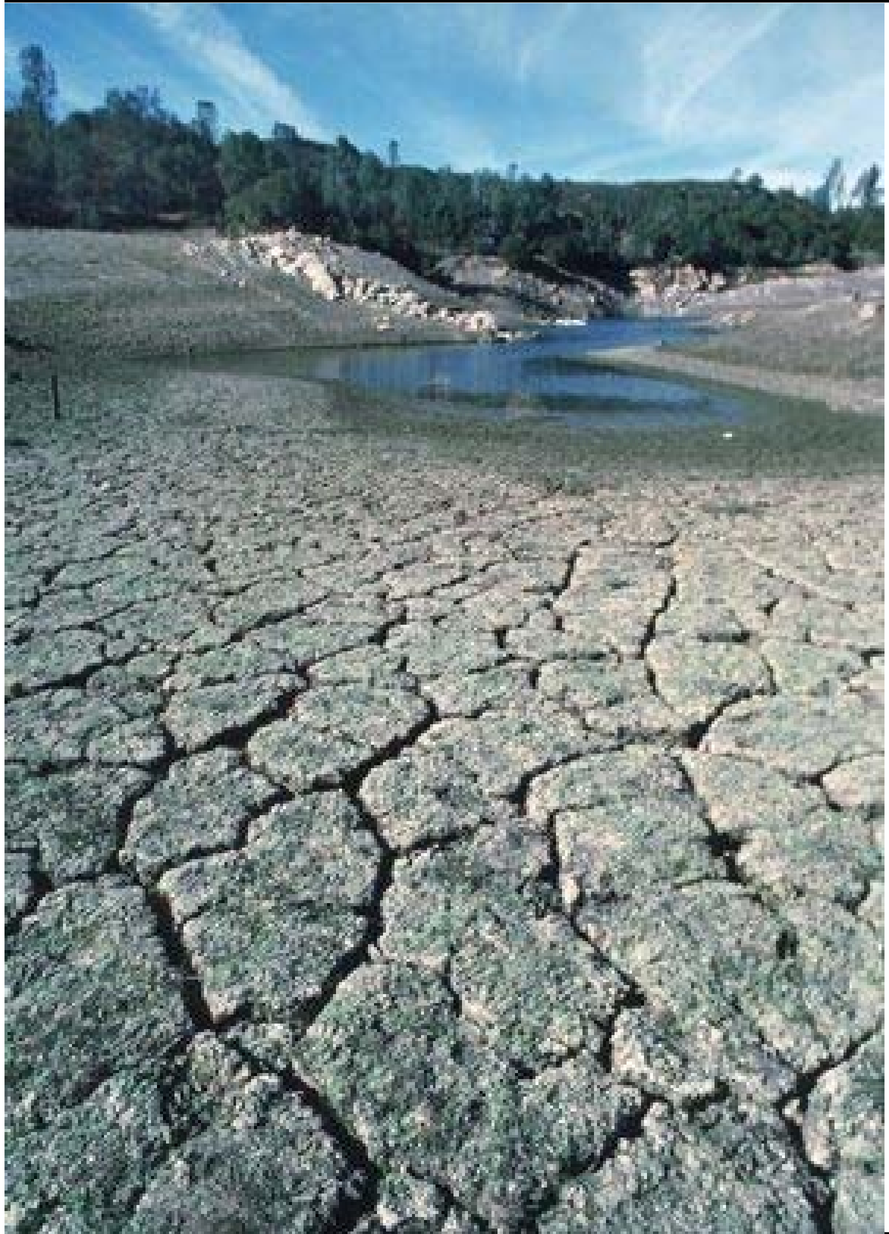


A Survey of Drought Indices: Input, Output, and Available Data Sets

Bisher Imam

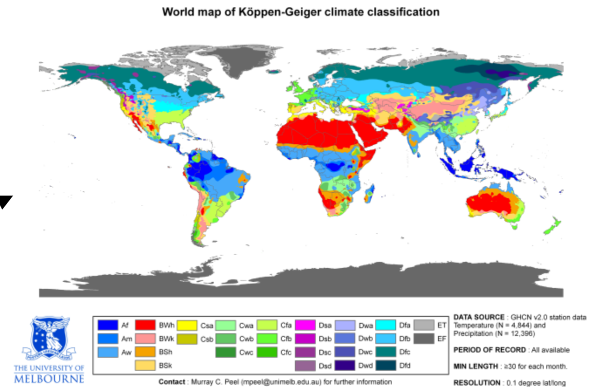
Center for Hydrometeorology and Remote Sensing, University of California, Irvine

Water Resources in Developing Countries:
Planning and Management in Climate Change Scenarios
ICTP, Trieste, Italy, April 27 through May 8, 2009

Aridity

Aridity

- **Concept**
  - Applies to normal conditions (Climatology)
  - The Degree to which climate lacks effective, life promoting moisture
  - Used to classify climate zones
- **Index**
  - P | p(T)
    - Koppen/Geiger Climate Classification (1918)
  - P | PET
    - C. W. Thornthwaite (1948)
    - M. I. Budyko (1958)
    - UNEP

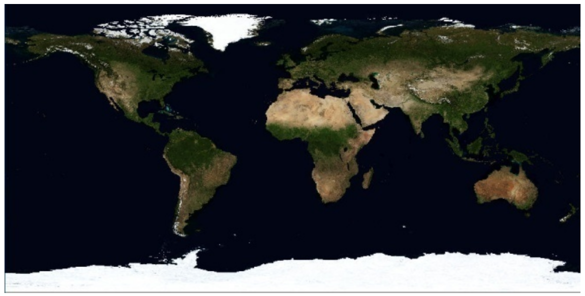


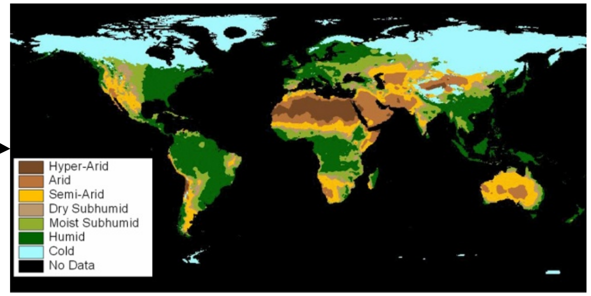
$$I_a = 100 \times \frac{deficit}{demand}$$

$$I_h = 100 \times \frac{surplus}{demand}$$

$$I_m = I_h - I_a$$

$$AI = \frac{P}{PET}$$





Aridity Indices: Examples

Thonthwaite

$$I_a = 100 \times \frac{deficit}{demand}$$ for deficit months

$$I_h = 100 \times \frac{surplus}{demand}$$ for surplus months

$$I_m = I_h - I_a$$

Im	*Classification*
Im < -66.7	Arid
-66.7 < *Im* < -33.6	Semi-Arid
-33.6 < *Im* < 0.0	Dry Sub-humid
0.0 < *Im* < 20.0	Moist Sub-humid
20.0 < *Im* < 100.0	Humid
Im > 10.00	Per-humid

UNEP

$$AI = \frac{P}{PET}$$

AI	*Classification*
Ai > 1.00	Humid
1.00 > Ai > 0.90	Moist sub-humid
0.90 > Ai > 0.65	Dry sub-humid
0.50 > Ai > 0.20	Semi-Arid
0.20 > Ai > 0.05	Arid
A < 0.05	Hyperarid

Drought: An Early index of Drought

"The country has reason to make careful note of either extreme. When the water rises to only twelve cubits, it experiences the horrors of famine; when it attains thirteen, hunger is still the result; a rise of fourteen cubits is productive of gladness; a rise of fifteen sets all anxieties at rest; while an increase of sixteen is productive of unbounded transports of joy. The greatest increase known, up to the present time, is that of eighteen cubits, which took place in the time of the Emperor Claudius; the smallest rise was that of five, in the year of the battle of Pharsalia, the river by this prodigy testifying its horror"

Pliny the Elder, Naturalis Historia, Book V, First Century AD

Some (Visible) Impacts

Some (Visible) Impacts

Recent Extreme Drought Conditions in the U.S. Southwest

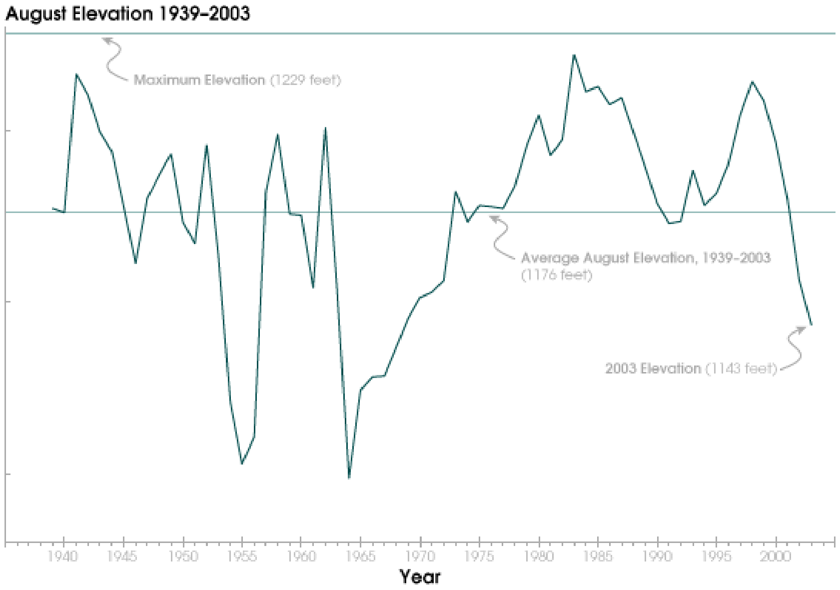
Normal Years

Sever Multi-year Drought through 2004

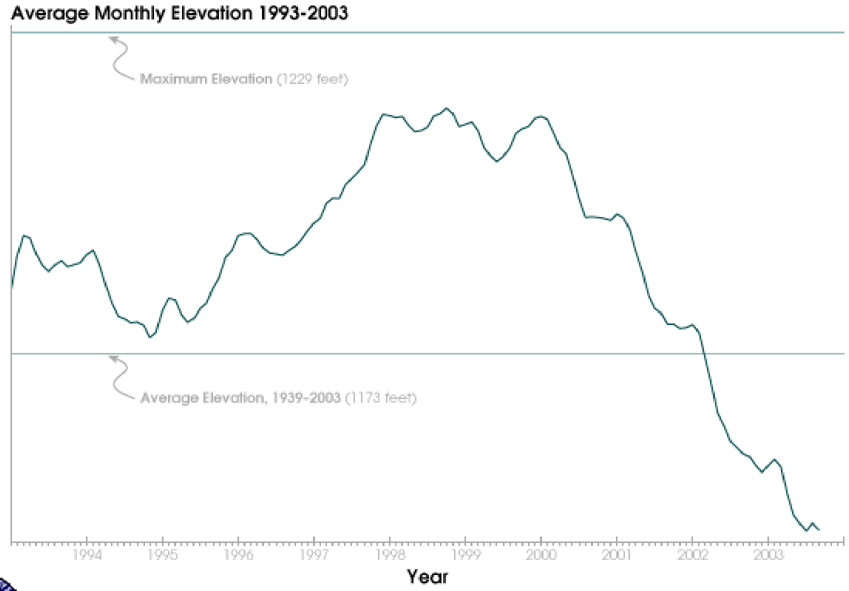
Lake Powell, Colorado River, USA

Source: J. Kane SRP 2004

Water Resources: (Hydrologic Drought)

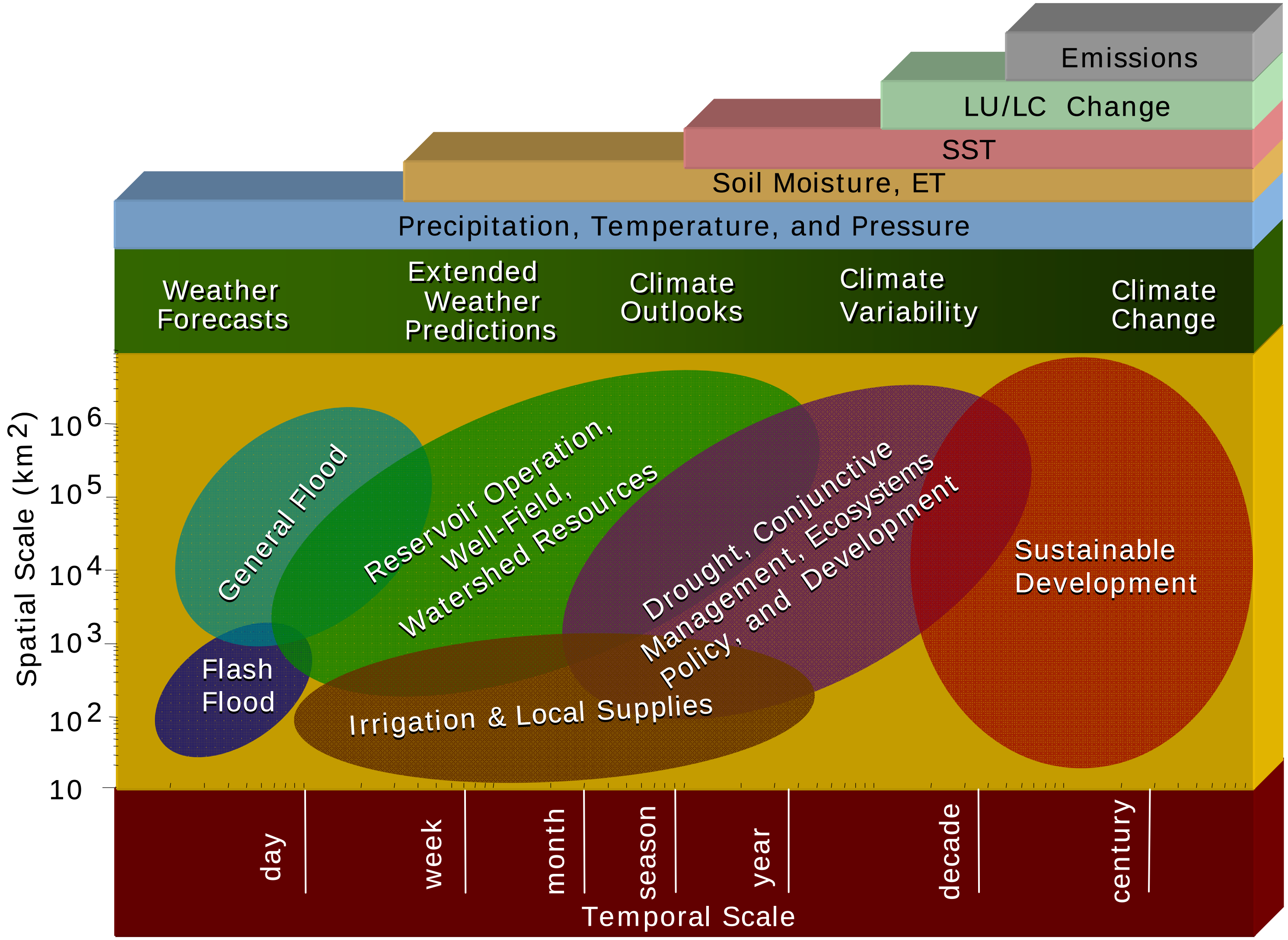


May 3, 2000



May 28, 2003

Water Resources Issues: Spatial & Temporal Scales



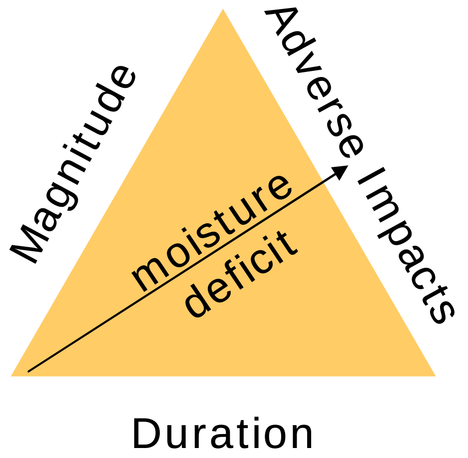
Drought: Definition

- Many Possible Definitions
- It is a normal and recurring feature of climate
- It occurs in all climatic zones
- Varies in characteristics from one region to another

