Investigating Soil Moisture–Convective Precipitation Feedbacks Using Satellite and In Situ Soil Moisture

THE OHIO STATE UNIVERSITY

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Objectives

The SMAP mission provides an opportunity to enhance our understanding of soil moisture–precipitation coupling and the role of land surface heterogeneity on deep convection initiation. The objectives of this project are:

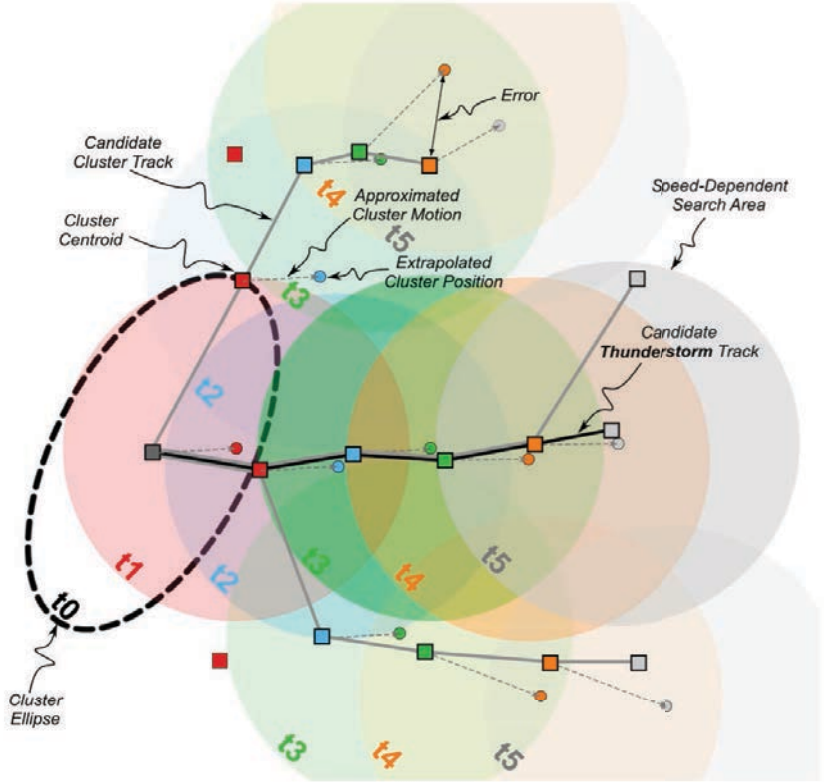
(1) Evaluate whether deep convection initiation occurs preferentially over wet or dry soils,

(2) Identify how these preferences vary over time and space,

(3) Determine how soil moisture heterogeneity and gradients influence initiation of deep convection.

Methods: ThOR

Thunderstorm Observation by Radar (ThOR) algorithm to identify convective events. ThOR is an automated method for identifying deep convection using radar and cloud-to-ground lightning data.



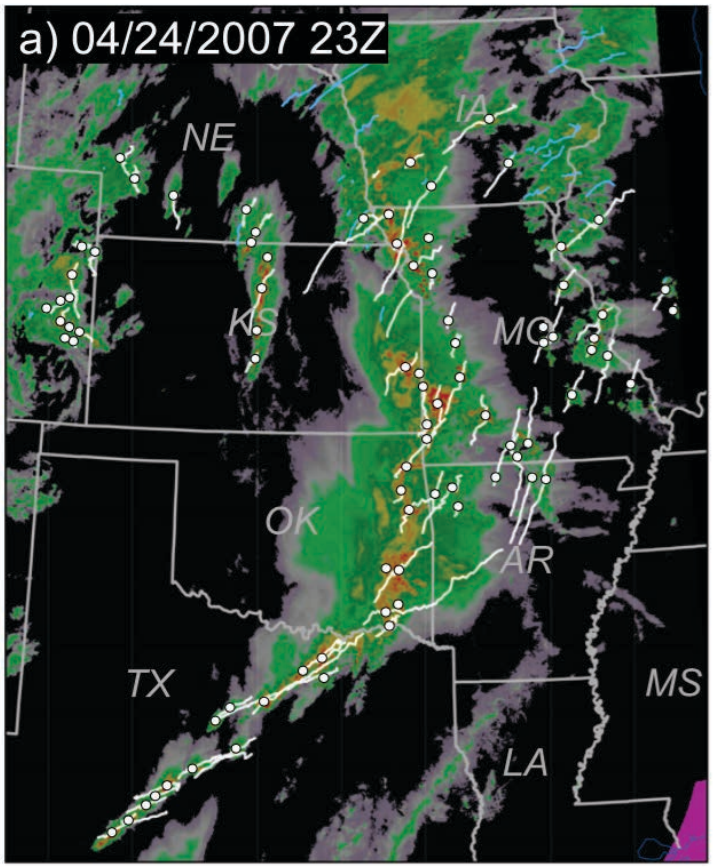


Illustration of the tracking procedure used in ThOR (Houston et al. 2015).

Methods: ThOR

Executing ThOR requires the following steps:

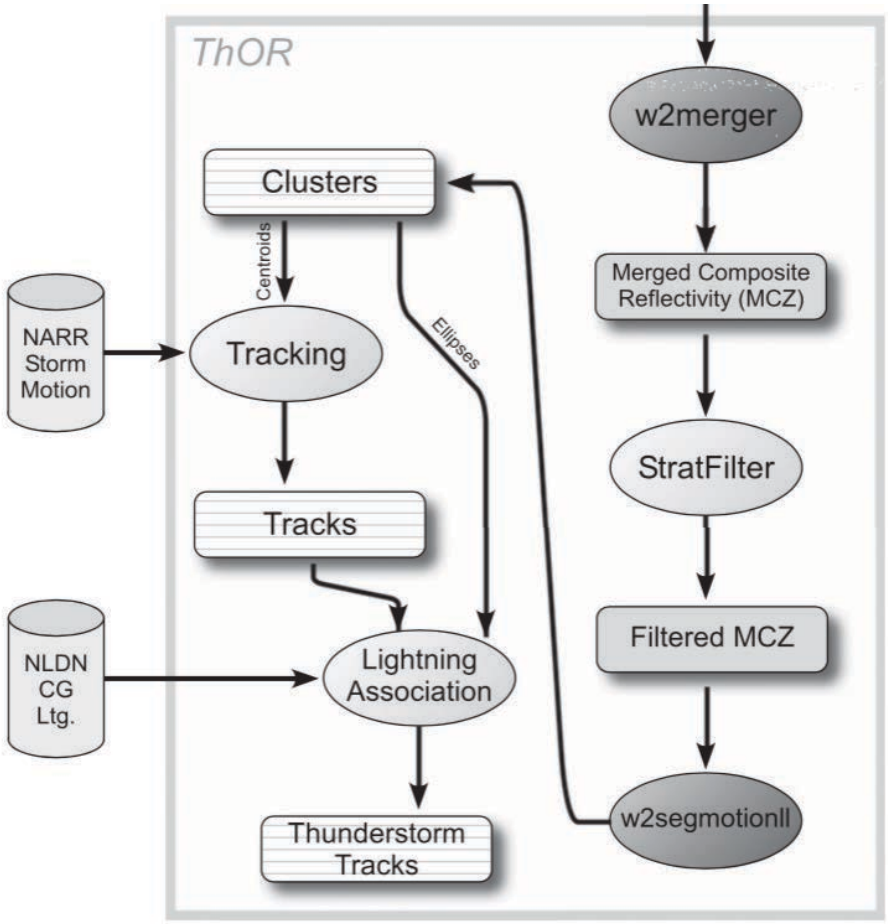
a. Event identification using cloud-to-ground lighting observed by the National Lightning Detection Network;

b. Retrieval of Level II radar data from NCDC;

c. Retrieval of North American Regional Reanalysis (NARR) storm motion grids;

d. WSR-88D radar quality control and pre-processing;

e. Running the ThOR algorithm.

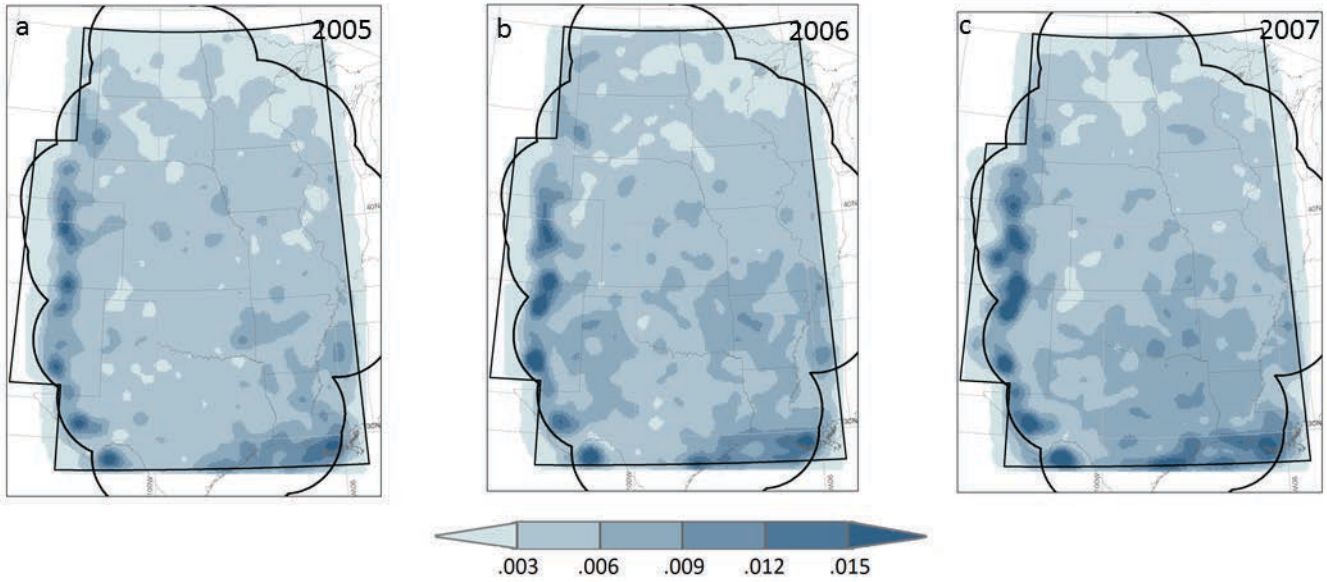


Houston et al. 2015

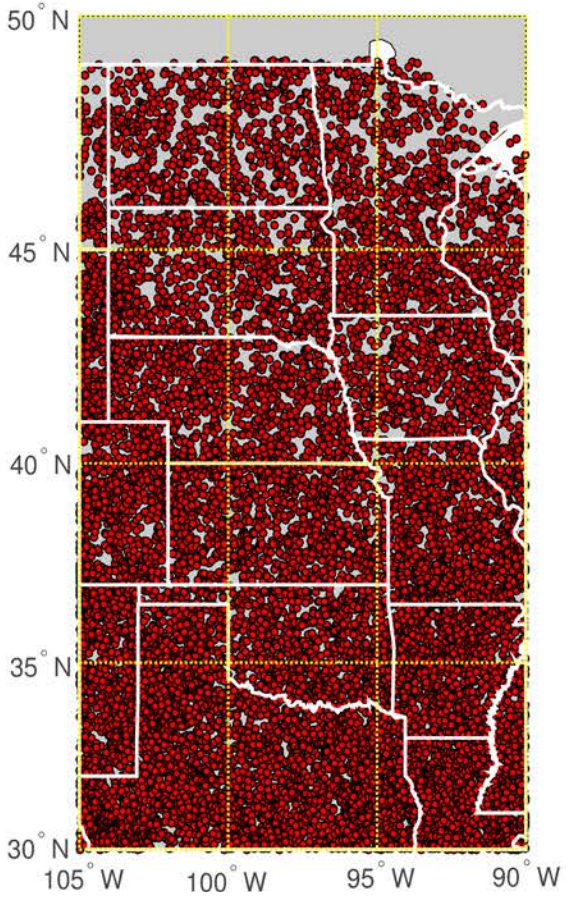
Methods: ThOR

ThOR was used to identify the location of convective initiation in the central United States from 2005 to 2007:

- May – September, afternoon events (1200 – 2000 LST)
- No precipitation occurring within 50 km of initiation point between 0000 and 1200 LST
- 16,084 events were identified

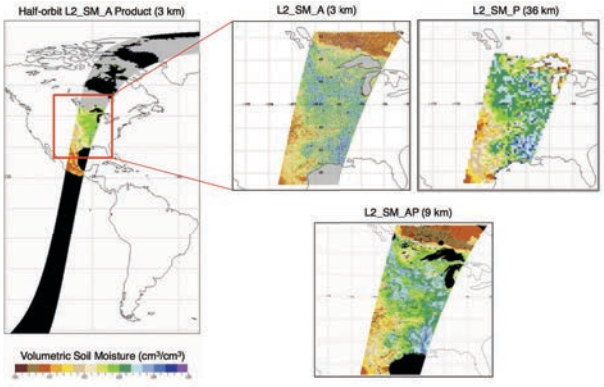


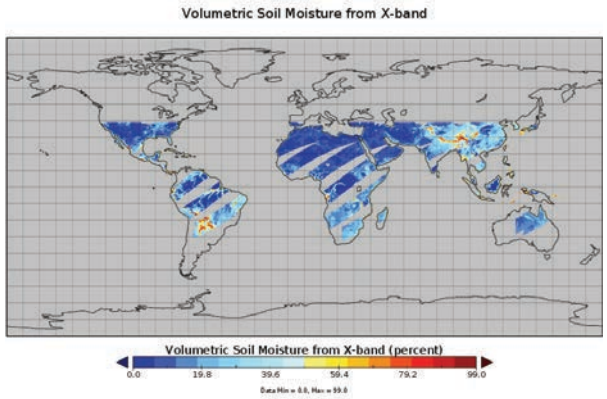
Kernel density of initiation points for the central United States: (a) 2005, (b) 2006, and (c) 2007. Values are points per km^2.

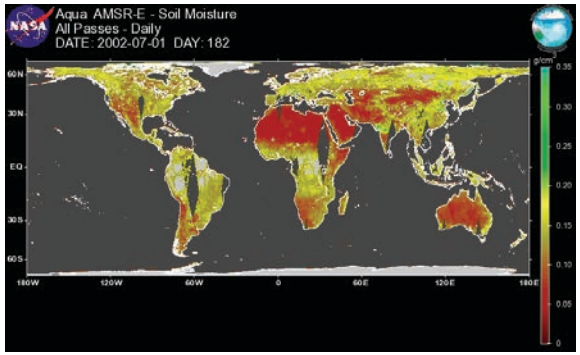


Methods: Soil Moisture

- Soil moisture data: SMAP, AMSR-E, TMI (TRMM), ECV (ESA-CCI)
- Daily volumetric water content (VWC) from May to September, 2005-2007
- VWC converted to anomalies (z-scores) by subtracting the sample mean μ_s and dividing by the sample standard deviation σ_s where the sample is the climatological 15-day window surrounding the calendar day

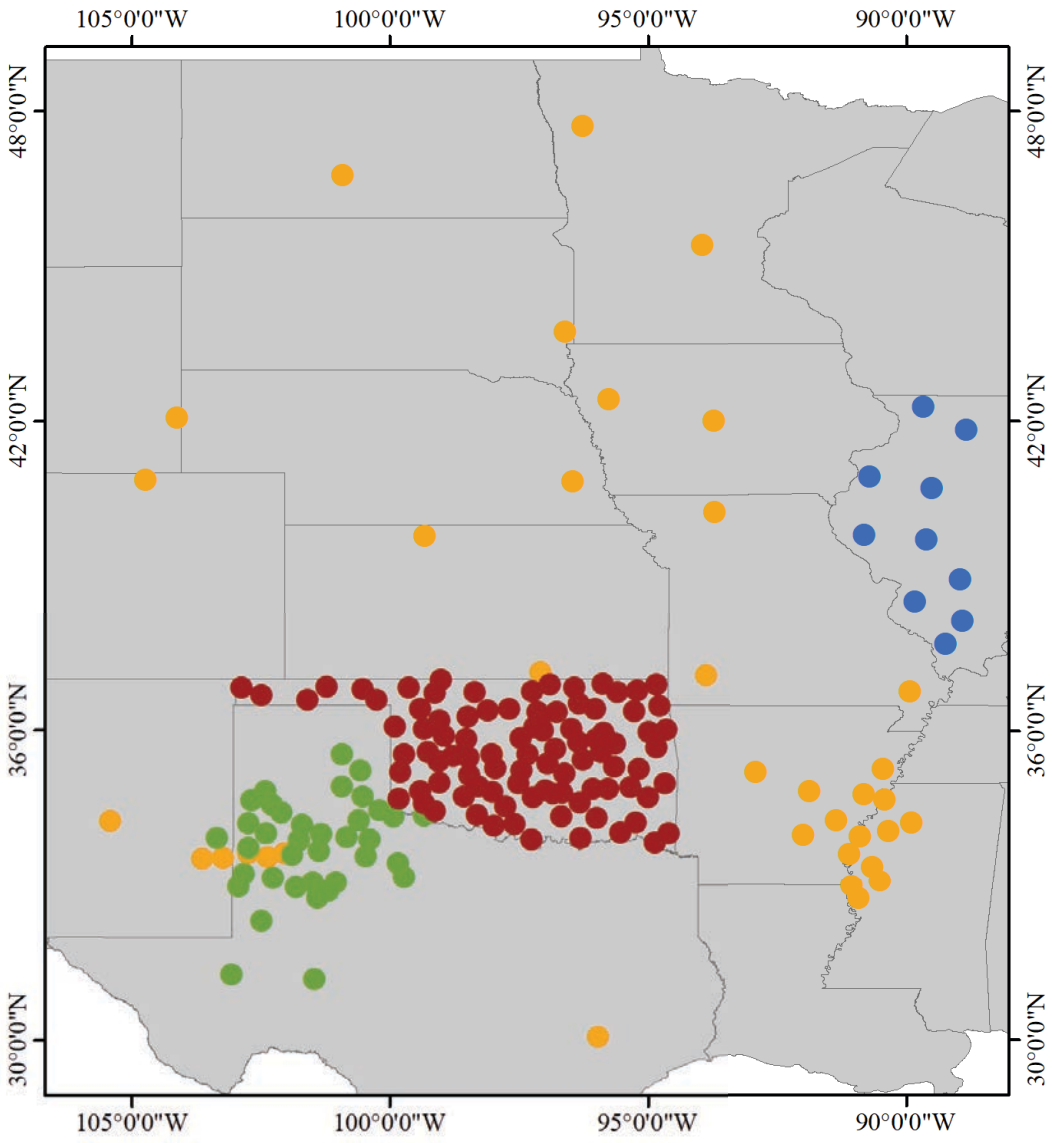






Product	Version	Frequency	Spatial Resolution	Spatial Extent	Temporal Extent
AMSR-E	LPRM_AMSRE_SOILM3.002	10.65 GHz (X-band)	0.25°	Global	2003 – 2010
TMI	LPRM_TMI_NT_SOILM3.001	10.65 GHz (X-band)	0.25°	40°N - 40°S, 180°E - 180°W	1998 – 2015
ECV	SM v03.2 COMBINED	Varied	0.25°	Global	1979 – present

