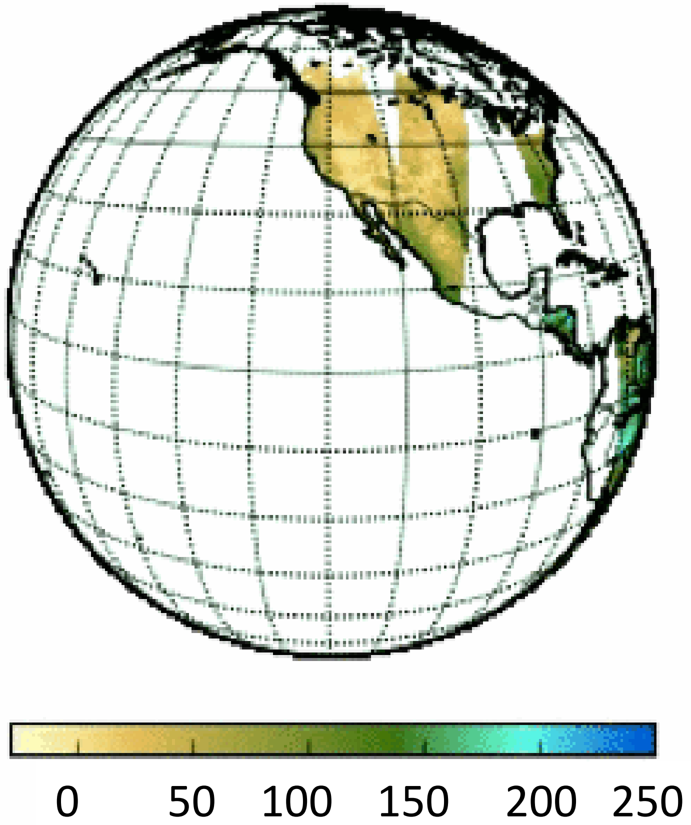

ET using SMAP (W m^{-2}) [*Purdy, Fisher, et al., in prep*]

SMAP Soil Moisture Data To Improve Remotely Sensed Global Estimates of Evapotranspiration

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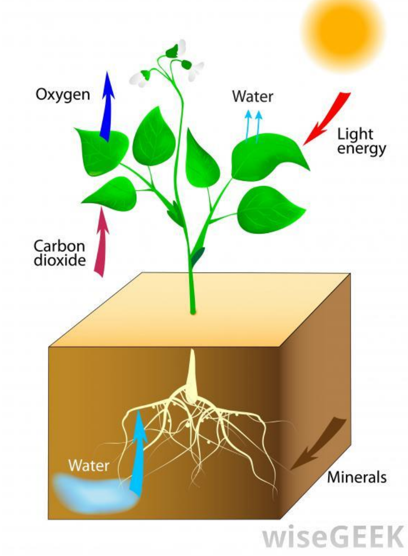
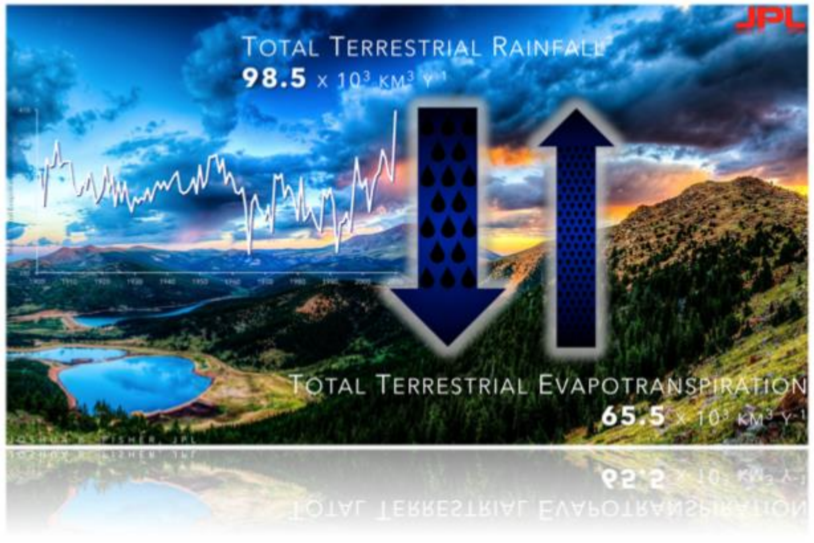
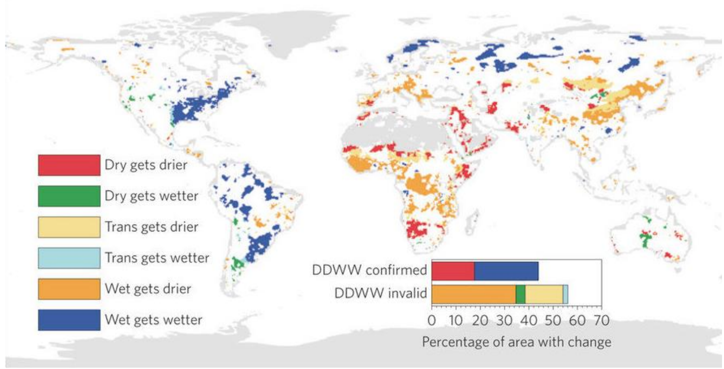
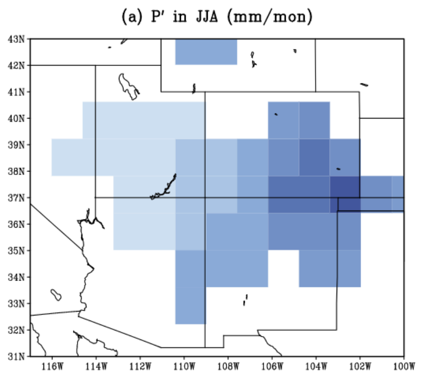
ET is a key climate variable & observations support critical research

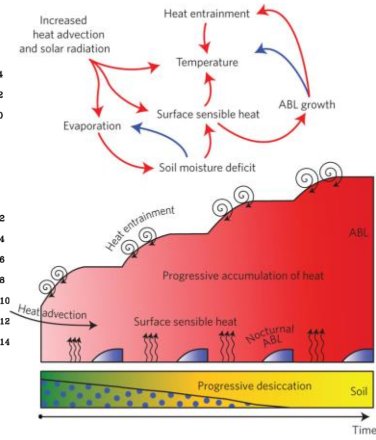
- ET connects the carbon, energy, and water cycles
- ET is the 2nd largest variable in the global water cycle returning 2/3rd of precipitation to the atmosphere
- Energy cycle is poised to intensify drying land globally
- Plants are becoming increasingly vulnerable to droughts as atmospheric demands for ET outweigh water supplies
- Monitoring agricultural water use
- Quantify human impact on the regional water cycles
- Study land-atmosphere-feedbacks including heat waves





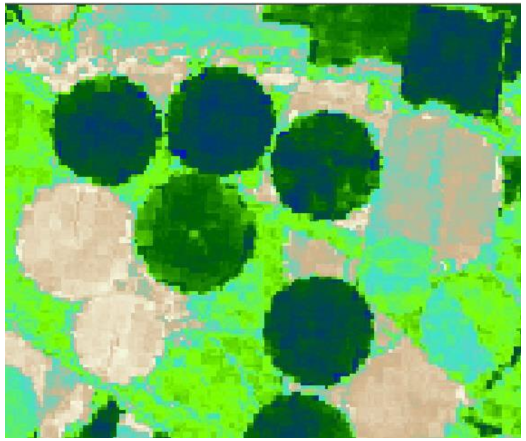


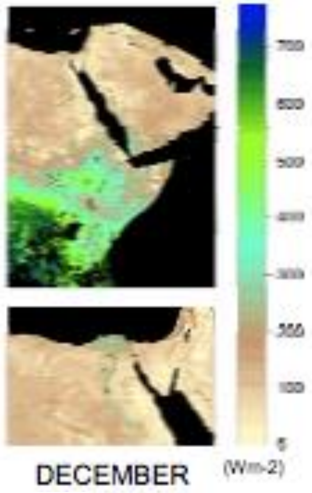


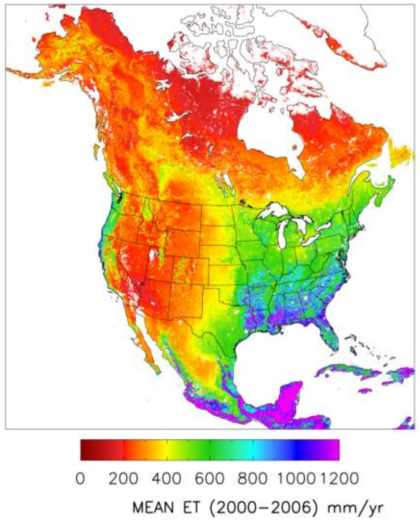


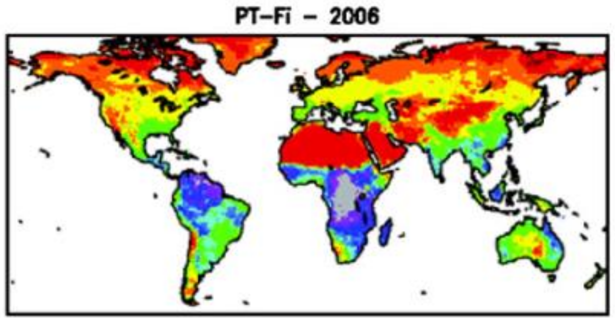
ET remote sensing

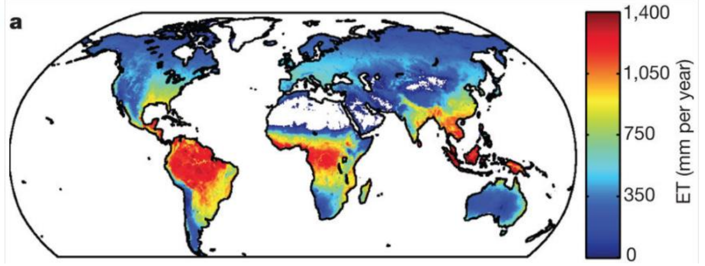
- Numerous remote sensing algorithms exist that quantify ET
- These models can be classified as:
    - One-source energy balance algorithms, [*Allen et al.*, 2007]
    - Two-source energy balance (TSEB) algorithms [*Anderson et al.*, 2007]
    - Statistical regression tree algorithms [*Jung et al.*, 2011]
    - Energy and vapor transport combination models [*Cleugh et al.*, 2007; *Fisher et al.*, 2008; *Mu et al.*, 2011]
- Remote sensing algorithm inter-comparison evaluations identified strengths and weaknesses of each model; **PT-JPL has outperformed other RS models (core of upcoming ECOSTRESS mission)**
- **Few approaches remain both physically defensible and globally applicable** without reliance on data assimilation and prognostic land surface models.