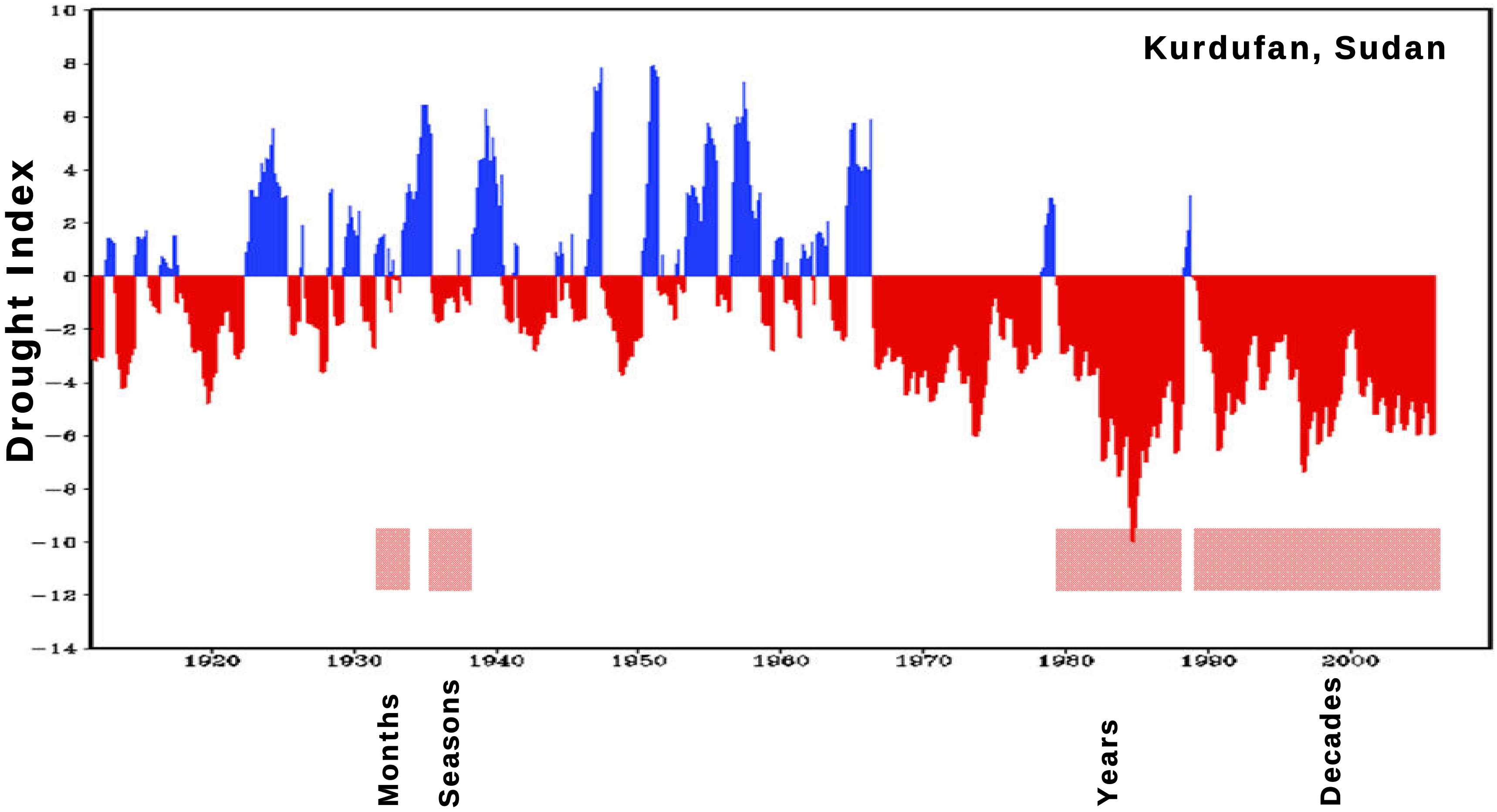
Drought originates from deficiency of precipitation over an extended period of time, usually a season or more resulting in water shortage for some activities

Drought is a persistent and abnormal moisture deficiency having adverse impacts on vegetation, animals, or people

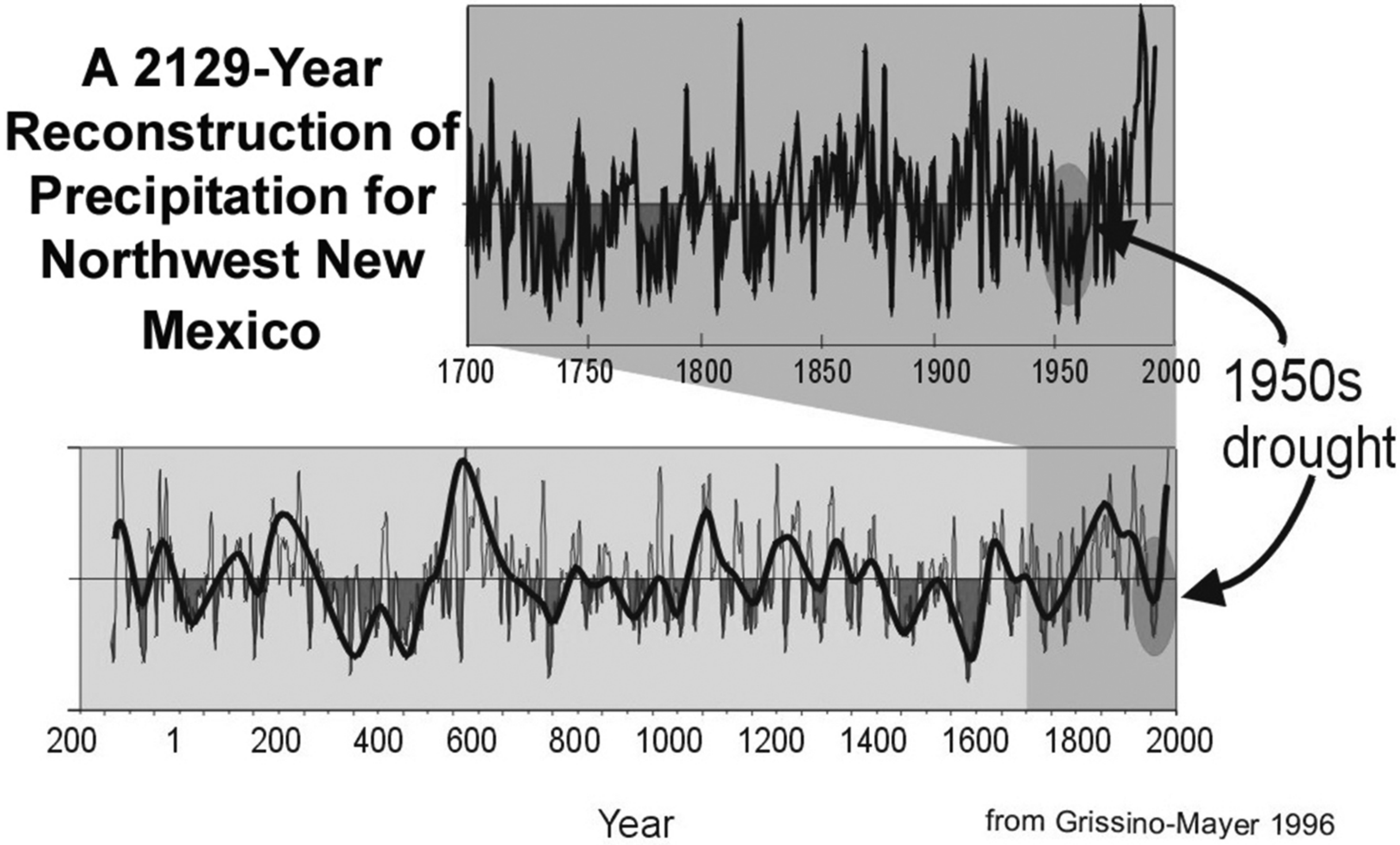
Drought is a creeping disaster
- develops slowly and can last long
- difficult to quantify
- long lasting impacts



Drought: Temporal Scales

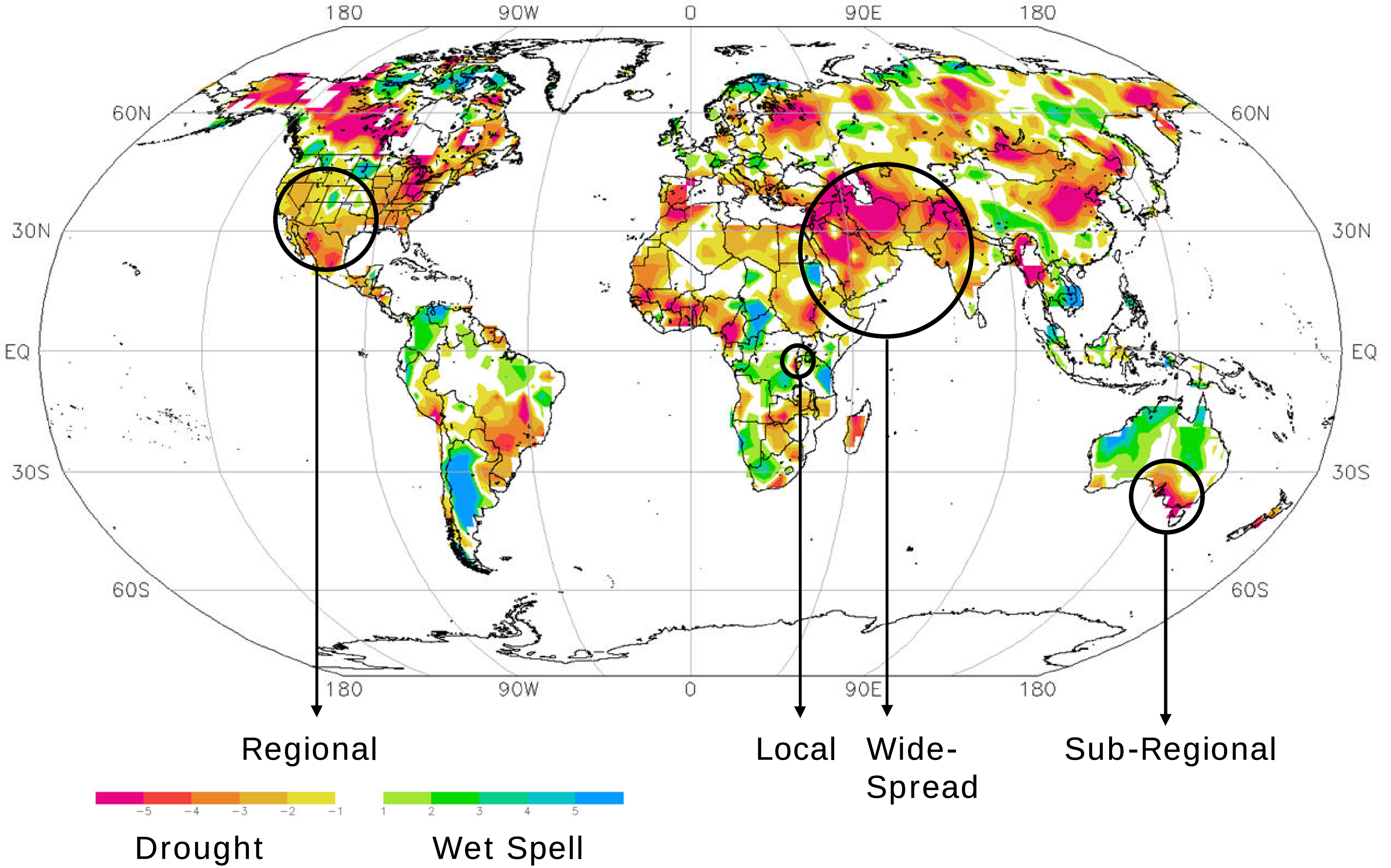


Drought: Temporal Scales (Paleo-climate)

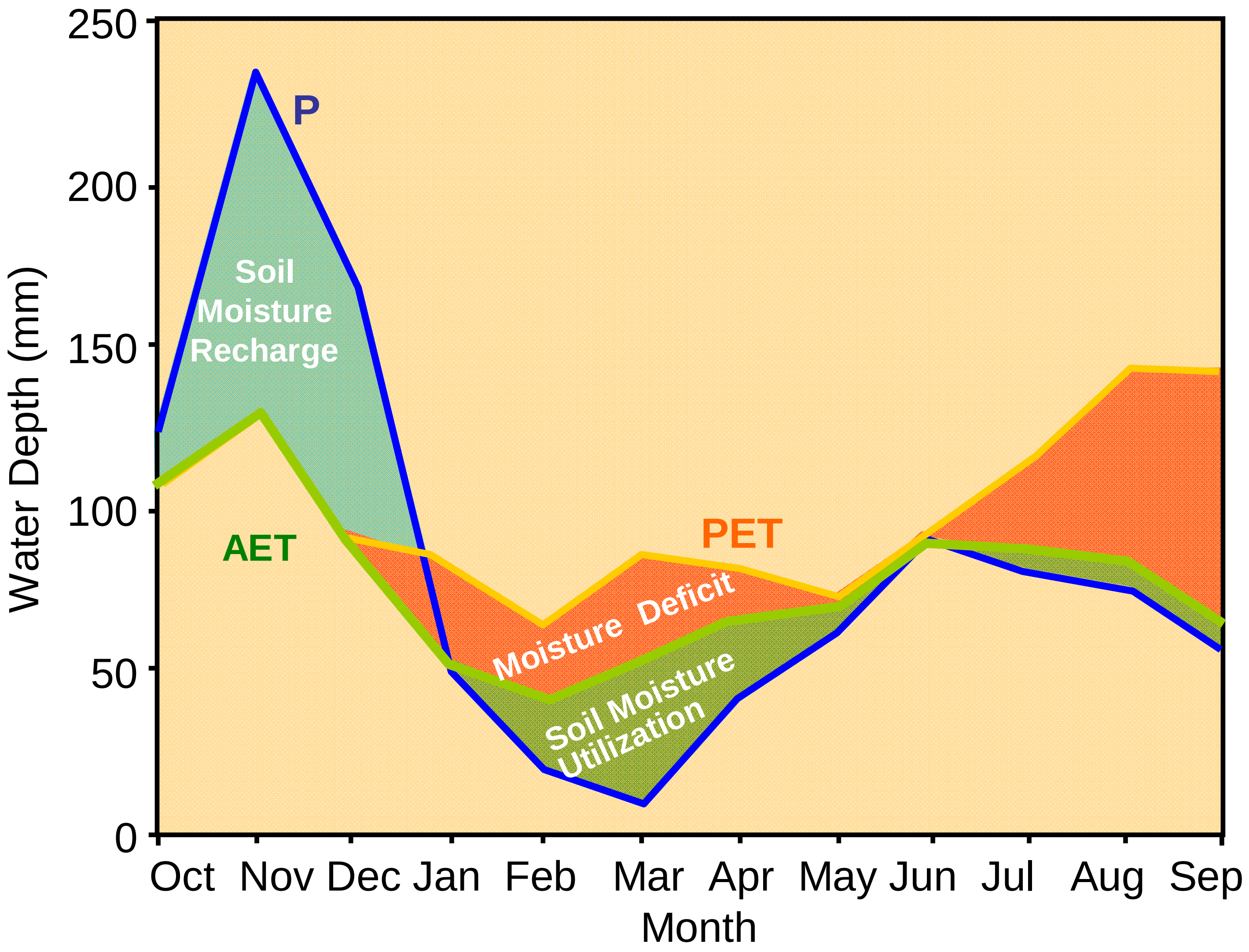


Multi-decades
Century?