Methods: Soil Moisture



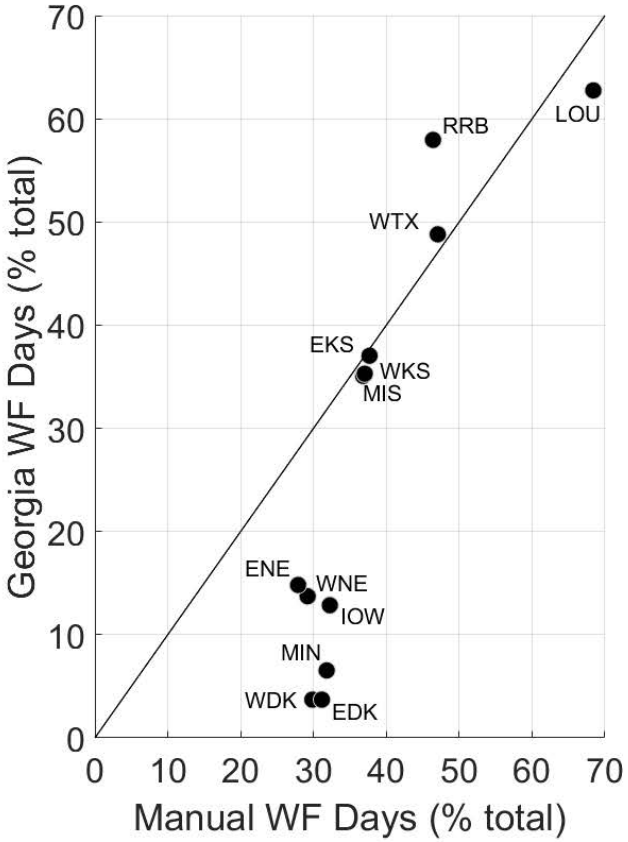
- In situ soil moisture data from 177 stations
- Daily volumetric water content (VWC) from May to September, 2005-2007
- VWC converted to anomalies (z-scores) by subtracting the sample mean μ_s and dividing by the sample standard deviation σ_s where the sample is the climatological 15-day window surrounding the calendar day

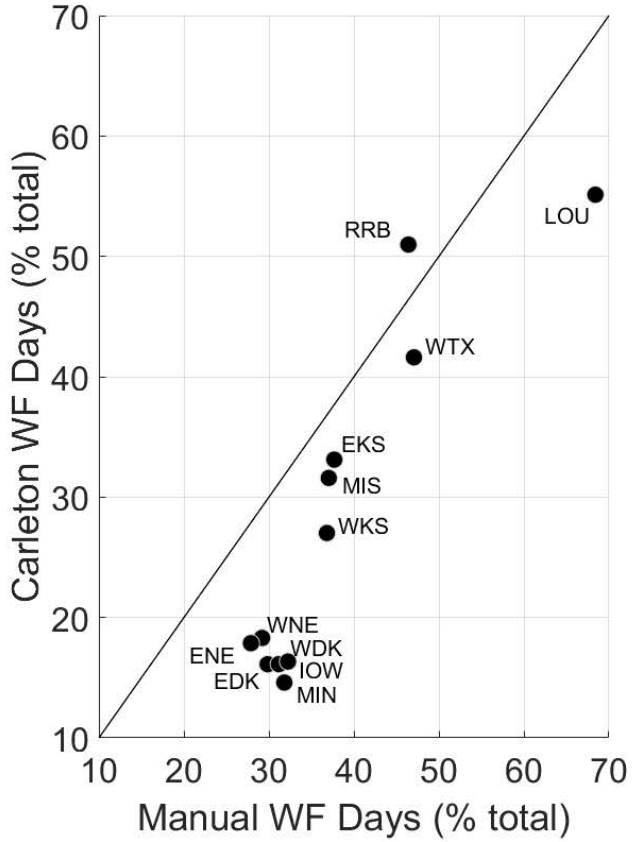
Methods: Synoptic Forcing

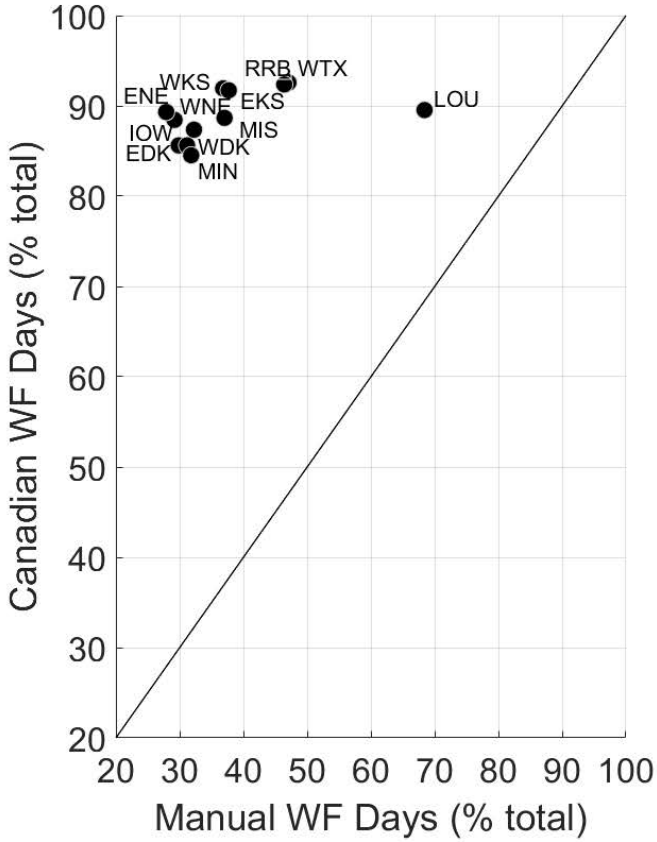
- Each storm was classified as synoptically-forced or weakly-forced using a manual method:
  - Daily 0700 LST NWS weather maps (including upper-level disturbances)
  - Region broken into 12, 5° x 5° areas; daily forcing classified for each area separately
  - Weakly forced event: no synoptic forcing mechanism (fronts, dry lines, troughs, low pressure systems, etc.) within 250 km of the area

- Georgia method (Brown and Arnold, 1998; Dixon and Mote, 2003)
  - Area-averaged, 3-hour 500 mb winds within the 5° x 5° area < 15 knots, area-averaged, 3-hour surface wind speeds < 10 knots (MERRA-2)
- Carleton method (Carleton *et al.* 2008a,b)
  - The spatial range of (0000 and 1200 UTC-averaged) 500 mb winds within each 5° x 5° area < 12 m/s
- Canadian method (Brimelow *et al.* 2011)
  - Area-averaged 500 mb daily omega less than or equal to -1

Results: Event Classification



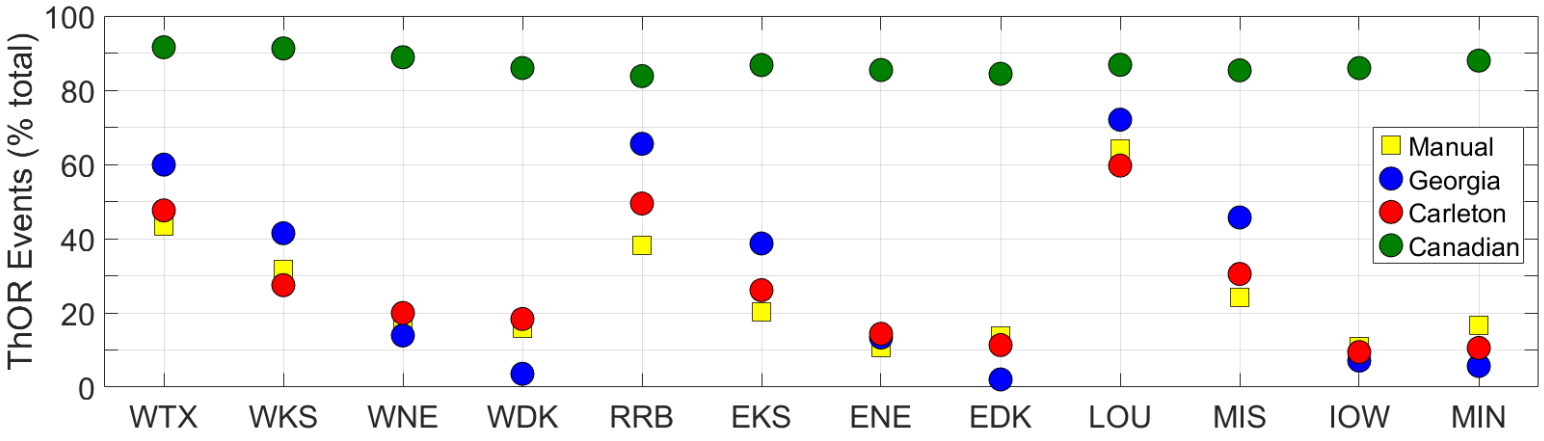




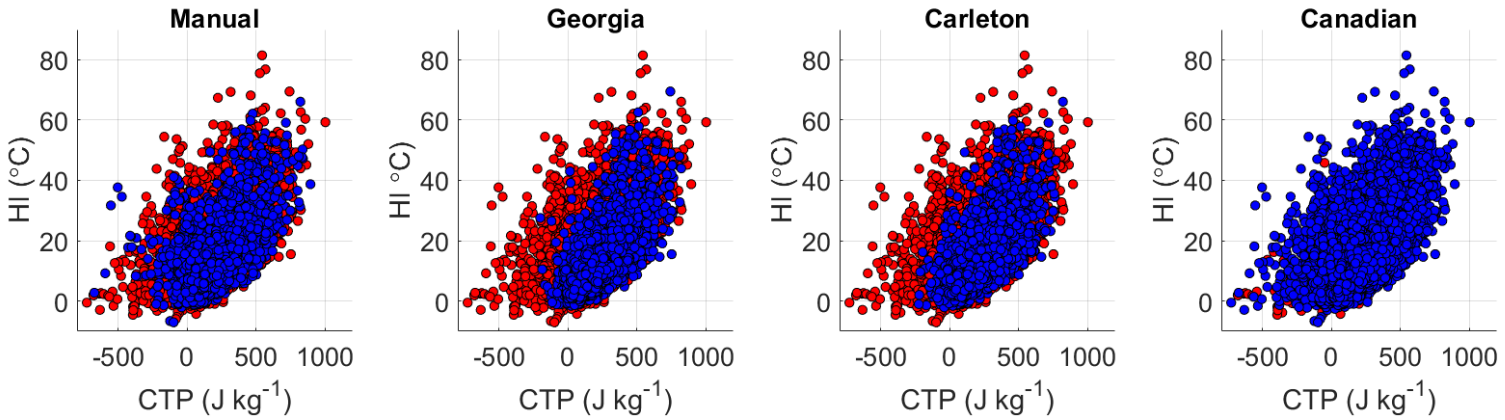
- The Georgia and Carleton methods performed similarly well (both underestimate northern areas)

- Canadian method overestimates weakly forced events in all regions

Results: Event Classification



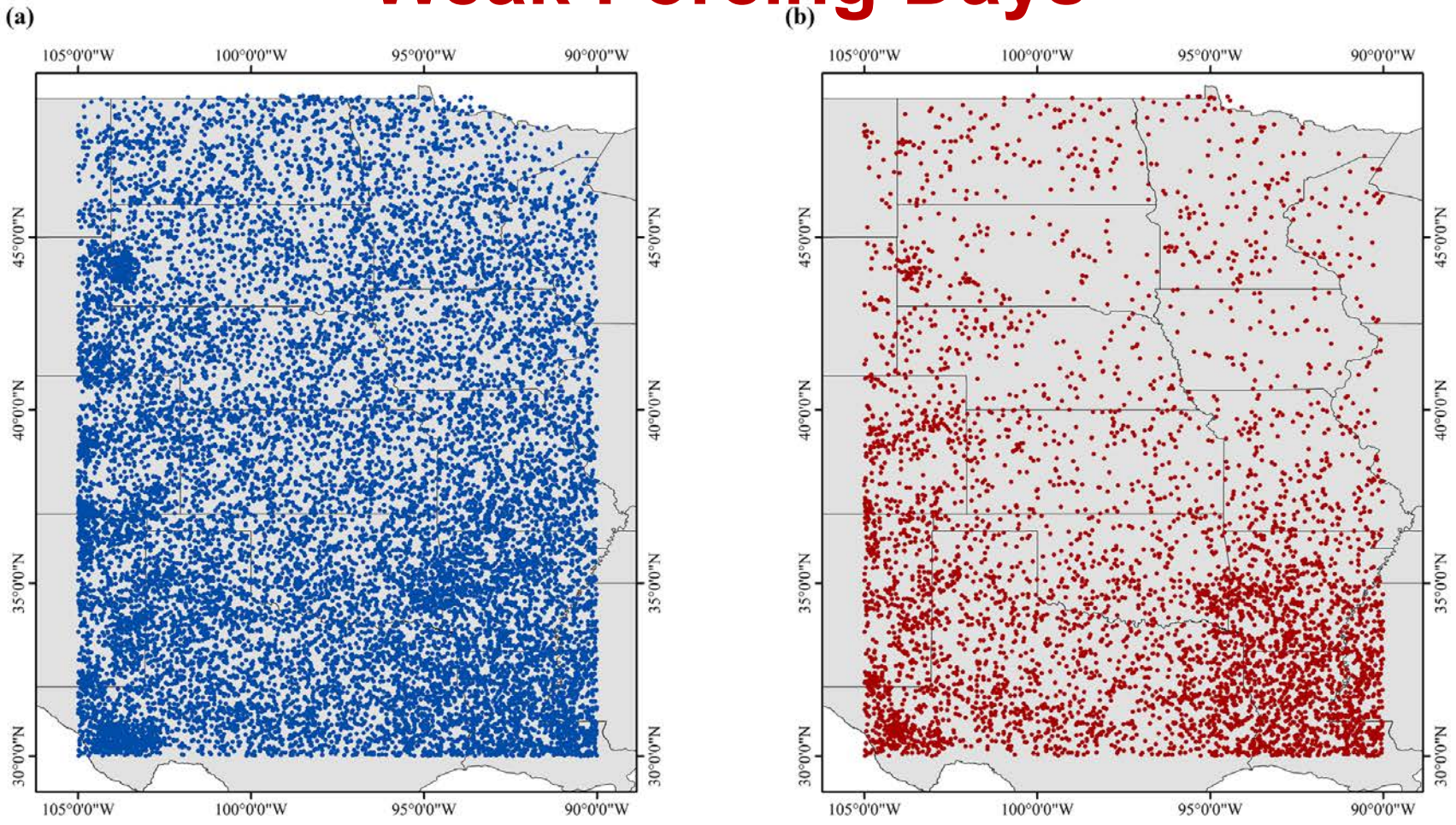
Top: percent of ThOR afternoon events classified as "weakly forced" by each of the four classification methods.



Bottom: all ThOR events plotted in dual CTP-HI space, calculated from MERRA-2. Red points show synoptically forced events, blue points show weakly forced events.

