Observed Changes in Extremes Affecting California: What and Why

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Hydrologic Extremes and Water Management in a Warmer World:
A California Perspective
California Department of Water Resources, Western RISA Programs
San Diego, CA 2011 May 19-20

Western Regional
Climate Center

Intensity - Duration - Frequency (IDF) Curves *

What is our expectation of

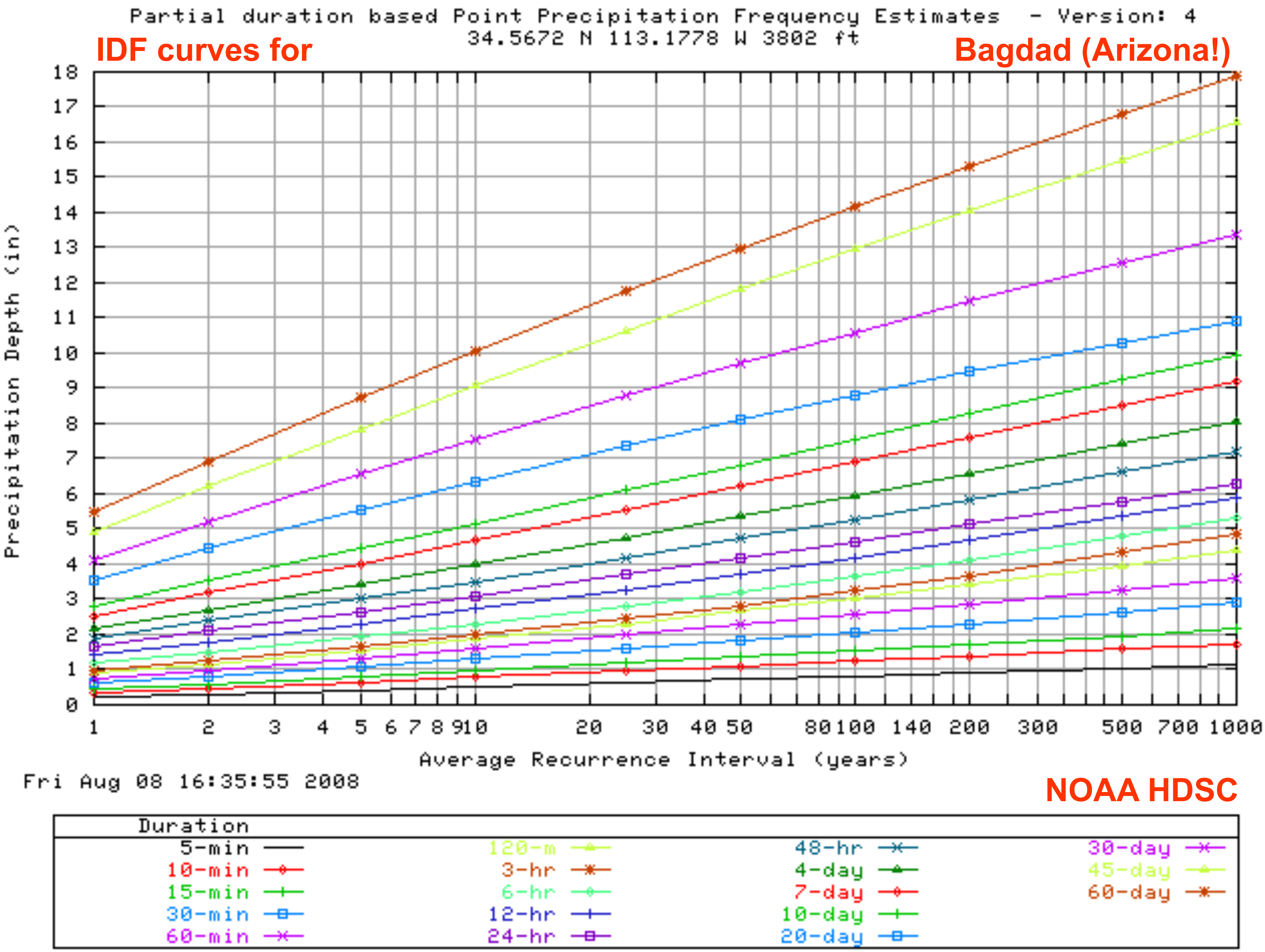
1) How much, 2) Over what time interval, 3) How often ?

* Note: Often show accumulation rather than intensity
(sums versus rates)

Much, much scrutiny
Very widely used
Critical for infrastructure design
Scientific, legal, financial underpinnings

These and other climatic extremes built into building codes

IDF curves for Bagdad (Arizona!)



NOAA HDSC


Bagdad
Airport
Bagdad
1 mi
1 km
©2011 Google - Imagery ©2011 DigitalGlobe, GeoEye, USDA Farm Service Agency, Map data ©2011 Google - Terms of Use
Report a proble

7 miles

Extremes matter

Societal physical and behavioral infrastructure are built around:

- Central tendencies - the many
  - High probability / low consequence events
- Distribution tails - the few
  - Low probability / high consequence events

Huge societal investments ($B, $$B, $$$B) to withstand rare events

Where do we obtain these probabilities?
- Pertinent decisions are about the future: hence, these are forecasts
- The commonsense assumption: Past is Prologue
  - The past as a reliable guide to the future
  - Past statistics = Future statistics
- The past (as established "fact") has built-in credibility as a forecast
  - Automatic, relatively painless buy-in
- Climate stationarity is implicit in this assumption

Two major audiences to satisfy:

- Scientific
  - What is intellectually defensible, accurate, correct?

- Societal
  - Acceptance by the engineering profession
    - Methodologies that are understandable, transparent, etc
      - Practical and implementable
  - Acceptance by the planning community
    - Huge $$$ at stake in building for extremes
  - Acceptance by political process

For both audiences
- Stationary climate
  - Reasonably constrained range of options
  - Considerable experience base to work from
- Nonstationary climate
  - Many more possible options to choose from
    - Lots of ways to “be nonstationary”
  - Experience base very limited

Not “just” a science problem, but a joint science-society problem

Stationarity

There does not seem to be a uniform meaning for this word

Often used in a statistical sense

Values that are i.i.d.
independent and identically distributed
- each new event independent of the last
- always drawn from the same statistical distribution(s)

In a physical sense

The causal mechanisms in the physical world (that generate the statistics) continue to occur, and to interact with each other, in approximately the same manner, over the time period for which stationarity is claimed.

However, in the physical world, the temporal characteristics of physical causation are constantly changing, all the time, on all time scales

Stationarity concept must contain embedded implicit time scales

The climate system as an operator

$y = f(x)$, where x is input, operated on by f, with output y

$s = H(\text{ppt; parameters})$, where

ppt falls as input from sky (rain or snow) ...
... is operated on by Hydrologic system H ...
... with output s (some kind of hydrologically relevant quantity)

s could represent streamflow, lake level, groundwater status, etc

H
- is not linear in ppt
- is sometimes simple, usually very complex, often extremely complex
- is dependent on many parameters representing state of system
    - Some of these themselves depend on the climate system (feedbacks)
    - Some of these are externally manipulated (e.g., human activities)
- could be natural (catchment, basin, major river system, lake, etc)
- need not be “natural” (roof, parking lot, tailings pond, alfalfa field, etc)
- acts as a kind of complex time filter

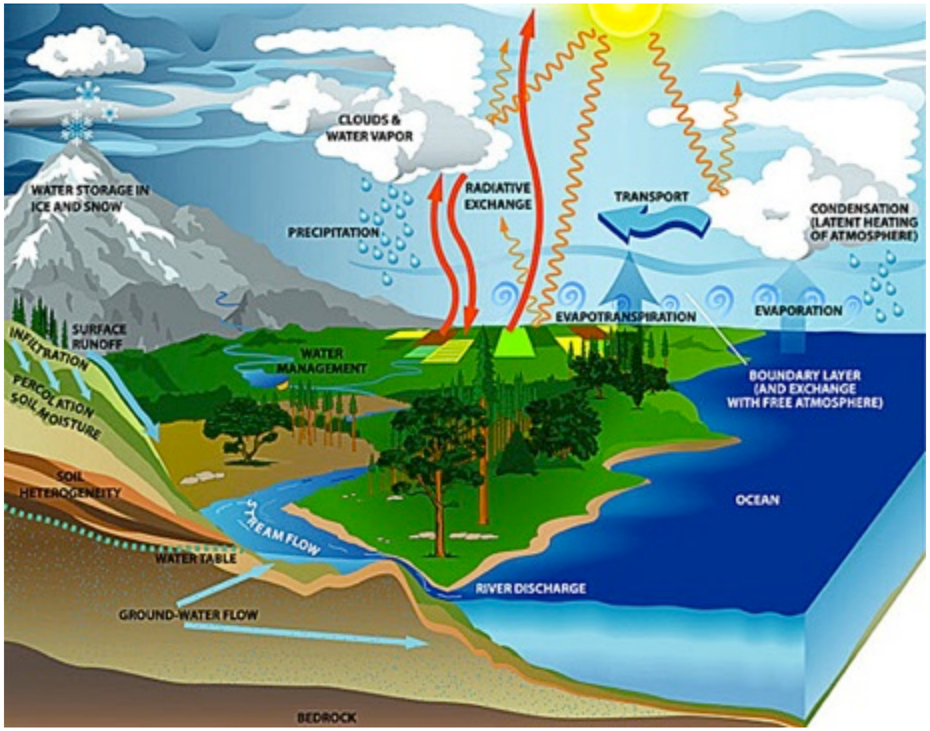
Variability in output s may result from variability in input ppt or in H or both
  That is, nonstationarity in s could result from driver or system nonstationarity

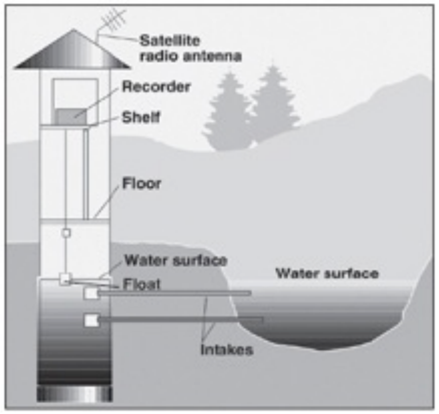
Rarity of input ppt need not produce same rarity in output s
  25 year precipitation event need not produce 25 year hydro event

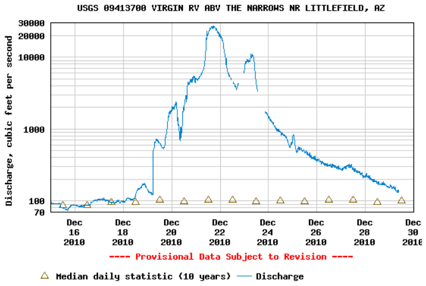
ppt

H

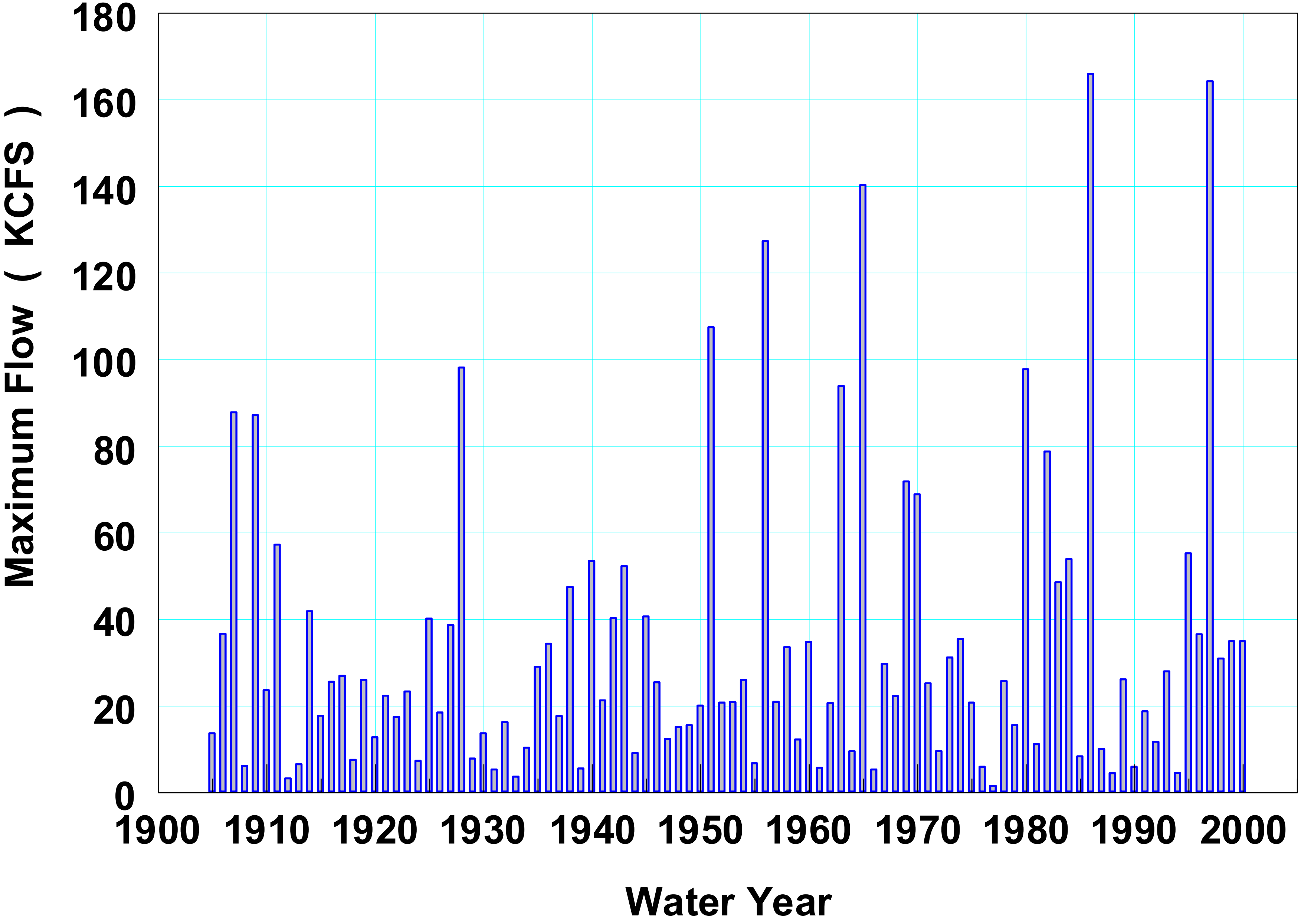
s


CLOUDS & WATER VAPOR
WATER STORAGE IN ICE AND SNOW
PRECIPITATION
RADIATIVE EXCHANGE
TRANSPORT
CONDENSATION (LATENT HEATING OF ATMOSPHERE)
EVAPOTRANSPIRATION
EVAPORATION
SURFACE RUNOFF
INFILTRATION
PERCOLATION
SOIL MOISTURE
WATER MANAGEMENT
BOUNDARY LAYER (AND EXCHANGE WITH FREE ATMOSPHERE)
SOIL HETEROGENEITY
STREAM FLOW
OCEAN
WATER TABLE
RIVER DISCHARGE
GROUND-WATER FLOW
BEDROCK


Satellite radio antenna
Recorder
Shelf
Floor
Water surface
Float
Water surface
Intakes


USGS 09413700 VIRGIN RV ABV THE NARROWS NR LITTLEFIELD, AZ
Discharge, cubic feet per second
30000
20000
10000
1000
100
70
Dec 16 2010
Dec 18 2010
Dec 20 2010
Dec 22 2010
Dec 24 2010
Dec 26 2010
Dec 28 2010
Dec 30 201
---- Provisional Data Subject to Revision ----
△ Median daily statistic (10 years)
Discharge

American River @ Fair Oaks (Sacramento CA)
Annual Maximum Three-Day Average Flow
Reconstructed Natural Flow below Folsom Reservoir



National Research Council

January 1999

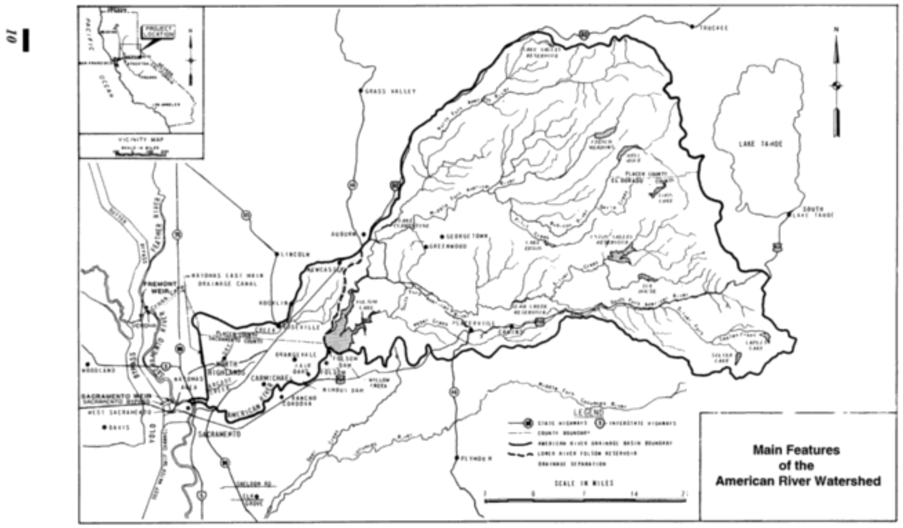
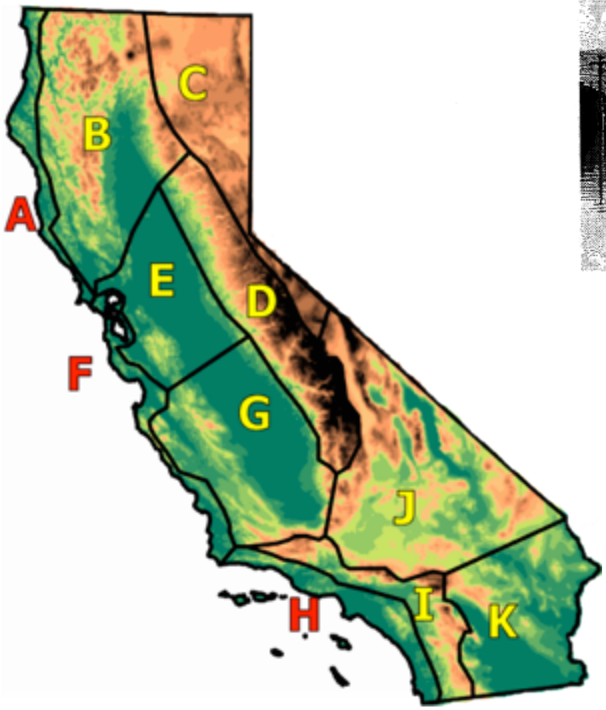
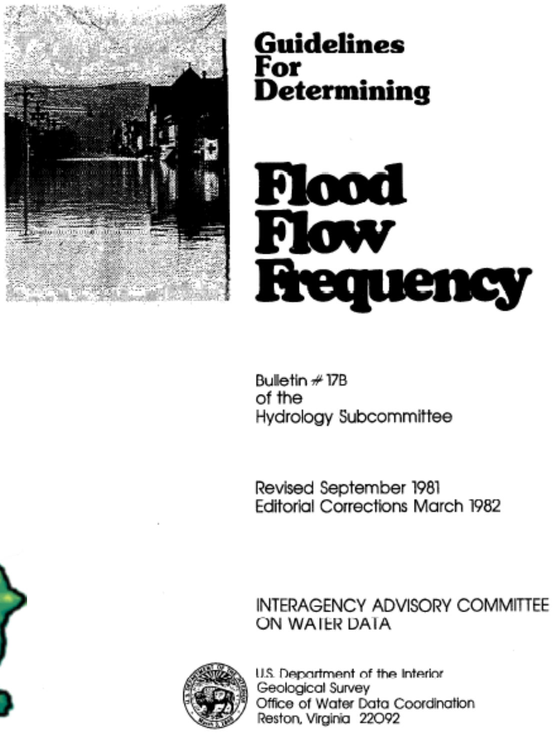


FIGURE 1.1 Main features of the American River watershed. SOURCE: Sacramento District, USACE, 1991.





Guidelines For Determining

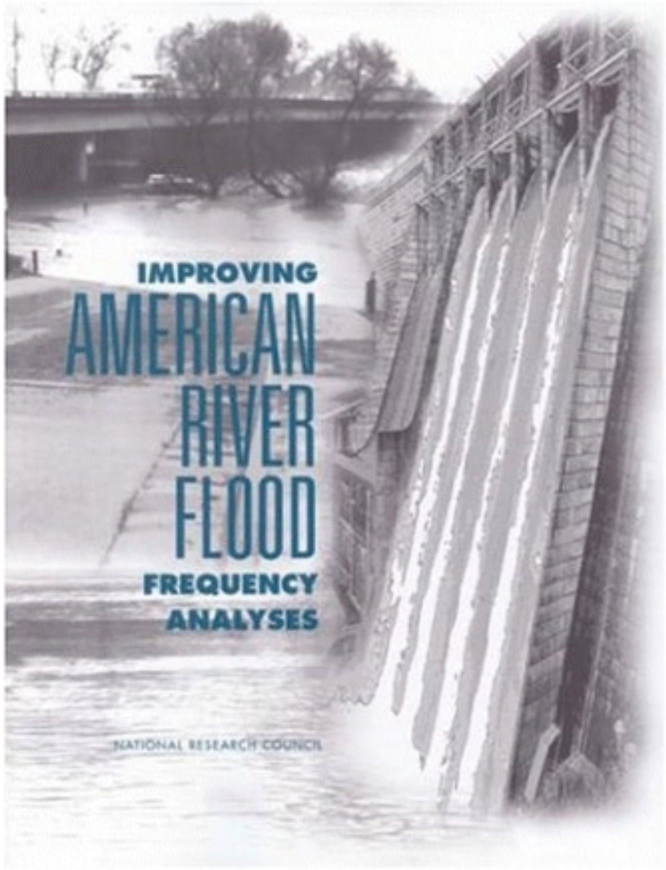
Flood Flow Frequency

Bulletin # 17B
of the
Hydrology Subcommittee

Revised September 1981
Editorial Corrections March 1982

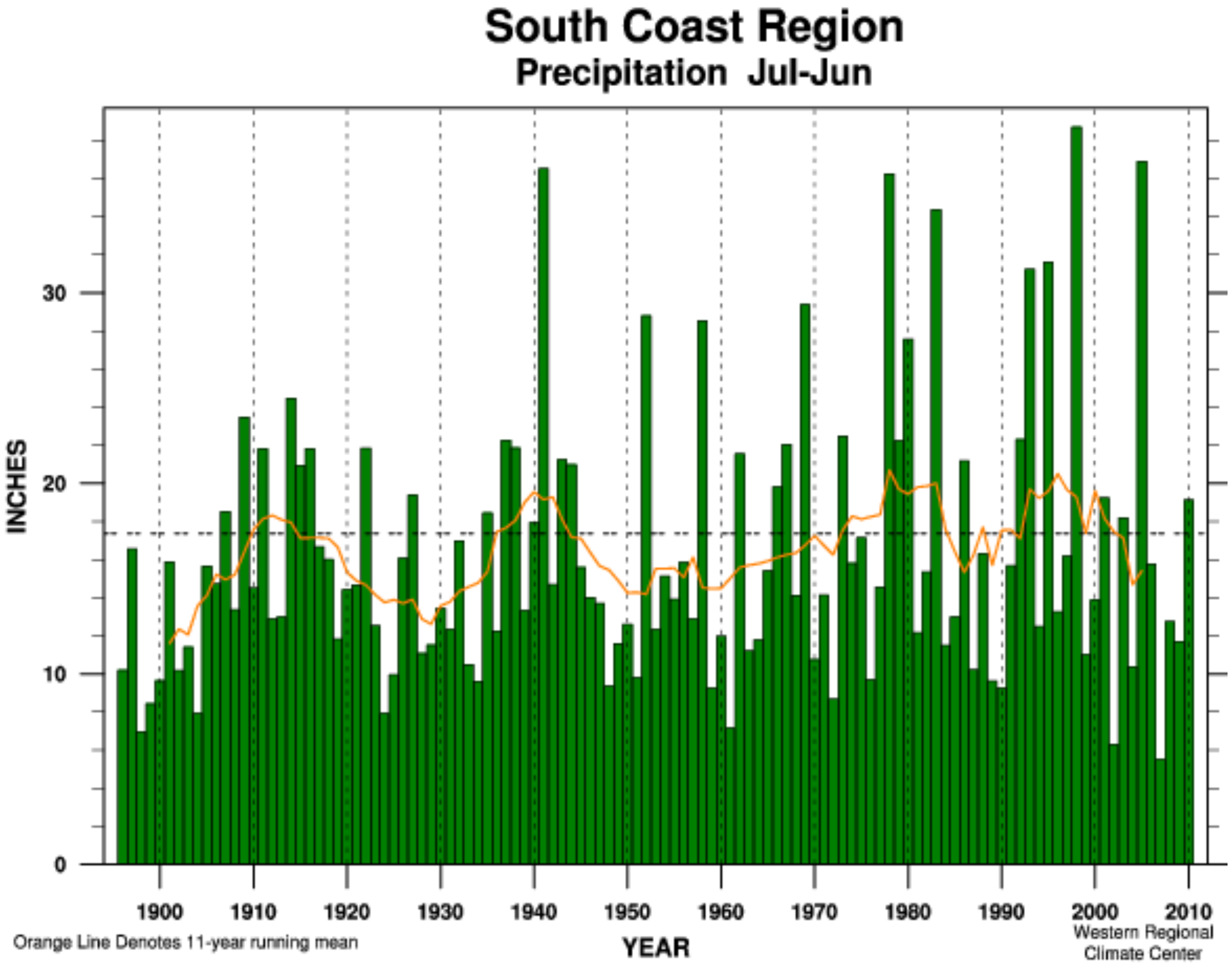
INTERAGENCY ADVISORY COMMITTEE
ON WATER DATA

U.S. Department of the Interior
Geological Survey
Office of Water Data Coordination
Reston, Virginia 22092



IMPROVING
AMERICAN
RIVER
FLOOD
FREQUENCY
ANALYSES

NATIONAL RESEARCH COUNCIL



Linear Trend 1895-present + 3.51 ± 3.82 in. (+ 20 ± 21%) per 100 yr

Linear Trend 1949-present + 3.18 ± 11.75 in. (+ 18 ± 67%) per 100 yr

Linear Trend 1975-present -11.67 ± 31.24 in. (- 67 ± 179%) per 100 yr

Wettest Year 38.71 in. (222%) in 1998 MEAN 17.38 in.

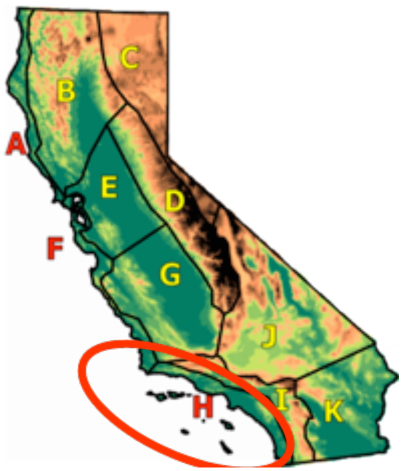
Driest Year 5.49 in. (31%) in 2007 STDEV 8.11 in.

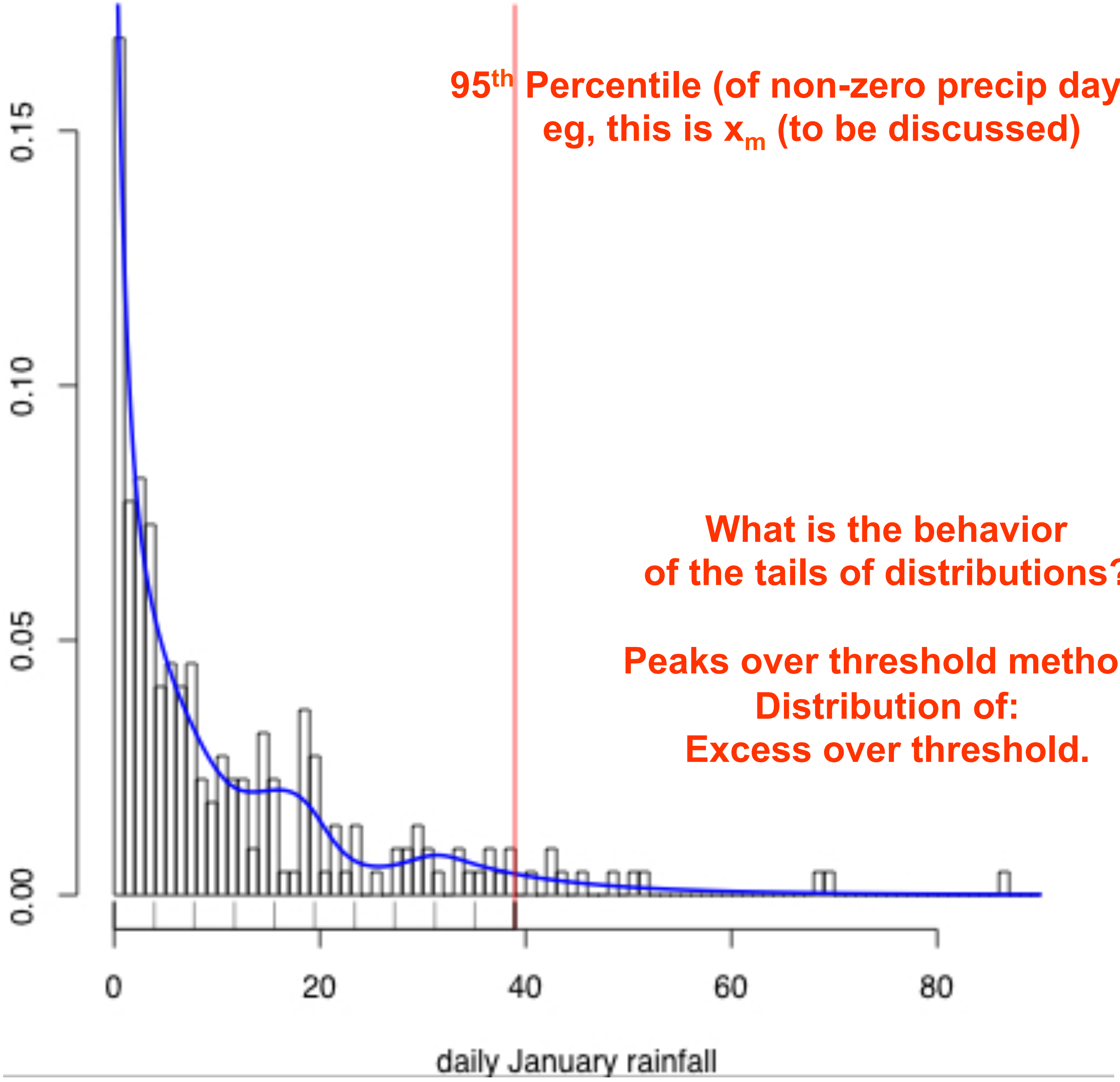
Jul-Jun 2010 19.12 in. (110%) RANK 85 of 115

Water Year
Oct-Sep
Precip

South
Coastal
California

1895/96
thru
2009-10





95^{th} Percentile (of non-zero precip days)
eg, this is x_m (to be discussed)

What is the behavior
of the tails of distributions?

Peaks over threshold method.
Distribution of:
Excess over threshold.

Note:

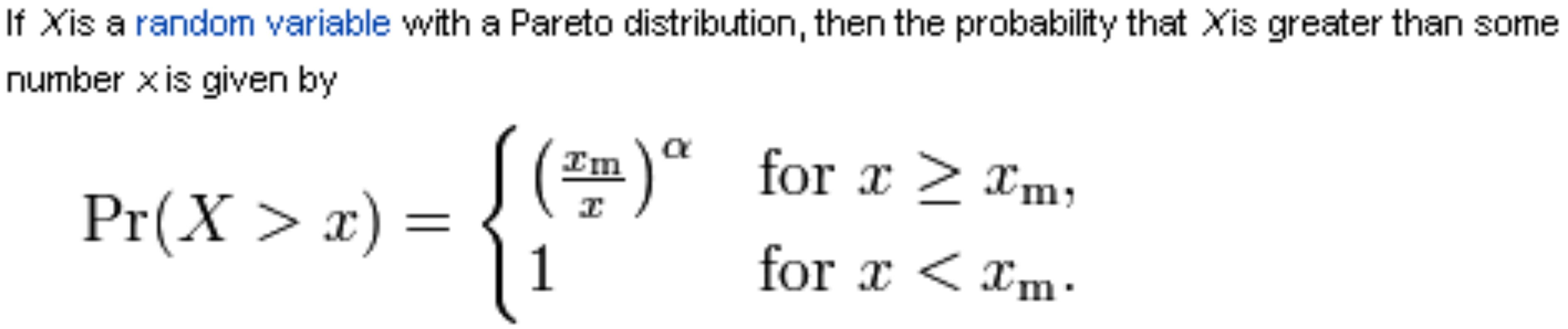
Typical distributions with exponential tails:

Binomial
Normal
Lognormal
Gamma
Gumbel
Weibull
Double (or Stretched or extended) exponential

Typical distributions with heavy tails:

Pareto
Cauchy
Frechet
Stable laws

Pareto Distribution



If X is a random variable with a Pareto distribution, then the probability that X is greater than some number x is given by

$$\Pr(X > x) = \begin{cases} \left(\frac{x_\mathrm{m}}{x}\right)^\alpha & \text{for } x \geq x_\mathrm{m}, \\ 1 & \text{for } x < x_\mathrm{m}. \end{cases}$$

Applies to

Frequency distribution of wealth

Sizes of cities

Sizes of internet files

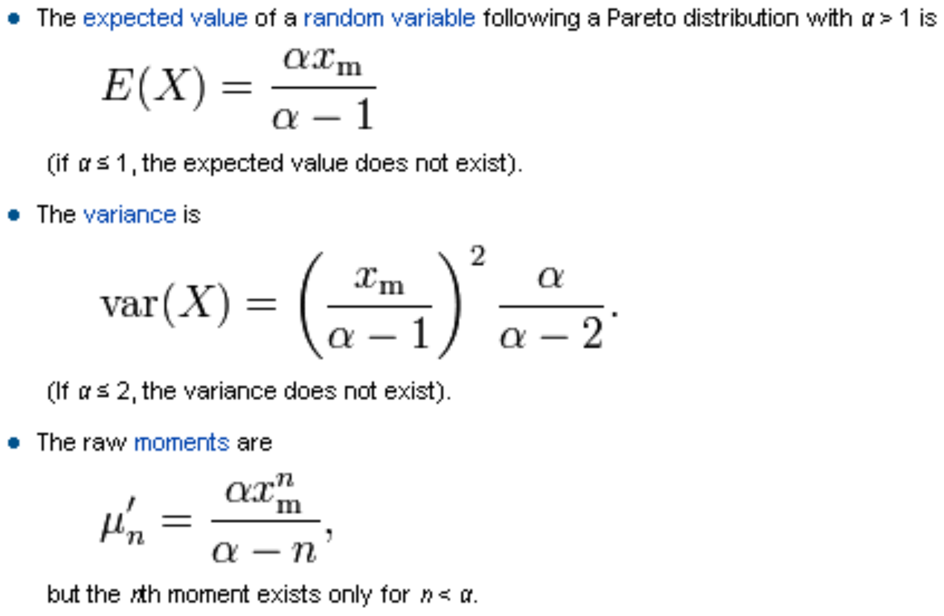
Sizes of Bose-Einstein condensate clusters

Sizes of sand grains

Sizes of meteorites

Sizes of forest fires

Sizes of insurance losses



- The expected value of a random variable following a Pareto distribution with $\alpha > 1$ is

$$E(X) = \frac{\alpha x_\mathrm{m}}{\alpha - 1}$$

(if $\alpha \leq 1$, the expected value does not exist).

