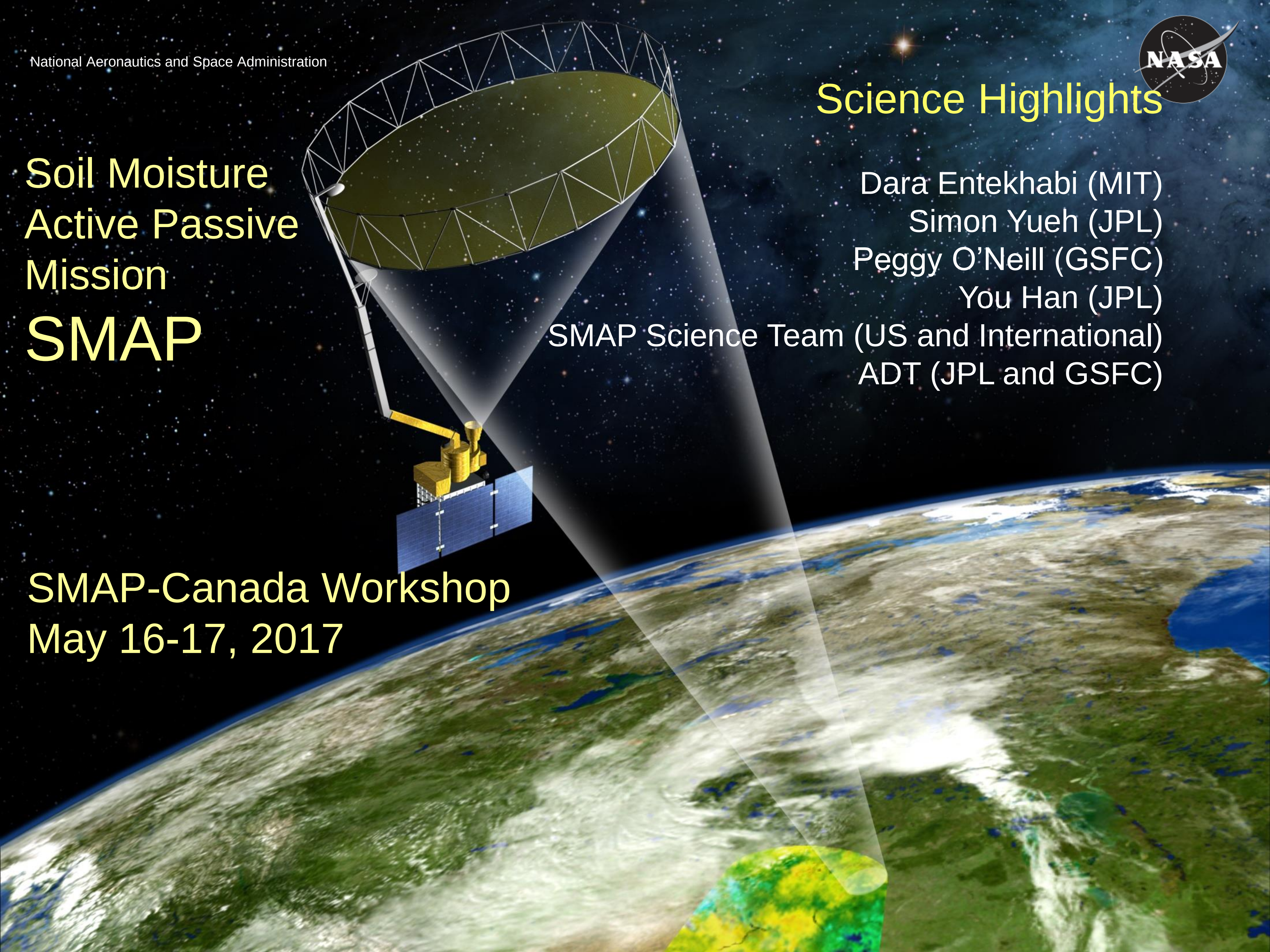
National Aeronautics and Space Administration



Soil Moisture Active Passive Mission

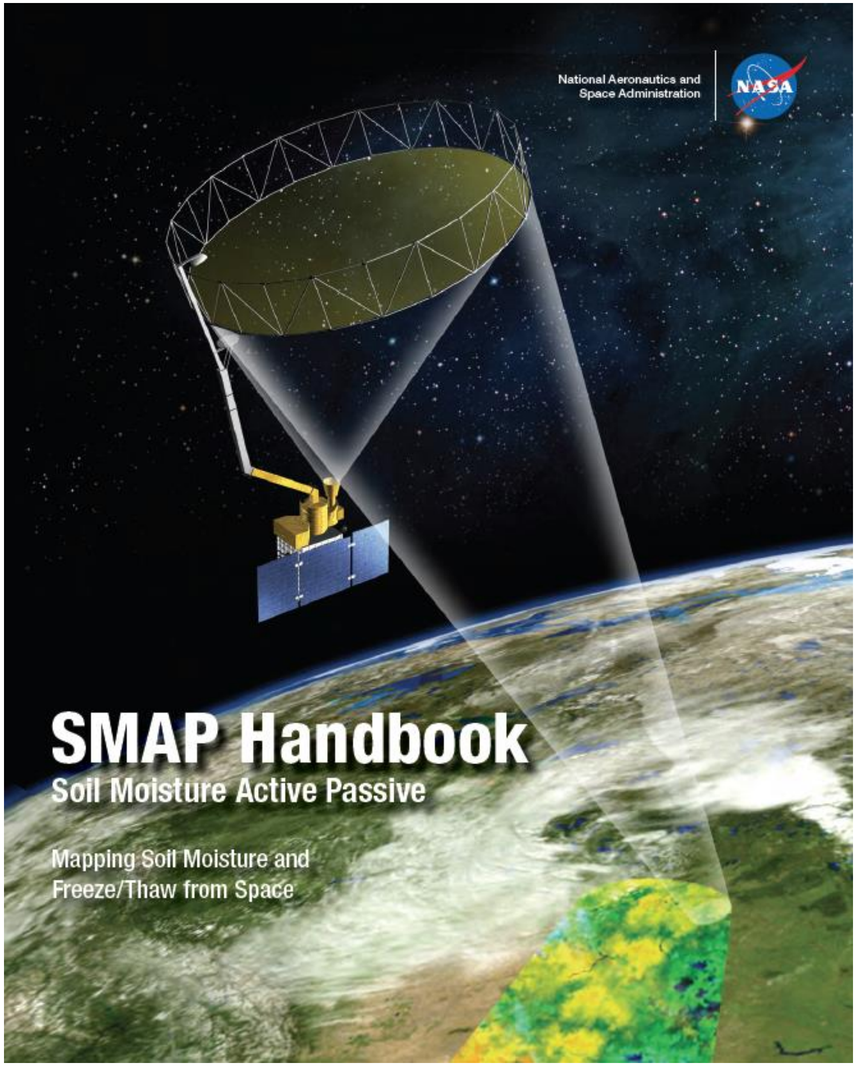
SMAP

Science Highlights

Dara Entekhabi (MIT)
Simon Yueh (JPL)
Peggy O'Neill (GSFC)
You Han (JPL)
SMAP Science Team (US and International)
ADT (JPL and GSFC)

SMAP-Canada Workshop
May 16-17, 2017

SMAP Mission Concept



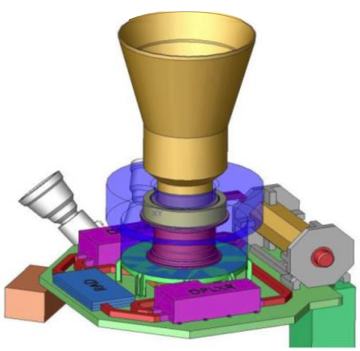
L-band unfocused SAR and radiometer system, offset-fed 6 m light-weight deployable mesh reflector. Shared feed for

- 1.2 GHz Radar 1-3 km (30% nadir gap)
  HH, VV and HV
- 1.4 GHz Radiometer at 40 km (-3 dB)
  H, V, 3^{rd} and 4^{th} Stokes

Conical scan, fixed incidence angle at 40˚

Contiguous 1000 km swath 2-3 days revisit

Sun-synchronous 6am/6pm orbit (680 km)



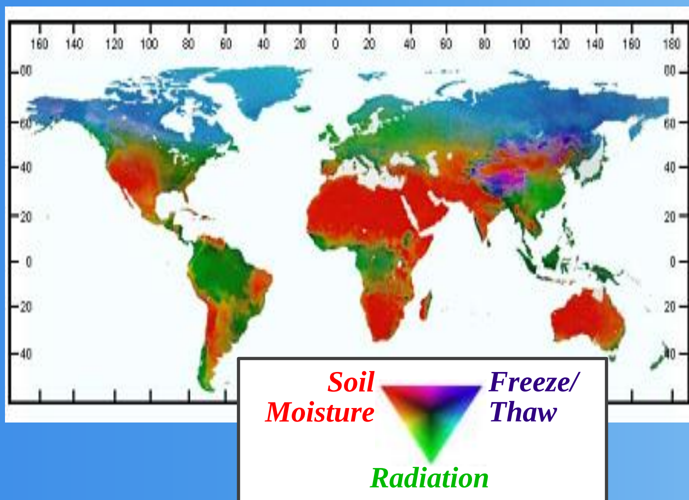
Electronic Version at http://smap.jpl.nasa.gov/Imperative/

Print Version Available (182 Pages): smap_science@jpl.nasa.gov

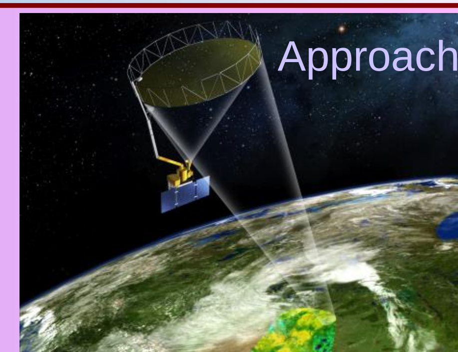
SMAP Science and Application Returns

Science Returns

Soil Moisture *Links* the Global Land Water, Energy, and Carbon Cycles



1. Estimating global surface water and energy fluxes
2. Quantifying net carbon flux in boreal landscapes
3. Reducing uncertainty of climate model projections

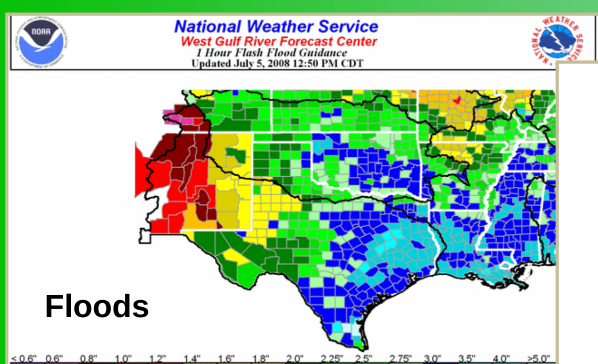


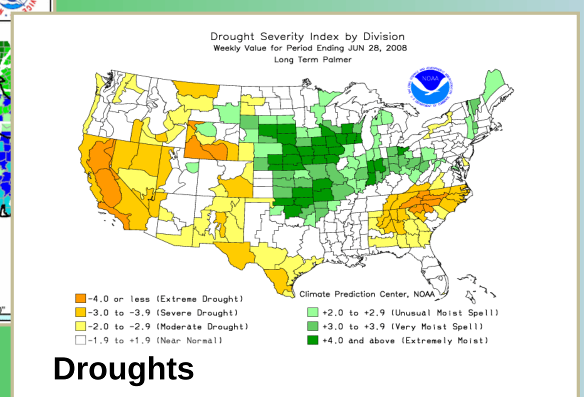
L-band (~21 cm; All-Weather; Canopy Penetration; Sensing Depth)

6m conically scanning (14 rpm) antenna for 1000 km swath

Global coverage every 2-3 days

Applications Returns





4. Enhancing weather forecasts
5. Improving flood prediction and drought monitoring

Core Science Objective

EARTH SYSTEM SCIENCE PATHFINDER
(ESSP) MISSIONS

HYDROS STEP 2
SECTION F

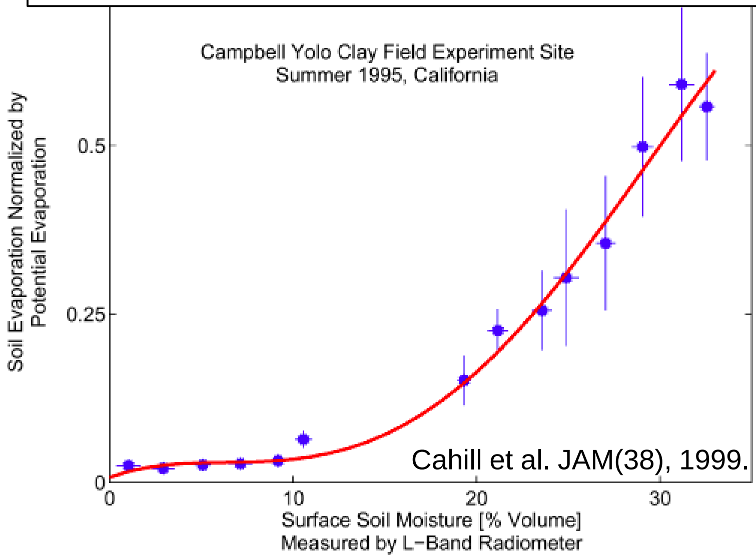


Figure F.1-2. A ground-based L-band radiometer is used to make the soil moisture field measurements to estimate the surface control on evaporation (fitted red line). Global HYDROS soil moisture measurements, together with meteorological and hydrological data, will allow for the first time a quantification of influential processes such as this across diverse climatic and seasonal regimes.

SMAP L1 Science Requirements and Mission Success Criteria

2.0 SCIENCE DEFINITION

2.1 BASELINE SCIENCE OBJECTIVES

The SMAP Project will implement a spaceborne earth observation mission designed to collect measurements of surface soil moisture and freeze/thaw state, together termed the hydrosphere state. SMAP hydrosphere state measurements will yield a critical data set that will enable science and applications users to:

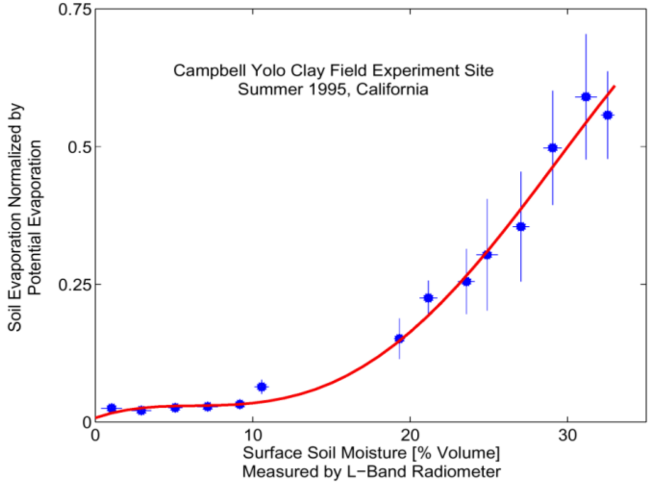
- Understand processes that link the terrestrial water, energy and carbon cycles;
- Estimate global water and energy fluxes at the land surface;

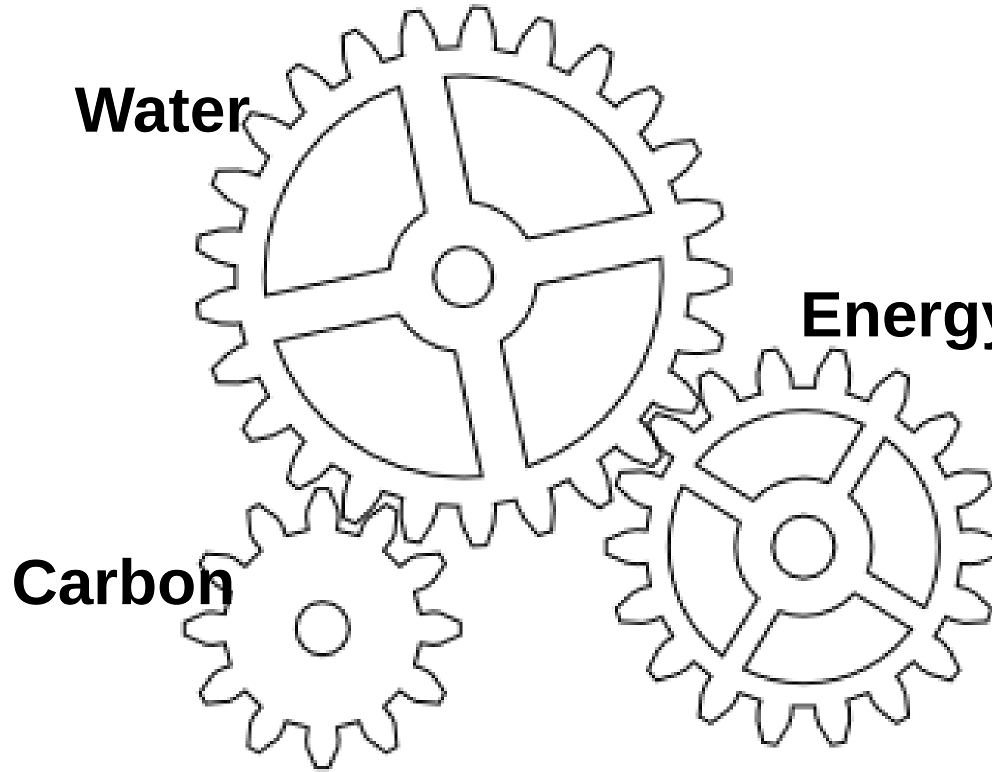
Multiple approaches being pursued and coordinated (R. Koster, G. Salvucci, J. Kimball, D. Entekhabi and others).

Estimate with least reliance on models and parameterizations (i.e., be observations-driven).

Relate function to vegetation type, seasonal climate and soil texture.

Sources of Earth System Model Discrepancies and Uncertainties

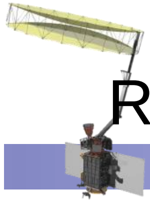




Cycles are Gears That Turn Together

But The Closure Relations *Linking* Them are Parameterized

This is a Major Source of Uncertainty in Models



Demonstration Model: Role of Water-Energy-Carbon Balance Closure Function

$$\frac{d\ \text{Soil Water}}{dt} = \text{Precipitation} - \text{Evaporation}$$

$$\frac{d\ \text{Temperature}}{dt} = \text{Incoming Radiation} - \text{Turbulent Heat Flux}$$

$$\frac{d\ \text{Carbon}}{dt} = \text{Assimilation} - \text{Respiration}$$

$$\frac{dS}{dt} = P - E(S,T)$$

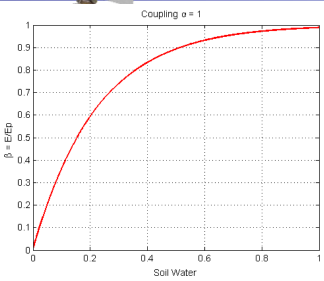
$$C\frac{dT}{dt} = R^{-} - E_s \sigma T^4 - L \cdot E(S,T) - H$$

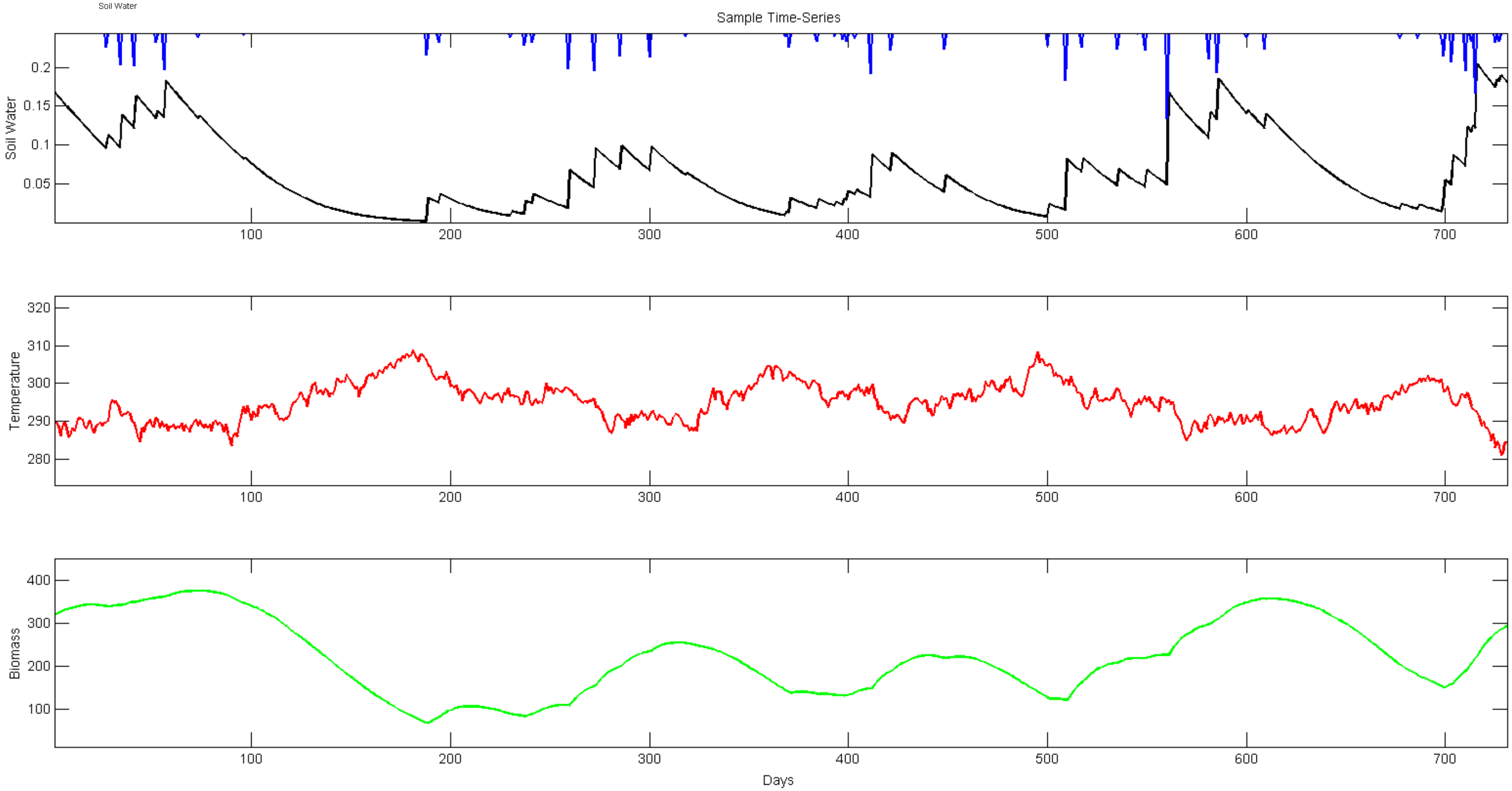
$$\frac{dB}{dt} = c \cdot E(S,T) - B/\tau$$

All coupled together through: $E(S,T) = \beta(S) \cdot E_p$

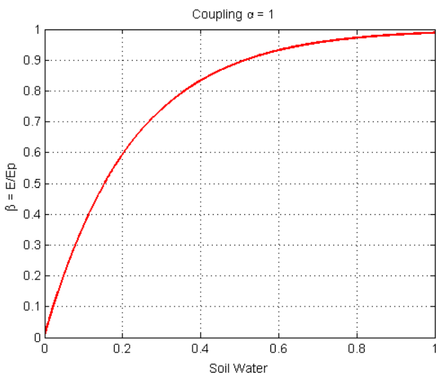
$\beta(S)$ is hence the closure function between the water, energy and carbon budgets.

