Drought: Monitoring, Estimation and Prediction

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Drought – nature of the problem

- Annual cost of $6-8 billion in the U.S. (higher than other natural disasters like earthquakes and hurricanes)
- 1988 drought cost ~$62 billion (most costly U.S. disaster before hurricane Katrina)
- Significant social consequences (e.g. Dust Bowl)
- Challenges in operational drought monitoring
- How have drought characteristics changed in the 20th century?
- Short-term and long-term forecast/prediction

Outline

- Drought characterization using model-derived indices
- Drought real-time monitoring (national and regional)
- Forecast of drought recovery
- 20th century U.S. (single- and multi-model) drought history reconstruction
- Global drought characterization

Existing methods for drought characterization

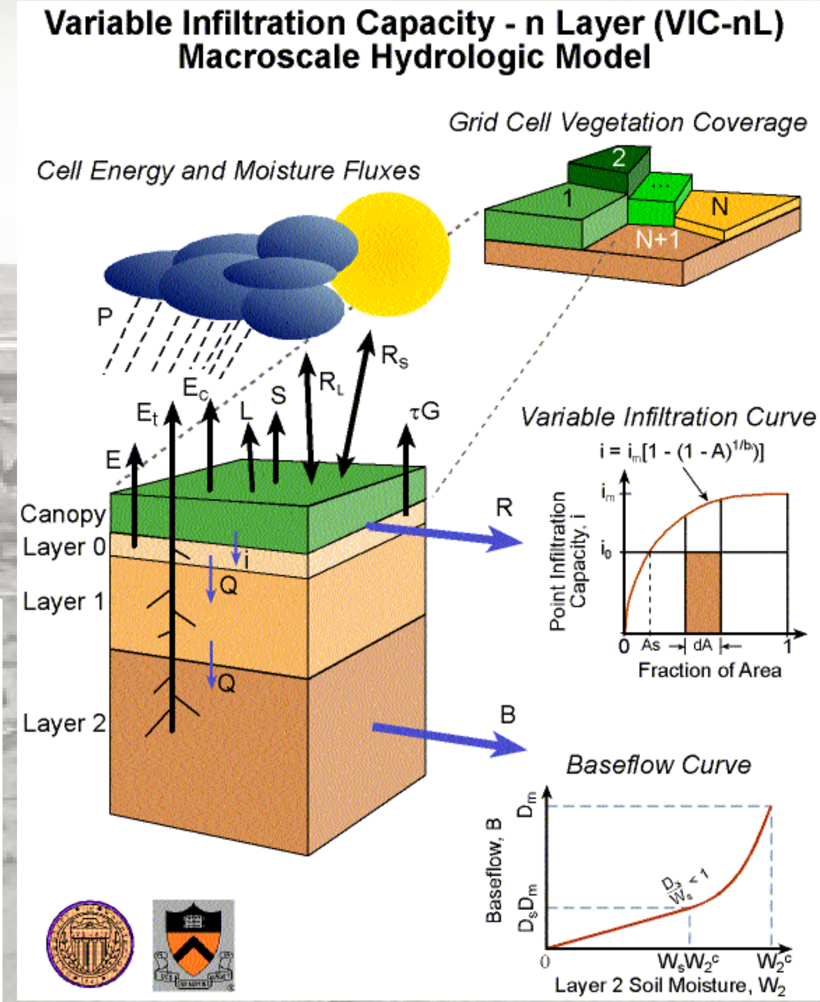
- Palmer Drought Severity Index (PDSI)
  - Simple water balance approach, standardized
  - Problems with cold land processes
  - Different termination criteria for different types of drought
- Standardized Precipitation Index (SPI)
  - Precipitation deficit for multiple scales
  - Index differentials correspond to different probabilities of occurrence
- Surface Water Supply Index (SWSI)

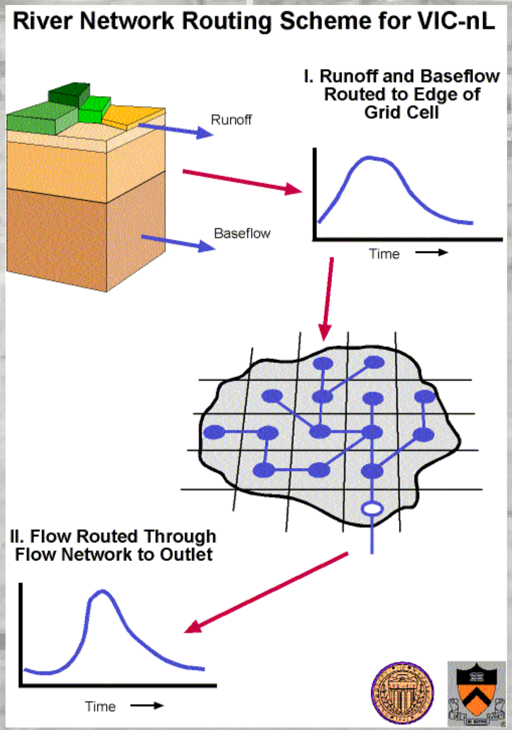
An alternative approach

- Use of hydrology models to produce spatially and temporally continuous dataset of variables **directly** related to drought
- Soil moisture and streamflow
- Long-term precipitation and temperature U.S. dataset (1915-present)
- Need method for objective identification and estimation of drought characteristics
- Allows for consistent monitoring and prediction of drought conditions

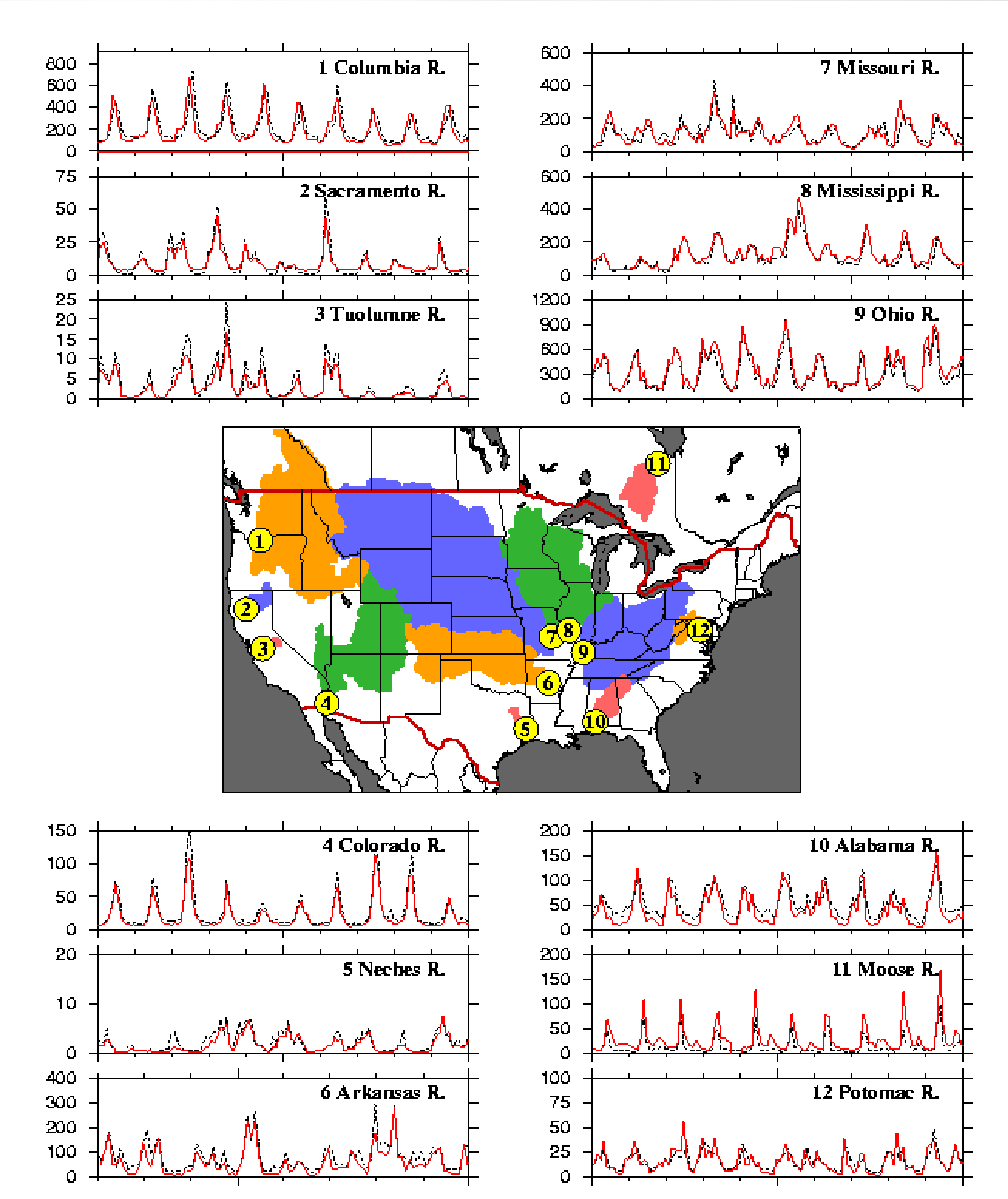
Variable Infiltration Capacity model

- Solves energy and water balance over gridded domain
- Sub-grid variability in topography, land cover and soil moisture
- Streamflow estimated by routing runoff and baseflow through stream network





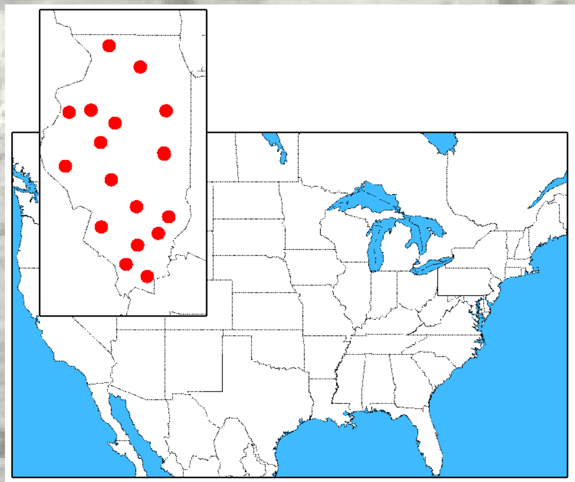
Streamflow evaluation



- Retrospective simulations (1950-99)
- Monthly streamflow compared between VIC and gauge measurements

Soil moisture evaluation

- Comparison with 19 soil moisture observing stations in Illinois



Obs.
Model

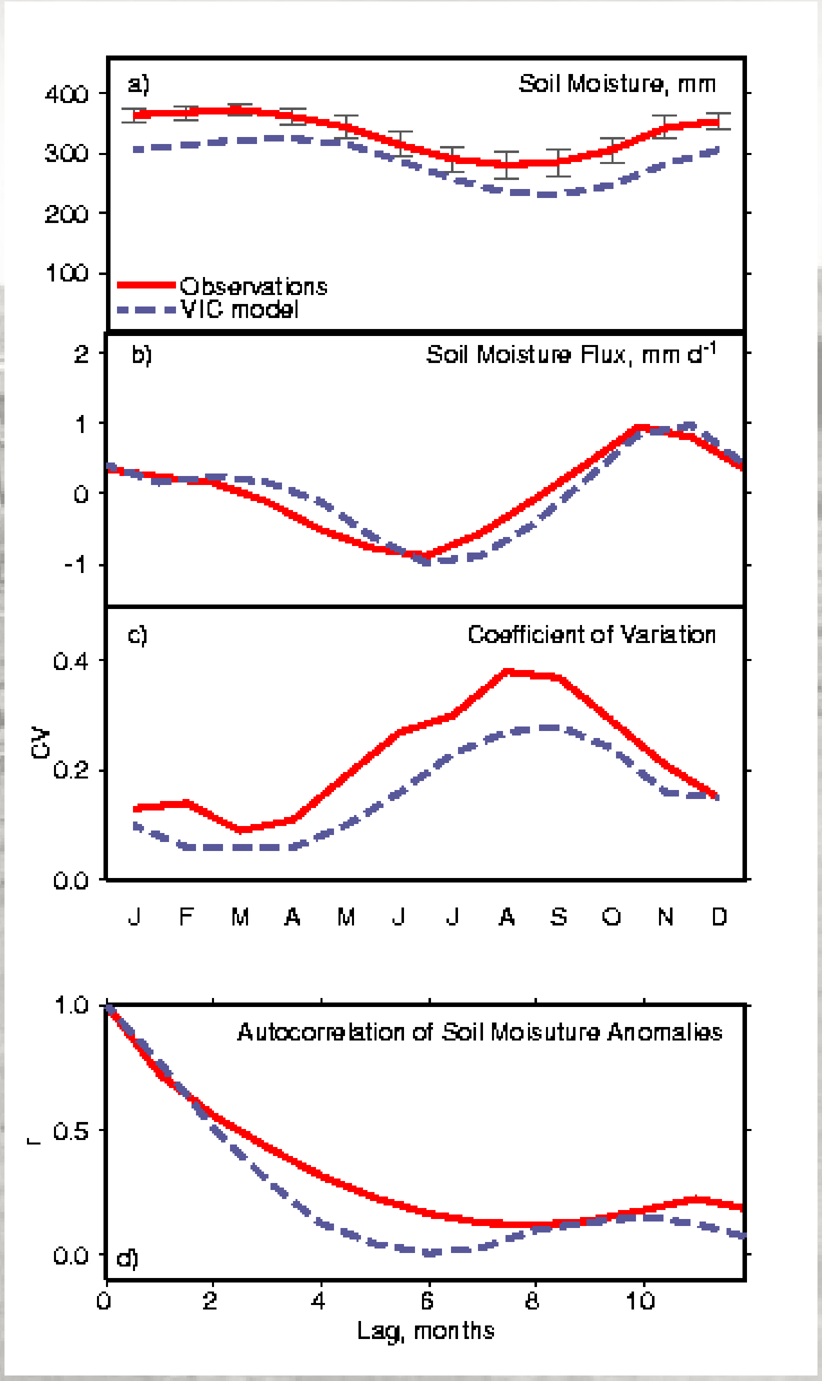
Maurer et al. 2002

Moisture Level

Moisture Flux

Variability

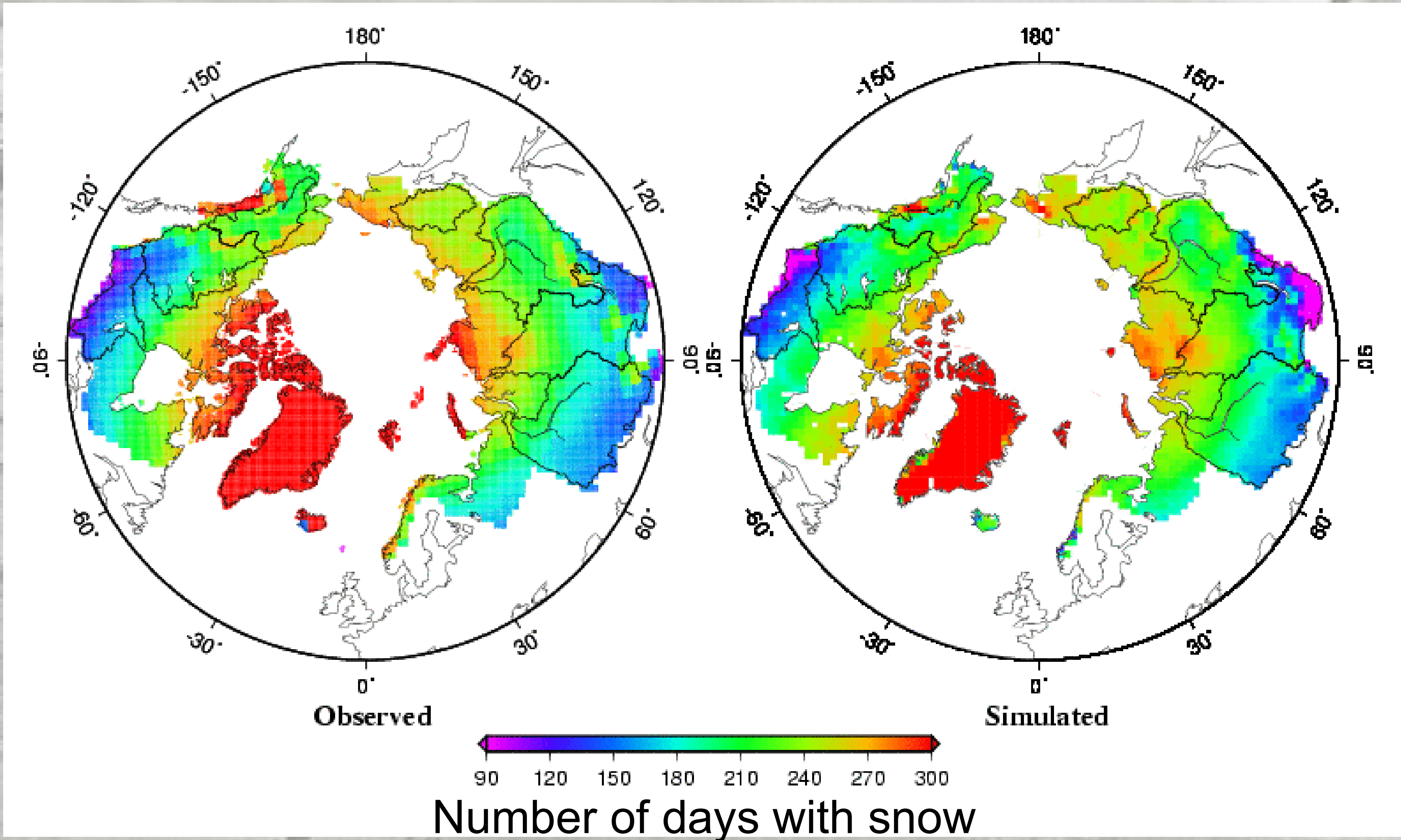
Persistence



Snow cover extent evaluation

NOAA-NESDIS weekly snow charts

VIC



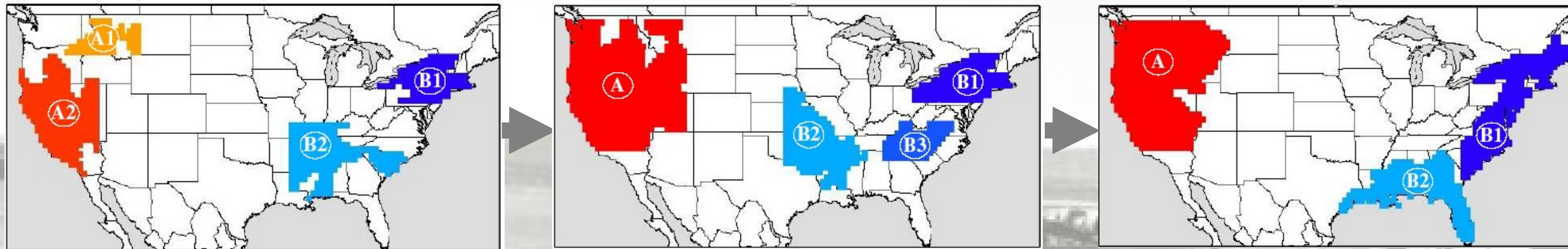
Drought characterization

- Soil moisture and runoff used as indicators of agricultural and hydrological drought
- Expressed as percentiles relative to climatology
- Drought defined from threshold
- Duration = number of consecutive time steps below threshold
- Severity = cumulative departure from threshold
- Intensity = duration-averaged severity

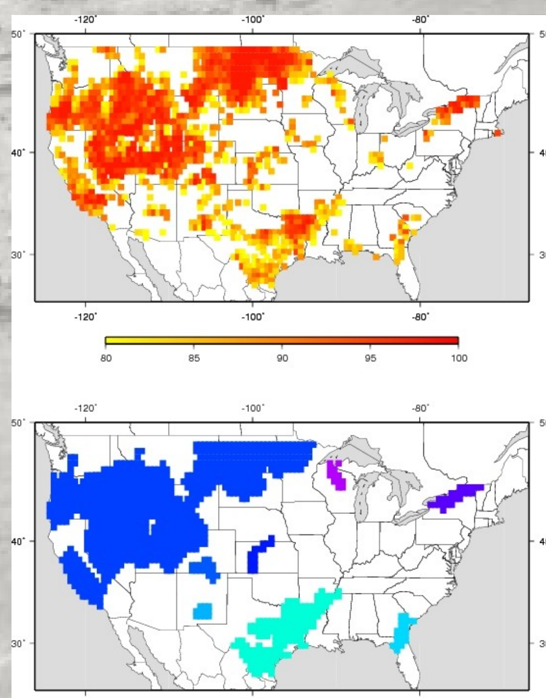
Drought spatial identification

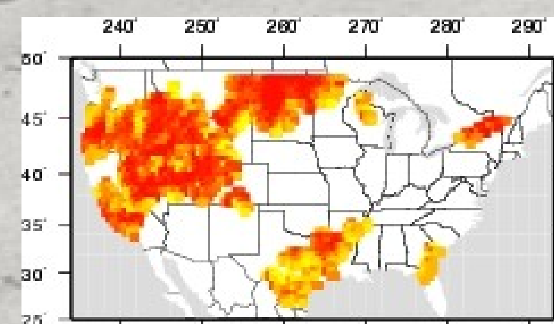
- Maps of soil moisture/runoff percentiles
- Spatial contiguity constraint used for initial drought segmentation
- Drought classification using constraints on
  - Minimum area
  - Minimum distance between drought "clusters"
  - Distance from drought "center"
- Temporal continuity constraint by
  - "drought tracking" in retrospective analysis
  - drought transition probability in real-time implementation

Month 1 Month 2 Month 3



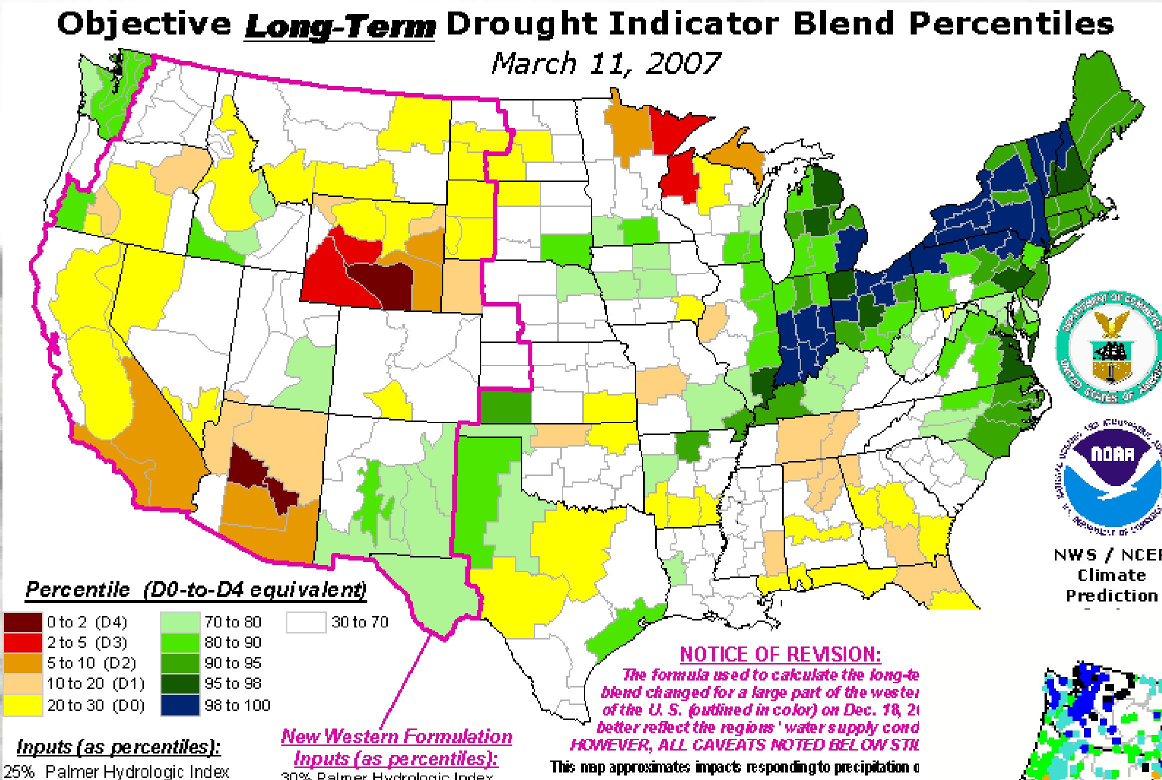
- Example classification and final drought severity map

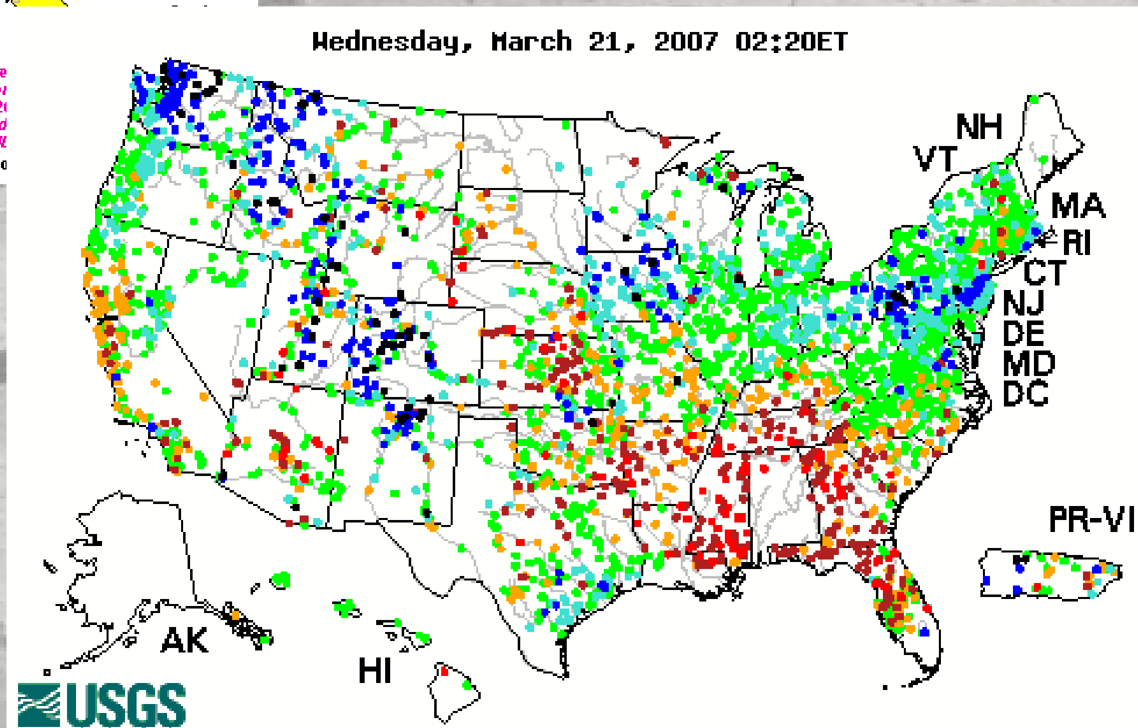




Drought Monitoring

U.S. Drought Monitor



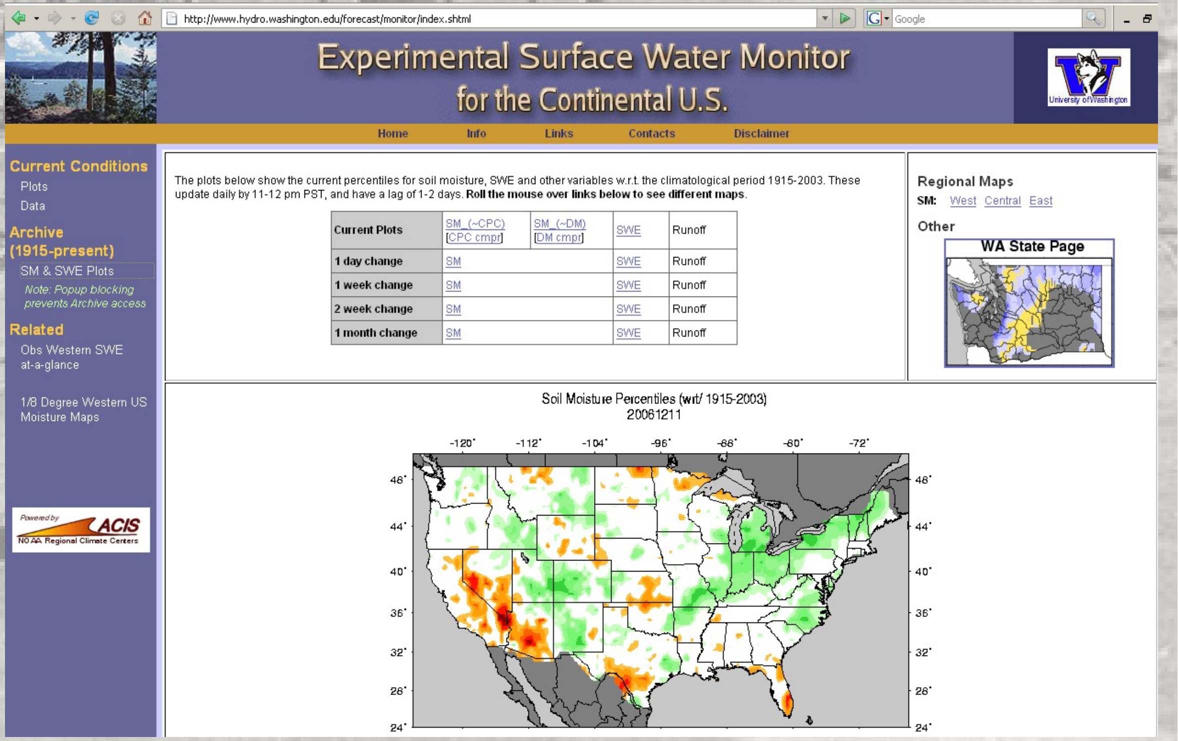


Inputs (as percentiles):

