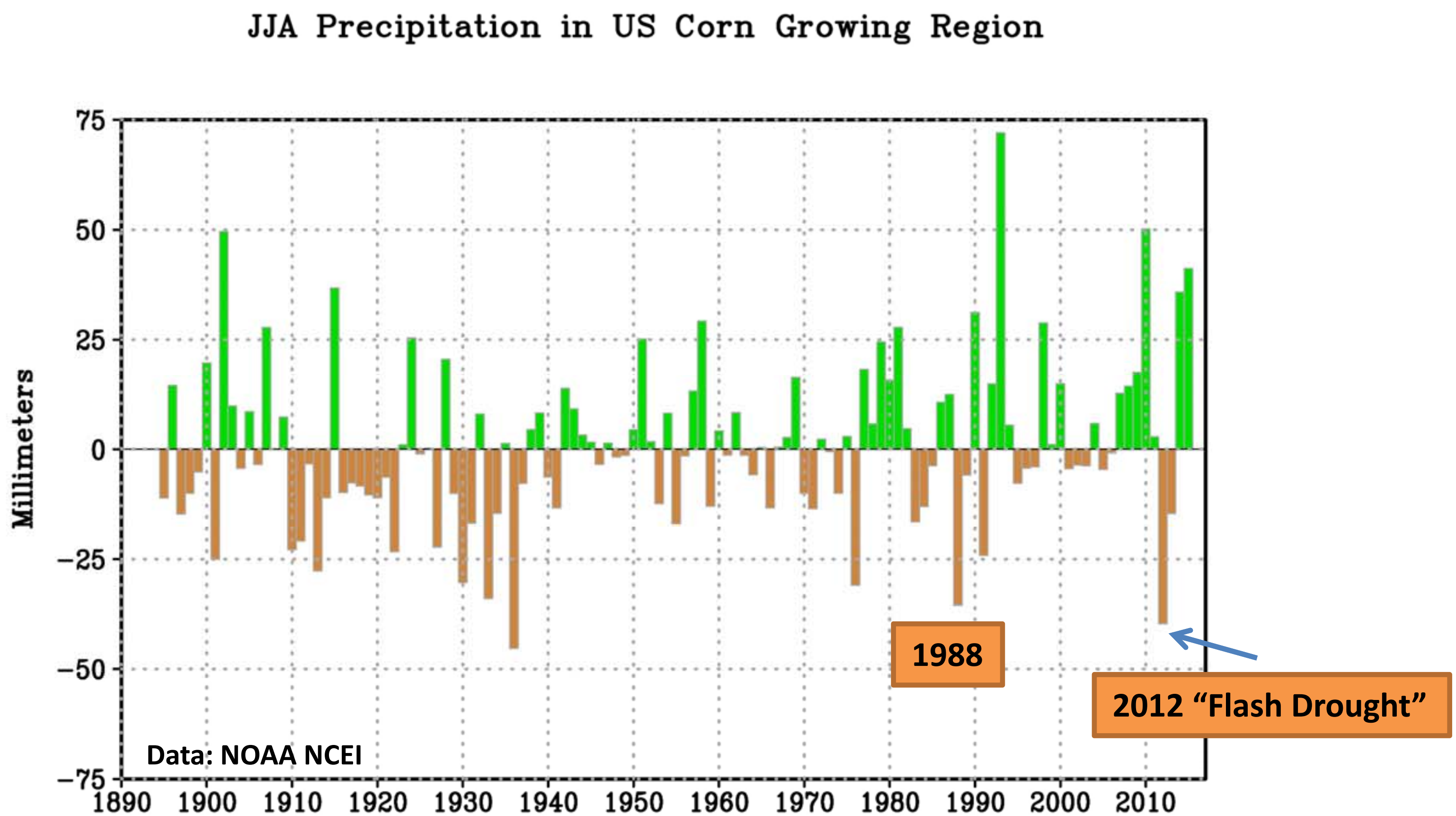
The Physics of Great Plains Drought:
Its Predictability and Its Changed Risk in a Warmer World

Martin Hoerling and Ben Livneh

University of Colorado Boulder

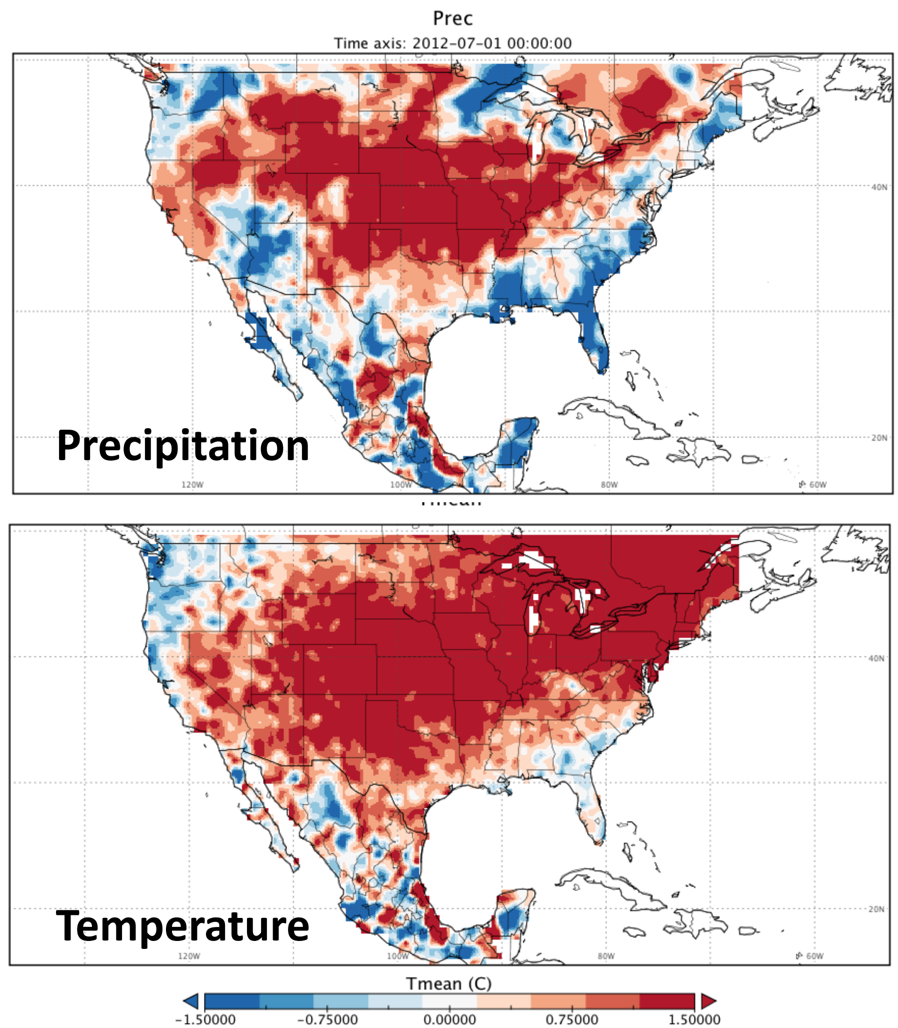
CIRES
Cooperative Institute for Research in Environmental Sciences

Are Droughts and Rainfall Deficits Synonymous?



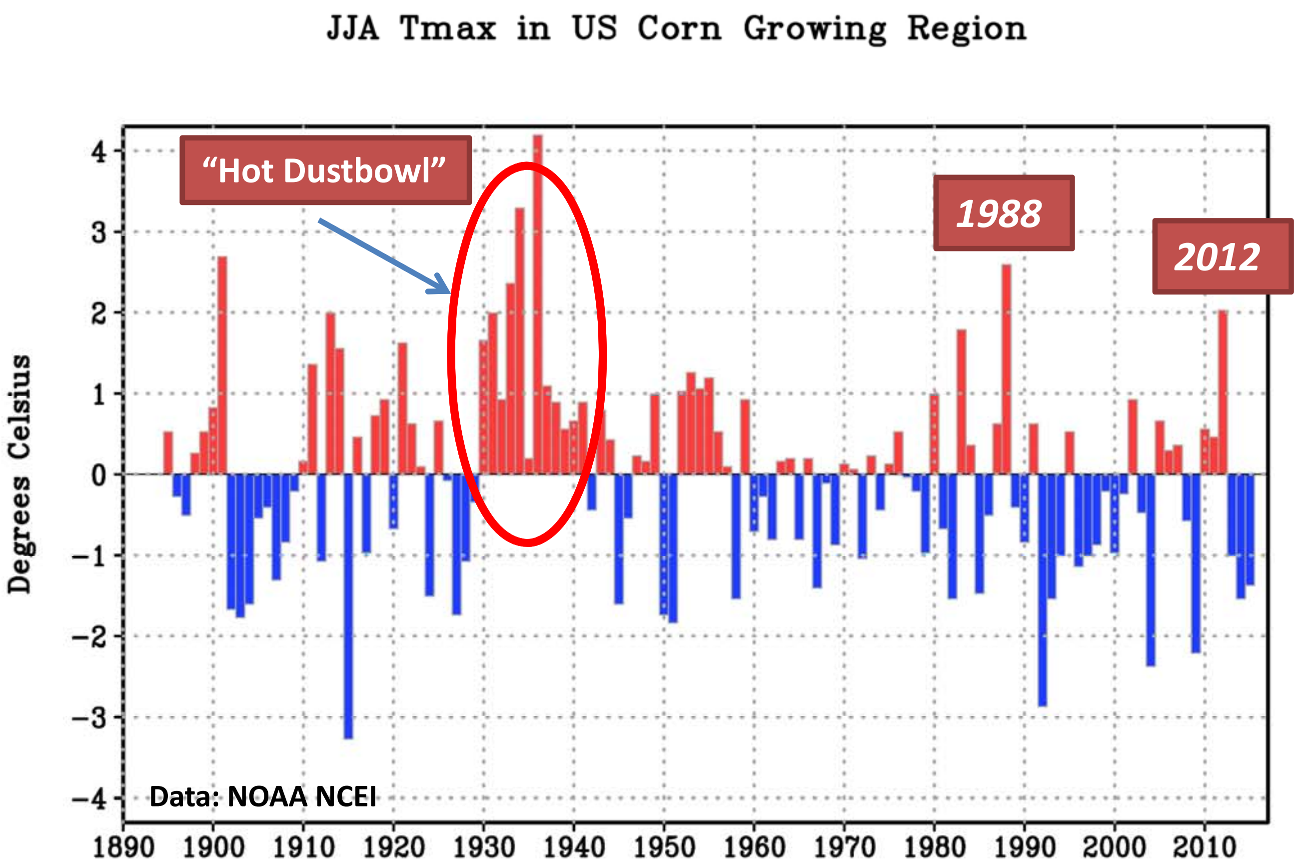
Is The Drought Prediction Problem Merely The Seasonal Rainfall Prediction Problem?

May-August *Standardized Anomaly*, 1981-2010 reference period:

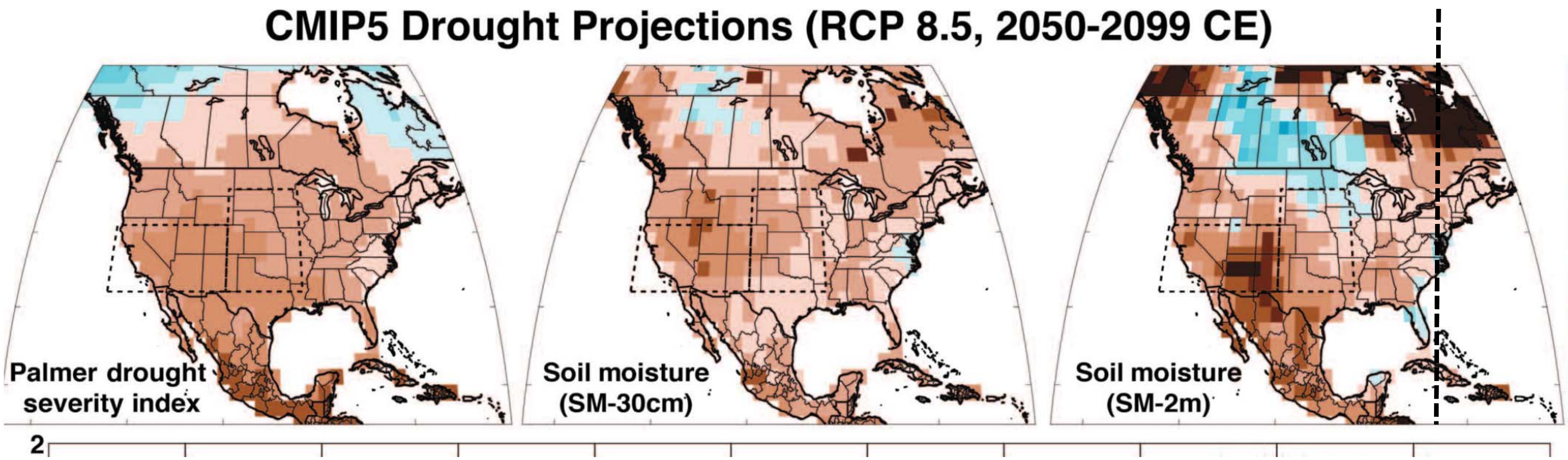


Livneh et al. (2015) Gridded Station Data[1]

How Are Droughts Linked to High Temperatures?