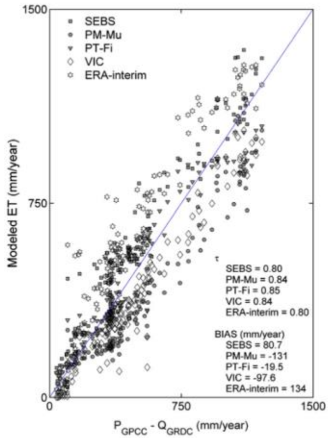


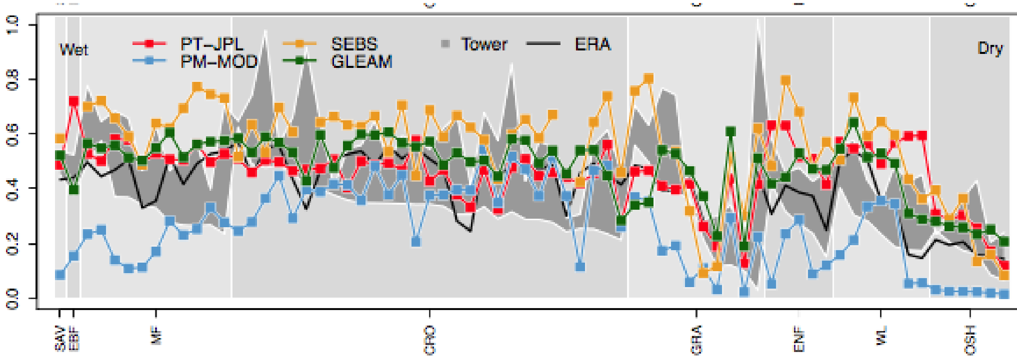








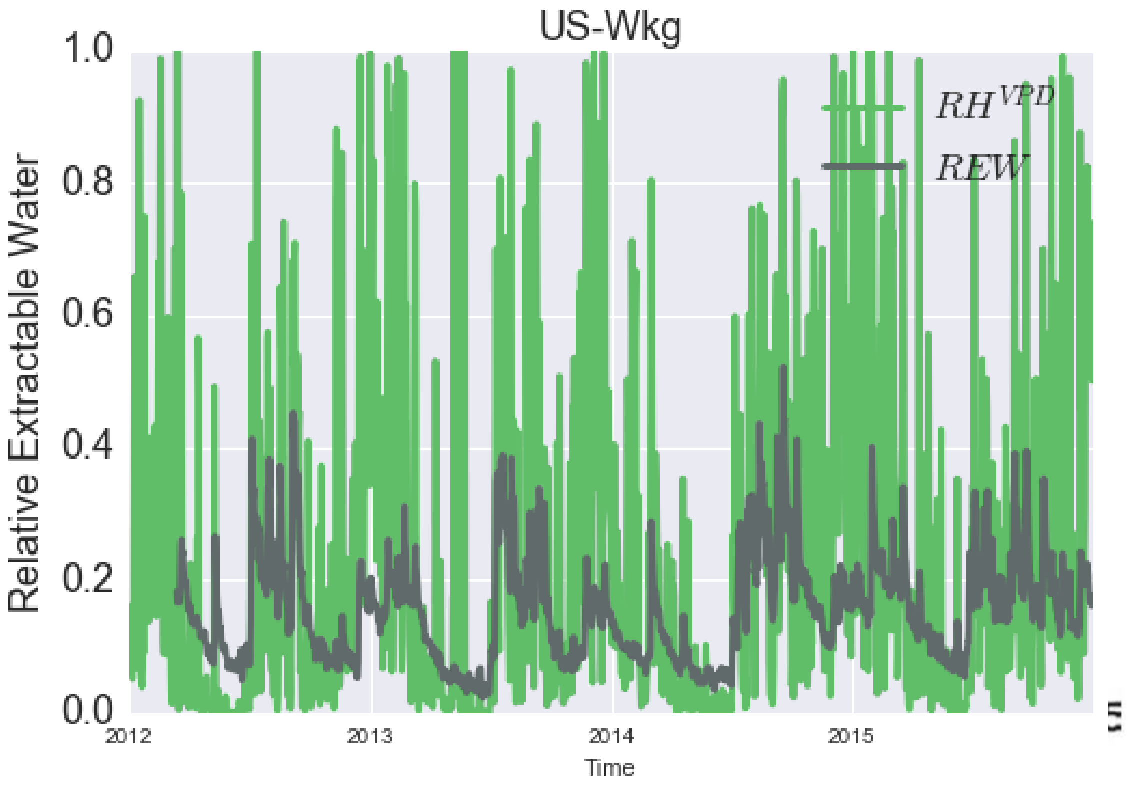




PT-JPL

The Priestley Taylor function is used to calculate Potential ET

Ecophysiological constraints, *f*-functions, [scalars between 0 and 1] are used to reduce PET to actual ET.



$$ET = ET_T + ET_S + ET_I$$

$$ET_T = (1 - f_{WET}) f_G f_T f_M \alpha \frac{\Delta}{\lambda(\Delta + \gamma)} R_N{}^C$$

$$ET_S = [f_{WET} + \boldsymbol{f_{SM}}(1 - f_{WET})] \alpha \frac{\Delta}{\lambda(\Delta + \gamma)} (R_N{}^s - G)$$

$$ET_I = f_{WET} \alpha \frac{\Delta}{\lambda(\Delta + \gamma)} R_N{}^C$$

Ecophysiological Constraints

Transpiration

$$f_M = \frac{f_{APAR}}{f_{APARmax}}$$

$$f_T = e^{\left(-\left(\frac{Ta - Topt}{Topt}\right)^2\right)}$$

$$f_G = \frac{f_{APAR}}{f_{IPAR}}$$

Evaporation

$$f_{SM} = RH^{VPD}$$

Both

$$f_{WET} = RH^4$$

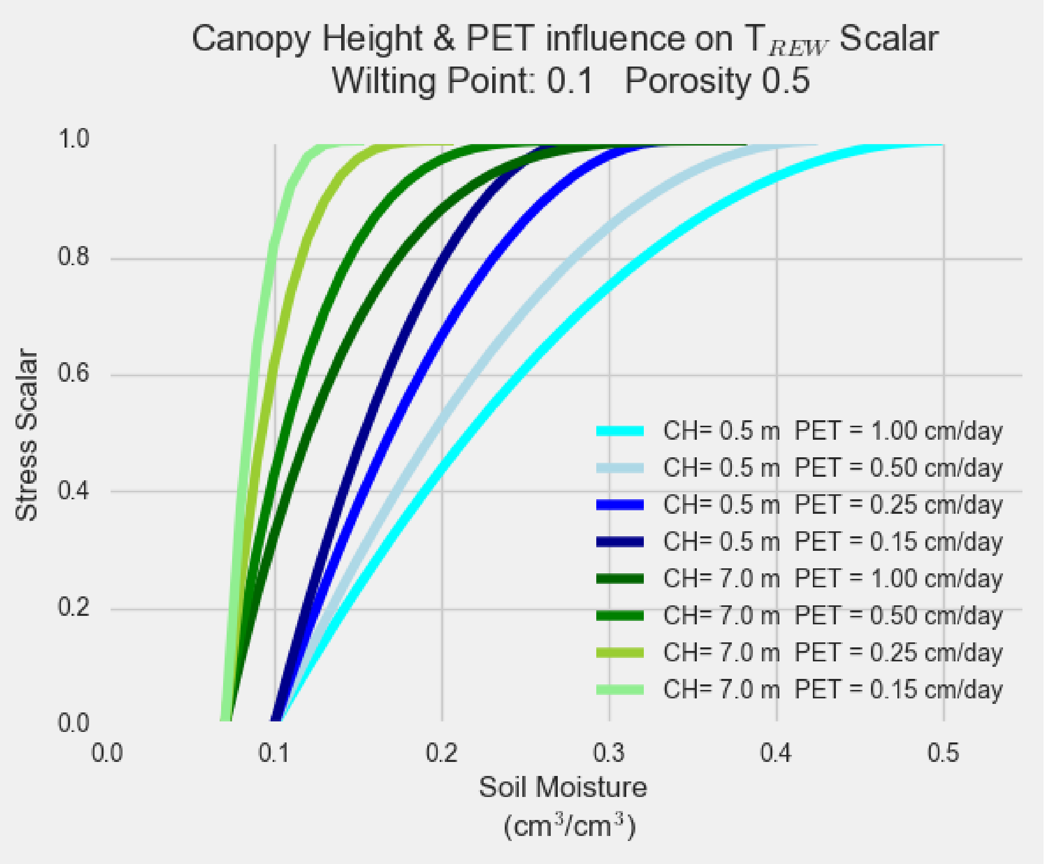
No Soil Moisture

(*Fisher et al.*, 2008)

Ecophysiological & SM limitations to ET

We incorporate explicit soil moisture constraints in PT-JPL on ET_T and ET_S.

We replace the fM constraint with a new soil moisture constraint f_{TSMAP}



$$ET = ET_T + ET_S + ET_I$$

$$ET_T = (1 - f_{WET})\boldsymbol{f_{TREW}} f_G f_T \alpha \frac{\Delta}{(\Delta + \gamma)} R_N^C$$

$$ET_S = [f_{WET} + \boldsymbol{f_{REW}}(1 - f_{WET})]\ \alpha \frac{\Delta}{(\Delta+\gamma)} (R_N^S - G)$$

$$ET_I = f_{WET} \alpha \frac{\Delta}{(\Delta + \gamma)} R_N^C$$

New Soil Moisture Constraints

Transpiration

$$f_{TREW} = 1 - \left(\frac{\theta_{CR} - \theta_{obs}}{\theta_{CR} - \theta_{wp_{CH}}} \right)^{CH_{scalar}}$$

