

# **Soil Moisture Remote Sensing Science and Applications**

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J. Wen, K. Yang, C. Shi, Y. Zheng, R. Wu, et al.**

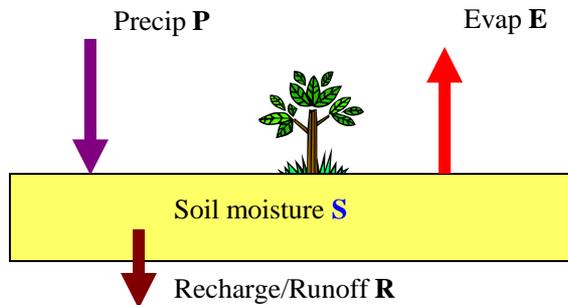
# Outline

- ❖ **Why Soil Moisture**
- ❖ **Soil Moisture Remote Sensing Science**  
*MW, TIR*
- ❖ **Satellite soil moisture product systems**  
*SMOPS, GET-D*
- ❖ **Soil Moisture Data Applications**  
*NWP, Drought, Flood, Crop, etc.*

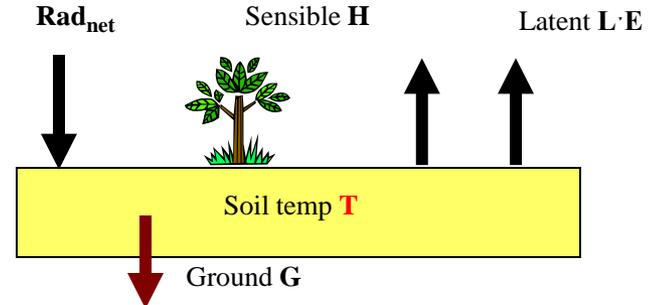
# Why Soil Moisture for NOAA

Soil moisture controls land surface **mass** and **energy** partitioning through impacting evapotranspiration

## Mass balance



## Energy balance



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



$$c \frac{dT}{dt} = Rad_{net}(T) - H(T) - L \cdot E(T, S)$$

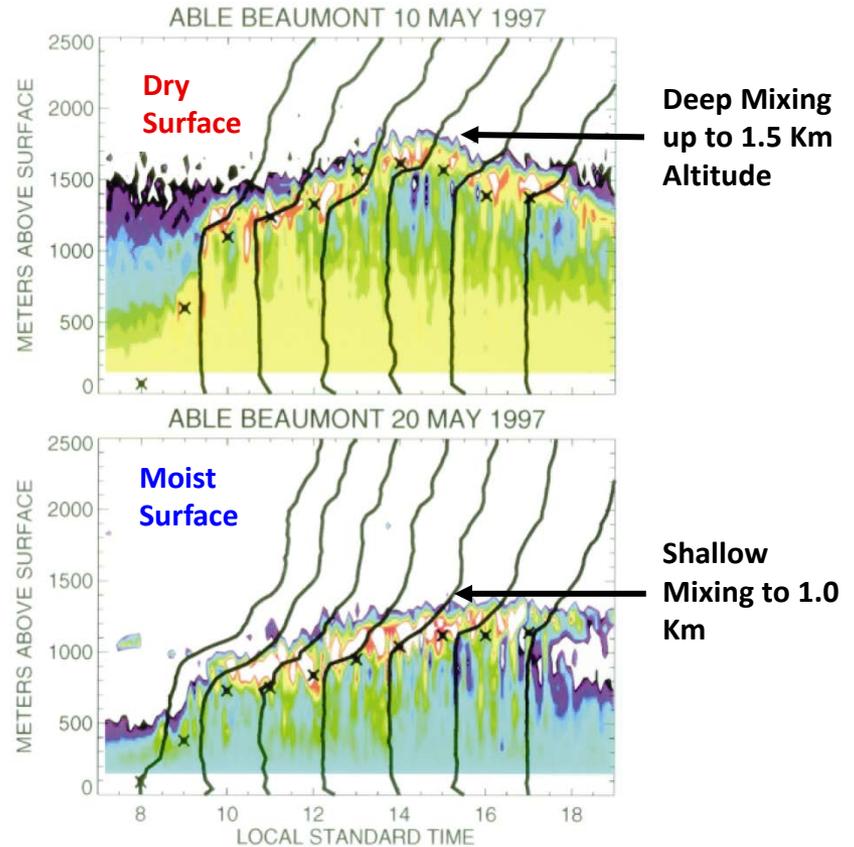
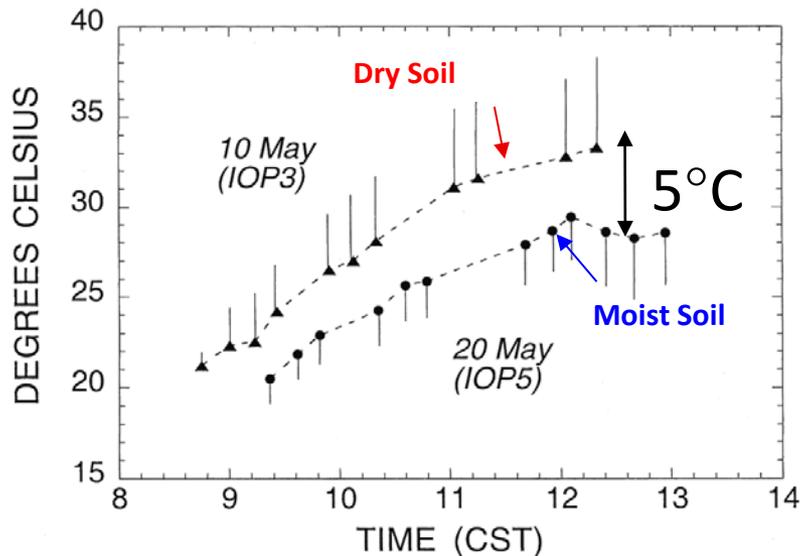
Evaporation & soil moisture **couple mass & energy balances** at land surface

$L$  is the latent heat of vaporization:  $2.5 \times 10^6$  [J/kg]

# Why Soil Moisture for NOAA

Over land actual evapotranspiration depends on both incident energy and soil moisture.

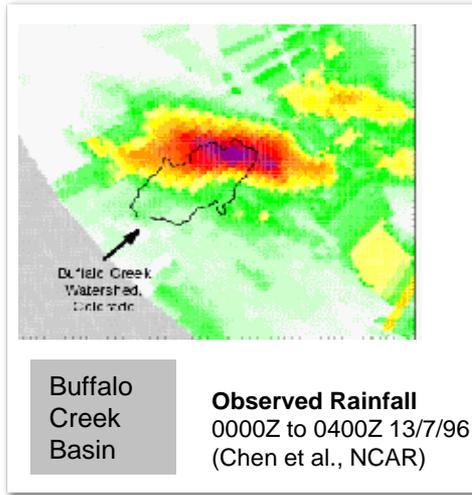
- May 10** Dry soil, clear, mild winds. ( $LE \approx H$ )
- May 18** 90 mm Rain
- May 20** Moist soil, clear, mild winds. ( $LE > H$ )



CASES'97 Field Experiment,  
*BAMS*, 81(4), 2000.

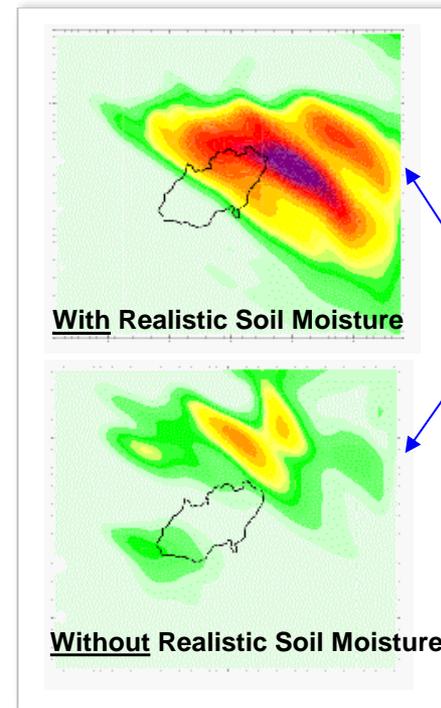
# Soil Moisture Impact on Weather Forecasting

Observed Rainfall from intense storm in Colorado:



24-Hours Ahead  
Atmospheric Model  
Forecasts

Model forecasts with and w/o soil moisture:



**Actual storm event is forecasted accurately only if soil moisture information is available.**

## Soil Moisture Data Will Improve Numerical Weather Prediction (NWP) Over the Continents by Accurately Initializing Land Surface States

"The experience of the last ten years at ECMWF has shown the importance of soil moisture...Soil moisture is a major player on the quality of weather parameters such as precipitation, screen-level temperature and humidity and low-level clouds."

**Anthony Hollingworth, ECMWF**

"The strong motivation for this land data assimilation and land-monitoring space missions such as Hydros is that the land states of soil moisture, soil ice, snowpack, and vegetation exert a strong control on ...the heating and moistening of the lower atmosphere...forecast of tomorrow's heat index, precipitation, and severe thunderstorm likelihood."

**Louis Uccellini, NCEP**

# Soil Moisture Impacts on Others



Drought & Ag Production

## Military Mobility

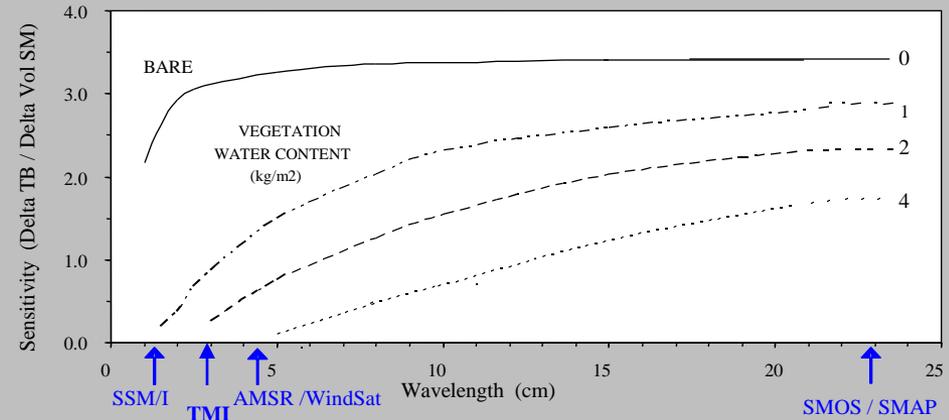


# Soil Moisture Remote Sensing Science

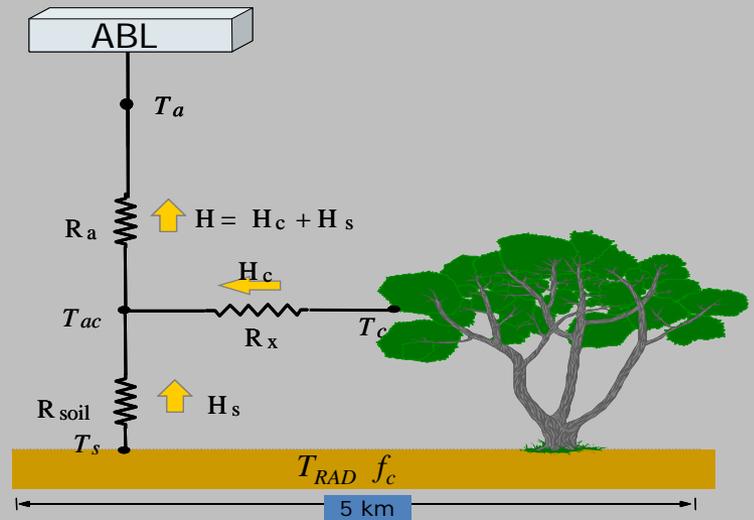
## Two ways to retrieve soil moisture from satellites:

- Microwave (MW):** Observed MW brightness temperature depends on soil dielectric constant that is related to soil moisture:
  - Strength:** higher reliability based on direct physical relationships
  - Weakness:** antenna technology limits spatial resolution
- Thermal Infrared (TIR):** Observed surface temperature changes result from surface energy balance that is dependent on soil moisture:
  - Strength:** TIR sensor could have higher spatial resolution
  - Weakness:** relies on land surface energy balance model that is prone to input data errors.

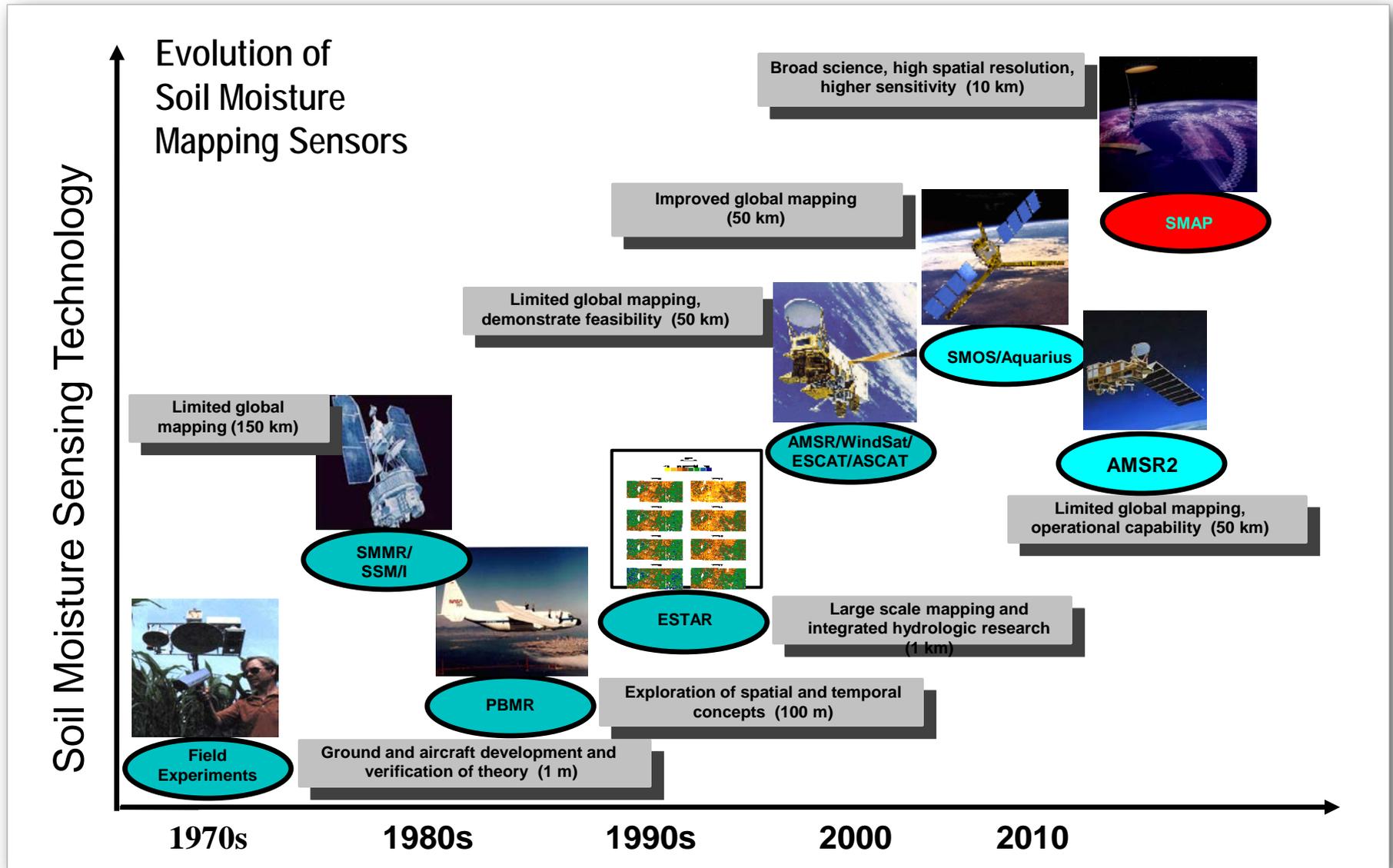
Microwave Sensitivity By Wavelength and Vegetation Density