- The variance is

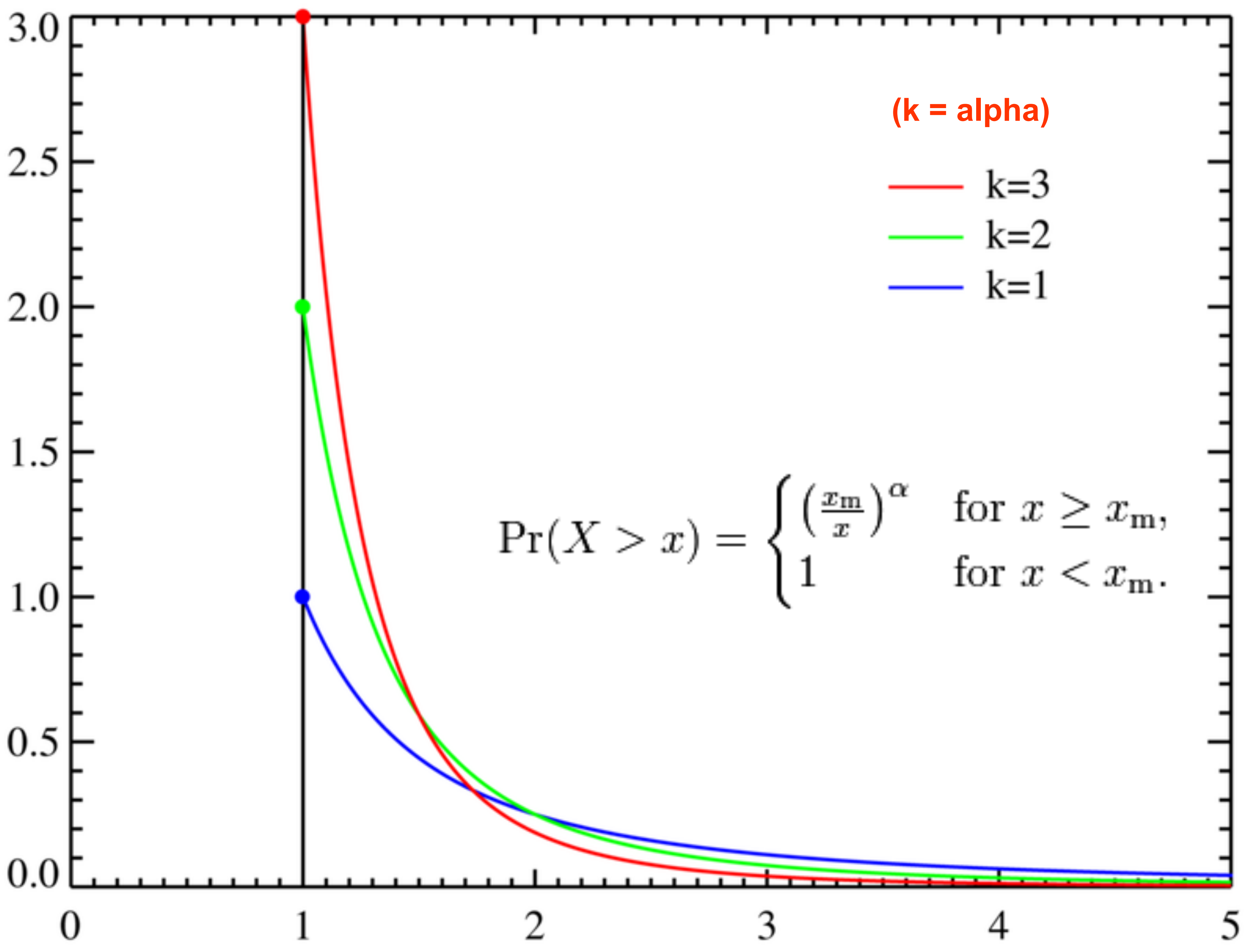
$$\mathrm{var}(X) = \left(\frac{x_\mathrm{m}}{\alpha - 1}\right)^2 \frac{\alpha}{\alpha - 2}.$$

(If $\alpha \leq 2$, the variance does not exist).

- The raw moments are

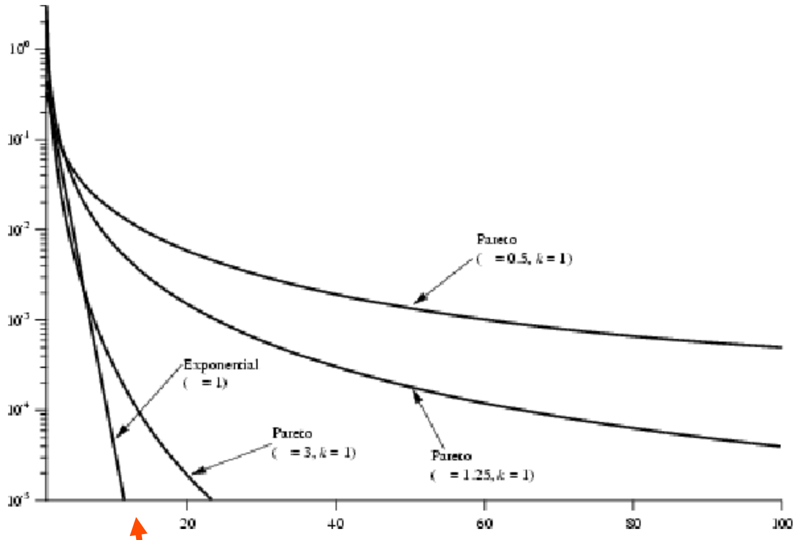
$$\mu_n' = \frac{\alpha x_\mathrm{m}^n}{\alpha - n},$$

but the nth moment exists only for $n < \alpha$.



$$\Pr(X > x) = \begin{cases} \left(\frac{x_\mathrm{m}}{x}\right)^\alpha & \text{for } x \ge x_\mathrm{m}, \\ 1 & \text{for } x < x_\mathrm{m}. \end{cases}$$

A random variable that follows a heavy tailed distribution (such as Pareto) can be extremely large with non-negligible probability



Pareto, alpha = 1

Pareto, alpha = 2

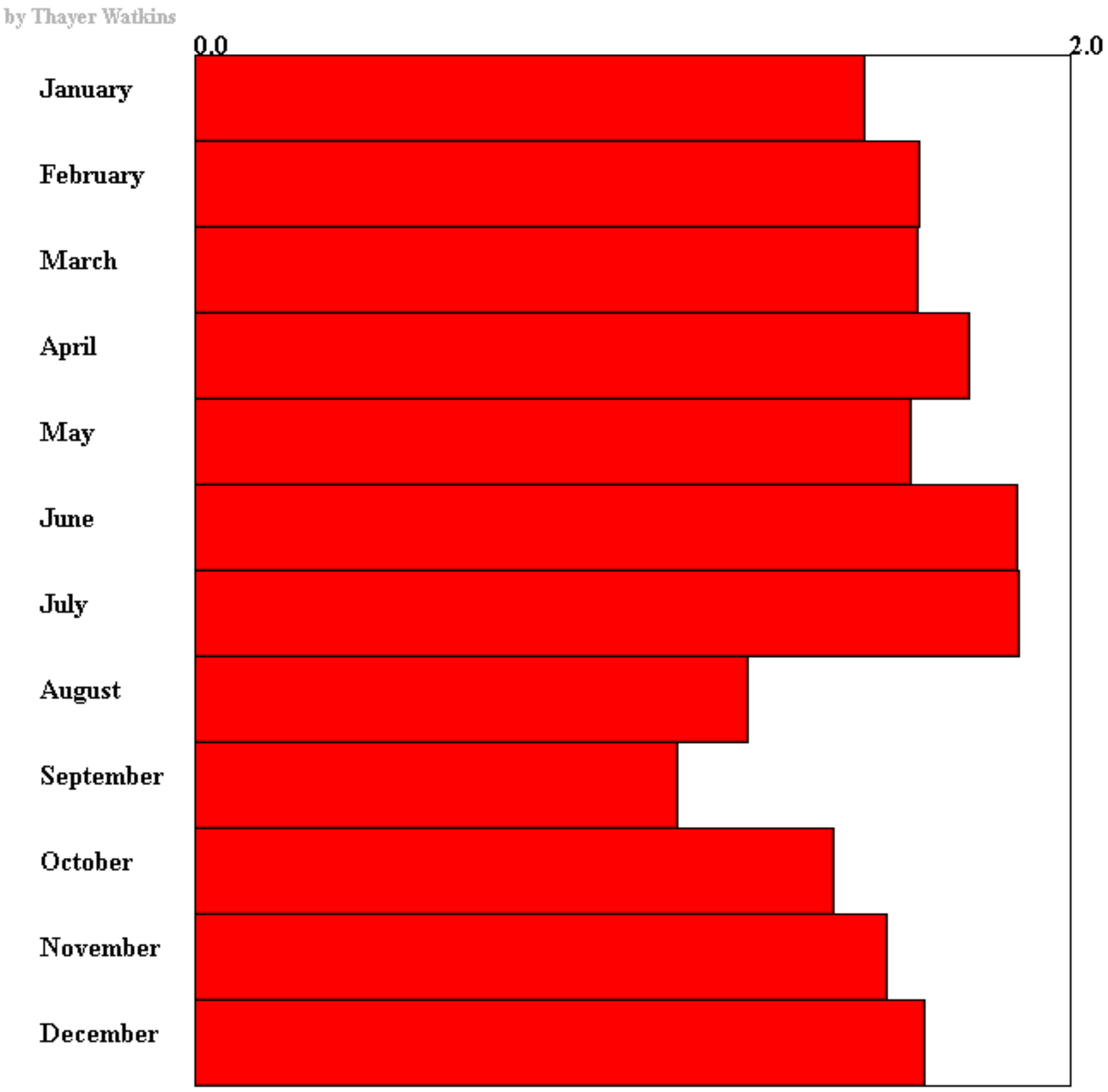
Pareto, alpha = 3

Pareto, alpha = infinity (exponential)

“The biggest one is yet to come.” - Jim Goodridge CA DWR

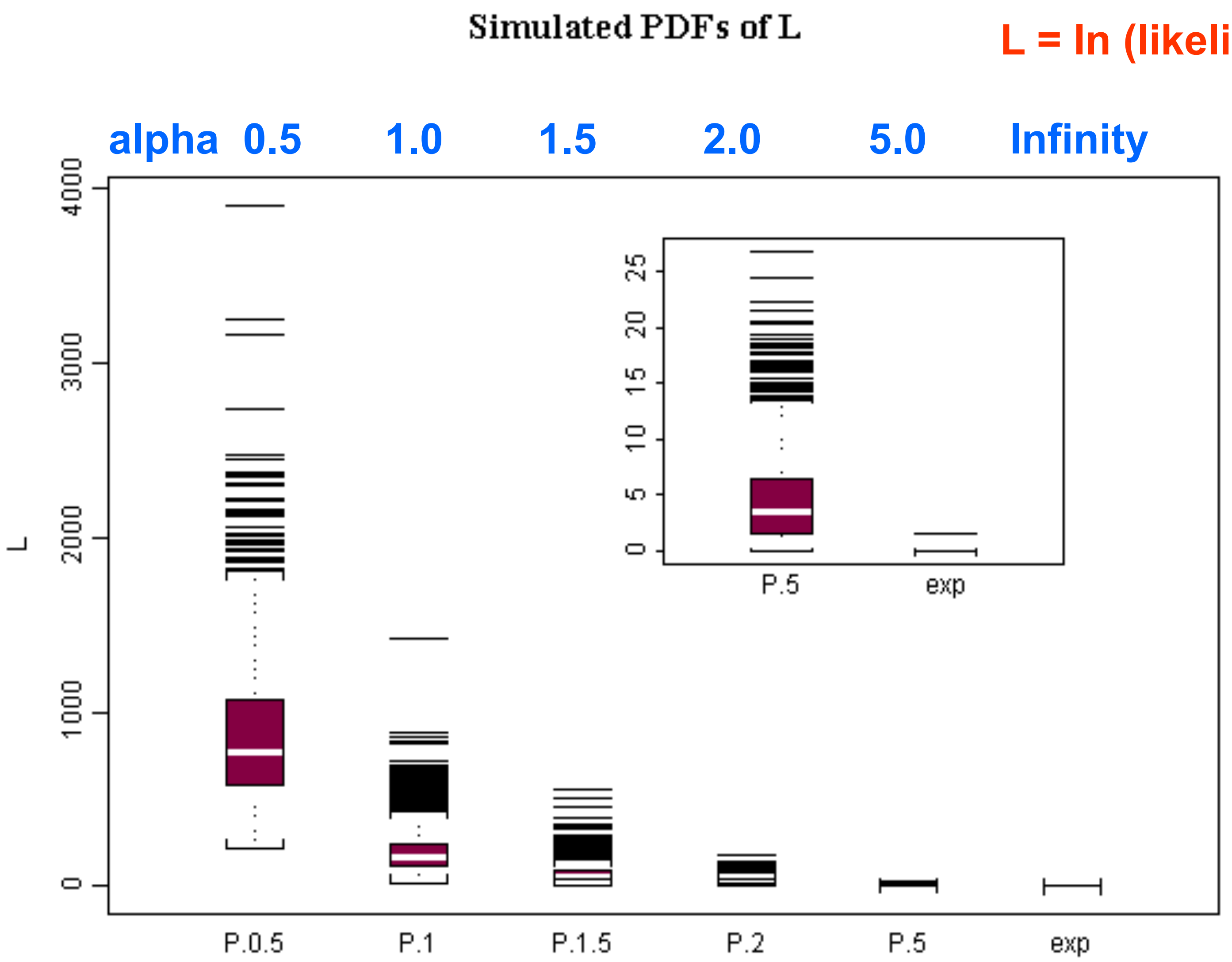
Pareto alpha

San Jose CA
Monthly Precip
1908-2000



Alpha Parameter of Rainfall Distributions in San Jose

L = ln (likelihood ratio)



Panorska, A.K., A. Gershunov, and T.J. Kozubowski (2007).

From diversity to volatility: Probability of daily precipitation and extremes. Nonlinear Dynamics in Geosciences (A. Tsonis and J. Elsner, Eds.), Springer, New York, pp 465-484.

Heavier tails

Exponential

Figure 1 (from Panorska et al. 2007). The graph contains 6 boxplots of simulated distributions of L. The first five boxplots were done using 10,000 observations of L from Pareto samples of size 1,000 with α varying from 0.5 (first boxplot) to 5 (second to the last boxplot). The last boxplot corresponds to 10,000 observations of L from exponential samples of size 1,000. The inset blows up the last two boxplots.

Redder = heavier tails

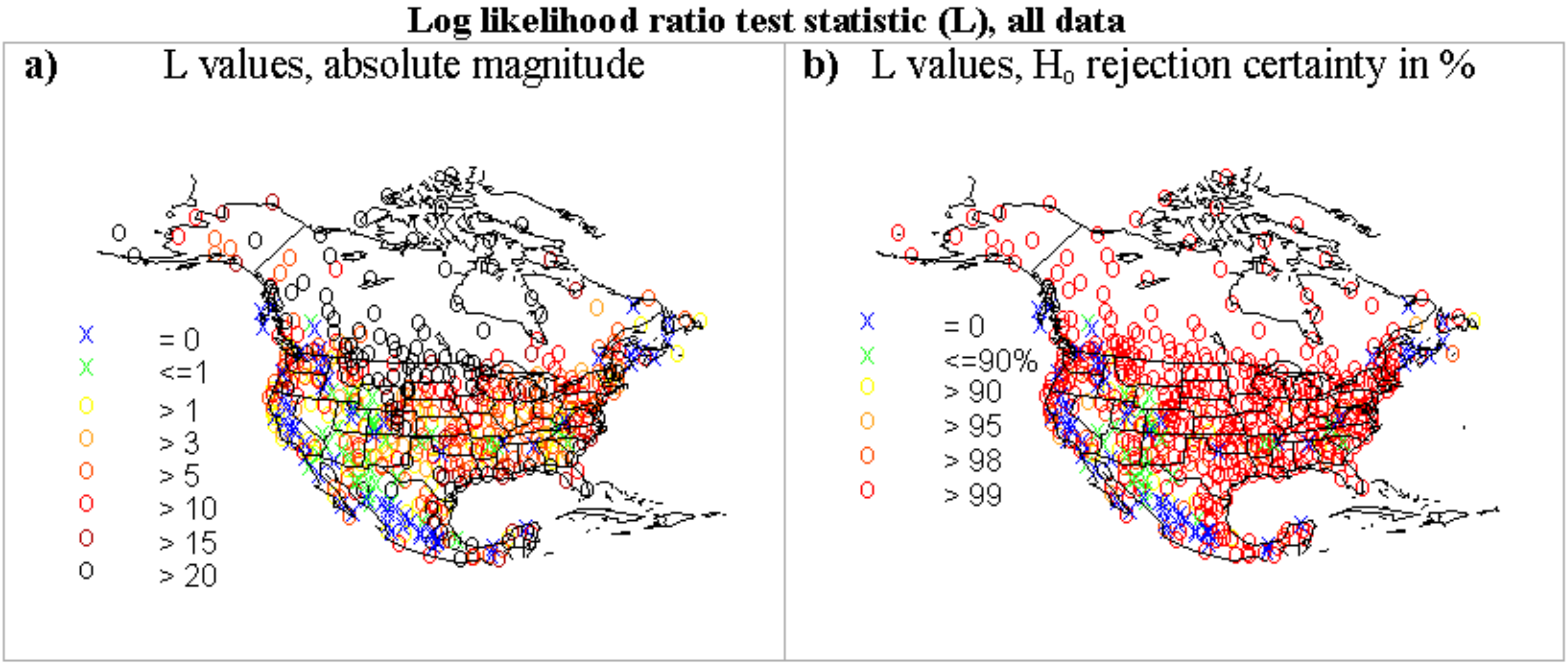
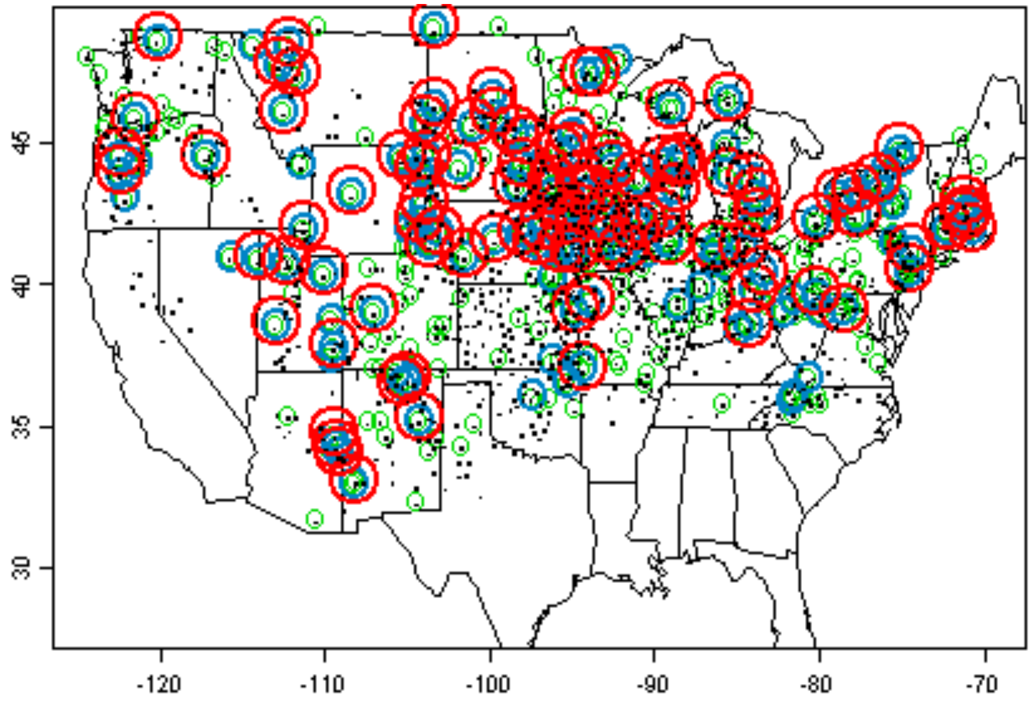


Figure 2 (from Panorska et al. 2006). Log likelihood ratio (L) computed for daily excesses over local 75th percentile at each of the 560 stations. **(a)** Values close to zero, L <= 1 (blue and green x's) represent approximately exponential tails, while yellow, red and black circles represent progressively heavier tails. **(b)** Level of confidence, $(1 - \gamma)*100$, for rejecting the null hypothesis (H_o) of exponential tails. Blue x's represent exponential tails, green x's represent stations at which the H_o cannot be rejected with reasonable (90%) confidence. Yellow and progressively redder circles represent stations at which H_o can be rejected with 90, 95, 98 and 99% confidence in favor of the Pareto alternative. For example, H_o can be rejected at 81% of stations with 95% confidence.

Percentiles are for days with measurable precipitation. A.P. tried 50-95 percentile.

Snowfall

Values from Kunkel et al



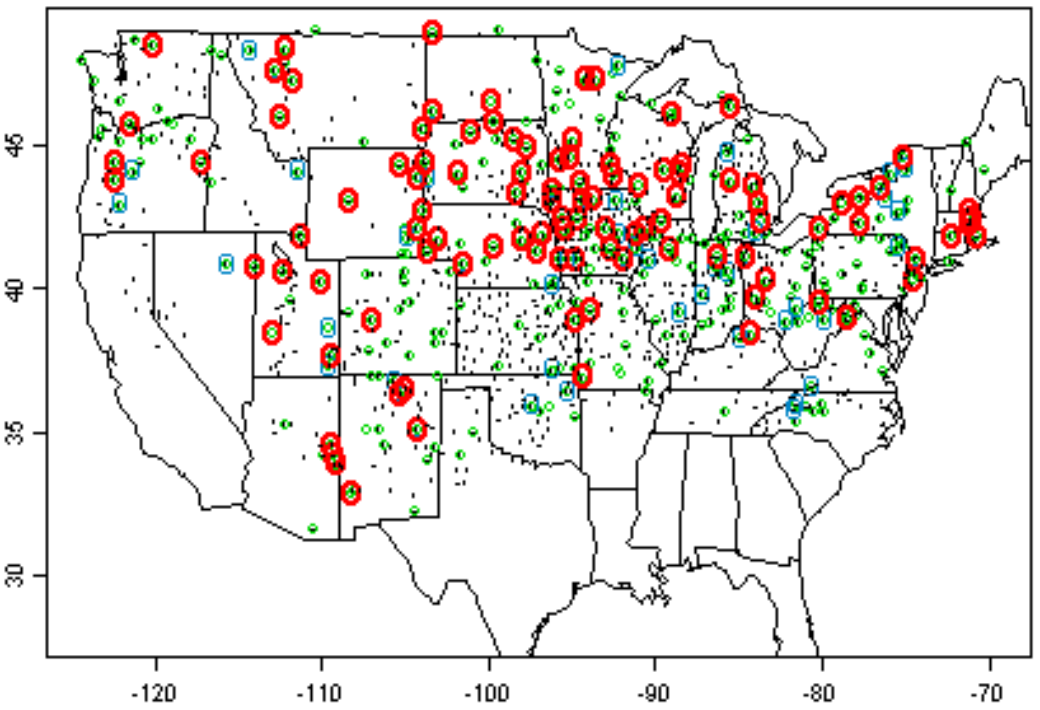
Same for the quality controlled larger station subset – 1124 stations.

This was done with a flexible choice of three thresholds (80th, 90th and 95th %-iles used in the peaks over threshold approach, see Panorska et al. 2007 for details) and six confidence levels ranging from 0.005 to 0.1.

- Small green circles represent heavy tails outcome for at least one threshold choice at lowest confidence – happens at 30% of the stations
- Larger blue circles represent heavy tails outcome for at least half of the possible threshold/confidence choices
- Big red circles represent heavy tails all around – this happens at 10% of the stations

Snowfall

Values from Kunkel et al



Same thing with reasonably-sized circles. Here, we can better see that heavy tails are observed only at a minority of stations, even in the northern Plains and the Mid-West, where much of the heavy-tailed behavior is observed.

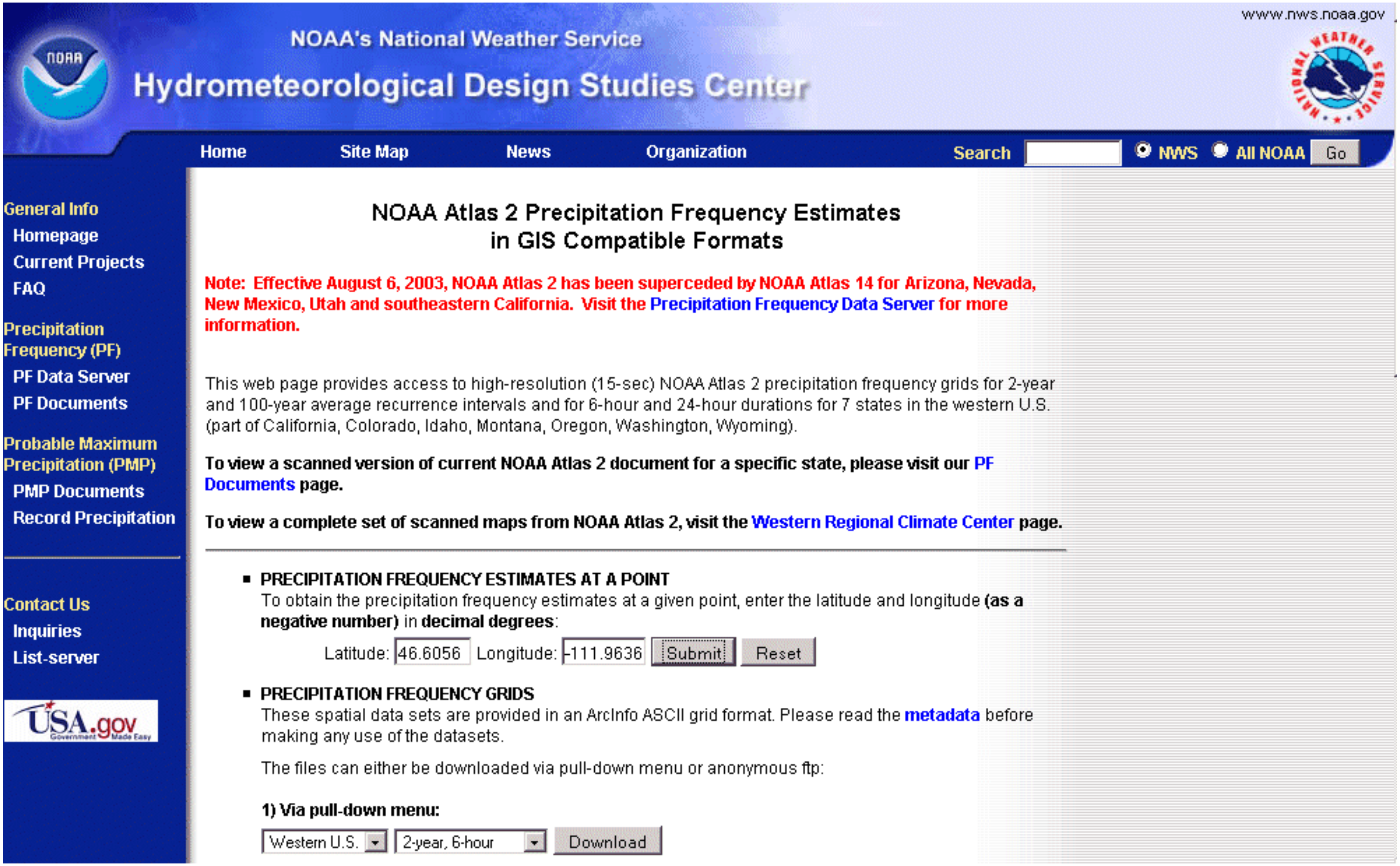
On the whole, depending on threshold and significance level choice, snow accumulations at 10 – 30% of stations are heavy tailed. This is consistent with the result of Panorska et al. 2007 (figure 3a) where all precipitation (SWE in case of snow) at 37% of North American stations was estimated as heavy tailed in DJF using the 80th %-ile threshold with 95% confidence. Also, the spatial pattern of snow accumulation heavy tails generally agrees with the spatial pattern of wintertime heavy precipitation tails.

Panorska, Gershunov, Redmond

PRECIPITATION STATISTICS AT SELECTED STATIONS

Station	Log likelihood ratio (L)	$P[p > 0]$ (%)	75th %-ile($p_{p>0}$) (mm)	$\mathrm{Max}_{obs}(p)$ (mm)	100-yr event Exp and Pareto (mm)	Pareto $P[p > p_{exp}^{100}]$ (%)
Sacramento	1.60	16	10.7	96	85 and 99	2.3
Nashville	3.15	26	16	153	127 and 154	3.4
St. Louis	4.93	30	11.2	142	114 and 144	4.1
Houston	15.2	27	16.3	253	195 and 292	6.5
Fargo	28.6	27	5.8	118	85 and 167	12.0
Miami	41.8	36	13.7	377	181 and 346	9.8

Table 2. Precipitation statistics at selected stations for the common observational period 1950 – 2001: L; probability of precipitation (i.e. % of days with recorded precipitation); 75th percentile of daily total on days with precipitation; maximum recorded daily total; the estimated 100-year event assuming exponential and Pareto tails; and the Pareto probability of exceeding the exponential 100-yr event. The last column can be interpreted as the factor by which the 100-yr event estimated assuming exponential tail is more likely to occur assuming Pareto tail. Alternatively, the Pareto return period for an exponential 100-yr event is 100 years divided by the value in the last column at a specific station. So, for example, in Sacramento, the 100-yr event estimated using the exponential assumption, can be expected, according to the Pareto assumption, to be exceeded in a 44 yr period (i.e. 100/2.3), while in Miami, it should be exceeded within 10 years (100/9.8).



NOAA Atlas 2 Precipitation Frequency Estimates in GIS Compatible Formats

Note: Effective August 6, 2003, NOAA Atlas 2 has been superceded by NOAA Atlas 14 for Arizona, Nevada, New Mexico, Utah and southeastern California. Visit the Precipitation Frequency Data Server for more information.

This web page provides access to high-resolution (15-sec) NOAA Atlas 2 precipitation frequency grids for 2-year and 100-year average recurrence intervals and for 6-hour and 24-hour durations for 7 states in the western U.S. (part of California, Colorado, Idaho, Montana, Oregon, Washington, Wyoming).

To view a scanned version of current NOAA Atlas 2 document for a specific state, please visit our PF Documents page.

To view a complete set of scanned maps from NOAA Atlas 2, visit the Western Regional Climate Center page.

- **PRECIPITATION FREQUENCY ESTIMATES AT A POINT**
  To obtain the precipitation frequency estimates at a given point, enter the latitude and longitude **(as a negative number)** in **decimal degrees**:

  Latitude: 46.6056 Longitude: -111.9636 Submit Reset

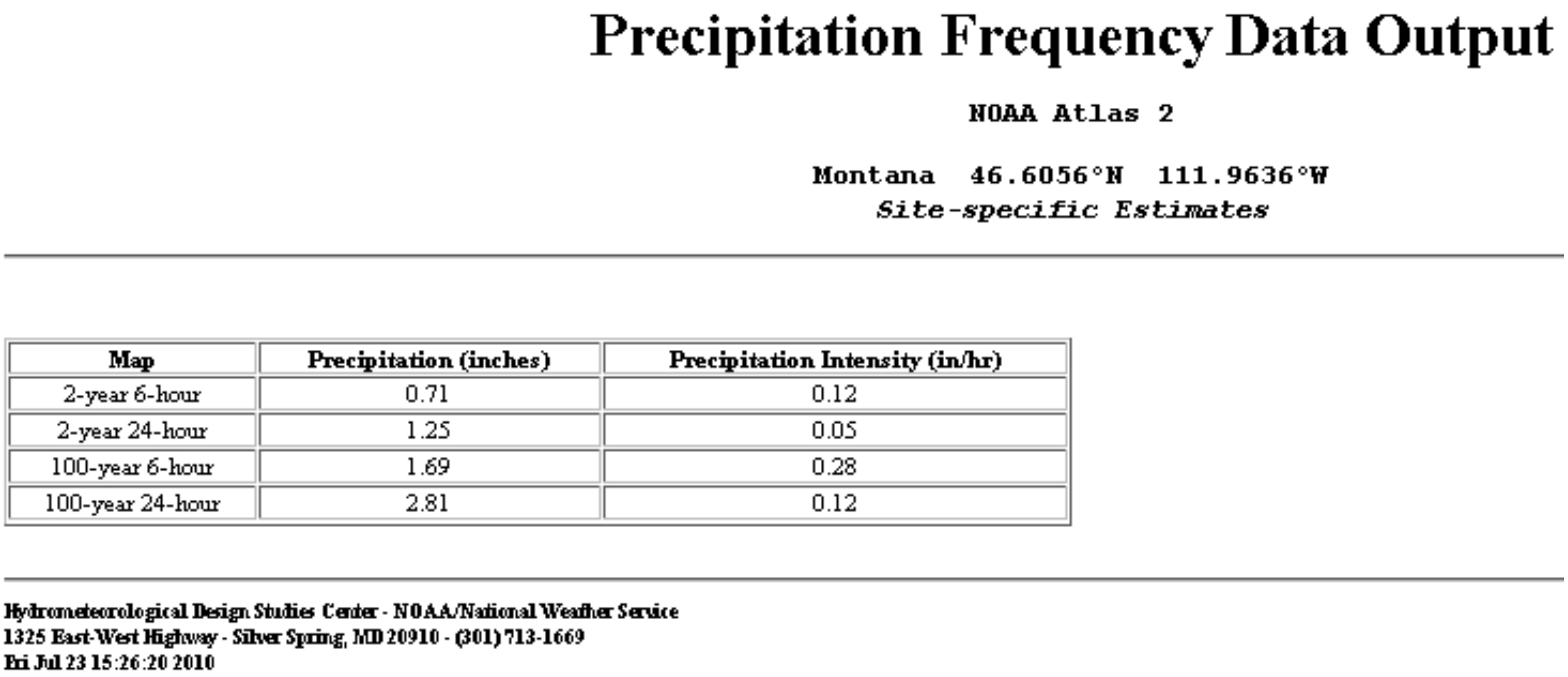
- **PRECIPITATION FREQUENCY GRIDS**
  These spatial data sets are provided in an ArcInfo ASCII grid format. Please read the **metadata** before making any use of the datasets.