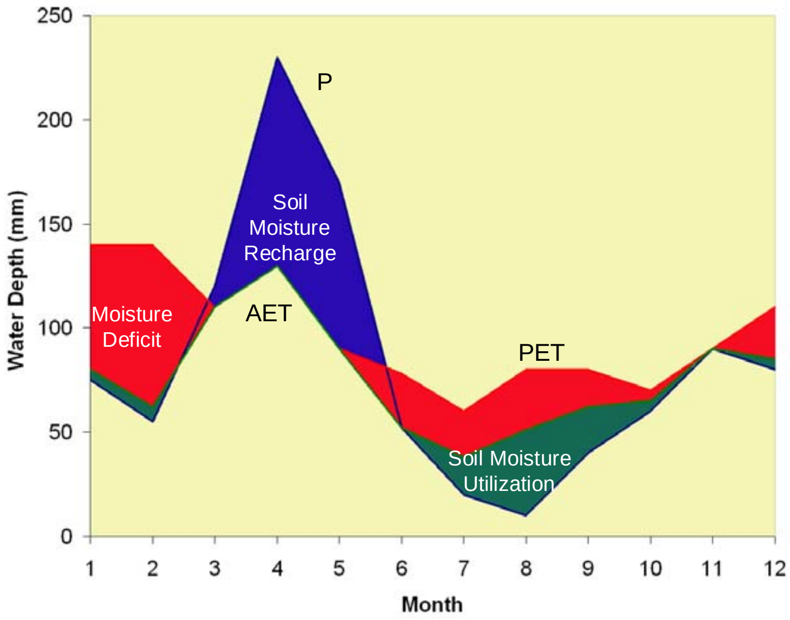
Drought: Spatial Scale

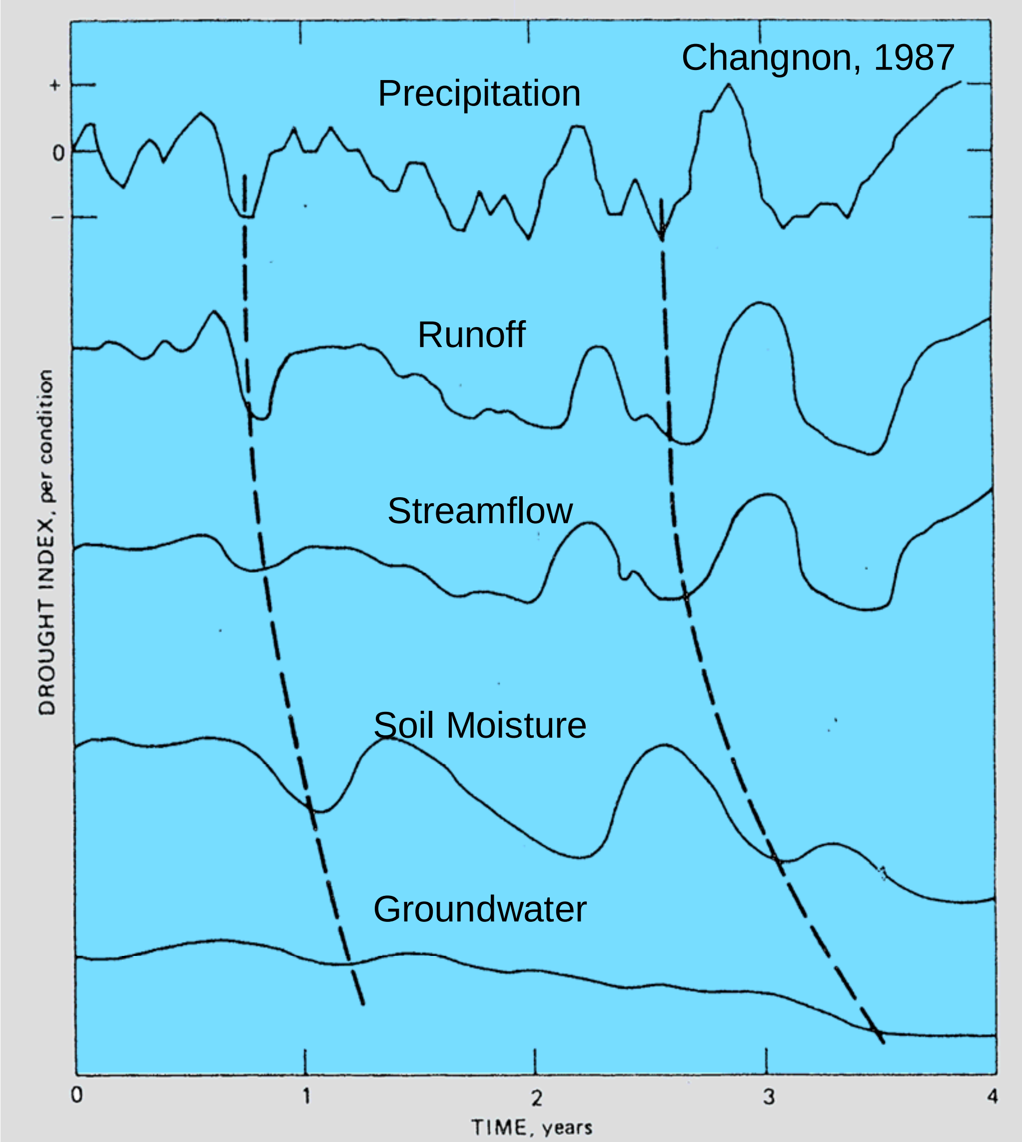


Monthly Water Balance

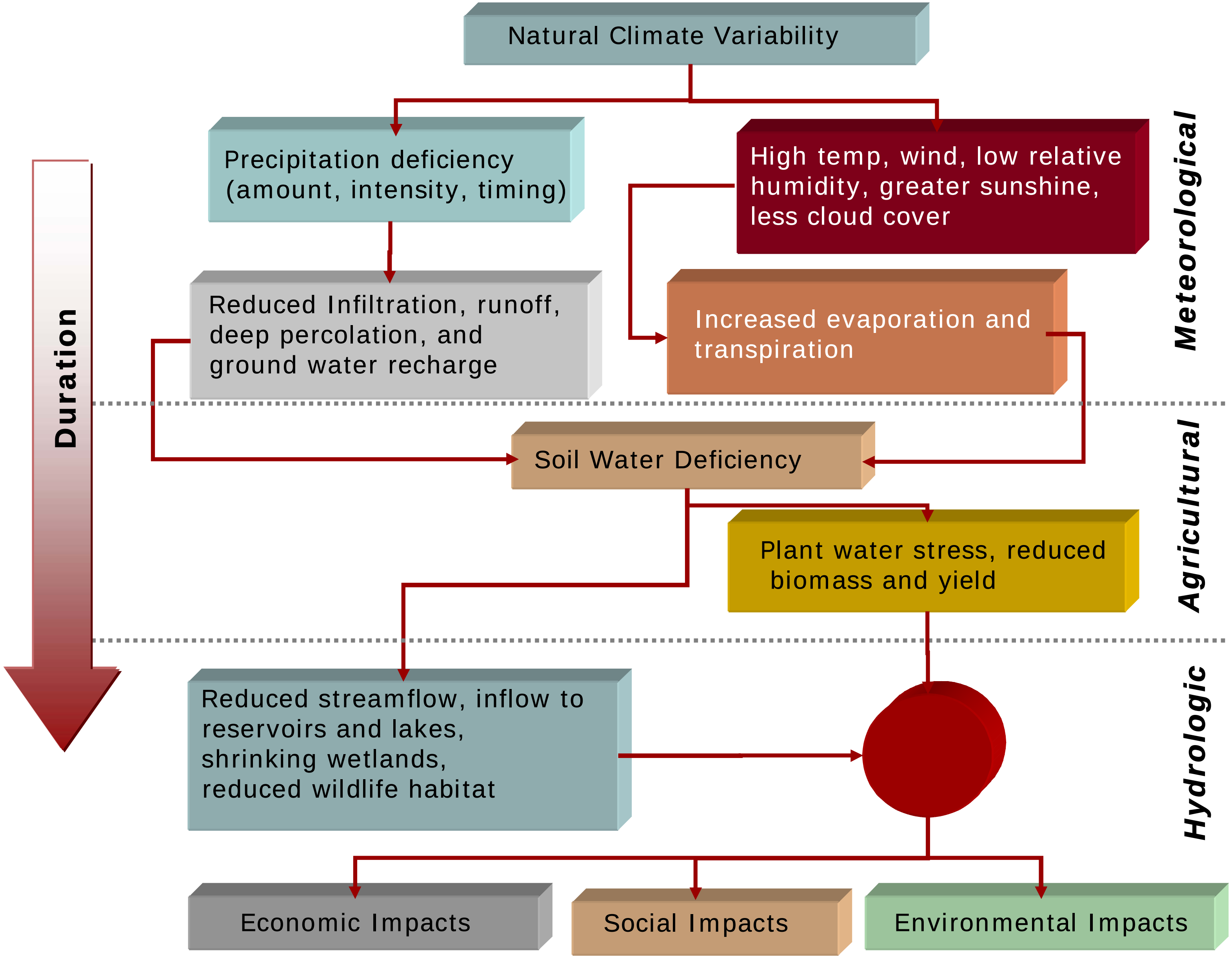


Changnon, 1987

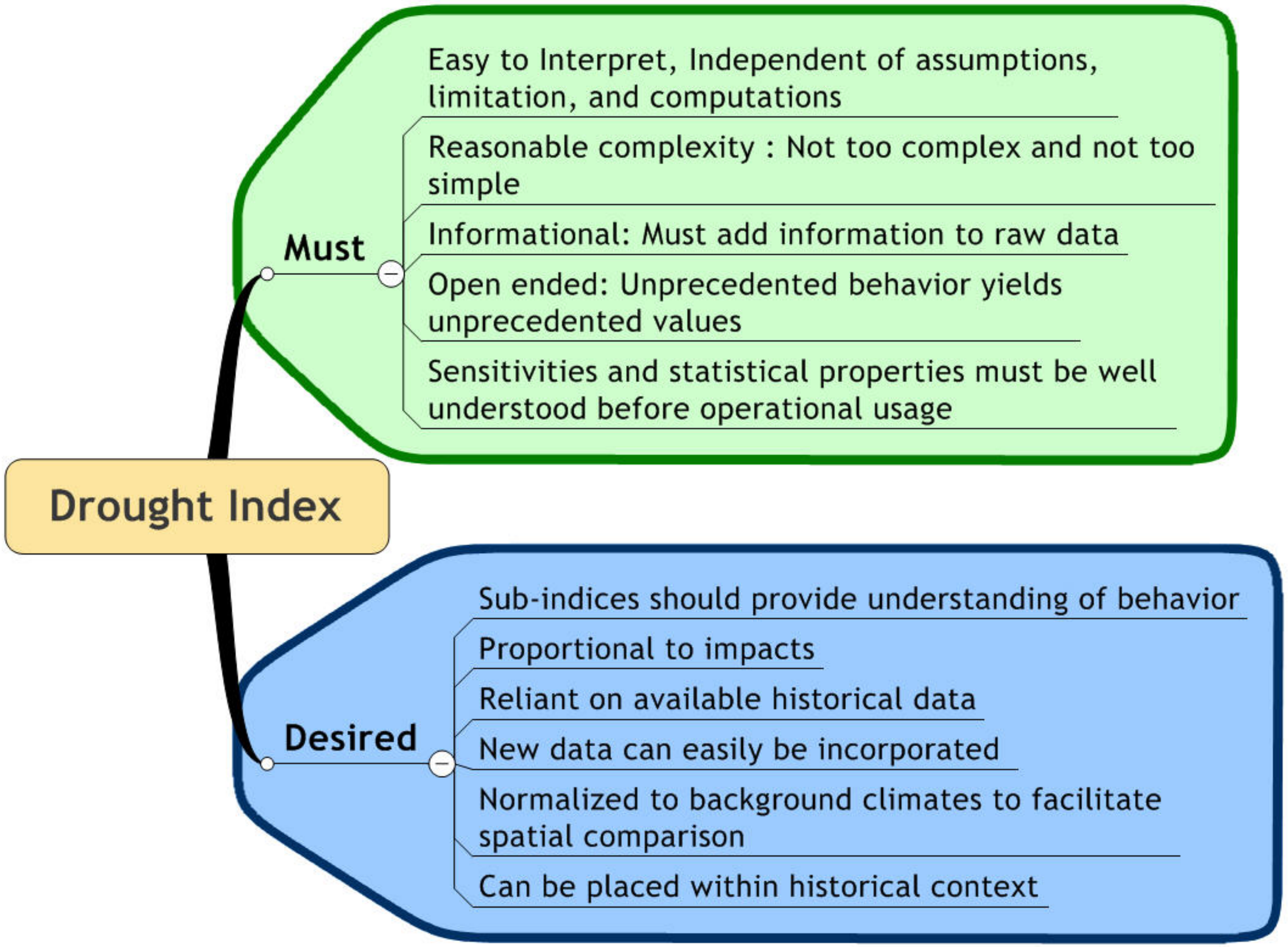

250
200
150
100
50
0
Water Depth (mm)
1
2
3
4
5
6
7
8
9
10
11
12
Month
P
Soil Moisture Recharge
AET
PET
Moisture Deficit
Soil Moisture Utilization


Changnon, 1987
Precipitation
Runoff
Streamflow
Soil Moisture
Groundwater
DROUGHT INDEX, per condition
+
0
–
0
1
2
3
4
TIME, years

Types of Droughts



Desirable Characteristics of Drought Indices



After, Redmond 1991, and 2002

Historical Evolution

Statistical

- Rainy days
- Percent of normal
- Deciles
- Standardized Precipitation Index (SPI)

Deficit-based

- Palmer Drought Severity Index (PDSI)
- Crop Moisture Index (CMI)
- Soil Moisture Index (SMI)

Satellite-based

- Vegetation Condition Index
- Normalized Difference Vegetation Index
- Maximum Snowpack Extent