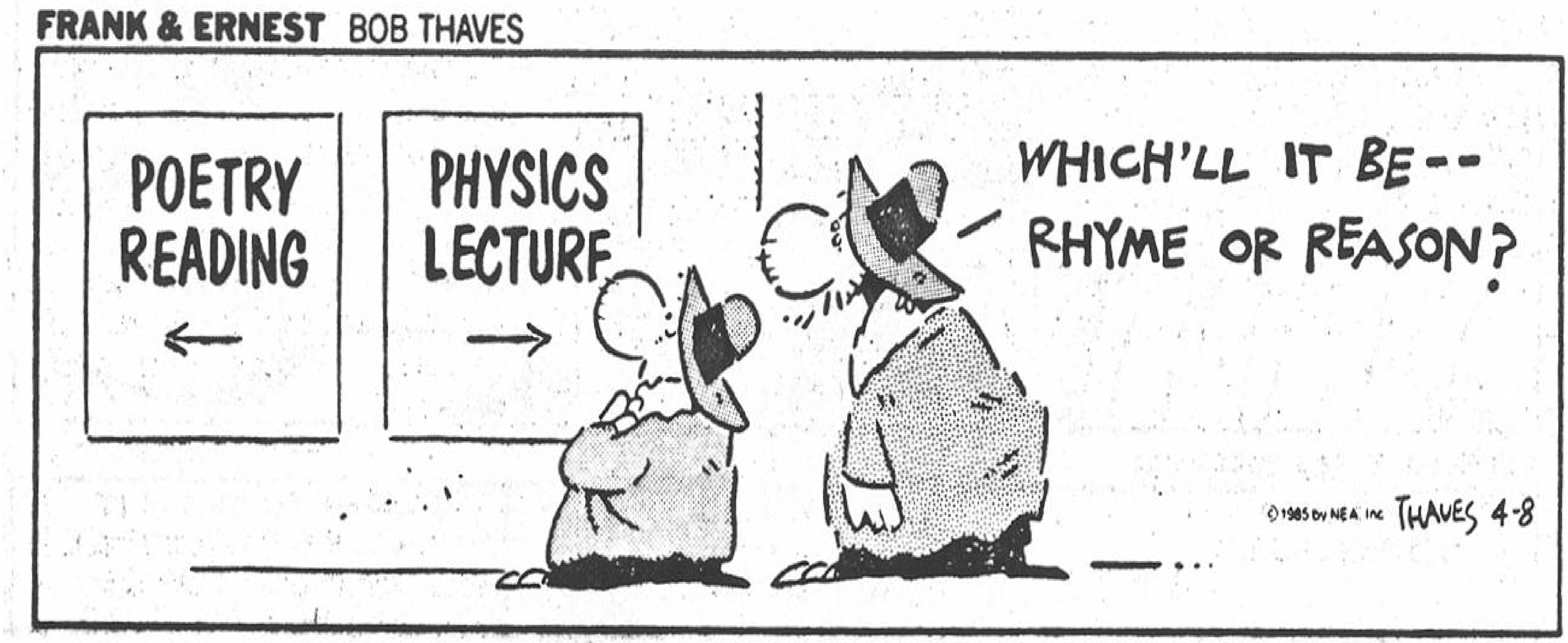
How Will Droughts Change As Climate Warms?



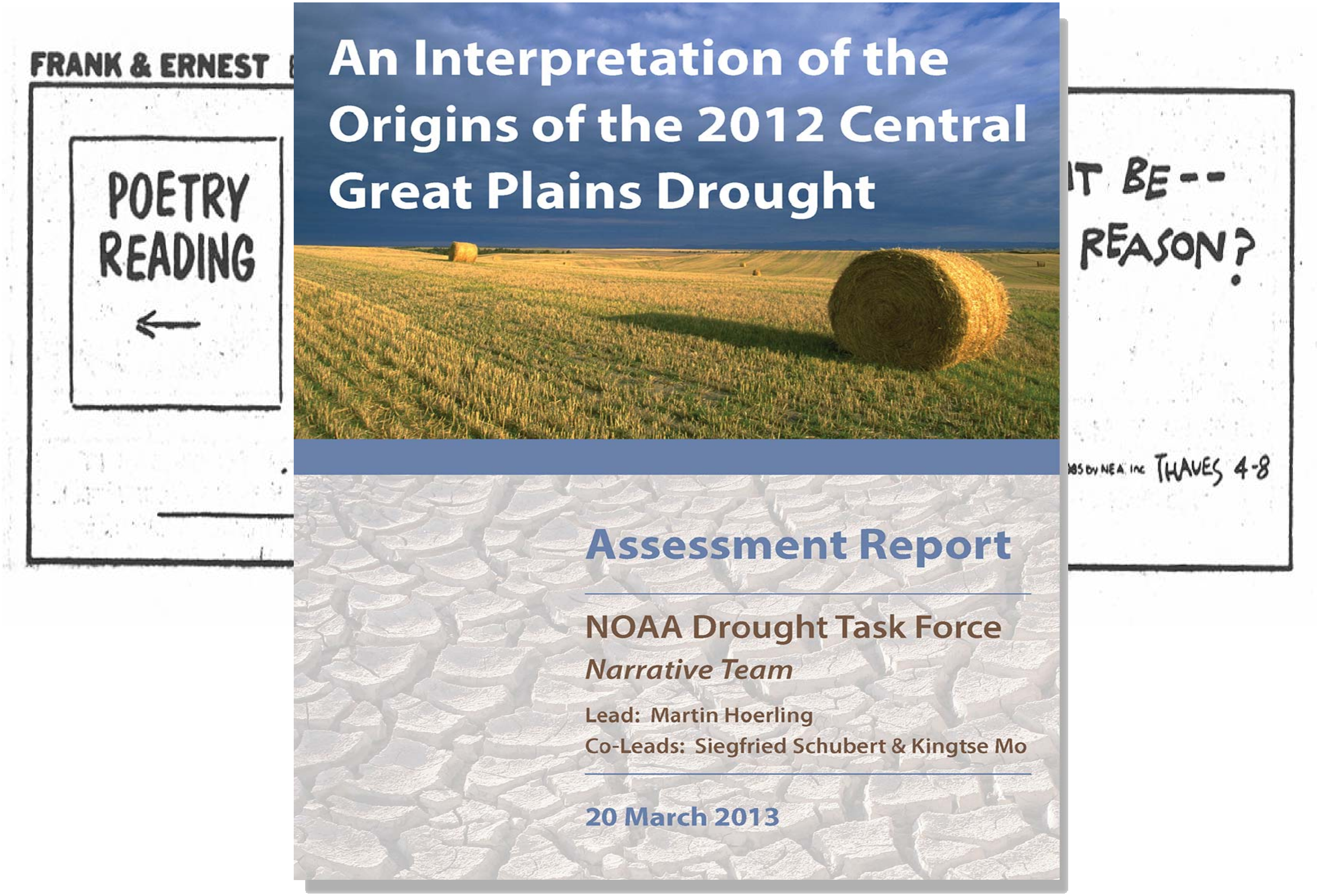
Merged Time Series of Paleo-Reconstructed Drought and Climate Model Projections

Cook et al. 2015: "Unprecedented 21st Century Drought Risks in the American Southwest and Central Plains

On the Fundamental Physics of Great Plains Drought

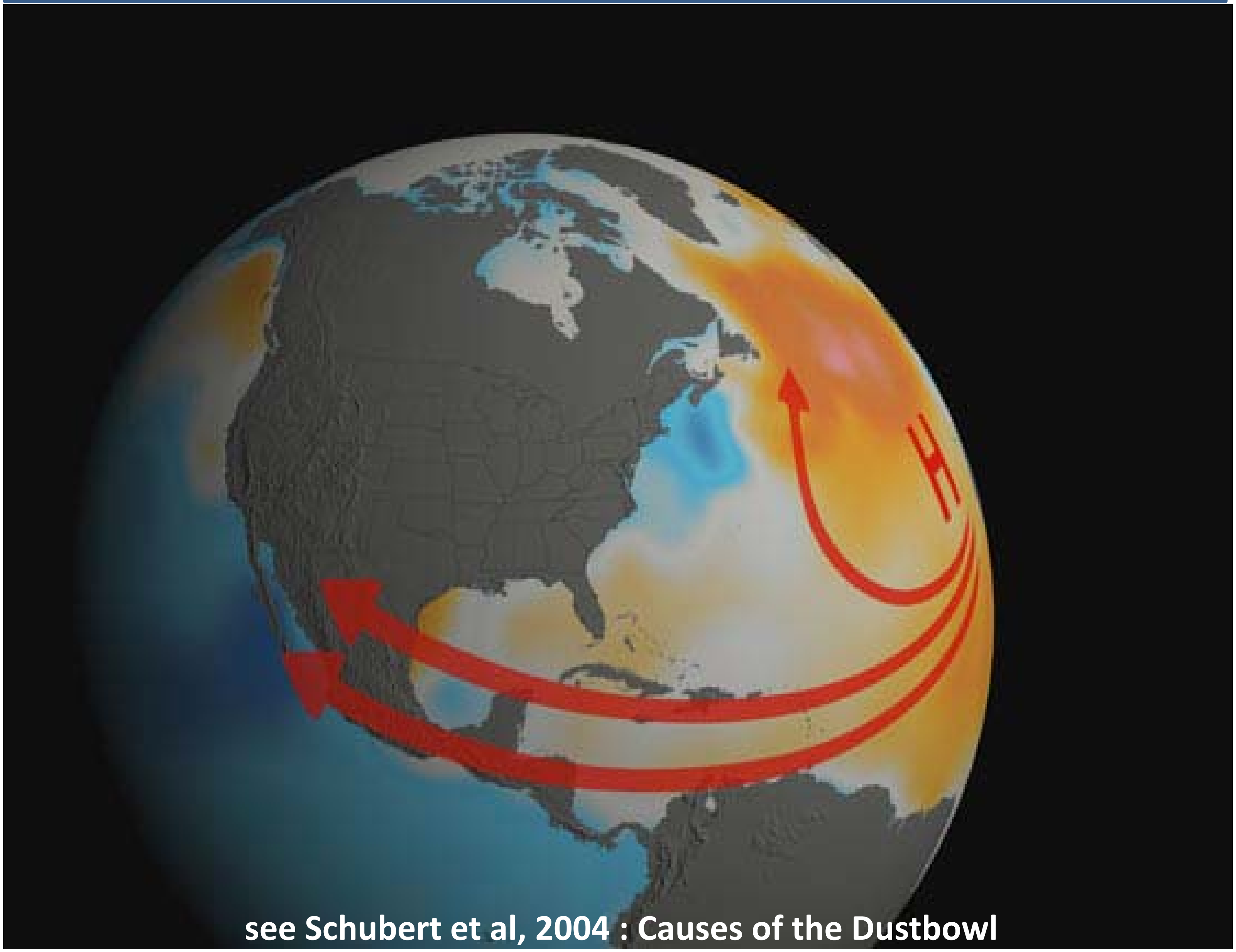


On the Fundamental Physics of Great Plains Drought



The Gulf Source of Moisture….Bermuda High

2012 (as in 1930s): Gulf Moisture Untapped



Executive Summary: Meteorological Causes for The 2012 Drought

The 2012 Central Plains Drought developed suddenly, with near normal antecedent precipitation during winter and spring giving little forewarning of subsequent failed rains. The event did not appear to be just a progression or a continuation of the prior year's record drought over the southern Plains, but appeared to be a discrete extreme event that developed in situ over the central US.

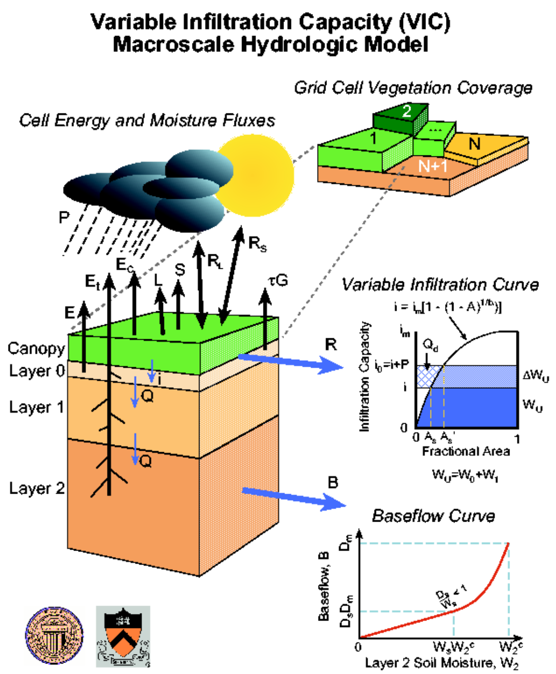
Executive Summary: Meteorological Causes for The 2012 Drought

The proximate cause for the drought was principally a reduction in atmospheric moisture transport from the Gulf of Mexico. Climate simulations and empirical analysis suggest that neither the effects of ocean surface temperatures nor changes in greenhouse gas concentration's produced a substantial summertime dry signal over the Central Plains during 2012. The interpretation is of an event resulting largely from internal atmospheric variability having limited long lead predictability.

