Variability and Change in Hydrologic Extremes

Kelly Redmond

Western Regional Climate Center

Desert Research Institute

Reno NV

Montana Hydrology Workshop
Helena MT 2010 July 27-28

Western Regional
Climate Center

Iowa dam fails, threatens Iowa towns

Meanwhile, storms unleash twisters, floods in other areas of Midwest

Waterloo Courier via AP

Dam fails in Iowa floods

Saturday
2010 July 24

Julie Koehn / AP

Maquoketa River water gushes out of the Delhi Dam as areas surrounding the Maquoketa River continue to flood on Saturday.

24 Jul 9:26 am	72	70	94	S	10	10.00	-RA	SCT005	BKN060	OVC150		29.86	29.157	T				
24 Jul 8:51 am	70	69	97	S	12	5.00	-RA BR	BKN006	OVC022		1010.9	29.87	29.167	0.04				
24 Jul 8:38 am	70	70	100	S	10	5.00	-RA BR	BKN007	OVC022			29.88	29.176	0.03				
24 Jul 8:04 am	70	68	94	NNE	3	6.00	-RA BR	SCT009	OVC024			29.90	29.196	0.02				
24 Jul 7:51 am	70	68	93	NE	8	4.00	RA BR	SCT009	BKN022	OVC041	1011.9	29.90	29.196	0.18				
24 Jul 7:27 am	70	68	94	NNE	3	4.00	-RA BR	SCT007	BKN022	OVC035		29.91	29.206	0.13				
24 Jul 7:10 am	70	68	94	NNE	8	2.50	-TSRA BR	SCT007	OVC020			29.89	29.186	0.10				
24 Jul 6:51 am	69	68	96	WNW	3	2.50	TSRA BR	BKN005	BKN018	OVC036	1012.2	29.90	29.196	0.68	3.56	6.17	72	69
24 Jul 6:46 am	70	70	100	WNW	3	2.00	TSRA BR	BKN005	BKN018	OVC036		29.90	29.196	0.66				
24 Jul 6:31 am	70	68	94	WNW	7G18	1.00	+TSRA BR	BKN005	BKN018	OVC036		29.96	29.255	0.17				
24 Jul 6:13 am	70	68	94	E	8	6.00	-TSRA BR	BKN005	BKN018	OVC036		29.85	29.147	0.14				
24 Jul 5:51 am	69	68	96	E	5	2.00	+TSRA BR	BKN005	BKN014	OVC050	1010.7	29.86	29.157	0.70				
24 Jul 5:38 am	70	68	94	NE	6	4.00	+TSRA BR	BKN005	BKN016	OVC055		29.88	29.176	0.41				
24 Jul 5:14 am	70	68	94	E	8	4.00	TSRA BR	FEW011	BKN055CB	OVC070		29.88	29.176	0.28				
24 Jul 4:54 am	70	68	94	E	6	1.75	+RA BR	SCT009	BKN055	OVC070		29.89	29.186	0.07				
24 Jul 4:51 am	70	68	93	E	5	8.00	+RA	BKN024	BKN048	OVC060	1011.8	29.90	29.196	0.20				
24 Jul 4:35 am	70	66	88	E	7	8.00	-RA	BKN024	BKN048	OVC060		29.90	29.196	0.18				
24 Jul 4:28 am	70	66	88	ESE	9	5.00	-TSRA BR	BKN013	BKN020	OVC045		29.91	29.206	0.18				
24 Jul 4:08 am	70	68	94	E	9	2.00	-TSRA BR	BKN013	BKN020	OVC045		29.89	29.186	0.16				
24 Jul 3:54 am	70	70	100	E	9	1.00	+TSRA BR	SCT013	BKN020			29.92	29.216	0.04				
24 Jul 3:51 am	71	69	93	E	8	1.00	+TSRA BR	SCT009	BKN022	OVC045	1012.6	29.92	29.216	0.75				
24 Jul 3:32 am	72	70	94	N	13G33	1.25	+TSRA BR	FEW009	BKN045CB	OVC055		29.91	29.206	0.13				
24 Jul 3:29 am	72	70	94	NNW	14G33	2.50	+TSRA BR	FEW009	BKN045CB	OVC055		29.91	29.206	0.06				
24 Jul 3:02 am	72	70	94	SE	14	9.00	-TSRA	FEW003	BKN050CB	OVC075		29.86	29.157	T				
24 Jul 2:51 am	71	70	96	SE	15	6.00	-RA BR	FEW003	BKN055	OVC070	1011.0	29.87	29.167	0.31				
24 Jul 2:44 am	72	70	94	SE	13	6.00	-RA BR	FEW003	BKN060	OVC075		29.88	29.176	0.31				
24 Jul 2:30 am	72	70	94	SSE	10	4.00	-RA BR	FEW027	BKN036	OVC080		29.91	29.206	0.29				
24 Jul 2:17 am	72	70	94	SSE	9	3.00	TSRA BR	BKN022CB	OVC090			29.92	29.216	0.25				
24 Jul 1:51 am	71	70	96	S	6	1.00	+TSRA BR	FEW008	BKN018CB	OVC036	1013.4	29.94	29.235	0.92				
24 Jul 1:31 am	72	70	94	CALM		1.00	+TSRA BR	FEW008	BKN016CB	OVC036		29.95	29.245	0.59				
24 Jul 1:04 am	72	70	94	SSW	8	1.25	+TSRA BR	OVC016				29.96	29.255	0.26				
24 Jul 12:53 am	72	70	94	SSW	6	1.25	+TSRA BR	OVC016				29.95	29.245	0.04				
24 Jul 12:51 am	71	69	93	SSW	6	1.50	+TSRA BR	BKN005	BKN009	OVC019	1013.2	29.94	29.235	1.99			77	70	94	70
24 Jul 12:34 am	72	70	94	SSW	12	1.00	+TSRA BR	BKN005	BKN009	OVC011		29.92	29.216	1.74				
24 Jul 12:17 am	72	70	94	W	15G28	0.75	+TSRA BR	BKN005	BKN009	OVC013		29.91	29.206	1.40				
23 Jul 11:53 pm	73	72	94	WSW	9G20	0.75	+TSRA BR	SCT013	OVC046			29.90	29.196	0.07				
23 Jul 11:51 pm	73	72	96	SW	15	3.00	+TSRA BR	SCT023	OVC046		1011.9	29.90	29.196	0.33				
23 Jul 11:27 pm	73	72	94	S	7	4.00	-TSRA BR	FEW029	BKN046CB	OVC055		29.88	29.176	0.08				

Chicago O'Hare

Saturday 2010 July 24

ENGLISH HARBOUR CASINO 100% UP TO $800 FREE ENTRY INTO OUR WEEKLY

[20100724] … An unintentionally apt analogy

ROME CASINO $5000

Lake Delhi Dam Breaks Causing Potential Iowa Gambling Decreases

LUCKY 18 CASINO $1800 FREE! PLAY NOW US PLAYERS WELCOME

Certain events take place that casinos cannot prepare for and one of those events occurred on Saturday in Iowa. The Lake Delhi Dam broke on Saturday, and the state of Iowa is now under severe flood warnings.

Iowa is one of the states where casino gambling has taken center stage and the revenue generated from the casinos has helped bridge budget gaps that were created by the economic recession. Iowa currently ranks in the top half of US states in terms of the amount of casinos in the state.

The 300 foot long breach in the dam, meanwhile, has caused evacuations in Eastern Iowa. The area had experienced a large amount of rain in recent days, and the dam broke after not being able to handle the unusually high levels of rain. Residents of Hopkinton only had five minutes to evacuate when authorities alerted them of the potential flooding.

Cedar rapids is one of the areas that potentially could be hit the hardest by the flooding. Cedar rapids is not one of the city's where casinos are located, with the most recent license going to Lyon County back in May.

An outside chance exists that casinos located far away from the flooding could actually gain customers this weekend. With many residents being forced to evacuate their homes, casino resort areas may become places that residents target to stay until the flooding has subsided.

"I have a couple of friends in Iowa and they said that they are preparing for the worst," said Mary Stuart, who lives in West Palm Beach, Florida. "They had been wanting to go away all summer, but today they told me they were going to leave their houses and head towards Ameristar (Casino)."

In recent days, the Gulf Coast has been hit by a tropical wave that threatened casinos on the coast. Mississippi and Louisiana casinos dealt with forced closures due to Hurricane Katrina several years back.

General Info
- Homepage
- Current Projects
- FAQ

Precipitation Frequency (PF)
- PF Data Server
- PF Documents

Probable Maximum Precipitation (PMP)
- PMP Documents
- Record Precipitation

Contact Us
- Inquiries
- List-server

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

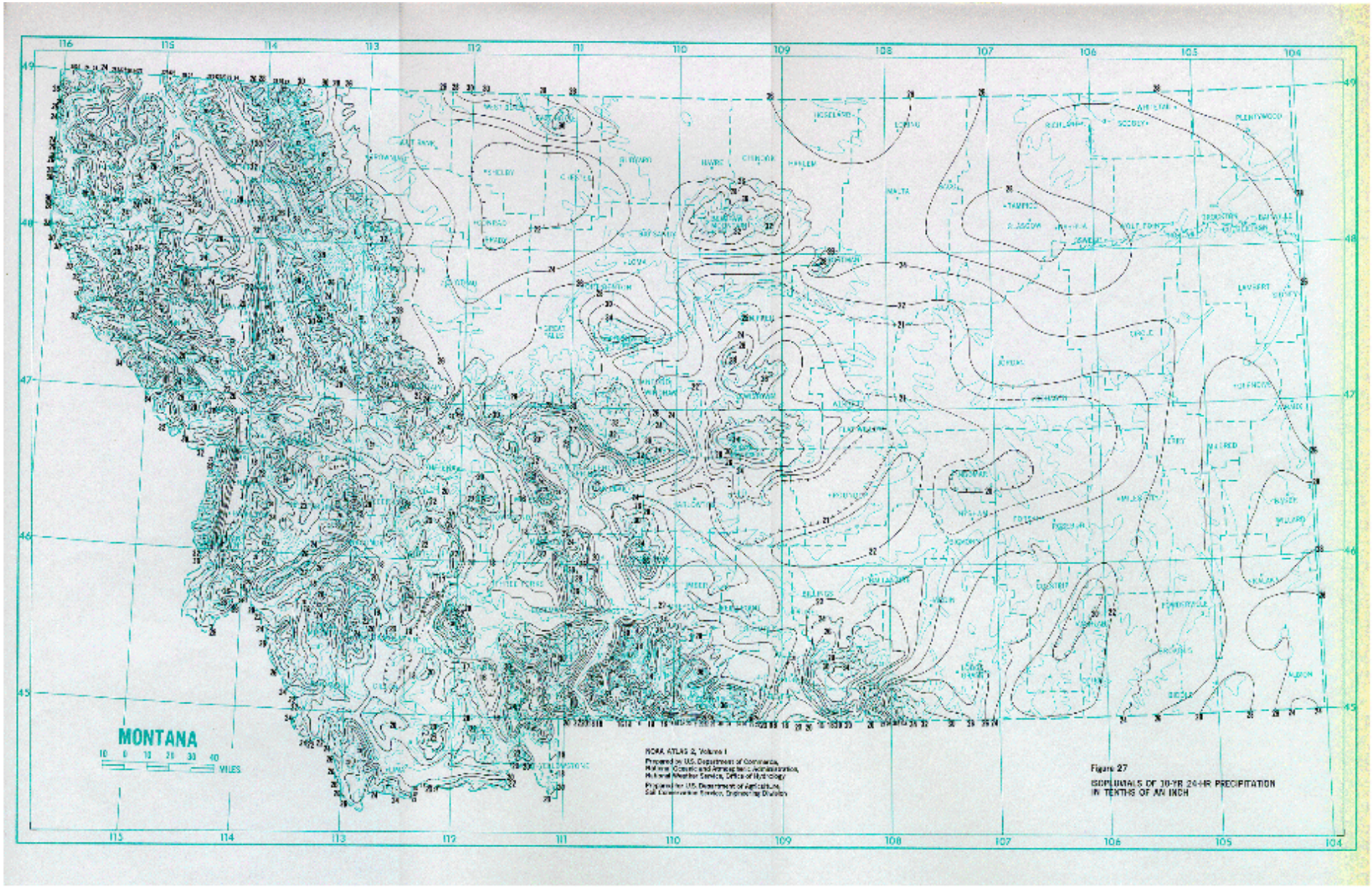
Western U.S. Precipitation Frequency Maps

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)

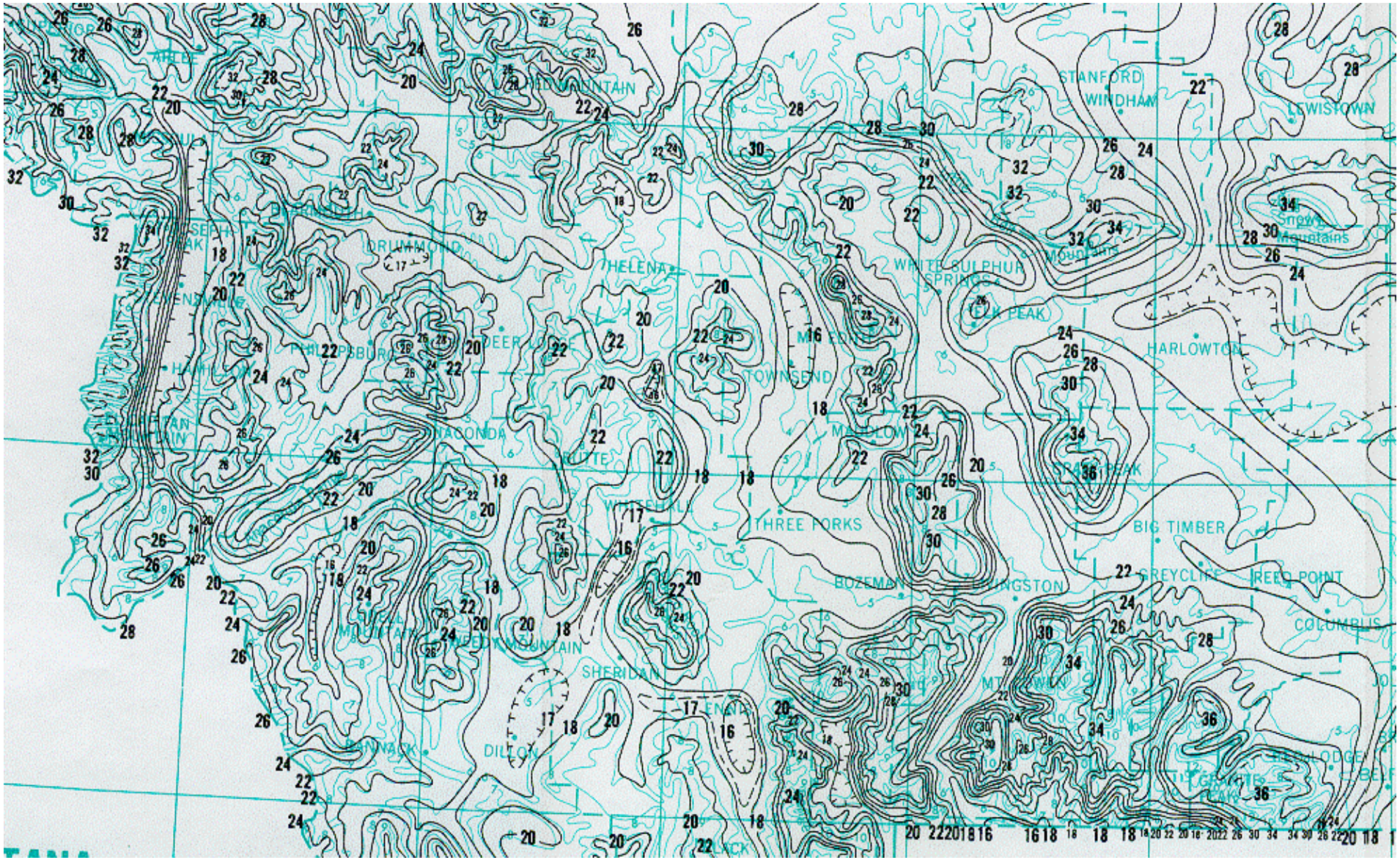
	2 Yr, 6 Hr	5 Yr, 6 Hr	10 Yr, 6 Hr	25 Yr, 6 Hr	50 Yr, 6 Hr	100 Yr, 6 Hr	2 Yr, 24 Hr	5 Yr, 24 Hr	10 Yr, 24 Hr	25 Yr, 24 Hr	50 Yr, 24 Hr	100 Yr, 24 Hr
Arizona	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Northern California	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Southern California	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Colorado	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓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

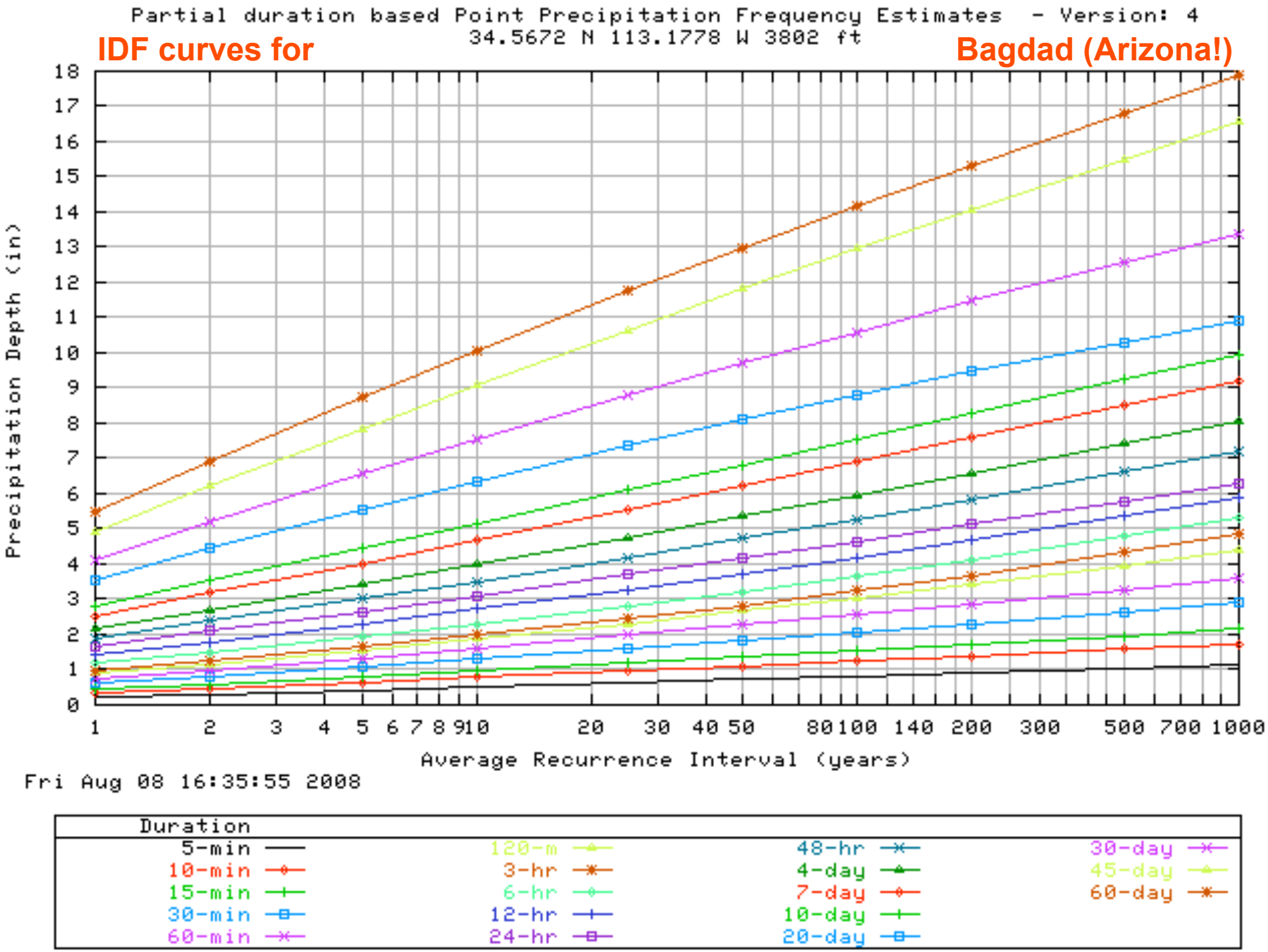
Western Regional Climate Center, wrcc@dri.edu

10-year 24-hour precipitation in tenths of inches



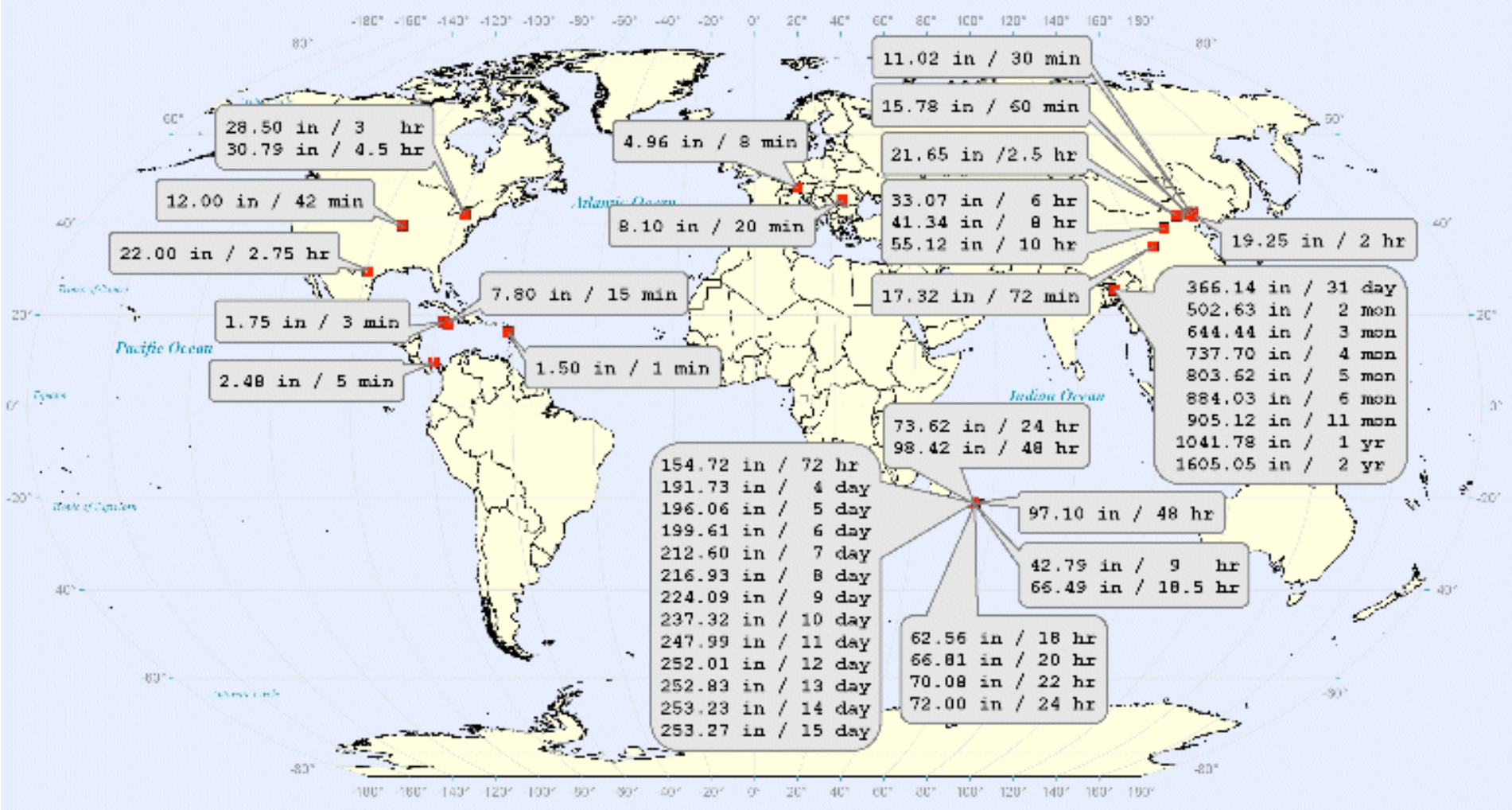
More detail … 10-year 24-hour precipitation in tenths of inches