  The files can either be downloaded via pull-down menu or anonymous ftp:

  1) Via pull-down menu:

  Western U.S. 2-year, 6-hour Download

For Helena MT ASOS Location



Precipitation Frequency Data Output

NOAA Atlas 2

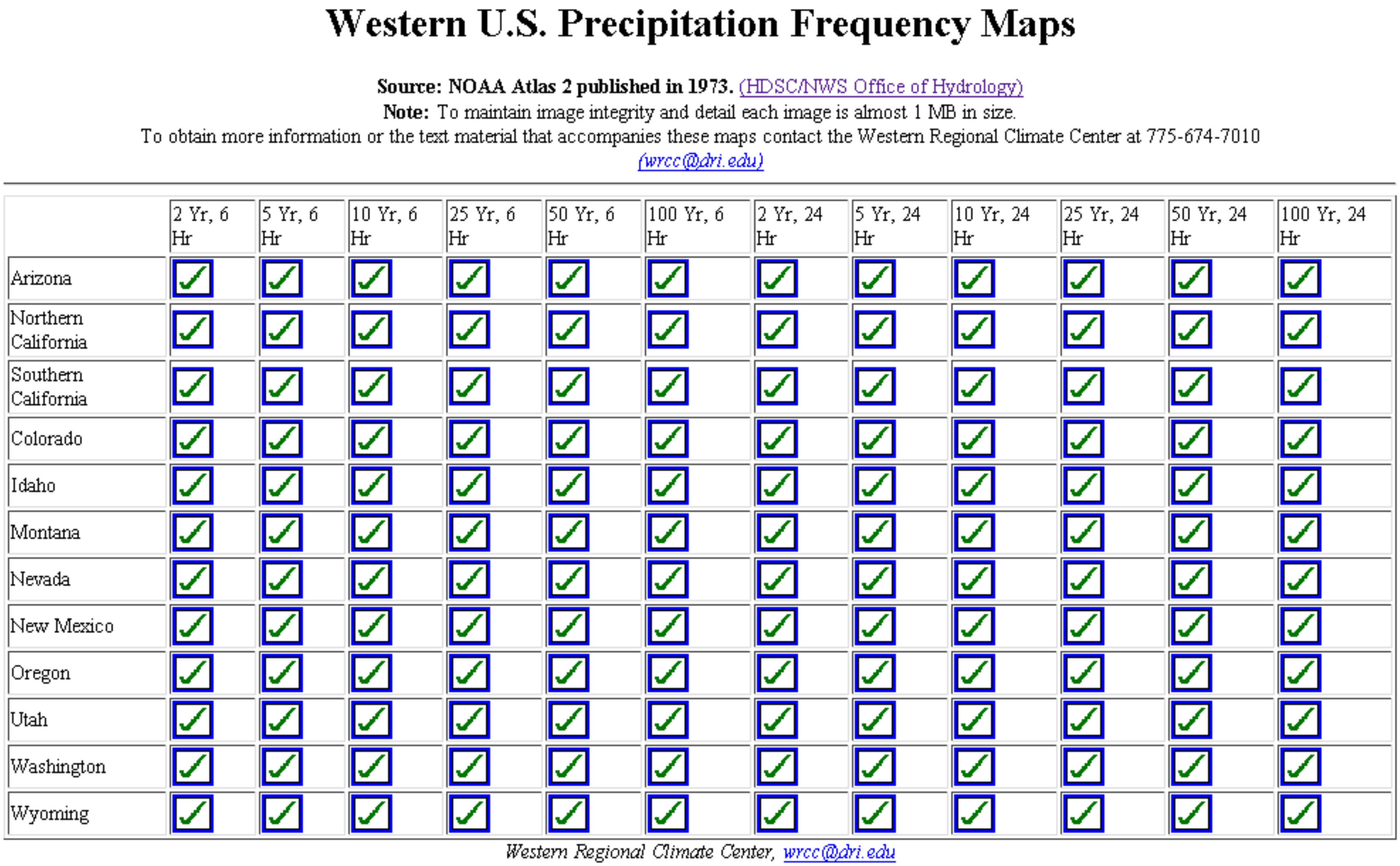
Montana 46.6056°N 111.9636°W
Site-specific Estimates

Map	Precipitation (inches)	Precipitation Intensity (in/hr)
2-year 6-hour	0.71	0.12
2-year 24-hour	1.25	0.05
100-year 6-hour	1.69	0.28
100-year 24-hour	2.81	0.12

Hydrometeorological Design Studies Center - NOAA/National Weather Service
1325 East-West Highway - Silver Spring, MD 20910 - (301) 713-1669
Fri Jul 23 15:26:20 2010

Using AZ example and ratios
100/2 = 2.3, so est 100yr = 2.75”
10/2 = 1.5, so est 100yr = 1.87”

At WRCC: www.wrcc.dri.edu/pcpnfreq.html



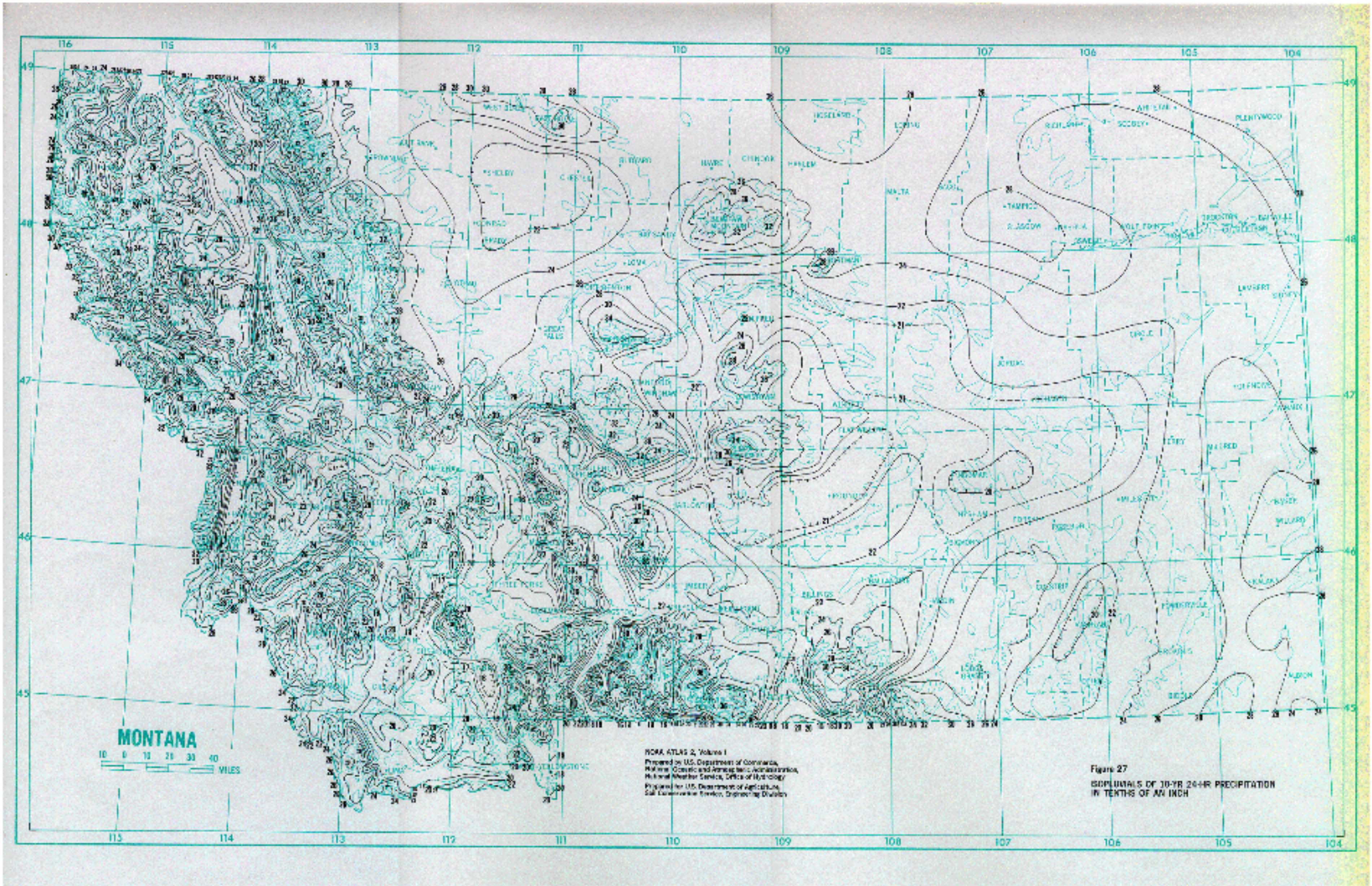
Western U.S. Precipitation Frequency Maps

Source: NOAA Atlas 2 published in 1973. (HDSC/NWS Office of Hydrology)
Note: To maintain image integrity and detail each image is almost 1 MB in size.
To obtain more information or the text material that accompanies these maps contact the Western Regional Climate Center at 775-674-7010
(wrcc@dri.edu)

	2 Yr, 6 Hr	5 Yr, 6 Hr	10 Yr, 6 Hr	25 Yr, 6 Hr	50 Yr, 6 Hr	100 Yr, 6 Hr	2 Yr, 24 Hr	5 Yr, 24 Hr	10 Yr, 24 Hr	25 Yr, 24 Hr	50 Yr, 24 Hr	100 Yr, 24 Hr
Arizona	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Northern California	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Southern California	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Colorado	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Idaho	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Montana	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Nevada	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
New Mexico	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Oregon	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Utah	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Washington	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Wyoming	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑

Western Regional Climate Center, wrcc@dri.edu

10-year 24-hour precipitation in tenths of inches

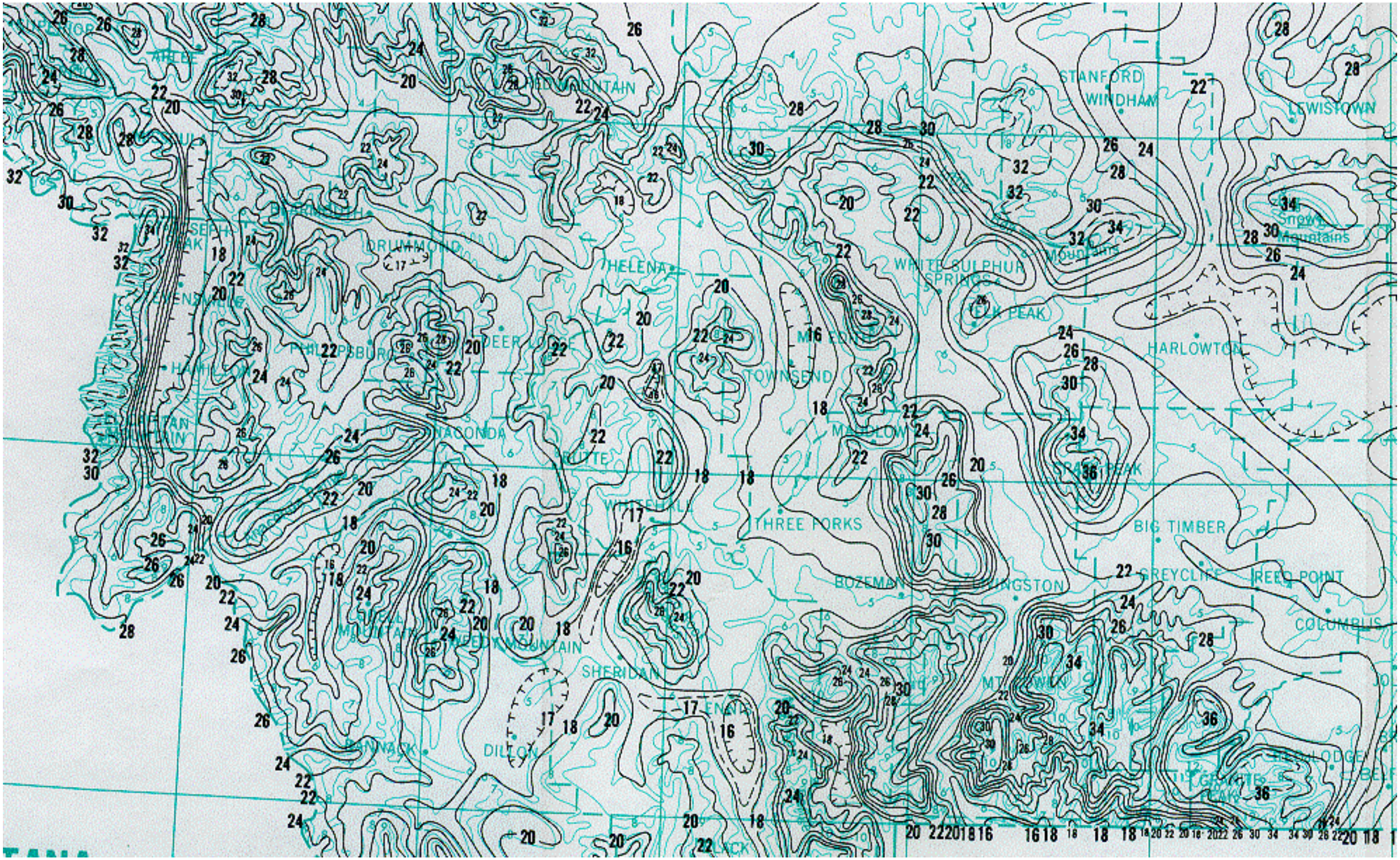


NOAA ATLAS 2, Volume I
Prepared by U.S. Department of Commerce,
National Oceanic and Atmospheric Administration,
National Weather Service, Office of Hydrology
Prepared for U.S. Department of Agriculture,
Soil Conservation Service, Engineering Division

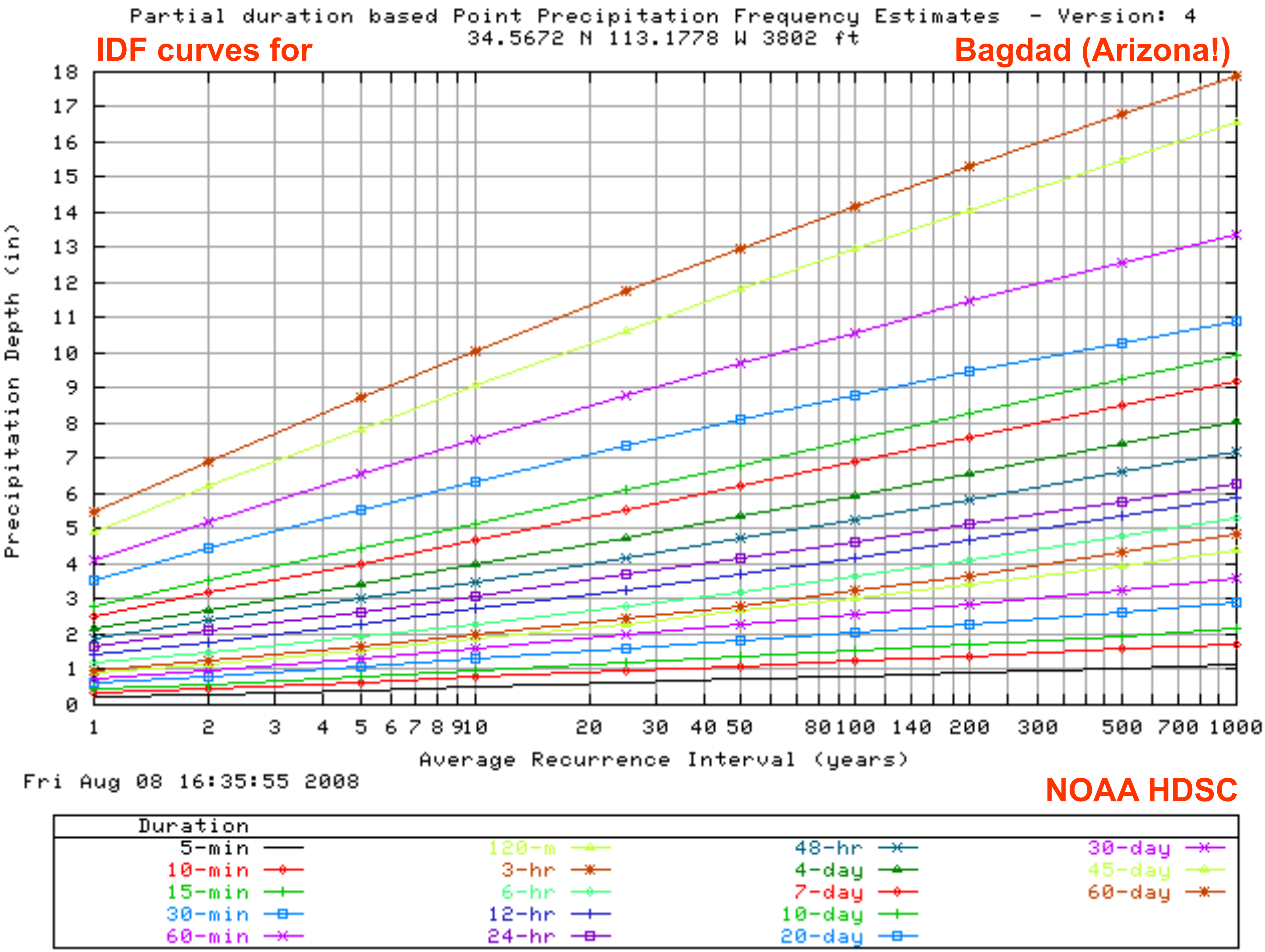
Figure 27

ISOPLUVIALS OF 10-YR 24-HR PRECIPITATION
IN TENTHS OF AN INCH

More detail … 10-year 24-hour precipitation in tenths of inches



IDF curves for Bagdad (Arizona!)



NOAA HDSC

NOAA's National Weather Service

Hydrometeorological Design Studies Center

Welcome to the Hydrometeorological Design Studies Center (HDSC)

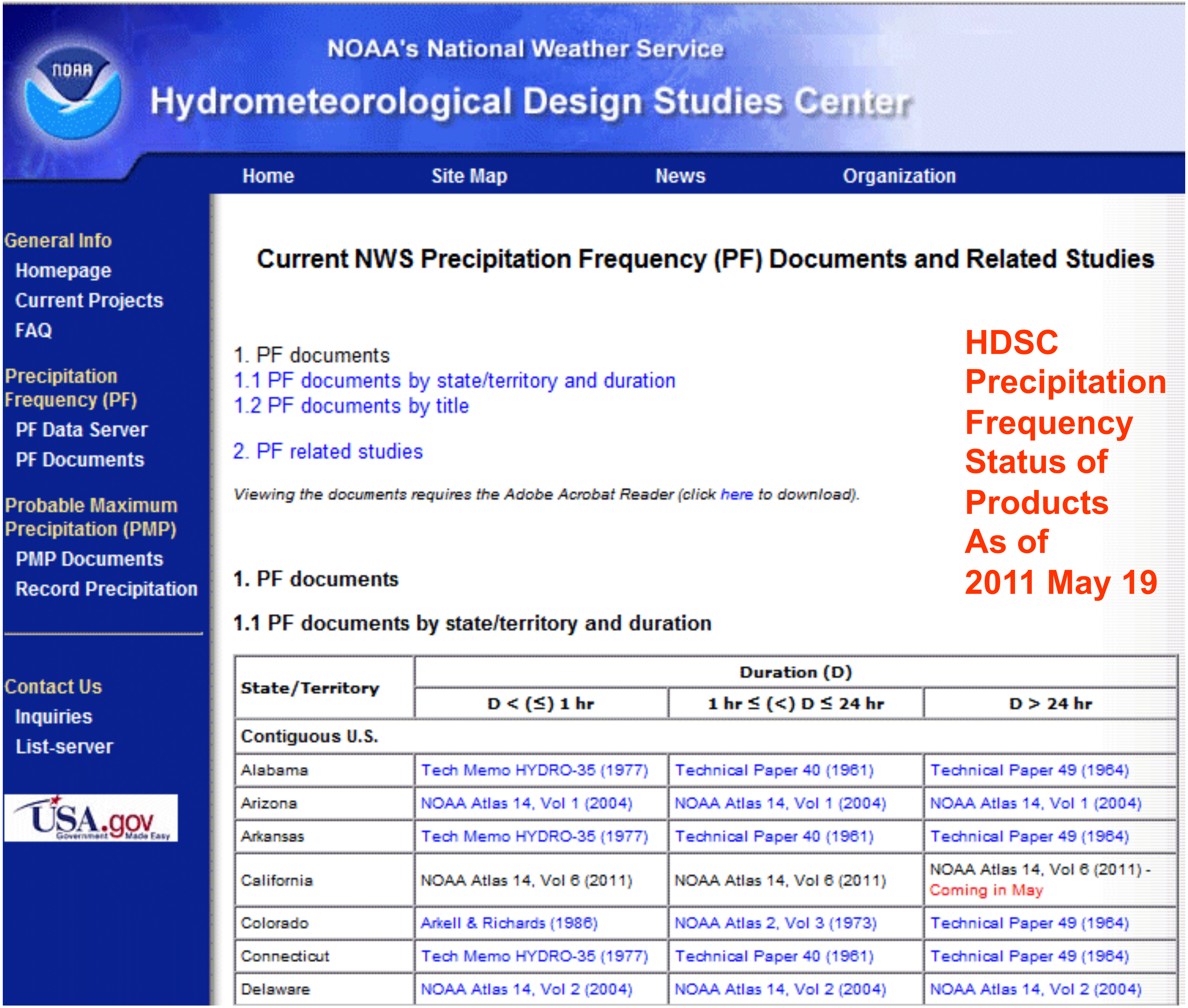
HDSC prepares **PRECIPITATION FREQUENCY** estimates for the Federal Government and provides related documents on this site.

Since 2003, HDSC has been updating precipitation frequency estimates as volumes of NOAA Atlas 14. HDSC has a list-server to distribute progress reports on current projects and occasional announcements.

HDSC discontinued **PROBABLE MAXIMUM PRECIPITATION** activities due to lack of funding, but copies of related NWS documents could be found on this site.

HDSC
Web Page
As of
2011 May 19

HDSC Precipitation Frequency Status of PF Products As of 2011 May 19



Current NWS Precipitation Frequency (PF) Documents and Related Studies

1. PF documents
1.1 PF documents by state/territory and duration
1.2 PF documents by title

2. PF related studies

Viewing the documents requires the Adobe Acrobat Reader (click here to download).

1. PF documents

1.1 PF documents by state/territory and duration

State/Territory	Duration (D)		
	D < (≤) 1 hr	1 hr ≤ (<) D ≤ 24 hr	D > 24 hr
Contiguous U.S.			
Alabama	Tech Memo HYDRO-35 (1977)	Technical Paper 40 (1961)	Technical Paper 49 (1964)
Arizona	NOAA Atlas 14, Vol 1 (2004)	NOAA Atlas 14, Vol 1 (2004)	NOAA Atlas 14, Vol 1 (2004)
Arkansas	Tech Memo HYDRO-35 (1977)	Technical Paper 40 (1961)	Technical Paper 49 (1964)
California	NOAA Atlas 14, Vol 6 (2011)	NOAA Atlas 14, Vol 6 (2011)	NOAA Atlas 14, Vol 6 (2011) - Coming in May
Colorado	Arkell & Richards (1986)	NOAA Atlas 2, Vol 3 (1973)	Technical Paper 49 (1964)
Connecticut	Tech Memo HYDRO-35 (1977)	Technical Paper 40 (1961)	Technical Paper 49 (1964)
Delaware	NOAA Atlas 14, Vol 2 (2004)	NOAA Atlas 14, Vol 2 (2004)	NOAA Atlas 14, Vol 2 (2004)

Potential sources of heavy precipitation:

Frontal passages

Cyclonic storms

Orographic uplift

Tropical storms

Convergence zones

Embedded cumulus

Atmospheric rivers

Blocked atmospheric patterns

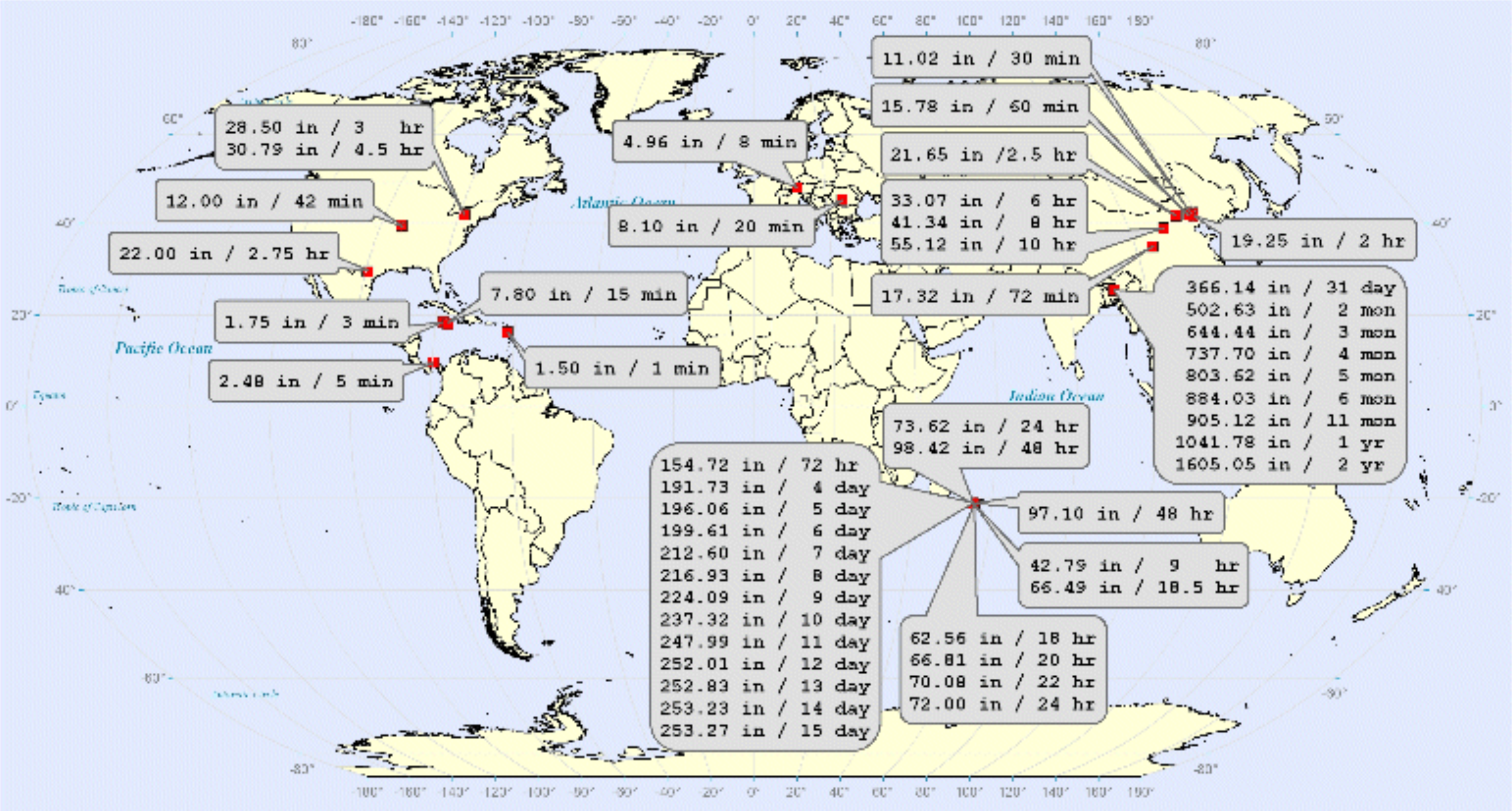
ENSO conditioning

MJO activity

Human effects (?)

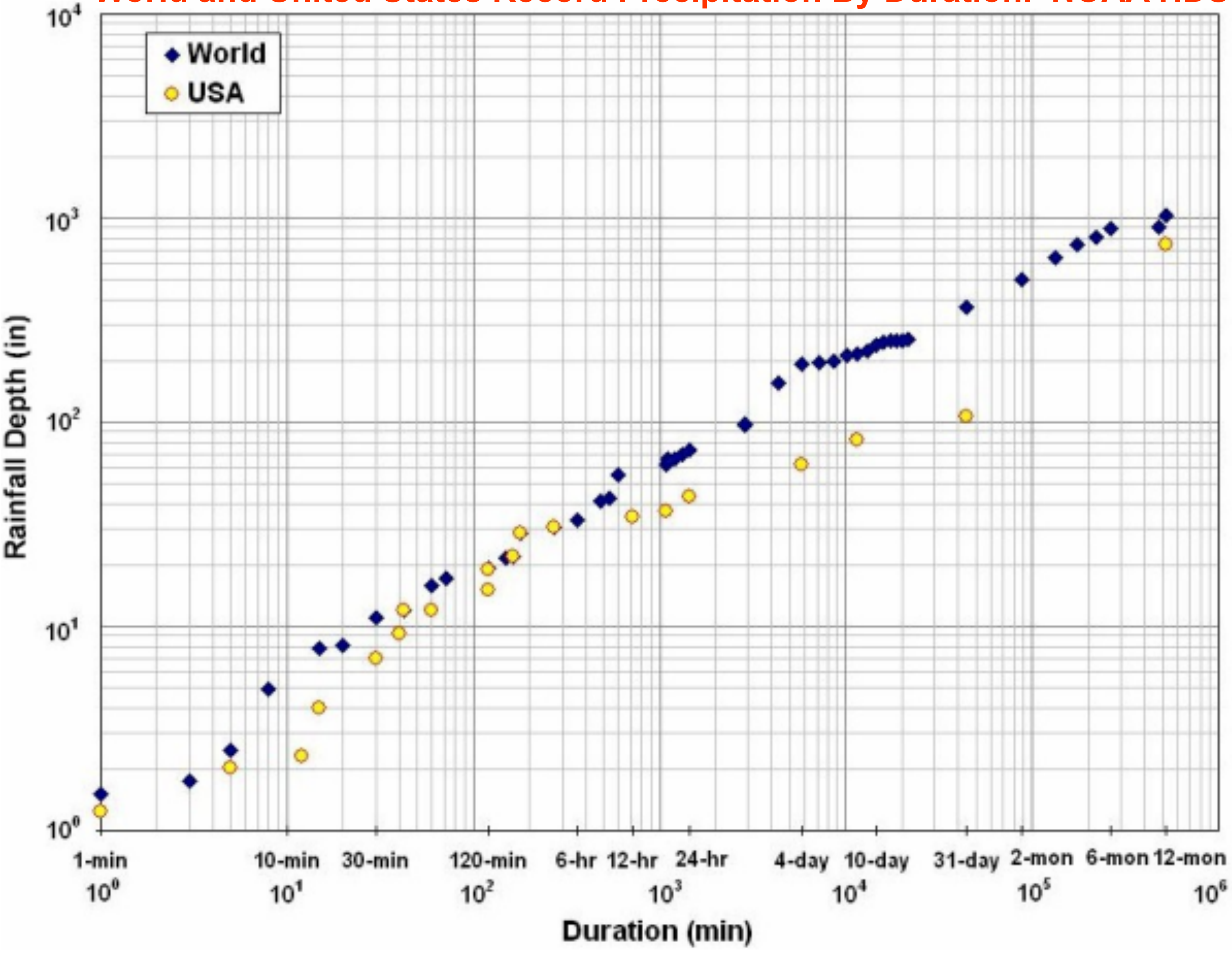
World record precipitation locations.

… A variety of circumstances



NOAA HDSC

World and United States Record Precipitation By Duration. NOAA HDSC.



To produce precipitation, and heavy precipitation:

It is not sufficient that there be abundant atmospheric moisture (humidity).

The main issue is that there must be a mechanism to wring out moisture.

(Examples: Sudan, Kuwait)

It is also not necessary that there be abundant atmospheric moisture.

If dry, there must be advective mechanisms to replenish moisture.

