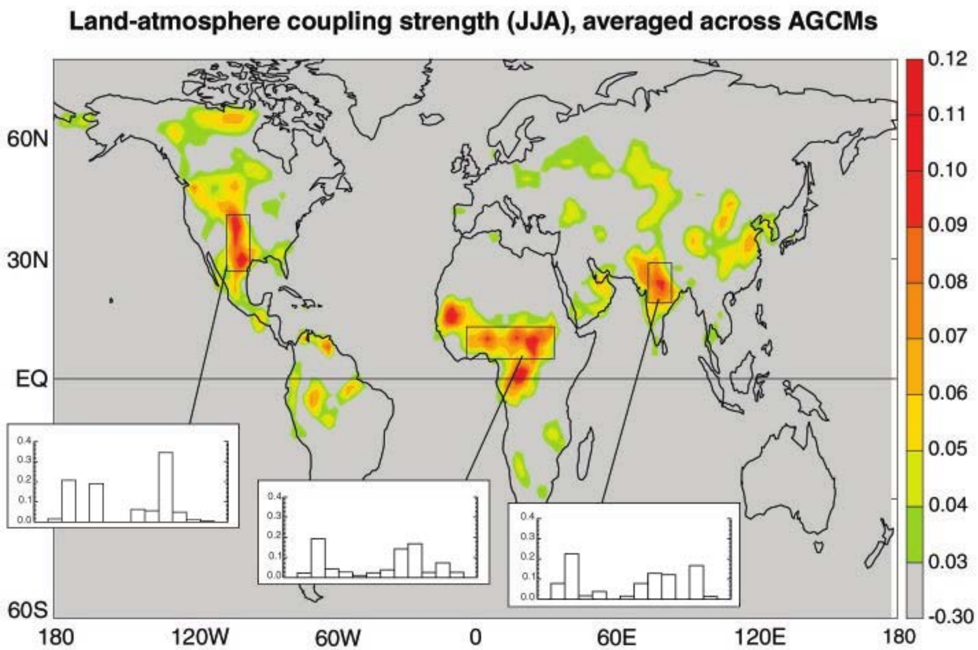
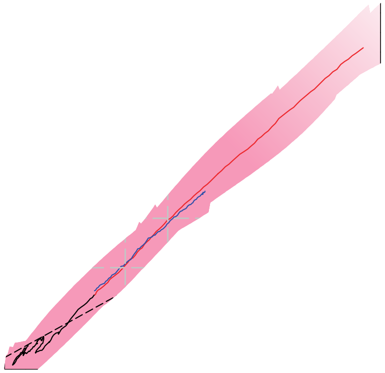


Fig. 1. The land-atmosphere coupling strength diagnostic for boreal summer (the Ω difference, dimensionless, describing the impact of soil moisture on precipitation), averaged across the 12 models participating in GLACE. (**Insets**) Areally averaged coupling strengths for the 12 individual models over the outlined, representative hotspot regions. No signal appears in southern South America or at the southern tip of Africa.

Koster, R. D. et al. (2004), Regions of strong coupling between soil moisture and precipitation, *Science*, *305*(5687), 1138–1140.

Land-atmosphere interactions

Impact of **soil moisture dynamics on extreme temperatures Tx**



Prescribed
soil moisture

Seneviratne et al. (2016), *Nature*

Solar Induced Fluorescence (SIF)