- Canadian method classifies nearly all ThOR events as "weakly forced"
- CTP-HI plots are similar to Findell's; weakly forced events are shifted in CTP space, more positive (atmosphere "primed" for soil moisture feedback)

Weak Forcing Days



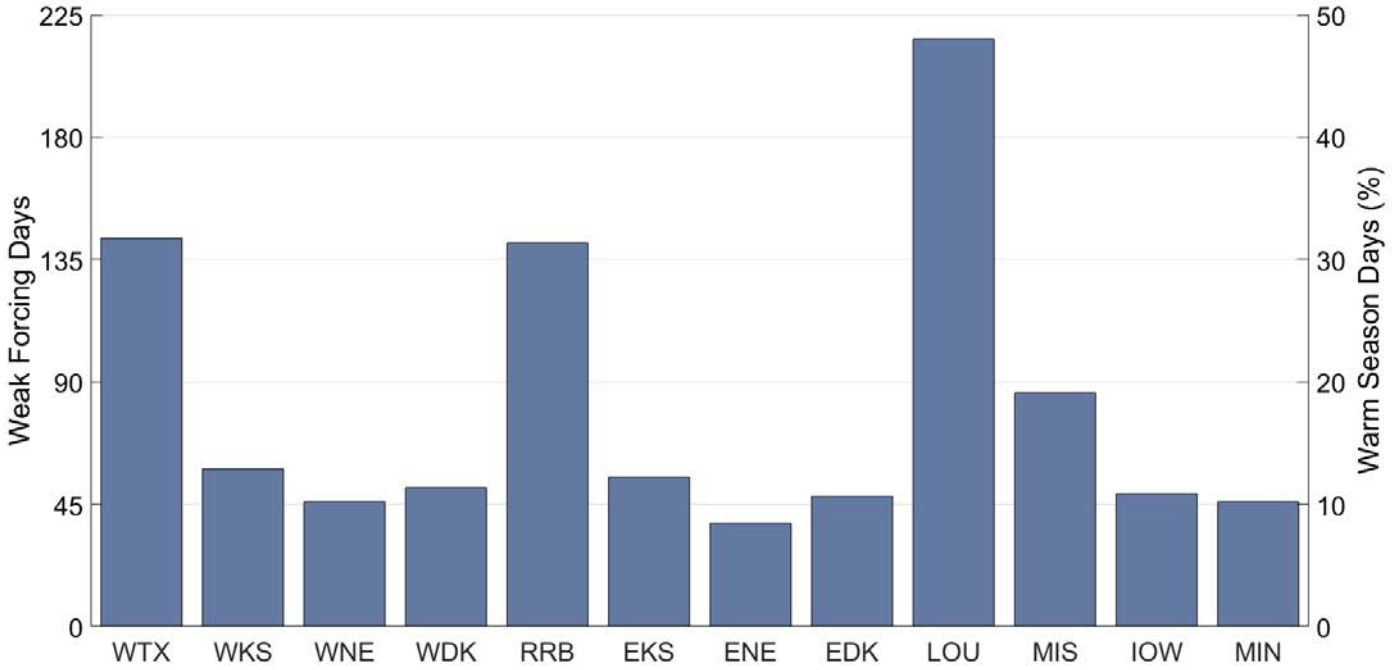
Spatial distribution of all the warm season afternoon ThoR initiation points, (a) all events, (b) weakly forced events.

Weak Forcing Days

- Each storm was classified as synoptically-forced or weakly-forced using a manual method

12 regions:

- West Texas (WTX
- West Kansas (WKS)
- West Nebraska (WNE)
- West Dakotas (WDK)
- Red River Basin (RRB)
- East Kansas (EKS)
- East Nebraska (ENE)
- East Dakotas (EDK)
- Louisiana (LOU)
- Missouri (MIS)
- Iowa (IOW)
- Minnesota (MIN)

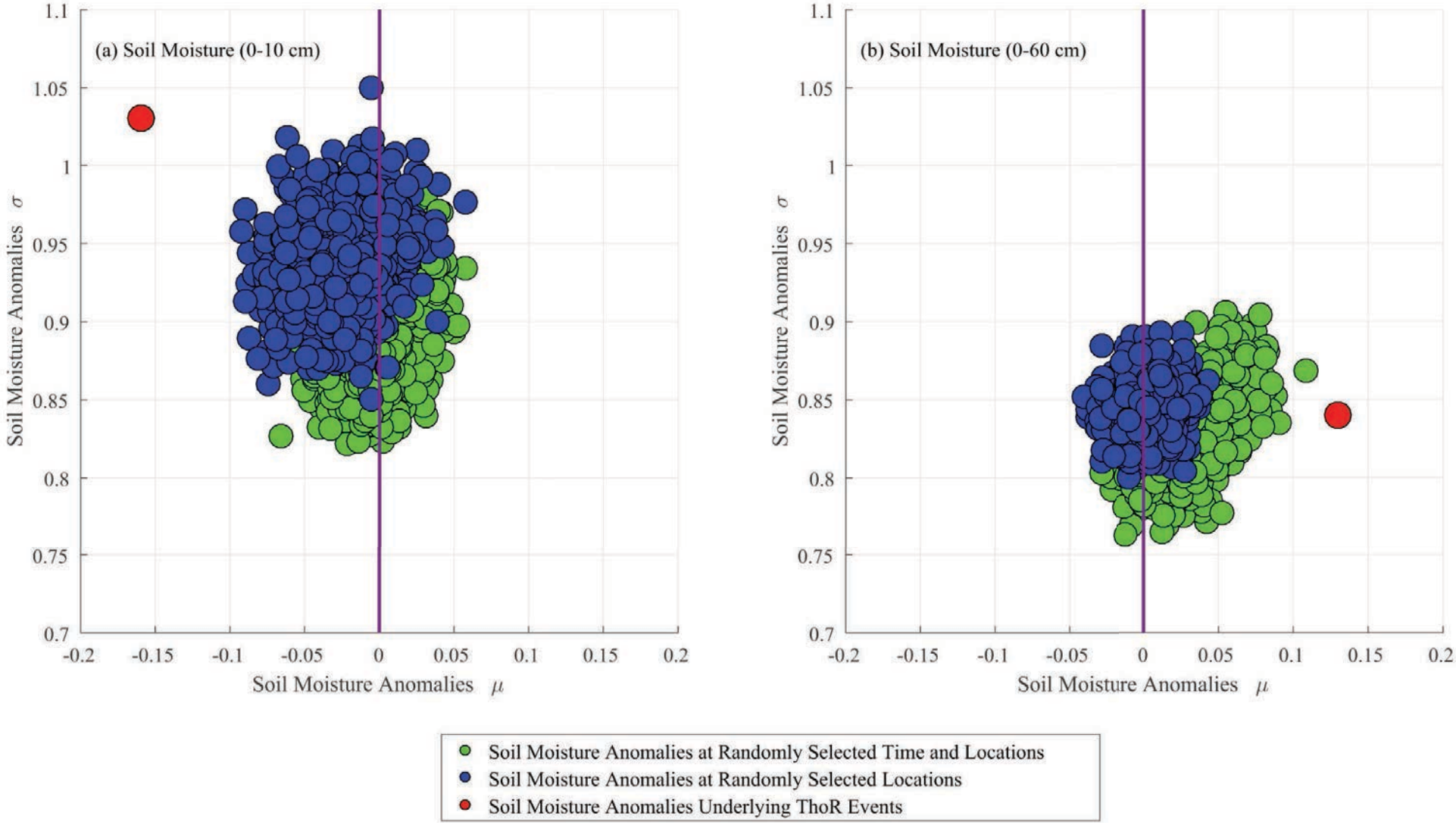


Total number of days with weak forcing in each region based on the manual classification

Results

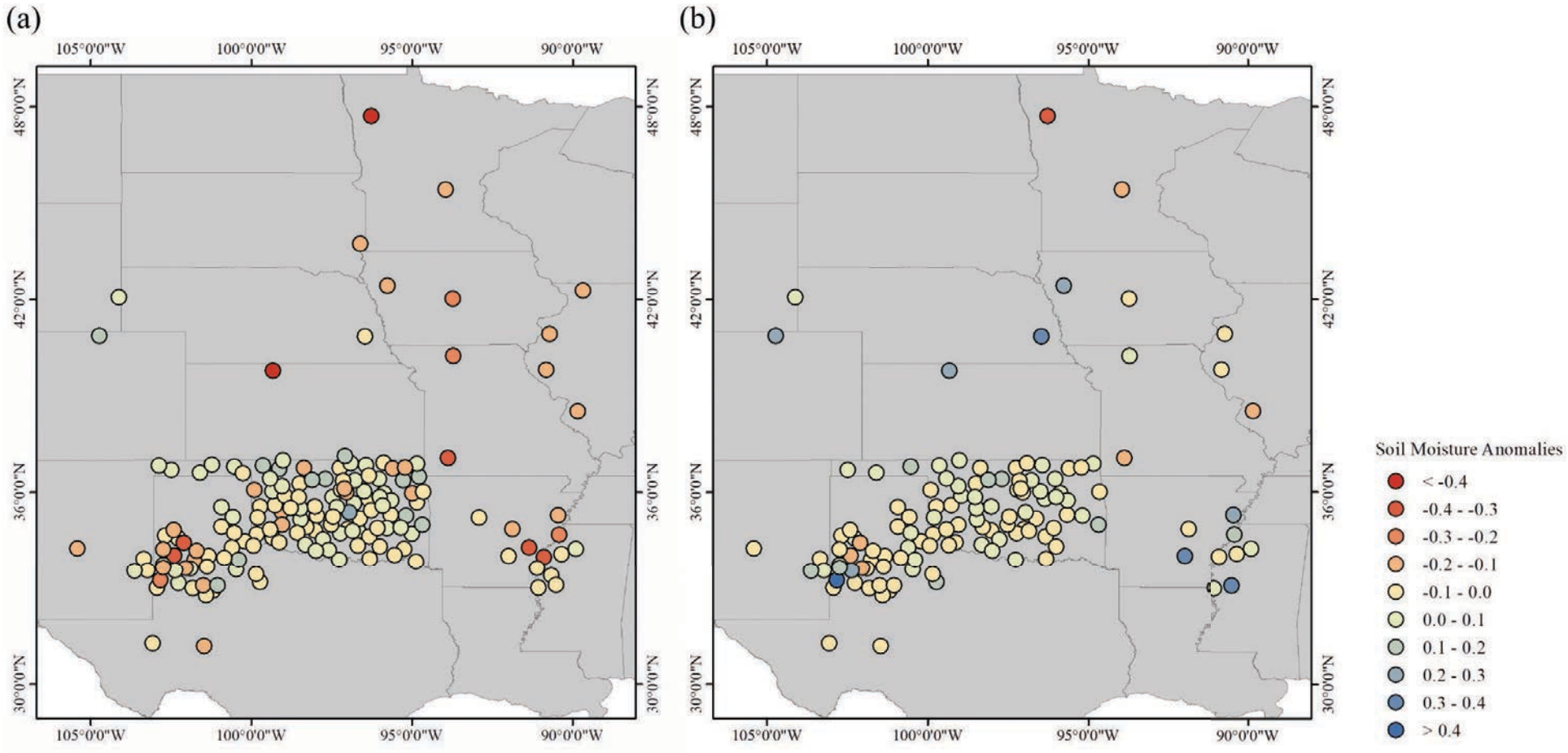
- Composited soil moisture underlying *n* convective events (where *n* = 16,084 events; less for WF events)
- Randomly select *n* points and composite soil moisture from those points
- Repeat this selection 1,000 times (bootstrap resampling with replacement)
- Compare the soil moisture associated with convective events to the randomly selected points

Results – In Situ Soil Moisture



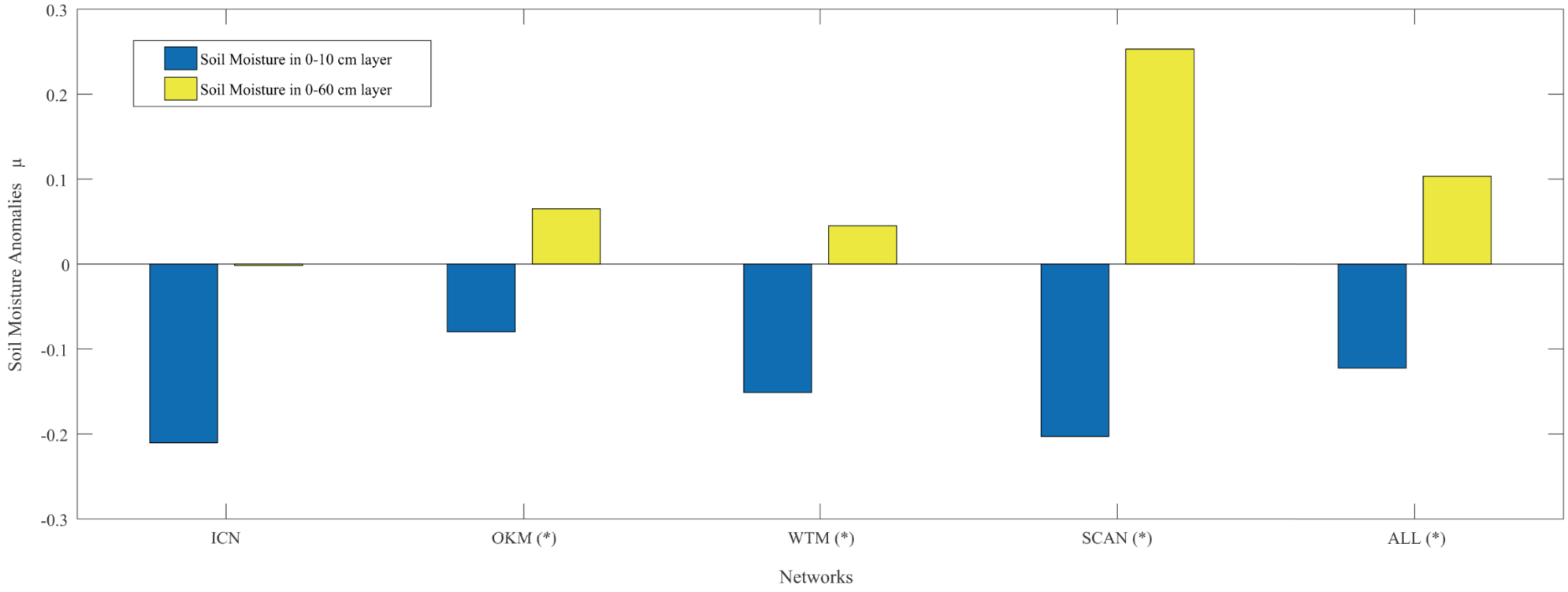
In situ soil moisture anomalies corresponding to the ThoR events (red) and random selections. (a) surface soil moisture (0 to 10 cm) and (b) deeper soil moisture (0 to 60 cm).

Results – In Situ Soil Moisture



Spatial pattern of in situ soil moisture anomalies corresponding to the ThoR events. (a) surface soil moisture (0 to 10 cm) and (b) deeper soil moisture (0 to 60 cm).

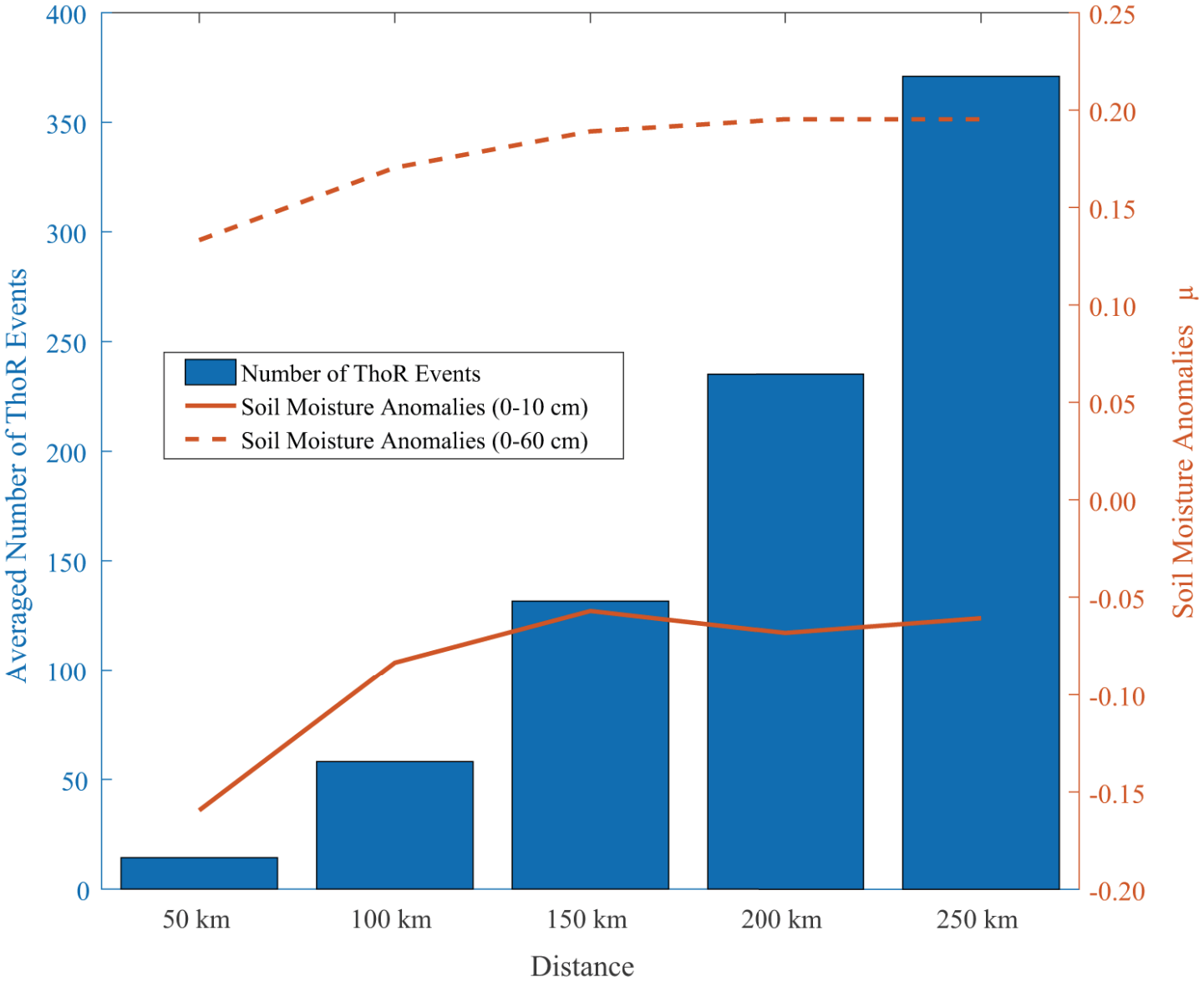
Results – In Situ Soil Moisture



"*" beside the network name denotes statistically significant differences between blue and yellow bar at 95% confidence level.