25% Palmer Hydrologic Index
20% 24-Month Precipitation
20% 12-Month Precipitation
15% 6-Month Precipitation
10% 60-Month Precipitation
10% CPC Soil Moisture Model

U.W. Surface Water Monitor

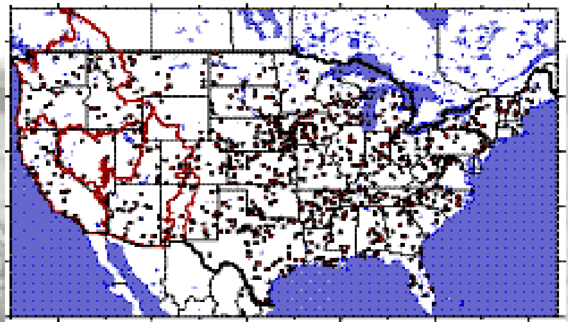
- Merges UW west-wide streamflow forecast system methods with NLDAS modeling advances
- Benefits from recent NCDC digital data record extension to 1915
- Provide daily maps of soil moisture, streamflow and SWE
- Additional products include 1-, 2- and 4-week changes



- http://www.hydro.washington.edu/forecast/monitor

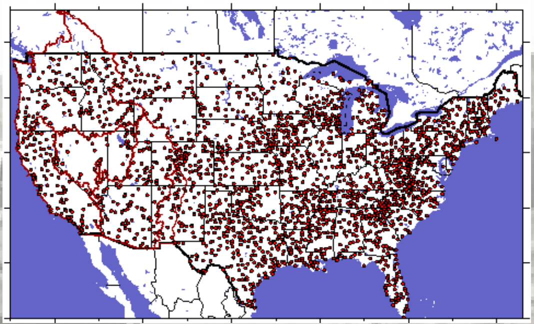
SW Monitor Schematic

1930s



NOAA ACIS
Prcp Tmax Tmin
Coop Stations

1955+



VIC Retrospective Simulation
Daily, 1915 to Near Current

Hydrologic
State

VIC Real-time
Spinup
Simulation

Hydrologic
State
(-1 Day)

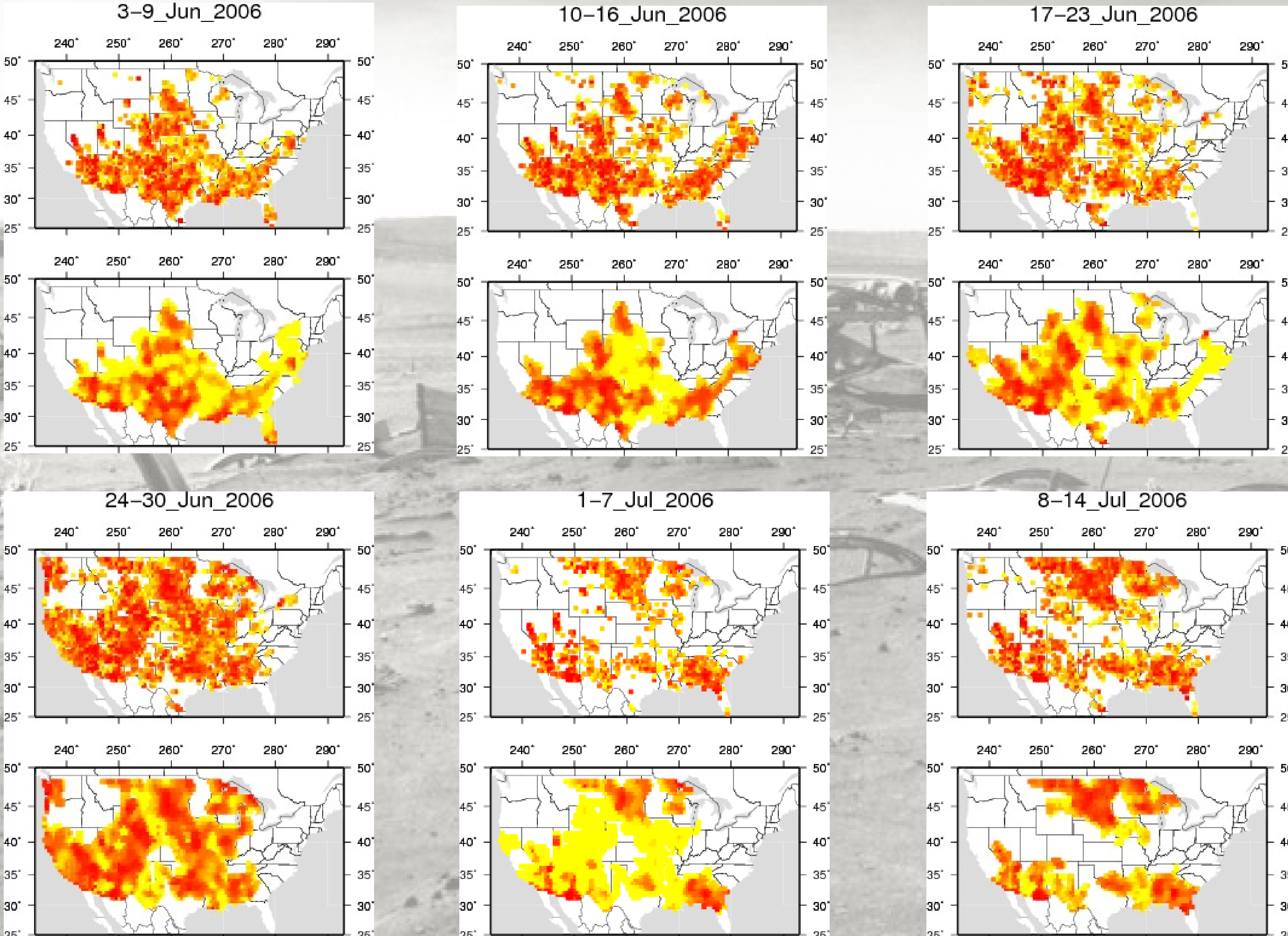
Hydrologic values,
anom’s, %-iles w.r.t.
retrospective **PDF**

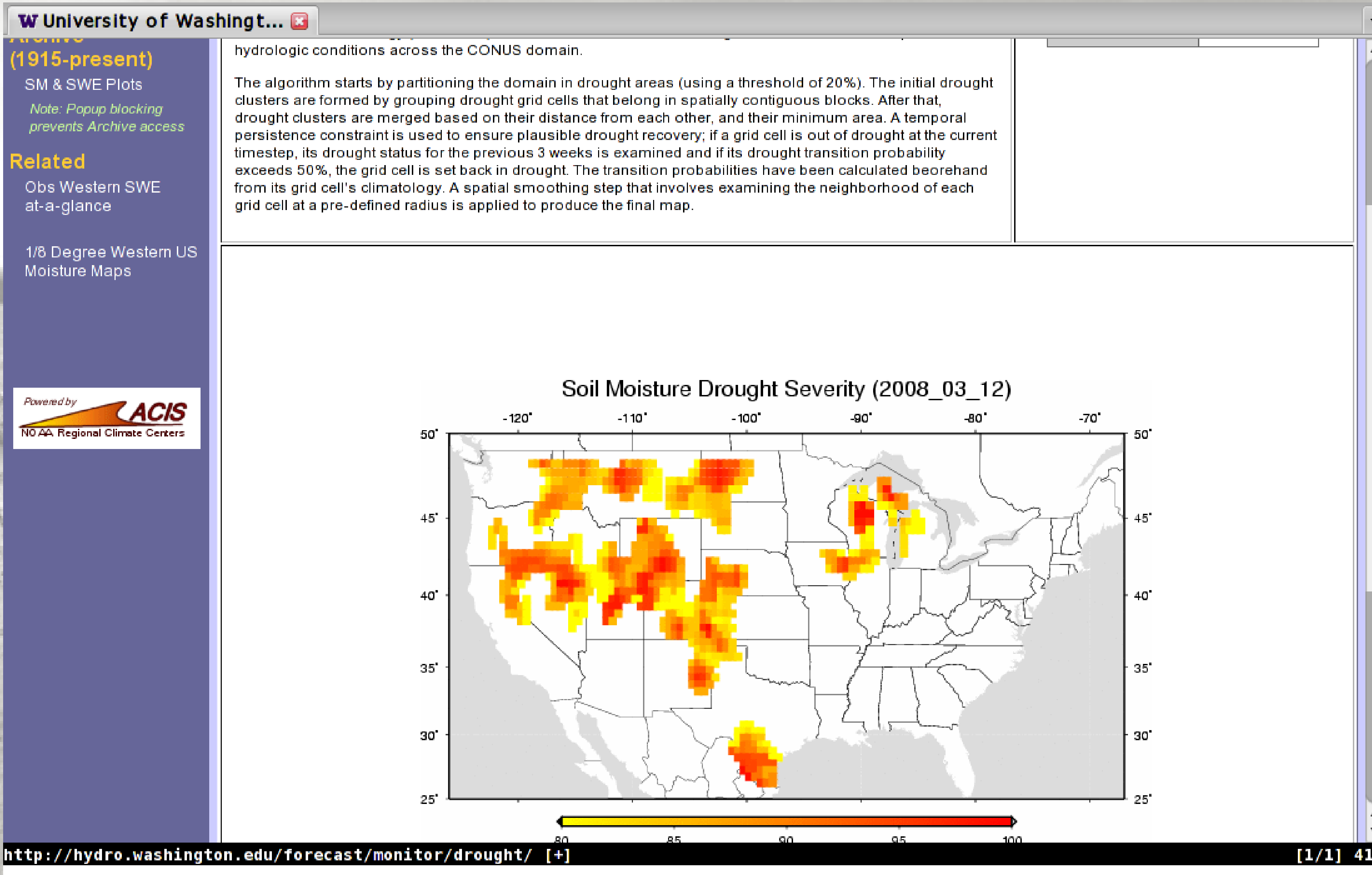
climatology (PDF)
of
hydrologic values
w.r.t. defined period

vals, anoms
%-iles
w.r.t. **PDF**

Weekly drought severity product

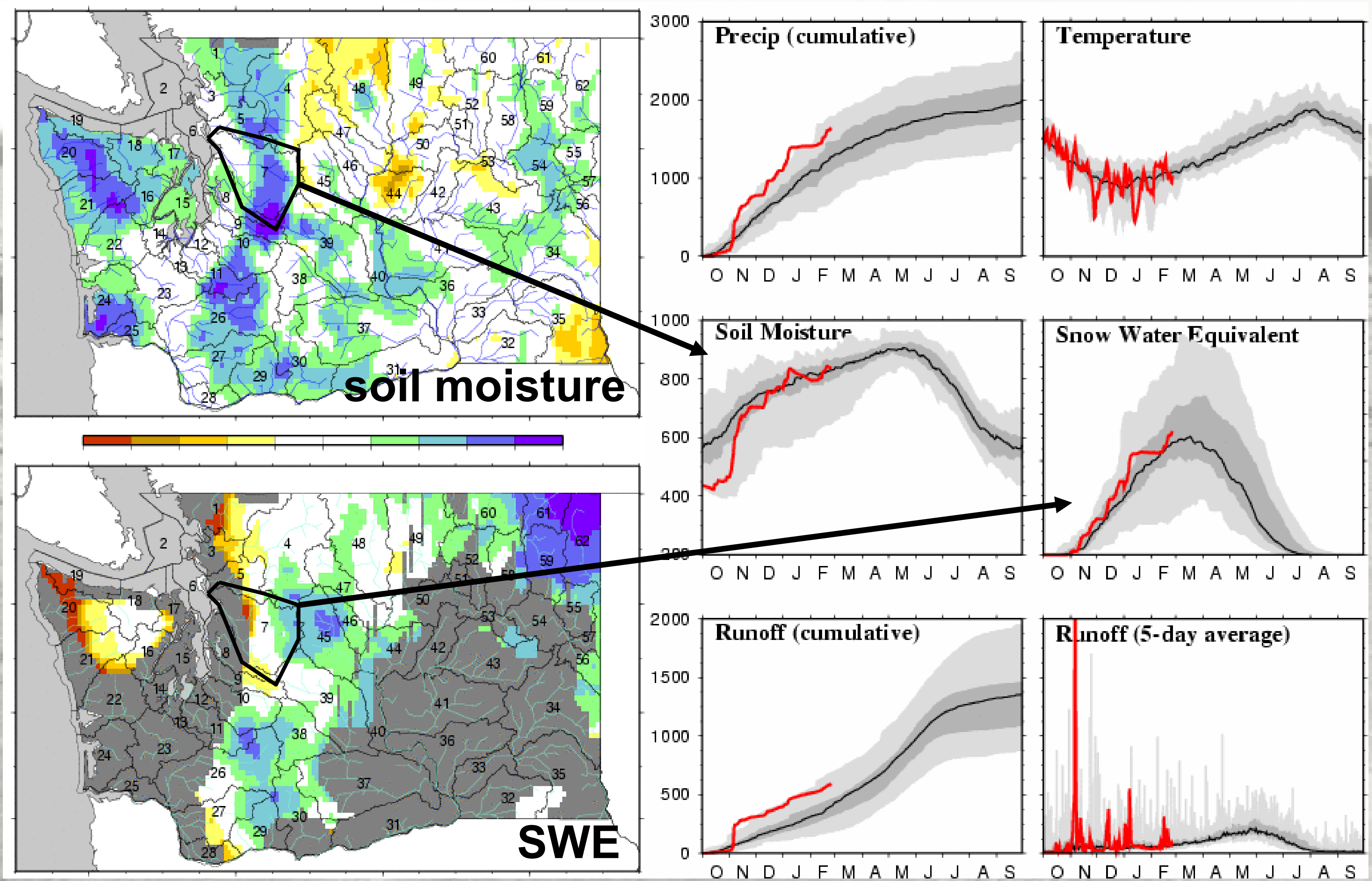
- Weekly soil moisture and runoff are expressed as percentiles (relative to climatology)
- Droughts are identified using similar methodology
- Only difference is that persistence is introduced by calculating drought transition probabilities from climatology (based on 3, 2, 1 week drought conditions)
- Pixels are kept in/out of drought based on 50% threshold on transition probability


3–9_Jun_2006
10–16_Jun_2006
17–23_Jun_2006
24–30_Jun_2006
1–7_Jul_2006
8–14_Jul_2006
240° 250° 260° 270° 280° 290°
50° 45° 40° 35° 30° 25°



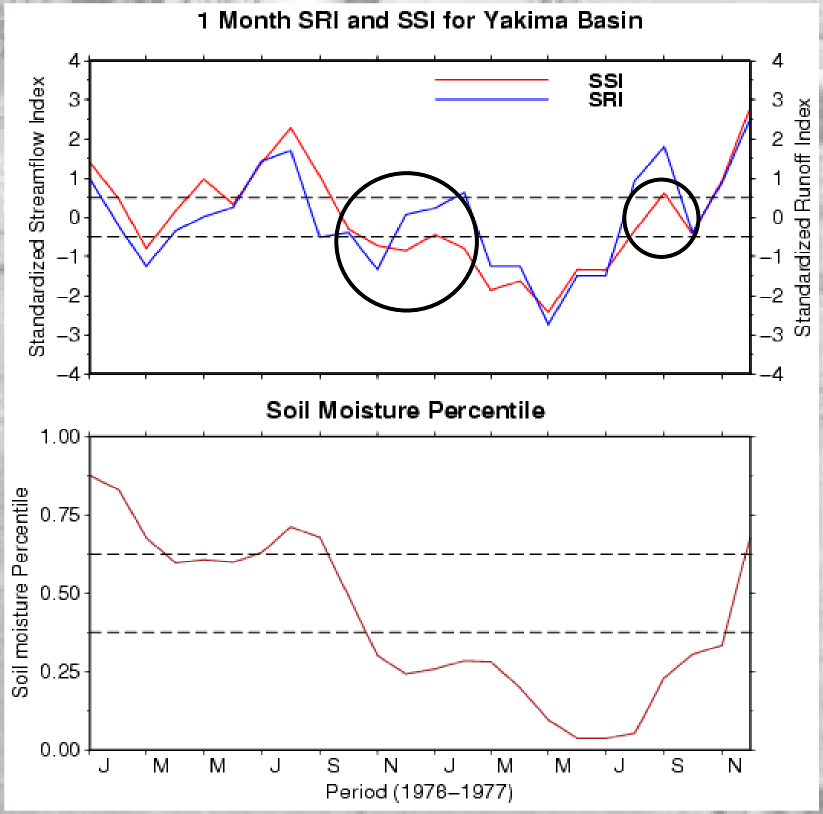
- http://www.hydro.washington.edu/forecast/monitor/drought

Regional monitoring (WA state)

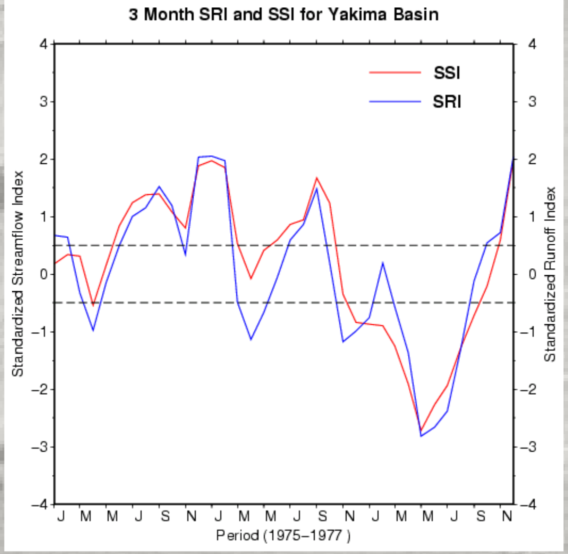


Standardized Runoff Index

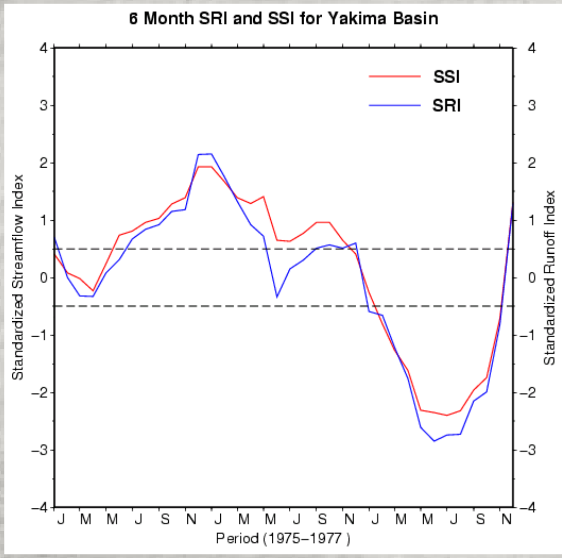
- Similar to SPI but using runoff (*Shukla and Wood*, 2007)
- Example of 1976-77 WA drought



3-month SRI



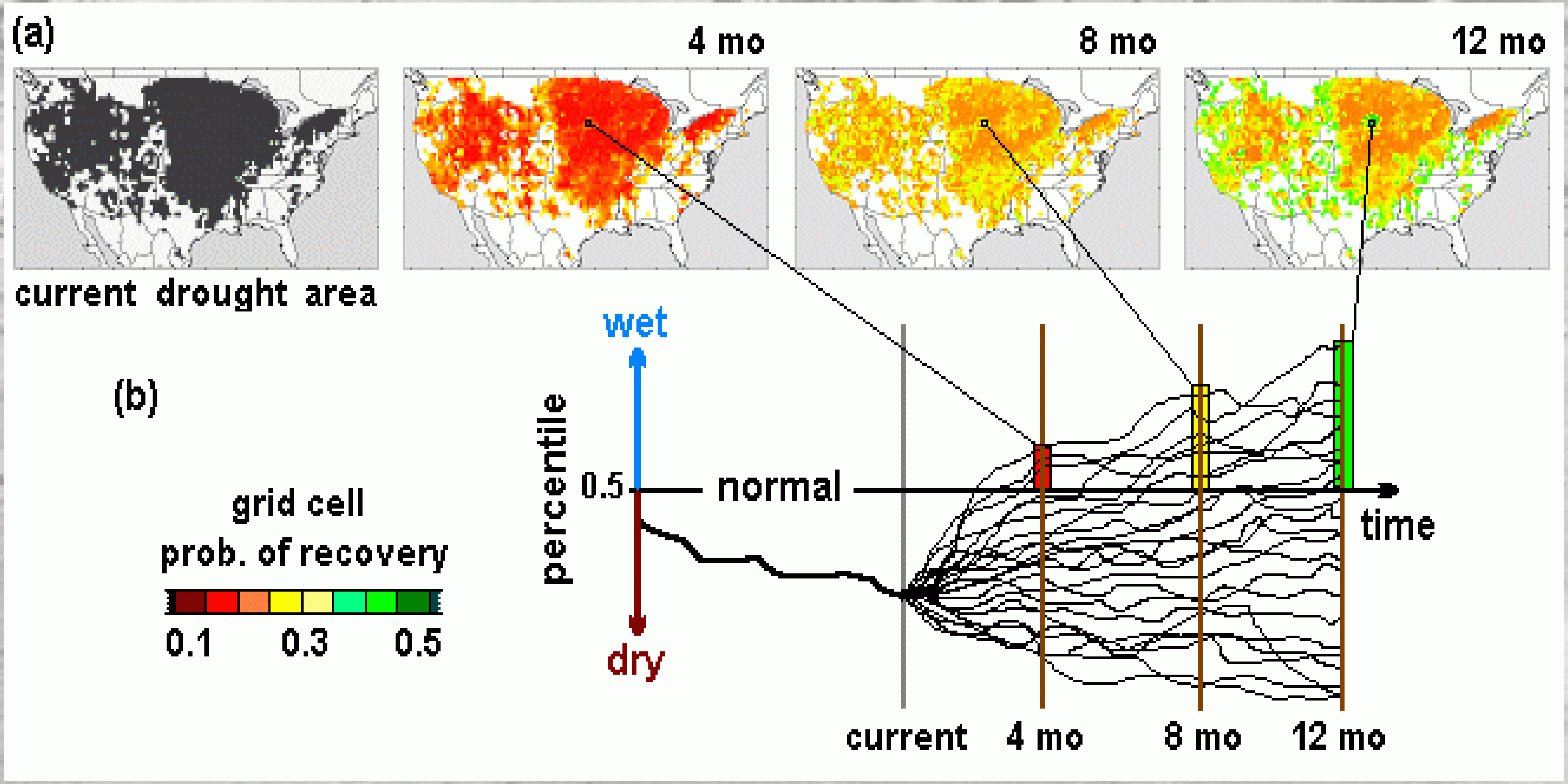
6-month SRI



Drought Recovery Forecasting

Drought recovery – the concept

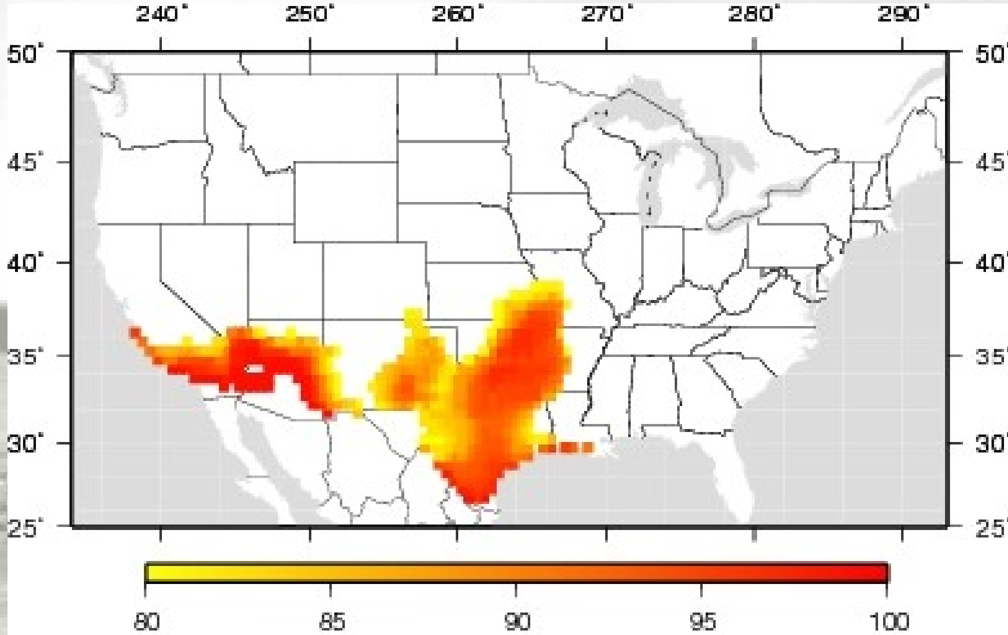
- Ensemble forecast of soil moisture/runoff conditions
- Probability of recovery at different lead-times