Partial duration based Point Precipitation Frequency Estimates - Version: 4
34.5672 N 113.1778 W 3802 ft
IDF curves for
Bagdad (Arizona!)
Precipitation Depth (in)
Average Recurrence Interval (years)
Fri Aug 08 16:35:55 2008
Duration
5-min
10-min
15-min
30-min
60-min
120-m
3-hr
6-hr
12-hr
24-hr
48-hr
4-day
7-day
10-day
20-day
30-day
45-day
60-day

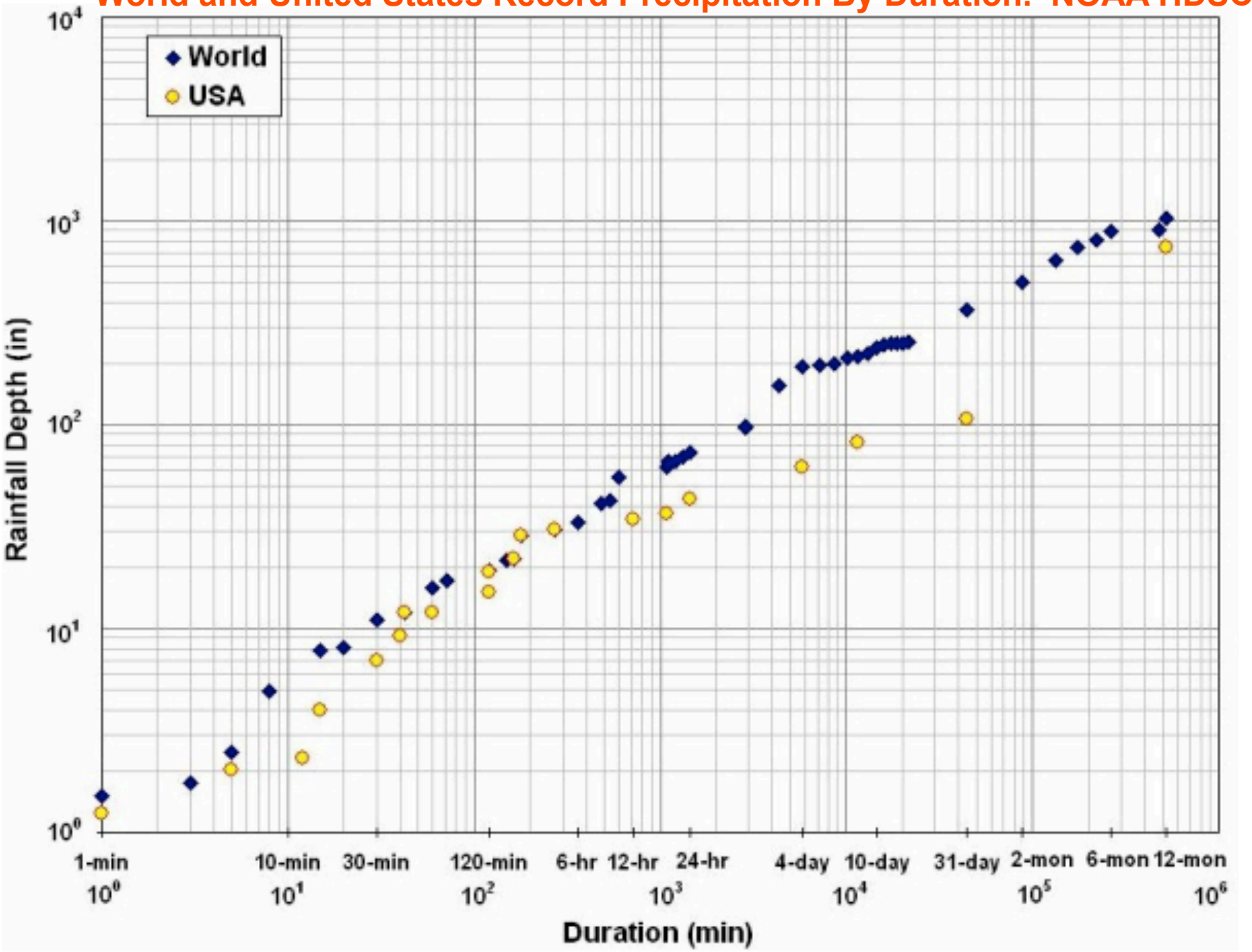
World record precipitation locations.

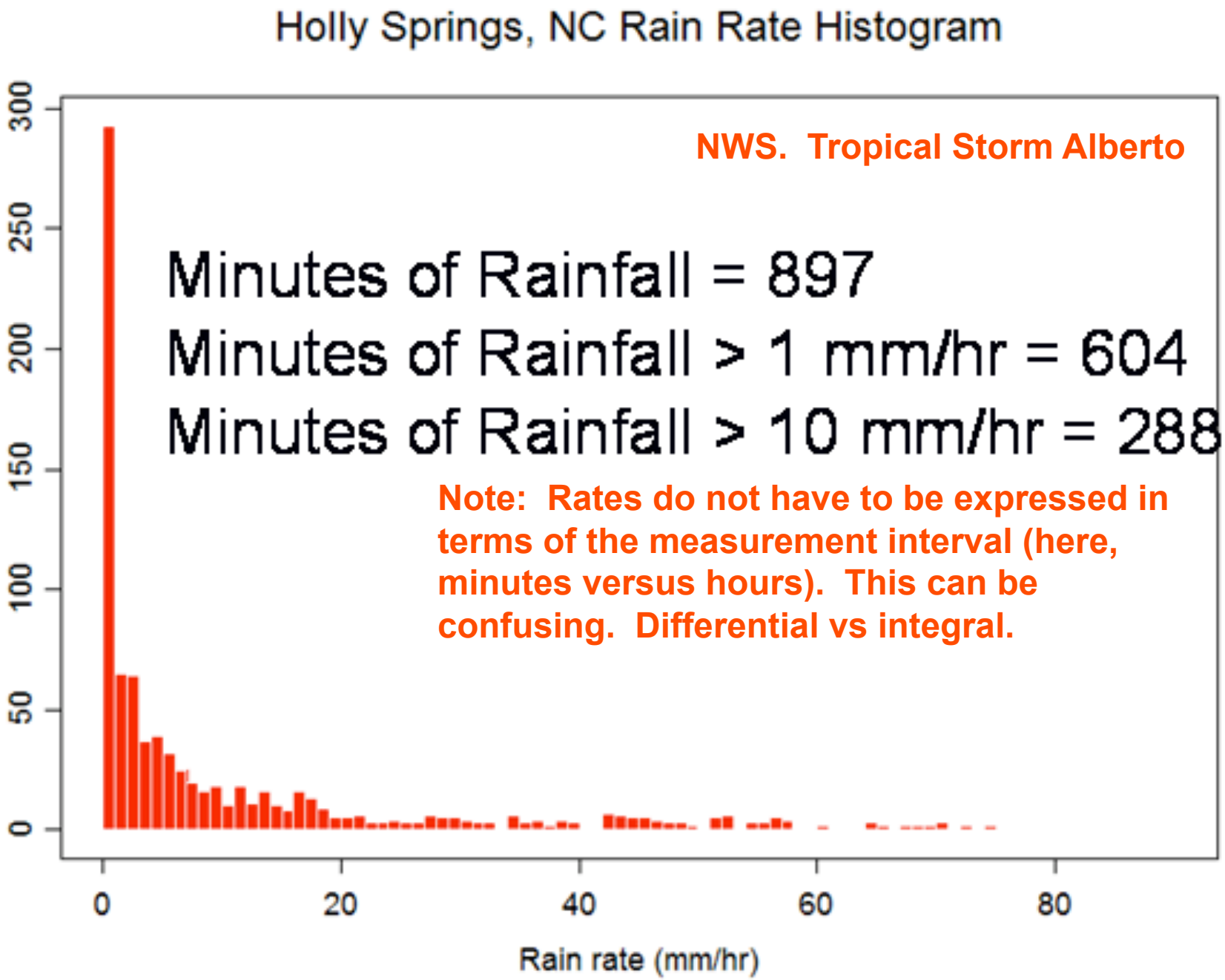
… A variety of circumstances

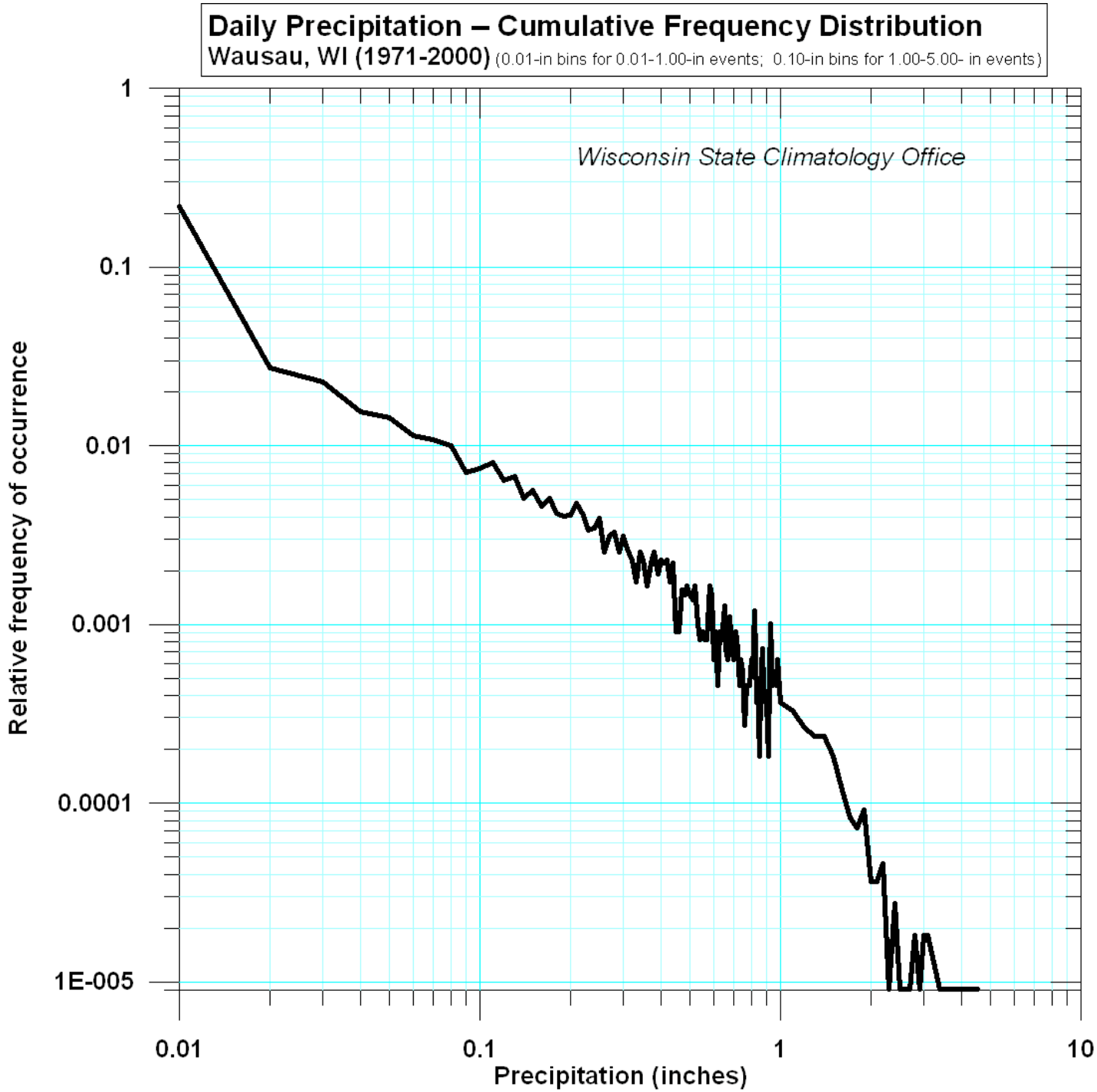


NOAA HDSC

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




Holly Springs, NC Rain Rate Histogram
NWS. Tropical Storm Alberto
Minutes of Rainfall = 897
Minutes of Rainfall > 1 mm/hr = 604
Minutes of Rainfall > 10 mm/hr = 288
Note: Rates do not have to be expressed in terms of the measurement interval (here, minutes versus hours). This can be confusing. Differential vs integral.
0
50
100
150
200
250
300
0
20
40
60
80
Rain rate (mm/hr)



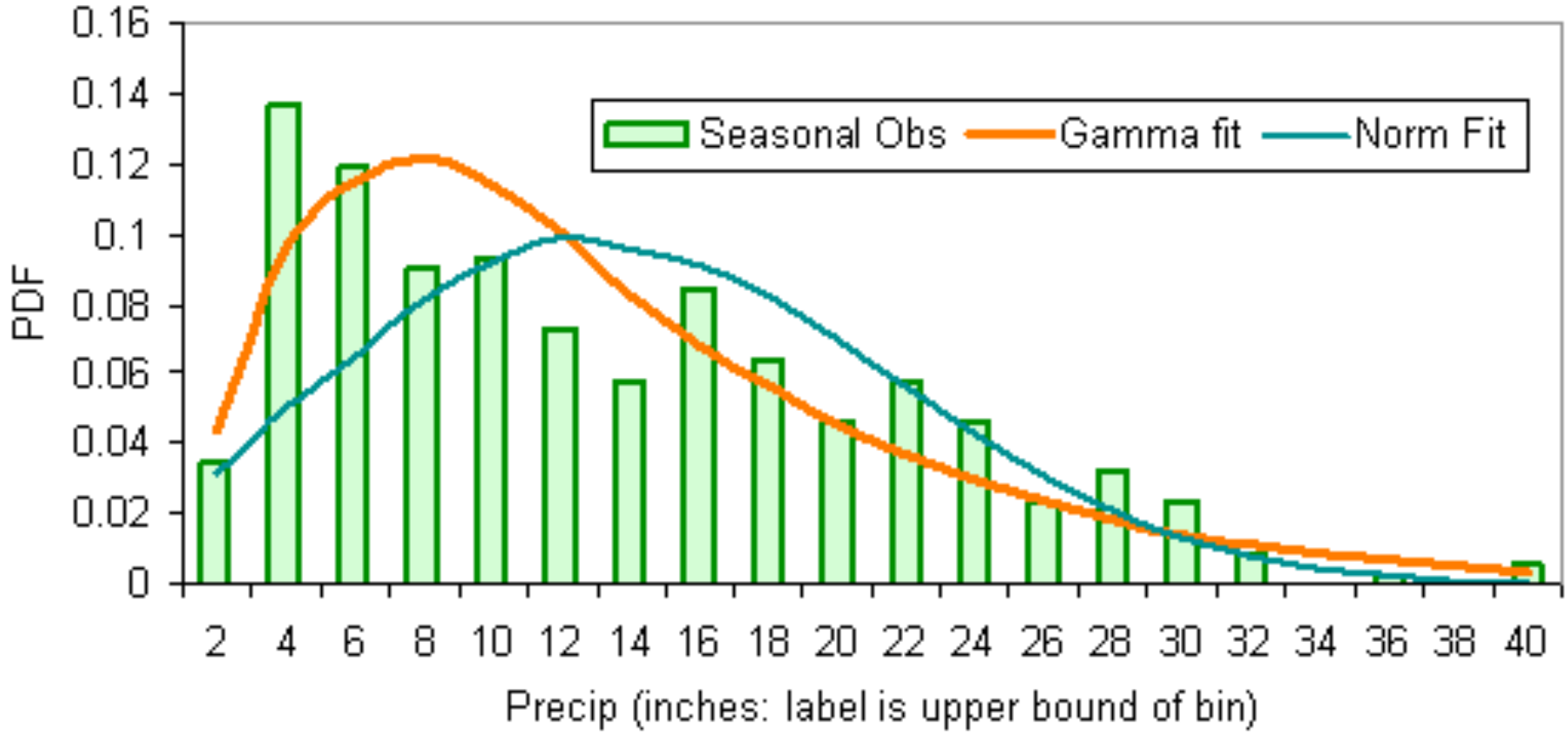
Wausau Wisconsin.

Daily precipitation on days with at least 0.01”

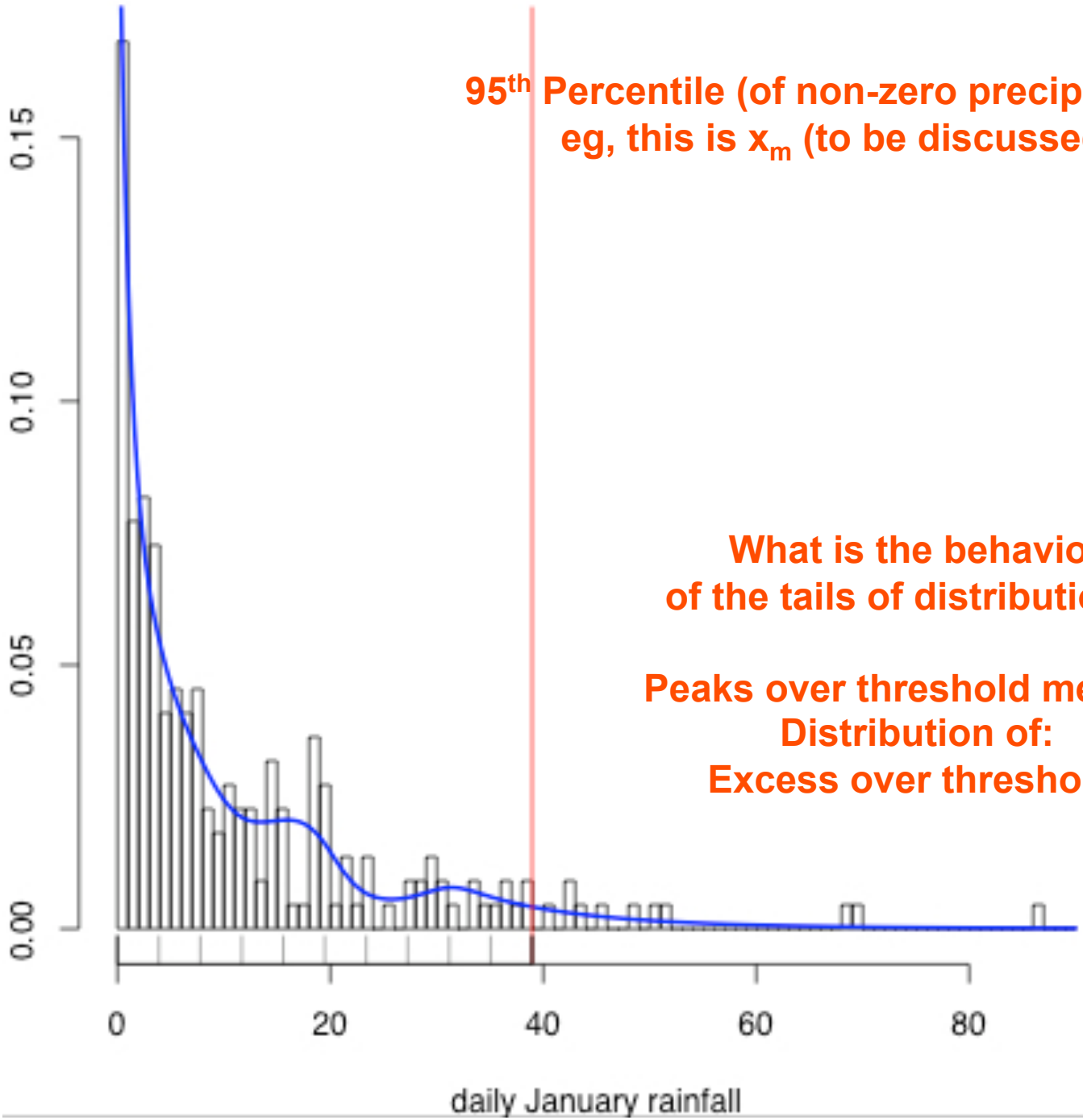
1971-2000

Precipitation occurs about 20-22 % of all days.

