

Drought in a Warming Climate: Causes for Change

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Definition of Drought, Associated Processes, and Indicators

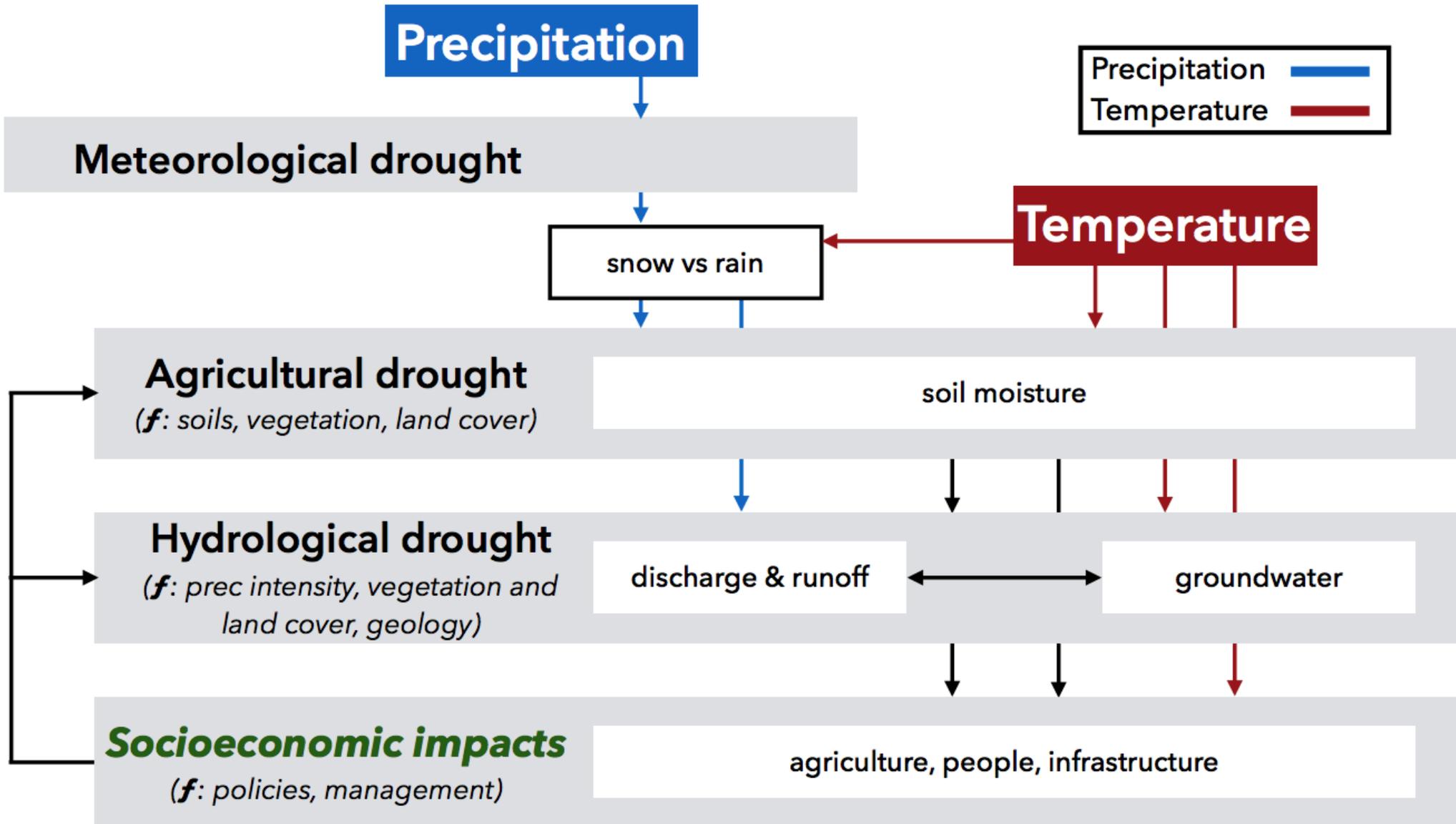


Diagram Credit: Cook et al., 2019

Definition of Drought, Associated Processes, and Indicators

Precipitation

Meteorological drought

Agricultural drought
(*f*: soils, vegetation, land cover)

Hydrological drought
(*f*: prec intensity, vegetation and land cover, geology)

Socioeconomic impacts
(*f*: policies, management)

Commonly used drought indicators:

SPI (standardized precipitation index) (*used in World Bank's Global Forecast Drought Tool*)

SSMI (standardized soil moisture index)

SPEI (standard precipitation-potential evapotranspiration index, P-PET);

PDSI (Palmer drought severity Index);

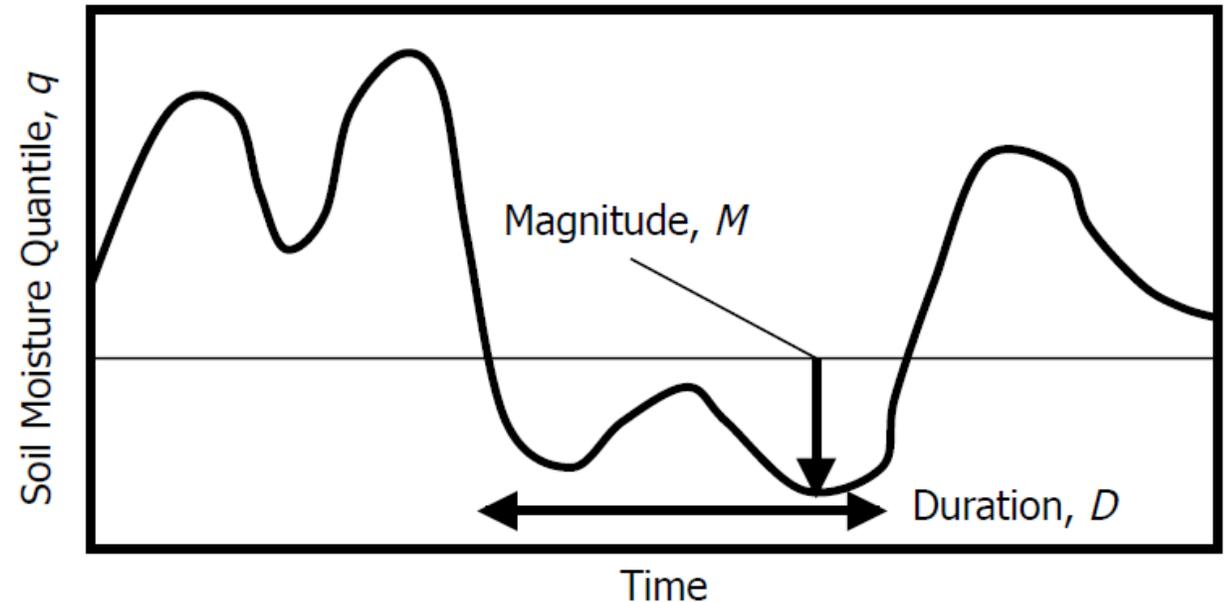
SRI (standardized runoff index);

WSRI (standardized water storage resilience index)

IDRI (Standardized inflow-demand reliability index);

Drought Characteristics (using soil moisture as an example)

- Drought Frequency (occurrence)
- Drought Extent
- Drought Duration
- Drought Intensity or Magnitude
- Drought Severity



Severity, $S = D \times M$

Extent, $A = \text{area in drought}$

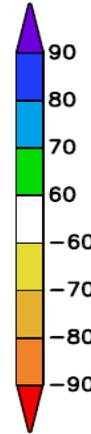
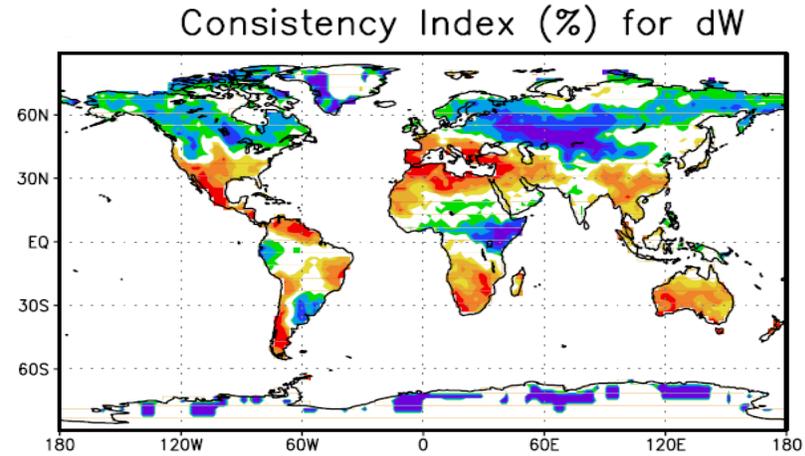
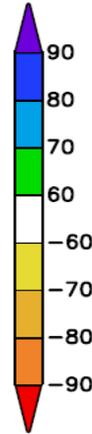
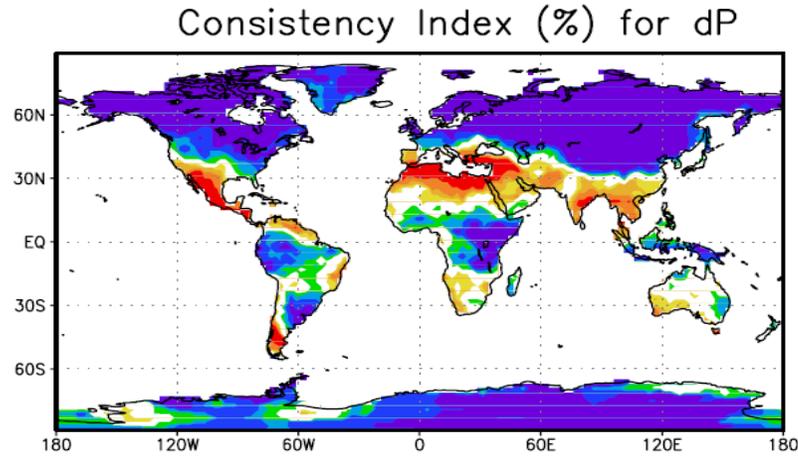
Diagram Credit: Sheffield et al., 2008

Drought Risk in a Warming Climate: Causes for Change

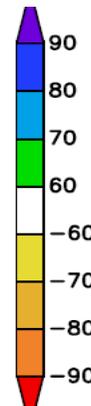
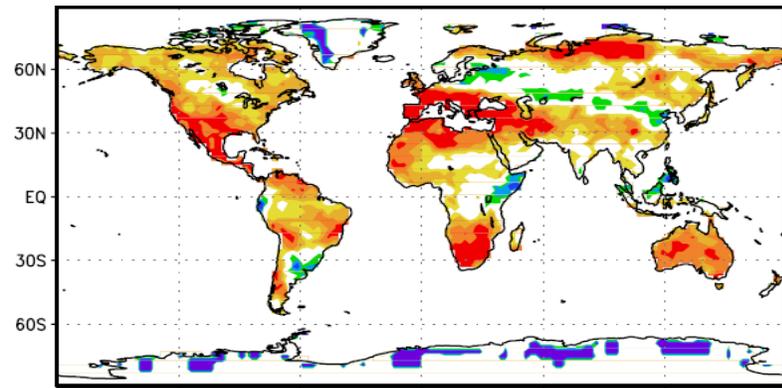
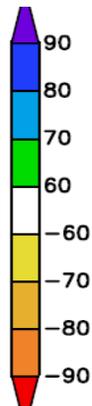
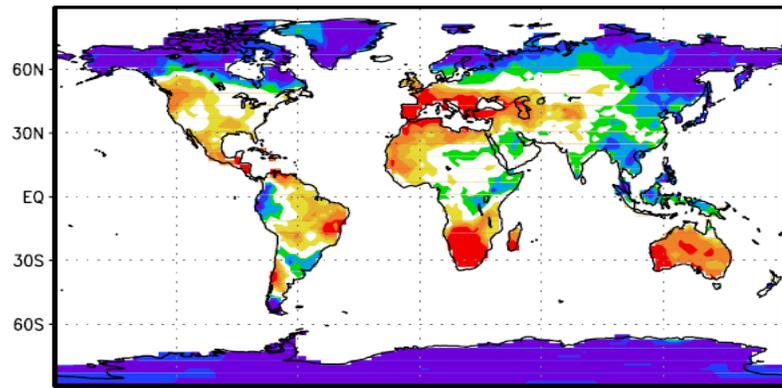
- Warming-induced acceleration of evapotranspiration (ET) exacerbates aridity: $T \uparrow \rightarrow ET \uparrow \rightarrow \text{Hydro/Ag drought risk} \uparrow$
 - Global average ET increases at approximately 2%/°C
- Warming-induced changes of precipitation characteristics lead to higher drought risk
 - Global average precipitation increases at $\sim 2 \text{ \%/}^\circ\text{C}$ (to balance ET) (Regional changes are highly variable)
 - Precipitation intensity (proportional to saturation specific humidity) increases at $\sim 7 \text{ \%/}^\circ\text{C}$ (Clausius-Clapeyron scaling rate) \rightarrow increased flood risks
 - 2% vs. 7% \rightarrow precipitation frequency \downarrow consecutive dry days $\uparrow \rightarrow$ drought risk \uparrow
- Warming-induced circulation changes may cause reduction of precipitation amount in some regions, increasing drought risk

