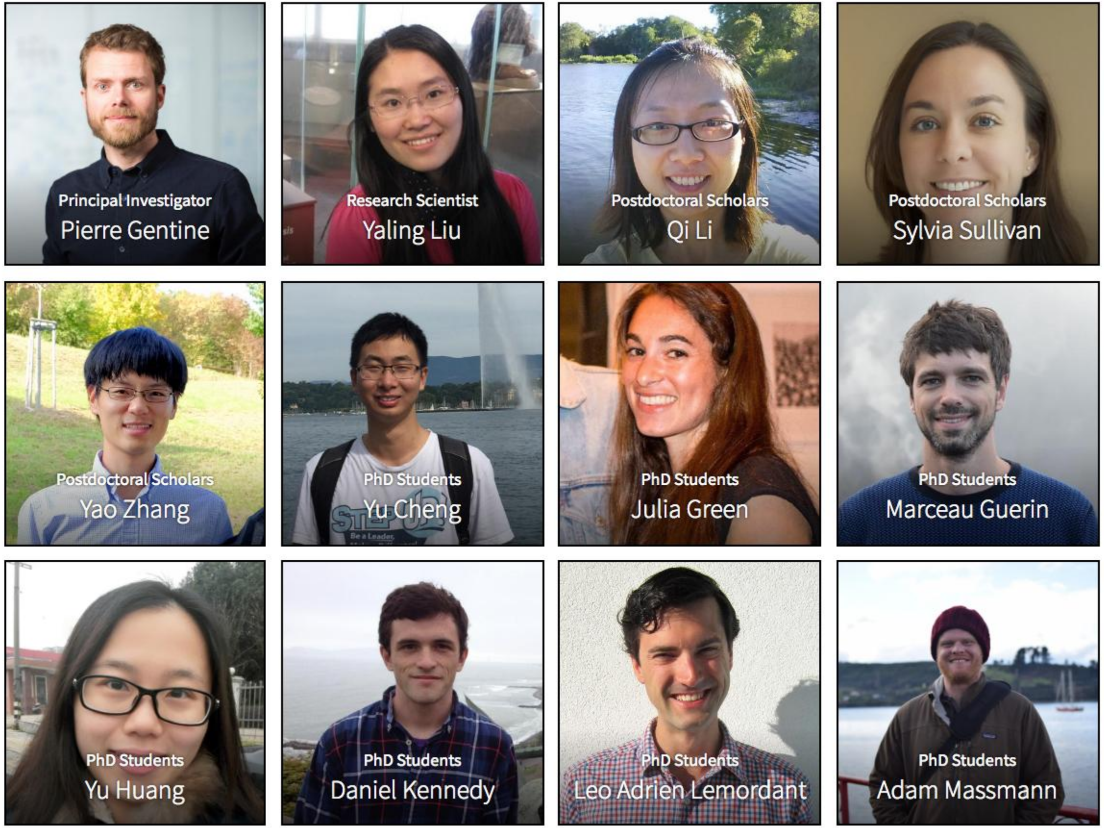
Implementing plant hydraulics in the NCAR Community Land Model (CLM)

and the implications for drought vulnerability

Daniel Kennedy, Pierre Gentine
Columbia University
Sean Swenson, Keith Oleson, Rosie Fisher, Dave Lawrence, and the LMWG

COLUMBIA | ENGINEERING
Gentine Lab

"Investigating the terrestrial carbon and water cycles using multiscale modeling and observations"



Community Land Model (CLM)

Motivation:

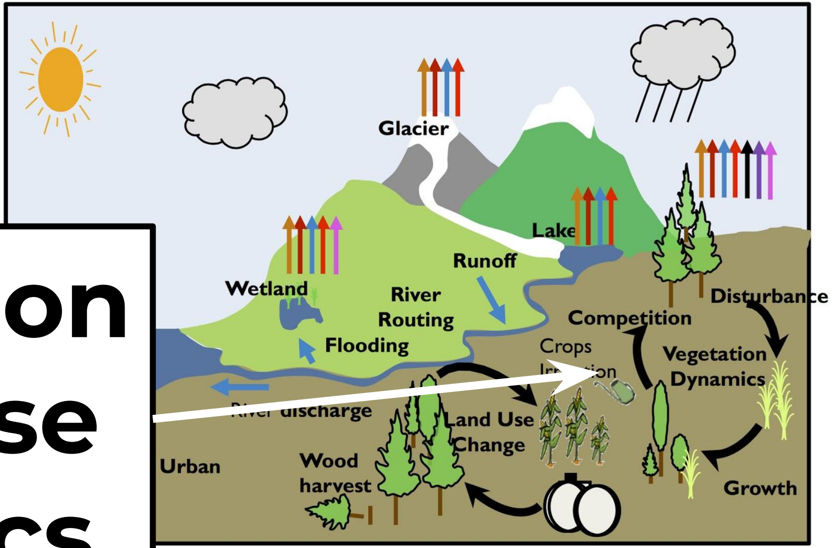
Land is the critical

interface through which

humar

to, anc

enviro



Vegetation water use dynamics

Comprehensive representations of land biogeophysics, hydrology, plant physiology, biogeochemistry, anthropogenic land use, and ecosystem dynamics

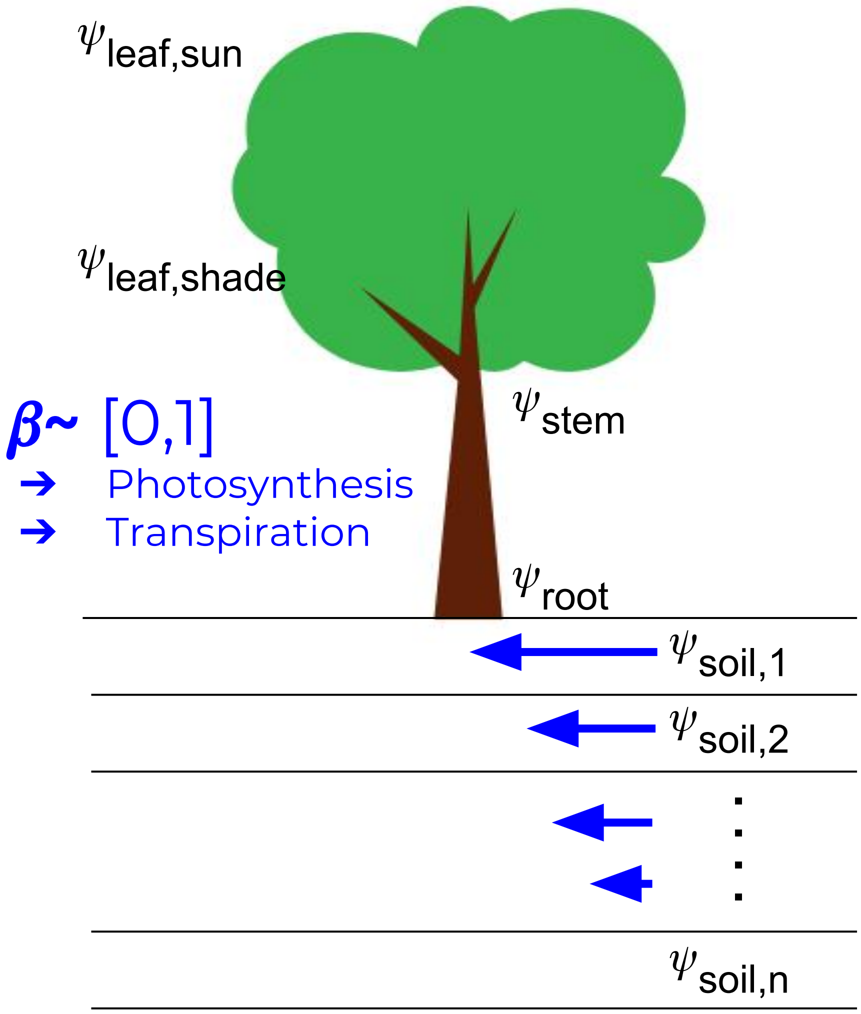
slide courtesy: Dave Lawrence

Plant Hydraulic Stress

- vegetation water use dynamics derived from prognostic vegetation water potential
- CLM5 default

1. water stress (β)
   - function of leaf water potential

2. root water uptake
   - utilizes Darcy's Law approximation
   - gradient based on root water potential
     - $q = -k\ (\psi_{root} - \psi_{soil})$



tree from vecteezy.com

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1. water stress (β)
   - function of leaf water potential
2. root water uptake
   - utilizes Darcy's Law approximation
   - gradient based on root water potential
     - q = -k (ψ_{root} - ψ_{soil})

Soil Moisture Stress

- vegetation water use dynamics parameterized directly with soil potential
- CLM4.5 default

1. water stress (β)
   - function of soil water potential
2. root water uptake
   - partitioning heuristic
   - gradient based on constant parameter
     - q = -k (ψ_c - ψ_{soil})

ψ_c = soil water potential with stomates fully closed

- varies by PFT
- typically around -2.5 MPa

Plant Hydraulic Stress

- vegetation water use dynamics derived from prognostic vegetation water potential
- CLM5 default

Soil Moisture Stress

- vegetation water use dynamics parameterized directly with soil potential
- CLM4.5 default

AGU100 ADVANCING EARTH AND SPACE SCIENCE

JAMES | Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE
10.1029/2018MS001500

Special Section:
Community Earth System Model version 2 (CESM2) Special Collection

Implementing Plant Hydraulics in the Community Land Model, Version 5

Daniel Kennedy[1], Sean Swenson[2], Keith W. Oleson[2], David M. Lawrence[2], Rosie Fisher[2], Antonio Carlos Lola da Costa[3], and Pierre Gentine[1]

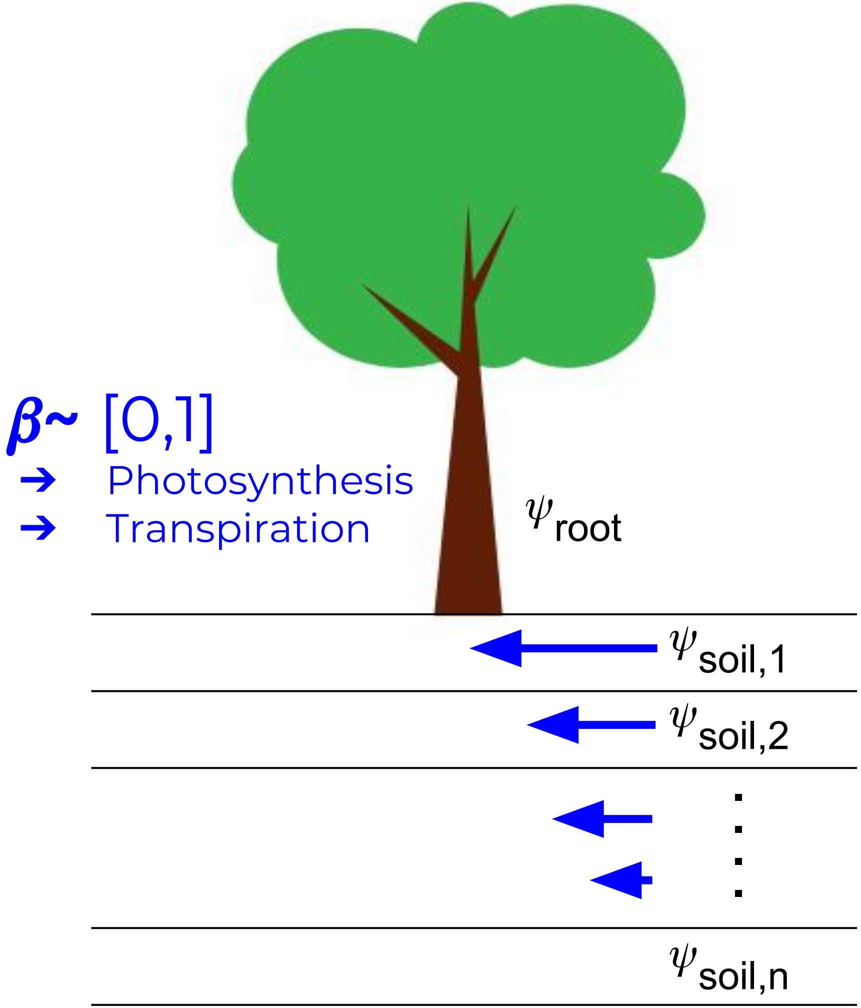
[1]Columbia University, New York, NY, USA, [2]National Center for Atmospheric Research, Boulder, CO, USA, [3]Centro de

Features output from a point simulation in Caxiuana, Brazil

Plant Hydraulic Stress

- vegetation water use dynamics derived from prognostic vegetation water potential
- CLM5 default

➔ Features compensatory root water uptake
  - prefers to use water near the surface, but has the flexibility to look deeper



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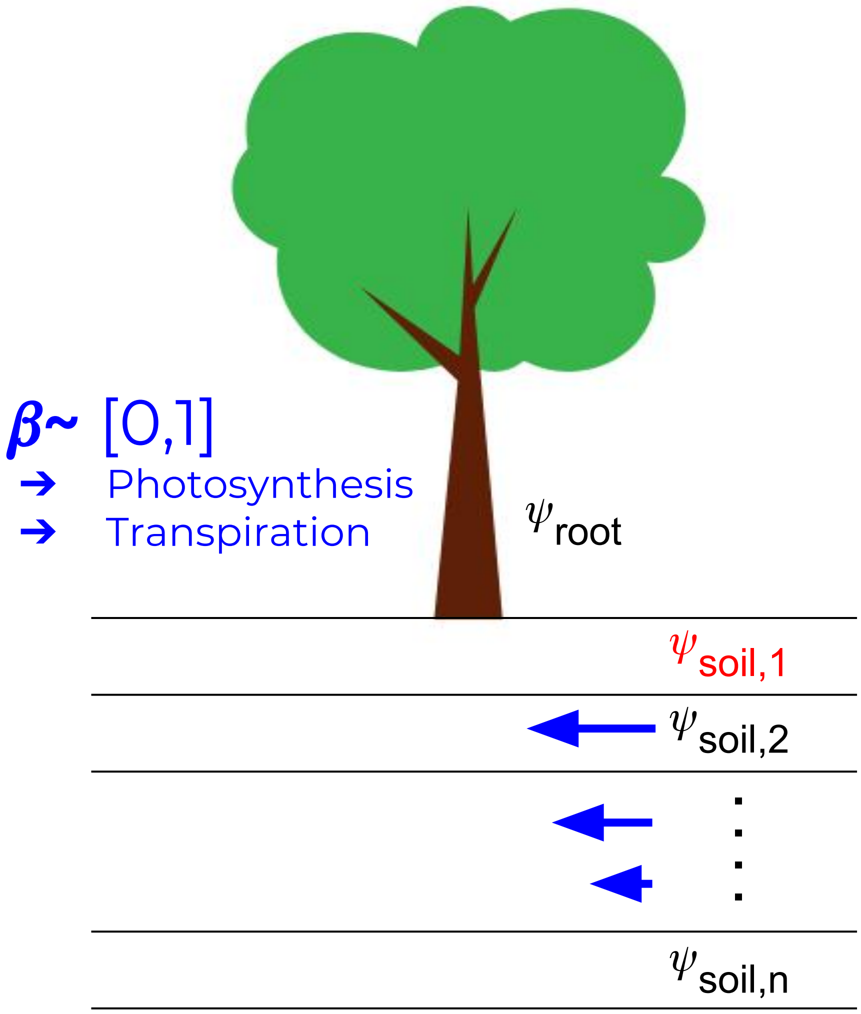

Plant Hydraulic Stress

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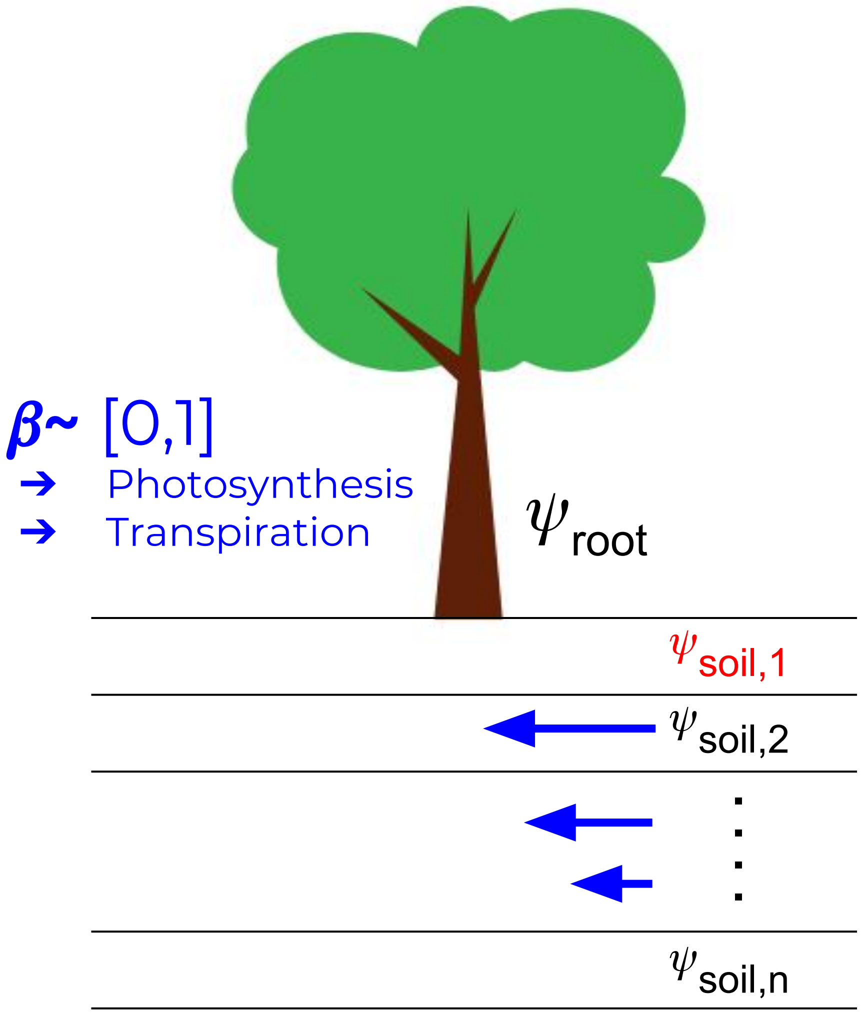