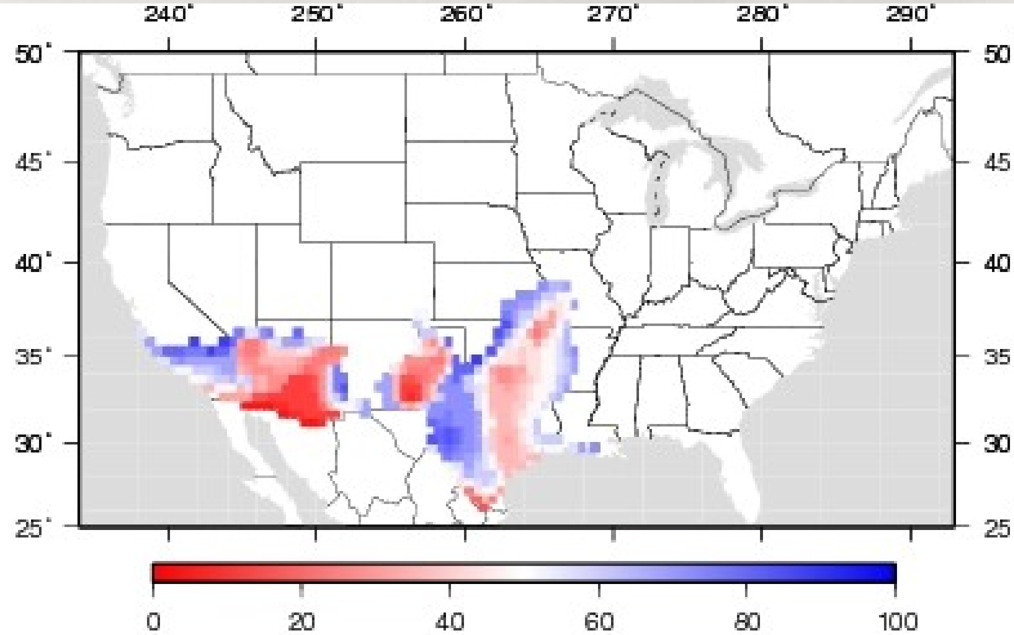
Drought recovery forecast example

- Hindcast example with southwestern U.S. drought of 2006
- Initial soil moisture conditions from VIC on 2/2006
- ESP forecast out to 6 months
- Probability of recovery = fraction of ensemble members with spatially averaged soil moisture percentile greater than drought threshold (0.20)

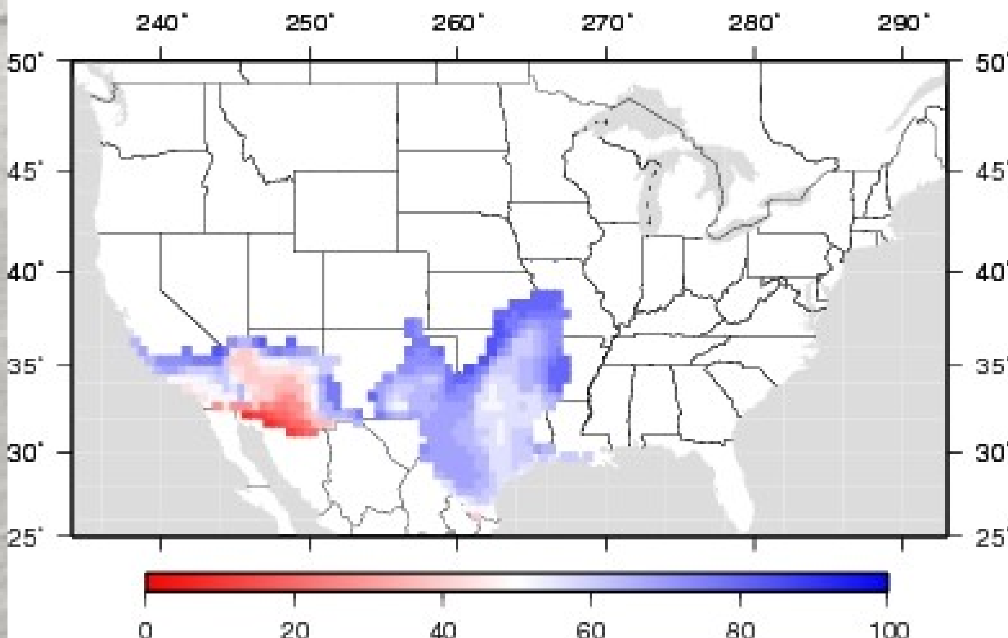
Initial drought severity (2/2006)



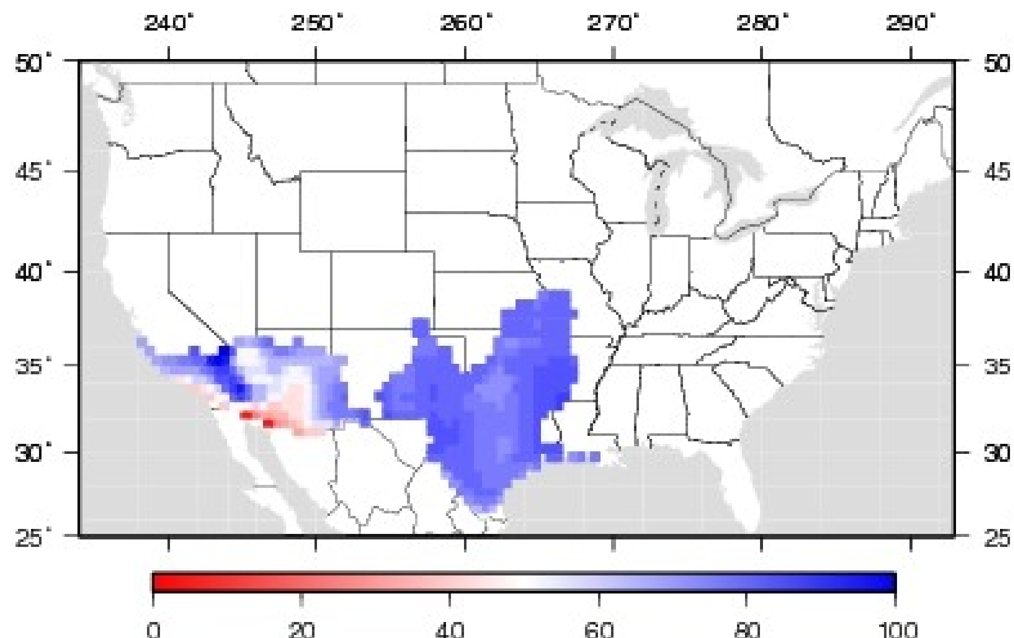
1-month lead forecast (3/2006)
Probability of recovery



3-month lead forecast (8/2006)



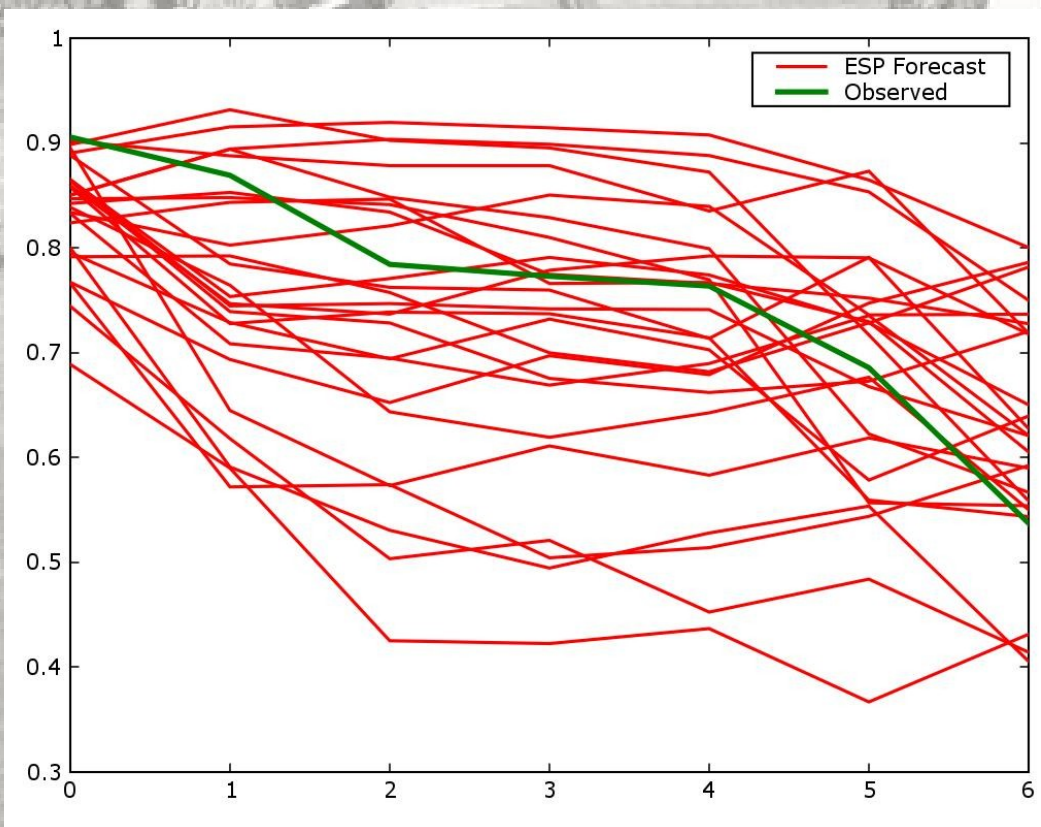
6-month lead forecast (8/2006)



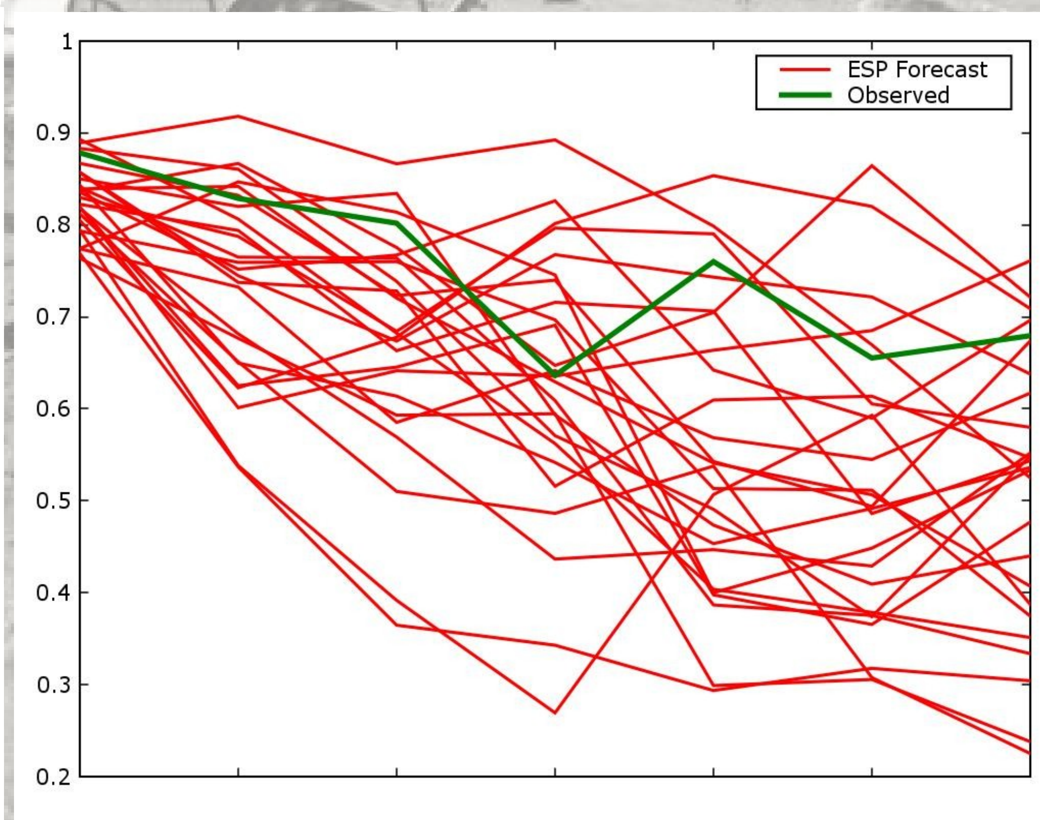
ESP forecasts

- Spatially-averaged drought severity (0-1) for each ensemble member along with "observed" severity

California-Arizona Drought



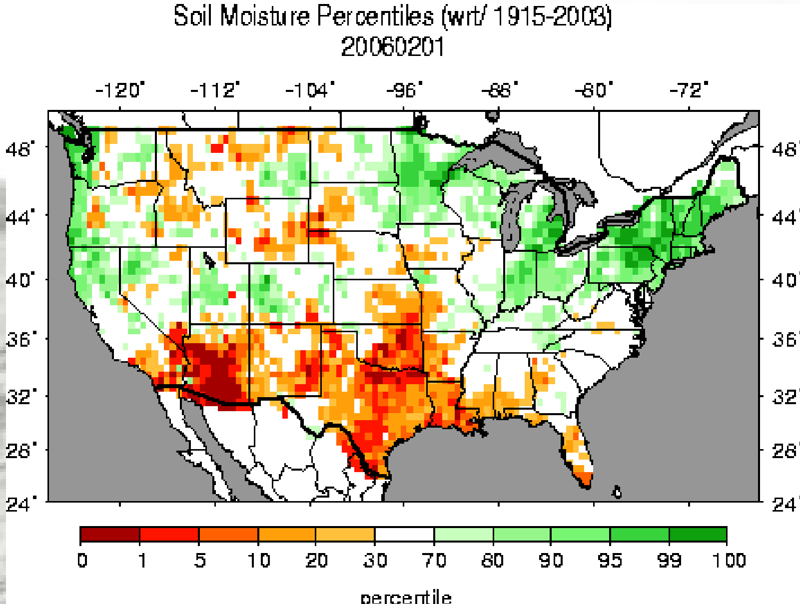
Texas Drought



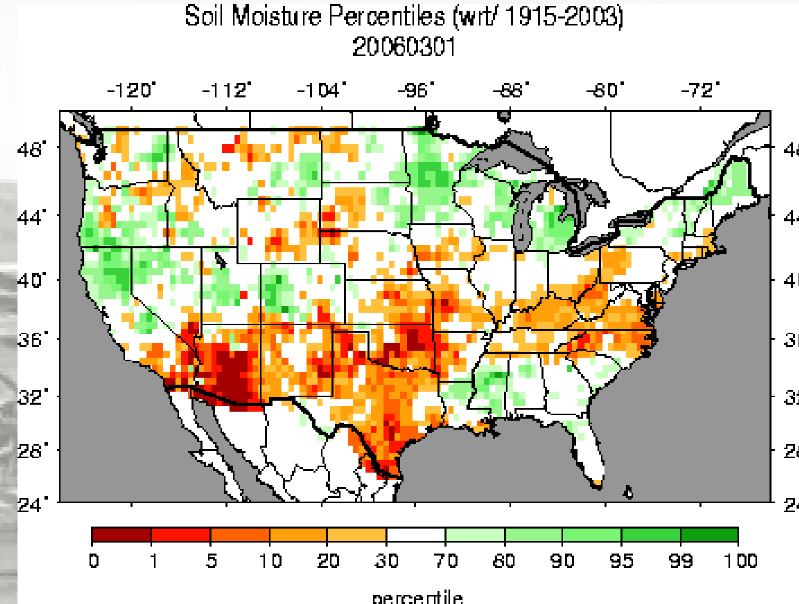
Forecast lead-time (months)

"Observed" conditions

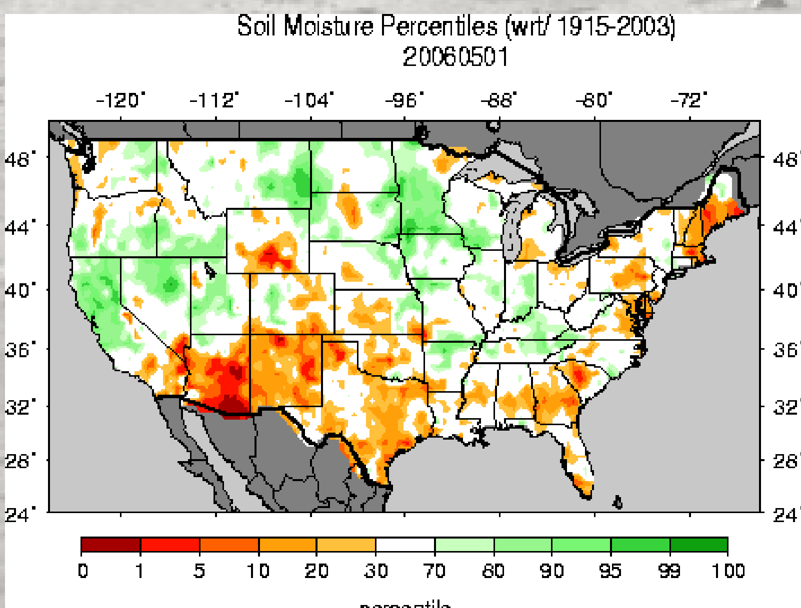
Initial Condition



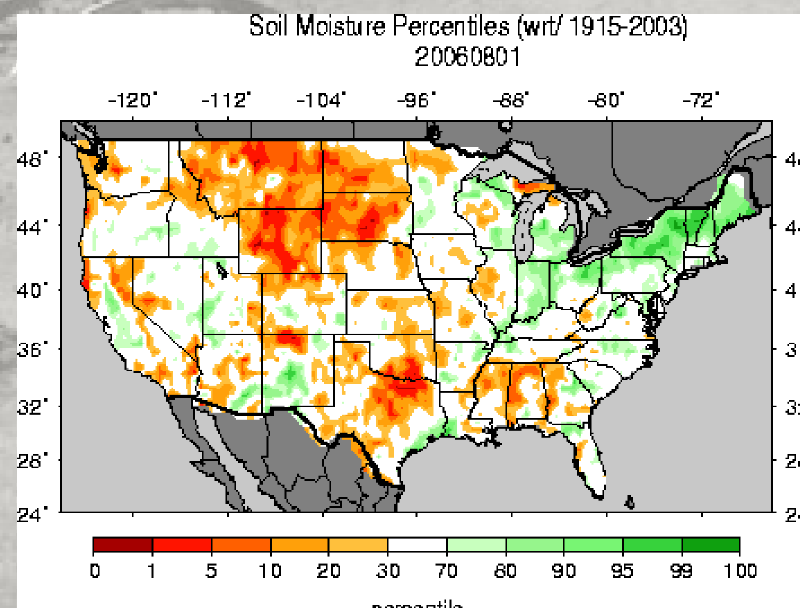
1-month lead forecast



3-month lead forecast



6-month lead forecast



U.S. Drought History Reconstruction

U.S. drought history reconstruction

- From drought classification maps we can calculate drought characteristics
  - Severity
  - Duration
  - Spatial extent
  - Intensity
- Historical comparison of U.S. 20th century droughts using Severity-Area-Duration analysis
- Examination of trends in drought characteristics

Severity-Area-Duration analysis

- Based on Depth-Area-Duration technique
- Starts at pixel with maximum drought severity and proceeds to the next most severe pixel of its neighborhood until all pixels belonging to drought are counted
- Spatially-averaged severities are calculated for different area categories (most severe 10, 20, 50 pixels etc)
- These severities are cumulative departures for pre-selected durations

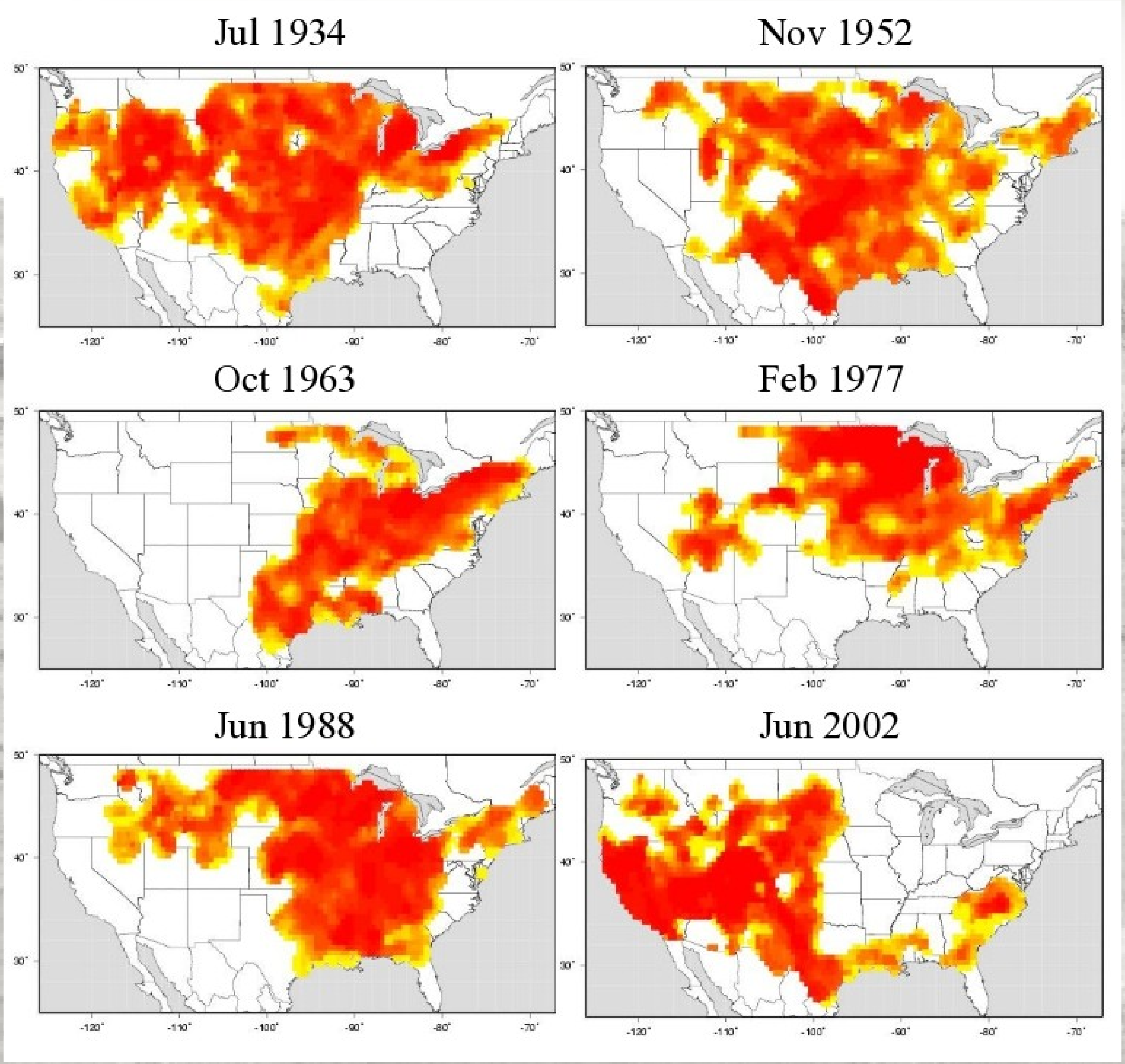
$$S = 1 - \frac{\sum P}{t}$$

S: severity

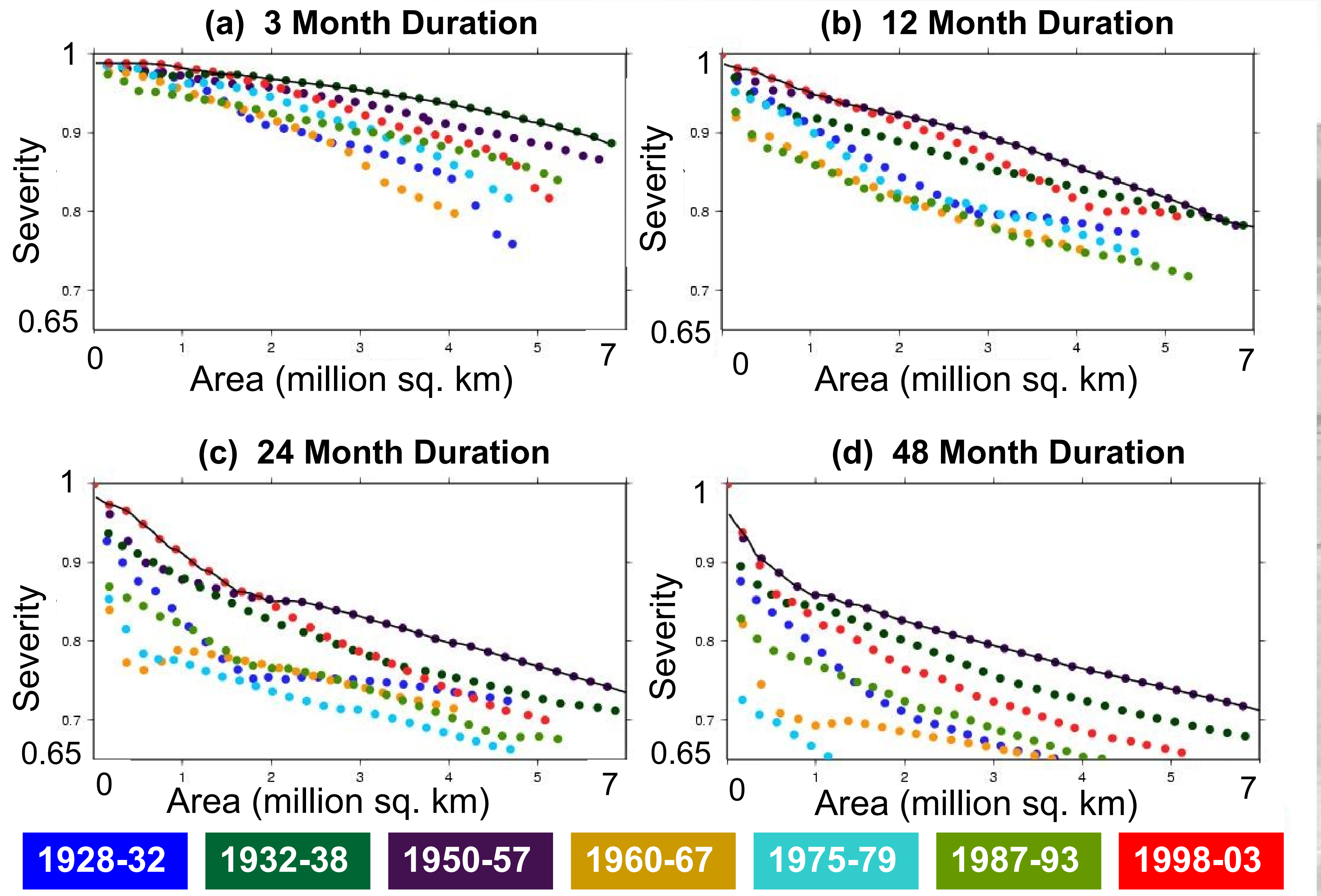
t: duration

P: percentile of soil moisture (runoff)