Seasonal Precipitation. Olympia Airport, WA.
Mean: 12.5". St Dev: 8.2" Shape Parameter: 1.97 Scale Parameter: 6.35



NWS PCU 2



95th 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

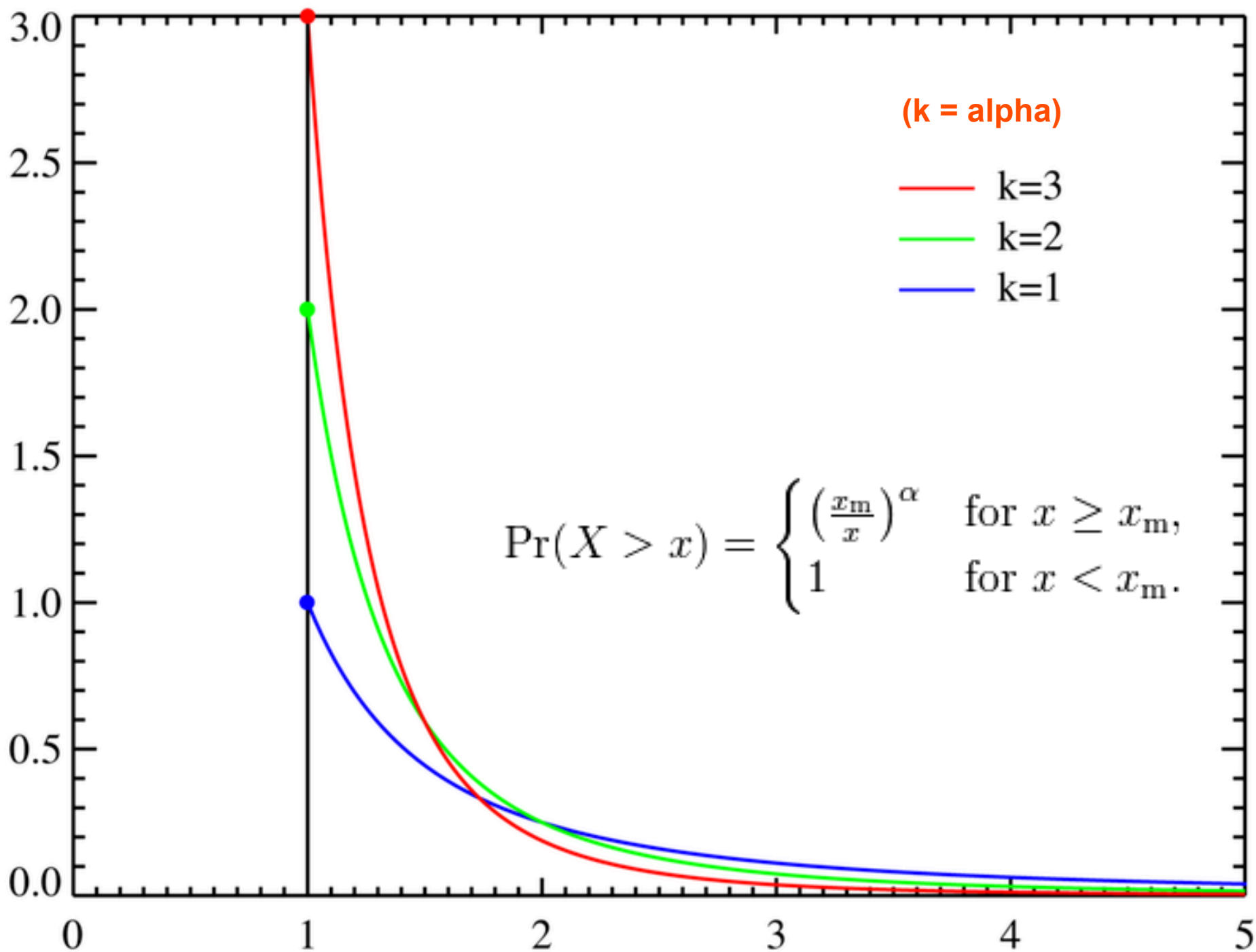
$$\operatorname{var}(X) = \left(\frac{x_{\mathrm{m}}}{\alpha - 1}\right)^2 \frac{\alpha}{\alpha - 2}.$$

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

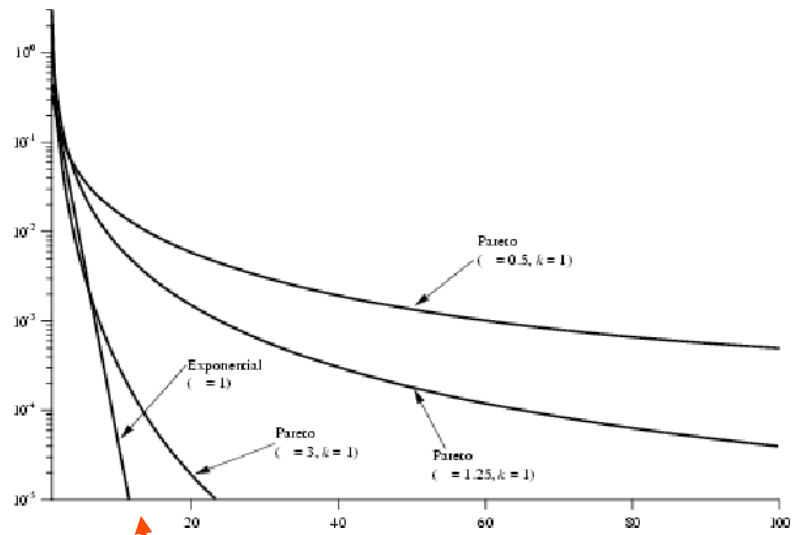
- The raw moments are

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

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


(k = alpha)
k=3
k=2
k=1
$\Pr(X > x) = \begin{cases} \left(\frac{x_m}{x}\right)^\alpha & \text{for } x \geq x_m, \\ 1 & \text{for } x < x_m. \end{cases}$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5

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



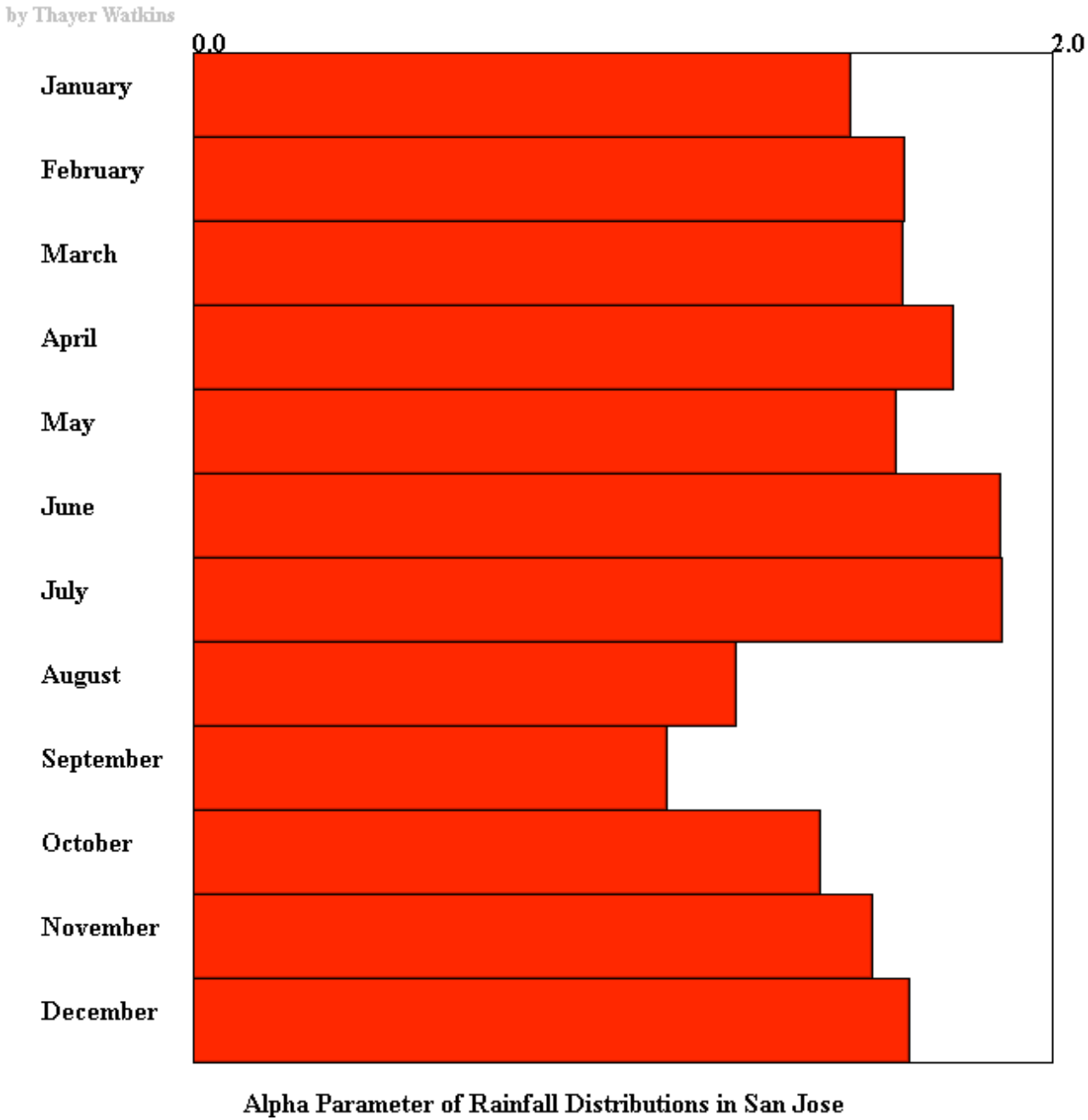
Pareto, alpha = 1

Pareto, alpha = 2

Pareto, alpha = 3

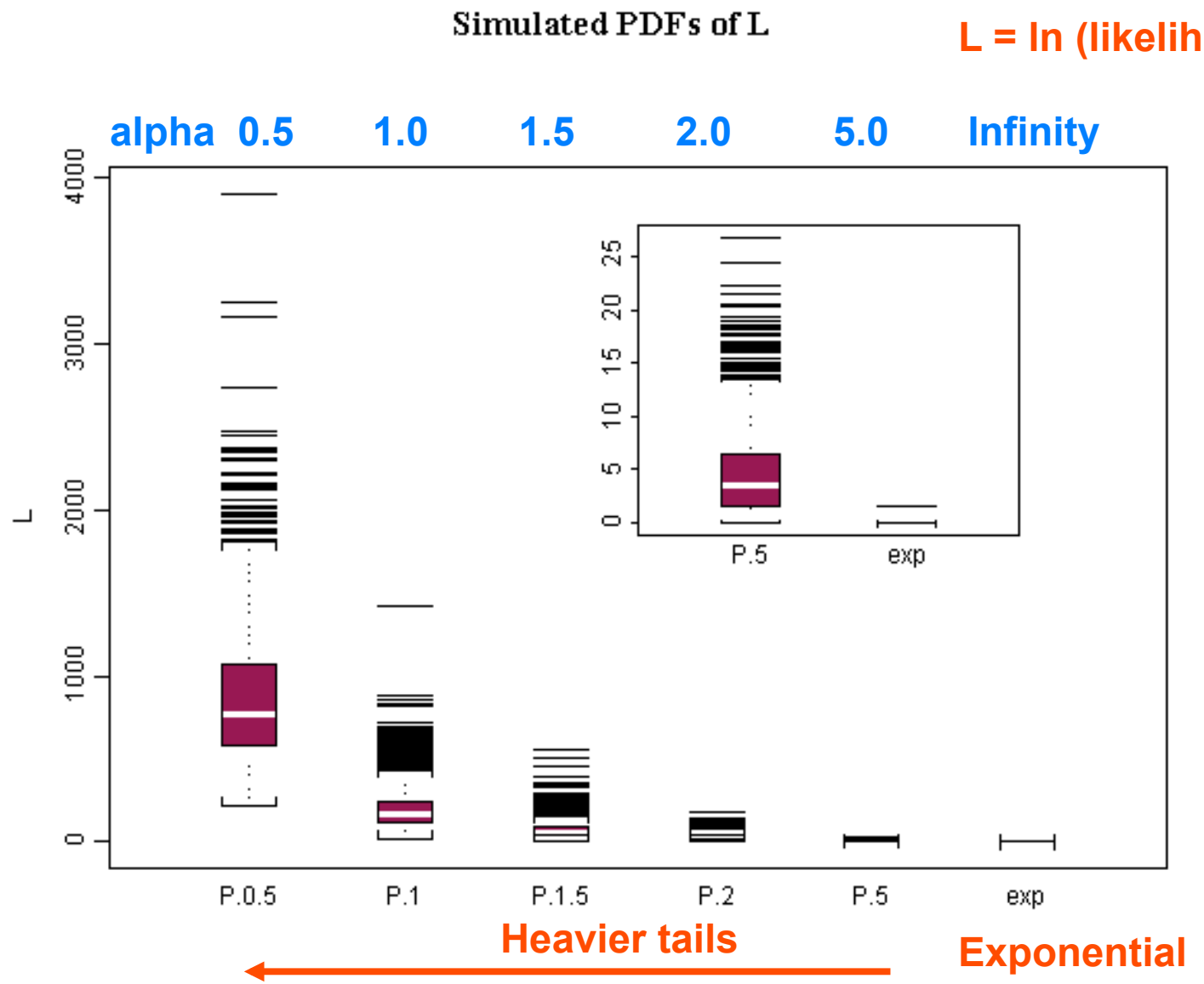
Pareto, alpha = infinity (exponential)

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



Pareto alpha

San Jose CA
Monthly Precip
1908-2000



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.

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

Log likelihood ratio test statistic (L), all data

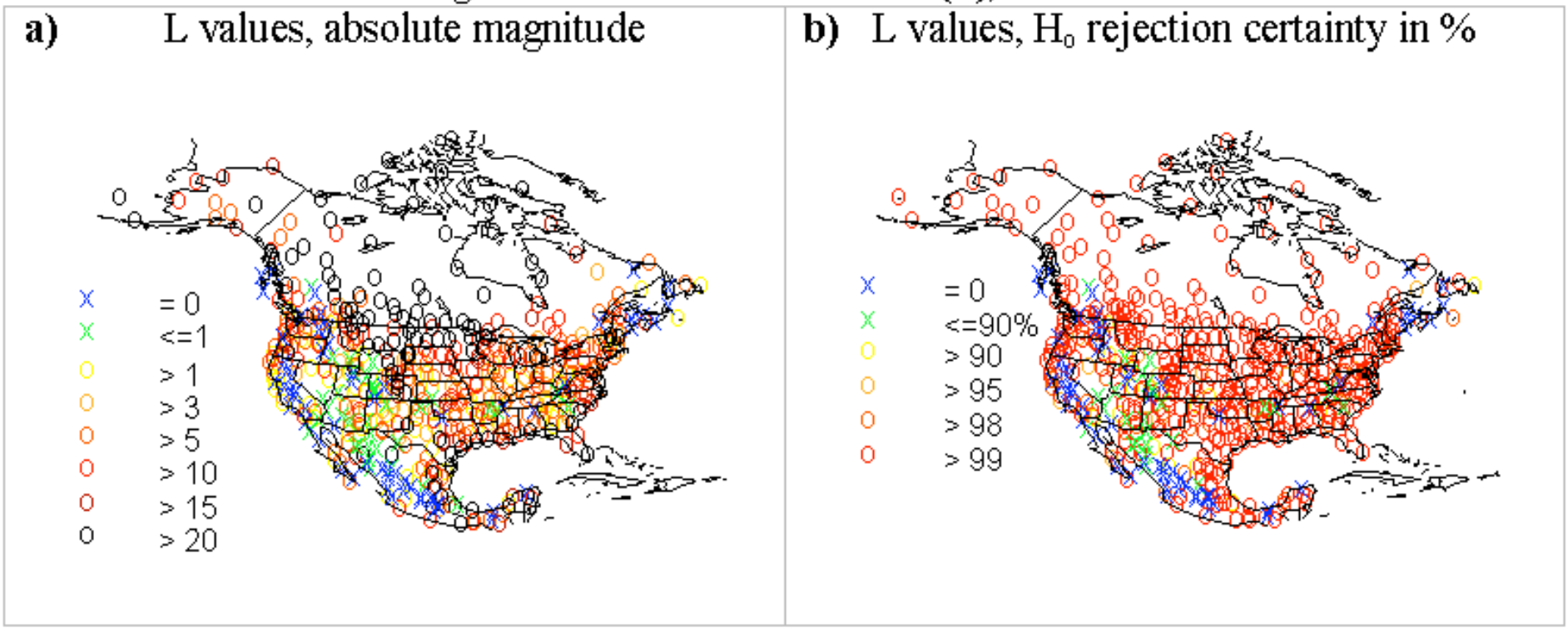
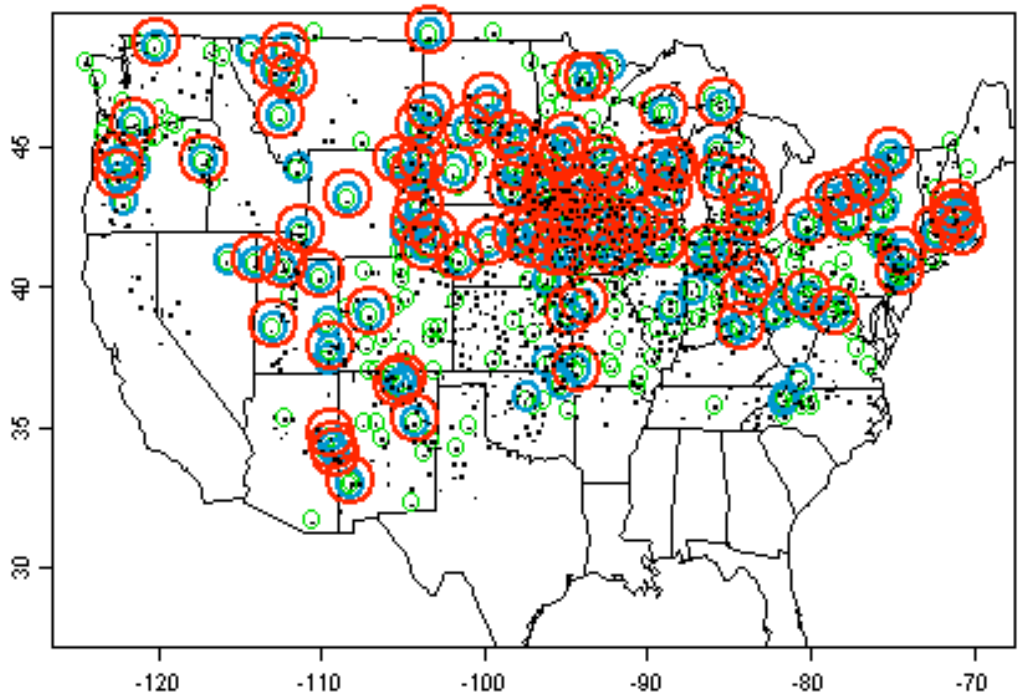


Figure 2 (from Panorska et al. 2006). Log likelihood ratio (L) computed for daily excesses over local 75th percentile at each of the 560 stations. **(a)** Values close to zero, L <= 1 (blue and green x's) represent approximately exponential tails, while yellow, red and black circles represent progressively 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



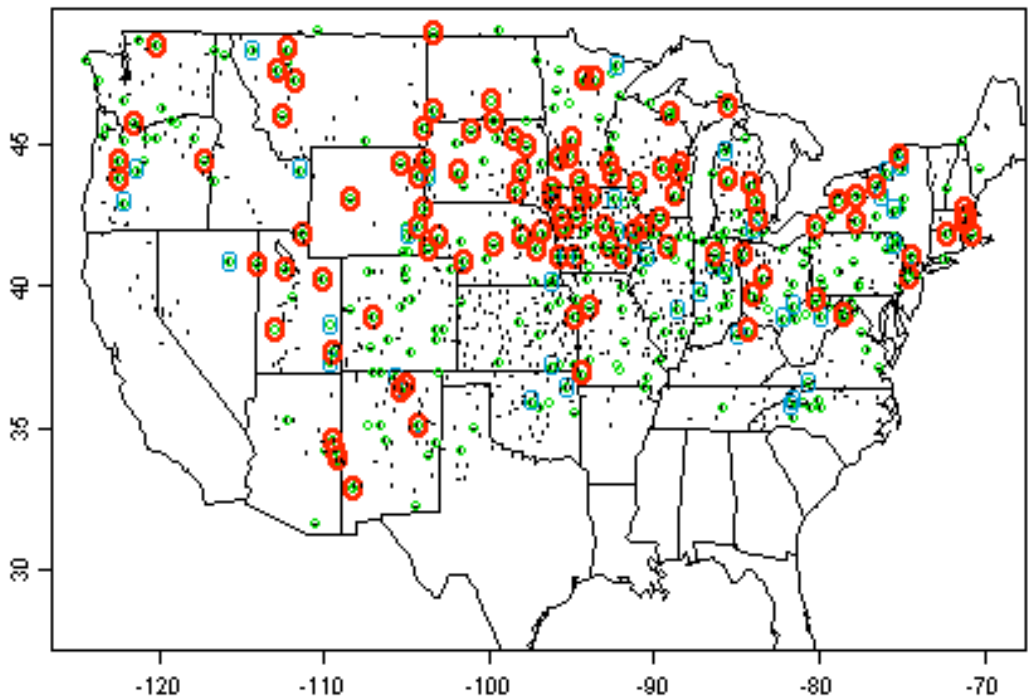
Same for the quality controlled larger station subset – 1124 stations.

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)	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).

Comments:

Exponential tails found where most precipitation has the same cause and consistent processes

Heavy tails found where there are a variety of storm types, mechanisms, and sources of precipitation

"Diversity is the mother of volatility." - Sasha Gershunov

Tails are heavier when all seasons are combined compared with single seasons.

Annual heavy tail needs at least one season with heavy tails.

No way to get heavy tails from combinations of exponential tails.

Models do not seem to be able to produce heavy tails

- Examined 60 years of 10x10 km CA-NV Kanamitsu model hourly data
- Likely stems from the way model precipitation is parameterized
- Appears to be a fundamental issue
  - Processes that produce fat tails not represented (e.g. Brownian motion ?)

But, perhaps statistical techniques could use model output to create heavy tails

Potential sources of heavy precipitation:

Frontal passages

Cyclonic storms

Orographic uplift

Tropical storms

Convergence zones

Embedded cumulus

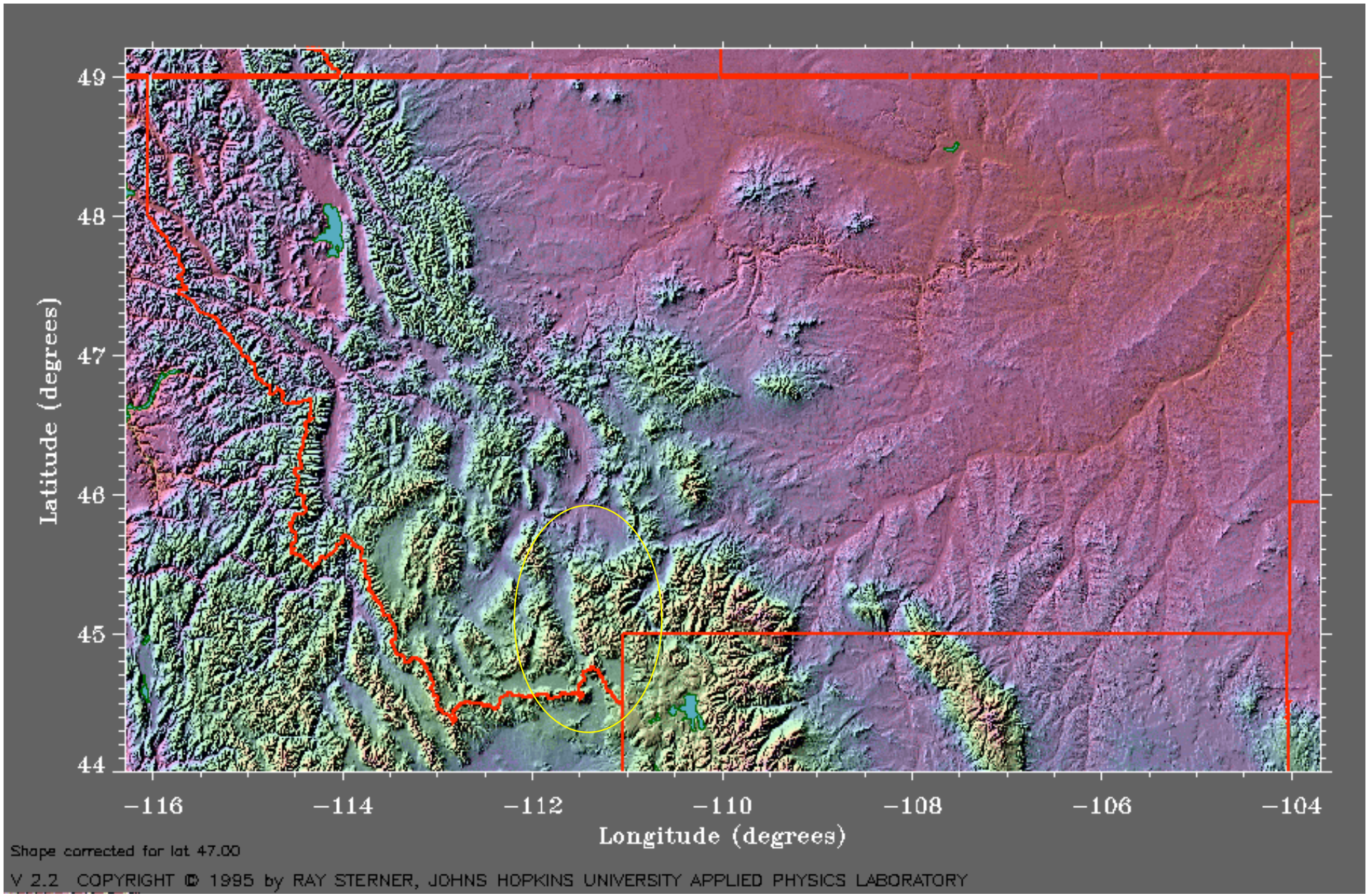
Atmospheric rivers

Blocked atmospheric patterns

ENSO conditioning

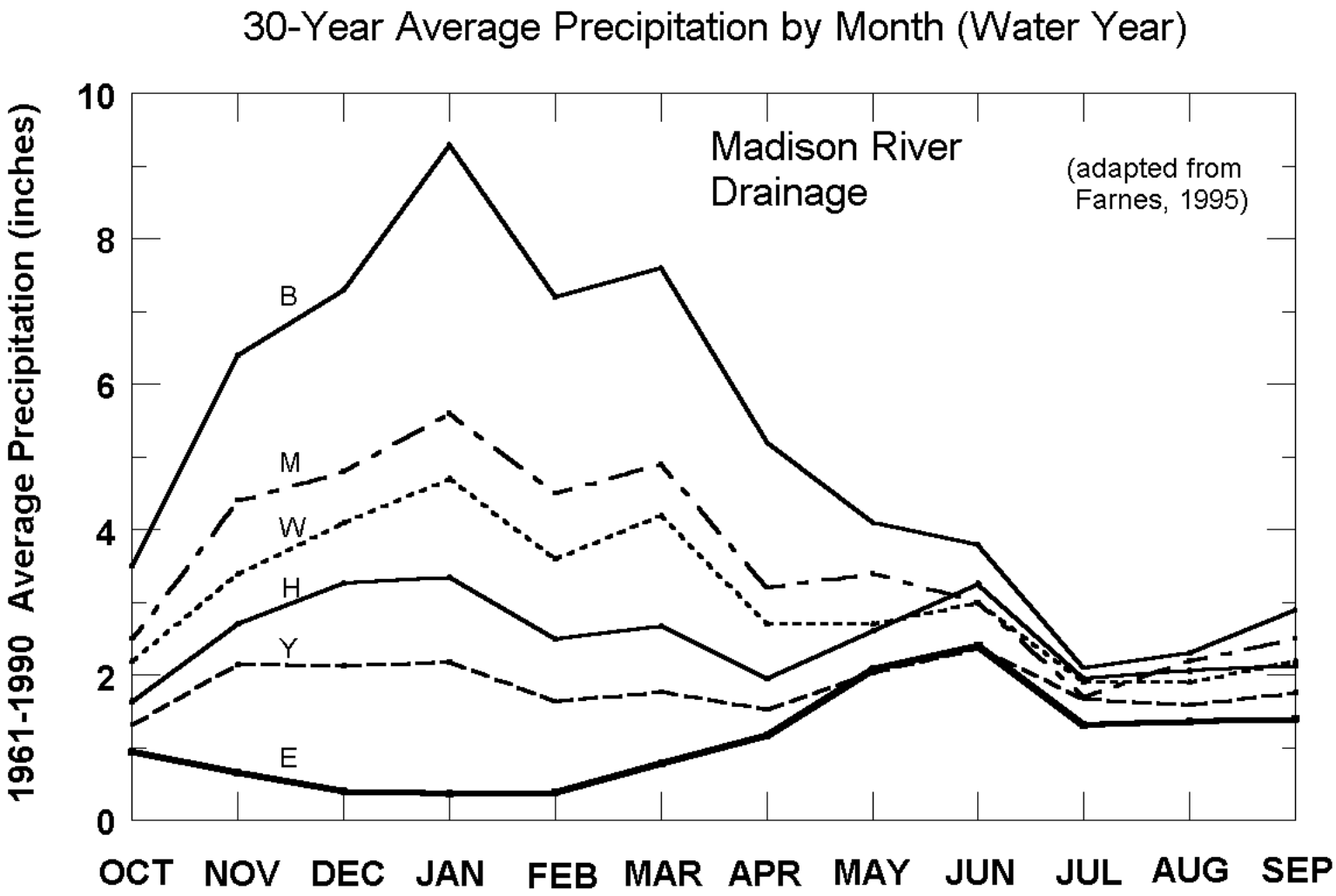
MJO activity

Human effects (?)

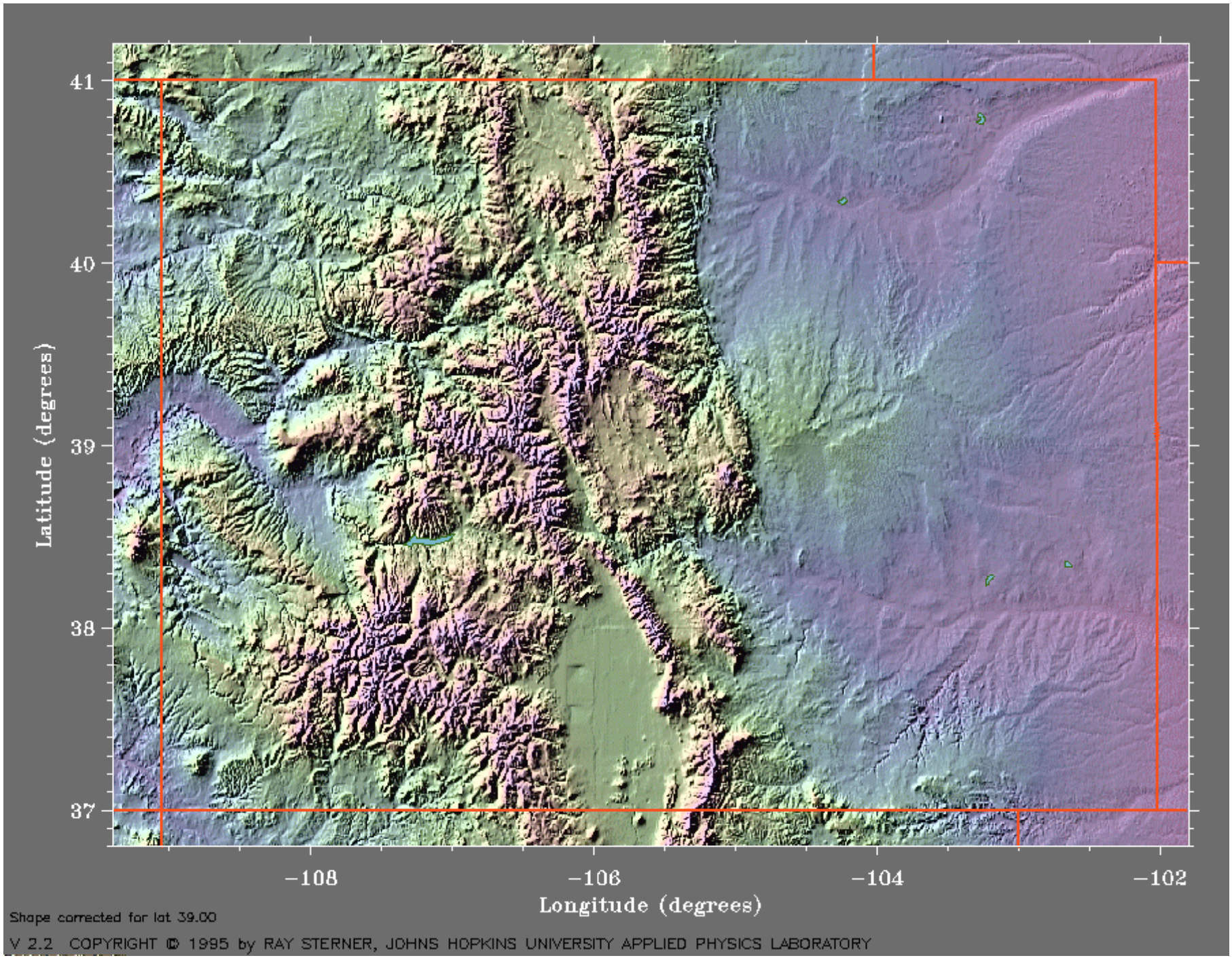


Madison Valley Seasonality Comparison Area.

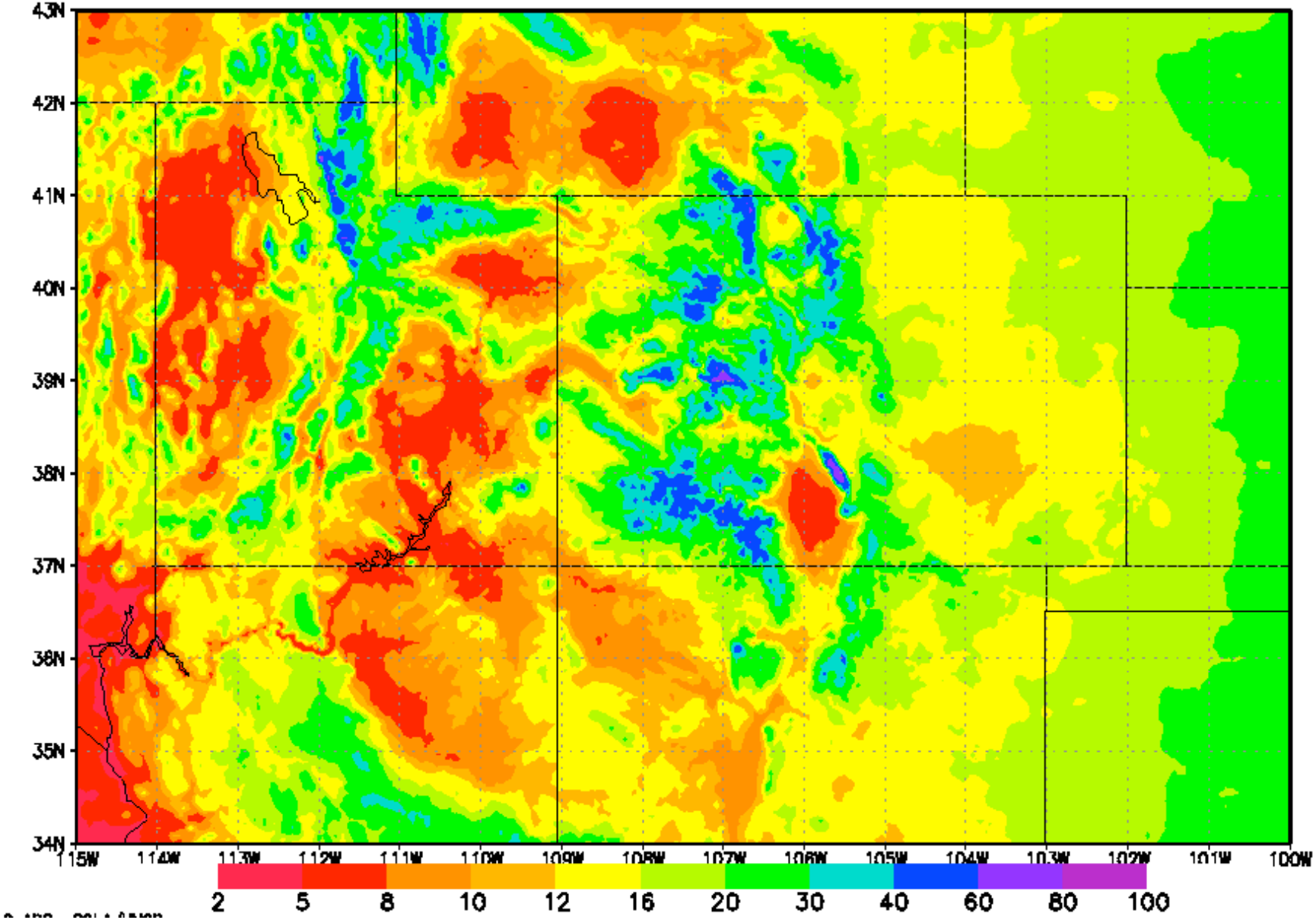
Adapted from Phil Farnes,
Western Snow Conference, 1995.

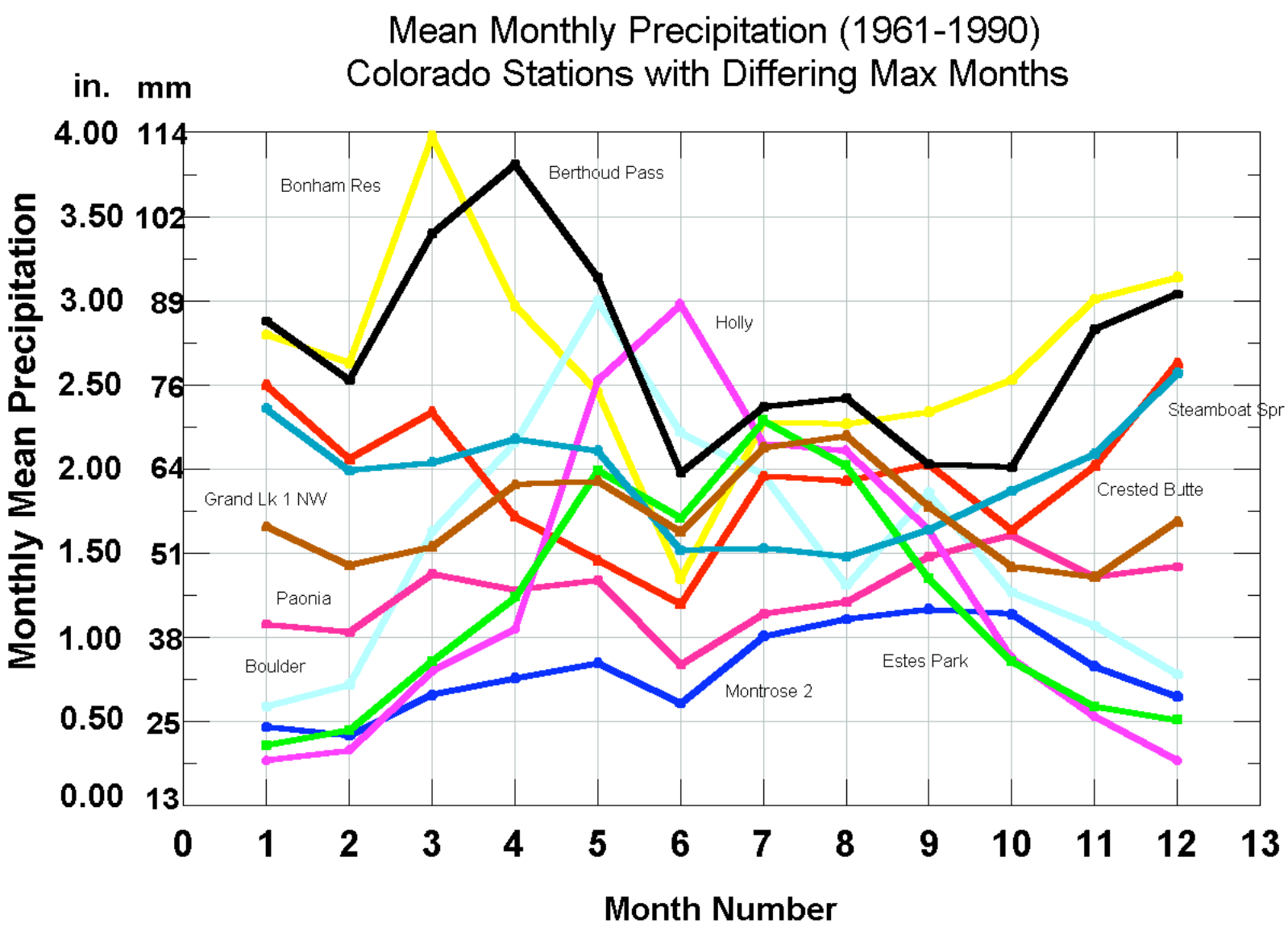


B - Black Bear	7950'/2423 m	M - Madison Plateau	7149'/2179 m
W - Whiskey Creek	6802'/2073 m	H - Hebgen Dam	6490'/1978 m
Y - West Yellowston	6660'/2030 m	E - Ennis	4954'/1510 m


41
40
39
38
37
Latitude (degrees)
−108
−106
−104
−102
Longitude (degrees)
Shape corrected for lat 39.00
V 2.2 COPYRIGHT © 1995 by RAY STERNER, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

Annual Precipitation (inches) 1961–90 (PRISM OSU/WRCC)





K. Redmond, 2003. p 29-48, Water and Climate in the Western United States. U Colorado Press.

A preliminary: Applications as forecasts

An implicit assumption that has pervaded much of applied climatology

Past is Prologue

Past statistics = Future statistics

The decision that uses the information is about the future

Therefore, past values often de facto forecasts

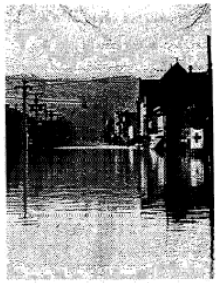
Not explicitly recognized as such

Past is considered reliable guide to the future

Climate stationarity is implicit in this assumption

Huge societal investments ($B, $$B, $$$B)

Bulletin 17 B



Guidelines For Determining

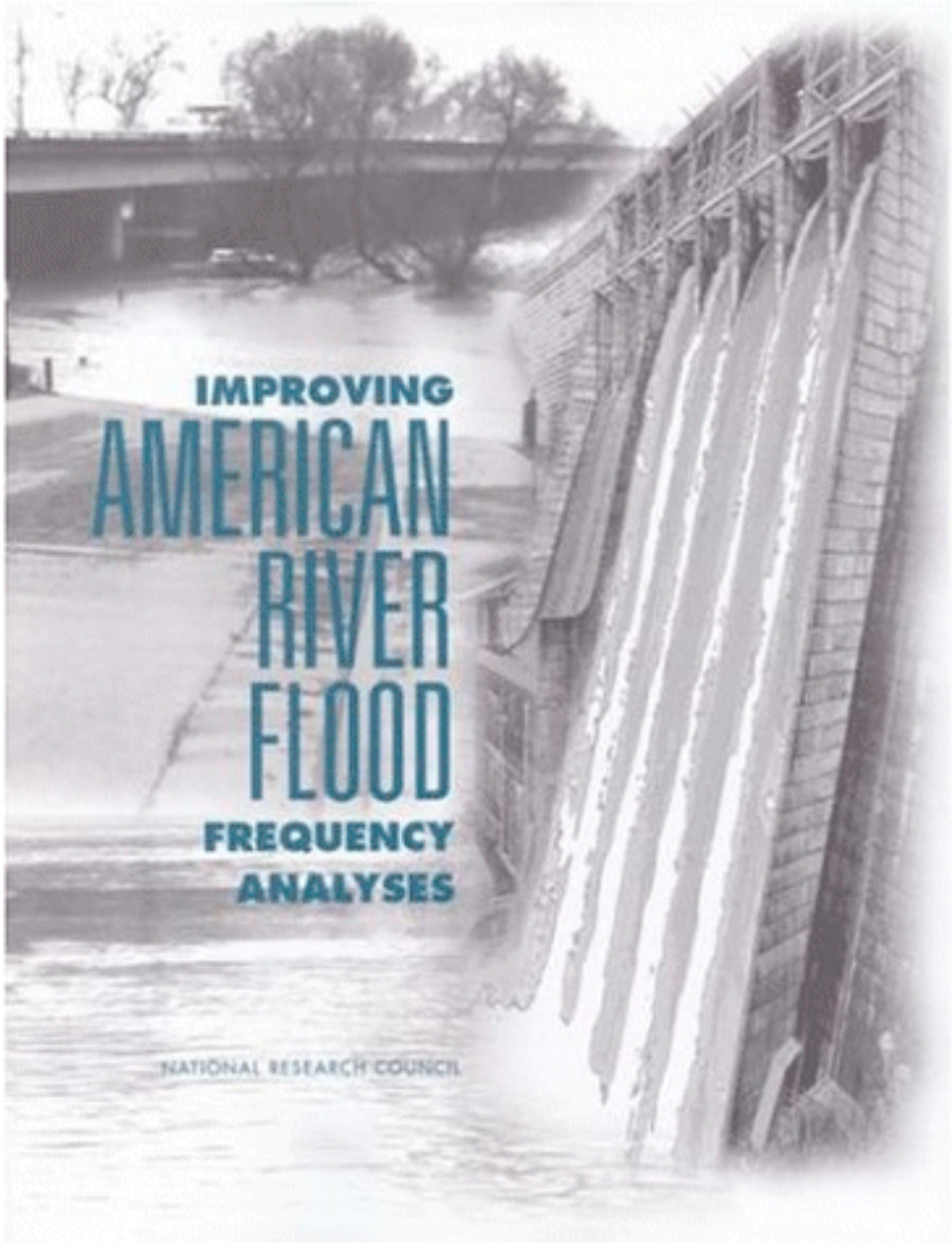
Flood Flow Frequency

Bulletin # 17B
of the
Hydrology Subcommittee

Revised September 1981
Editorial Corrections March 1982

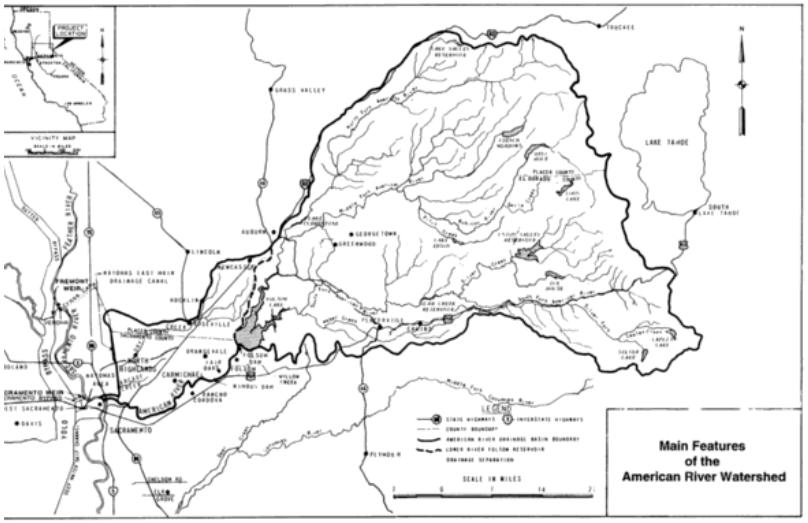
INTERAGENCY ADVISORY COMMITTEE
ON WATER DATA