CMIP3 Model Consensus in Projecting Changes of Precipitation (dP) and Soil Moisture (dW) (Wang, 2005: *Climate Dynamics*)

- DJF season



- JJA season



- Drought hotspots: southwest North America, Central America, part of South America, Mediterranean region, South Africa, Australia
- Widespread soil aridity signal globally, with precipitation being the main driver in some regions and temperature playing a major role in others especially in mid- and high-latitudes

Frequency of Short-term (4-6 months) Droughts

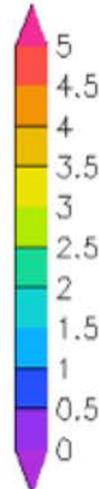
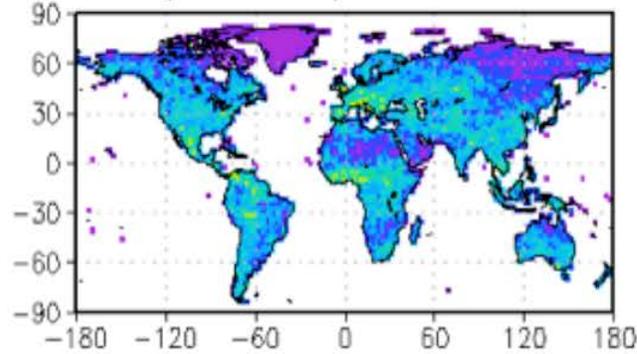
(Sheffield and Wood, 2008: Climate Dynamics; Wuebbles et al., 2014: BAMS; Sheffield, personal communication)

CMIP3

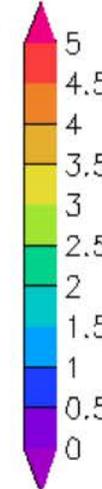
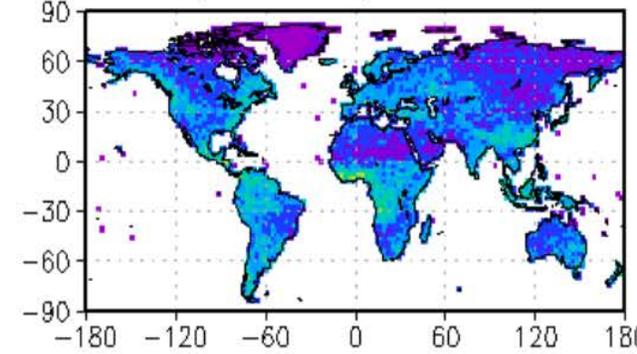
CMIP5

1961-1990

Frequency of 4-6 mo duration droughts
20C3M (1961-90) multimodel mean

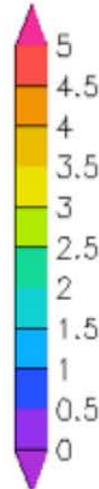
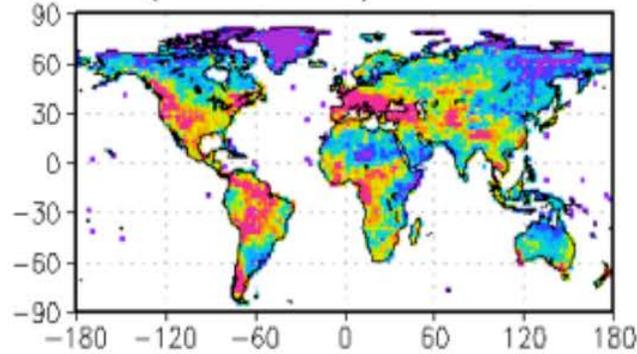


Frequency of 4-6 mo duration droughts
Historical (1961-90) multimodel mean

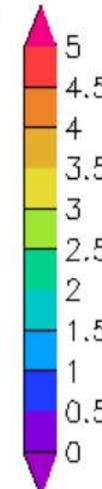
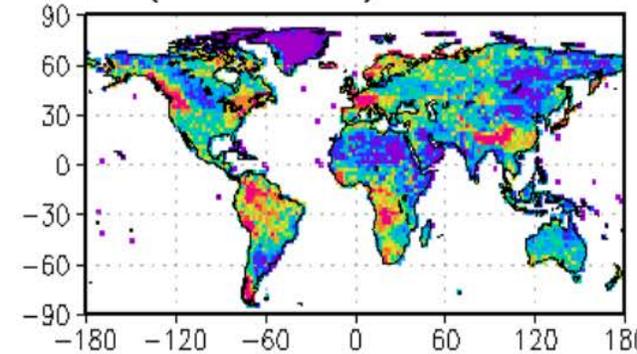


2070-2099

Frequency of 4-6 mo duration droughts
SRESA2 (2070-2099) multimodel mean

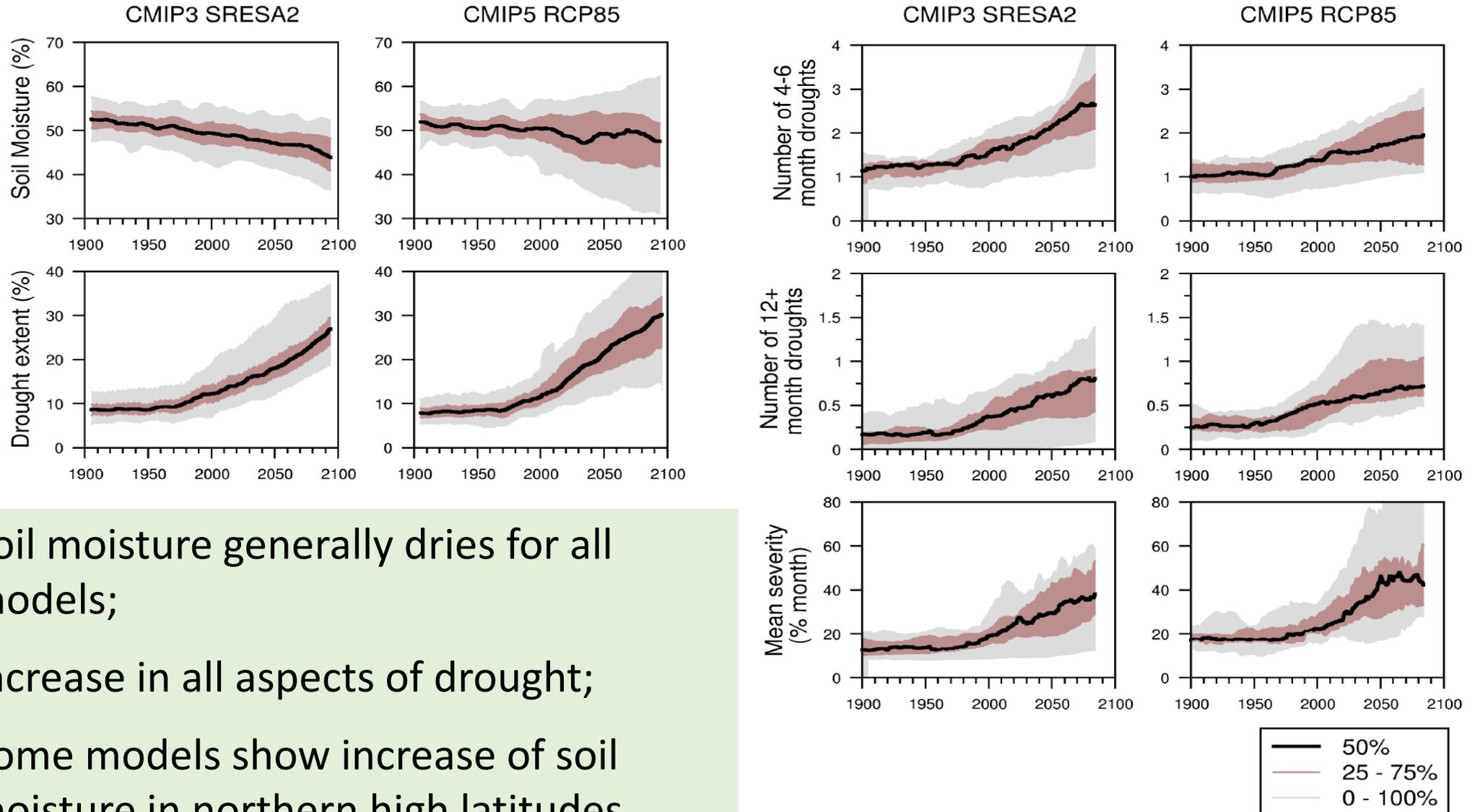


Frequency of 4-6 mo duration droughts
RCP85 (2070-2099) multimodel mean



CMIP3 and CMIP5 Model Spread in Projecting Soil Moisture and Drought Characteristics

(Sheffield and Wood, 2008: *Climate Dynamics*; Sheffield, personal communication; Wuebbles et al., 2014: *BAMS*)



- Soil moisture generally dries for all models;
- Increase in all aspects of drought;
- Some models show increase of soil moisture in northern high latitudes

Projected Future Changes in Multiple Drought Indices Based on 15 CMIP5 Models (Touma et al., 2015: Journal of Hydrology)

Global average precipitation increases with temperature (approximately 2% per degree of warming)