20th century agricultural drought



Soil moisture SAD curves



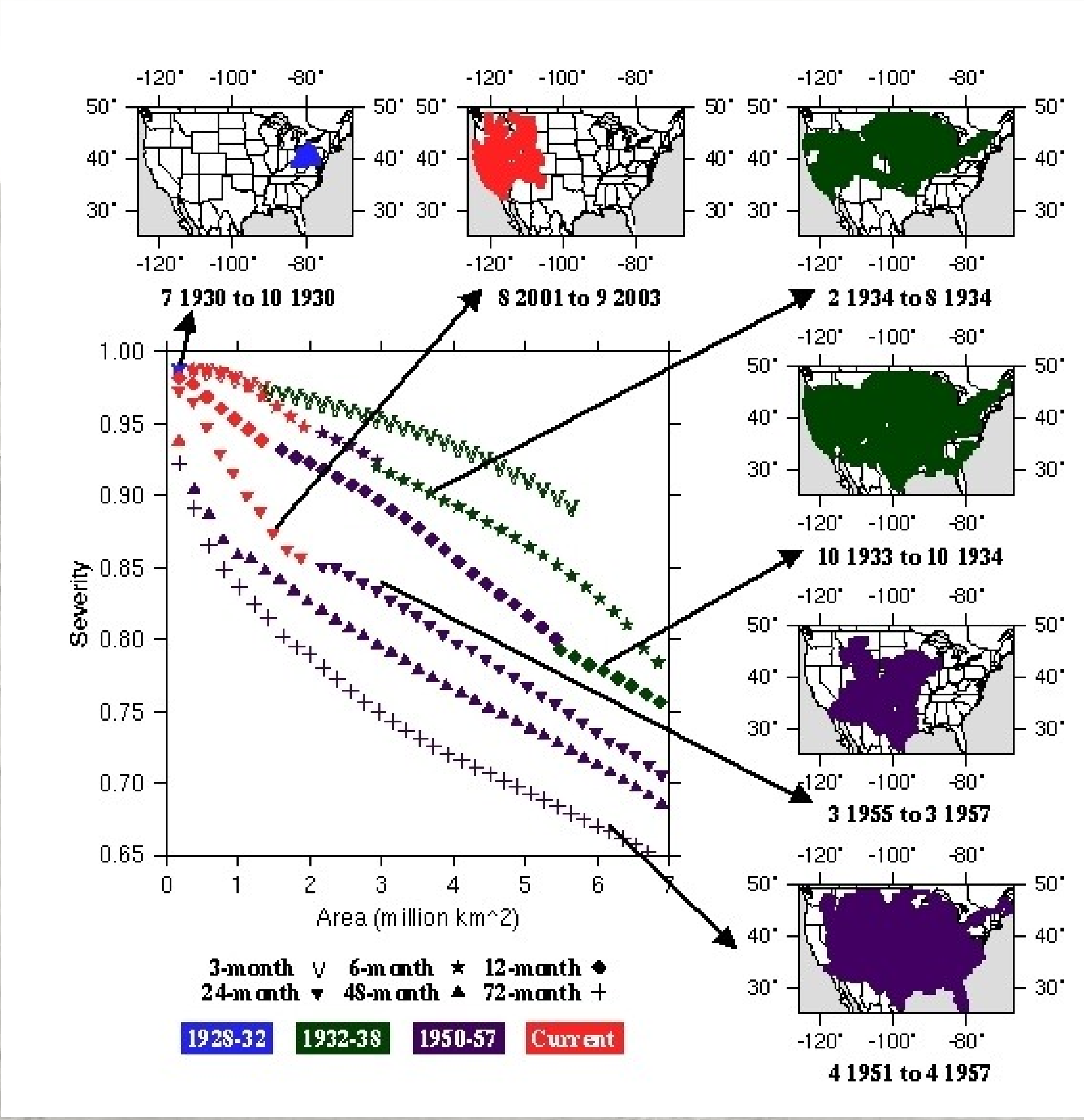
Soil moisture envelope SAD curves

1928-32

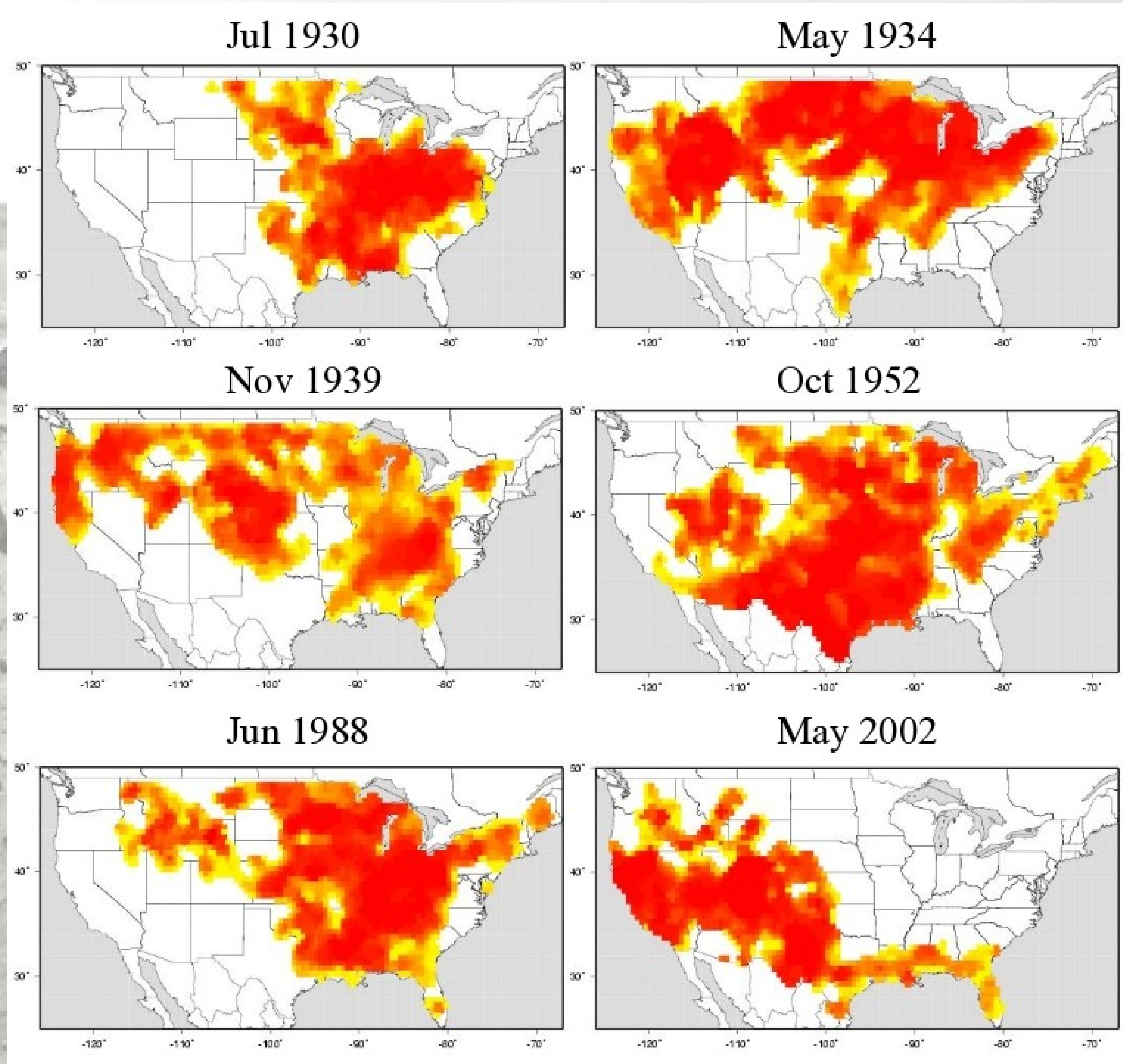
1932-38

1950-57

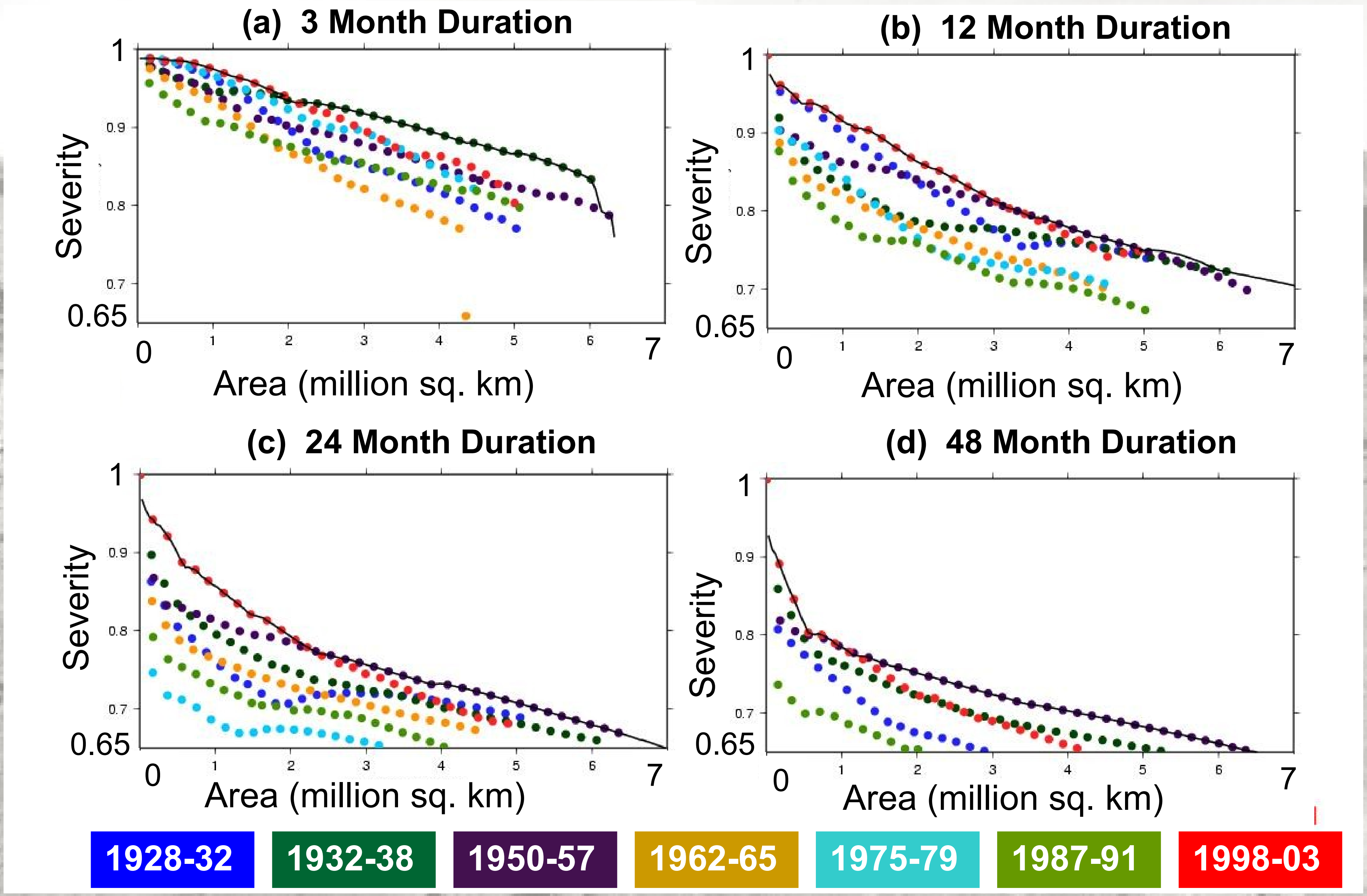
1998-2003



20^{th} century hydrological drought



Runoff SAD curves



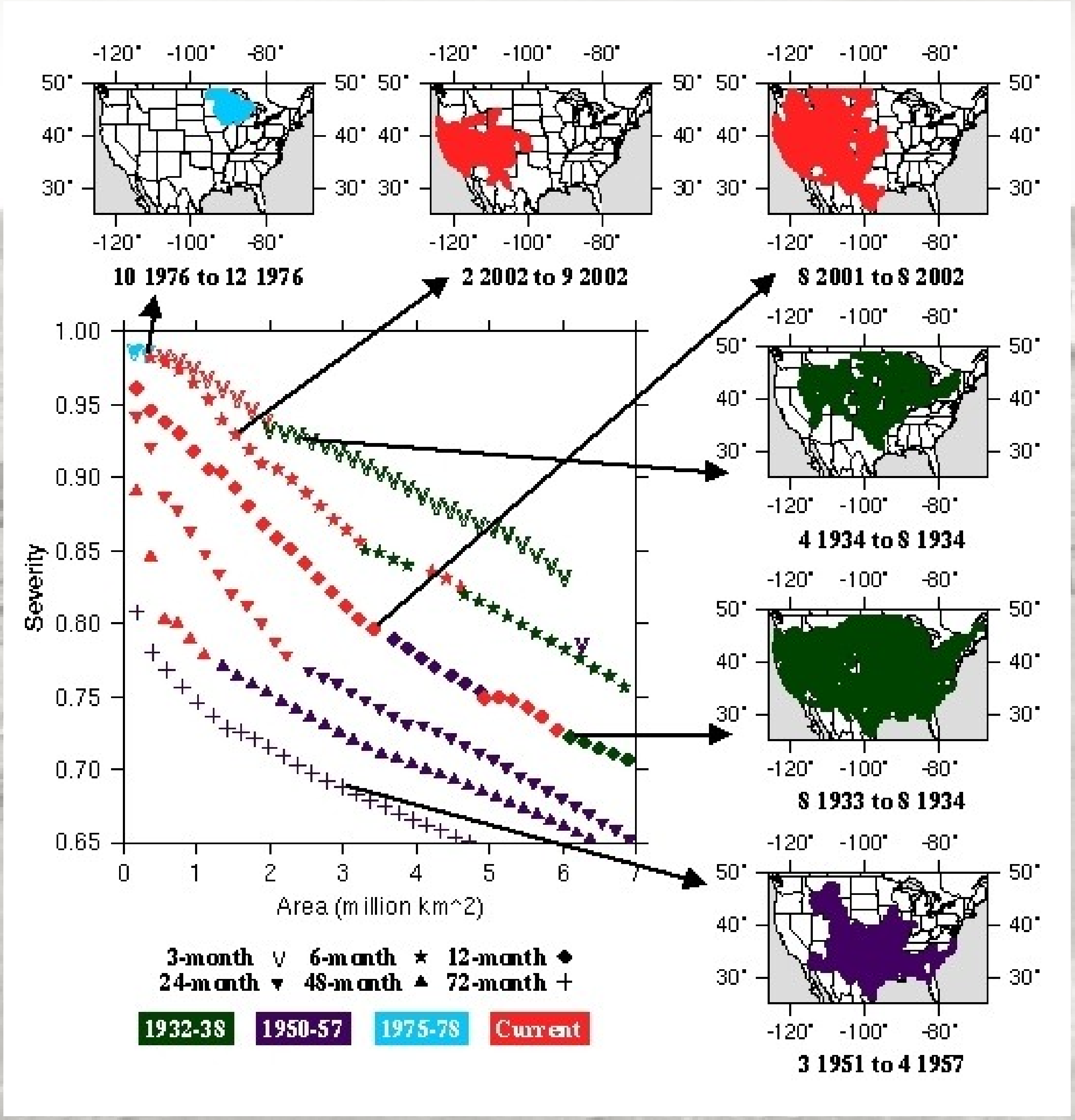
Runoff envelope SAD curves

1932-38

1950-57

1975-78

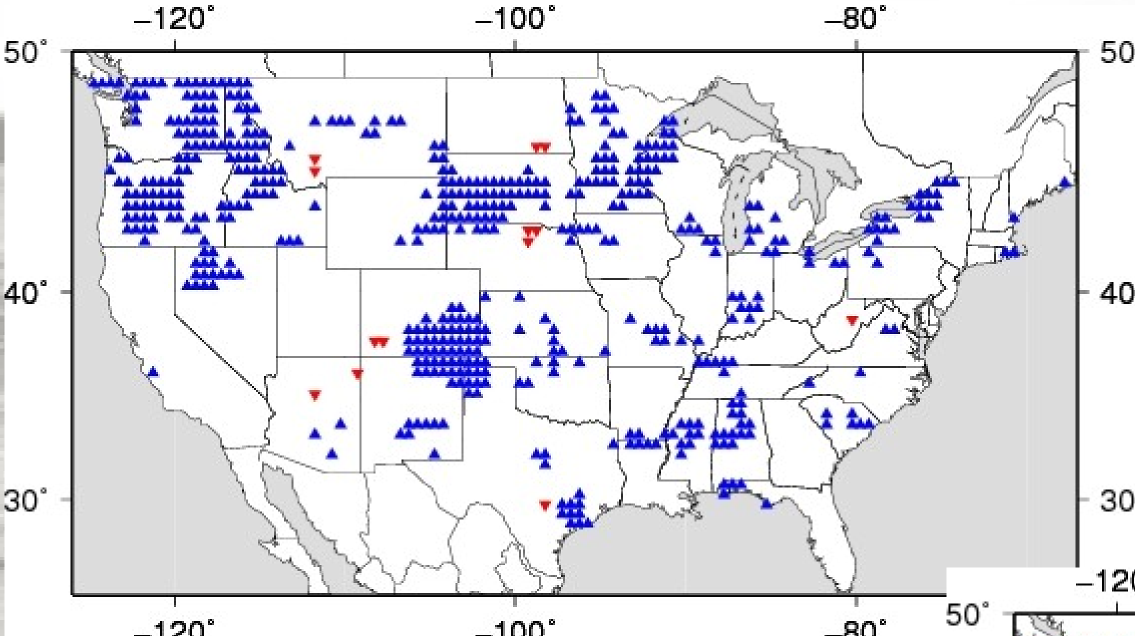
1998-2003



20th century U.S. drought trends

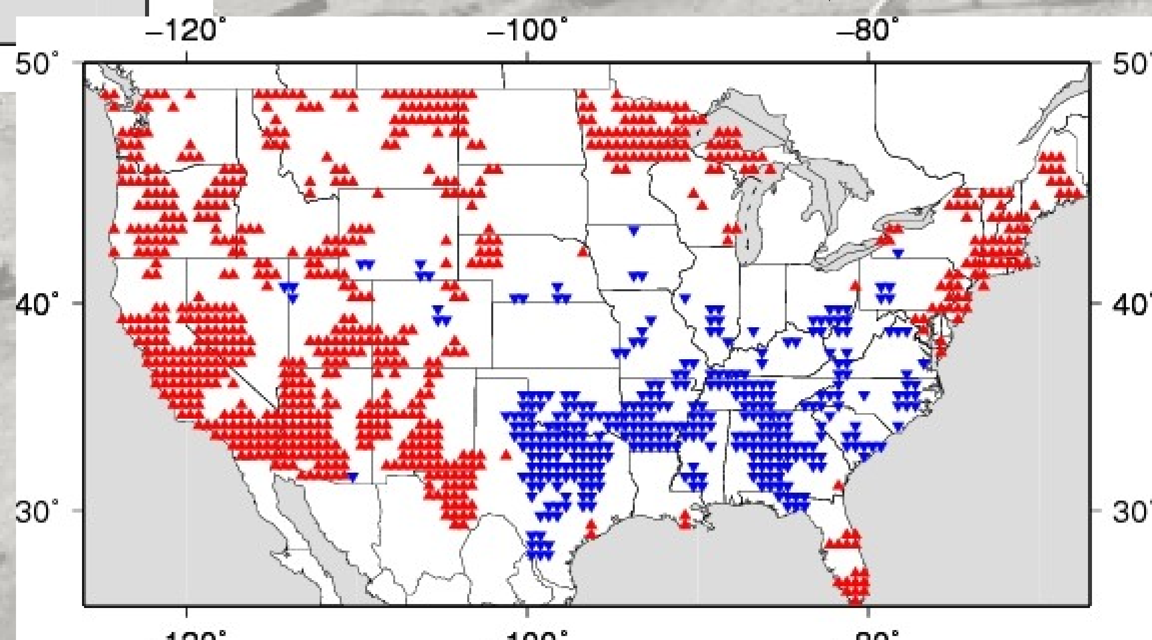
- Examine trends using the seasonal Mann-Kendall test
- Accounts for serial correlation between months
- Field significance evaluated using Monte Carlo approach (*Livezey and Chen,* 1983)
- Trends in drought indicators (soil moisture and runoff)
- Trends in drought characteristics (duration, intensity and spatial extent)

Trends in precipitation and temperature



Precipitation

Temperature

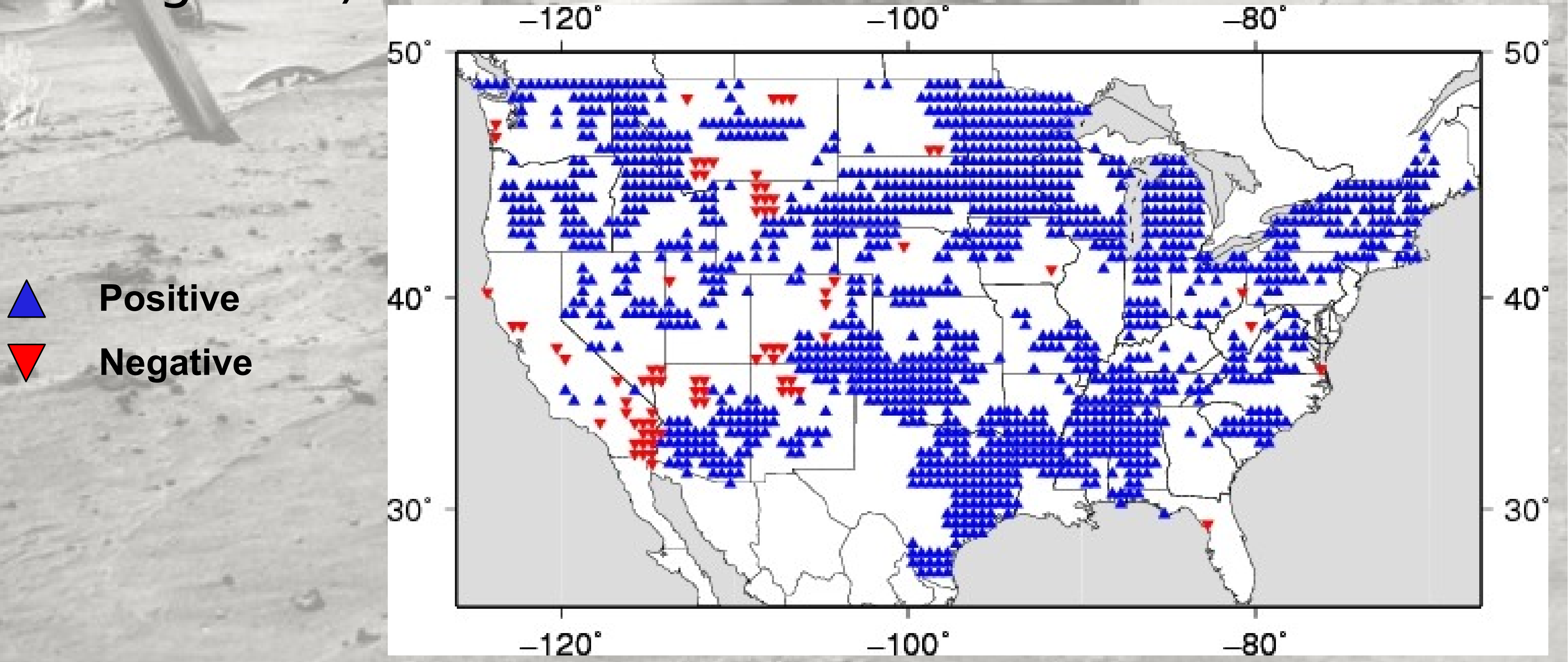


Warmer - Drier

Colder - Wetter

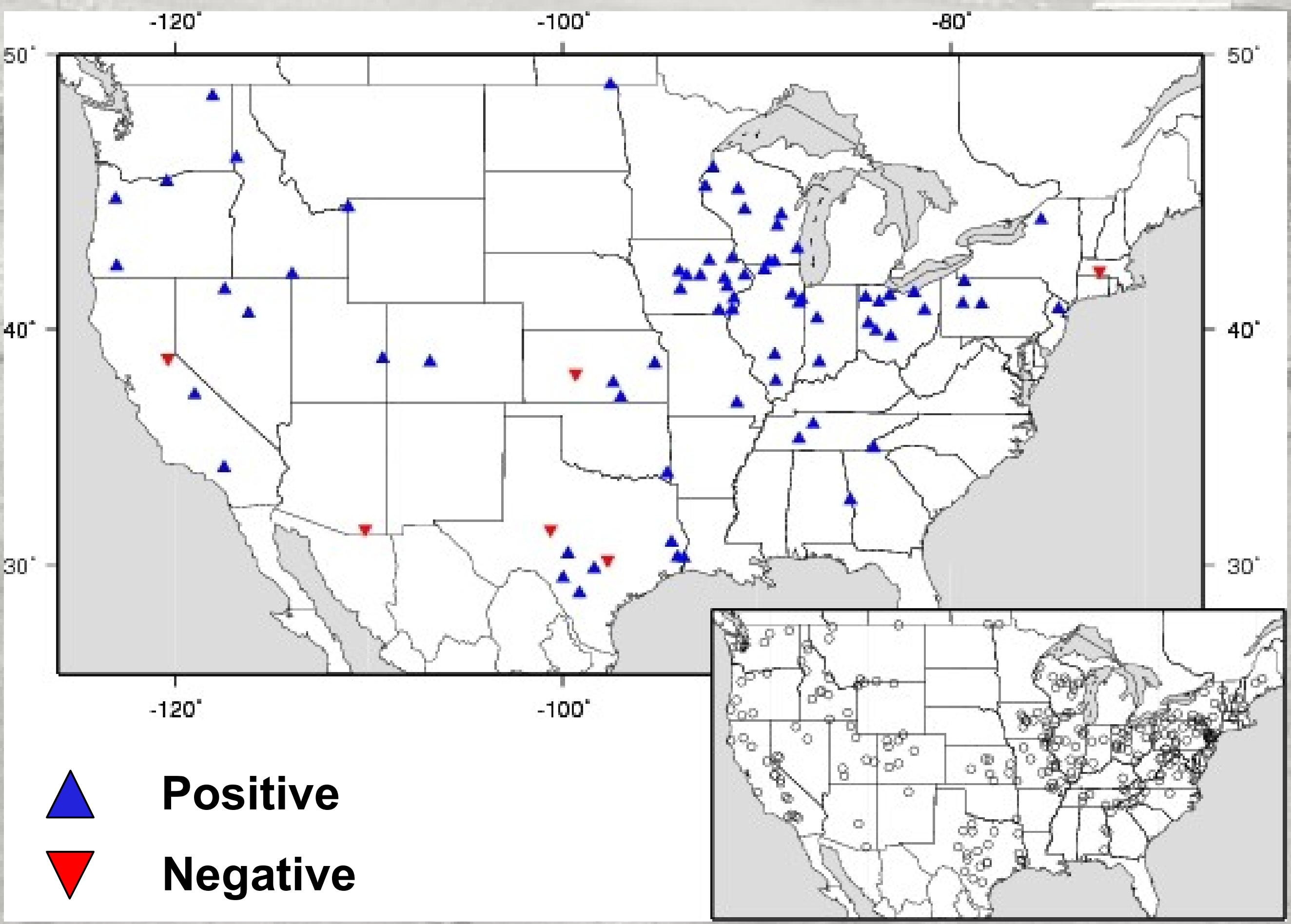
Model runoff annual trends

- 1925-2003 period selected to account model initialization effects
- Positive trends dominate (28% positive and 1% negative)



HCN streamflow trends

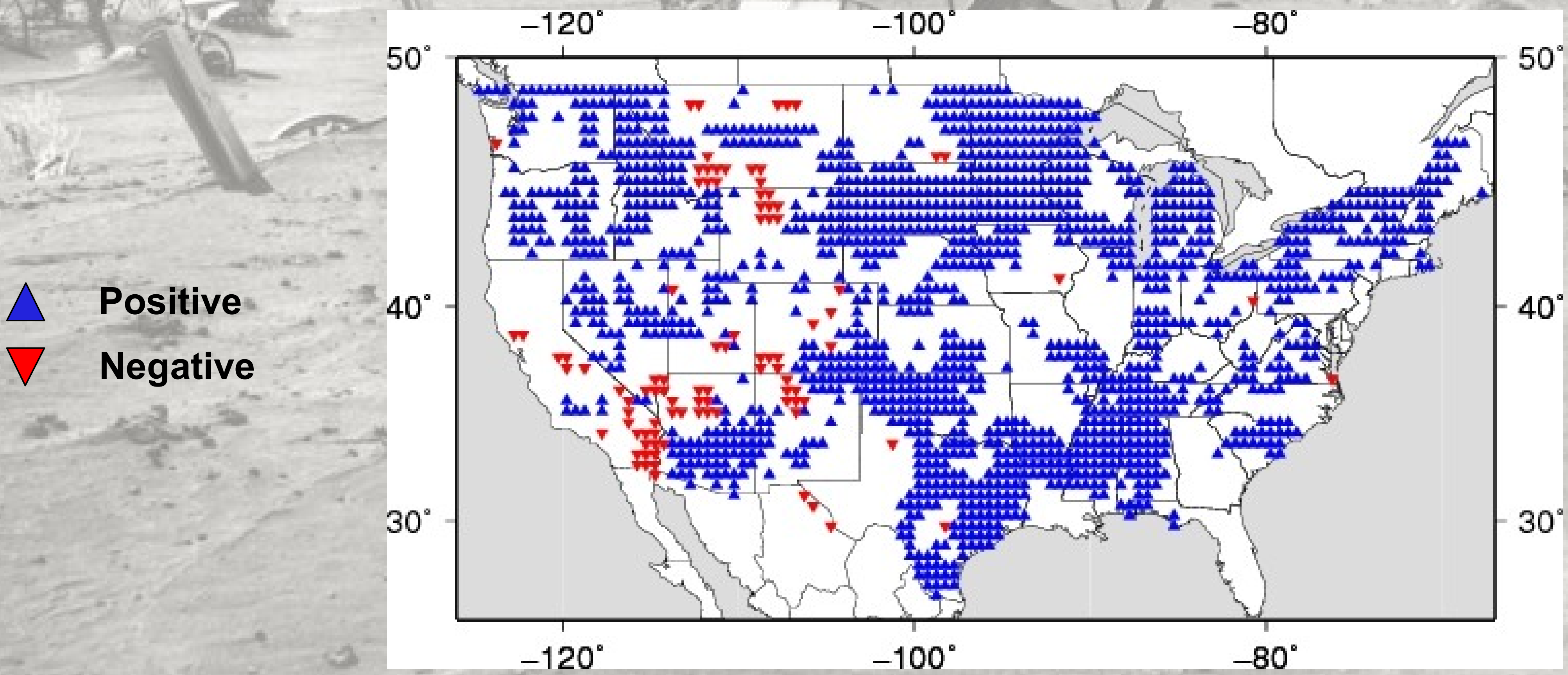
- Trend direction and significance from HCN generally agree with model-derived trends