(Example: Heavy winter snows near Lethbridge/Banff at -20 F)

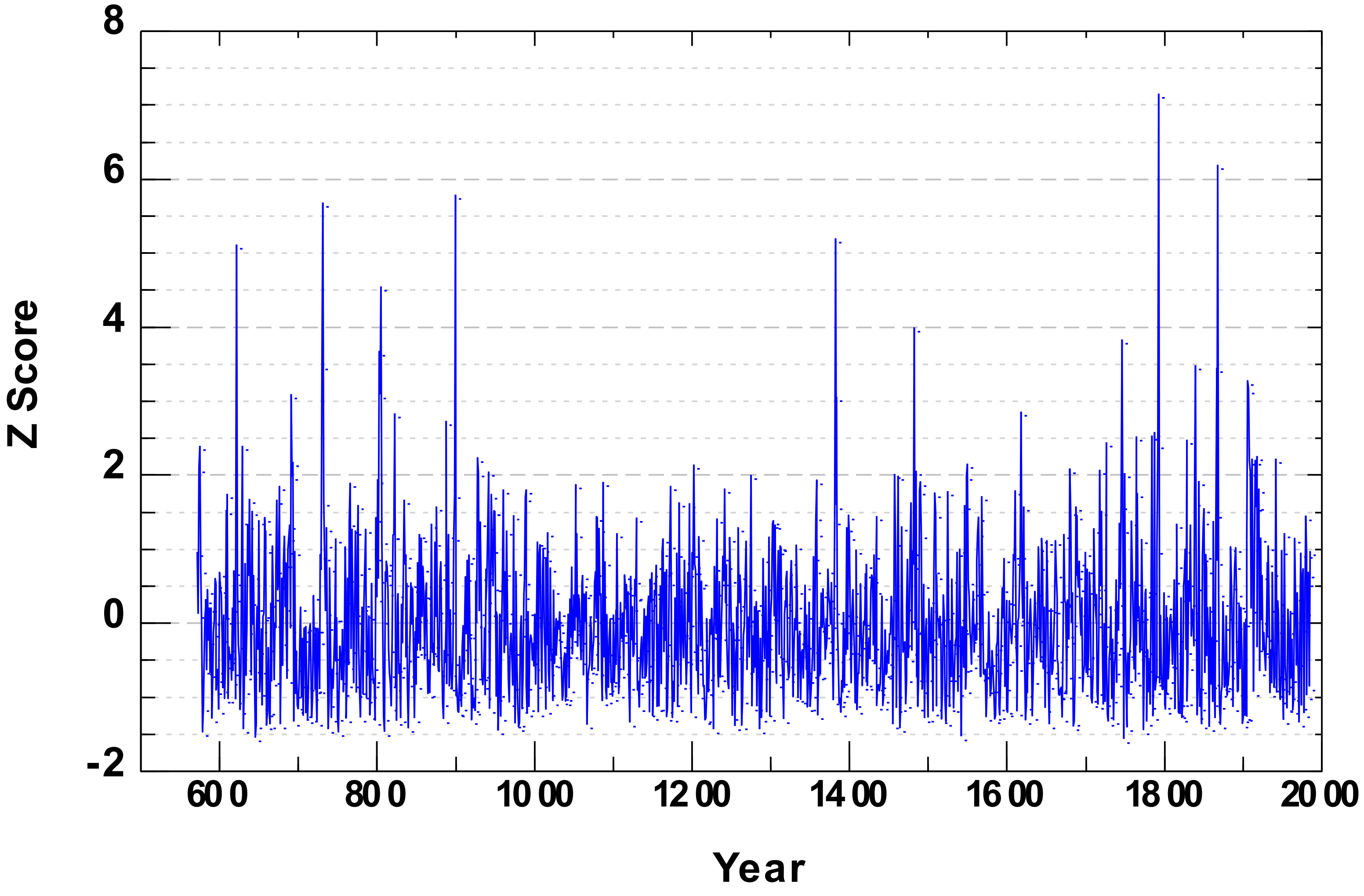
Heavy precipitation can result from

Abundant local moisture

But almost always also requires (especially at time scales > a few hours)

Replenishment and import as local supply is consumed

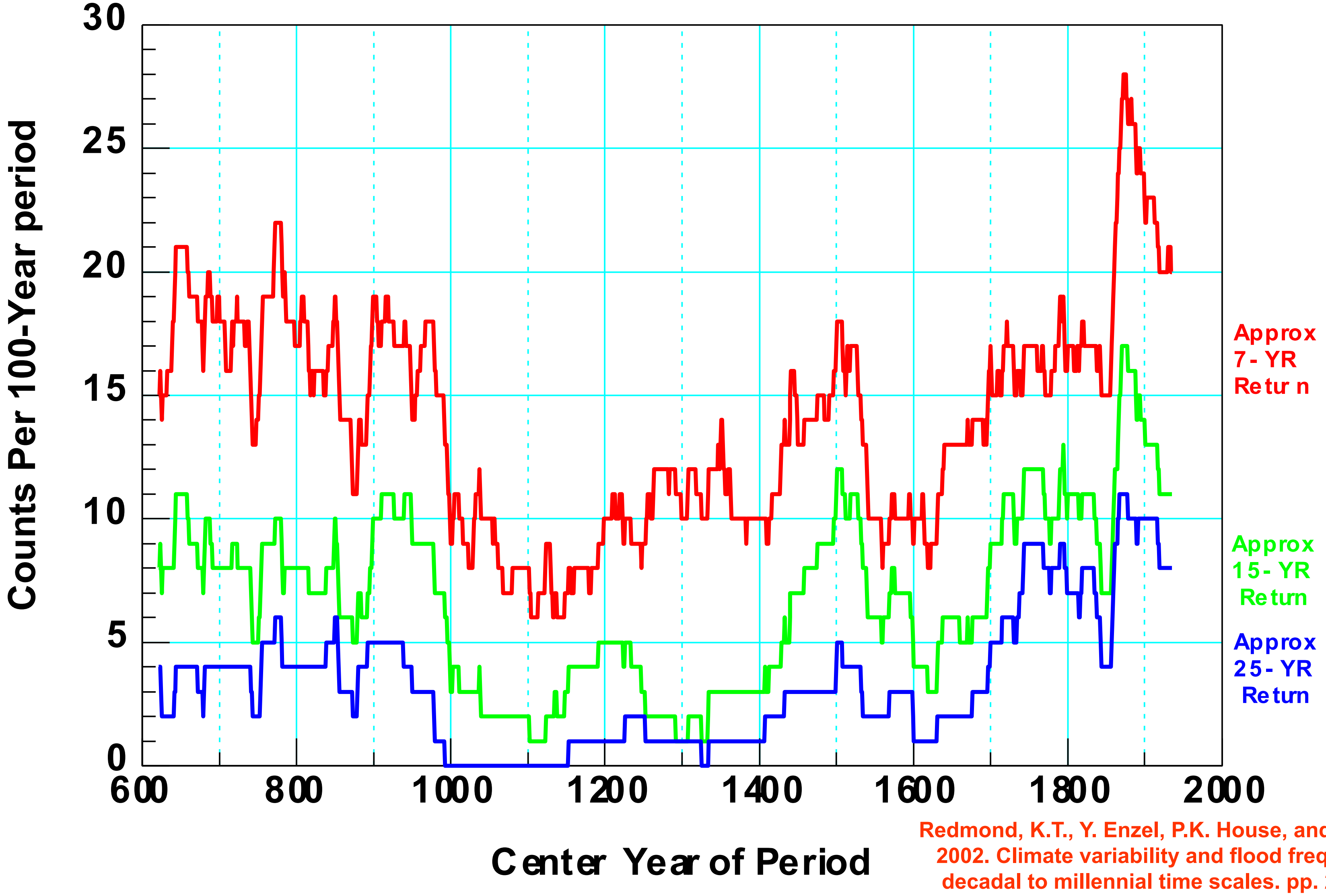
Verde River. Reconstructed Flow. 572-1985 A.D.
Standardized Units.



1414 Years

Redmond, K.T., Y. Enzel, P.K. House, and F. Biondi, 2002. Climate variability and flood frequency at decadal to millennial time scales. pp. 21-45, in *Principles and Applications of Paleoflood Hydrology,* editors: P.K. House, R.H. Webb, and V.R. Baker, American Geophysical Union, 385 pp.

Verde River Z Scores 572-1985 AD
Number of Counts per Running Hundred Years
top (1.0 or more), middle (1.5 or more), bottom (2.0 or more)



Redmond, K.T., Y. Enzel, P.K. House, and F. Biondi, 2002. Climate variability and flood frequency at decadal to millennial time scales. pp. 21-45, in *Principles and Applications of Paleoflood Hydrology*, editors: P.K. House, R.H. Webb, and V.R. Baker, American Geophysical Union, 385 pp.

“Stationarity is dead” *

Stationarity was never really fully alive.

“The history of climate is a nonstationary time series.” *

Corollaries:
There are no true climatic “normals”.
We never know enough. We can never stop observing.

* P.C.D. Milly, Julio Betancourt, Malin Falkenmark, Robert M. Hirsch, Zbigniew W. Kundzewicz, Dennis P. Lettenmaier, Ronald J. Stouffer, 2008. Stationarity is dead: Whither water management?. Science, 319 (5863), 573-574, 1 Feb 2008.

* Reid A. Bryson, 1997. The Paradigm of Climatology: An Essay. Bulletin of the American Meteorological Society, 78(3), 449-455.

Stationarity, if even alive, is not feeling well … “under the weather”

Climate change: The “present future” will slowly depart from its “prior future”
Stationarity slowly but progressively becoming a less valid assumption
Evidence points this way .... but is not completely unambiguous
How much until this departure is “significant” ?
(not so much in statistical terms, but in practical terms)
How do we adjust all the statistics of the past to reflect the expected future?

A thought experiment

Suppose we had a perfect (complete and accurate) observed time series of a climate element indefinitely far back into the past from a location of interest.

e.g. 1-minute measurements for the last 100, thousand, 10000, 100000, million years

We wish to make a decision about some future time interval

The expected lifetime of a culvert
The expected lifetime of a railroad bridge
The expected lifetime of a waste settlement lagoon
The expected lifetime of a major dam

In many cases, the interval may consist of the time until we next revisit the issue

(because human infrastructure is constantly being reshaped for many purposes)

The big question :

What part of the past is relevant to what part of the future?

How many years would we go back, for a decision related to how many years in the future?

The usual answer:

There's never enough data.
Beggars can't be choosers.
More is always better.

Karl and Knight, 1998. Fraction of annual total from upper 10th percentile, US Average.

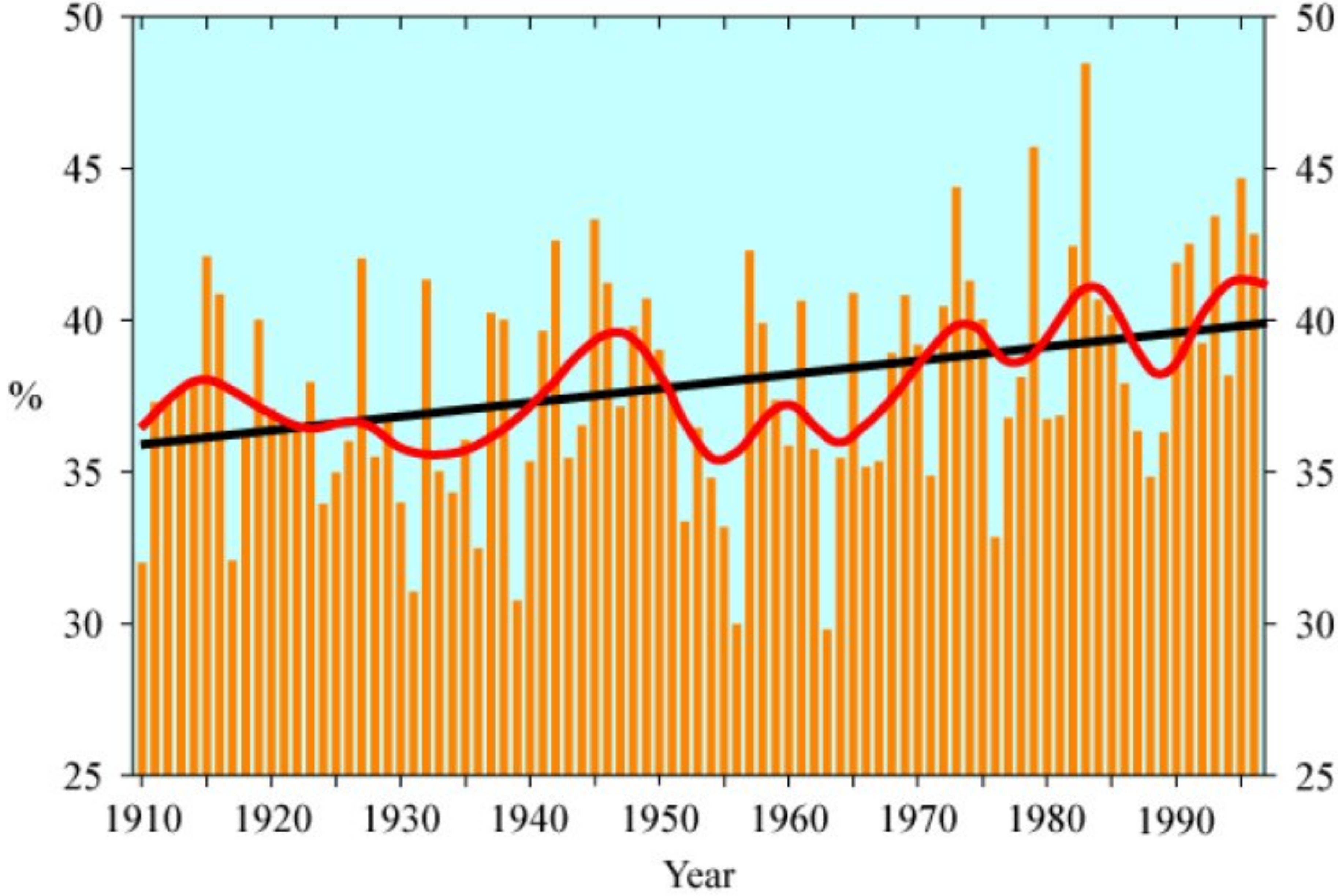
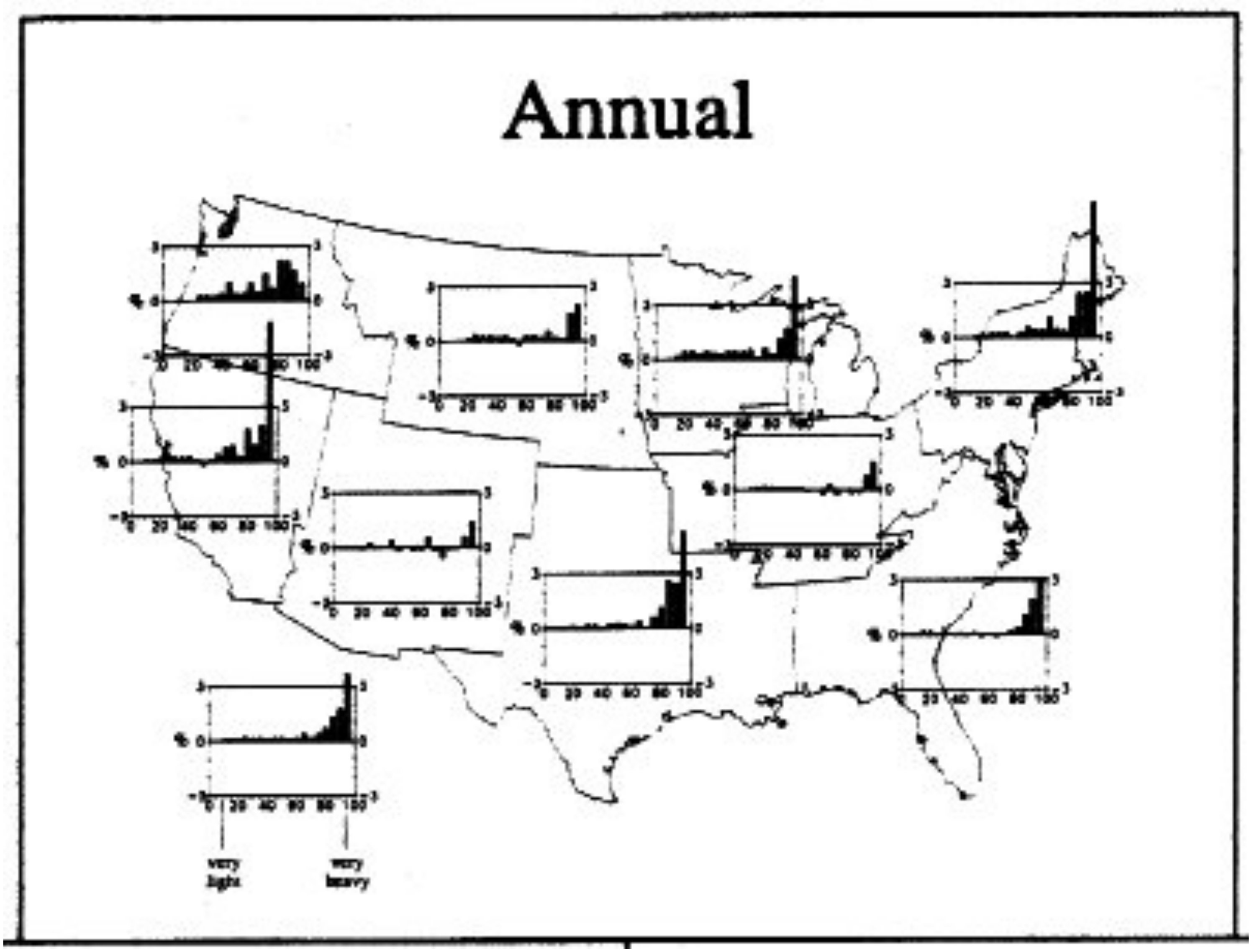


FIG. 2. Time series of the percent contribution of the upper 10 percentile of daily precipitation events to the total annual precipitation area-averaged across the United States. Smooth curve is a nine-point binomial filter, and the trend is also depicted.



Trends in Extreme Daily Precipitation, 1910-1996, by category.

Thomas R. Karl and Richard W. Knight, 1998. Secular Trends of Precipitation Amount, Frequency, and Intensity in the United States. ***Bulletin of the American Meteorological Society*** **, 79 (2), 231–241.**

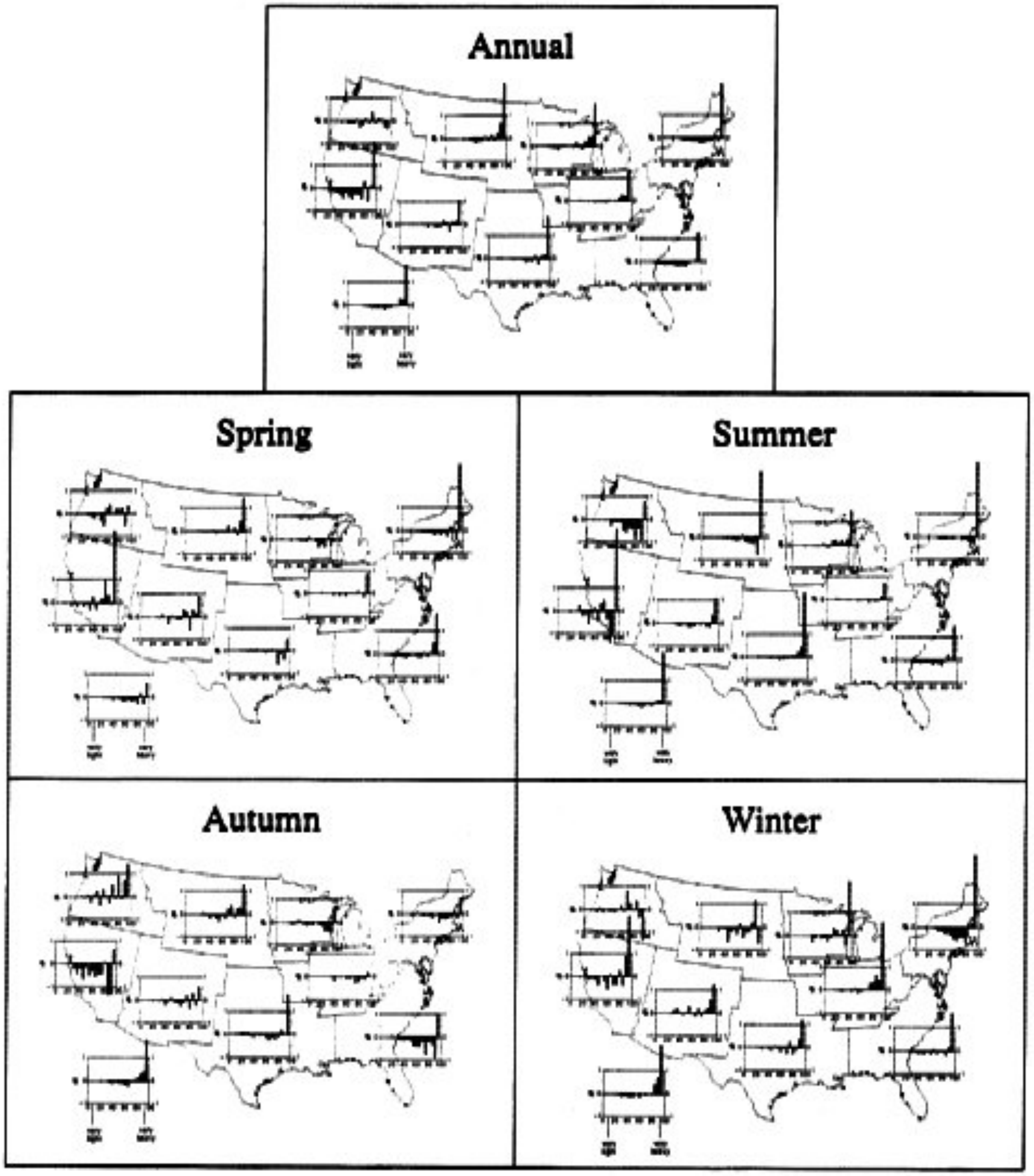


FIG. 5. The contribution to the trends in Fig. 1 attributed to trends in precipitation intensity. Trends are expressed as in Fig. 1.

Karl and Knight, 1998.

Contribution to change in total precipitation from different intensity classes.

1910-1996.

-- The intensity of precipitation has increased for very heavy and extreme precipitation days only.

-- The proportion of total annual precipitation derived from heavy and extreme precipitation events has increased relative to more moderate precipitation.

Trends in heavy (5 pct), very heavy (1 pct), and extreme (0.1 pct) daily precipitation.

1910-1999, USA.

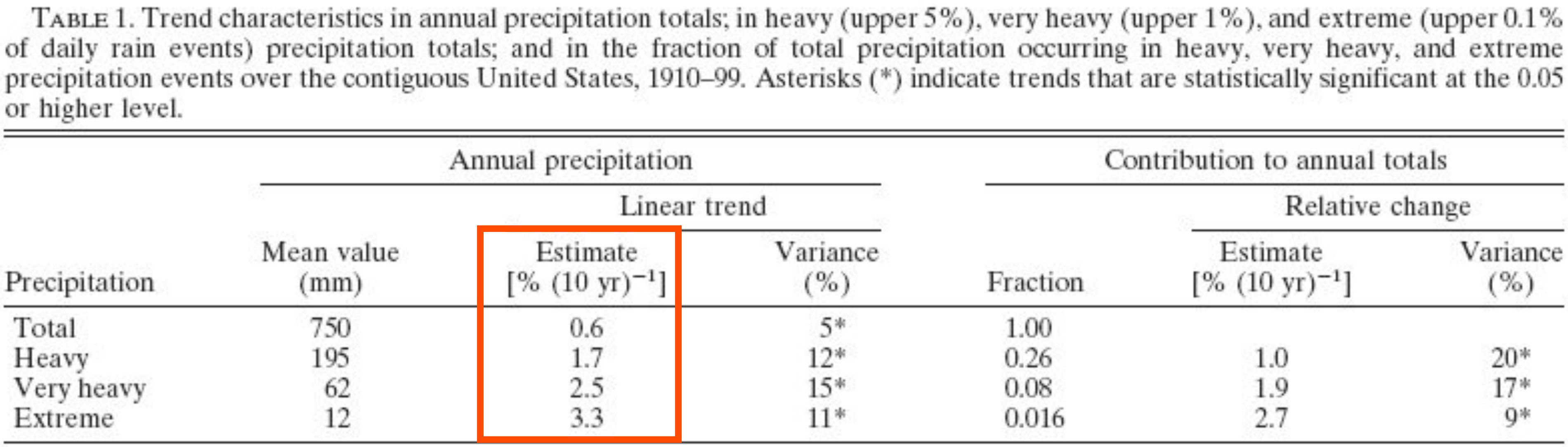


TABLE 1. Trend characteristics in annual precipitation totals; in heavy (upper 5%), very heavy (upper 1%), and extreme (upper 0.1% of daily rain events) precipitation totals; and in the fraction of total precipitation occurring in heavy, very heavy, and extreme precipitation events over the contiguous United States, 1910–99. Asterisks (*) indicate trends that are statistically significant at the 0.05 or higher level.

	Annual precipitation			Contribution to annual totals		
		Linear trend			Relative change	
Precipitation	Mean value (mm)	Estimate $[\% \ (10\ \mathrm{yr})^{-1}]$	Variance (%)	Fraction	Estimate $[\% \ (10\ \mathrm{yr})^{-1}]$	Variance (%)
Total	750	0.6	5*	1.00		
Heavy	195	1.7	12*	0.26	1.0	20*
Very heavy	62	2.5	15*	0.08	1.9	17*
Extreme	12	3.3	11*	0.016	2.7	9*

Pavel Ya. Groisman, Richard W. Knight, David R. Easterling, Thomas R. Karl, Gabriele C. Hegerl, and Vyacheslav N. Razuvaev, 2005. Trends in Intense Precipitation in the Climate Record *Journal of Climate*, 18 (9), 1326–1350.

Trends in number of days with heavy (5 pct), very heavy (1 pct), and extreme (0.1 pct) daily precipitation. 1910-1999, USA.

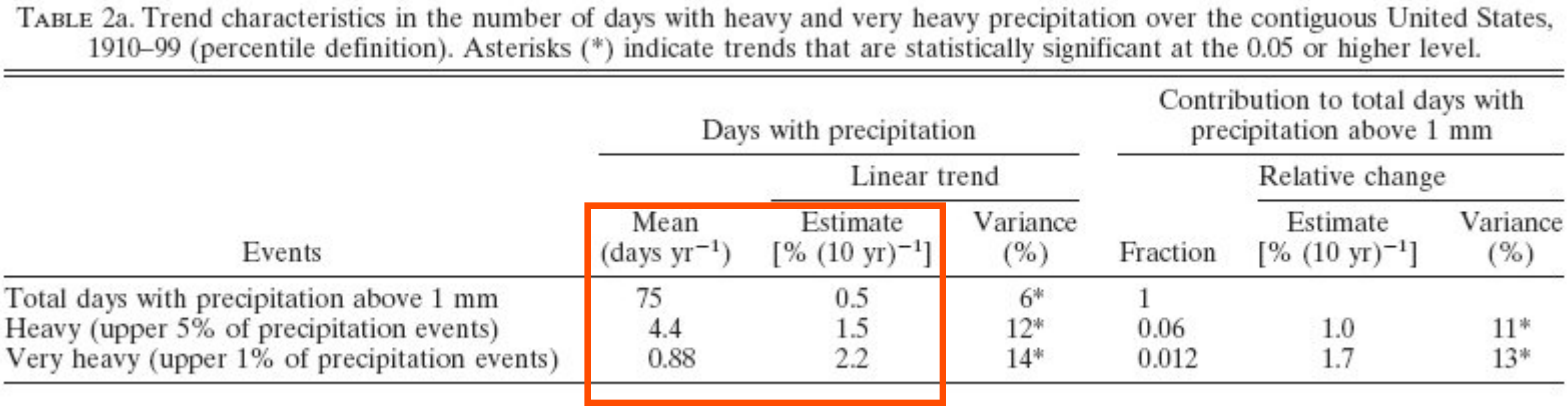


TABLE 2a. Trend characteristics in the number of days with heavy and very heavy precipitation over the contiguous United States, 1910–99 (percentile definition). Asterisks (*) indicate trends that are statistically significant at the 0.05 or higher level.

	Days with precipitation			Contribution to total days with precipitation above 1 mm		
		Linear trend			Relative change	
Events	Mean (days yr^{-1})	Estimate [% (10 yr)$^{-1}$]	Variance (%)	Fraction	Estimate [% (10 yr)$^{-1}$]	Variance (%)
Total days with precipitation above 1 mm	75	0.5	6*	1		
Heavy (upper 5% of precipitation events)	4.4	1.5	12*	0.06	1.0	11*
Very heavy (upper 1% of precipitation events)	0.88	2.2	14*	0.012	1.7	13*

Pavel Ya. Groisman, Richard W. Knight, David R. Easterling, Thomas R. Karl, Gabriele C. Hegerl, and Vyacheslav N. Razuvaev, 2005. Trends in Intense Precipitation in the Climate Record *Journal of Climate*, 18 (9), 1326–1350.

Extreme Precipitation Index

United States

1895-2000.

Selected durations

And

Return periods (1, 5, 20 yrs)

(Station density effects removed)

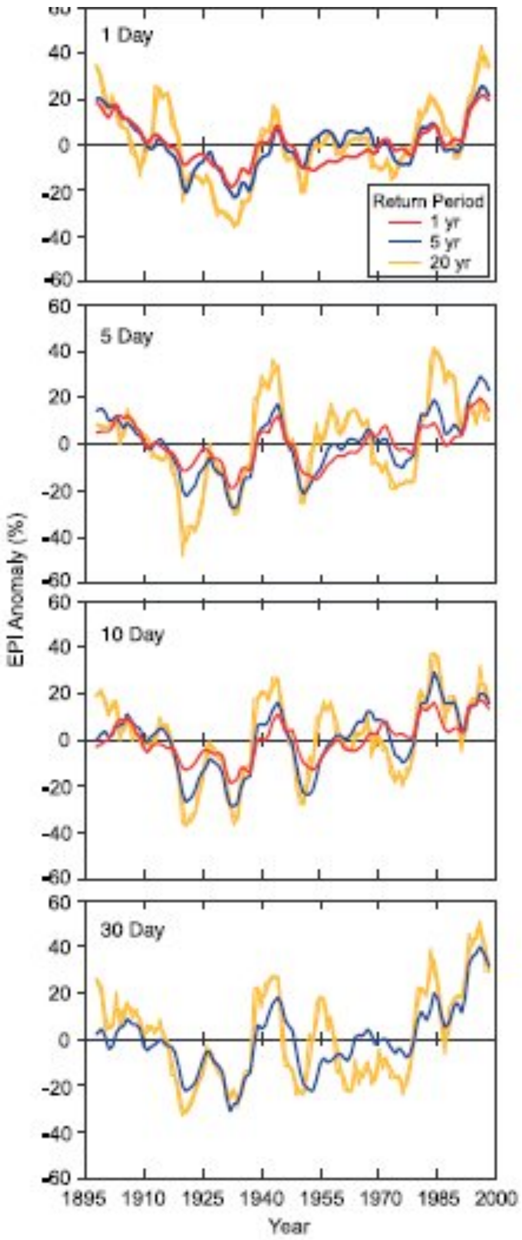


Figure 2. Time series of anomalies of the Extreme Precipitation Index, expressed in %, for various combinations of duration and return period. The time series have been smoothed with a 7-yr moving average filter. Return periods of 1 year (red), 5 years (blue), and 20 years (orange) are plotted on each graph.

1-Day

5-Day

10-Day

30-Day

Ken E. Kunkel, Dave R. Easterling, Kelly T. Redmond, and Ken G. Hubbard, 2003.

Temporal variations of extreme precipitation events in the United States: 1895-2000.

Geophysical Research Letters, 30:1717.

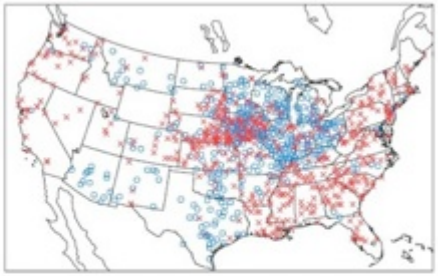
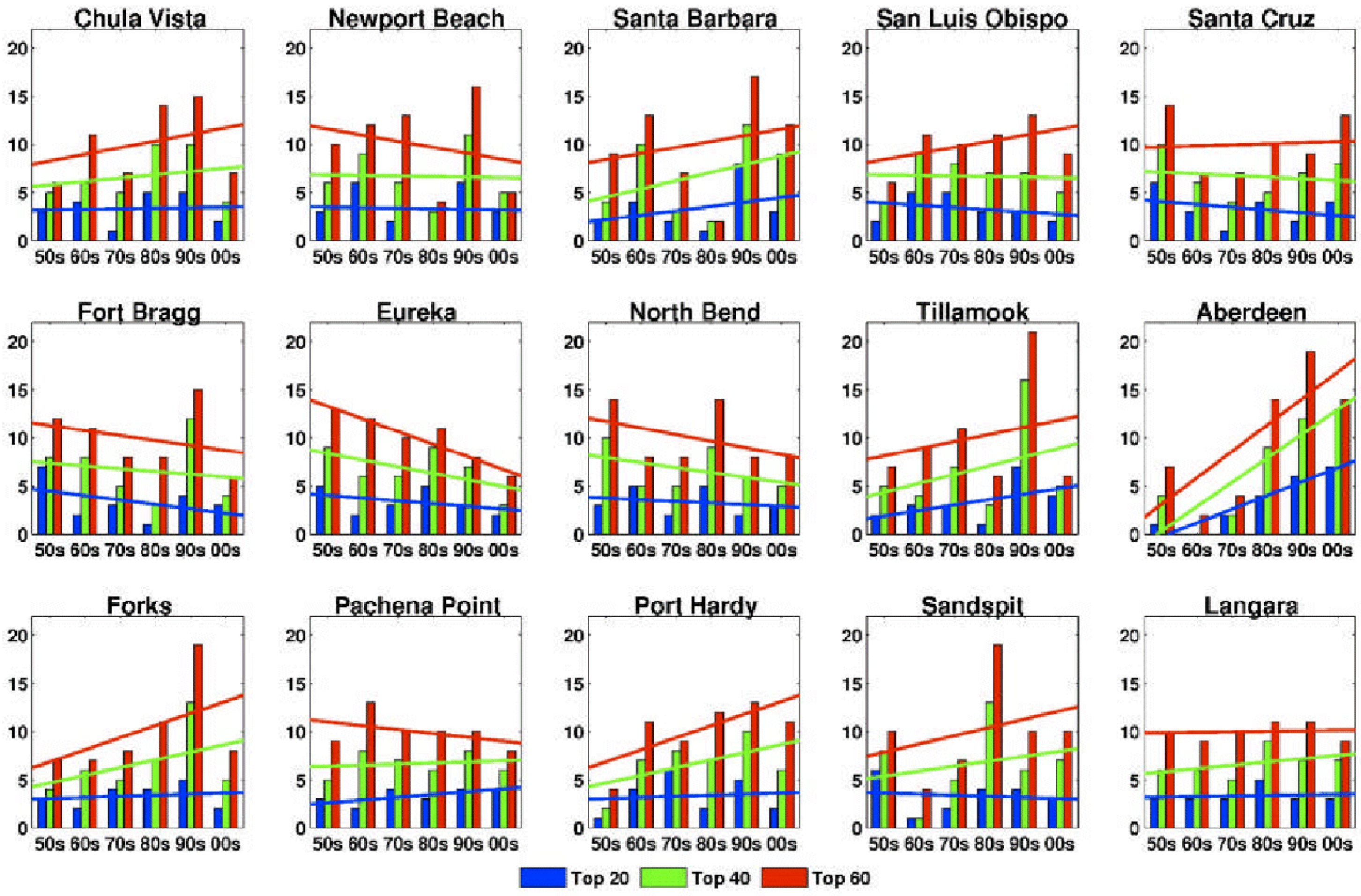


Figure 1. Location of stations with less than 10% missing daily precipitation data for 1895–2000. The symbol 'o' (in blue) indicates that long-term data were available prior to CDMP while the symbol 'x' (in red) indicates newly available long-term stations.