Two-Source Model (ALEXI)



# MW Soil Moisture Remote Sensing Technology



# **MW Soil Moisture Remote Sensing: Retrieval Algorithm Science**

# Soil Moisture Retrieval Algorithms

## Multi-channel Inversion Algorithm (MCI):

(Njoku & Li, 1999)

$$\min \{ \chi^2 = \sum_{i=1}^6 \left( \frac{T_{B,i}^{obs} - T_{B,i}^{cmp}}{\sigma_i} \right)^2 \}$$

$$T_{B,i}^{cmp} = T_s \{ e_{r,p} \exp(-\tau_i / \cos\theta) + (1 - \omega) [1 - \exp(-\tau_i / \cos\theta)] [1 + R_{r,i} \exp(-\tau_i / \cos\theta)] \}$$

$$\tau_i = b * \text{VWC}$$

$$R_{r,i} = R_s \exp(h \cos^2\theta)$$

$$R_s = f(\epsilon) \quad \text{-- Fresnel Equation}$$

$$\epsilon = g(\text{SM}) \quad \text{-- Mixing model}$$

$$T_{B,i}^{obs} = T_{B06h}, T_{B06v}, T_{B10h}, T_{B10v}, T_{B18h}, T_{B18v}$$

# Soil Moisture Retrieval Algorithms

## Land Parameter Retrieval Model (LPRM):

(Owe, de Jeu & Holmes, 2008)

$$\min \{ \chi^2 = \sum_{i=1}^6 \left( \frac{T_{B,i}^{obs} - T_{B,i}^{cmp}}{\sigma_i} \right)^2 \}$$

$$T_{B,i}^{cmp} = T_s \{ e_{r,p} \exp(-\tau_i / \cos\theta) + (1 - \omega) [1 - \exp(-\tau_i / \cos\theta)] [1 + R_{r,i} \exp(-\tau_i / \cos\theta)] \}$$

$$\tau = f(MPDI), MPDI = (T_{Bv} - T_{Bh}) / (T_{Bv} + T_{Bh})$$

$$e_h = f(e_s, h, Q)$$

$$e_s = f(\epsilon) \quad \text{-- Fresnel equation}$$

$$\epsilon = f(SM) \quad \text{-- Mixing model (Dobson '85, others)}$$

$$T_s = f(T_{B37v}) \text{ or } T_s^{LSM}$$

$$T_{Bh}^{obs} = T_{B06h}, T_{B10h} \text{ or } T_{B18h}$$

# Soil Moisture Retrieval Algorithms

**Single Channel Retrieval (SCR) Algorithm:**

(Jackson, 1993)

$$T_{B10h} = T_s [1 - R_r \exp(-2\tau / \cos\theta)]$$

$$R_r = R_s \exp(h \cos^2\theta)$$

$$R_s = f(\varepsilon) \quad \text{-- Fresnel Equation}$$

$$\varepsilon = g(\text{SM}) \quad \text{-- Mixing model}$$

$$T_s = \text{reg}_1(T_{B37v}) \text{ or } T_s^{\text{LSM}}$$

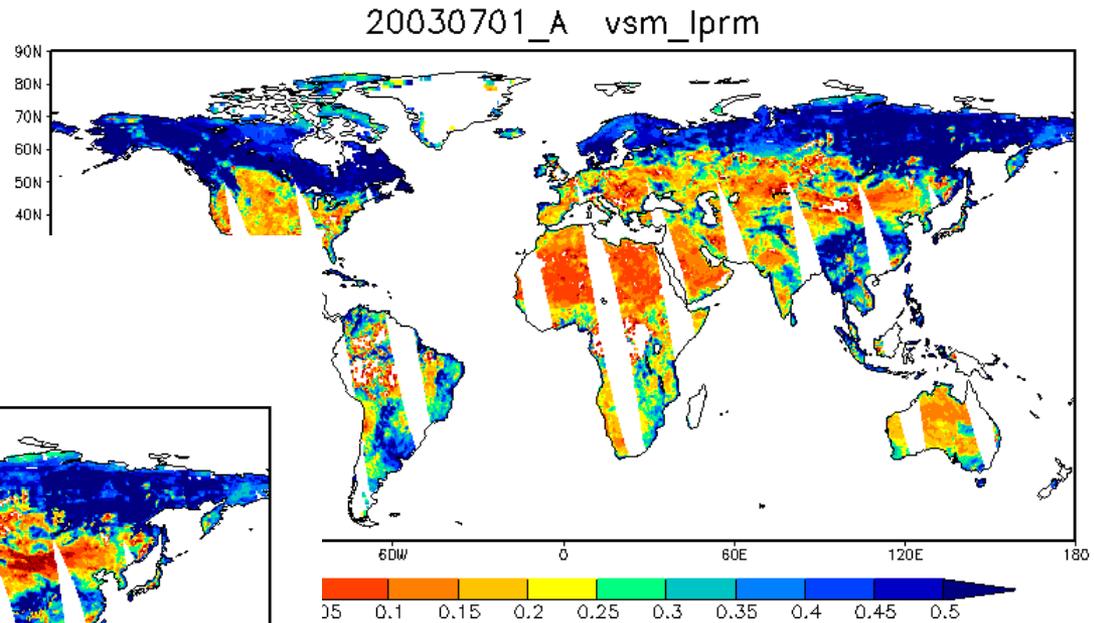
$$\tau = b * \text{VWC}$$

$$\text{VWC} = \text{reg}_2(\text{NDVI})$$

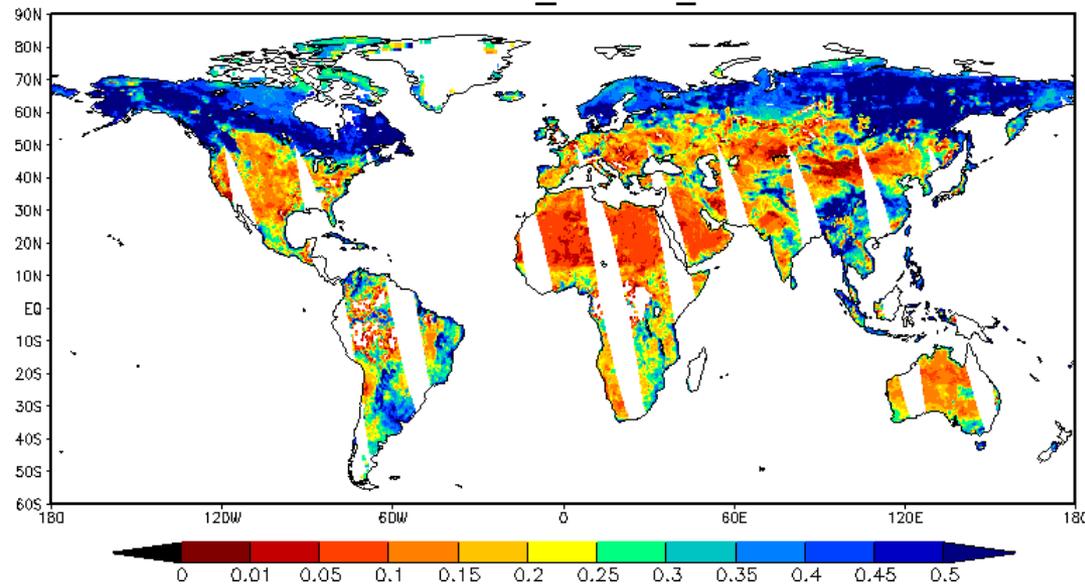
**SCR can be applied to different sensors for a consistent satellite soil moisture data product.**

# Impact of $\tau = f(\text{MPDI})$ on SM Retrievals:

**LPRM with**  
 $\tau = f(\text{MPDI})$



20030701\_A vsm\_mci

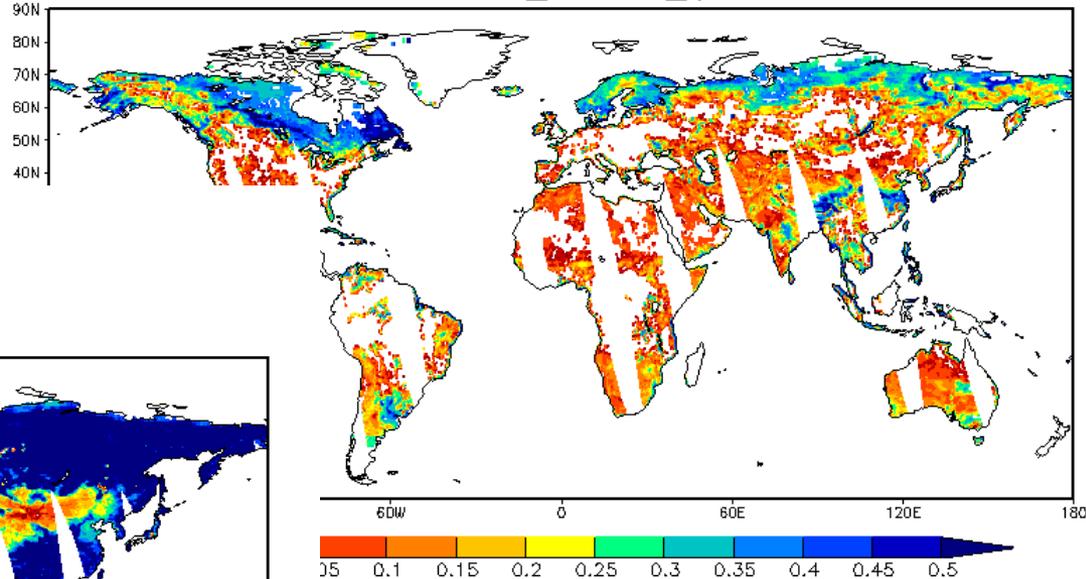


**MCI with**  $T_s = f(T_{B37V})$

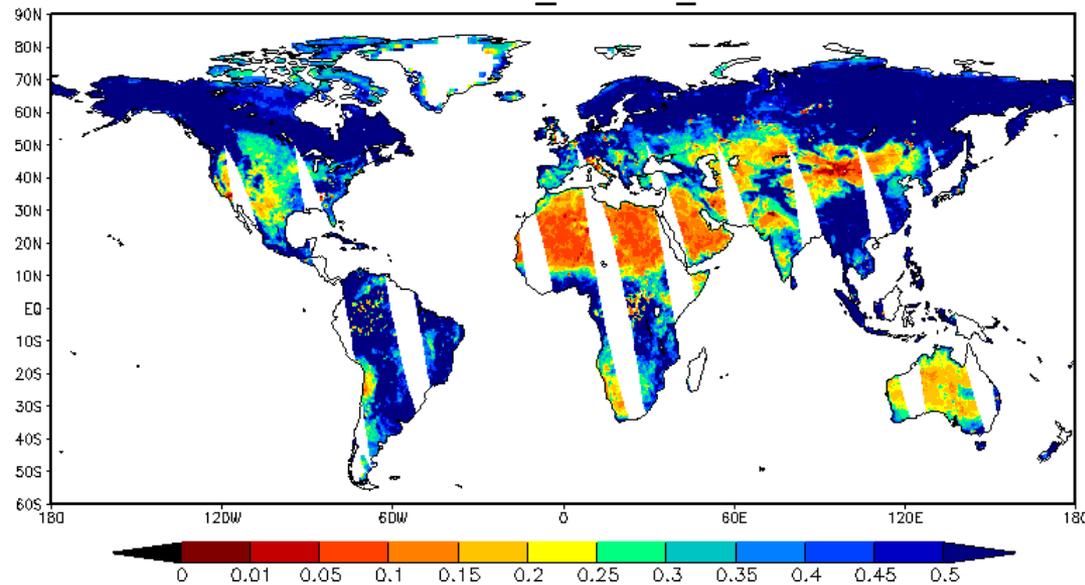
# Impact of $T_s$ error on LPRM/MCI Retrievals:

$T_s + 2K$

20030701\_A vsm\_lprm



20030701\_A vsm\_mci

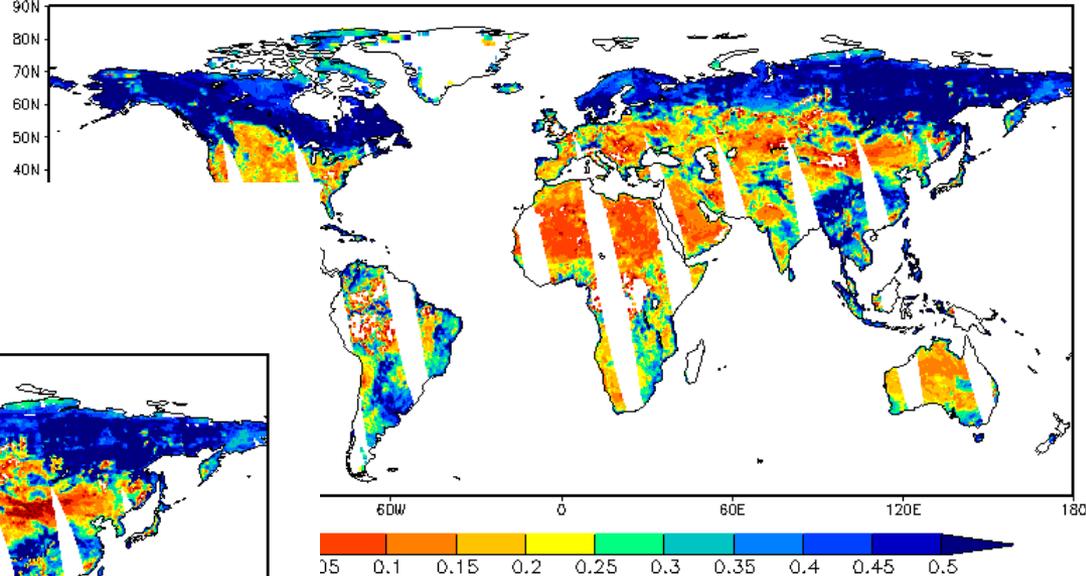


$T_s - 2K$

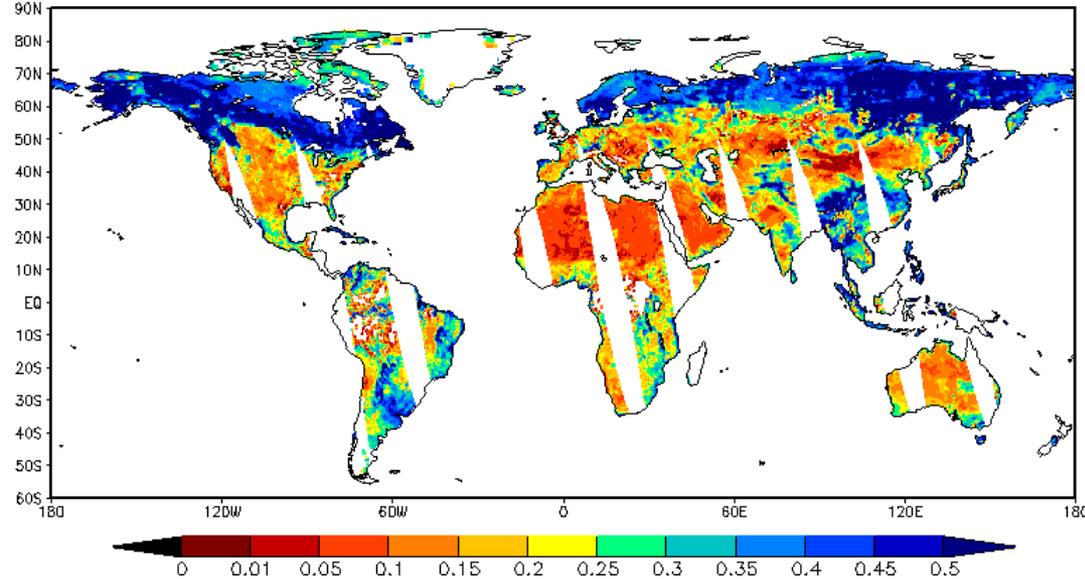
# Impact of $T_s$ error on LPRM/MCI Retrievals:

**No  $T_s$  errors**

20030701\_A vsm\_lprm



20030701\_A vsm\_mci

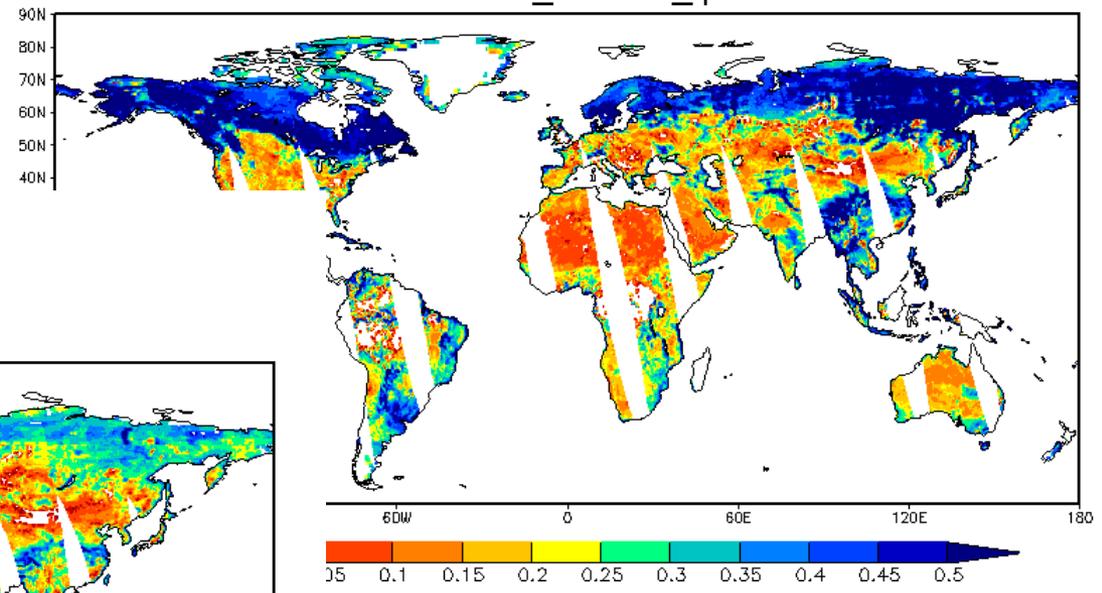


**No  $T_s$  errors**

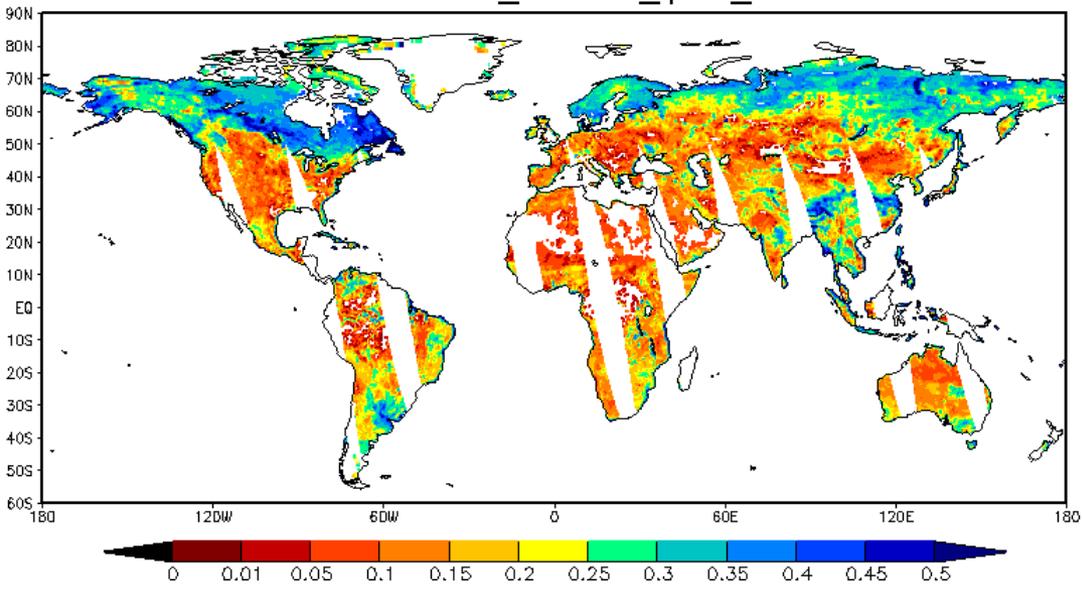
# Impact of $T_b$ error on LPRM/MCI Retrievals:

$T_{bh} + 2K$   
 $T_{bv} - 2K$

20030701\_A vsm\_lprm



20030701\_A vsm\_lprm\_1

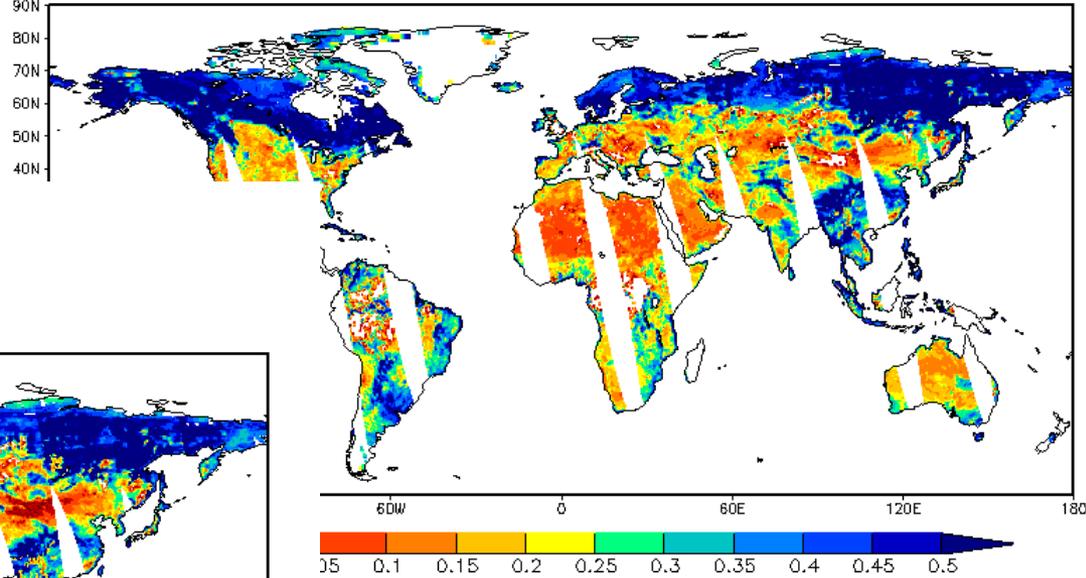


$T_{bh} - 2K$   
 $T_{bv} + 2K$

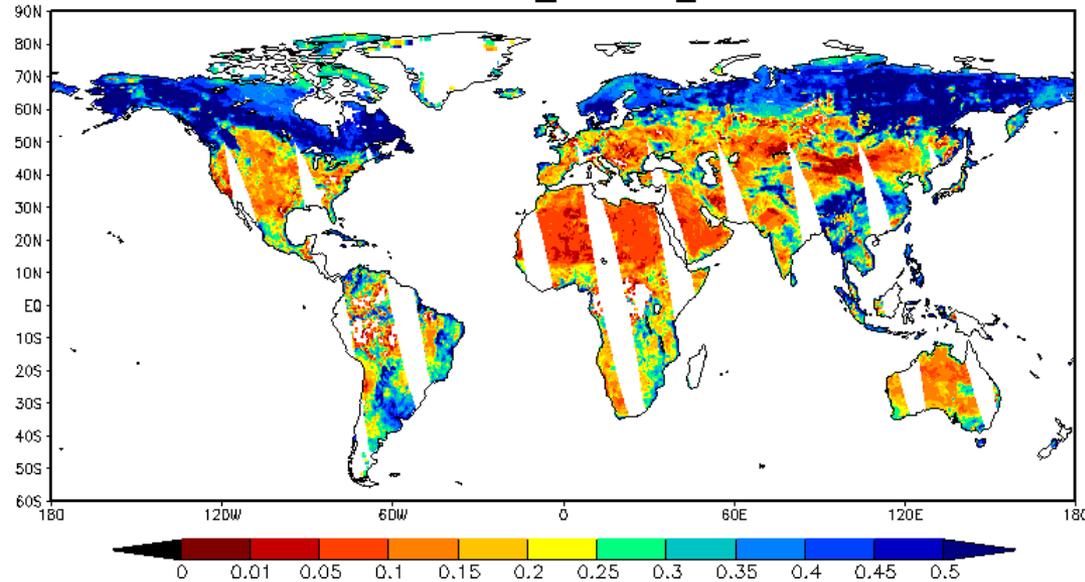
# Impact of $T_b$ error on LPRM/MCI Retrievals:

**No  $T_b$  errors**

20030701\_A vsm\_lprm



20030701\_A vsm\_mci

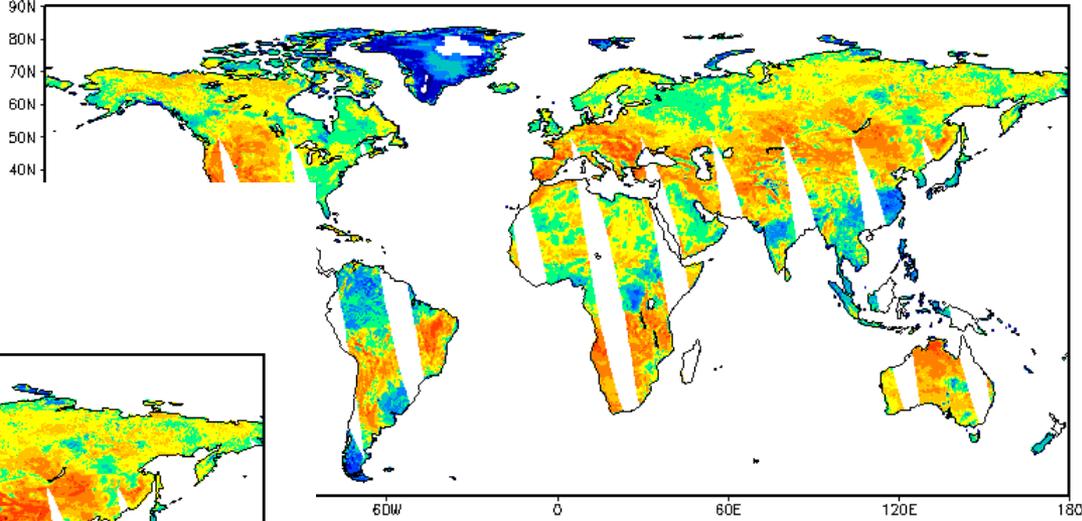


**No  $T_b$  errors**

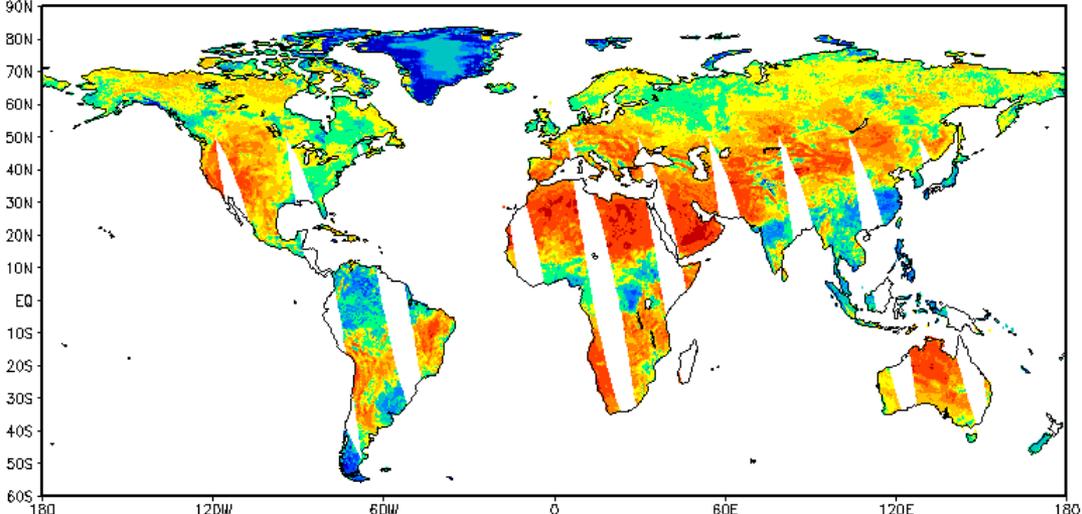
# Impact of Tau error on SCA Retrievals:

$\tau + 0.01$

20030701\_A vsm\_scr2\_n



20030701\_A sm\_glds\_n

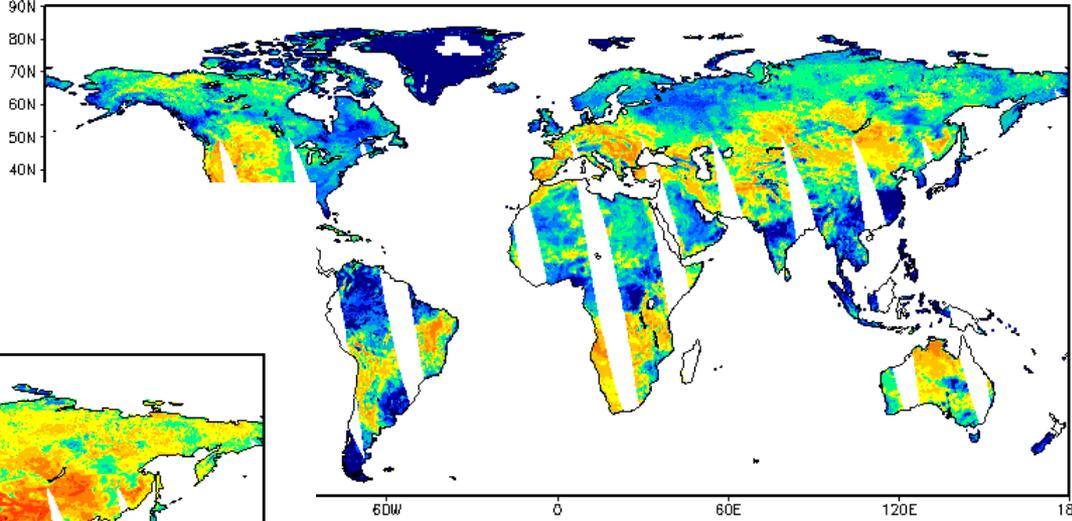


No  $\tau$  error

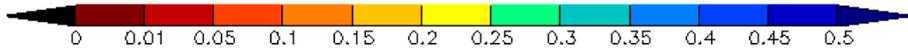
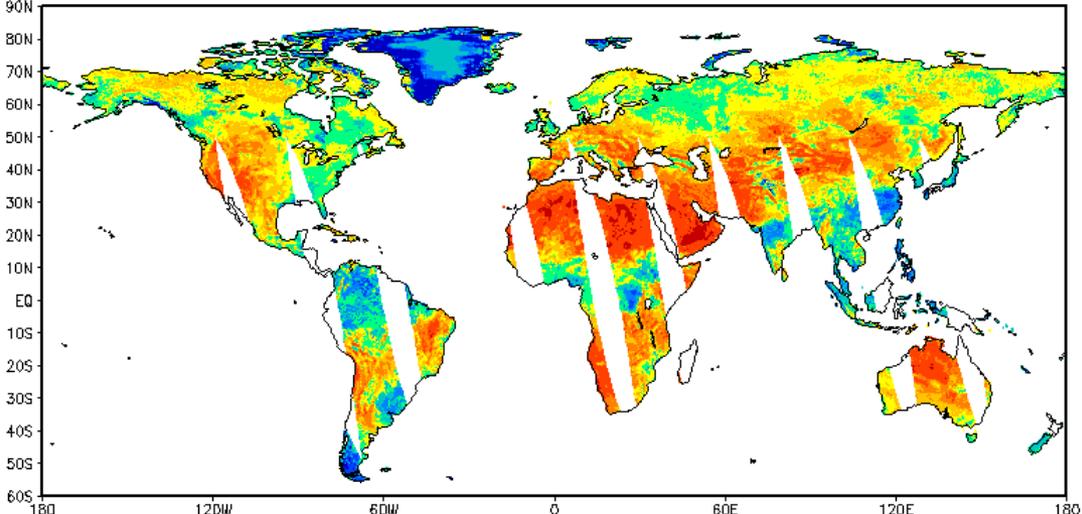
# Impact of Tau error on SCA Retrievals:

$\tau + 0.05$

20030701\_A vsm\_scr2\_n



20030701\_A sm\_glds\_n

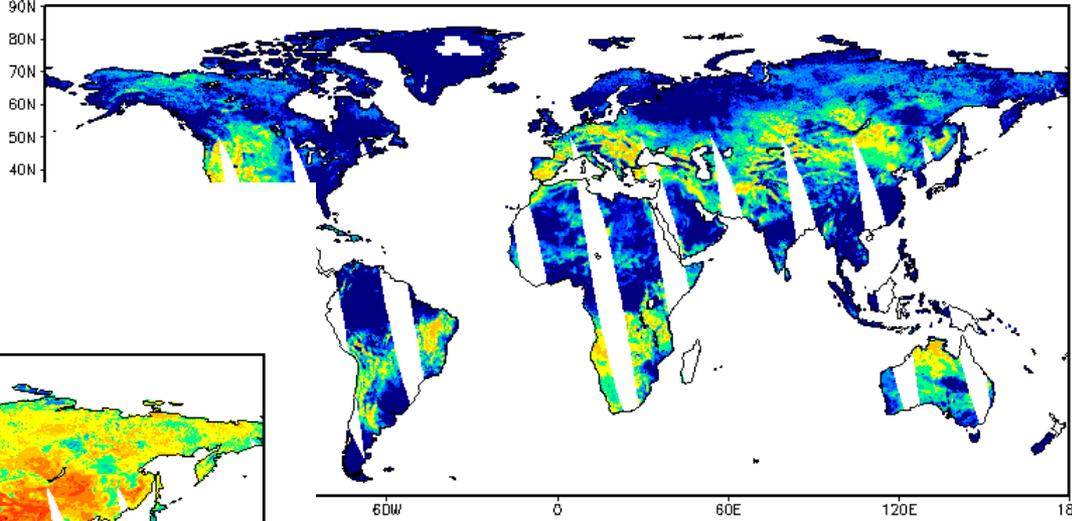


No  $\tau$  error

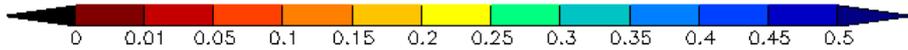
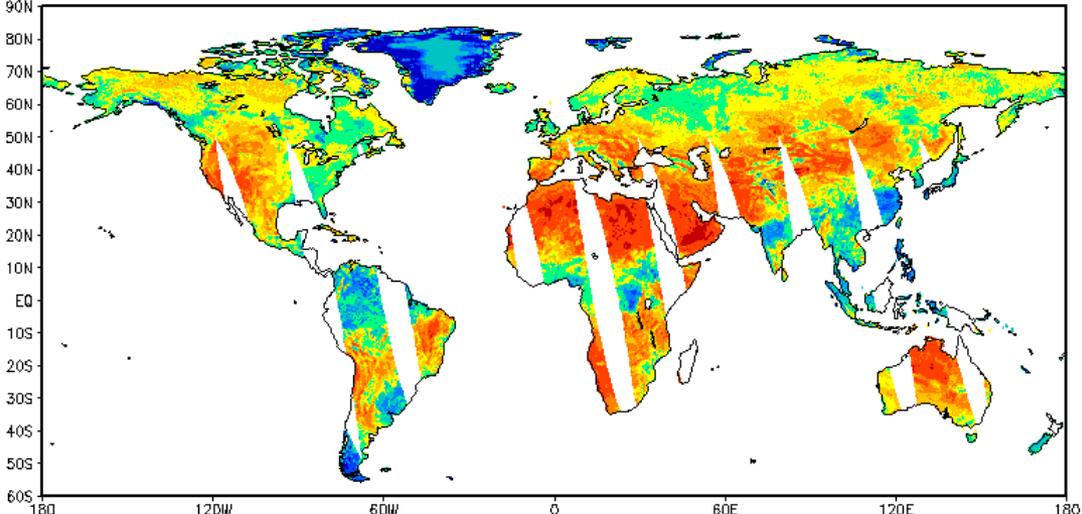
# Impact of Tau error on SCA Retrievals:

$\tau + 0.1$

20030701\_A vsm\_scr2\_n



20030701\_A sm\_glds\_n

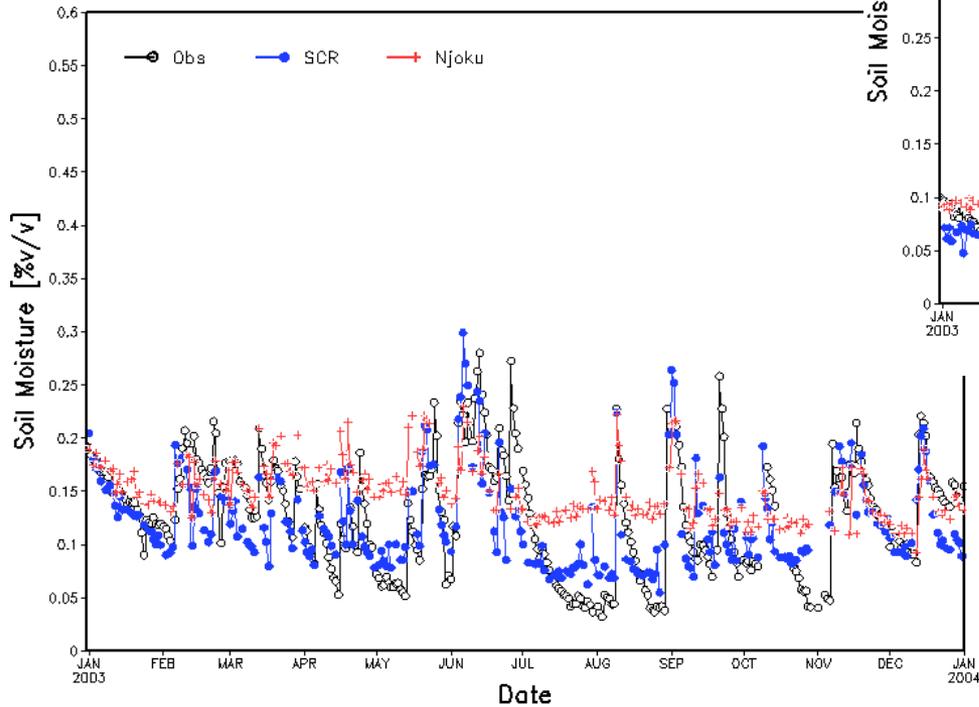


No  $\tau$  error

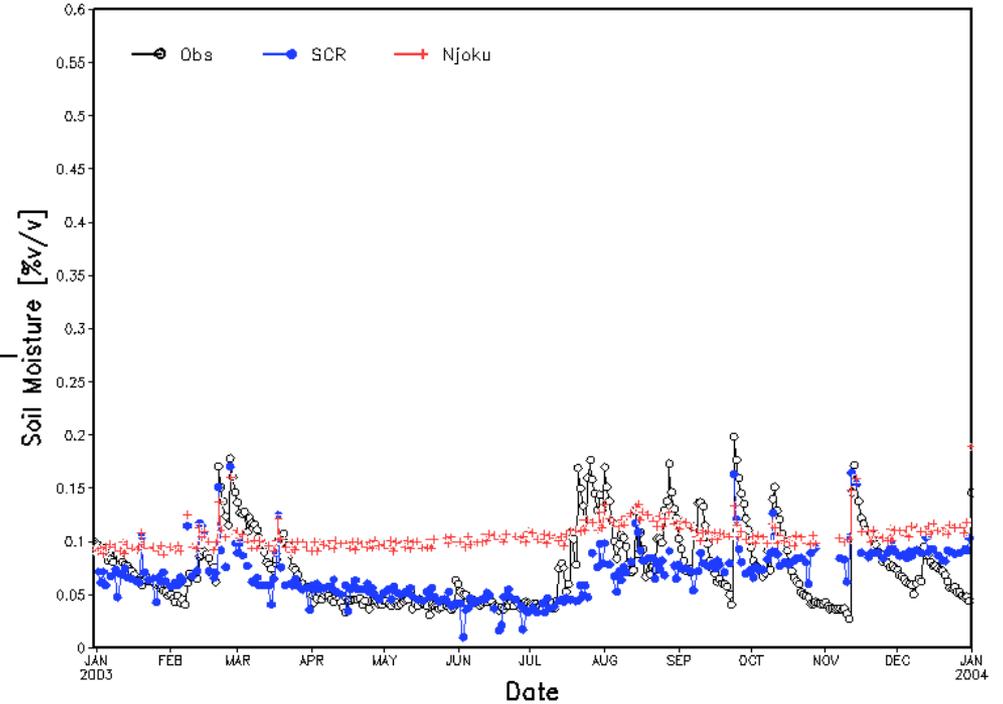
# Soil Moisture Retrieval Validation

## SCR and MCI Compared with In Situ Measurements

AMSR-E Soil Moisture Retrievals Site LW

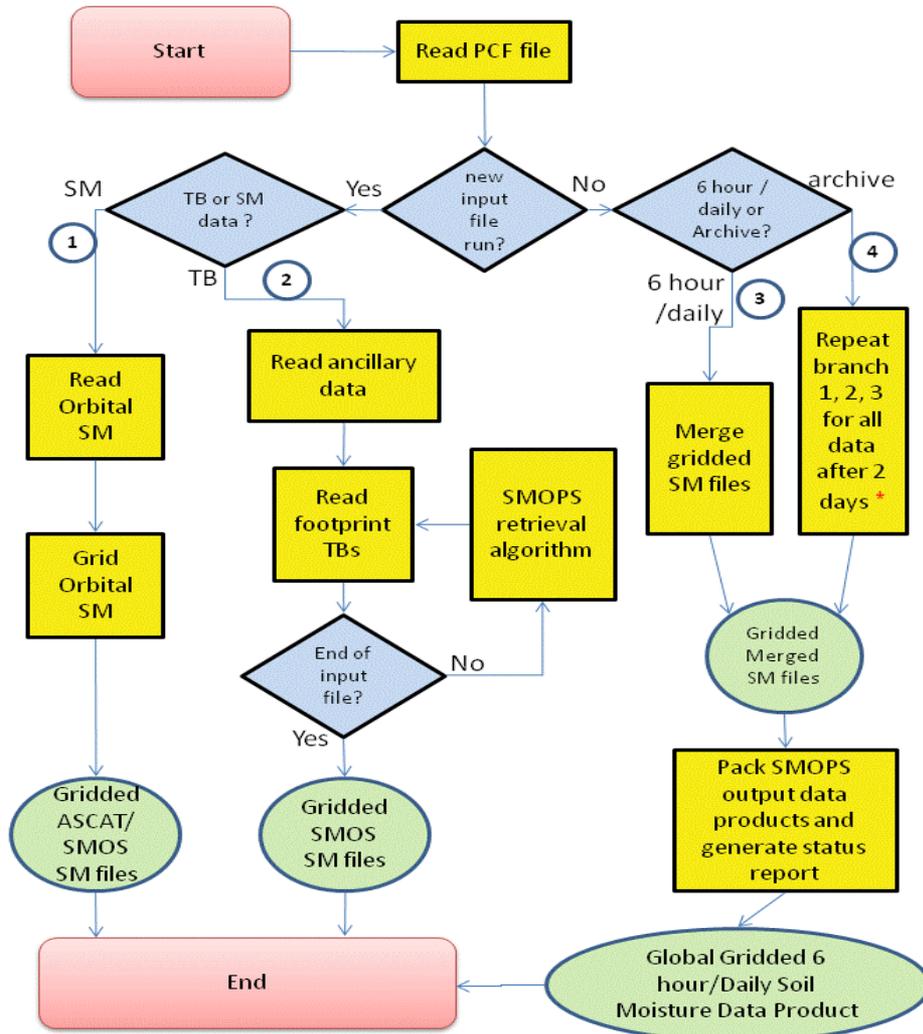


AMSR-E Soil Moisture Retrievals Site WG



# Soil Moisture Operational Product System (SMOPS)

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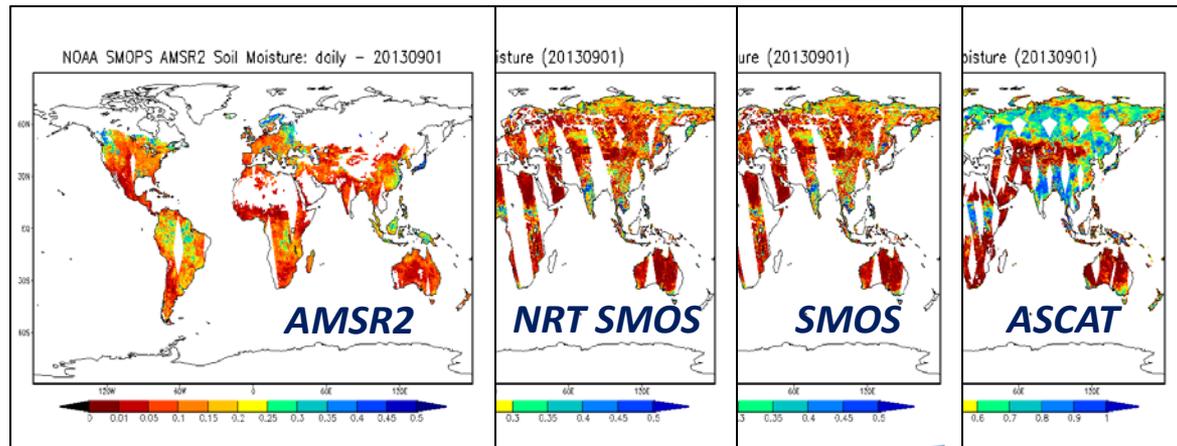
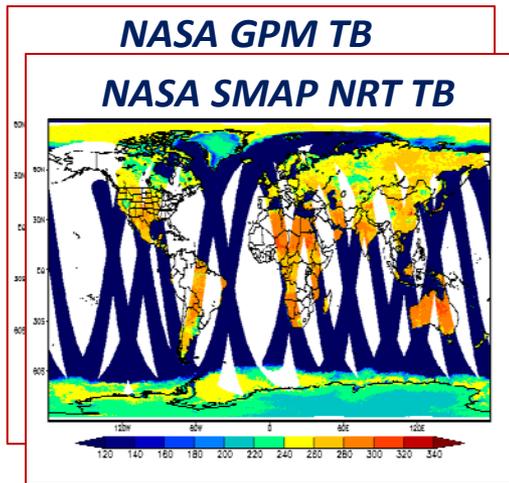
- ① SM ingesting
- ② SM retrieving
- ③ SM merging
- ④ Reprocessing for the archive product