$$\theta_{CR} = (1 - p)(\theta_{POR} - \theta_{wp_{CH}}) + \theta_{wp_{CH}}$$

$$p = \frac{1}{1 + PET} - a \frac{1}{1 + CH}$$

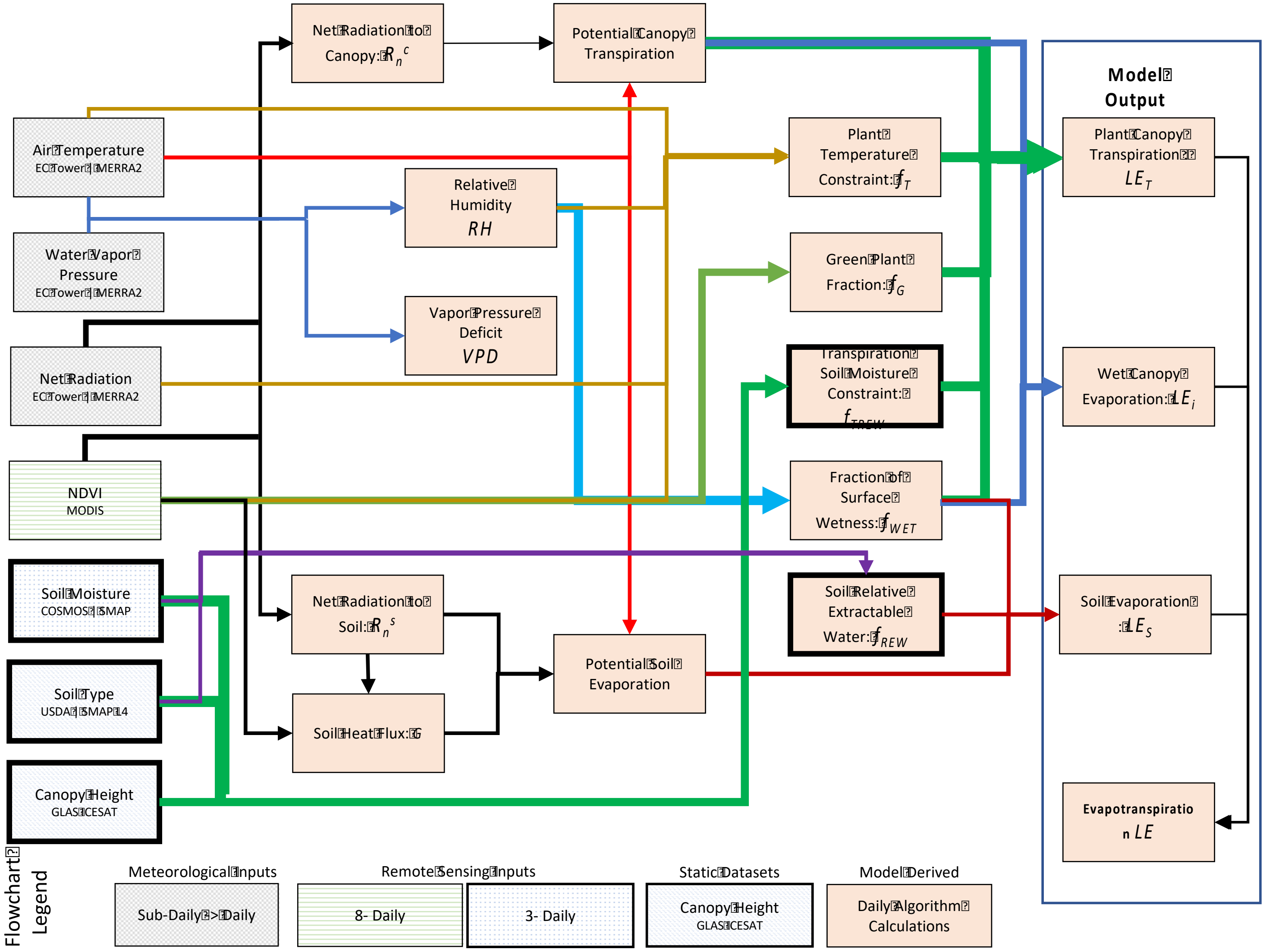
$$\theta_{WP_{CH}} = \frac{\theta_{WP}}{CH_{scalar}}$$

Evaporation

$$f_{REW} = \frac{\theta_{obs} - \theta_{wp}}{\theta_{POR} - \theta_{wp}}$$

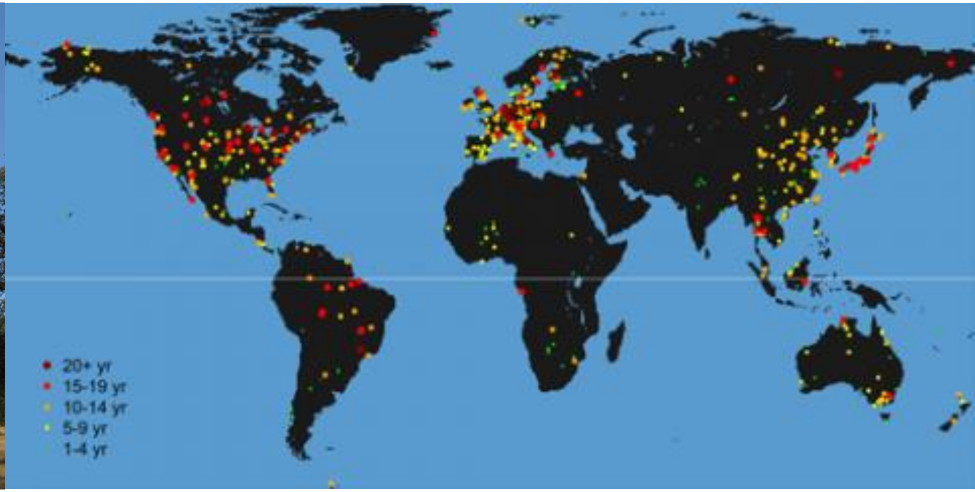
Methods: data-flow diagram

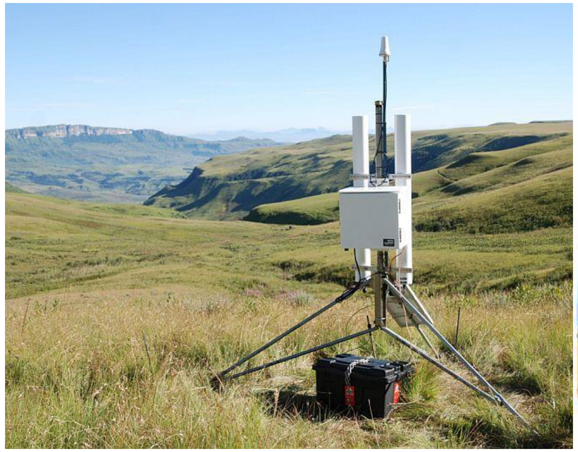
- Test new SM stress functions in situ
- Evaluate these changes across multiple sites
- Apply these globally with SMAP and other gridded forcing datasets
- Evaluate gridded model output in situ and globally

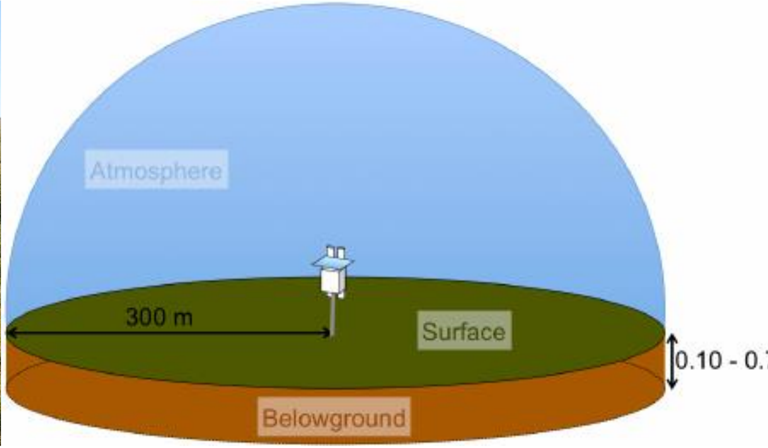


Eddy Covariance & COSMOS observations

- Eddy covariance towers provide continuous global observations of carbon and water exchange at the earths surface
- The COsmic-ray Soil Moisture Observation System provides integrated measurement of surface water availability at scales similar to EC observations