Plant Hydraulic Stress

- vegetation water use dynamics derived from prognostic vegetation water potential
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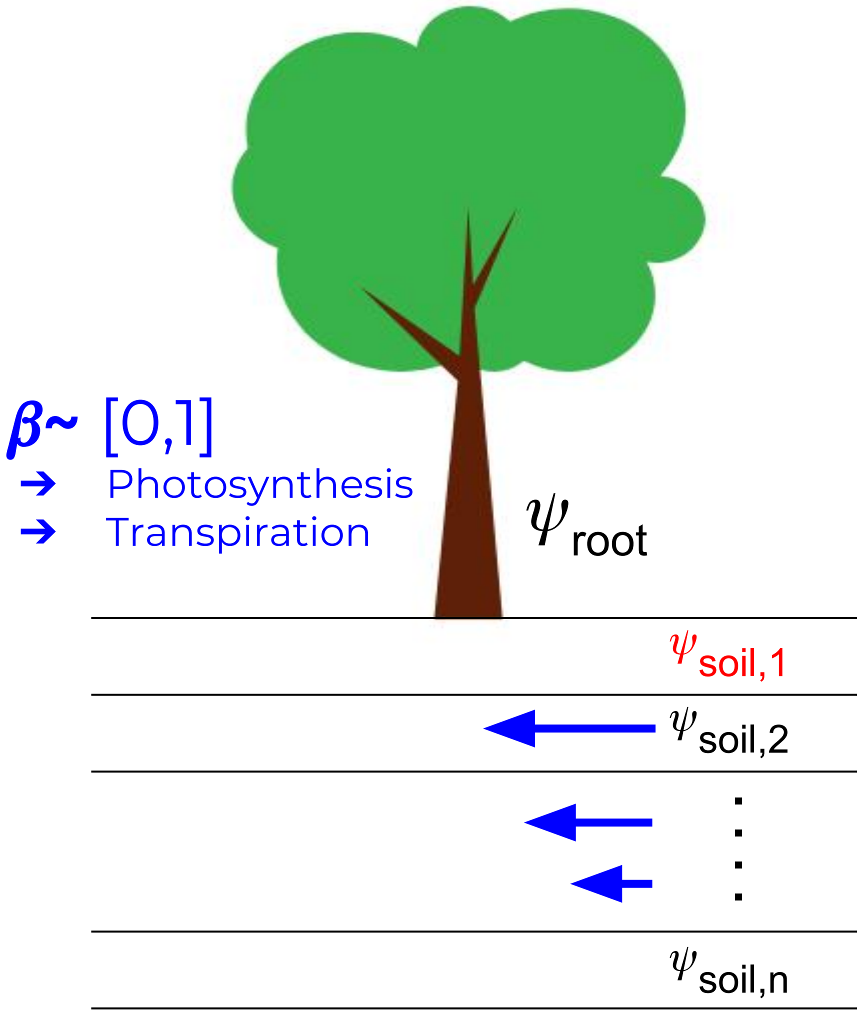
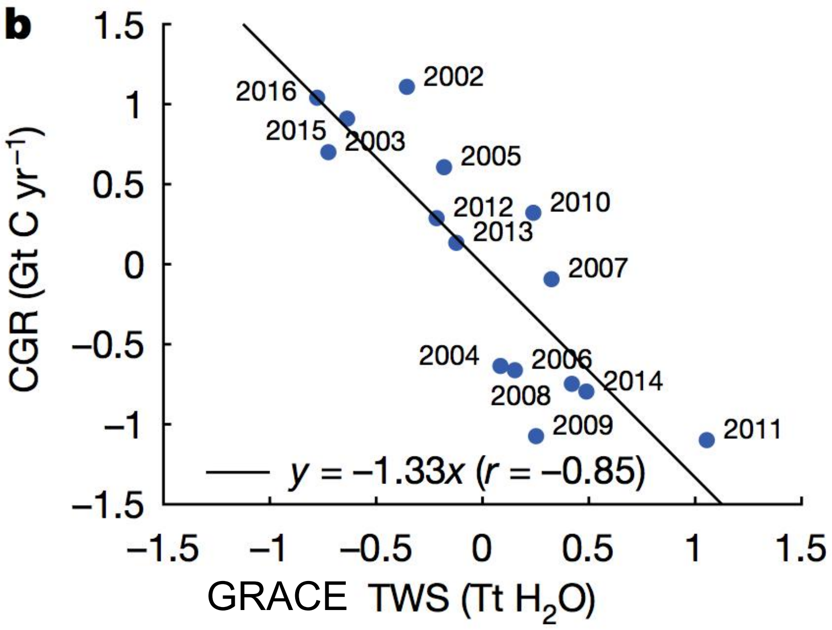
→ Features compensatory root water uptake
  - ◆ prefers to use water near the surface, but has the flexibility to look deeper

How will this influence the model?



tree from vecteezy.com

How will PHS root water uptake affect the global carbon cycle?



Humphrey et al. 2018

Interannual variability in the atmospheric carbon growth rate has been linked to total water storage

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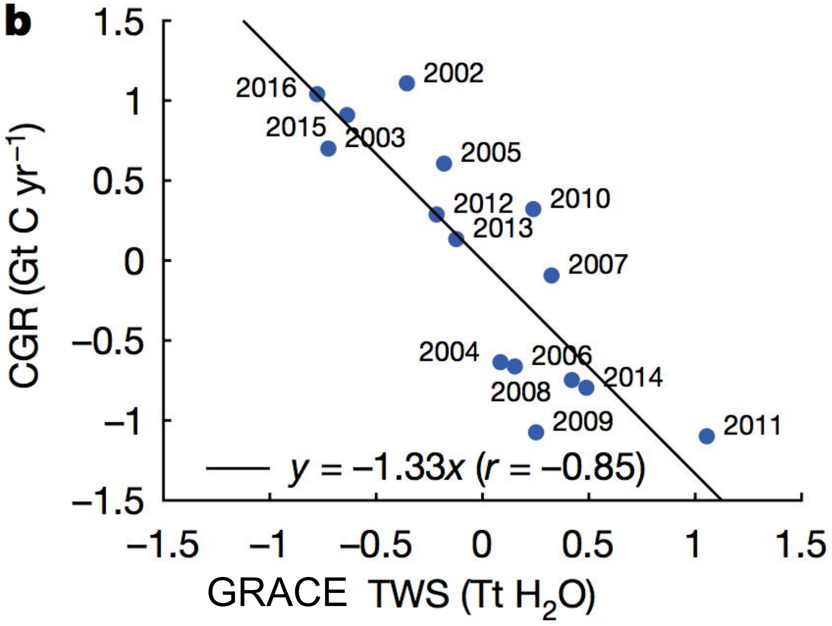


Humphrey et al. 2018

Interannual variability in the atmospheric carbon growth rate has been linked to total water storage…

but this relationship is not well-represented in TRENDYv3

How will PHS root water uptake affect the vertical distribution of soil water?

CMIP5 Simulations project stronger drying trends in the top 10cm of the soil column

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL071921

Divergent surface and total soil moisture projections under global warming

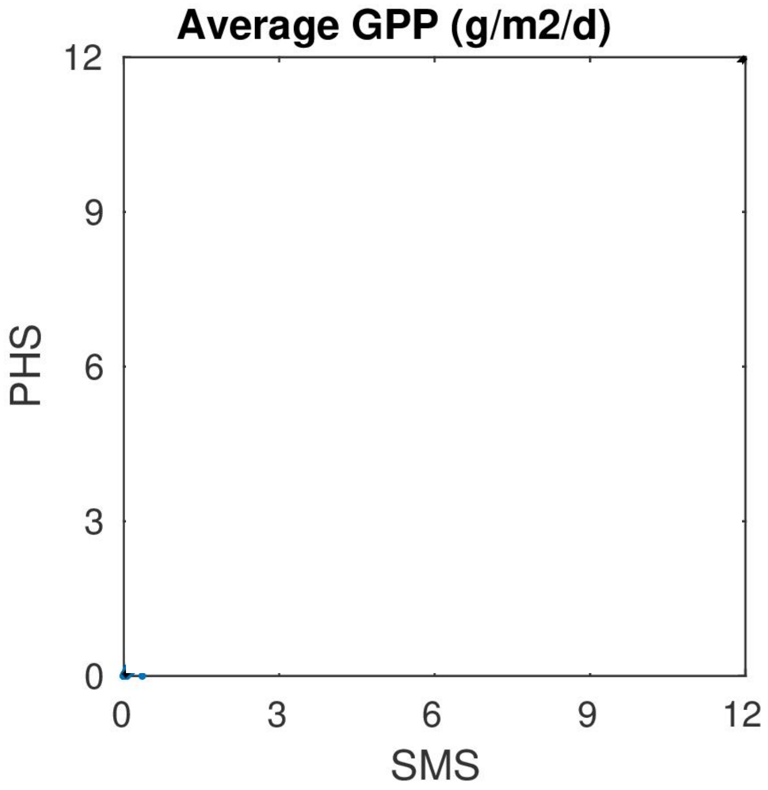
Alexis Berg[1], **Justin Sheffield**[1,2], **and P. C. D. Milly**[3]

[1]Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey, USA, [2]Geography and Environment, University of Southampton, Southampton, UK, [3]U.S. Geological Survey, and NOAA/Geophysical Fluid

Key Points:

- We identify a robust vertical gradient of projected soil moisture changes under global warming with more negative changes near the surface

What are the effects of plant hydraulics globally?



Simulation details

- 2 simulations (PHS,SMS)
- CLM5 (global)
- satellite phenology
- 1850-2014
- only difference is PHS/SMS

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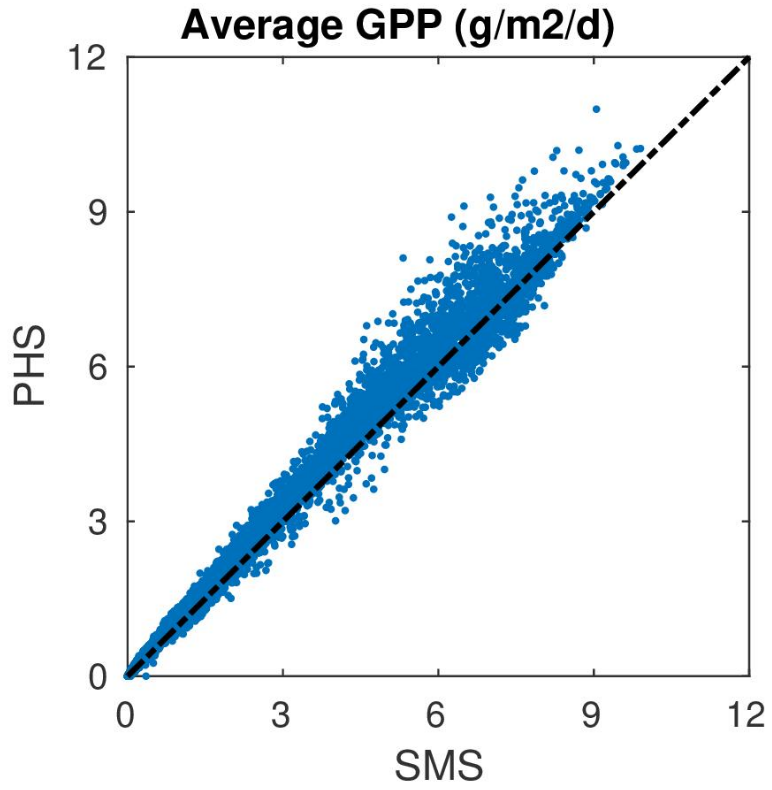


PHS features higher GPP on average

- plotting average GPP (1914-2013) for every gridcell
- Overall, GPP is ~7% higher with PHS
- Meaning that water stress is lower with PHS

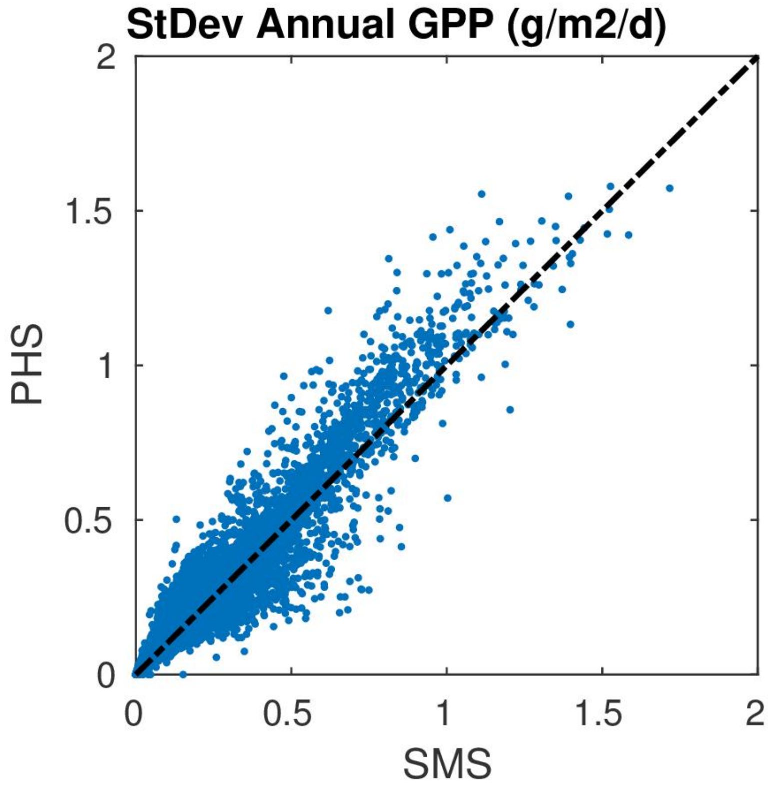
Simulation details

- 2 simulations (PHS,SMS)
- CLM5 (global)
- satellite phenology
- 1850-2014
- only difference is PHS/SMS

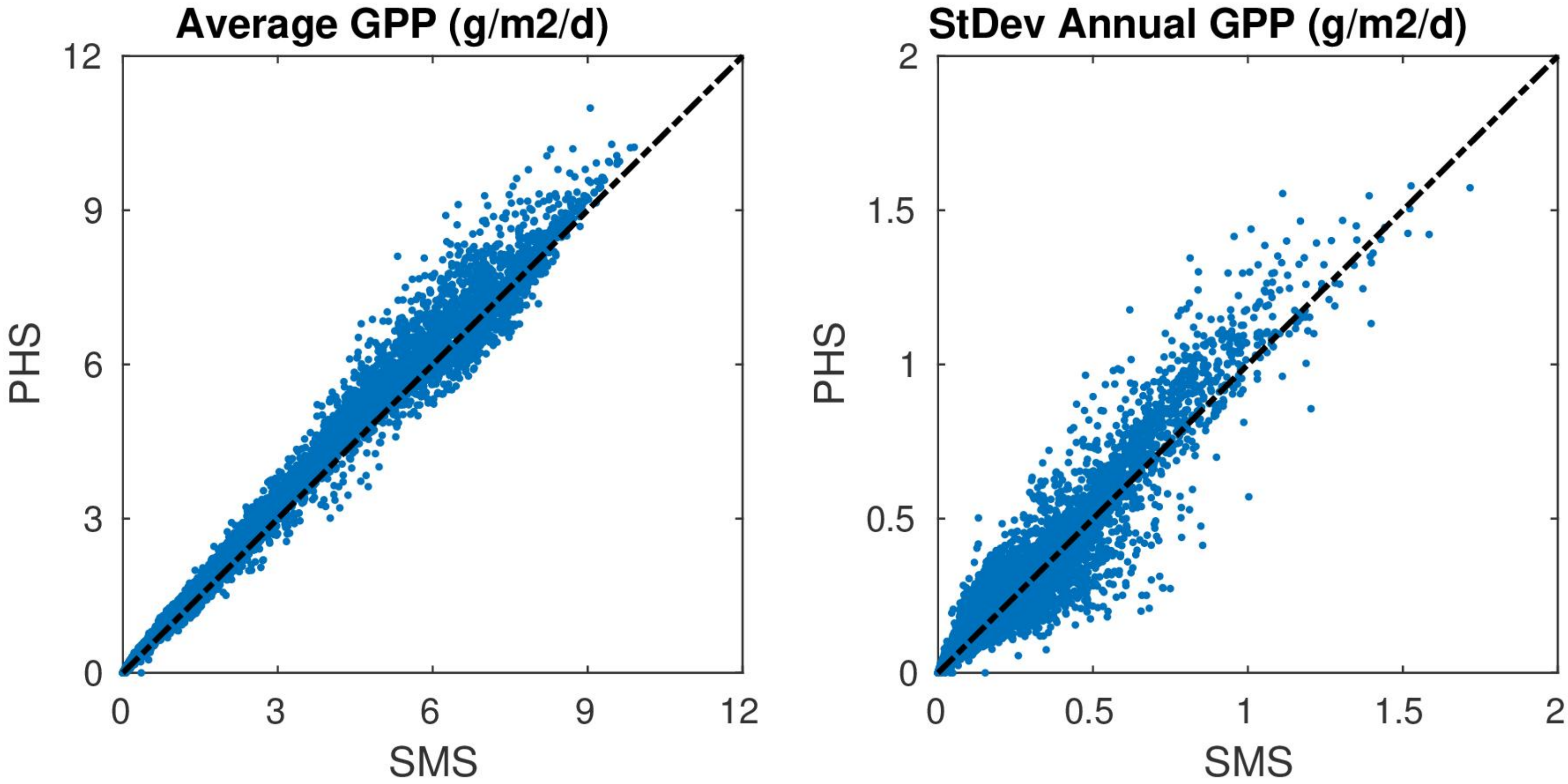
PHS also features higher GPP interannual variability

- plotting StDev of annual GPP (1914-2013) for every gridcell
- mixed bag, but overall GPP IAV increases with PHS (+7%)

What are the effects of plant hydraulics globally?



What does this mean for drought vulnerability in CLM5?



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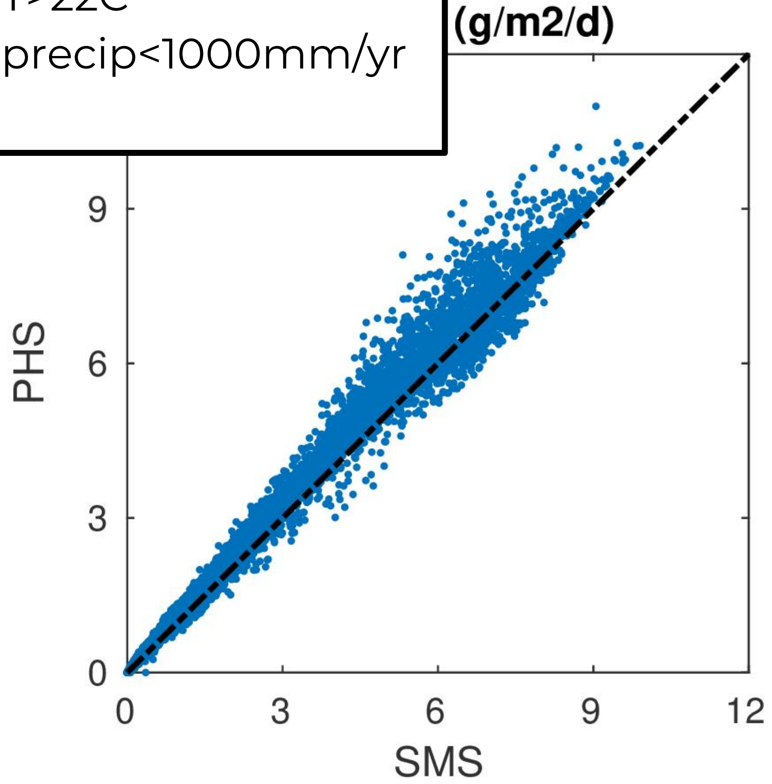
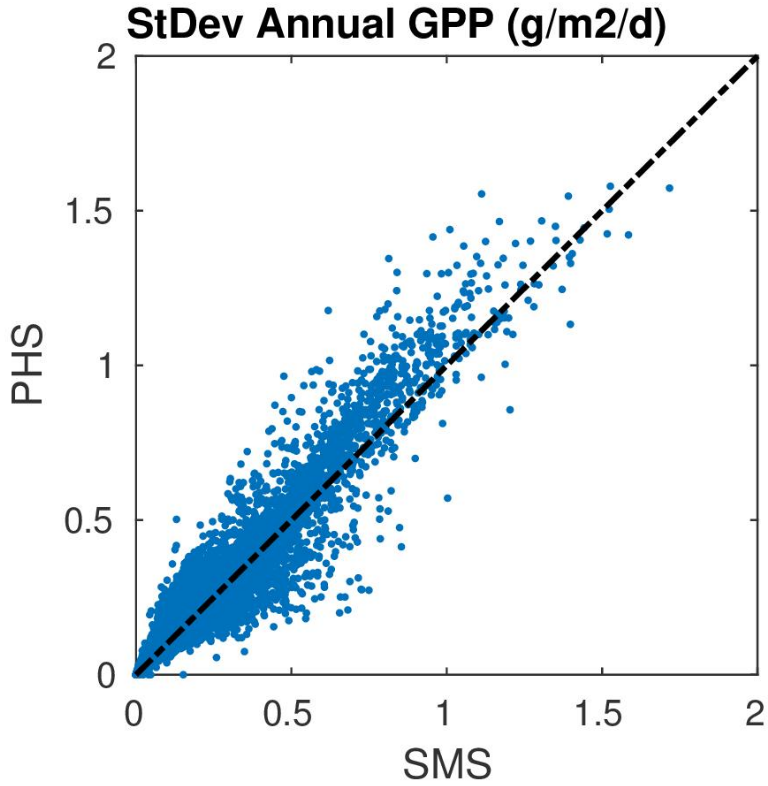
Area of interest:

- dry tropics
- T>22C
- precip<1000mm/yr





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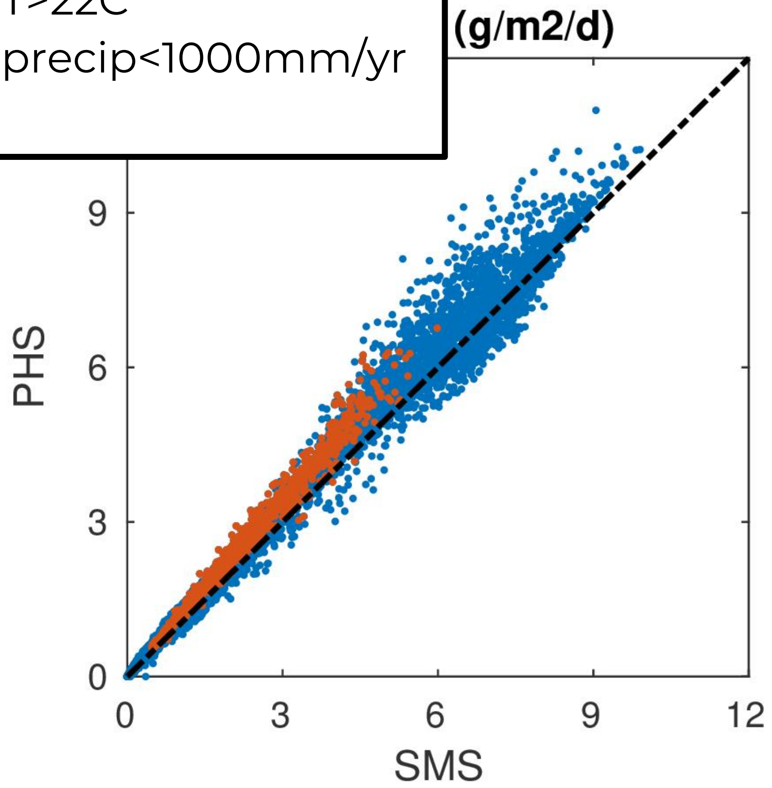

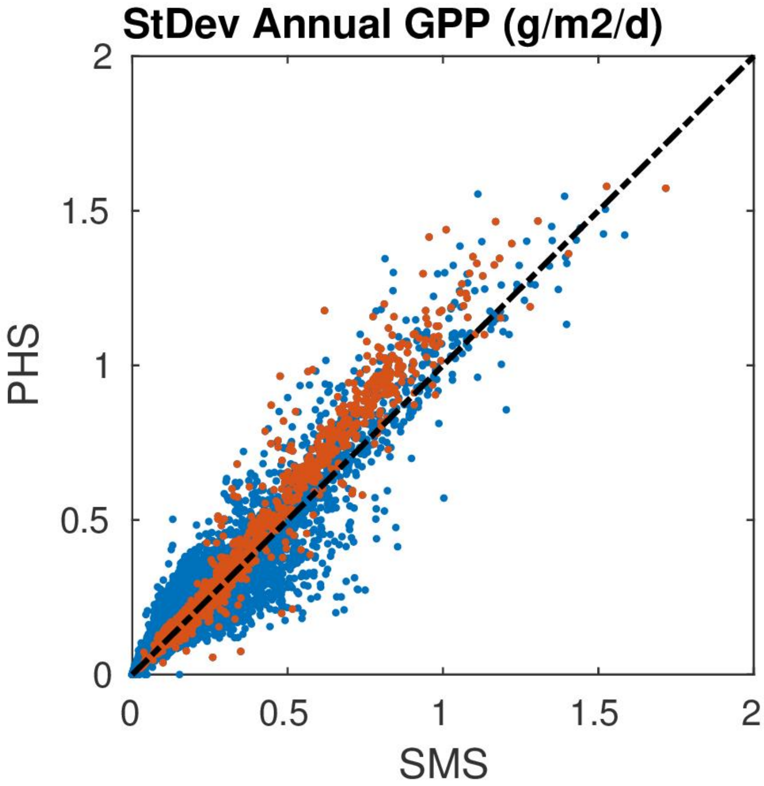

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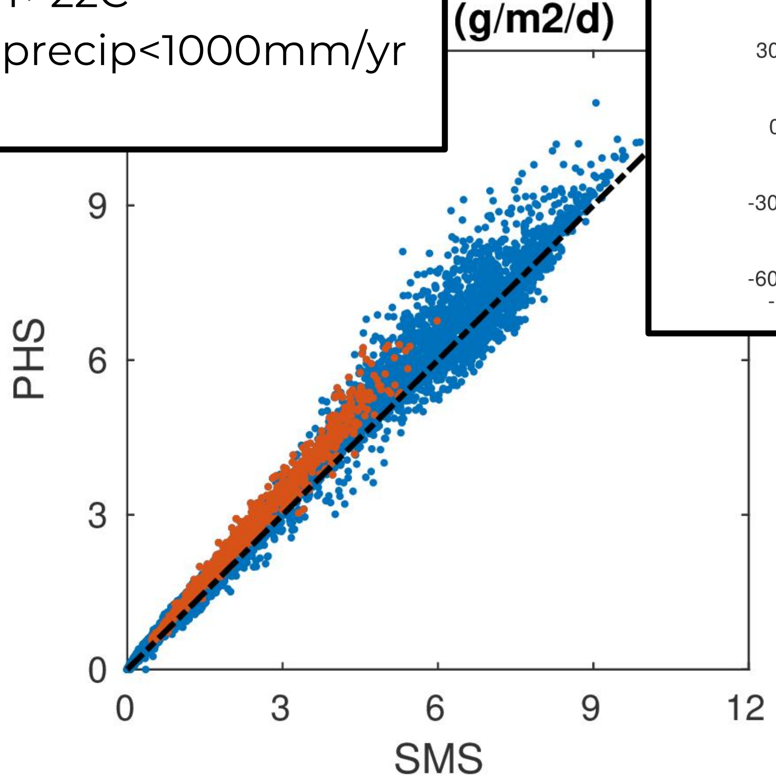
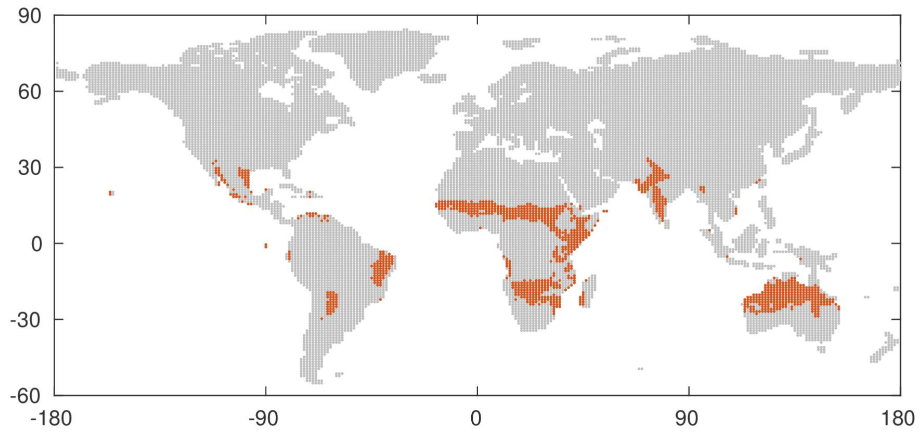
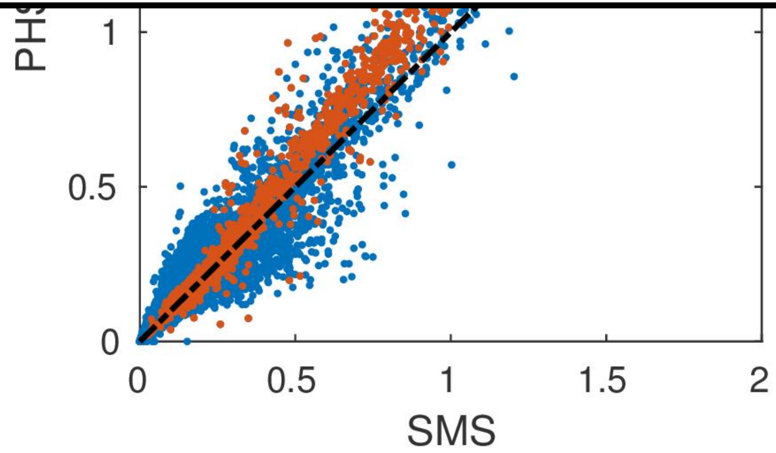
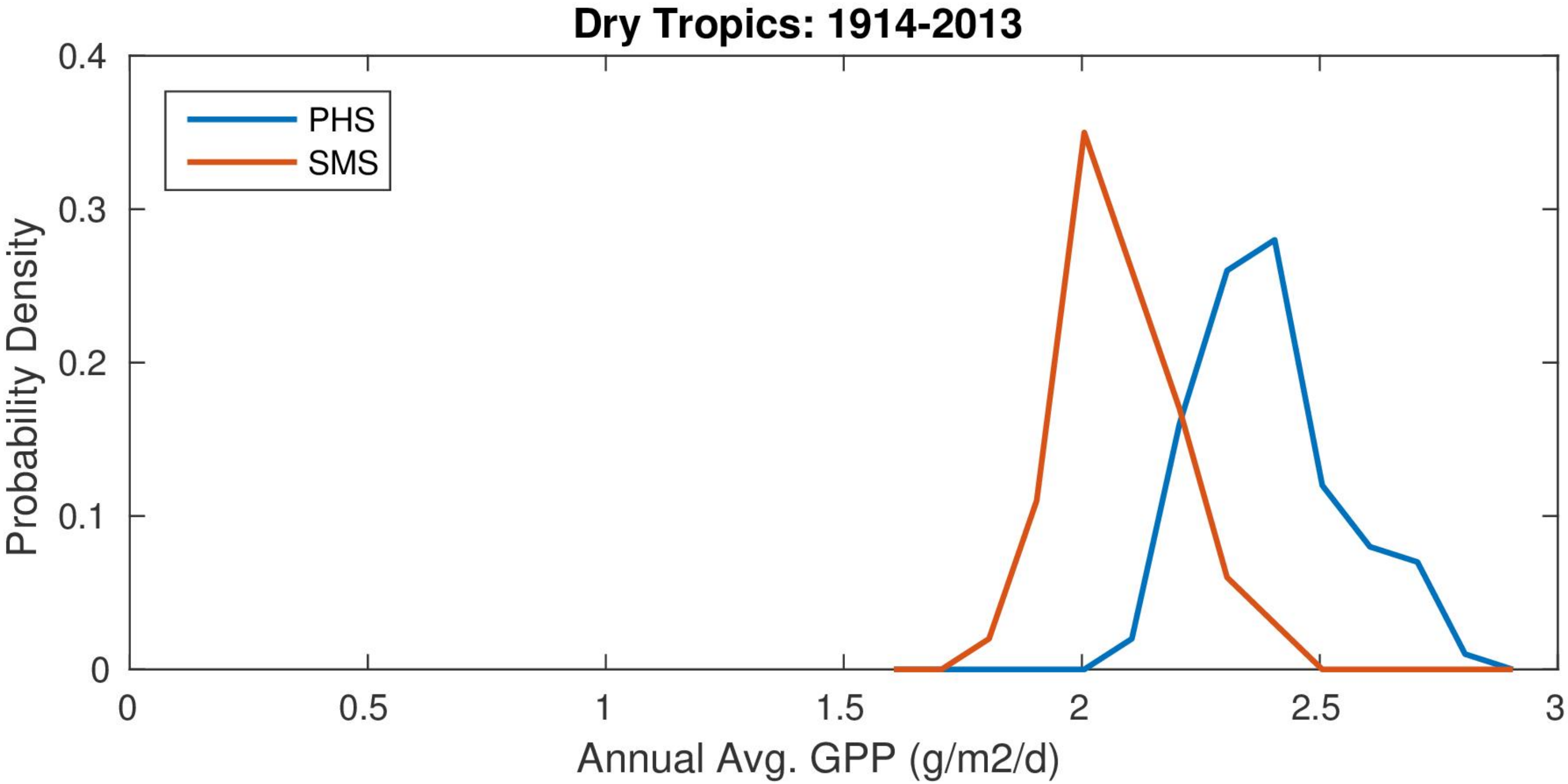






GPP distributions in aggregate



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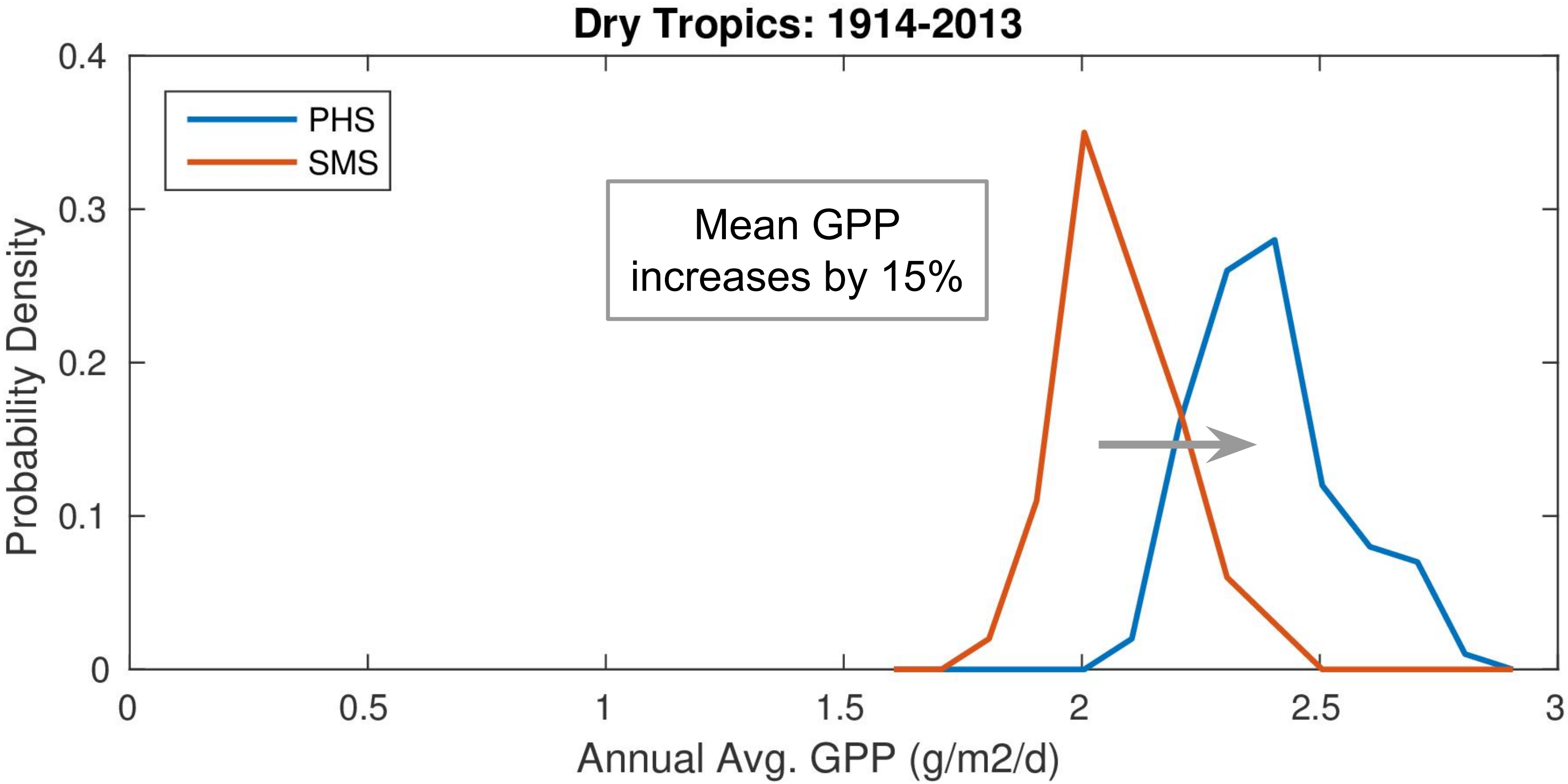

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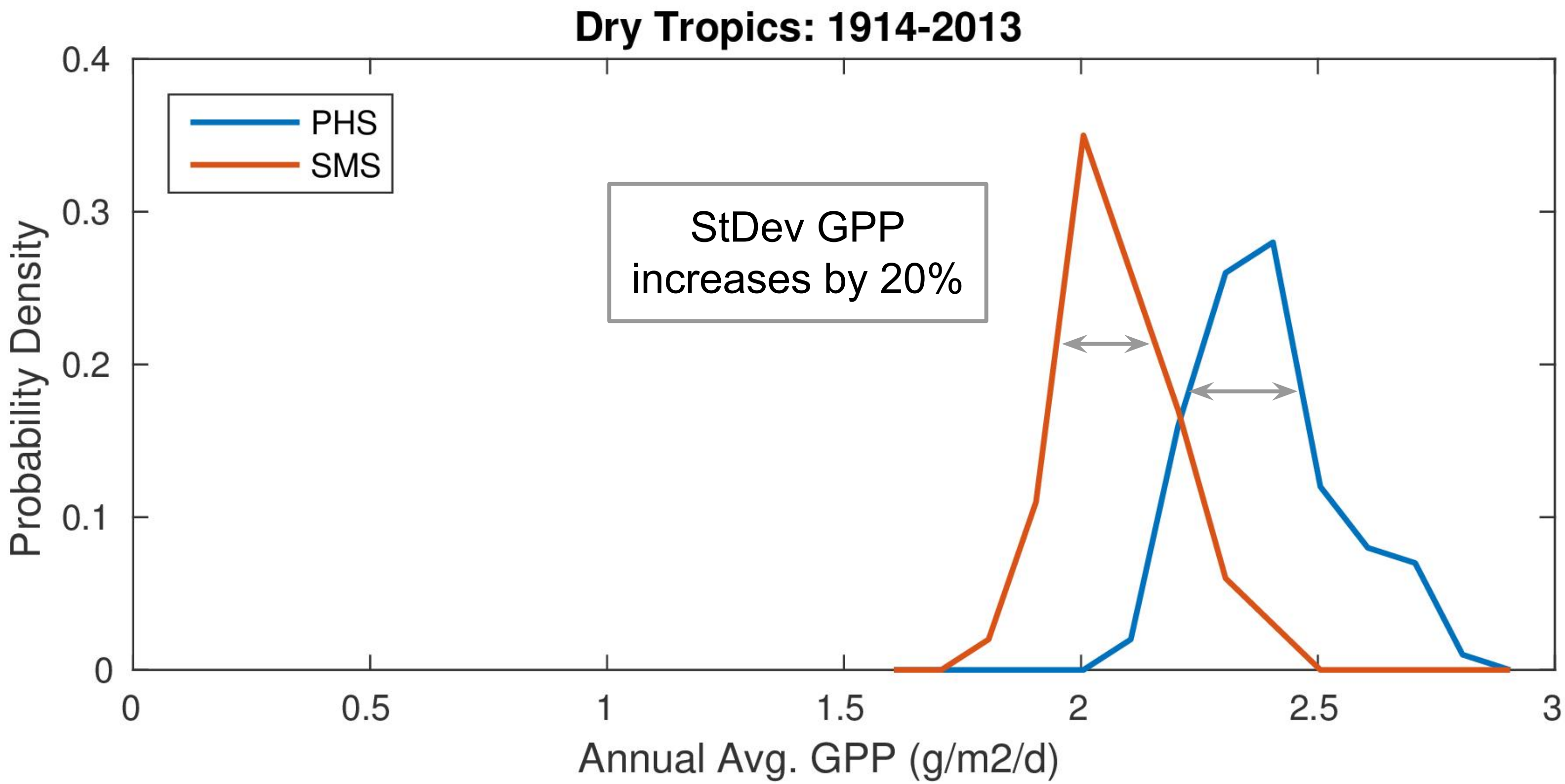