Physics of Land Surface Response

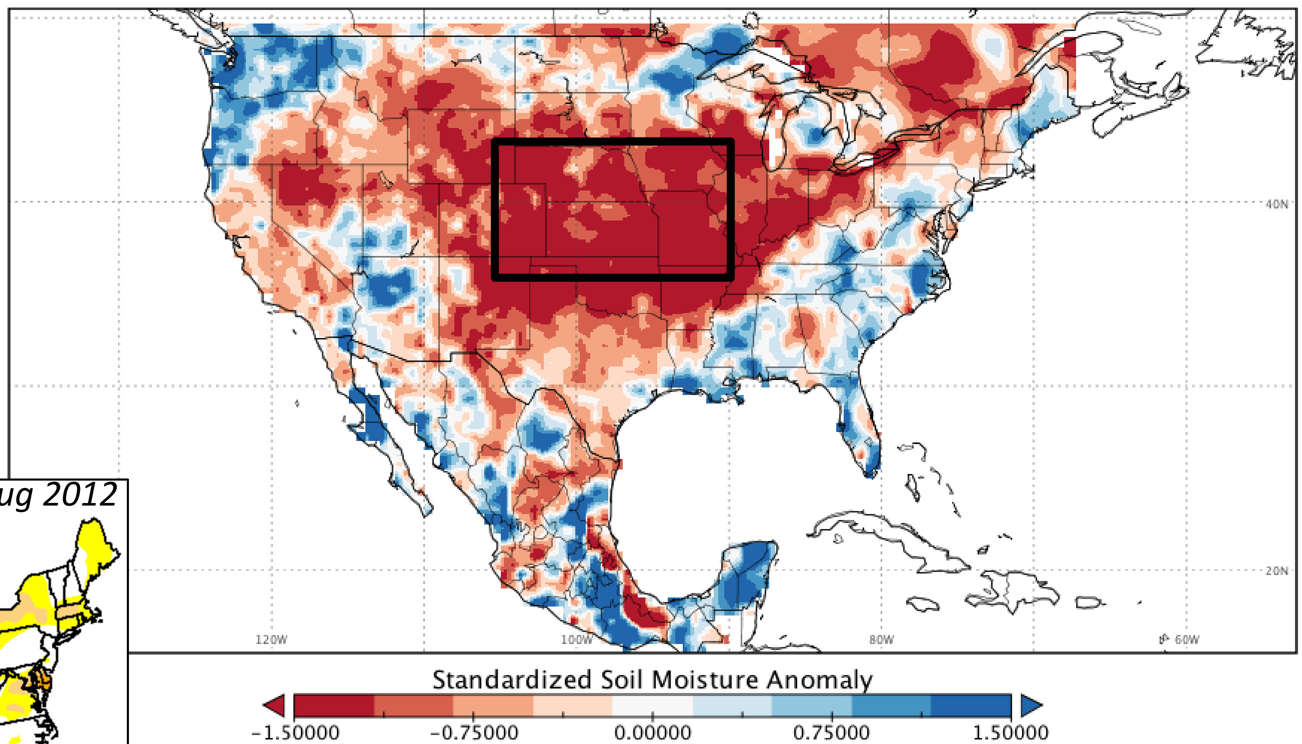
- *Land-surface oriented understanding of proximal causes of drought.*
- *Land surface model experiments—2012 Great Plains Drought*
- *Predictability of Drought ---- from a Land Surface Perspective*
- *Exploring Drought Severity in a Warmer World*

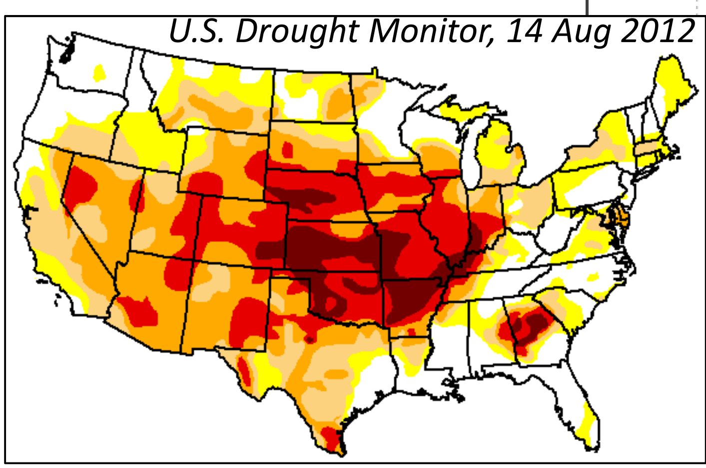
Soil Moisture Deficits in 2012



- **VIC soil moisture deficits** (top 1m of soil)
- **<u>August</u>** Standardized Anomaly, 1981-2010 reference period:

VIC Simulated Soil Moisture: August 2012

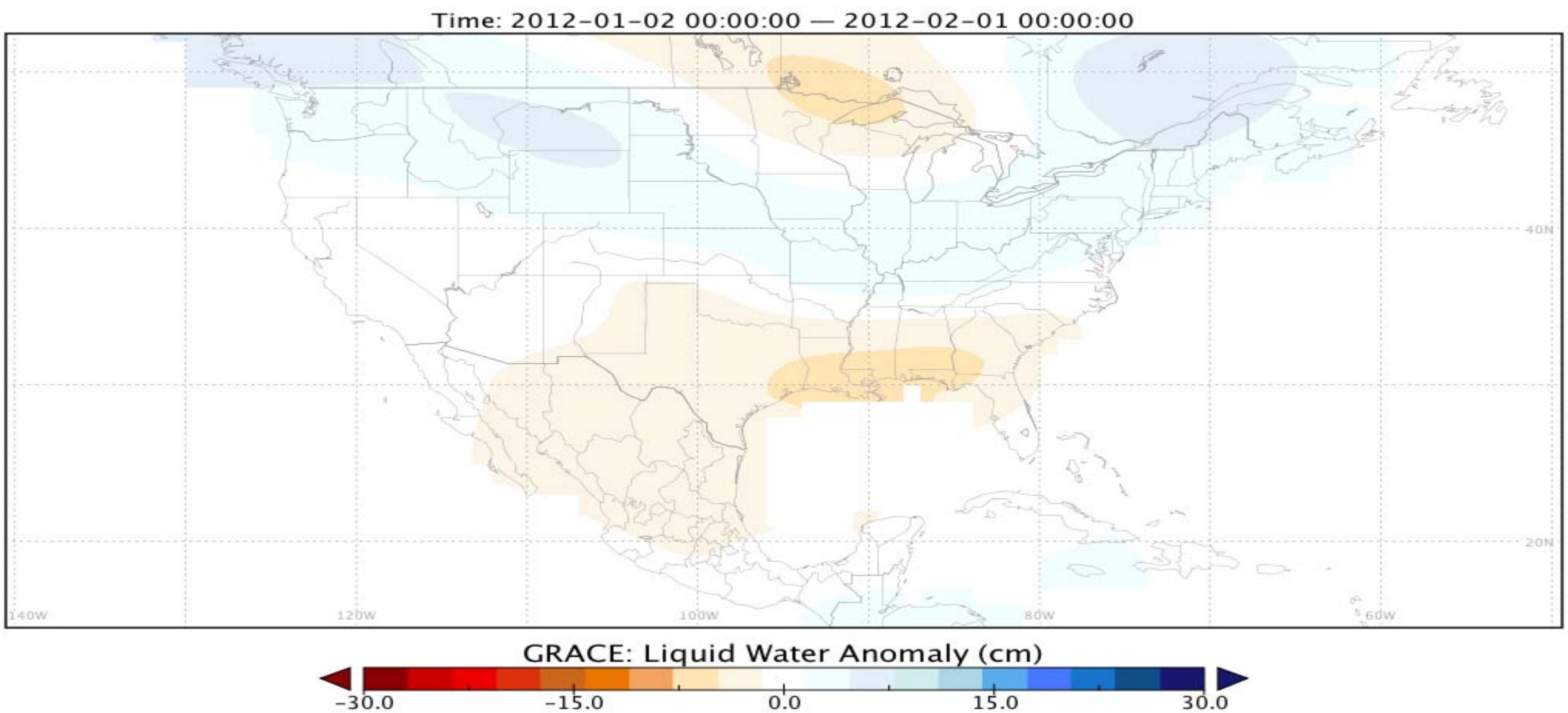




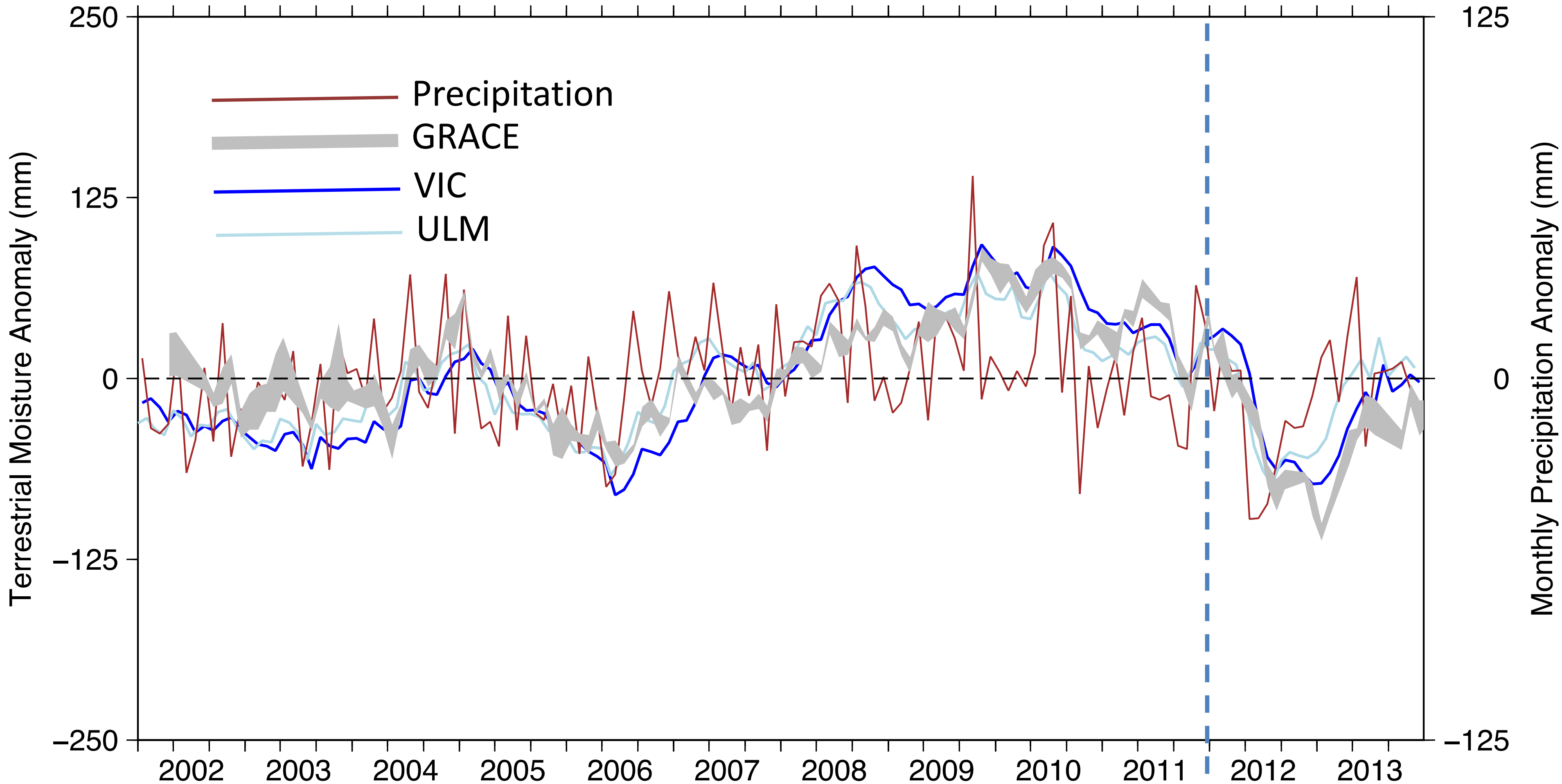
http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx

Validation Data

- Gravity Recovery and Climate Experiment (GRACE) twin satellites
- Short record (since 2002), means long-term changes inferred by models.
- Parallel Simulations Using the Unified Land Surface Model