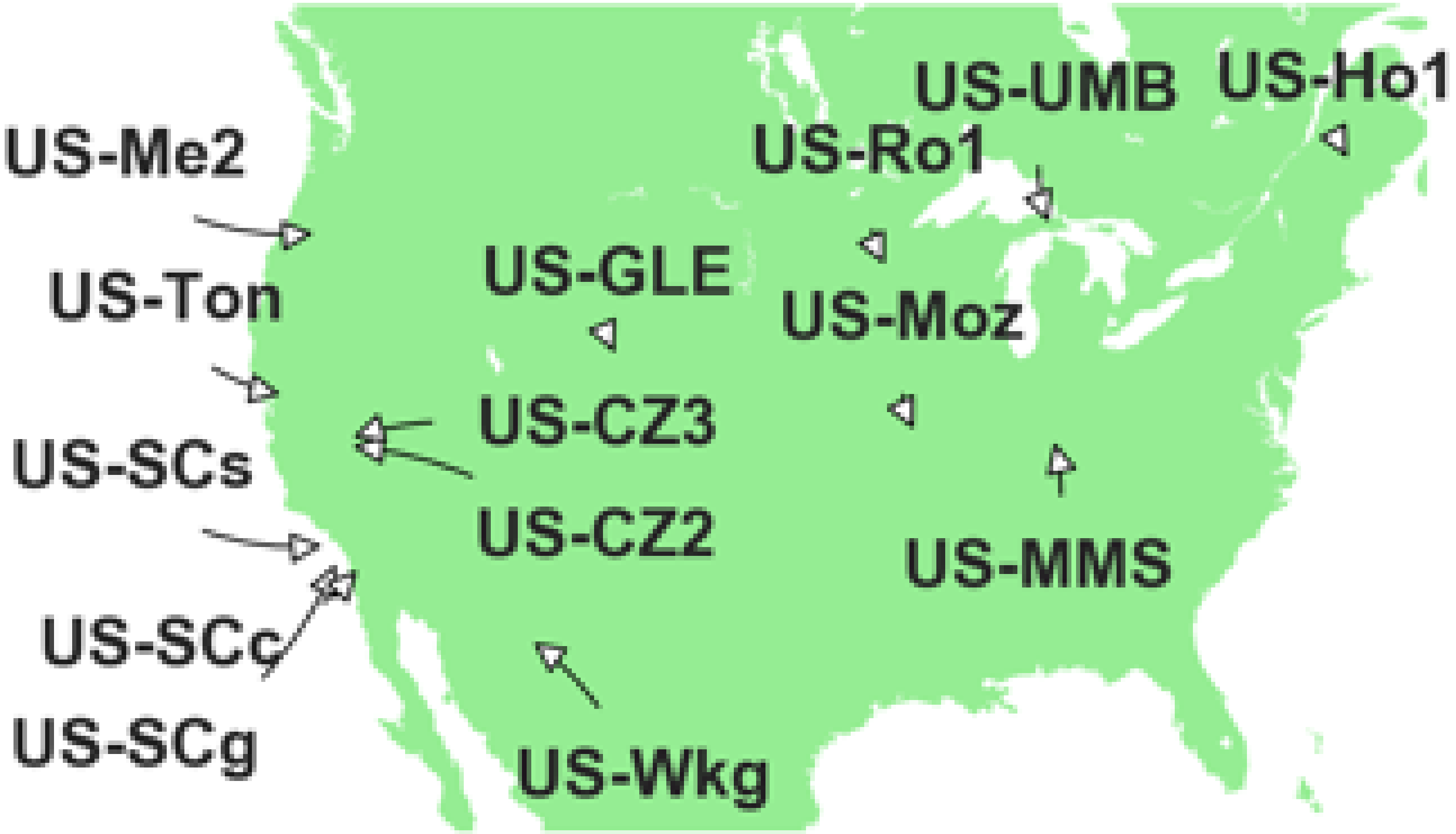




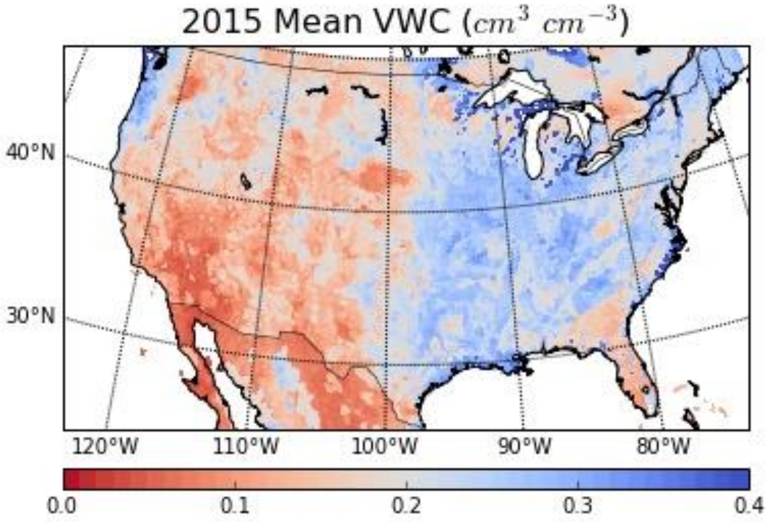


ET modeling with COSMOS soil moisture

Flux tower & COSMOS locations

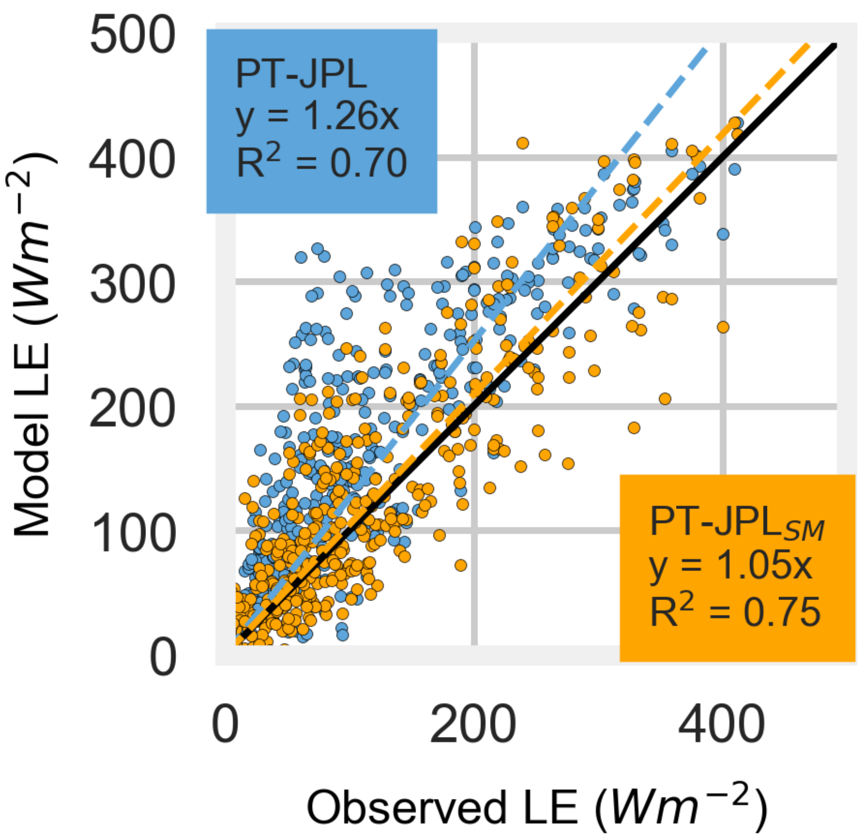


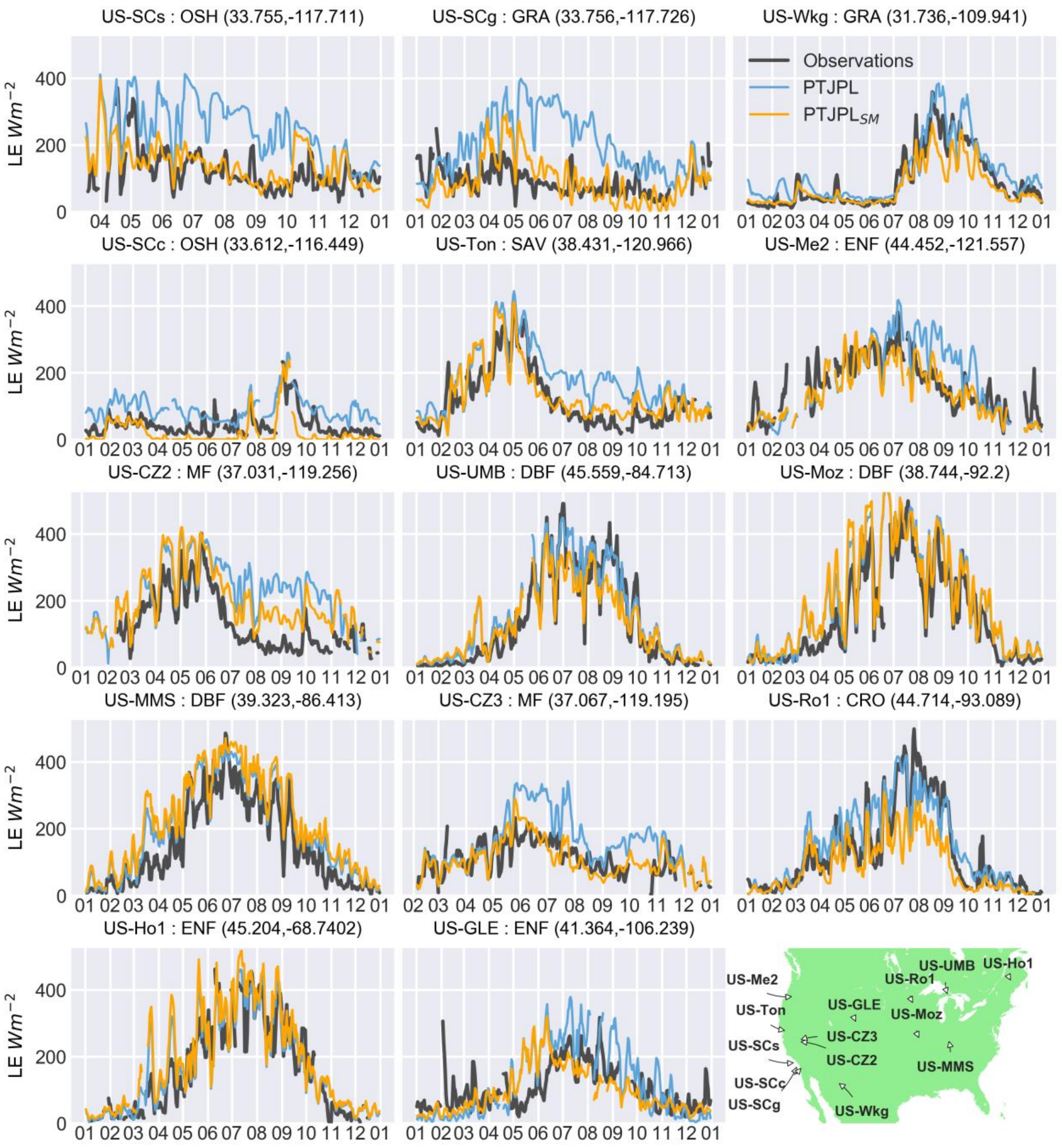
Surface Soil Water Availability



In situ results

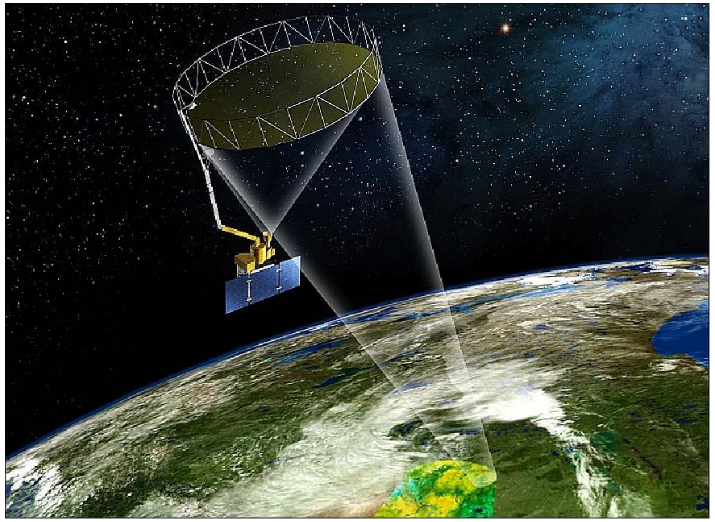
- Improvements notable in water-limited regions (AI > 1)

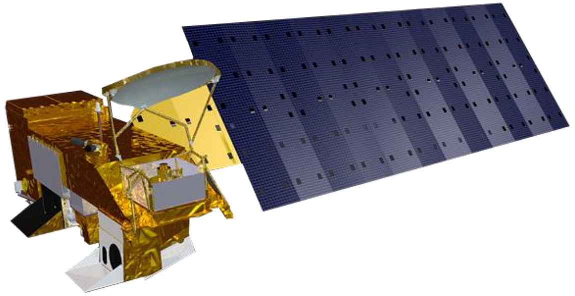


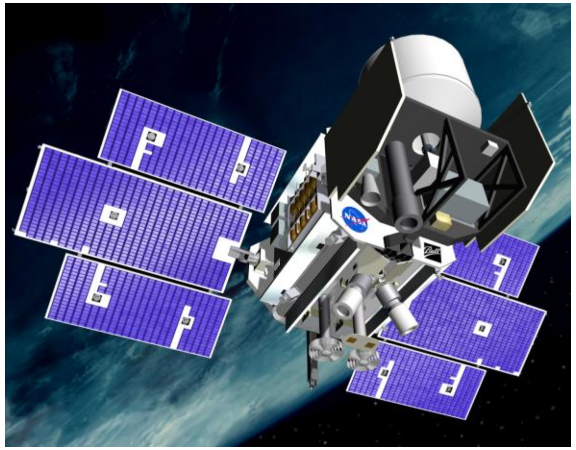


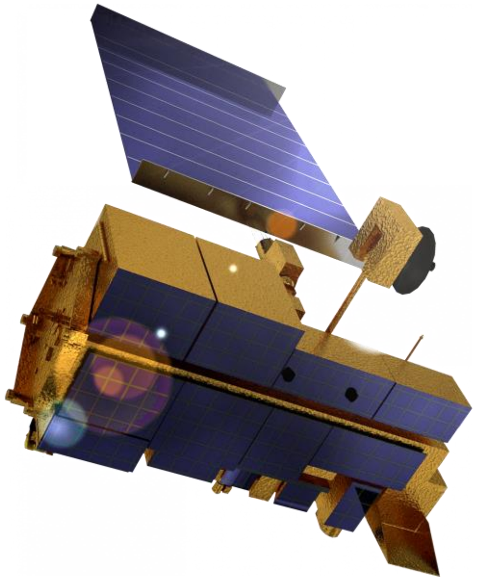
NASA instruments applied in PT-JPLSM global ET generation