- **Solar-Induced Fluorescence (SIF)**

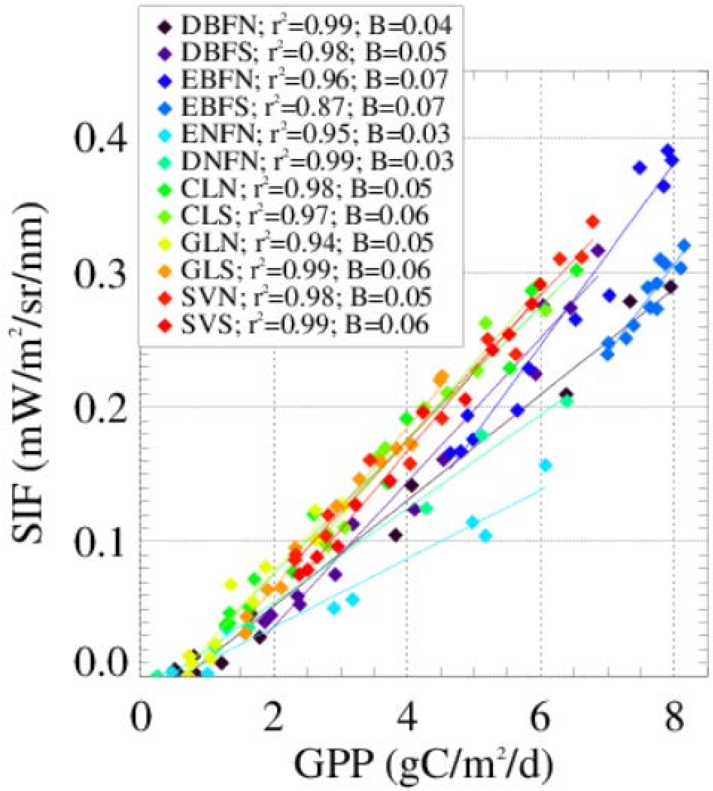
During photosynthesis a plant absorbs energy through its chlorophyll

- % used for ecosystem gross primary production (GPP)
- % lost as heat
- % re-emitted (SIF: **byproduct**)

Relationship between GPP and SIF is ~ linear

Responds to stressors (water, light, T)

We can then relate surface flux to water stress



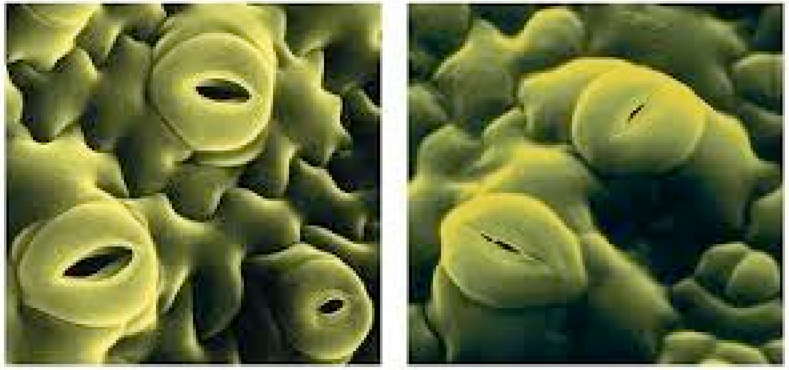
Guanter, L., et al. 2013

Solar Induced Fluorescence (SIF)

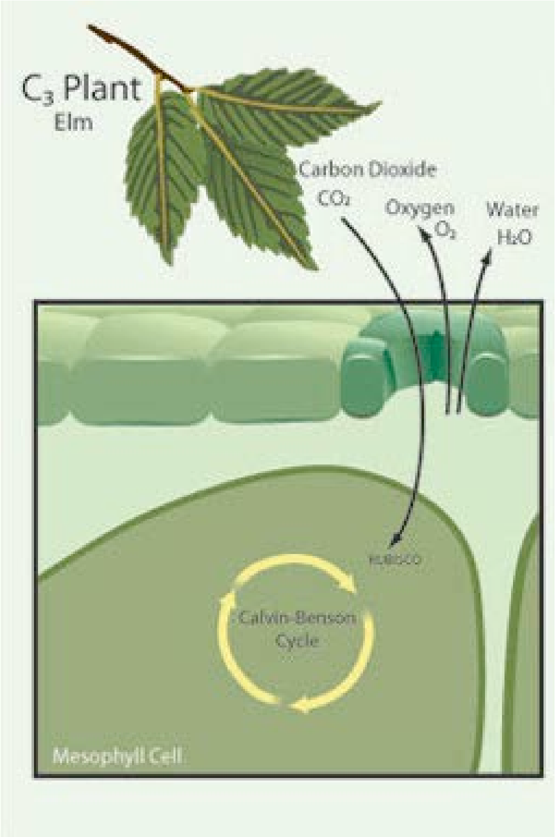
How can we constrain ET magnitude?