Three-Variable Demonstration Model

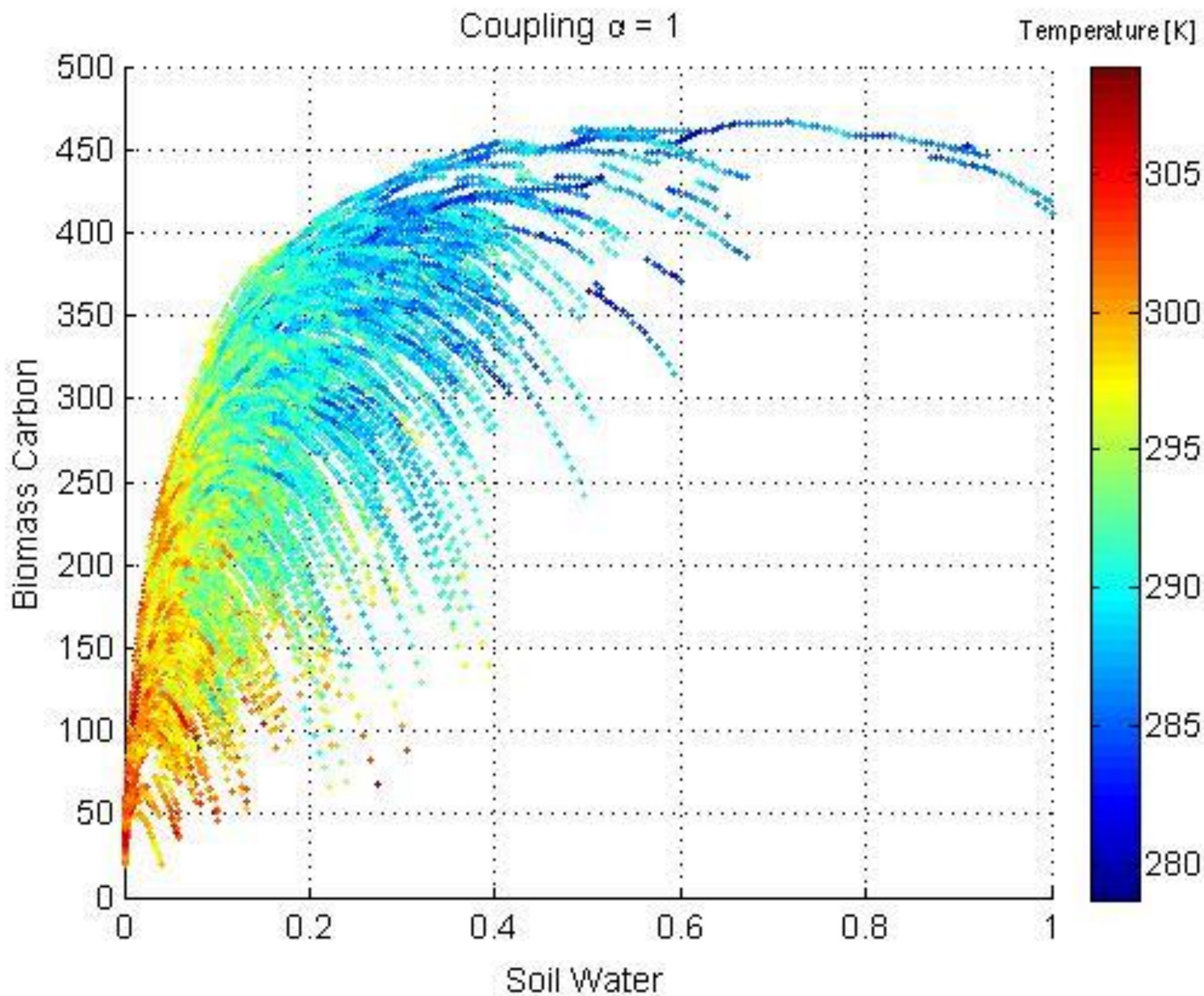




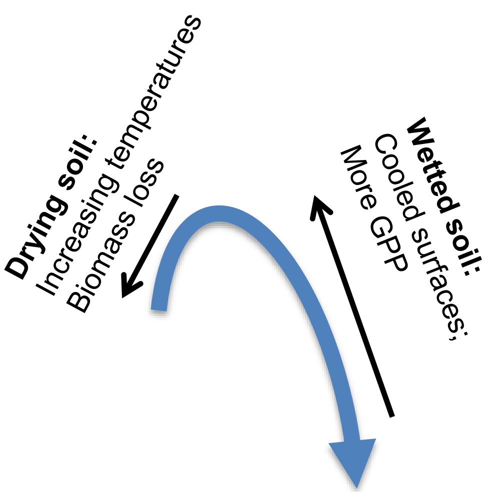
Co-Variations of States: Dependence on Closure Function



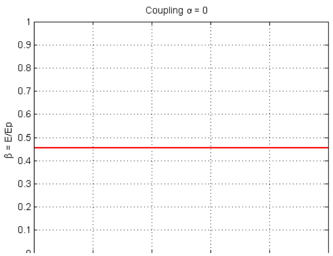
Sample state-space diagram for the demonstration three-equation model.



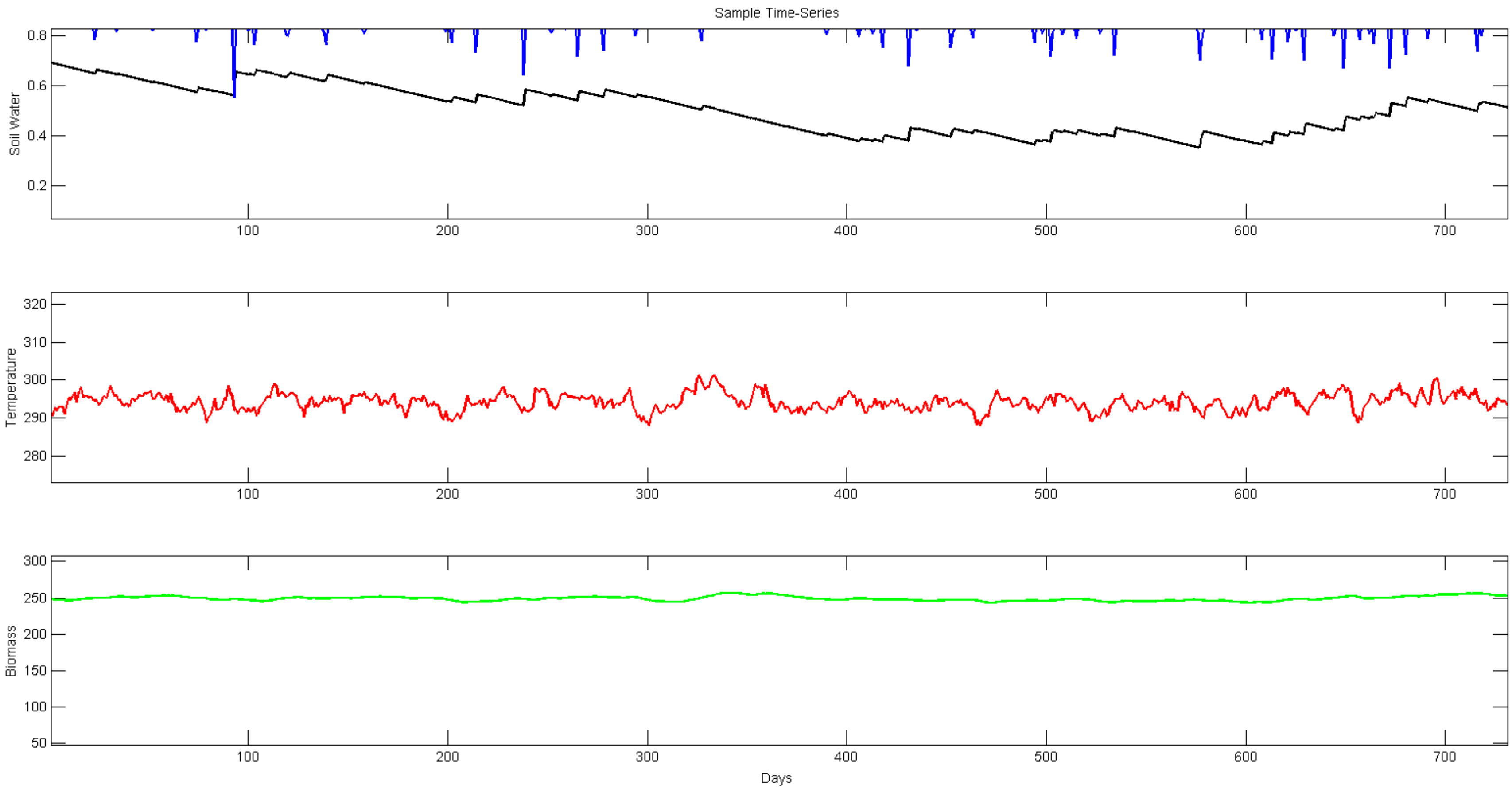
Inter-Storm Loops:



Rate of Covariation Dependent on Closure Slope/Shape



Without the closure function (see left) co-variations muted in the three variables.

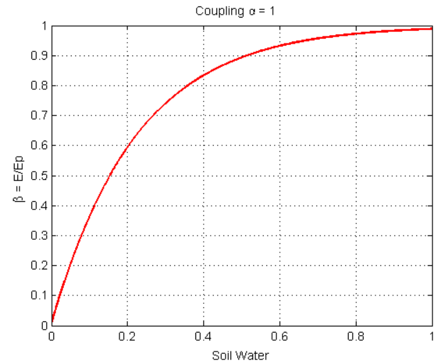


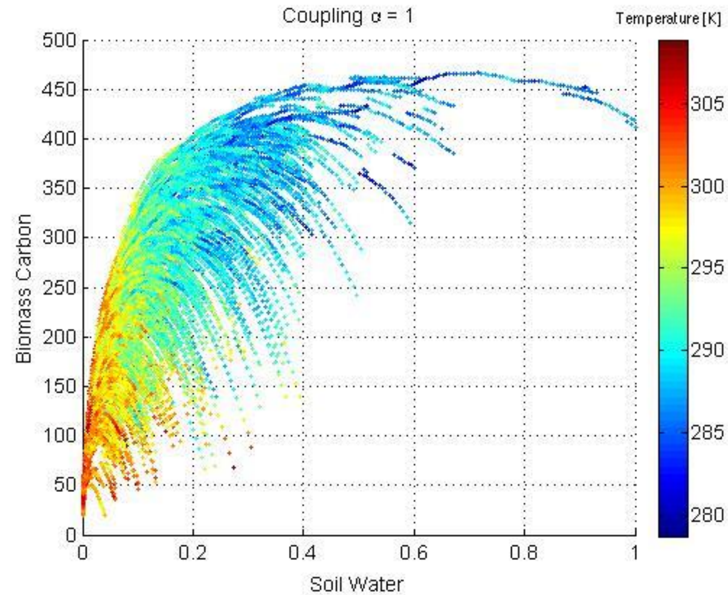
Cycles Interrupted

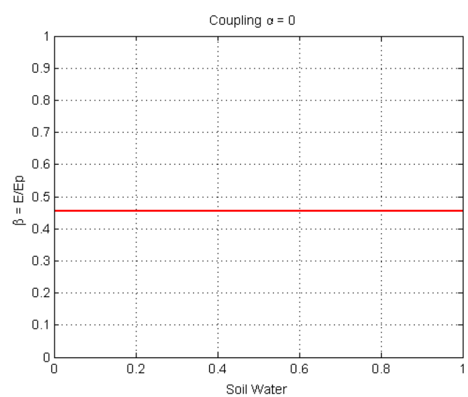
Sample state-space diagram for the demonstration three-equation model.

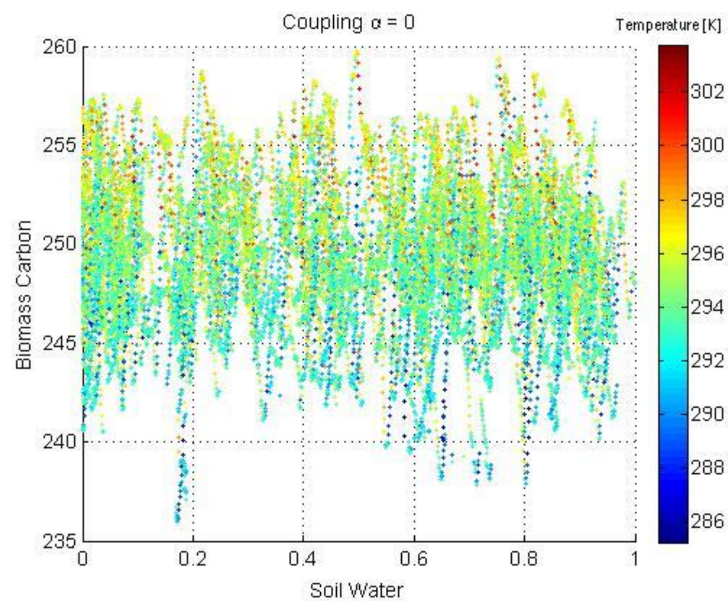
Without closure, co-variations disappear.

But this is extreme contrast case.









Parameterized Closure Functions But Without Strong Evidence

NOAH

model grid cell and

$$\beta = \left(\frac{\Theta_1 - \Theta_w}{\Theta_{ref} - \Theta_w}\right)^f \qquad (7)$$

represents a normalized soil moisture availability term where Θ_w is the wilting point and Θ_{ref} is the field capac-

CLM

functional type and the soil water potential of each soil layer

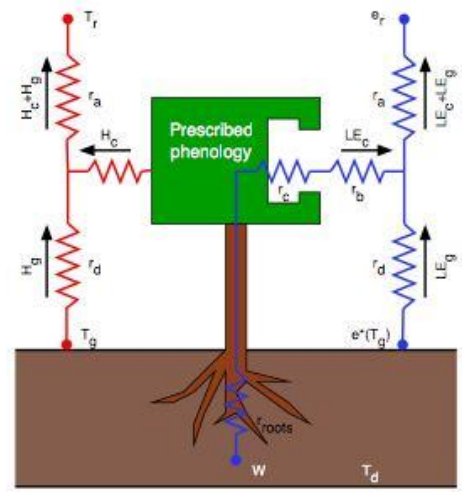
$$\beta_t = \sum_i w_i r_i \geq 1\times 10^{-10} \qquad (8.10)$$

where w_i is a soil dryness or plant wilting factor for layer i, and r_i is the fraction of roots in layer i.

The plant wilting factor w_i is

$$w_i = \left\{ \frac{\psi_{max} - \psi_i}{\psi_{max} + \psi_{sat,i}} \quad \text{for } T_i > T_f \right\} \qquad (8.11)$$

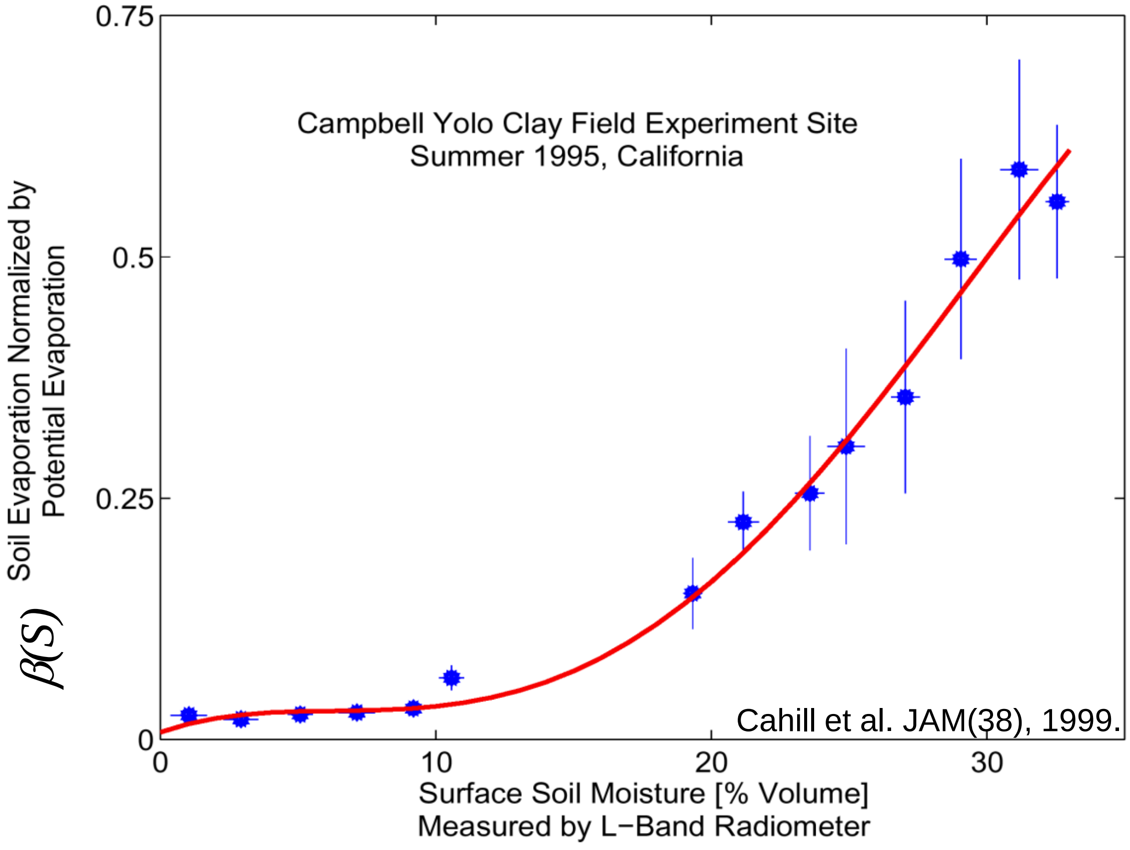
$$\beta = \begin{cases} \frac{1}{4}\left[1 - \cos\left(\frac{\theta_1}{\theta_{fc}}\pi\right)\right]^2 & \theta_1 < \theta_{fc} \\ 1 & \theta_1 \geq \theta_{fc} \quad \text{or} \quad q_{air} > \alpha q_{sat}(T_g) \end{cases}, \qquad (5)$$



R. Stöckli and P. L. Vidale (ETH)

How well have we measured/estimated?

Only measured at a few flux tower sites. But valid for the footprint of flux tower (does not scale to a global model grid area) and only known for a few landscape types.



To estimate this closure function, **independent** observations of

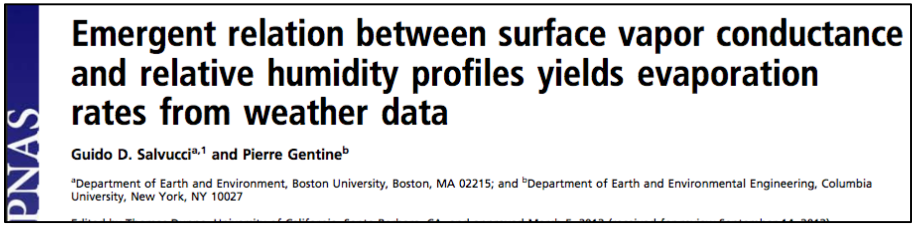
soil moisture state

and

evaporation flux

are required. Globally.

Evaporation



PNAS

Emergent relation between surface vapor conductance and relative humidity profiles yields evaporation rates from weather data

Guido D. Salvucci[a,1] and Pierre Gentine[b]

[a]Department of Earth and Environment, Boston University, Boston, MA 02215; and [b]Department of Earth and Environmental Engineering, Columbia University, New York, NY 10027

Water Resources Research

RESEARCH ARTICLE

10.1002/2014WR016072

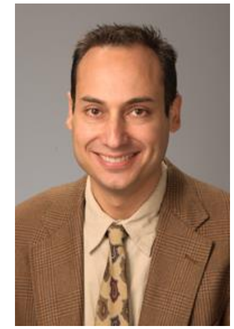
Key Points:

- Surface conductance is estimated without detailed knowledge of surface state

Evapotranspiration based on equilibrated relative humidity (ETRHEQ): Evaluation over the continental U.S.