- SMAP
  - SMAP_L3_A
  - SMAP_L3_P
  - SMAP_L3_P_E
- MODIS
  - Terra: MOD13A2
  - Aqua: MYD13A2
- ICE-Sat
  - Forest canopy height









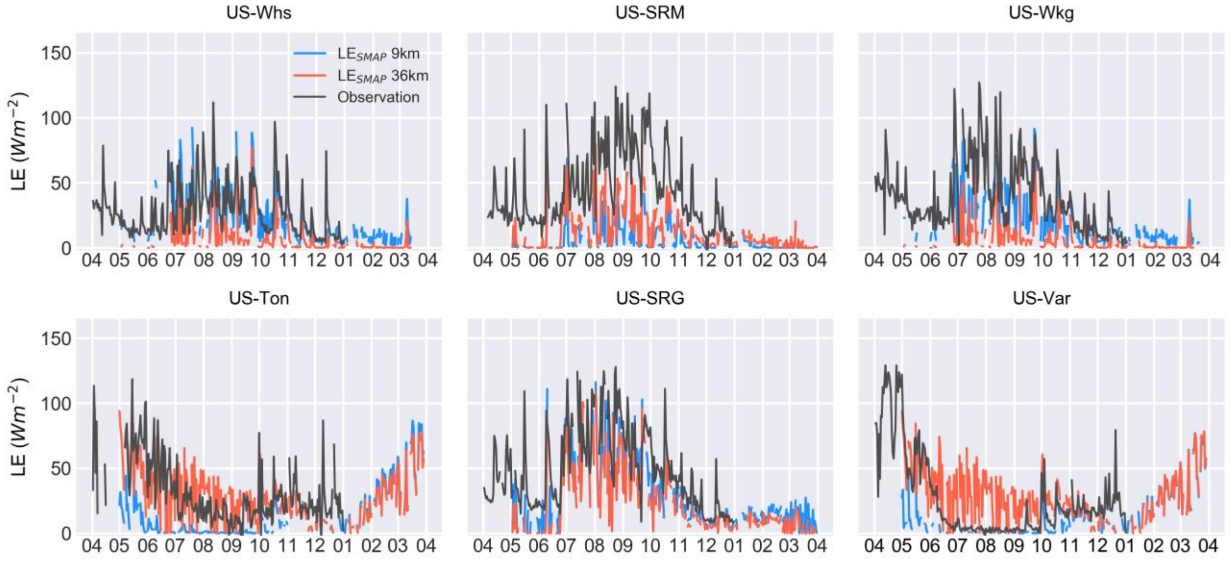
Global ET generation with $PT\text{-}JPL_{SM}$

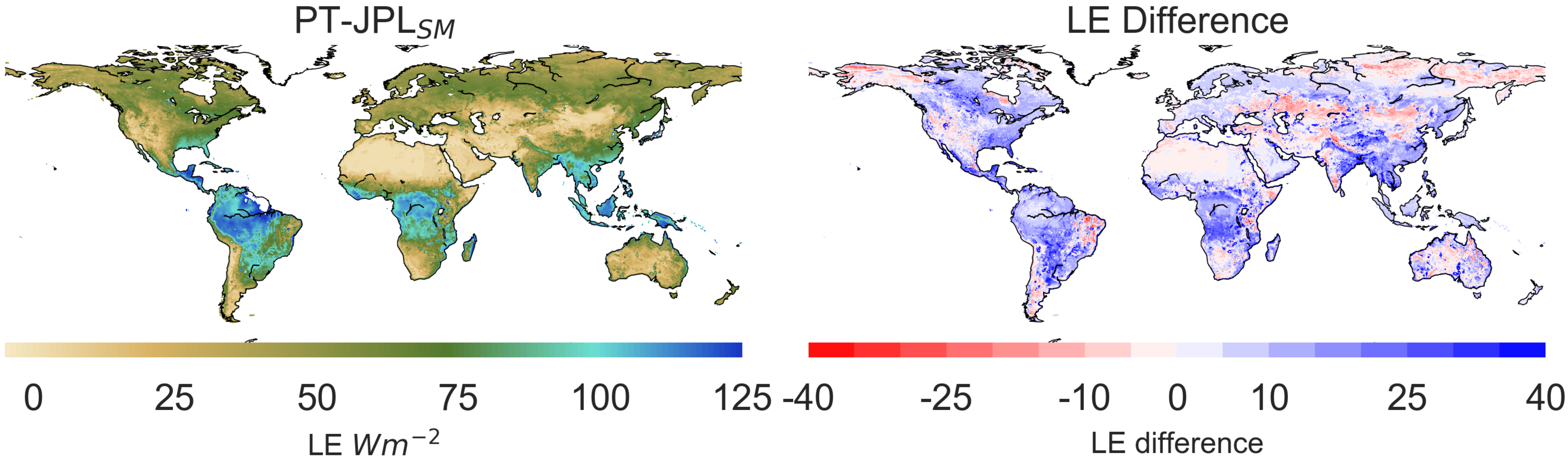
- Runs completed with ET modeled at 9km, 36km
- Evaluate 9km and 36km data at EC towers with gridded forcing
- Identify areas of change in ET compared to original model and driving mechanism

Variable	Product Name	Time Available	Frequency	Spatial Resolution	Reference
Net Radiation	MERRA2 M2T1NXLND	1979-present	Daily	0.5^o x 0.5^o	GMAO 2015a
Temperature	MERRA2 M2I1NXASM	1979-present	Daily	0.5^o x 0.5^o	GMAO 2015b
Vapor Pressure	MERRA2 M2I1NXASM	1979-present	Daily	0.5^o x 0.5^o	GMAO 2015b
NDVI	MOD13A2 MYD13A2	2000-present	8-Daily	5km x 5km	NASA LP DAAC 2017
Soil Moisture	SPL3SMP_E v1 SPL3SMP v4	4-2015-present	3-Daily	9km x 9km 36km x 36km	Oneil et al., 2016a Oneil et al., 2016a
Soil Properties	SPL4SMLM	NA	NA	9km x 9km	Das et al., 2013
Canopy Height	NA	NA	NA	1km x 1km	Simmard et al., 2011

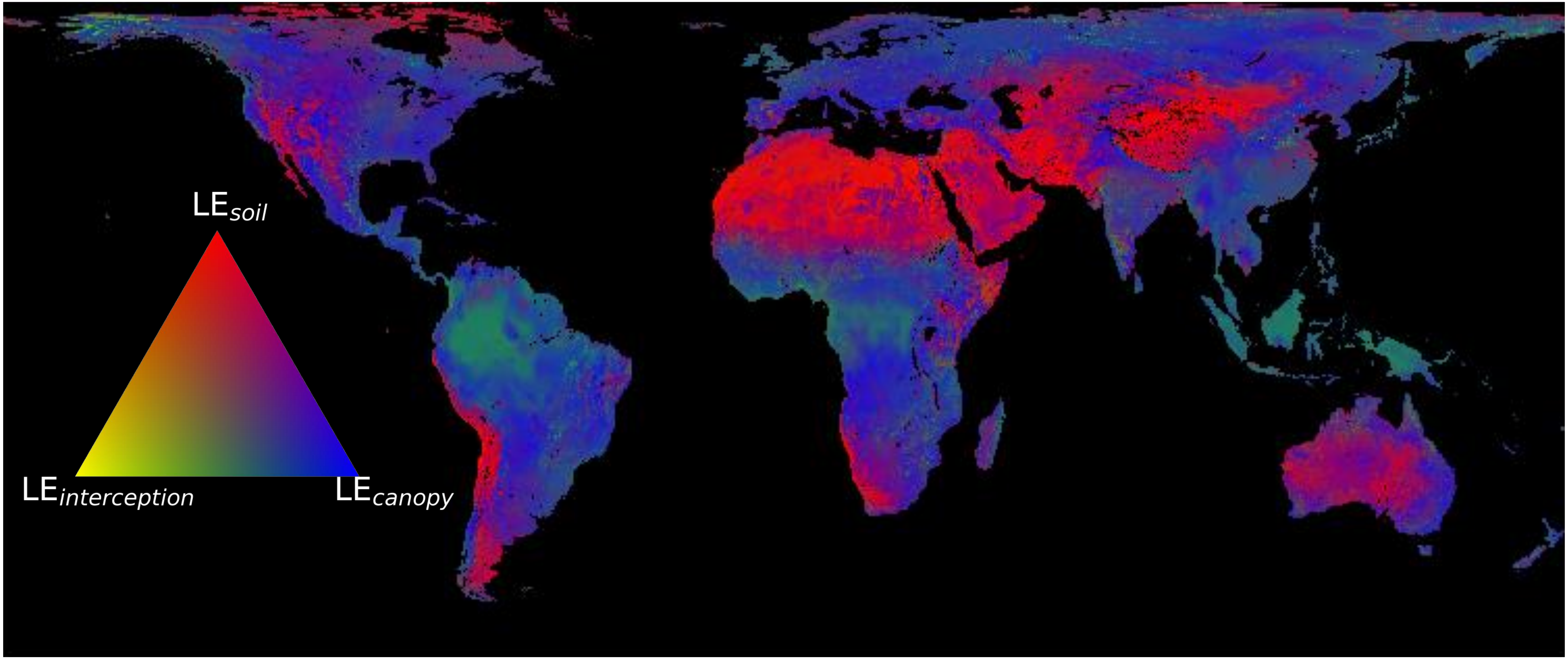
Global ET comparison

- Good agreement for both ET at 9km and 36km at tower sites
- Global differences show decreased ET in arid regions