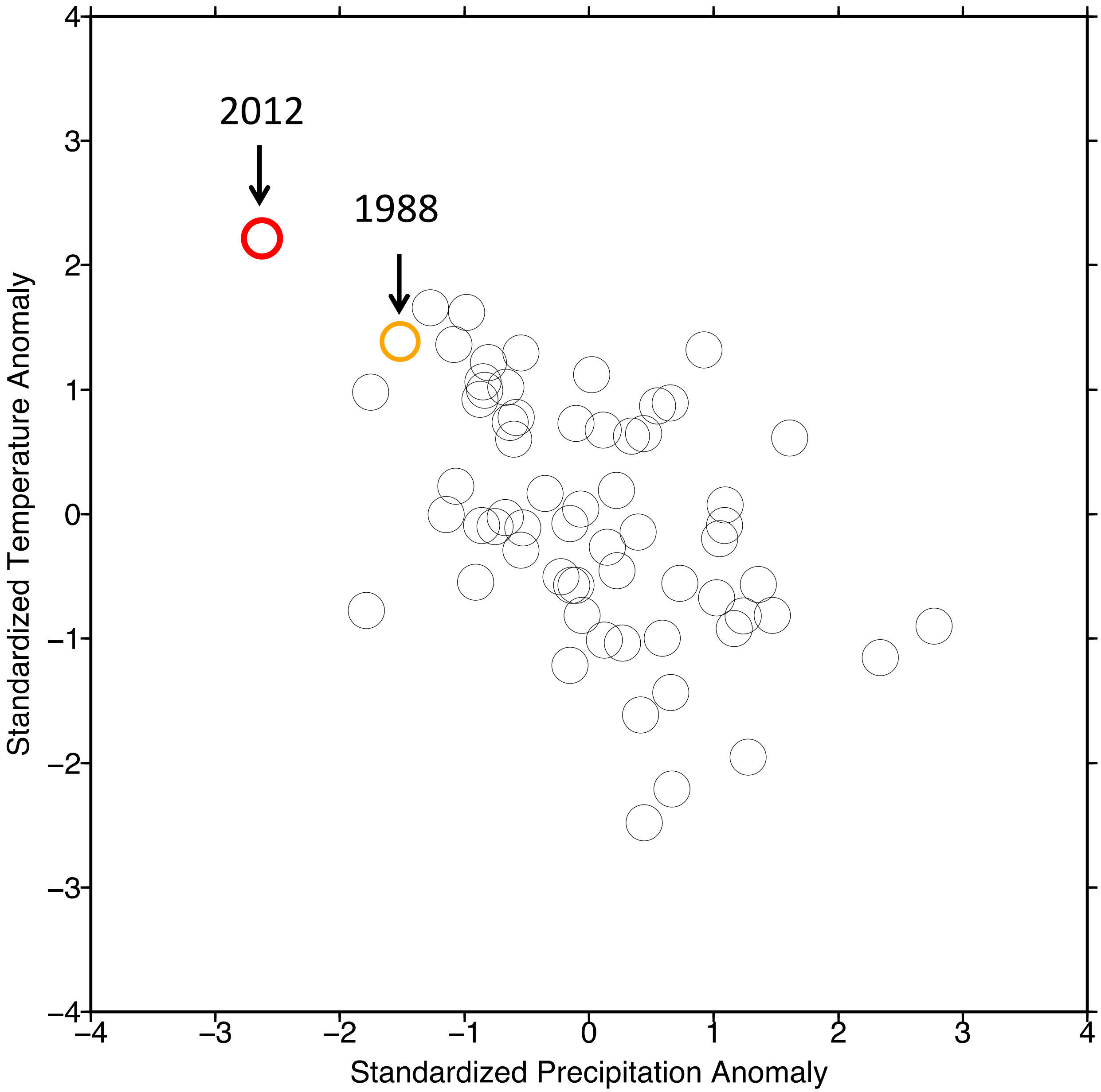


Central Great Plains Moisture Anomalies



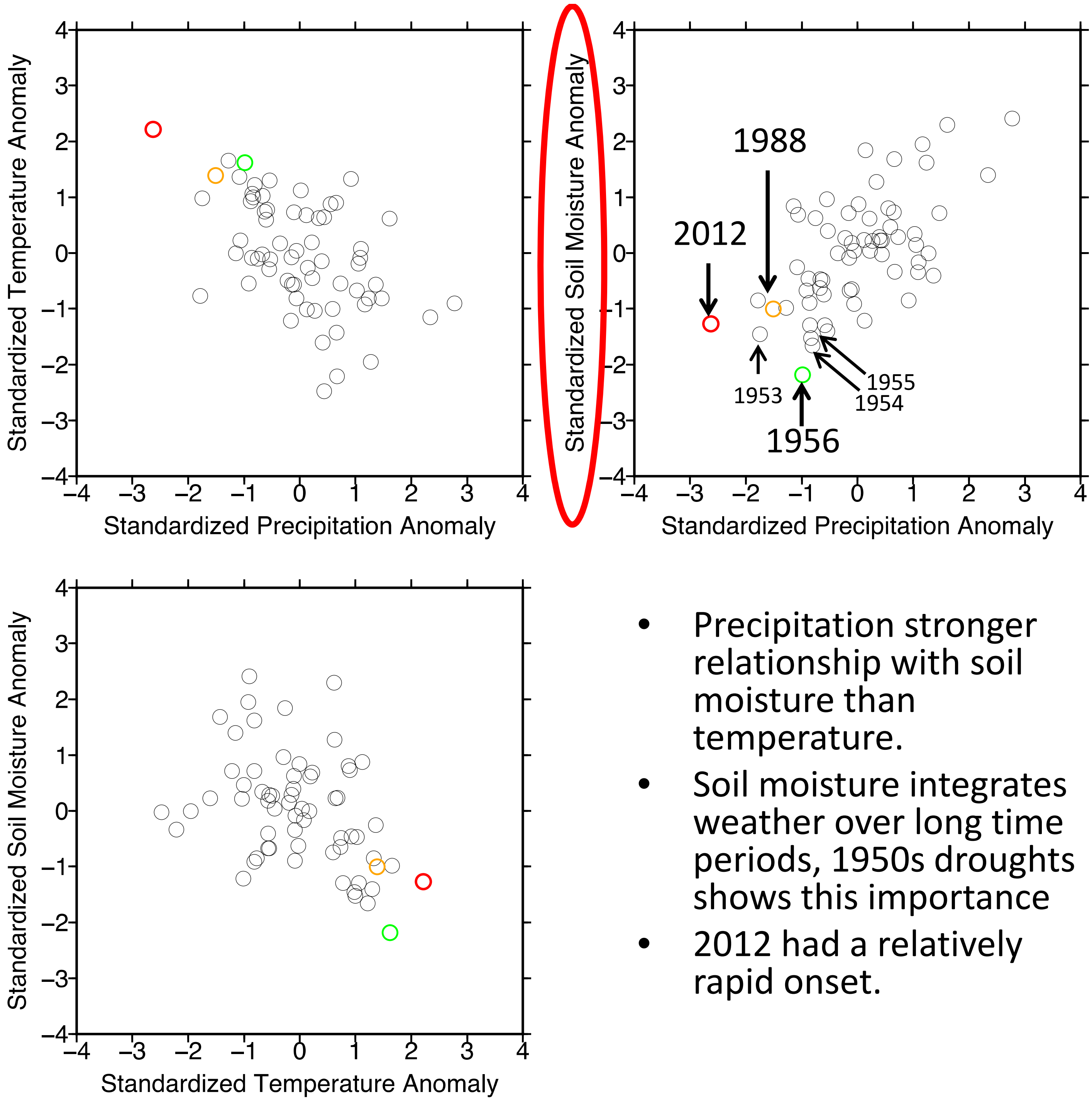
Monthly anomalies (2002-2013) for observed precipitation (right ordinate axis), GRACE, ULM, and VIC terrestrial water (left ordinate axis) averaged over the Great Plains domain.

Historical Context of Meteorological Anomalies



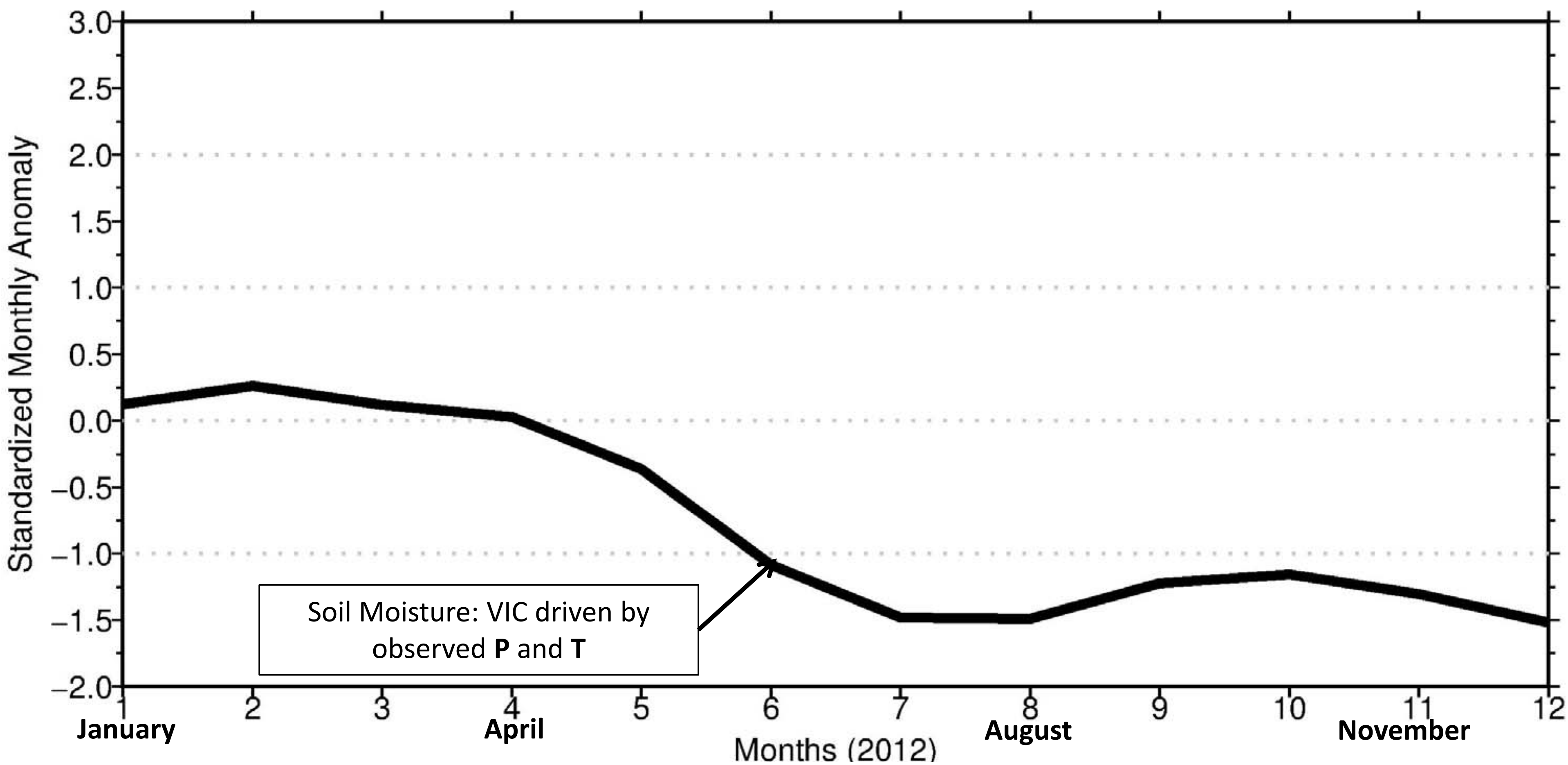
*Central Great Plains domain.

- May-August conditions (1950-2013) standardized by the same reference period (1981-2010)
- P vs T relationship is of importance for drought

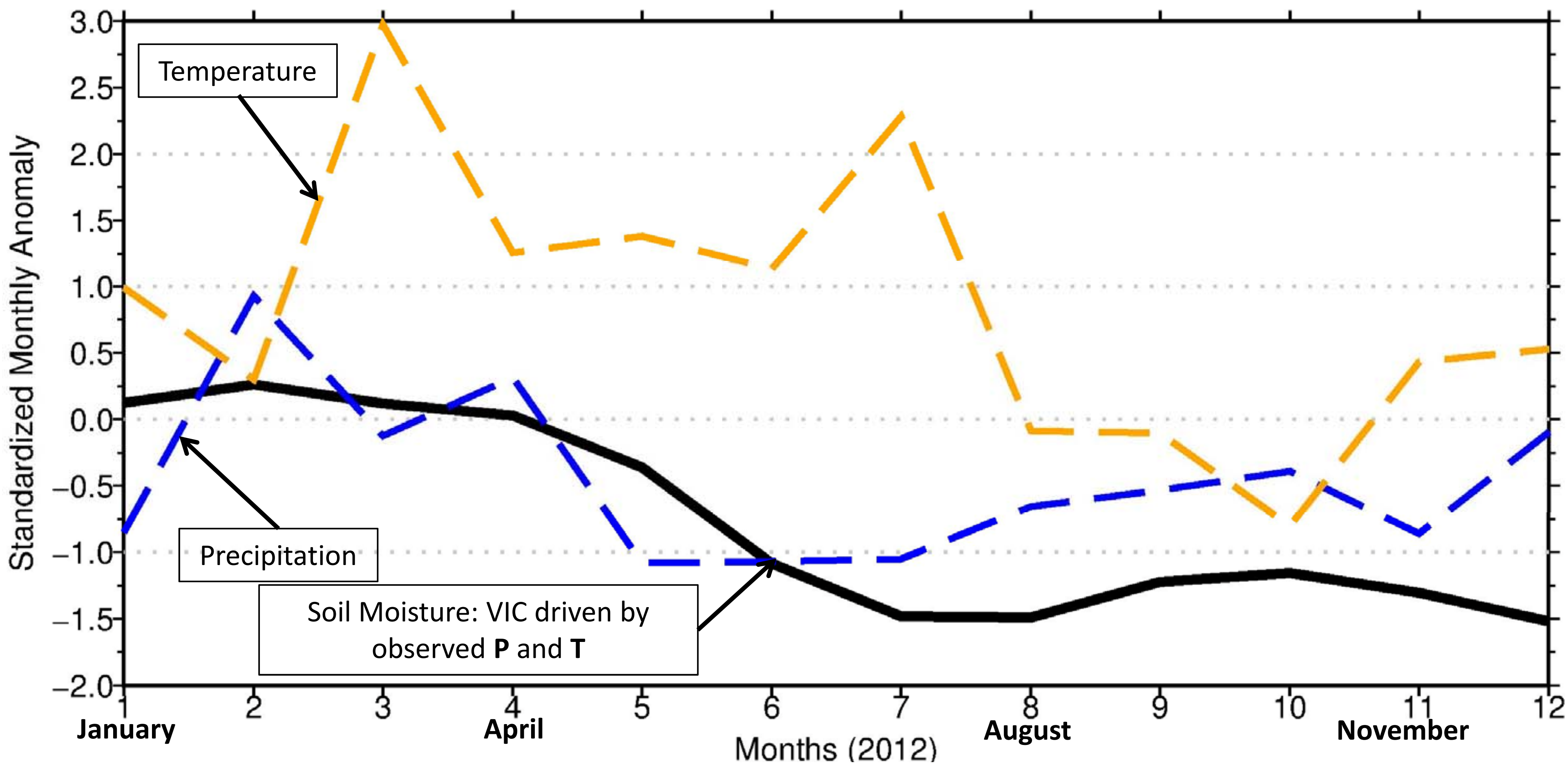


- Precipitation stronger relationship with soil moisture than temperature.
- Soil moisture integrates weather over long time periods, 1950s droughts shows this importance
- 2012 had a relatively rapid onset.