\* All data acquired within the 6 hour or whole day time period arrived in the past 48 hours

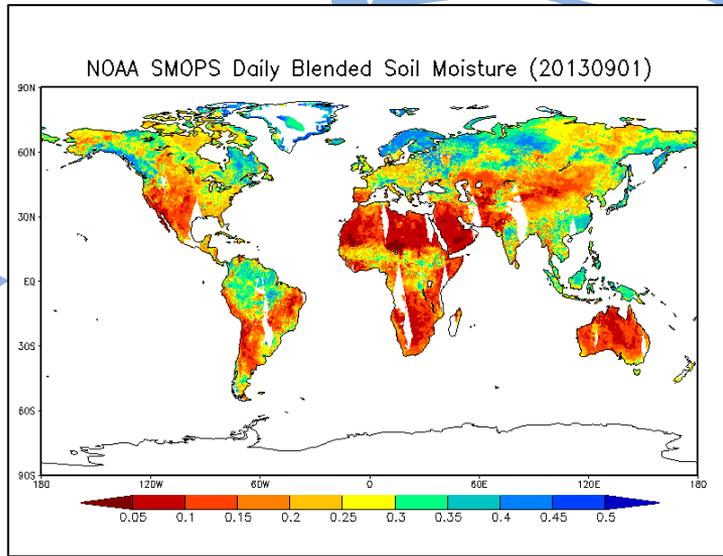
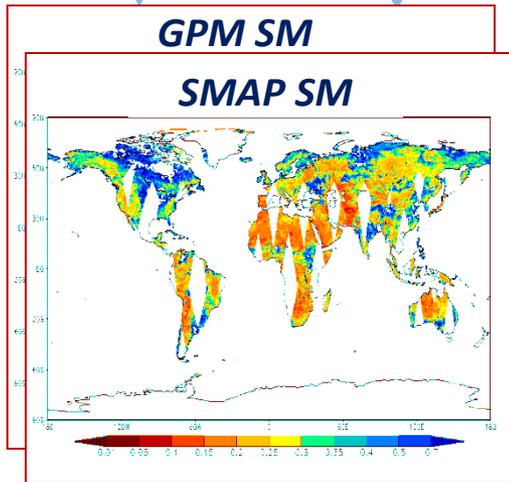


# Soil Moisture Operational Product System

## SMOPS 2.0/3.0



**NOAA Ancillary Data**



NWP models  
NCEP  
GFS/NAM  
NLDAS/GLDAS  
AFWA, etc

*NESSIS SMOPS 3.0 upgraded over the current SMOPS 2.0 will ingest NASA SMAP NRT and GPM TB data to retrieve global soil moisture with NOAA ancillary Data*



# SMOPS Product Suite

Products	Description	Format	Projection	Spatial Coverage	Spatial Resolution	Main Purpose
SMOPS 6-Hour Product	SMOPS 6-hour Gridded Soil Moisture	GRIB2	Lat/Long	Global	0.25 degree (720x1440)	For operational use
SMOPS Daily Product	SMOPS Daily Gridded Soil Moisture	GRIB2	Lat/Long	Global	0.25 degree (720x1440)	For operational/research use
SMOPS Archive Product	SMOPS Daily Gridded Soil Moisture	netCDF4	Lat/Long	Global	0.25 degree (720x1440)	For research use

# SMOPS Product Data Layers



Soil Moisture Product	SMOPS Version 1.3	SMOPS Version 2.0	SMOPS Version 3.0
SMOPS Blended	√ (1)	√ (1)	√ (1)
NOAA AMSR-E	√ (2)	×	×
NOAA NRT SMOS	×	√ (2)	√ (2)
ESA SMOS	√ (3)	√ (3)	√ (3)
EUMETSAT ASCAT-A	√ (4)	√ (4)	√ (4)
EUMETSAT ASCAT-B	√ (5)	√ (5)	√ (5)
NOAA WindSat	√ (6)	×	×
NOAA AMSR2	×	√ (6)	√ (6)
NOAA GMI	×	×	√ (7)
NOAA NRT SMAP	×	×	√ (8)
NASA SMAP	×	×	√ (9)

# NOAA Soil Moisture Operational Product System (SMOPS)



<http://www.ospo.noaa.gov/Products/land/smops/index.html>

OSPO Home

DOC NOAA NESDIS OSPO

NOAA OFFICE OF SATELLITE AND PRODUCT OPERATIONS  
NATIONAL ENVIRONMENTAL SATELLITE, DATA, AND INFORMATION SERVICE

ORGANIZATION SERVICES PRODUCTS OPERATIONS

### NESDIS Operational Soil Moisture Products

The Soil Moisture Operational Products System (SMOPS) combines soil moisture retrievals from multi-satellites/sensors to provide a global soil moisture map with more spatial and temporal coverage. The SMOPS first retrieves soil moisture from WindSat<sup>1</sup> onboard the Coriolis satellite and then combines its baseline retrievals with those from other available satellites/sensors, including ASCAT and SMOS, to improve the spatial and temporal coverage of the WindSat observations.

*\*SMOPS is currently updated to generate basic retrievals from WindSat after the original baseline sensor AMSR-E failed. Soil moisture retrievals from AMSR2 onboard GCOM-W will be added in the future.*

The global soil moisture maps are generated in 6-hourly and daily intervals with the latest 6 and 24 hours worth of soil moisture retrievals from multi-satellites/algorithms, and mapped with a cylindrical projection on 0.25 x 0.25 degree grids. For each grid point of the map, the output includes soil moisture values (%vol/vol) of the surface (top 1-5 cm) soil layer with associated quality information and metadata. The 6-hourly product is available in GRIB2 format at standard forecast times (00Z, 06Z, 12Z and 18Z), and daily product is available in both GRIB2 and netCDF4 formats.

SMOPS Home

[Algorithm Description](#)

Satellite/Sensors:  
[ASCAT](#) | [SMOS](#) | [WindSat](#) | [AMSR2](#) | [AMSR-E](#)

Product Animation:  
[Daily](#) | [6-hourly](#)

Validation:  
[In Situ](#) | [Time Series](#)

Monitoring:  
[Product](#) | [Time Series](#) | [Processing](#) | [Timeliness](#)

[Test Data](#)

[Documents](#)

[IPT Members](#)

[Links](#)

NOAA SMOPS Blended Soil Moisture: Daily -- 20141111

0 0.01 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5

Details on the algorithm can be found at [Algorithm Description](#).

- Developed by NOAA/NESDIS/STAR
- Operationally running at NOAA/NESDIS/OSPO

Operational data access contact:  
[Limin.Zhao@noaa.gov](mailto:Limin.Zhao@noaa.gov)

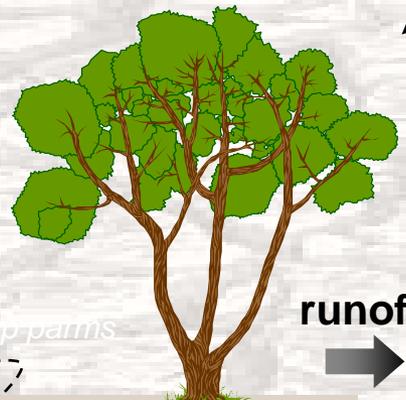
Science and historical data contact:  
[Xiwu.Zhan@noaa.gov](mailto:Xiwu.Zhan@noaa.gov),  
[Jicheng.Liu@noaa.gov](mailto:Jicheng.Liu@noaa.gov),

# **TIR Soil Moisture Remote Sensing: Retrieval Algorithm Science**

### PRECIPITATION



↑  
**transpiration & evaporation**  
*Vegetation stress params*



↑ *Bare soil evap params*  
**soil evaporation**

**runoff** →

**Sfc moisture**

**infiltration**

*Soil hydraulic params*

**Rootzone moisture**

→ **Root uptake**

**drainage**

*Soil moisture holding capacity*

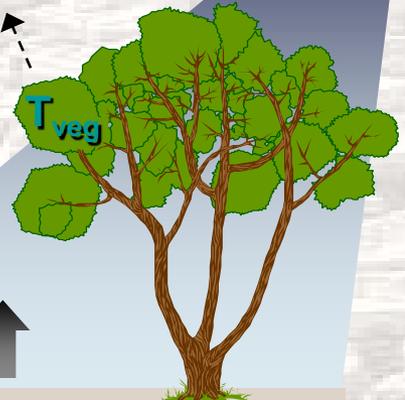
*Root distribution params*

**WATER BALANCE APPROACH**  
("forward modeling")

### SURFACE TEMPERATURE

→  $T_{soil} \ \& \ T_{veg}$

↑  
**transpiration & evaporation**



$T_{veg}$

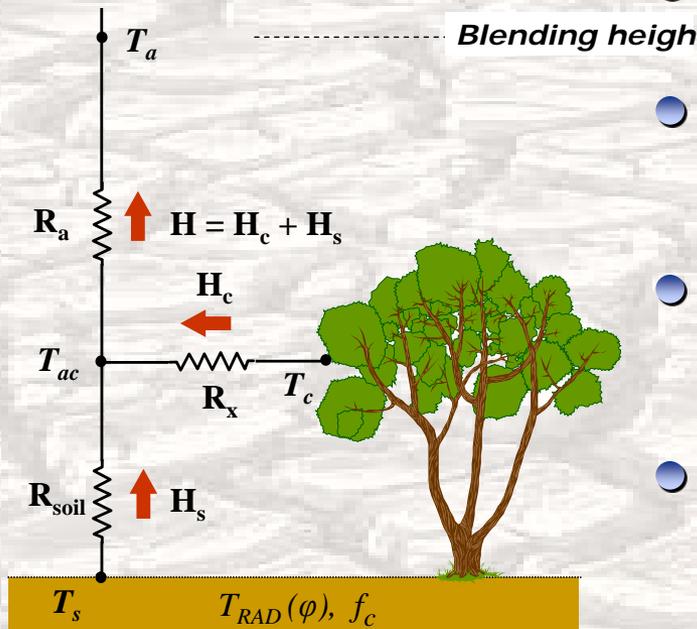
$T_{soil}$

→ **soil evaporation**

*Given known radiative energy inputs, how much water loss is required to keep the soil and vegetation at the observed temperatures?*

**REMOTE SENSING APPROACH**  
("inverse modeling")

# Two-Source Energy Balance (TSEB)



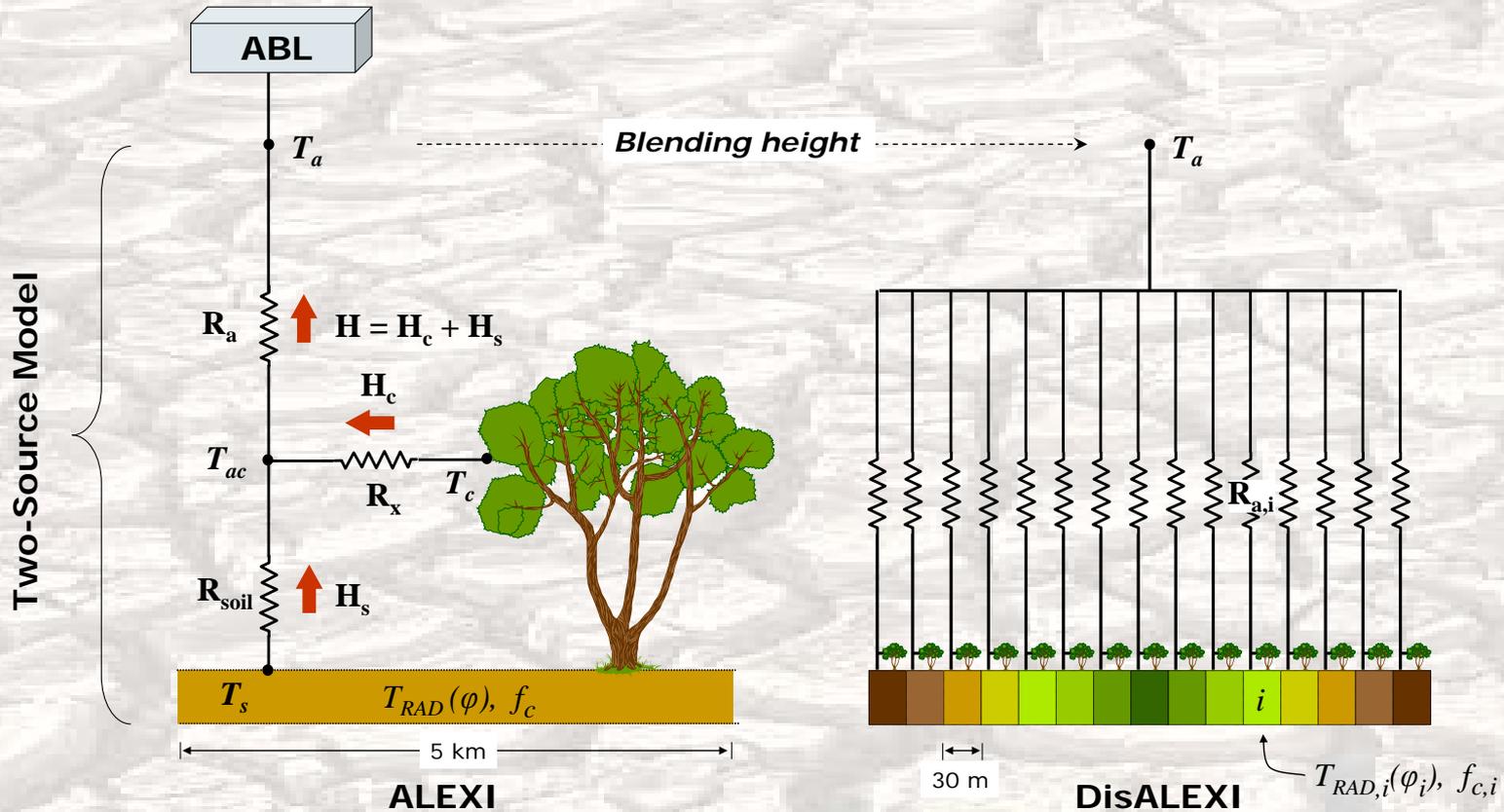
- $T_{RAD}(\theta) \sim f_c(\theta)T_c + [1-f_c(\theta)]T_s$
- Canopy and soil H from T network
- Canopy transpiration ( $LE_c$ ) from PT or LUE scheme
- Soil evaporation as residual:  
 $LE_s = RN - H - G - LE_c$

Norman, J. M., W. P. Kustas, and K. S. Humes (1995) *Agric. For. Meteorol.*, 77, 263-293.