GPP (**CO_2 uptake**) is directly related to transpiration *T* (**H_2O release**)

$$GPP = wue\, T$$

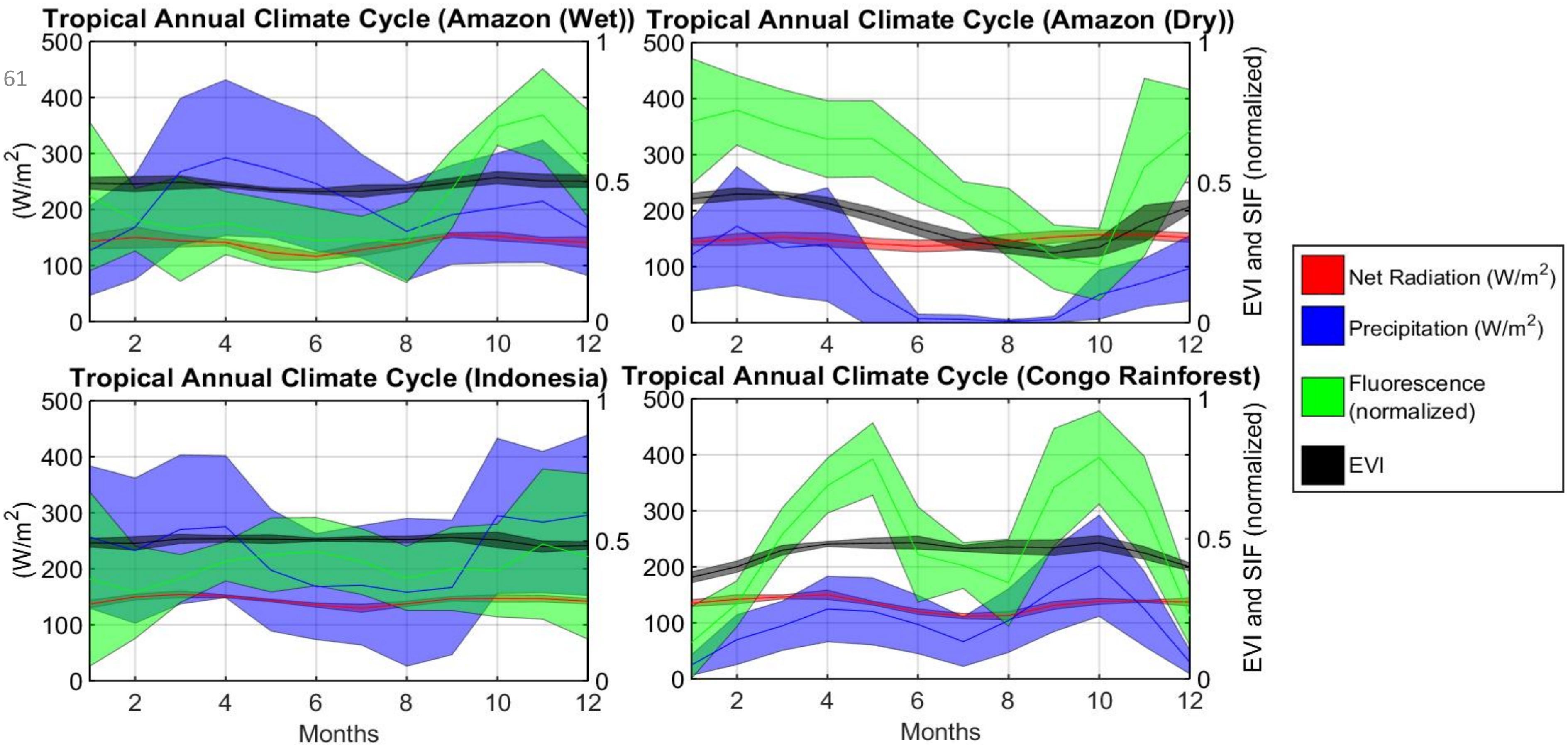


(a) Stomata open (b) Stomata closed



SIF is thus a good **proxy for *T*** (main flux)