Composite Impact-based

- US-Drought Monitor
- Total Water Deficit

In-situ data
- Precipitation
- Temperature
- Streamflow
- Reservoir Storage

Models
- Simple Water Balance
- Land Surface Models (VIC)
- Data assimilation systems

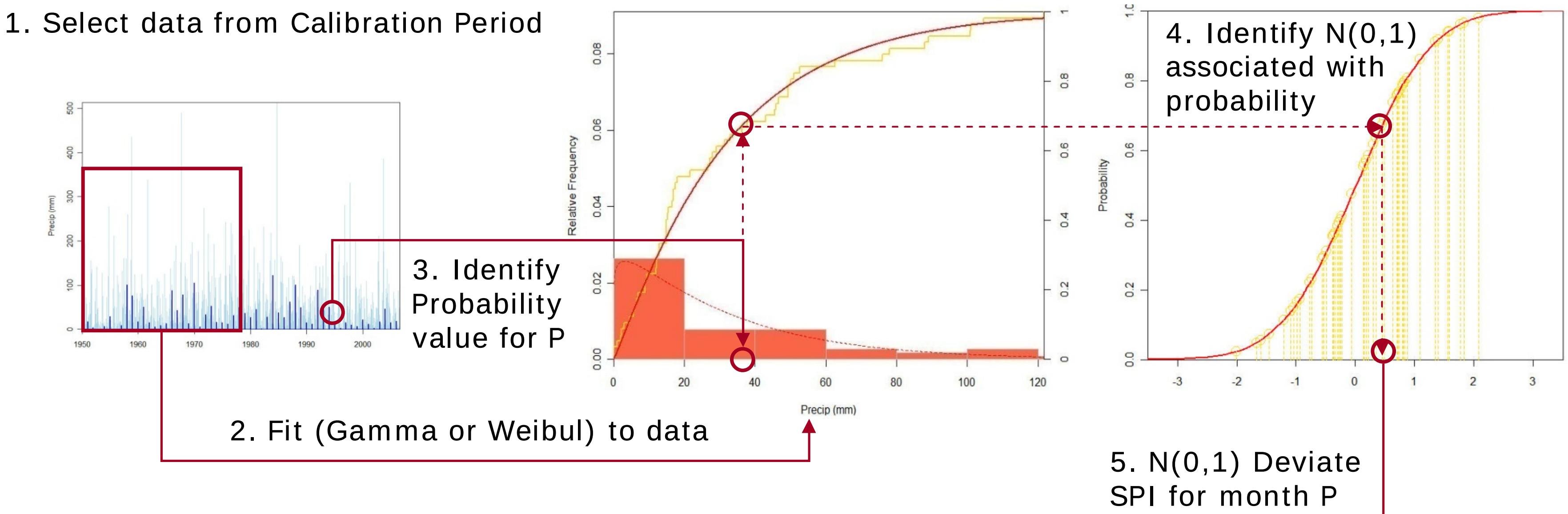
Remote Sensing
- Snow
- Vegetation
- LS temperature
- Topography
- Reservoir Levels (Future)

Impact Models

Comparison (Giorgos Kallis, 2008)

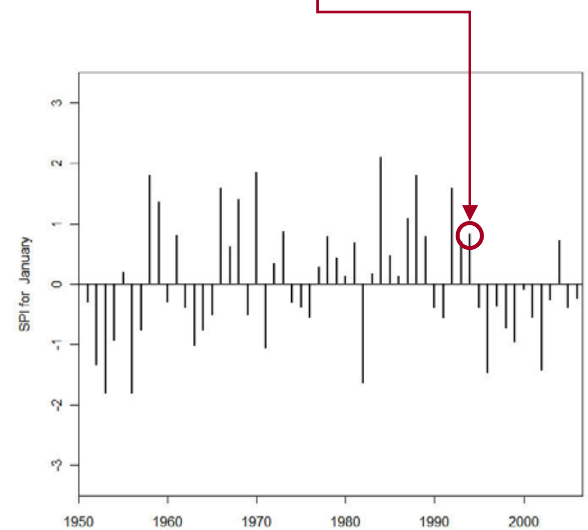
Metric	Data[a]	Calculation	Drought definition and severity scale	Strengths	Weaknesses
Days of rain	R	Consecutive days with little or no R, or total R during a specified period of time	Drought if days with no rain > place-specific maximum or R for given period <place-specific minimum R	Intuitive and communicative Easy to measure	Not comparable. Valid only for specific application in specific region (11) Does not assess increasing or decreasing severity Abrupt termination of drought
Percent of average rainfall (runoff or streamflow)	R (RF, SF)	Divide actual R (or RF, SF) for a given period by multiyear average for this period	Drought if percent <place-specific minimum The lower the percent, the more intense the drought	Intuitive and communicative Easy to measure Useful for reservoir management	Average is not the same as normal in variable climates (mean ≠ median) (145) Cannot compare departure from average for locations with different climates
Deciles (146)	R	Divide distribution of occurrences over a long-term R record into tenths of distribution (deciles)	Scale: deciles 1–10 Drought if R in third through fourth decile Extreme drought in deciles 1–2 (i.e., R not exceeding 10%–20% of record)	Easy to measure Accurate statistical measurement of departure from normal, comparable across contexts	Impacts from statistical departures vary depending on local conditions Accurate calculations require a long data record

Statistical Indices: Standardized Precipitation Index (SPI)

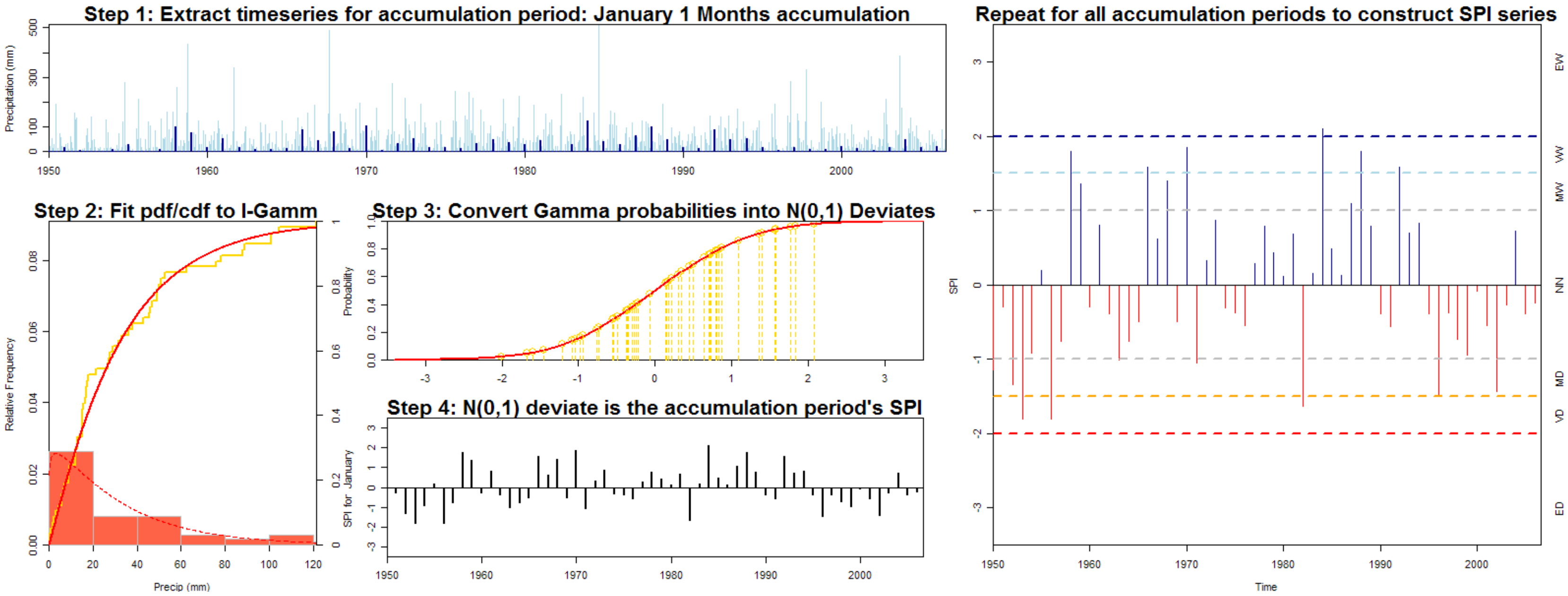


T.B. McKee, N.J. Doesken, and J. Kleist (1992)

For the selected accumulation period and duration
Select data from the calibration period
Fit Probability distribution (Gamma or Weibul)
For the Entire Period
- Identify value of CDF corresponding to p
- Identify SPI as the N(0,1) deviate corresponding to CDF(P)



DEMO



near normal	abnormally moist	moderately moist	very moist	extremely moist	exceptionally moist
-0.50 to +0.50	+0.51 to +0.79	+0.80 to +1.29	+1.30 to +1.59	+1.60 to +1.99	+2.00 and above

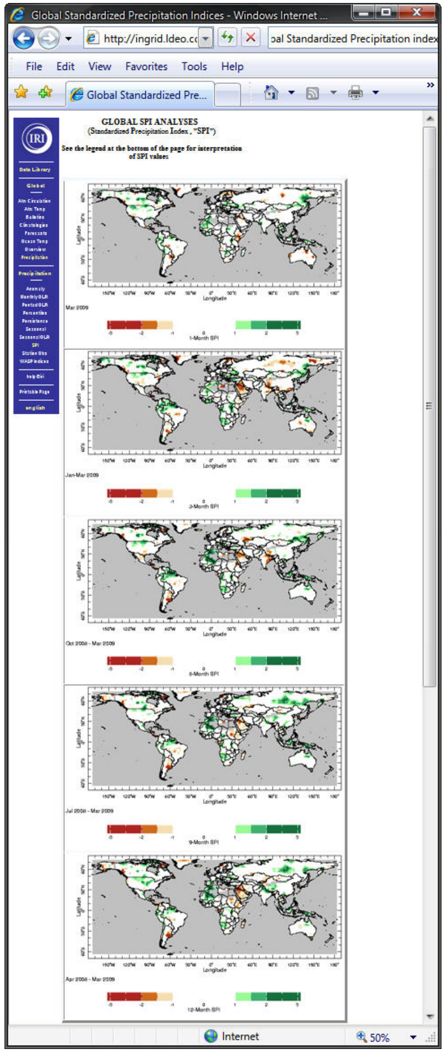
exceptionally dry	extremely dry	severely dry	moderately dry	abnormally dry	near normal
-2.00 and below	-1.99 to -1.60	-1.59 to -1.30	-1.29 to -0.80	-0.79 to -0.51	-0.50 to +0.50

Characteristics of SPI

- Can be computed for any duration, generally (1,3,6,9,12,and 24) months
- Can account for long term precipitation deficit (9 months +)
- Requires long term precipitation data
- Best possible distribution is still subject of research
- Has high correlation with PDSI (at longer duration)
- Mean SPI for any location is 0
- Applicable to station and gridded data (Satellite data)

Available Global Monitoring of SPI

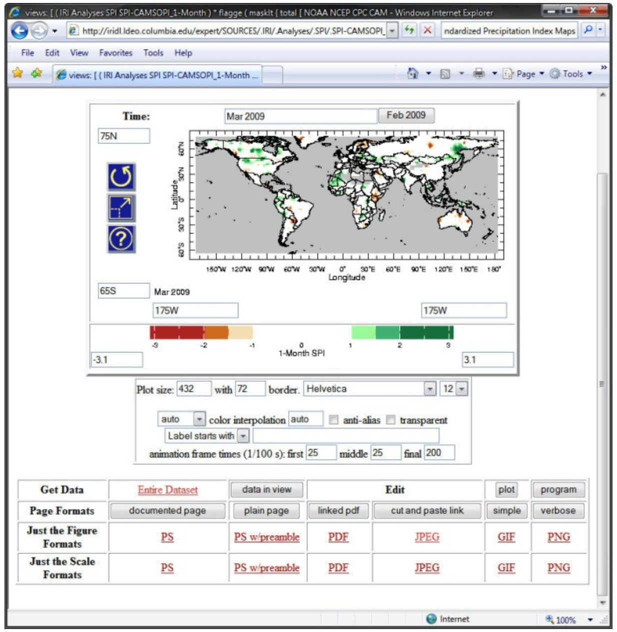
http://ingrid.ldeo.columbia.edu/maproom/.Global/.Precipitation/SPI.html



	SPI Values	Category
	= 2.00	Extremely Wet
	1.50 to 1.99	Severely Wet
	1.00 to 1.49	Moderately Wet
	-0.99 to 0.99	Near Normal
	-1.00 to -1.49	Moderately Dry
	-1.50 to -1.99	Severely Dry
	<= -2.00	Extremely Dry

1, 3, 6, 9, and 12 Months

Interactive tool to plot and visualize



Palmer Indices: brief procedure

Compute monthly water budget using hydrologic accounting for a long series and Obtain coefficients

$$\alpha_i = \frac{\overline{ET_i}}{\overline{PE_i}} \qquad \beta_i = \frac{\overline{R_i}}{\overline{PR_i}}$$

$$\gamma_i = \frac{\overline{RO_i}}{\overline{PRO_i}} \qquad \delta_i = \frac{\overline{L_i}}{\overline{PL_i}},$$

Two bucket model
Thornthwaite (PE)
ET, Loss, Recharge, Run-Off
Requires AWC in soil

Determine the amount of moisture required for climatically appropriate for existing conditions (CAFEC: Normal) weather during each month.

$$\hat{P} = \alpha_i \mathrm{PE} + \beta_i \mathrm{PR} + \gamma_i \mathrm{PRO} - \delta_i \mathrm{PL}.$$

Compute the precipitation departure from CAFEC value

$$d = P - \hat{P}$$

Convert the departures to indices of moisture anomaly Palmer *Z* Index using K (climatic characteristic factor)

$$Z = dK.$$

$$K_i' = 1.5 \log_{10}\left(\frac{\frac{\overline{PE_i} + \overline{R_i} + \overline{RO_i}}{\overline{P_i} + \overline{L_i}} + 2.8}{\overline{D_i}}\right) + 0.5$$

$$K_i = \frac{17.67}{\sum_{j=1}^{12} \overline{D_j} K_j'} K_i'.$$

Average Moisture Departure

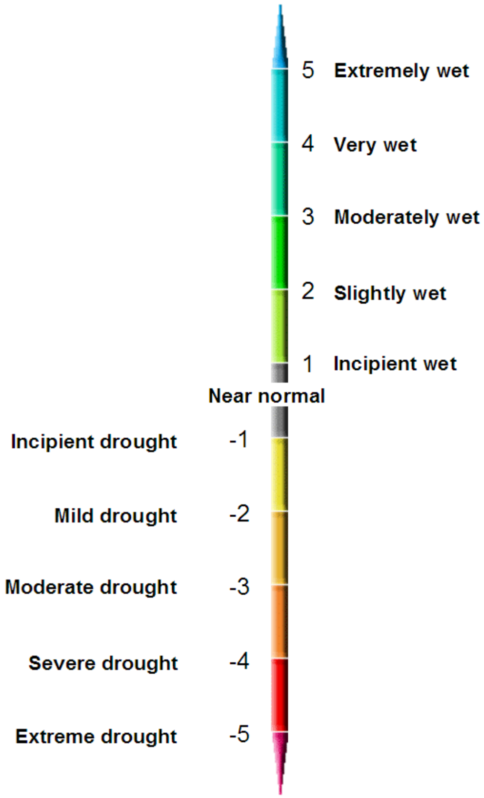
Calculate Palmer Drought Severity Index (PDSI) ant Its derivatives

$$X_i = 0.897 X_{i-1} + \left(\frac{1}{3}\right) Z_i.$$

Duration factors

PDSI: Further Developments

PDSI Scale



Karl, 1986: PHDI (Palmer Hydrological Drought Index)

Different treatment of the end of a dry spell to reflect water availability (soil moisture, runoff) as opposed to meteorological end based on weather.