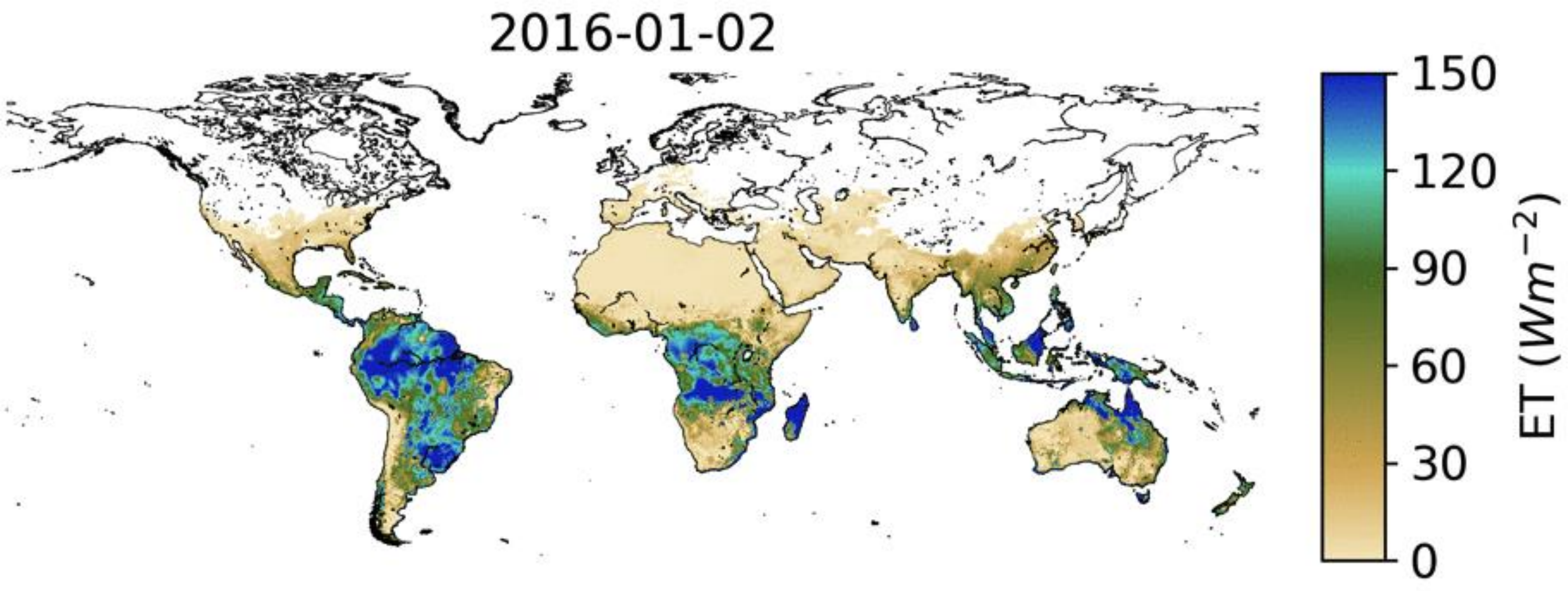


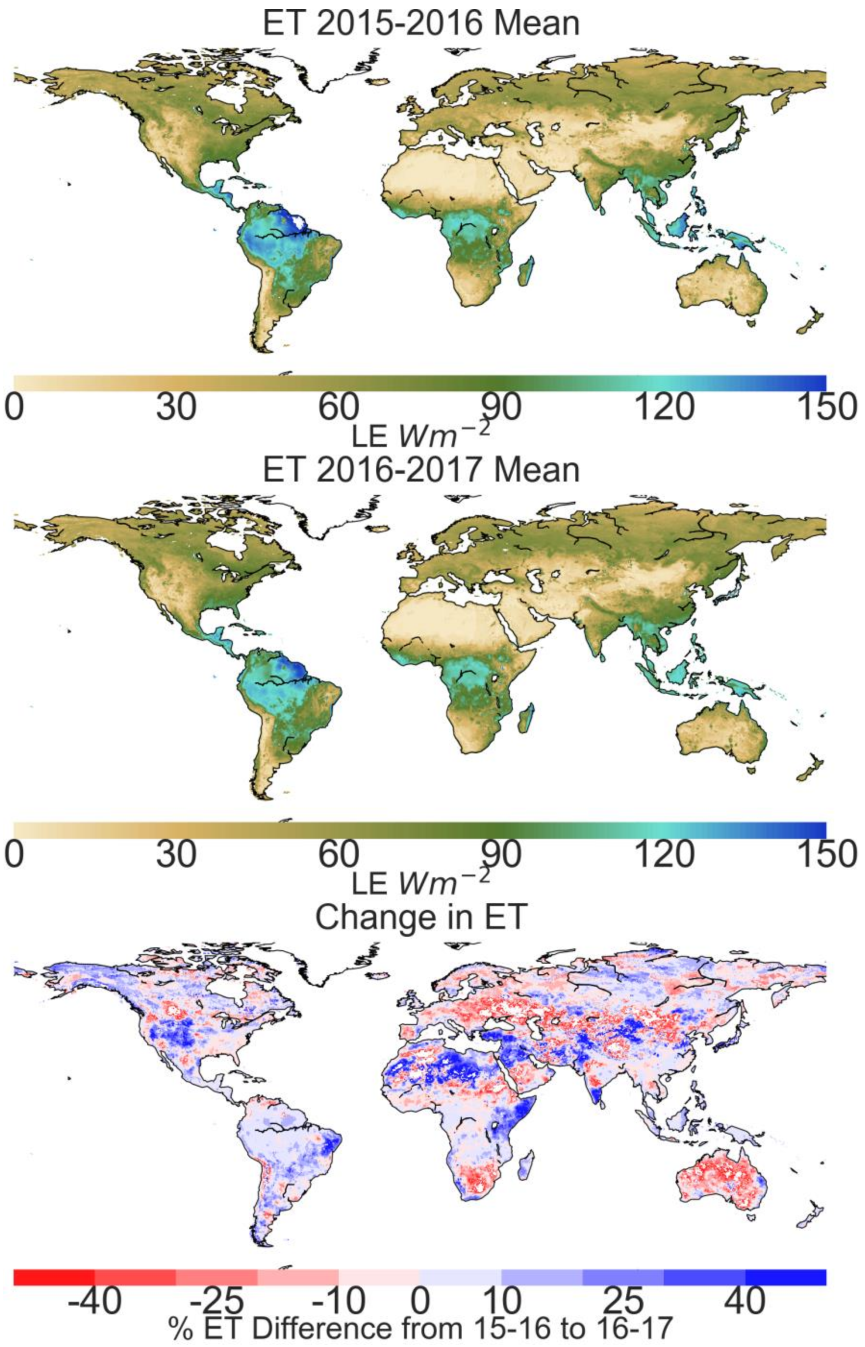
ET Partitioning



Intra and Inter Annual Variability

- Annual changes in ET show expected patterns associated with El Nino | La Nina
- Pronounced seasonal change driving by radiation and temperature but artifacts from precipitation events show through

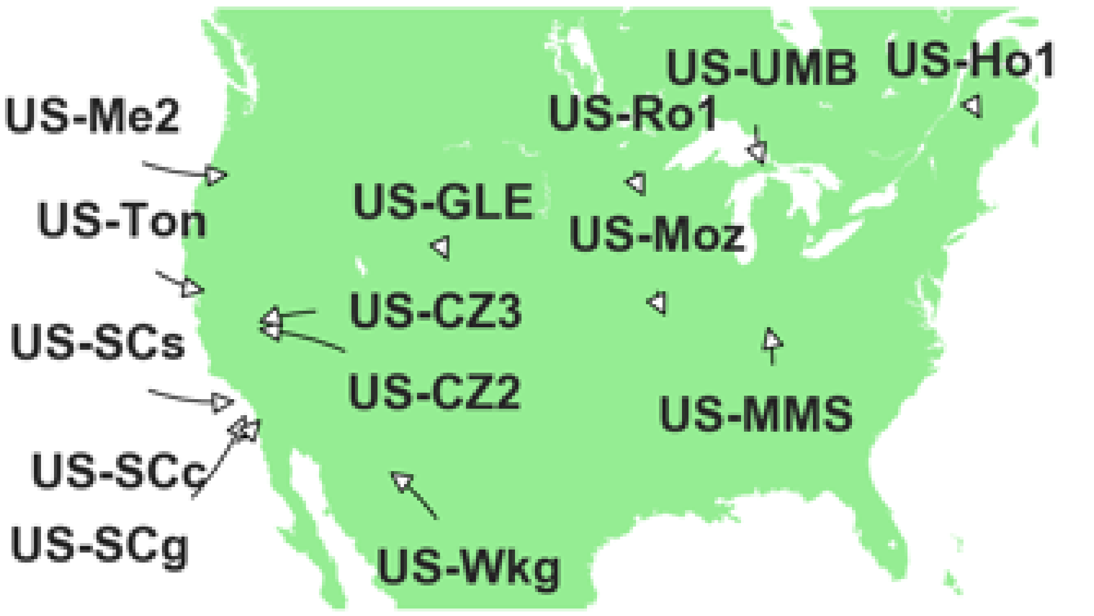




Results

Site	PT-JPL BIAS	PT-JPL R^2	PT-JPL RMSE	PT-JPL$_{SM}$ BIAS	PT-JPL$_{SM}$ R^2	PT-JPL$_{SM}$ RMSE
US-SCs	137.8	0.37	145.1	32.9	0.55	46.9
US-SCg	105.5	0.01	137.9	8.2	0.41	33.7
US-Wkg	21.4	0.94	27.6	10.6	0.94	30.7
US-SCc	54.0	0.76	56.3	17.6	0.77	22.9
US-Ton	67.3	0.79	75.9	20.5	0.85	35.9
US-Me2	21.1	0.65	65.2	6.1	0.84	31.2
US-CZ2	87.9	0.63	106.6	63.1	0.77	77.7
US-UMB	29.4	0.90	50.3	15.5	0.80	62.0
US-Moz	43.3	0.97	49.4	49.2	0.96	56.3
US-MMS	52.5	0.97	57.6	71.5	0.95	77.1
US-CZ3	33.7	0.62	60.2	12.6	0.61	37.5
US-Ro1	19.1	0.90	40.0	38.4	0.89	64.3
US-Ho1	46.4	0.88	62.0	66.6	0.85	83.5
US-GLE	15.4	0.79	55.9	15.8	0.41	51.9

Aridity Index	PT-JPL BIAS	PT-JPL R^2	PT-JPL RMSE	PT-JPL$_{SM}$ BIAS	PT-JPL$_{SM}$ R^2	PT-JPL$_{SM}$ RMSE
AI > 1	70.71	0.59	87.80	22.71	0.73	39.86