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

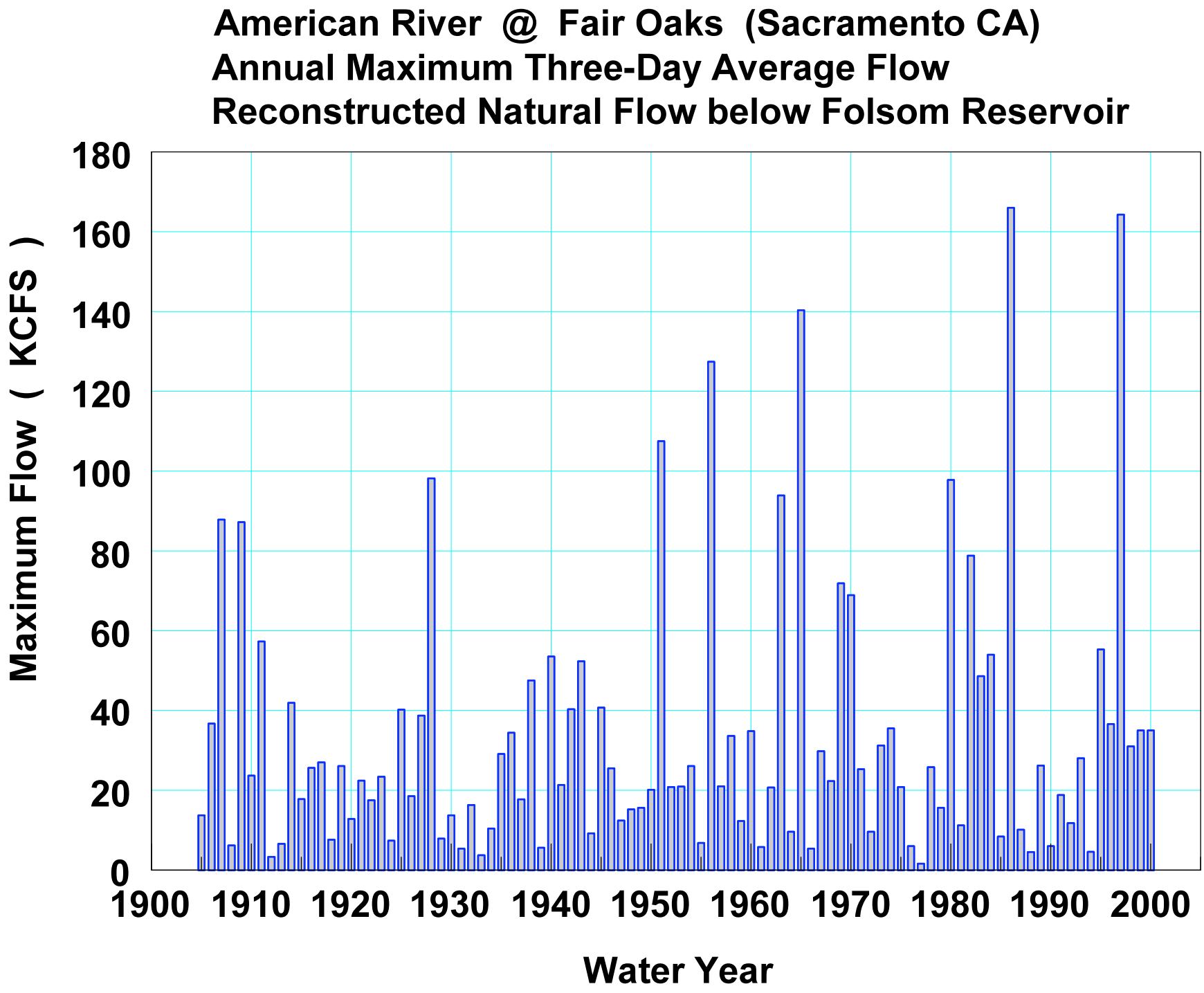


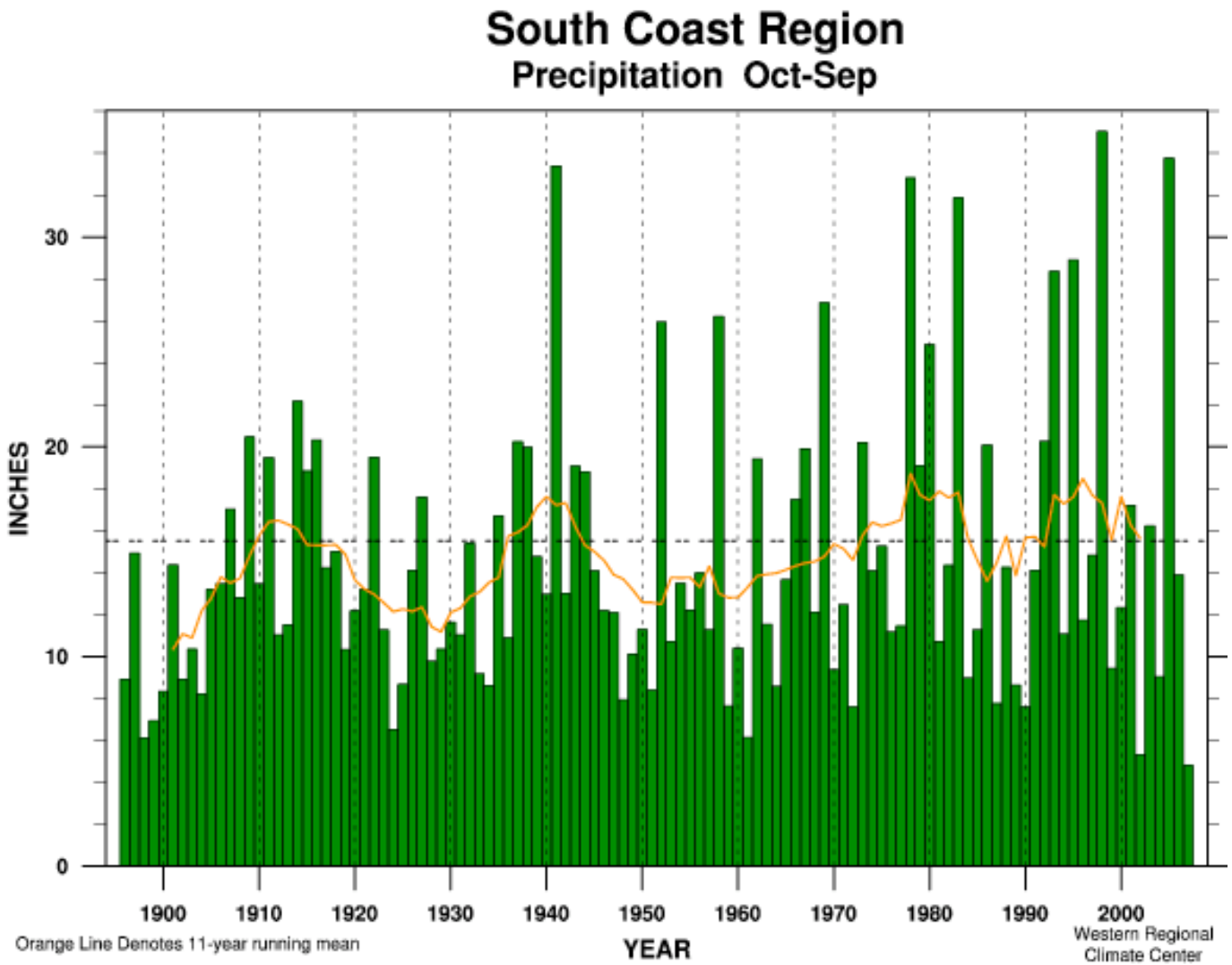
National Research Council

January 1999



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


American River @ Fair Oaks (Sacramento CA)
Annual Maximum Three-Day Average Flow
Reconstructed Natural Flow below Folsom Reservoir
Maximum Flow (KCFS)
0
20
40
60
80
100
120
140
160
180
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Water Year

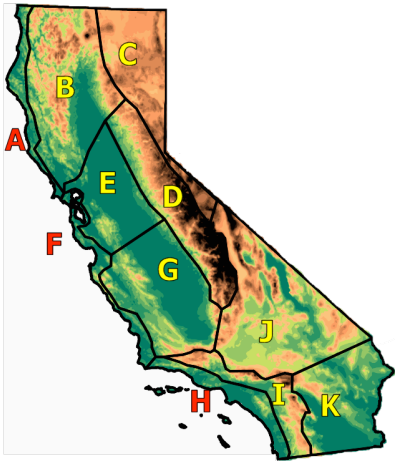


Linear Trend 1895-present	+ 3.60 ± 3.72 in.	(+ 23 ± 23%) per 100 yr			
Linear Trend 1949-present	+ 4.82 ± 12.01 in.	(+ 31 ± 77%) per 100 yr			
Linear Trend 1975-present	- 8.52 ± 34.69 in.	(- 54 ± 223%) per 100 yr			
Wettest Year	35.03 in. (225%)	in 1998		MEAN	15.51 in.
Driest Year	4.81 in. (31%)	in 2007		STDEV	7.57 in.
Oct-Sep 2007	4.81 in. (31%)			RANK	1 of 112

Water Year Oct-Sep Precip

South Coastal California

1895/96 thru 2006/07



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

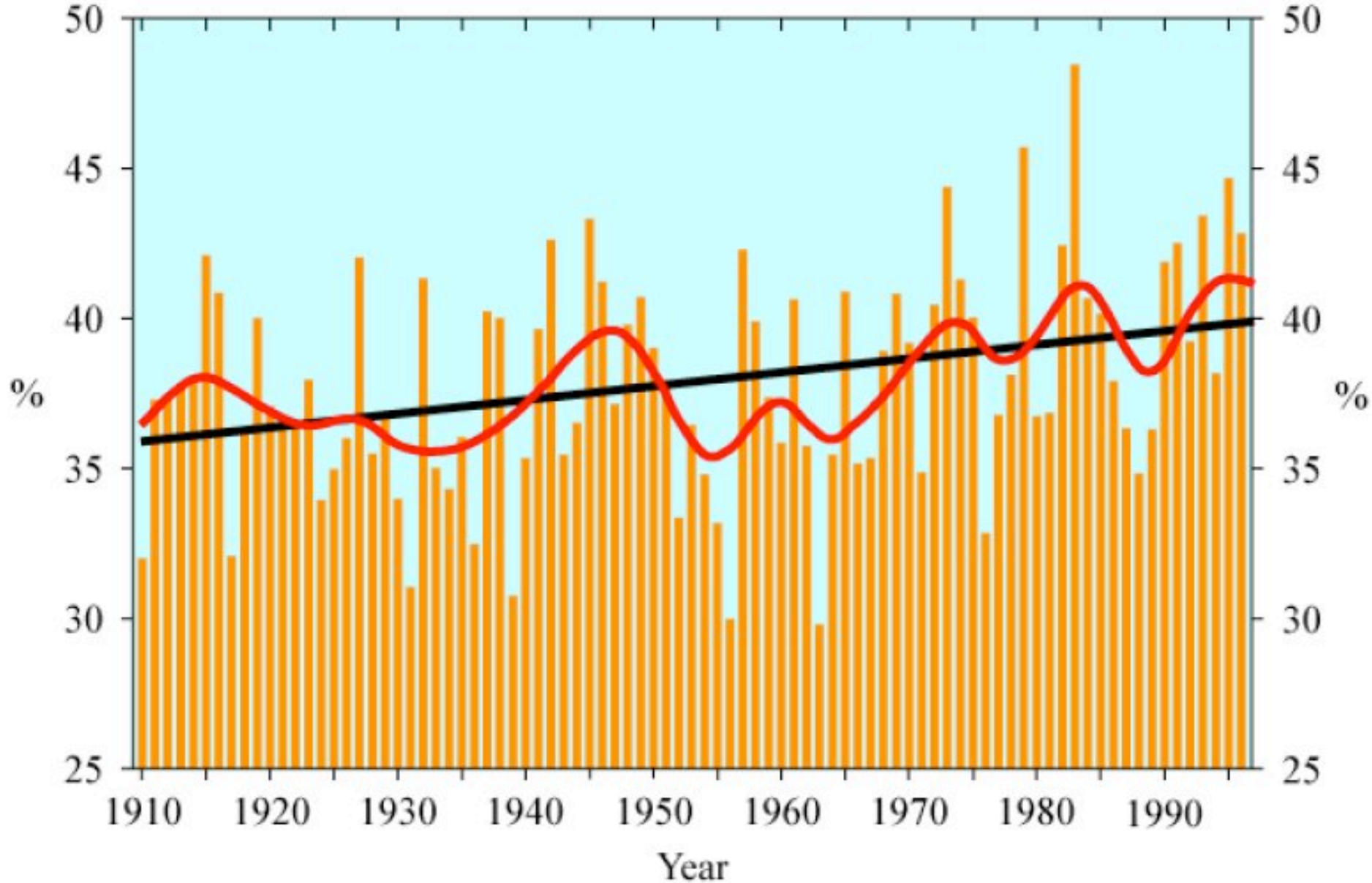
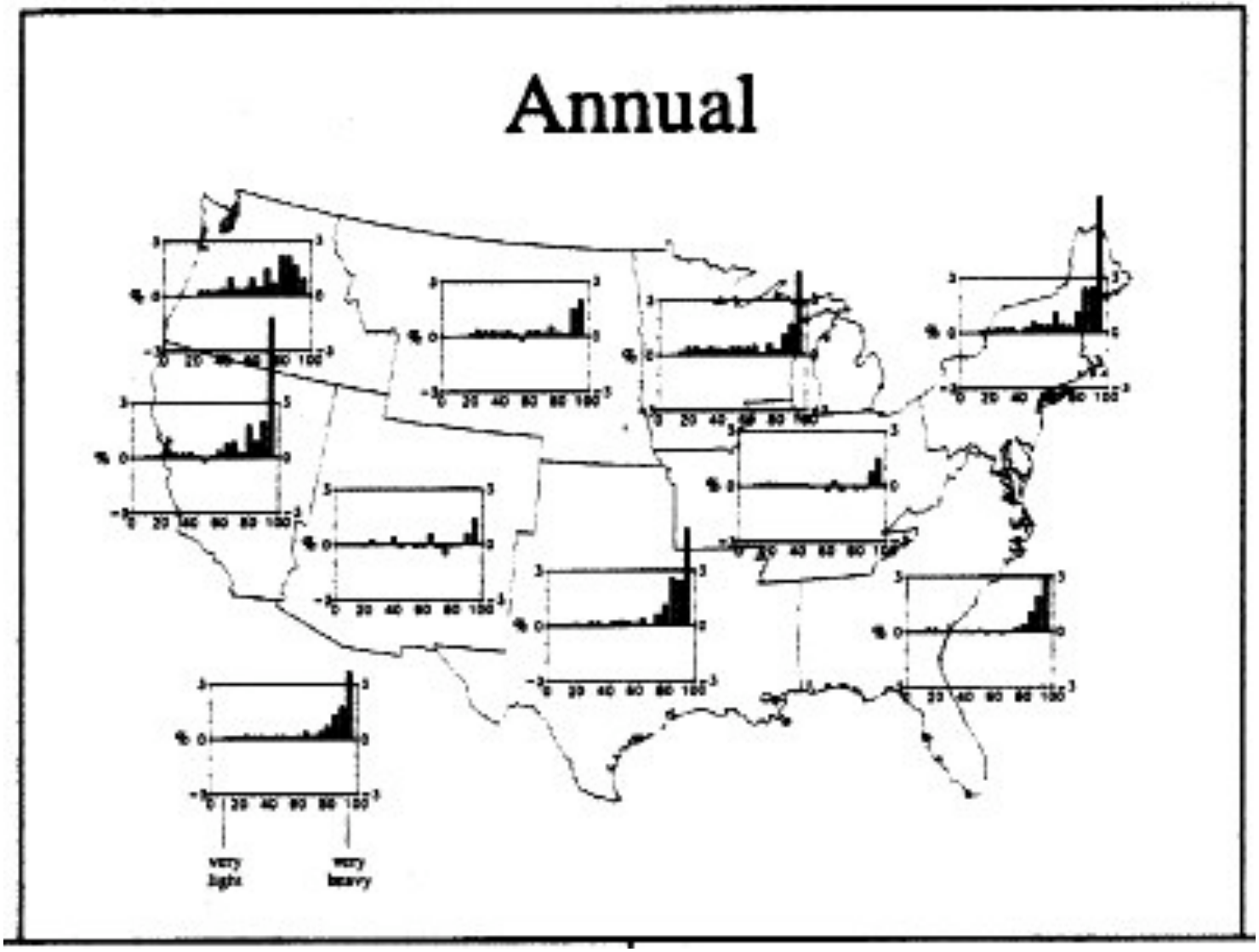


FIG. 2. Time series of the percent contribution of the upper 10 percentile of daily precipitation events to the total annual precipitation area-averaged across the United States. Smooth curve is a nine-point binomial filter, and the trend is also depicted.



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.

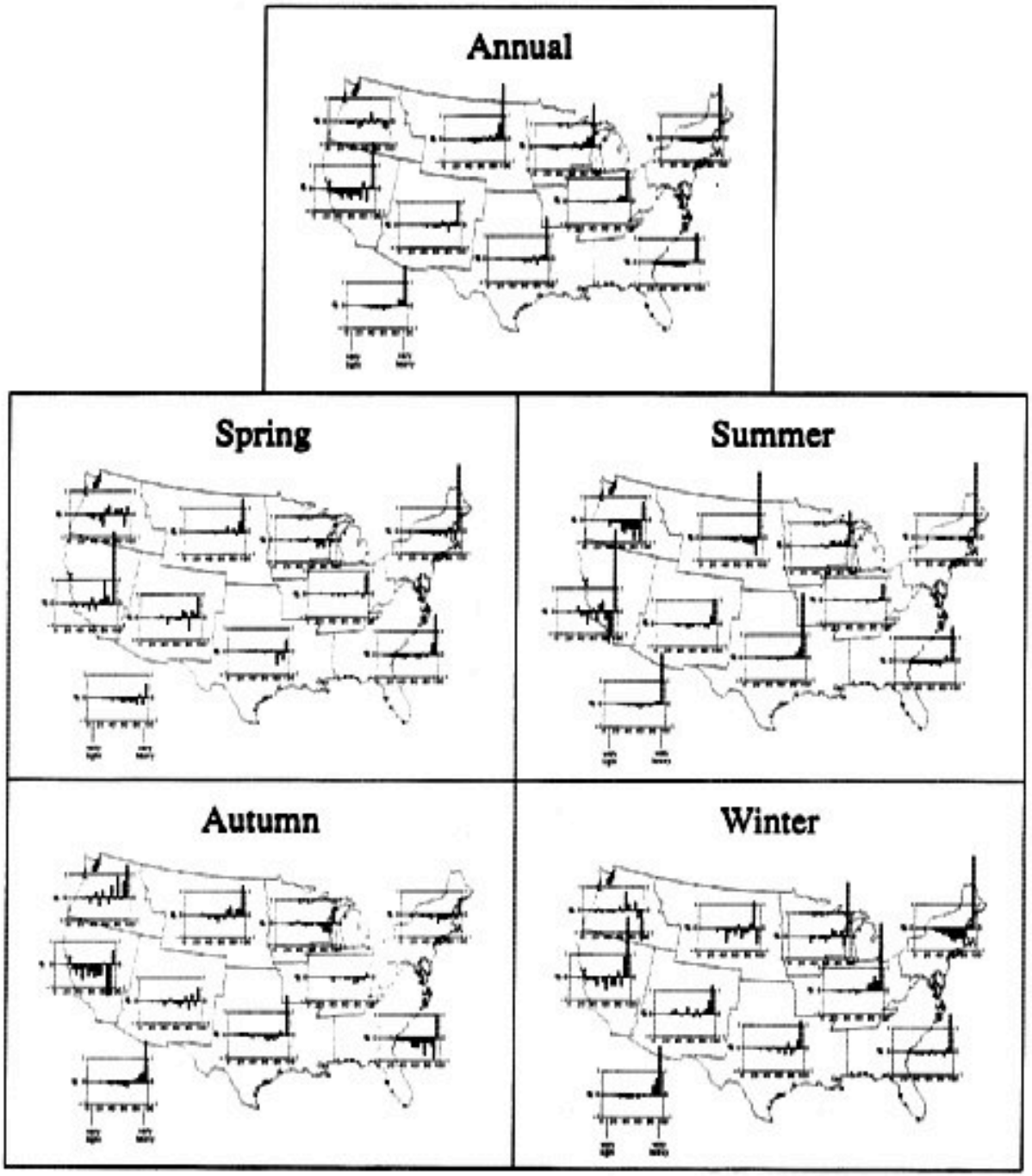


FIG. 5. The contribution to the trends in Fig. 1 attributed to trends in precipitation intensity. Trends are expressed as in Fig. 1.

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 yr)$^{-1}$]	Variance (%)	Fraction	Estimate [% (10 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.

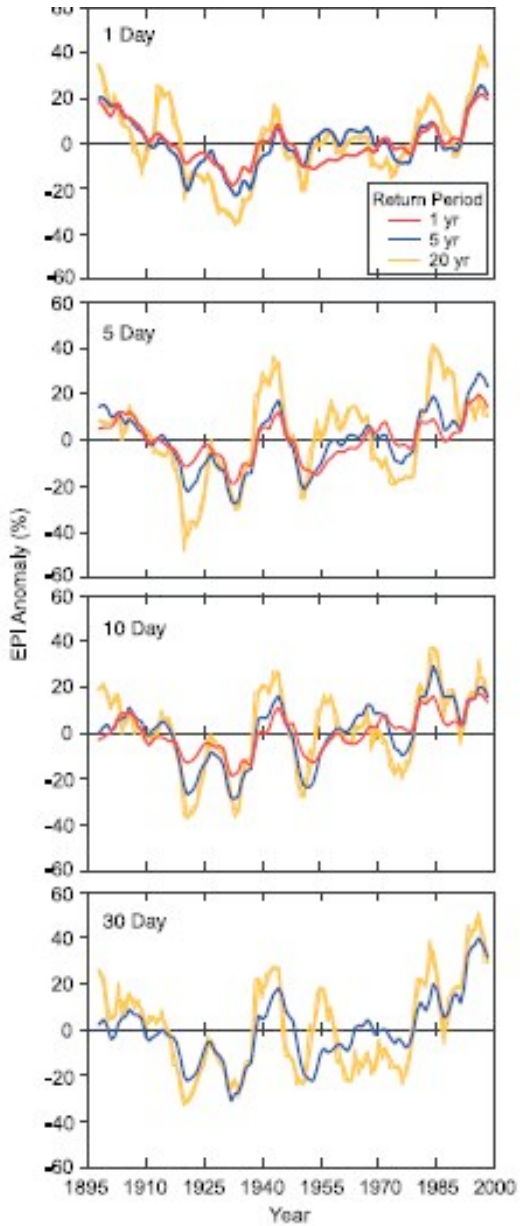


Figure 2. Time series of anomalies of the Extreme Precipitation Index, expressed in %, for various combinations of duration and return period. The time series have been smoothed with a 7-yr moving average filter. Return periods of 1 year (red), 5 years (blue), and 20 years (orange) are plotted on each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

1-Day

5-Day

10-Day

30-Day

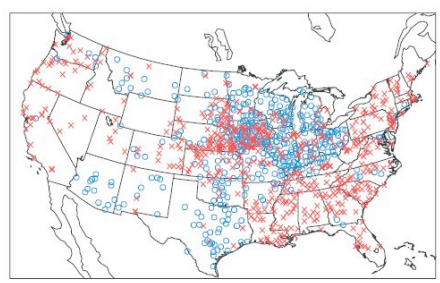


Figure 1. Location of stations with less than 10% missing daily precipitation data for 1895–2000. The symbol 'o' (in blue) indicates that long-term data were available prior to CDMP while the symbol 'x' (in red) indicates newly available long-term stations.

Extreme Precipitation Index

United States

1895-2000.