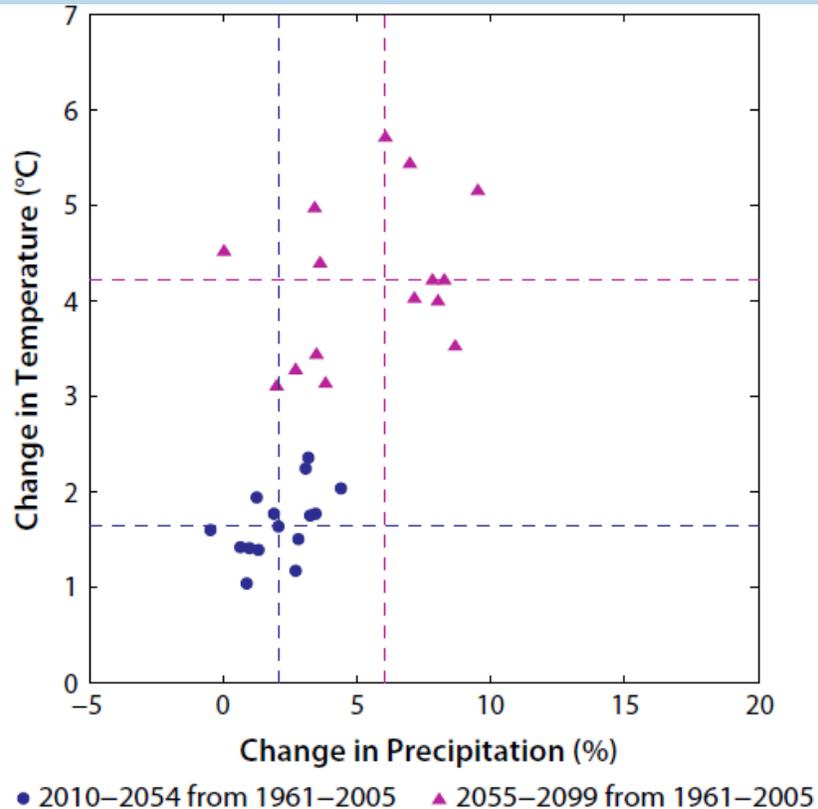
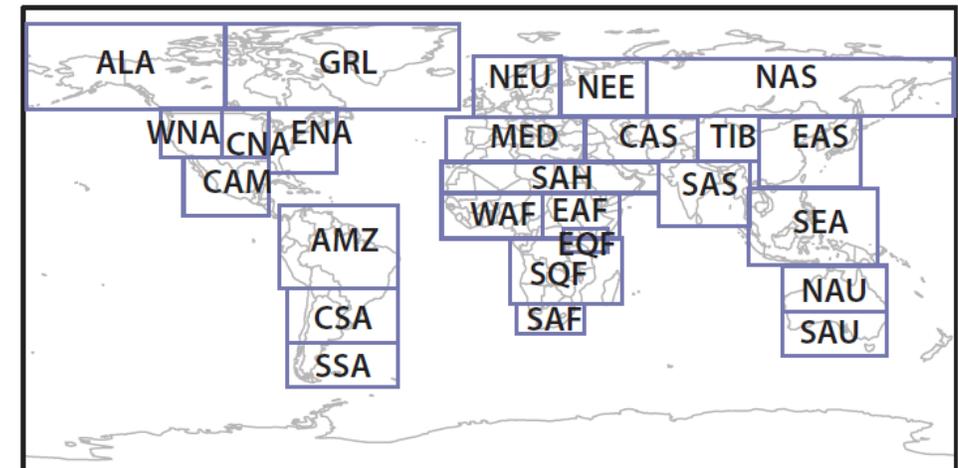
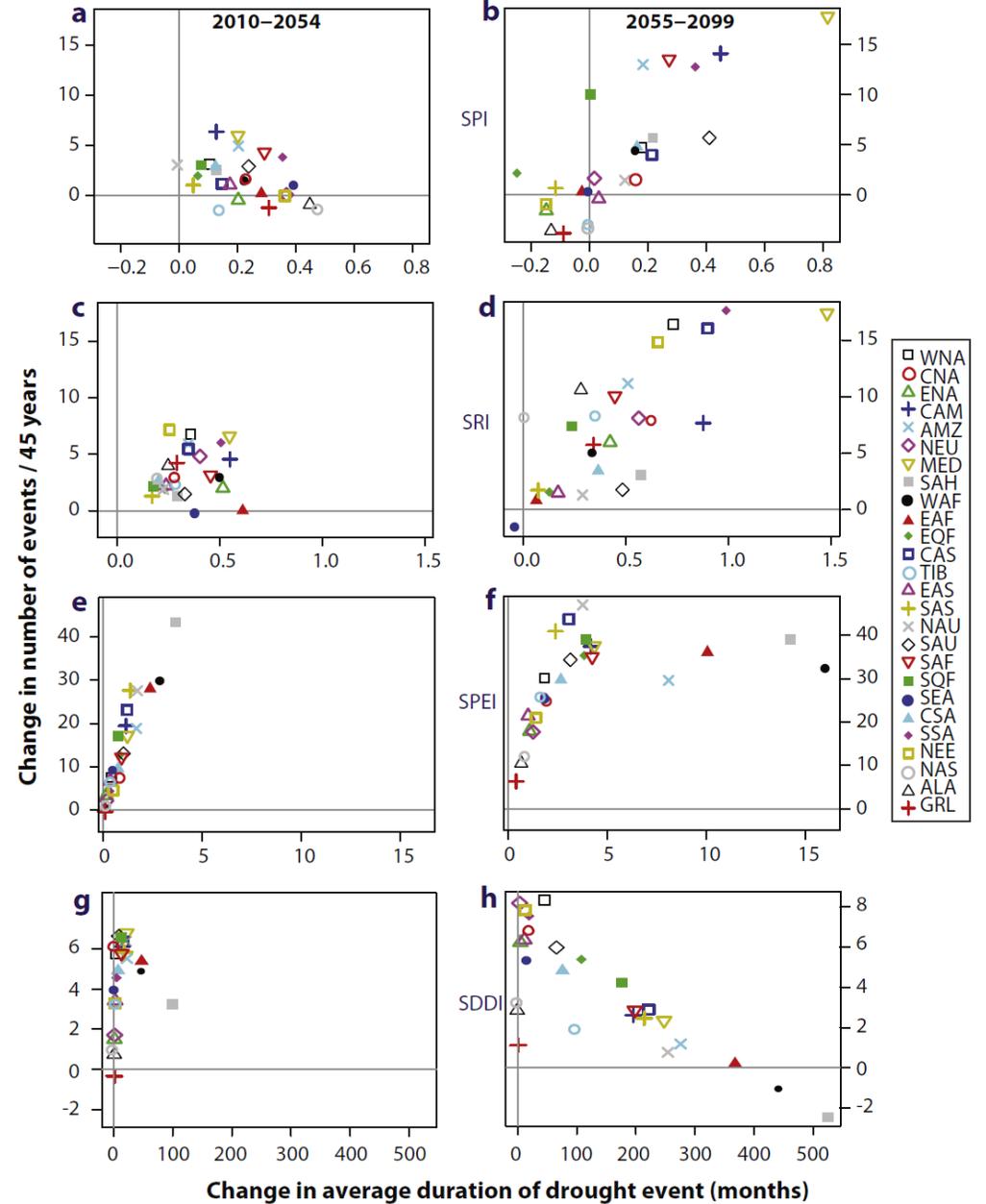
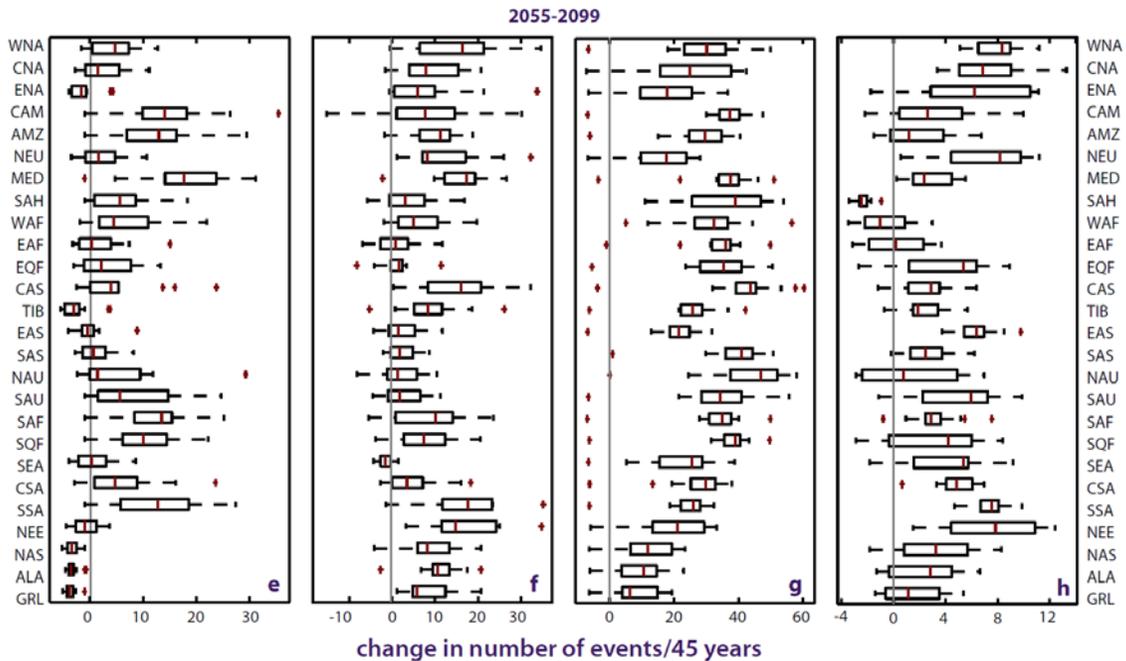
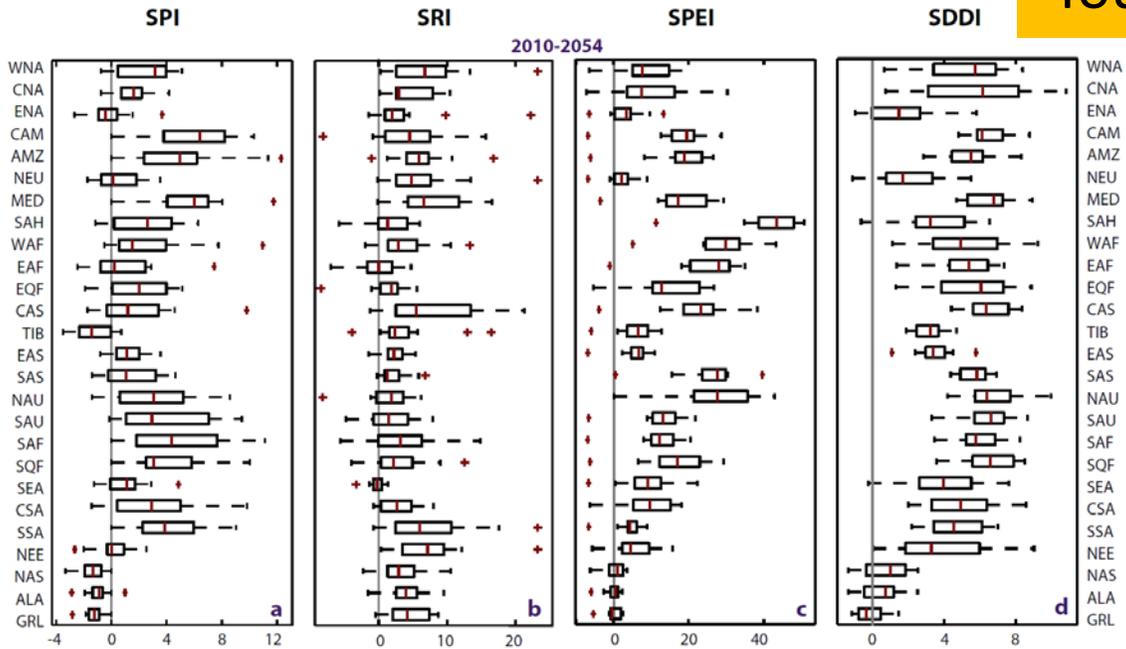


Fig. 1. Change of mean global land surface precipitation (%) versus temperature (°C) for early future (2010–2054) and late future (2055–2099) from the baseline period (1961–2005) for each GCM. The dashed lines mark the GCM ensemble median.

SPI: the Standardized Precipitation Index;
SRI: Standardized Runoff Index;
SPEI: the Standardized Precipitation-Potential Evapotranspiration (P-PET) Index;
SDDI: the Supply-Demand Drought Index.