Heim 2005: Weakly basis calculation of PDSI

Wells et. al. 2004, Self calibrating PDSI

Allows for the calculation of climatic characteristic and duration factors using site specific data instead of Palmer's empirical estimates

Dai, 2004: Global PDSI data set for 100+ years.

Metric	Data[a]	Calculation	Drought definition and severity scale	Strengths	Weaknesses
Palmer Drought Severity Index (PDSI) (147)	R, T, ET, SM, RF	Calculates a series of water balance terms for a generic two-layer soil model. Fluctuations in the hypothetical moisture supply are compared to a reference set of water balance terms to compute dimensionless cumulative departure of moisture supply	Scale: −6 to 6 (typically −4 to 4) Drought if <0 −0.5 to −0.99 incipient dry spell −2 to 2.99 moderate drought −4 and less extreme drought	Takes evapotranspiration and soil moisture into account Most effective where impacts sensitive to soil moisture Factors in antecedent conditions Calculable from basic data	Arbitrary algorithms (148) Nonintuitive classification Undefined generic timescale (7); may lag drought termination (8) Complex computation and reduced transparency Calibrated for U.S. Great Plains' conditions; limited applicability in locations with climatic extremes, mountainous terrain, or snow-pack unless calibrated (but see 18)
Standardized Precipitation Index (SPI) (7)	R	The long-term R record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for location and desired period is 0.	Scale: −2 and less, to 2 and more Drought when SPI continuously <0 −1 to −1.49 moderate −1.5 to −1.99 severe −2 and less extreme	Can be computed at different timescales as they relate to different types of drought (agricultural, streamflow, groundwater) Uses only one input variable (R) so calculations are simpler than PDSI	Long climatic record needed Changes from month to month as new data is incorporated Does not consider hydroenvironmental factors and seasonal differences in evapotranspiration

1) Retrospective Simulation

After: E. Wood, 2006 Princeton University

Forcings → VIC LSM → Retrospective Soil Moisture

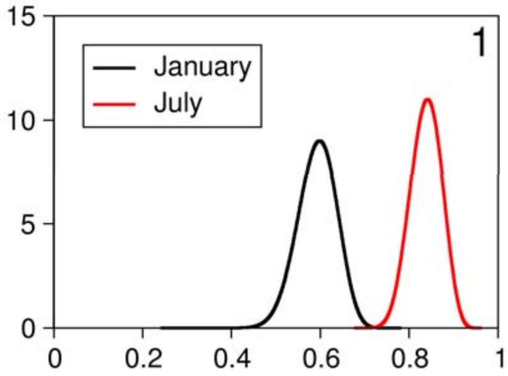
2) Calculate Soil Moisture Index

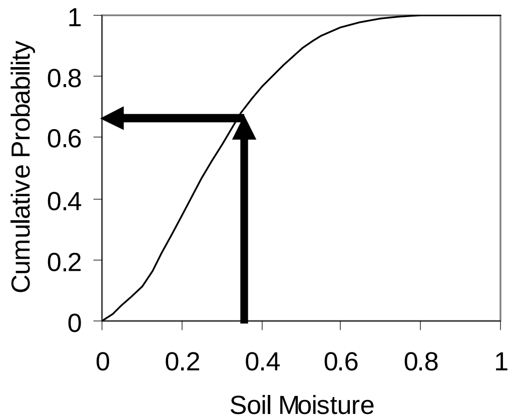
L-Moments → Fit beta distribution → Calculate Index

$$L_{mean}(\mu_s) = \lambda_1$$

$$L_{CV}(\sigma_s / \mu_s) = \frac{\lambda_2}{\lambda_1}$$

$$L_{skew}(\gamma_s) = \frac{\lambda_3}{\lambda_2}$$

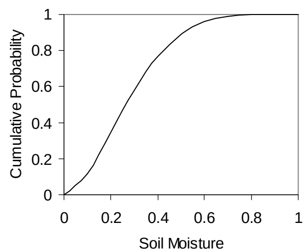


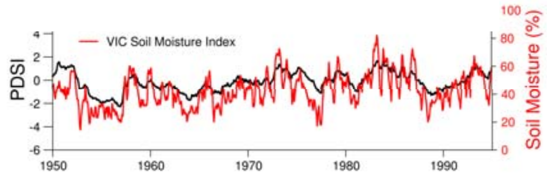


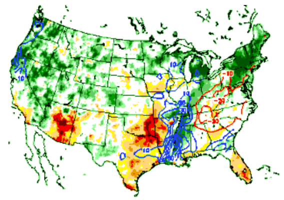
3) Drought Analysis

Historic soil moisture

Realtime soil moisture

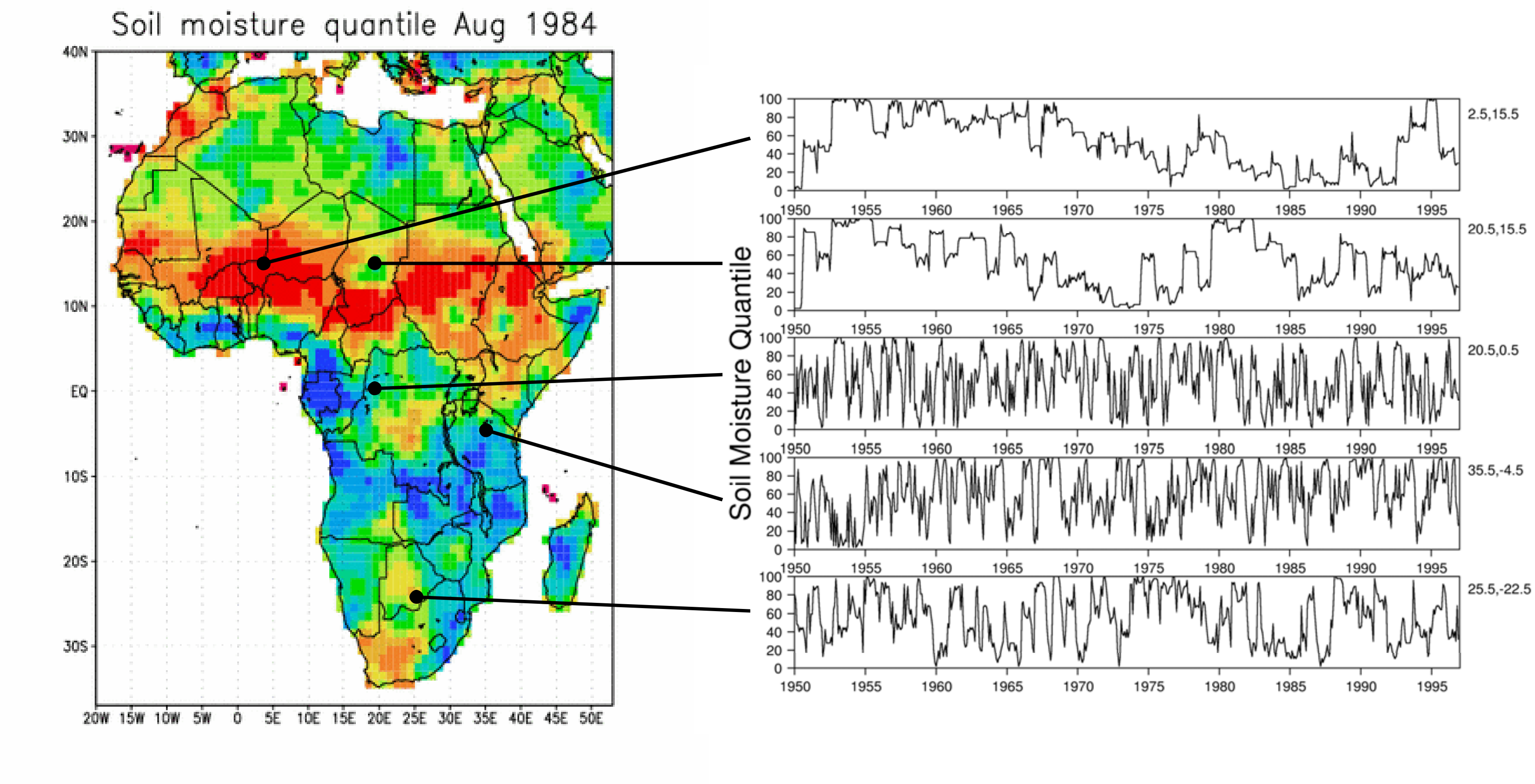




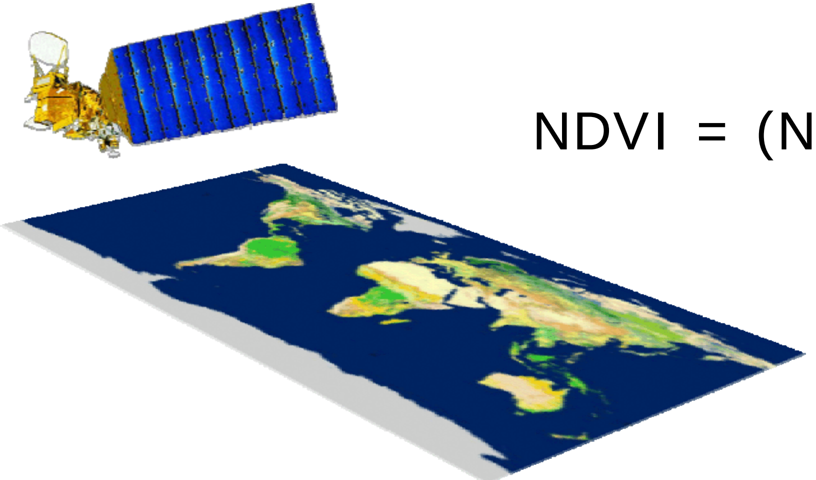


Example: VIC-based Soil Moisture Quantile (Aug, 1984)

Princeton University



Satellite Based Drought Monitoring



$$NDVI = (NIR - VIS)/(NIR + VIS)]$$

VHI – Vegetation Health Index:
Estimates vegetation health (condition) based on combination of vegetation greenness (Normalized Difference Vegetation Index, NDVI) and temperature (Brightness Temperature, BT).

VCI – TCI - Vegetation & Temperature Condition Indices:

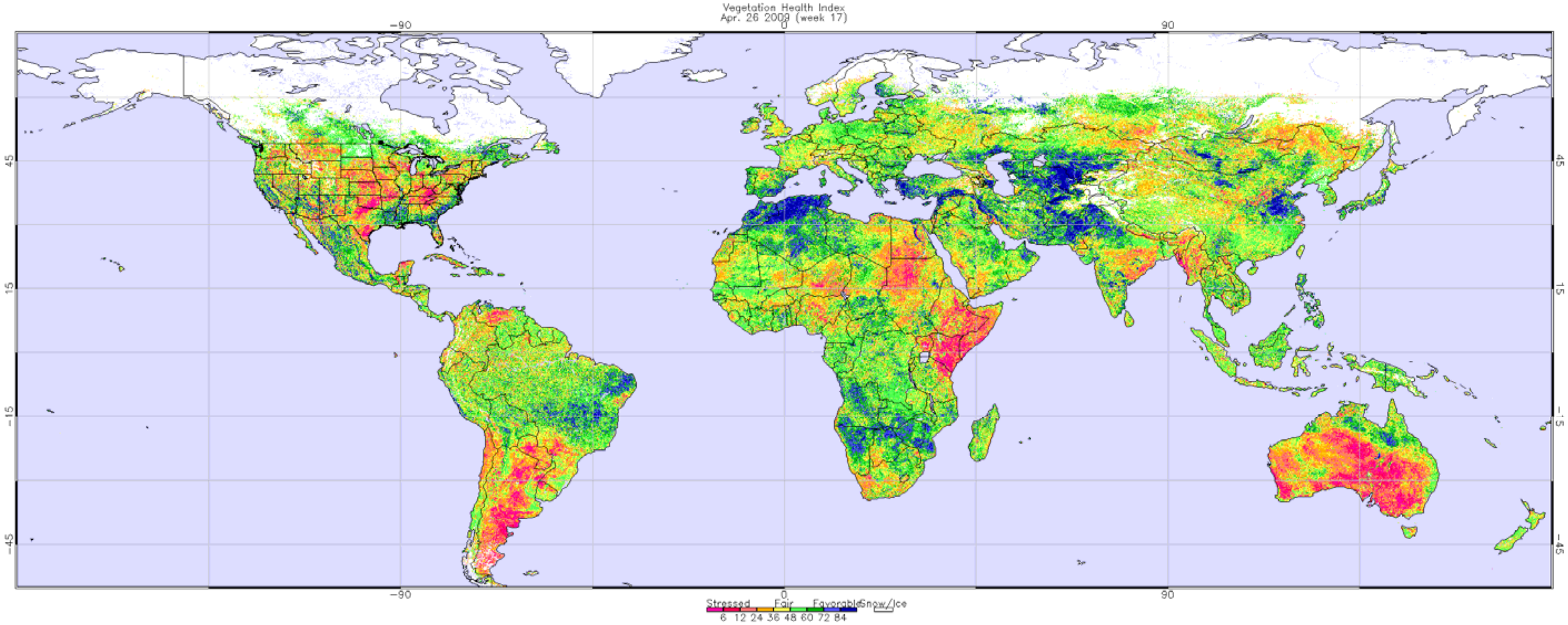
$$VCI = 100(NDVI - NDVI_{min})/(NDVI_{max} - NDVI_{min})$$

$$TCI = 100(T_{max} - T)/(T_{max} - T_{min})$$

Estimate moisture and thermal conditions, respectively, based on NDVI and BT.