Example: Tropical Climate

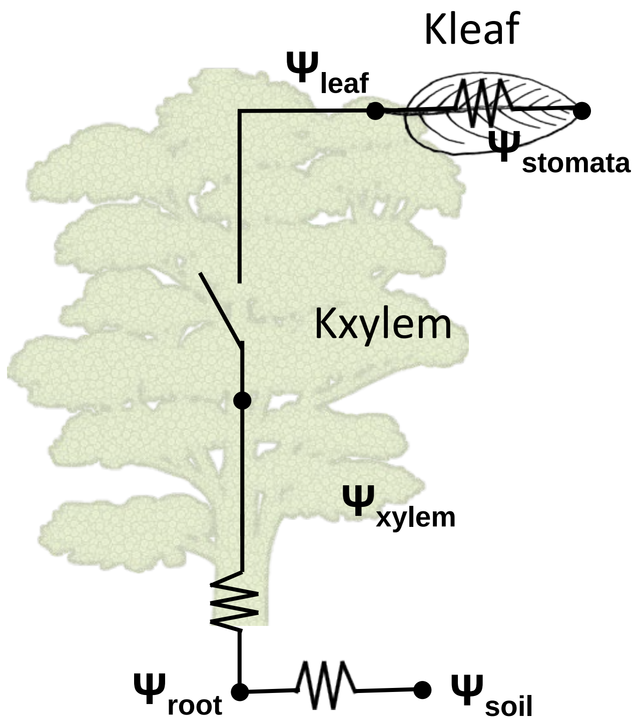


Except for Indonesia all tropical regions exhibit some seasonal cycle due to light/water limitations