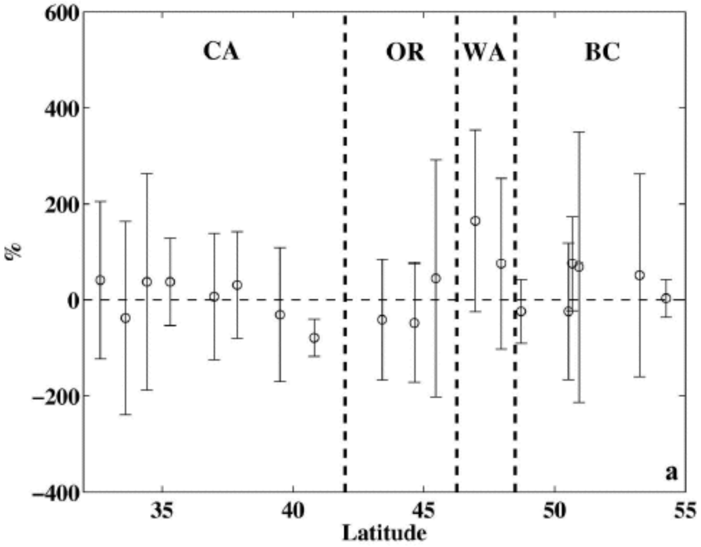
West Coast Precipitation. Annual Series of 2-Day Maximum.

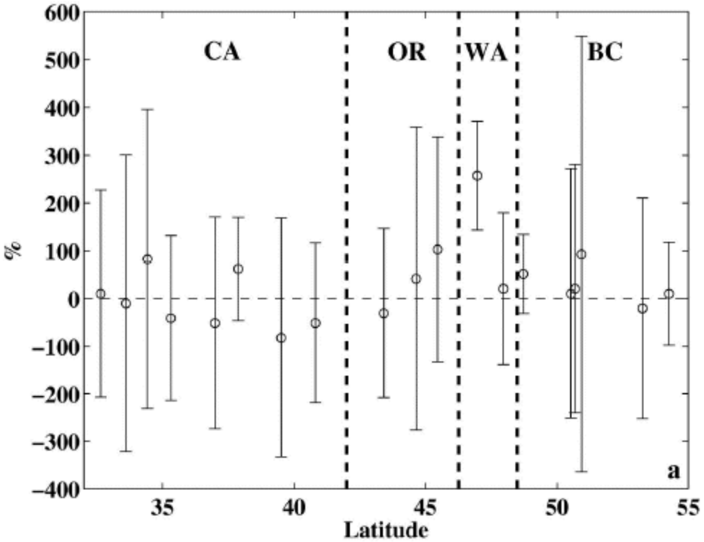
Number of events per decade.

Trends 1950-2009.



Cliff Mass, Adam Skalenakis, Michael Warner, 2011.
Extreme Precipitation over the West Coast of North America: Is There a Trend? J. Hydrometeorology. 10.1175/2010JHM1341.1



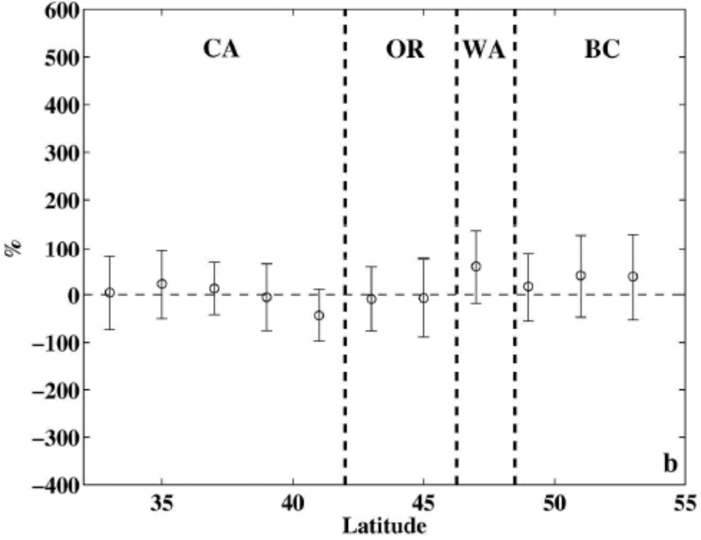


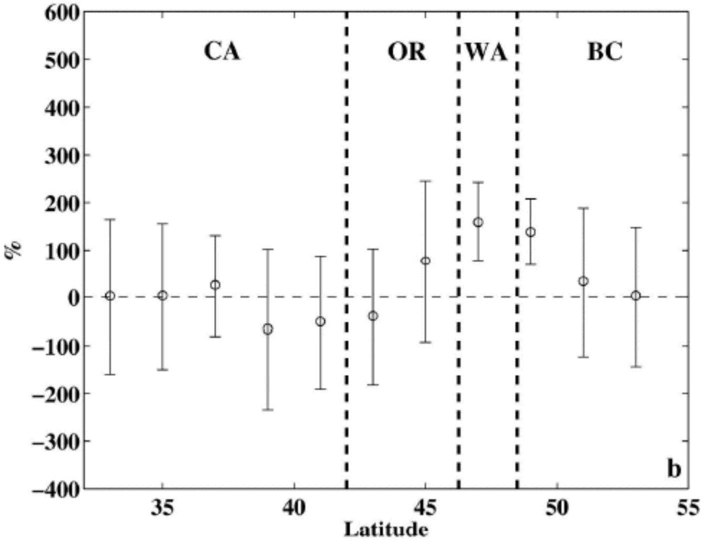
By Station

Top 60 (once per year)

Max 2-Day Precipitation Trends 1950-69

Top 20 (once per three years)





By Latitude

Figure 3: Sixty-year trends for the top 60 events for all stations (a) and for averages of the stations over 2° latitude bands (b). The trends are given in percent change relative to the mean over the 60-year period. The vertical dotted lines indicate the state boundaries and the brackets indicate the 95% interval derived from using formula (1).

Figure 4: Sixty-year trends for the top 20 events for all stations (a) and for averages of the stations over 2° latitude bands (b). The trends are given in percent change over the 60-yr period. The vertical dotted lines indicate the state boundaries and the brackets indicate the 95% interval derived from using formula (1).

Cliff Mass, Adam Skalenakis, Michael Warner, 2011. Extreme Precipitation over the West Coast of North America: Is There a Trend? J. Hydrometeorology. 10.1175/2010JHM1341.1

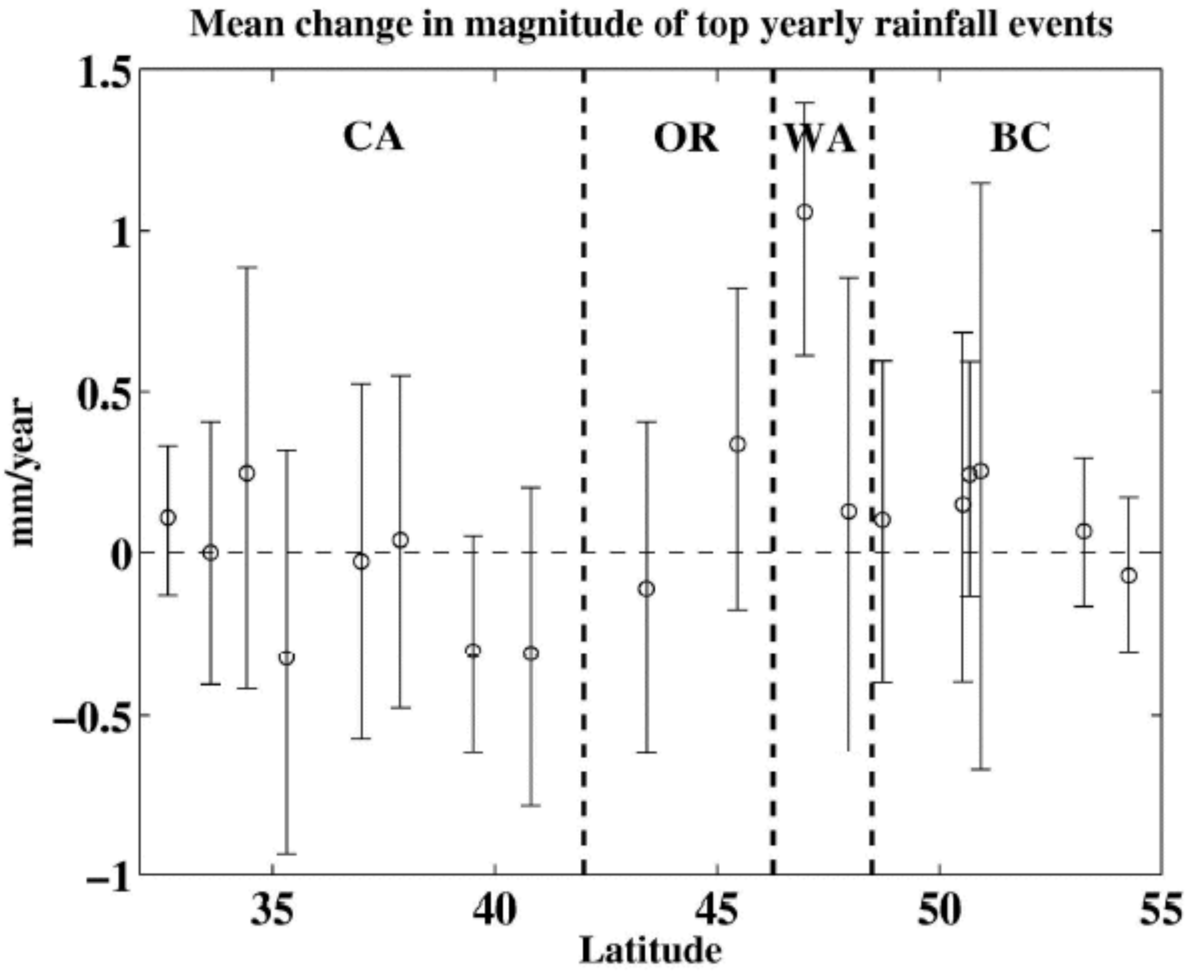


Figure 5: Sixty-year trends (mm per year) for the maximum annual two-day precipitation for coastal locations from southern California to British Columbia. The vertical dotted lines indicate the state boundaries and the brackets indicate the 95% confidence interval derived from using formula (1).

Trends 1950-2009
Annual Max 2-Day
Precipitation

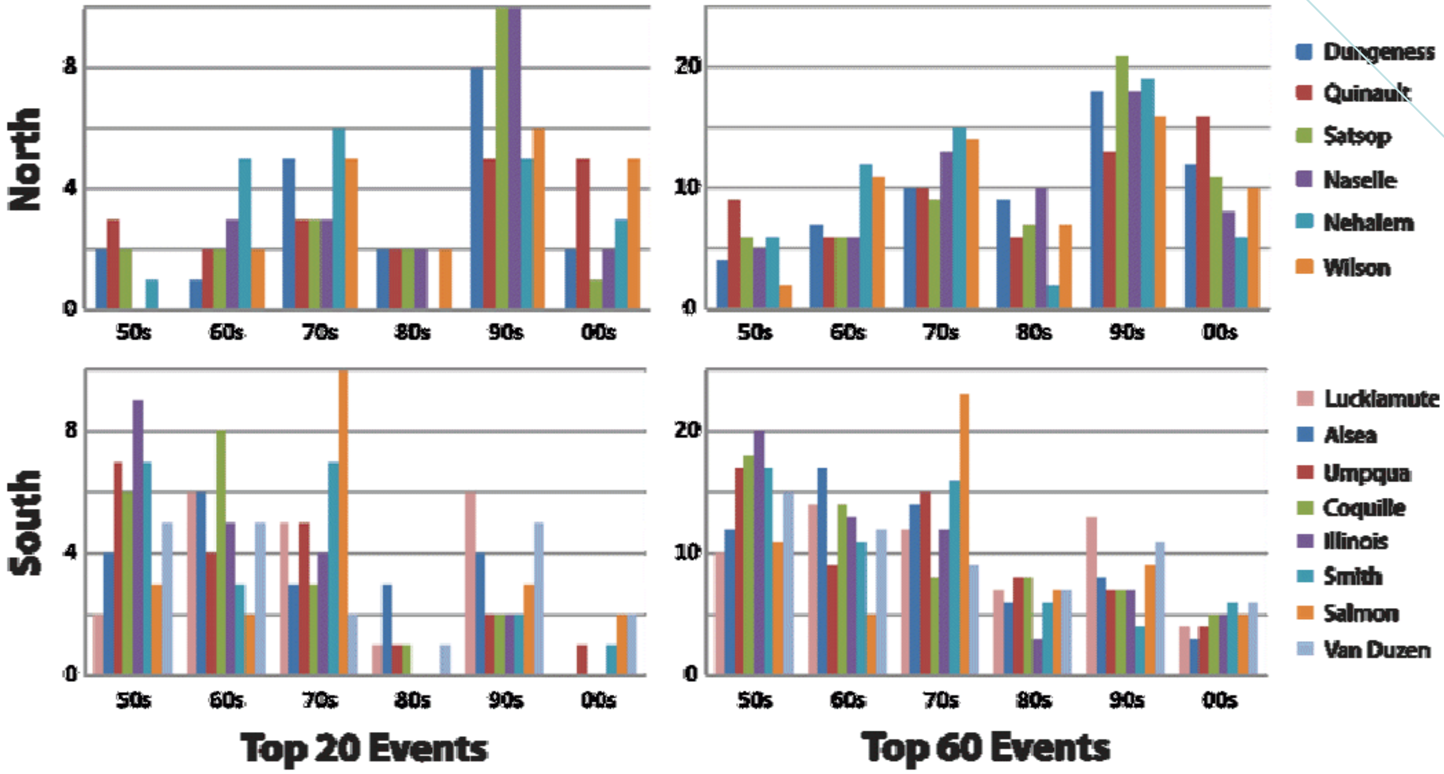
Units in mm/day
rather than
percentages

Cliff Mass, Adam Skalenakis, Michael Warner, 2011.
Extreme Precipitation over the West Coast of North America: Is There a Trend? J. Hydrometeorology. 10.1175/2010JHM1341.1

West Coast Streamflow. Annual Series of 1-Day Maximum Discharges.

Number of events per decade.

Trends 1950-2009.



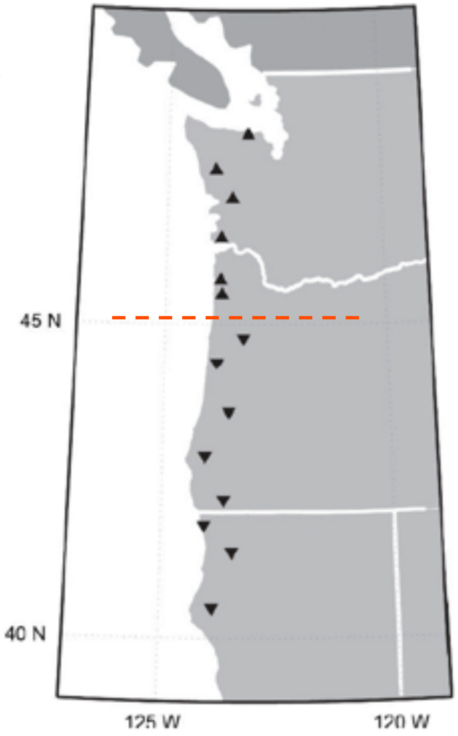


Figure 7: Decadal variation of the top 20 and 60 average daily discharges for 1950-2009 for unregulated rivers north and south of 45°N latitude.

Cliff Mass, Adam Skalenakis, Michael Warner, 2011.
Extreme Precipitation over the West Coast of North America: Is There a Trend? J. Hydrometeorology. 10.1175/2010JHM1341.1

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Vol. 332 no. 6028 pp. 451-455
DOI: 10.1126/science.1197219

REPORT

Global Trends in Wind Speed and Wave Height

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ABSTRACT

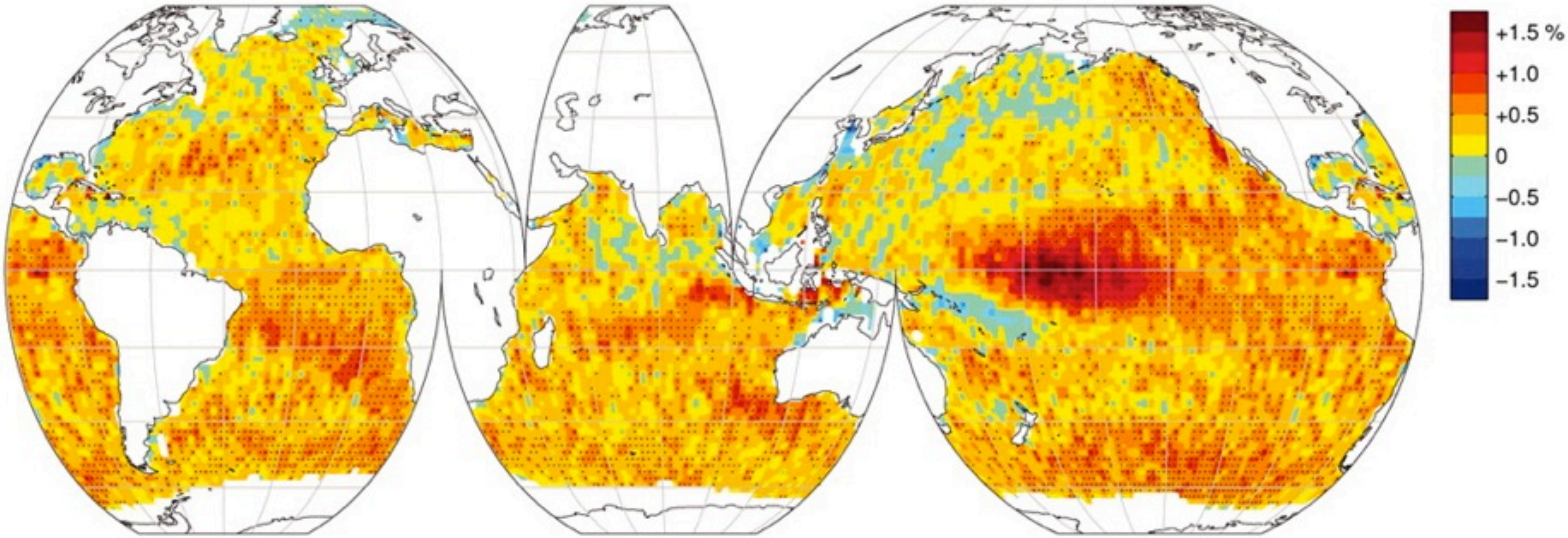
Studies of climate change typically consider measurements or predictions of temperature over extended periods of time. Climate, however, is much more than temperature. Over the oceans, changes in wind speed and the surface gravity waves generated by such winds play an important role. We used a 23-year database of calibrated and validated satellite altimeter measurements to investigate global changes in oceanic wind speed and wave height over this period. We find a general global trend of increasing values of wind speed and, to a lesser degree, wave height, over this period. The rate of increase is greater for extreme events as compared to the mean condition.

Young, Zieger, Babanin, 2011. Global Trends in Wind Speed and Wave Height. Science, 332 (6028), 451-455.

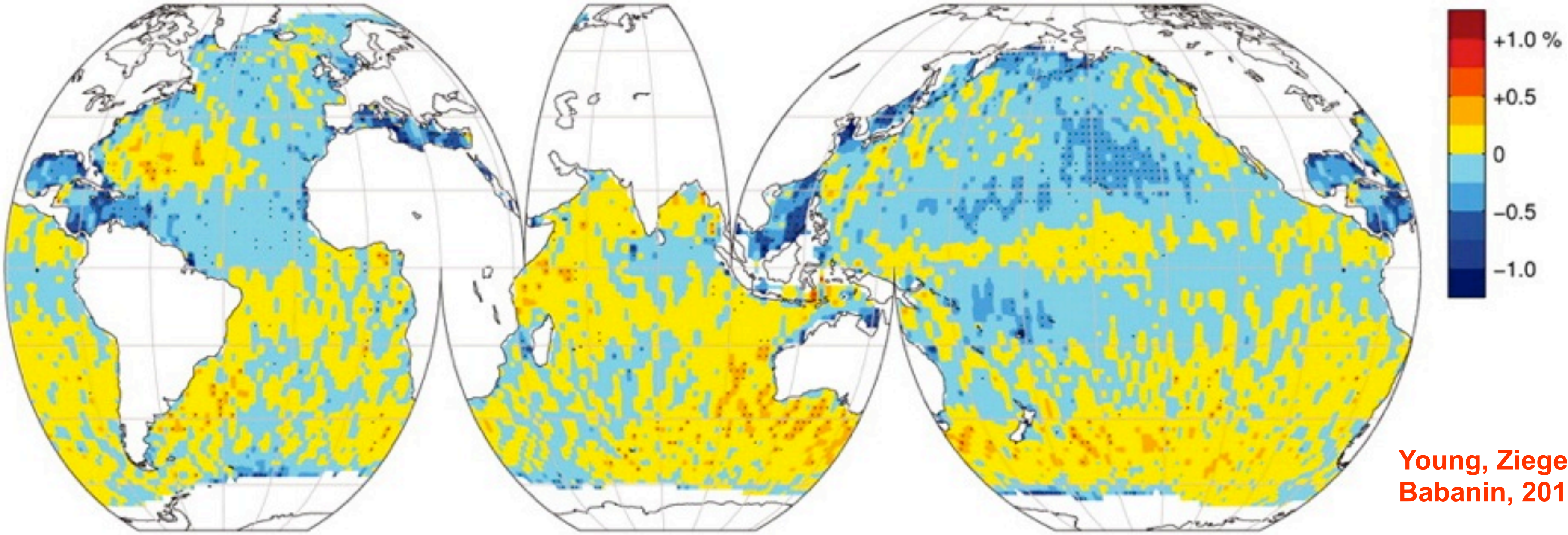
Mean Wind Speed Trends

1991-2008.

mean wind speed (1991–2008)



mean significant wave height (1985–2008)

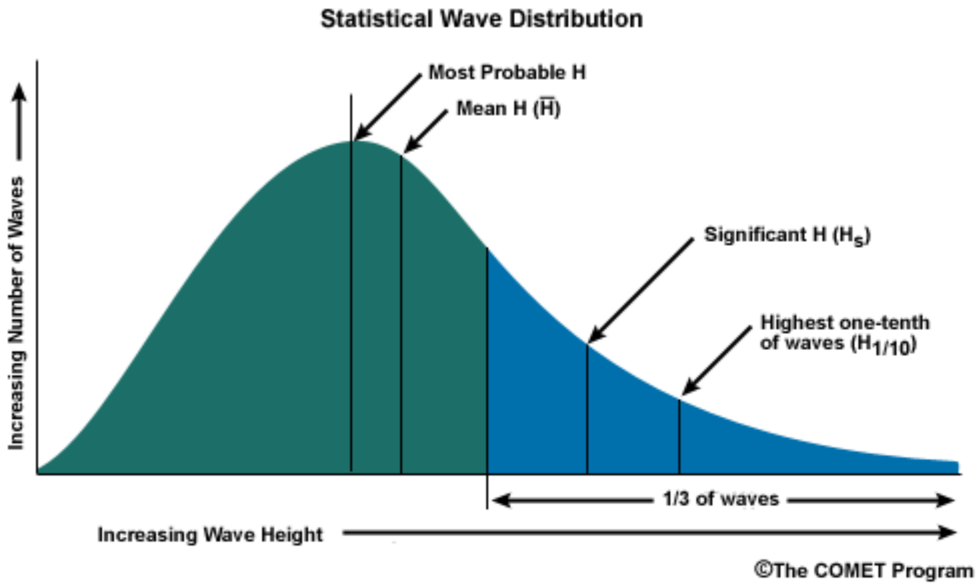


Young, Zieger, Babanin, 2011.

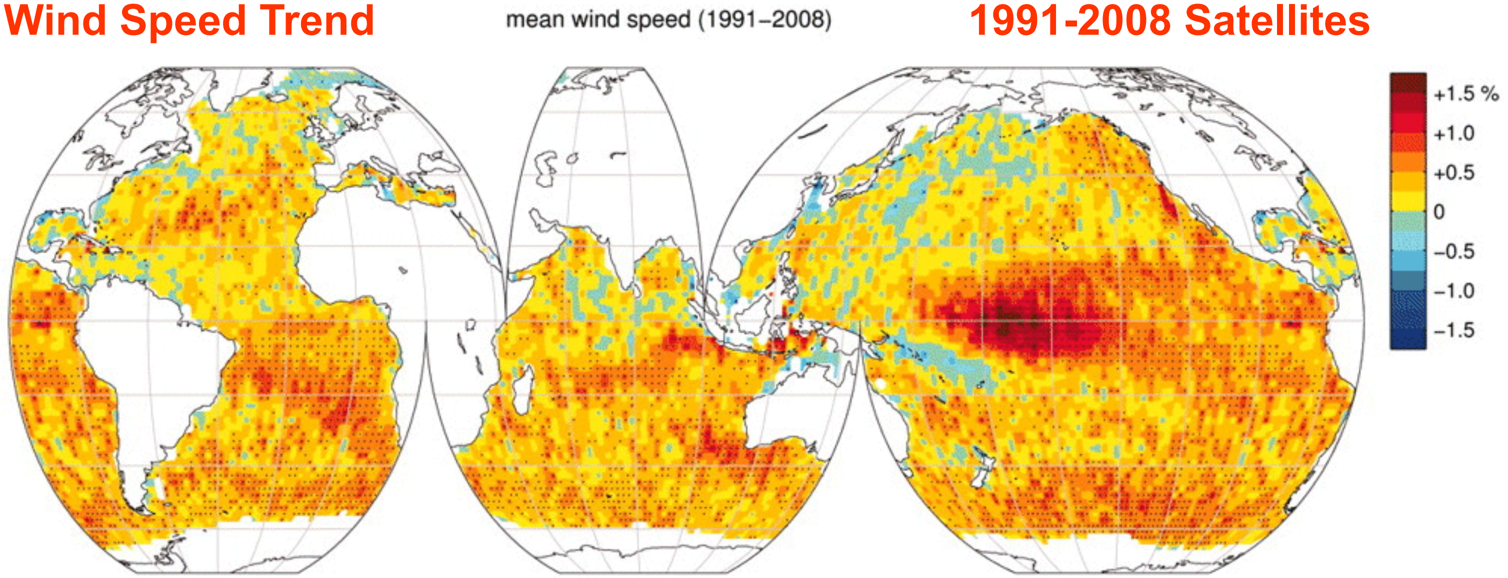
Satellite Winds and Waves

7 satellites since 1985, analysis thru 2008
GEOSAT difficulties with wind, so record starts 1991, thru 2008
Separate distributions each month, thus, seasonal cycle to remove
1 billion altimeter observations, 90,000 per 2x2 deg grid, 300 per month
Very well correlated with buoy data of wind and waves
RMS error of satellite-derived waves less than 0.2 meter
RMS error of satellite-derived winds less than 1.5 m/s for 10-m wind

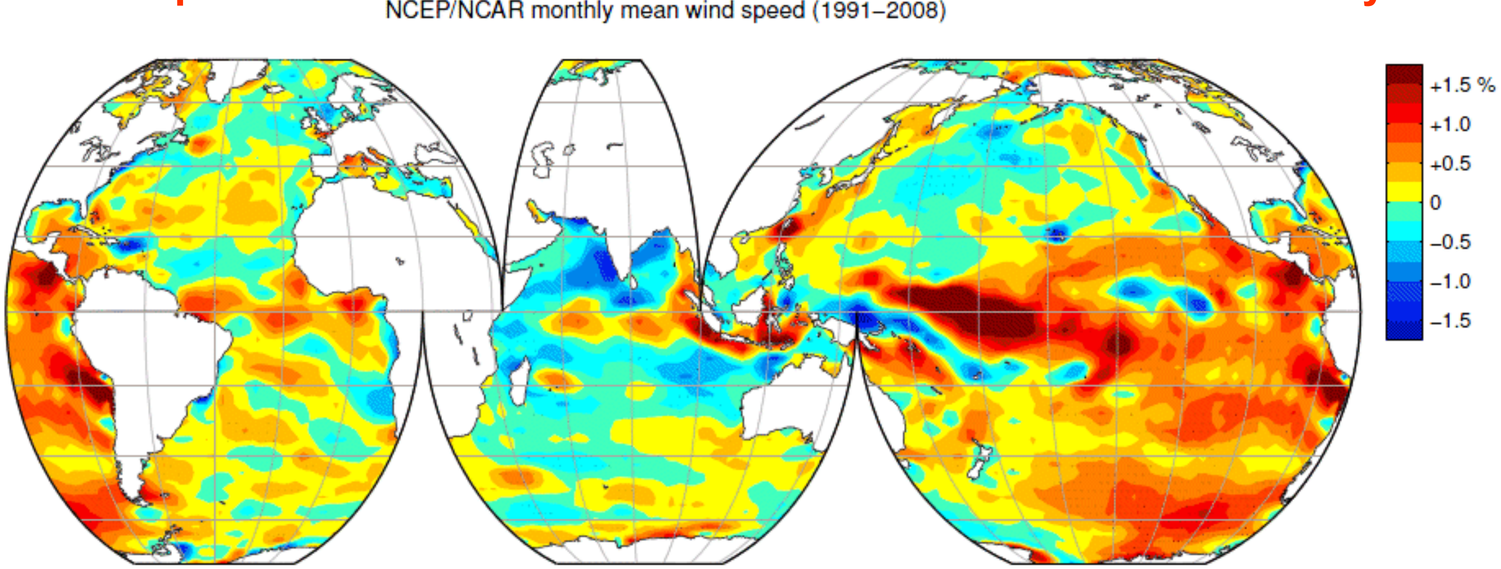
Rayleigh distribution, Hs=10 m: .1 > 10.7 m, .01>15.1 m, .001>18.6 m



Mean Wind Speed Trend **1991-2008 Satellites**



Mean Wind Speed Trend **1991-2008 Reanalysis**

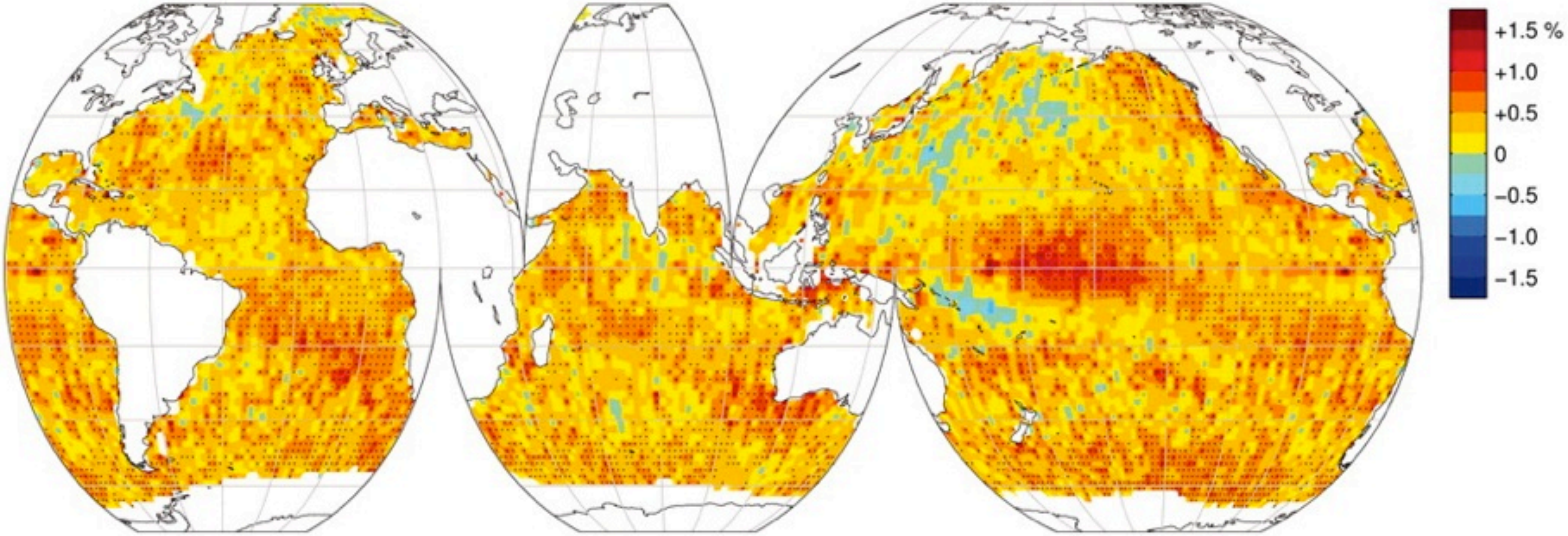


Young, Zieger, Babanin, 2011.

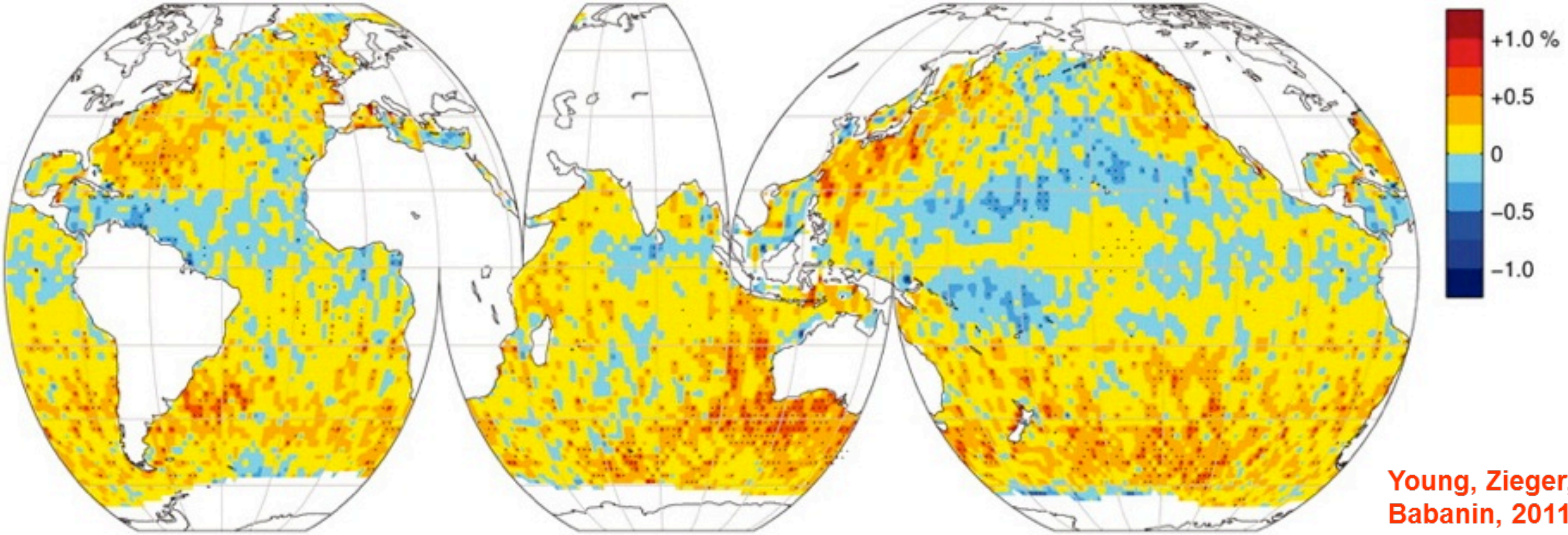
Figure S6: Colour contour plot of mean monthly wind speed trend (% per annum) from the NCEP/NCAR reanalysis data (*25*). Points which are statistically significant according to the SK test are shown with dots. This figure can be directly compared with Fig. 1.

