Characteristics of Drought over the United States Simulated in CMIP Experiments

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Section C34

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Introduction

Drought is a major water management issue facing the western region of the United States. The **impact of drought may be mitigated** if future projections of water resources are available for careful planning. Most projections rely on simulations from atmosphere – ocean coupled models. For example, the Intergovernmental Panel on Climate Change (IPCC) Coupled Model Intercomparison Project (CMIP) 3 experiments were performed by several coupled models with different CO2 scenarios. An important question is whether the drought and persistent wet episodes in the CMIP model simulations are realistic. **What are the conditions that a model must capture to simulate realistic drought?** Extreme events are often selected based on anomalies defined as departures from the model's climatology. Does a model need to have a realistic climatology in order to simulate realistic drought and persistent wet spells? The answers to these questions will help us to interpret model projections of water resources.

Datasets

Observations: Precipitation Ensemble (0.5 degrees) created using:
- CPC Unified dataset (1950-2010)
- University of Washington Precipitation dataset (1915-2007)

NLDAS Total Soil Moisture Ensemble (1916-2006)
- Obtained from University of Washington
- VIC, Noah, and Sacramento models

ERSST v2 SSTs (1910-2009, 2 degrees)

Models: WCRP 20th Century climate change model simulations (CMIP3):
- GFDL CM2.0 (144x90km, 700yrs)
- GFDL CM2.1 (144x90km, 420yrs)
- MPI Echam5 (192x96km, 814yrs)
- HadCM3 (96x72km, 280yrs)

Three versions of the NCEP CFS:
- T62 (250km, 66yrs), OSU LSM, MOM3
- T126 (100km, 420yrs), OSU LSM, MOM3
- T382 (35km, 200yrs), Noah LSM, MOM3

Classifying Drought

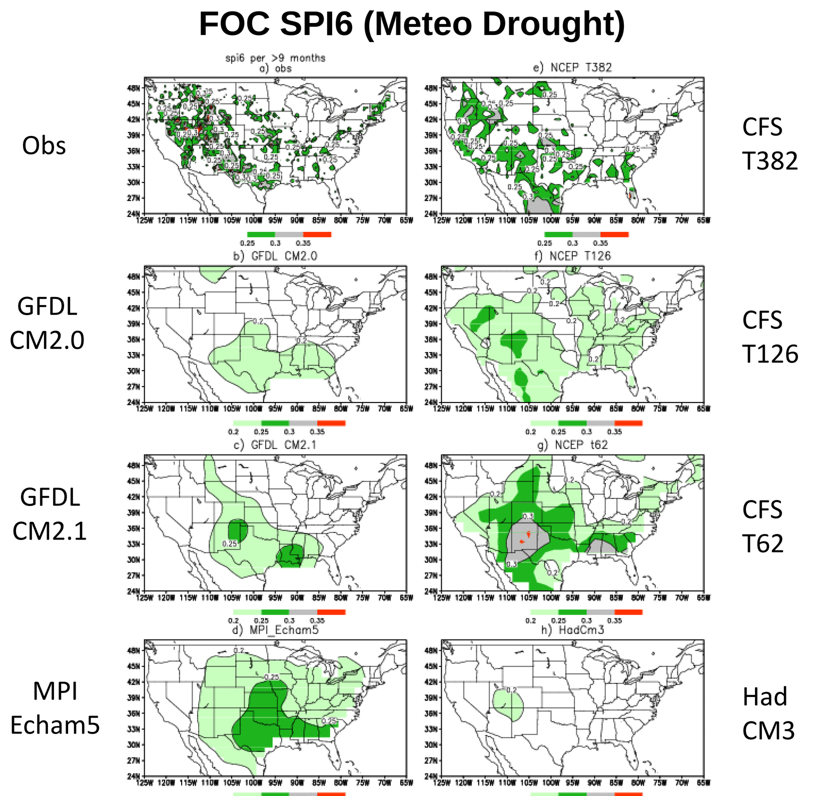
Meteorological Drought: Measured by precipitation (P) deficit
Classified by the 6-month Standardized Precipitation Index (SPI6)

Agricultural Drought: Measured by total soil moisture (SM) deficit
Classified by SM anomaly percentiles