Anisohydric species are more sensitive to soil moisture state

Bottom up stress

Ψ_{leaf} drops drastically

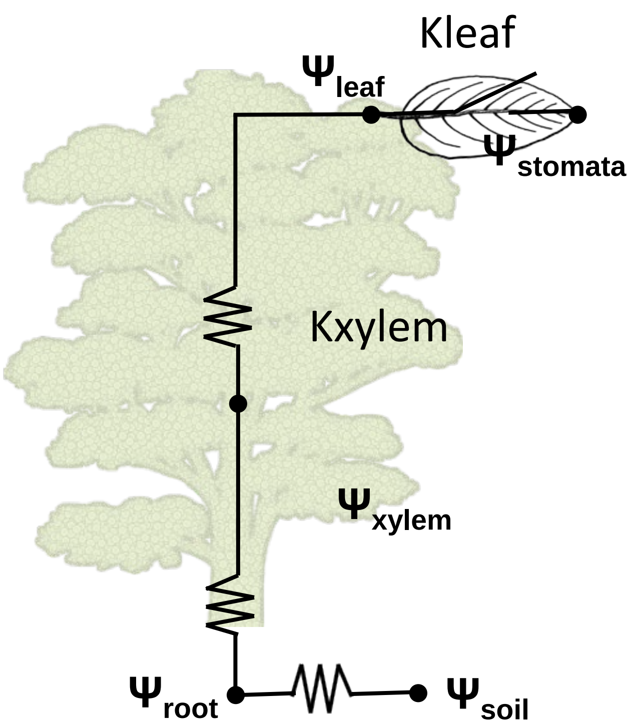


Kennedy et al. in prep
CLM implementation

Isohydric species are more sensitive to VPD and atmospheric demand

Top down stress

$\Psi_{leaf} \sim \Psi_{soil}$

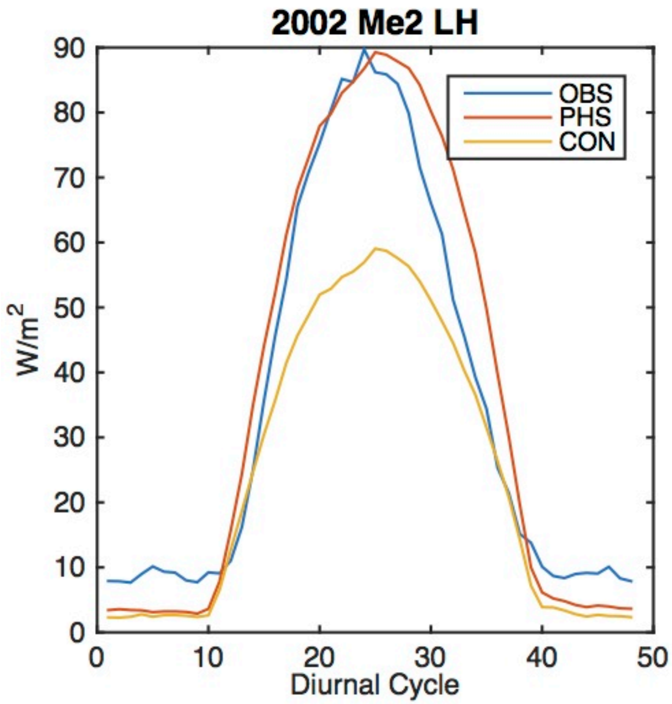


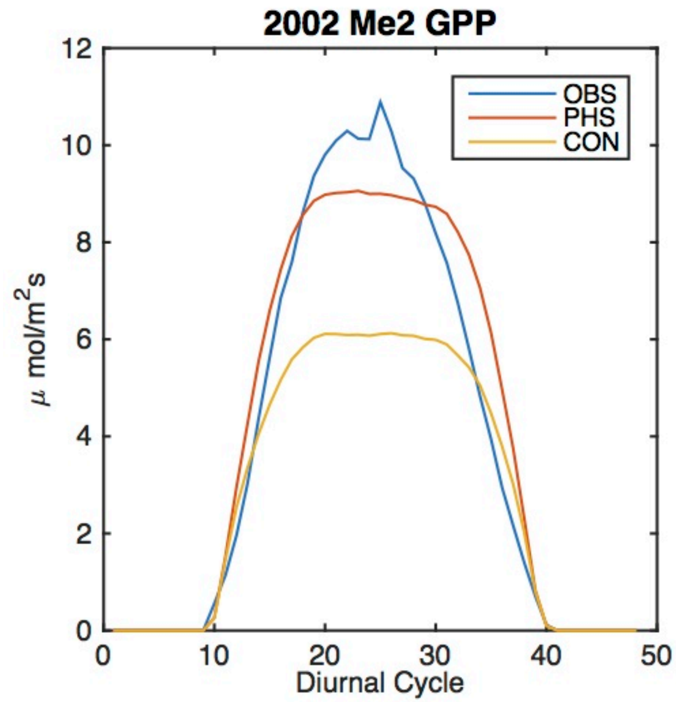
Kennedy et al. in prep
CLM implementation