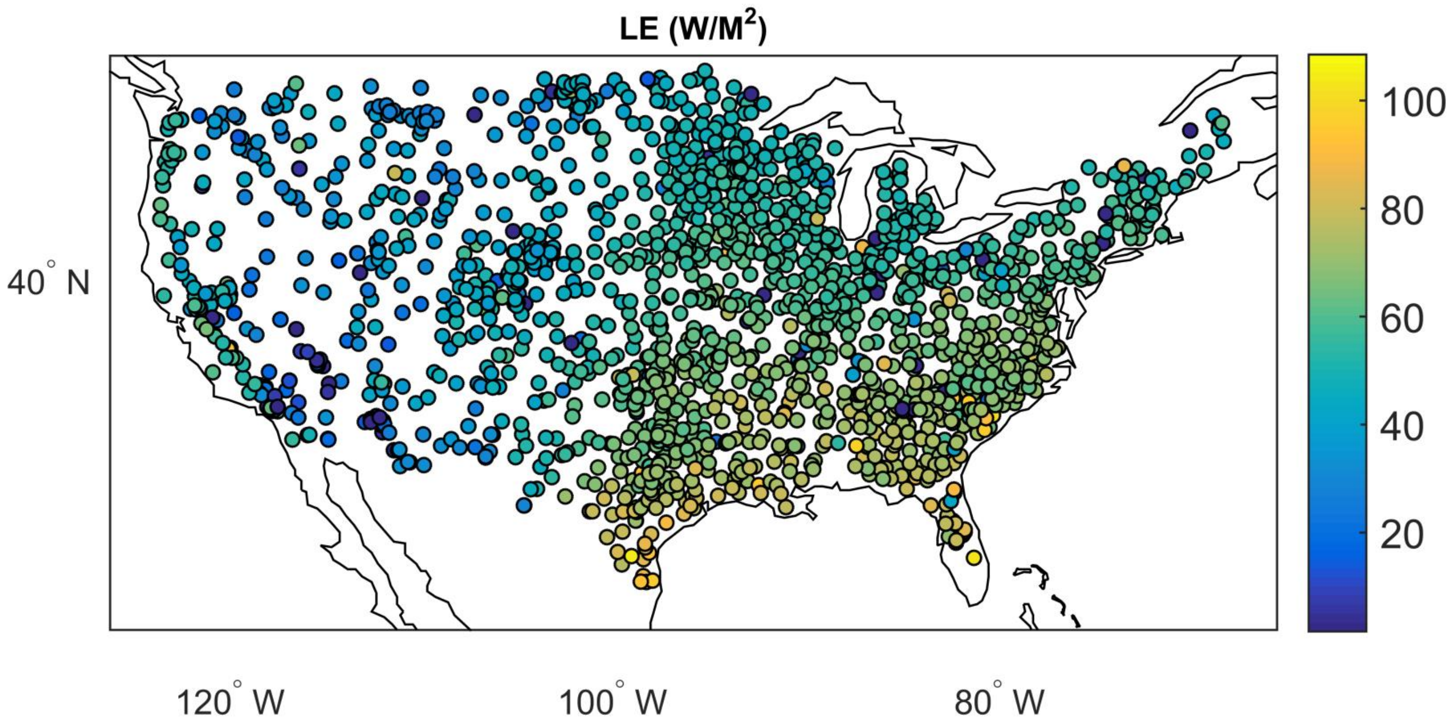
Angela J. Rigden[1] and Guido D. Salvucci[1]

[1]Department of Earth and Environment, Boston University, Boston, Massachusetts, USA



Guido Salvucci
(Boston Univ.)

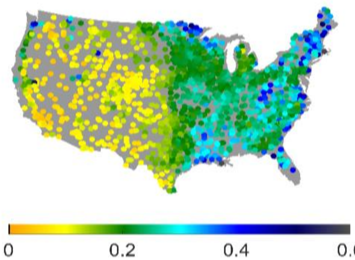
Pierre Gentine
(Columbia Univ.)



April 1, 2015 to
March 30, 2016

Coupling of Terrestrial Water, Energy and Carbon Cycles

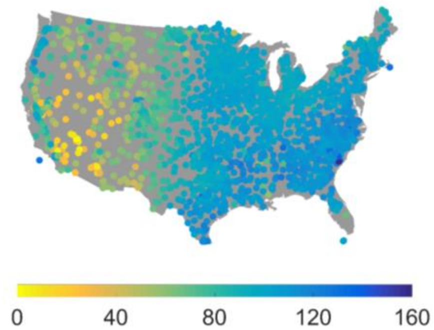
SMAP L2

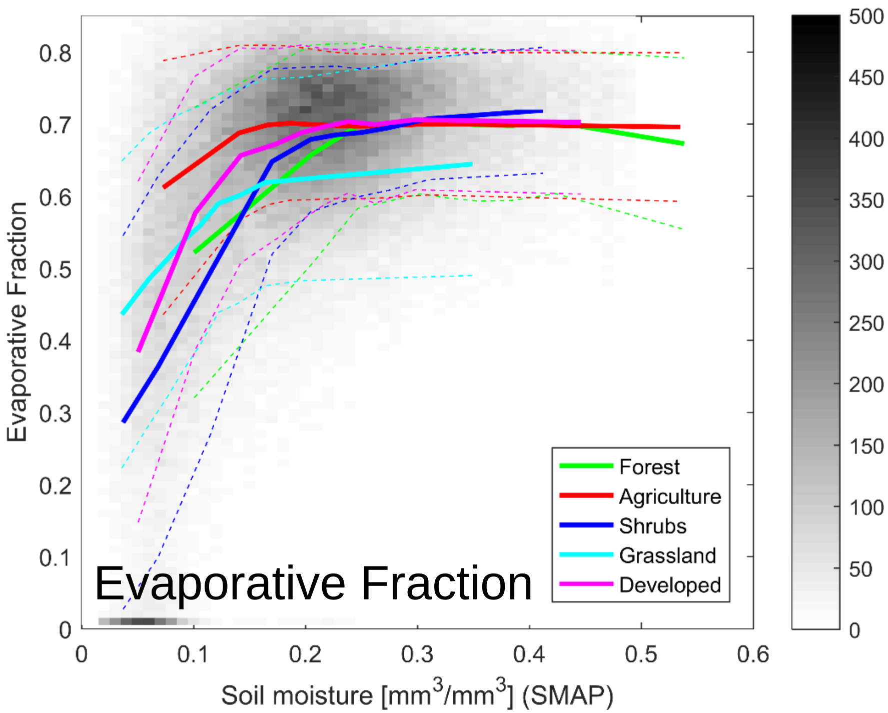


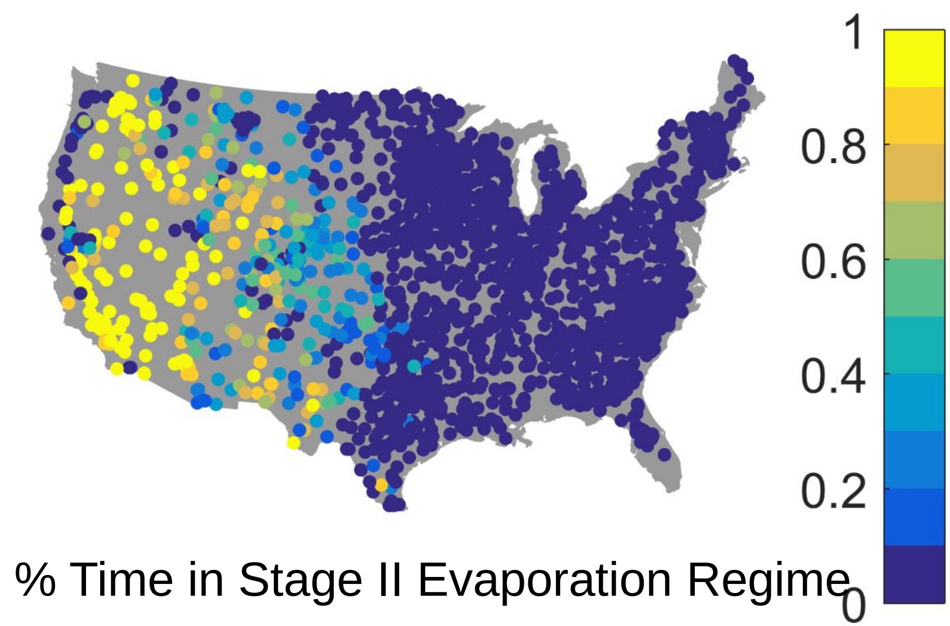
+

ETRHEQ (Evaporation Rate)

(Salvucci & Gentine, PNAS 2013)

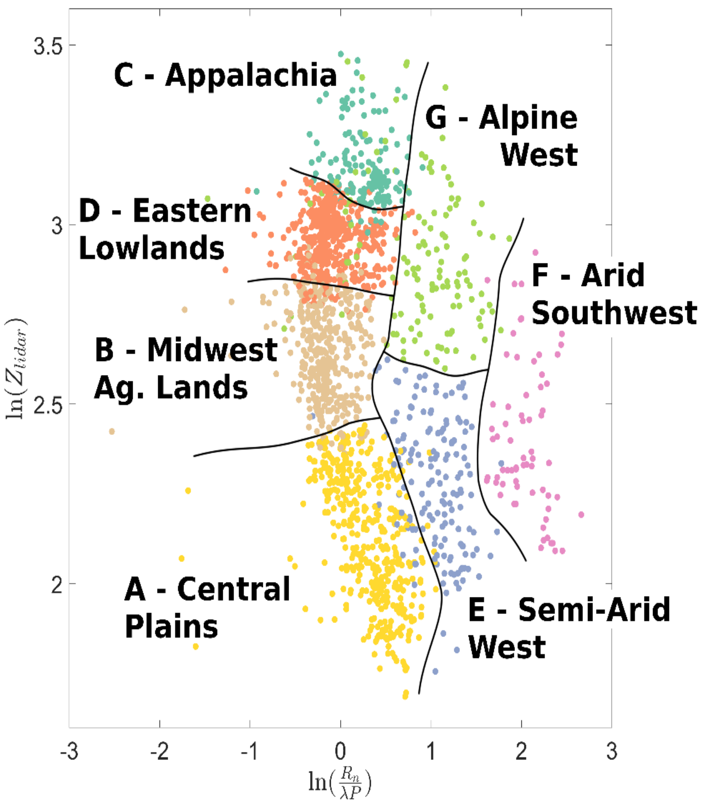


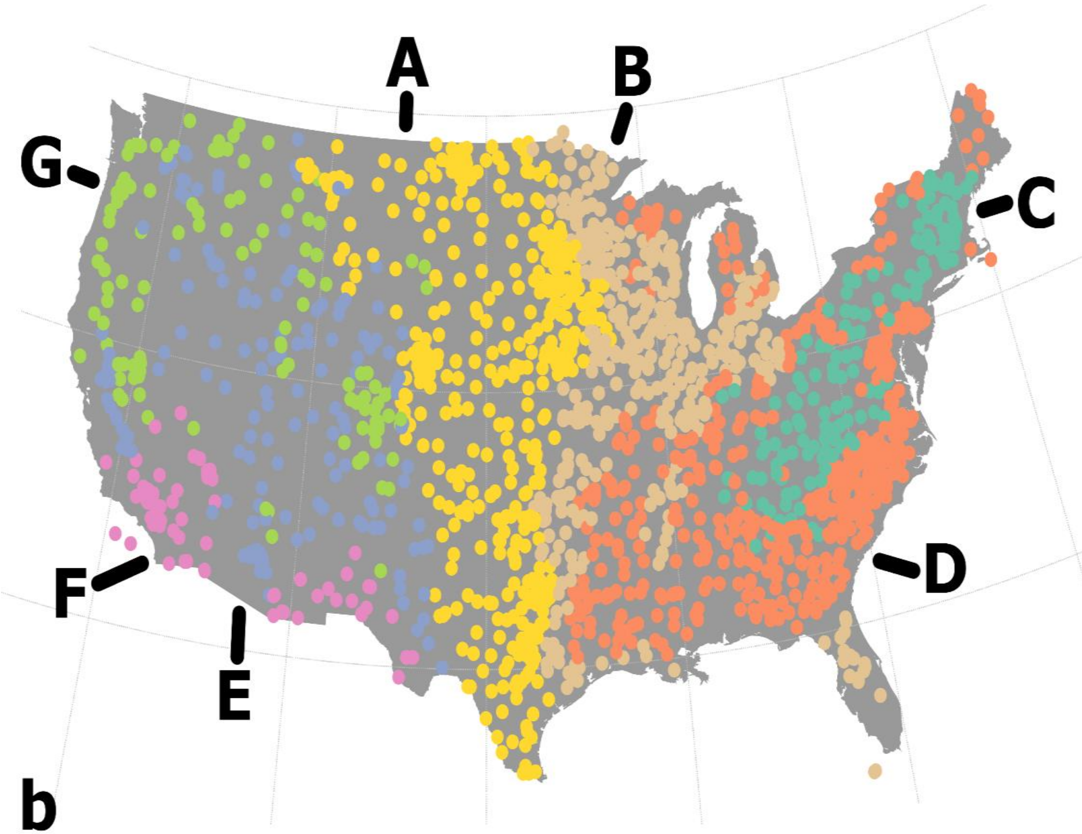




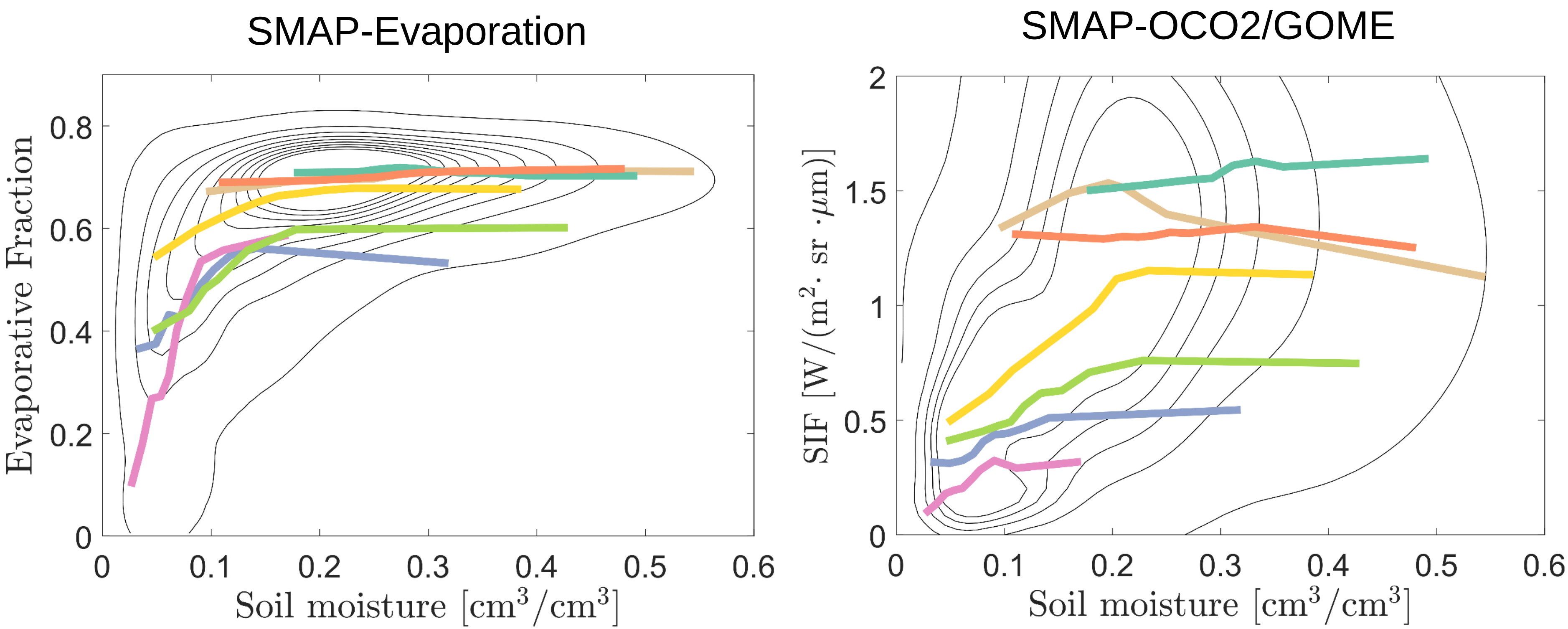
Gianotti, Rigden, Salvucci and Entekhabi (2017)

Ecohydrological Regions





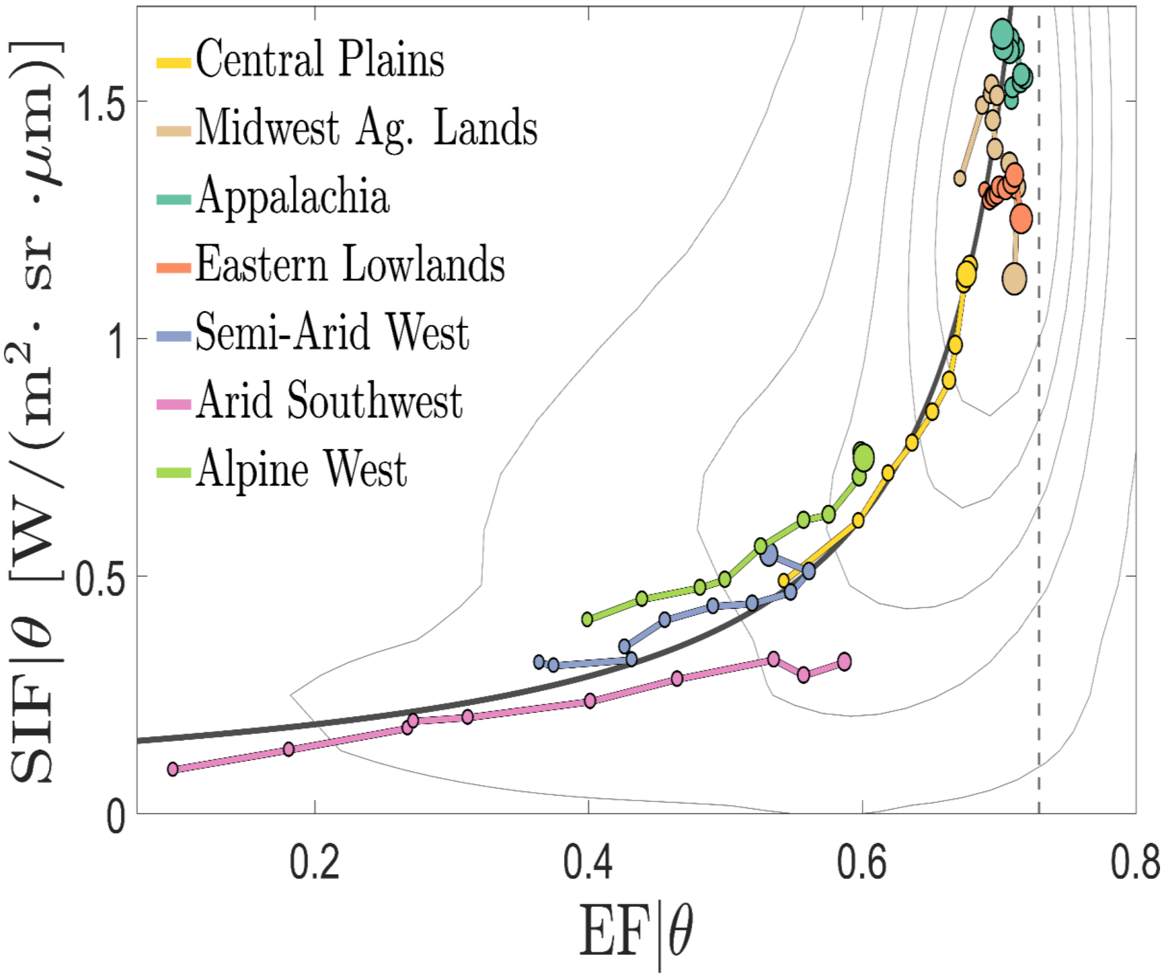
Soil Moisture Controls on Water and Carbon Cycles



A – Central Plains
B – Midwest Agricultural Lands
C – Appalachia
D – Eastern Lowland Forests
E – Semi-arid West
F – Arid Southwest
G – Alpine West

SIF|θ vs EF| θ

Gianotti, Rigden, Salvucci and Entekhabi (2017)

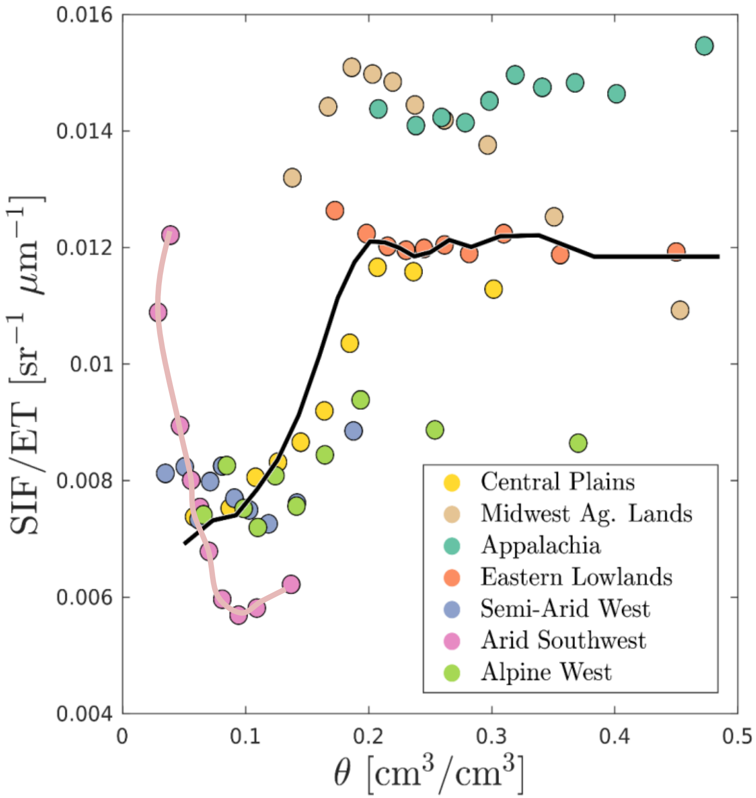


- Connects EF vs θ and SIF vs θ curves
- AIC\prefer a single relationship over independent relationships by region
- Convex shape implies landscape-level Water Use Efficiency increases with EF (opposite of physiological WUE)