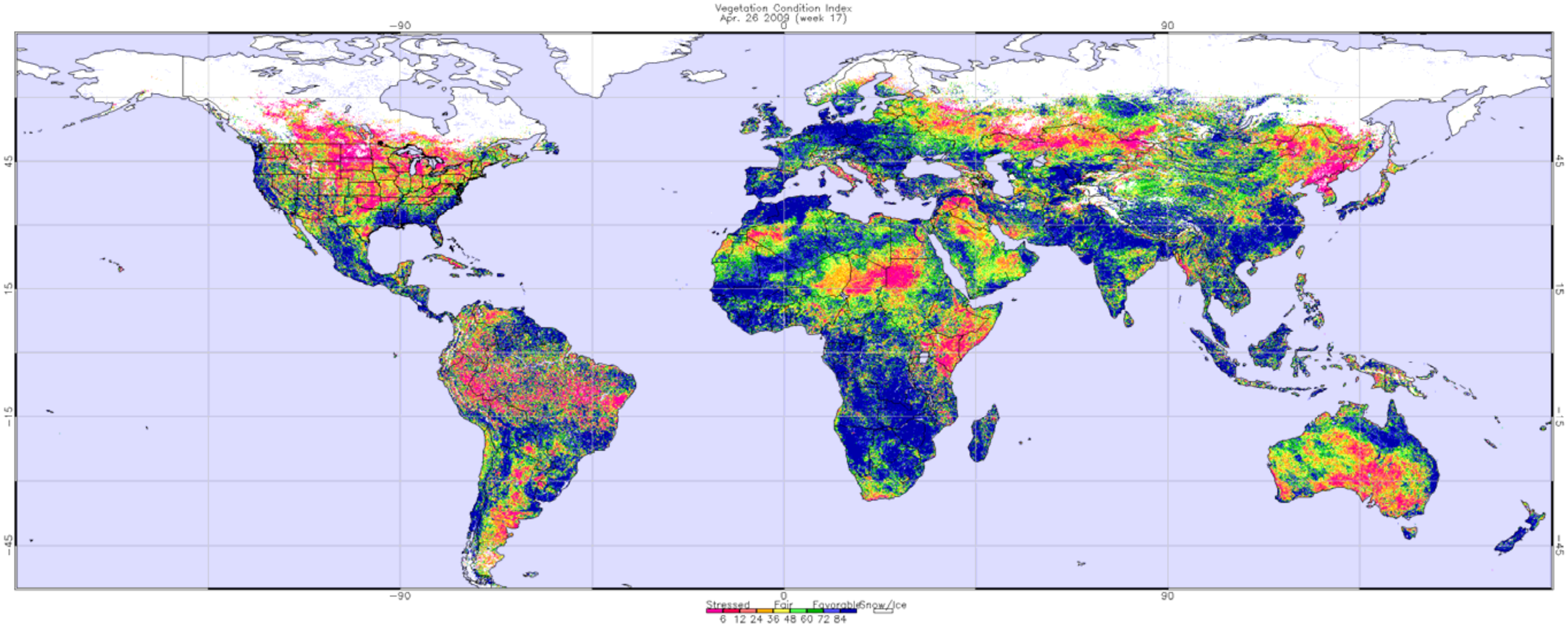
Fire Risk Index:
Index showing if conditions of vegetation are suitable for fire development.

Example: VHI (Current)

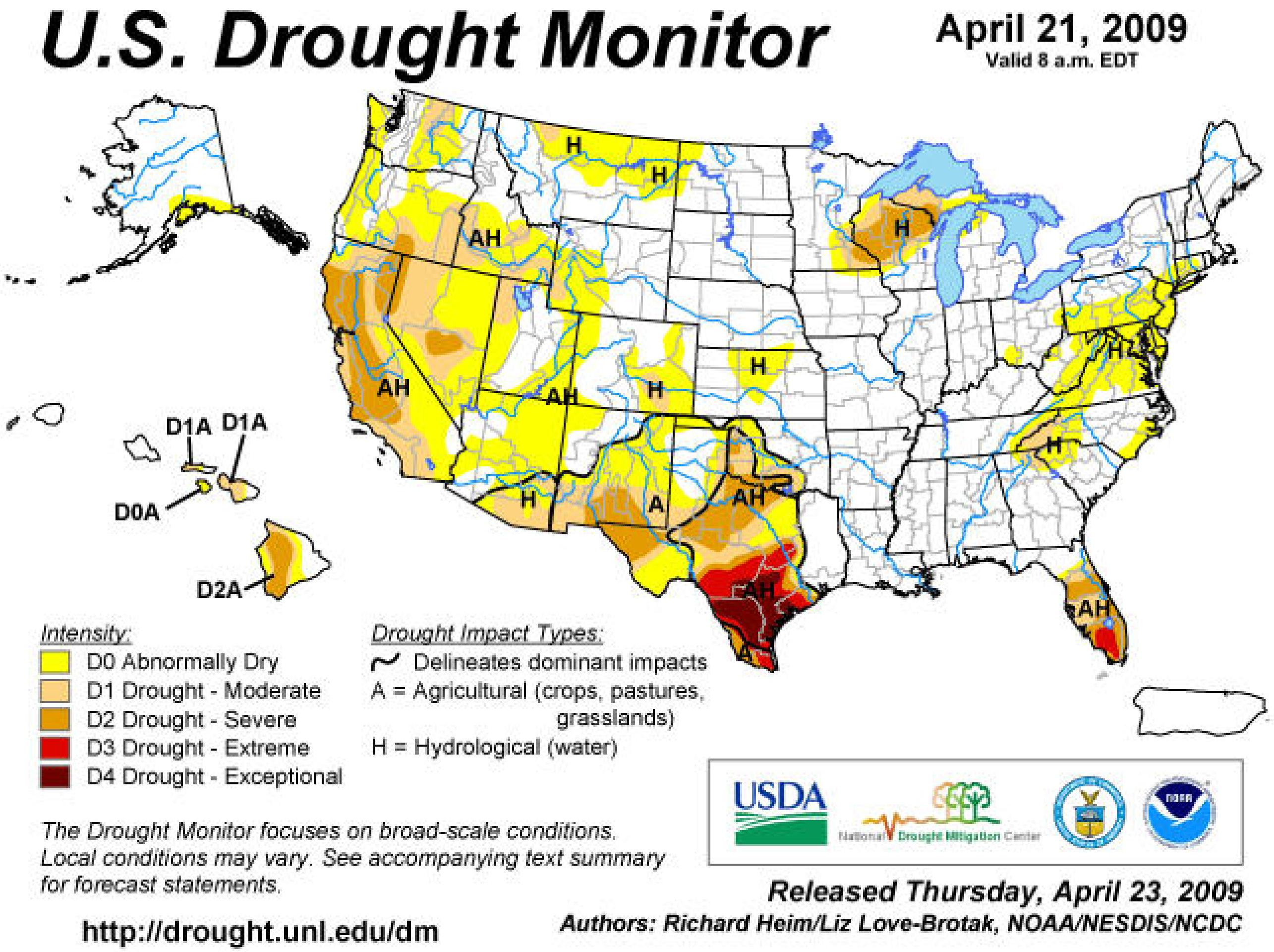


http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_currentImage.php

Example: VCI (Current)



http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_currentImage.php


U.S. Drought Monitor
April 21, 2009
Valid 8 a.m. EDT
H
H
AH
H
AH
AH
H
H
H
H
D1A
D1A
D0A
D2A
H
A
AH
AH
AH
A
Intensity:
D0 Abnormally Dry
D1 Drought - Moderate
D2 Drought - Severe
D3 Drought - Extreme
D4 Drought - Exceptional
Drought Impact Types:
Delineates dominant impacts
A = Agricultural (crops, pastures, grasslands)
H = Hydrological (water)
The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.
USDA
National Drought Mitigation Center
NOAA
http://drought.unl.edu/dm
Released Thursday, April 23, 2009
Authors: Richard Heim/Liz Love-Brotak, NOAA/NESDIS/NCDC

Components

Blend

Table 2. The association of the six key objective drought indicators with the magnitude of drought severity in the Drought Monitor.							
Drought Monitor classification							
Drought type		Associated ranges of objective indicators					
Category	Description	Palmer drought	CPC soil moisture	USGS weekly	Percent of normal	Standardized precipitation	Satellite vegetation
D0	Abnormally dry	−1.0 to −1.9	21–30	21–30	< 75% for 3 months	−0.5 to −0.7	36–45
D1	Moderate drought	−2.0 to −2.9	11–20	11–20	< 70% for 3 months	−0.8 to −1.2	26–35
D2	Severe drought	−3.0 to −3.9	6–10	6–10	< 65% for 6 months	−1.3 to −1.5	16–25
D3	Extreme drought	−4.0 to −4.9	3–5	3–5	< 60% for 6 months	−1.6 to -1.9	6–15
D4	Exceptional drought	−5.0 or less	0–2	0–2	< 65% for 12 months	−2.0 or less	1–5

Table 1. The categories of drought magnitude used in the Drought Monitor. Each category is associated with its percentile chance of happening in any given year out of 100 yr.

Category	Drought condition	Percentile chance
D0	Abnormally dry	20 to ≤30
D1	Drought—moderate	10 to ≤20
D2	Drought—severe	5 to ≤10
D3	Drought—extreme	2 to ≤5
D4	Drought—exceptional	≤ 2

Source: Svoboda, et. al., BAMS, Aug 2002

Sectoral Impact

Table 3. The categories of drought magnitude used in the Drought Monitor and associated impacts in the agriculture (A), water (W), and fire (F) categories.

Category	Agriculture (A)	Water (W)	Fire (F)
D0	Slows farm activity, and crop and pasture growth	Steamflow below average	Fire risk above average
D1	Some damage to crops and pastures	Streamflow, reservoir, and well levels are low; some water shortages develop	Fire risk high
D2	Crop and pasture losses likely	Water shortages common; water restrictions imposed	Fire risk very high
D3	Major crop/pasture losses	Widespread water shortages and restrictions	Fire risk extreme
D4	Exceptional and widespread crop/ pasture losses	Shortages of water in stream, reservoirs, and wells creating emergencies	Fire risk exceptionally dangerous

Source: Svoboda, et. al., BAMS, Aug 2002

Metric	Data[a]	Calculation	Drought definition and severity scale	Strengths	Weaknesses
Vegetation Condition Index (VCI) (19)	GVI	Satellite measures visible and near-IR radiance as a proxy for health of vegetation. Vegetation associated to drought severity, adjusted for land climate, ecology, and weather conditions	Scale: 0–100 Drought if VCI <50 (mean)	Real-time monitoring of onset and progression of drought. Good for early warnings Useful for areas not covered well by precipitation or hydrological stations (Africa)	Limited utility during cold seasons when vegetation is dormant Ground conditions other than drought affect vegetation index
Total water deficit (149)	SF	Sum of flows below some truncation level (mean or impact-related minimum) Product of time during which flows are below truncation level and average departure of streamflow	Drought if deficit >0	Intuitive and communicative Easy to measure	Long streamflow record needed River regulation and other human impacts distort streamflow record Problems in scaling up from individual streams to region/ river basin
Days of supply remaining (150)	RS, D	Calculates the days a reservoir (or system) can satisfy demand using storage capacity, forecasted future inflows, and predicted demands	Drought if days <system-specific threshold	Communicative Takes demand into account	System-specific thresholds; limited comparability Sensitive to models' assumptions about demand and inflows

Drought Prediction and Outlook

Source: http://www.nws.noaa.gov/ost/climate/STIP/33CDPW/Luof1.jpg

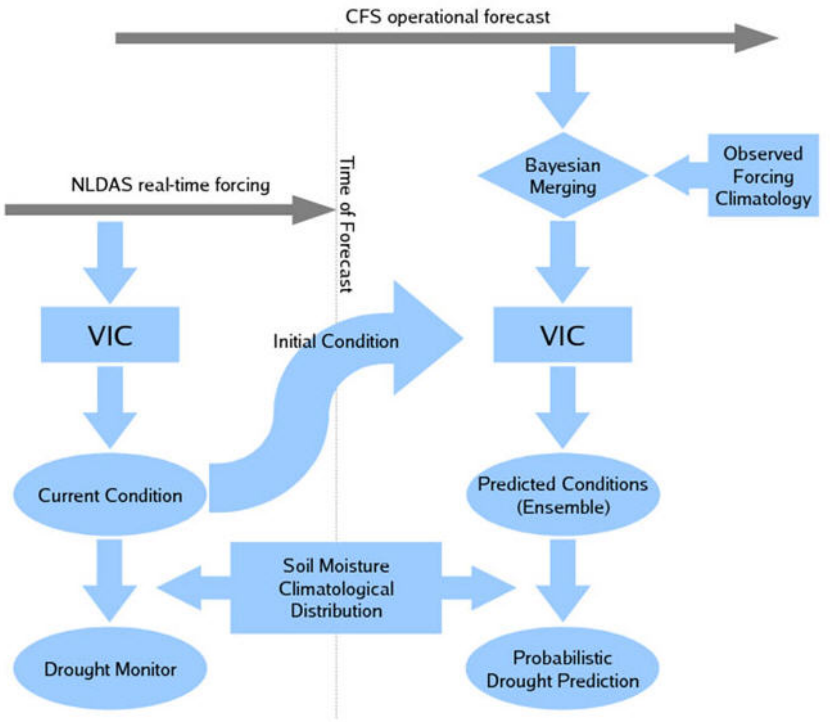
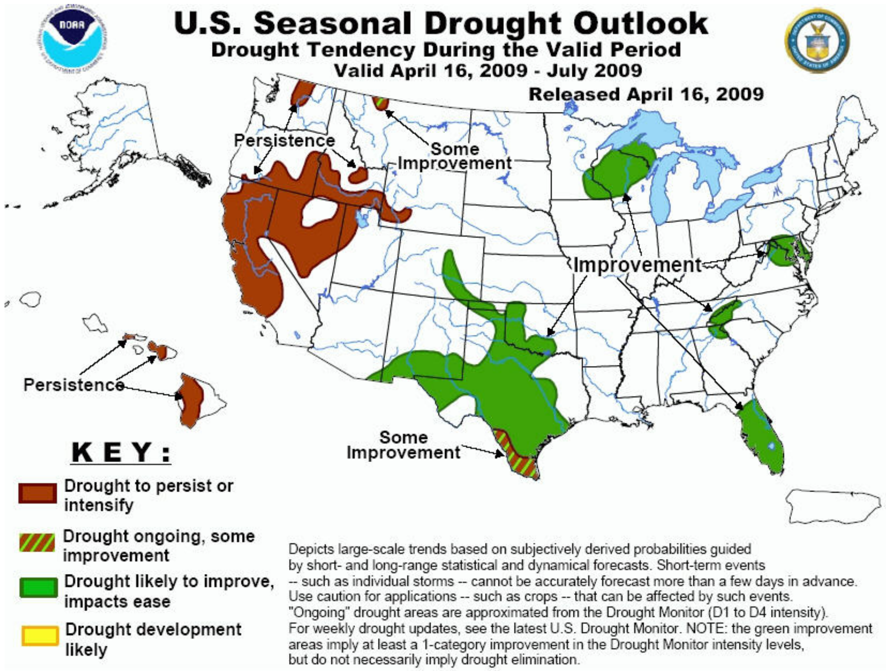
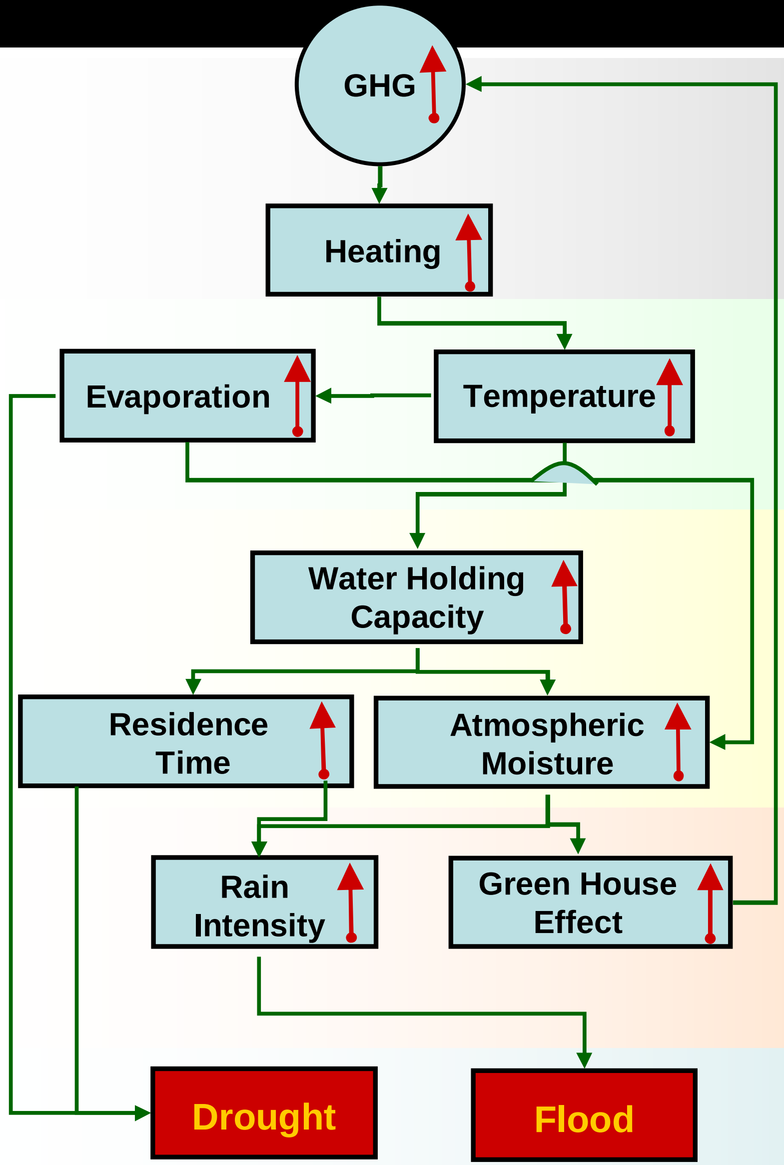


Fig. 1. Schematic diagram of the drought monitoring and prediction system (DMAPS) implemented for the US.



http://www.cpc.ncep.noaa.gov/products/expert_assessment/seasonal_drought.html



0

Increased GHG Concentration leads to heating of the atmosphere

1

Higher temperature Leads to higher rates of evaporation from and evapotranspiration Leading to faster depletion of soil moisture (Drought conditions).