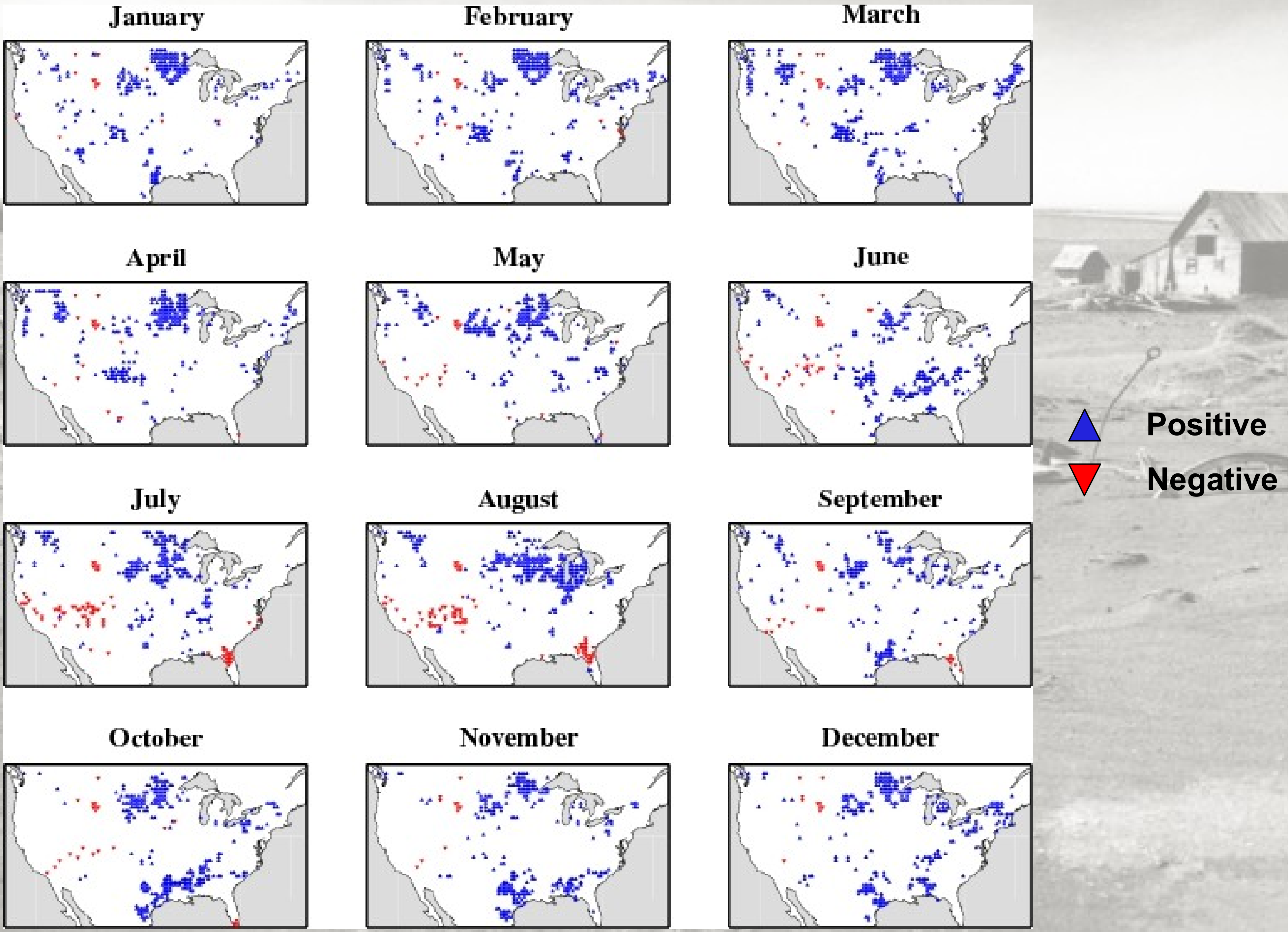
- Subset of stations used
- Mostly positive trends
- Qualitatively similar features to model trends

Model soil moisture annual trends

- Positive trends for 48% of CONUS
- Negative trends for 3% of the domain

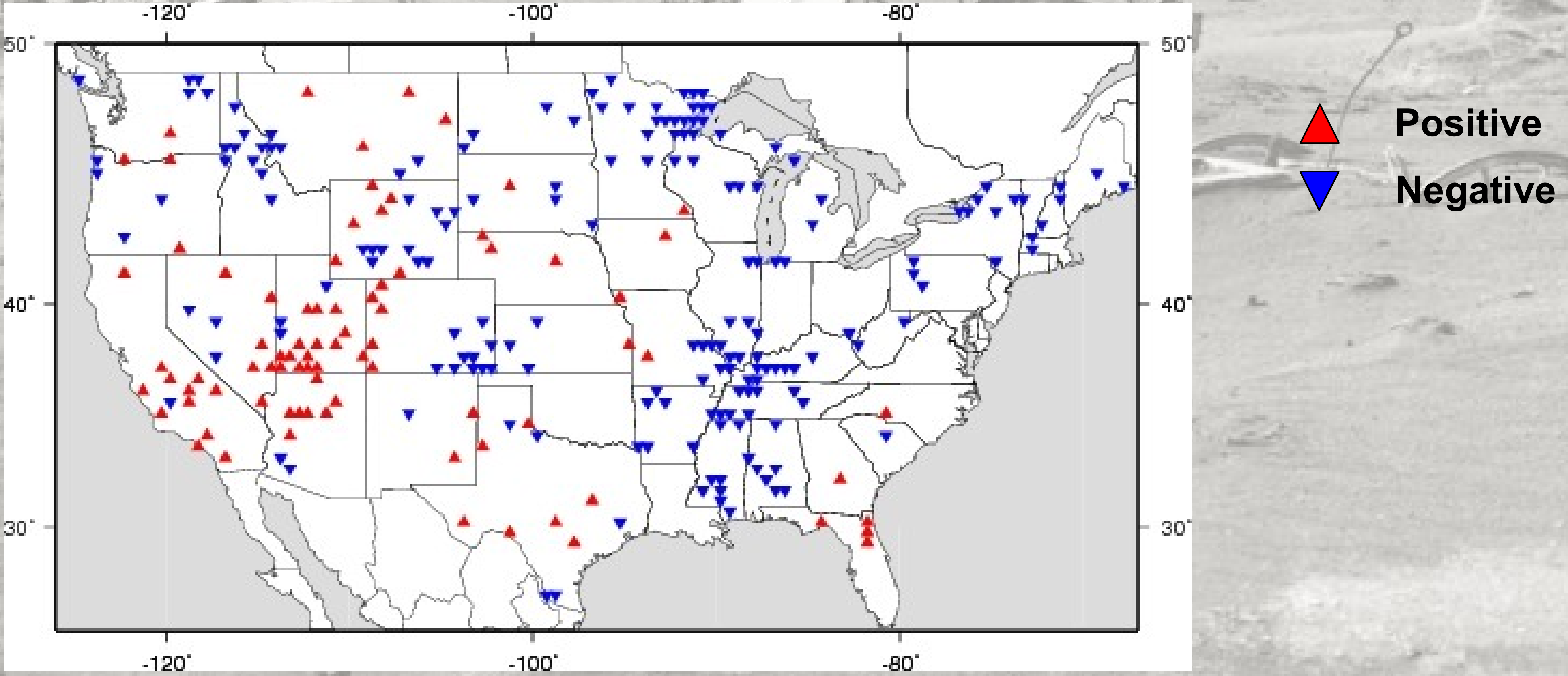


Seasonal trends in soil moisture



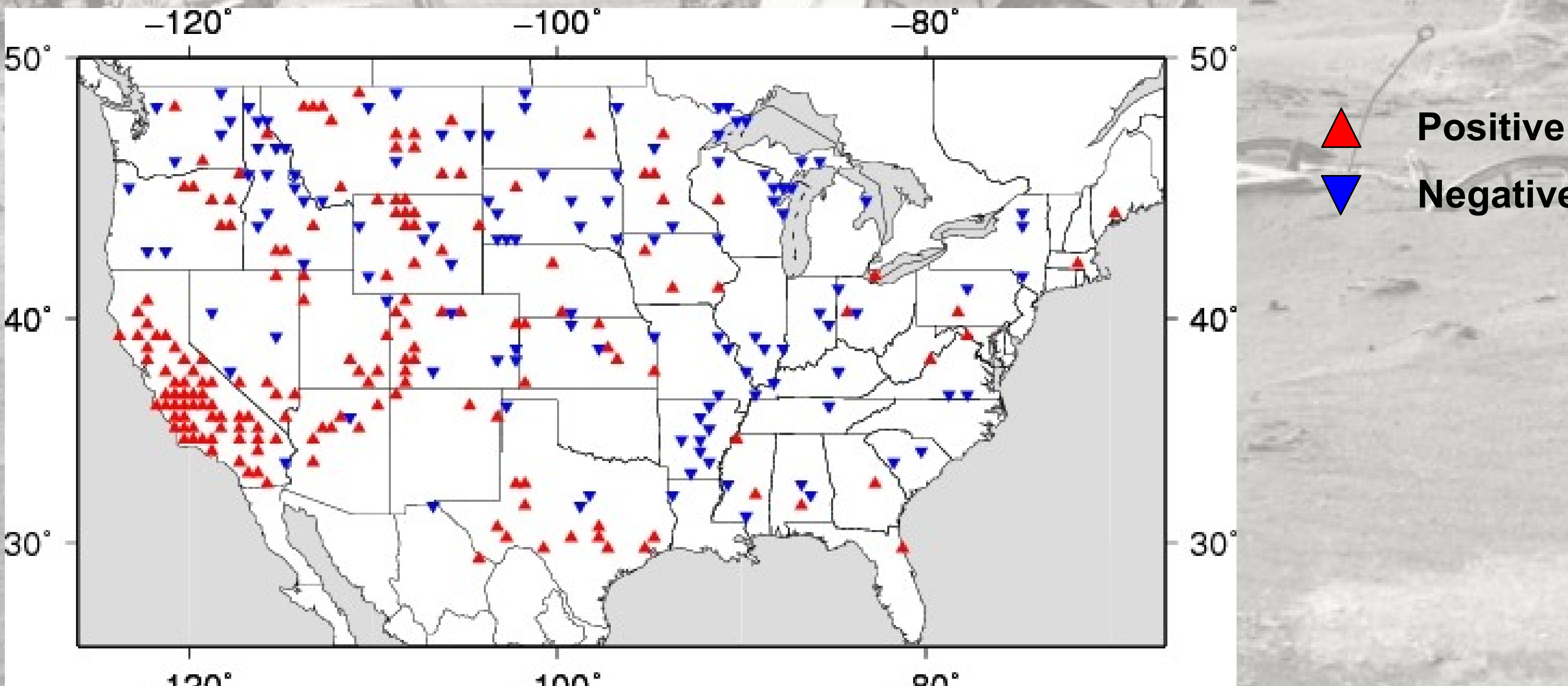
Trends in agricultural drought severity

- Constructed time series of cumulative departure from 20th percentile threshold (soil moisture)



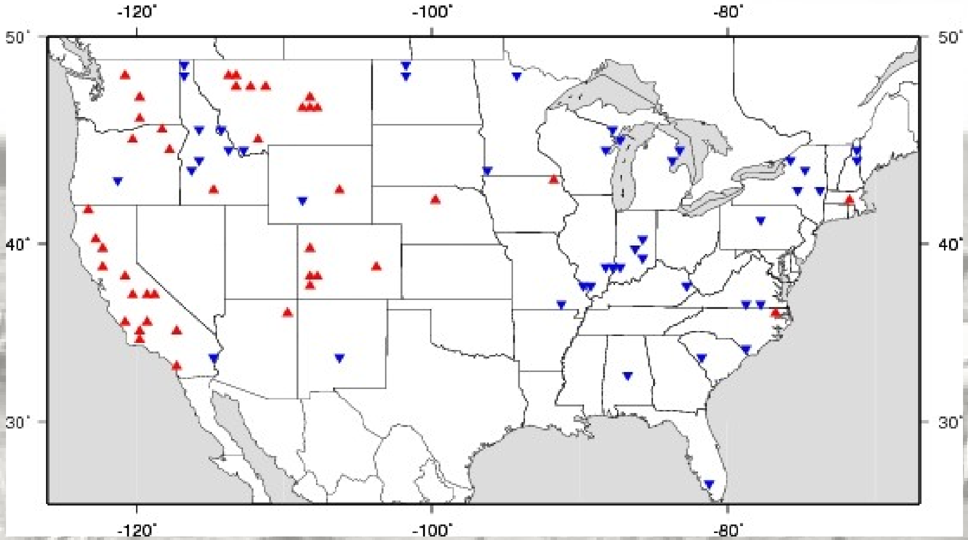
Trends in hydrological drought severity

- Constructed time series of cumulative departure from 20th percentile threshold (runoff)

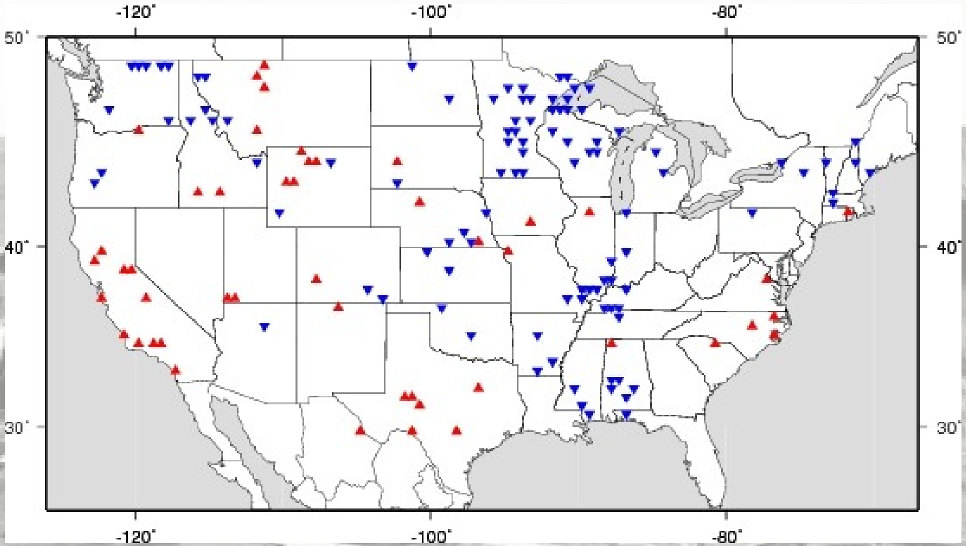


Trends in drought duration

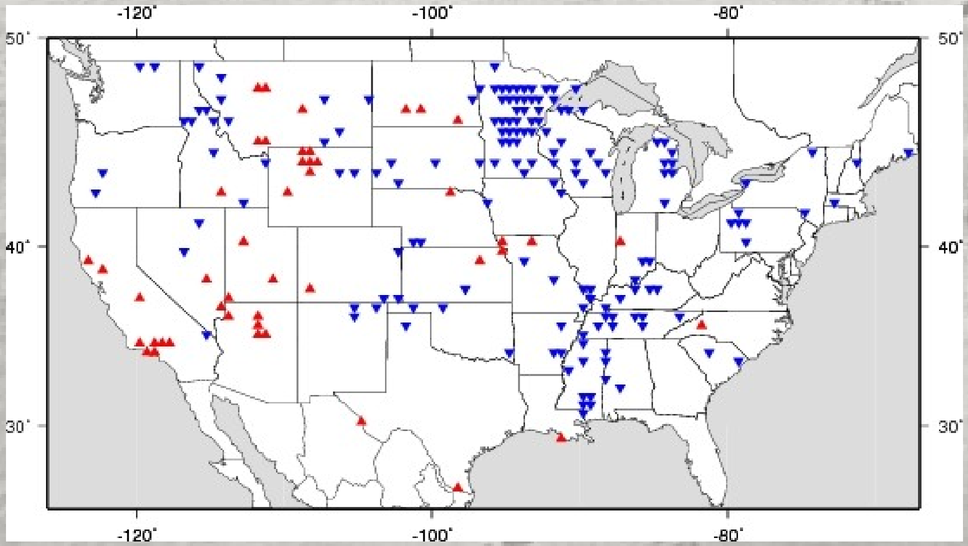
Severity 90%



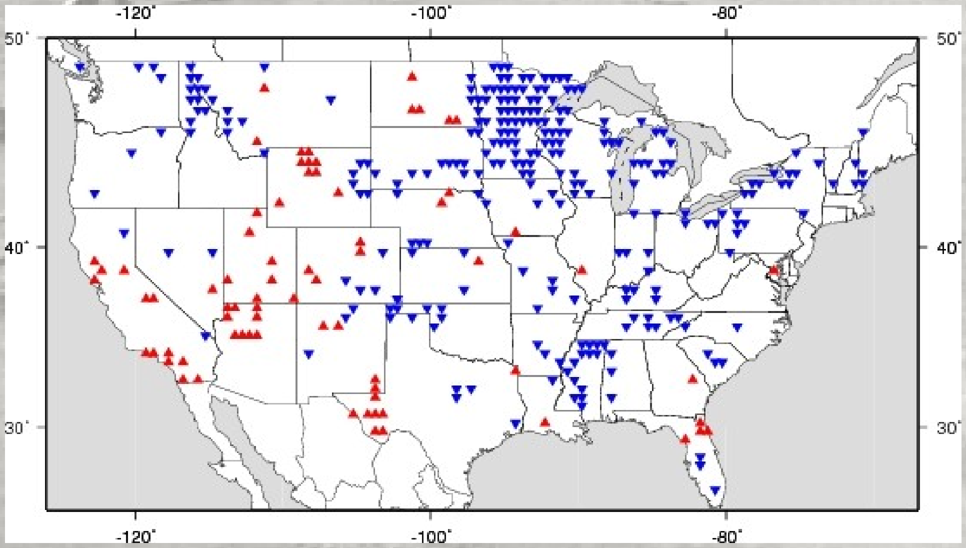
Severity 80%



Severity 70%



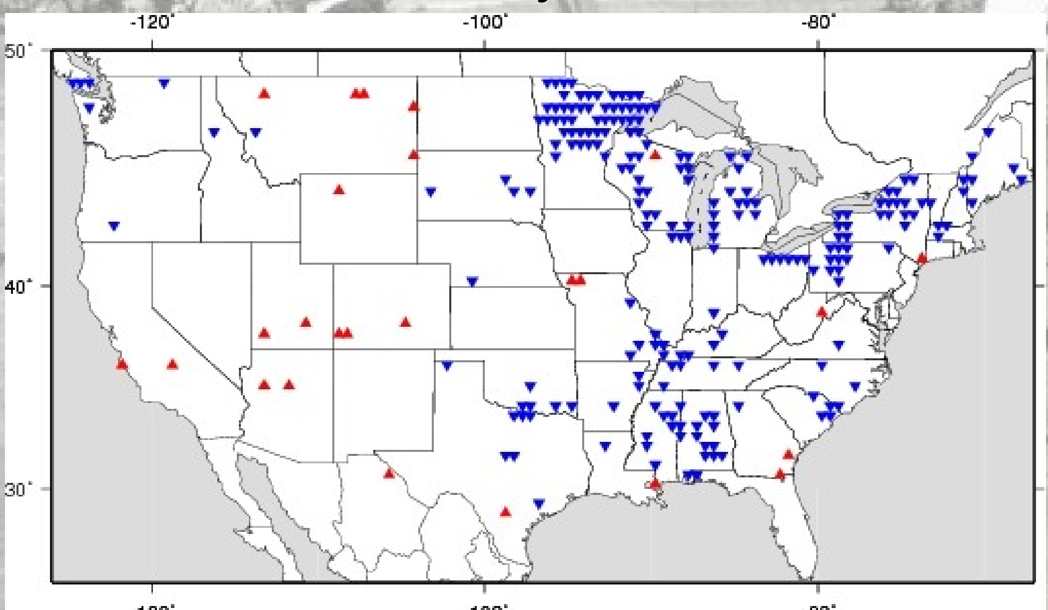
Severity 60%



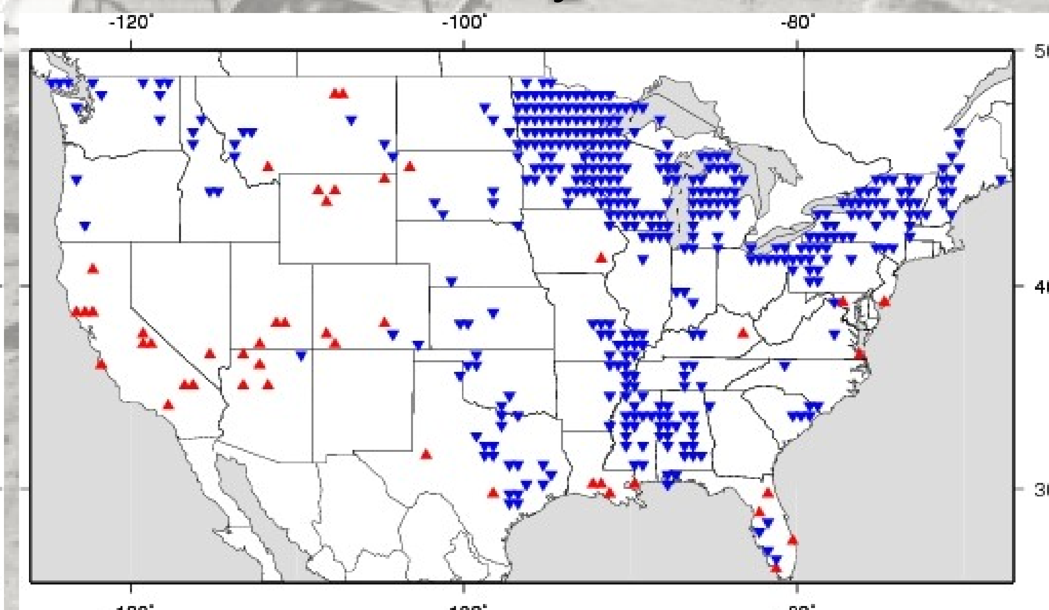
Trends in drought frequency

- Number of drought events (for different thresholds) per year

Severity 90%



Severity 80%



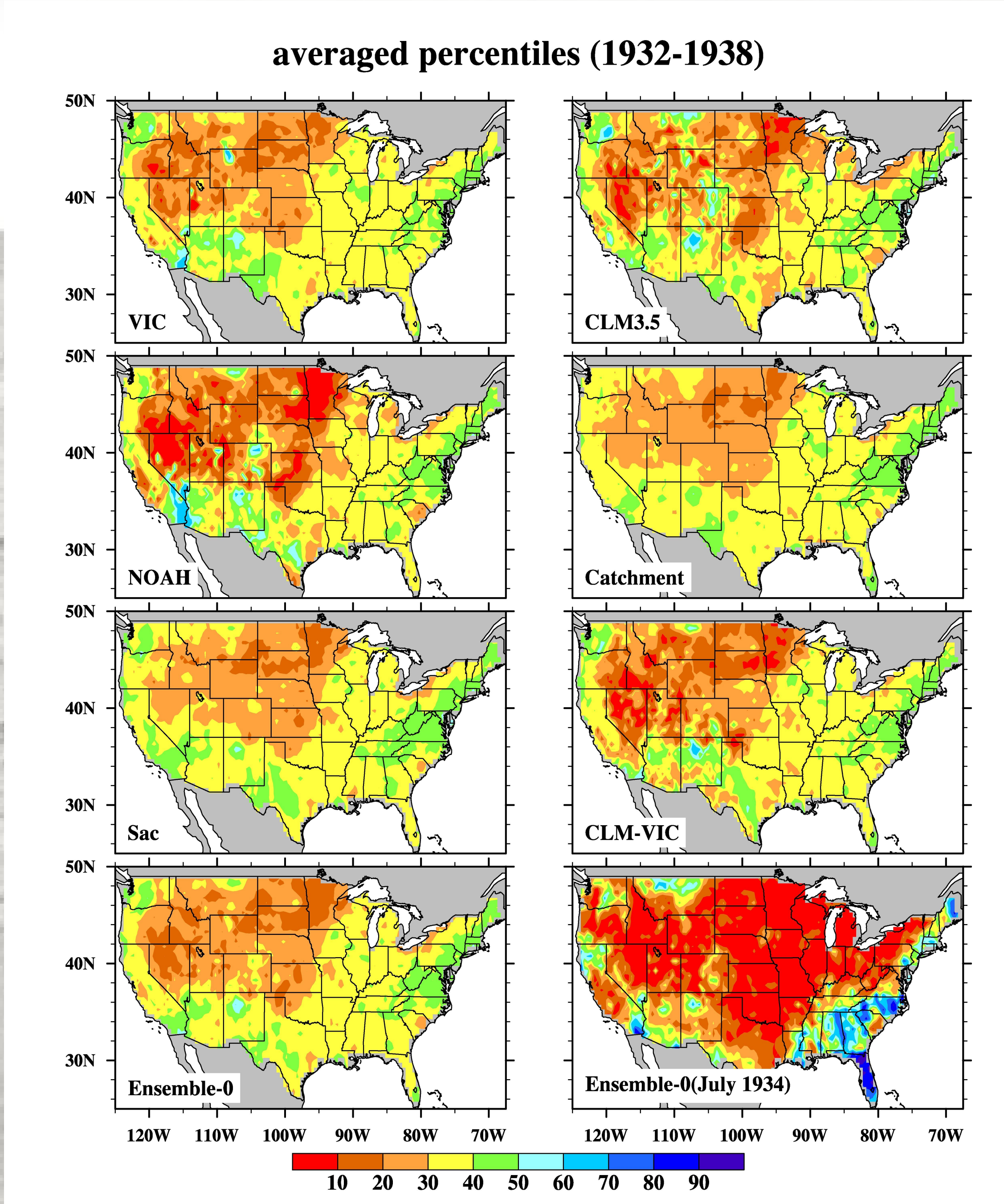
Positive

Negative

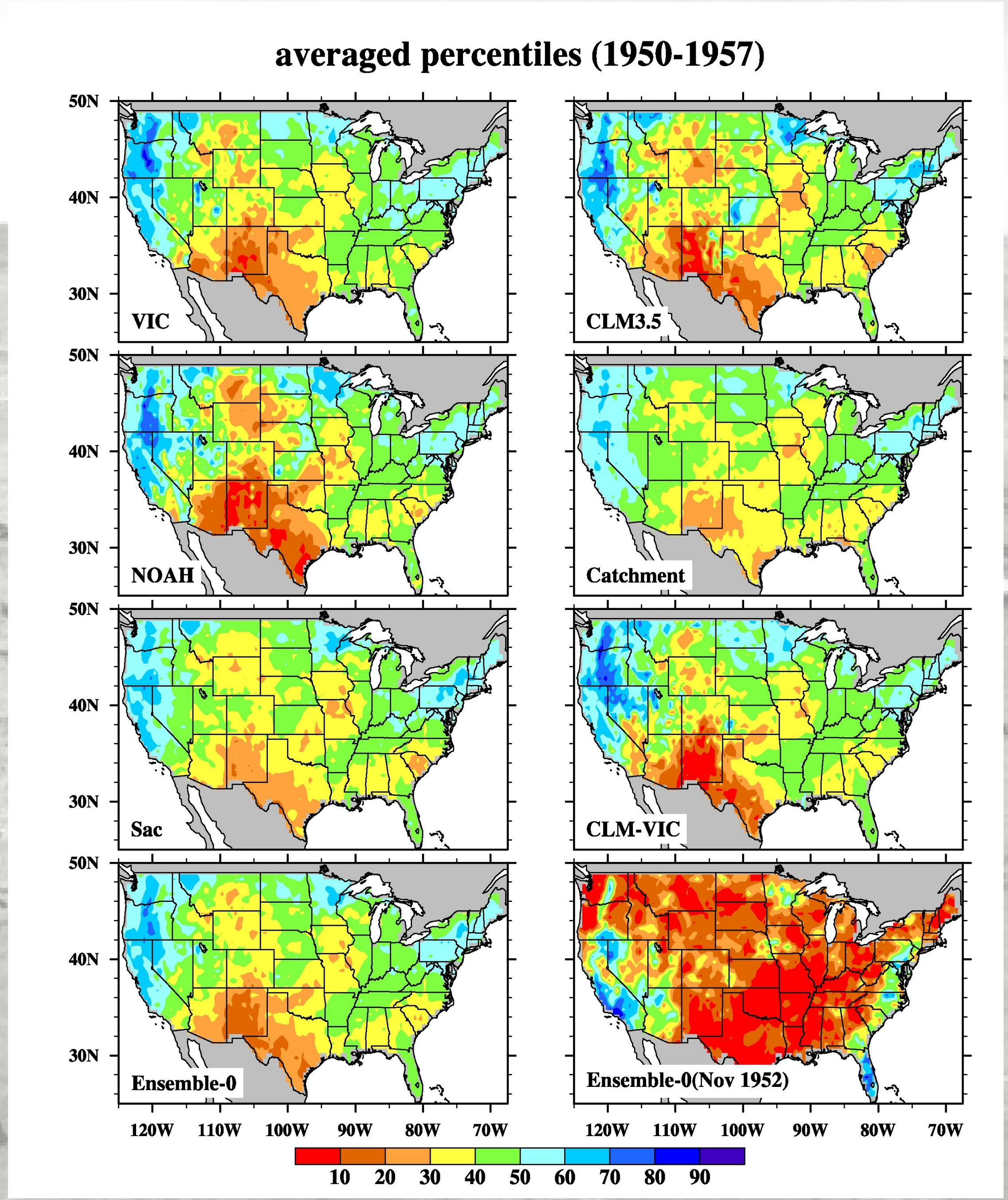
Multi-model drought history reconstruction