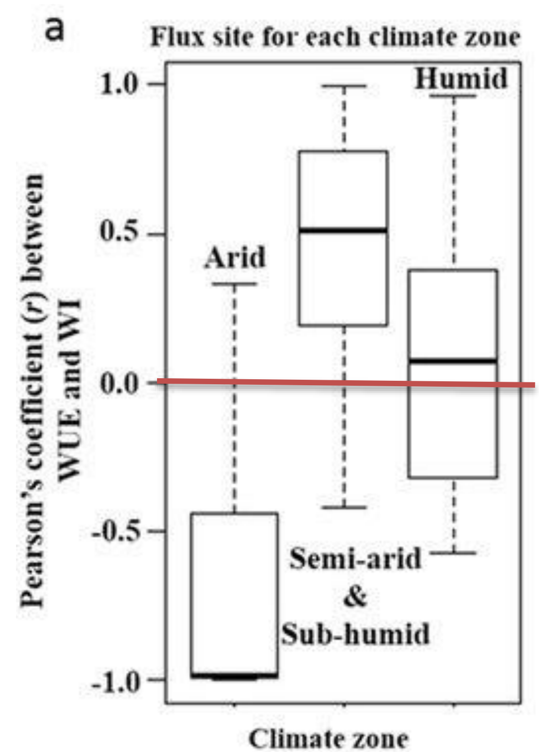
Landscape-Level “Water Use Efficiency (WUE)”

SIF/ET is WUE at the landscape scale

Decreases with θ for the arid regions, then increases with θ for semi-arid regions and flat for humid regions (in agreement with Yang *et al.*[1])



Gianotti, Rigden, Salvucci and Entekhabi (2017)

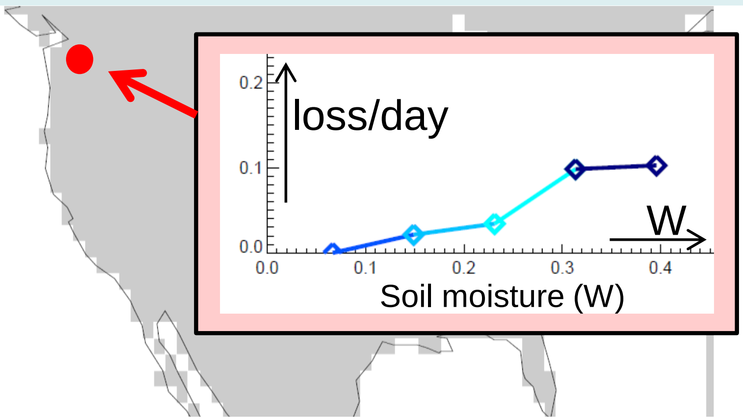


[1] Yang, Y. *et al.* Contrasting responses of water use efficiency to drought across global terrestrial ecosystems. *Nature,* **6,** 23284 (2016). [WI=Wetness Index]_

SMAP Estimates of Surface Hydrology Loss Functions

R. Koster (NASA GSFC)

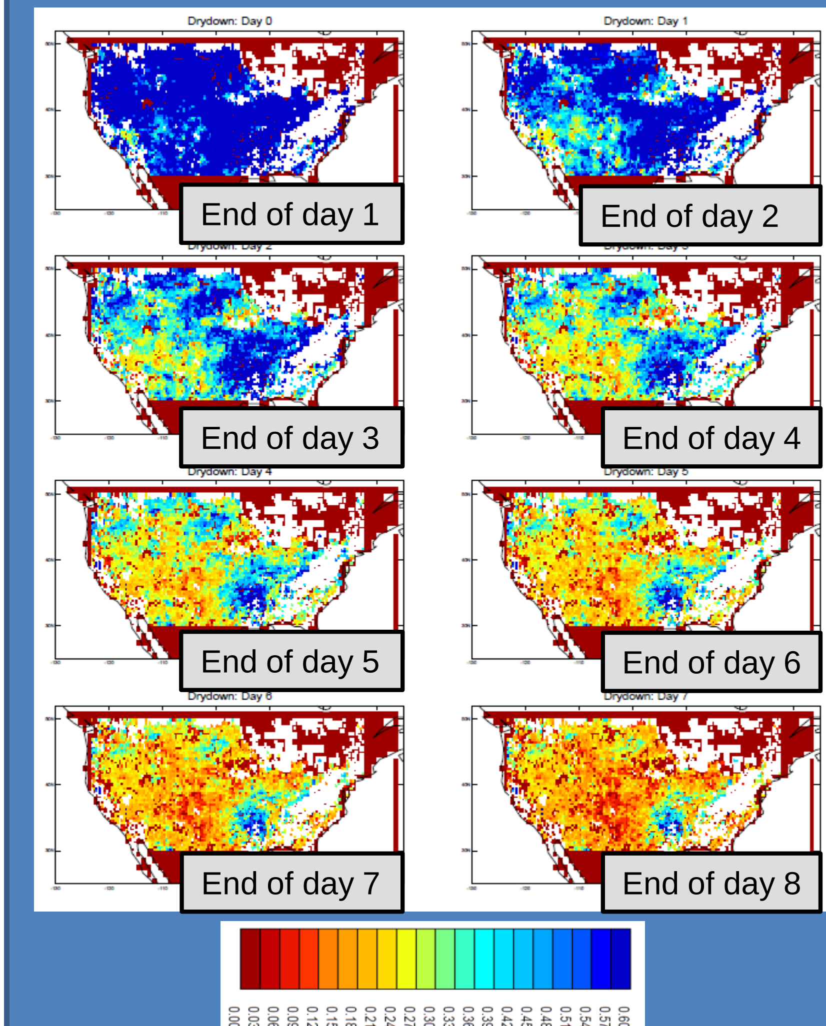
Spatial distributions of soil moisture loss function (loss from evaporation and drainage) can be extracted from collocated SMAP and precipitation measurements for summertime:



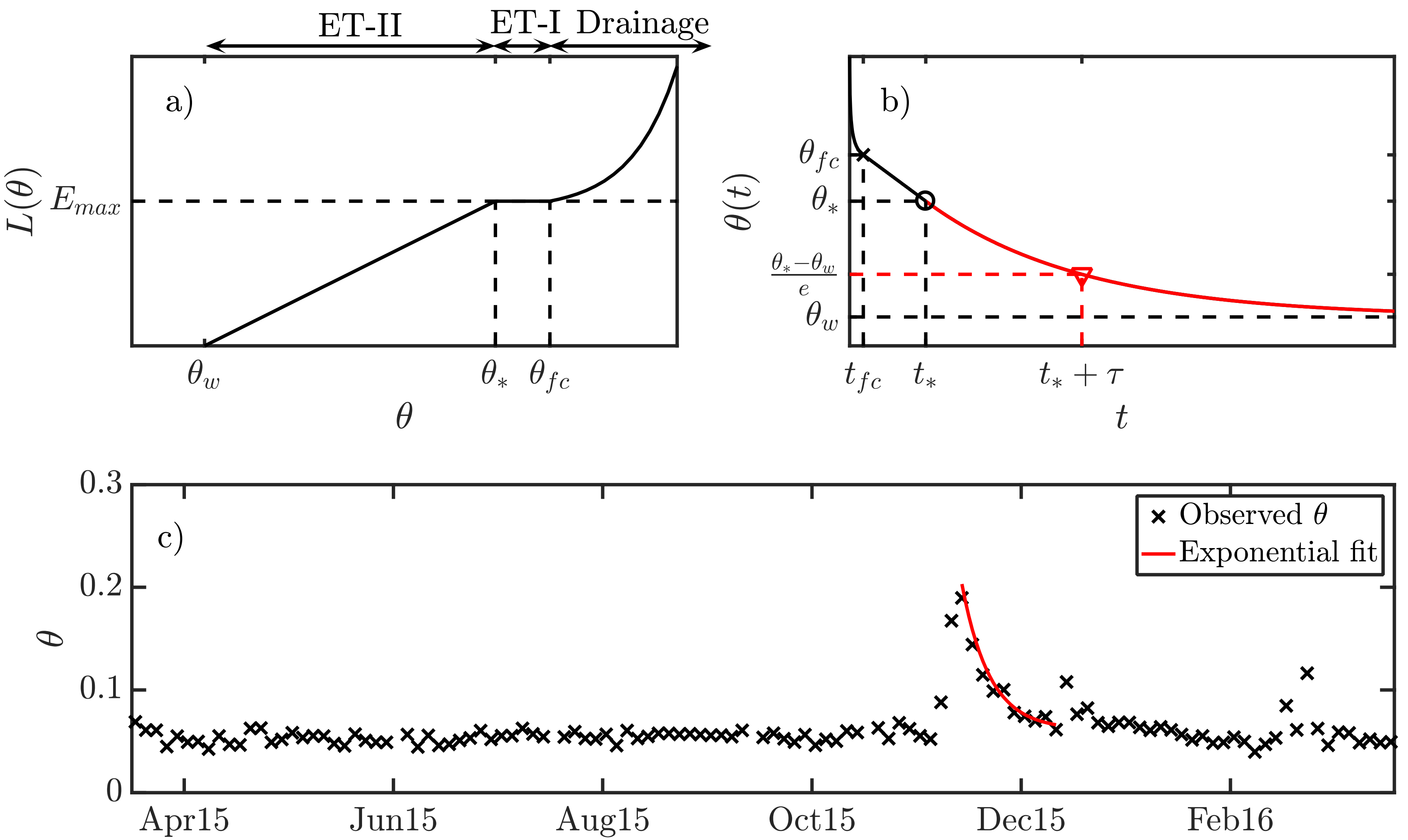
Derived loss functions are highly valuable:

– Improved precipitation estimation
– "Filling-in" of missing data; accurate forecasts of soil moisture several days into the future
– Characterization of regional differences in hydrological behavior (figure on right)

Loss function analysis: Begin with wet soil everywhere and examine *drydown*

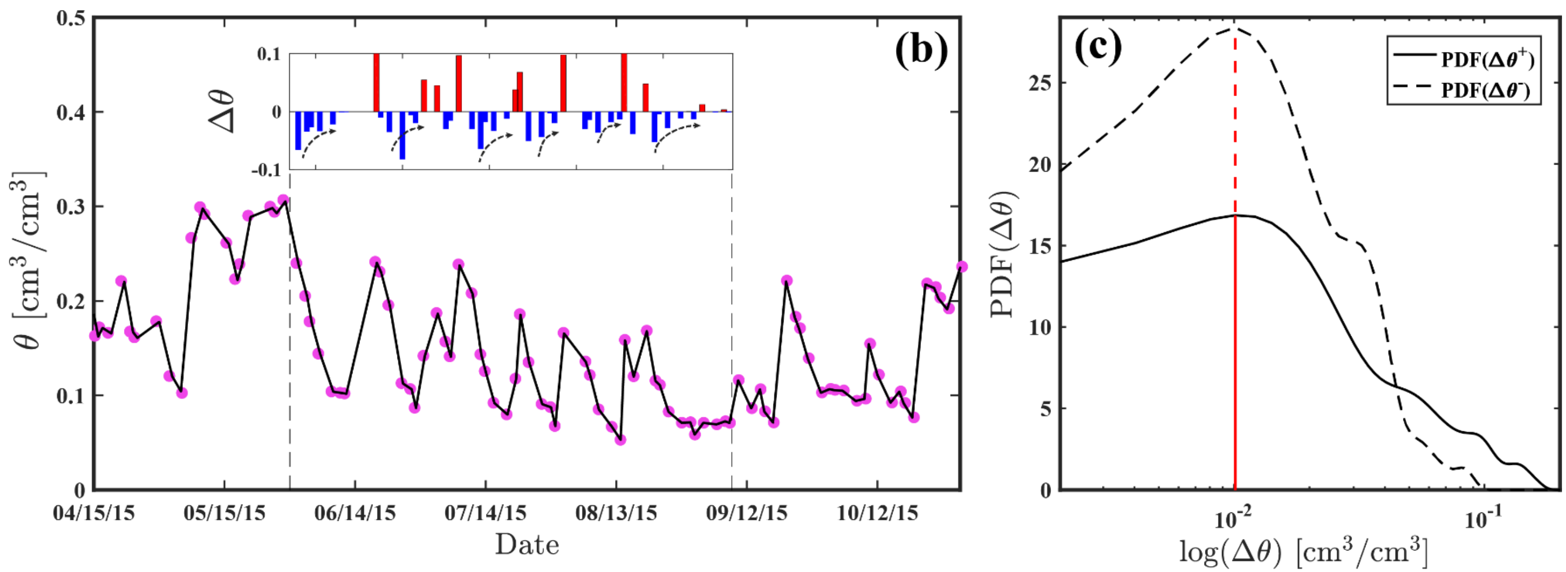


Stages of Drydowns: Landscape Water Loss



McColl, Wang, Peng, Akbar, Gianotti, Pan and Entekhabi, 2017: Global characterization of surface soil moisture drydowns , *GRL*.

Landscape Water Loss Function: Observation-Driven Estimates



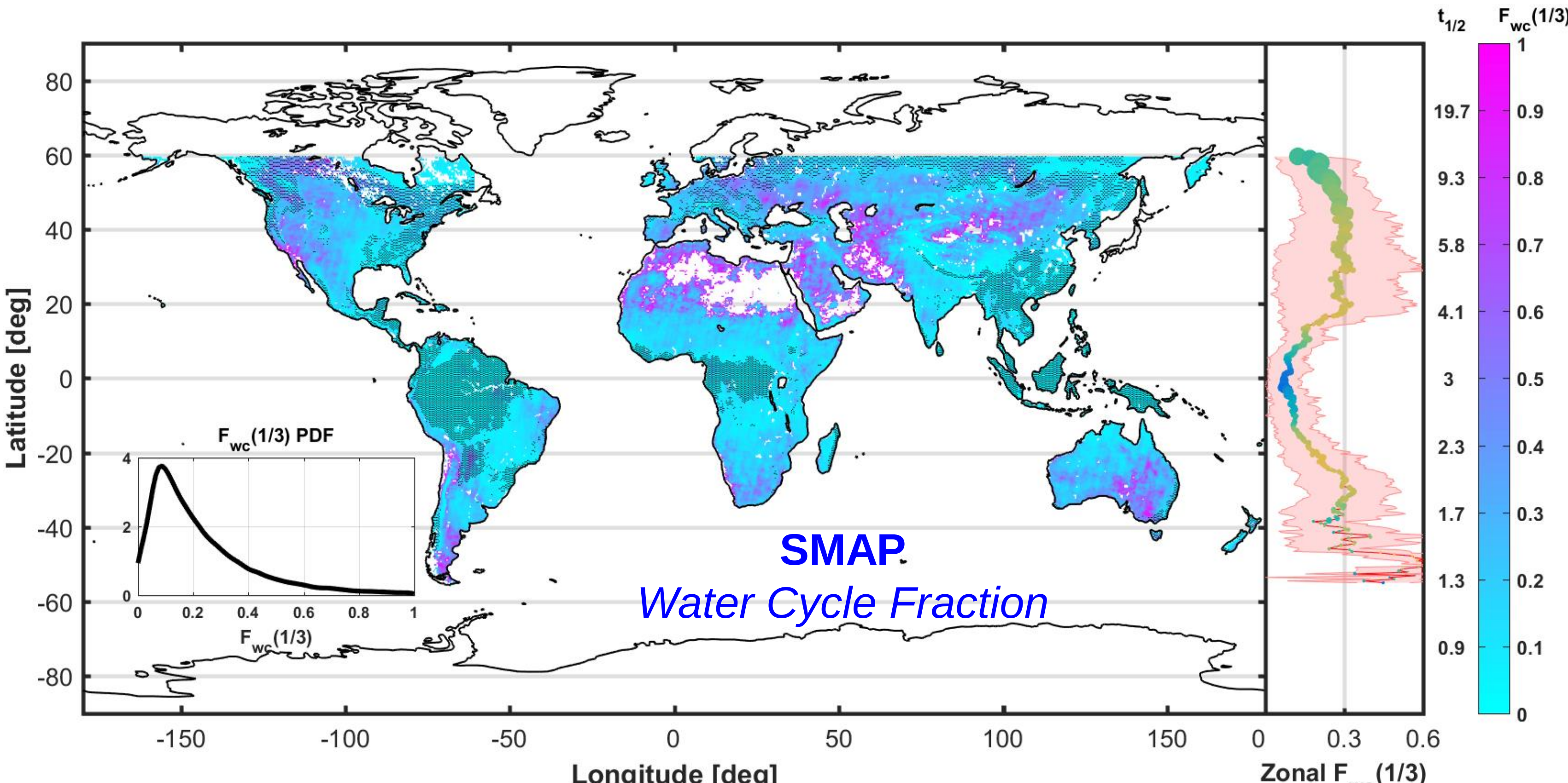
$$\Delta\theta_{i_+} = \begin{cases} \Delta\theta_i, \text{ if } \Delta\theta_i > 0 \\ 0, \text{ otherwise} \end{cases}$$

$$\Delta\theta_{i_-} = \begin{cases} \Delta\theta_i, \text{ if } \Delta\theta_i < 0 \\ 0, \text{ otherwise} \end{cases}$$

Soil Moisture and the Terrestrial Water Cycle: Positive Increments

McColl, Alemohammad, Akbar, Konings, Yueh and Entekhabi, 2017: The global distribution and dynamics of surface soil moisture, *Nature-Geoscience*, 10(2).

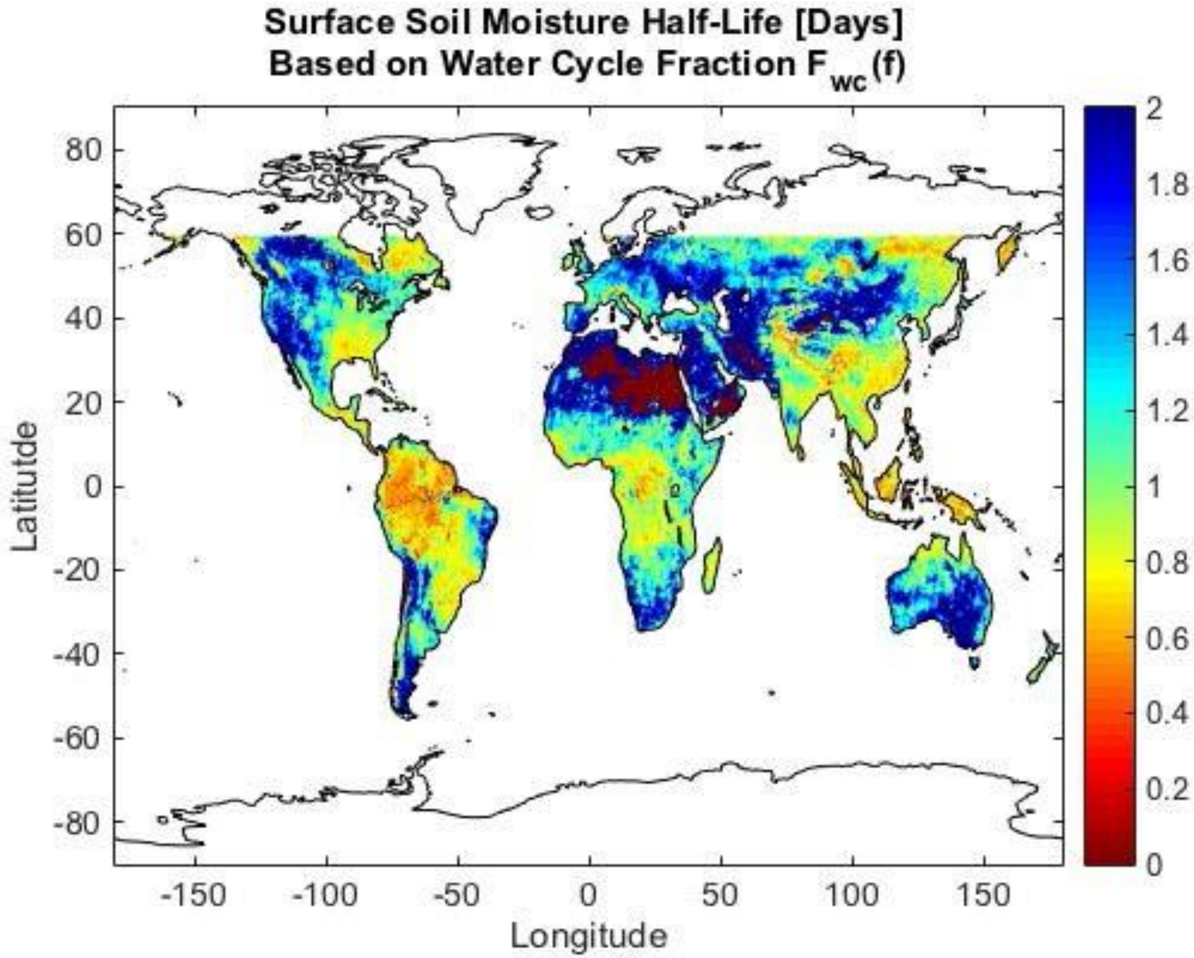
$$\Delta\theta_{i_+} = \begin{cases} \Delta\theta_i, \text{ if } \Delta\theta_i > 0 \\ 0, \text{ otherwise} \end{cases}$$



Even Though Soil Moisture is 0.001% of the Global ***Water Budget***, it Captures About 20% of the ***Water Cycle***