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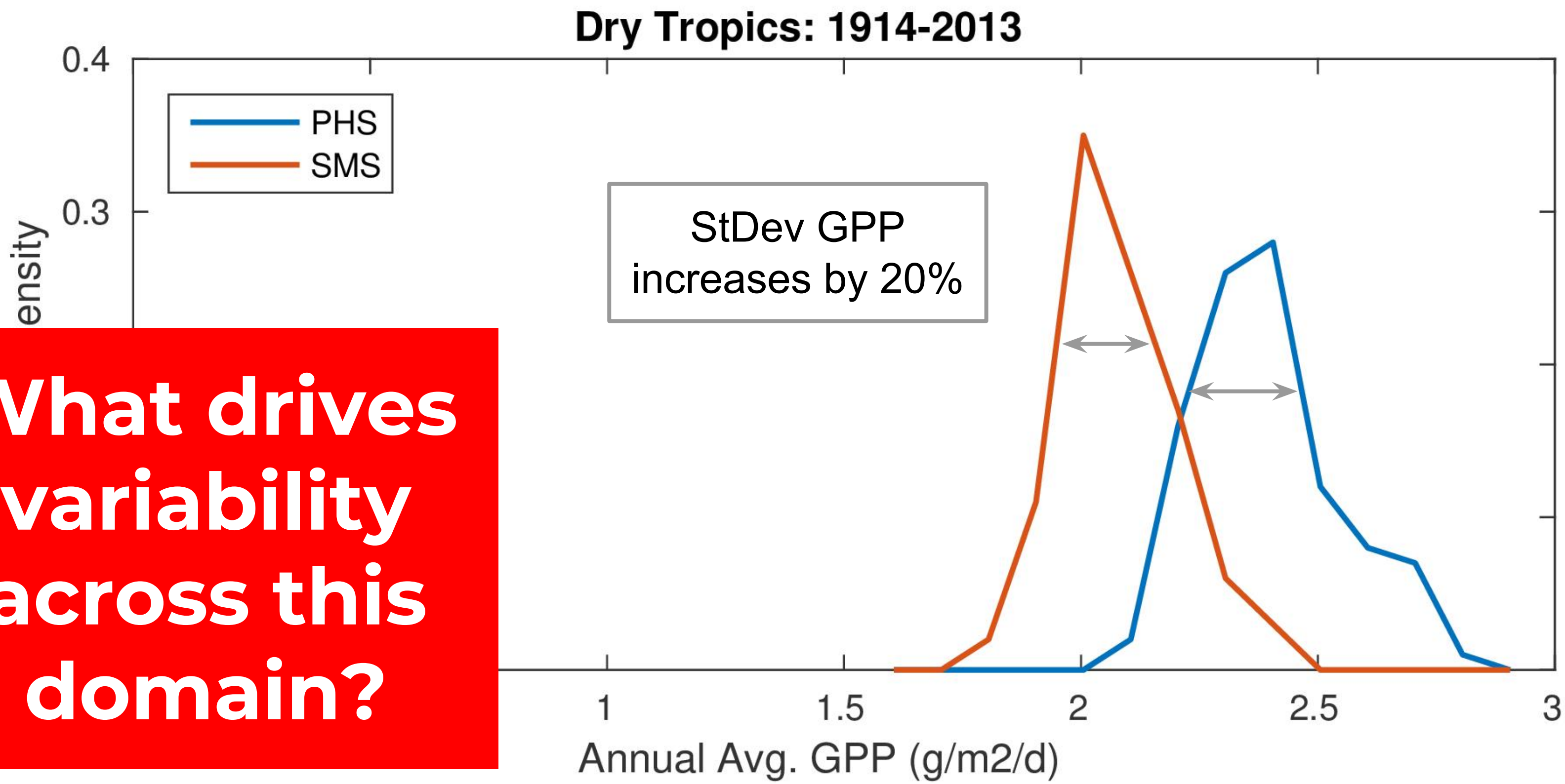
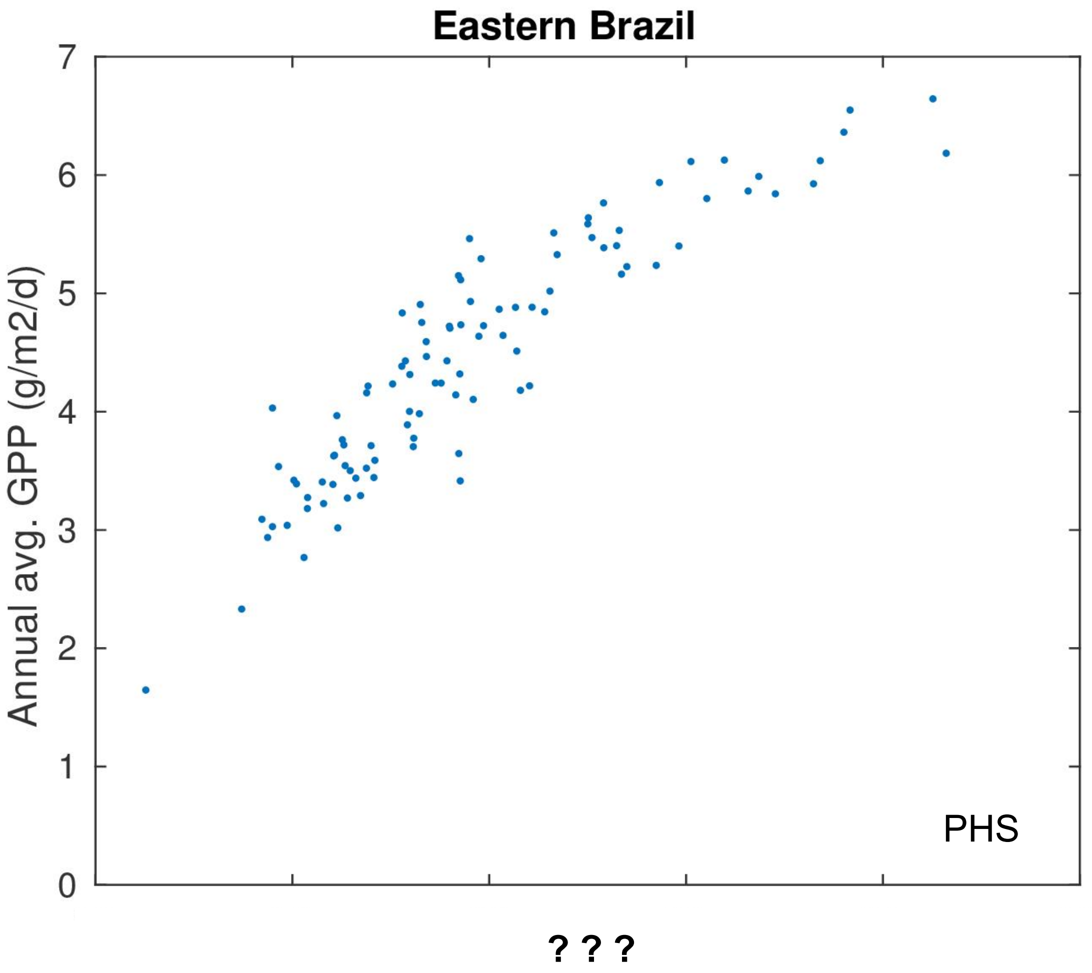
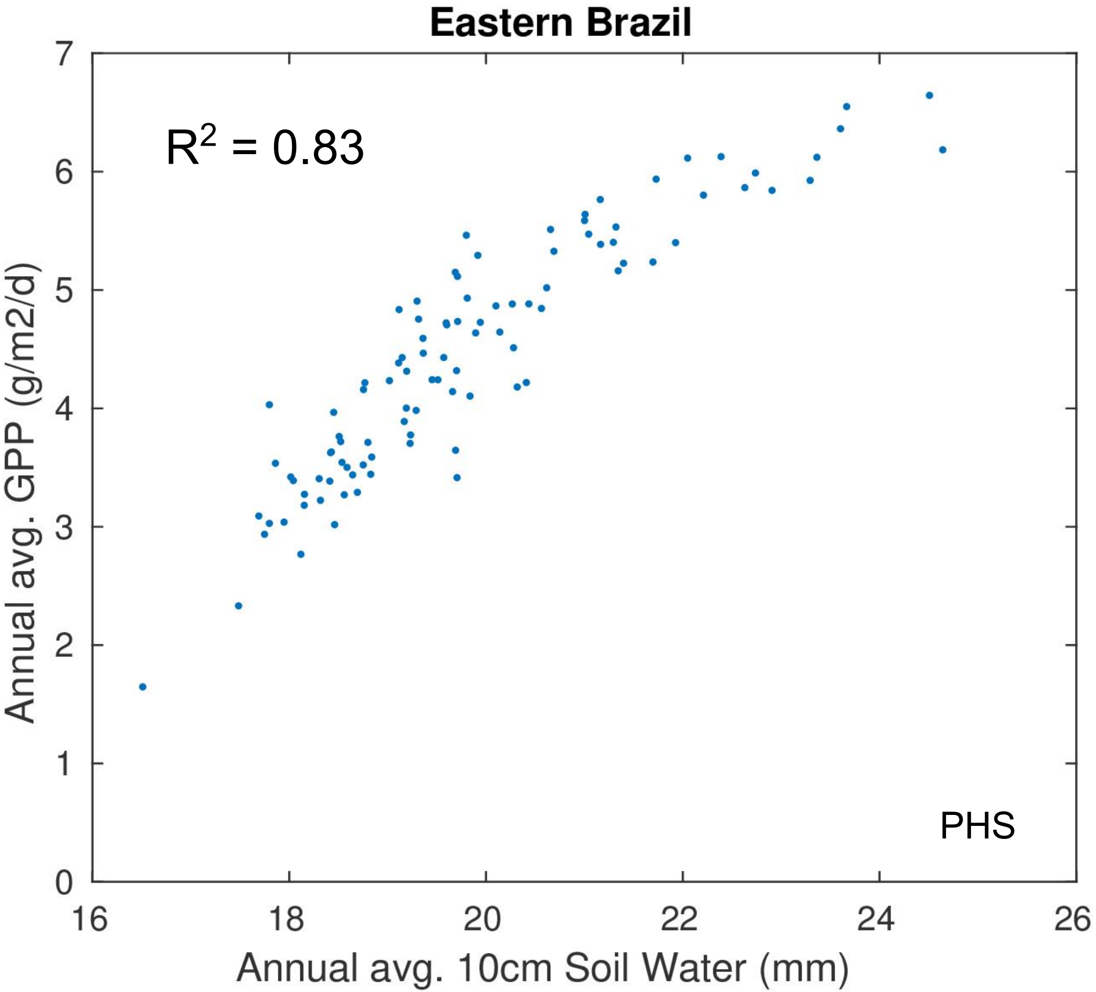


What drives variability across this domain?



What drives model interannual variability in GPP?

- example gridcell
- each point represents one year
  - 1914-2013
- σ = 1.03 g/m2/d



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~soil moisture~

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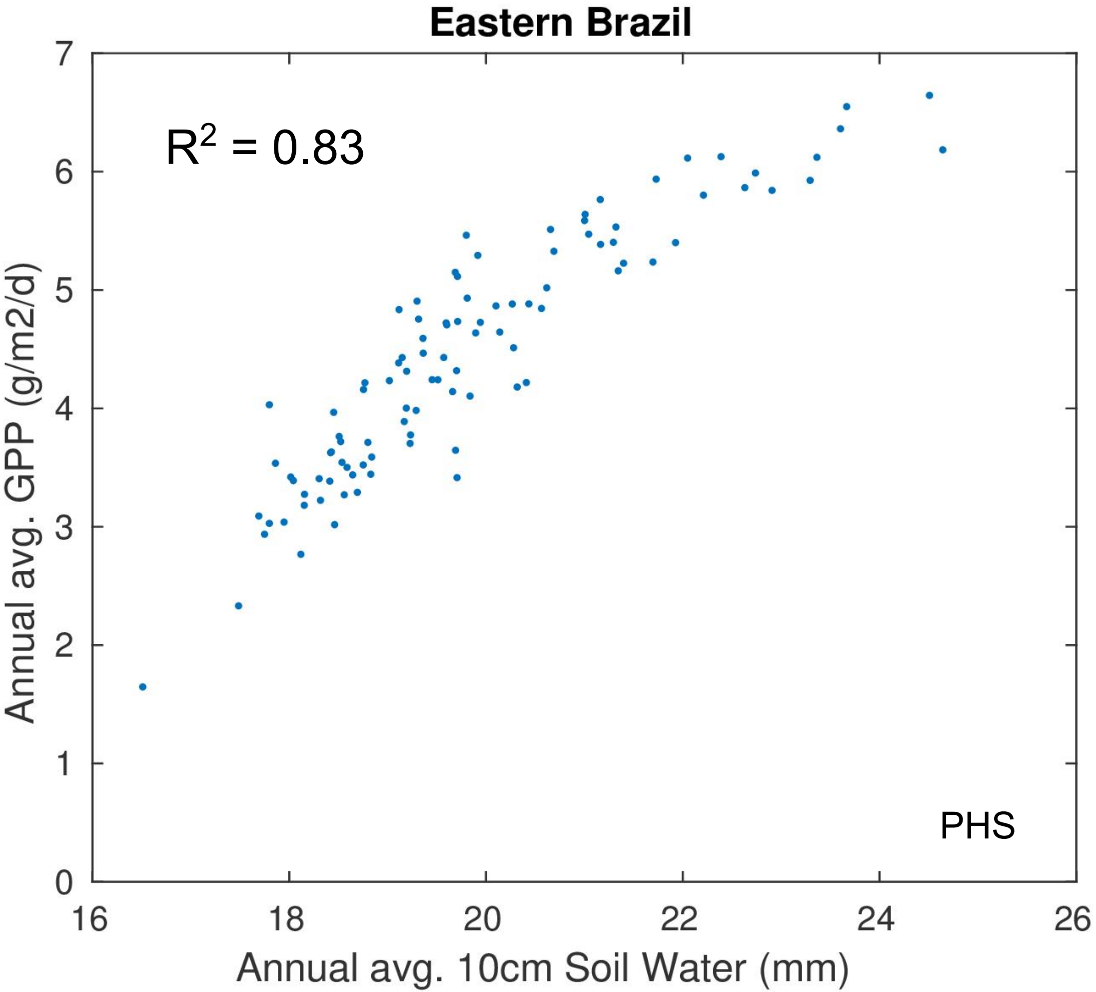


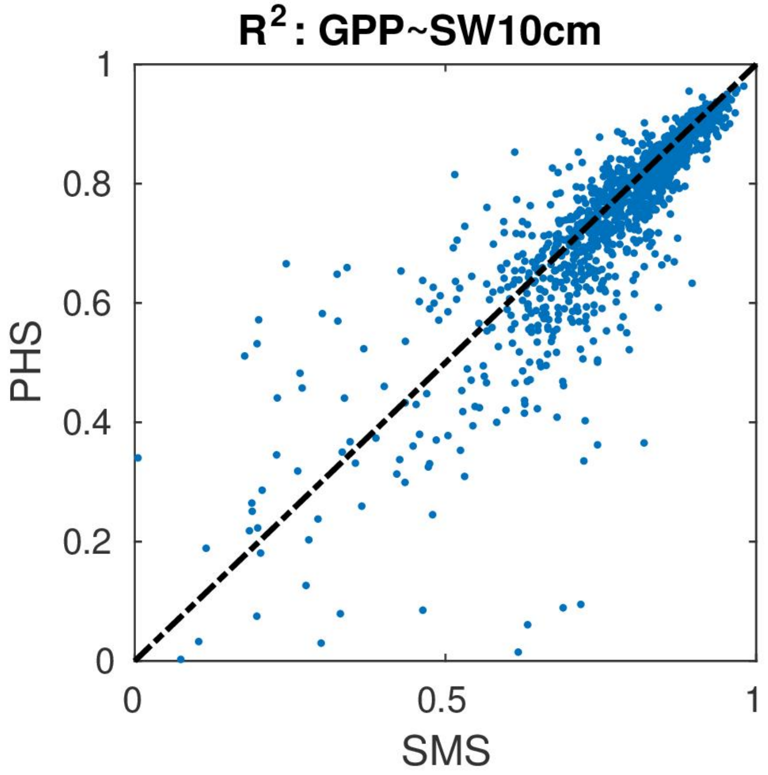
What drives model interannual variability in GPP?

~soil moisture~

- example gridcell
- each point represents one year
  - 1914-2013
- σ = 1.03 g/m2/d

- is this true across the full domain?
- with both models?

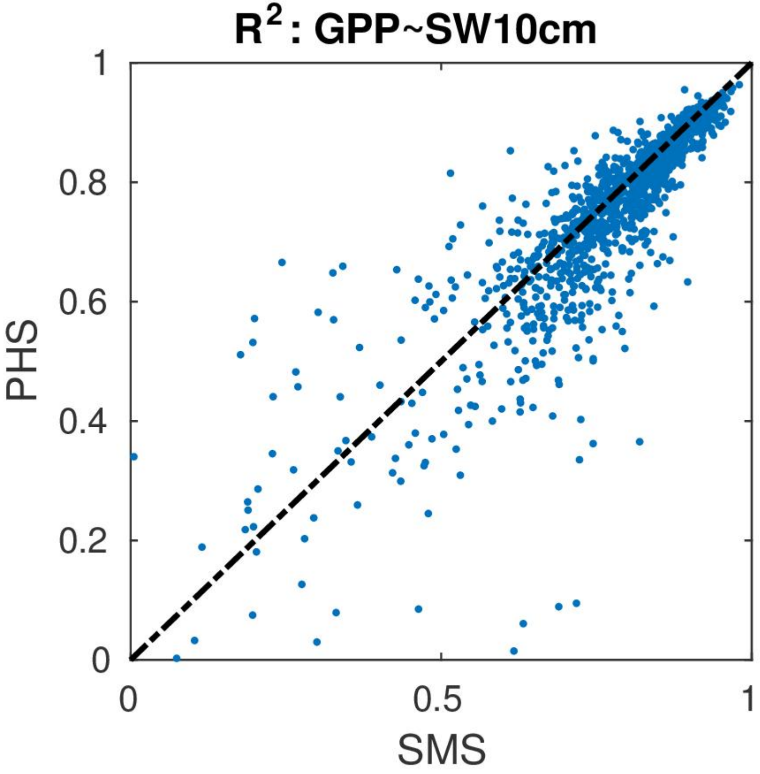
Model vs. Model across the dry tropics domain



Plot details:

- Each point is a different grid cell
- Looking at the correlation between GPP and 10cm soil water
- Computed from time-series of annual average values (1914-2013)