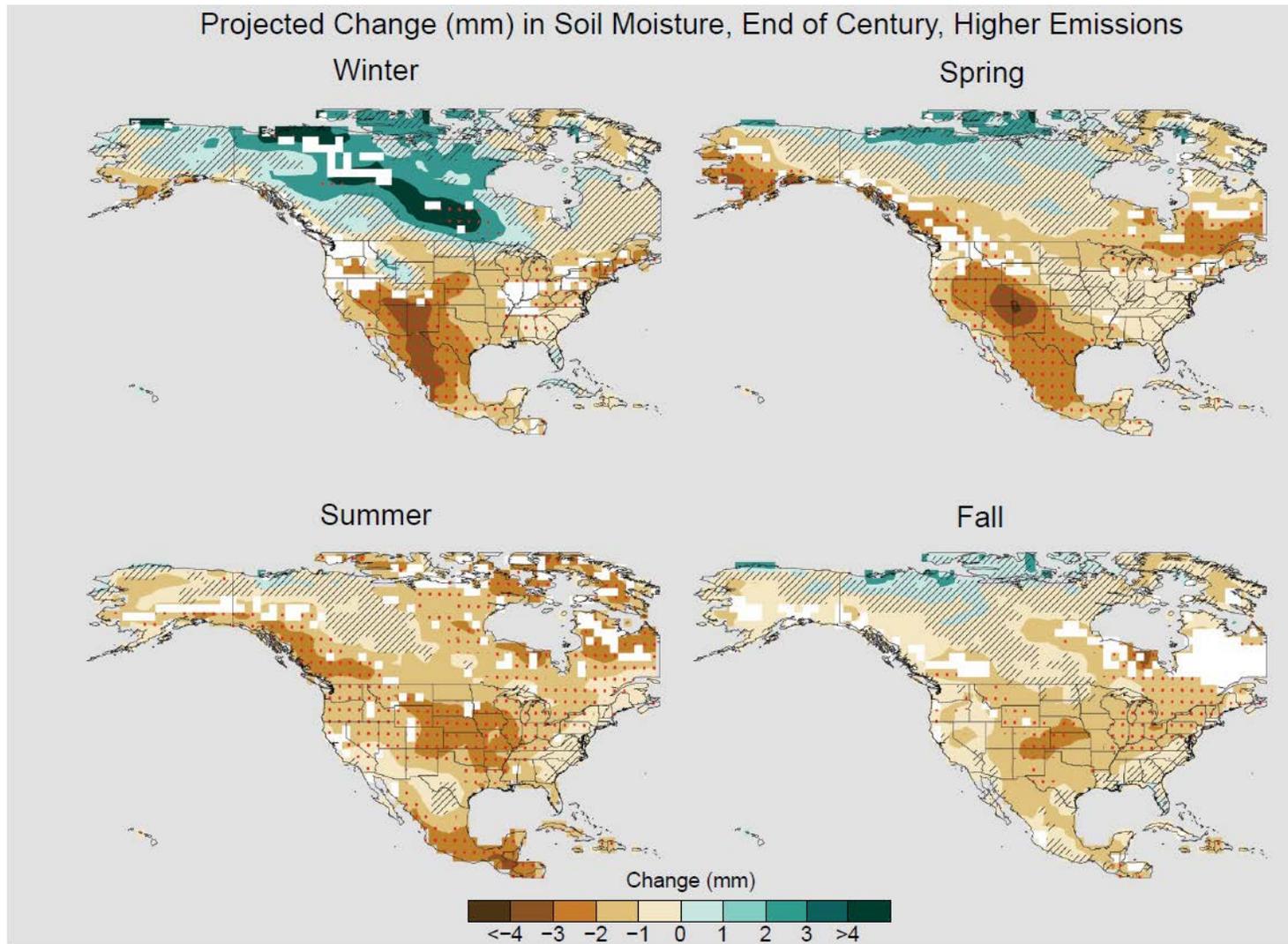
Reference Period: **1961-2005**





Decrease of near-surface soil moisture is projected across the U.S.

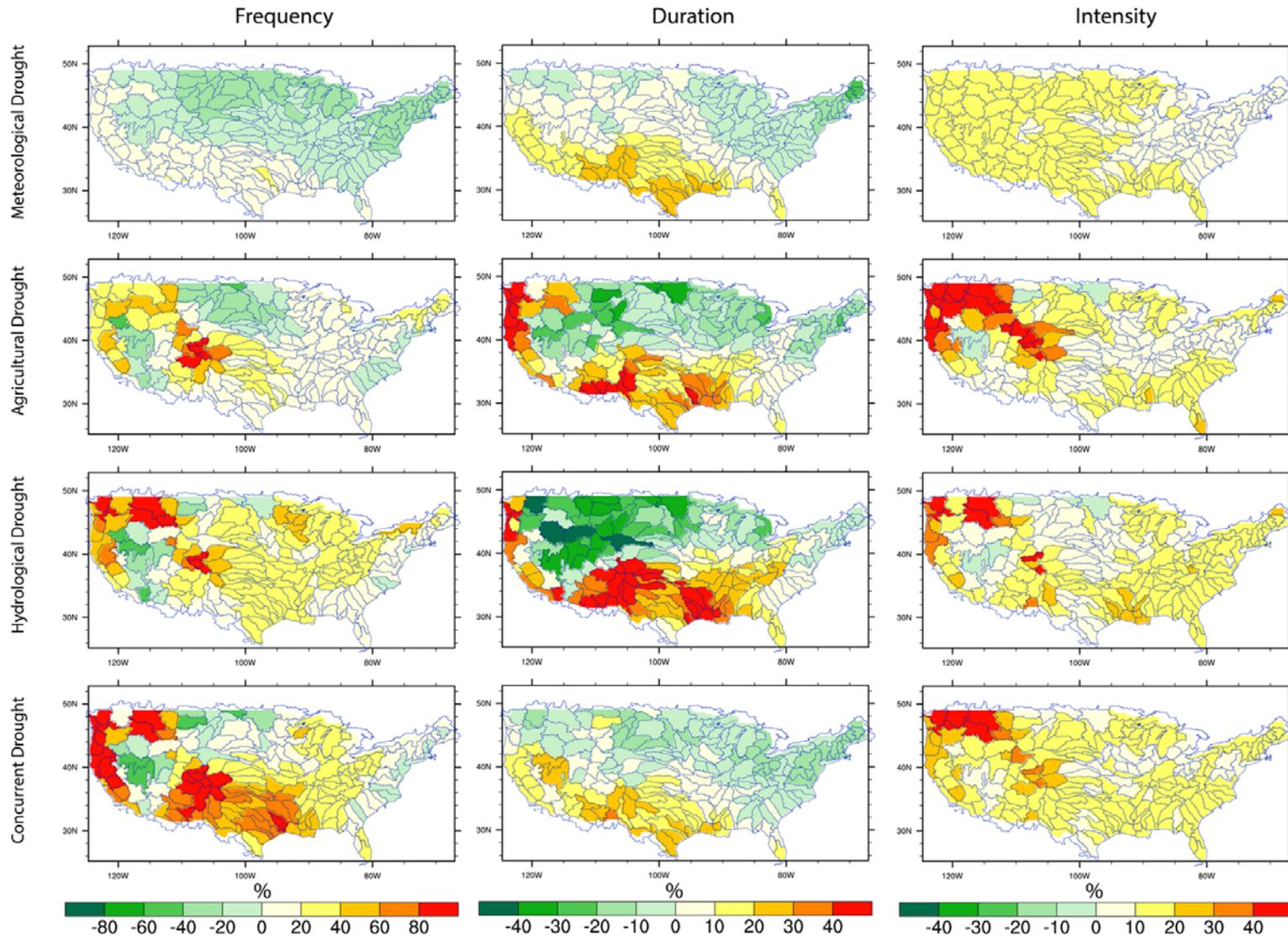
(Wehner et al., 2017: *CSSR: 4th National Climate Assessment*)



- Hashing indicates small changes relative to natural variability;
- Stippling indicates large changes relative to natural variability
- Blank indicates lack of model consensus in projecting the direction of change

Note: Over a large fraction of the global land including a large fraction of the U.S., moisture in deeper soil is projected to increase (Berg et al., 2017: *GRL*)

Projected Changes (%) of Drought Characteristics Under 1.5°C Global Warming (Huang et al., 2017: *Scientific Reports*)



Based on ensemble mean of results from a hydrological model (VIC) driven with 97 sets of downscaled CMIP5 climate forcing corresponding to 1.5°C global warming in each GCM under each emission scenario:

- Much stronger hydrological and agricultural drought signals than meteorological drought
- All aspects of drought increase in Southwest U.S. (a drought hotspot)
- Increase of hydrological and agricultural drought frequency and intensity in the Northwest

(Note: only one hydrological model is used.)

Wild Fires from satellite observations (Dennison et al., 2014: *Geophysical Research Letters*)