Both VPD and soil moisture regulate vegetation stress and EF

Model implementation

More resilient ecosystems



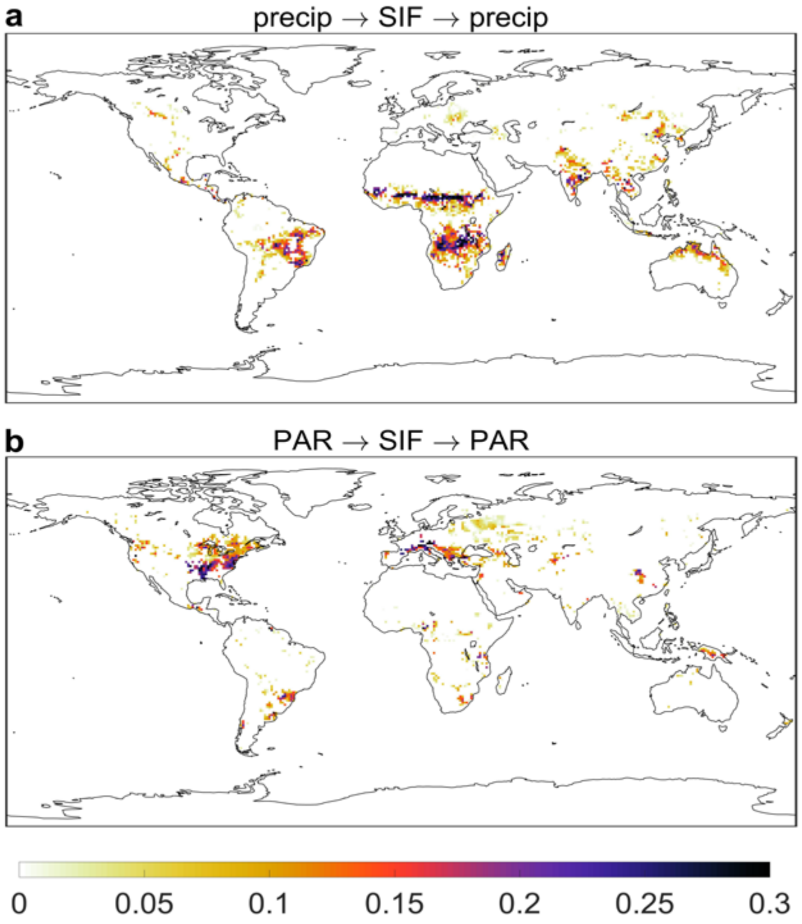


Kennedy et al. in prep
CLM implementation

In this example: can still perform photosynthesis under water stress
Down potential gradient flow, instead of bulk average in root zone