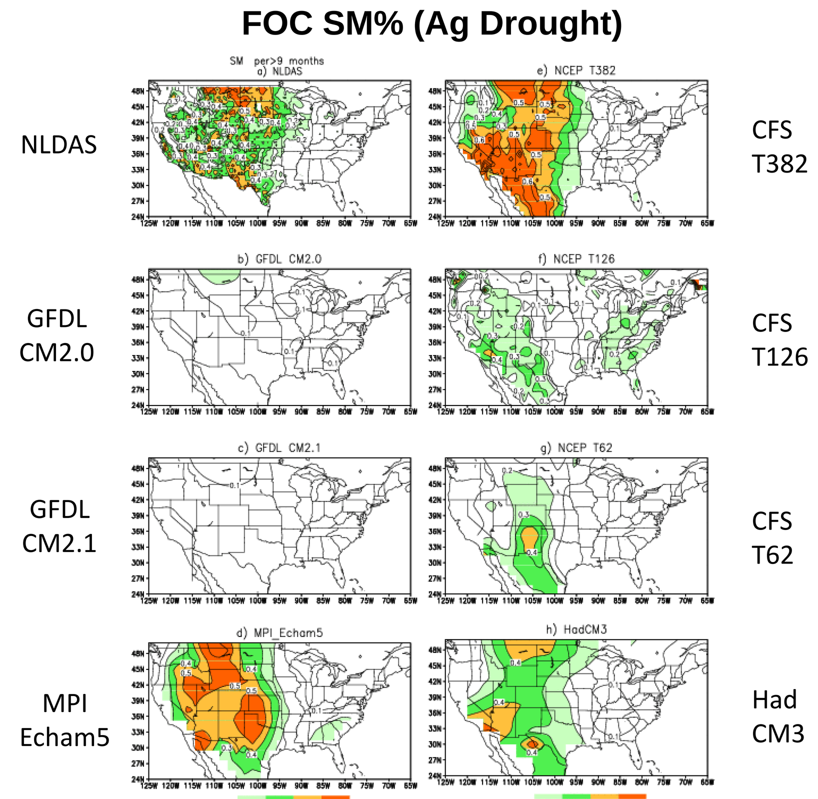
Extreme Events: An extreme negative (positive) event is selected when the SPI6 index or the SM percentile is below (above) a certain threshold for 3 or more months.
Thresholds for dry(wet) events: SPI = -0.8(0.8) and SM% = 20% (80%)

Frequency of Occurrence (FOC) = $\frac{\text{Np (number of months that extreme events persist over 9 months)}}{\text{N (number of months that extreme events occur)}}$

FOC SPI6 (Meteo Drought)



FOC SM% (Ag Drought)



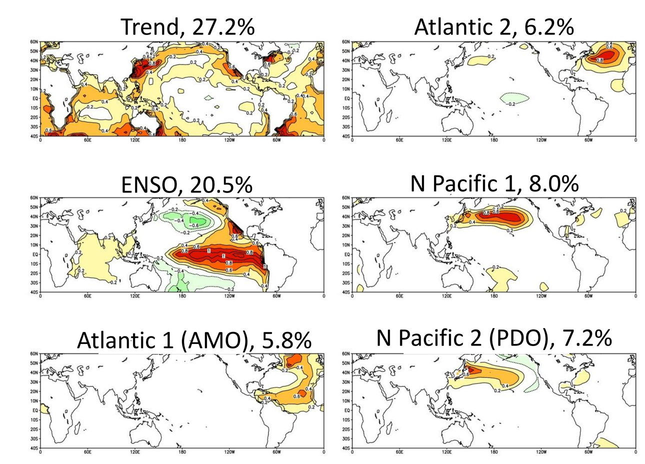
There are **two hydroclimate regimes** over the United States (US). The western interior region is very dry, and drought is more likely to persist for more than 6 months. The eastern US, is relatively wet and rainfall anomalies are less persistent. The **east-west contrast** is evident in the top left plots above for both SPI6 and SM%. The variability in the N central US in the SM is because of snow melt not contained in SPI6.