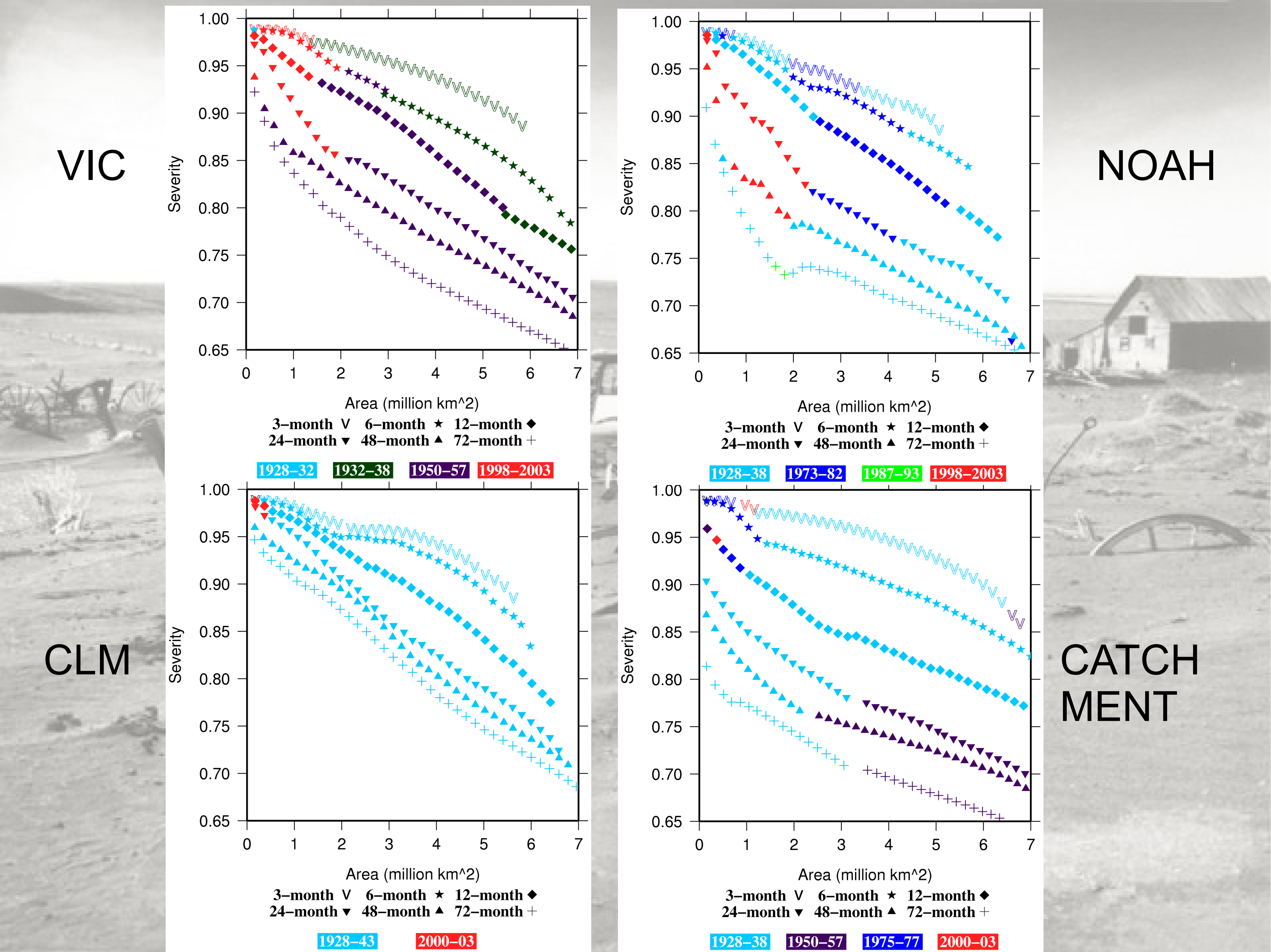
- Extending of this work includes the application of the same methodology for an ensemble of models
  - Soil moisture percentiles calculated after model averaging (Ensemble-0)
  - Soil moisture percentiles calculated from averaged normalized model values (Ensemble-1)

Soil moisture (1932-38)

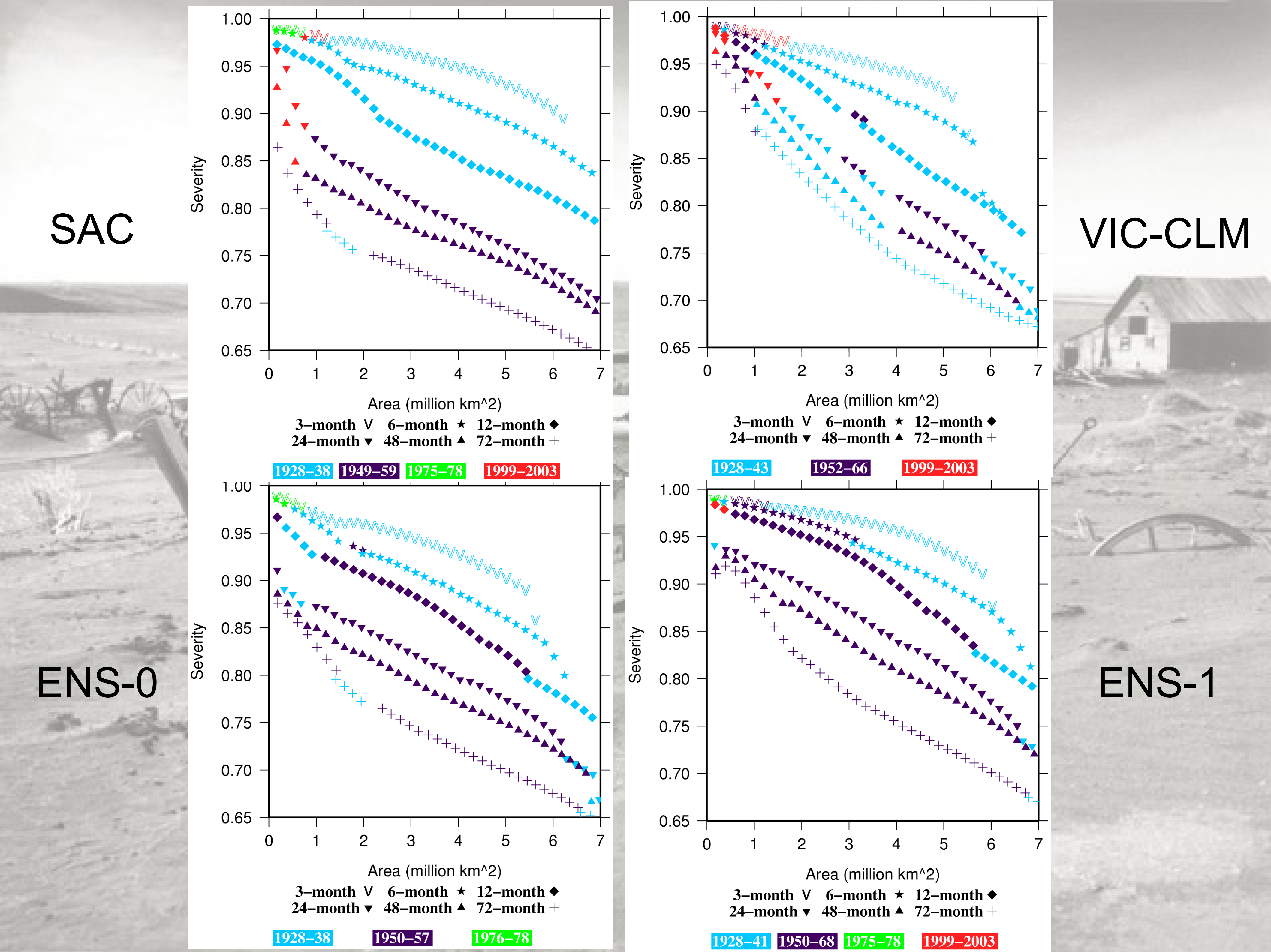


Soil moisture (1950-57)

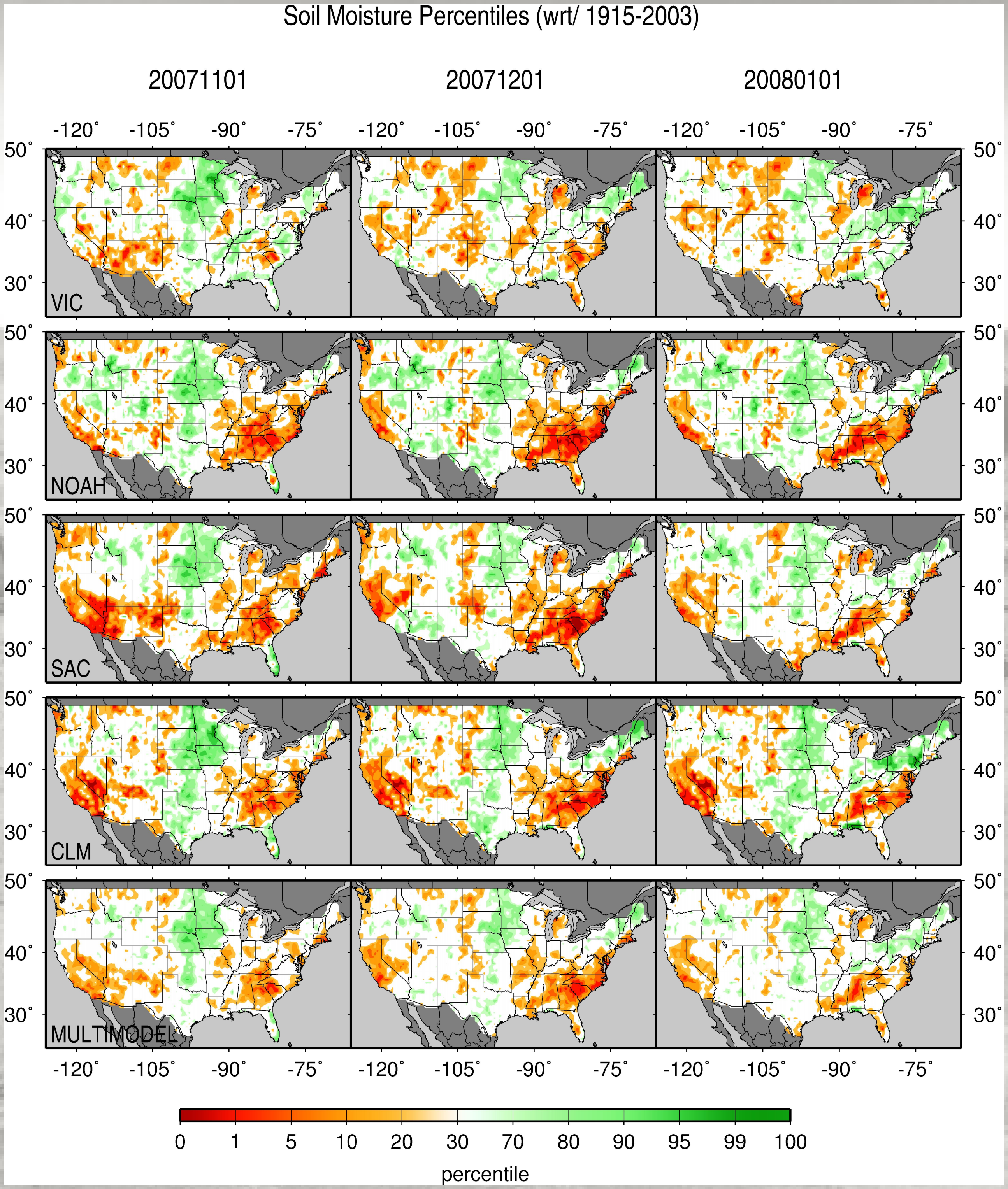




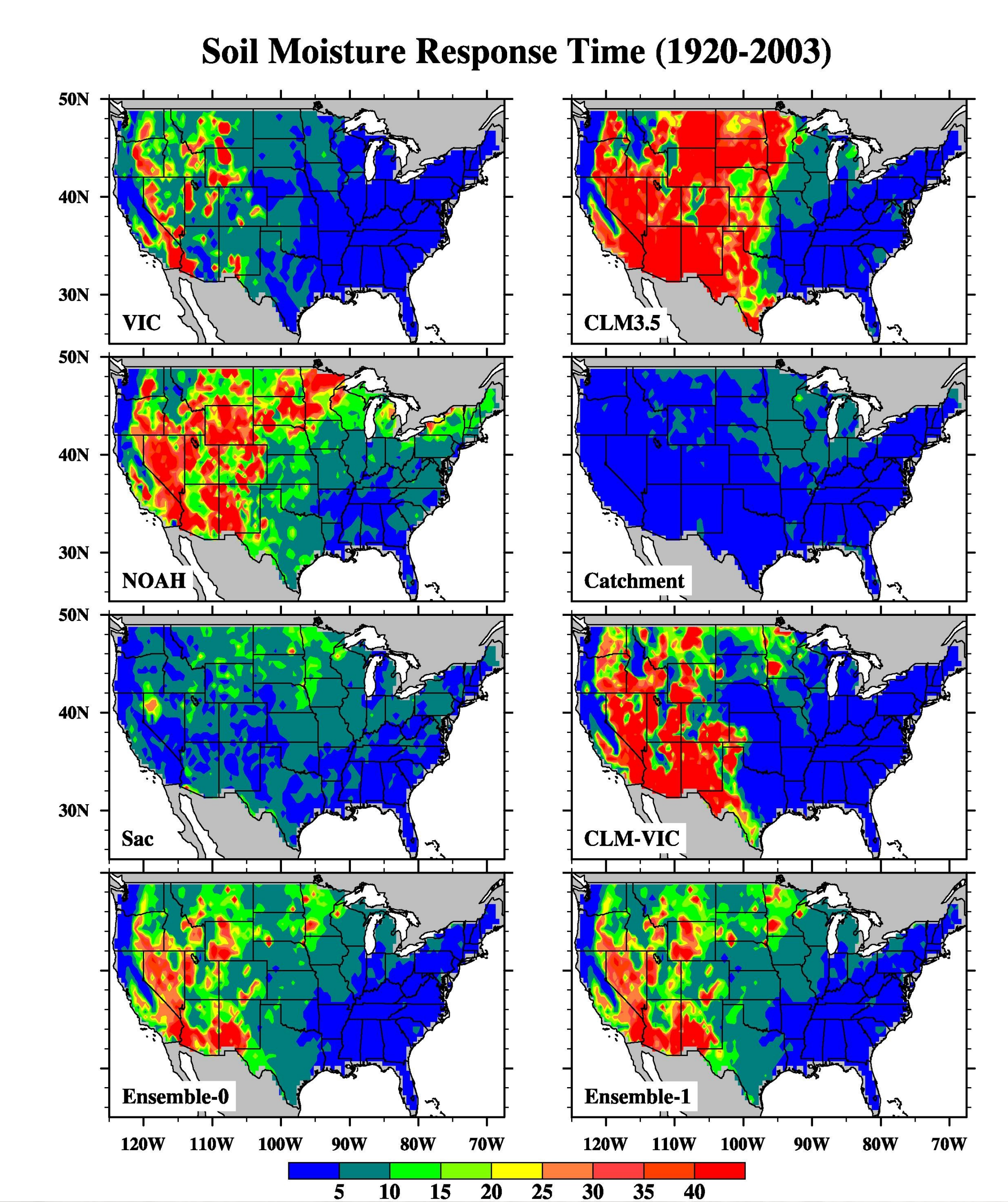
VIC
NOAH
CLM
CATCH MENT
Severity
Area (million km^2)
3–month V 6–month ★ 12–month ◆
24–month ▼ 48–month ▲ 72–month +
1928–32 1932–38 1950–57 1998–2003
1928–38 1973–82 1987–93 1998–2003
1928–43 2000–03
1928–38 1950–57 1975–77 2000–03


SAC
VIC-CLM
ENS-0
ENS-1
Severity
Area (million km^2)
3–month V 6–month ★ 12–month ◆
24–month ▼ 48–month ▲ 72–month +
1928–38 1949–59 1975–78 1999–2003
1928–43 1952–66 1999–2003
1928–38 1950–57 1976–78
1928–41 1950–68 1975–78 1999–2003

- Drought evolution (Nov-Dec 2007 and Jan 2008)
- Soil moisture percentiles



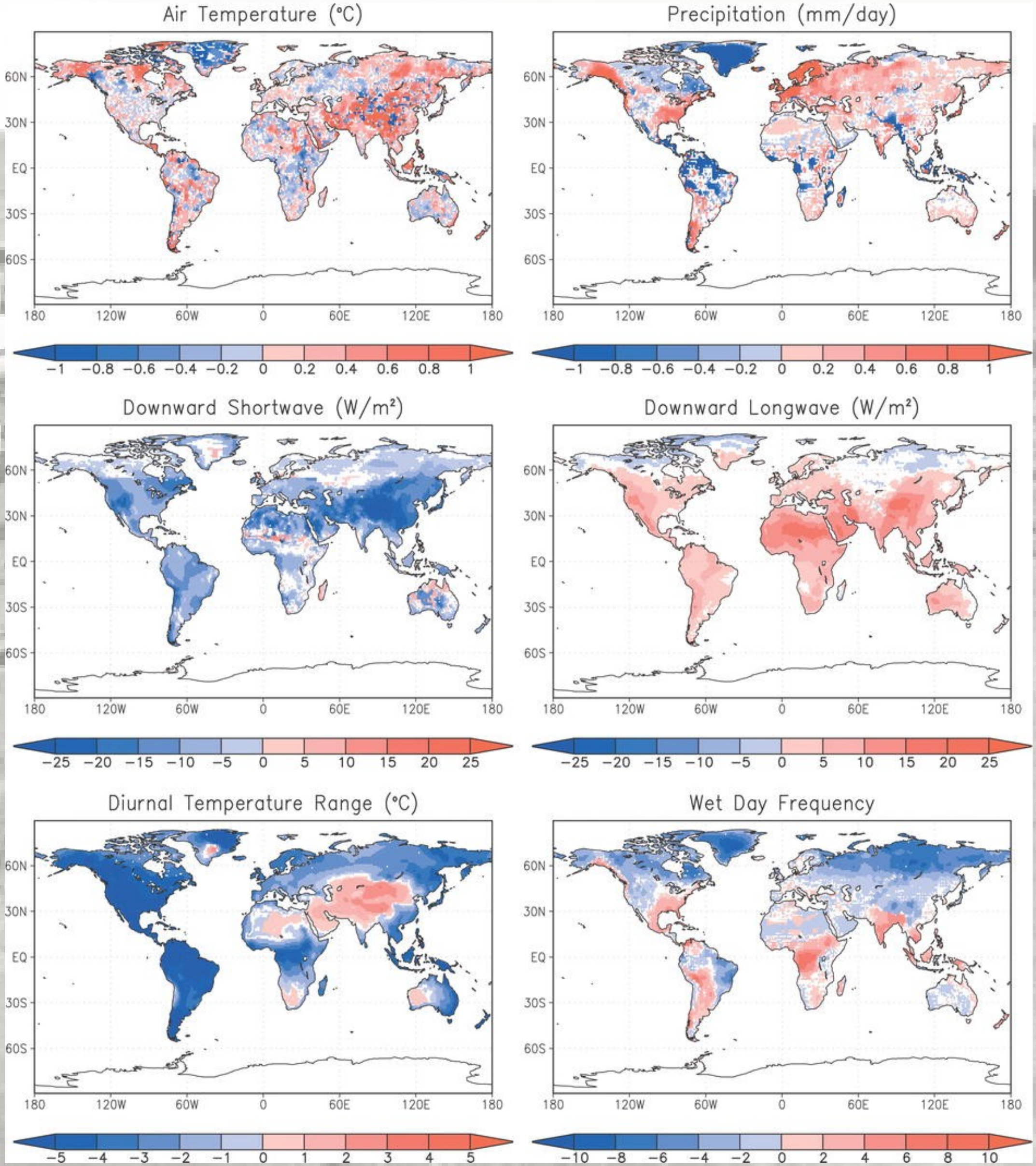
- Soil moisture response time
- Essentially autocorrelation length
- Higher in western U.S.
- Large differences between models



Global drought in the second half 20th century

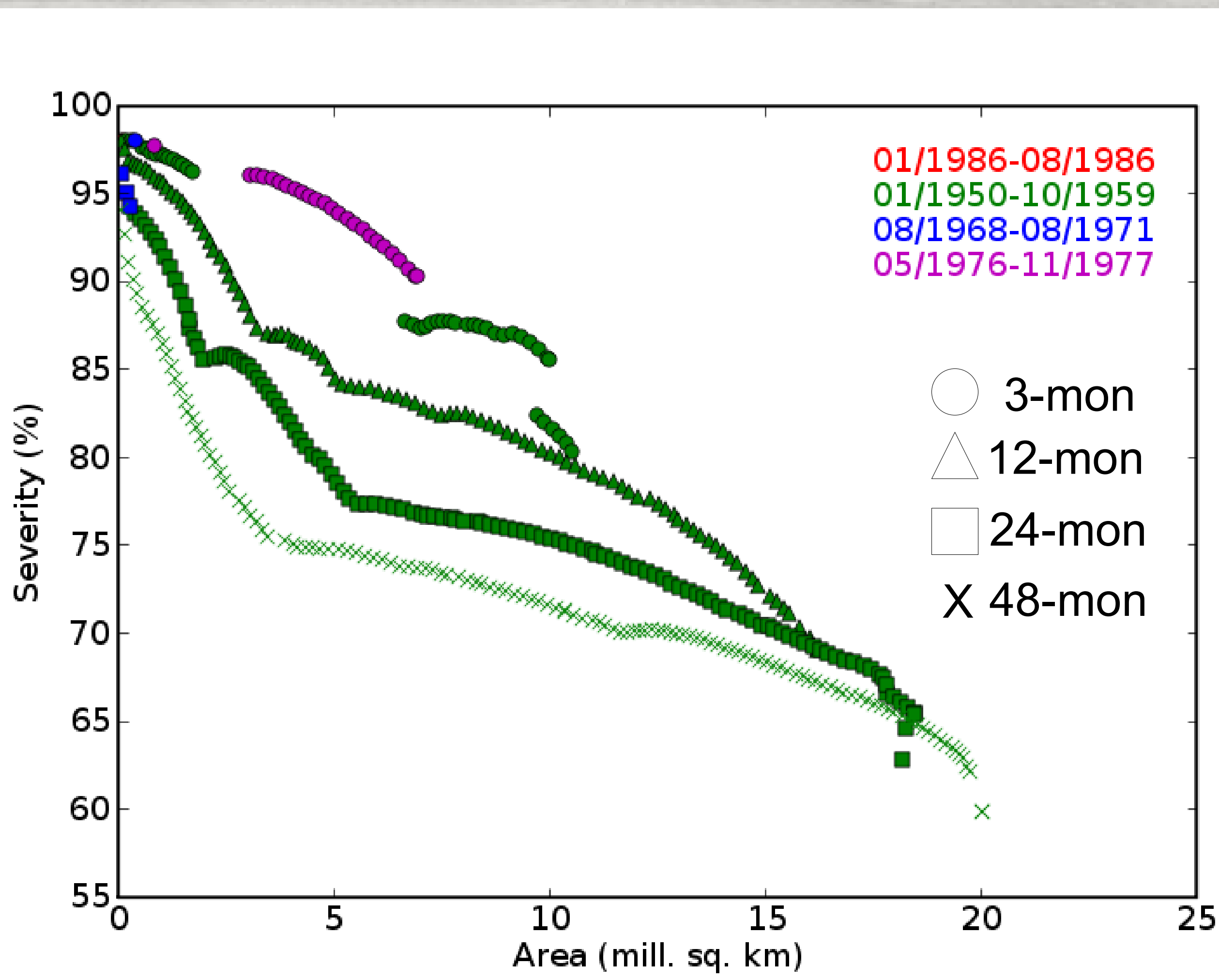
Methodology

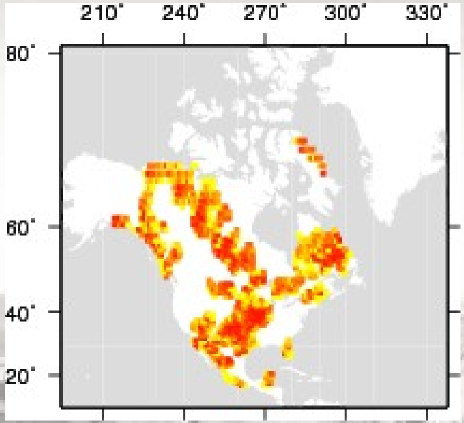
- Available global meteorological dataset from variety of sources (*Sheffield et al.*, 2006)
- Hybrid dataset from NCEP/NCAR, GPCP, TRMM, ISCCP, ERBE
- Study period 1950-2000
- SAD analysis on continents