2

Hotter atmosphere has a higher water holding capacity. More moisture remains in the atmosphere and the rate recycling through precipitation slows down. Increased evaporation rate leads to even higher amounts of atmospheric moisture, and water vapor, being a GHG can contribute to further heating.

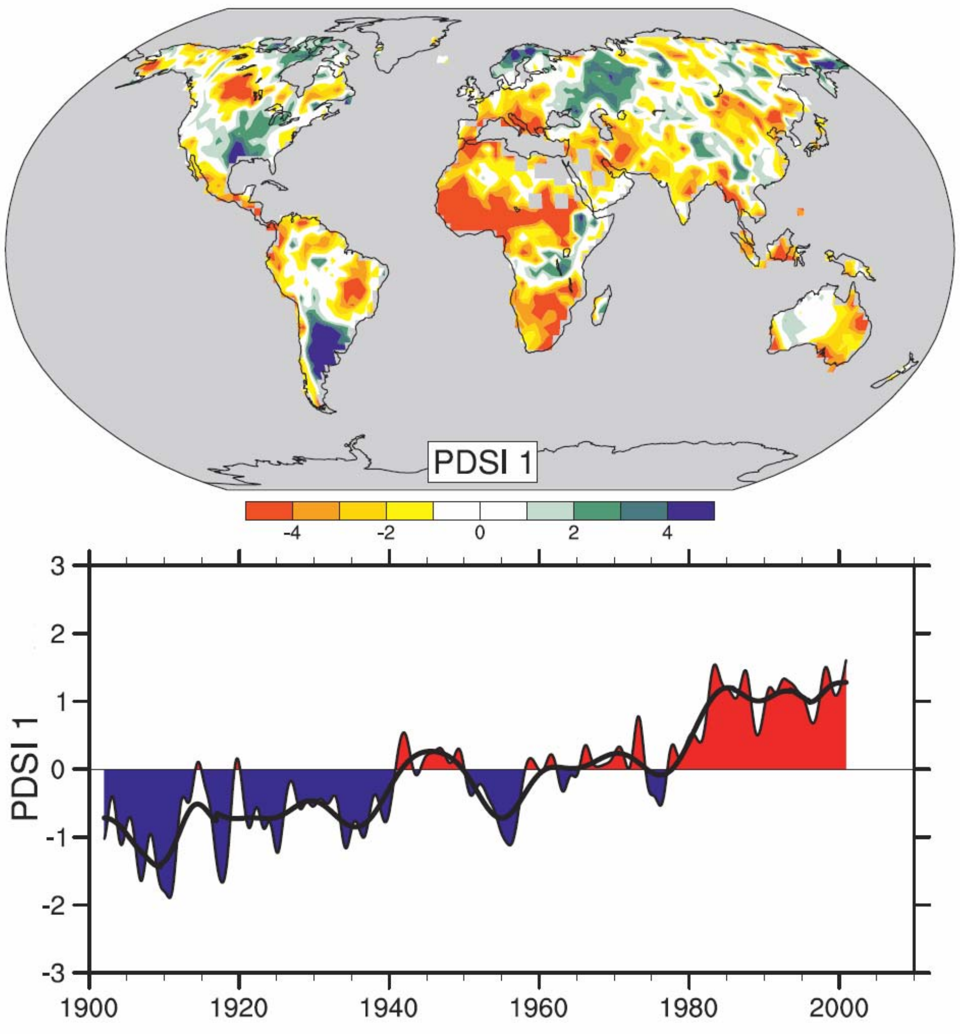
3

More vapor is available for precipitation, but at lesser frequency of events. Rainfall variability increases and the probability of extreme events may increase despite of little or no change in total annual precipitation. Water vapor is a GHG and its increase may exasperate the problem.

4

On the earth's surface, more extreme events are likely. Snow seasons shortens and the intense precipitation causes flood. The lower frequency of rain days and increased evapotranspiration contribute to drought conditions.

20th Century



Spatial/Temporal Combination

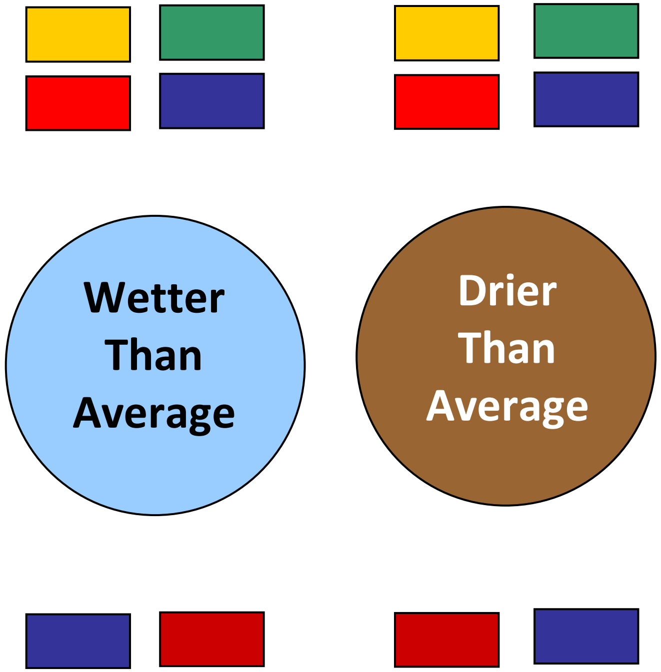
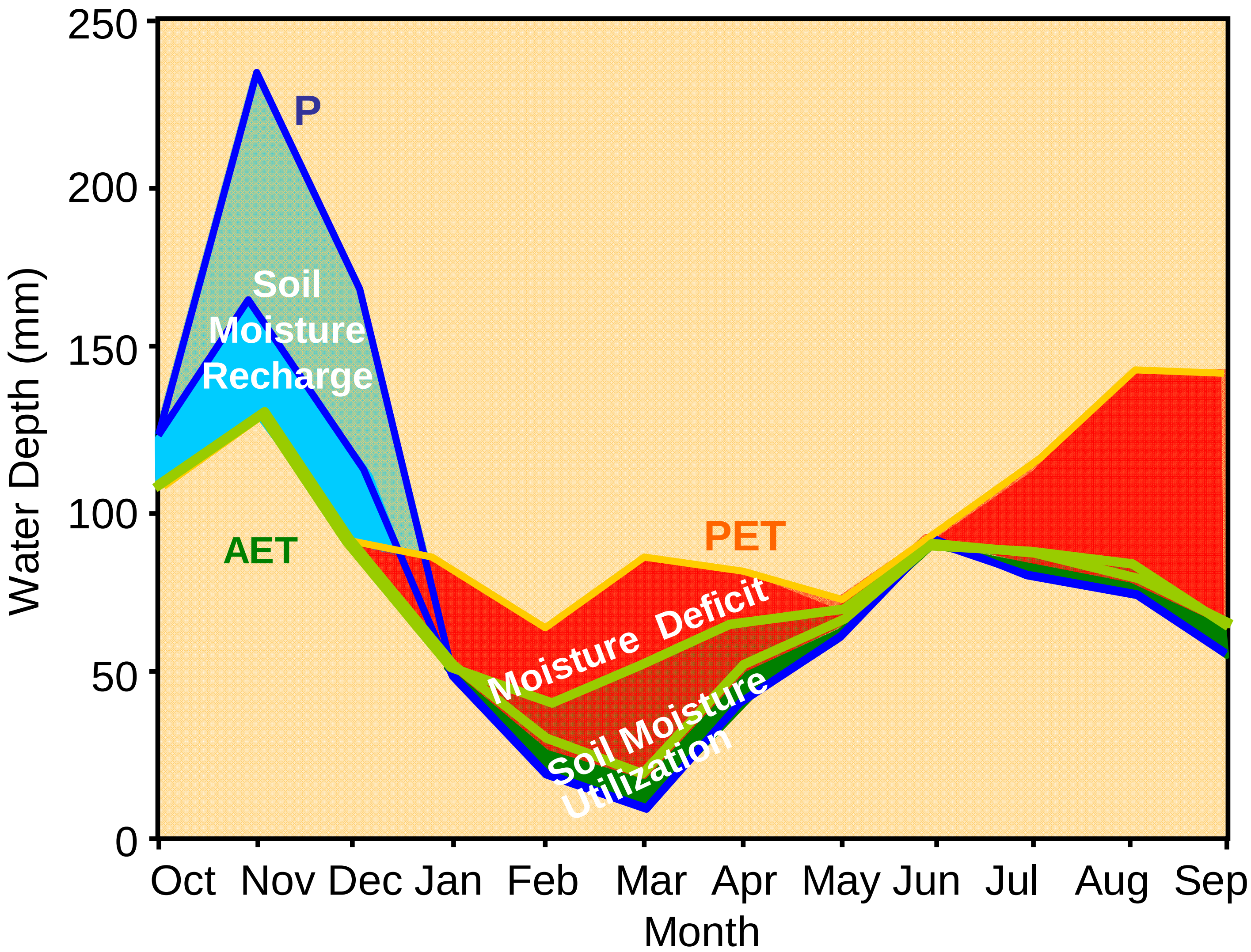


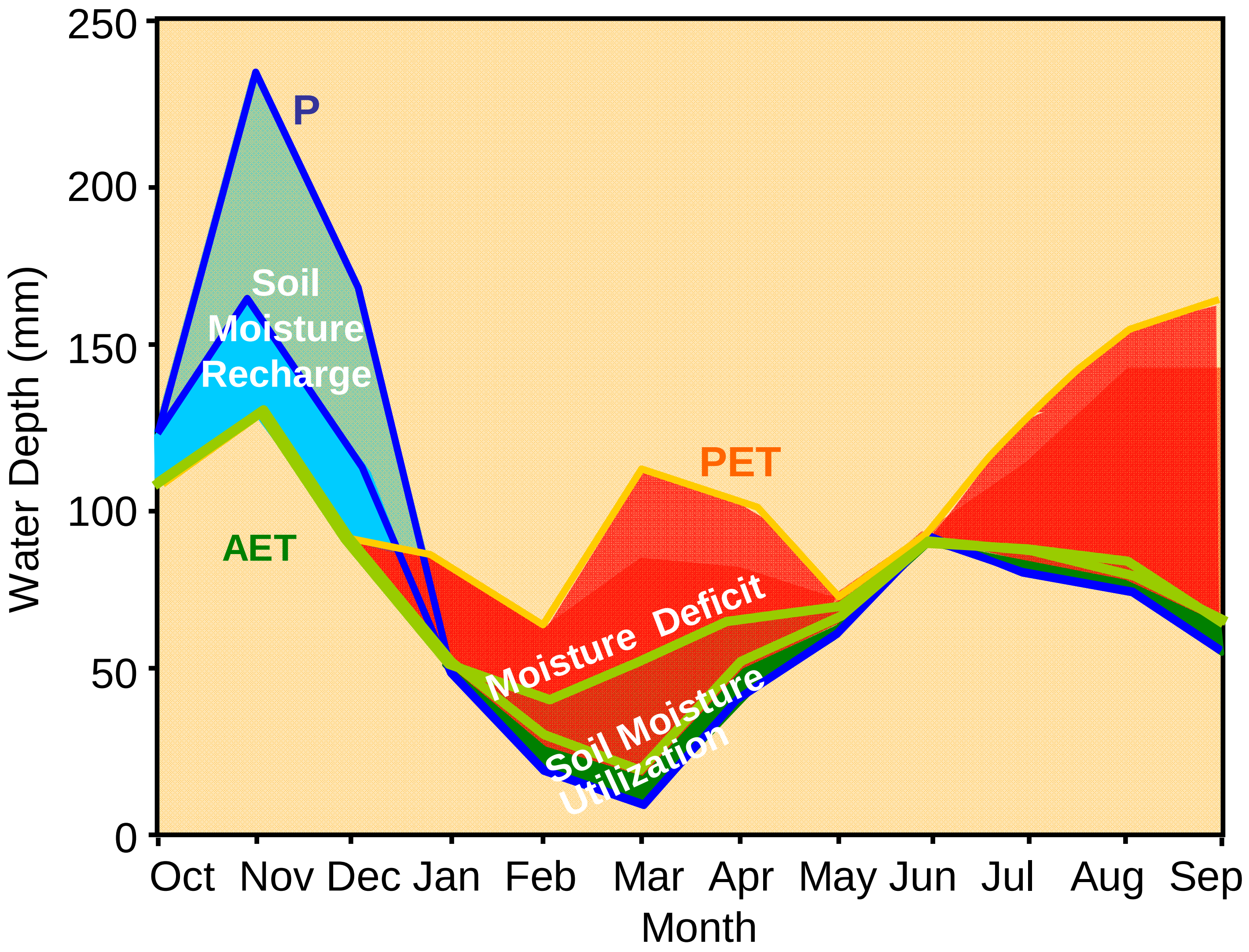
Figure 13. *The most important spatial pattern (top) of the monthly Palmer Drought Severity Index (PDSI) for 1900 to 2002. PDSI is the most commonly used drought index Red and orange areas are drier when the values in the lower panel are positive (red) and wetter during the time when the values in the lower panel are negative (red). Conversely, green and blue areas are wetter when the values in the lower panel are positive (red) and dryer when the values of the lower panel are negative (blue). Adapted from Dai et al. (2004) and IPCC 2007.*