Local scale

Surface temp:  $T_{RAD}$  - Infrared thermometer  
 Air temp:  $T_a$  - Micromet tower

# Atmosphere-Land Exchange Inverse (ALEXI)



Regional scale

Surface temp:  $\Delta T_{RAD}$  - GOES  
 Air temp:  $T_a$  - MODIS

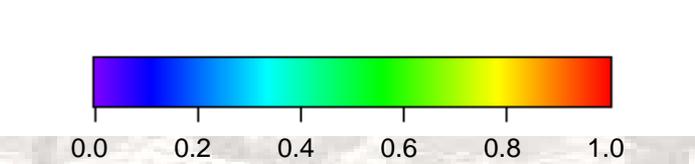
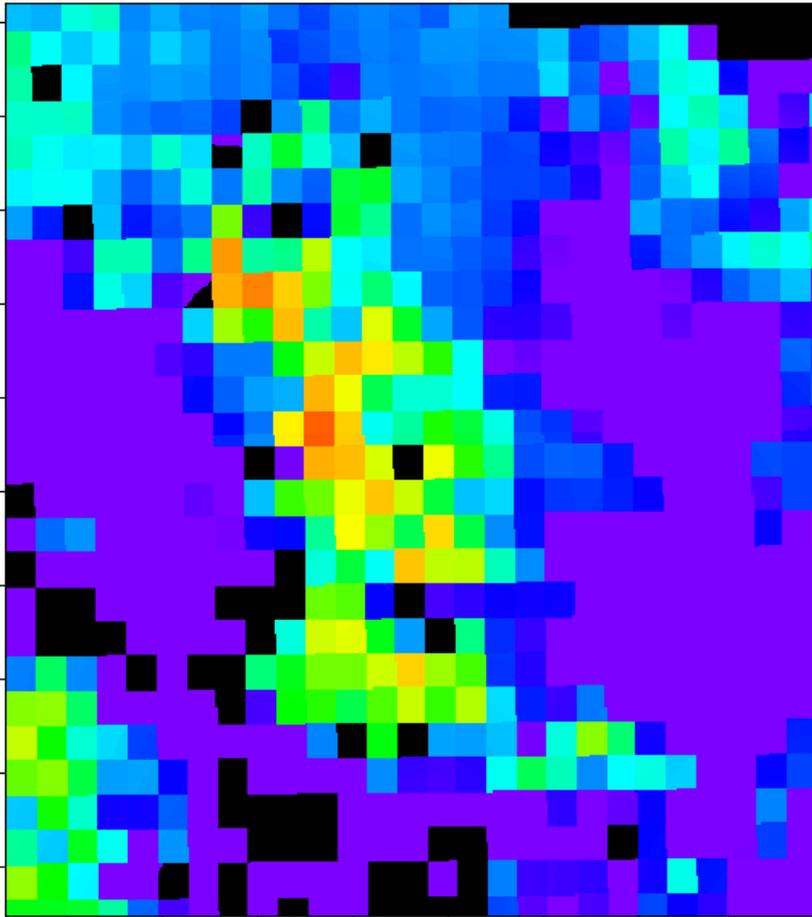
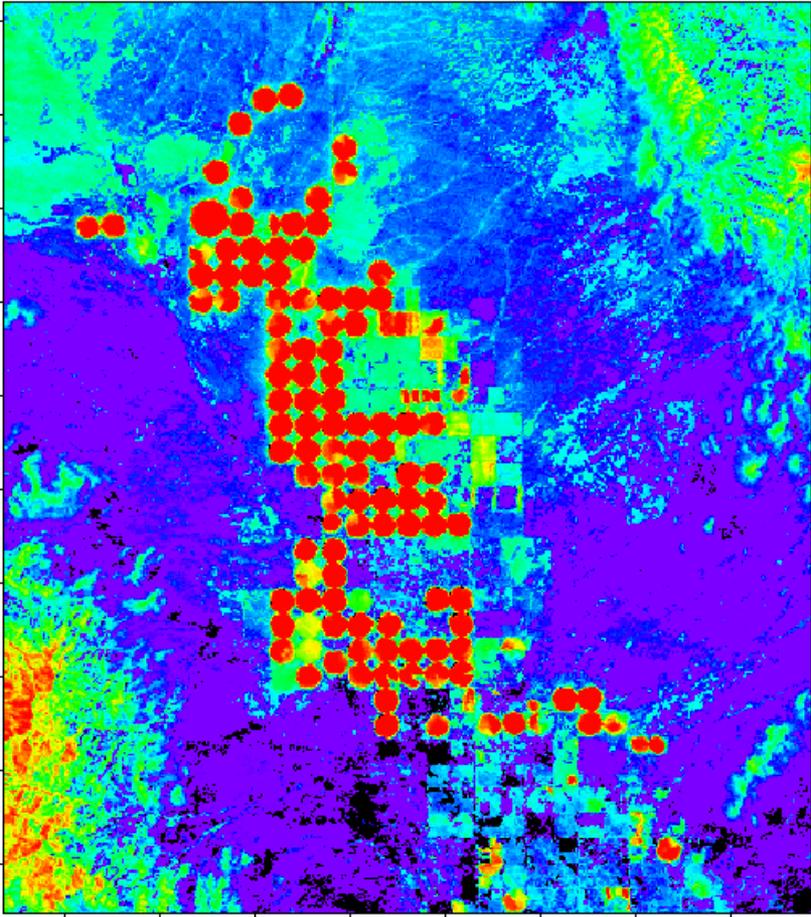
Landscape scale

$T_{RAD}$  - TM, ASTER, MODIS  
 $T_a$  - ALEXI

# Sensitivity to irrigation

Landsat 7 – 60m

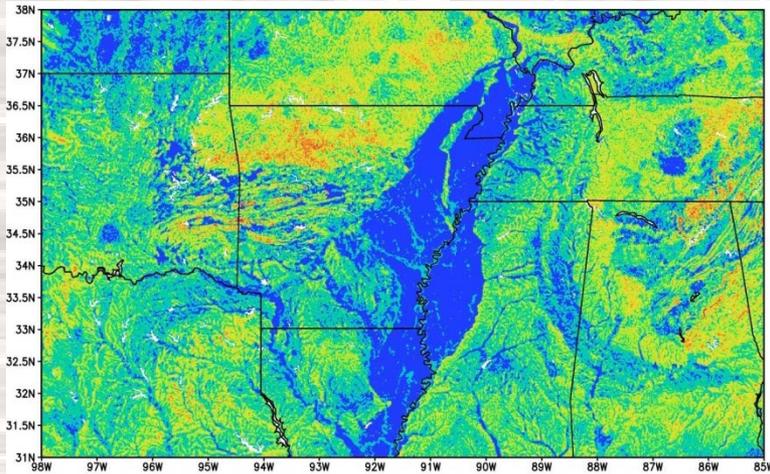
MODIS – 1km



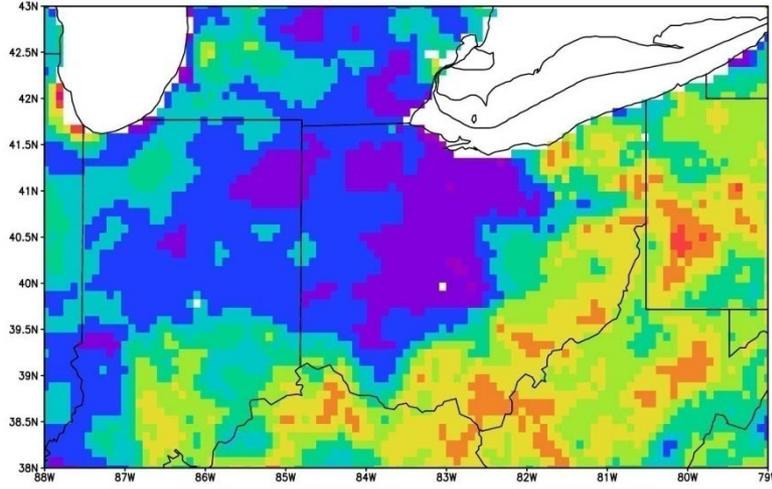
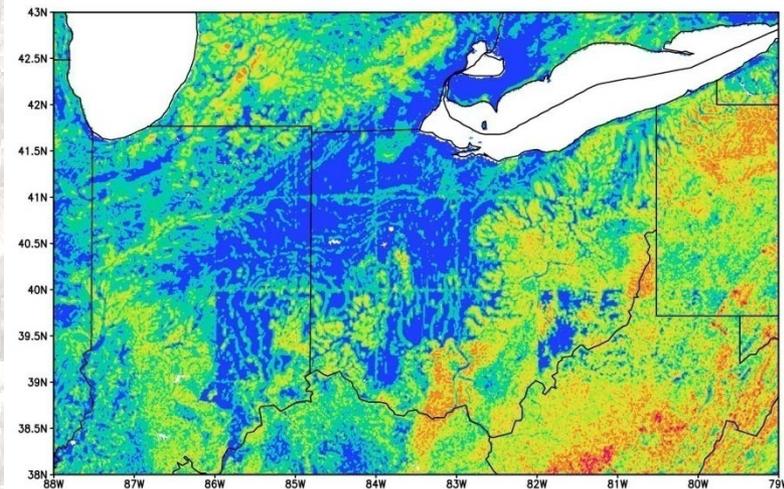
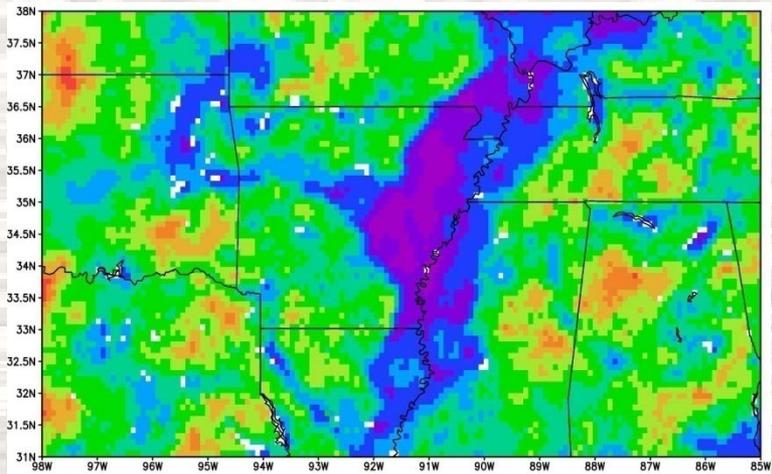
$$\frac{ET}{PET}$$

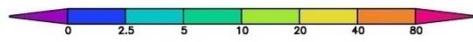
# Sensitivity to shallow water tables

Simulated climatological water table\*



Temporal variability in ET/PET



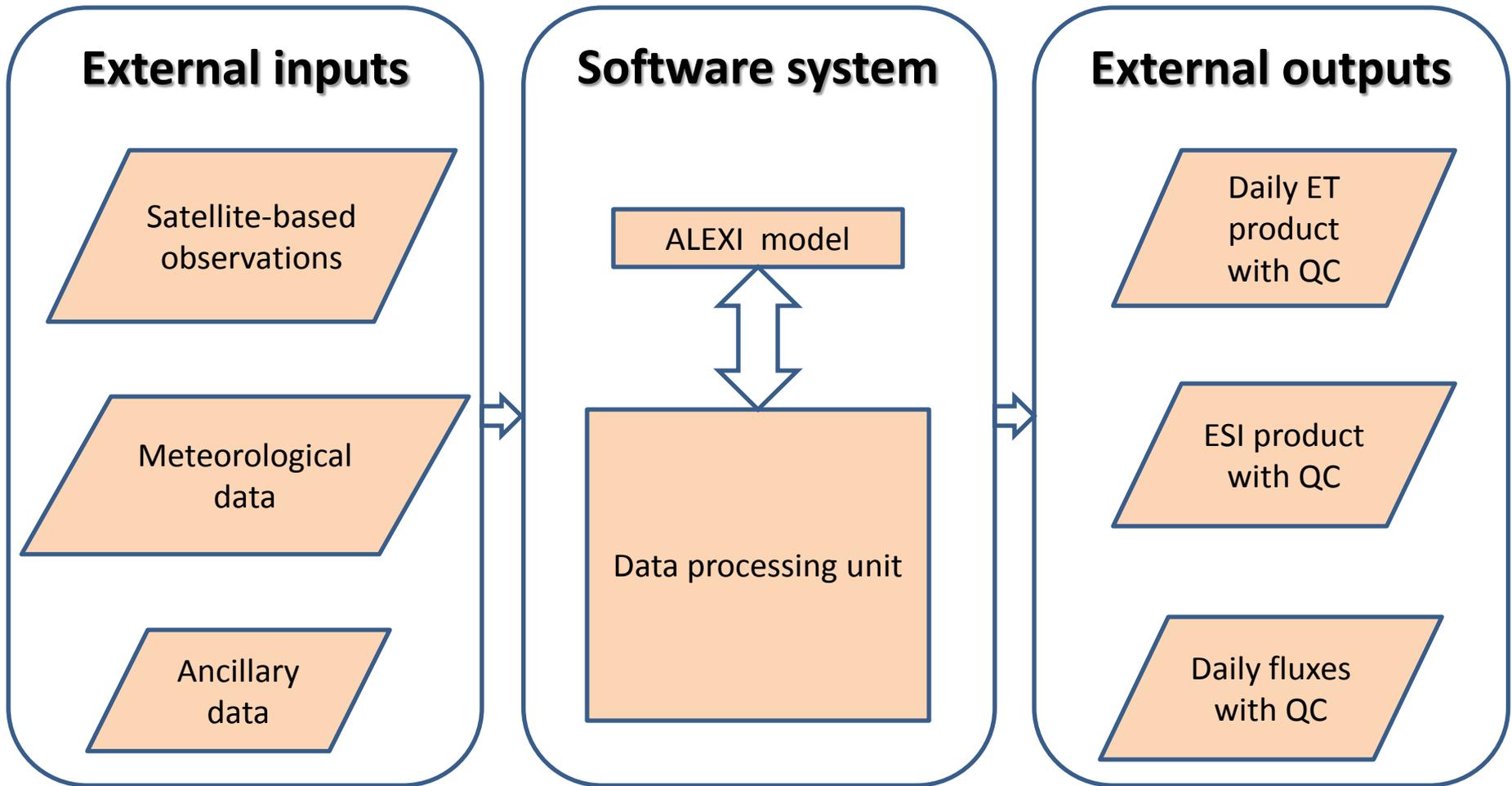
shallow  deep

low  high

\* Miquez-Macho et al, BAMS, 90, 663-672

# GOES ET and Drought Product System (GET-D)

# GET-D General Architecture



# GET-D Input Data

Name	Category	Source	Description
Brightness temperature	Satellite observation	GOES	GOES East/West Imagery; 11micron/3.9 micron brightness temperature
Insolation	Satellite observation	GSIP	GSIP real time insolation
Vegetation Index	Satellite observation	VIIRS	VIIRS EVI
Snow mask	Satellite observation	NOAA IMS	IMS Daily Northern Hemisphere Snow and Ice Analysis
Air temperature	Meteorological data	CFS	Surface and pressure level profiles
Specific humidity	Meteorological data	CFS	Surface and pressure level profiles
Geopotential height	Meteorological data	CFS	Surface and pressure level profiles
Wind speed	Meteorological data	CFS	Surface
Downwelling longwave radiation	Meteorological data	CFS	Surface
Land Cover	Ancillary data	University of Maryland	Land cover classes in 1km resolution (static)
Albedo	Ancillary data	MODIS	Surface Albedo from MODIS (static)
Clear day insolation	Ancillary data	GSIP	Clear day insolation (static)

# GET-D Output Products

Variables	Description
ET product with QC	Daily ET map
ESI products with QC	2,4,8, 12-week composite drought map
Flux products with QC	Daily sensible heat, soil heat, downward short wave radiation, long wave down/up ward radiation and net radiation
Coverage	North America
Spatial Resolution	8km

# GET-D Websites

NESDIS-STAR:

[https://www.star.nesdis.noaa.gov/smcd/emb/droughtMon/products\\_droughtMon.php](https://www.star.nesdis.noaa.gov/smcd/emb/droughtMon/products_droughtMon.php)

NESDIS-OSPO:

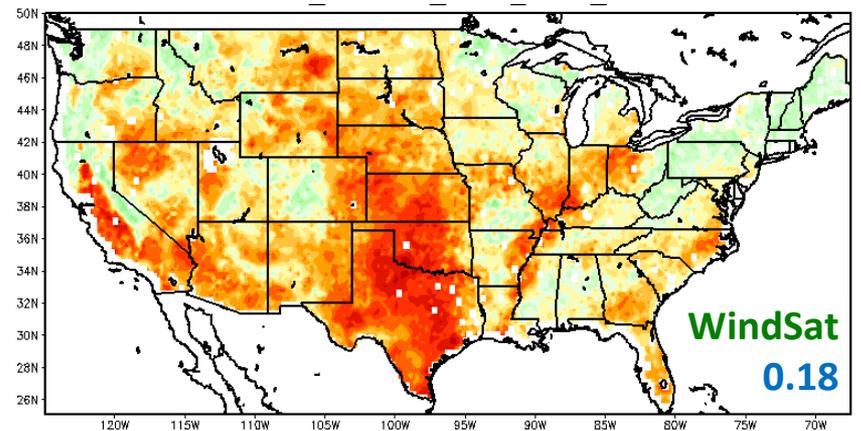
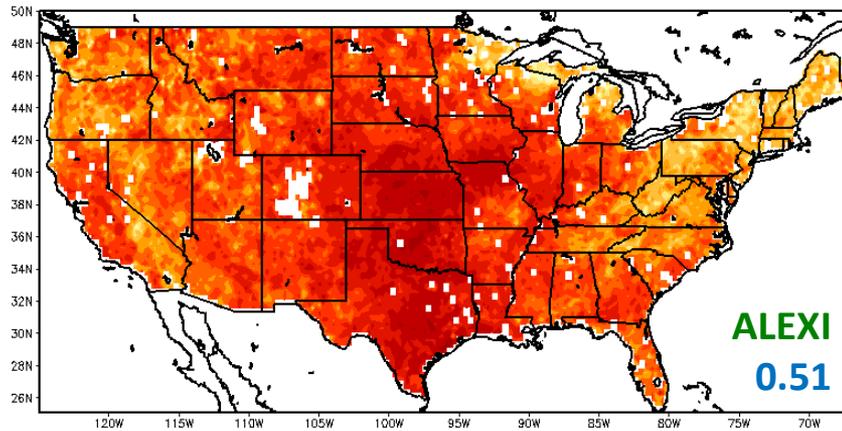
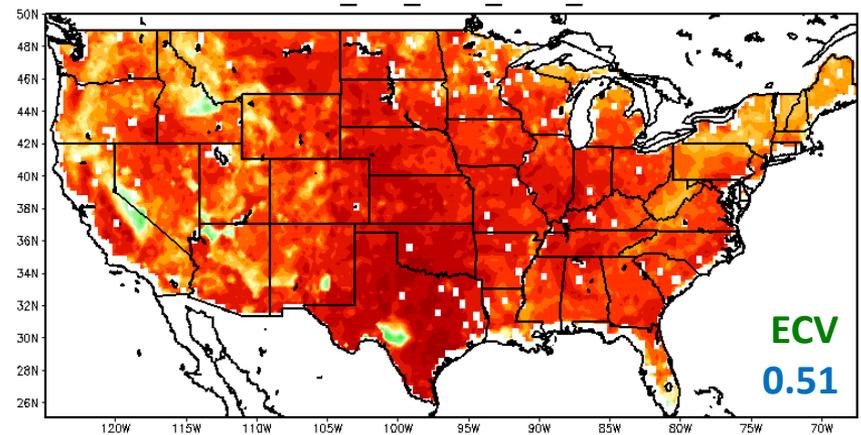
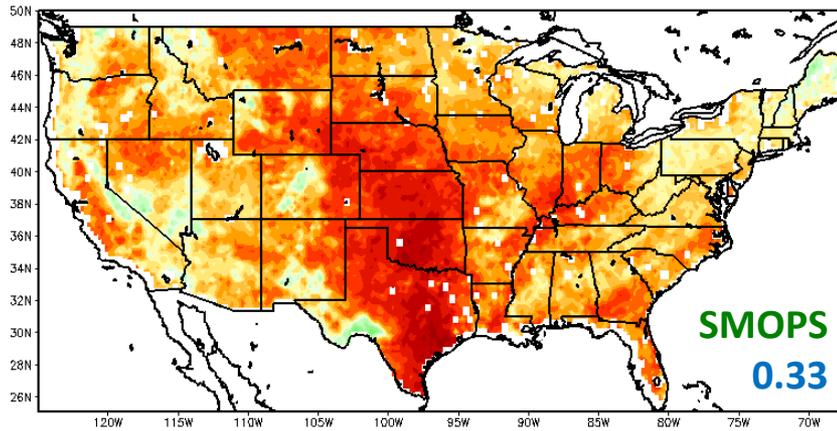
<http://www.ospo.noaa.gov/Products/land/getd/>

The screenshot shows the NOAA STAR website interface for the SMCD EMB Drought Monitoring Site. The header includes the NOAA STAR logo and navigation links. The main content area displays a map of North America titled "GET-D ESI 04 Week Composite 28 Nov 2016". The map uses a color scale from -2.5 (dark red) to 2.5 (dark green) to represent evapotranspiration and drought indices. The interface includes controls for selecting parameters, dates, and animating products. A legend at the bottom of the map shows the color scale and the NOAA/NESDIS/OSPO logo.

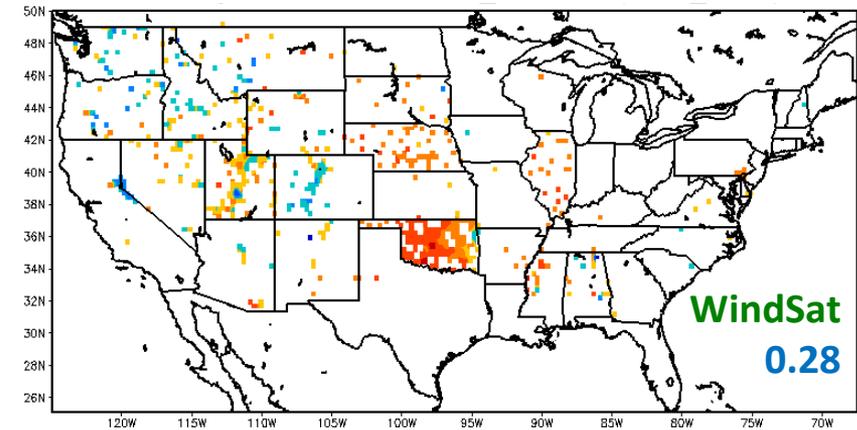
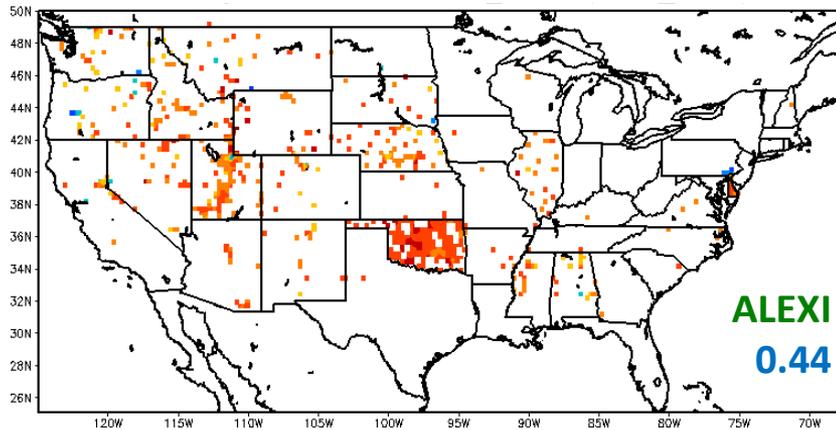
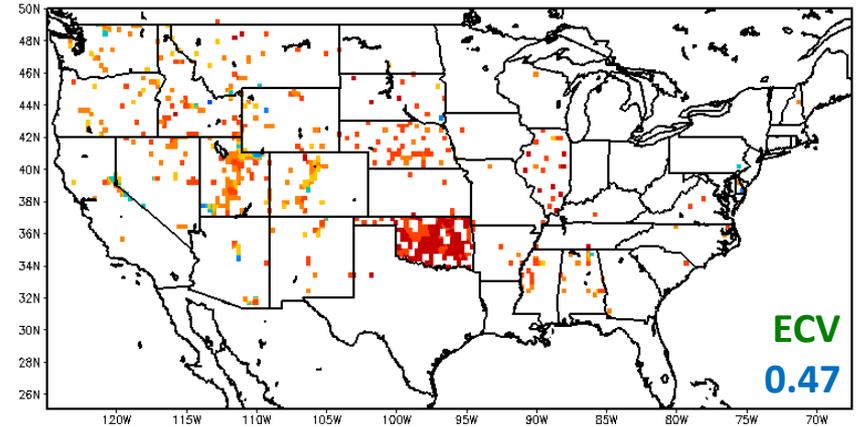
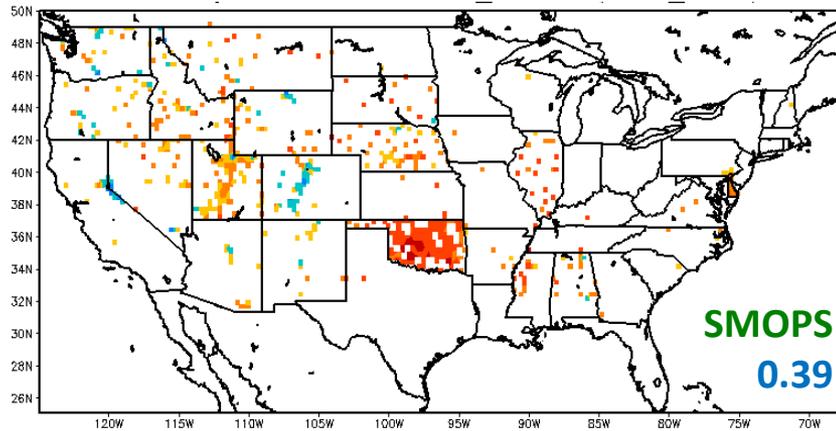
The screenshot shows the NOAA OSPO website page for GOES Evapotranspiration and Drought (GET-D). The header includes the NOAA logo and navigation links. The main content area features a title "GOES Evapotranspiration and Drought (GET-D)" and a detailed description of the system. Below the text are four maps showing "Current 2 Week", "Current 4 Week", "Current 8 Week", and "Current 12 Week" composites. A sidebar on the right lists "Vegetation Products" and "Documents". The footer contains contact information and a page update date of April 14, 2016.

# Product Accuracy Validation

# Comparison with NLDAS Noah LSM Estimates

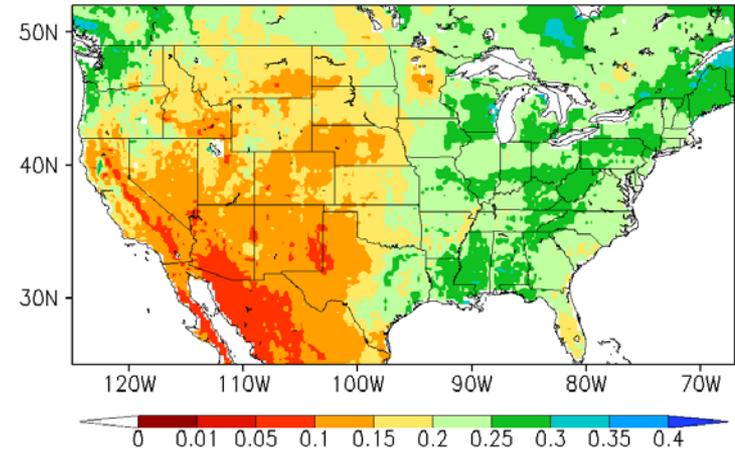


# Comparison with *in situ* Measurements

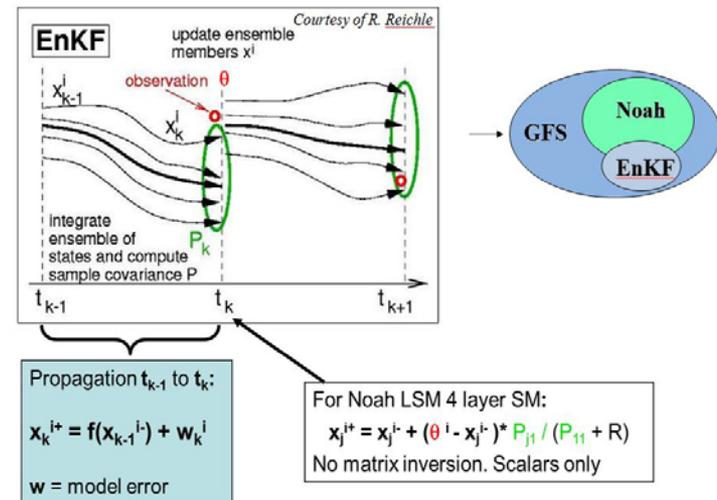


# Soil Moisture Product Applications

# Assimilation of SM in NCEP GFS



SMOPS blended product over CONUS in Apr 2012

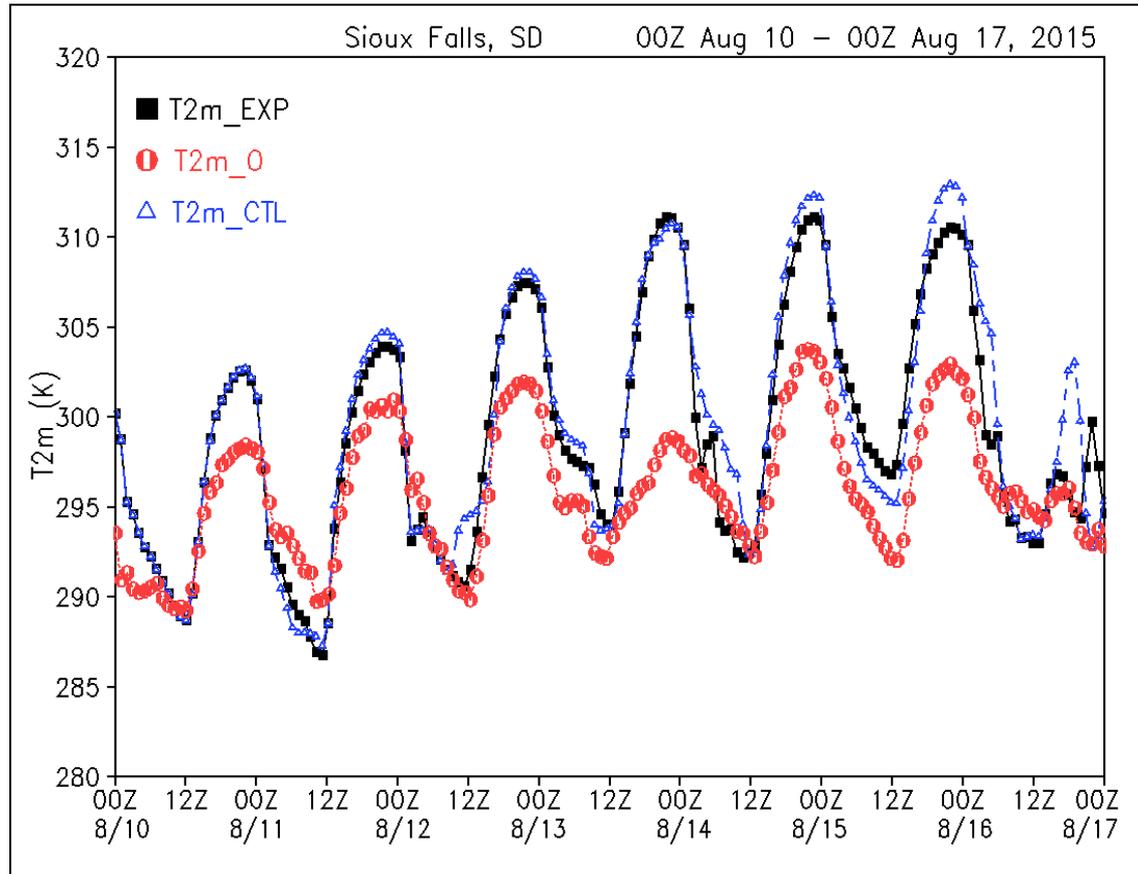


A Simplified EnKF data assimilation utility implemented in NCEP GFS

❖ SMOPS combines soil moisture retrievals from multiple satellites sensors to provide a global climatologically consistent soil moisture map with more spatial and temporal coverage.