Model vs. Model across the dry tropics domain

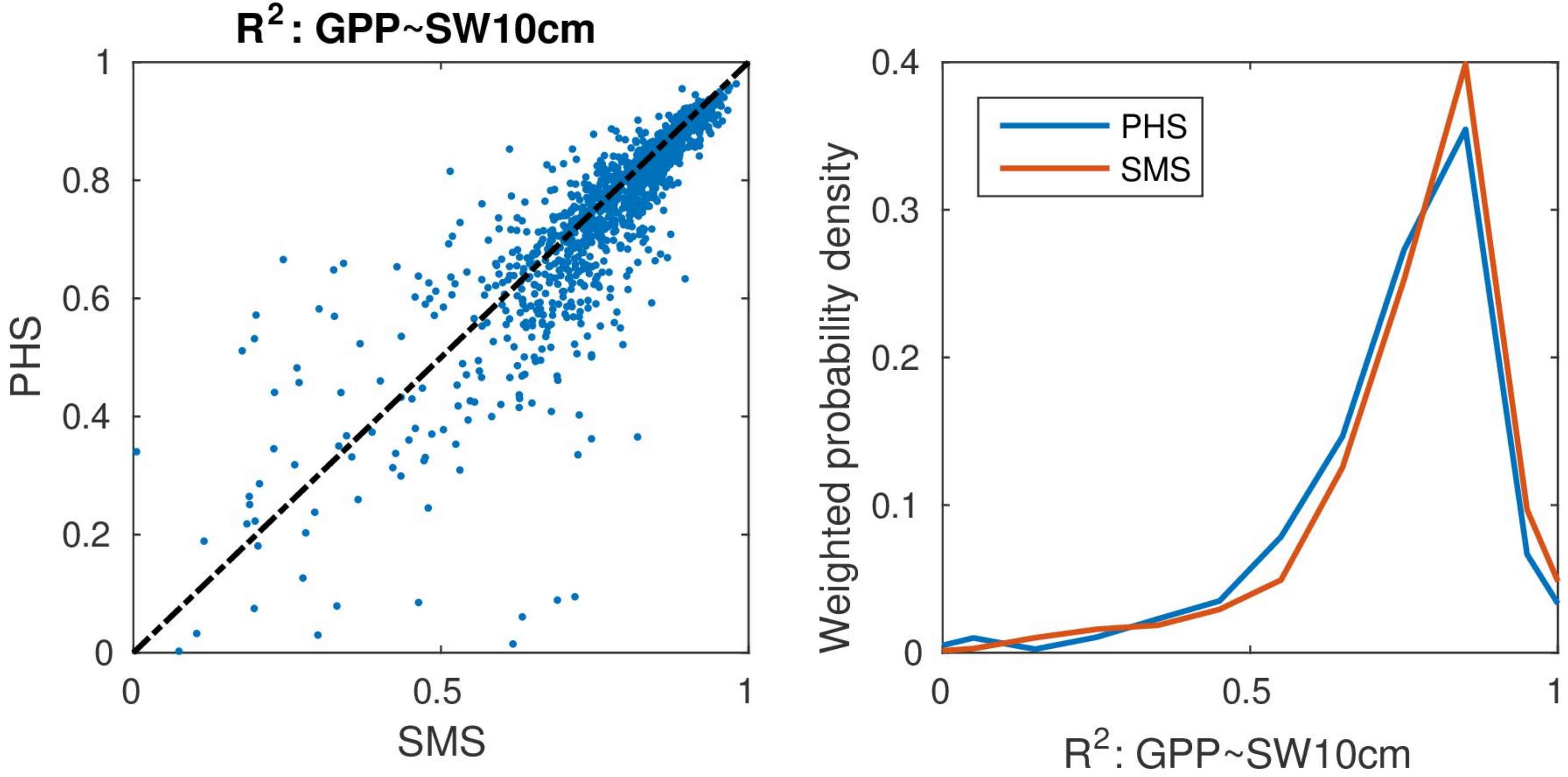


Plot details:

- Each point is a different grid cell
- Looking at the correlation between GPP and 10cm soil water
- Computed from time-series of annual average values (1914-2013)

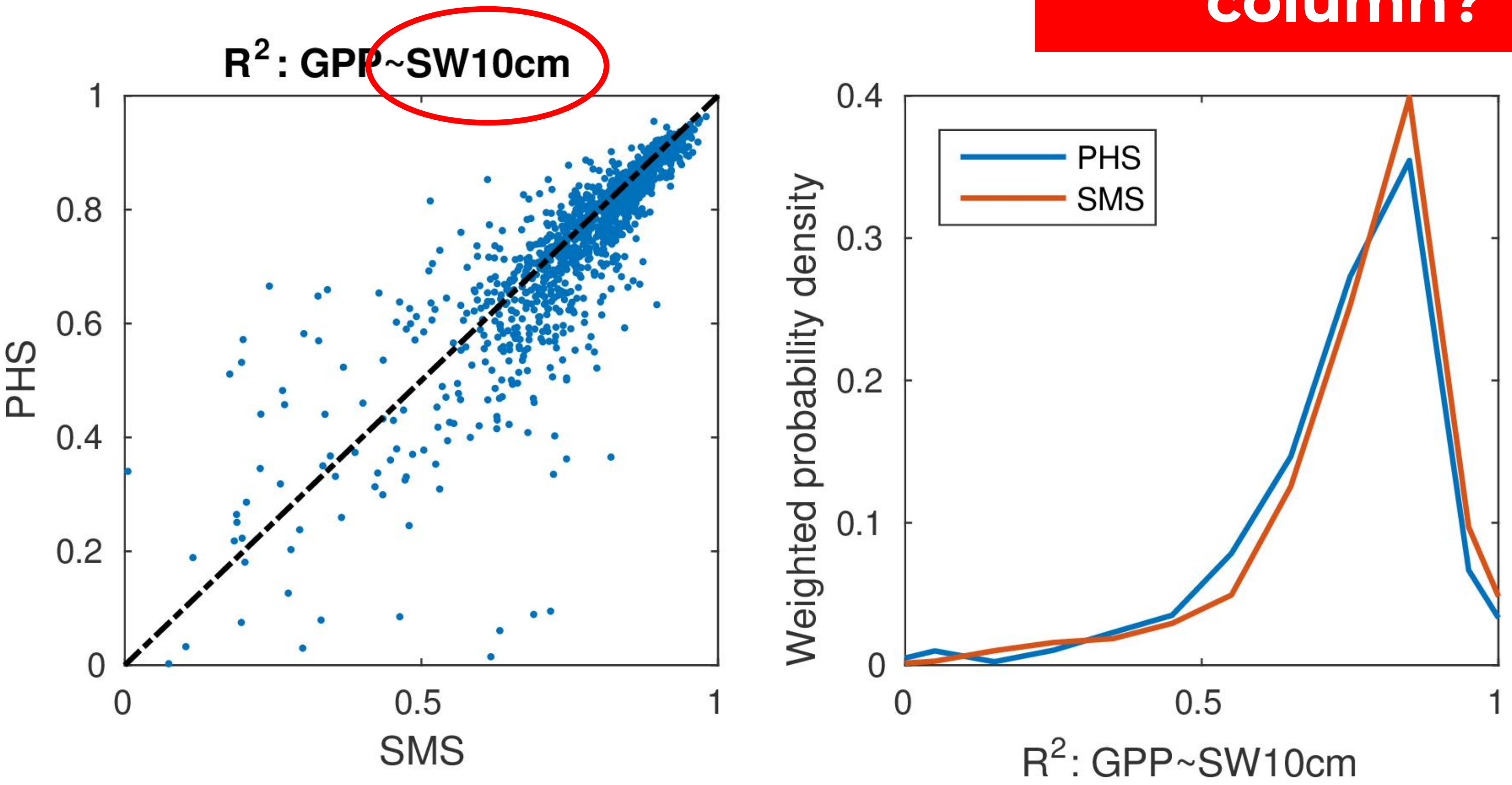
- Overall: soil water explains a very large portion of the interannual variability in GPP
- True for both models

Model vs. Model across the dry tropics domain



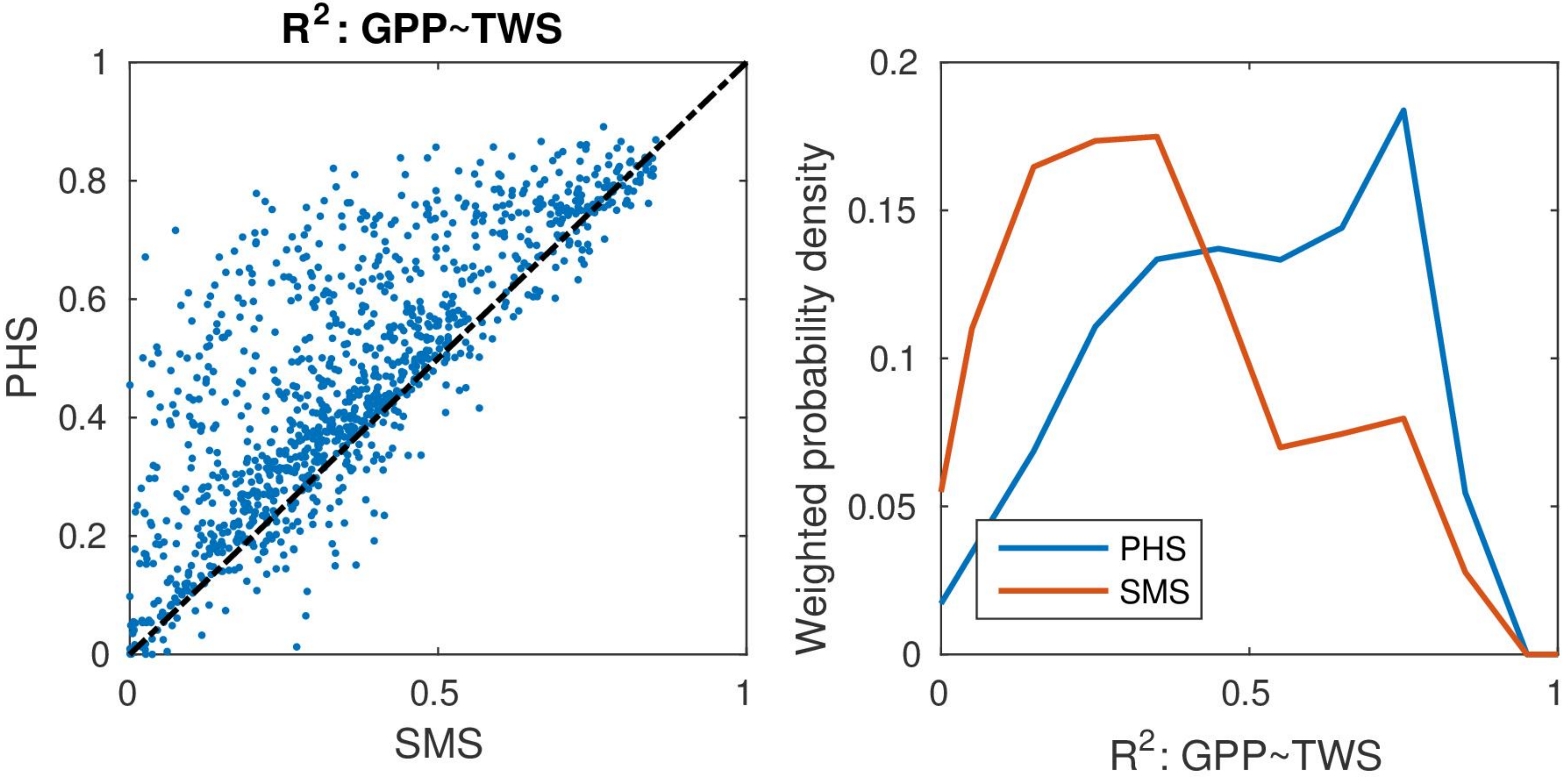
Model vs. Model across the dry tropics domain

What about the rest of the soil column?



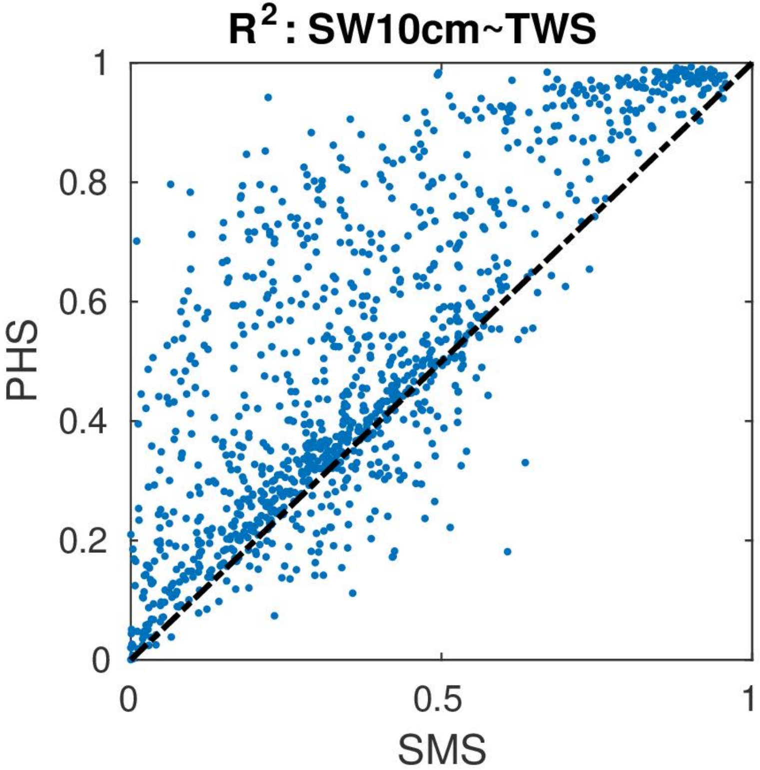
Model vs. Model
across the dry tropics domain

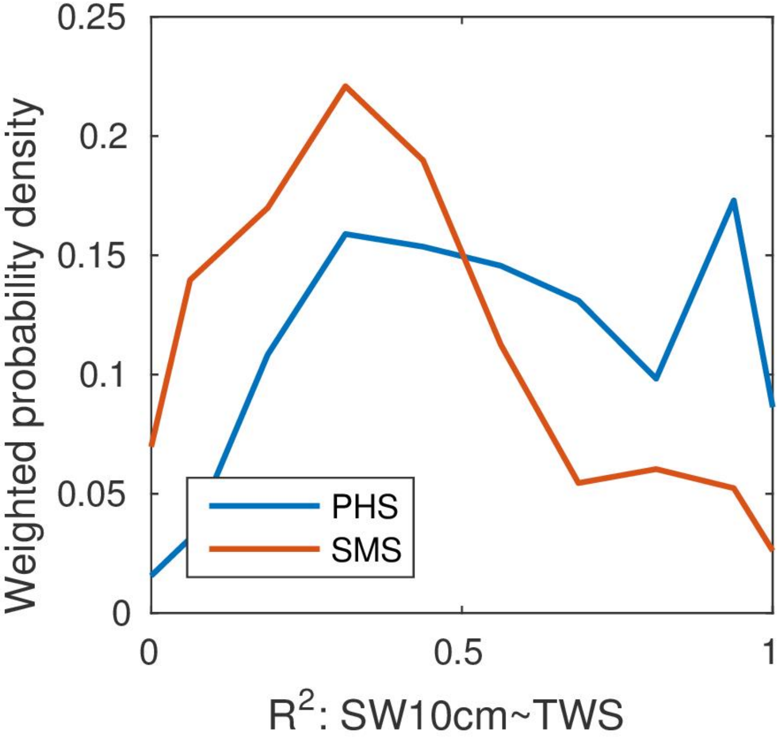
PHS: GPP more closely coupled with Total Water Storage (TWS)

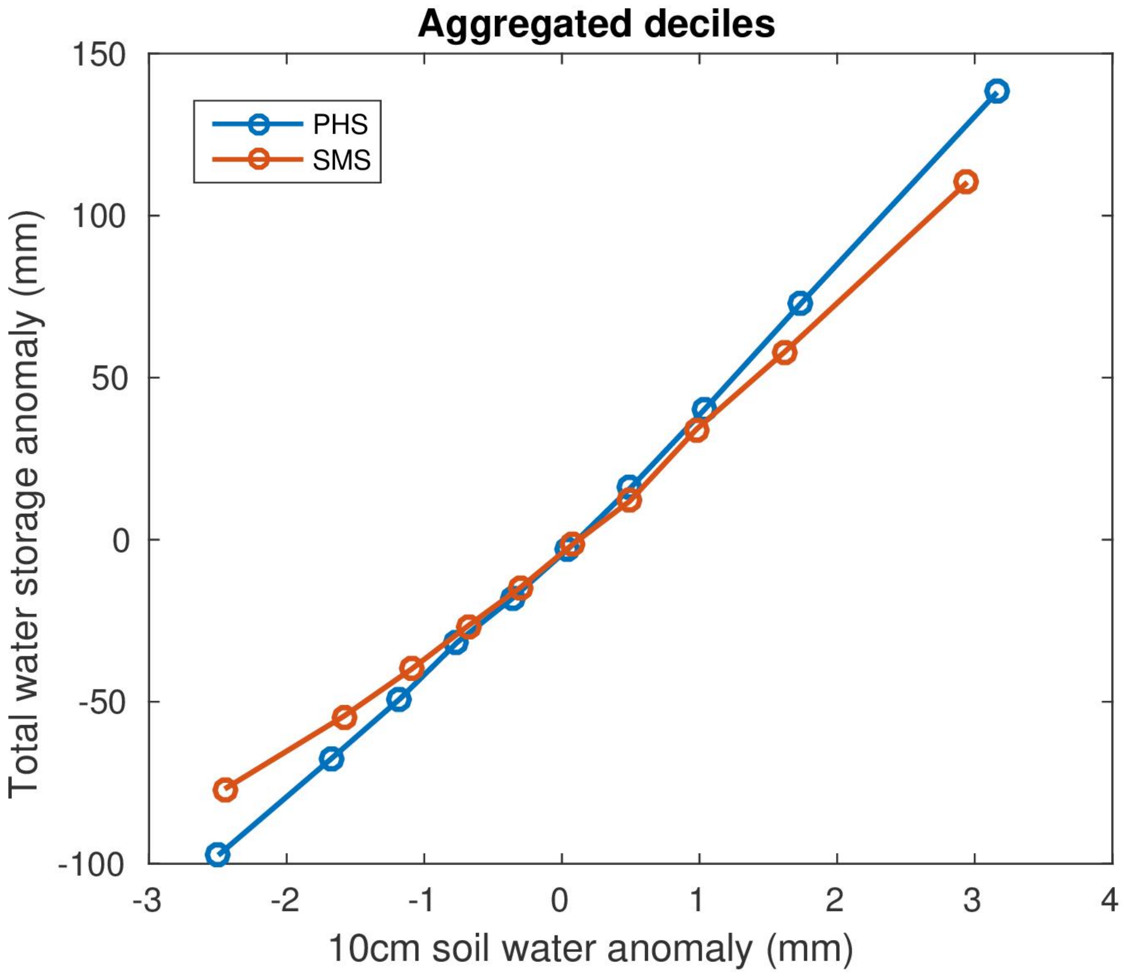


Model vs. Model across the dry tropics domain

PHS: Likewise Total Water Storage (TWS) more closely coupled with 10cm soil water