For both types of drought, the **CFS T382 best captures the variability**. For meteorological drought (SPI6), the CFS T126 is not as pronounced as observed, while the CFS T62 maximum is shifted southeastward. The HadCM3 shows the maximum in the correct location, but the magnitude is too low. The other models do not capture the east-west contrast. For agricultural drought, the MPI Echam5 and HadCM3 also capture the variability. The CFS T126 and T62 do show extreme events in the west, but miss the snow melt in the north. The CFS T126 also shows too many events in the southeast.

SST Modes in Models

The seasonal cycle provides favorable conditions for P anomalies to persist but does not trigger drought. Over the US, **drought is modulated by ENSO**. A model must have the correct SSTA modes, and also capture the P responses to these modes, in order to simulate realistic drought characteristics.

Rotated EOF on Observed annual mean SSTAs



Rotated EOF Analysis on Observations (right):
- Trend mode – shows warming trends in the three southern oceans. Drought and wet spells over the western mountains and Southern Plains are often influenced by long term trends. The trend mode enhances the persistence of P.
- ENSO mode - modulates drought. Has a large impact on P over the US.
- Atlantic SST modes - represent the evolution of SSTAs in the Atlantic. Atlantic Multi-Decadal Oscillation (AMO) modulates the ENSO impact on P over the US.
- Pacific SST modes - the North Pacific mode and the Pacific Decadal Oscillation (PDO). The PDO modulates the impact of ENSO on P over the west in winter. Both modes have impact on droughts over North America in summer.

SST Modes and Variance

Model	Trends	ENSO	ATL1	ATL2	NPAC1	NPAC2
Observed	27.2	20.5	5.8	6.2	8.0	7.2
GFDL CM2.0	-	14.2	6.8	-	22.0	4.8
GFDL CM2.1	7.1	27.3	-	-	-	3.2
MPI Echam5	-	22.4	7.9	7.2	-	5.1
HadCM3	-	14.7	6.7	-	3.1	10.3
CFS T382	19.2	39.0	-	5.1	4.1	7.2
CFS T126	-	17.3	-	9.3	-	5.7
CFS T62	-	29.4	-	10.2	4.0	-

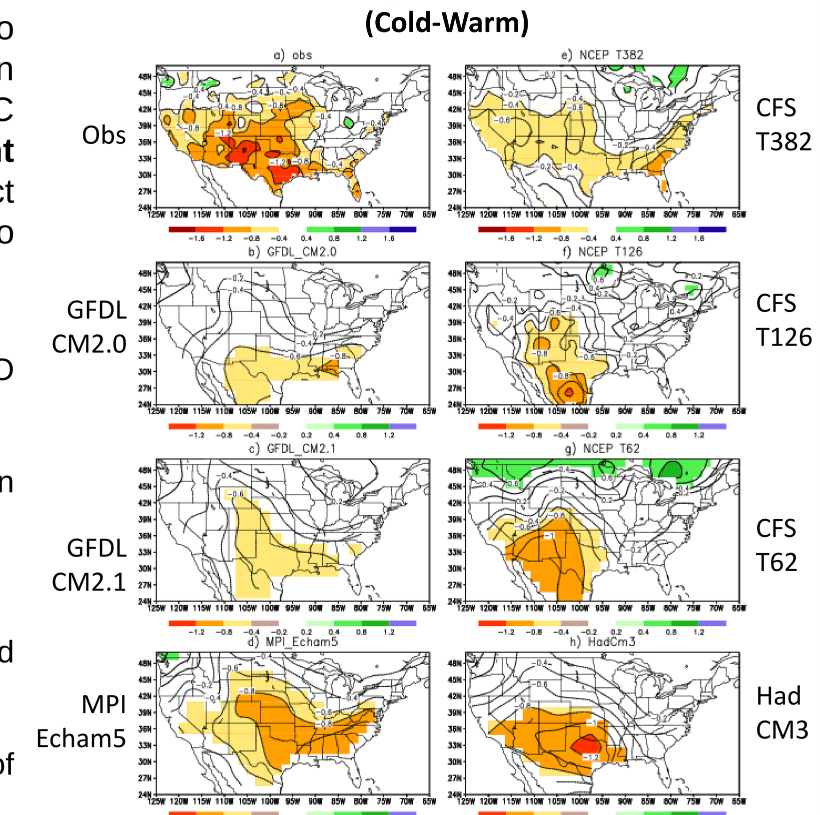
CFS T382
- ENSO mode dominates impact of SSTAs on P (39% of variance). Caused by one run with 4-yr oscillations between warm and cold ENSO
- Has mode similar to trend mode, but variance explained is too small, does not impact P.
- Does not have Atlantic 1, but has mode similar to Atlantic 2. Because each member is only 50-yrs, it is difficult to isolate multi-decadal variations like AMO and PDO.