Time Evolution of Soil Drying and Meteorology

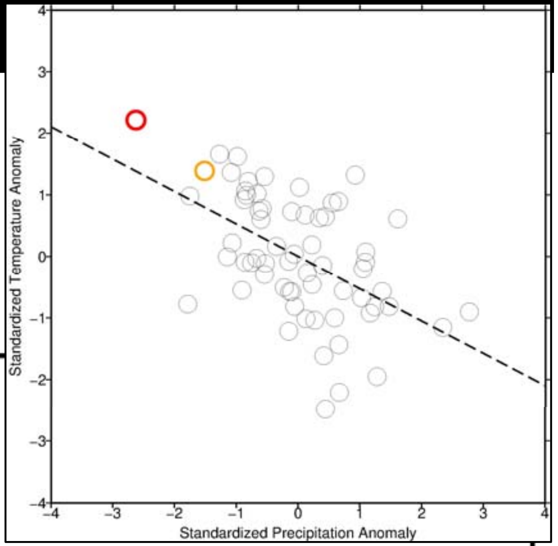


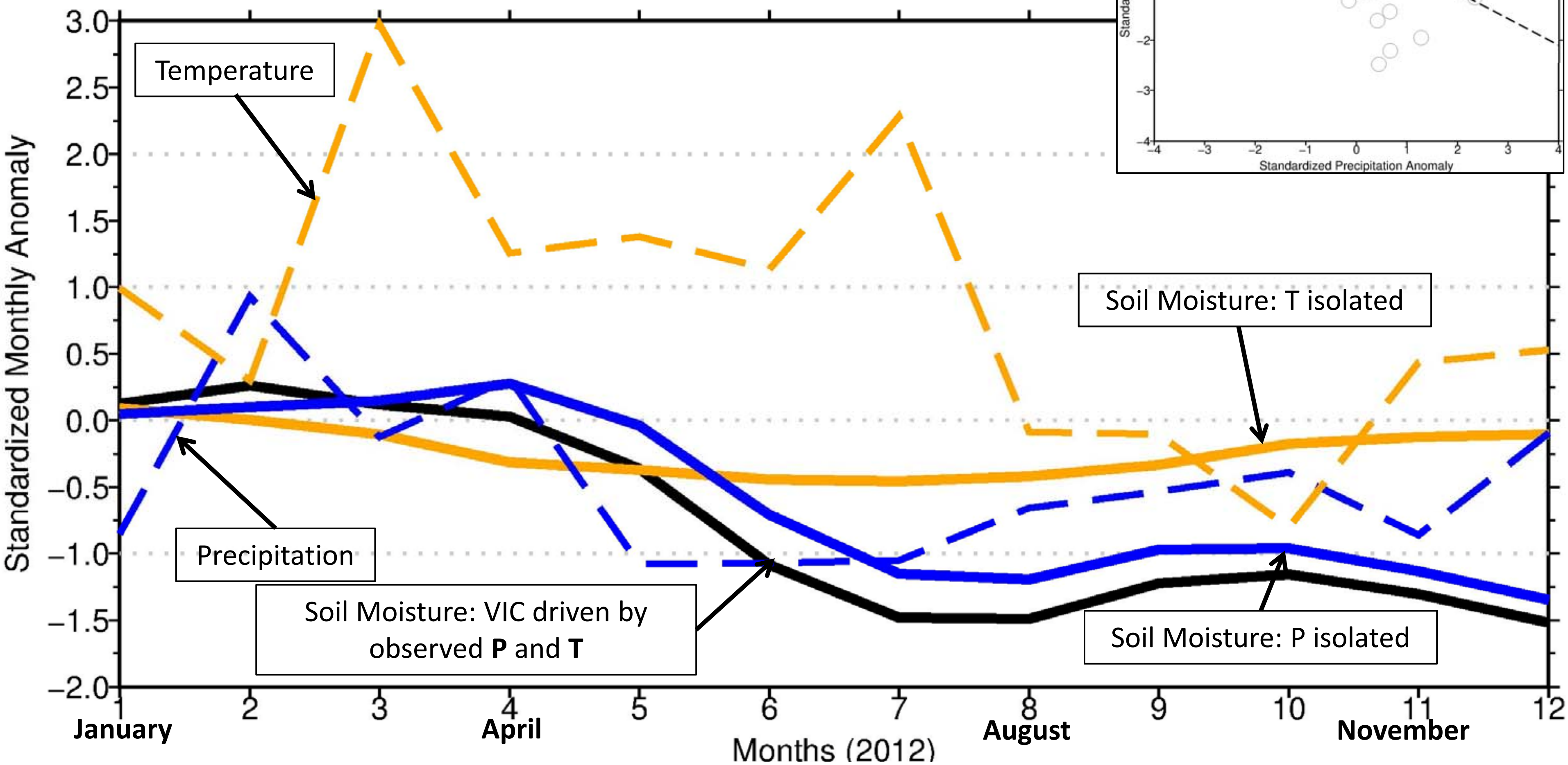
Time Evolution of Soil Drying and Meteorology



Time Evolution of Soil Drying and Meteorology

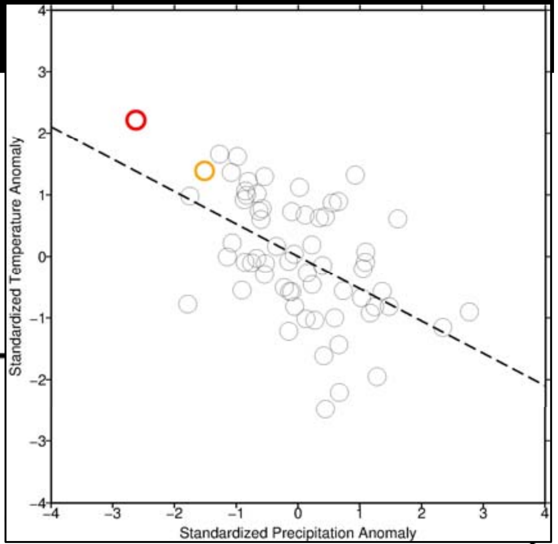
- Recall, T and P come together, so the P-isolated sensitivity might be understated
- Apply the regression to *adjust* monthly temperatures during the precipitation deficit case [based on monthly regressions at each point]

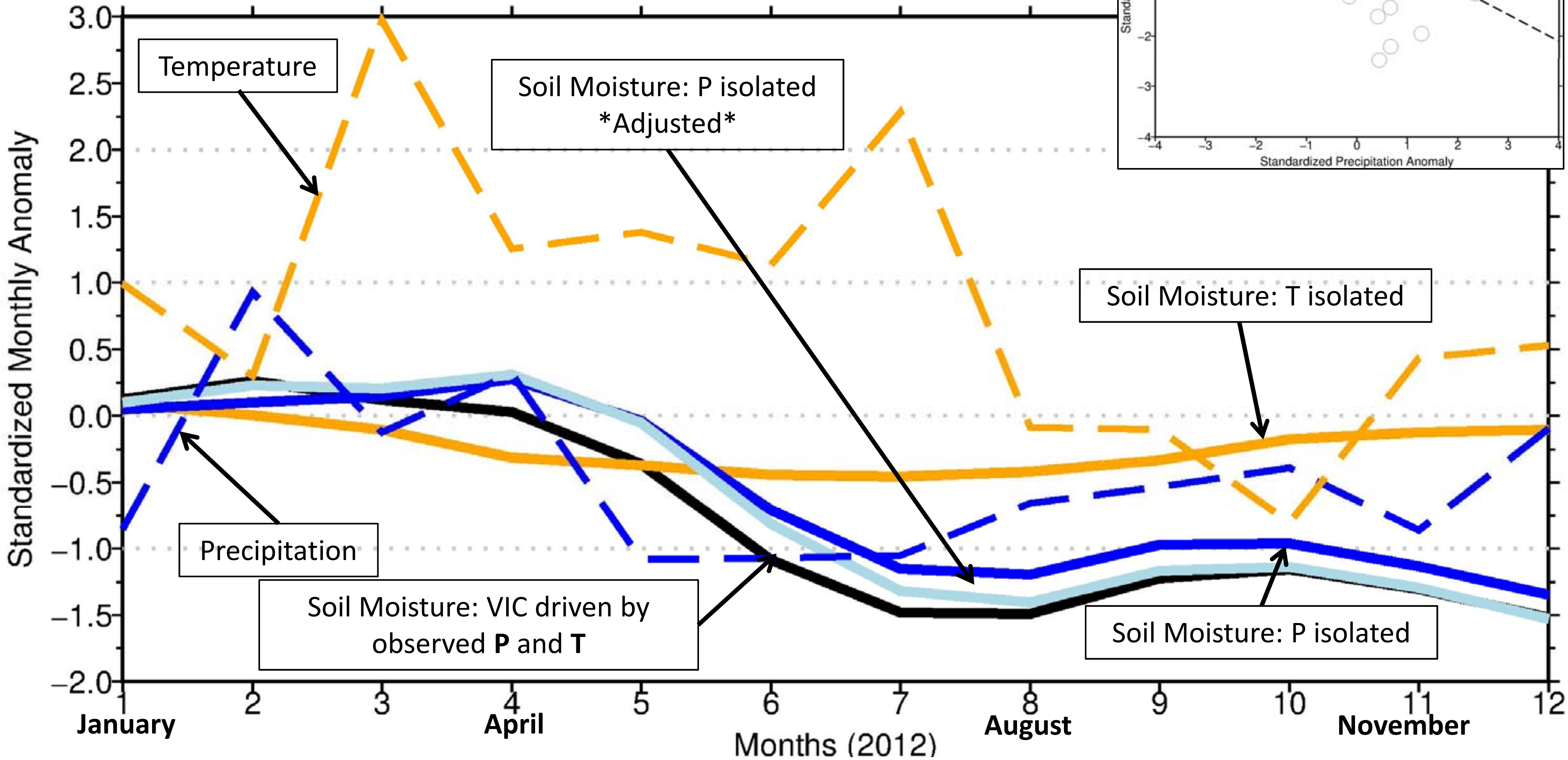




Time Evolution of Soil Drying and Meteorology

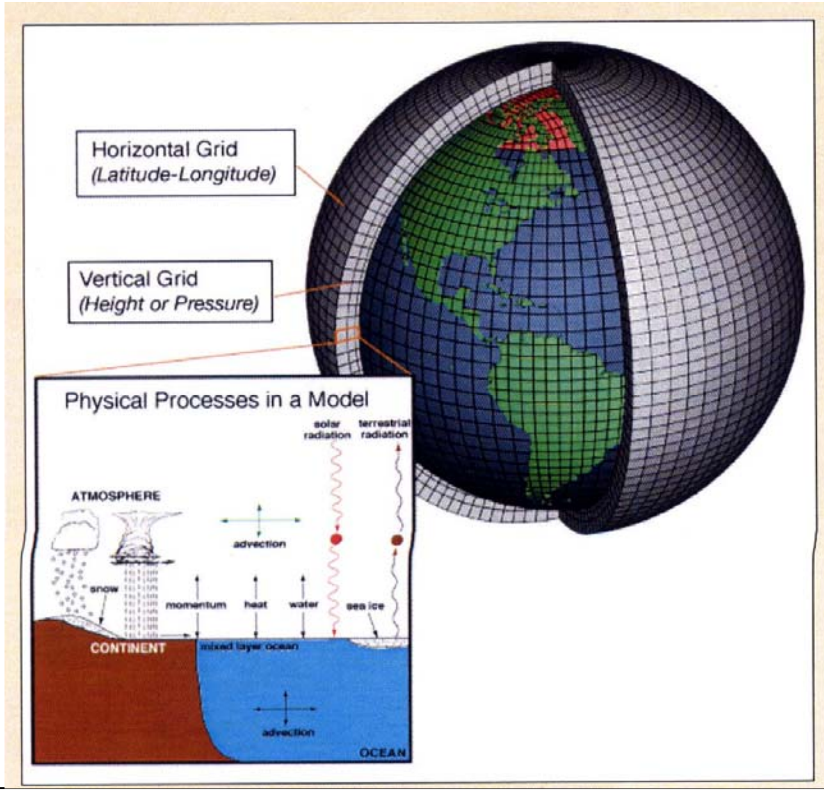
- Recall, T and P come together, so the P-isolated sensitivity might be understated
- Apply the regression to *adjust* monthly temperatures during the precipitation deficit case [based on monthly regressions at each point]