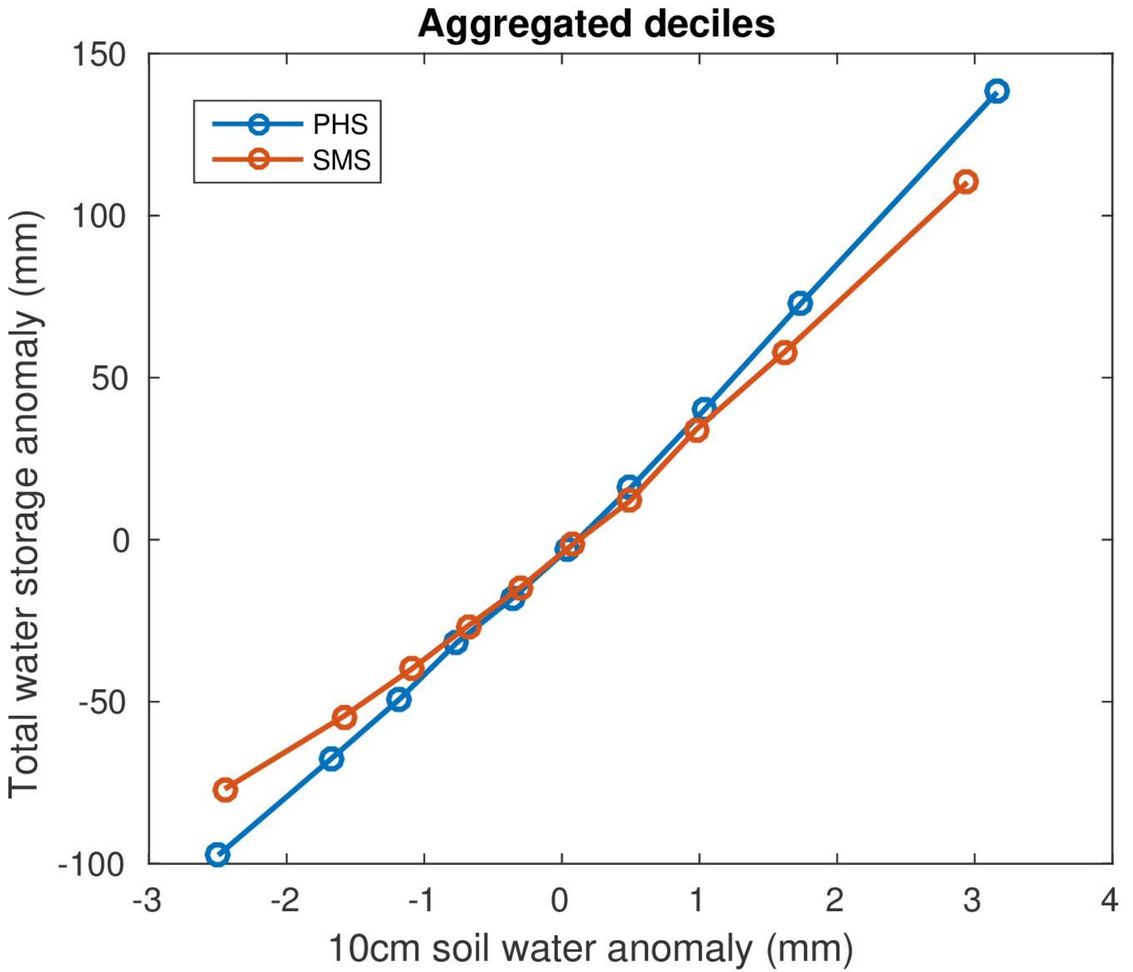






Plot details

- bin each gridcell into deciles based on 10cm soil water
  - 10 yrs per decile
- then average across the full study area



Plot details

- bin each gridcell into deciles based on 10cm soil water
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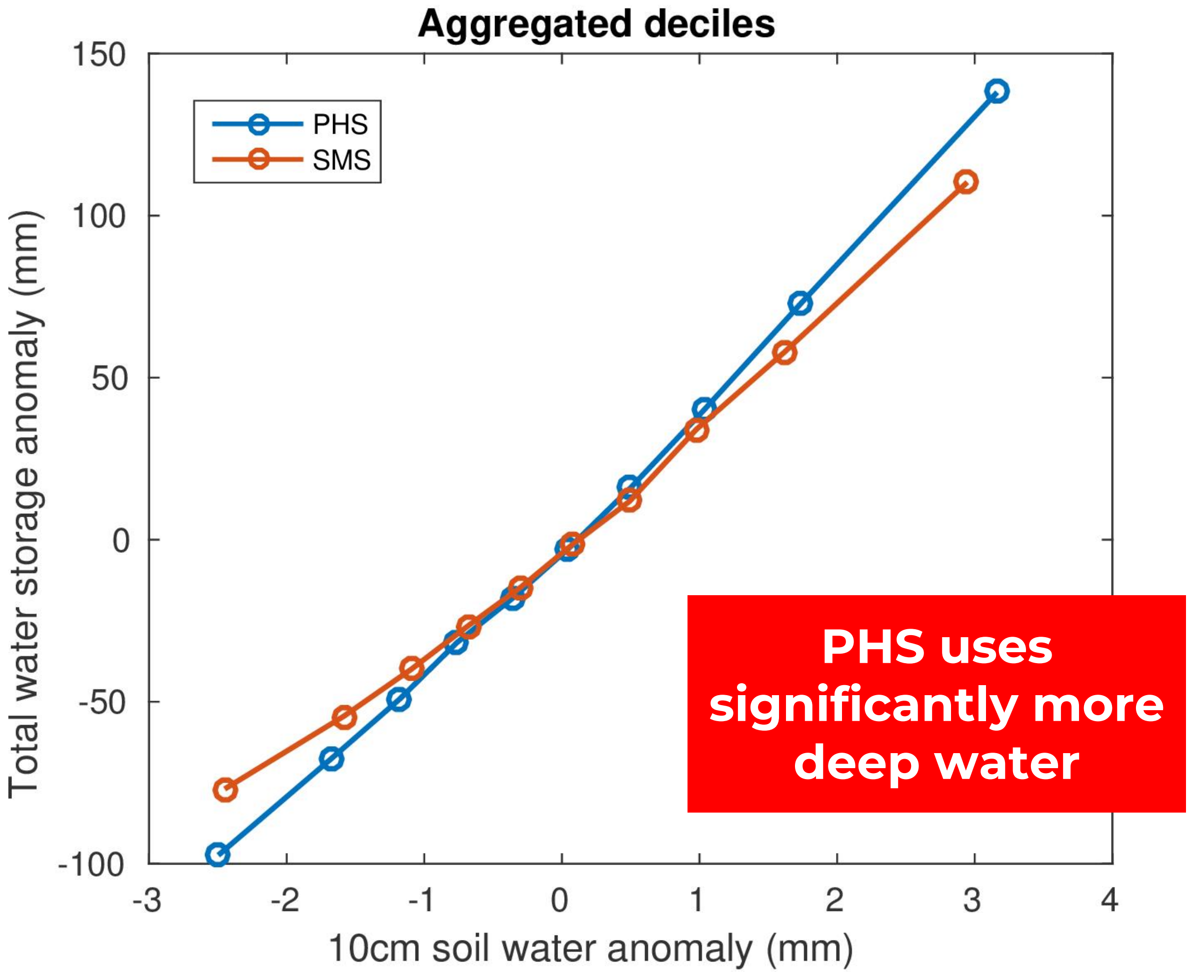
- PHS yields ~41.5 mm TWS for every 1mm from the top 10cm
- SMS = 35.1



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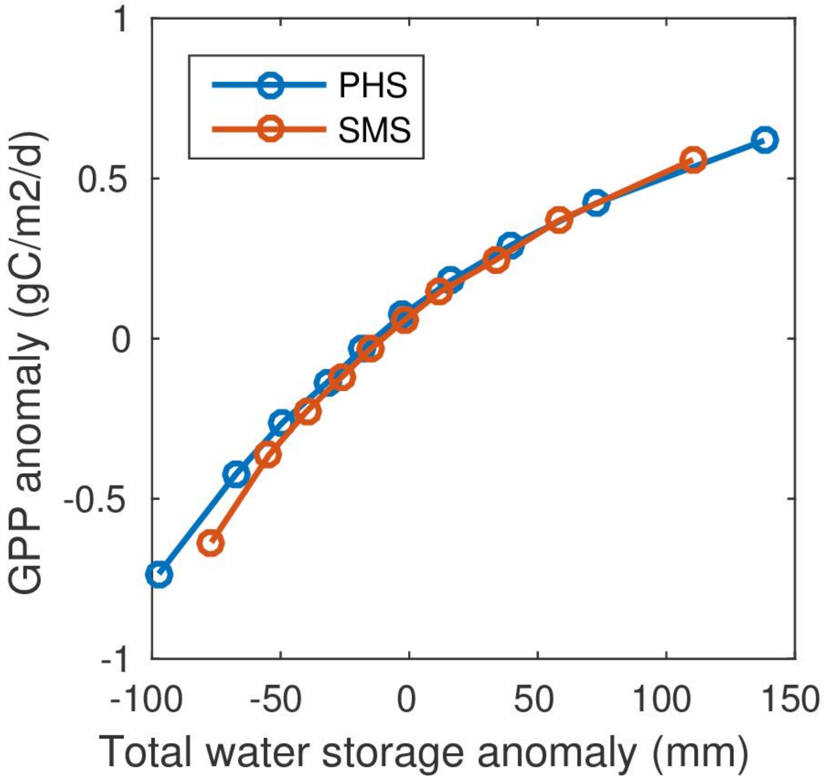
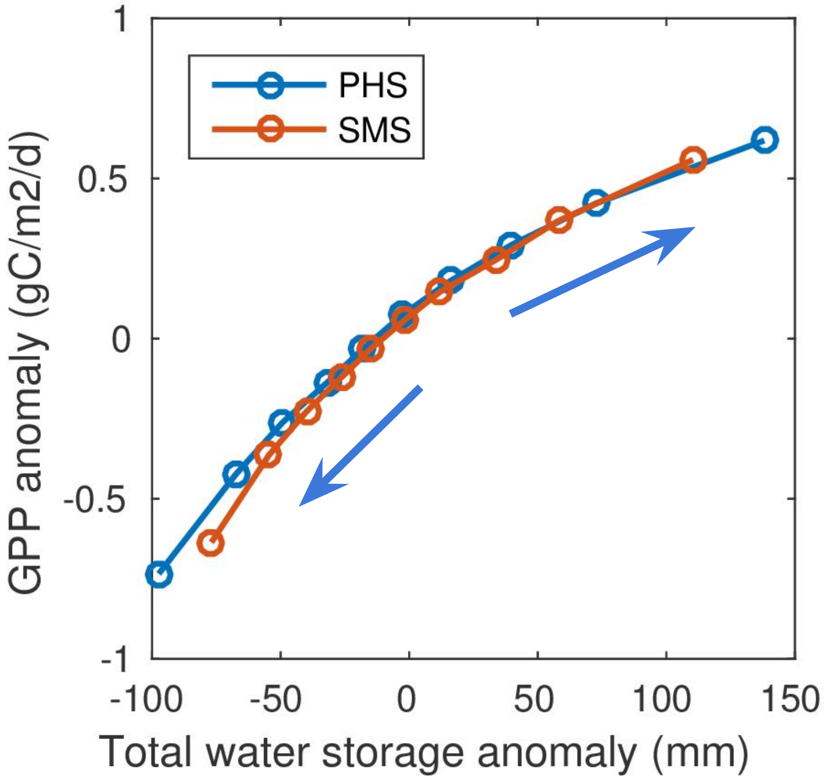
GPP vs. TWS



- SMS productivity looks slightly more sensitive to TWS anomalies (steeper slope)

GPP vs. TWS



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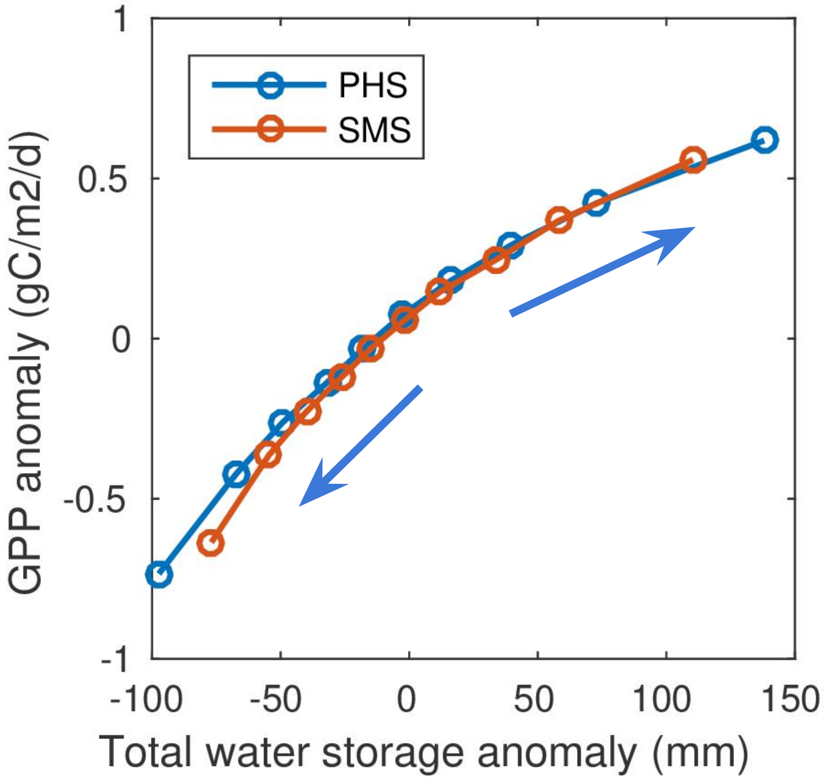
- But PHS samples a wider range of TWS

GPP vs. TWS



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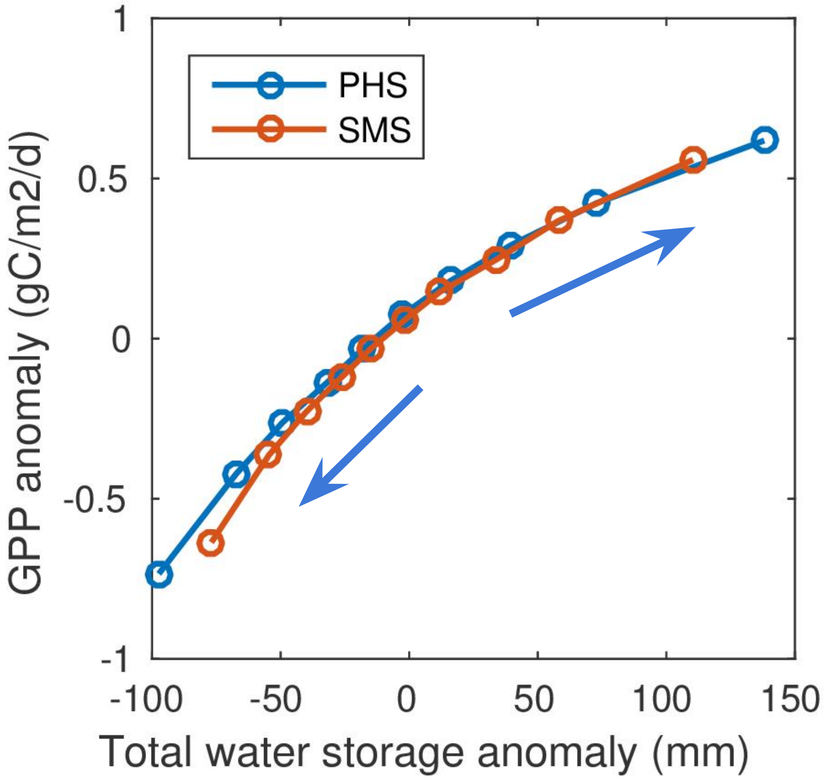
- **Associated with the observed increase in GPP variability**

GPP vs. TWS

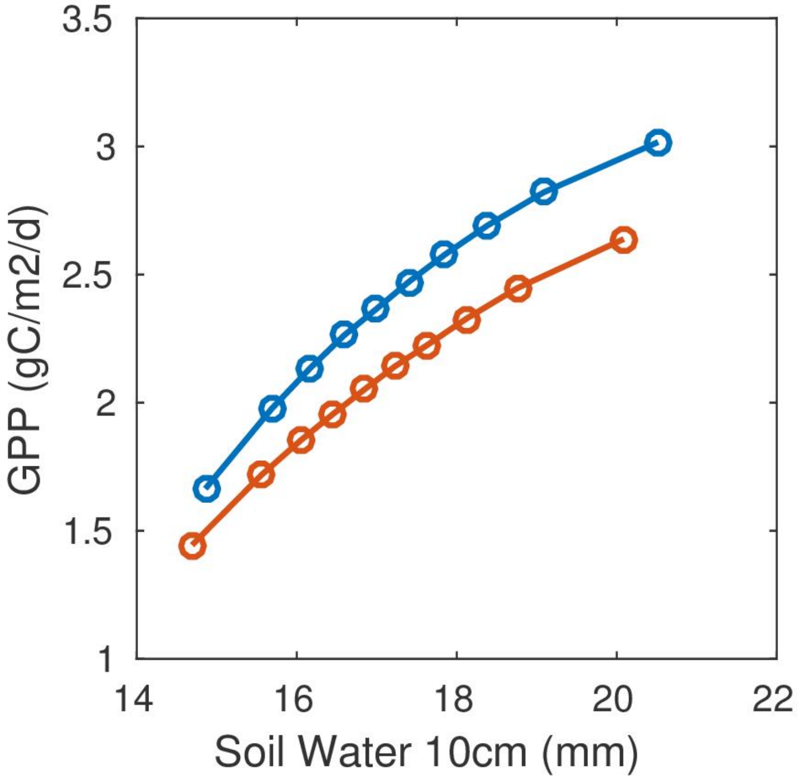


- SMS productivity looks slightly more sensitive to TWS anomalies (steeper slope)
- But PHS samples a wider range of TWS
- **Associated with the observed increase in GPP variability**

- How does this affect
  - 10cm soil water?
  - Mean GPP?

- PHS GPP is about 15% higher
  - requires higher ET
- Despite this, surface soils are slightly wetter with PHS
  - partially explains higher GPP

GPP vs. SW10cm



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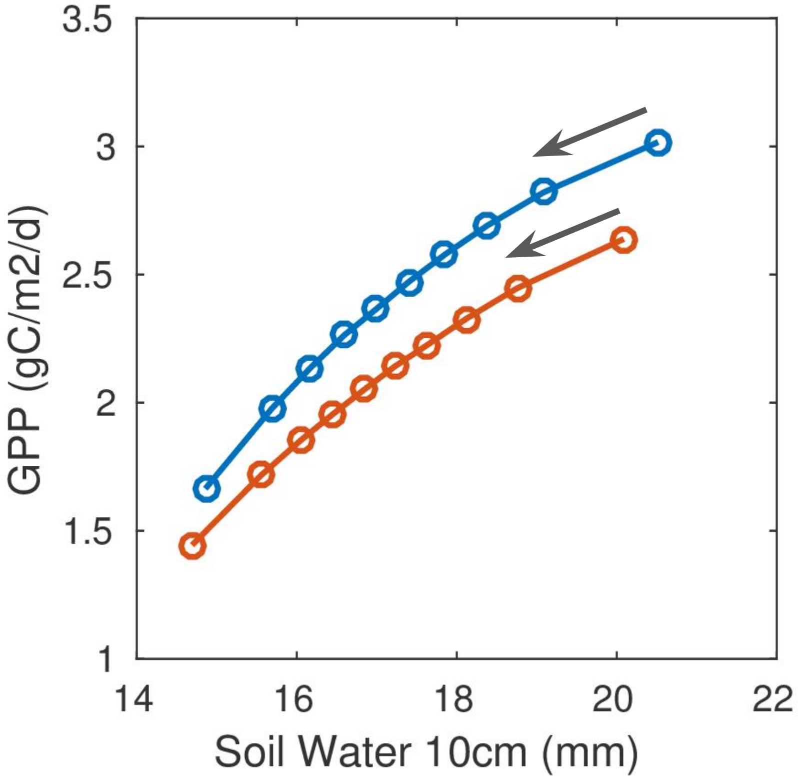
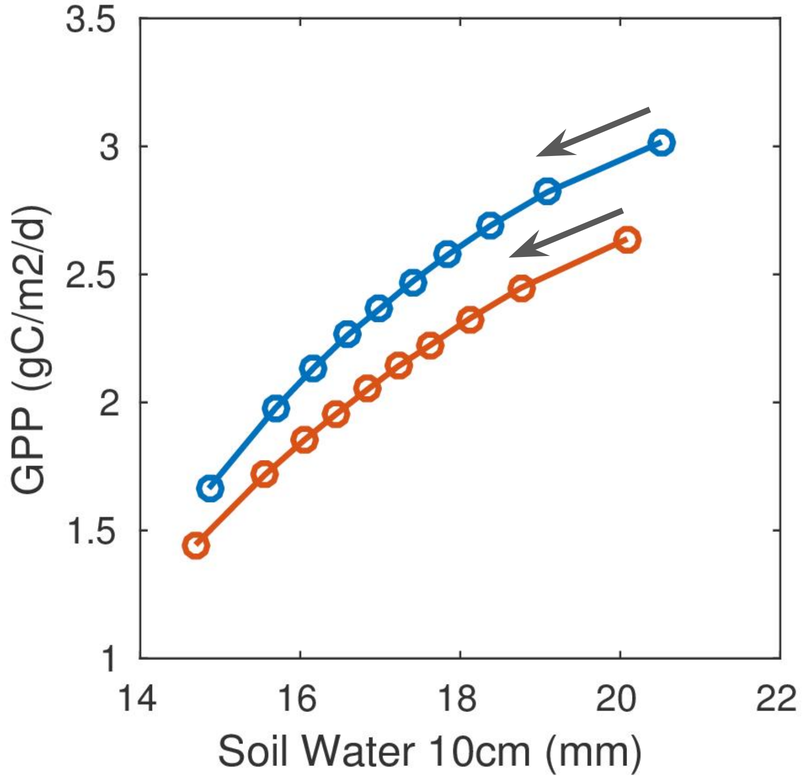