Selected durations

And

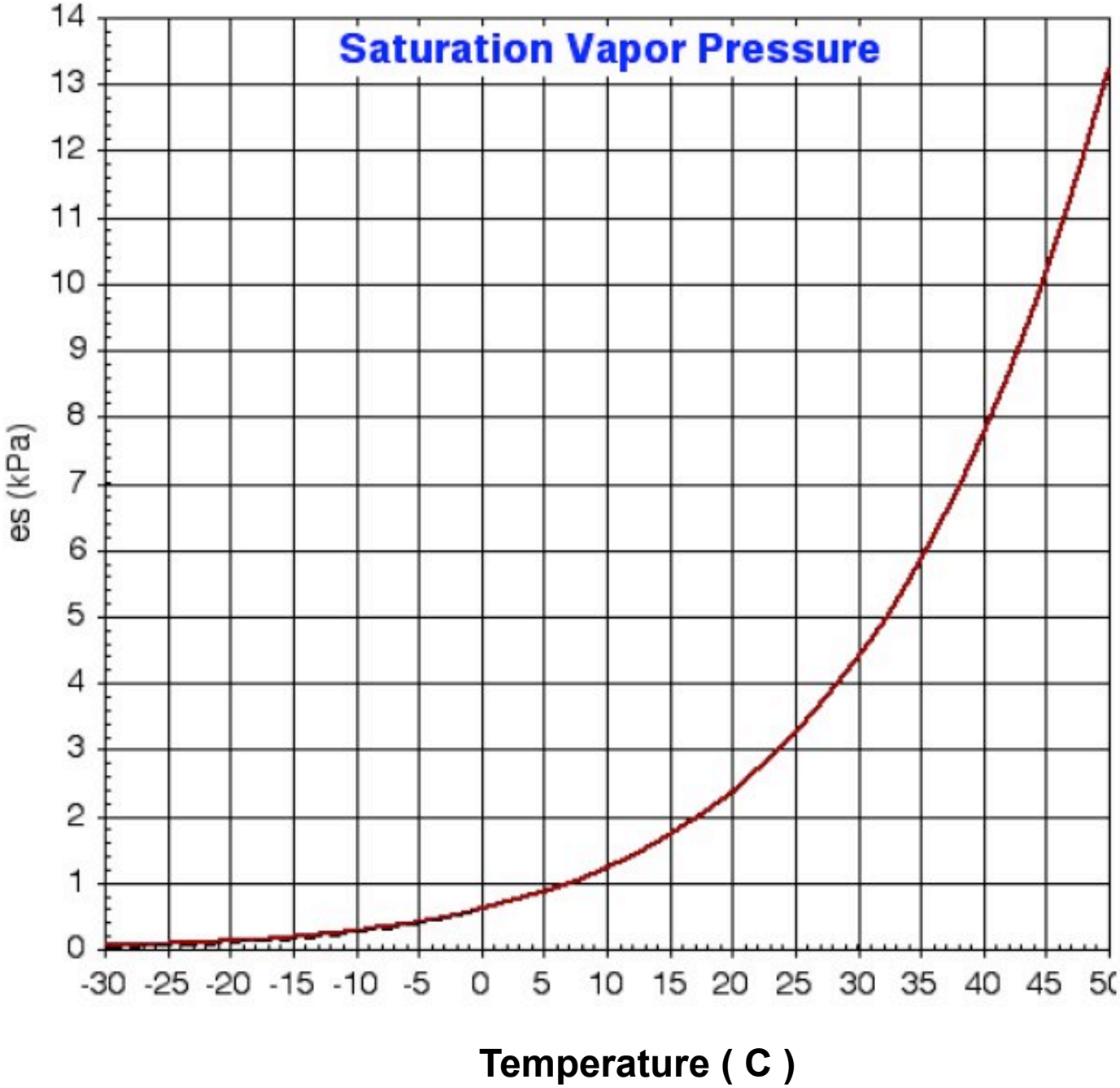
Return periods (1, 5, 20 yrs)

(Station density effects removed)

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.


Saturation Vapor Pressure
es (kPa)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
-30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50
Temperature (C)

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

Another view

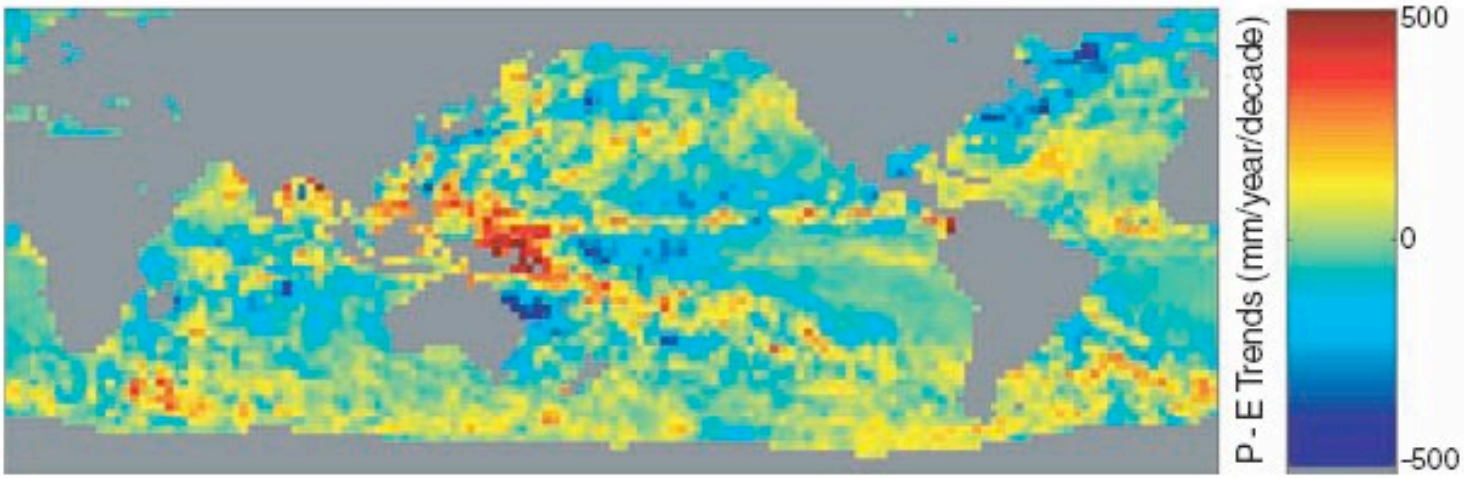


Fig. 3. Trends in satellite-derived $P - E$ for the period July 1987 through August 2006. The largest change was over the warm pool in the western Pacific: a wet area that became wetter.

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.

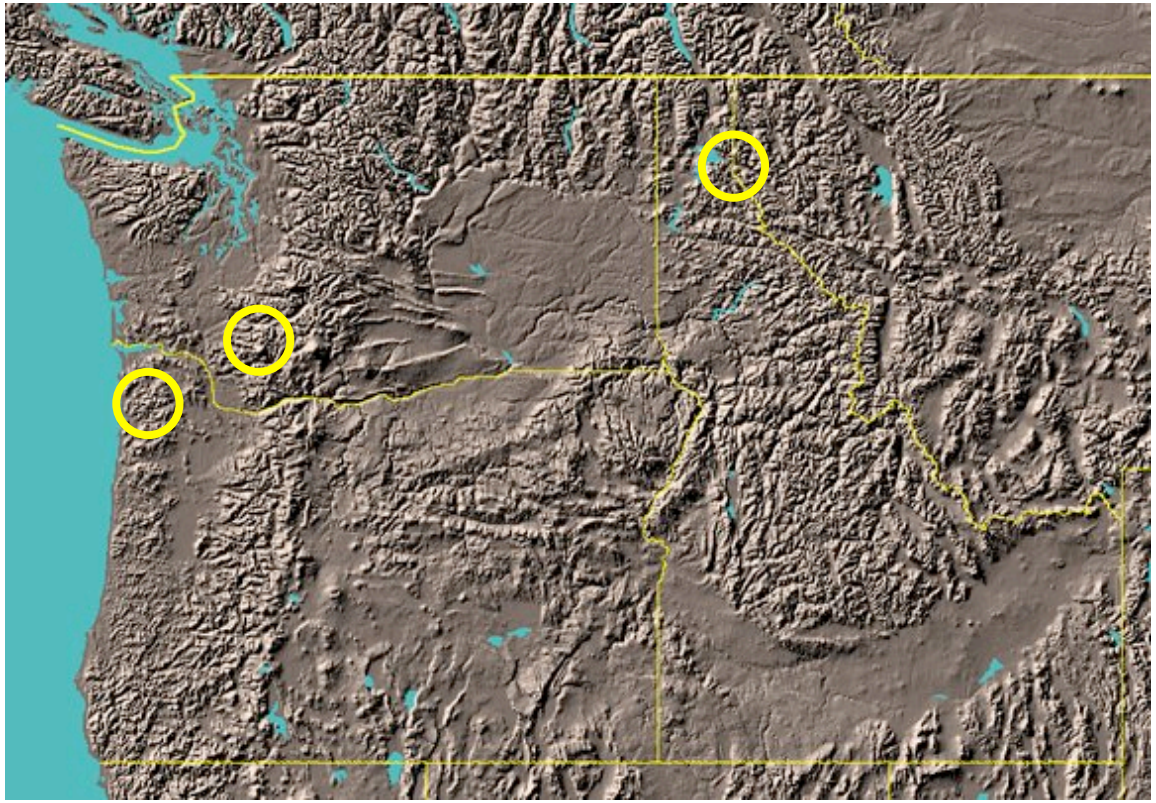
Parameter	Mean	Standard deviation	Trend
Evaporation	961 mm year^{-1}	10.1 mm year^{-1} (1.1%)	12.6 ± 4.8 mm year^{-1} decade^{-1} (1.3 ± 0.5% decade^{-1})
Precipitation	950 mm year^{-1}	12.7 mm year^{-1} (1.3%)	13.2 ± 4.8 mm year^{-1} decade^{-1} (1.4 ± 0.5% decade^{-1})
Total water	28.5 mm	0.292 mm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

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



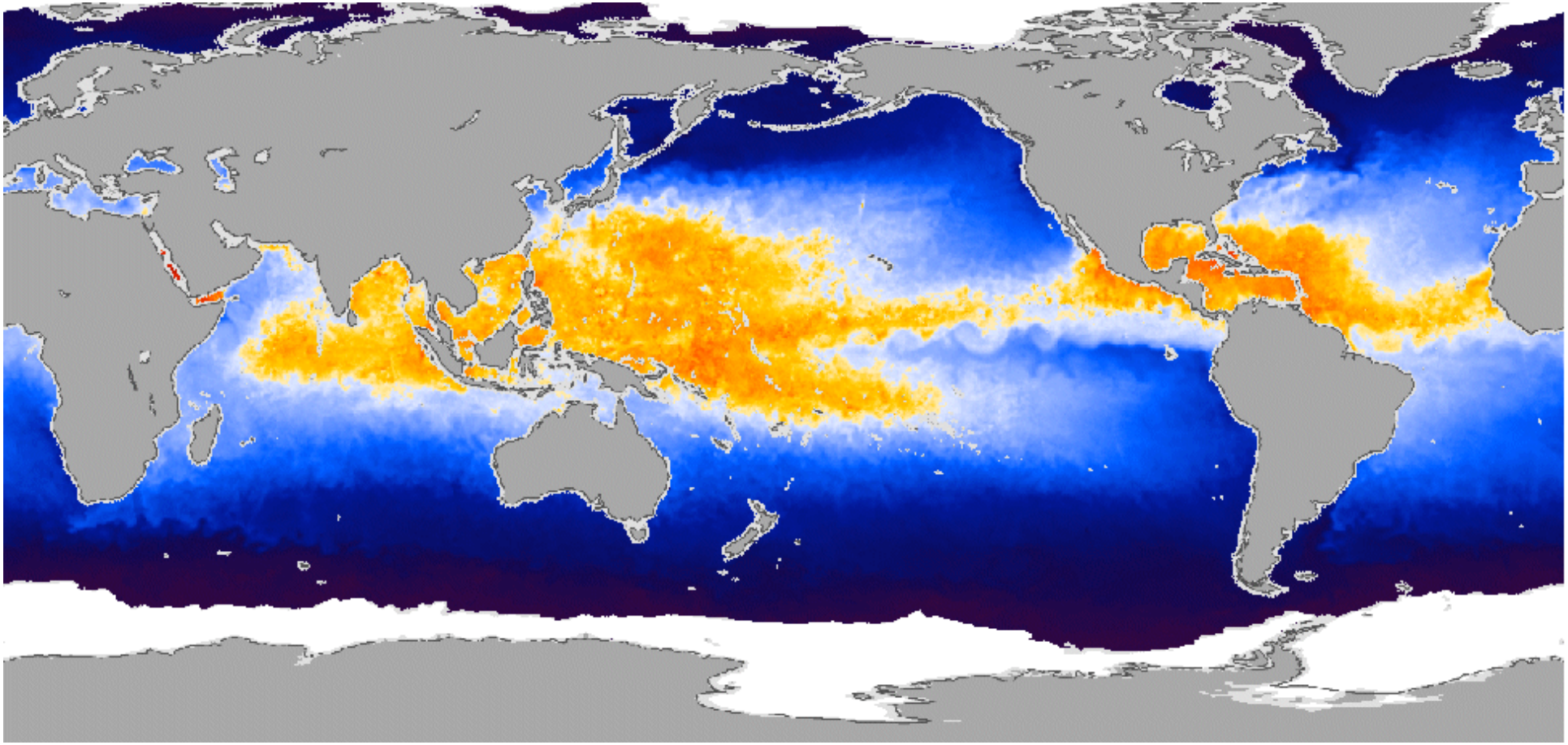
Old records broken by

23 % - Oregon

06 % - Washington

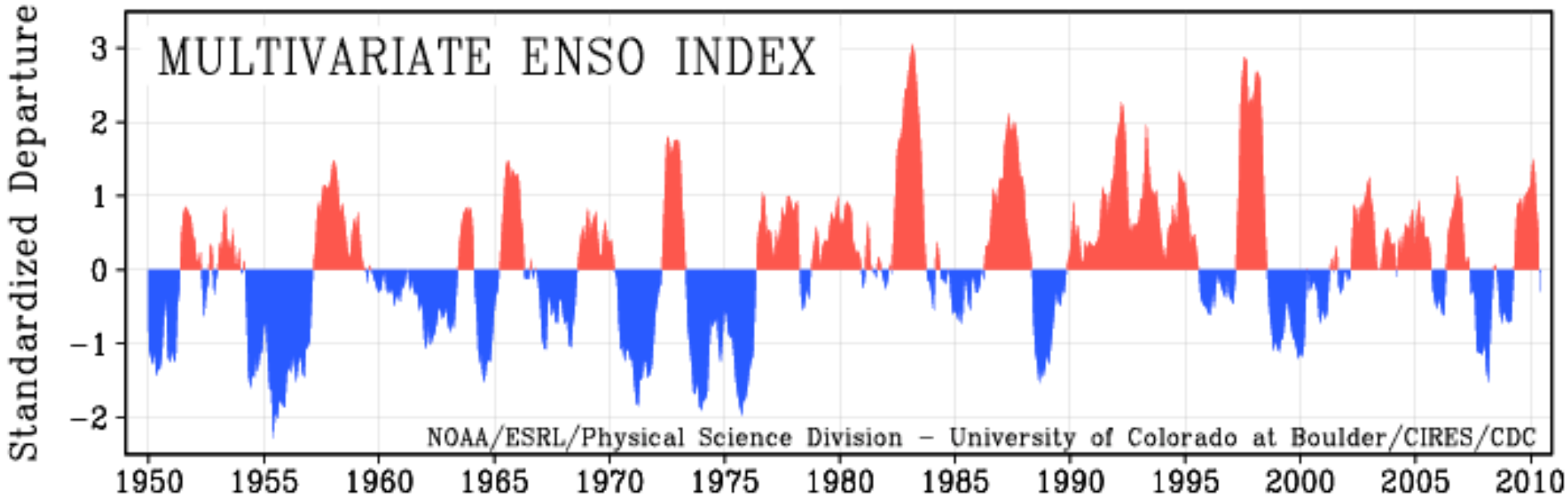
31 % - Idaho

The World's Warm Oceans



Thru June 2010

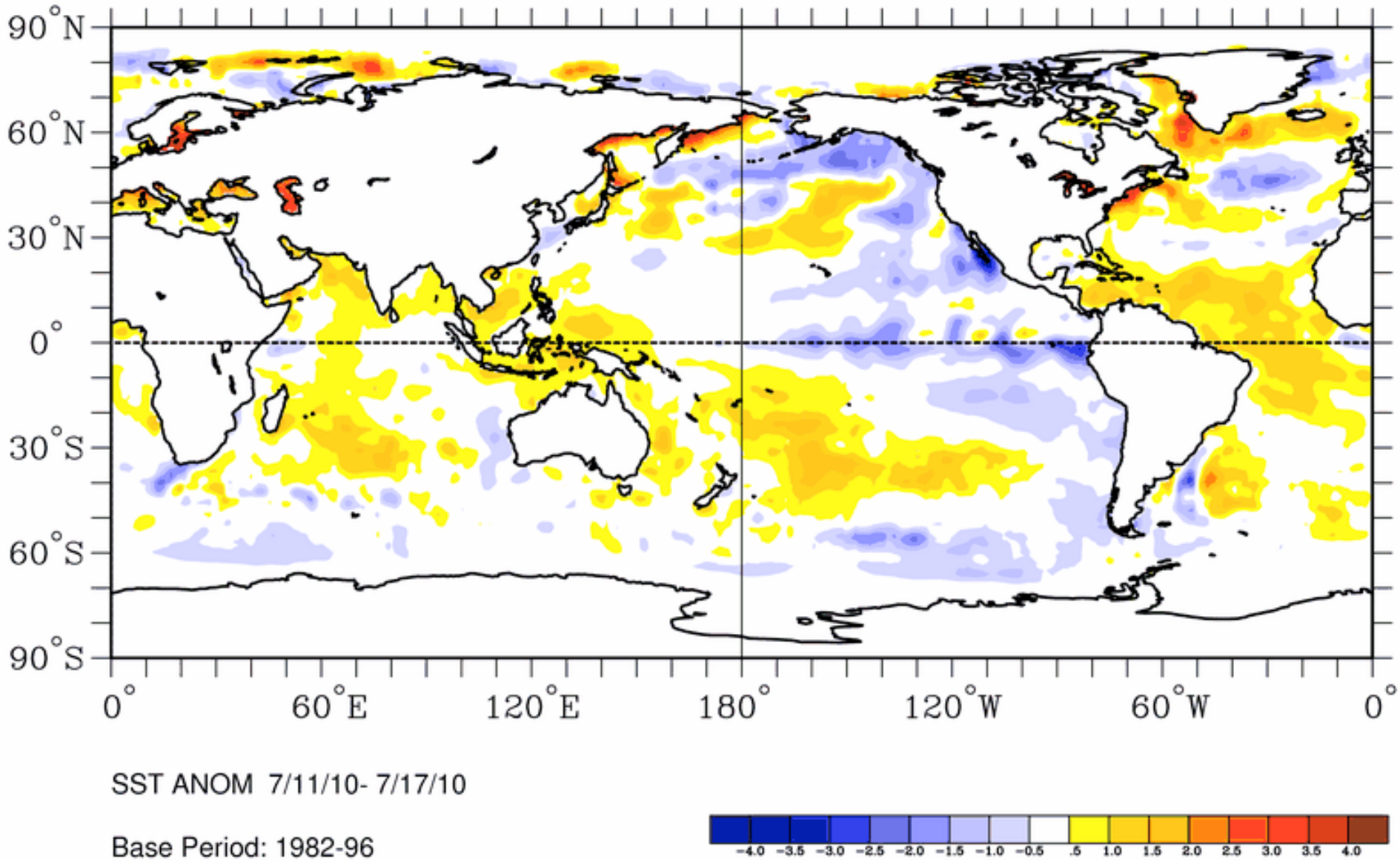
Typically “El Nino”



Typically “La Nina”

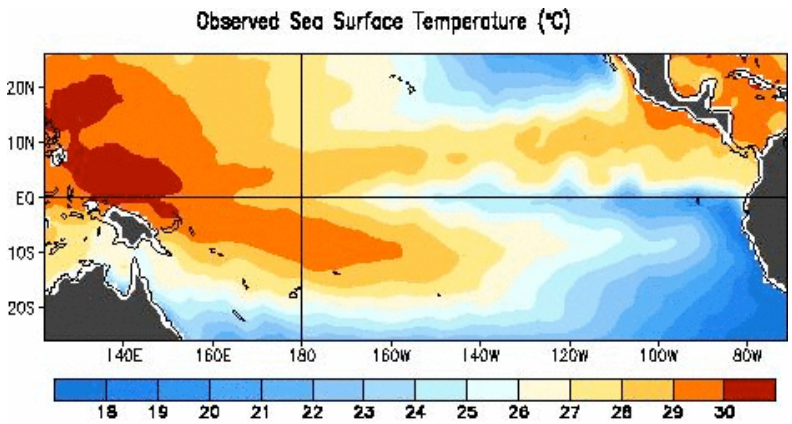
Courtesy Klaus Wolter & Mike Timlin,
NOAA Climate Diagnostics Center

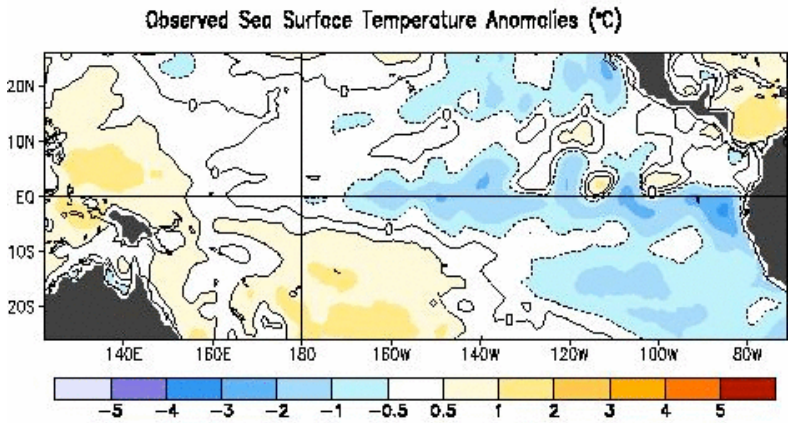
Global Sea Surface Temperature Departure from Average, 2010 July 11-17