Soil Moisture Memory

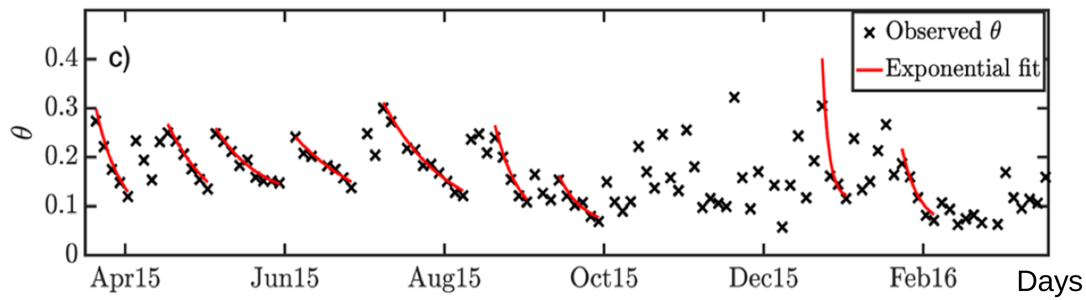
$$t_{1/2} = -\frac{f^{-1}}{log_2\left(F_{wc}(f)\right)}$$

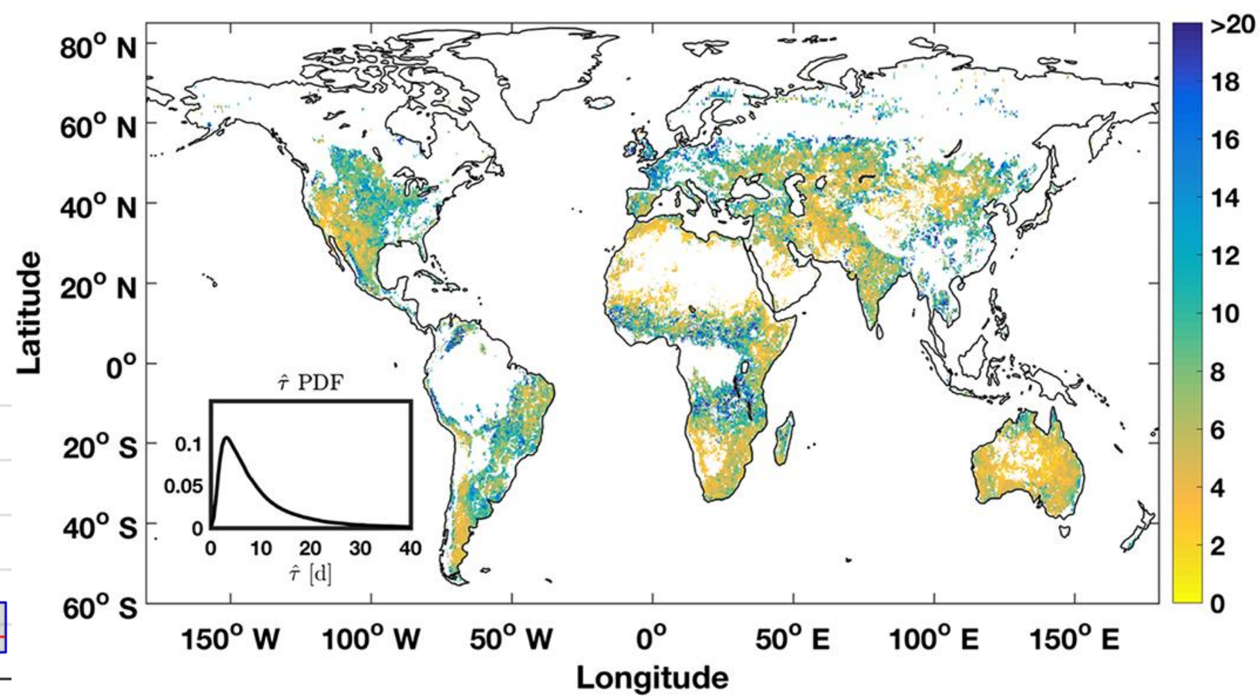


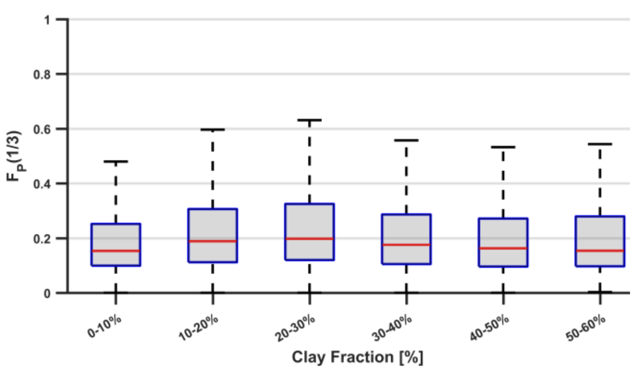
Soil Moisture Memory

McColl et al., 2017b: Global characterization of surface soil moisture drydowns, 44, *Geophysical Research Letters*.

Memory of surface soil moisture can extend to days especially where land-atmosphere coupling is significant and forecast skill can be extended.

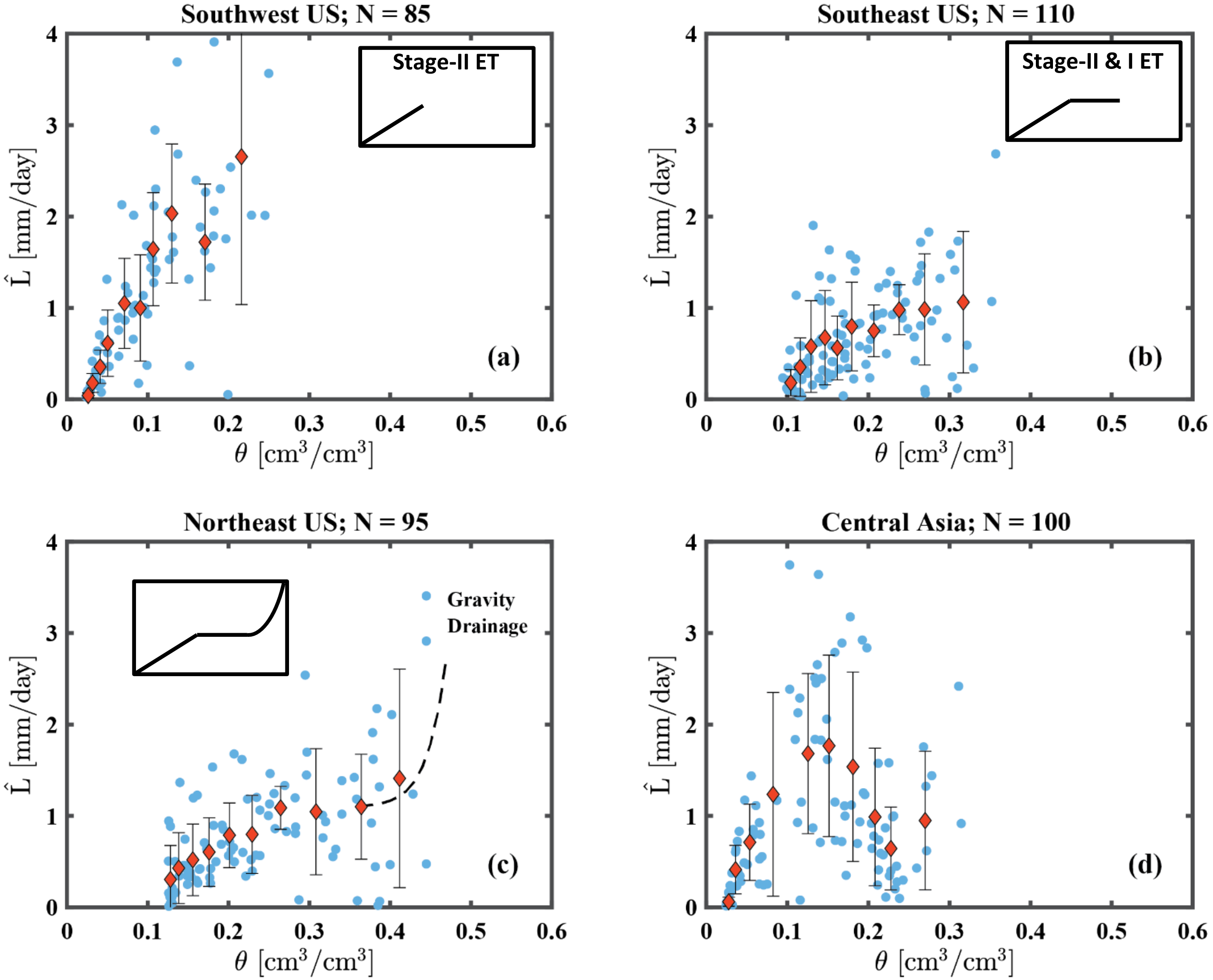






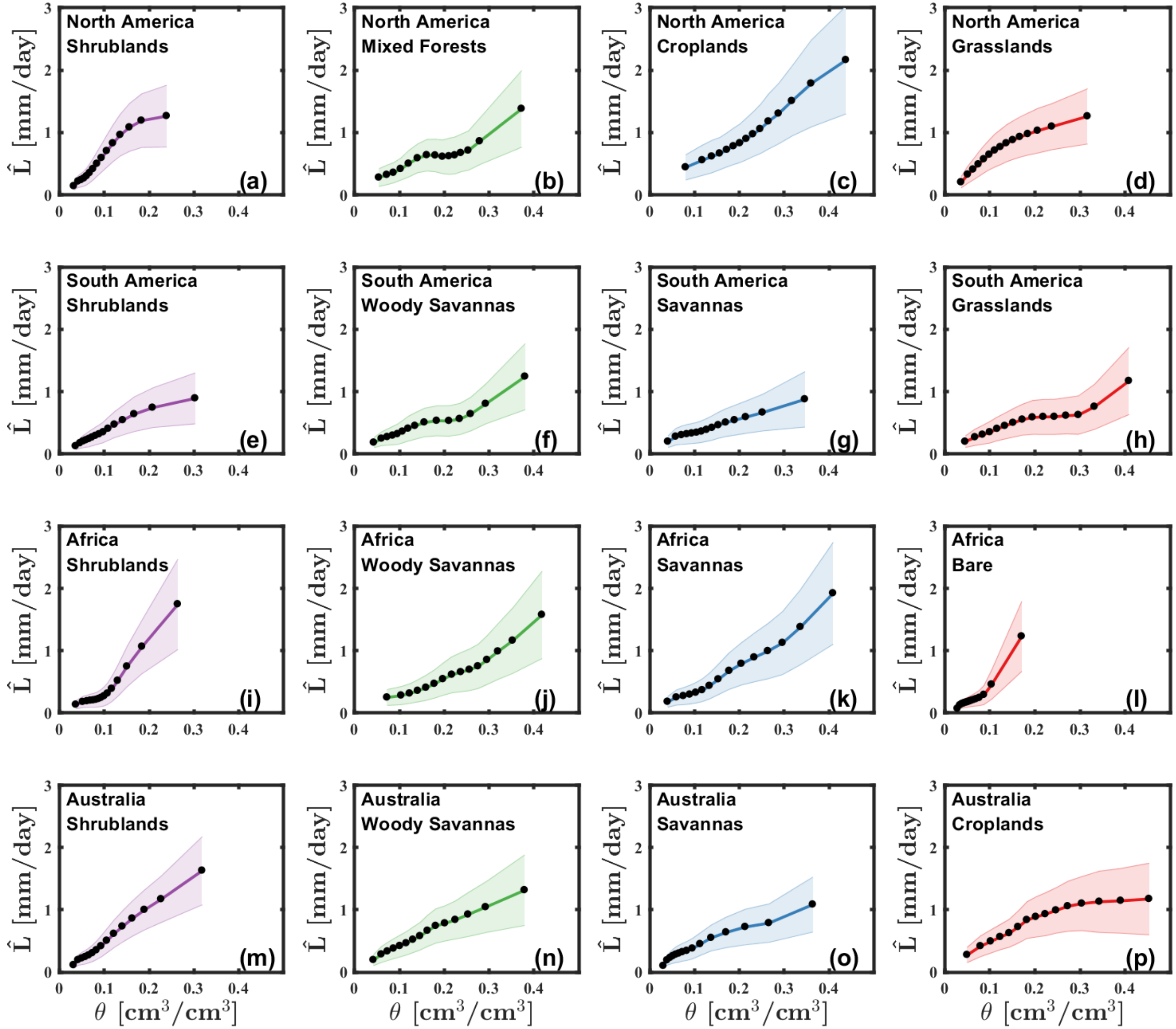
Observation-Driven Estimates of Landscape Water Loss: Negative Increments

$$\Delta\theta_{i\_} = \begin{cases} \Delta\theta_i, \text{ if } \Delta\theta_i < 0 \\ 0, \text{ otherwise} \end{cases}$$

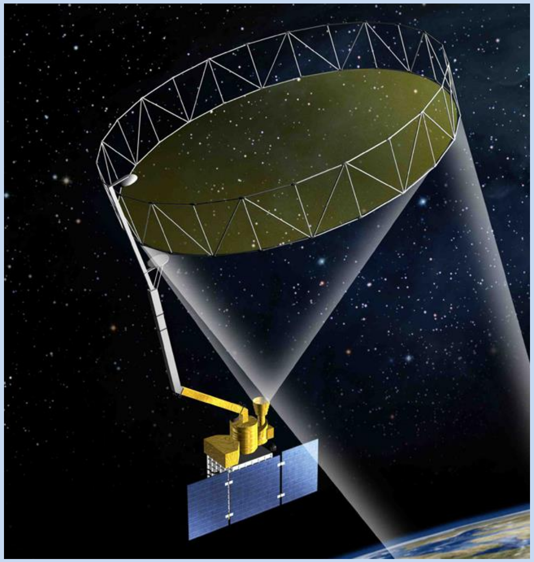


Akbar, McColl, Gianotti, Haghighi and Entekhabi, 2017: Estimation of the Ecosystem-scale soil water losses from satellite observations of soil moisture, *Geophysical Research Letters*

Loss Function for Different IGBP Classes

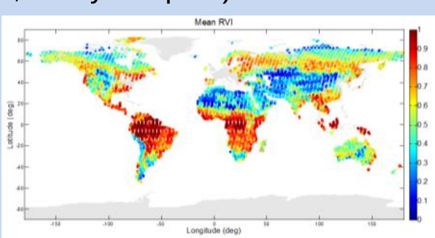


Global Ecology in the SMAP, OCO-2, and ICESat-2 Era



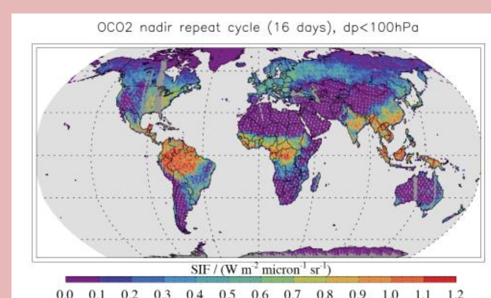
Radar Vegetation Index
(3 km, 4 Days Repeat)

Radiometer Vegetation µwave Opacity
(40 km, 3 Days Repeat)



Canopy Water Content and Stress

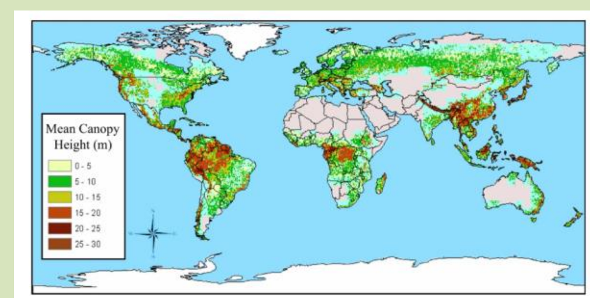
Solar-Induced Chlorophyll Fluorescence



Frankenberg et al., 2014: Prospects for chlorophyll fluorescence remote sensing from the OCO-2, RSE 147, 1-12.

GPP

Canopy Height



Abdalati et al., The ICESat-2 Laser Altimetry mission, Proc. IEEE, 98, 735-751.

Structure

Radiative Transfer

$$T_B = T_s \cdot (1 - r) \cdot e^{-\tau} + T_s \cdot (1 - e^{-\tau}) \cdot (1 - \omega) \cdot (1 + r \cdot e^{-\tau})$$

Attenuation (Vegetation)

Scattering (Vegetation)

Surface Emission (Soil Moisture)

Canopy Emission (Vegetation)

Surface Reflection (Soil/Vegetation)

Beyond Baseline Algorithm:

Observations: TB_H, TB_V

Unknowns: ε_s, τ, ω

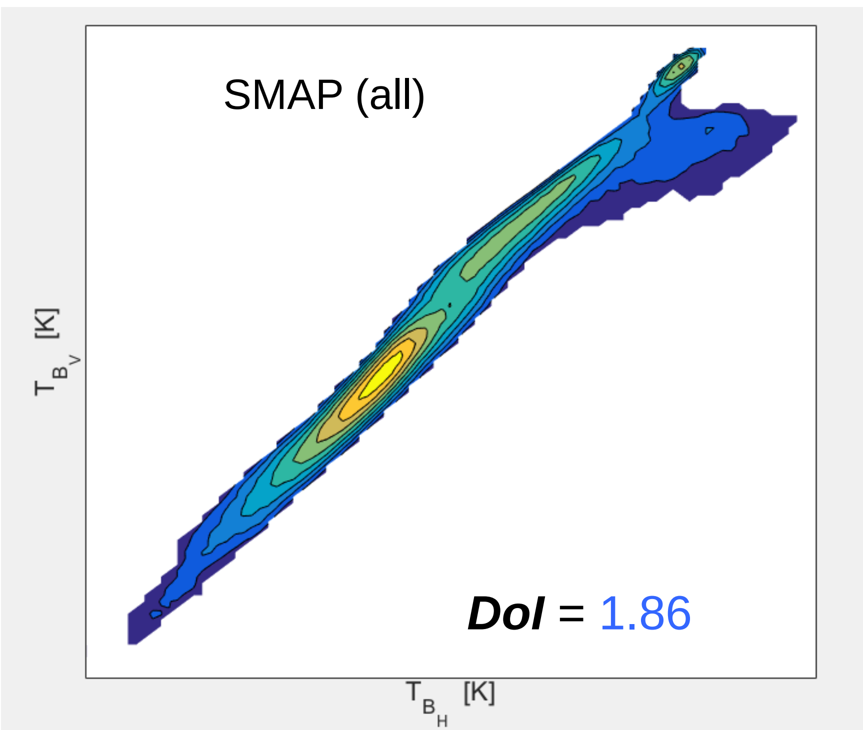
Retrieving Vegetation Effects Without Relying on Optical Ancillary Data

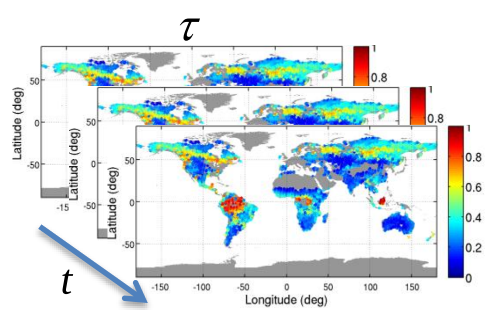
DoI: Konings, McColl, Piles, Entekhabi, 2015: How Many Parameters Can Be Maximally Estimated From a Set of Measurements? *GRSL* 12(5)

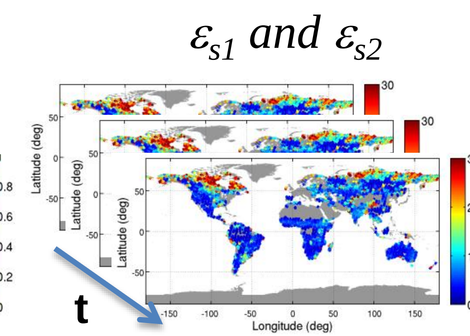
$$I(X;Y) = \int_Y \int_X p(x,y) \log\left(\frac{p(x,y)}{p(x)\,p(y)}\right) dx\, dy,$$

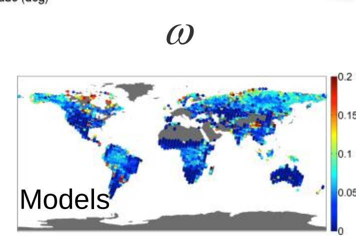
N = 2 overpasses (**4** Measurements):