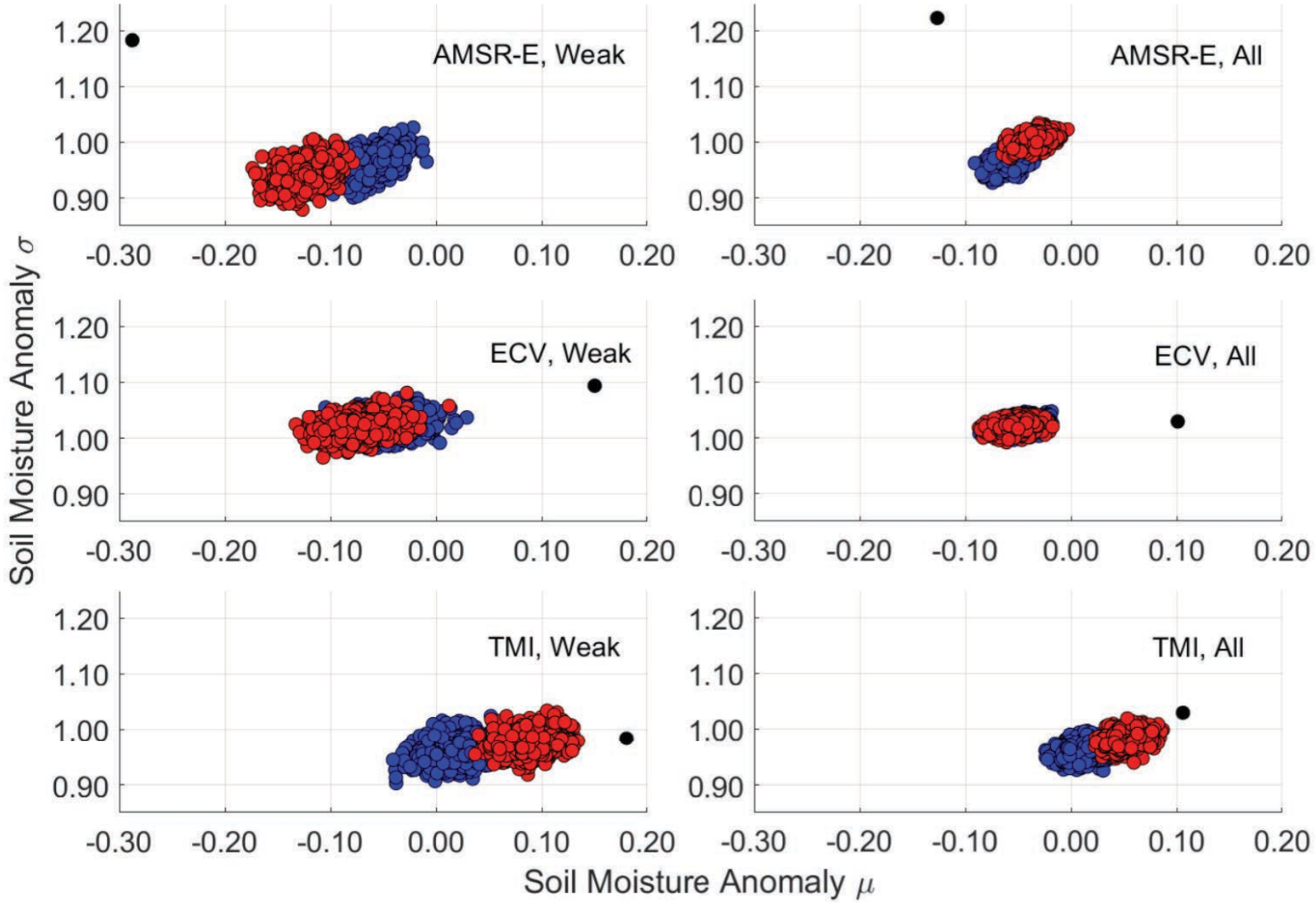
Network-specific in situ soil moisture anomalies corresponding to the ThoR events. Blue bar is surface soil moisture and yellow bar is deeper soil moisture.

Results – In Situ Soil Moisture



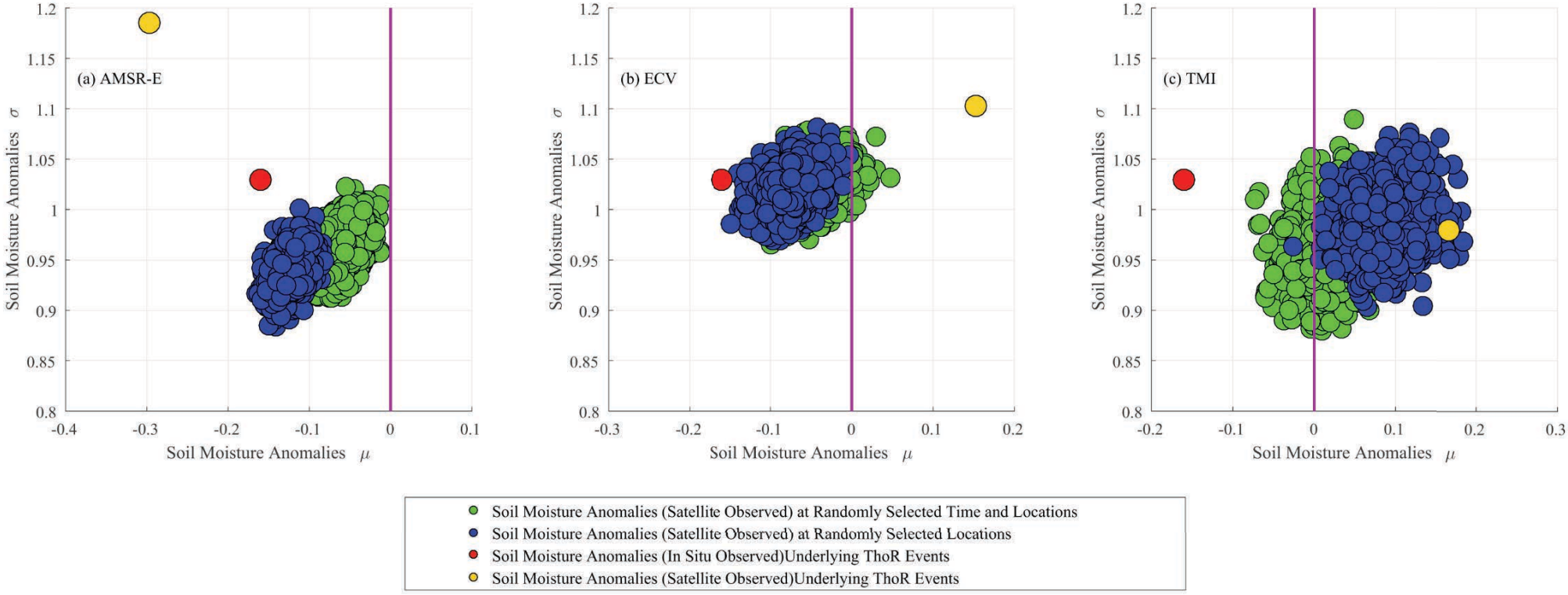
Sensitivity analysis that shows how changing the size of the buffer used to select ThOR events effects the soil moisture-convection coupling relationship.

Results – Satellite-Derived Soil Moisture



Panels show mean and standard deviation of soil moisture anomalies underlying afternoon thunderstorm events (black point), those from distributions of randomly selected points in space (red points), and those from distributions of randomly selected points in space and time (blue).

Results – In-Situ vs. Satellite Soil Moisture



Comparison of in situ soil moisture anomalies and (a) AMSR-E, (b) ECV and (c) TMI soil moisture anomalies, which are corresponding to the ThoR events and random selection.

Results – Summary

To test how sensitive the results are to the methods used, the study was repeated using different methods:

Dataset: AMSR-E, ECV, TMI

Forcing: all, weakly forced

Classification: manual, Georgia, Carleton (results not shown here)

Calculate 2-way ANOVA with interaction to determine which methods have the largest influence on the results:

A. Dataset and by convective forcing

Source	F-stat	p-value
Dataset	297.84	0.00
Forcing	0.10	0.75
Interaction	23.80	0.00

B. Dataset and by classification method

Source	F-stat	p-value
Dataset	861.35	0.00
Classification Method	6.96	0.00
Interaction	4.29	0.00

What do we know?

- Wet/dry preferences are significantly different between datasets:
  - AMSR-E & in situ (0 to 10 cm) have a statistically significant dry preference
  - TMI and ECV have a statistically significant wet preference

- Separating weakly forced events makes a difference AMSR-E, but not for TMI or ECV

- **There is substantial variability in the sign and strength of soil moisture-precipitation coupling strength due to the datasets and methods that are used**

Next Steps

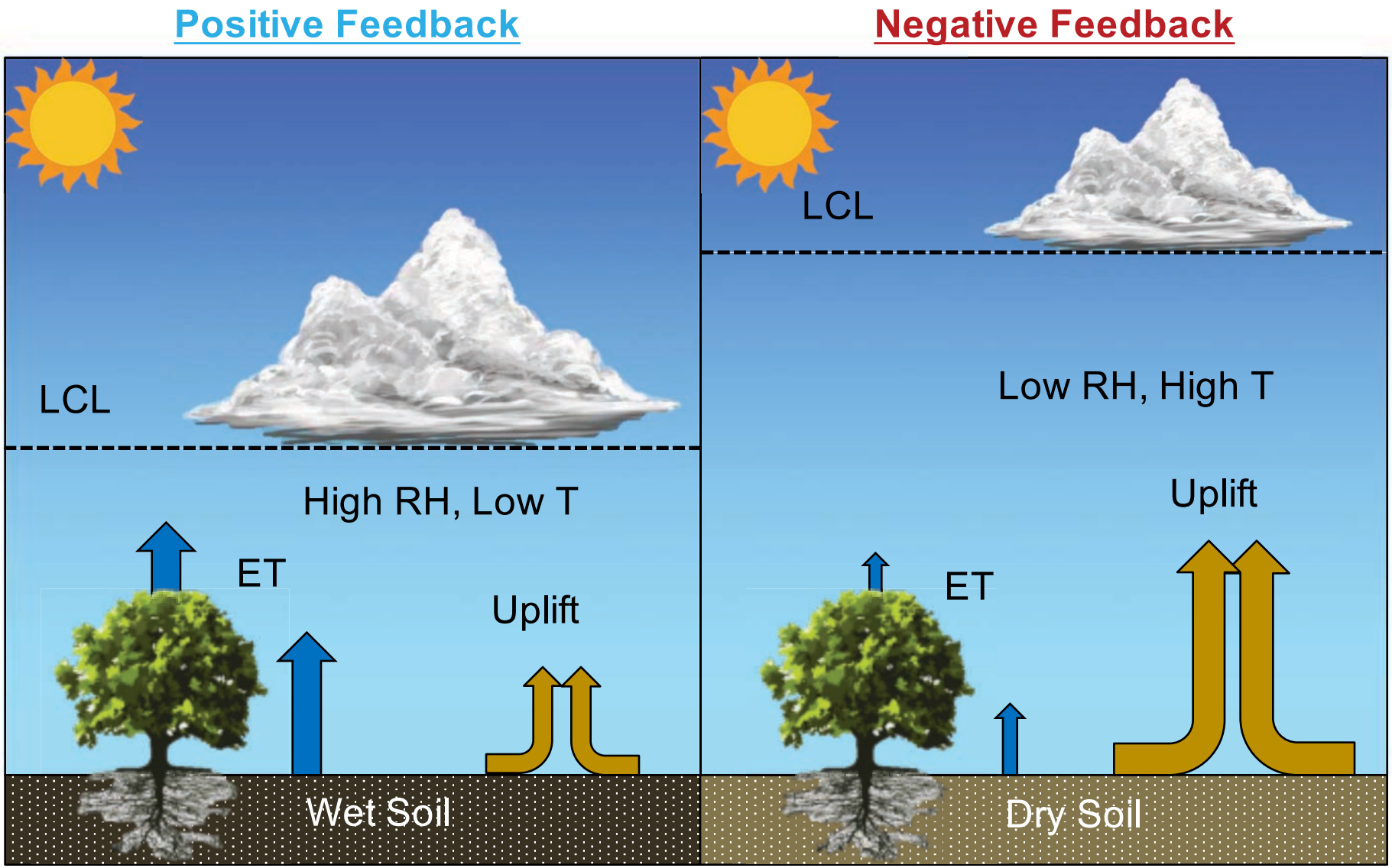
- Finish processing ThOR events (2008-2017)
- Evaluate whether deep convection initiation occurs preferentially over wet or dry soils using SMAP
- Identify how these preferences vary over time and space
- Determine how soil moisture heterogeneity and gradients influence initiation of deep convection

Acknowledgements

- This research is funded by NASA Science Utilization of SMAP (Grant: NNX16AO97G) and NSF Climate & Large-scale Dynamics (CAREER ATM-1056796)

- Major contributors:
  - Trent Ford, Adam Houston
  - Research Assistance:
  - Shanshui Yuan, Yuechun Wang, Lisa Goldstein

Soil Moisture-Precipitation Feedbacks



LETTER

doi:10.1038/nature11377

Afternoon rain more likely over drier soils

Christopher M. Taylor[1], Richard A. M. de Jeu[2], Françoise Guichard[3], Phil P. Harris[1] & Wouter A. Dorigo[4]

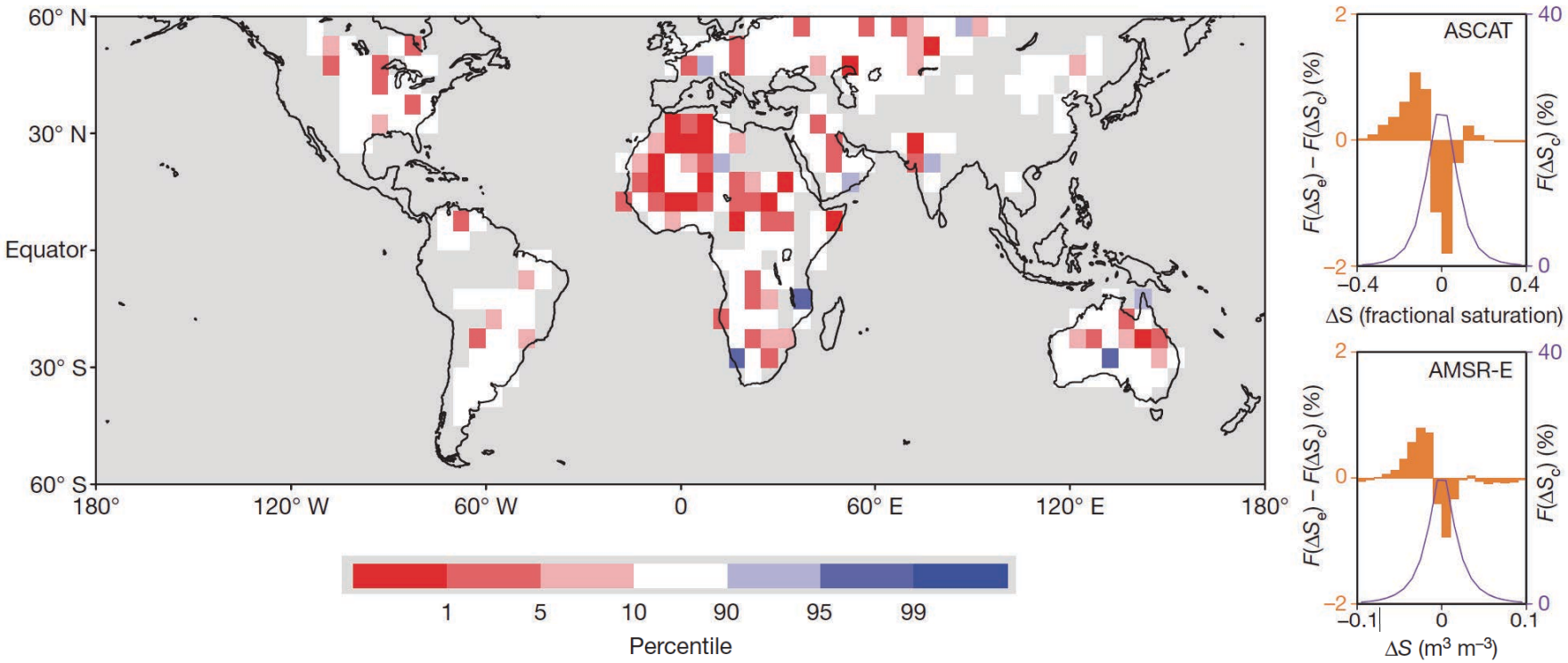


Figure 1 | Preference for afternoon precipitation over soil moisture anomalies. Percentiles of the observed variable $\delta_e = \text{mean}(\Delta S_e) - \text{mean}(\Delta S_c)$ for each $5^\circ \times 5^\circ$ box under a null assumption that no feedback exists. Null sampling distributions of δ values were estimated for each box by re-sampling without replacement from the combined set of event and non-event ΔS values. Low (high) percentiles indicate where rainfall maxima occur over locally dry (wet) soil more frequently than expected. Grey denotes $5^\circ \times 5^\circ$ cells containing fewer than 25 events. The map is based on a merging of two separate analyses using either ASCAT or AMSR-E soil moisture. For each $5^\circ \times 5^\circ$ cell, the relative quality of the two data sets is tested independently to determine which product is used (Supplementary Figs 5, 6). Insets: frequency histograms $F(\Delta S_c)$ of soil moisture difference in the global control sample (purple), and the difference $F(\Delta S_e) - F(\Delta S_c)$ between the histograms of the global event and global control samples (orange shading). The total number of events (n_e) is 29,729 for ASCAT and 73,623 for AMSR-E. Note the different units for ΔS for ASCAT (fractional saturation) and AMSR-E ($m^3\ m^{-3}$).

