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

- Moisture Level
- Moisture Flux
- Variability
- Persistence

Maurer et al. 2002
Snow cover extent evaluation

NOAA-NESDIS weekly snow charts

VIC

Number of days with snow
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

Objective Long-Term Drought Indicator Blend Percentiles
March 11, 2007

Notice of Revision:
The formula used to calculate the long-term blend changed for a large part of the western U.S. (painted in color) on Dec. 18, to better reflect the region's water supply considerations.

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

• [Website link](http://www.hydro.washington.edu/forecast/monitor)
SW Monitor Schematic

1930s

NOAA ACIS
Prep Tmax Tmin
Coop Stations

1955+

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

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

vals, anom’s
%-iles w.r.t. PDF

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

Hydrologic State

VIC Real-time Spinup Simulation

Hydrologic State
(-1 Day)
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
The algorithm starts by partitioning the domain into drought areas (using a threshold of 20%). The initial drought clusters are formed by grouping drought grid cells that belong in spatially contiguous blocks. After that, drought clusters are merged based on their distance from each other, and their minimum area. A temporal persistence constraint is used to ensure plausible drought recovery; if a grid cell is out of drought at the current timestep, its drought status for the previous 3 weeks is examined and if its drought transition probability exceeds 50%, the grid cell is set back in drought. The transition probabilities have been calculated beforehand from its grid cell’s climatology. A spatial smoothing step that involves examining the neighborhood of each grid cell at a pre-defined radius is applied to produce the final map.
Regional monitoring (WA state)

soil moisture

Precip (cumulative)

Temperature

Soil Moisture

Snow Water Equivalent

Runoff (cumulative)

Runoff (5-day average)
Standardized Runoff Index

- Similar to SPI but using runoff (Shukla and Wood, 2007)
- Example of 1976-77 WA drought
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. 20\textsuperscript{th} 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

\[ S = 1 - \sum \frac{P}{t} \]

- \( S \): severity
- \( P \): percentile of soil moisture (runoff)
- \( t \): duration
20\textsuperscript{th} century agricultural drought
Soil moisture SAD curves

(a) 3 Month Duration

(b) 12 Month Duration

(c) 24 Month Duration

(d) 48 Month Duration

<table>
<thead>
<tr>
<th>Period</th>
<th>Area (million sq. km)</th>
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<td>1928-32</td>
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<td>1975-79</td>
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<td>1998-03</td>
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Soil moisture envelope SAD curves

1928-32
1932-38
1950-57
1998-2003
20\textsuperscript{th} century hydrological drought
Runoff SAD curves

(a) 3 Month Duration

(b) 12 Month Duration

(c) 24 Month Duration

(d) 48 Month Duration

Area (million sq. km)

Severity

0 1 2 3 4 5 6 7

0 0.65 0.8 1

0 0.65 0.8 1

0 0.65 0.8 1

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

- 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 20\textsuperscript{th} 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)
• 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
S. America – SAD envelope curves

- Two 1960s droughts dominant, mostly over Amazon
- Late 1980s drought in the southern cone
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)
Asia – SAD envelope curves

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

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

![Graphs showing area in drought over time for different regions](chart.png)
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
- 20th 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 ?