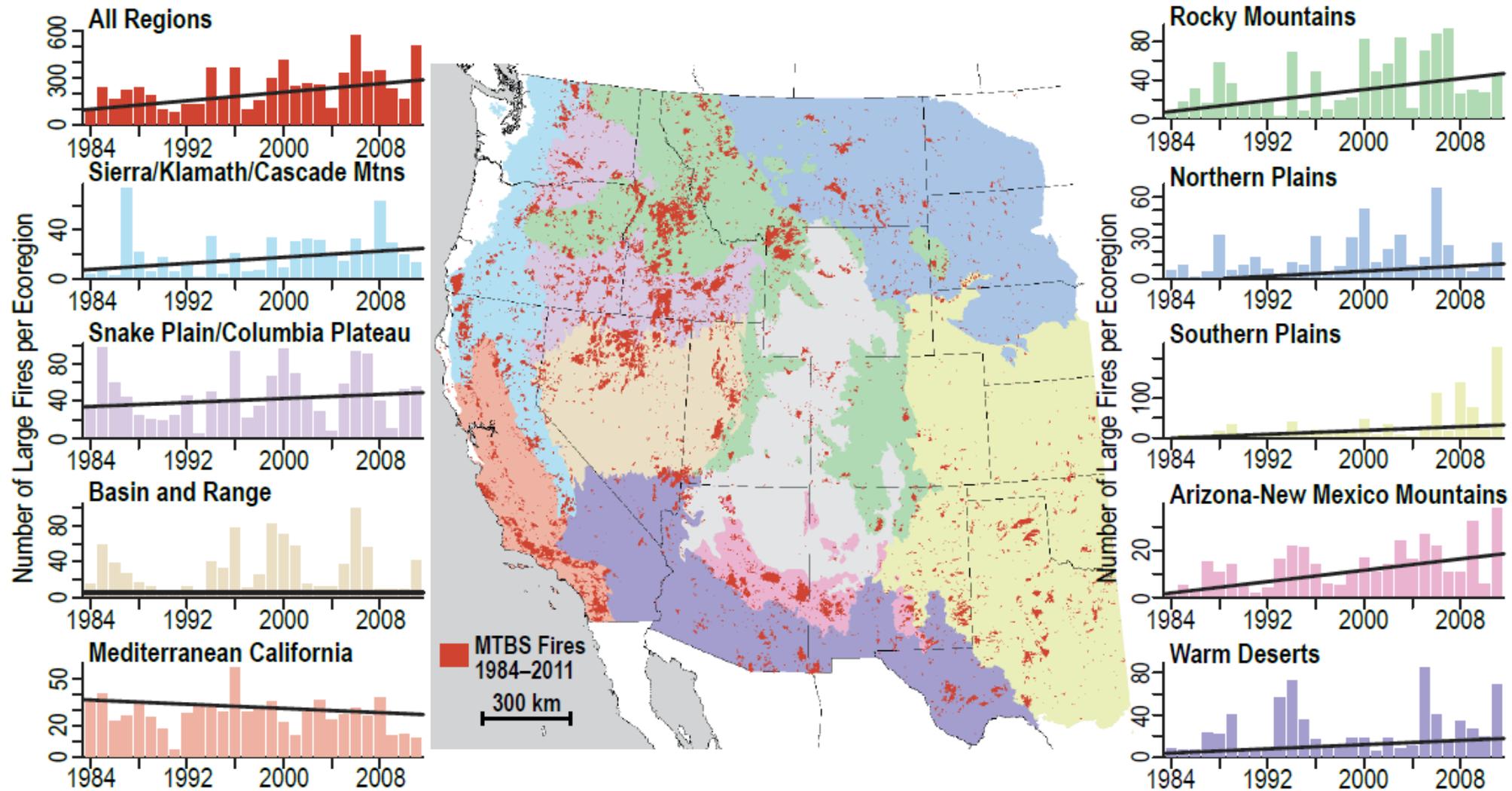
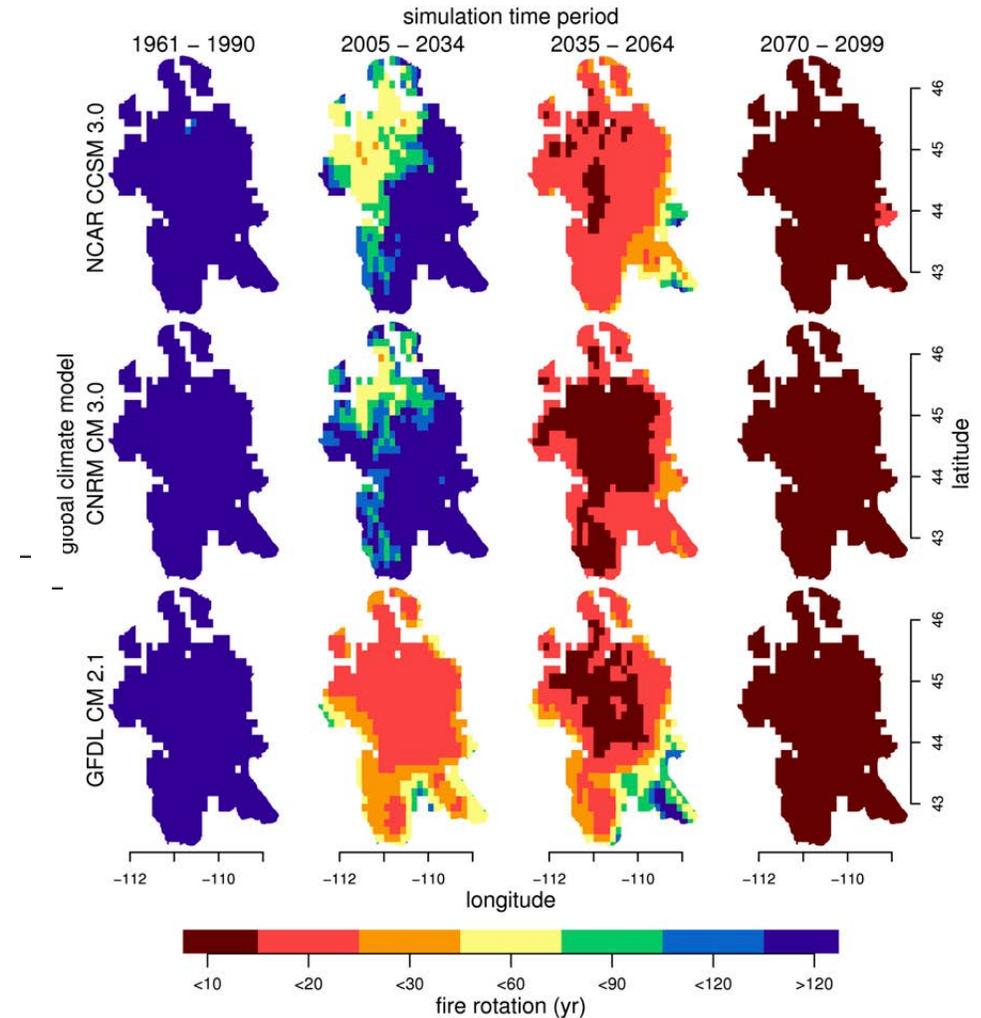
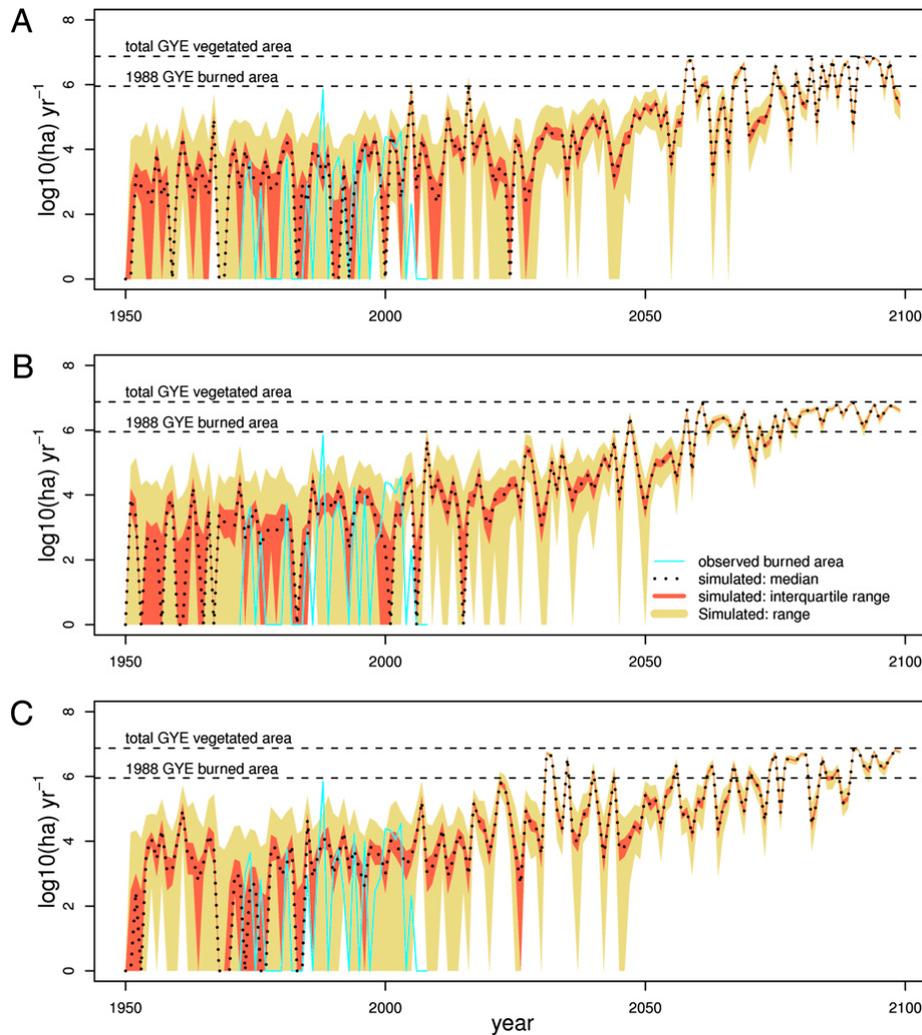


Figure 8.3: Trends in the annual number of large fires in the western United States for a variety of ecoregions. The black lines are fitted trend lines. Statistically significant at a 10% level for all regions except the Snake Plain/Columbian Plateau, Basin and Range, and Mediterranean California regions. (Figure source: Dennison et al.¹⁰⁸).

Observed and simulated fires in Yellowstone (Westerling et al., 2011: *PNAS*)

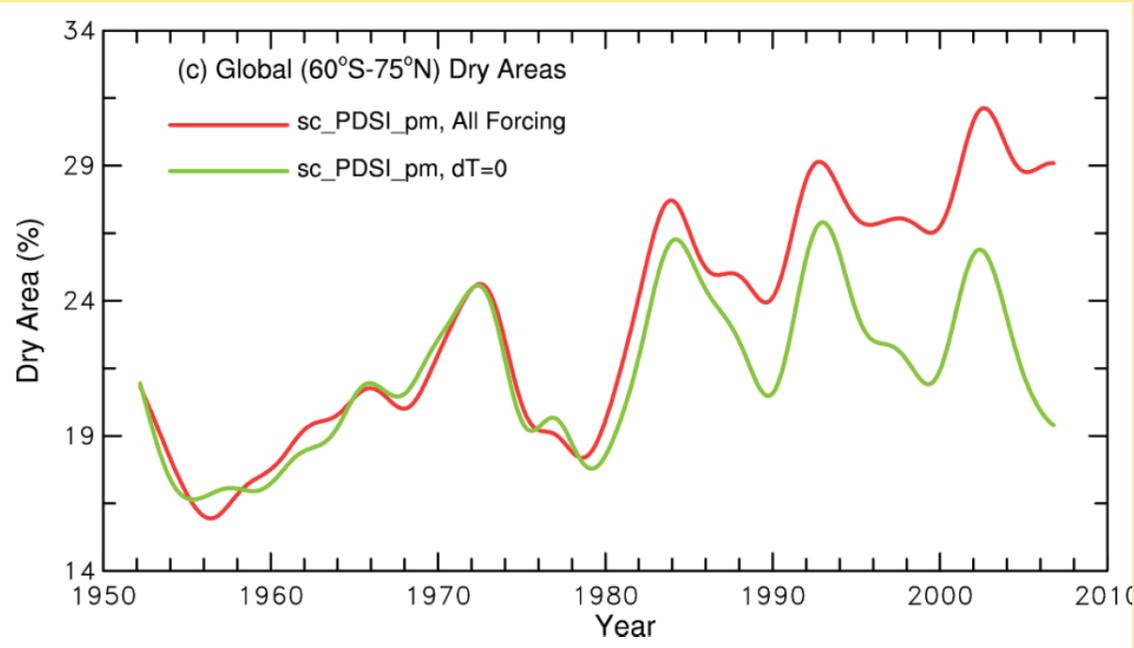


Fire projections based on downscaled SRES A1 climate:

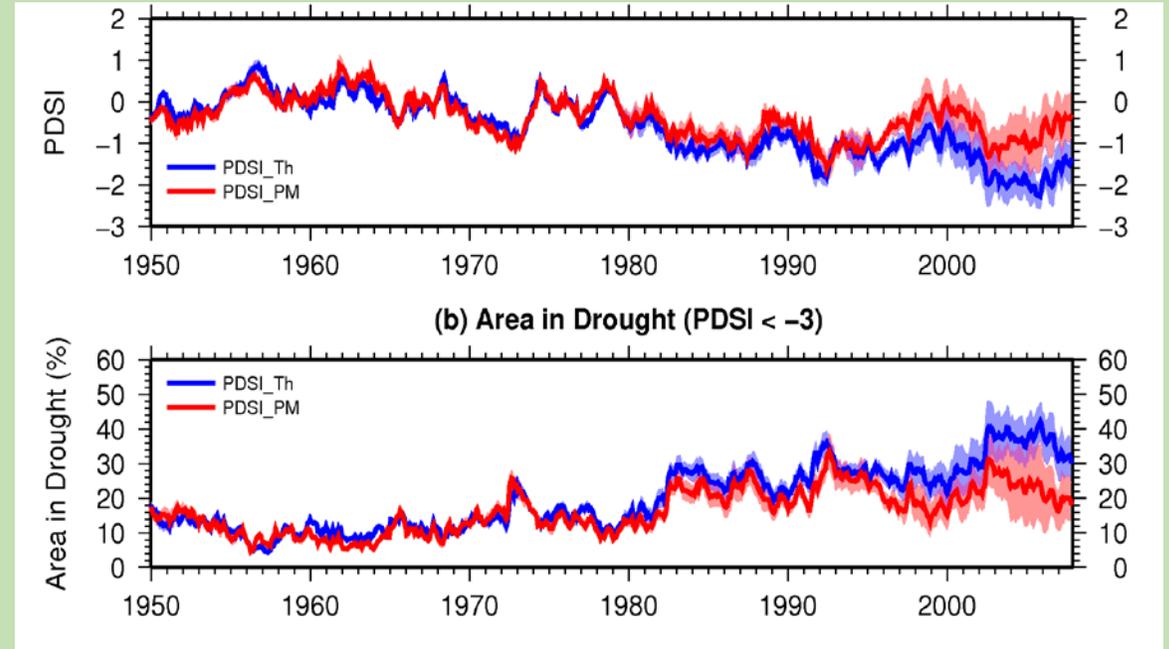
- Significant increase of fire frequency in the future (based on all three models)
- Significant increase of burned area during each fire in the future (based on all three models)

Observational data from Recent Past: Trend or no Trend?

- Dai, 2013, *Nature Climate Change*: Global aridity has increased substantially, with strong contribution from warming since the 1980s.