Conclusions

- The PT-JPL$_{SM}$ ET model improves modeled ET in water limited regions
- Global estimates show good agreement with EC towers
- Compared to original model, decreases seen in areas where soil evaporation is largest fraction of ET
- Inter-annual variation shows patterns expected for El Nino – La Nina transition

Moving Forward

- Apply similar analysis to the Penman Monteith approach
- Expand record to analyze how soil moisture impacts drought identification using ESI
- Characterize dominant controls on ET in space and time
- Link water and carbon cycles from space with ET and OCO-2 SIF

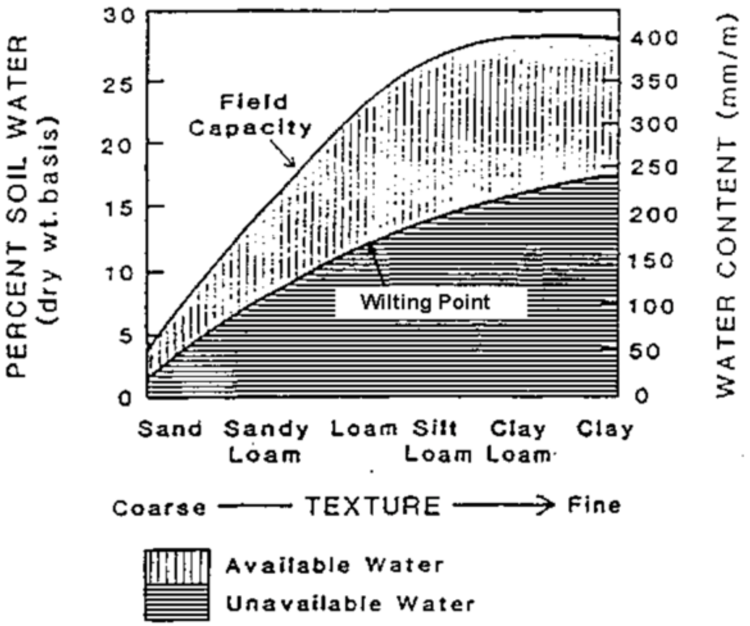
Acknowledgements
Funding provided by: NASA SUSMAP
NASA Earth and Space Science Fellowship

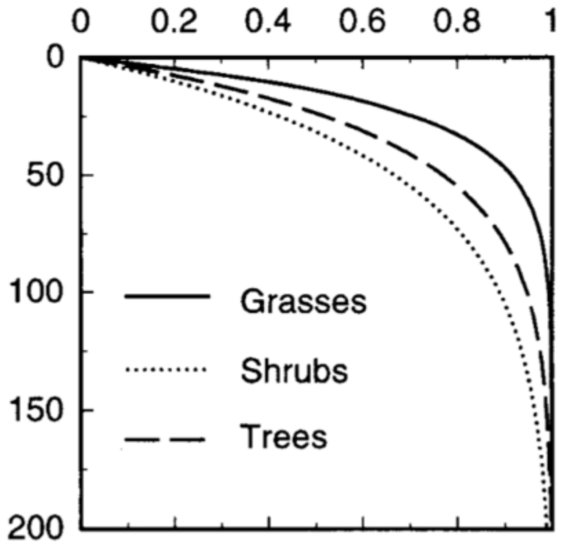
We thank the FLUXNET, AMERIFLUX, COSMOS, NASA organizations for providing open access data.

Supplemental Slides

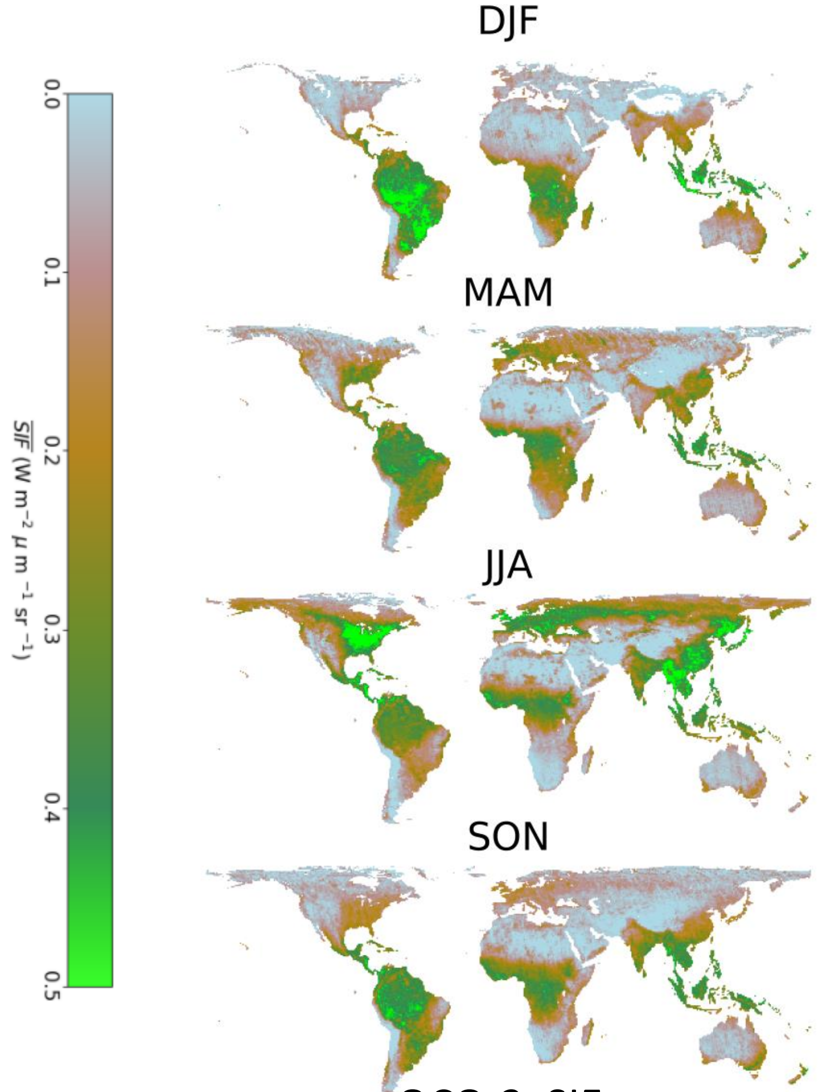
Transpiration SM stress formulation

- Soil moisture only matters relative to the soil properties
- Canopy height can be indicator of potential rooting depth