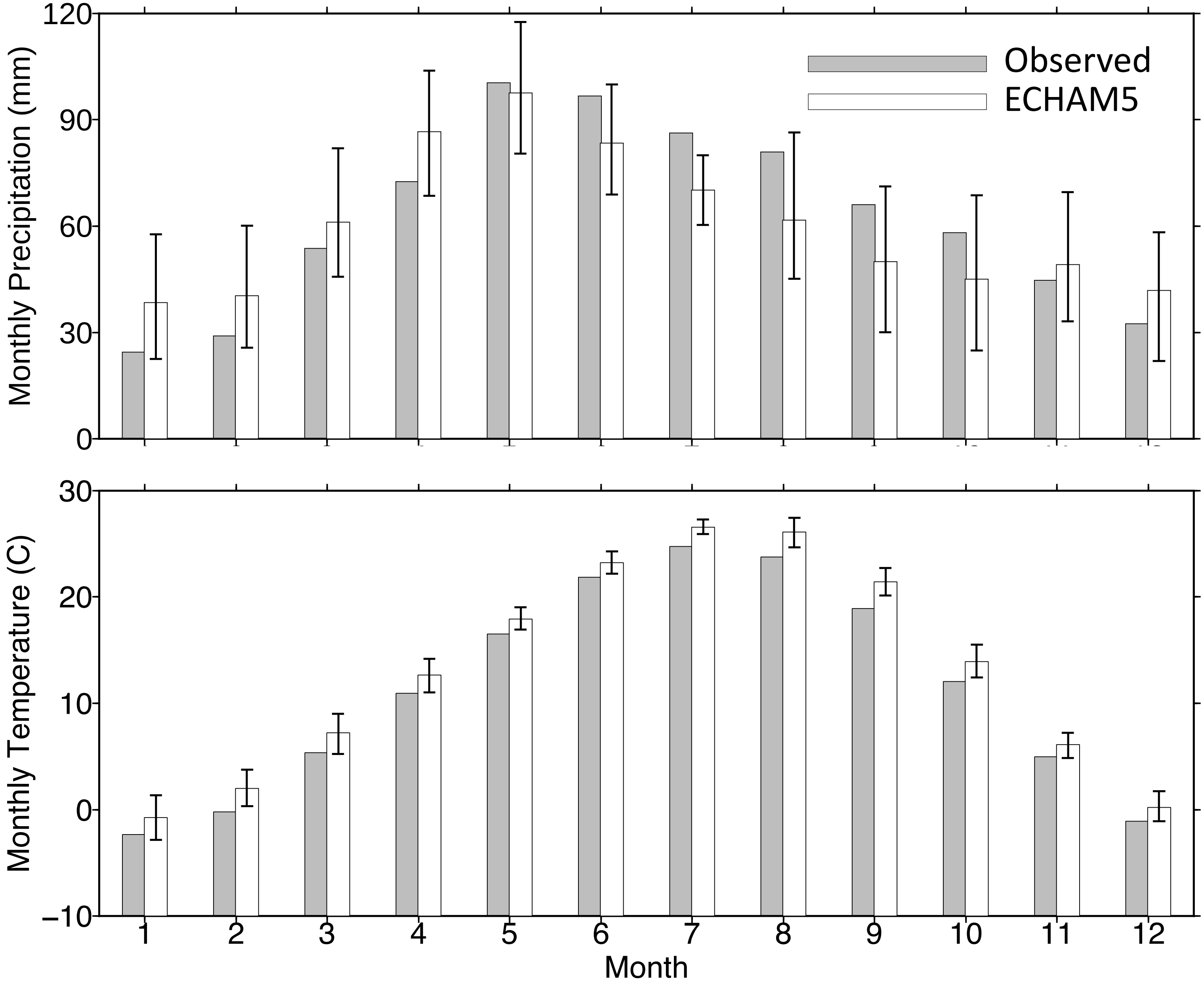
GCM Ensemble to Explore General Drought Characteristics and Predictability

Overcomes the limited observed sample size (e.g. 64 years)



° 1050 years of '*current climate*' simulations. 30 ECHAM-5 ensemble members, 1979-2013.
° AMIP-style driven with observed Greenhouse Gases (GHG) and Sea Surface Temperatures
° Global 85 km spatial resolution
° Interactive Land Surface

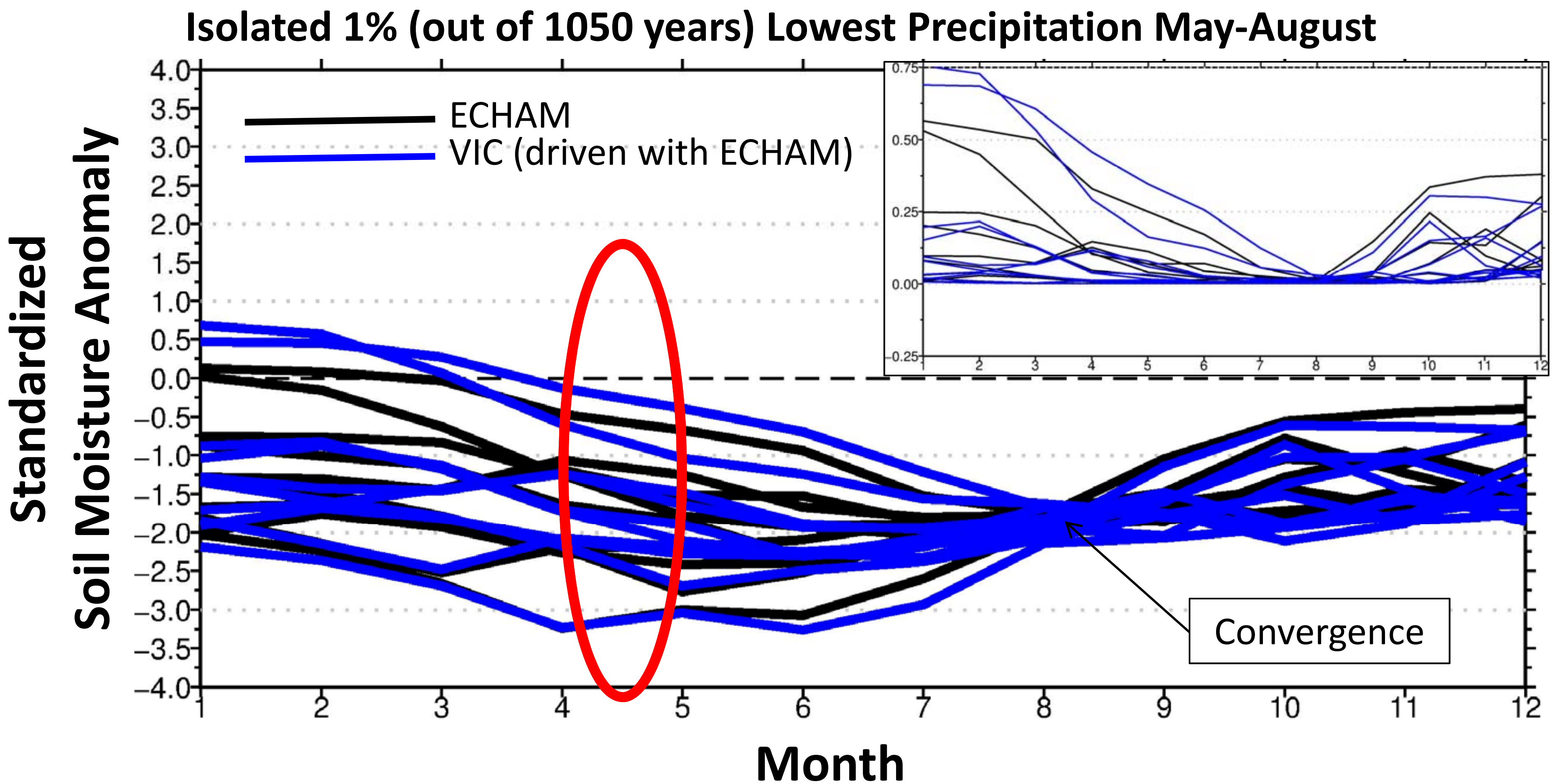
(*see Seager and Hoerling 201, JClimate*)



Mean monthly meteorology (1979-2013) over the Great Plains domain for observations [Livneh et al., 2015] and a 30-member ensemble mean ECHAM5 values (white bar); error bars denote minimum and maximum member values.

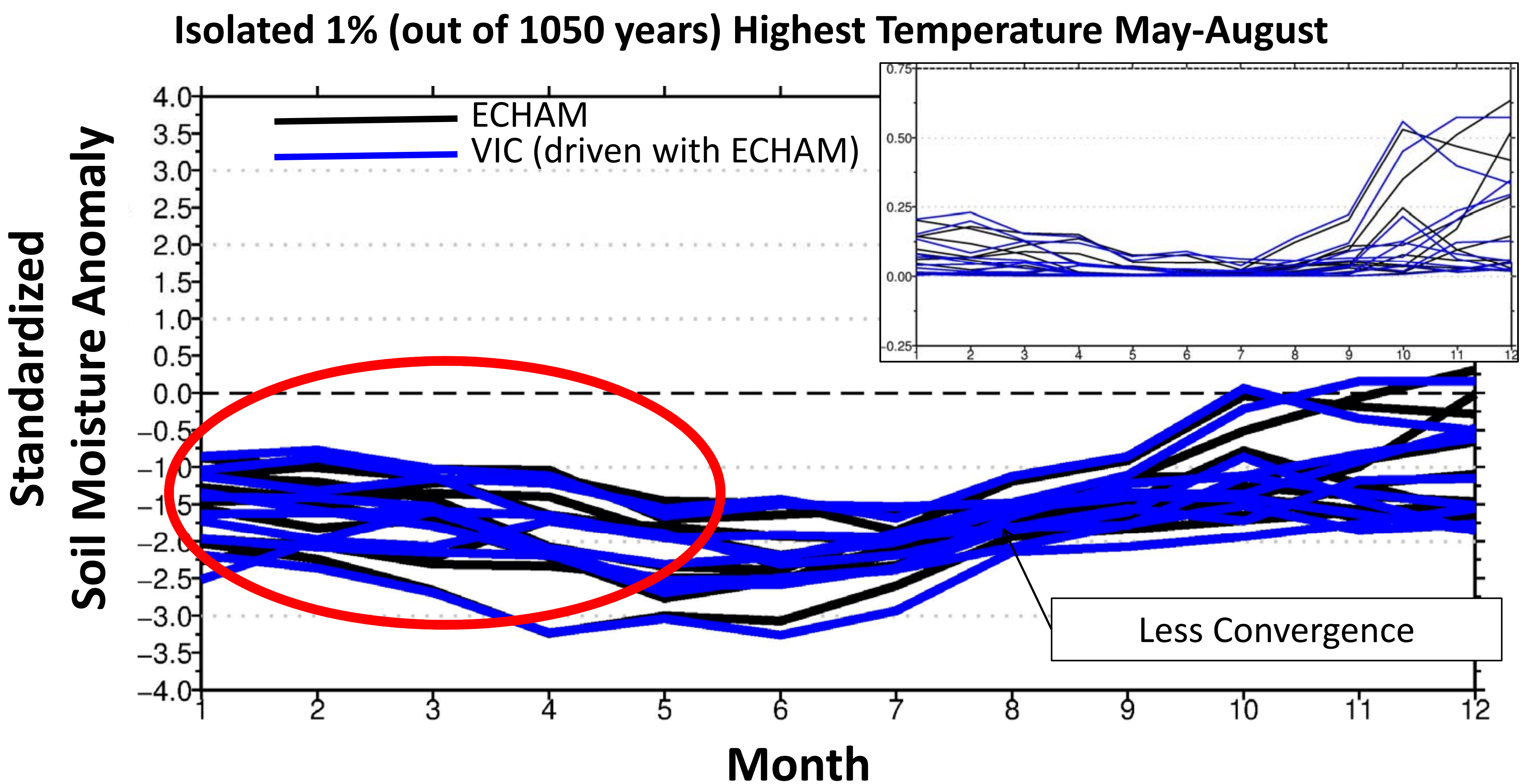
Importance of Initial Conditions

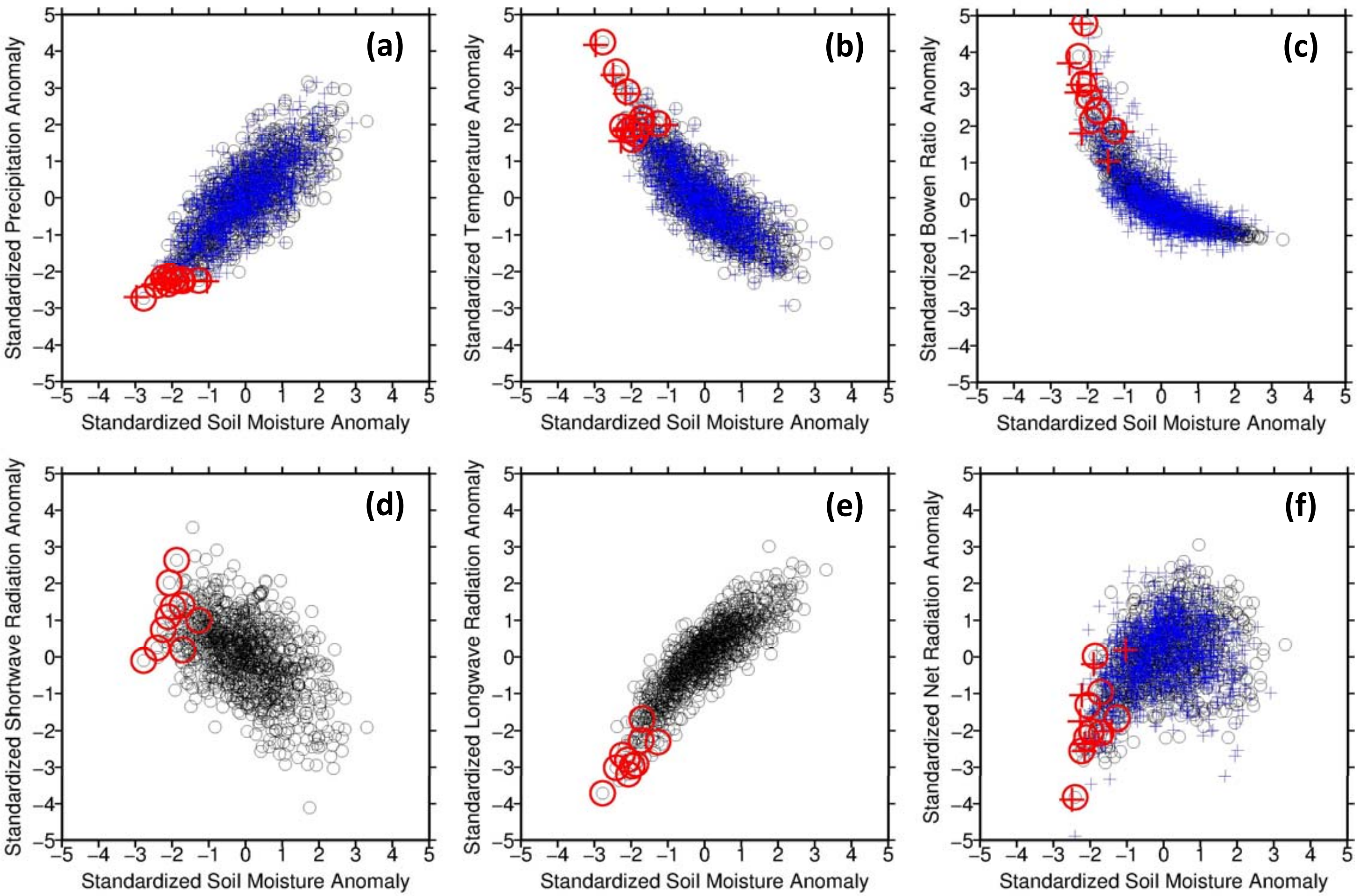
Prominence of Precipitation Control on Soil Moisture