- PHS GPP is about 15% higher
  - requires higher ET
- Despite this, surface soils are slightly wetter with PHS
  - partially explains higher GPP
- Access to deep water allows higher GPP with similar surface drying

Conclusions:

- PHS uses more ‘deep’ soil water (beyond 10cm)
- Leads to higher GPP
- But also associated with higher IAV, higher correlation with TWS

GPP vs. SW10cm

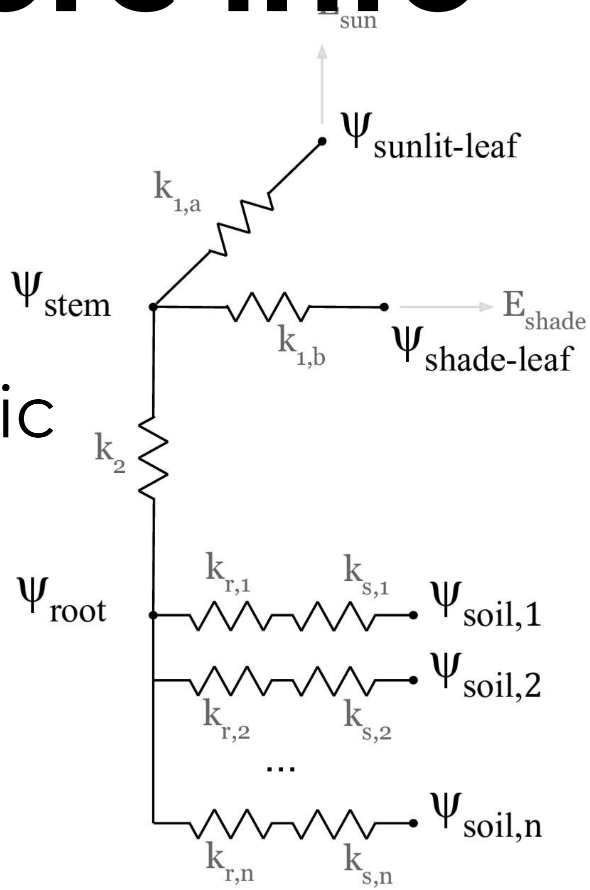


where to find more info

CLM Technical note
- Section 2.11
- cesm.ucar.edu/models/cesm2/land/

Model development paper
- Implementing plant hydraulics in the Community Land Model, version 5
- Kennedy et al. 2019, *JAMES*

Plant
Hydraulic
Stress



djk2120@columbia.edu

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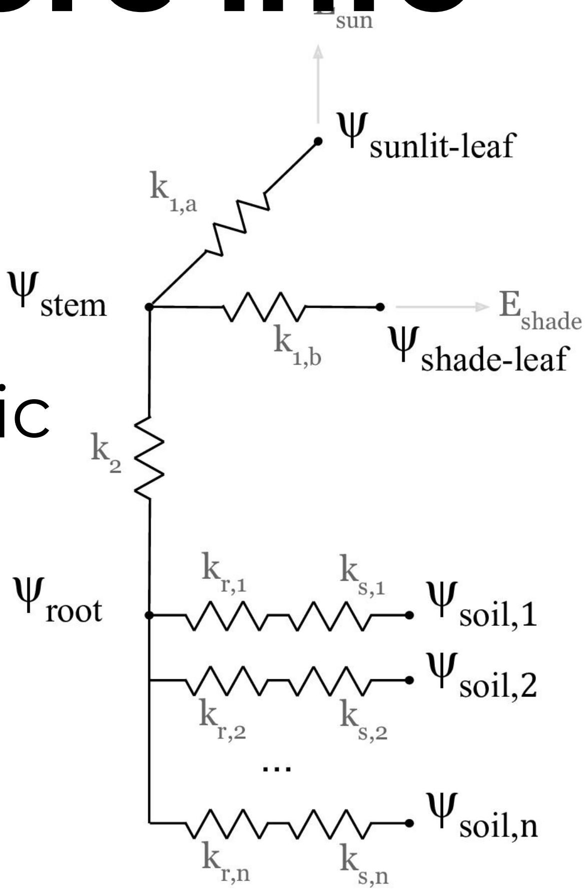
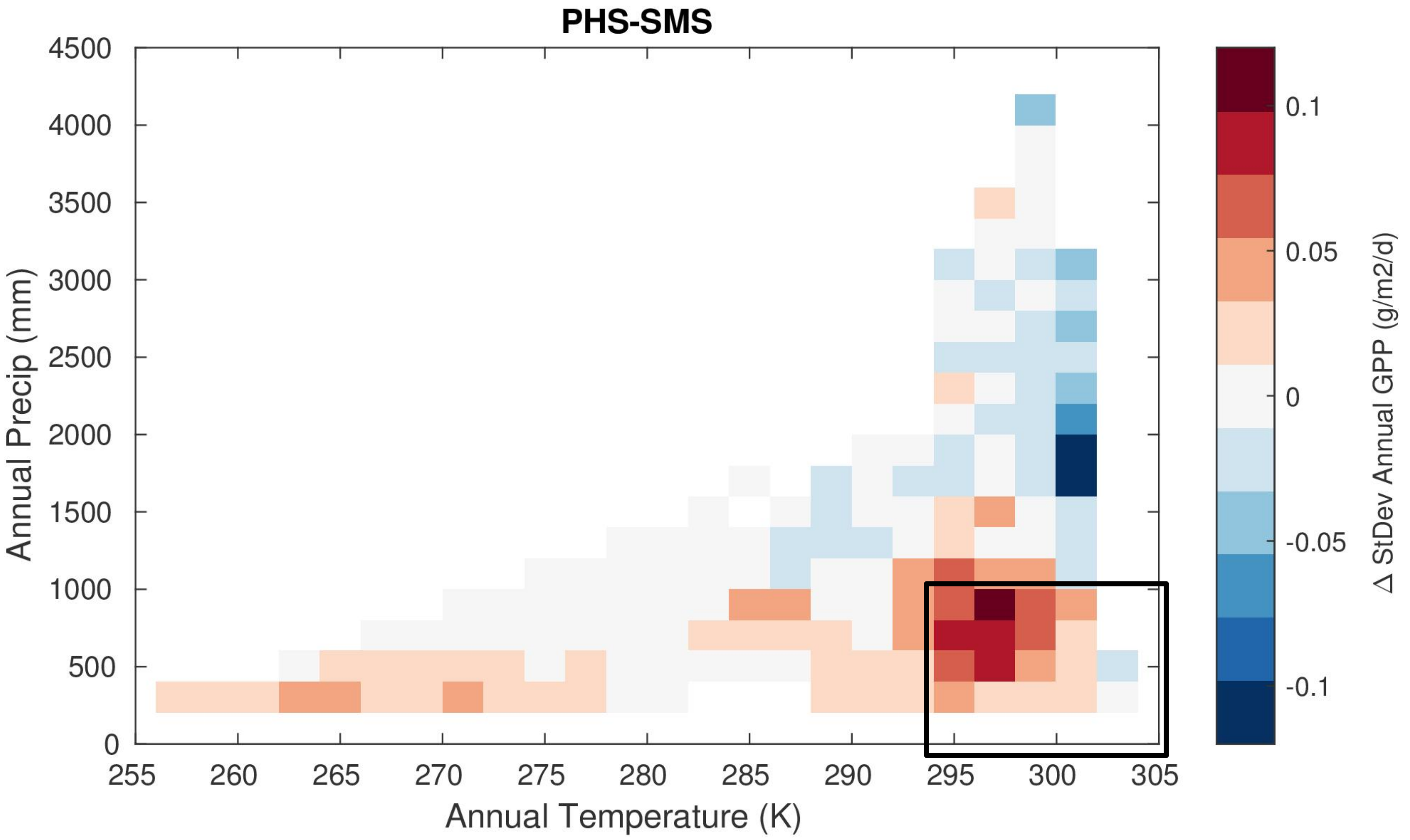


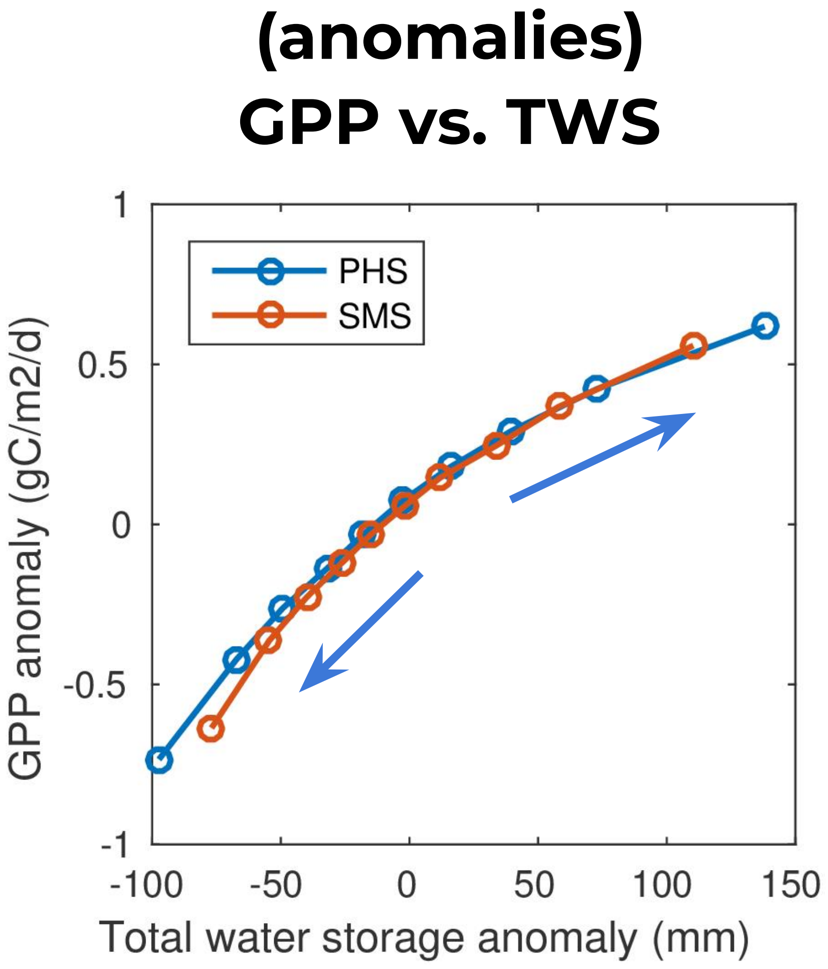
thanks!

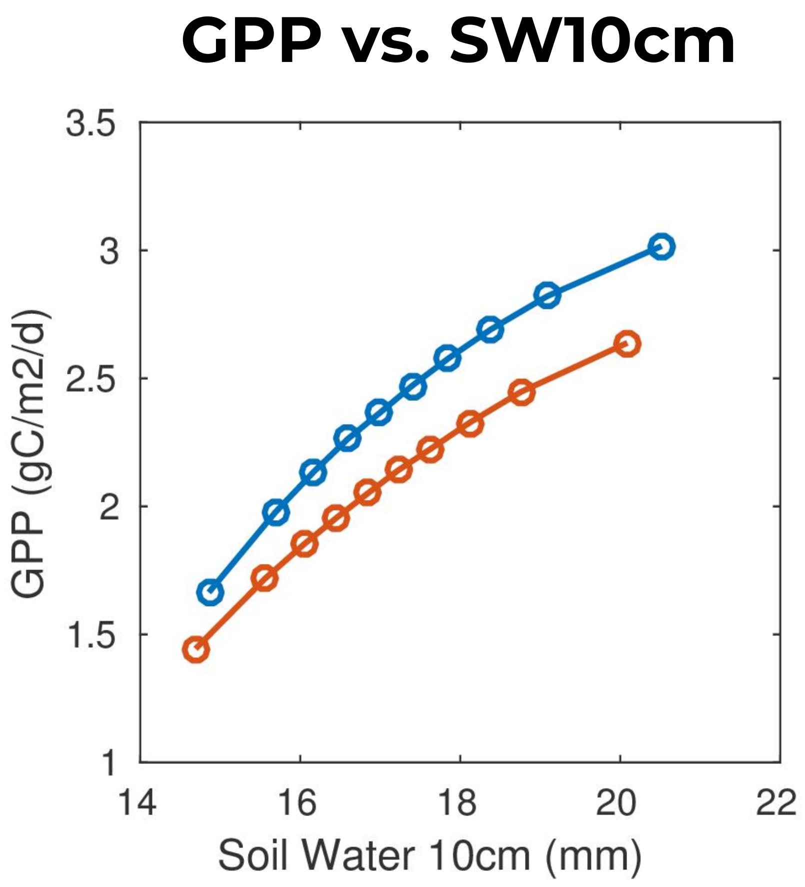
djk2120@columbia.edu

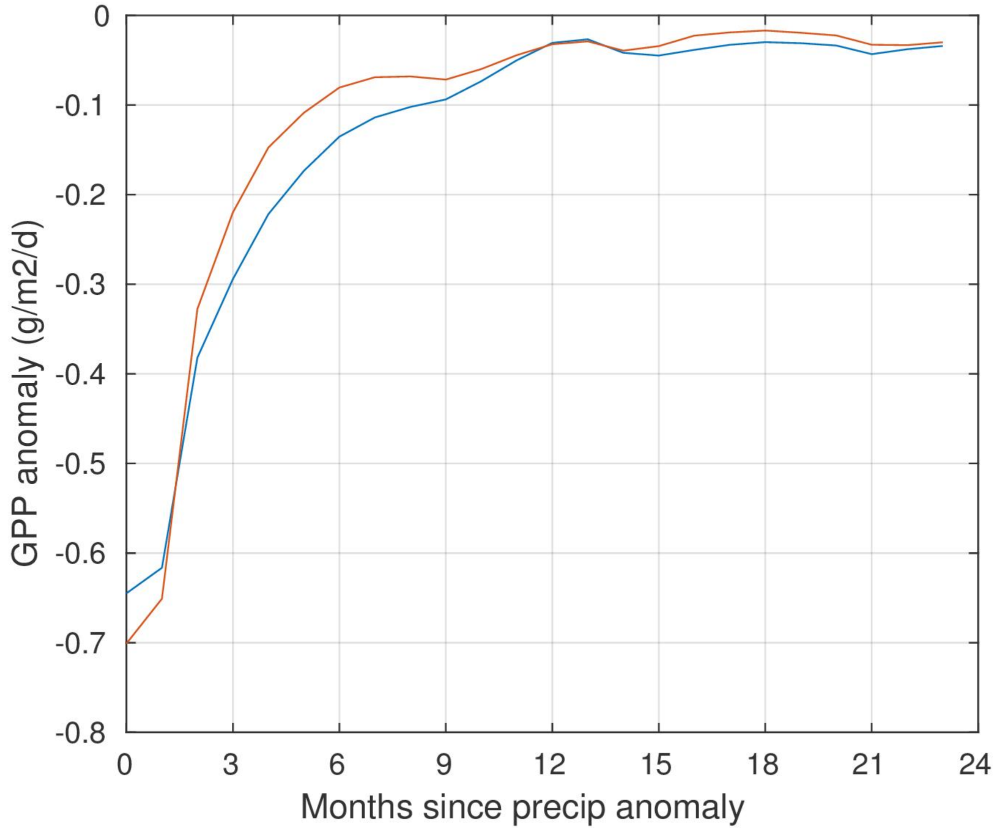
extra slides



PHS-SMS
Annual Precip (mm)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
255
260
265
270
275
280
285
290
295
300
305
Annual Temperature (K)
0.1
0.05
0
-0.05
-0.1
Δ StDev Annual GPP (g/m2/d)


(anomalies)
GPP vs. TWS
PHS
SMS
1
0.5
0
-0.5
-1
-100
-50
0
50
100
150
GPP anomaly (gC/m2/d)
Total water storage anomaly (mm)

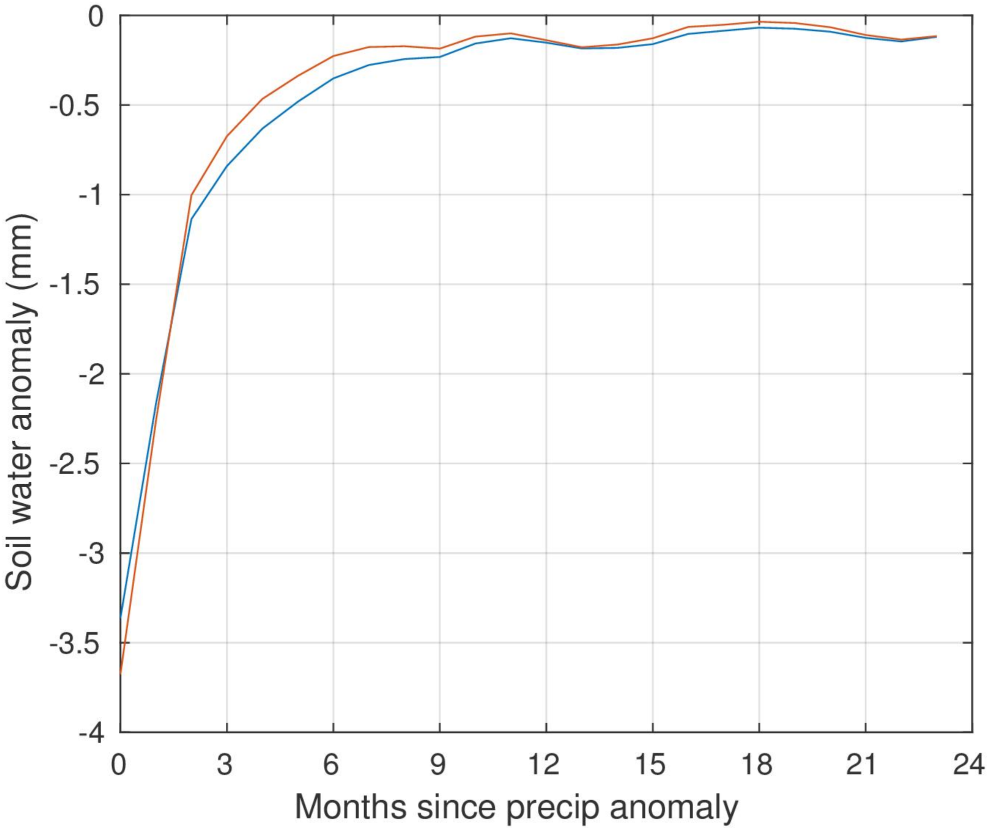

GPP vs. SW10cm
3.5
3
2.5
2
1.5
1
14
16
18
20
22
GPP (gC/m2/d)
Soil Water 10cm (mm)



Precip anomalies have longer coupling to GPP (with PHS)

- lost GPP (year 1)
  - PHS = 1.23 PgC
  - SMS = 1.08 PgC
- lost GPP (year 2)
  - PHS = 0.18 PgC
  - SMS = 0.14 PgC