Causal biosphere-atmosphere feedbacks

- Feedback strength

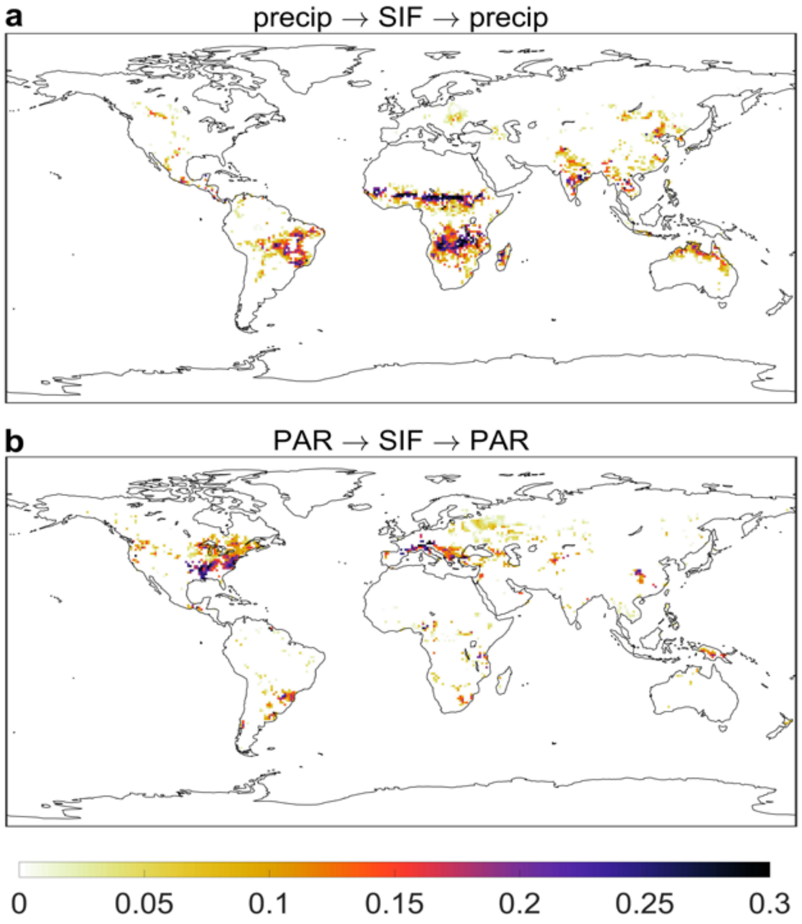


Fraction of Variance explained

Green, Gentine et al. in revision

Causal biosphere-atmosphere feedbacks

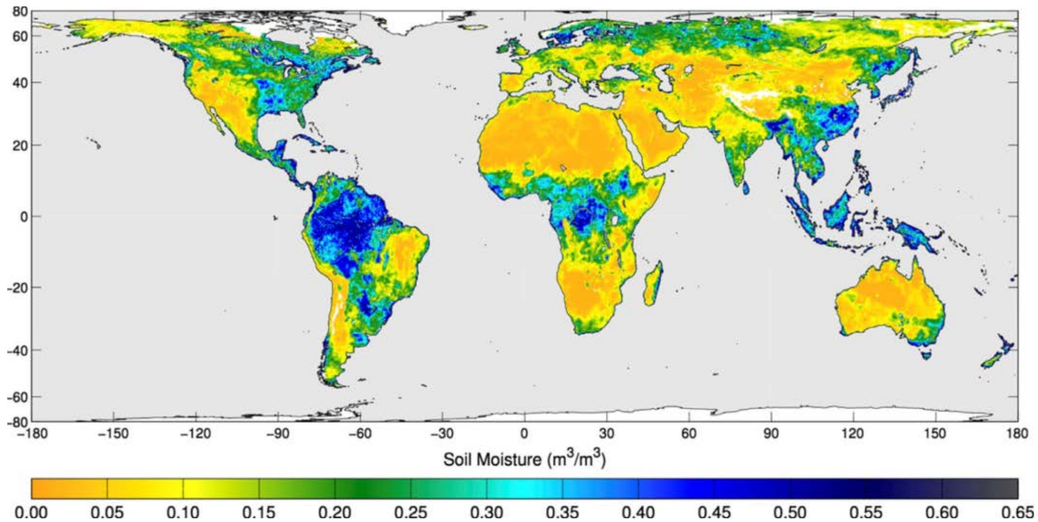
- Feedback strength: comparison with models