90th Pctl Wind Speed Trend 1991-2008.

90th percentile wind speed (1991–2008)



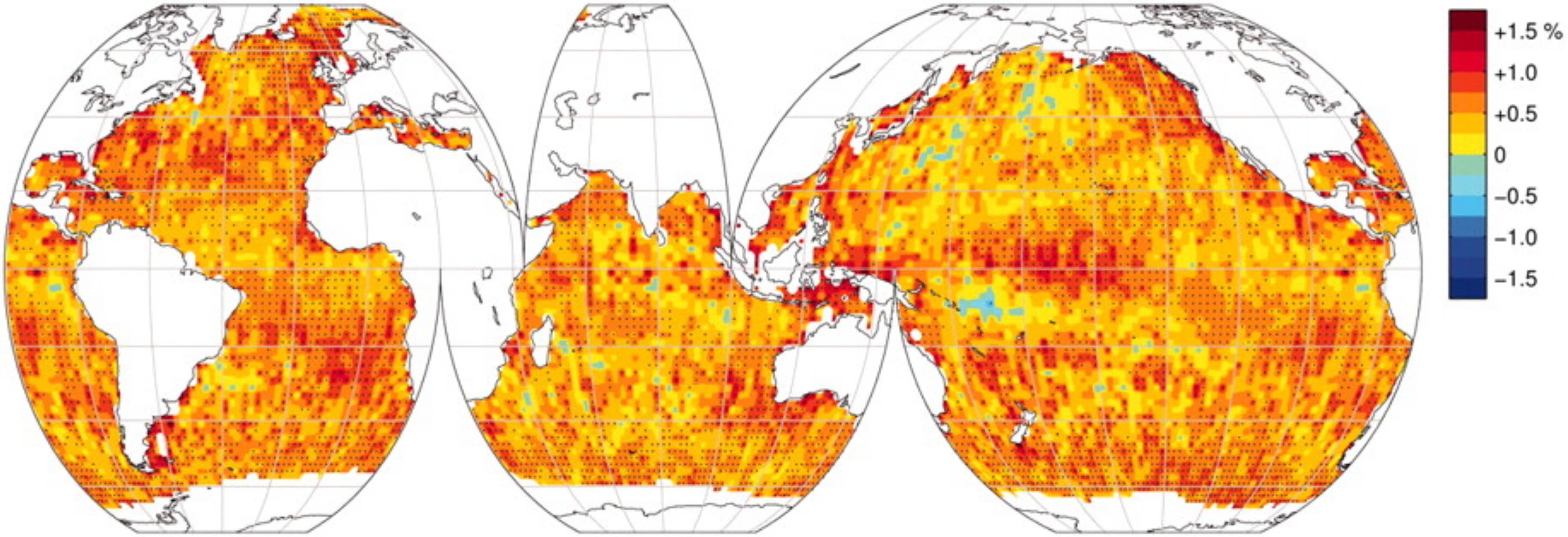
90th percentile significant wave height (1985–2008)



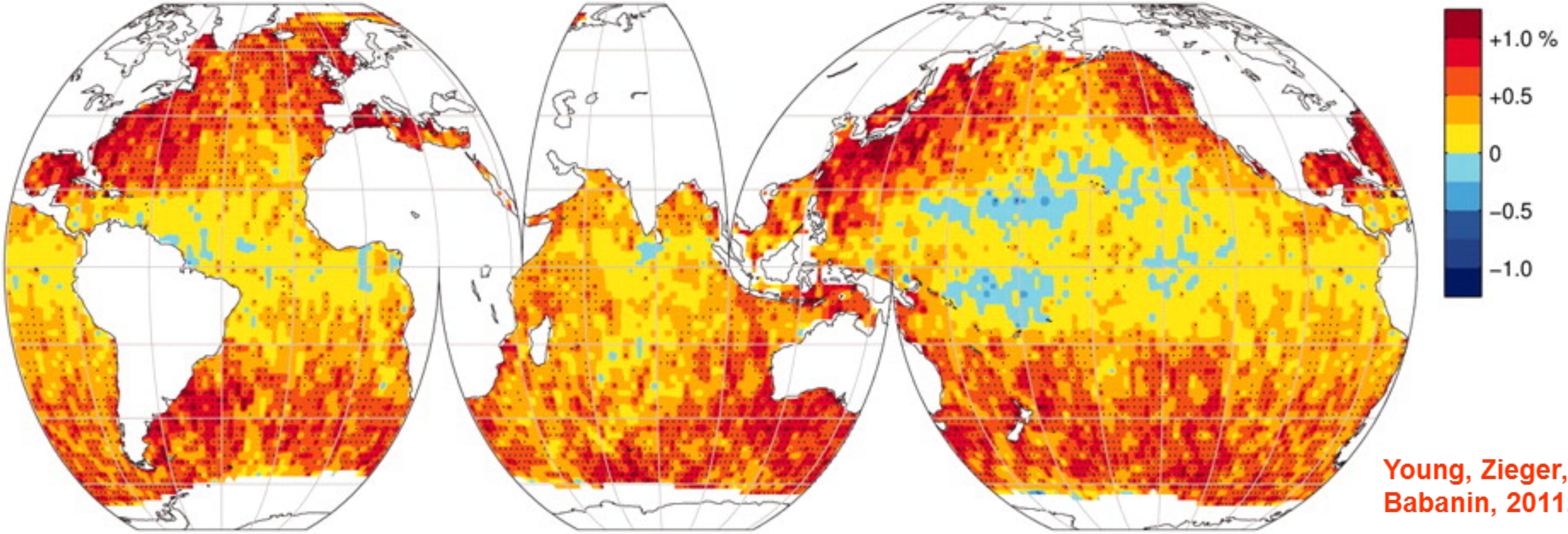
Young, Zieger, Babanin, 2011.

99th Pctl Wind Speed Trend 1991-2008.

99th percentile wind speed (1991-2008)



99th percentile significant wave height (1985-2008)



Young, Zieger, Babanin, 2011.

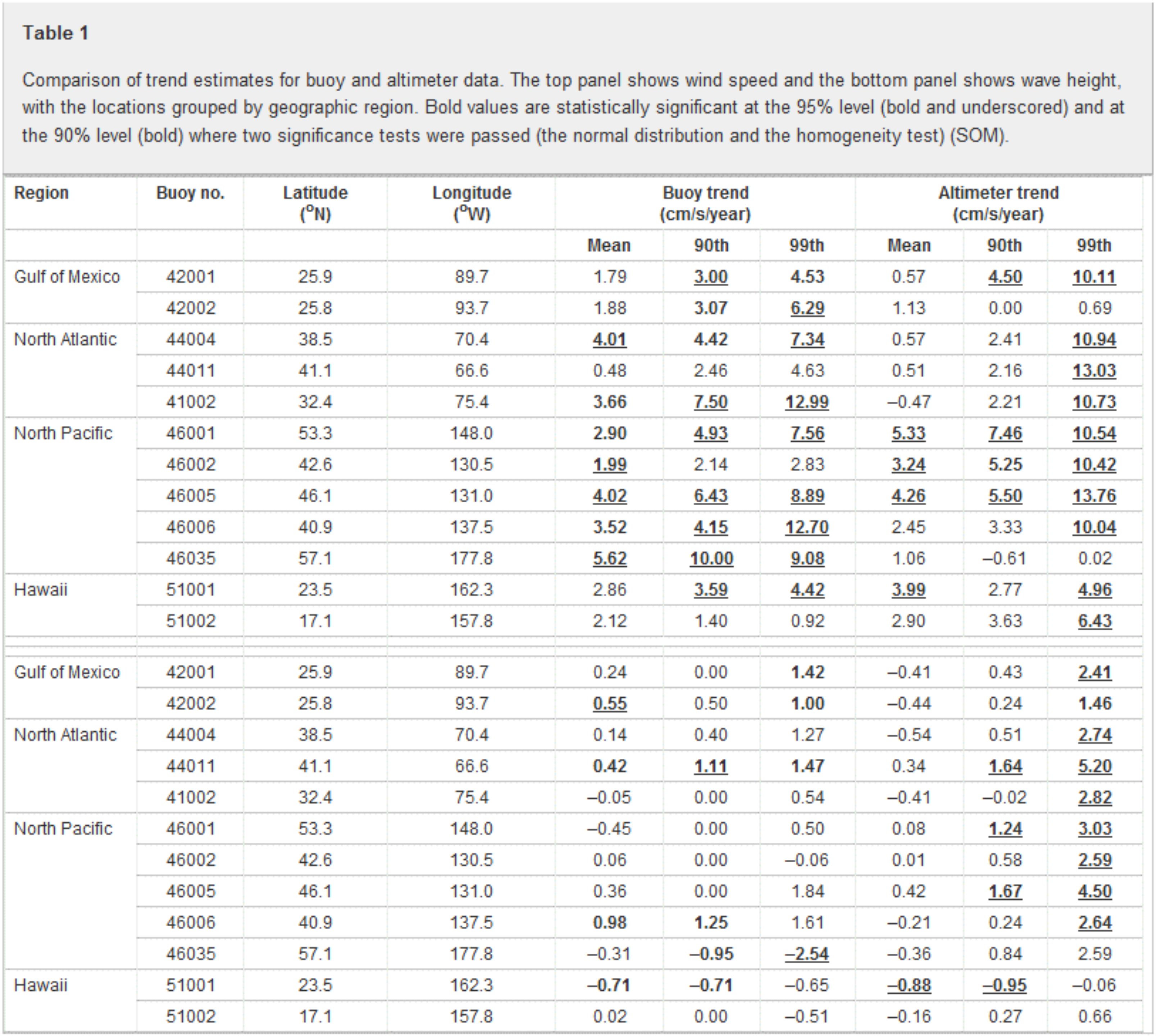


Table 1

Comparison of trend estimates for buoy and altimeter data. The top panel shows wind speed and the bottom panel shows wave height, with the locations grouped by geographic region. Bold values are statistically significant at the 95% level (bold and underscored) and at the 90% level (bold) where two significance tests were passed (the normal distribution and the homogeneity test) (SOM).

Region	Buoy no.	Latitude (°N)	Longitude (°W)	Buoy trend (cm/s/year)			Altimeter trend (cm/s/year)		
				Mean	90th	99th	Mean	90th	99th
Gulf of Mexico	42001	25.9	89.7	1.79	**3.00**	**4.53**	0.57	**4.50**	**10.11**
	42002	25.8	93.7	1.88	**3.07**	**6.29**	1.13	0.00	0.69
North Atlantic	44004	38.5	70.4	**4.01**	**4.42**	**7.34**	0.57	2.41	**10.94**
	44011	41.1	66.6	0.48	2.46	4.63	0.51	2.16	**13.03**
	41002	32.4	75.4	**3.66**	**7.50**	**12.99**	–0.47	2.21	**10.73**
North Pacific	46001	53.3	148.0	**2.90**	**4.93**	**7.56**	**5.33**	**7.46**	**10.54**
	46002	42.6	130.5	**1.99**	2.14	2.83	**3.24**	**5.25**	**10.42**
	46005	46.1	131.0	**4.02**	**6.43**	**8.89**	**4.26**	**5.50**	**13.76**
	46006	40.9	137.5	**3.52**	**4.15**	**12.70**	2.45	3.33	**10.04**
	46035	57.1	177.8	**5.62**	**10.00**	**9.08**	1.06	–0.61	0.02
Hawaii	51001	23.5	162.3	2.86	**3.59**	**4.42**	**3.99**	2.77	**4.96**
	51002	17.1	157.8	2.12	1.40	0.92	2.90	3.63	**6.43**
Gulf of Mexico	42001	25.9	89.7	0.24	0.00	**1.42**	–0.41	0.43	**2.41**
	42002	25.8	93.7	**0.55**	0.50	**1.00**	–0.44	0.24	**1.46**
North Atlantic	44004	38.5	70.4	0.14	0.40	1.27	–0.54	0.51	**2.74**
	44011	41.1	66.6	**0.42**	**1.11**	**1.47**	0.34	**1.64**	**5.20**
	41002	32.4	75.4	–0.05	0.00	0.54	–0.41	–0.02	**2.82**
North Pacific	46001	53.3	148.0	–0.45	0.00	0.50	0.08	**1.24**	**3.03**
	46002	42.6	130.5	0.06	0.00	–0.06	0.01	0.58	**2.59**
	46005	46.1	131.0	0.36	0.00	1.84	0.42	**1.67**	**4.50**
	46006	40.9	137.5	**0.98**	**1.25**	1.61	–0.21	0.24	**2.64**
	46035	57.1	177.8	–0.31	**–0.95**	**–2.54**	–0.36	0.84	2.59
Hawaii	51001	23.5	162.3	**–0.71**	**–0.71**	–0.65	**–0.88**	**–0.95**	–0.06
	51002	17.1	157.8	0.02	0.00	–0.51	–0.16	0.27	0.66

Young, Zieger, Babanin, 2011.

Soda Springs Store
March 27, 2011

Tom Knudson
Sacramento Bee

Serene Lakes
March 27, 2011

Tom Knudson
Sacramento Bee

Tuolumne Meadows RAWS Elev. 8680 ft. April, 2011

PRECIPITATION: Draw a straight line (—) through hours precipitation was observed, and a waved line (~) through hours precipitation probably occurred unobserved. A.M. NOON P.M.

WEATHER (CALENDAR DAY): Mark 'X' for all types occurring each day: Fog, Ice pellets, Glaze, Thunder, Hail, Damaging winds. Time of obs. if different from the above.

Date	TEMPERATURE °F 24 hrs. ending at observation Max.	Min.	At obsn.	PRECIPITATION 24-hr. amounts Rain, Melted snow, etc.	Snow, Ice pellets, Hail	At obsn. Snow, Ice pellets, Hail, Ice on ground	Important weather conditions not included in "Weather" block, remarks, etc.
1	65	23				85"	Deepest Ap snow in 5yrs.
2	47	26				83	
3	49	17				82	
4	59	12				80	
5	62	12				79	
6	47	19				77	
7	23	17		0.90"	11"	88	* On April 8th
8	26	-9				85	observers left for good
9	31	0				83	due to no telephone or
10	45	-1				79	electricity all winter.
11	46	15				77	Fuel for generator was
12	46	12				76	nearly gone.
13	25	13		0.20"	2"	78	Precip is estimated.
14	44	8				76	
15	52	21				73	
16	56	23				72	
17	56	23				69	
18	43	29				68	
19	51	24				66	
20	37	28		0.10"	1"	67	
21	42	25		0.10"	1"	65	
22	43	14		0.30"	4"	69	
23	39	26				67	
24	39	27				63	
25	41	20				62	
26	45	10				60	
27	57	21				57	
28	45	21				54	
29	41	17				53	
30	42	18				52	
31	—	—			—	—	
Av.	44.3	17.4	30.9	Sum 1.60"	19"	☒	
Extremes	65°	-9°		Greatest 0.90"	11"	88"	

Observer

Post office California

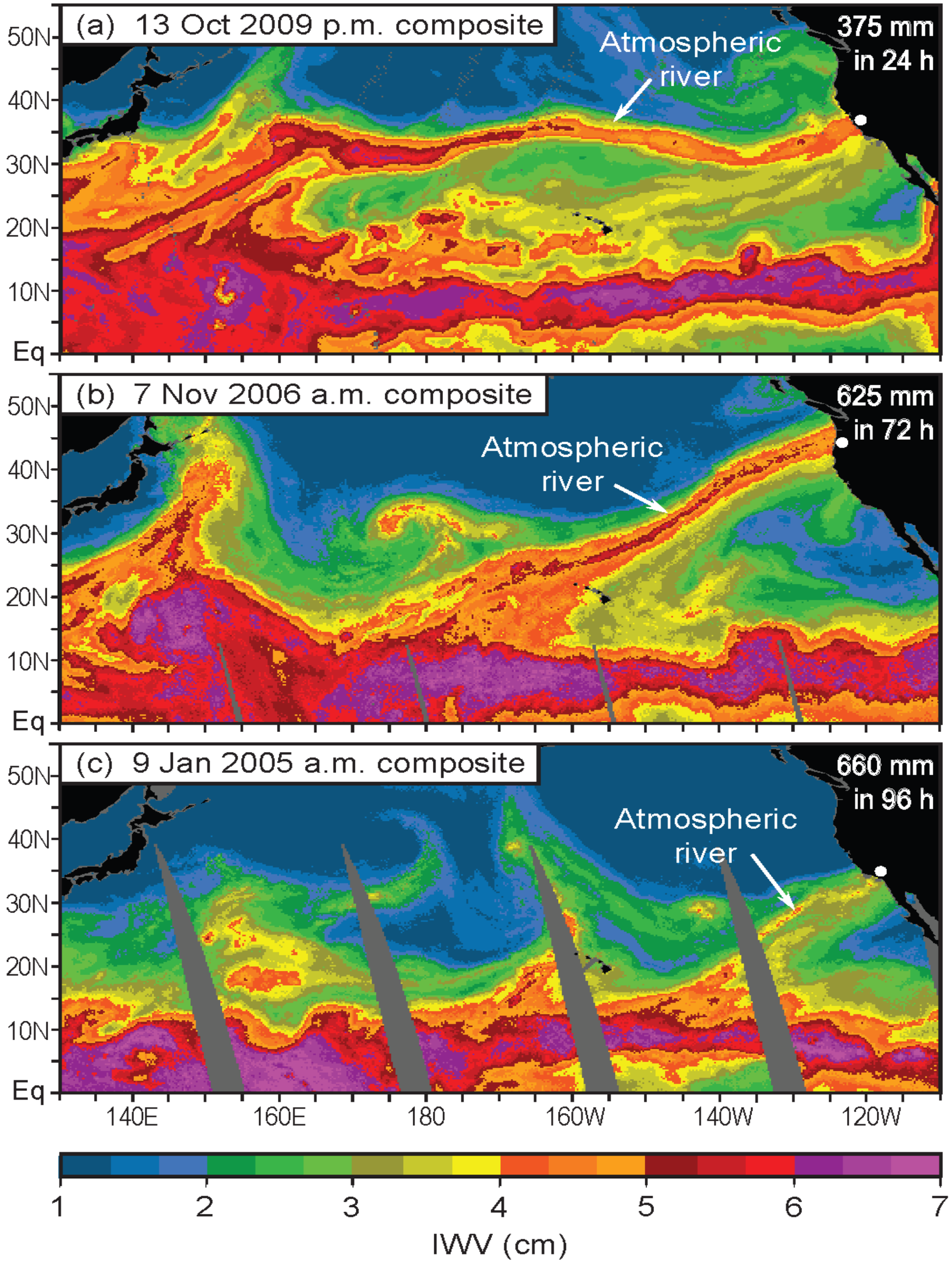
Departures:
Precip -0.38"
Snowfall -6.4"
Temp -2.0°

South

Central Sierra Snow Lab

East

Photo: Dave Simeral



A Key HMT Finding:

- atmospheric rivers are a key to extreme precipitation and flooding, as well as water supply and stream flow on the U.S. West Coast

Examples of AR events that produced extreme precipitation on the US West Coast, and exhibited spatial continuity with the tropical water vapor reservoir as seen in SSM/I satellite observations of IWV.

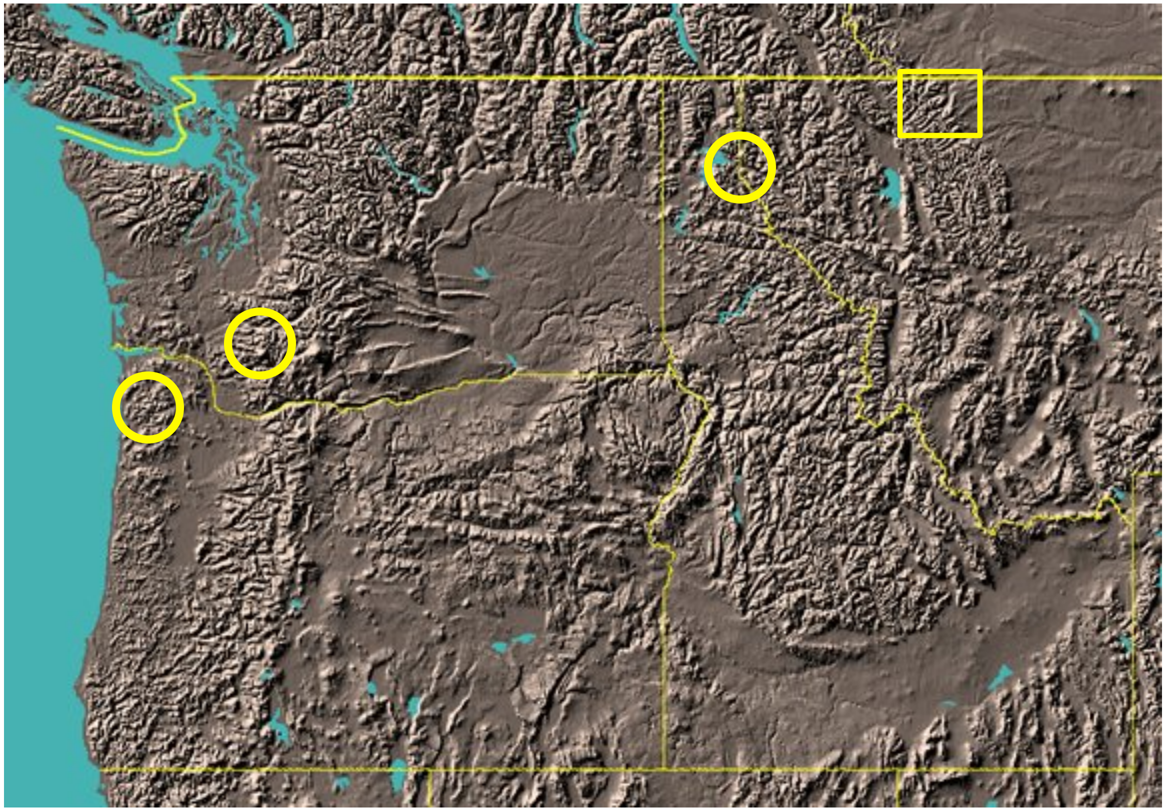
Thanks to Marty Ralph

November 6-7, 2006. One storm, three state daily precipitation records !!!

Never in U.S. history have two state records been set on the same day.

Preliminary State-Record Maximum 24-Hour Precipitation

New Record:	June Lake, Washington, elevation 3,340 feet	15.20 inches on November 6-7, 2006
Former Record:	Mt. Mitchell, Washington, elevation 3,600 feet	14.26 inches on November 23-24, 1986
New Record:	Lee's Camp, Oregon, elevation 660 feet	14.30 inches on November 6-7, 2006
Former Record:	Port Orford, Oregon, elevation 150 feet	11.65 inches on November 19, 1996
New Record:	Bear Mountain, Idaho, elevation 5,400 feet	9.40 inches on November 6-7, 2006
Former Record:	Rattlesnake Creek, Idaho, elevation 4,000 feet	7.17 inches on November 23, 1909



Old records broken by

23 % - Oregon

06 % - Washington

31 % - Idaho

Square:

Many Glacier Lodge

Many Glacier, Nov 2006. NPS.

Another view

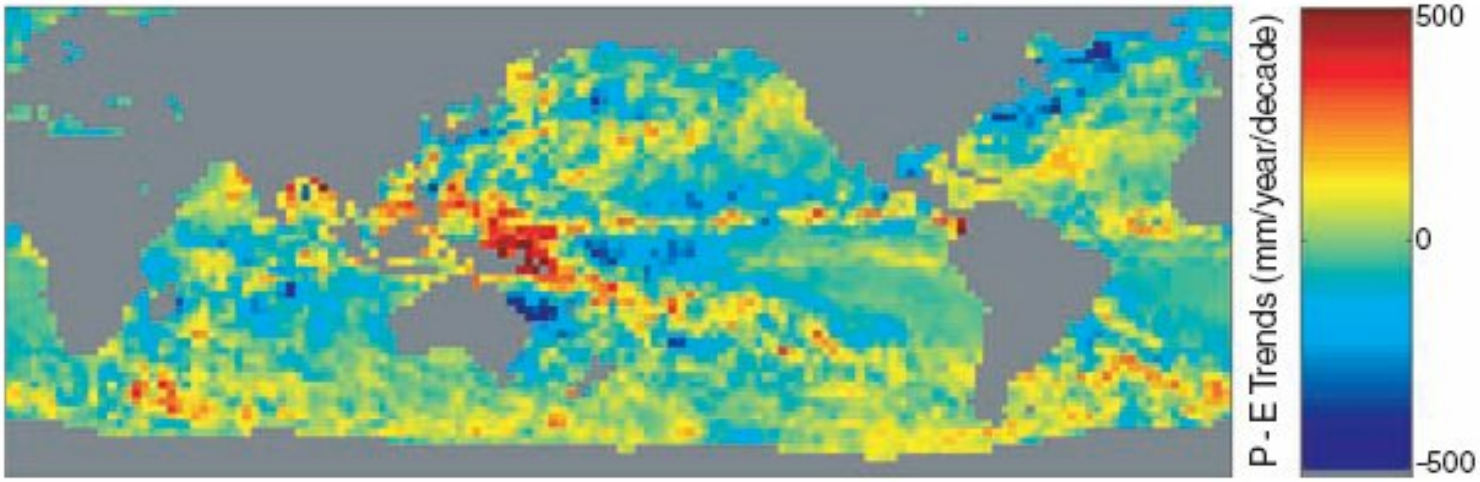


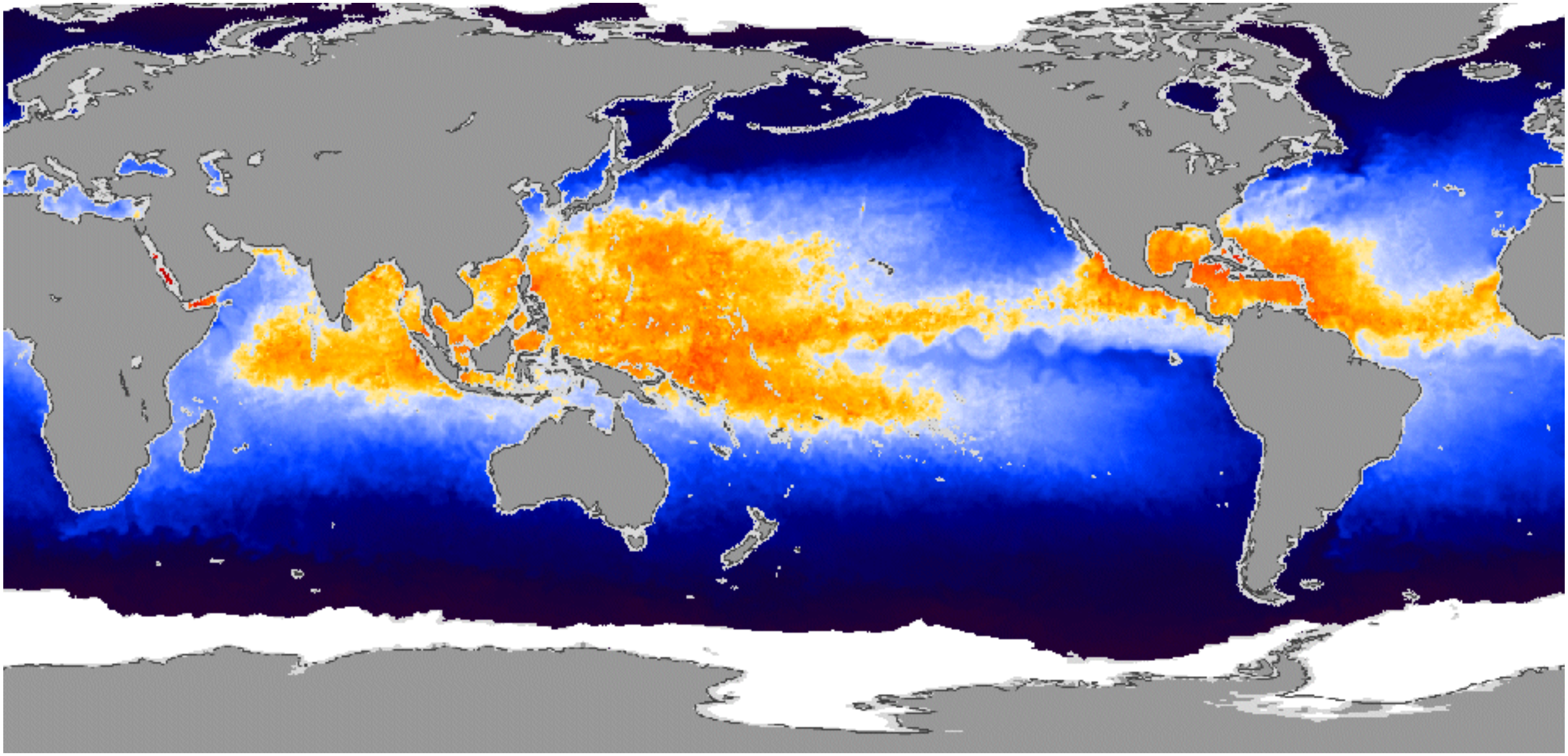
Fig. 3. Trends in satellite-derived *P* − *E* for the period July 1987 through August 2006. The largest change was over the warm pool in the western Pacific: a wet area that became wetter.

Table 1. Statistics on the variation of global evaporation, global precipitation, and over-ocean water vapor for the period July 1987 through August 2006. The error bars on the trends are given at the 95% confidence level. The values in parentheses are in terms of percentage change, rather than absolute change.

Parameter	Mean	Standard deviation	Trend
Evaporation	961 mm year^{-1}	10.1 mm year^{-1} (1.1%)	12.6 ± 4.8 mm year^{-1} decade^{-1} (1.3 ± 0.5% decade^{-1})
Precipitation	950 mm year^{-1}	12.7 mm year^{-1} (1.3%)	13.2 ± 4.8 mm year^{-1} decade^{-1} (1.4 ± 0.5% decade^{-1})
Total water	28.5 mm	0.292 mm (1.0%)	0.354 ± 0.114 mm decade^{-1} (1.2 ± 0.4% decade^{-1})

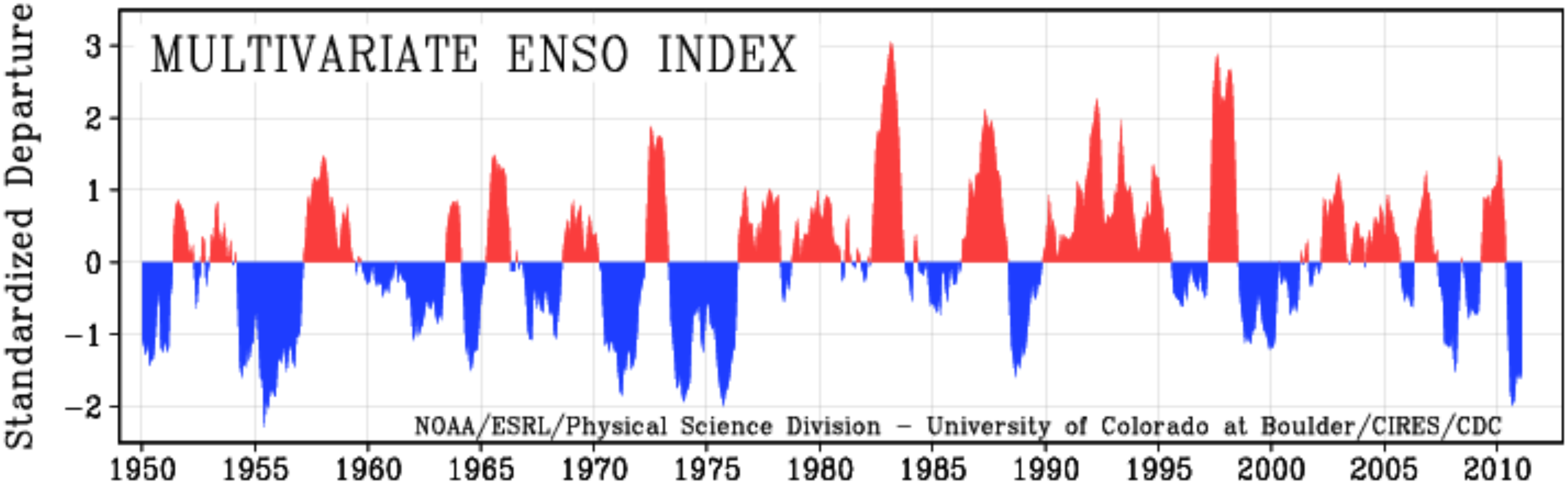
Frank J. Wentz, Lucrezia Ricciardulli, Kyle Hilburn, Carl Mears, 2007. How much more rain will global warming bring? Science, 317, 233-235.