Other models
- ENSO mode is also dominant mode (14-29% of variance). Not all models have two Pacific and Atlantic modes.
- MPI Echam5 and HadCM3, which have longer runs, both have Atlantic 1 similar to AMO mode with a decadal cycle. They also have a mode similar to PDO, but it does not have clearly defined decadal cycles.

Response to SST Forcing

All models have the ENSO mode, but some are not able to capture the impact of ENSO on P and SPI6. The similarity between the pattern of the ENSO SPI6 composite difference (top left) and FOC suggests that **ENSO plays a major role in modulating persistent events.** Models must exhibit ENSO and be able to capture the impact of ENSO on SPI6 or the low frequency component of P in order to simulate realistic drought.

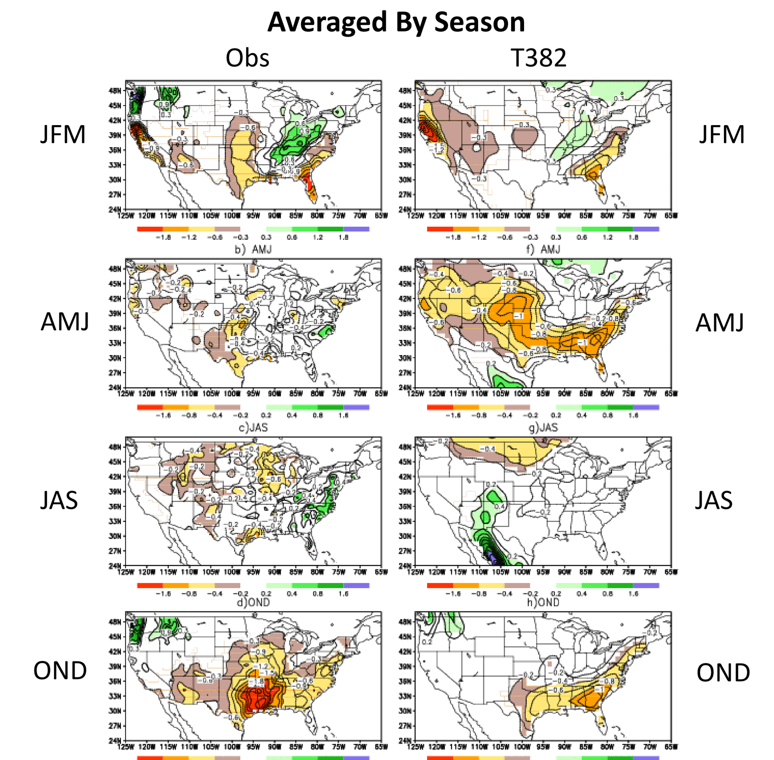
ENSO Composite SPI Difference (Cold-Warm)



Observations:
Southwest and Great Plains – Dryness/wetness during cold/warm ENSO events.
Eastern Region – Weak anomalies along Gulf coast and Florida because:
1. Weak P seasonal cycle and wetness over the region. Lack of rainfall in winter can be compensated by summer rainfall or vice versa
2. ENSO has opposite impact on rainfall for summer and winter

Models:
GFDLs, MPI Echam5: Negative SPI6 values located over Gulf States and SE
CFS T126 and T62: Large negative values over SW and errors in N
HadCM3: Captures SPI6 pattern well, but ENSO only explains 13% of variance. Explains realistic, but weak, pattern simulation of FOC.
CFS T382: Negative values over west and SE, captures east-west contrast well

ENSO Composite P Difference Averaged By Season



Seasonality of P During ENSO
There are two possibilities for why P errors occur:
1. The model is not able to capture atmospheric responses to ENSO.
2. The model simulates the atmospheric responses, but is not able to capture rainfall.