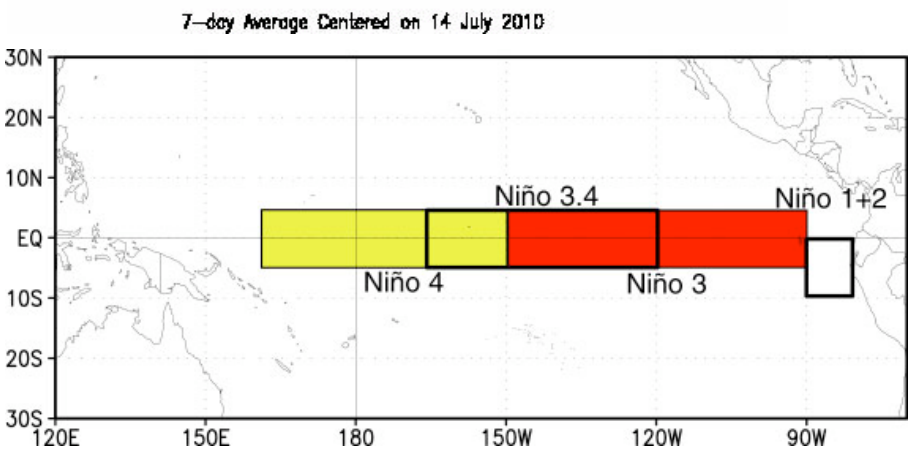


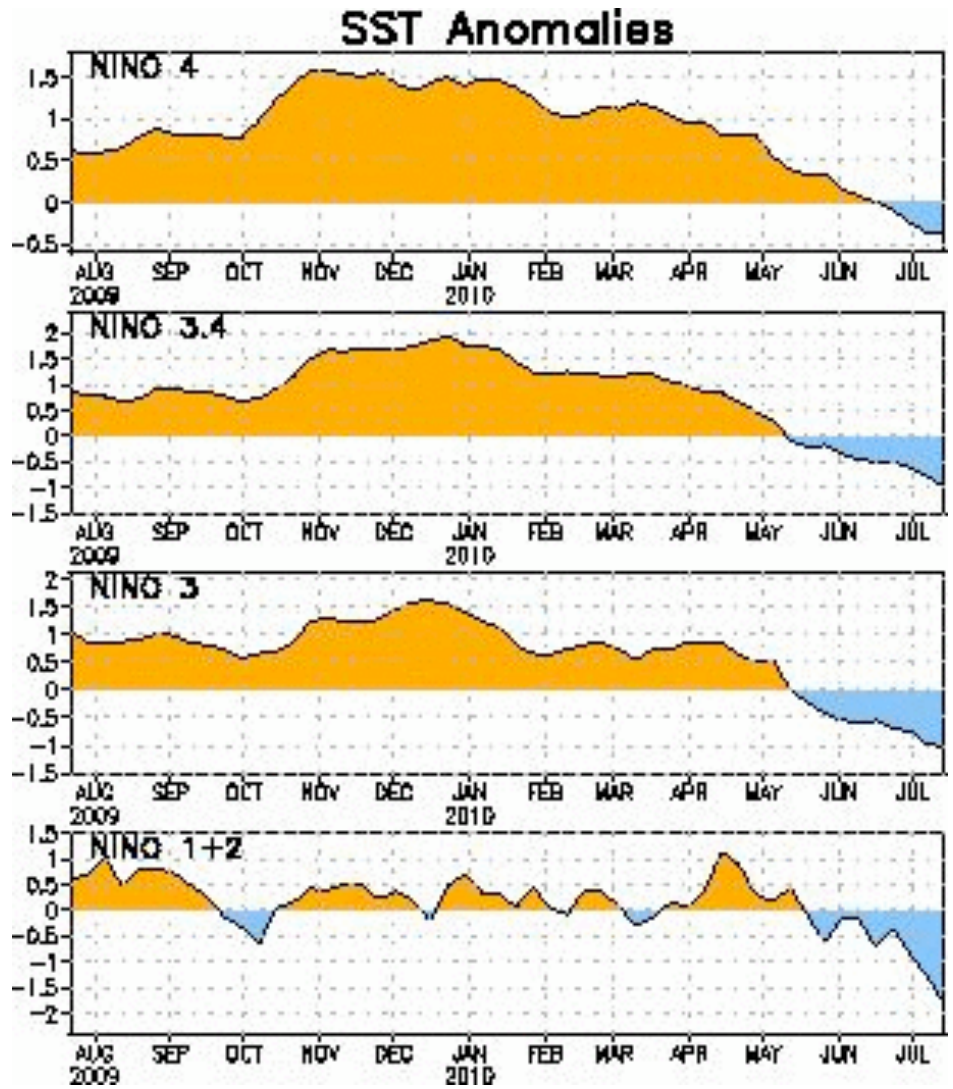
NOAA Physical Science Division, ESRL

Recent Evolution of Equatorial Pacific SST Departures

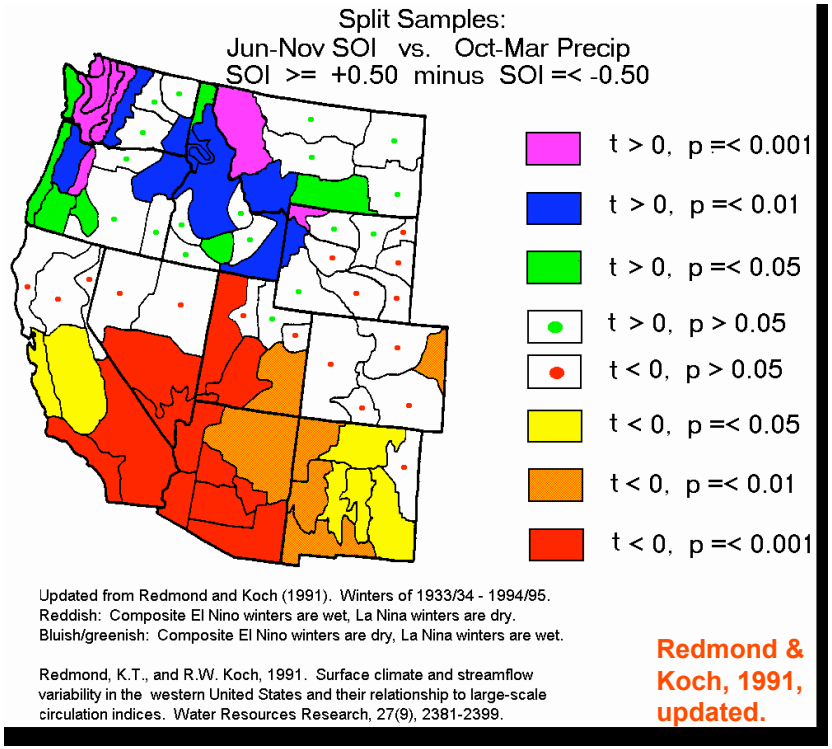


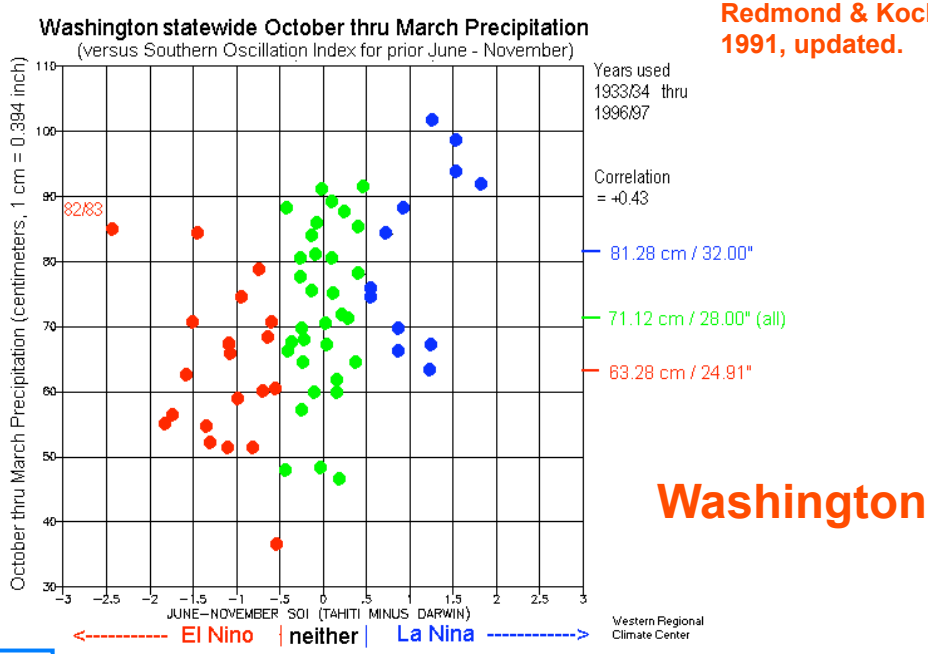




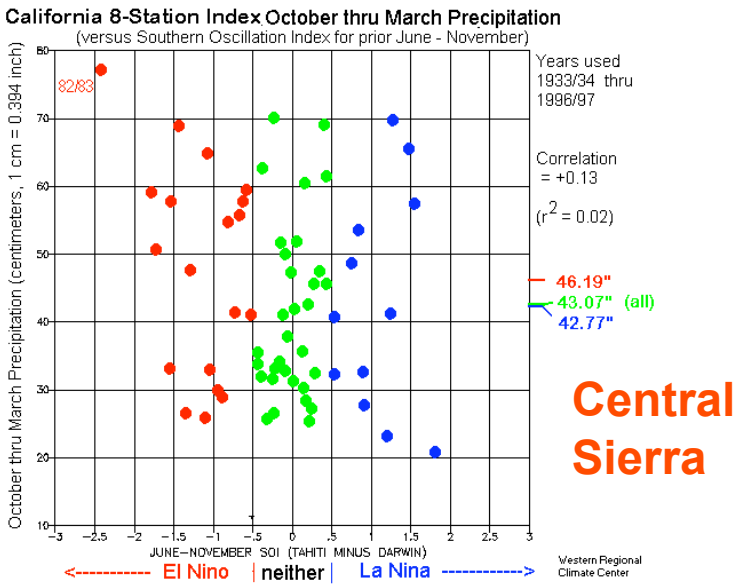


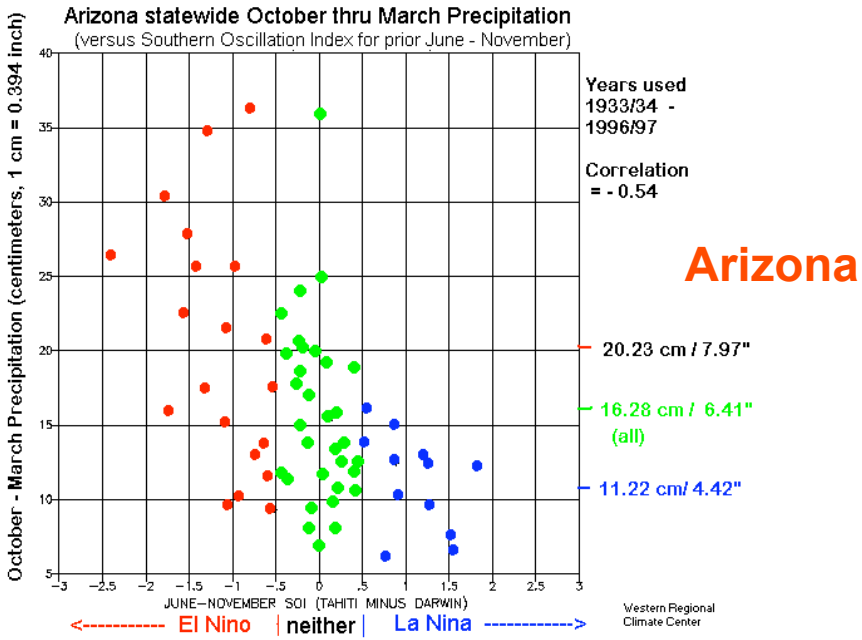
Updated through 2010 July 11-17

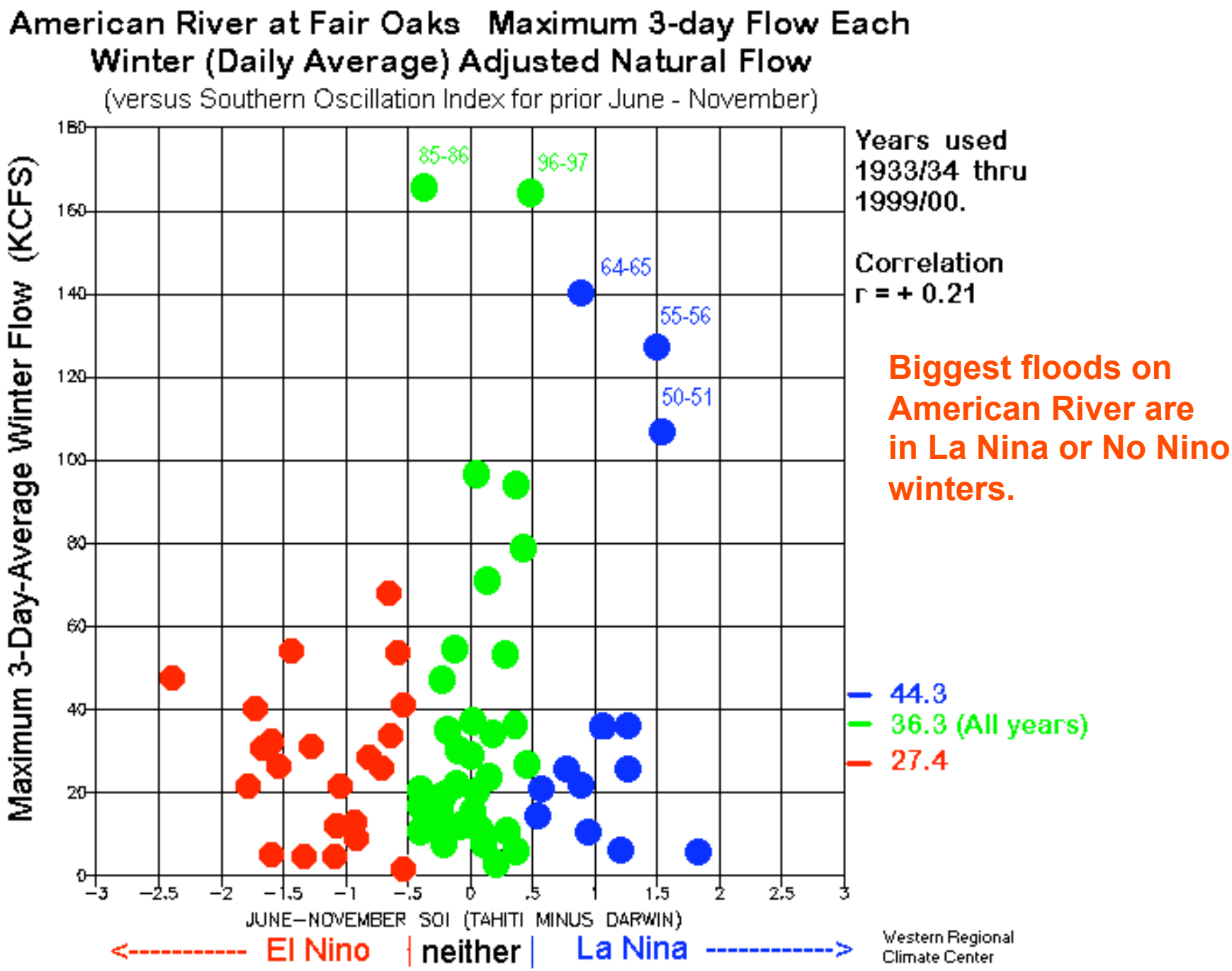

Split Samples:
Jun-Nov SOI vs. Oct-Mar Precip
SOI >= +0.50 minus SOI =< -0.50
t > 0, p =< 0.001
t > 0, p =< 0.01
t > 0, p =< 0.05
t > 0, p > 0.05
t < 0, p > 0.05
t < 0, p =< 0.05
t < 0, p =< 0.01
t < 0, p =< 0.001
Updated from Redmond and Koch (1991). Winters of 1933/34 - 1994/95.
Reddish: Composite 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 statewide October thru March Precipitation
(versus Southern Oscillation Index for prior June - November)
October thru March Precipitation (centimeters, 1 cm = 0.394 inch)
Years used 1933/34 thru 1996/97
Correlation = +0.43
82/83
81.28 cm / 32.00"
71.12 cm / 28.00" (all)
63.28 cm / 24.91"
JUNE–NOVEMBER SOI (TAHITI MINUS DARWIN)
<---------- El Nino | neither | La Nina ---------->
Western Regional Climate Center
Washington

ENSO

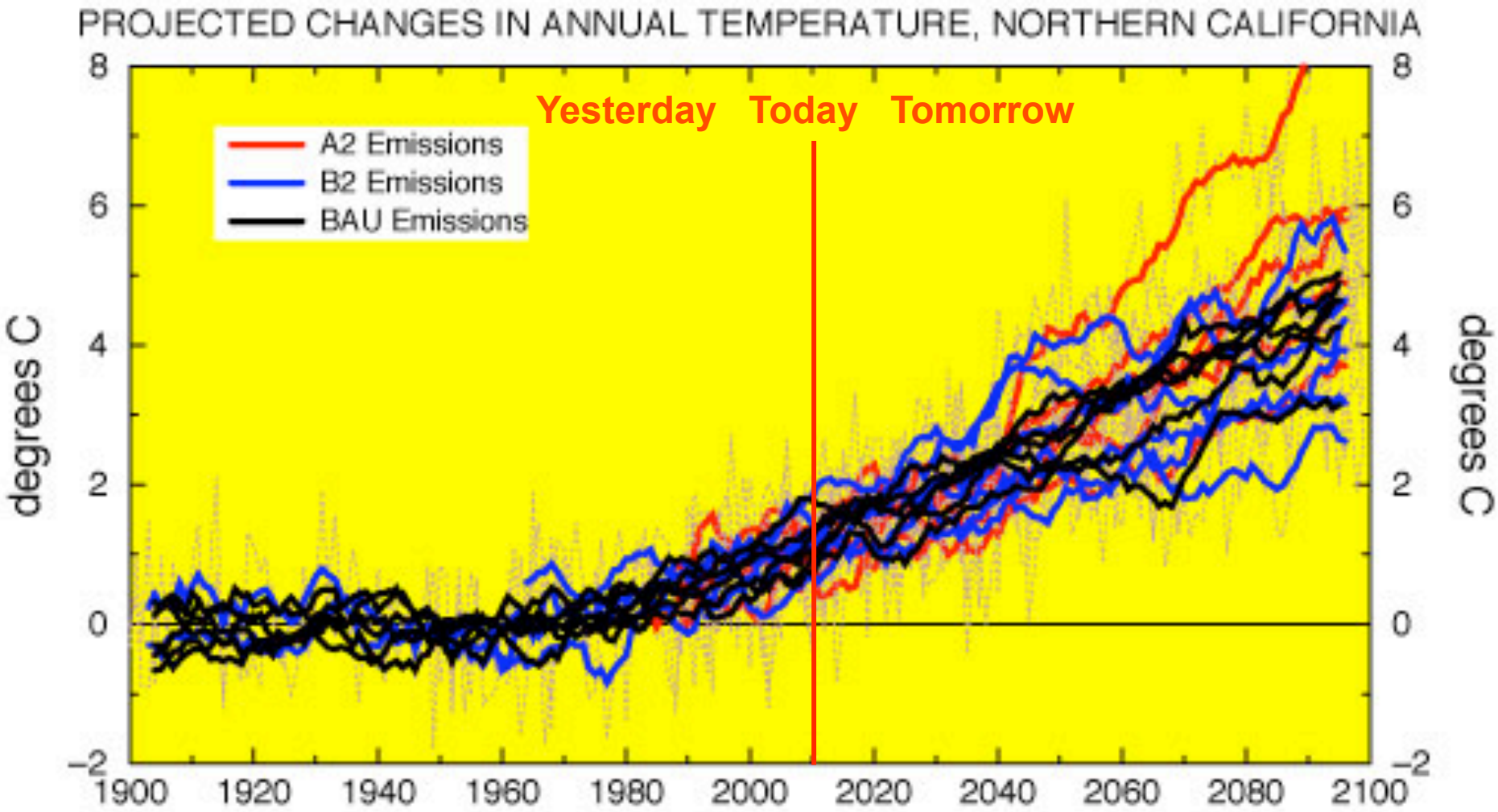

California 8-Station Index October thru March Precipitation
(versus Southern Oscillation Index for prior June - November)
October thru March Precipitation (centimeters, 1 cm = 0.394 inch)
Years used 1933/34 thru 1996/97
Correlation = +0.13
(r^2 = 0.02)
82/83
46.19"
43.07" (all)
42.77"
JUNE–NOVEMBER SOI (TAHITI MINUS DARWIN)
<---------- El Nino | neither | La Nina ---------->
Western Regional Climate Center
Central Sierra


Arizona statewide October thru March Precipitation
(versus Southern Oscillation Index for prior June - November)
October - March Precipitation (centimeters, 1 cm = 0.394 inch)
Years used 1933/34 - 1996/97
Correlation = - 0.54
20.23 cm / 7.97"
16.28 cm / 6.41" (all)
11.22 cm/ 4.42"
JUNE–NOVEMBER SOI (TAHITI MINUS DARWIN)
<---------- El Nino | neither | La Nina ---------->
Western Regional Climate Center
Arizona

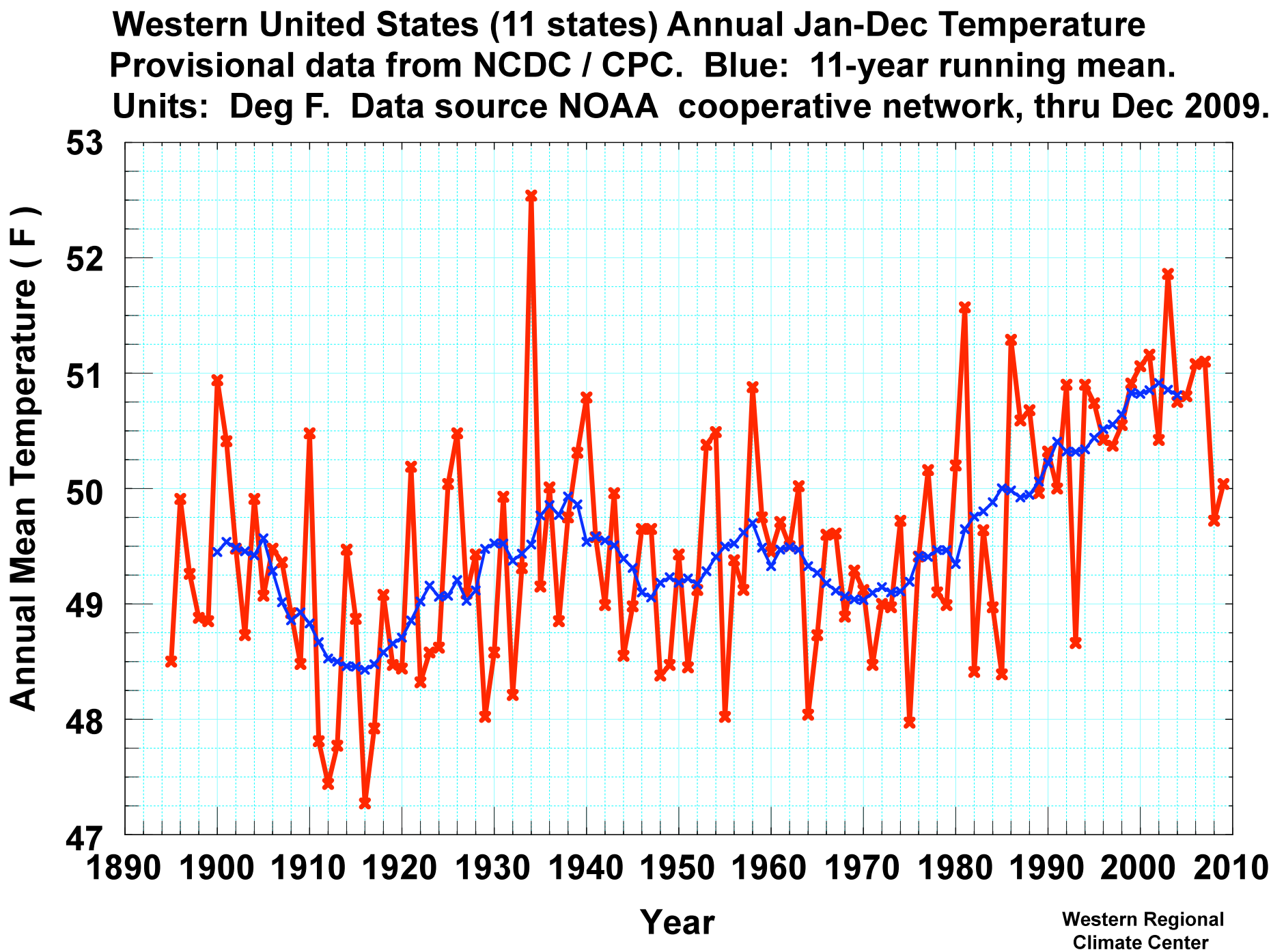

American River at Fair Oaks Maximum 3-day Flow Each Winter (Daily Average) Adjusted Natural Flow
(versus Southern Oscillation Index for prior June - November)
Maximum 3-Day-Average Winter Flow (KCFS)
85-86
96-97
64-65
55-56
50-51
Years used 1933/34 thru 1999/00.
Correlation r = + 0.21
Biggest floods on American River are in La Nina or No Nino winters.
44.3
36.3 (All years)
27.4
JUNE–NOVEMBER SOI (TAHITI MINUS DARWIN)
<---------- El Nino | neither | La Nina ---------->
Western Regional Climate Center