The World's Warm Oceans



Thru February 2011

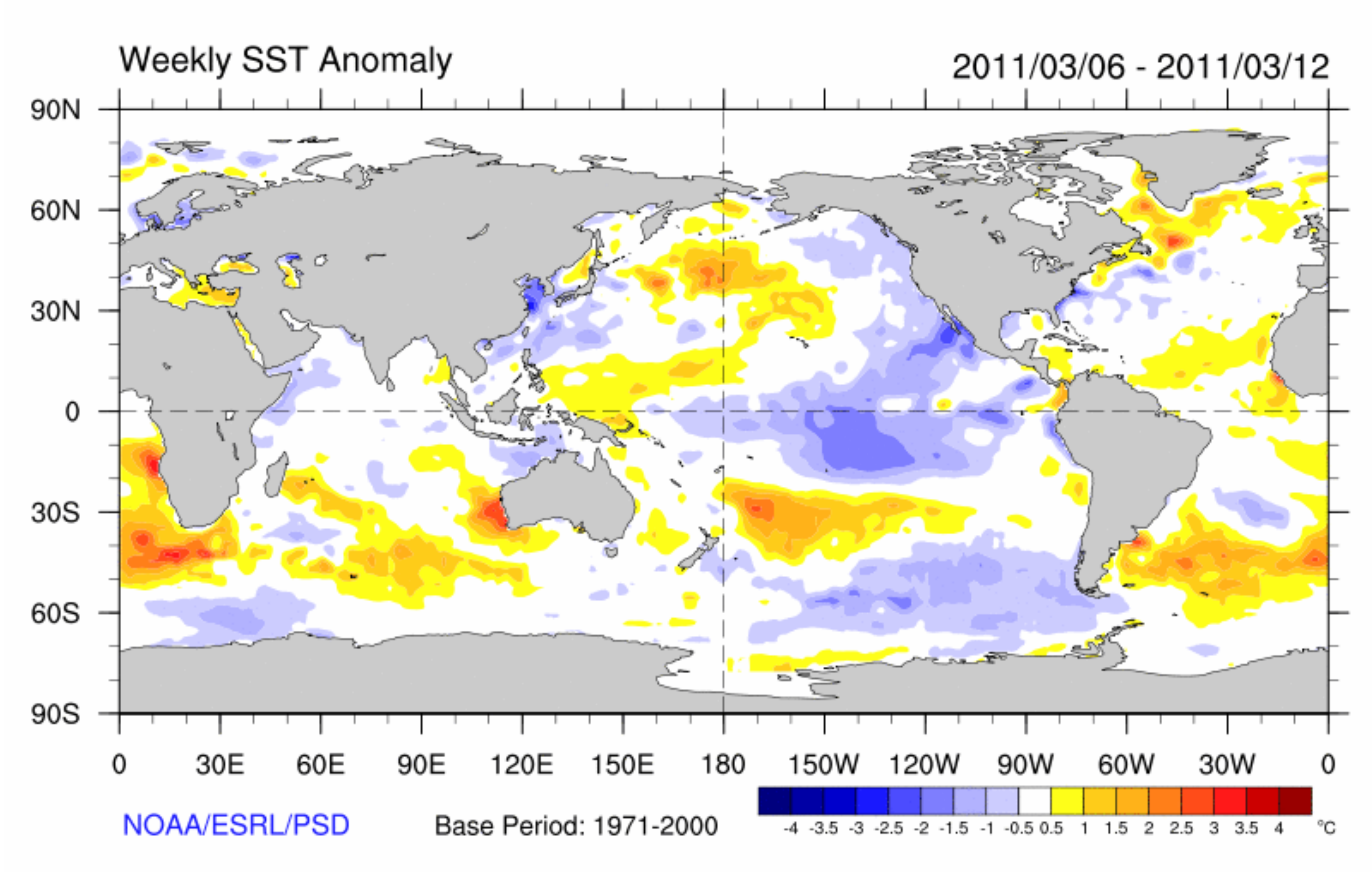
Typically “El Nino”



Typically “La Nina”

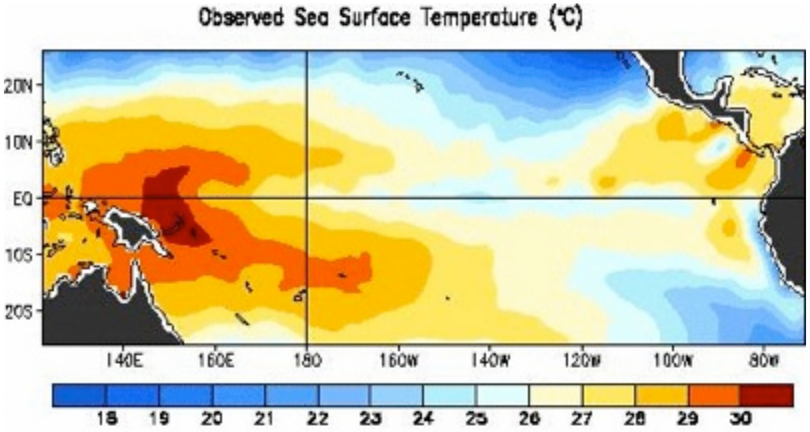
Courtesy Klaus Wolter & Mike Timlin,
NOAA Climate Diagnostics Center

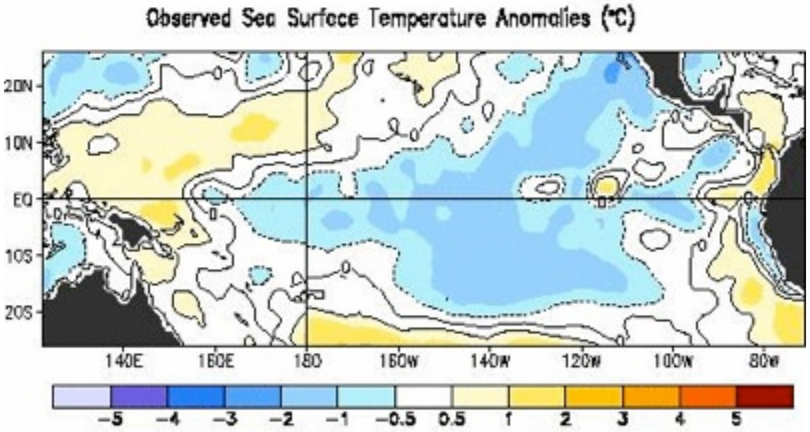
Global Sea Surface Temperature Departure from Average, 2011 March 6-12



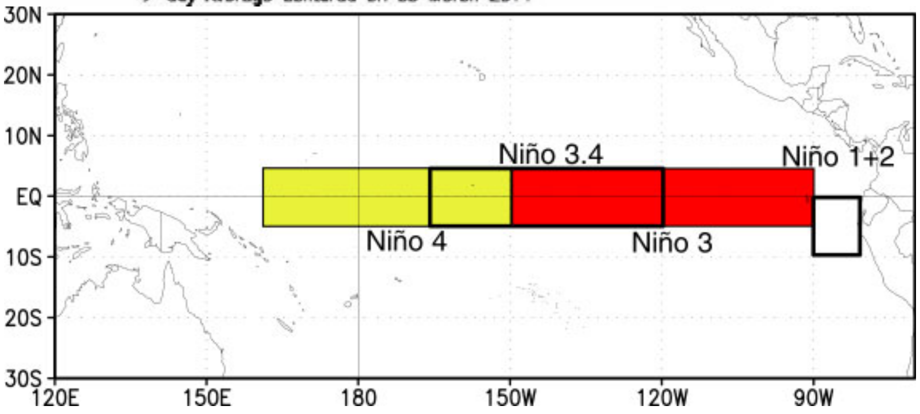
NOAA Physical Science Division, ESRL

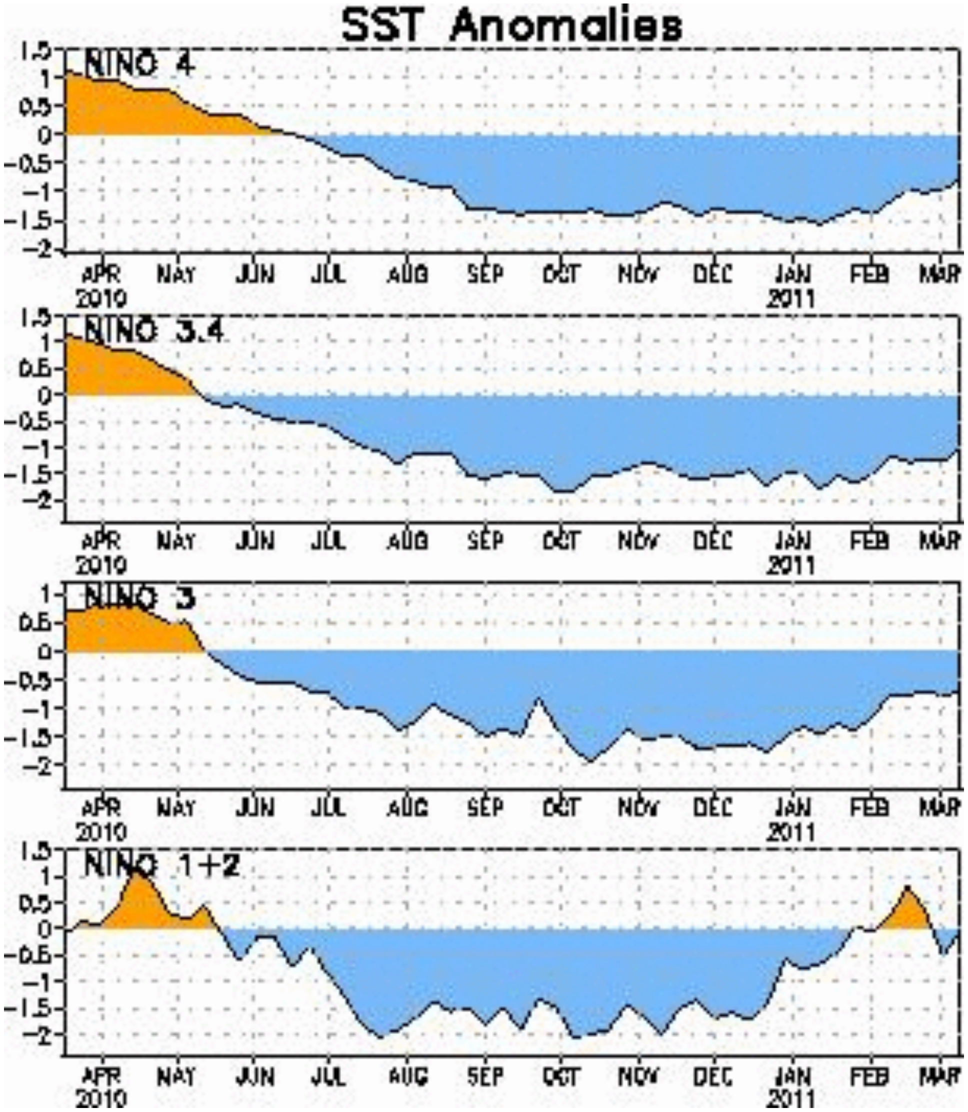
Recent Evolution of Equatorial Pacific SST Departures





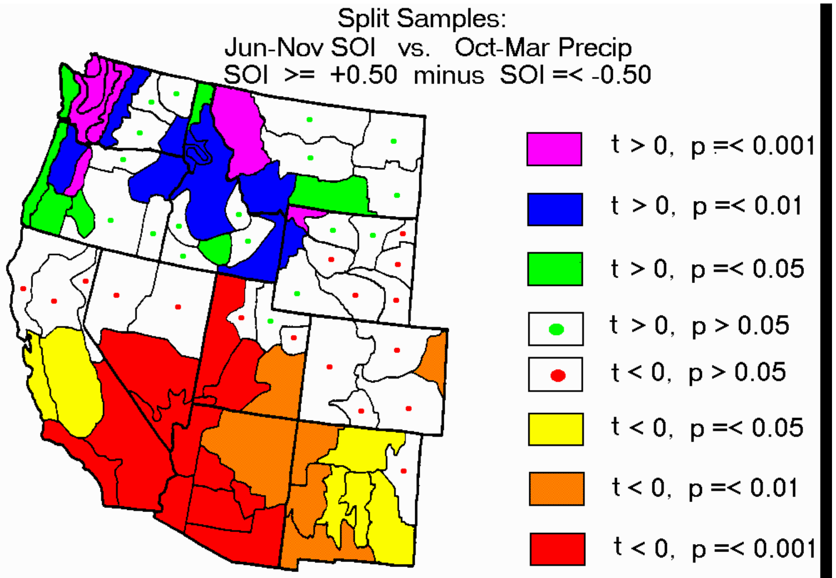
7–day Average Centered on 09 March 2011





Updated through 2011 March 6-12

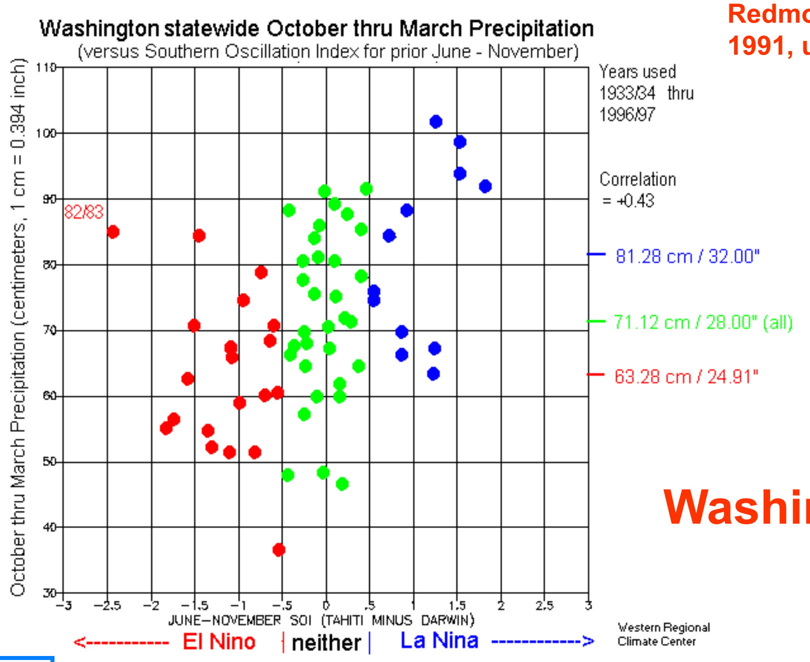
ENSO



Updated from Redmond and Koch (1991). Winters of 1933/34 - 1994/95.
Reddish: Composite El Nino winters are wet, La Nina winters are dry.
Bluish/greenish: Composite El Nino winters are dry, La Nina winters are wet.

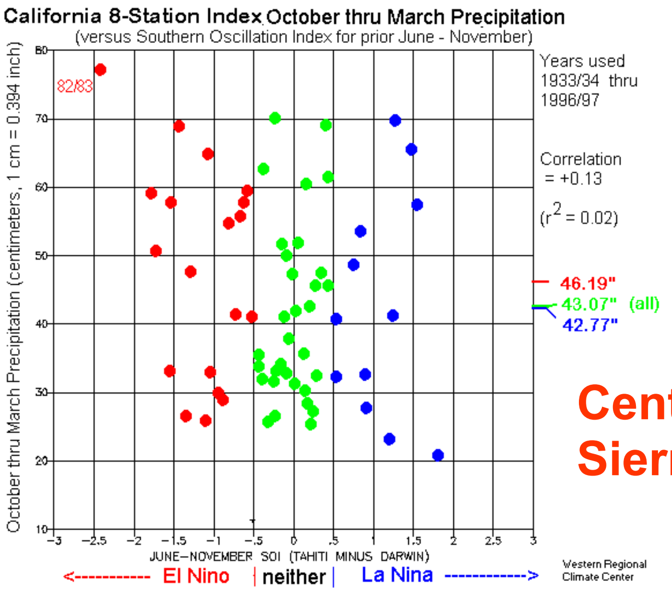
Redmond, K.T., and R.W. Koch, 1991. Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. Water Resources Research, 27(9), 2381-2399.

Redmond & Koch, 1991, updated.

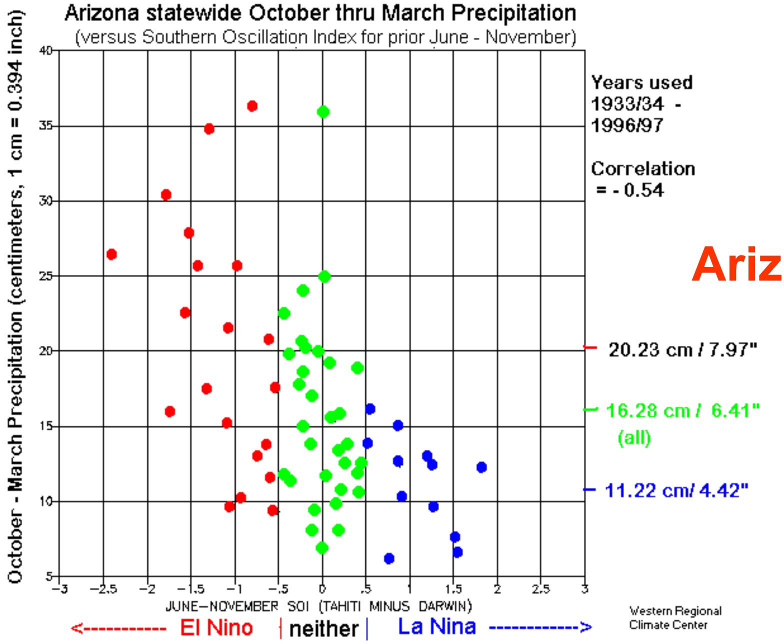


Redmond & Koch, 1991, updated.

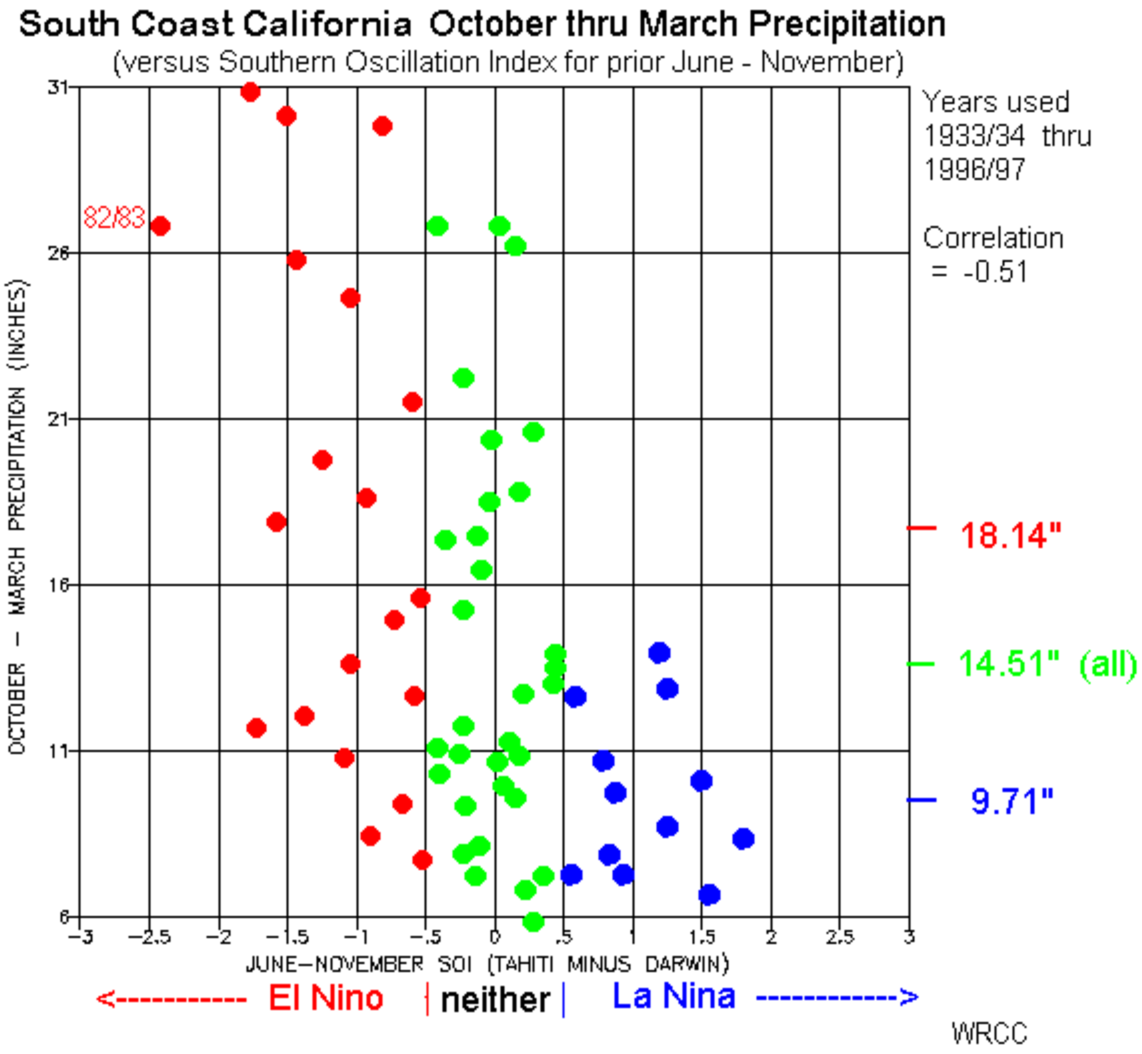
Washington



Central Sierra



Arizona



p.s.

South Coast California

Has never (=64 years)
had a wet La Nina winter

Temporal Variability of Orographic Effect on Precipitation

Sacramento (10’)

Versus

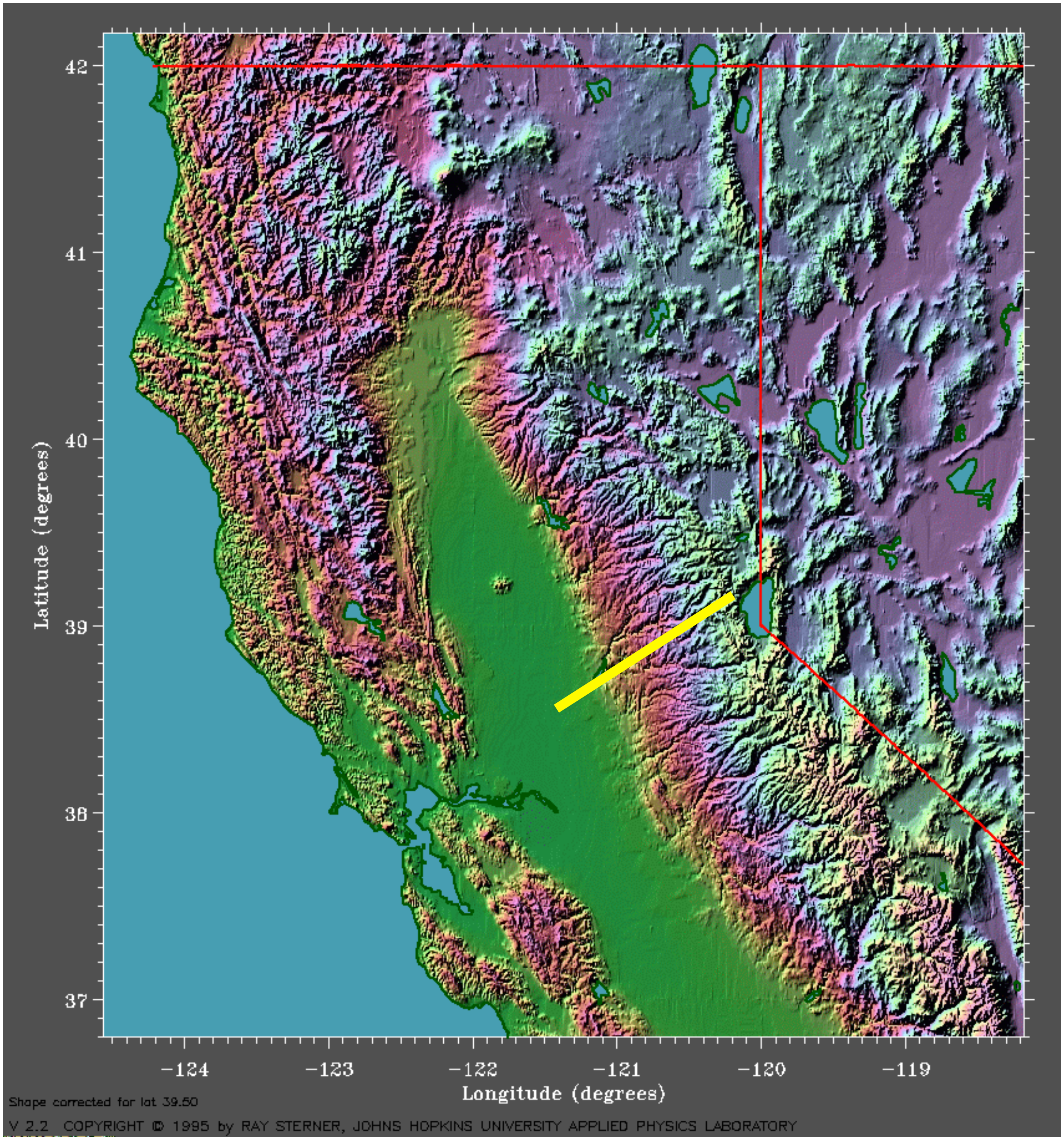
Tahoe City (6230’)

July thru June

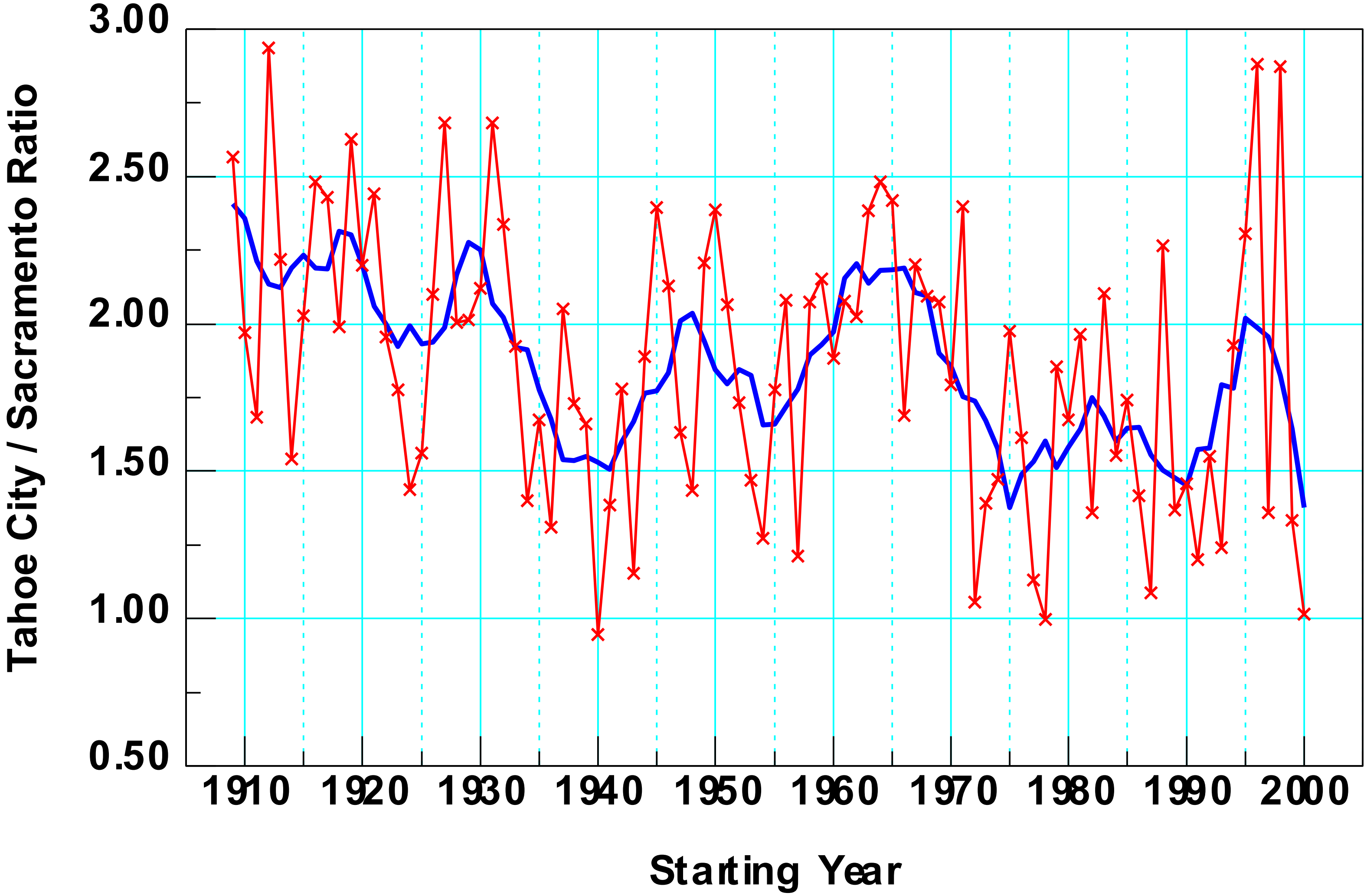
Oct-March Percent of Annual:

83% at Tahoe

88% at Sacramento

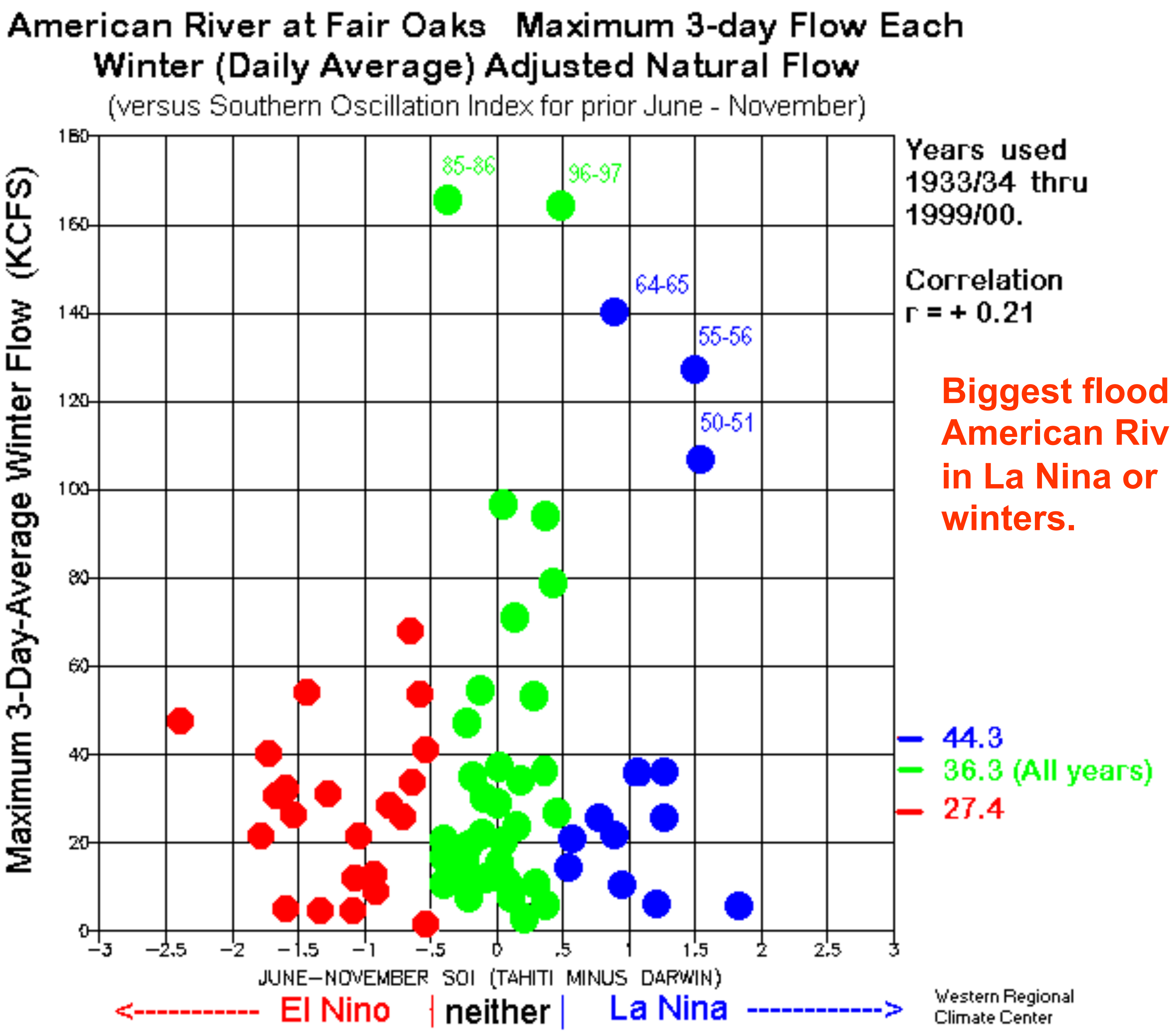


Ratio of June thru July Precipitation
Tahoe City / Sacramento. 1909-10 thru 2000-01.
Blue: 7-year running mean.



(Average Ratio is 1.76)

200102 :
~1.7 thru Feb



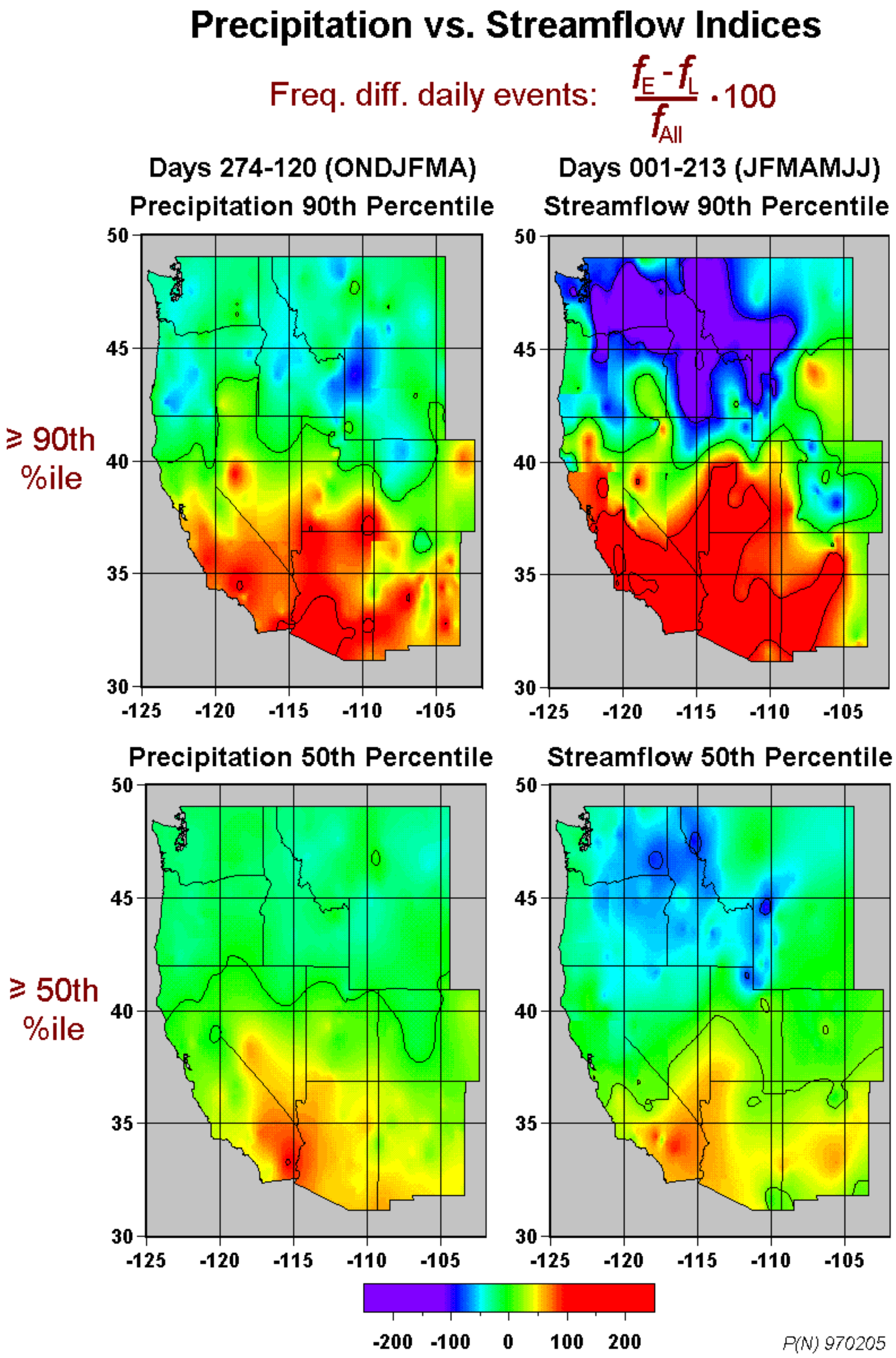
American River at Fair Oaks Maximum 3-day Flow Each Winter (Daily Average) Adjusted Natural Flow

(versus Southern Oscillation Index for prior June - November)

Biggest floods on American River are in La Nina or No Nino winters.