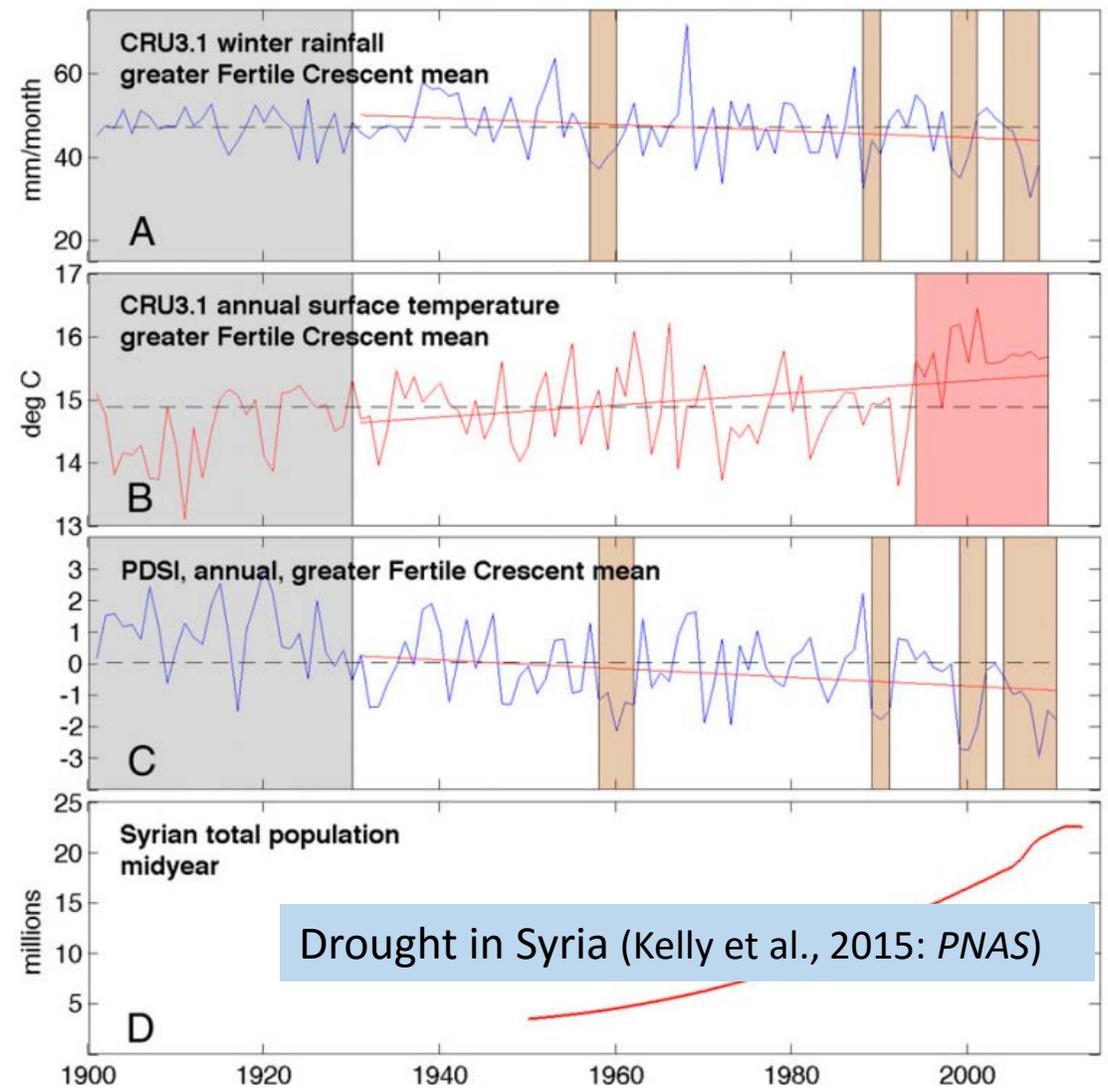
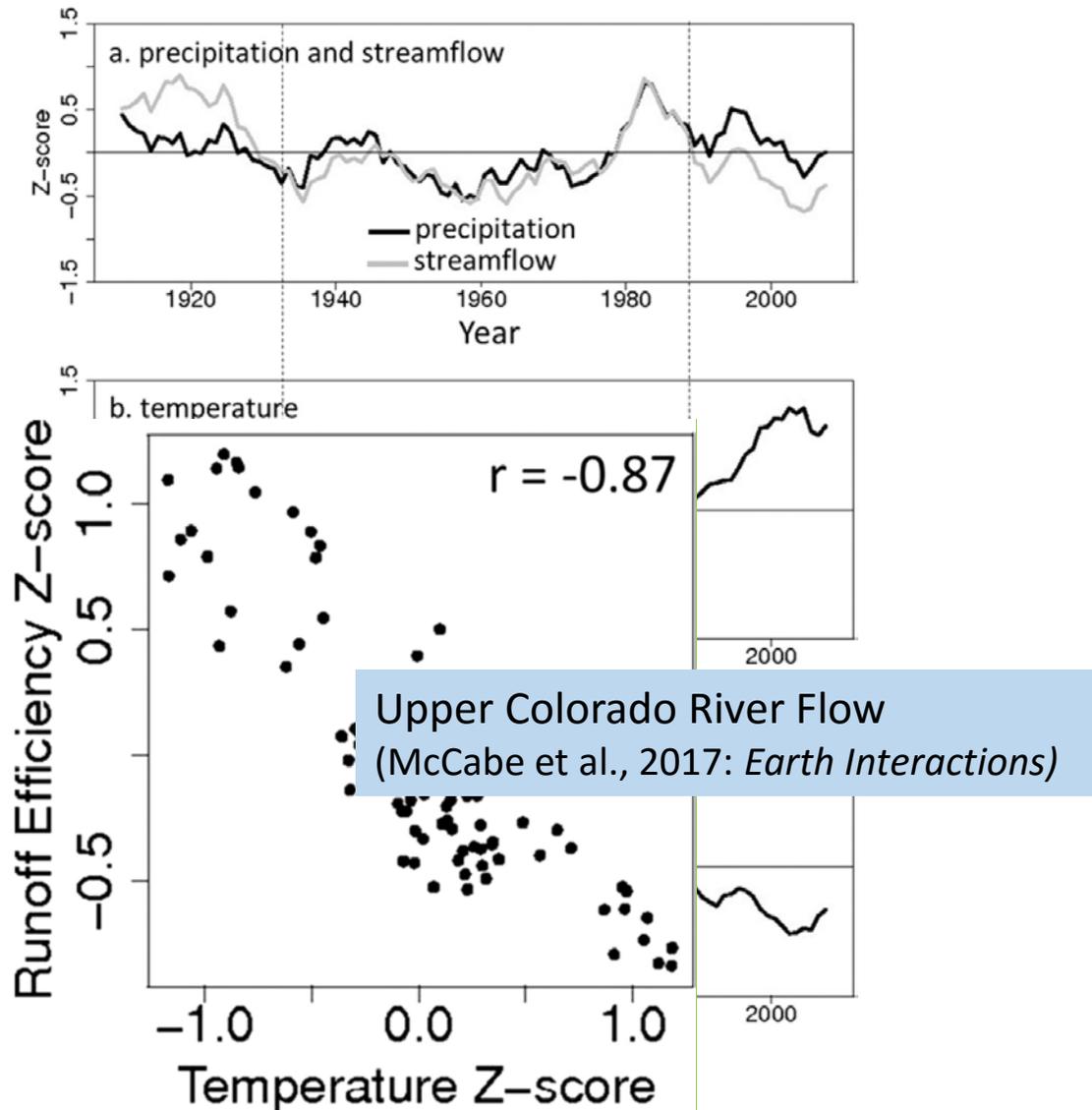


- Sheffield et al., 2012, *Nature*: Little change in drought severity and extent during the period of 1950-2008.



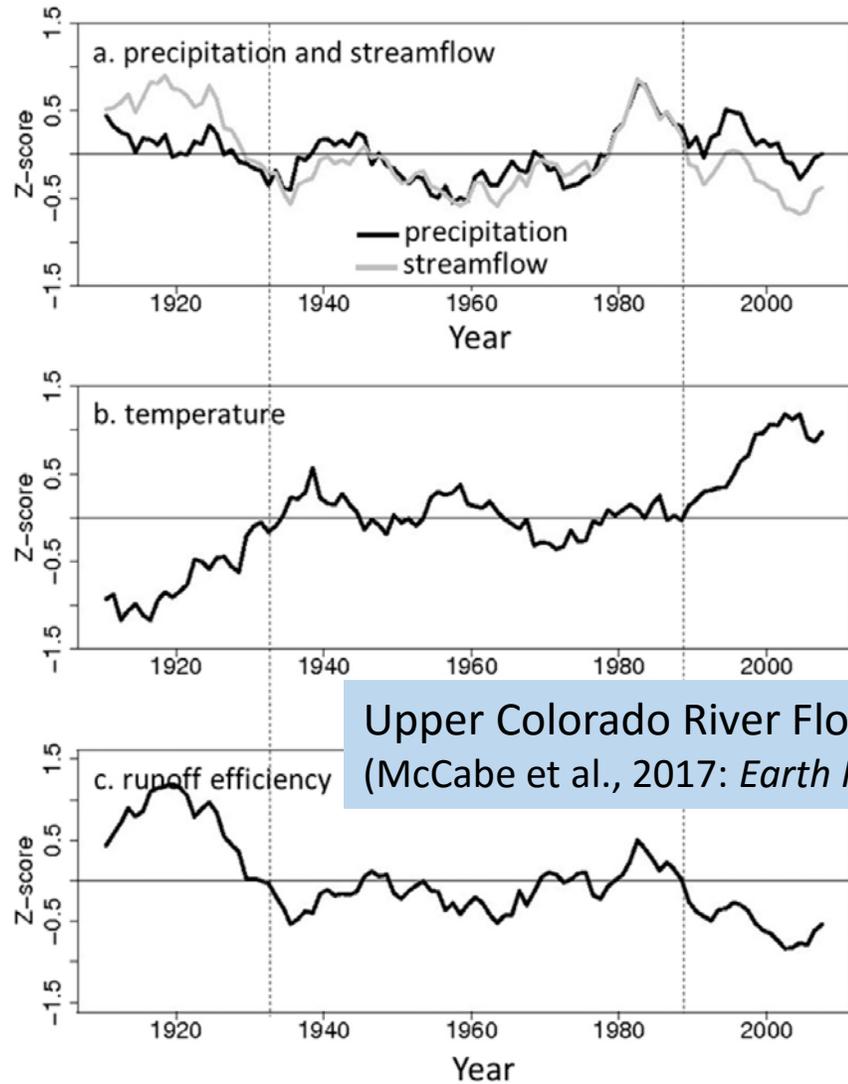
Since then, an increasing number of studies have detected changes towards greater aridity at regional scales, and the role of climate change has been increasingly identified (or implicated) as a major cause.