Potential Impacts

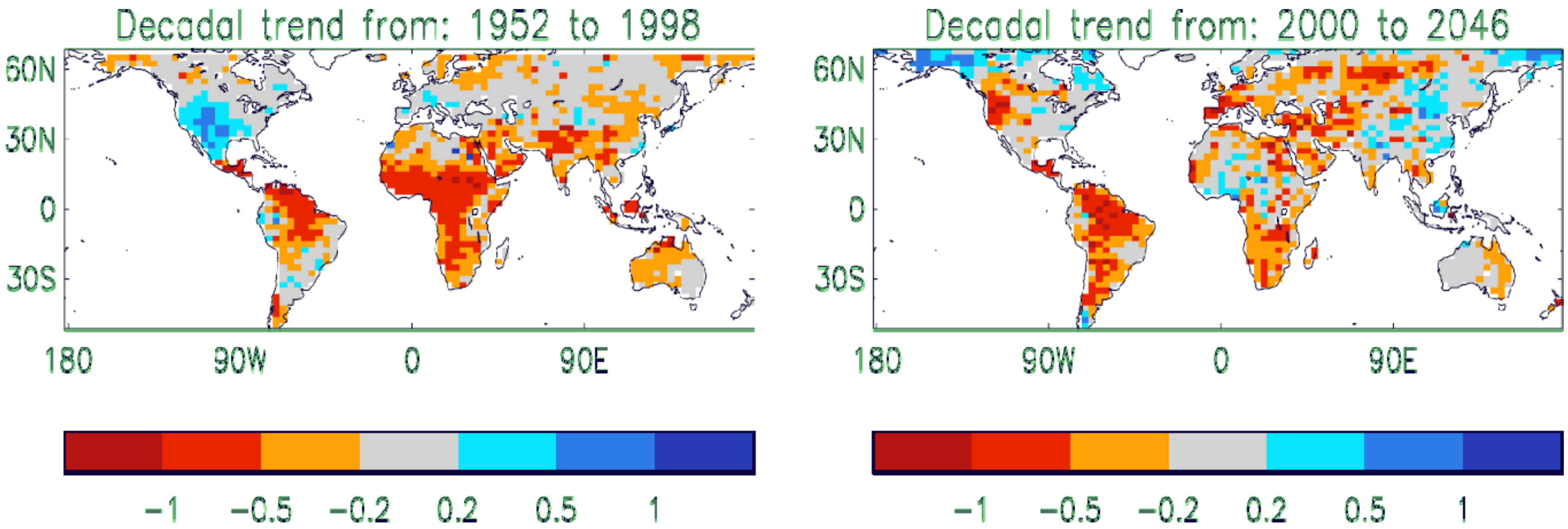


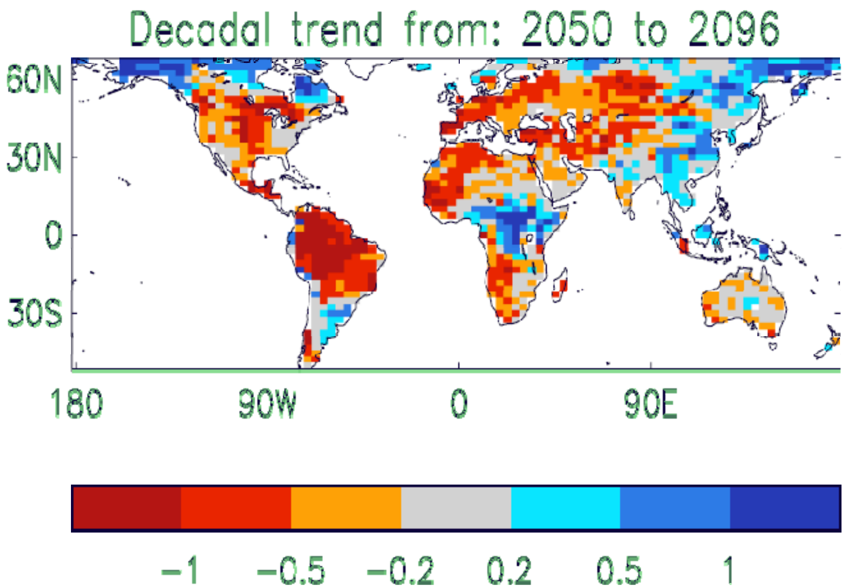
Changnon, 1987

Potential Impacts



Changnon, 1987

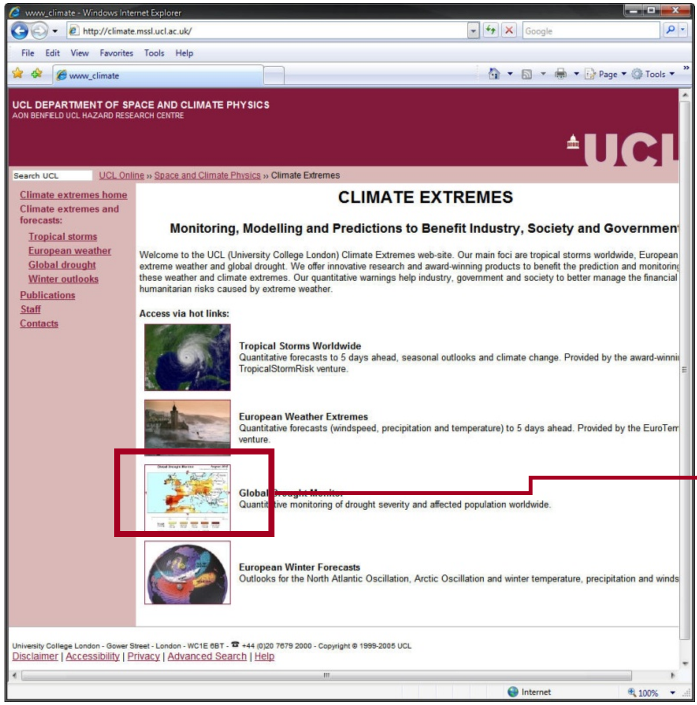


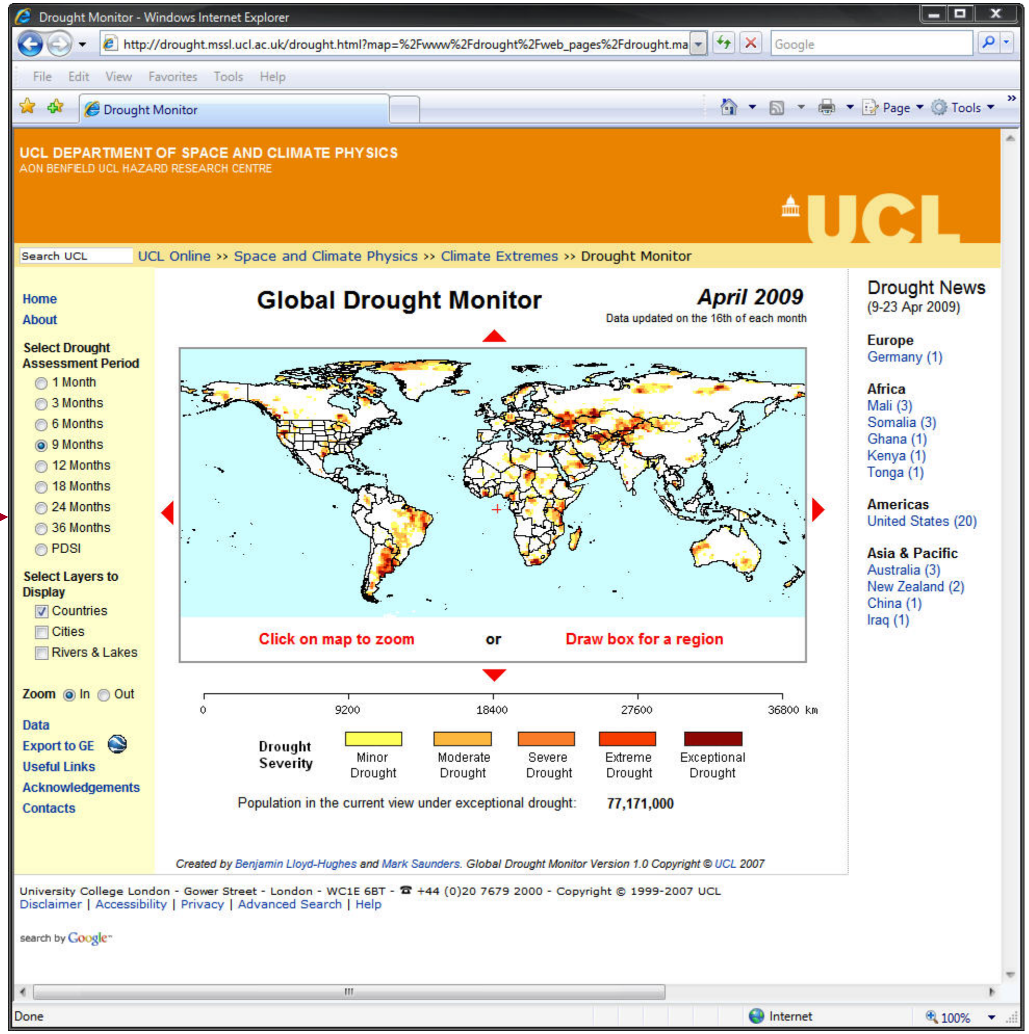


Changes in Drought Severity.

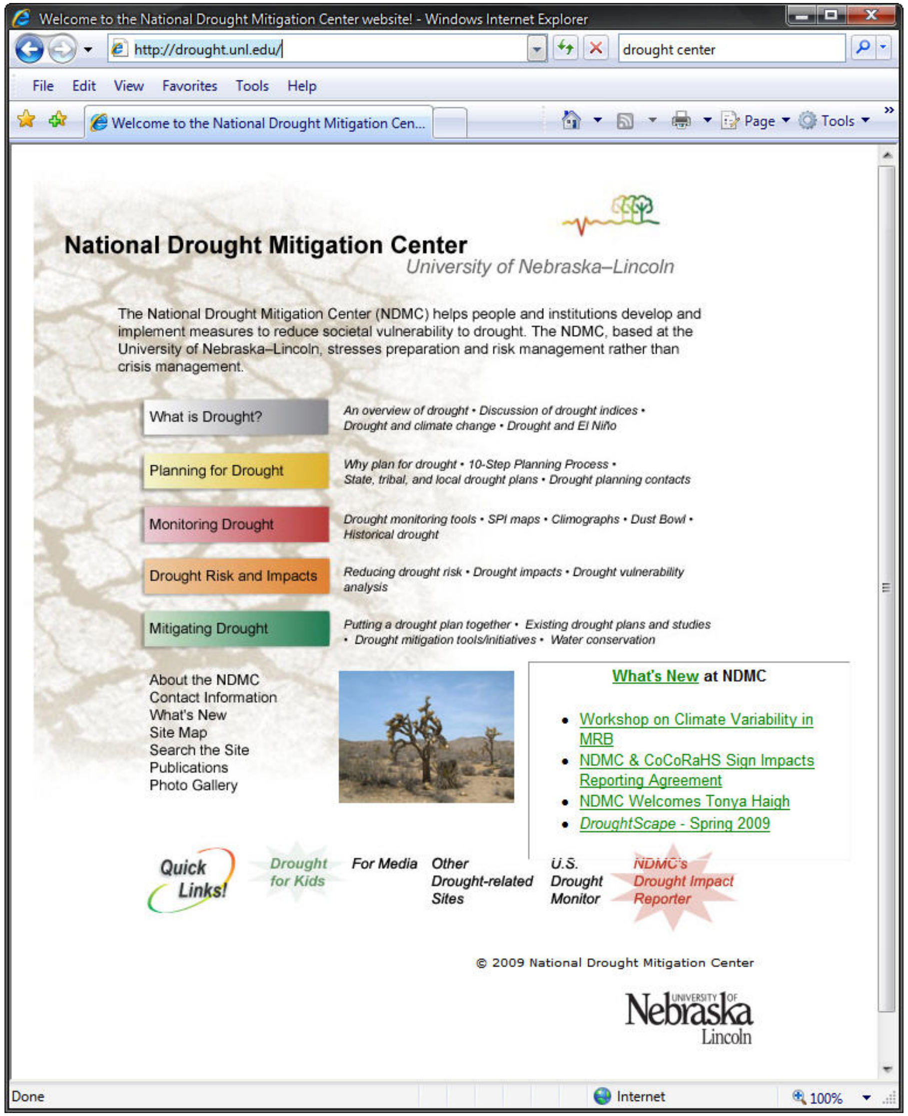
HadCM3 A2 scenario (Burke and Brown, 2006)

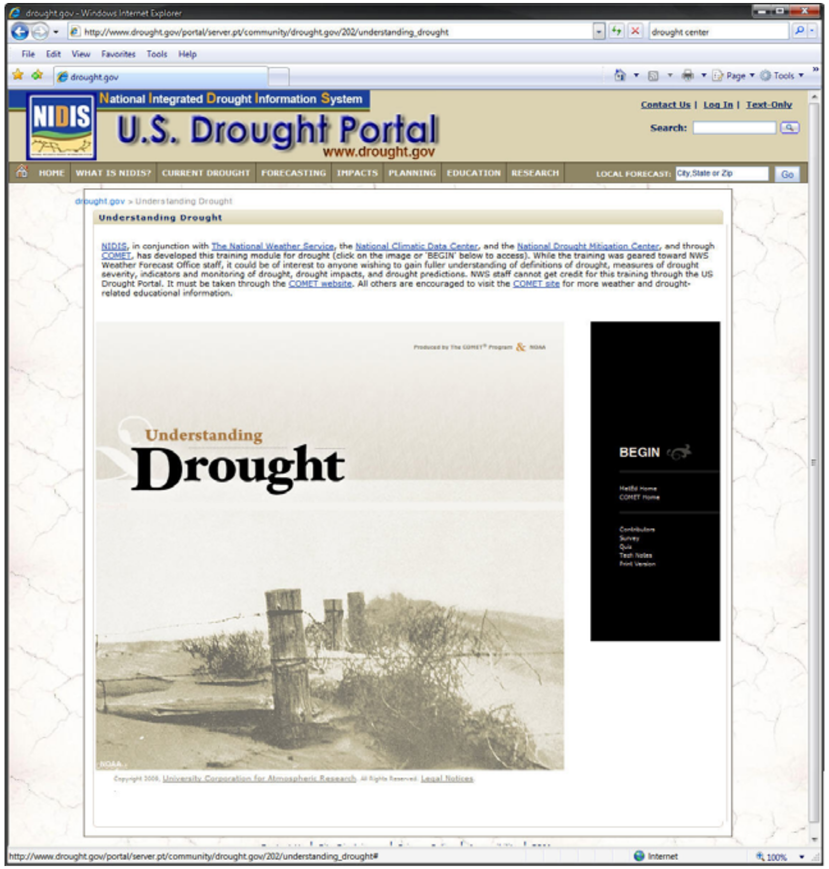
Global Drought Information





Information and Resources





http://drought.unl.edu/

http://drought.unl.edu/