2 x *DoI* = 2 x 1.86 = **3.7**

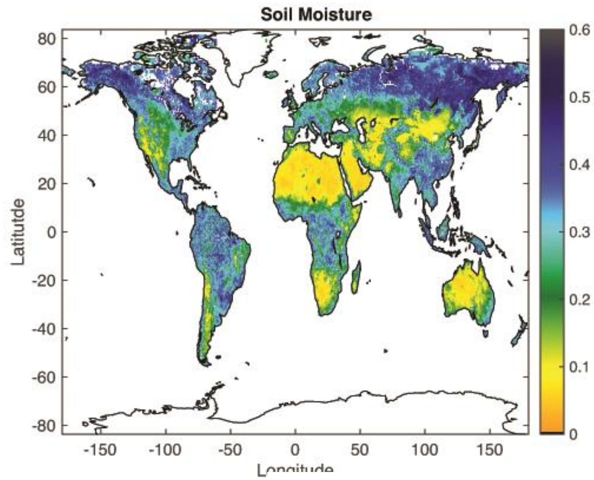




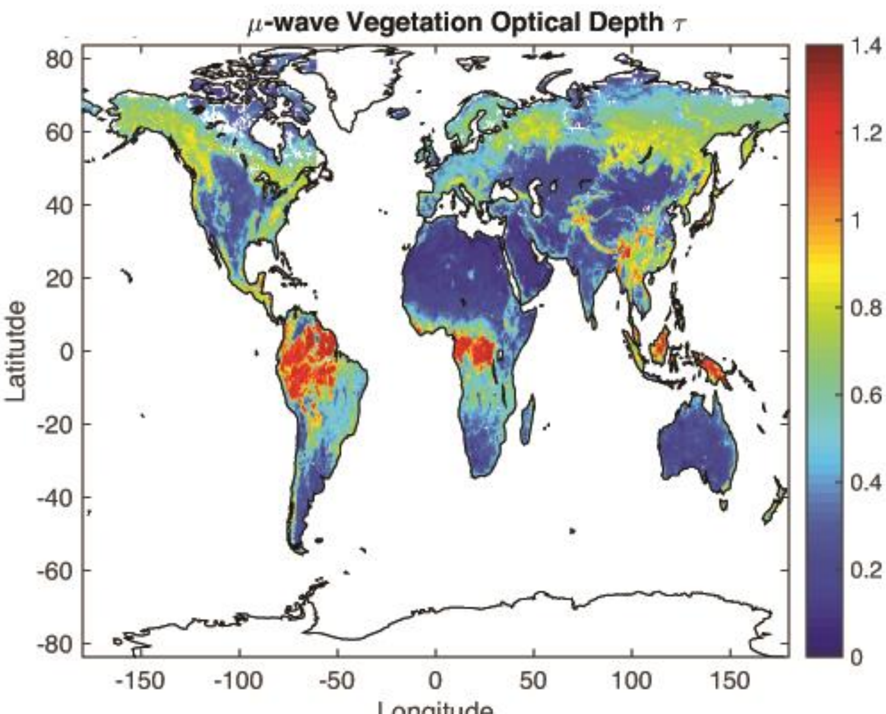


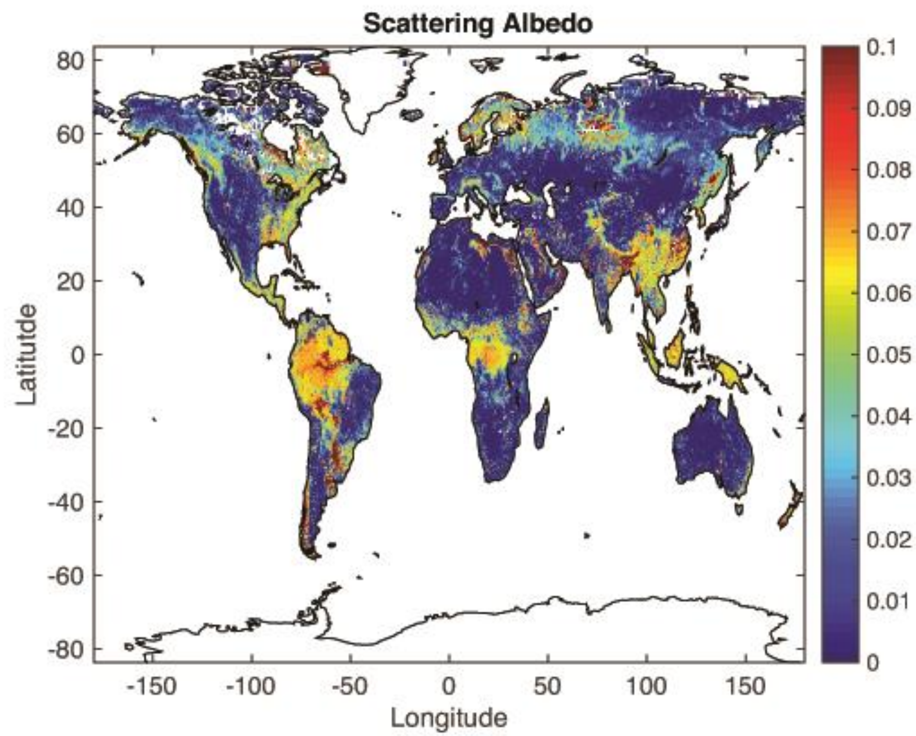


Climatology of Retrievals



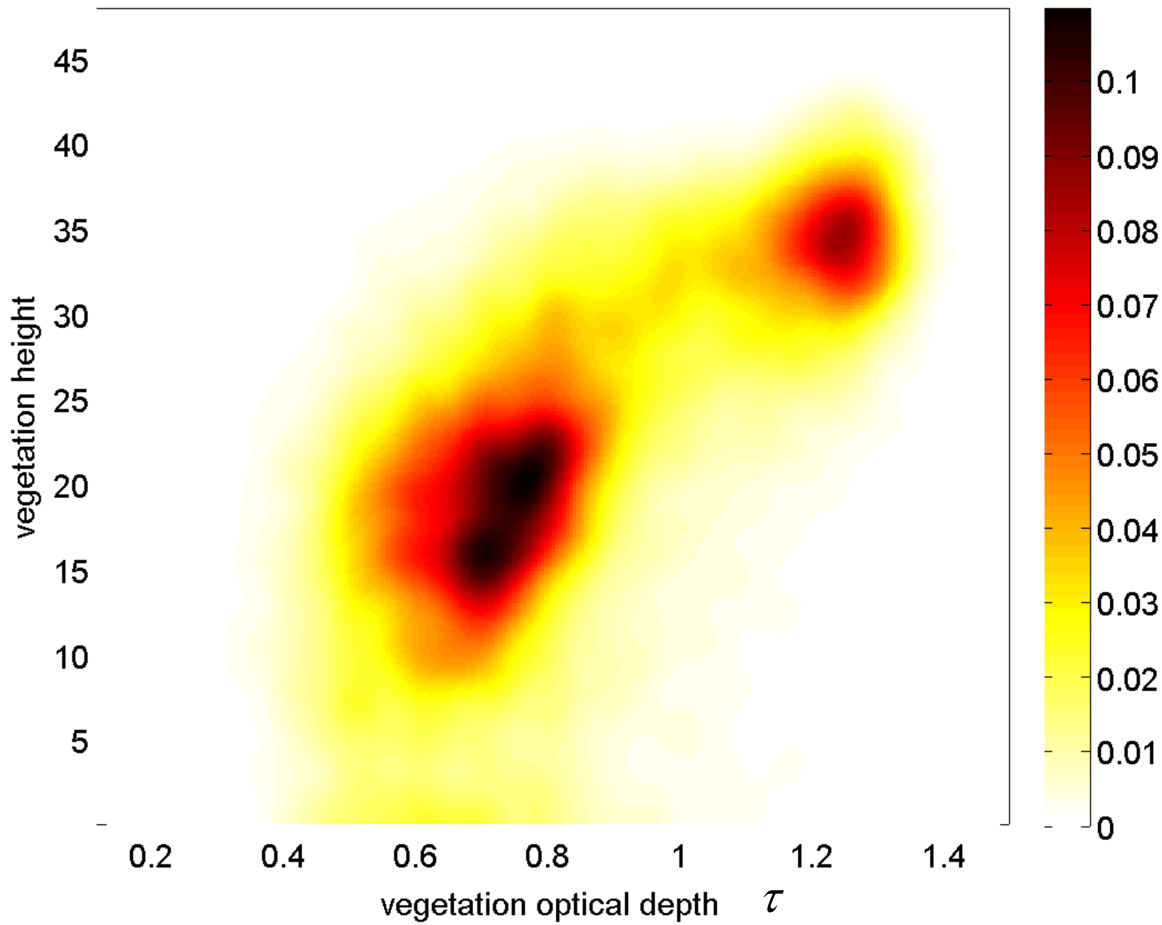
Konings, Piles, Das and Entekhabi, 2017: L-Band vegetation optical depth and scattering albedo estimation from SMAP, *Remote Sensing of the Environment*





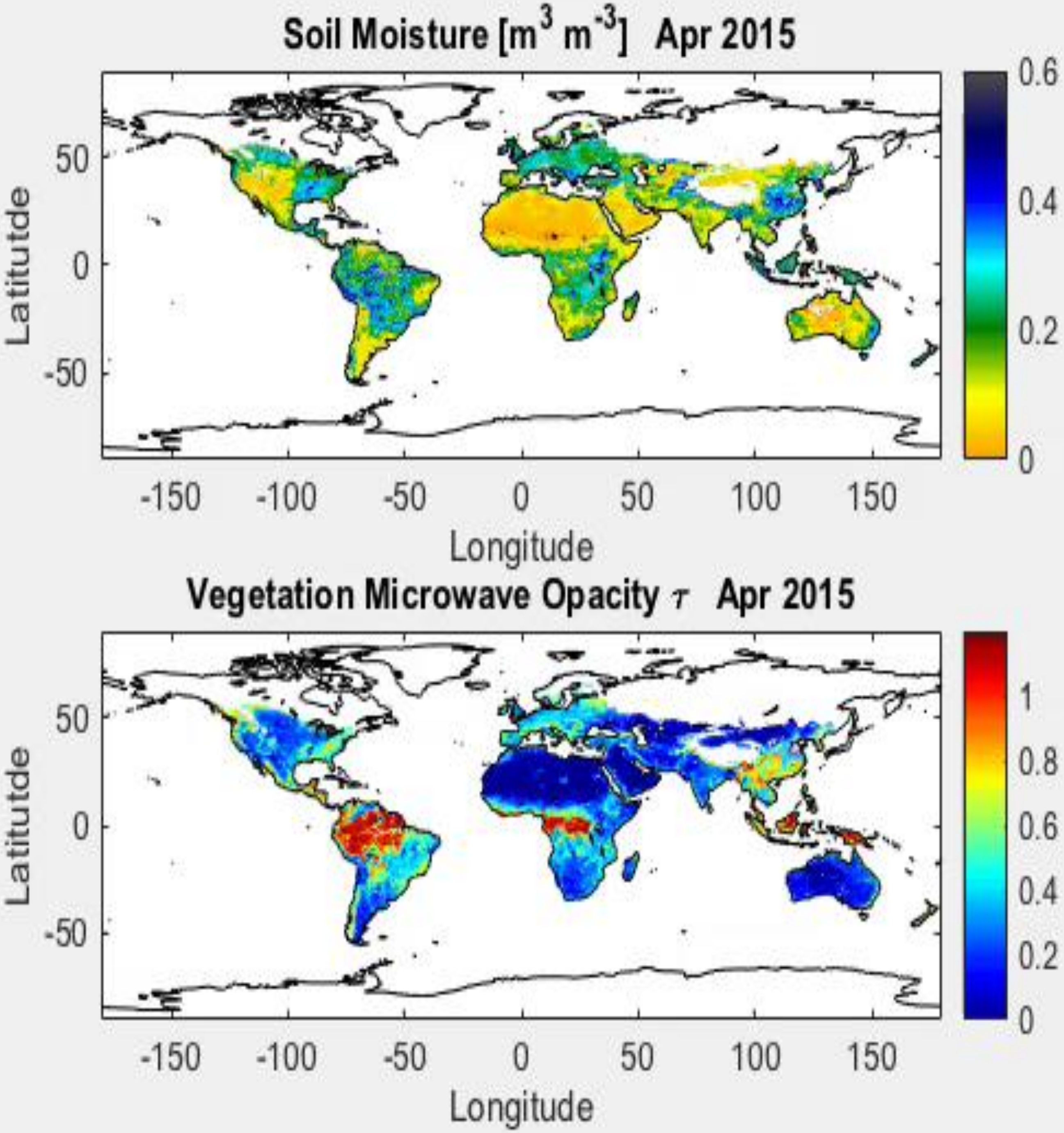
Microwave Interactions With Vegetation

GLAS/ICESat



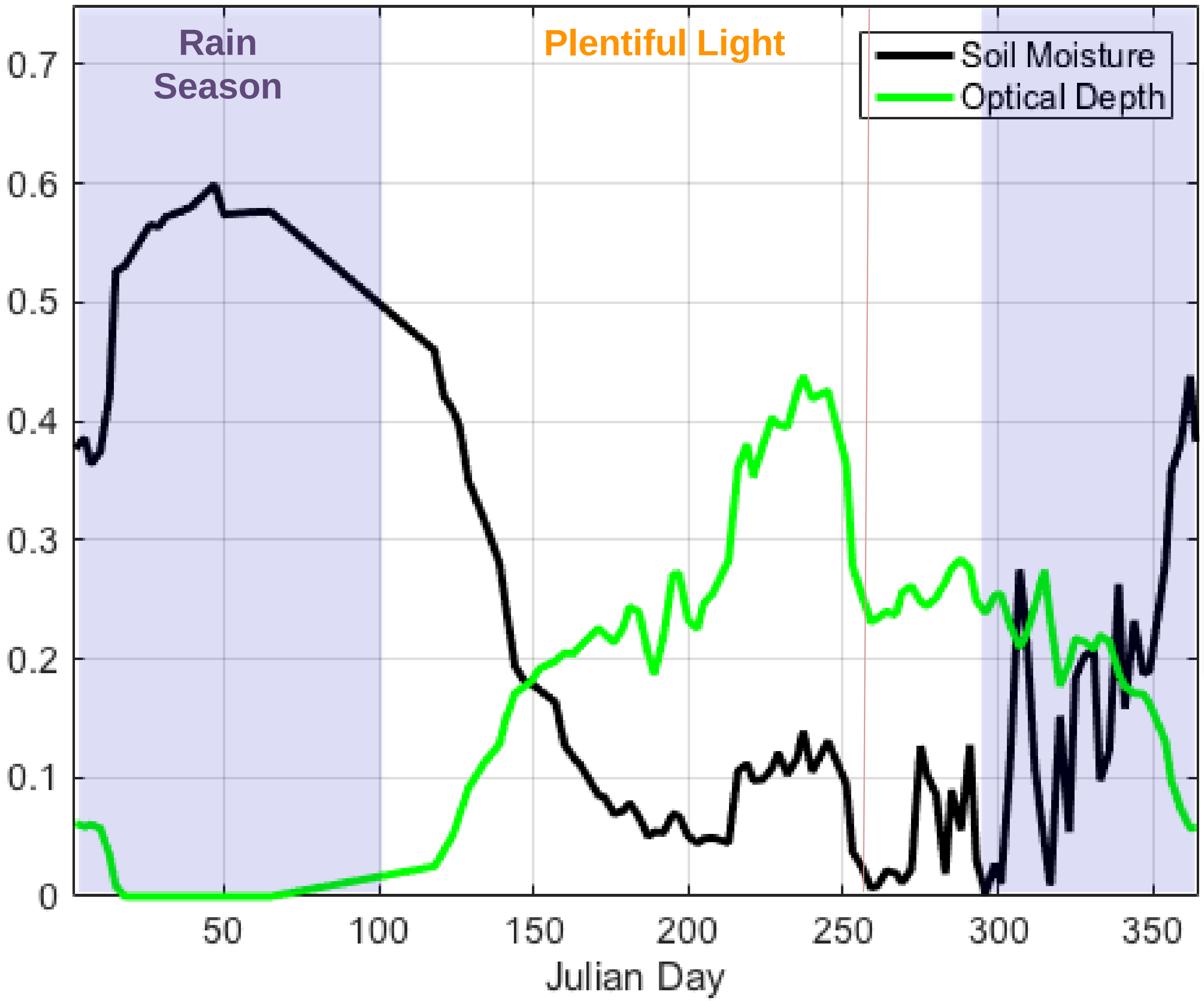
SMAP

Rötzer, Montzka, Entekhabi, Konings, McColl, Piles, Vereecken, 2017: Relationship between vegetation optical depth and HV-backscatter from the Aquarius mission, *IEEE Transactions of Geoscience and Remote Sensing*.

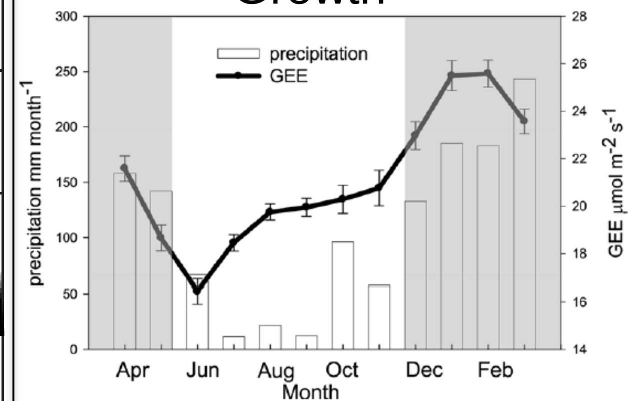


Soil Moisture [m3 m-3] Apr 2015
Latitutde
Longitude
50
0
-50
-150
-100
-50
0
50
100
150
0.6
0.4
0.2
0
Vegetation Microwave Opacity τ Apr 2015
Latitutde
Longitude
1
0.8
0.6
0.4
0.2
0

Dry Tropical Forest Phenology



Growth



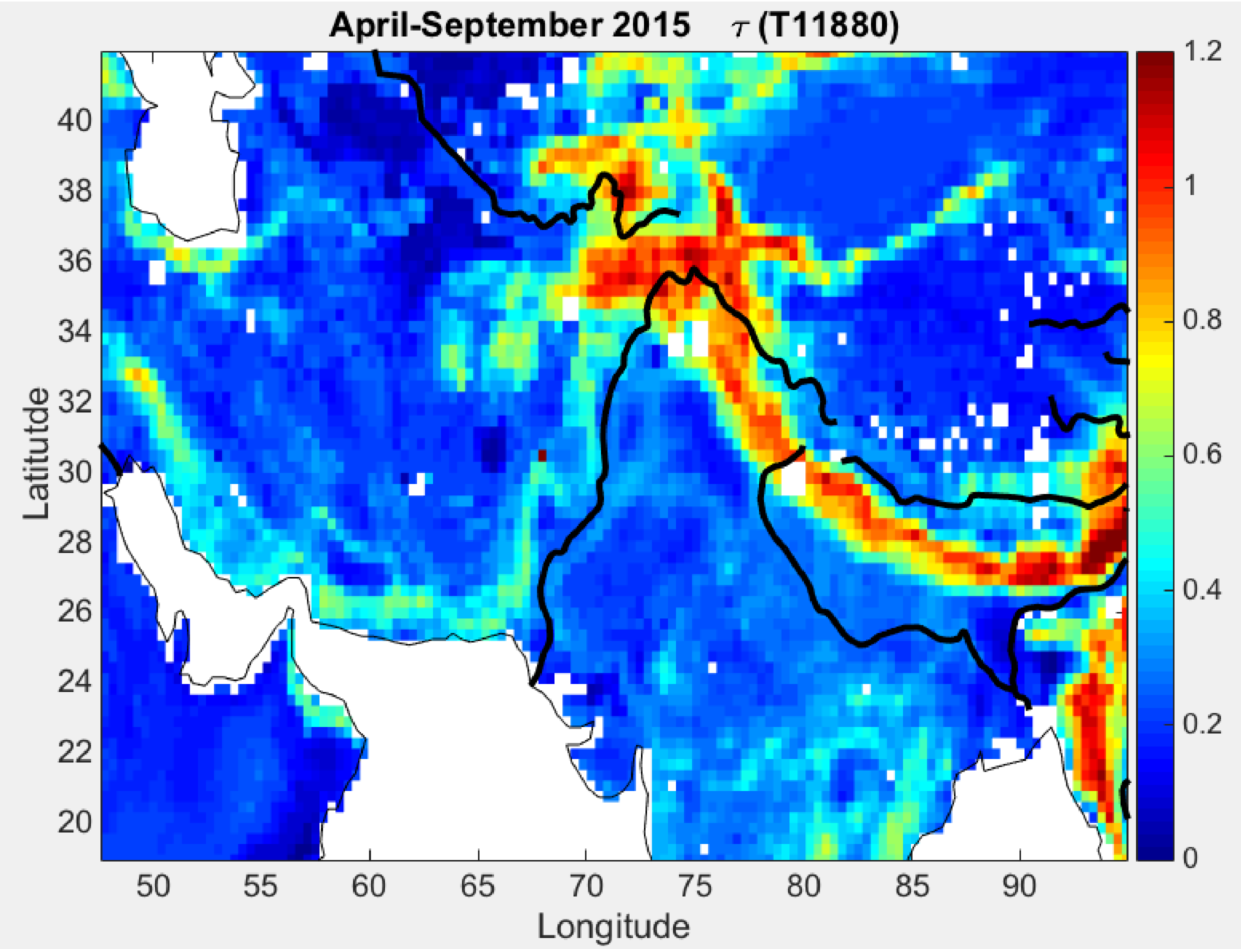
Doughty and Golden, 2008: Seasonal patterns of tropical forest LAI and CO2 exchange, *JGR-Biogeosciences*, vol. 113.

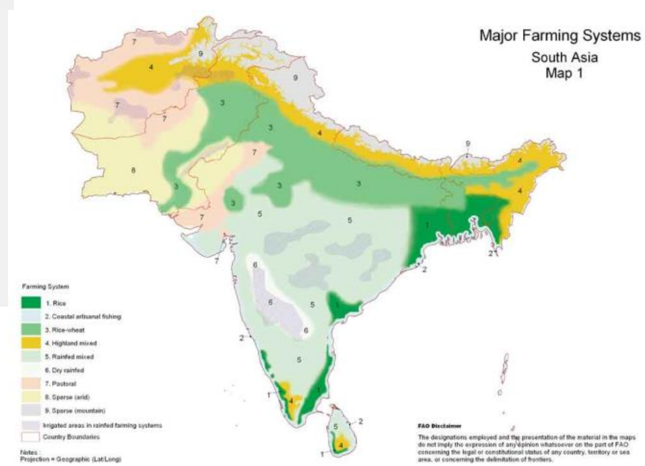
Flushing

Rivera et al., 2002: Increasing day-length induces spring flushing of tropical dry forest trees in the absence of rain. *Trees,* vol. 16.