❖ Positive impact has been shown on the model performance, particularly for precipitation forecasts by assimilating SMOPS blended product into GFS using a simplified EnKF

# Assimilation of SM in NCEP GFS

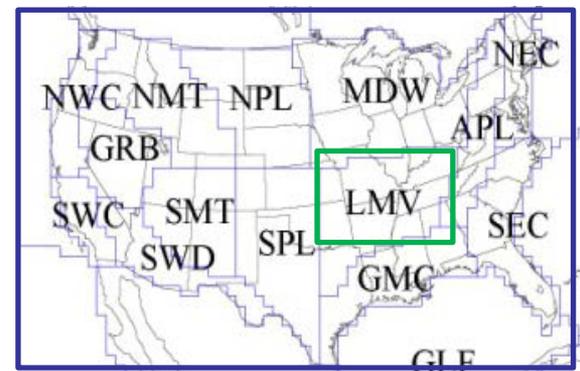


*Assimilating SMAP SM from 8/1 – 8/10/2015 Reduces the warm biases of NCEP GFS four (4) day forecasts of 2 meter air temperature*



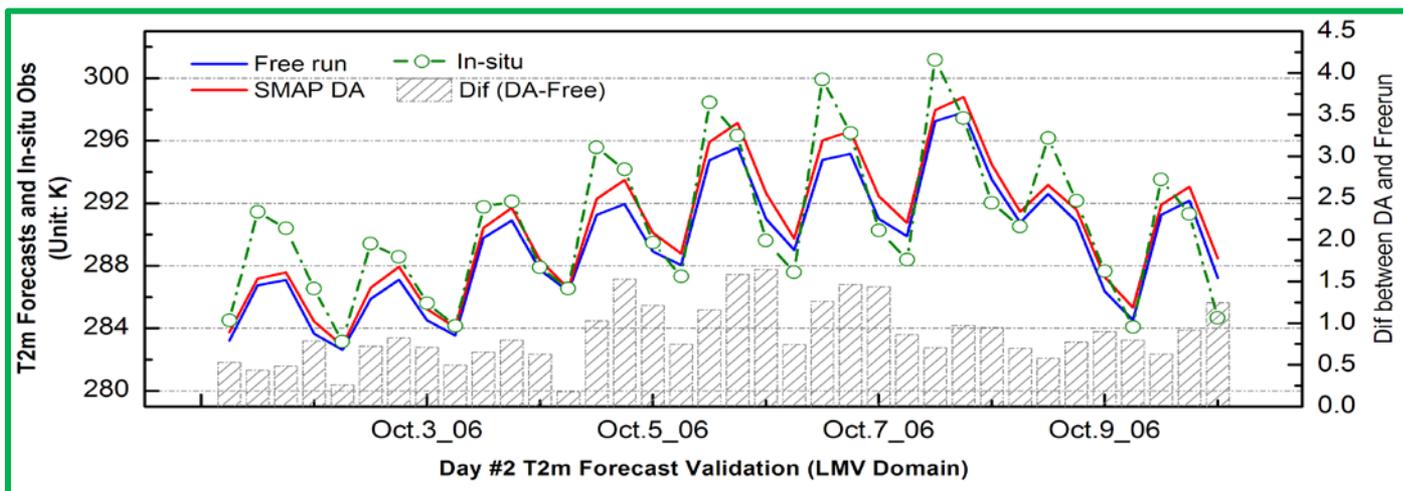
# T2m Forecasts compared with In-situ Observations (LMV Domain)

- ✦ Average T2m forecasts from WRF Free run and SMAP DA run compared with In-situ measurements
- ✦ Validation domains: LMV domain (~200 sites)
- ✦ Validation period: Day 2 forecast, Oct. 2nd – Oct. 9th, 2015
- ✦ Corrected daytime warm bias



Sub-regions in NCEP WRF-NMM forecast verification system

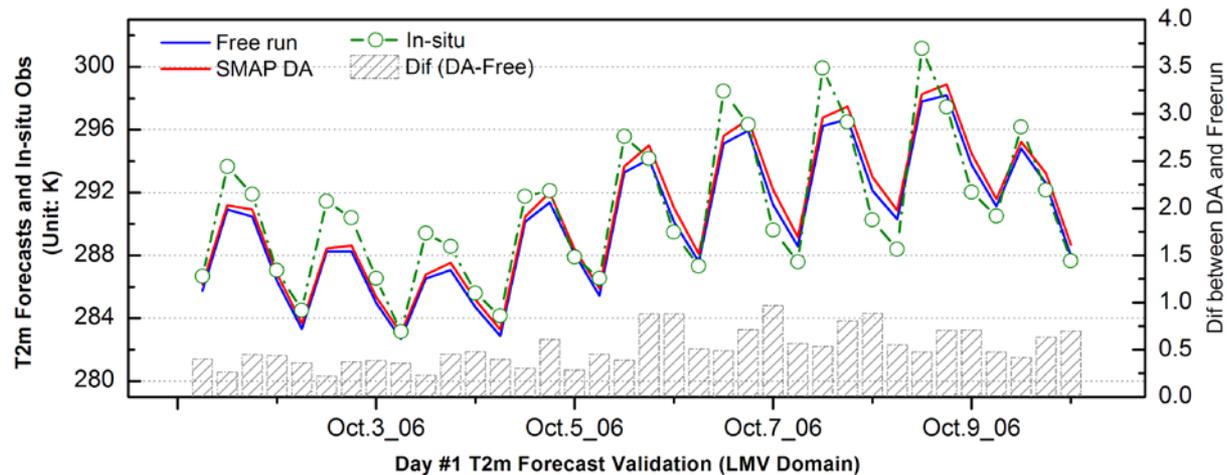
LMV



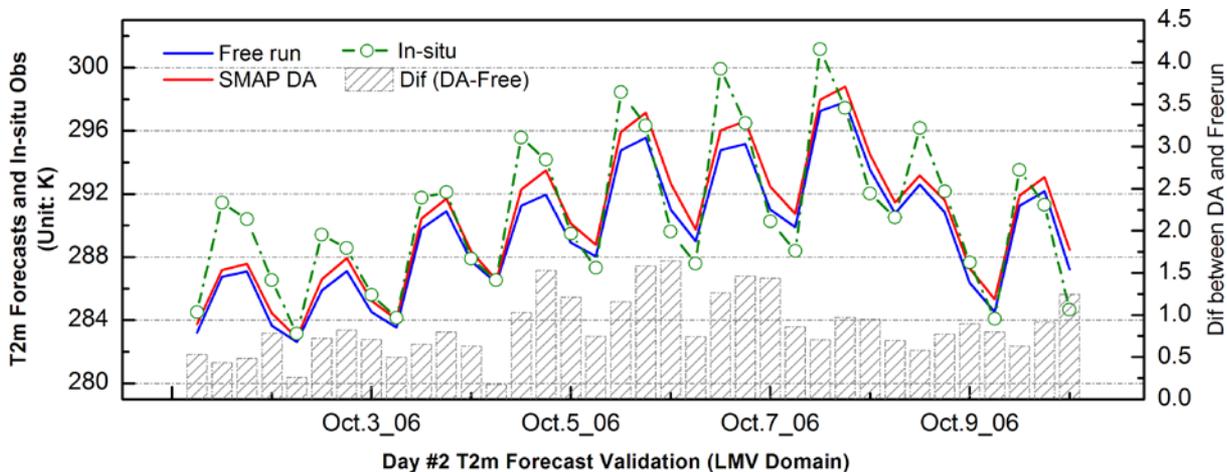


# T2m Forecasts compared with In-situ Observations (LMV Domain; 2-Day validation)

Day 1



Day 2





# Enhance Agricultural Drought Monitoring Using SNPP/JPSS Land EDRs for NIDIS

Jifu. Yin, X. Zhan, C. Hain, J. Liu, L. Fang, M. Ek, J. Huang, M. Anderson, M. Svoboda

- Objectives

- Improve current US and global drought monitoring via using near real time SNPP/JPSS land data products

- Primary sensors involved

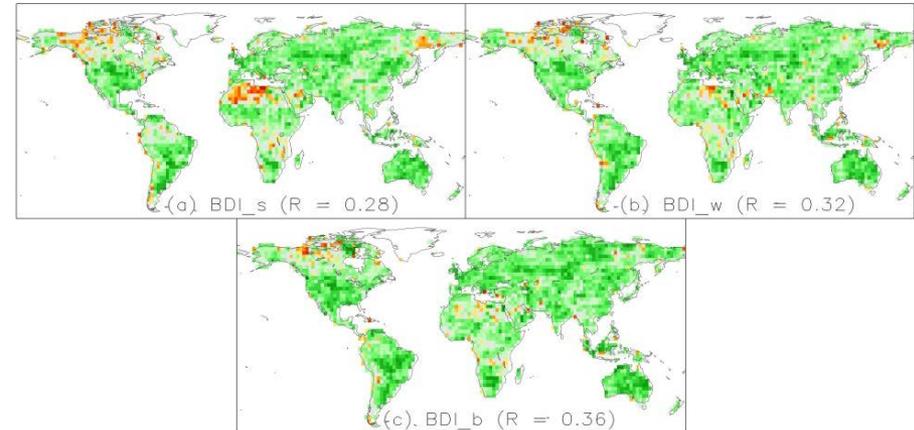
- S-NPP/VIIRS
- GCOM-W1/AMSR2

- Primary ground data

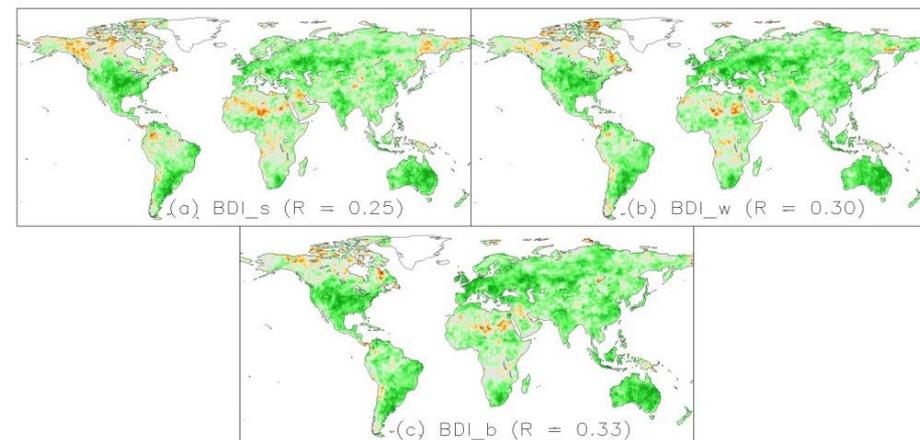
- Palmer Drought Severity Index (PDSI)
- Standardized Precip ET Index (SPEI)
- In situ observations

- Targeted end users

- NIDIS of USDA, NOAA and USGS
- NWS-NCEP

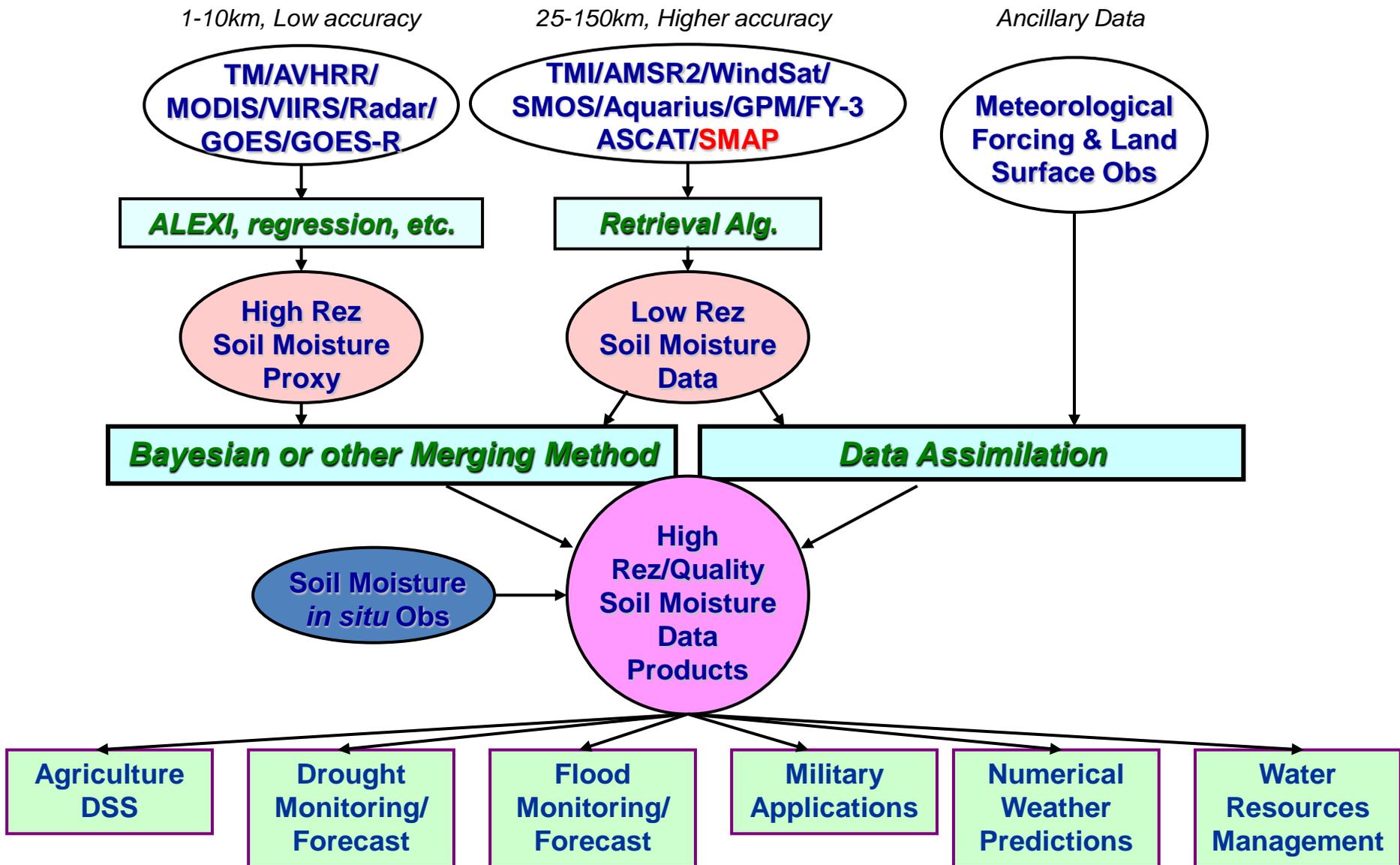


Correlations of **BDIs** with **PDSI**



Correlations of **BDIs** with **SPEI**

# Soil Moisture Science and Applications



**Thanks from NESDIS soil moisture gang!**