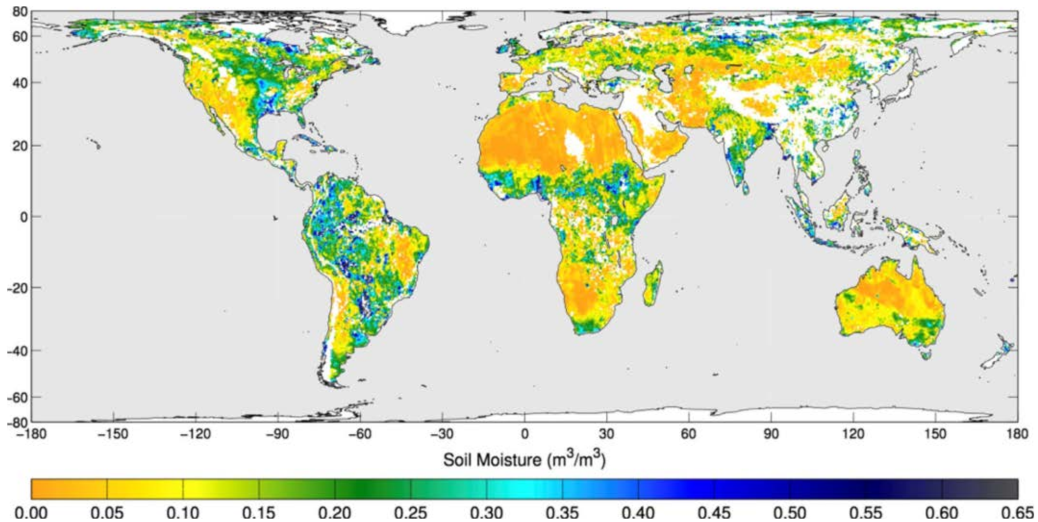
Fraction of Variance explained

Green, Gentine et al. in revision

Soil moisture: SMAP/SMOS



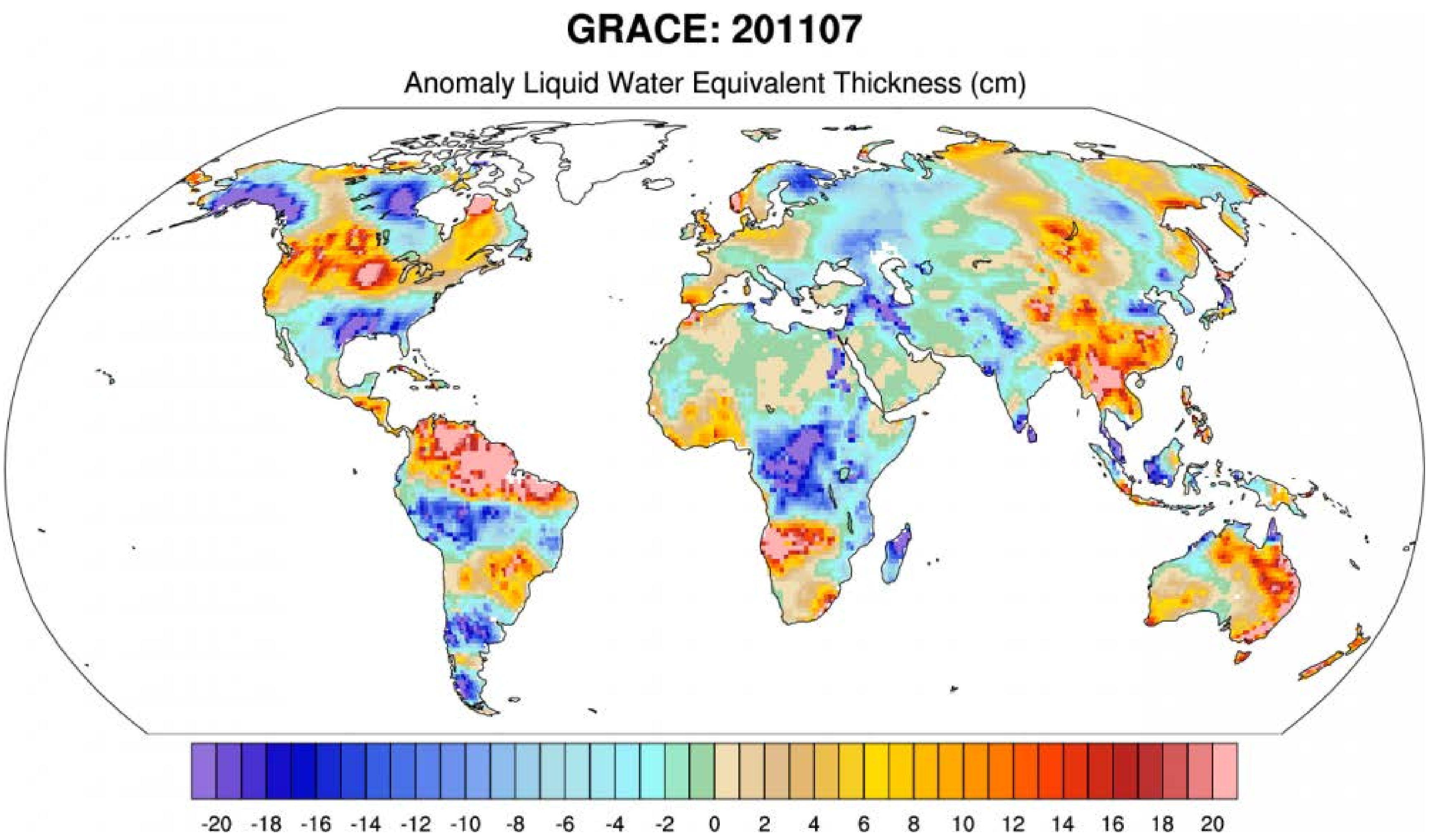
(a) SMAP Level 2 soil moisture between June 1–7, 2015 (version T11880)



(b) SMOS Level 3 soil moisture between June 1–7, 2015 (version 300)

SMOS and SMAP (better): but too short to look at trends

Total water: GRACE



Coarse but long term so can be used to understand trends