Importance of Initial Conditions

Antecedent Soil Moisture's Strong Effect of Summer Heat





MJJA standardized anomalies P, T, SM, & fluxes: ECHAM5 (circles) and VIC (crosses)

Lowest 1% MJJA precipitation simulations are highlighted in red.

Drought Sensitivity to Scenarios of Climate Change

- *What Severity for 2012 Drought in a Warmer/Drier World?*
- *What Intensity of Aridification in a Warmer/Drier World?*

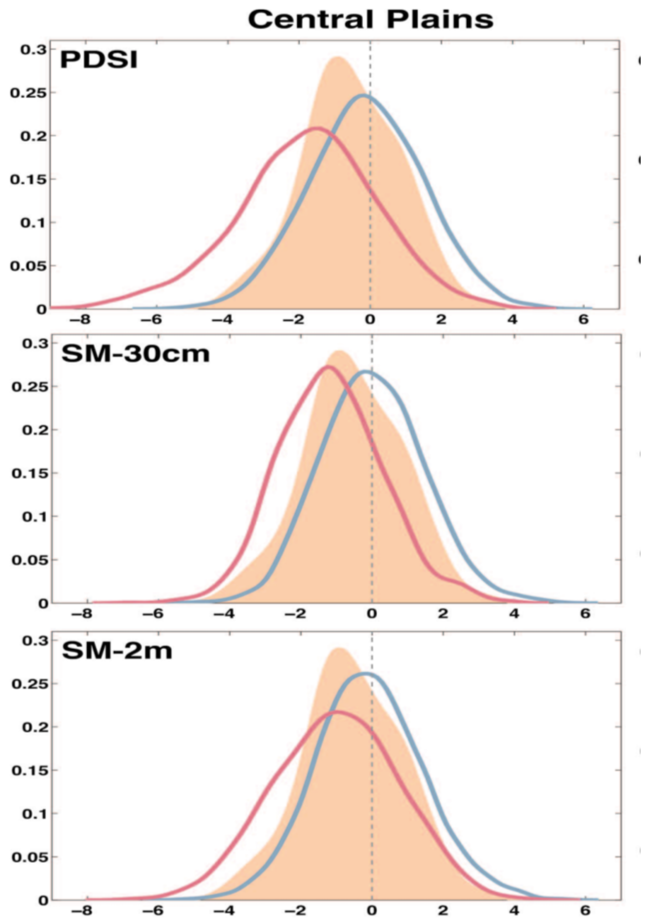


Fig. 4. Kernel density functions of PDSI, SM-30cm, and SM-2m for the Central Plains and Southwest, calculated from the NADA and the GCMs. The NADA distribution (brown shading) is from 1100–1300 CE, the timing of the medieval megadroughts.

From Cook et al. 2015

Drought Sensitivity to Scenarios of Climate Change

- *What Severity for 2012 Drought in a Warmer/Drier World?*
- *What Intensity of Aridification in a Warmer/Drier World?*

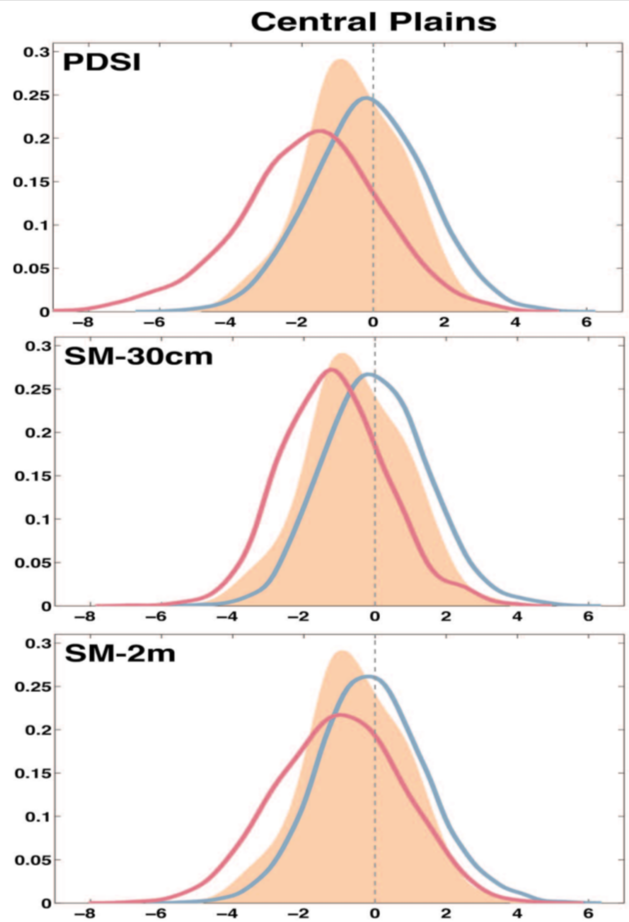
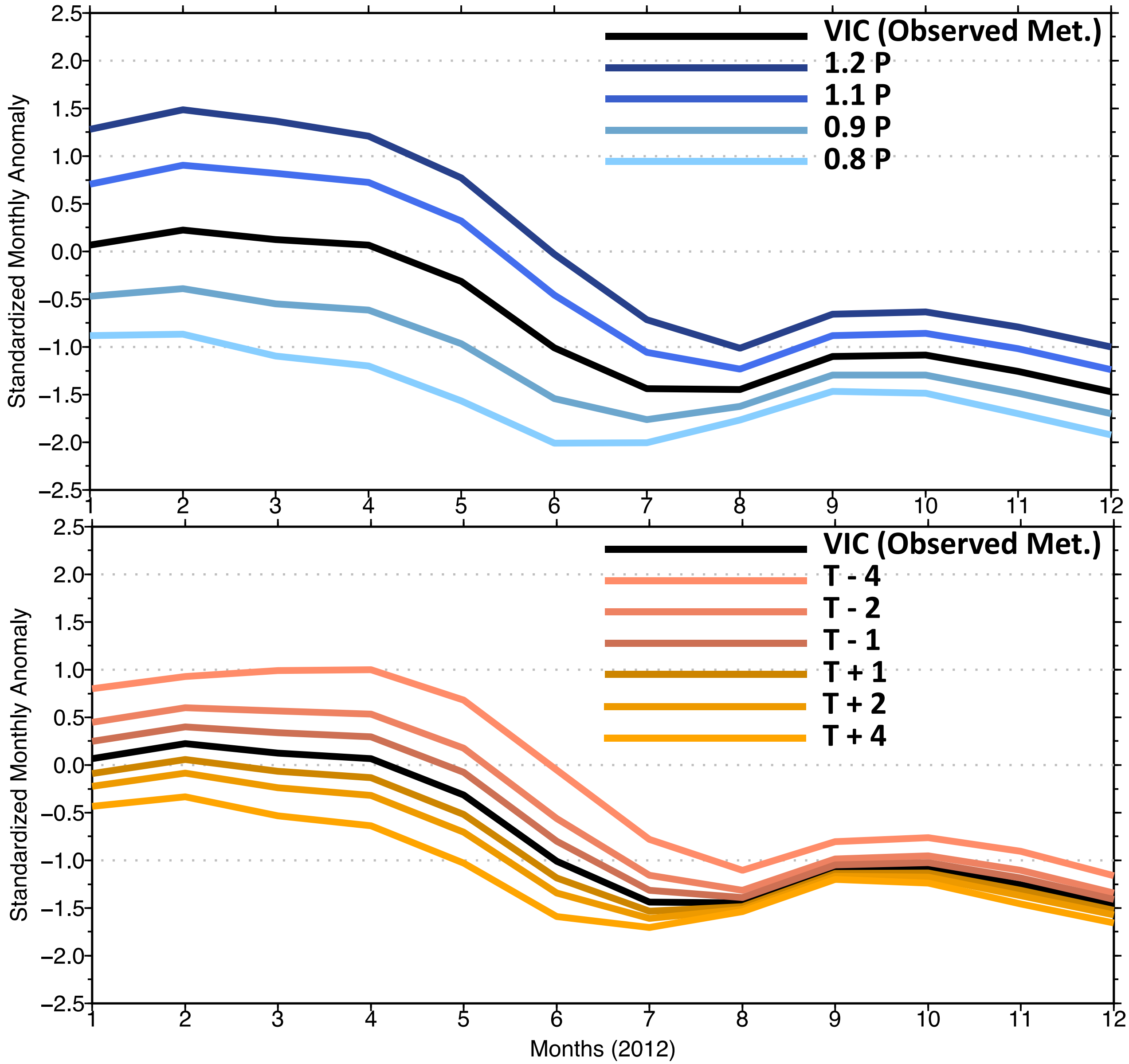


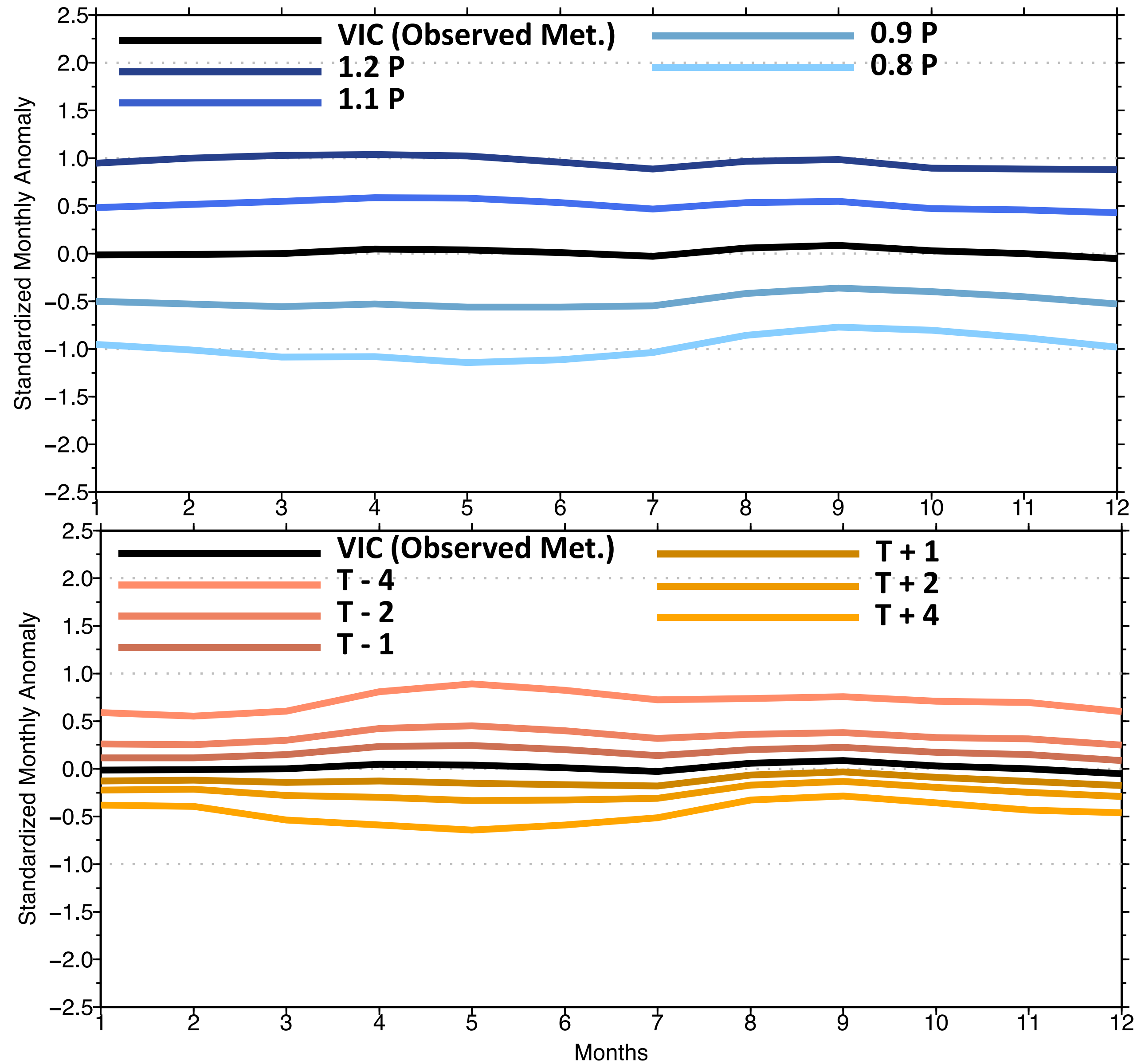
Fig. 4. Kernel density functions of PDSI, SM-30cm, and SM-2m for the Central Plains and Southwest, calculated from the NADA and the GCMs. The NADA distribution (brown shading) is from 1100–1300 CE, the timing of the medieval megadroughts.