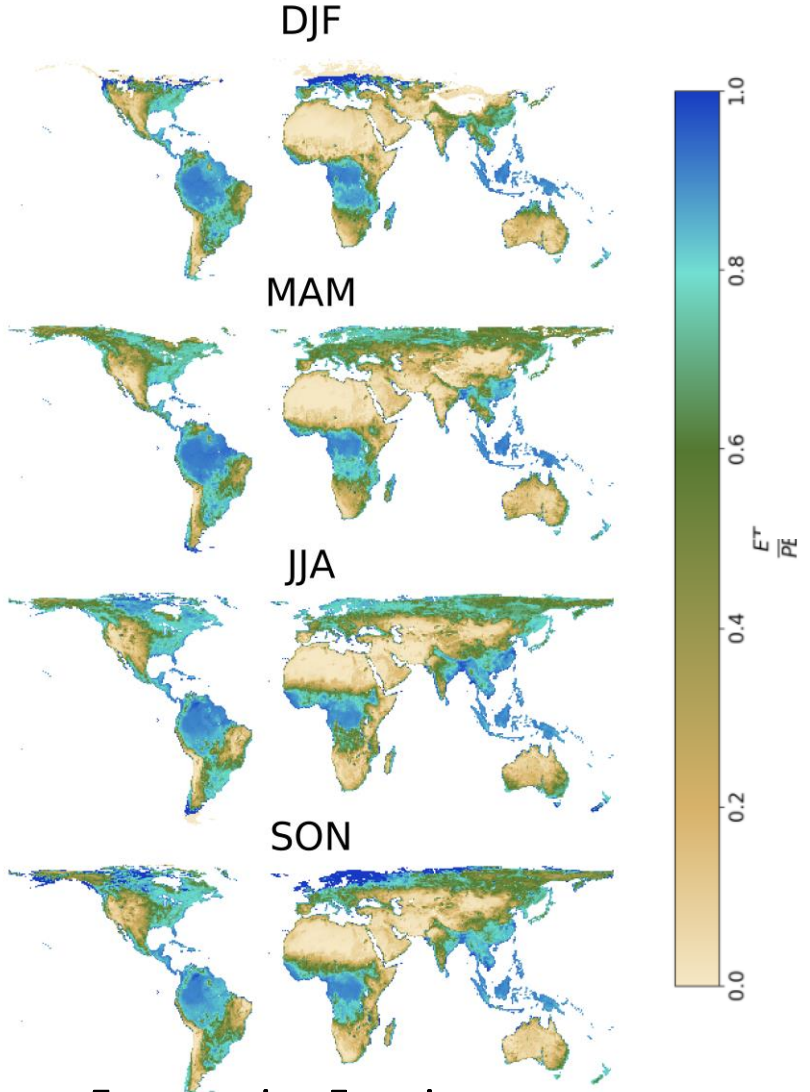




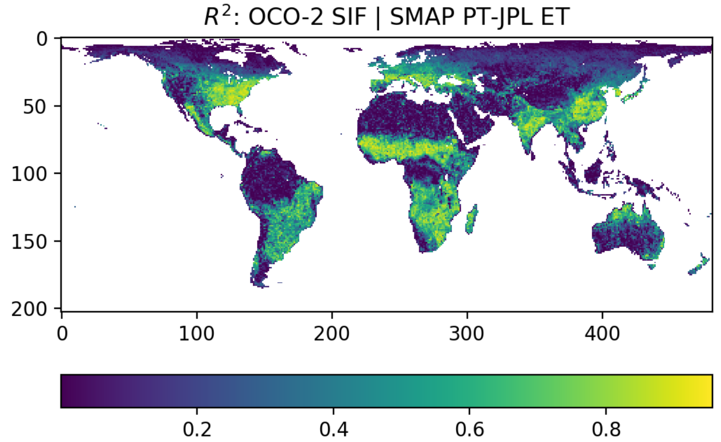
Link carbon and water cycle from space



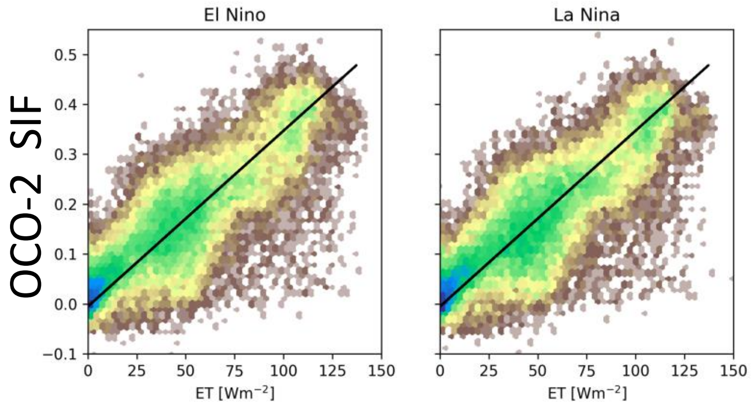
OCO-2 SIF



Evaporative Fraction

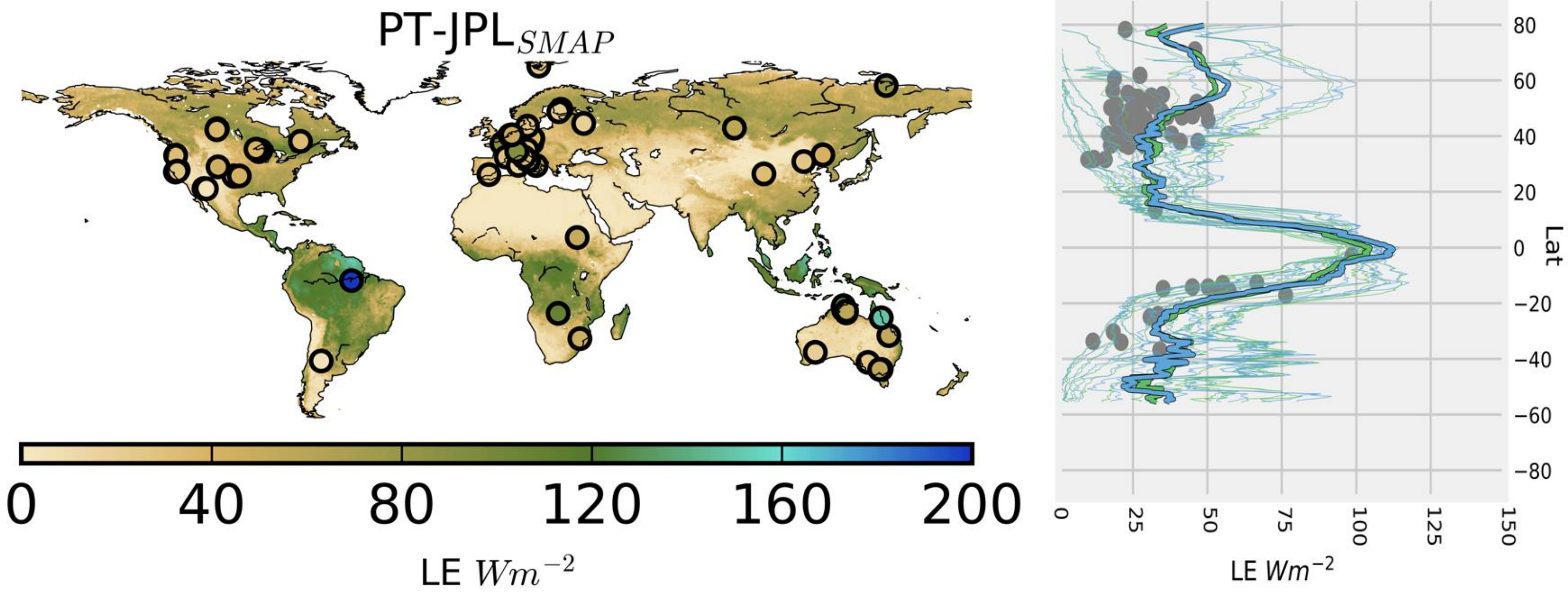


R^2

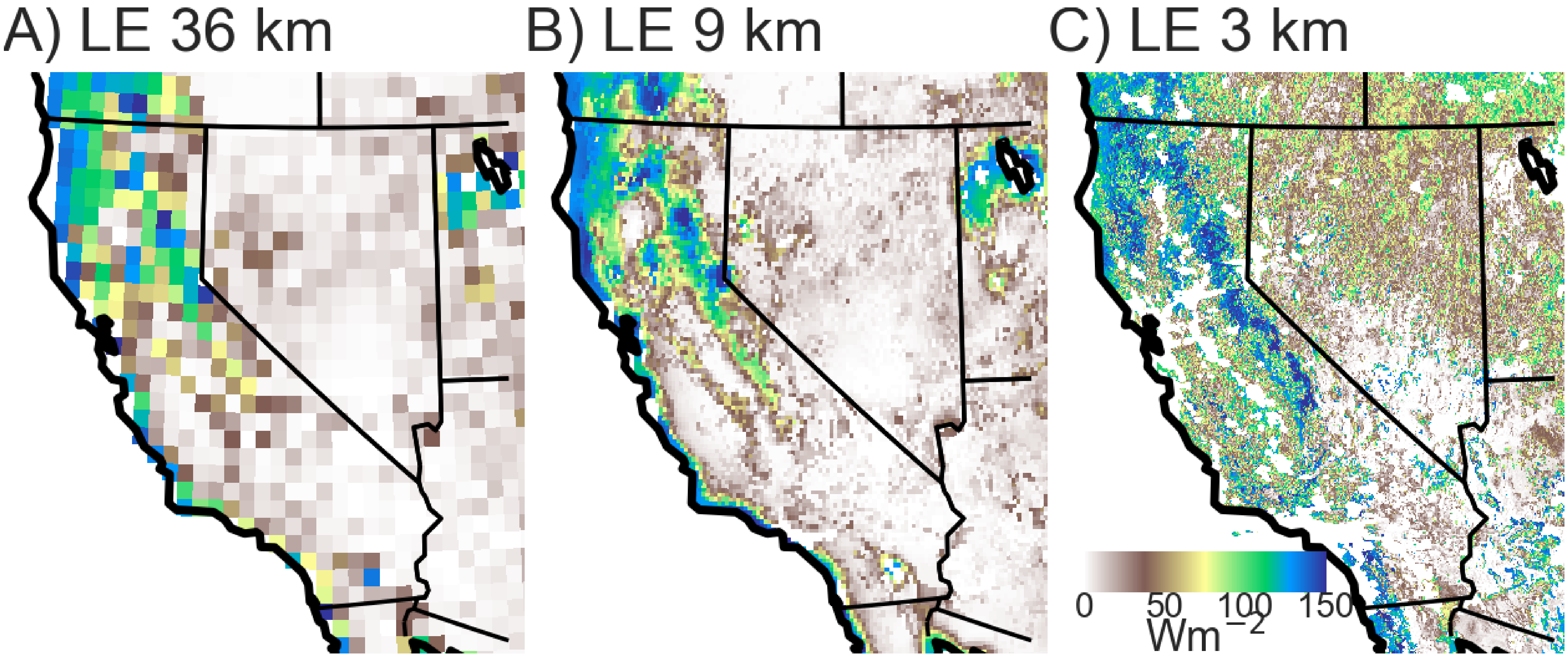


ET

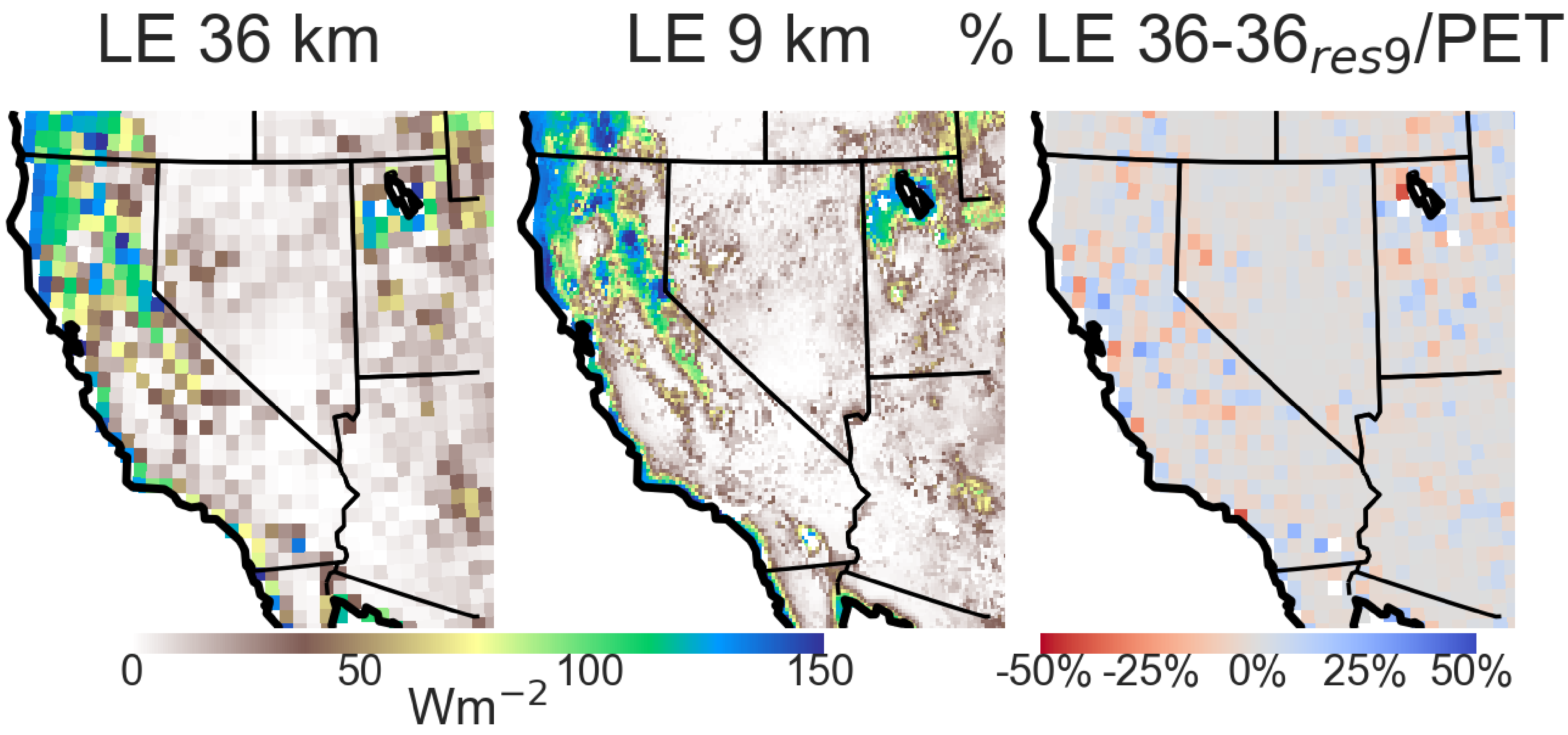
Long Term ET: PT-JPL$_{SM}$ and FLUXNET2015



Impact of resolution on ET quantification



Impact of resolution on ET quantification



Faster animation for slide 14