Which errors occur in the CFS T382 model?

Observations:
JFM: Dryness over CA, SW, Great Plains and East Coast, wetness over the Pacific NW and Ohio Valley
JAS: Wetness over the East Coast. Some rainfall is caused by tropical storms a coarse resolution model is unlikely to capture.

CFS T382: Realistic ENSO SPI composite, but seasonal ENSO P composites have errors.
JFM: Does not capture positive anomalies over Pacific NW, anomalies over Great Plains are too weak.
AMJ: Overly strong negative anomalies.
JAS: Too wet in SW, misses wetness in east, no tropical storm landfalls?
OND: Captures negative anomalies over Great Plains and SE, but magnitudes are too weak.

So, the **model only needs to capture low frequency P** responses to ENSO to simulate realistic drought.

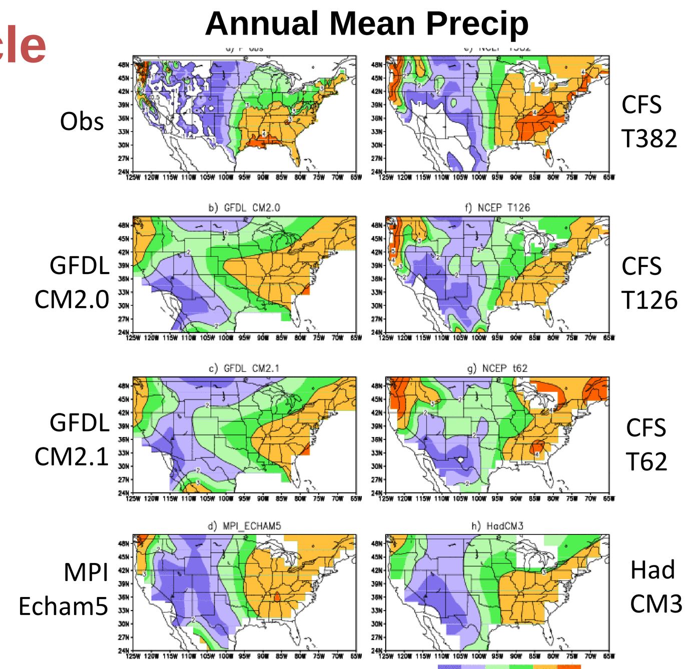
Seasonal Cycle

Observations:
Western Interior:
Little rainfall, large water holding capacity, small annual cycle

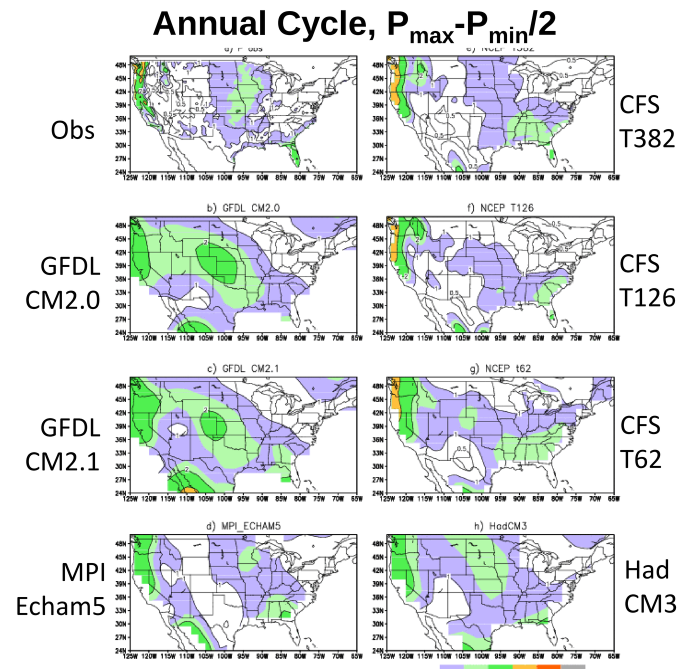
Central US:
Strong seasonal cycle

Southeast:
Wet, rain consistent throughout the year, drought is relieved quickly so extreme events are rare.