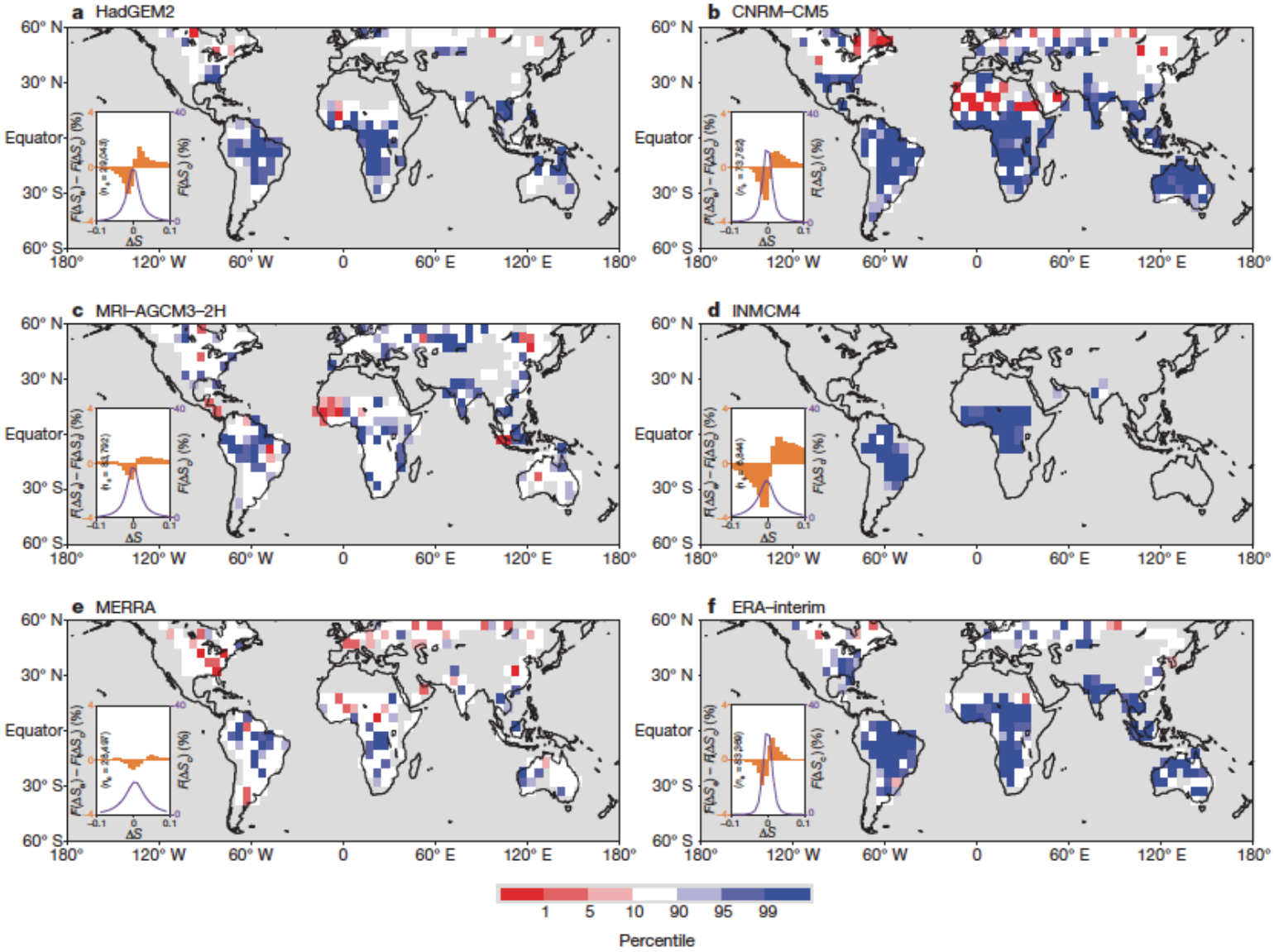
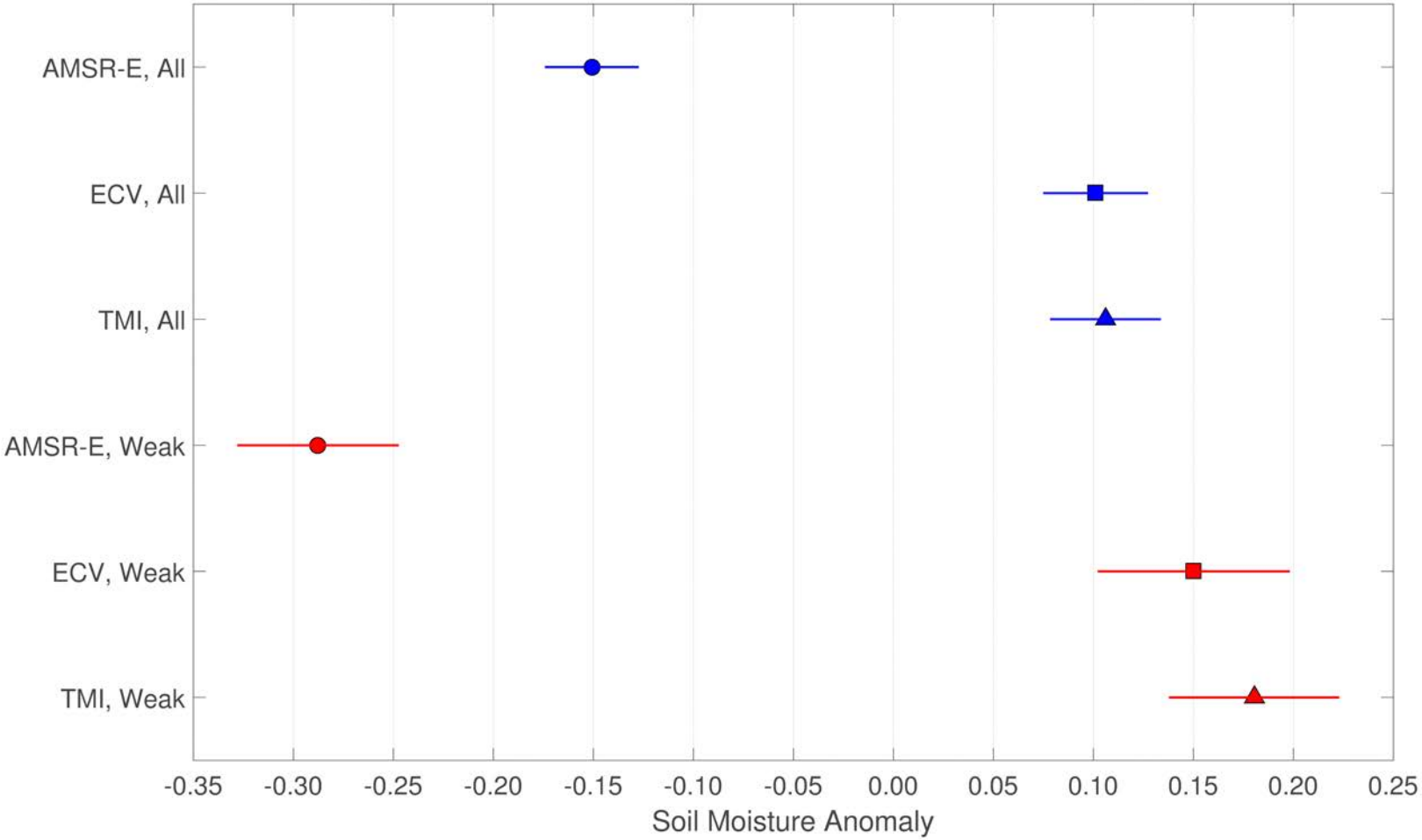


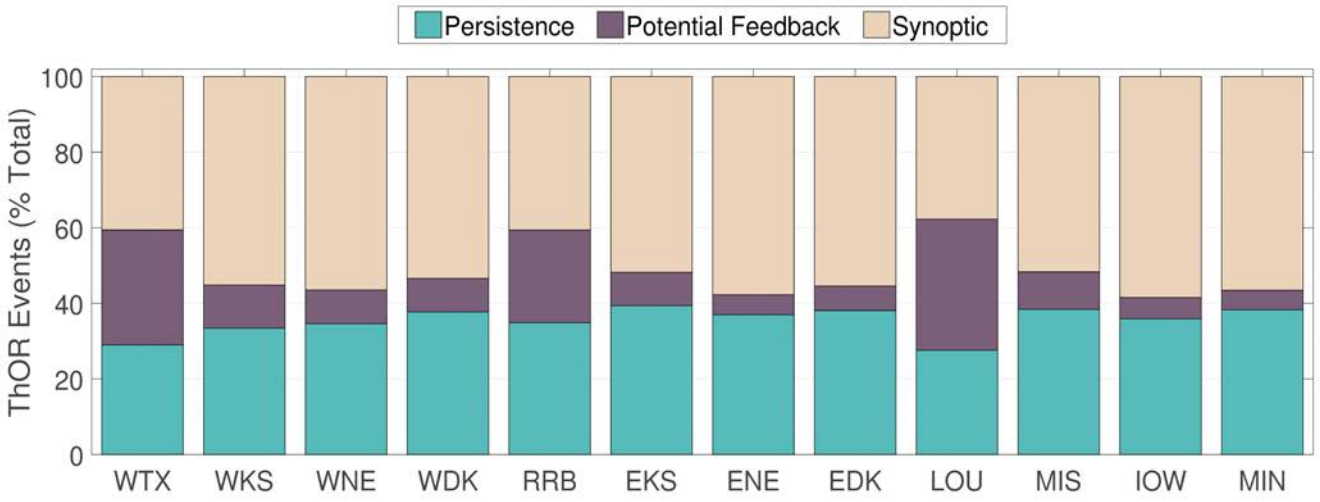
Figure 3 | Simulated preference for afternoon precipitation over soil moisture anomalies. As for Fig. 1 but using diagnostics from integrations by four climate models (**a**–**d**) and two atmospheric reanalysis models (**e**, **f**). Blue (red) shading indicates convective precipitation more likely over wetter (drier) soils. The models used are: **a**, HadGEM2; **b**, CNRM-CM5; **c**, MRI-AGCM3-2H; **d**, INMCM4; **e**, MERRA; and **f**, ERA-Interim. Inset as for Fig. 1, with ΔS in $m^3 m^{-3}$. Further details of the models are in Supplementary Information, with maps of the number of events in each model in Supplementary Fig. 11.

Results – Summary

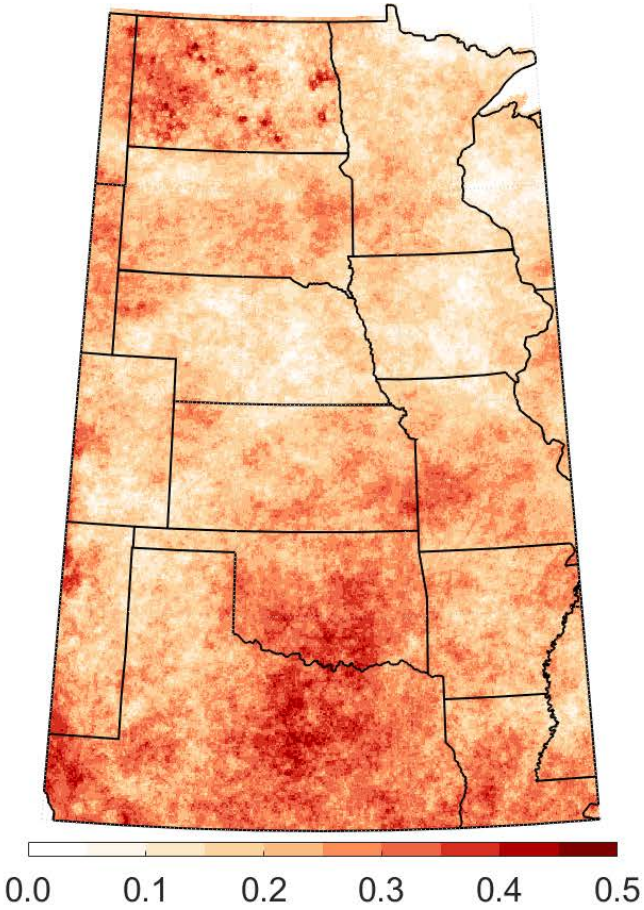


Distributions of soil moisture anomalies grouped by dataset and by convective forcing (weak = weakly-forced; all = synoptic + WF). Statistically significant differences between distributions exist at the 95% confidence level if the lines do not overlap.