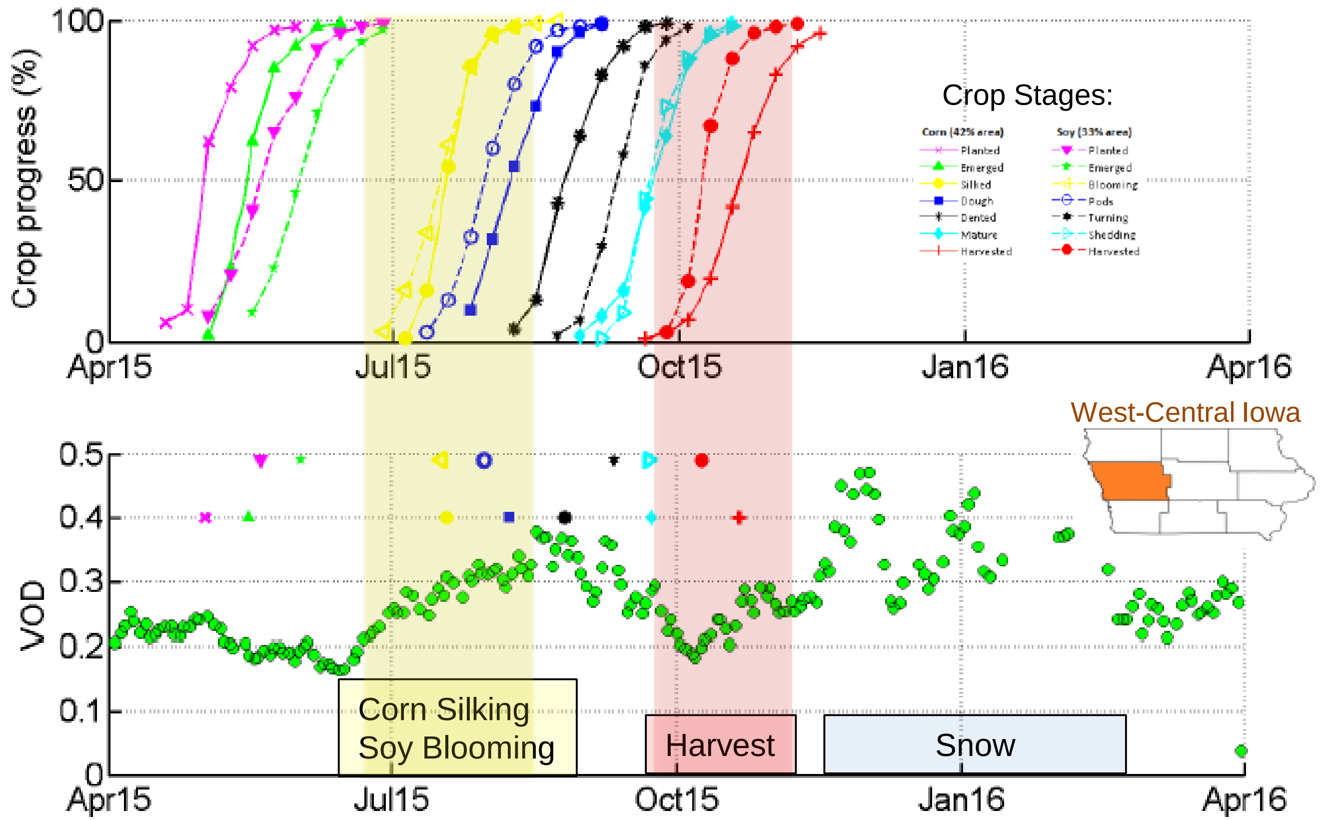
Feldman, Konings, Piles and Entekhabi, 2017.

Agriculture over Indus Valley and North India





Agroecosystems

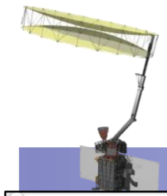


SMAP measurements are used to map the biomass of crops and vegetation.

Green biomass in vegetation is proportional to the microwave Vegetation Optical Depth (VOD: green symbols).

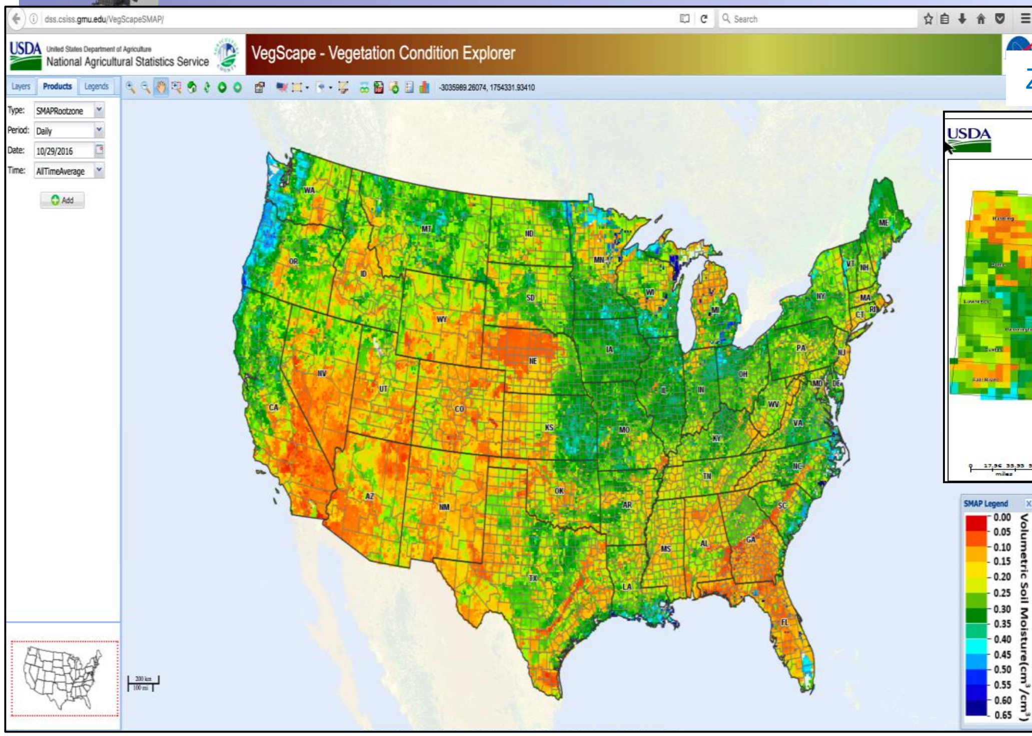
The growth phase of corn and soy crops across West-Central Iowa correspond to SMAP steady rise in VOD. The harvest period is characterized by sharp drops.

Piles, Konings, Chaparro, Akbar, Jagdhuber, Das, Entekhabi, 2017.

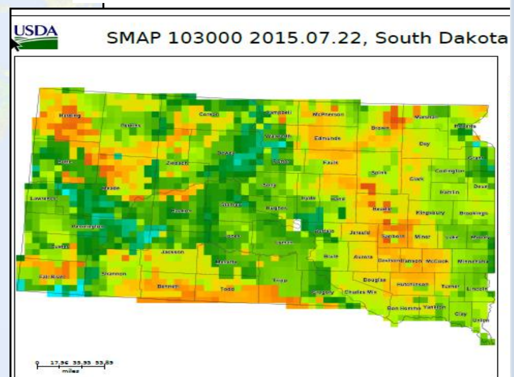


Improve National Cropland Soil Moisture Monitoring Using SMAP

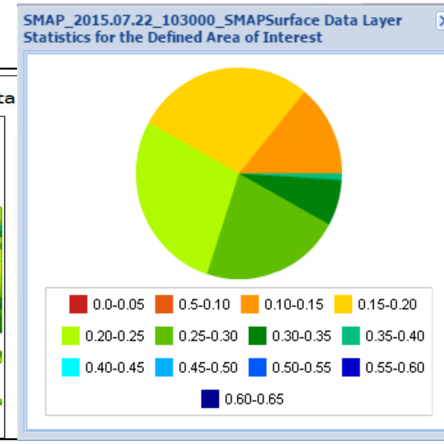
SMAP Early Adopter: USDA/NASS, Zhengwei Yang and Rick Muller



Zoom in to state/county level



Make plots for area of interest



Provide soil moisture statistics for area of interest

SMAP_2015.07.22_103000_SMAPSurface Data Layer Statistics for the Defined Area of Interest

Display Crop Area Only

Value	Category	Acreage	Percentage
0	0.0-0.05	91128.54	0
1	0.5-0.10	0	0
2	0.10-0.15	6766293.81	0.14
3	0.15-0.20	13281984.14	0.28
4	0.20-0.25	13122509.2	0.28
5	0.25-0.30	10388653.12	0.22
6	0.30-0.35	3235063.03	0.07
7	0.35-0.40	546771.22	0.01
8	0.40-0.45	91128.54	0
9	0.45-0.50	0	0
10	0.50-0.55	0	0
11	0.55-0.60	0	0
Total	13	47523531.6	1.0

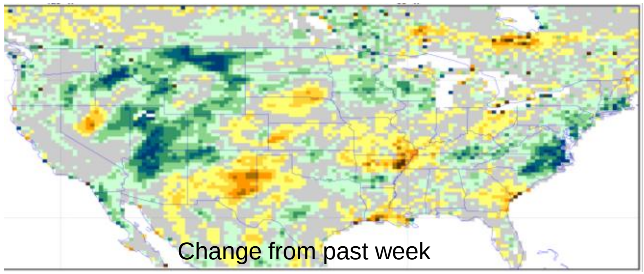
Note: Pixel and acreage counts are not official estimates. | SMAP Average is 0.27

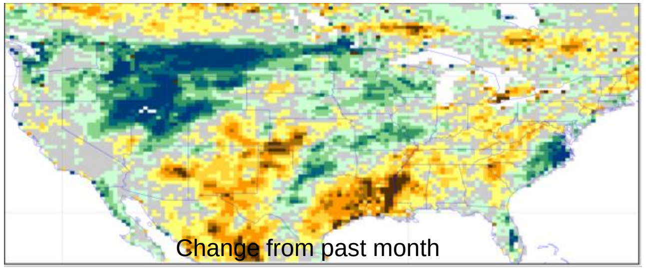
Using SMAP L4 surface and root-zone soil moisture data, a SMAP prototype on USDA's VegScape, an interactive vegetation condition explorer, illustrates online capabilities to visualize, disseminate, and analyze US cropland soil moisture condition.

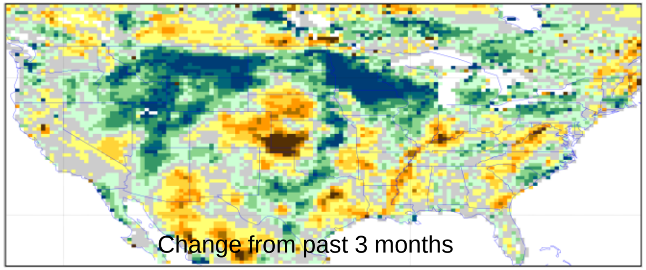
Implementation of VegScape-SMAP will reduce current survey costs and improve the objectivity and robustness of US national soil moisture condition monitoring operations.

Mapping Drought Extent and Recovery

Soil Moisture Change From SMAP

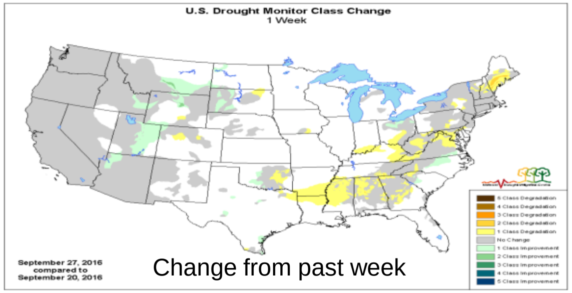




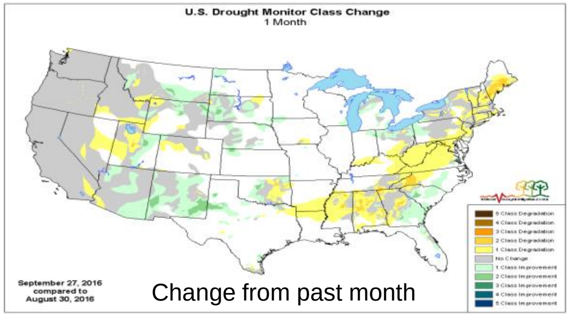


US Drought Monitor Change Maps

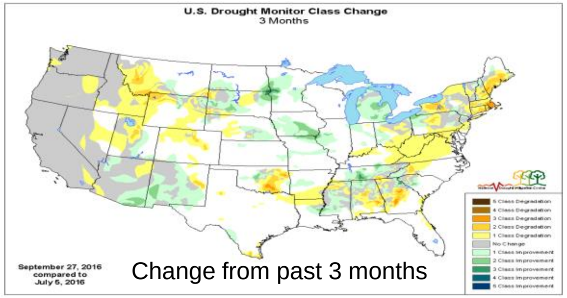
~



~



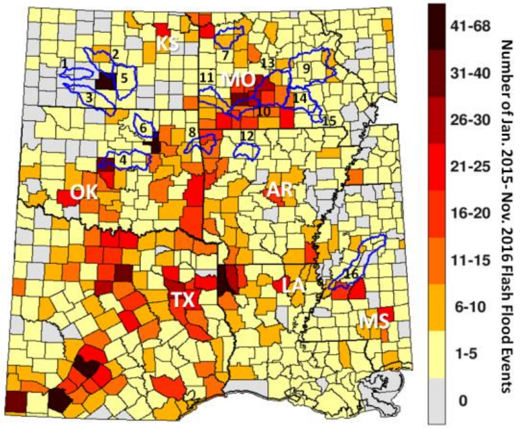
~

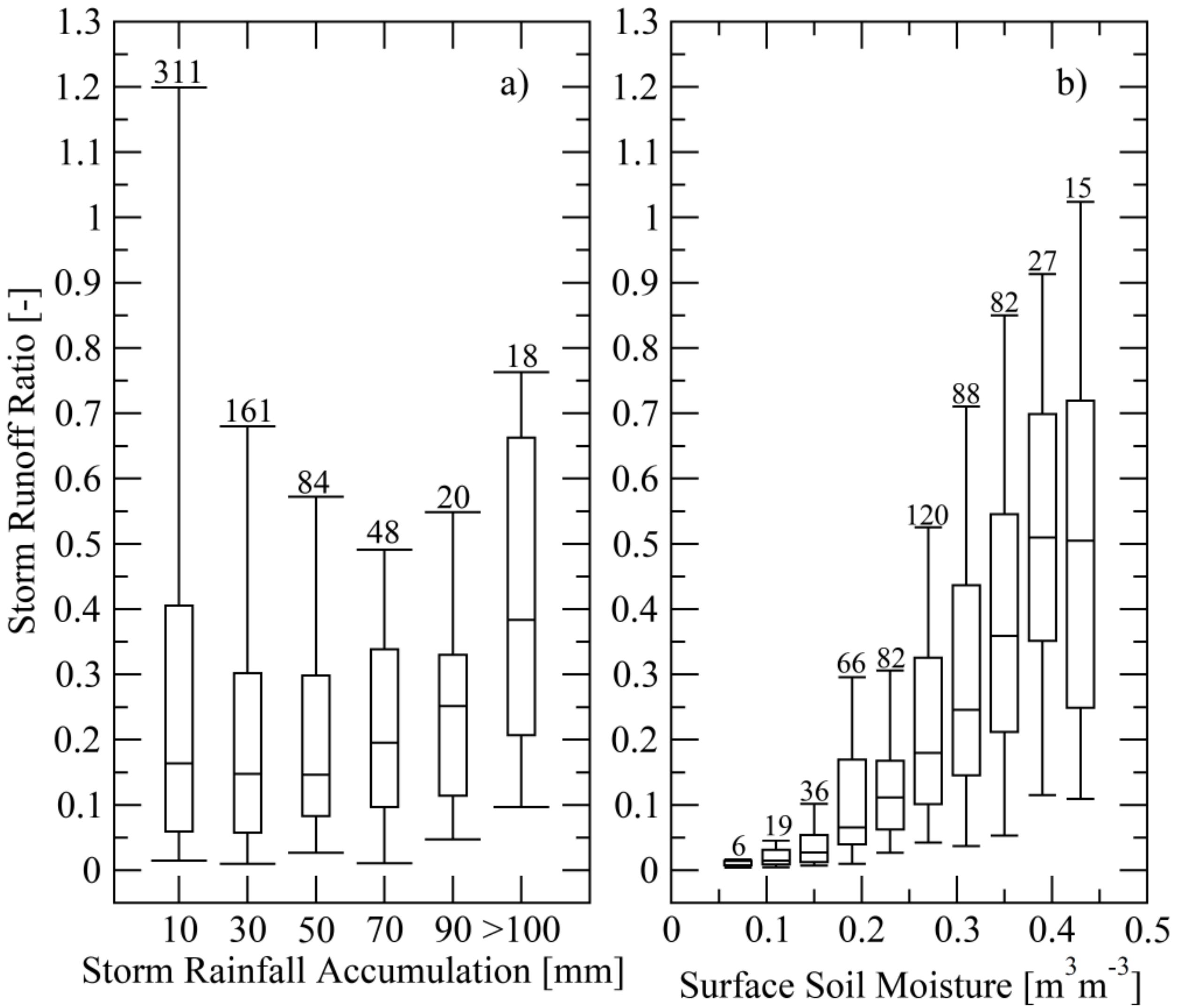


National Drought Mitigation Center (NDMC) provides information to State Climatologists who issues maps of drought severity and its recovery status. The SMAP Soil Moisture Change Maps provide NDMC broader coverage and complement the its operational *US Drought Monitor* product.

N. Das (SMAP Project) and NMDC

Flood Application





Crow, Chen, Reichle and Liu, 2017: L-band microwave remote sensing and land data assimilation improve the representation of pre-storm soil moisture conditions for hydrologic forecasting, *GRL*.

Flood Application

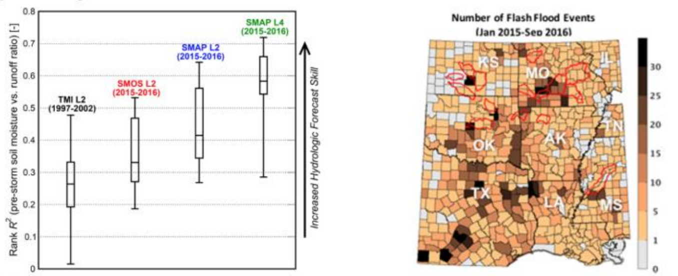
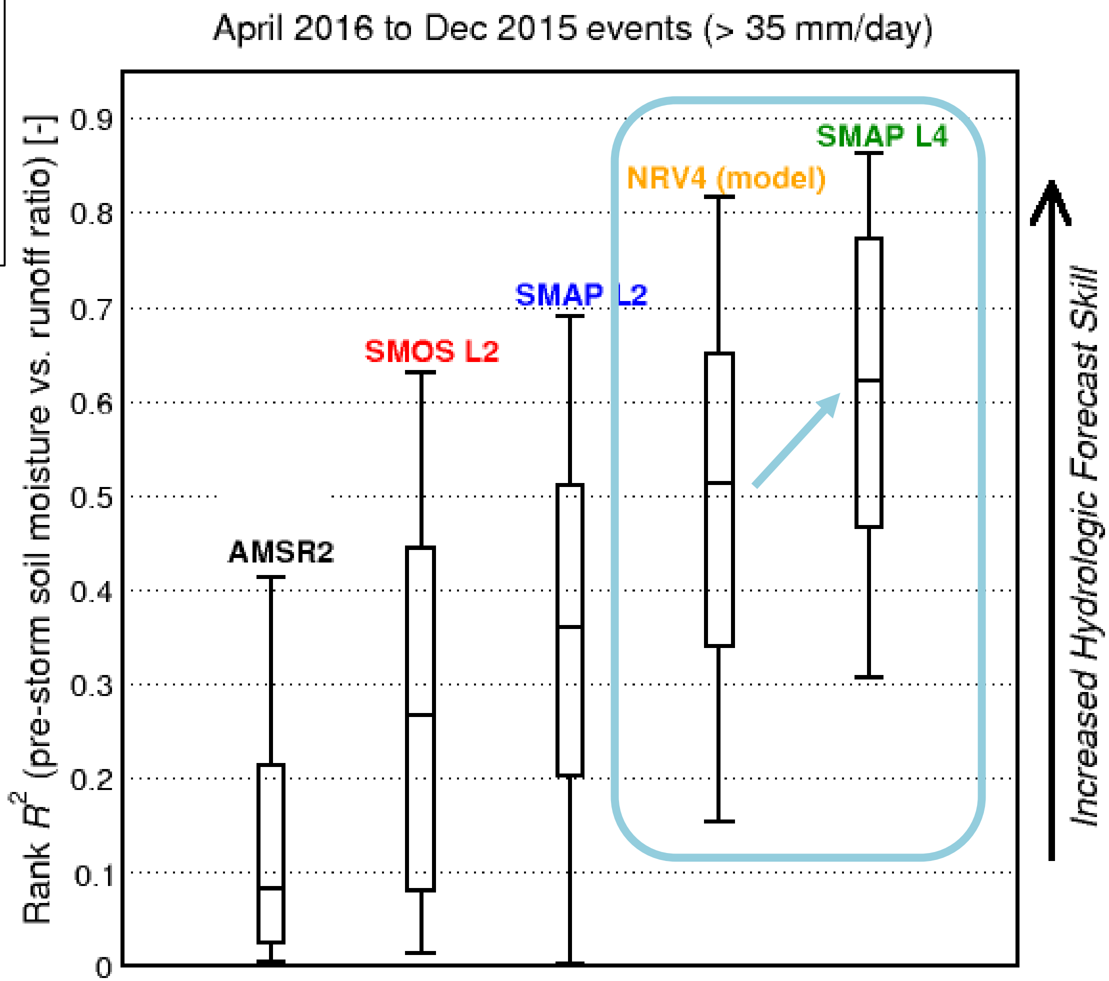


FIGURE 1.2-7: (Left) Skill of forecasting the land surface response to rainfall for satellite-based soil moisture products. Skill is measured as the rank coefficient of determination (R^2) between pre-storm soil moisture and subsequent storm-scale runoff ratio (i.e., total runoff divided by total rainfall) sampled across 16 basins. The SMAP Level 2 and Level 4 soil moisture products have the highest skill. Relatively lower values for the Tropical Rainfall Measurement Mission Microwave Imager (TMI) and Soil Moisture Ocean Salinity (SMOS) missions reflect skill obtained from earlier sensors. (Right) Boundaries (in red) of the 16 medium-scale (10^3–10^4 km^2) basins and total number of flash-flood events during January 2015–September 2016 in the south-central U.S.