"The CP drying is driven primarily by the increased evaporative demand. This increase in PET is one of the dominant drivers of global drought trends in the late 21st Century"

--- Cook et al. 2015

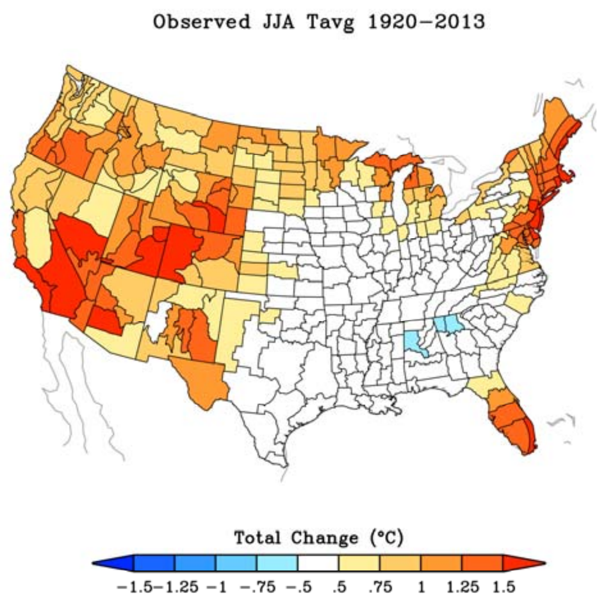


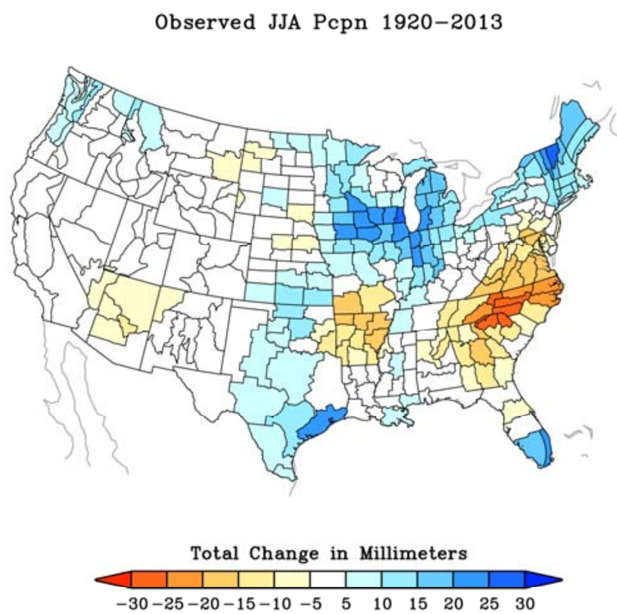
Monthly standardized anomalies for 2012 (relative to 1981-2010) for VIC simulations using observed meteorology in black, with (a) synthetic precipitation scaling shown in blue shading and (b) synthetic temperature deltas shown orange shading applied relative to observations for all months respectively.



Monthly standardized anomalies for the recent decade 2004-2013 (relative to 1981-2010) for VIC simulations using observed meteorology in black, with (a) synthetic precipitation scaling shown in blue shading and (b) synthetic temperature deltas shown orange shading applied relative to observations for all months respectively.

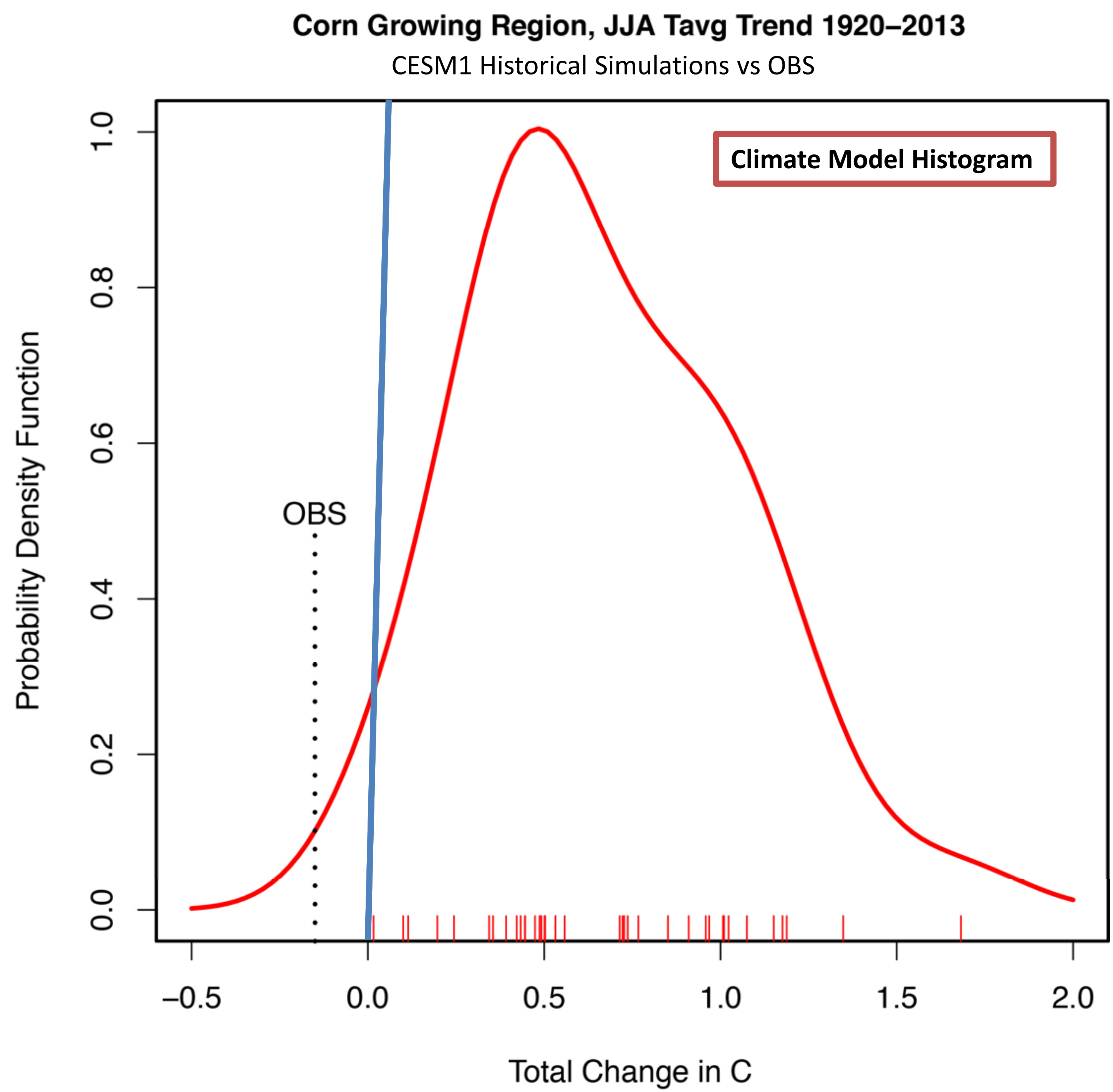
Why Has Great Plains Climate Become ***More*** Favorable for Ag?



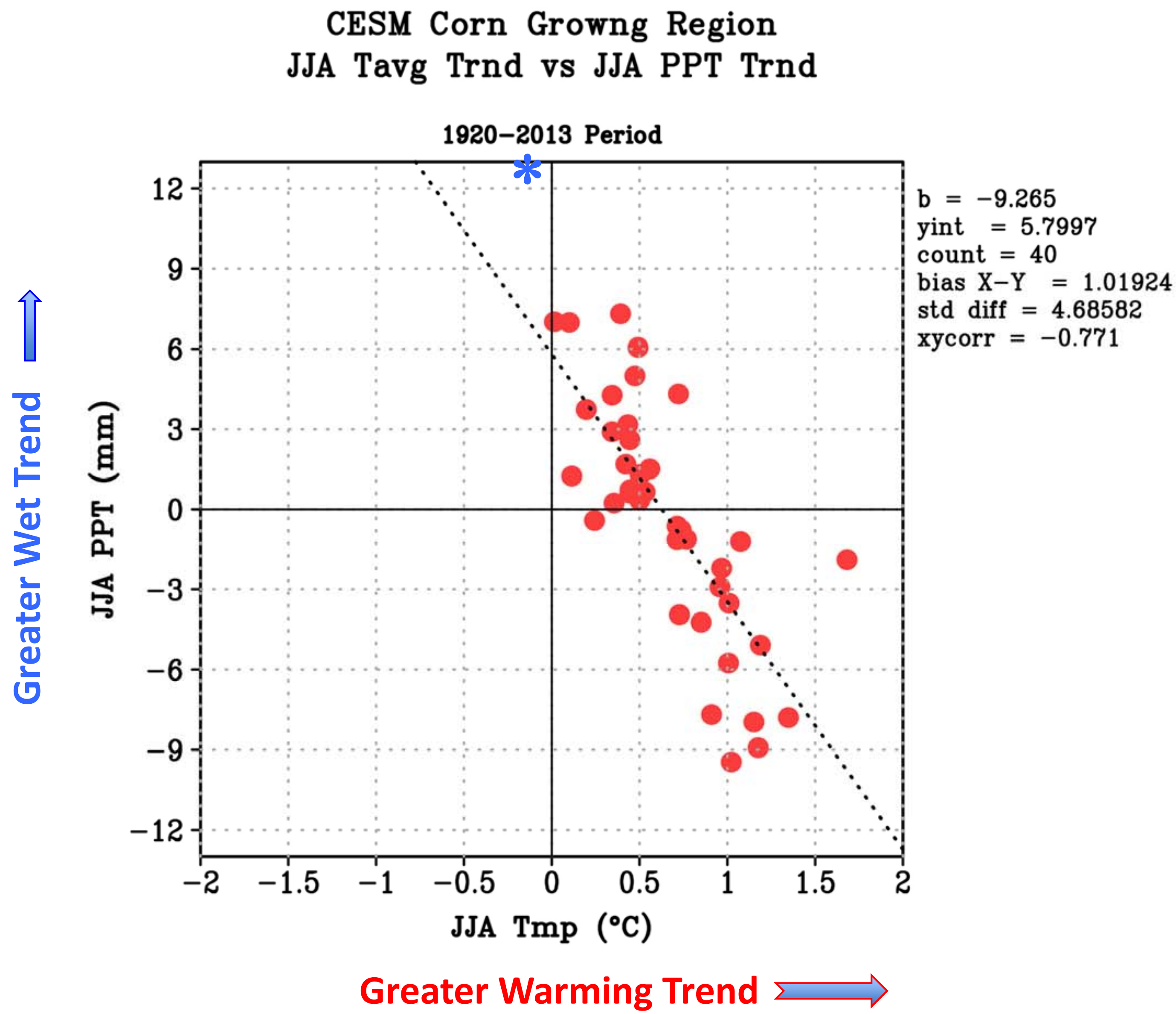


Diagnosis: *Calculate 1920-2013 Summertime Surface Temperature Trends in a New Large Ensemble (40-member) of Historical Simulations Using the Latest NCAR Community Modeling System (CESM1)*

Note *: There are Other Factors, Including Land Surface Change and Land Use Change, That Are Not Directly Treated Herein*


Corn Growing Region, JJA Tavg Trend 1920–2013
CESM1 Historical Simulations vs OBS
Climate Model Histogram
OBS
Probability Density Function
0.0
0.2
0.4
0.6
0.8
1.0
−0.5
0.0
0.5
1.0
1.5
2.0
Total Change in C

Large Century-Long Precipitation Trends Can Occur Due to Natural Variability
These Can Act to Mask/Enhance Human-Induced Warming



Summary

- **LSM simulations indicate precipitation explained ~ 70% of soil moisture depletion during the 2012 drought, and drove most of CP soil moisture variability since 1950.**

- **Energy balance reveals growing season temperature variability strongly driven by precipitation, indicating its even larger effect on soil moisture variability.**

- **A non-linear relationship between soil moisture and the Bowen ratio indicates an amplifier of heat waves during severe drought conditions.**

- **Antecedent wintertime meteorological and soil moisture conditions affect growing season soil moisture, which appreciably affects summer temperature.**

Summary

- **LSM simulations reveal only a modest soil moisture response to temperature, even for +4°C warming, indicating semi-permanent future drought conditions are unlikely to emerge from warming alone.**

- **Summer cooling in the Corn Belt has been a "Climate Surprise"**

- **Cooler summers have resulted from thermodynamic effects of increased rainfall, the latter likely due mostly to internal atmospheric variability.**