Regional Drought and Climate Change: Past Observations

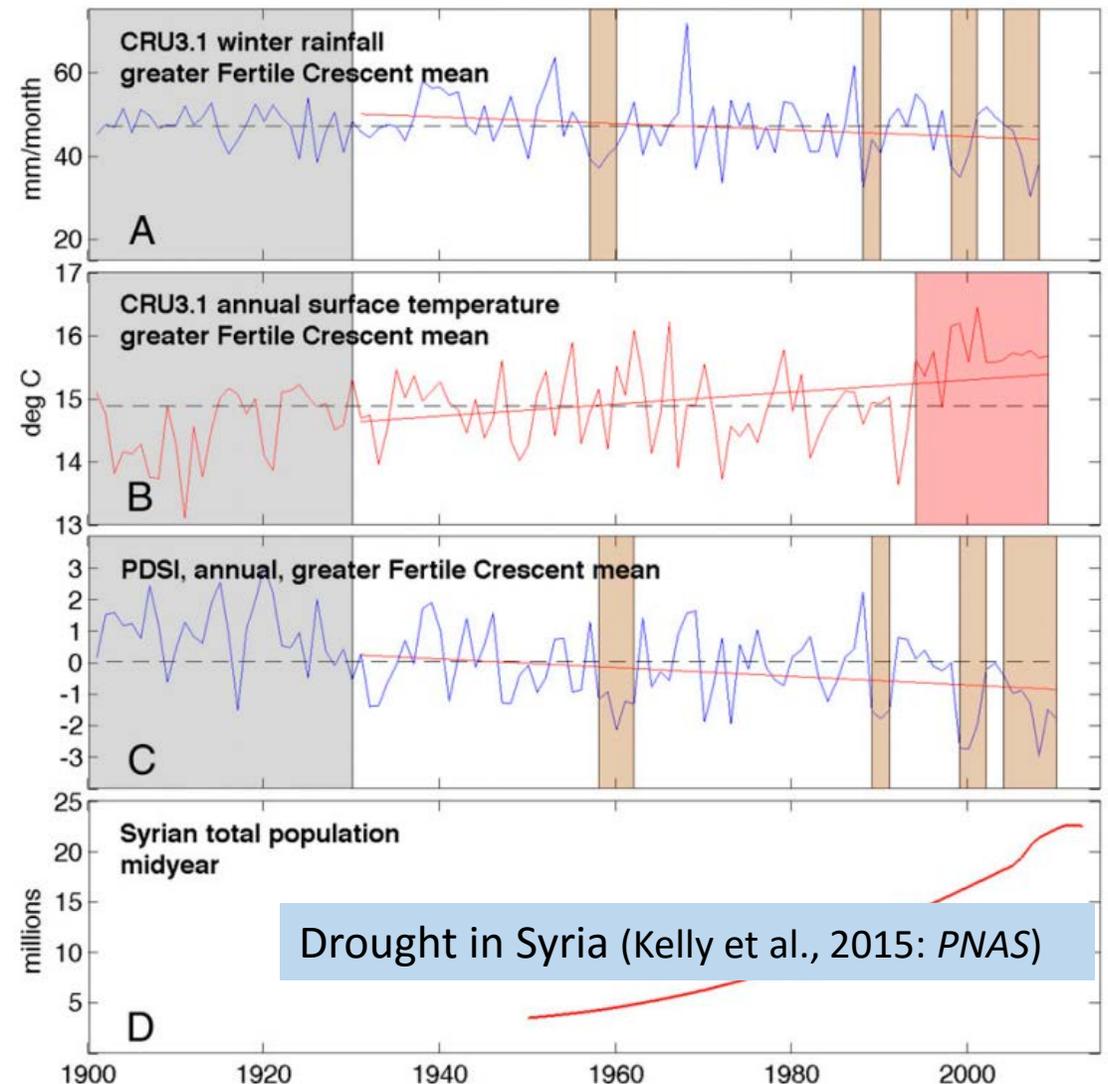


In both cases, warming-induced increase of ET or PET plays a major role in the increase of drought risk.

Regional Drought and Climate Change: Past Observations



Upper Colorado River Flow
(McCabe et al., 2017: *Earth Interactions*)



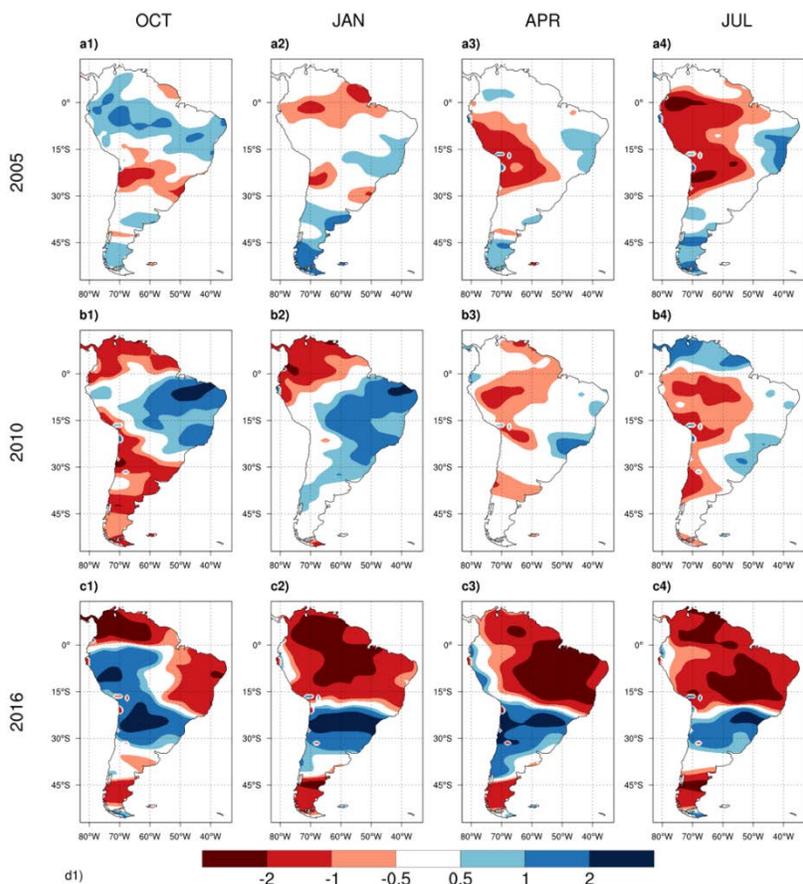
Drought in Syria (Kelly et al., 2015: *PNAS*)

In both cases, warming-induced increase of ET or PET plays a major role in the increase of drought risk.

Case Study on South American Drought: 1. Observations

(Erfanian et al., 2017, Scientific Reports)

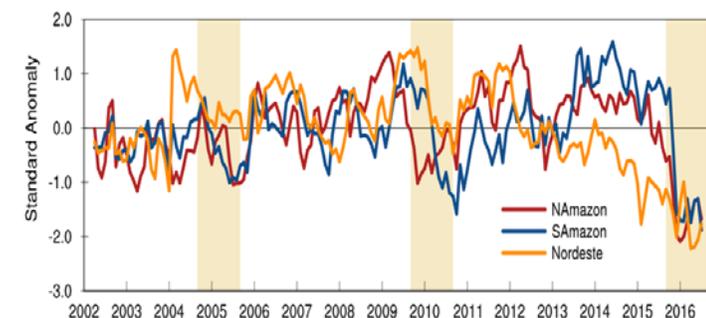
Terrestrial Water Storage (GRACE)



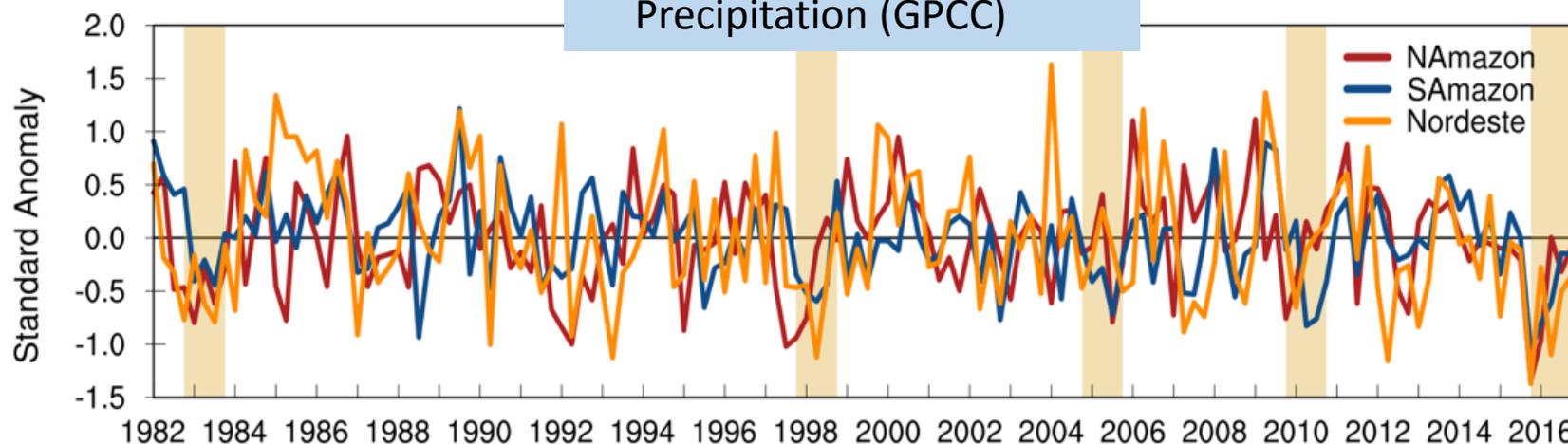
GRACE – Gravity Recovery and Climate Experiment satellite
 GPCC – Global Precipitation Climatology Center

- Precipitation deficit (meteorological drought) is the main driver for the drought signal in terrestrial water storage
- Warming further exacerbates the soil drought signal

Terrestrial Water Storage (GRACE)



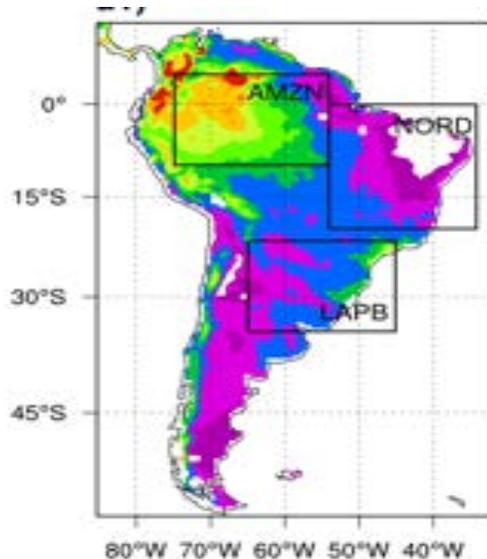
Precipitation (GPCC)



Case Study on South American Drought: 2. Regional Climate Model Simulations

(Erfanian et al., manuscript in preparation)

- **Numerical Experimental Design** using RegCM4-CLM4.5 (Wang et al., 2016)
 - **ALL:** (information not open to public yet)
 - **NAT:** (information not open to public yet)
- **Results:** Warming plays a major role in enhancing the precipitation deficit (intensity of meteorological drought) in the Amazon and Nordeste regions



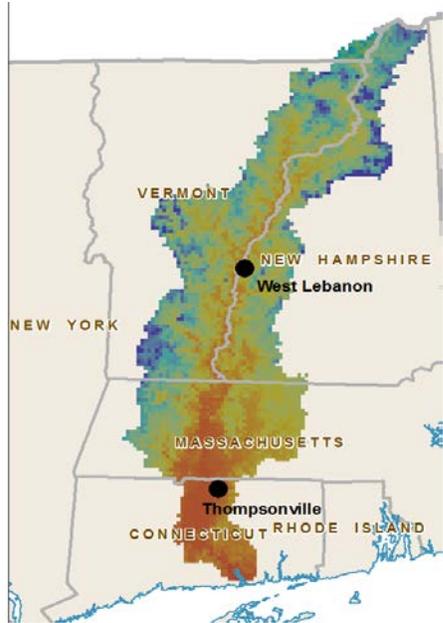
(Results not open to public yet)