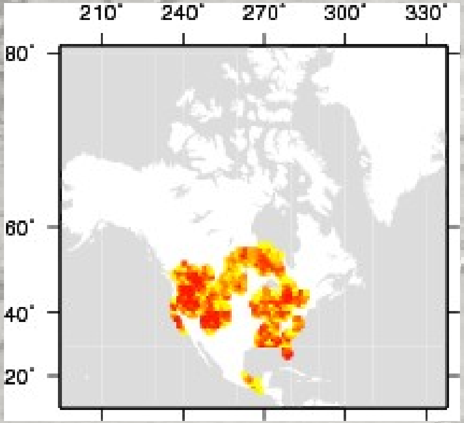
N. America – SAD envelope curves

- 1950s drought dominant
- 1977 western U.S. drought

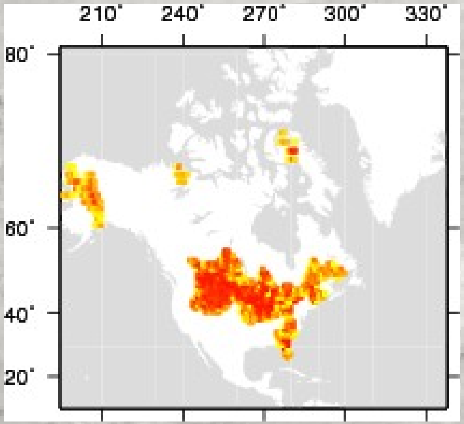




April 1956



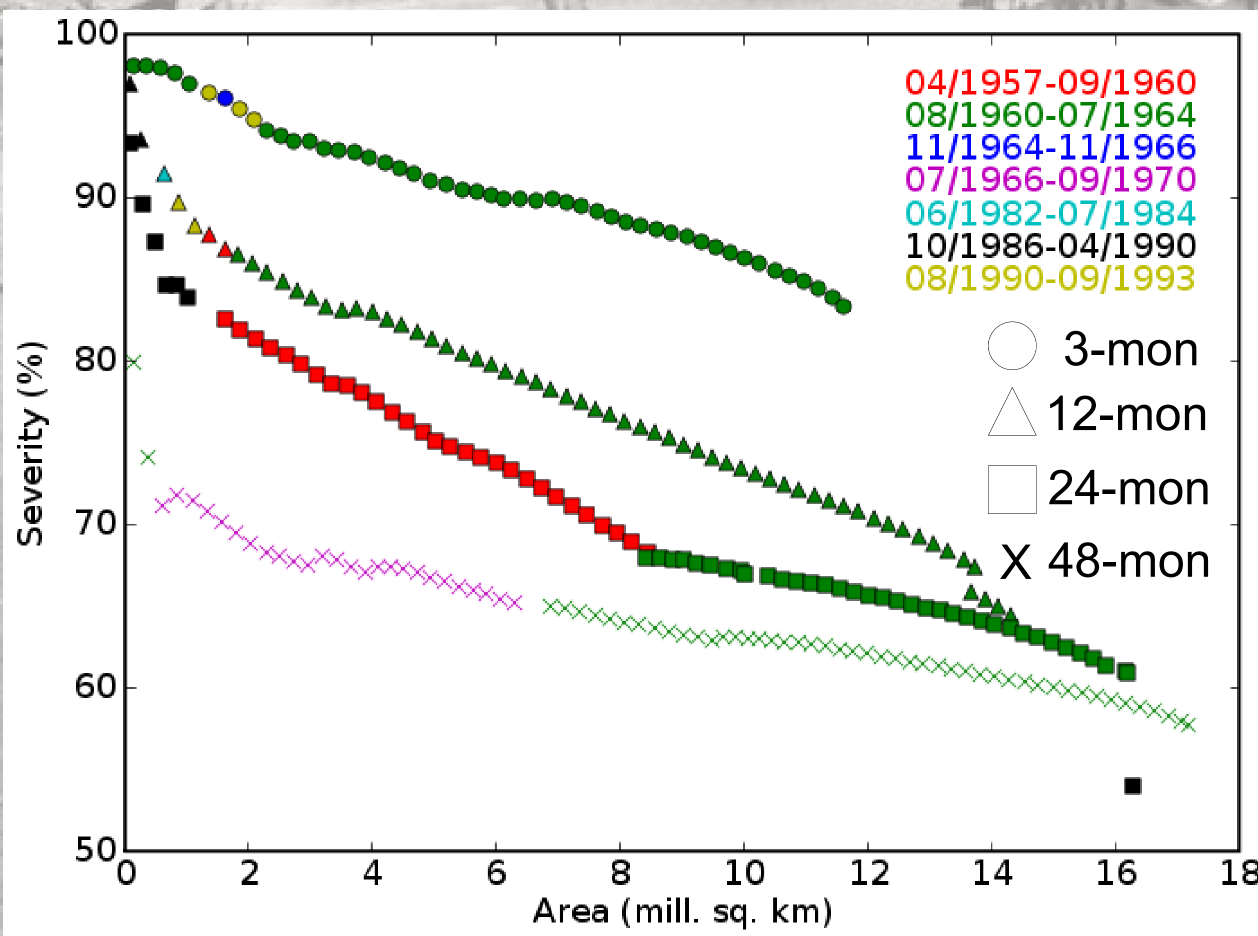
June 1977

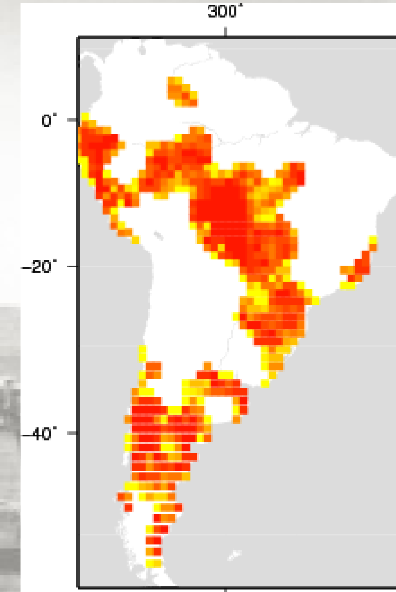


July 1988

S. America – SAD envelope curves

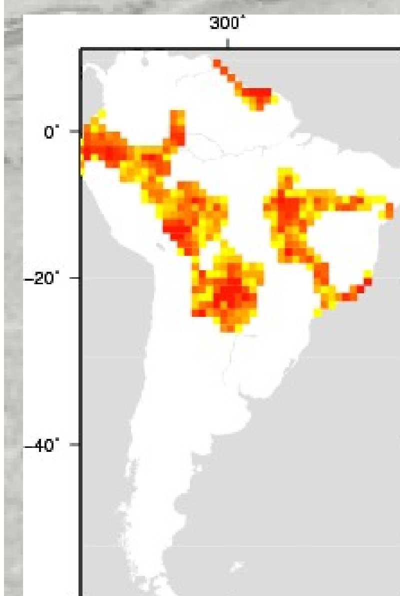
- Two 1960s droughts dominant, mostly over Amazon
- Late 1980s drought in the southern cone



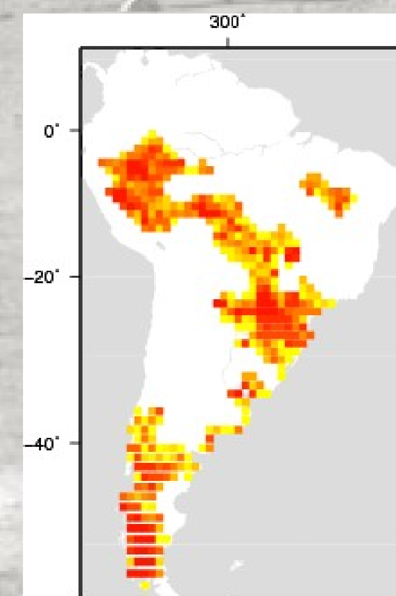


June 1968

November 1963

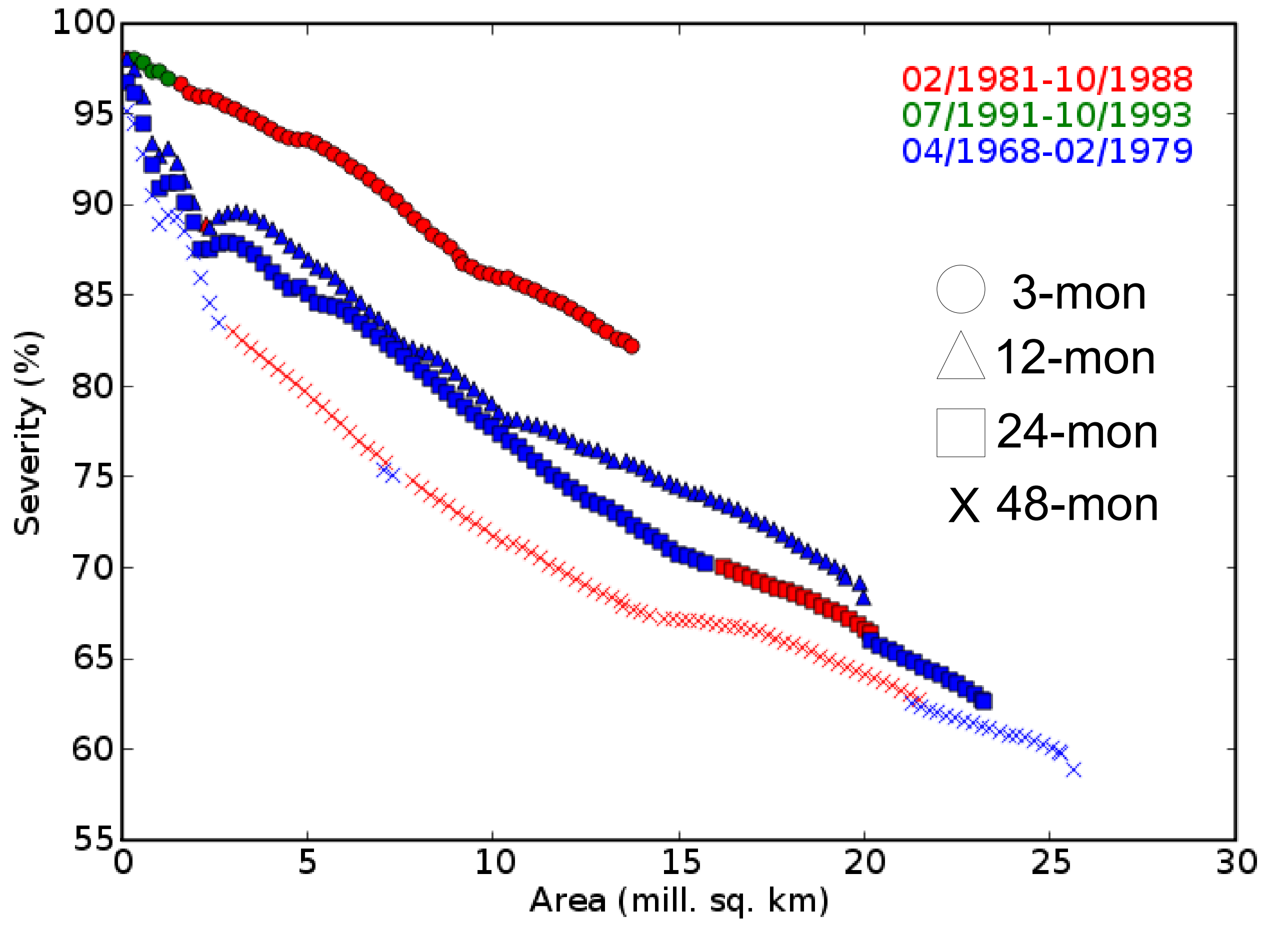


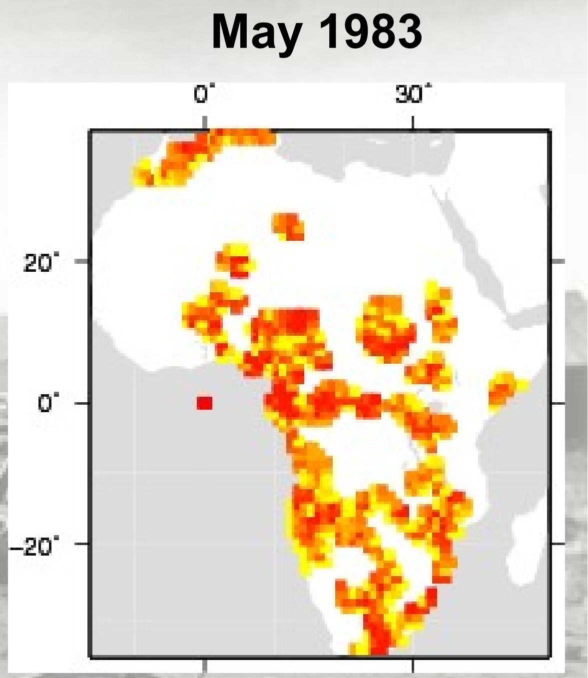
September 1988

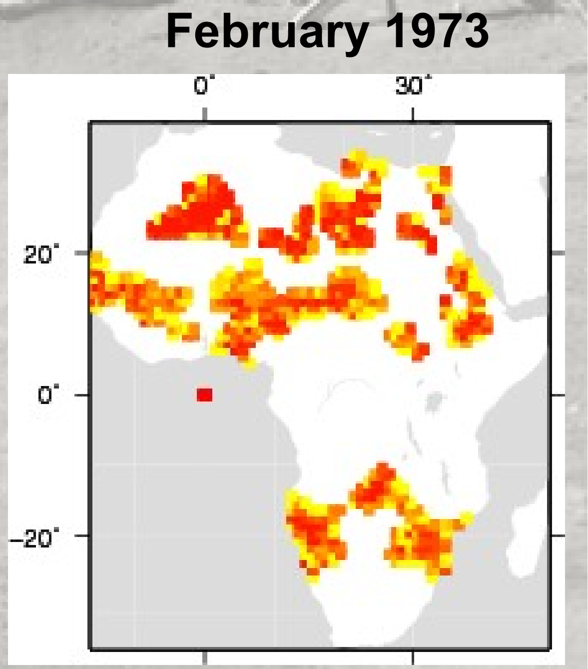


Africa – SAD envelope curves

- Sahel drought (late 1960s to late 1970s)
- Almost decade long 1980s drought (Nile, Congo and southern parts)

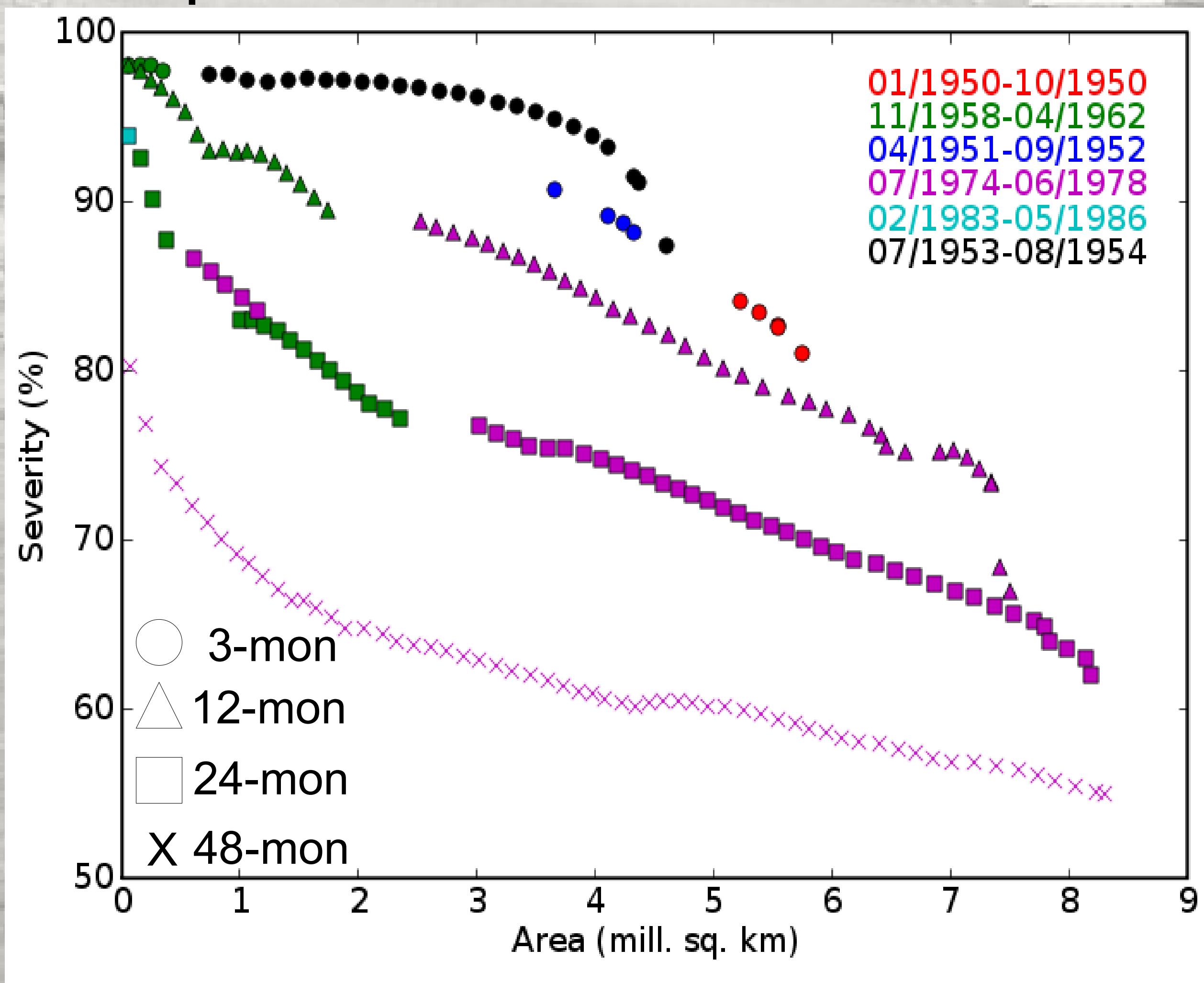


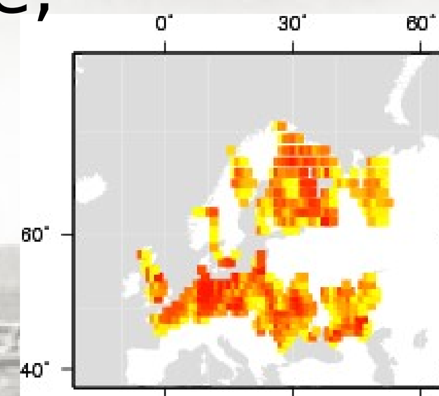




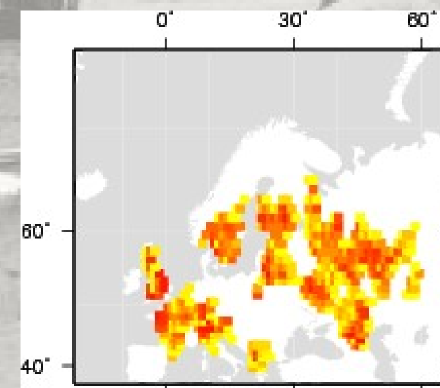
Europe – SAD envelope curves

- Mid to late 1970s drought (UK, France, SE Europe as well as Scandinavia)
- 3 events through 1950s (central Europe)

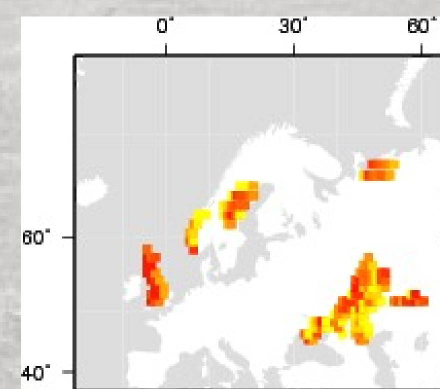




June 1959



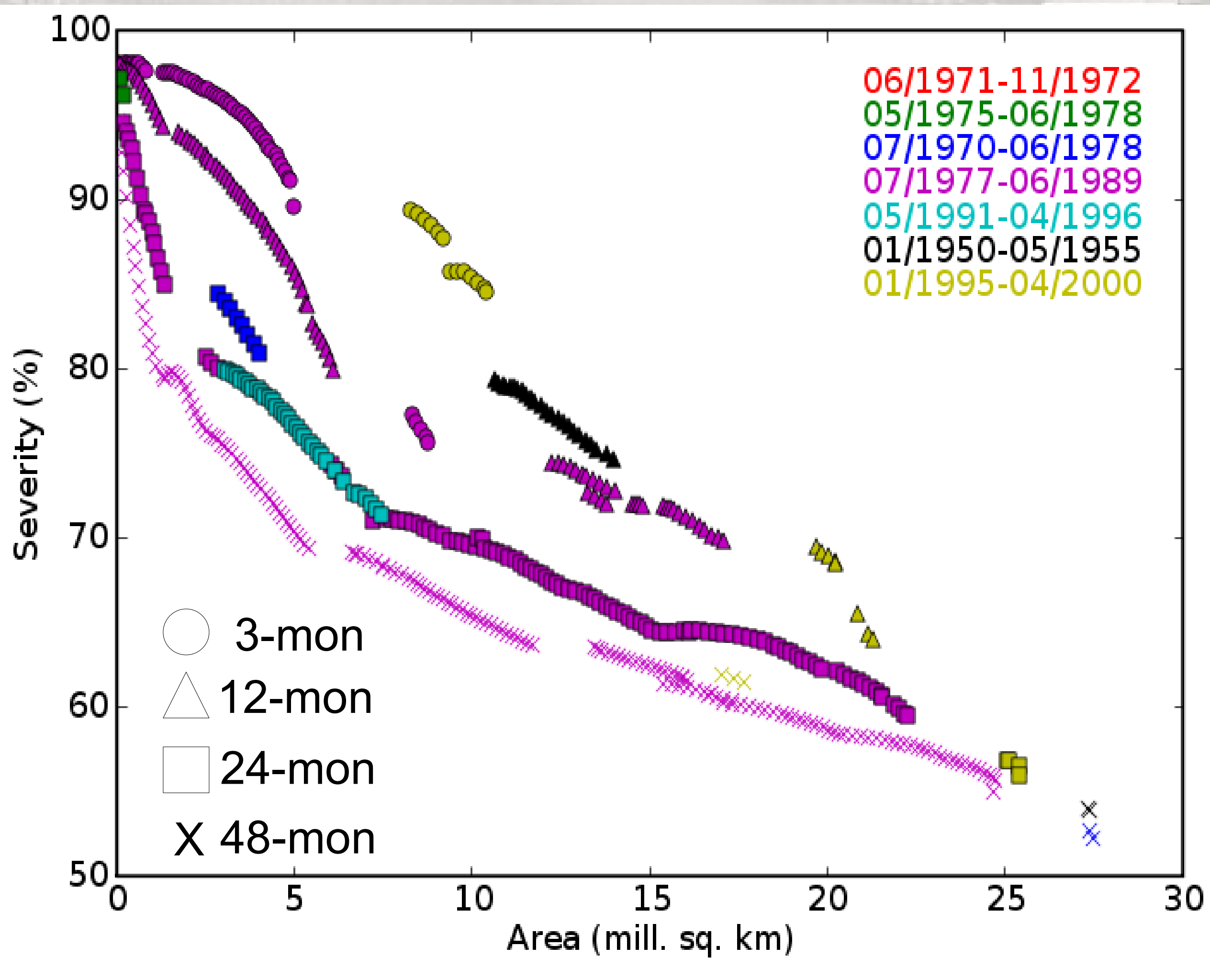
April 1976

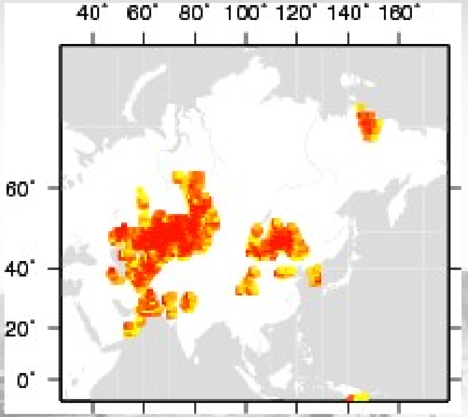


July 1984

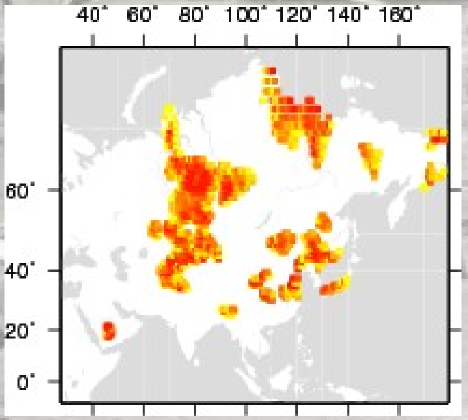
Asia – SAD envelope curves

- Extremely long drought (1951-68) – multiple events merged in time
- Early to mid-1990s drought (NE to central Asia)