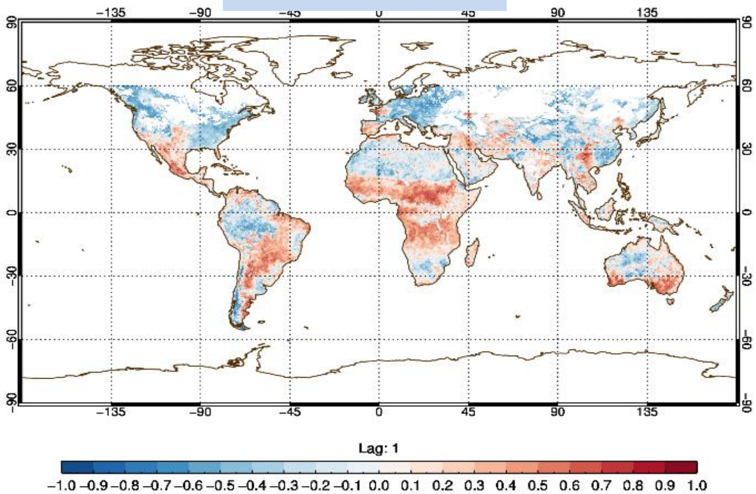


Source: W. Crow et al., 2017.

USDA FAS (Foreign Agricultural Service) Global Crop Assessment Decision Support System With SMAP Data

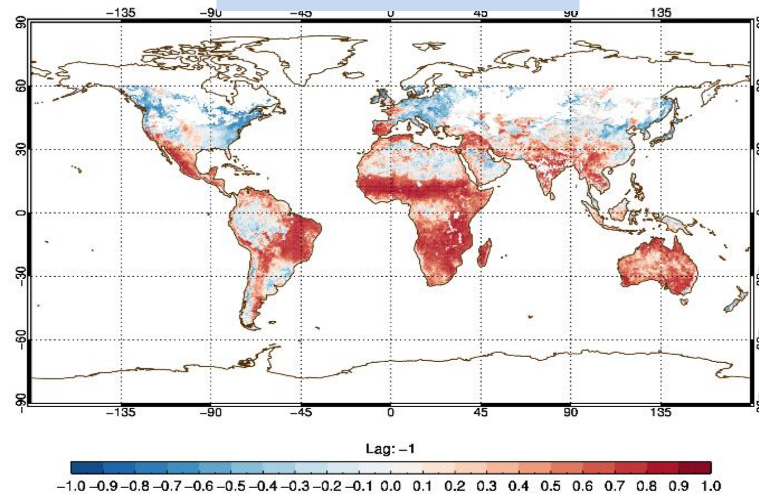
Plotted variable = Correlation between *current* monthly soil moisture levels and *future* (+ 1 month) vegetation health (NDVI).

Model Only



Correlation of *current* USDA FAS soil moisture product based on water balance modeling

Model + SMAP



Enhanced correlation observed *after* the assimilation of SMAP L3 retrievals.

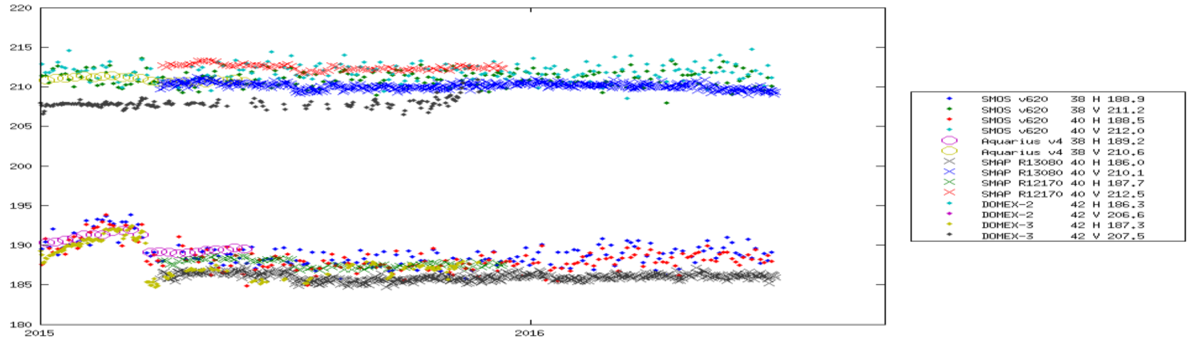
Higher correlation (more red) = Improved early detection of agricultural drought

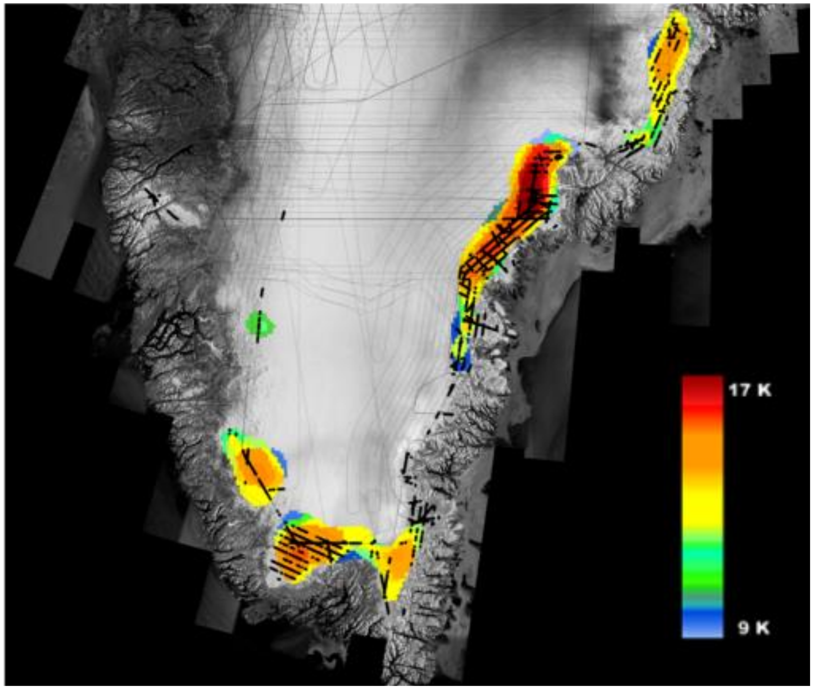
Work supported by a NASA Applied Sciences grant entitled "Enhancing the USDA Global Crop Production Decision Support System with NASA Soil Moisture Active Passive (SMAP) Satellite Observations"

PI – John Bolten (NASA/GSFC), I. Mladenova (GSFC/ESSIC), W. Crow (USDA ARS), C. Reynolds (USDA FAS)

Cryosphere

Antarctica Dome-C Calibration Site



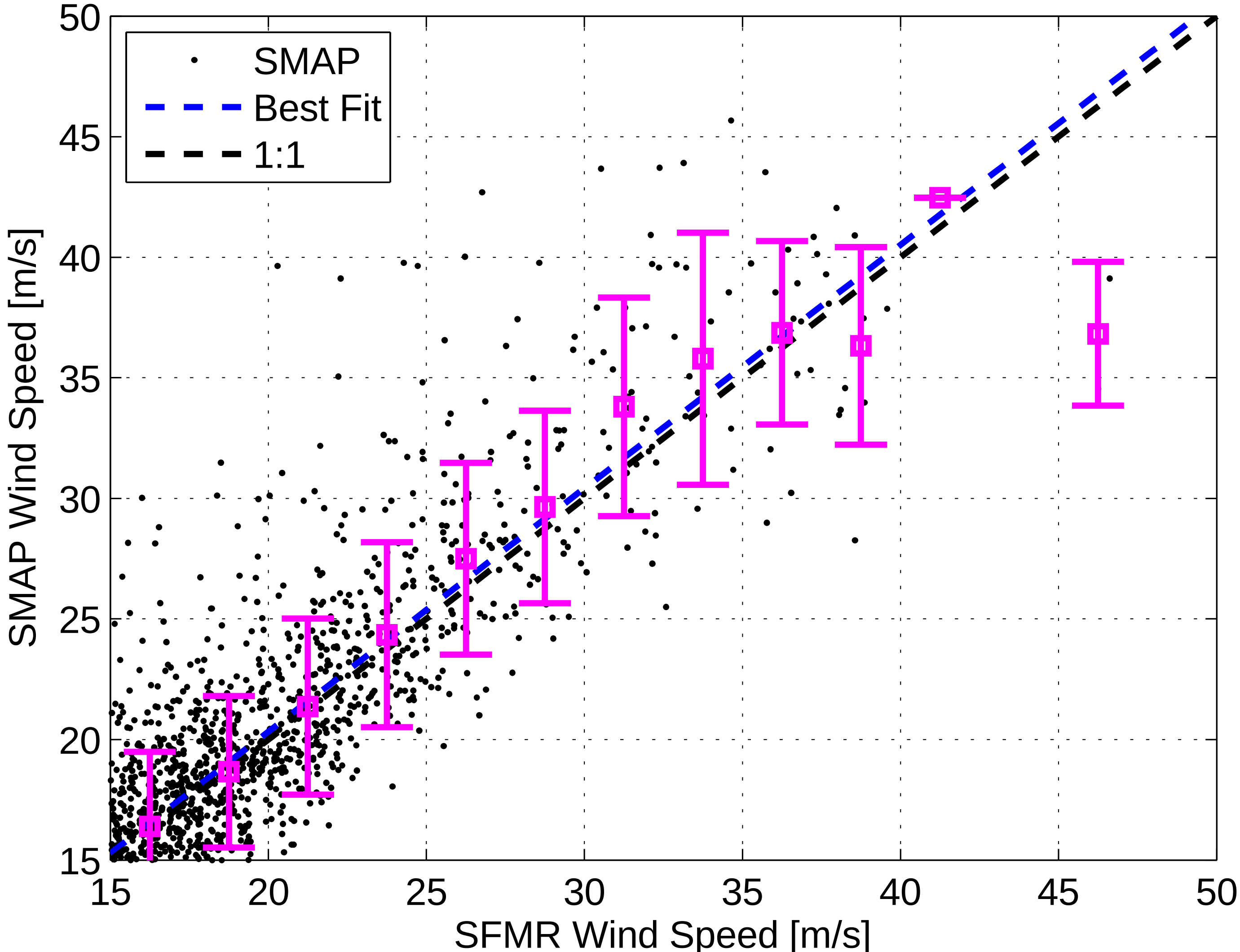


Miller, J, A. Bringer, K. C. Jezek, J.T. Johnson, R. R. Forster, T. A. Scambos, 2017: Spaceborne observation of Greenland's firn aquifer using L-band microwave radiometry, *Cryosphere*

Satellite firn aquifer maps over the Greenland ice sheet retrieved from SMAP using horizontally polarized brightness temperature differences (September average–April average)

SMAP Severe Ocean Wind

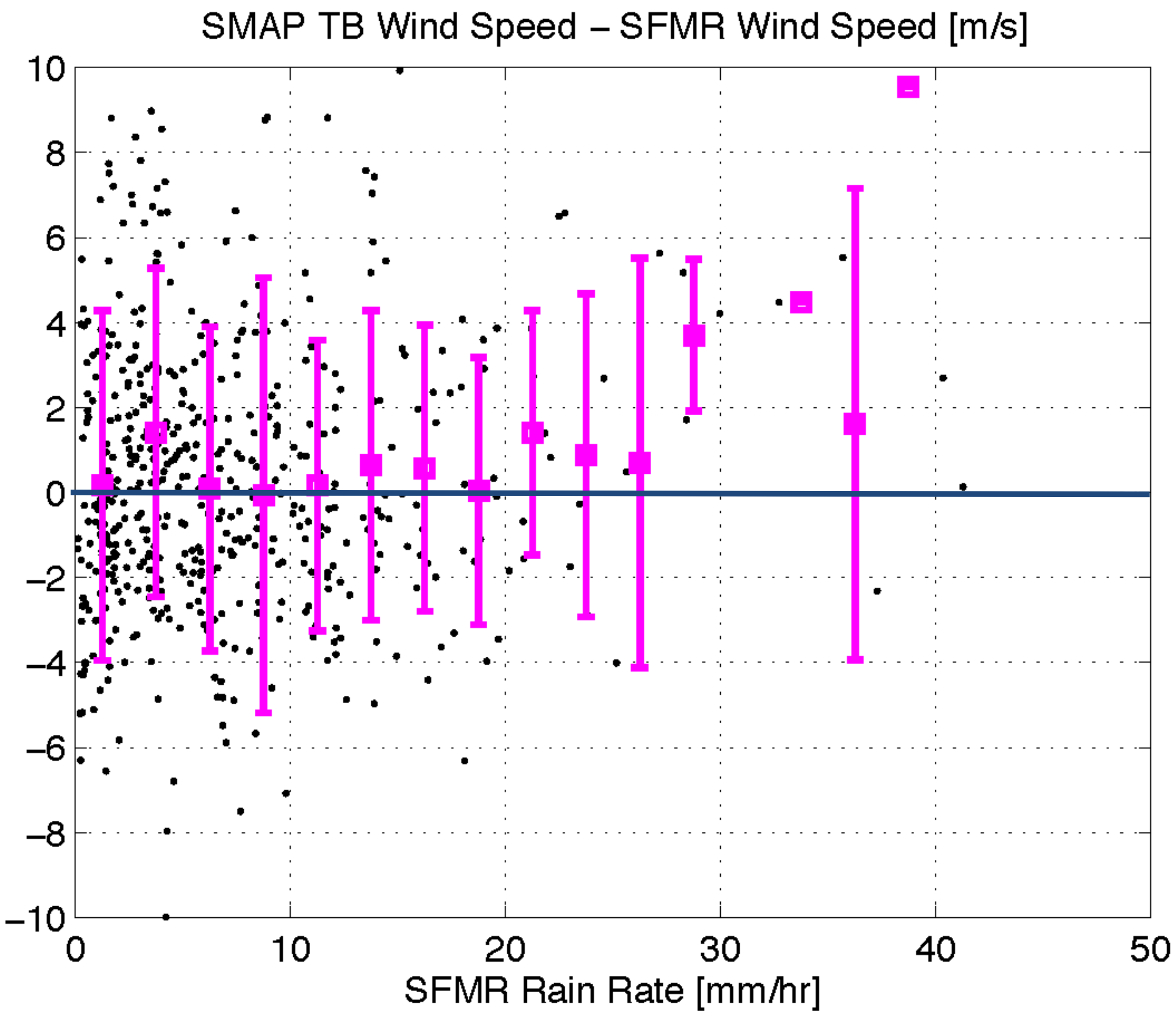
SMAP vs SFMR; Best Fit Slope: 1.01; Corr: 0.83
Mean Error Bar > 20 m/s: 3.15 m/s



SFMR wind averaged over 40 km along track

Source: S. Yueh, 2017.

SMAP Severe Ocean Wind

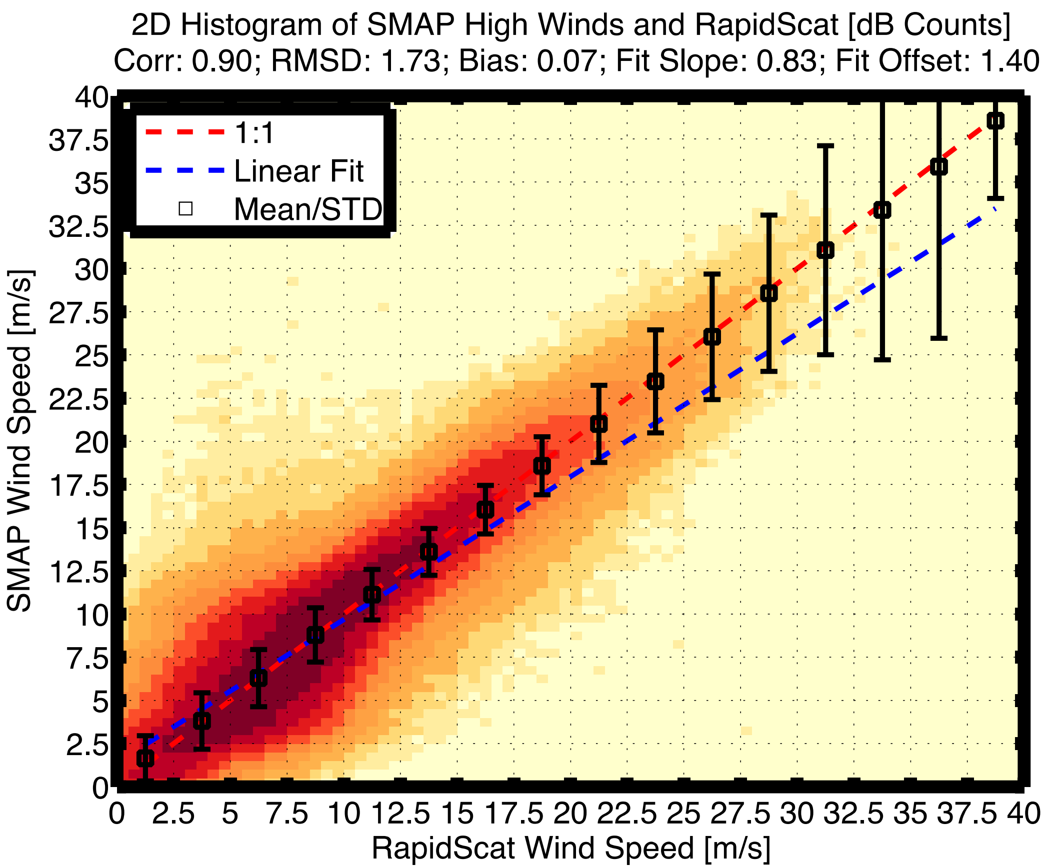


Source: S. Yueh, 2017.

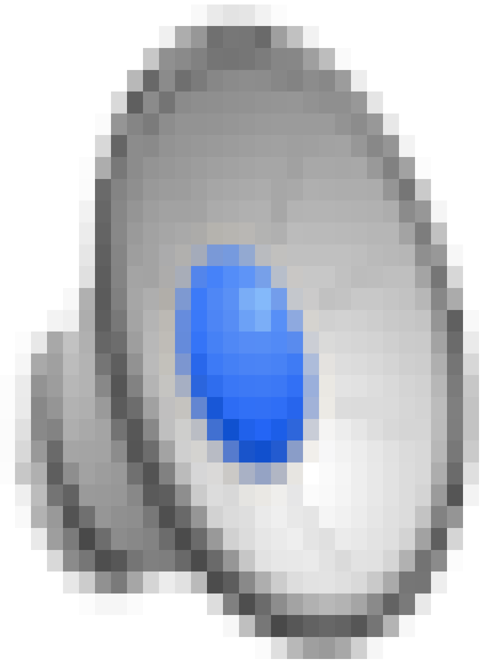
SMAP Severe Ocean Wind

- 13 million matchups of SMAP, RapidScat and Windsat within 90 minute of collocation under rain-free conditions identified by WindSat

- Find very small speed bias up to 40 m/s as compared to Rapidscat.

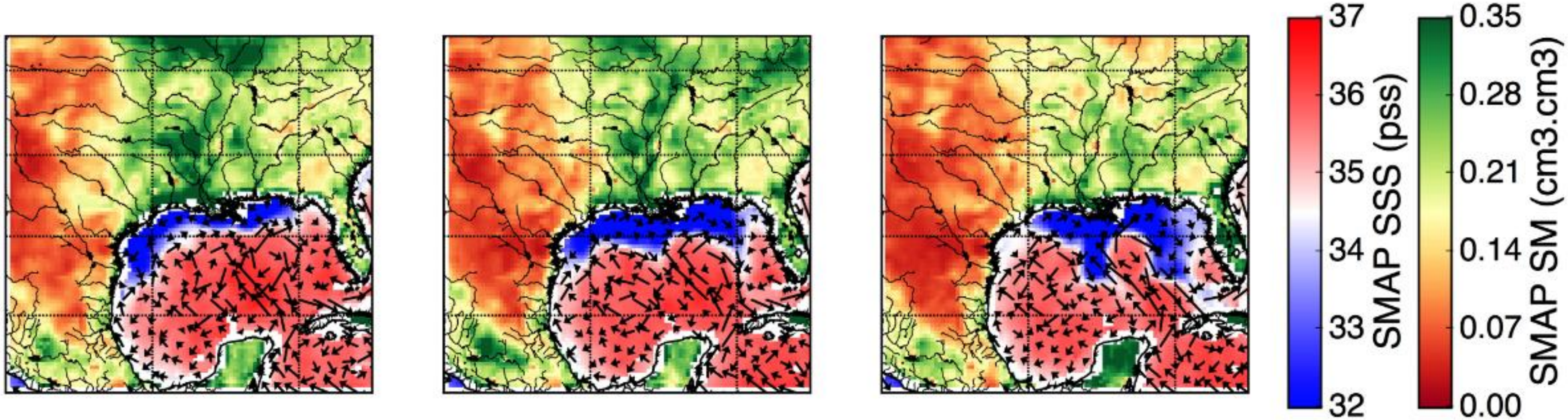


Source: S. Yueh, 2017.

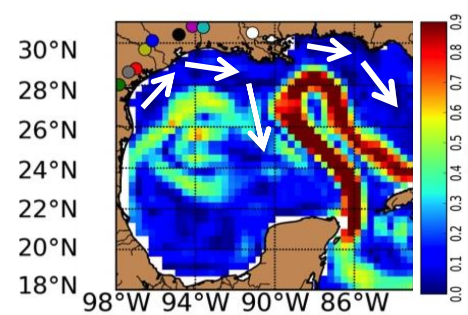


Linkage of Land and Ocean Branches of Water Cycle

Fournier, S., J. T. Reager, T. Lee, J. Vazquez-Cuervo, C. H. David, and M. M. Gierach, 2016: SMAP observes flooding from land to sea: The Texas event of 2015, *Geophys. Res. Lett.*, 43, 10,338–10,346



SMAP observed an unusual horseshoe-shaped plume of freshwater (dark blue) in the Gulf of Mexico after Texas flooding in May 2015. Louisiana is above the center of the plume, with Florida on the right and the Texas coastline at upper left.



Summary

- Exceptional quality global L-band radiometry
- Science uses in characterizing land, terrestrial biosphere and ocean water cycle branches
- Focus on first global characterization of the *link* between the land branches of the water, energy and carbon cycles: Determines how Earth System models respond to and propagate perturbations in one cycle to another