Cayan, Redmond, Riddle, 1999. Journal of Climate.

Top 10 % Winter Precipitation Events



Top 10 % Winter-Spring Streamflow Events

Predominance:

Red – El Nino

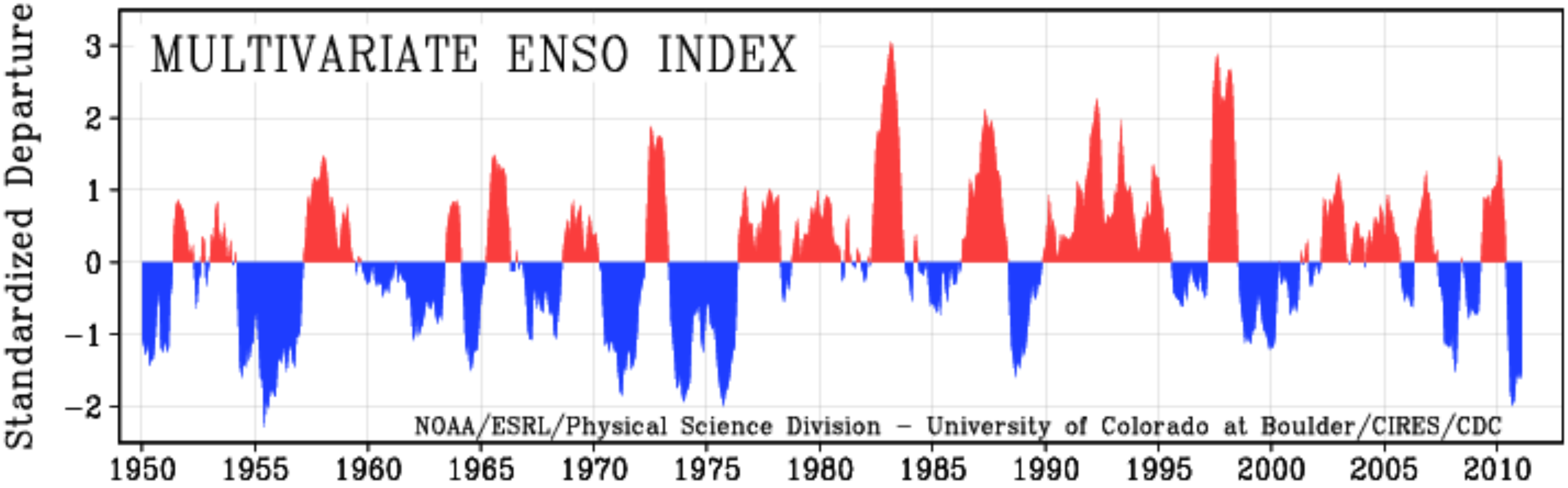
Blue – La Nina

Top 50 % Winter Precipitation Events

Top 50 % Winter-Spring Streamflow Events

Thru February 2011

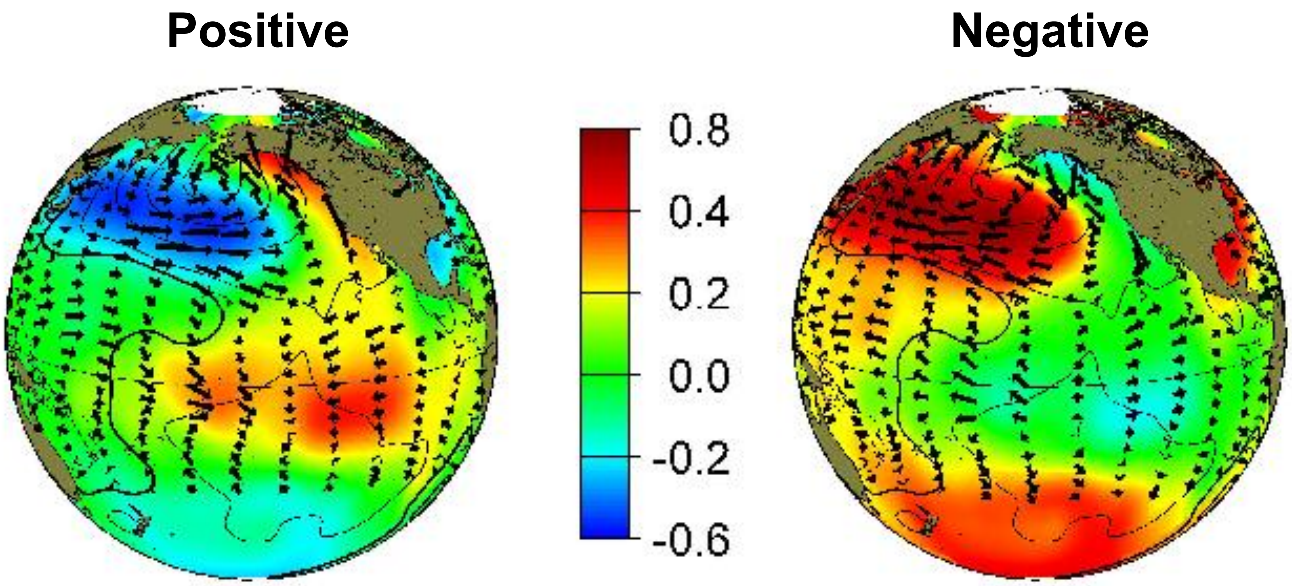
Typically "El Nino"



Typically "La Nina"

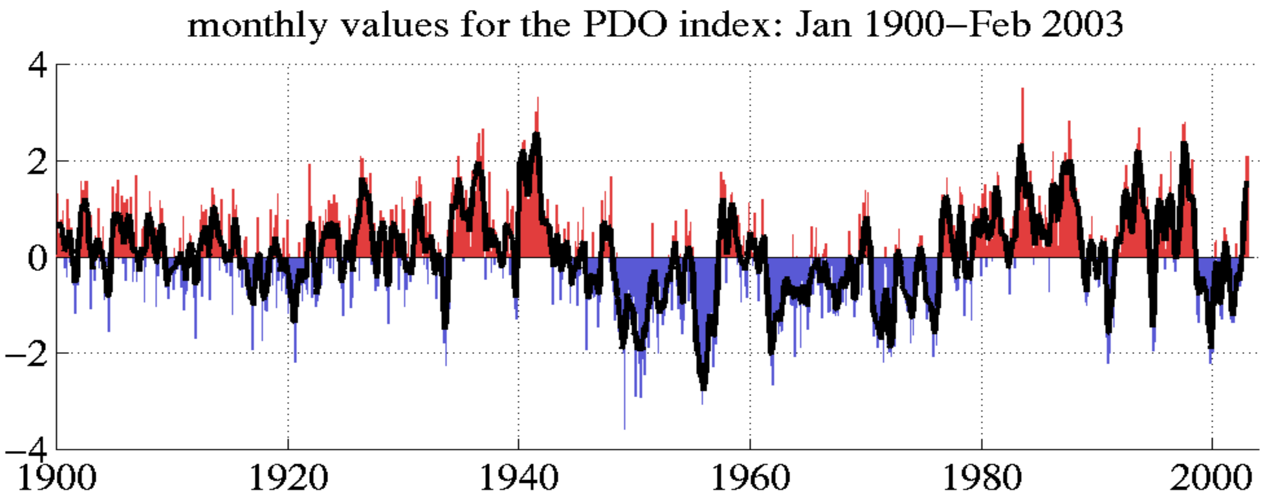
Courtesy Klaus Wolter & Mike Timlin,
NOAA Climate Diagnostics Center

Mantua et al.



PDO index values for 2009

January	-1.40
February	-1.55
March	-1.59
April	-1.65
May	-0.88



Ctsy
Nate Mantua

Percent change in annual precipitation and in amount on wettest day of the year, when both models agree on sign. 2 x CO2. Canadian Model 1 & Hadley Model 3.

Annual amount

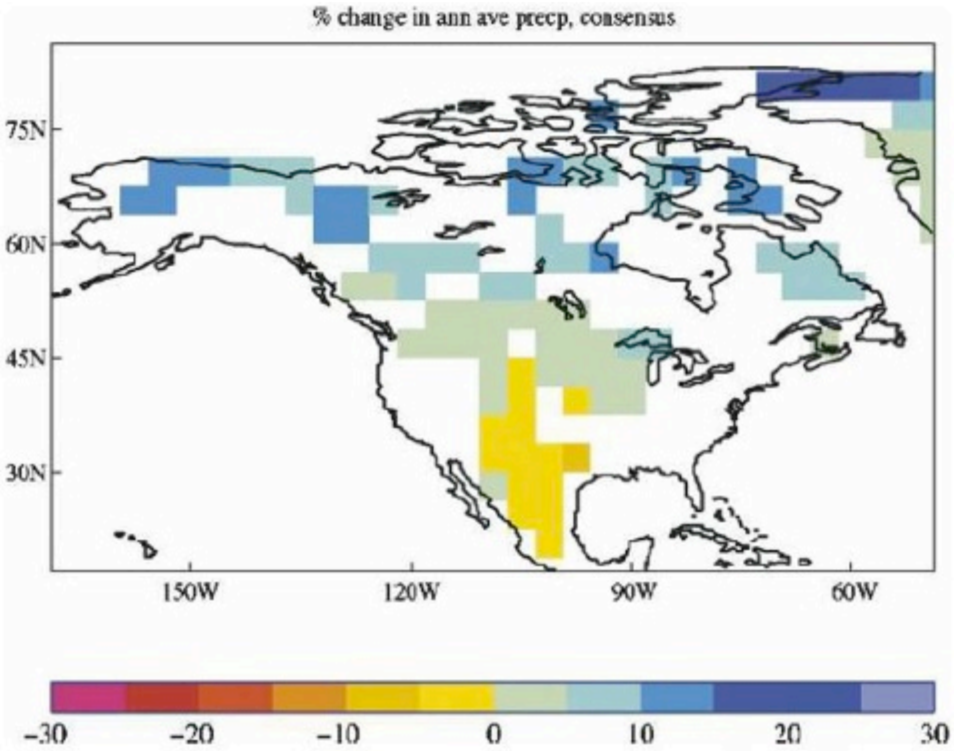
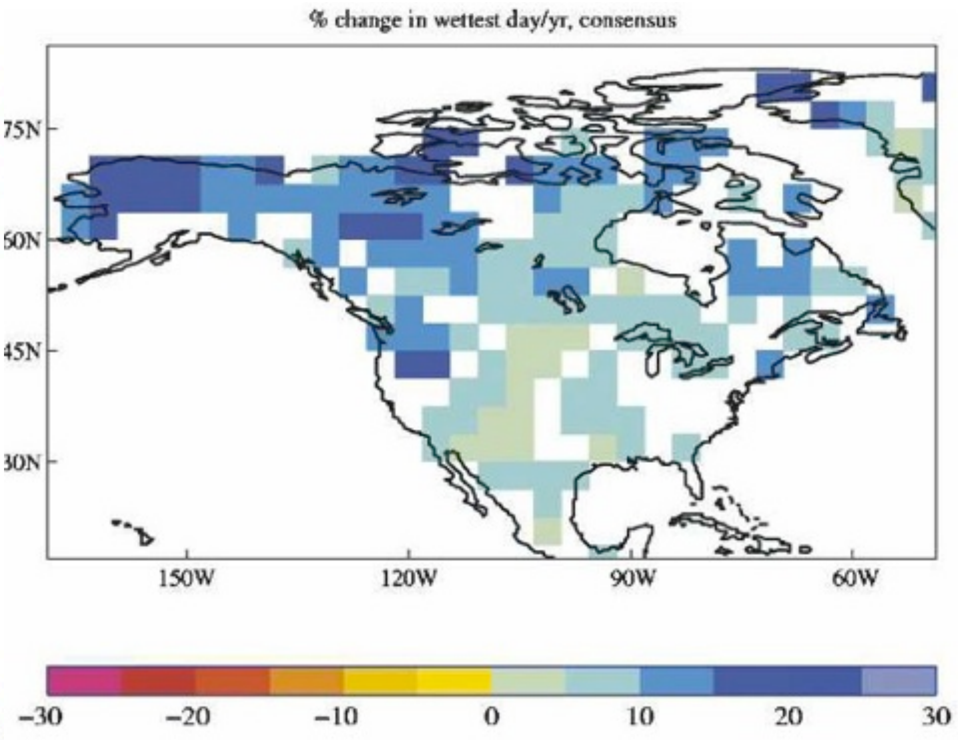


FIG. 13. Consensus estimates of changes in mean annual precipitation in the 2 × CO_2 experiments from CGCM1 and HadCM3 GCMs over North America. The red end of the scale depicts decreases and the blue increases. The pattern shows the average precipitation change between the models, it is only shown where the simulations with each model are consistent with the respective other model at the gridpoint level.

Wettest day

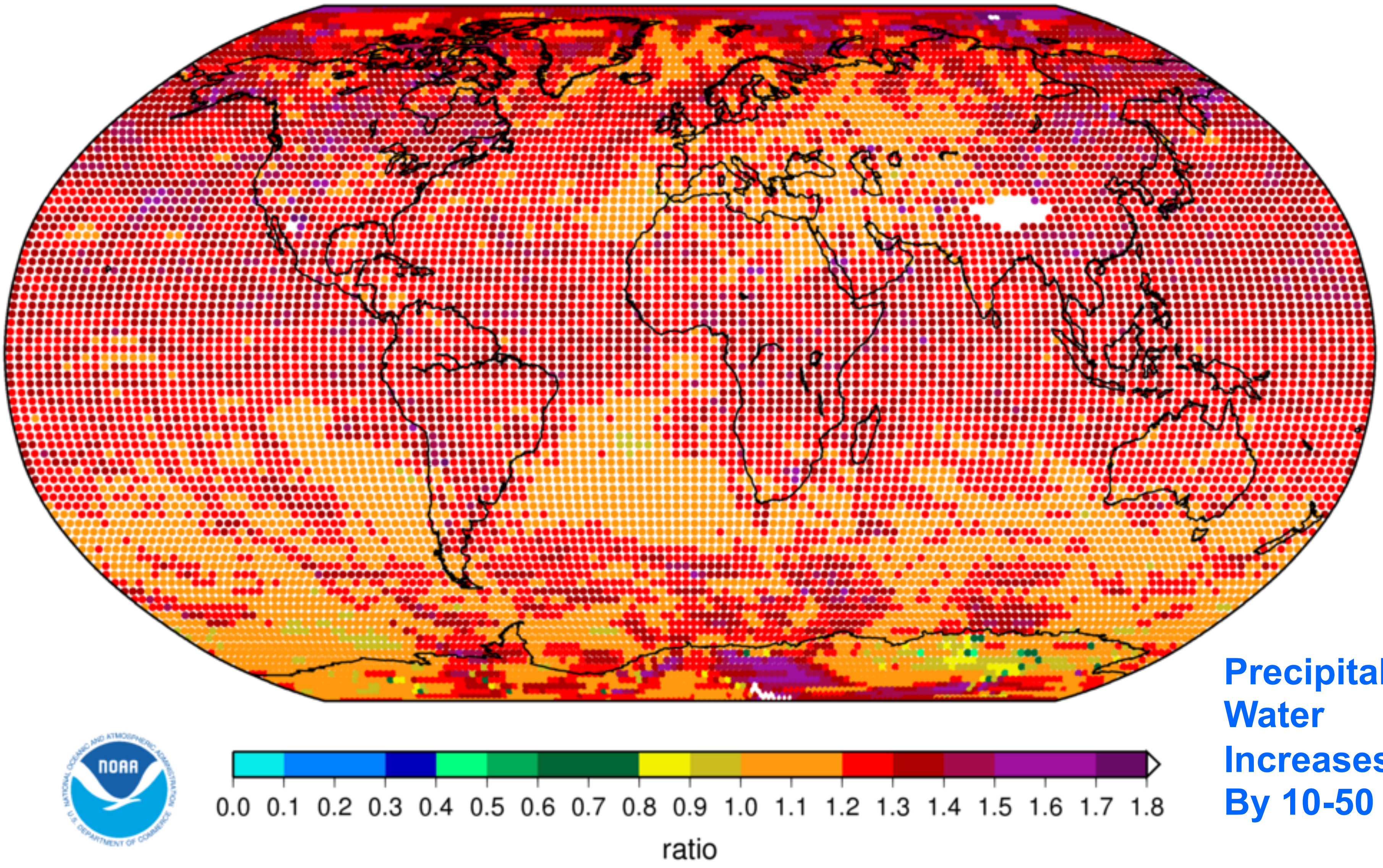


Pavel Ya. Groisman, Richard W. Knight, David R. Easterling, Thomas R. Karl, Gabriele C. Hegerl, and Vyacheslav N. Razuvaev, 2005. Trends in Intense Precipitation in the Climate Record *Journal of Climate*, 18 (9), 1326–1350.

GFDL 2.1 A2 Emissions Scenario

Ratio of Maximum Daily Precipitable Water (SRESA2 2071 to 2100 / 20C3M 1961 to 1990)

Note: Precipitable waters derived from model specific humidity, 20C3M = mean of ensembles 2,4,5

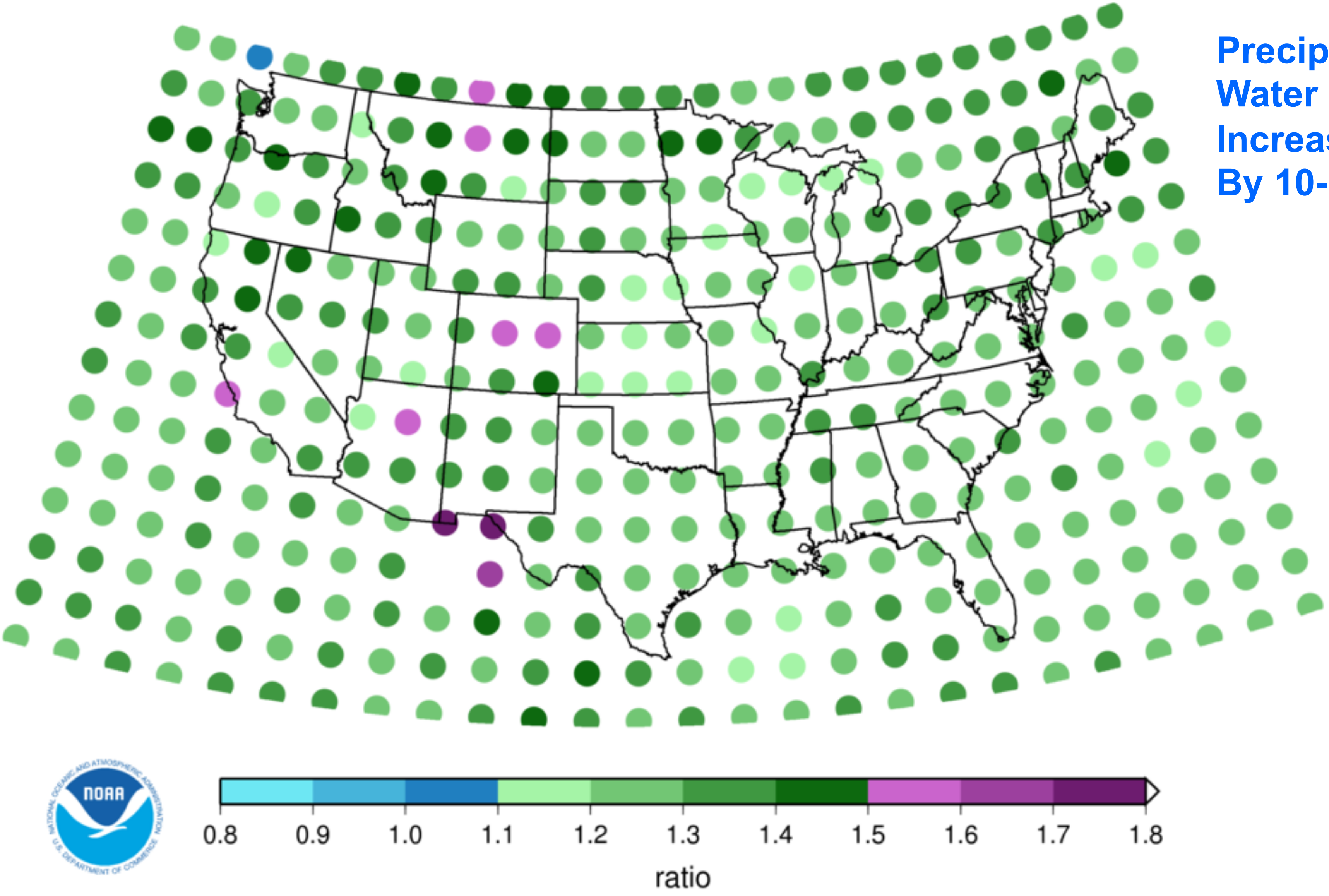


Precipitable Water Increases By 10-50 %

GFDL 2.1 A2 Emissions Scenario

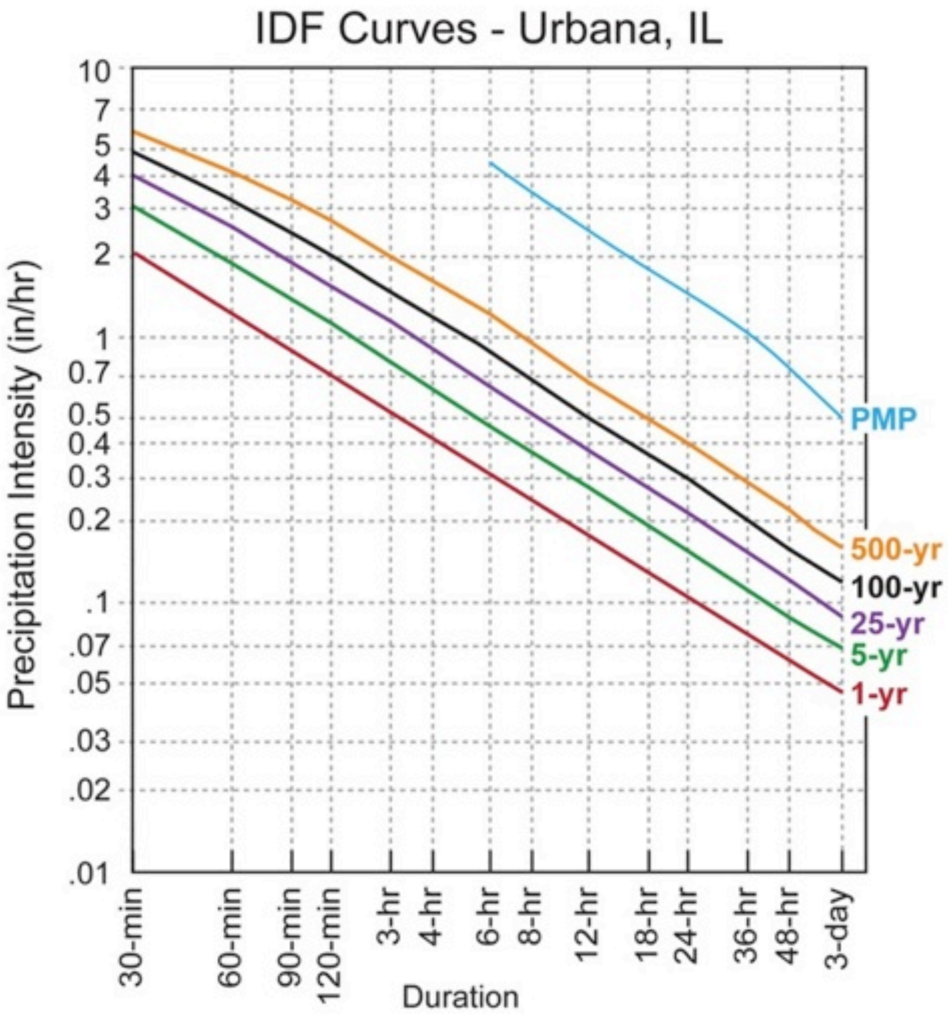
Ratio of Maximum Daily Precipitable Water (SRESA2 2071 to 2100 / 20C3M 1961 to 1990)

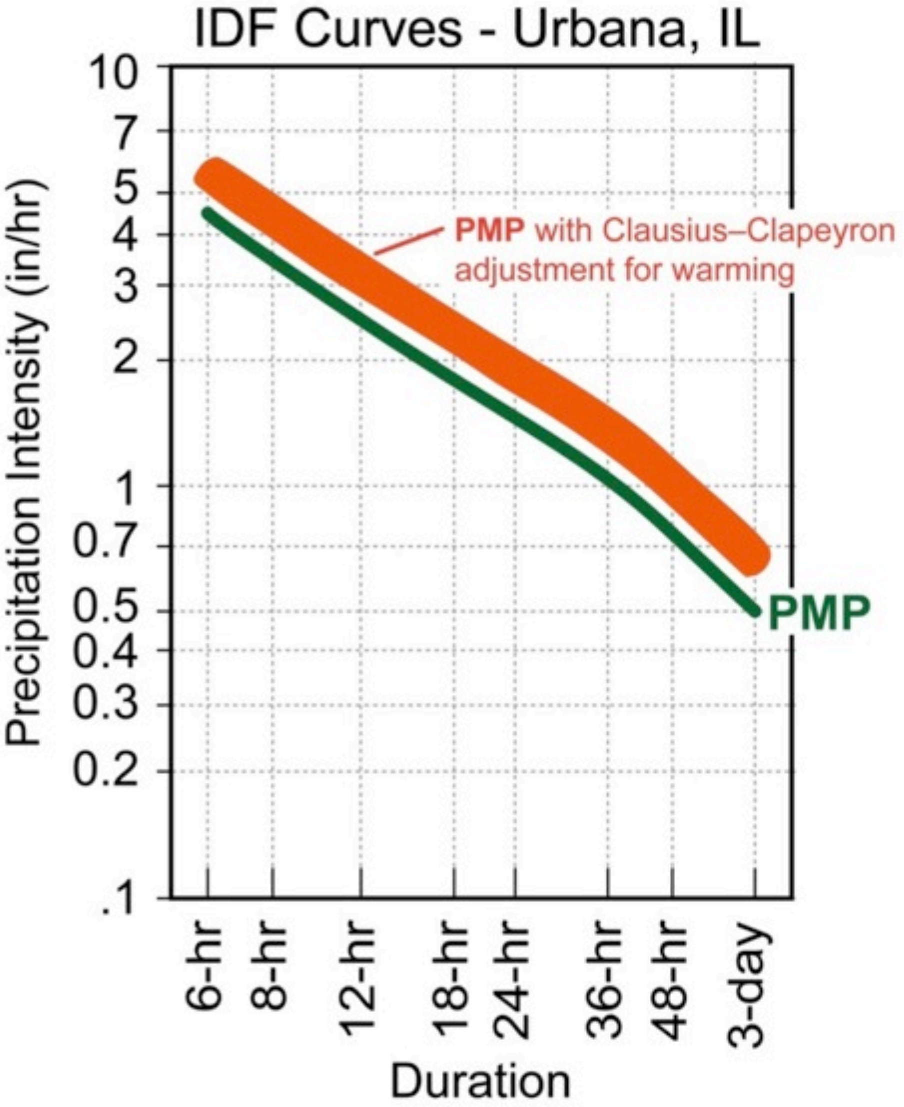
Note: Precipitable waters derived from model specific humidity, 20C3M = mean of ensembles 2,4,5

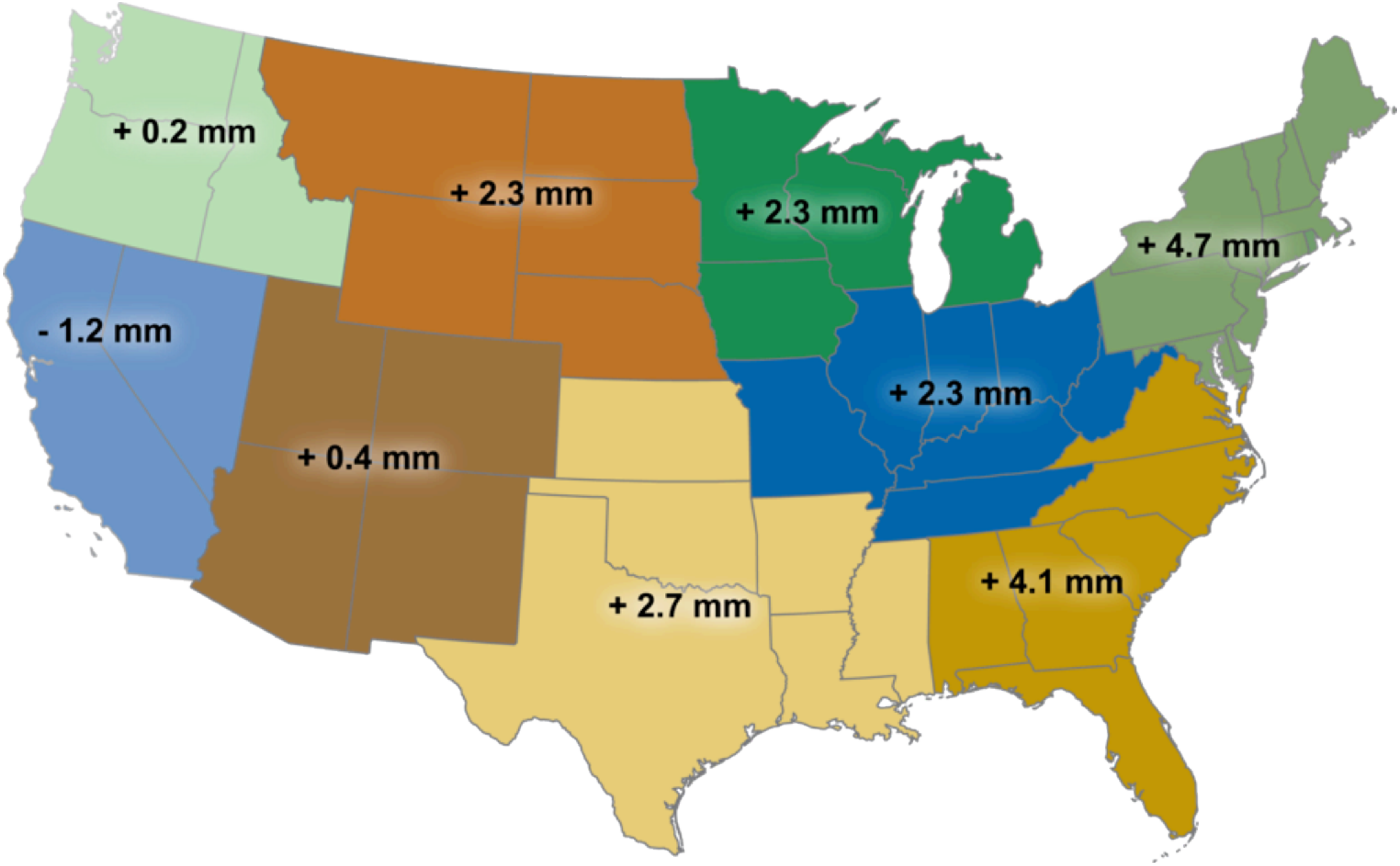


Precipitable Water Increases By 10-50 %

Urbana Illinois IDF Curves and Probable Maximum Precipitation
Present and Future Estimate from Clausius-Clapeyron Considerations







Difference in extreme event precipitable water:
1982-2009 minus 1961-1981

Some issues for consideration -1

How adequate are our observing systems to record the extremes of interest?

How adequate is our tracking of extremes?
- Ability to notice changes with relatively little delay
- Helps contribute to awareness of “changing extremes” possibilities

Extremes in hydrologic drivers versus extremes in hydrologic response
- Hydrologic systems as “filters”
  - Land use change as an example
    - Agriculture
    - Urban and impermeable surfaces
  - Same atmospheric sequence may not produce same hydro consequences

How well do / can models represent the properties of extremes?
- Ability to represent the entire probability distribution
- Ability to represent return intervals correctly
- Can models produce heavy-tailed distributions

Wet hydrologic extremes on short time scales exhibit heavy tails
- We may be underestimating the size and frequency of rare events

Orographic ratio connections to large scale climate

Some issues for consideration - 2

Atmospheric rivers as a weather - climate connection

Better understanding of MJO (Madden-Julian Oscillation) relationships to
- ENSO and other oscillations
- West Coast heavy precipitation probabilities
  - Windows of opportunity that may or not be realized (as heavy precip)

Multi-day duration episodes
- Slow-moving cutoff systems
- Sequences of multiple rapidly translating systems

The importance of a few singular events
- Increases from north to south
- Lack of a few events sets the stage for drought

Effect of non-precipitation hydrologic elements
- Changes in hydrologic events resulting from changes in temperature

Decadal-scale climate variability of extreme event likelihood

Social science investigations relating to risk perception
- Improved societal appreciation/understanding of probabilistic concepts

“The improbable is bound to happen one day.”

\- Emil Gumbel

“The biggest one is yet to come.”

\- Jim Goodridge
CA DWR

Thank You !

20101008