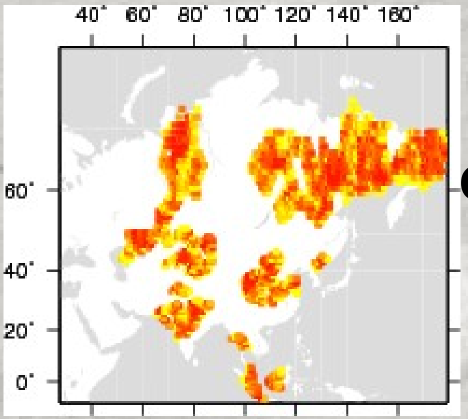




July 1951



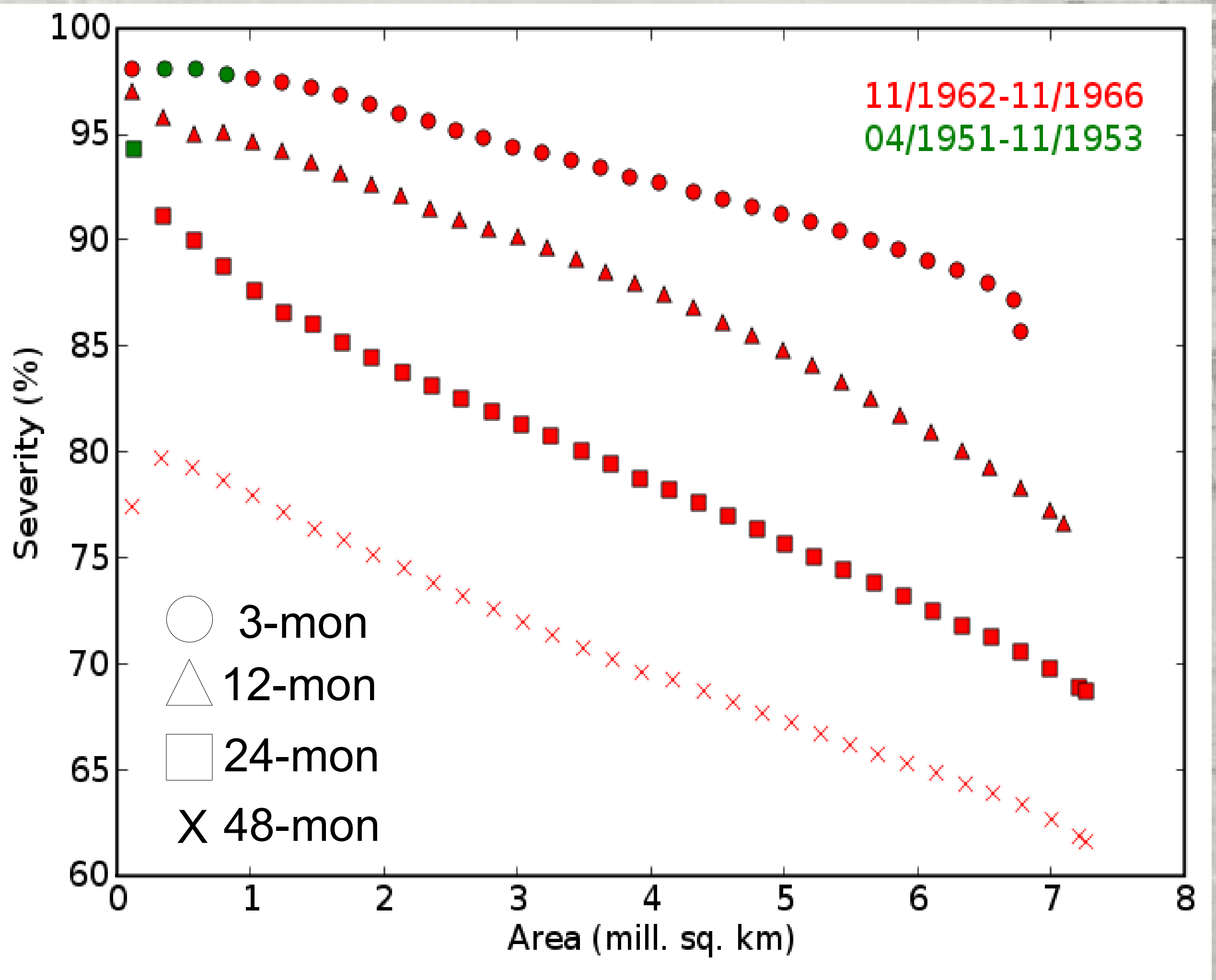
June 1982



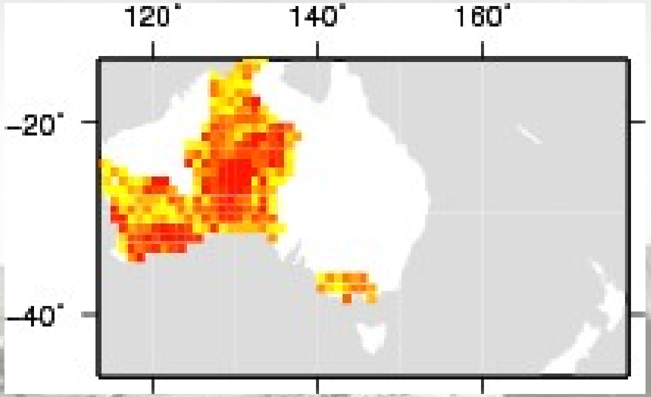
October 1991

Oceania – SAD envelope curves

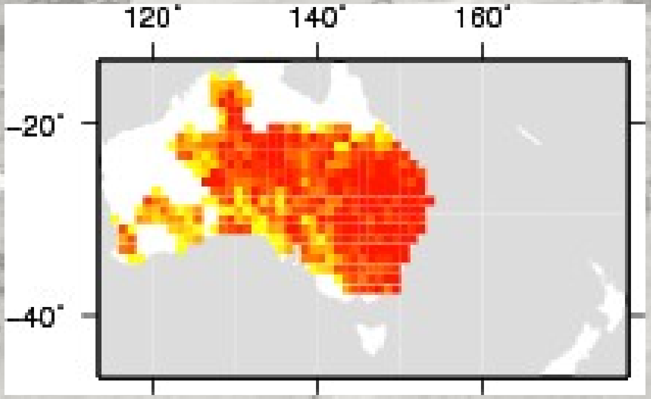
- Early to mid 1960s drought dominant
- Early 1950s event occupying smaller portion of curves



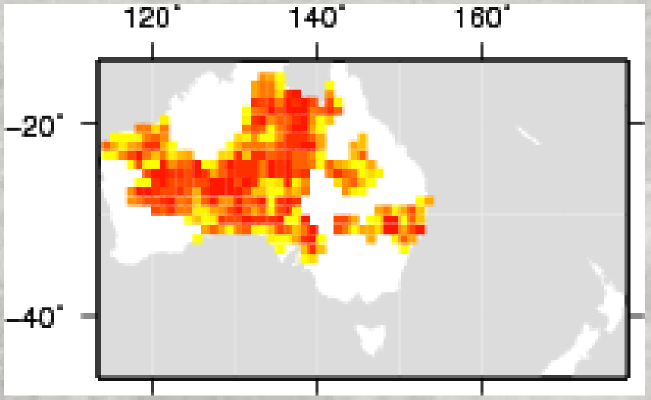
November 1961



March 1965

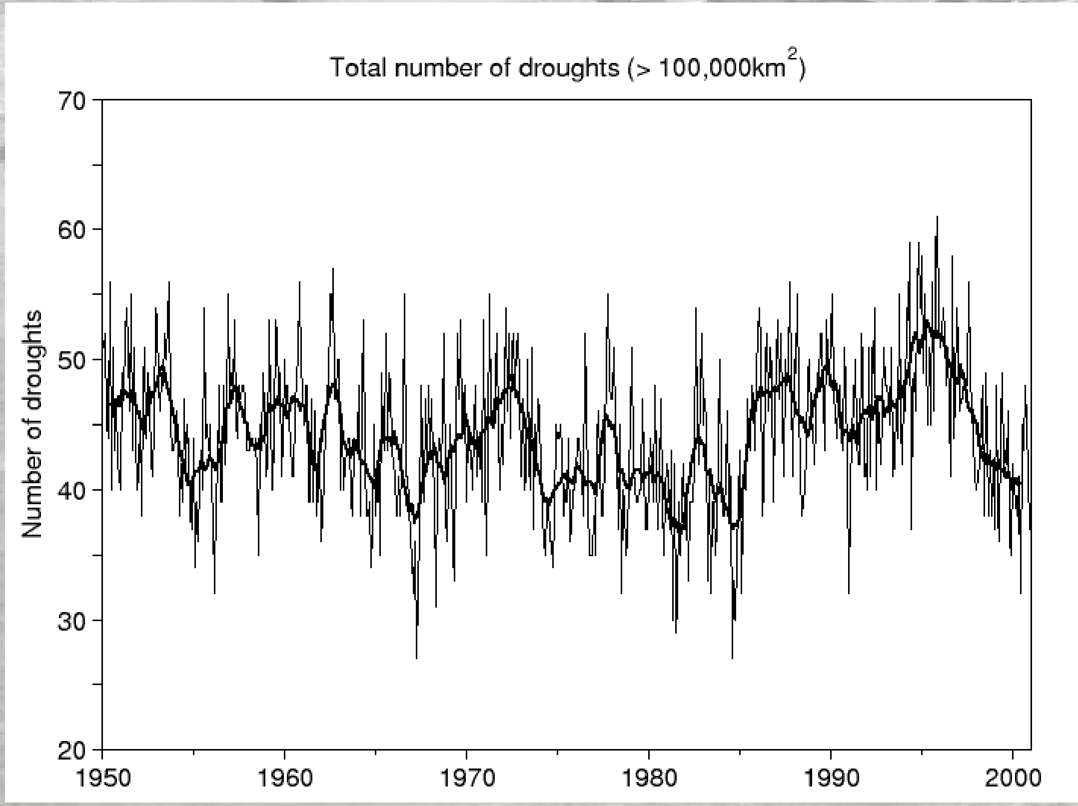


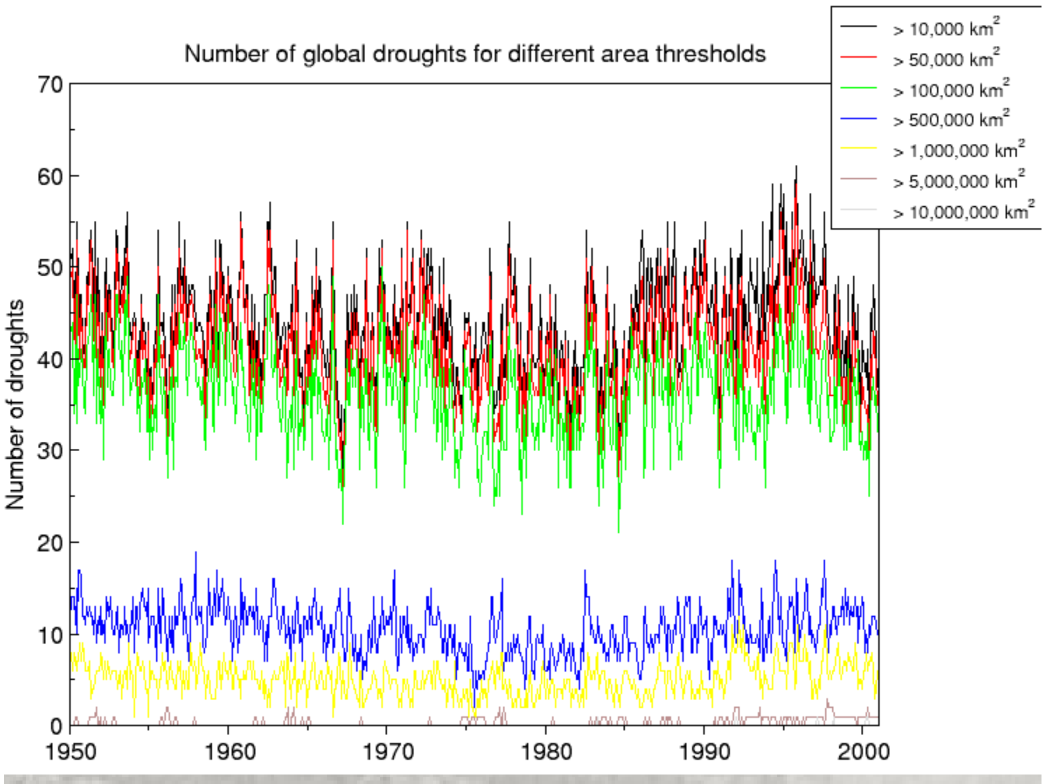
May 1986



Number of drought events

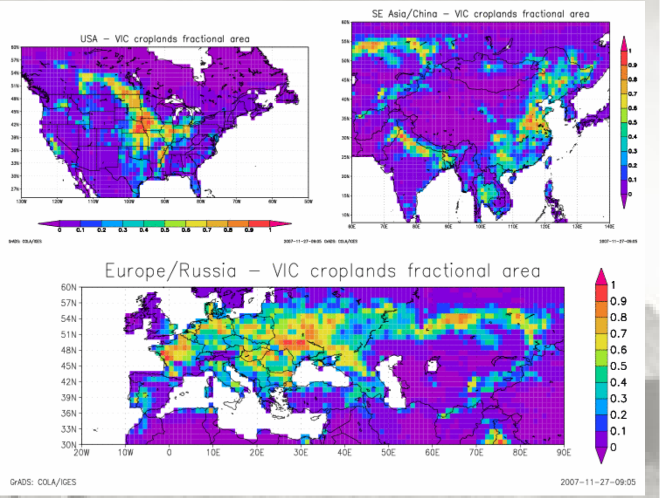
- Monthly time series of total number of droughts (**left**)
- Same but for different drought area thresholds (**right**)
- No apparent trends

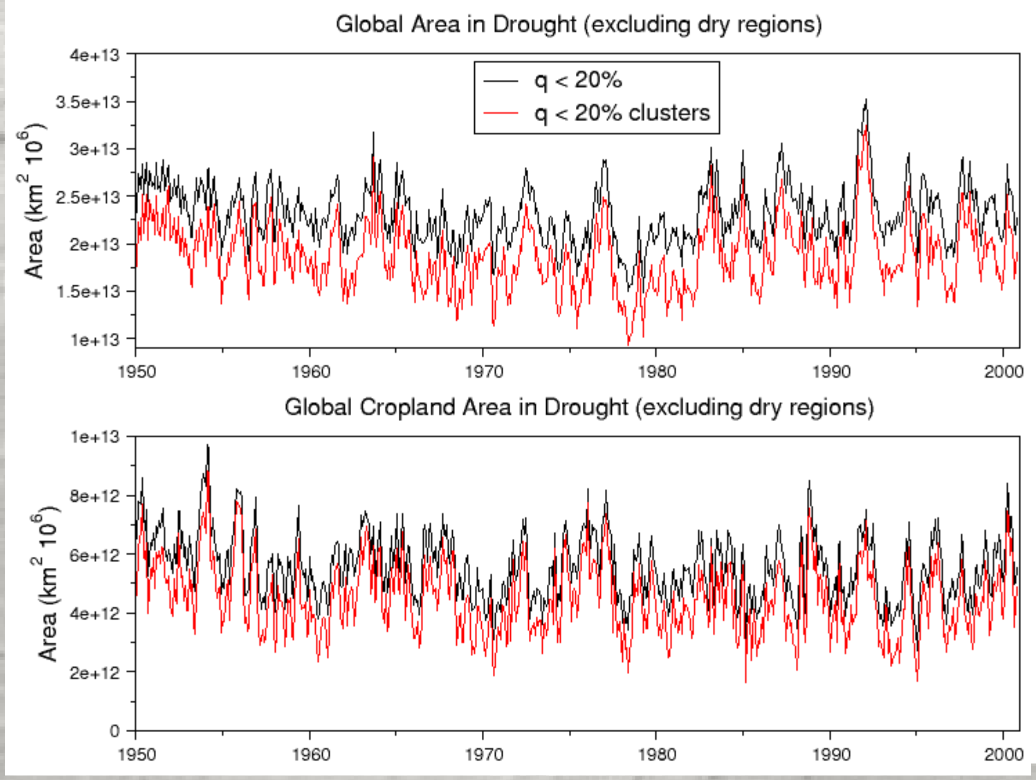


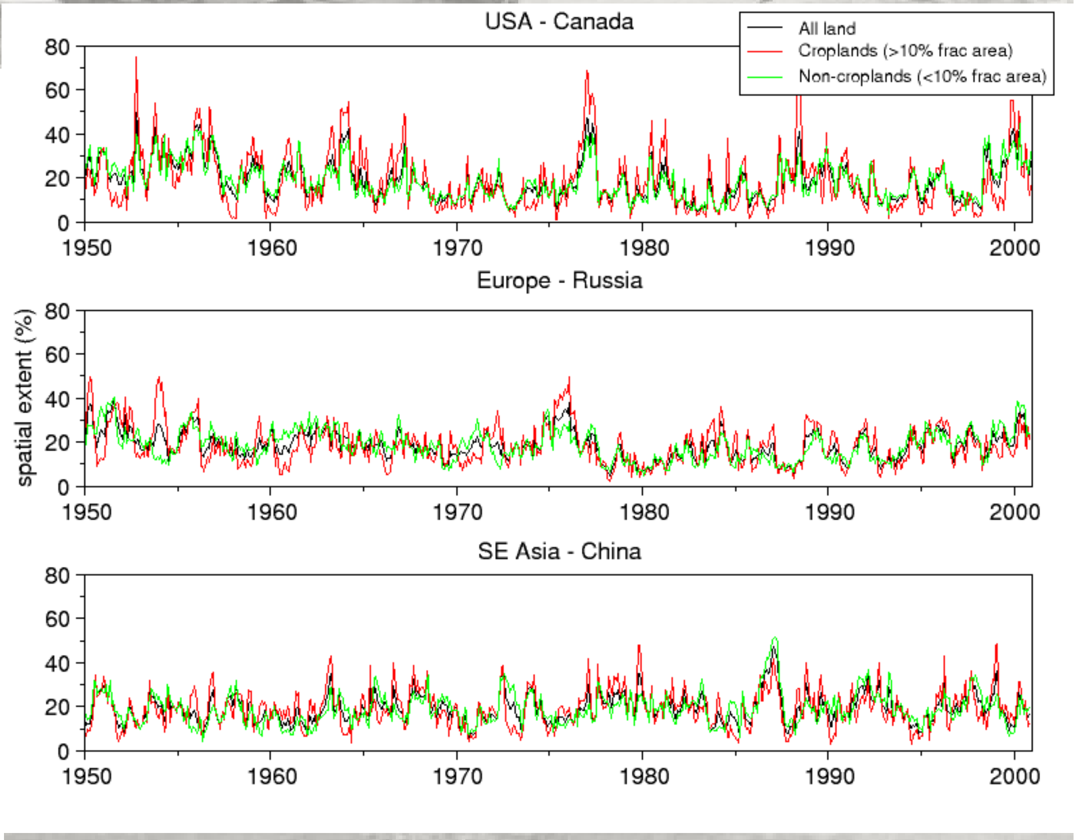


Droughts in croplands

- Fractional area of croplands
- Larger areas of croplands are in drought relatively more often (e.g. 1954, 1958, 1988) (**left plot**)
- More pronounced in USA-Canada and Eurasia (**right plot**)

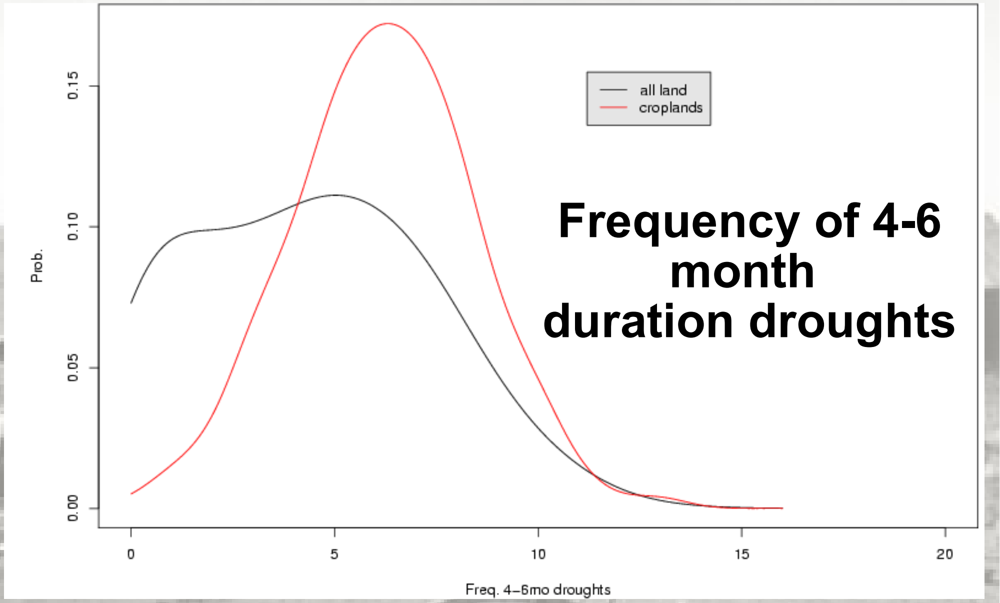


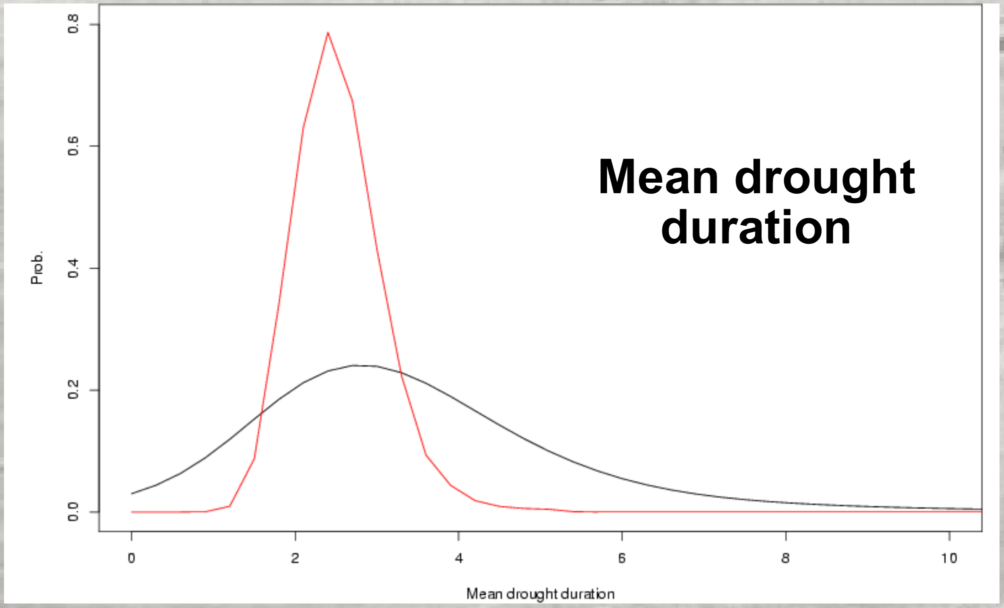


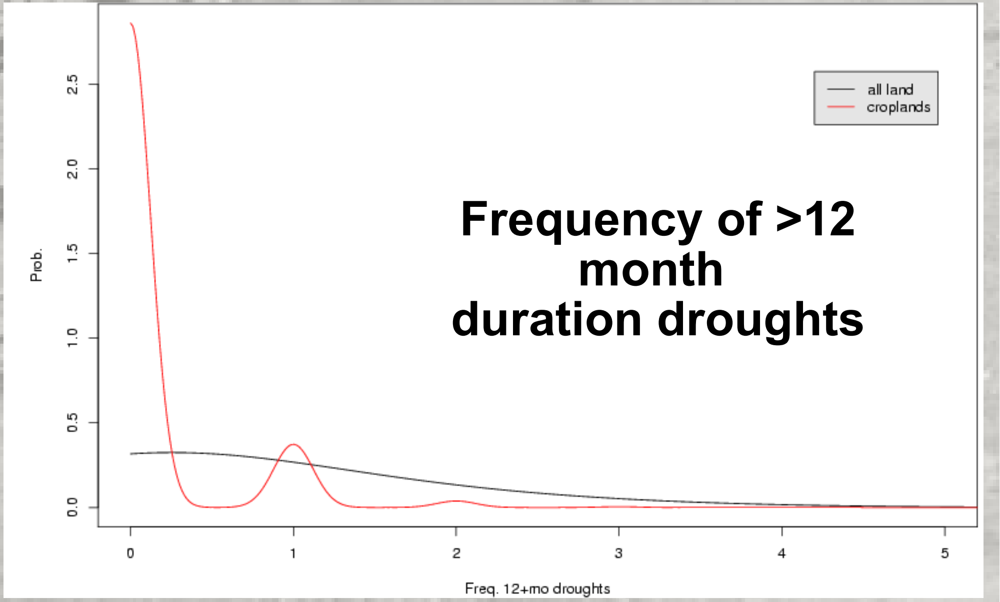


Cropland drought characteristics

- Smoothed PDFs of drought characteristics for croplands and all areas
- Croplands tend to have higher frequency of short-term droughts (reflecting their location)

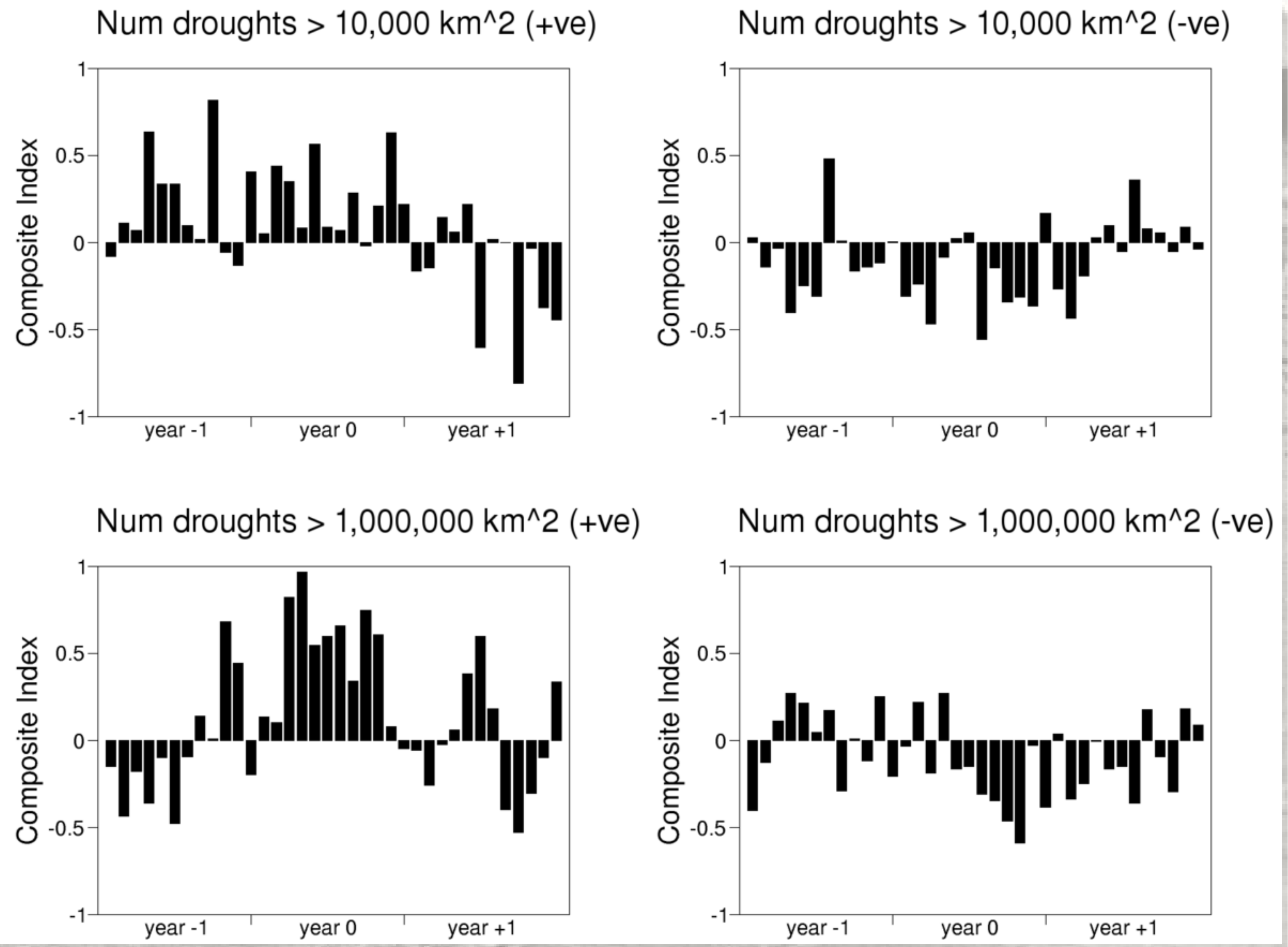






Composite analysis

- Composite index of number of large-area droughts globally for a 36-month window centered on positive (El Niño, **left**) and negative (La Niña, **right**) ENSO anomalies
- Appear to have pronounced effect on larger droughts



Summary

- Use of hydrology models to characterize droughts
- Spatio-temporal drought identification
- SW Monitor drought severity product
- Drought recovery forecasting
- 20^{th} century drought history reconstruction
- Trends in drought characteristics

Future research questions

- Ensemble GCM characterization of drought in the 21st century (comparison with 20th century drought)
- How much drought prediction skill is there in initial hydrologic conditions (e.g., soil moisture) vs climate prediction, and under what conditions, locations, and lead times?
- What level of complexity is required of land surface schemes to predict other drought-affected variables (especially streamflow, and effects of groundwater)?
- What effect have changes in drought characteristics over time (especially in the western U.S.) had on ability to represent drought probabilities?

Questions ?