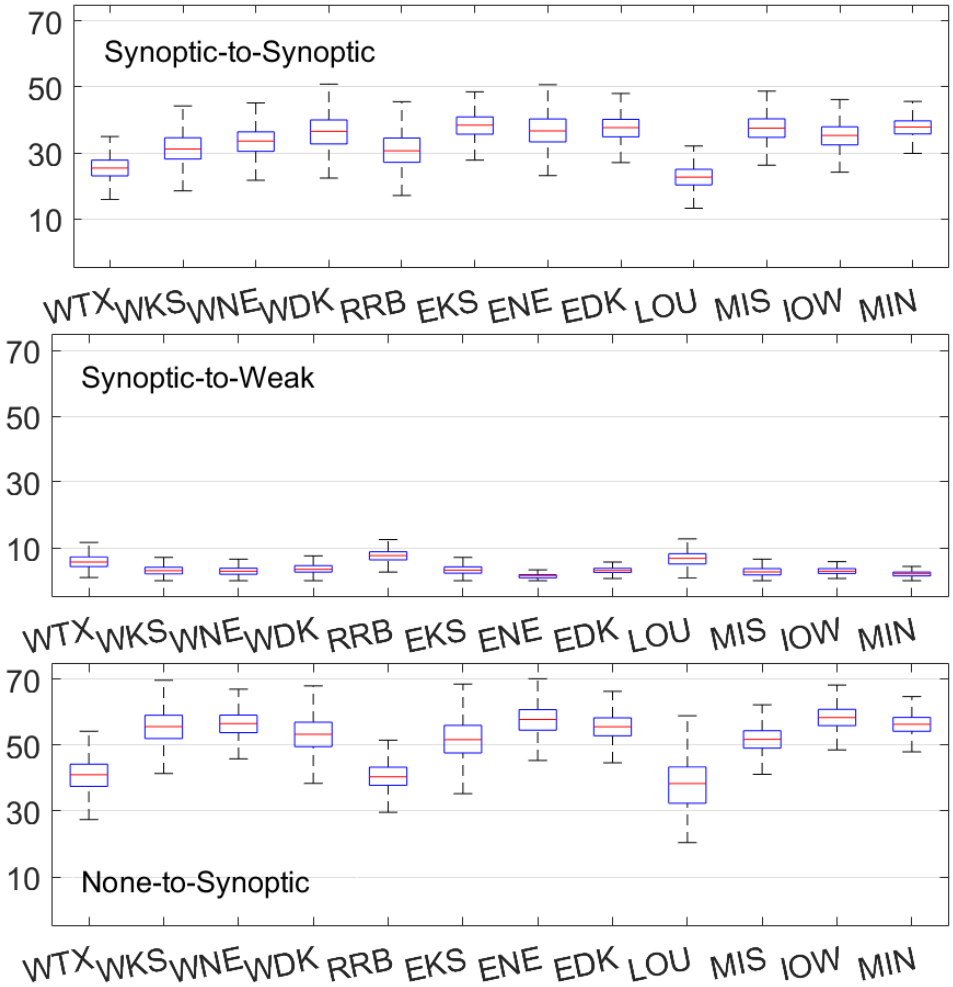
Atmospheric Persistence

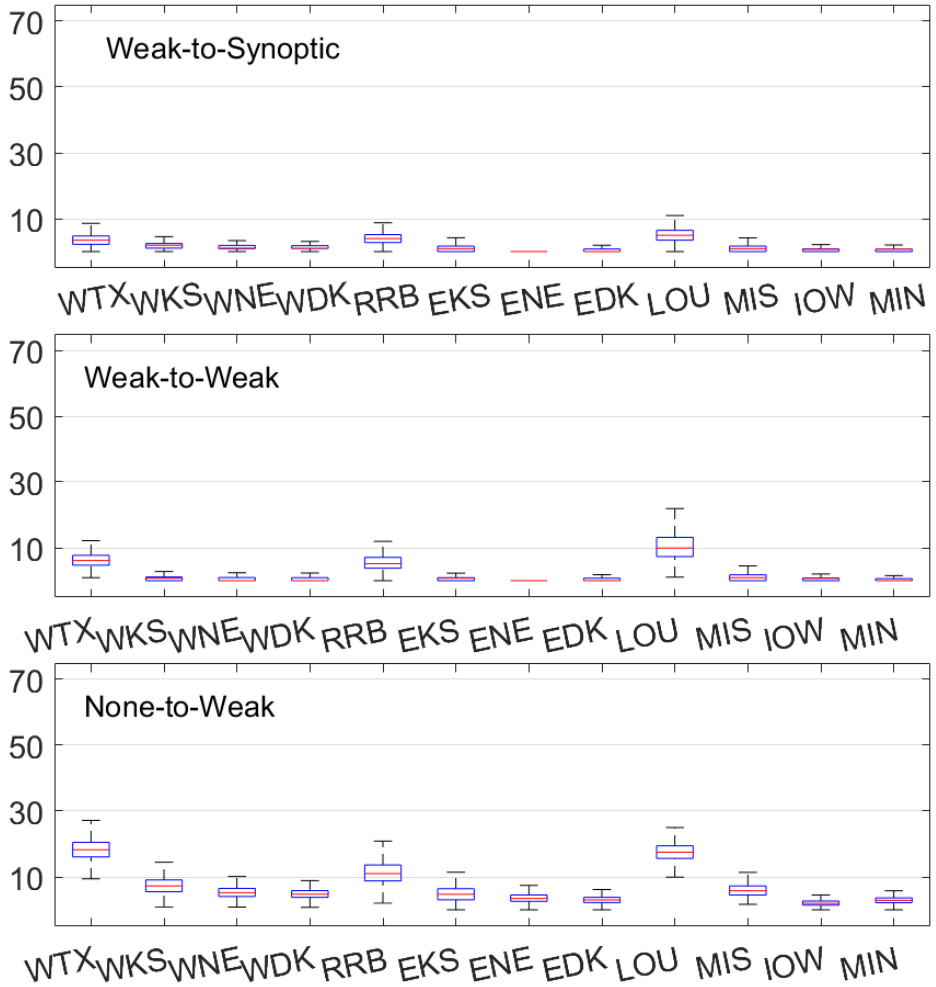


Percent of all ThOR events that fall into one of three categories. Events identified as "persistence" are those events that are synoptically forced and follow a weakly or synoptically forced event in the same place the day before. Events categorized as “potential feedback” are those that are weakly forced irrespective of what occurred the day before. Events categorized as “synoptic” are those that are synoptically forced and follow a day in which no event or precipitation occurred



Lag-1 daily precipitation autocorrelation calculated according to Wilks (1999).





ThOR events that occurred in PRISM grid cells that experienced precipitation the day before the event. So the Synoptic-to-Synoptic classification means that the event occurred on a synoptic day that followed a synoptic day. The boxplots show the distribution of the % of events in each grid cell within a region that is classified in that group.

Results – Event Classification

12 regions:

- West Texas (WTX
- West Kansas (WKS)
- West Nebraska (WNE)
- West Dakotas (WDK)
- Red River Basin (RRB)
- East Kansas (EKS)
- East Nebraska (ENE)
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- Louisiana (LOU)
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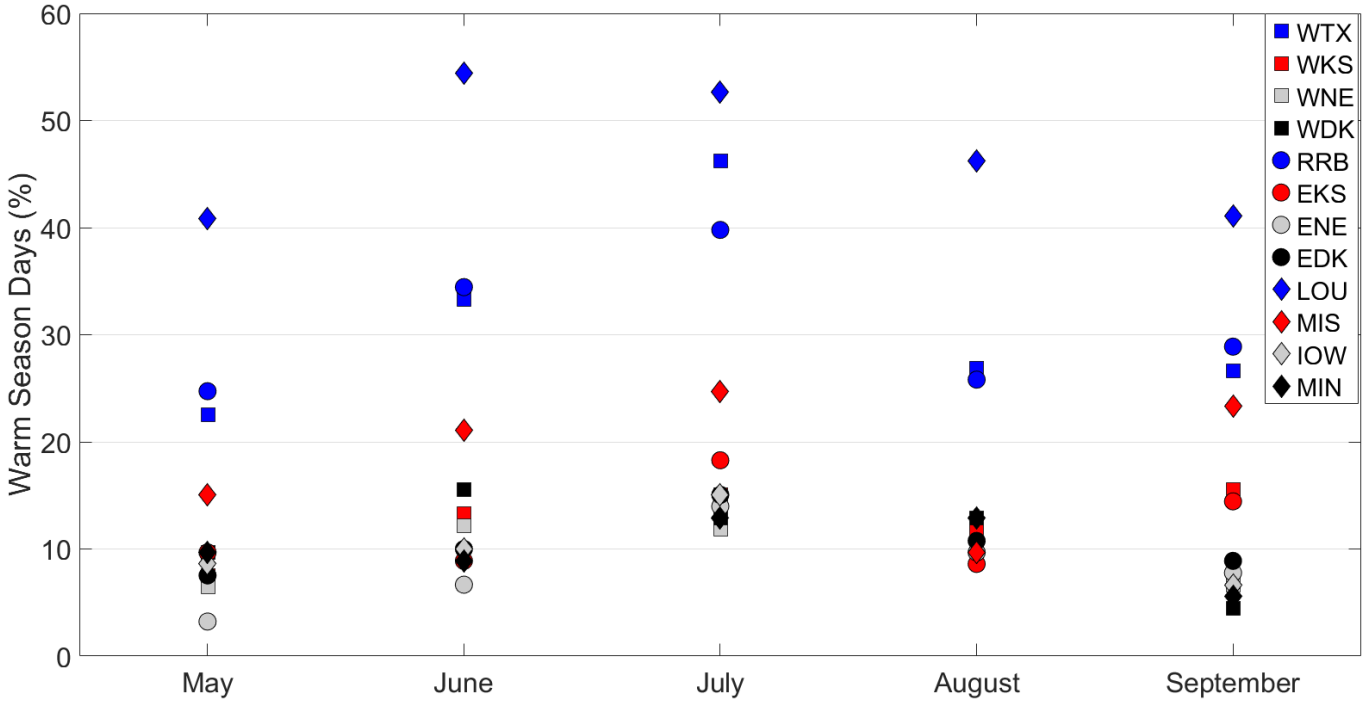
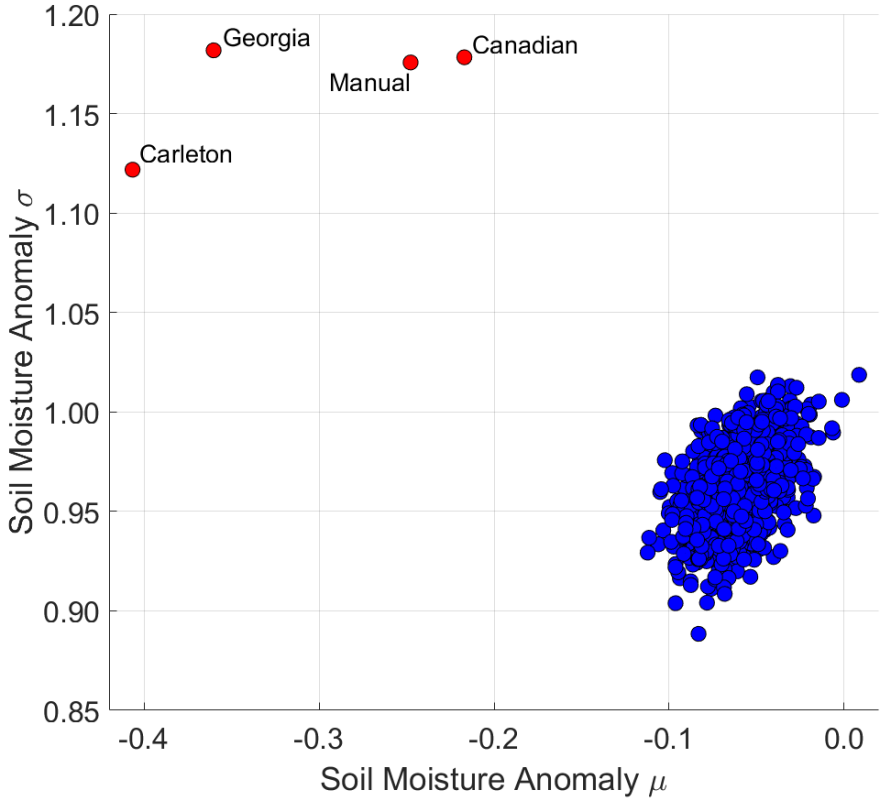
- Minnesota (MIN)



Percentage of warm season days in each month that are classified as weakly forced days based on the manual classification

Results – Wet/Dry Soil Preferences: AMSR-E

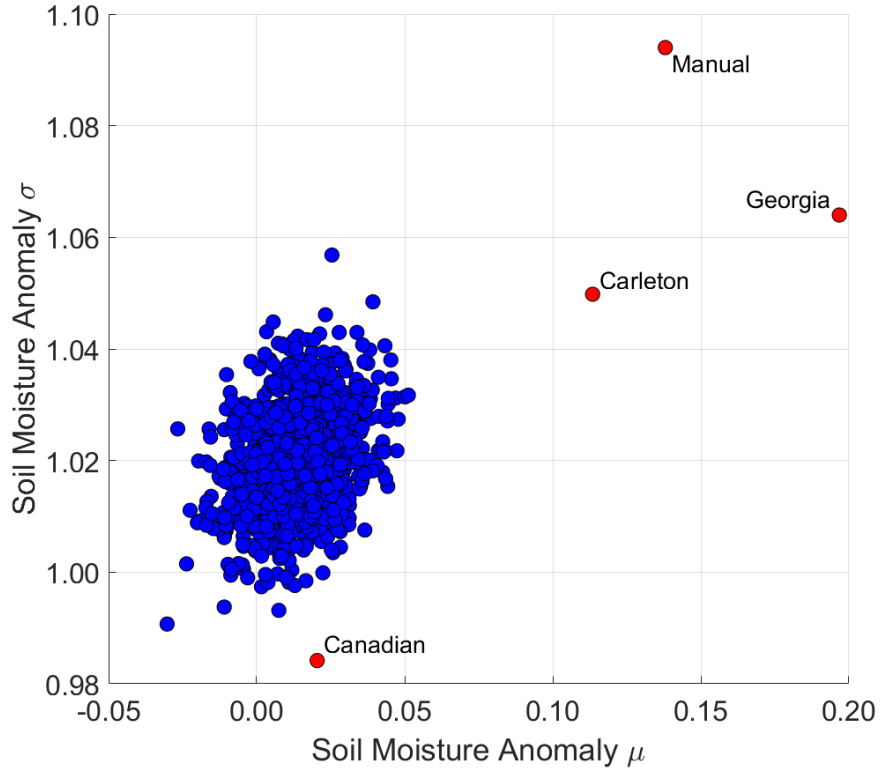
- Significant dry soil preference for AMSR-E is consistent amongst all "weakly forced" classification methods



Mean (x-axis) and standard deviation (y-axis) of randomly-selected samples (blue) and ThOR weakly forced events (red). The red points are separated by the different "weakly forced" classification methods

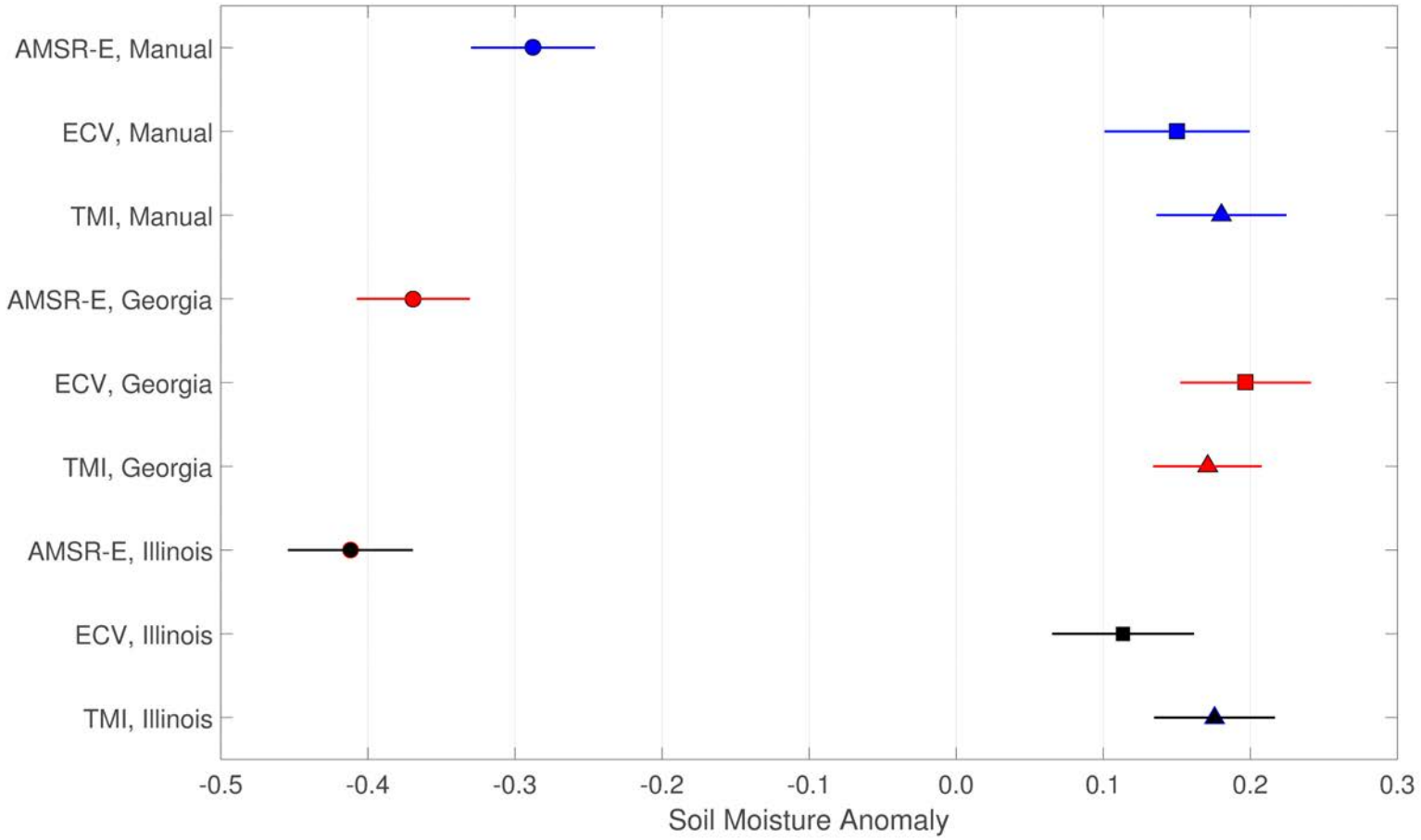
Results – Wet/Dry Soil Preferences: ECV

- Significant wet soil preference for ECV is consistent among manual, Georgia, and Carleton methods