Annual Mean Precip



Annual Cycle, P_{max}-P_{min}/2

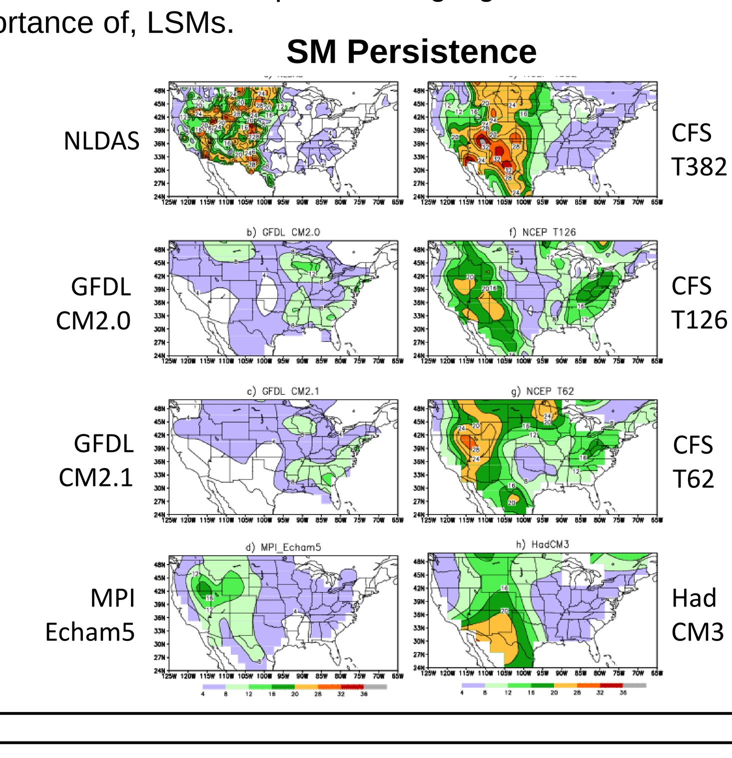


Models: To capture east-west contrast of FOC, **P climatology must capture dry west and wet east**. If the seasonal cycle is too strong in the west, then drought is less likely to persist due to the possibility of increased rainfall during the rainy season. The west and central US have the largest FOC values, so they are most susceptible to errors.

- CFS T382: Realistic annual mean and seasonal cycle. Captures dryness over west. Overestimates annual rainfall in wet region, but FOC is small, so net influence is small.
- CFS T126, MPI Echam5 and HadCM3: Drier in SE with weak seasonal cycle over western interior. Driest areas over the SW are also areas with large FOC values.
- GFDL CM2.0 & CM2.1 and CFS T62: Too wet and seasonal cycle too strong over west. It rains often. If an area is under drought, rainfall in the following seasons could relieve the situation.

FOC and SM persistence have a good correspondence. Soil moisture doesn't trigger drought, but persistence of soil moisture (measured by T_o) will prolong agricultural drought.
- NLDAS shows east-west contrast
- Anomalies for GFDL models don't persist, consistent with FOC
- HadCM3 and MPI_Echam5 capture east-west contrast but underestimate the values of T_o
- NCEP models show large T_o over western region, but maxima are located in different places. Highlights differences in, and importance of, LSMs.

SM Persistence



Conclusions

- Two hydroclimate regimes exist over the US
  - CFS T382 captures this FOC pattern for both meteorological (SPI6) and agricultural (SM) drought
  - HadCm3 and MPI Echam5 capture the contrast in SM
- P climatology must capture dry west and wet east
  - Strong seasonal cycle in west means drought is less likely to persist
- Model must have the correct SSTA modes and capture P responses to these modes
- ENSO SPI6 composite difference and FOC similarities suggests ENSO plays a major role in modulating persistent events.
  - Model only needs to capture low frequency P response to ENSO to simulate the east-west contrast of the FOC
- NCEP CFS T382 model, and HadCM3 to a lesser degree, are able to capture most of these features

- **Future work**
  - Compare CFS T382 to long-term simulations with CFS T126 and T62 using Noah LSM for true resolution comparison
  - Further analysis using CMIP 5 model simulations