Sources of Uncertainties in Projecting Future Drought

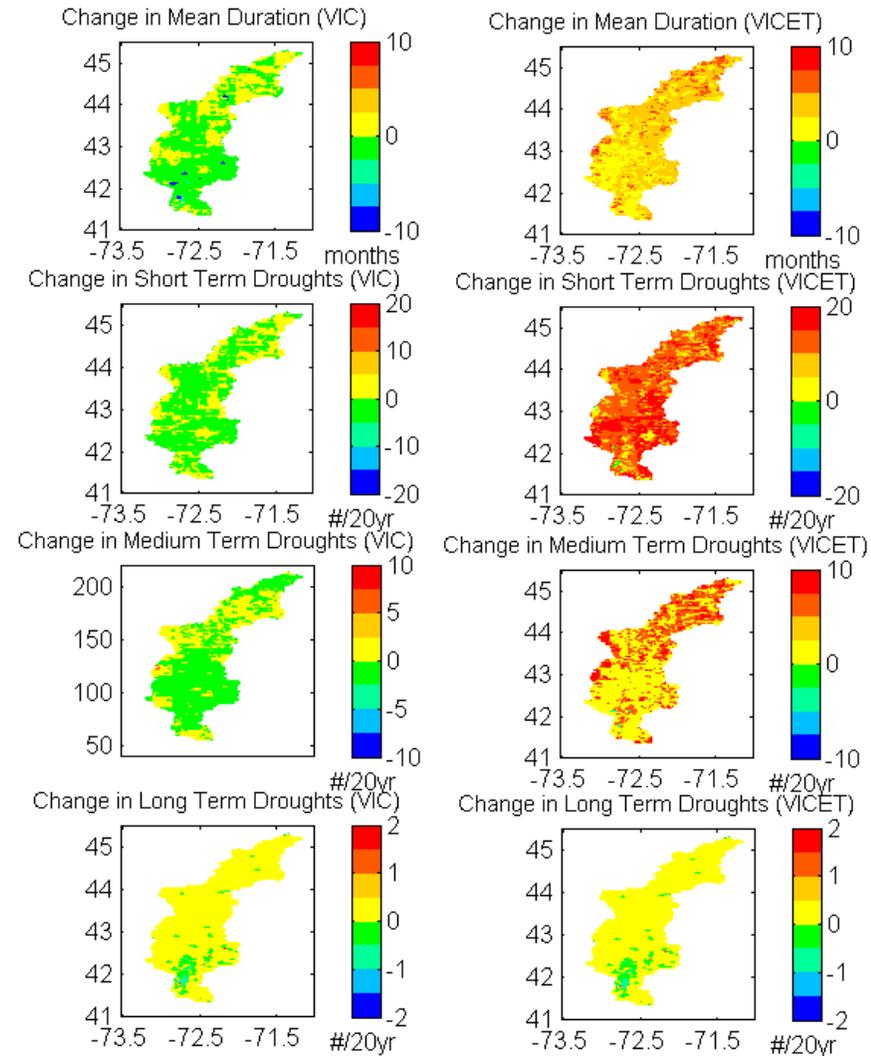
- Emission scenario: RCP2.6 no longer feasible; CO₂ concentration in past years closely tracks RCP8.5
- Scales (temporal and spatial): e.g., short-term vs. long-term droughts; soil moisture in shallow vs. deep soils
- Drought metrics: e.g., SPI vs. SRI vs. SPEI; duration vs. intensity
- Drought definition: e.g., moderate vs. severe drought
- Climate model dependence: a high degree of model consensus over some regions of drought “hotspots”; less consistent in others
- Impact model dependence: e.g., Large spread among hydrological models in regions of low runoff (Van Huijgevoort et al., 2013)
- Human decision making on water use and management
- Unknowns

Example: Hydrological Model Bias in the Connecticut River Basin (CRB)

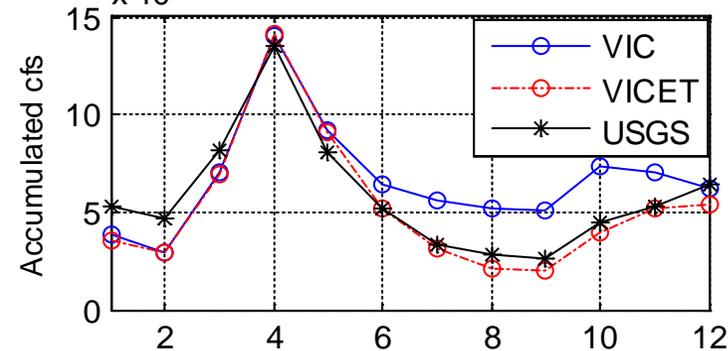
(Parr, Wang, and Bjerklie, 2015: Journal of Hydrometeorology)



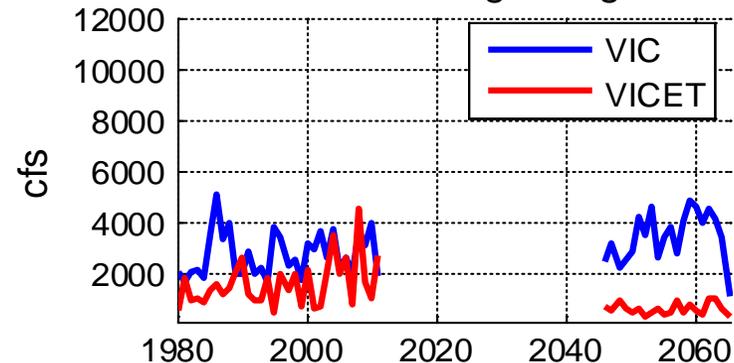
- The commonly used hydrological model VIC underestimates river flow in CRB due to overestimation of ET;
- Correcting the ET bias leads to a better performing version of the model, VICET;
- However, VIC and VICET differ in their future drought projections



Mean Monthly Discharge (Thompsonville)
 $\times 10^5$ 1980-1985 & 1996-2011

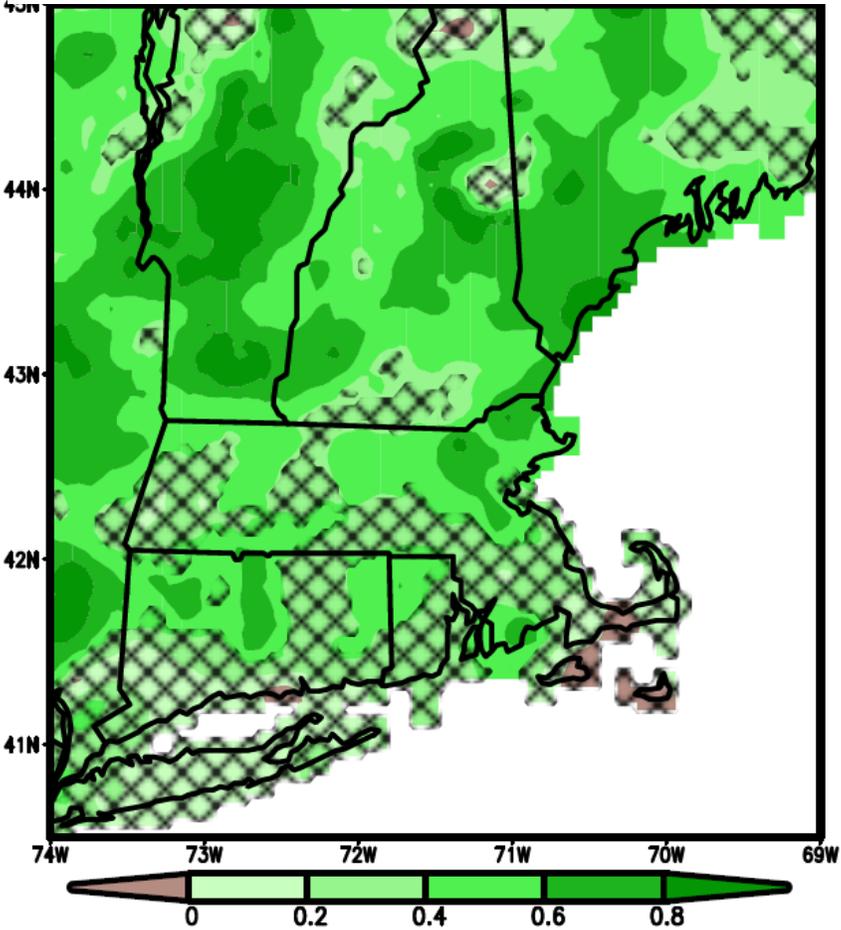


Minimum Discharge Magnitude

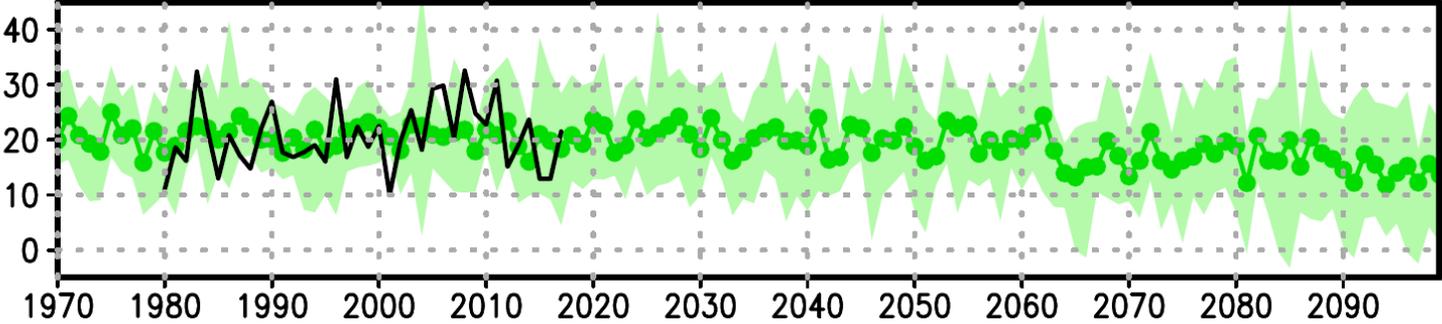


Past trend may not (yet) indicate future changes: Example from the U.S. Northeast (Wang et al., manuscript in preparation)

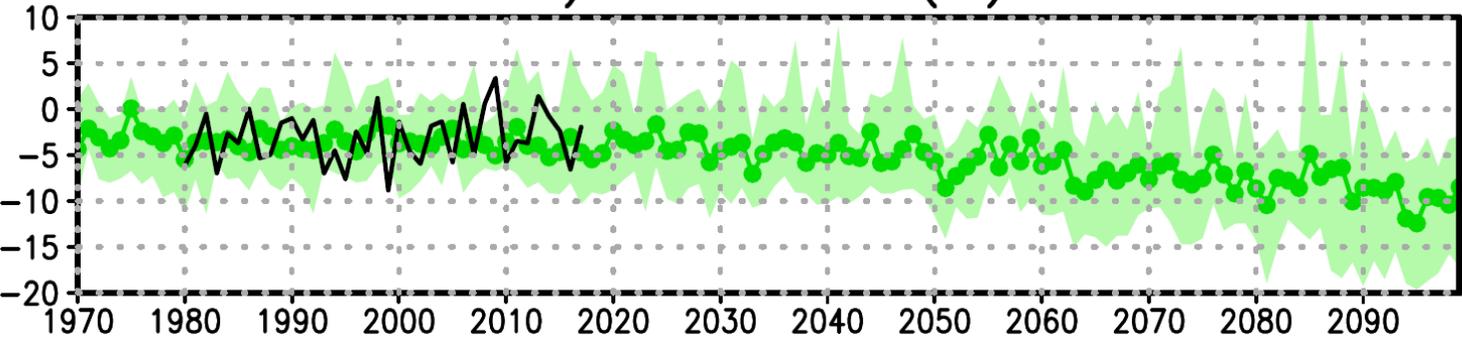
Past observed trend for JJA P-PET (in/dec)



a) Annual P-PET (in)



b) JJA P-PET (in)



Graph above: P-PET averaged over the U.S. Northeast, from past observations (black solid line) and multi-model ensemble simulations including the ensemble mean (green solid line with filled circle) and minimum and maximum (green shading).

Past: Increasing trend or no change in P-PET in both observation and models; **Future:** decreasing trend in P-PET

Concluding Remarks on Changes in the Physical Climate

- There has been a growing body of observational evidence for increasing drought risks at the regional scale (although in some regions, observational changes may not manifest until sometime in the future).
- Despite the projected increase of global average precipitation, climate models (in both CMIP3 and CMIP5) consistently project an increase of drought risks at the global scale, with a high degree of model consensus in several “hotspot” regions where precipitation is projected to decrease. (In these regions, hydrological and agricultural droughts are almost a certain outcome).
- Warming-induced ET changes exacerbate the drought signals, which can lead to generally larger increase in the frequency and severity of hydrological and agricultural droughts than meteorological drought. The degree of this exacerbation depends on region and specific drought aspects of interest.
- Impact models (e.g., hydrological model, fire models) are a major source of uncertainty in projecting future changes of drought risks.

Human decision making (e.g., water use and management) plays an important role in shaping the actual impact of drought.

To mitigate and adapt to the drought risks, the time to act is now!