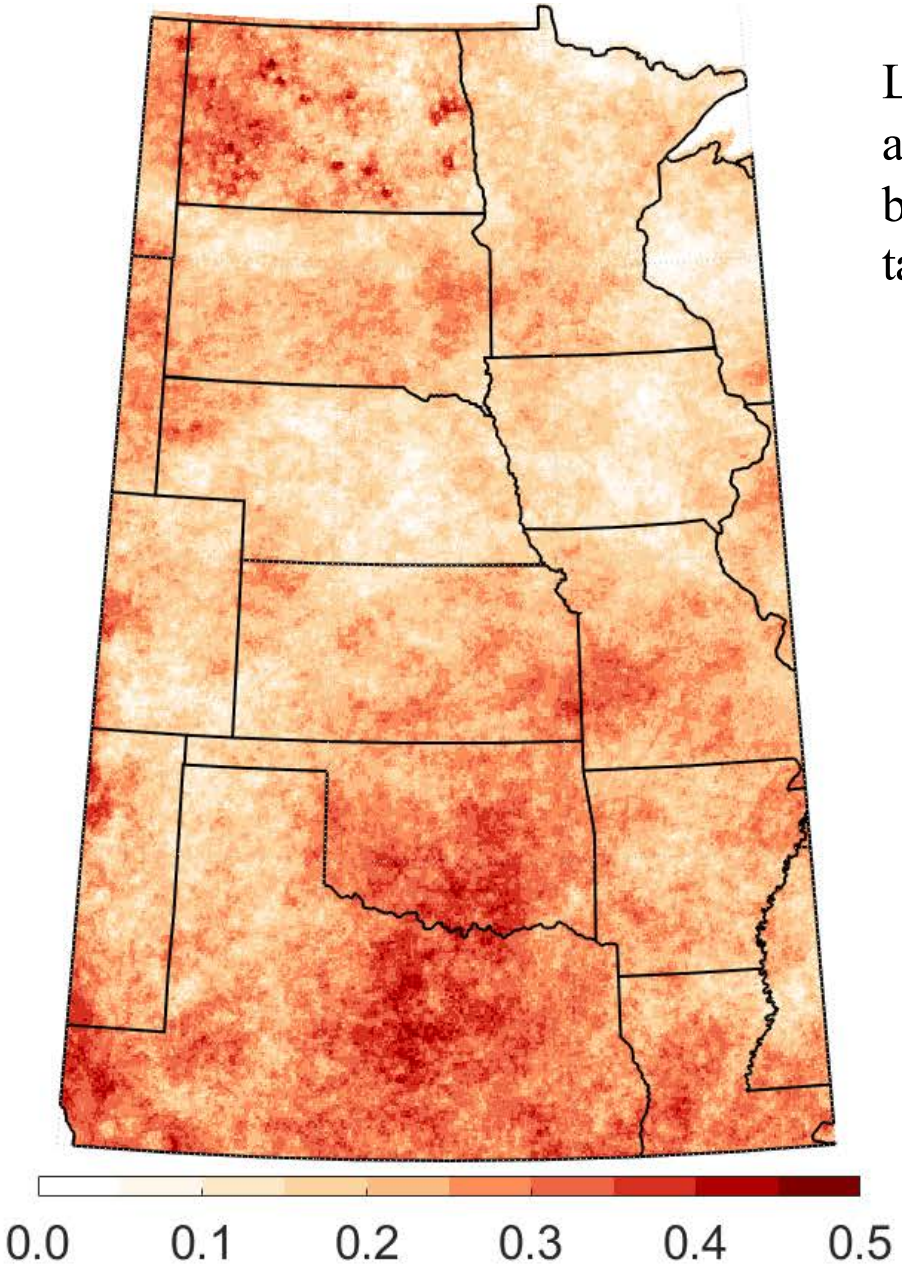
Mean (x-axis) and standard deviation (y-axis) of randomly-selected samples (blue) and ThOR weakly forced events (red). The red points are separated by the different "weakly forced" classification methods

Results – Sensitivity to Methods



Significant differences exist between all events and the WF events for AMSR-E, but not for ECV or TMI

Significant differences exist between AMSR-E and ECV/TMI for all event classification types



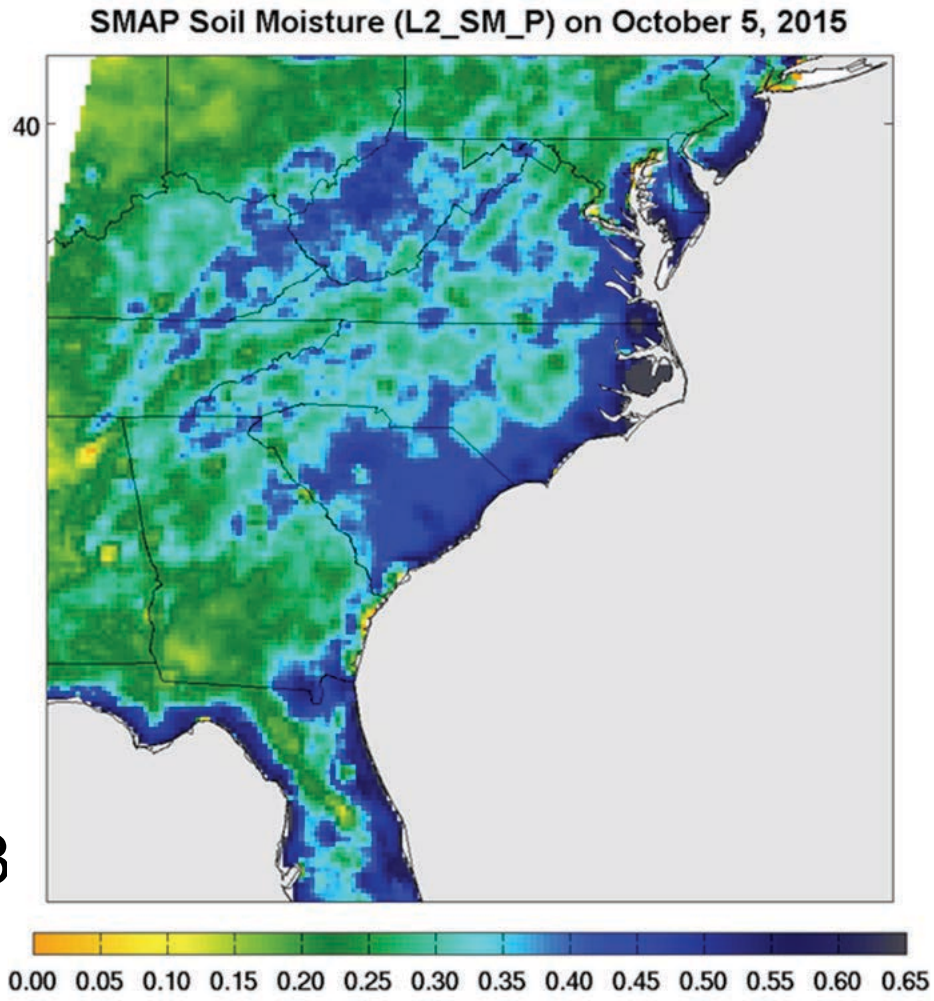
Lag-1 daily precipitation autocorrelation calculated according to Wilks (1999). Daily precipitation between May and September, 2005 – 2007 was taken from the PRISM gridded dataset.

Methods-NASA SMAP

NASA launched the SMAP satellite in January 2015.

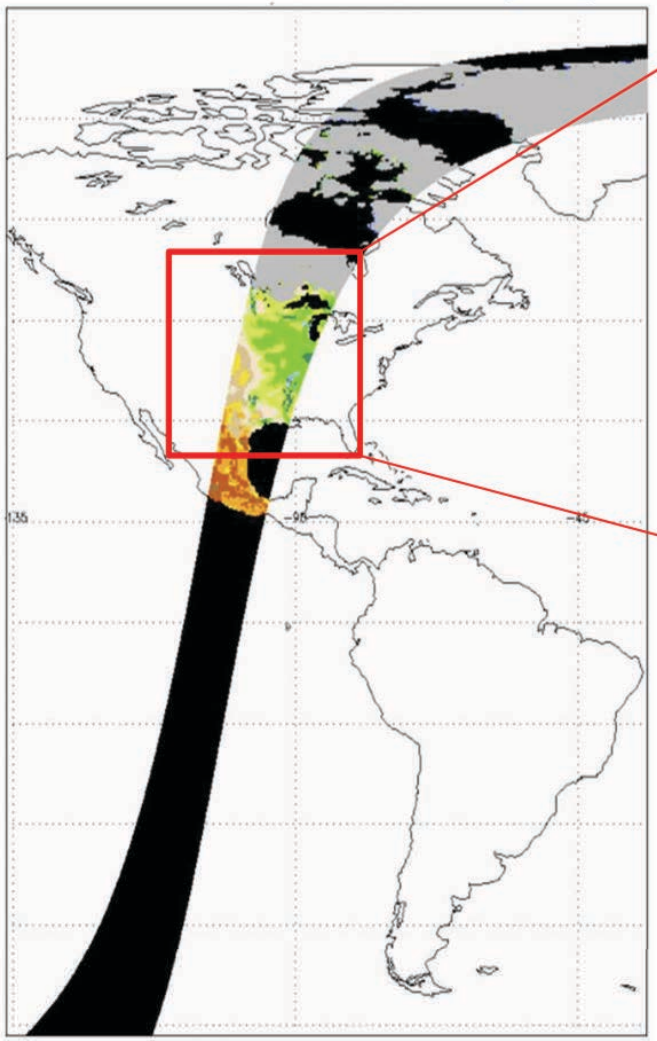
Measured soil moisture using both active (radar) and passive (radiometer) until the radar failed in July 2015. Since then, only radiometer data are available.

Provides global coverage every 2-3 days.

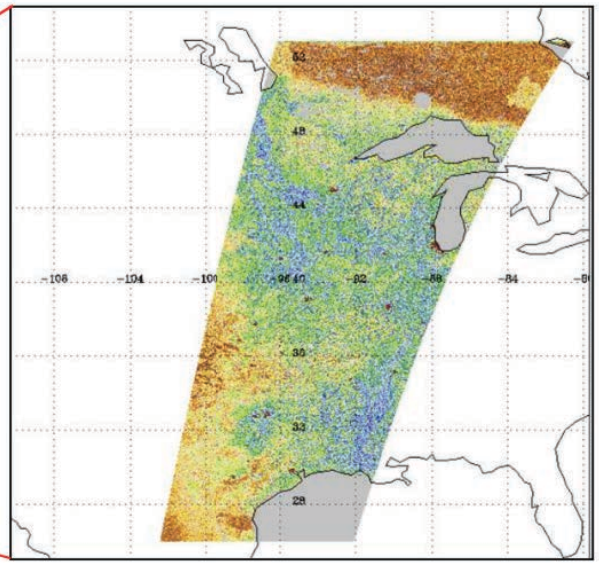


SMAP soil moisture (L2_SM_P) retrieval from Oct. 5, 2015

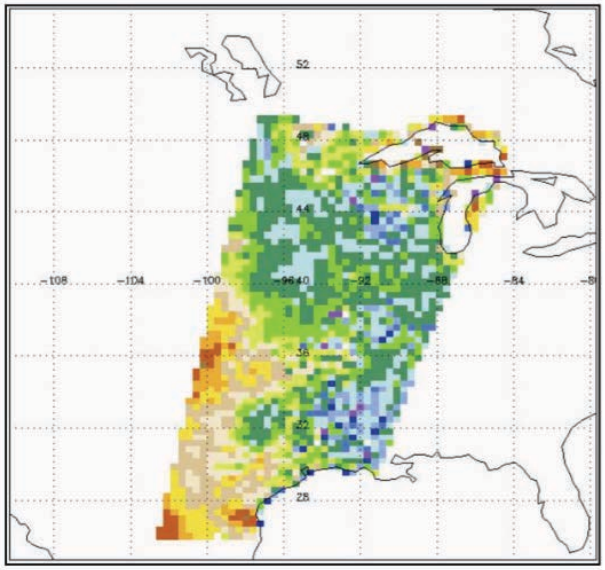
Half-orbit L2_SM_A Product (3 km)



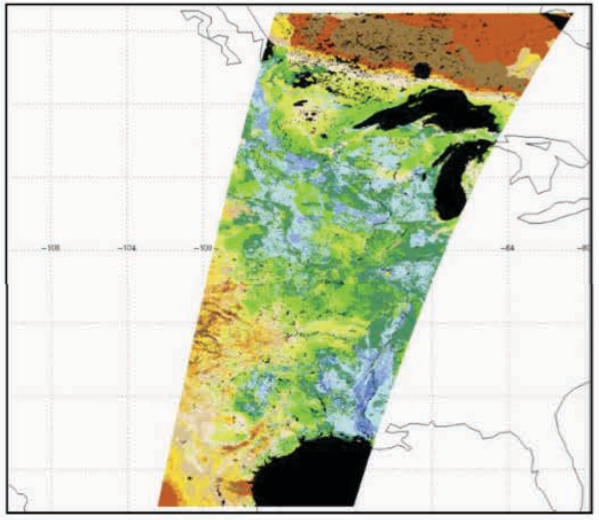
L2_SM_A (3 km)



L2_SM_P (36 km)



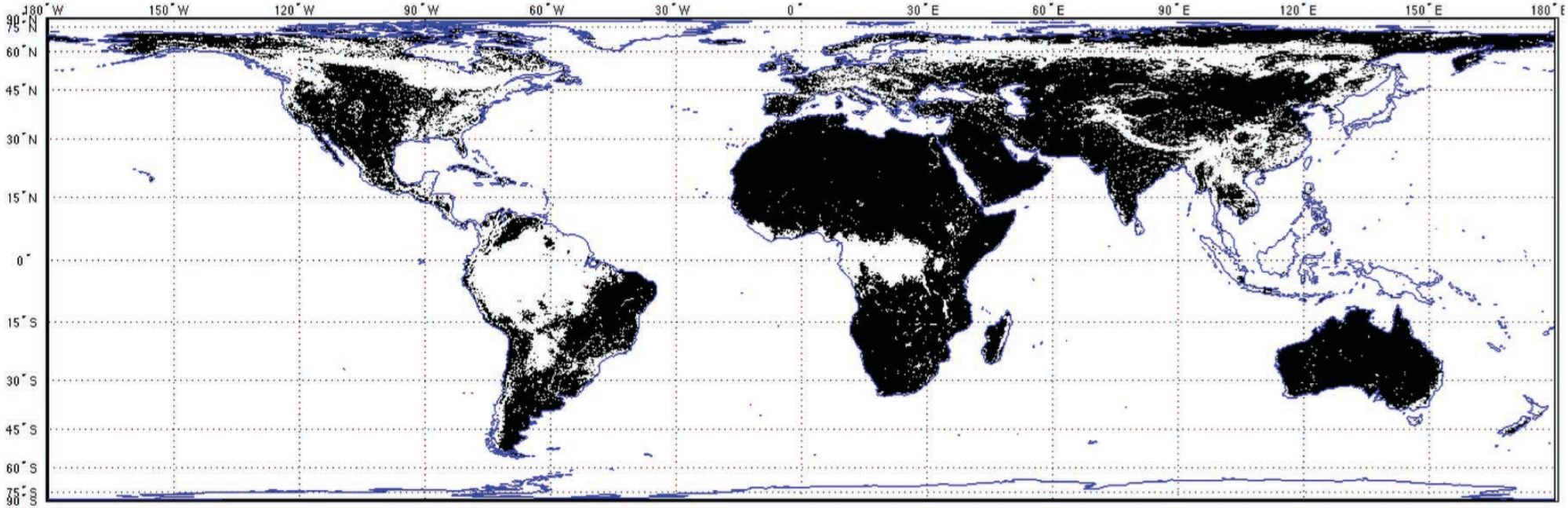
L2_SM_AP (9 km)



Volumetric Soil Moisture (cm^3/cm^3)

Product	Description	Gridding (Resolution)	Latency**	
L1A_Radiometer	Radiometer Data in Time-Order	-	12 hrs	Instrument Data
L1A_Radar	Radar Data in Time-Order	-	12 hrs	
L1B_TB	Radiometer T_B in Time-Order	(36x47 km)	12 hrs	
L1B_S0_LoRes	Low Resolution Radar σ_o in Time-Order	(5x30 km)	12 hrs	
L1C_S0_HiRes	High Resolution Radar σ_o in Half-Orbits	1 km (1-3 km)	12 hrs	
L1C_TB	Radiometer T_B in Half-Orbits	36 km	12 hrs	
L2_SM_A	Soil Moisture (Radar)	3 km	24 hrs	Science Data (Half-Orbit)
L2_SM_P	Soil Moisture (Radiometer)	36 km	24 hrs	
L2_SM_AP	Soil Moisture (Radar + Radiometer)	9 km	24 hrs	
L3_FT_A	Freeze/Thaw State (Radar)	3 km	50 hrs	Science Data (Daily Composite)
L3_SM_A	Soil Moisture (Radar)	3 km	50 hrs	
L3_SM_P	Soil Moisture (Radiometer)	36 km	50 hrs	
L3_SM_AP	Soil Moisture (Radar + Radiometer)	9 km	50 hrs	
L4_SM	Soil Moisture (Surface and Root Zone)	9 km	7 days	Science Value-Added
L4_C	Carbon Net Ecosystem Exchange (NEE)	9 km	14 days	

Limitations of NASA SMAP Retrievals



At 9 km:

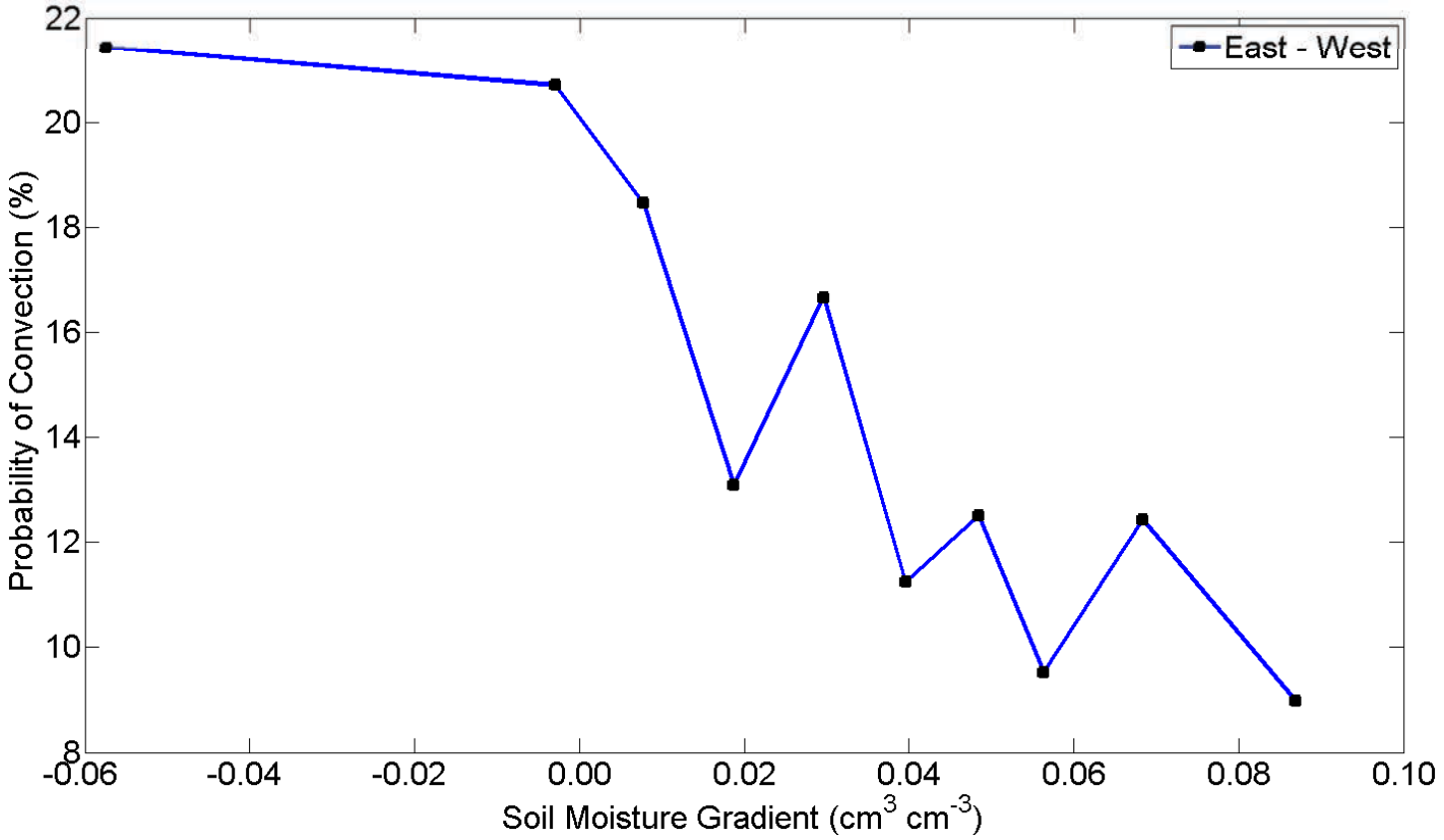
VWC ≤ 5 kg m^{-2}

Urban Fraction ≤ 0.25

Water fraction ≤ 0.1

Elevation Slope Standard Deviation ≤ 3 deg

Preliminary Results: Soil Moisture Gradients

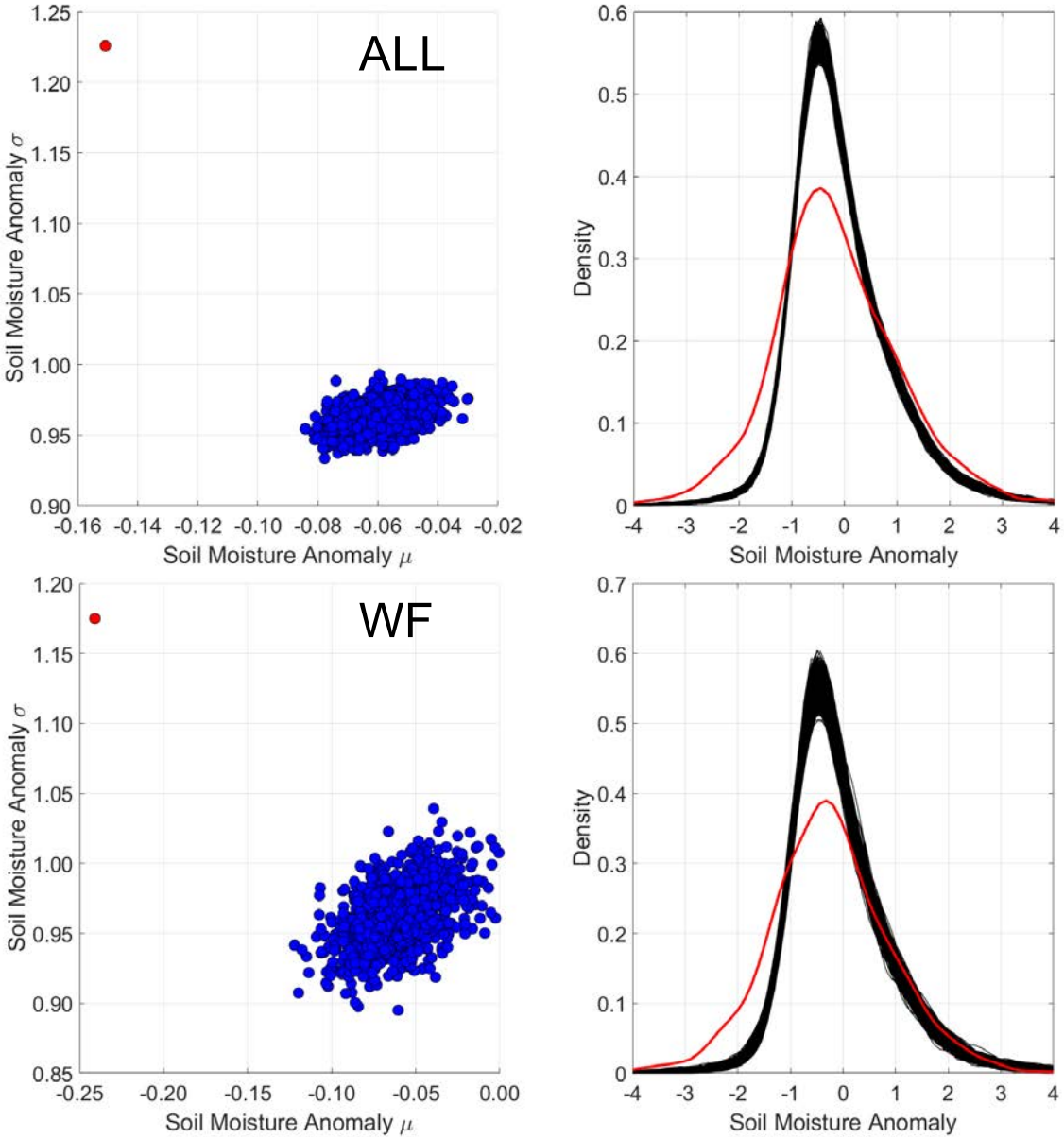


Variations in the probability of convective initiation as a function of the east-west soil moisture gradient in Oklahoma. Negative gradients represent wet soils in the west and dry soils in the east, positive gradients indicate the opposite. A 0.01 cm^3 cm^3 volumetric water content increase in the wet–dry soil moisture gradient corresponds with a 3% increase in the probability of convective precipitation initiation.

Results – AMSR-E

- ThOR events are statistically significantly drier, and more variable, than bootstrapped soil moisture

- Both all events (top left) and weakly forced events (bottom left) have a dry soil preference compared to the random samples

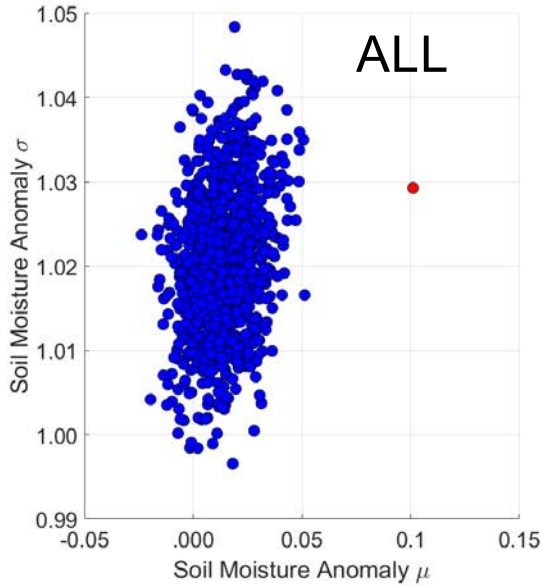


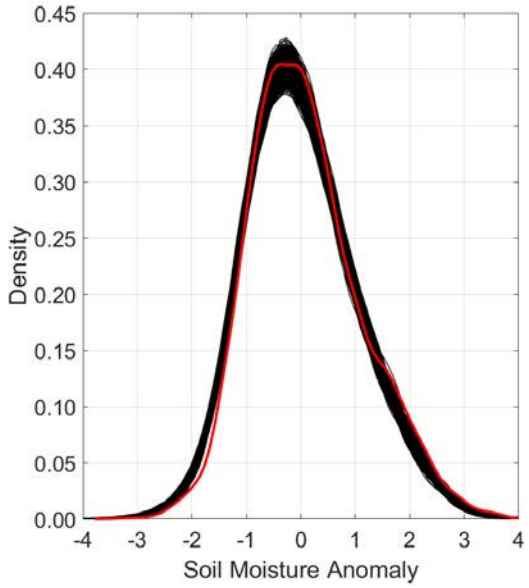
Left panels: mean (x-axis) and standard deviation (y-axis) of randomly-selected samples (blue) and ThOR events (red)

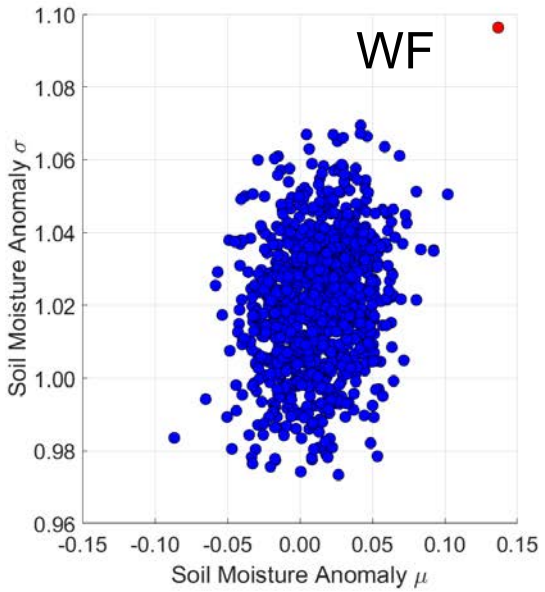
Right panels: soil moisture anomaly distributions from randomly-selected samples (black) and ThOR events (red).

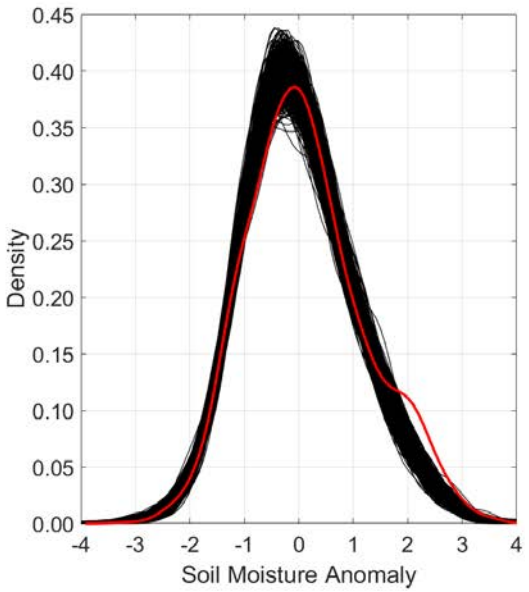
Results – ECV

- ThOR events (both weakly forced and all) show a statistically significant wet soil preference
- Subsetting to weakly forced events strengthens wet preference









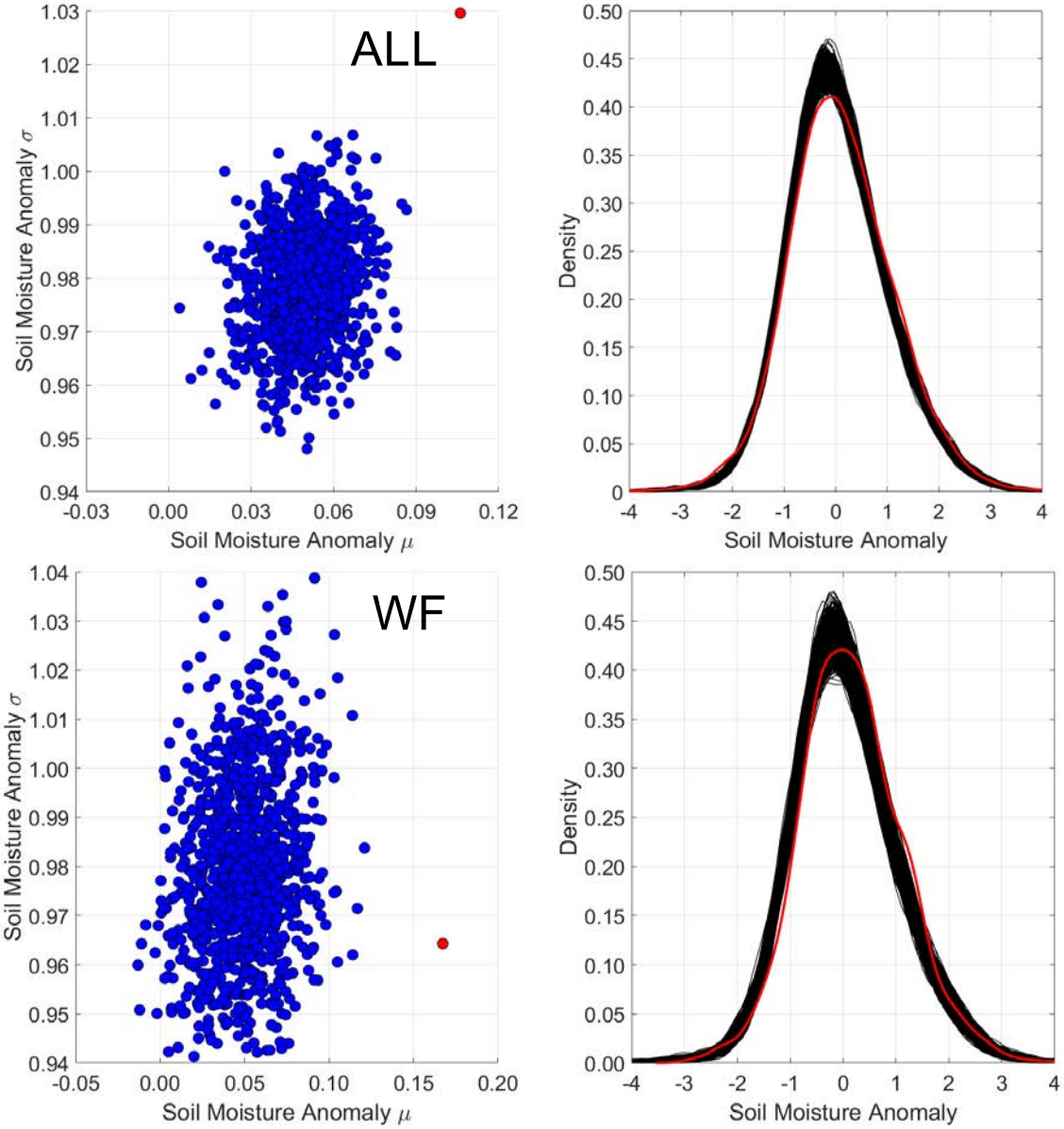
Left panels: mean (x-axis) and standard deviation (y-axis) of randomly-selected samples (blue) and ThOR events (red)

Right panels: soil moisture anomaly distributions from randomly-selected samples (black) and ThOR events (red).

Results – TRMM TMI

- ThOR events (both weakly forced and all) show a statistically significant wet soil preference

- Weakly forced events have less variability than all events



Left panels: mean (x-axis) and standard deviation (y-axis) of randomly-selected samples (blue) and ThOR events (red)

Right panels: soil moisture anomaly distributions from randomly-selected samples (black) and ThOR events (red).