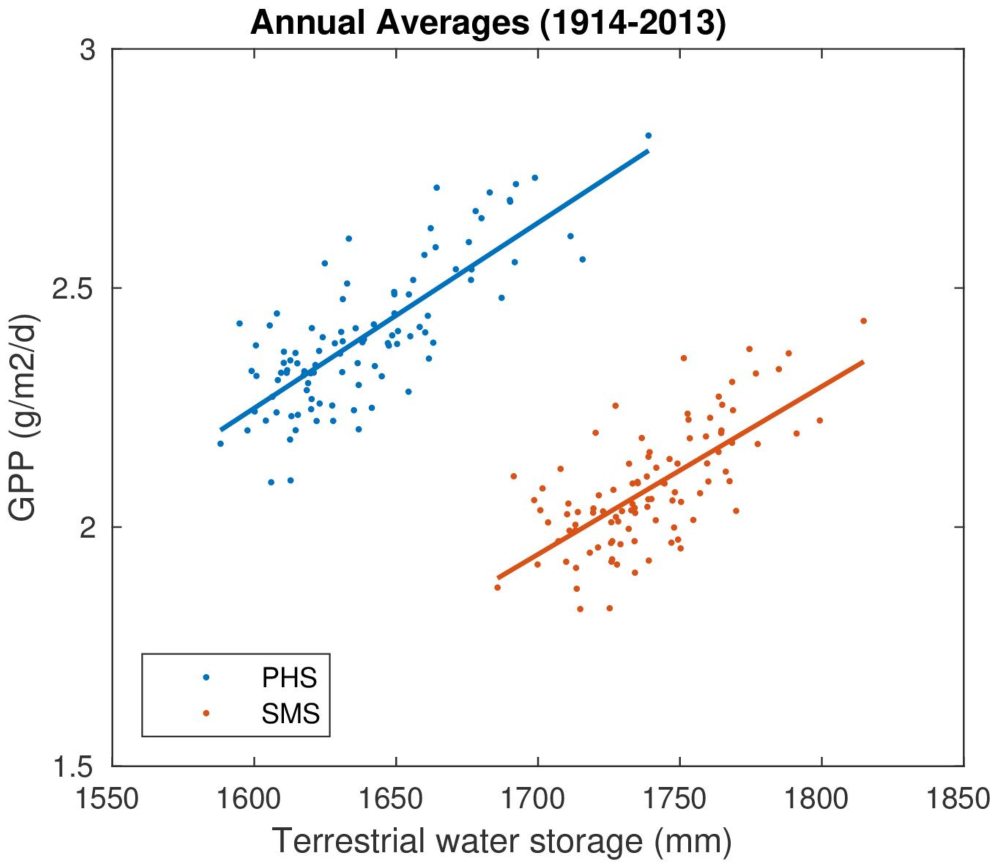
- monthly mean GPP
  - ~0.9 PgC
  - (for reference)



Similar pattern with soil water (top 10cm)

- lost GPP (year 1)
  - PHS = 1.23 PgC
  - SMS = 1.08 PgC
- lost GPP (year 2)
  - PHS = 0.18 PgC
  - SMS = 0.14 PgC

- monthly mean GPP
  - ~0.9 PgC
  - (for reference)

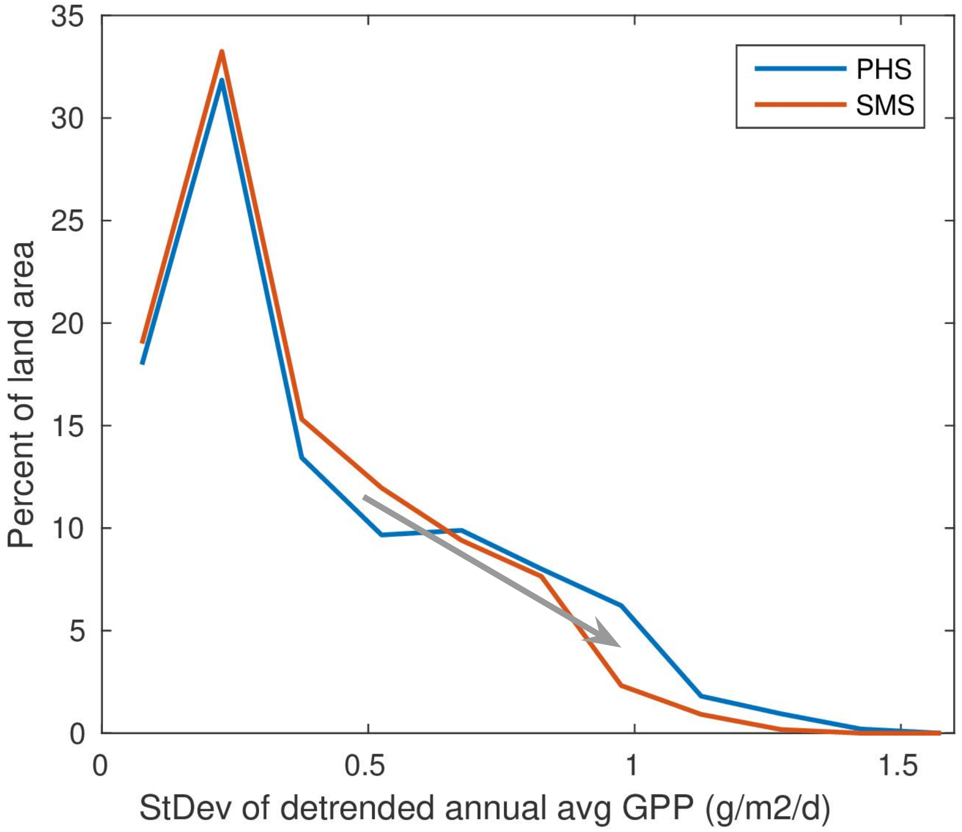


Annual Averages (1914-2013)
GPP (g/m2/d)
Terrestrial water storage (mm)
3
2.5
2
1.5
1550
1600
1650
1700
1750
1800
1850
PHS
SMS

PHS features higher variability in GPP

- distribution shifts to higher variability

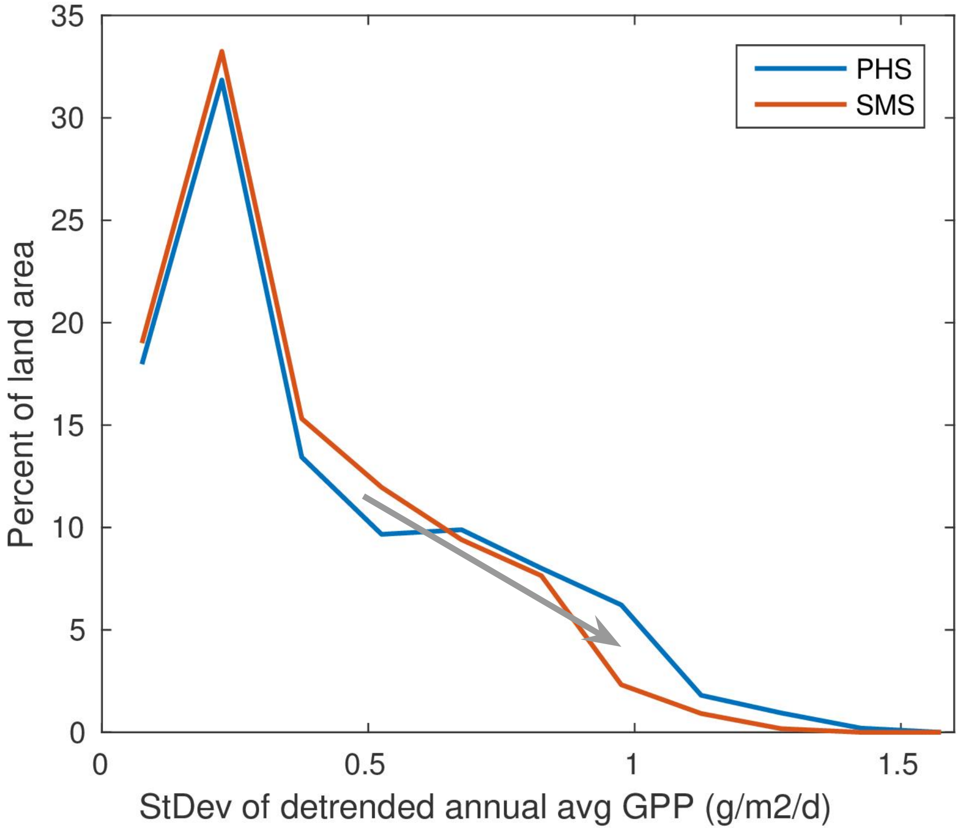
Interannual Variability also increases



PHS features higher variability in GPP

- distribution shifts to higher variability
- average stdev:
  - PHS = 0.41 g/m^2/d
  - SMS = 0.37 g/m^2/d

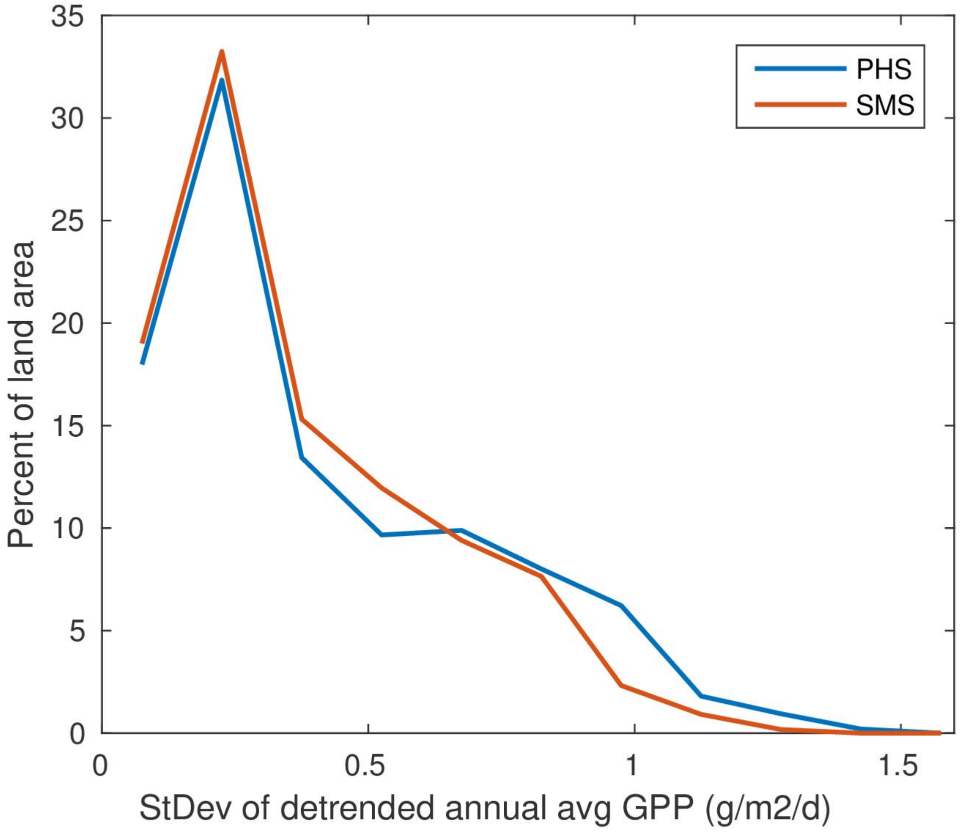
Interannual Variability also increases



PHS features higher variability in GPP

- distribution shifts to higher variability
- average stdev:
  - PHS = 0.41 $g/m^2/d$
  - SMS = 0.37 $g/m^2/d$
- approx 12% increase

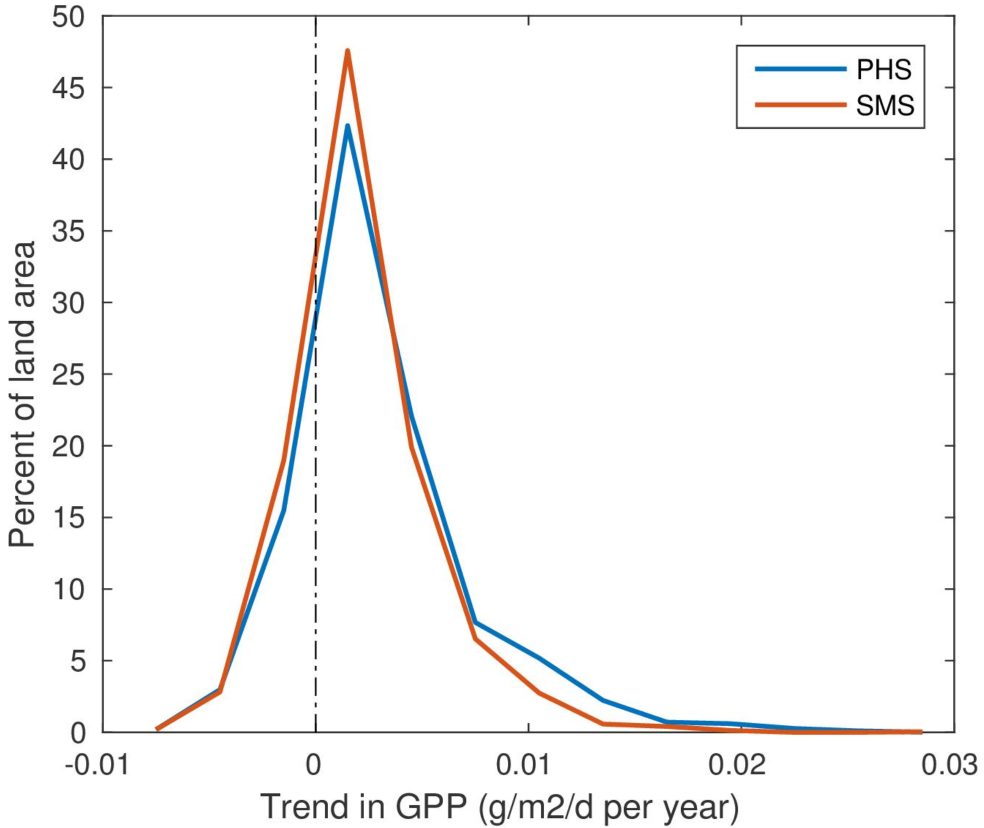
Interannual Variability also increases



PHS features higher trends in GPP

- distribution shifts to higher trends

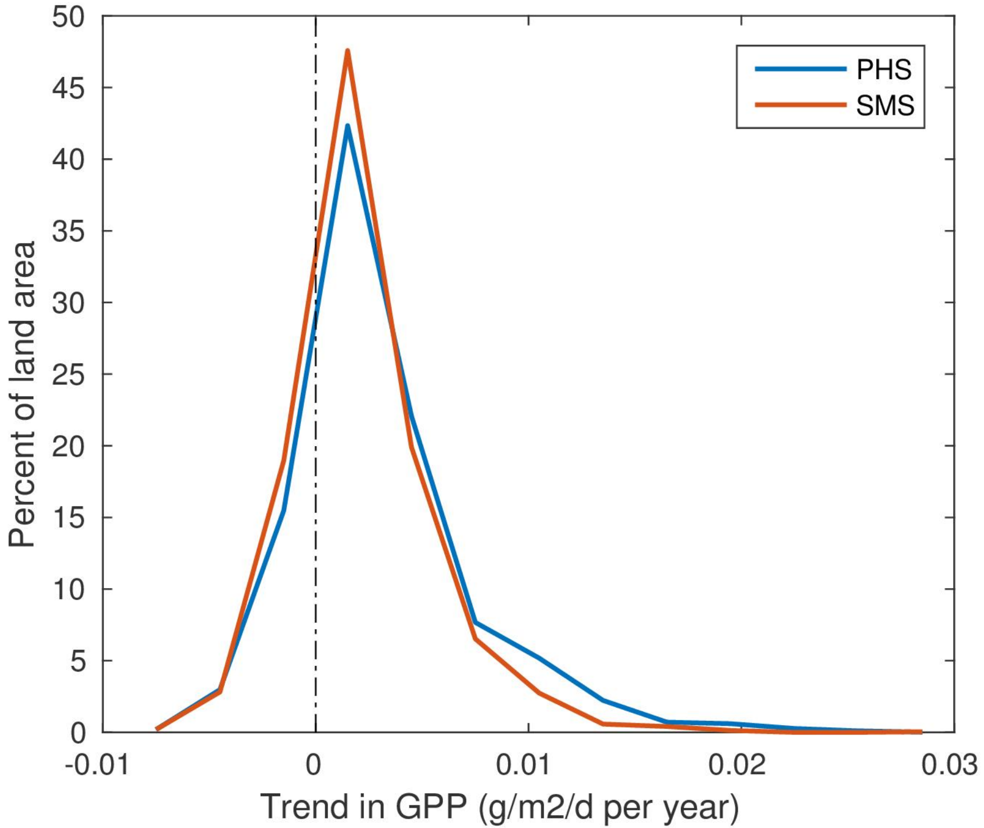
What are the trends in GPP over 1914-2013?



PHS features higher trends in GPP

- distribution shifts to higher trends
- integrated over the study domain, GPP trend adds **1.53 Pg/yr** with PHS

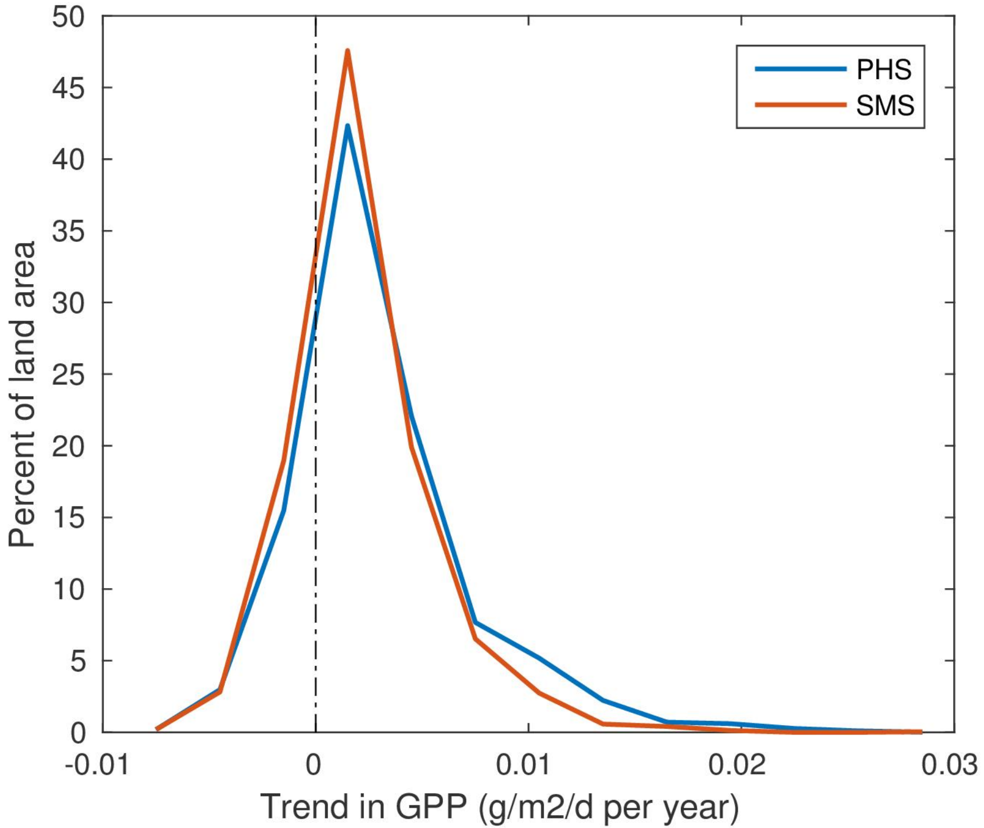
What are the trends in GPP over 1914-2013?



PHS features higher trends in GPP

- distribution shifts to higher trends
- integrated over the study domain, GPP trend adds **1.53 Pg/yr** with PHS
- compared to 1.06 Pg/yr with SMS

What are the trends in GPP over 1914-2013?



PHS features higher trends in GPP

- distribution shifts to higher trends
- integrated over the study domain, GPP trend adds **1.53 Pg/yr** with PHS
- compared to 1.06 Pg/yr with SMS
- (1914) GPP is approx. 11 Pg/yr

What are the trends in GPP over 1914-2013?