COPYRIGHT © 1997 by RAY STERNER

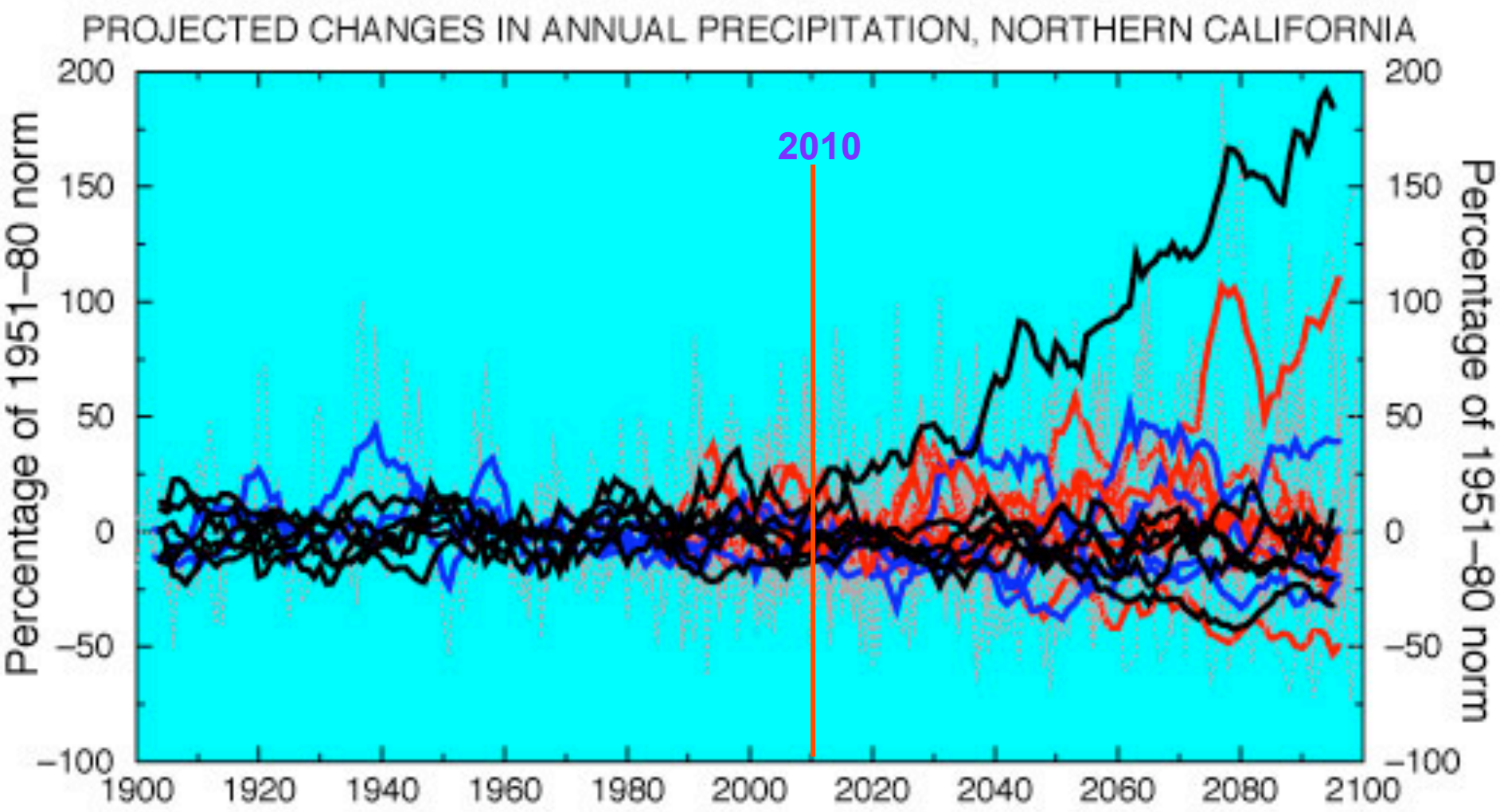
Courtesy of Mike Dettinger, USGS / Scripps.



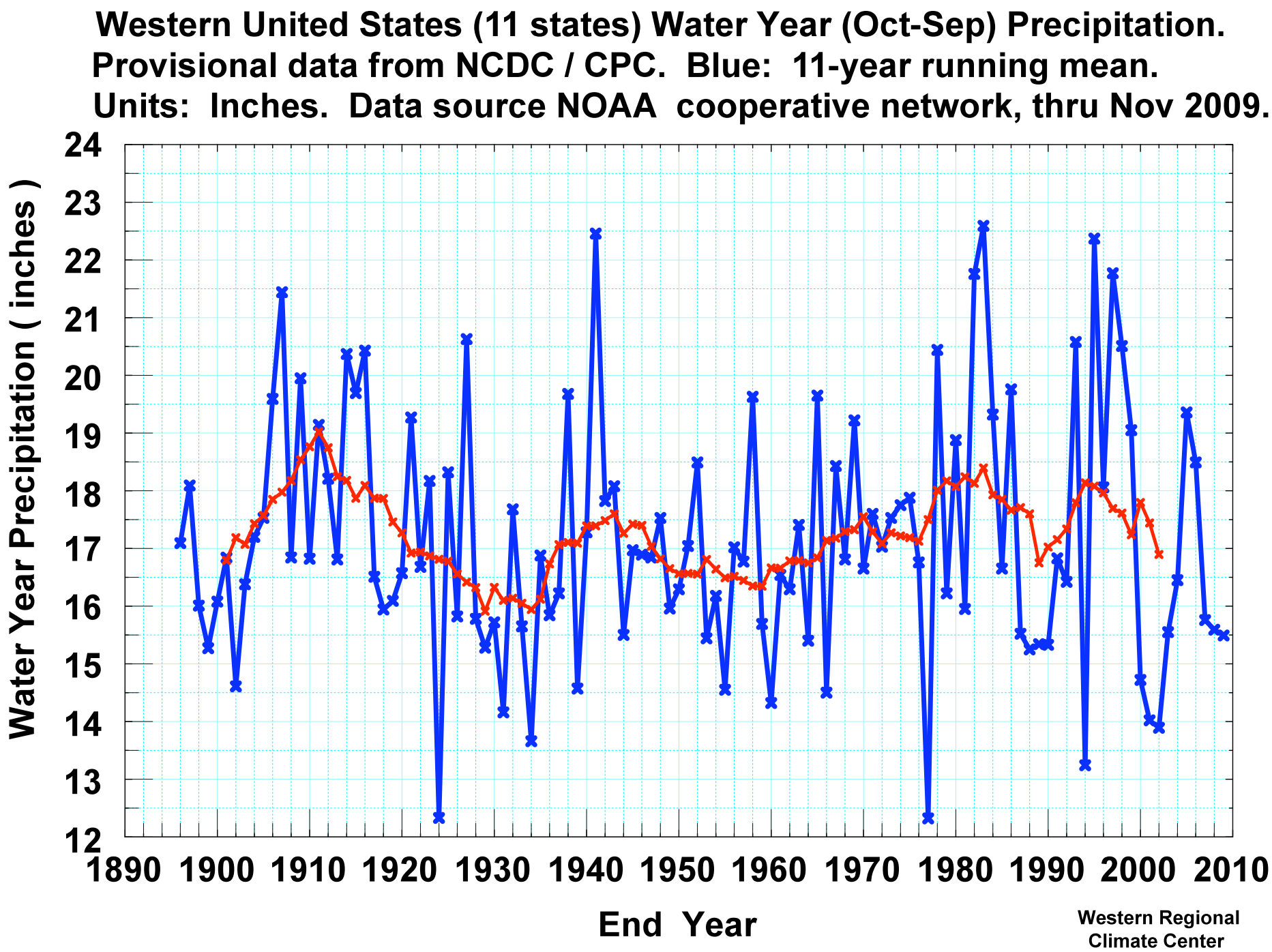
Dettinger MD. 2005. From climate change spaghetti to climate-change distributions for 21st Century California. San Francisco Estuary and Watershed Science. Vol. 3, Issue 1, (March 2005), Article 4. http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art4

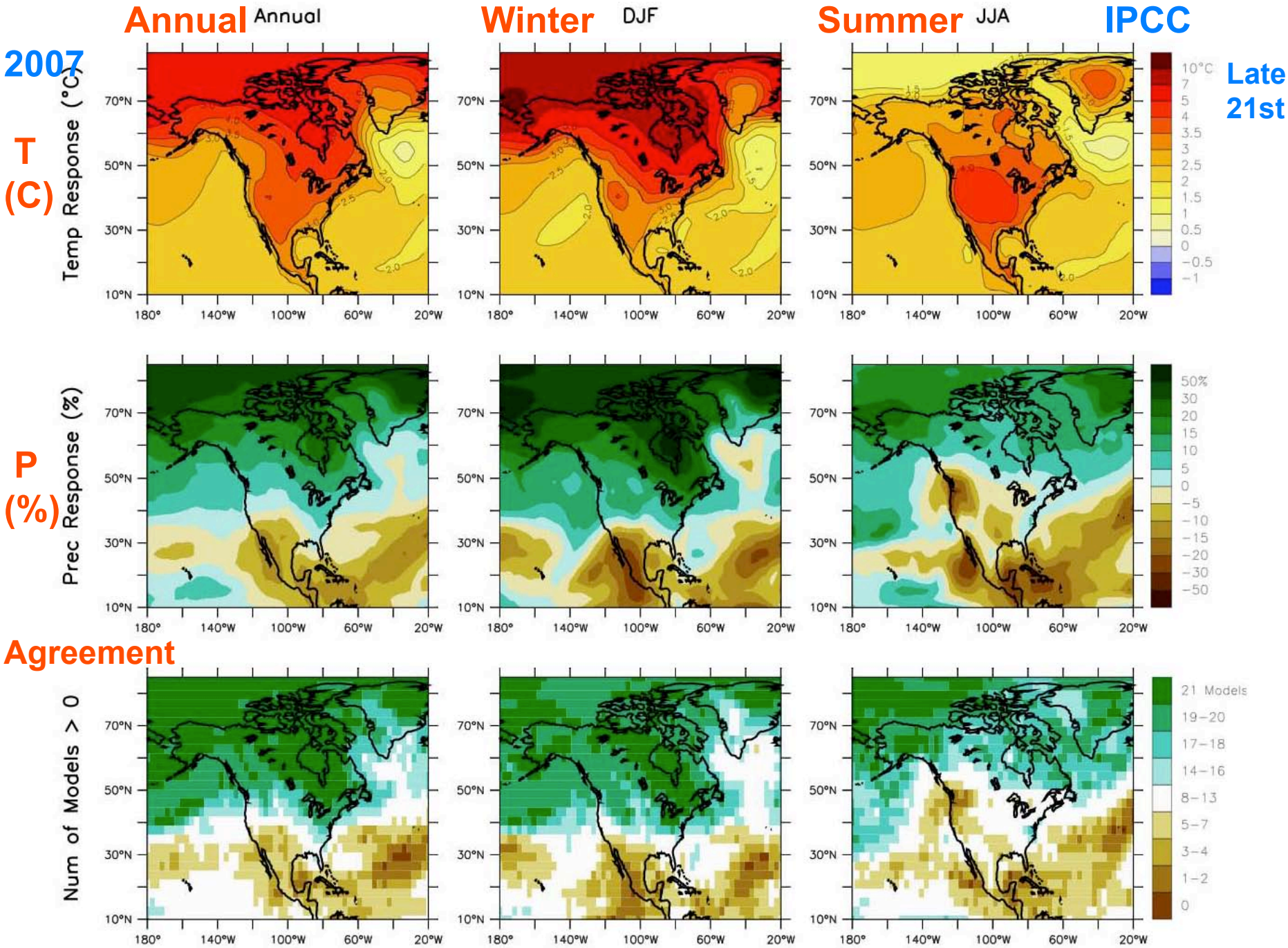

Western United States (11 states) Annual Jan-Dec Temperature
Provisional data from NCDC / CPC. Blue: 11-year running mean.
Units: Deg F. Data source NOAA cooperative network, thru Dec 2009.
Annual Mean Temperature (F)
53
52
51
50
49
48
47
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year
Western Regional
Climate Center

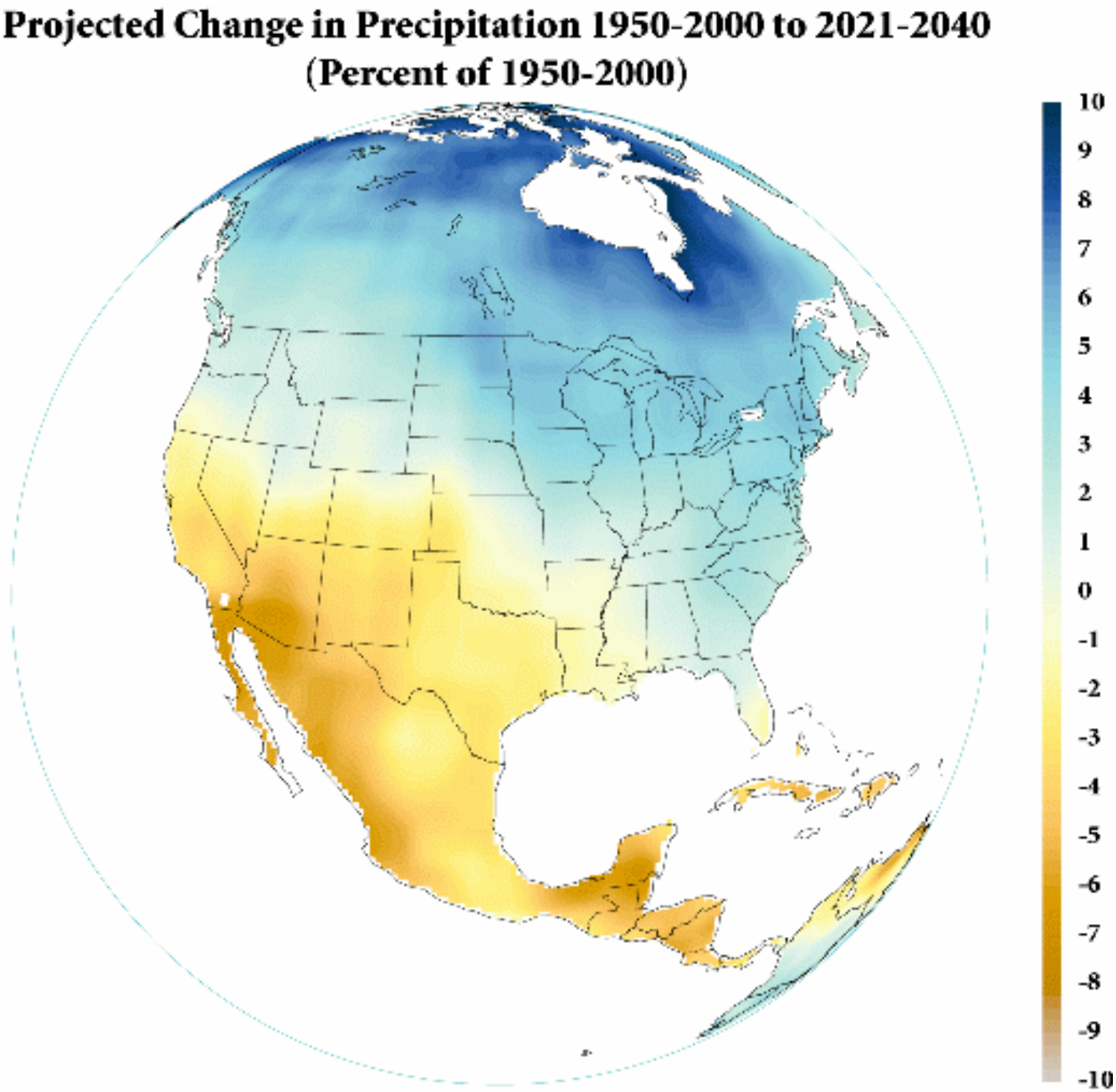
Courtesy of Mike Dettinger, USGS / Scripps.



Dettinger MD. 2005. From climate change spaghetti to climate-change distributions for 21st Century California. San Francisco Estuary and Watershed Science. Vol. 3, Issue 1, (March 2005), Article 4. http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art4


Western United States (11 states) Water Year (Oct-Sep) Precipitation.
Provisional data from NCDC / CPC. Blue: 11-year running mean.
Units: Inches. Data source NOAA cooperative network, thru Nov 2009.
Water Year Precipitation (inches)
24
23
22
21
20
19
18
17
16
15
14
13
12
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
End Year
Western Regional
Climate Center


Annual
Annual
Winter
DJF
Summer
JJA
IPCC
2007
Late 21st
T (C)
Temp Response (°C)
P (%)
Prec Response (%)
Agreement
Num of Models > 0
70°N
50°N
30°N
10°N
180°
140°W
100°W
60°W
20°W
10°C
7
5
4
3.5
3
2.5
2
1.5
1
0.5
0
−0.5
−1
50%
30
20
15
10
5
0
−5
−10
−15
−20
−30
−50
21 Models
19−20
17−18
14−16
8−13
5−7
3−4
1−2
0



Average of 19 climate models. 2007.

20 years from 2010

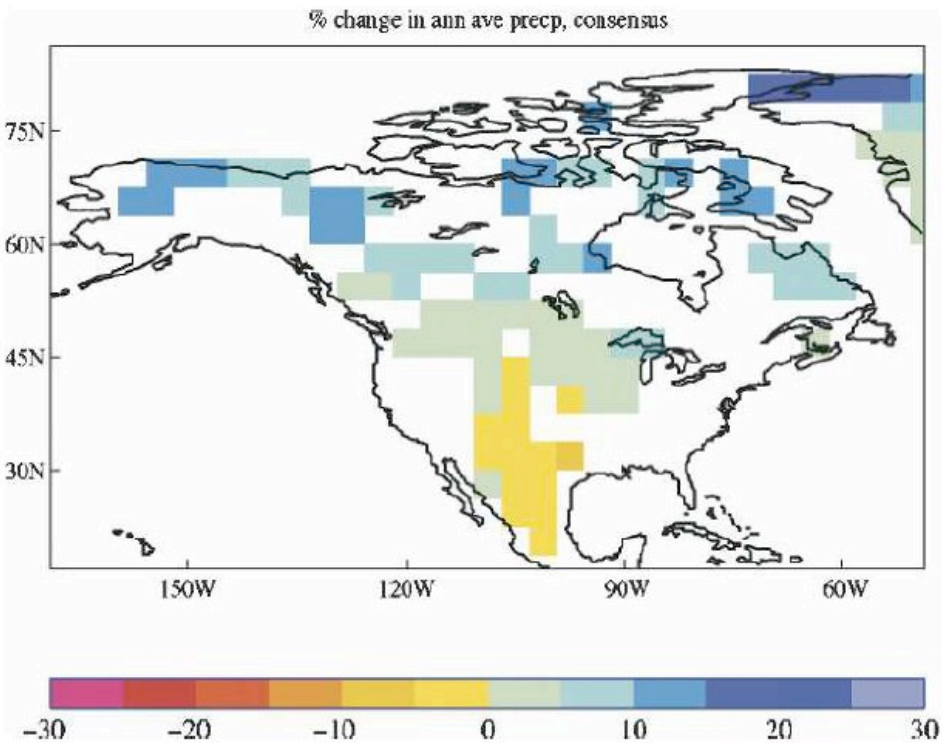
Figure by Gabriel Vecchi.

www.ldeo.columbia.edu/res/div/ocp/drought/science.shtml

R. Seager, M.F. Ting, I.M. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez, N. Naik, 2007. Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America. *Science*, DOI: 10.1126/science.1139601

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



Wettest day

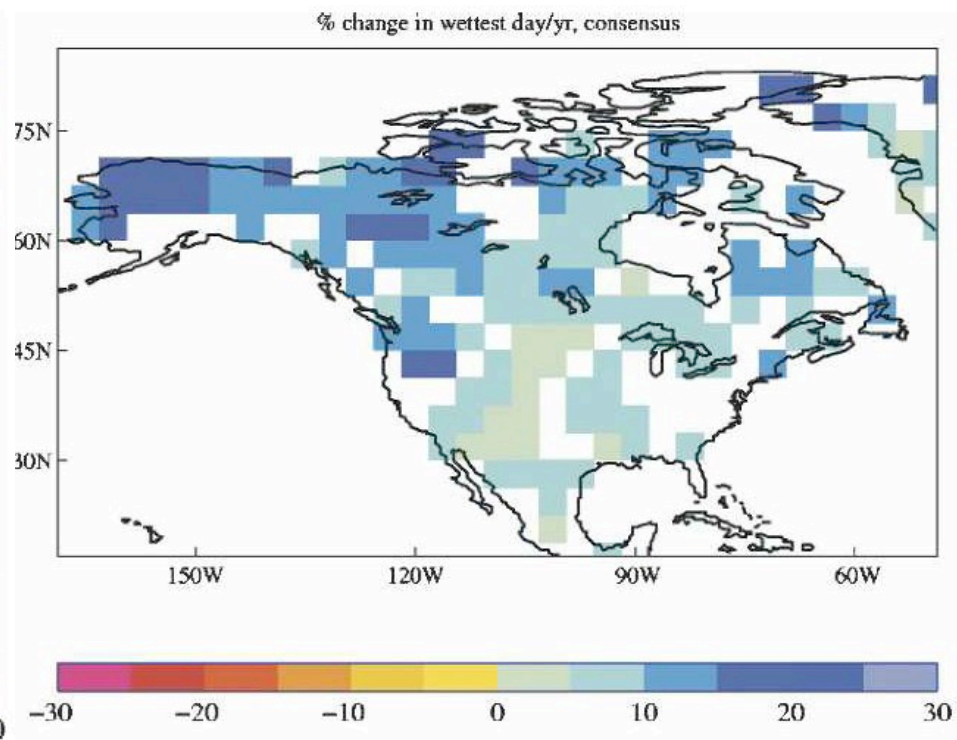


FIG. 13. Consensus estimates of changes in mean annual precipitation in the 2 × CO_2 experiments from CGCM1 and HadCM3 GCMs over North America. The red end of the scale depicts decreases and the blue increases. The pattern shows the average precipitation change between the models, it is only shown where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

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.

Climate as a complete statistical description of atmospheric behavior

From one perspective, climate draws its event from some (unknown) probability distribution

We know there is such a distribution, but we cannot generate it from first principles, and likely not from models (for a long time)

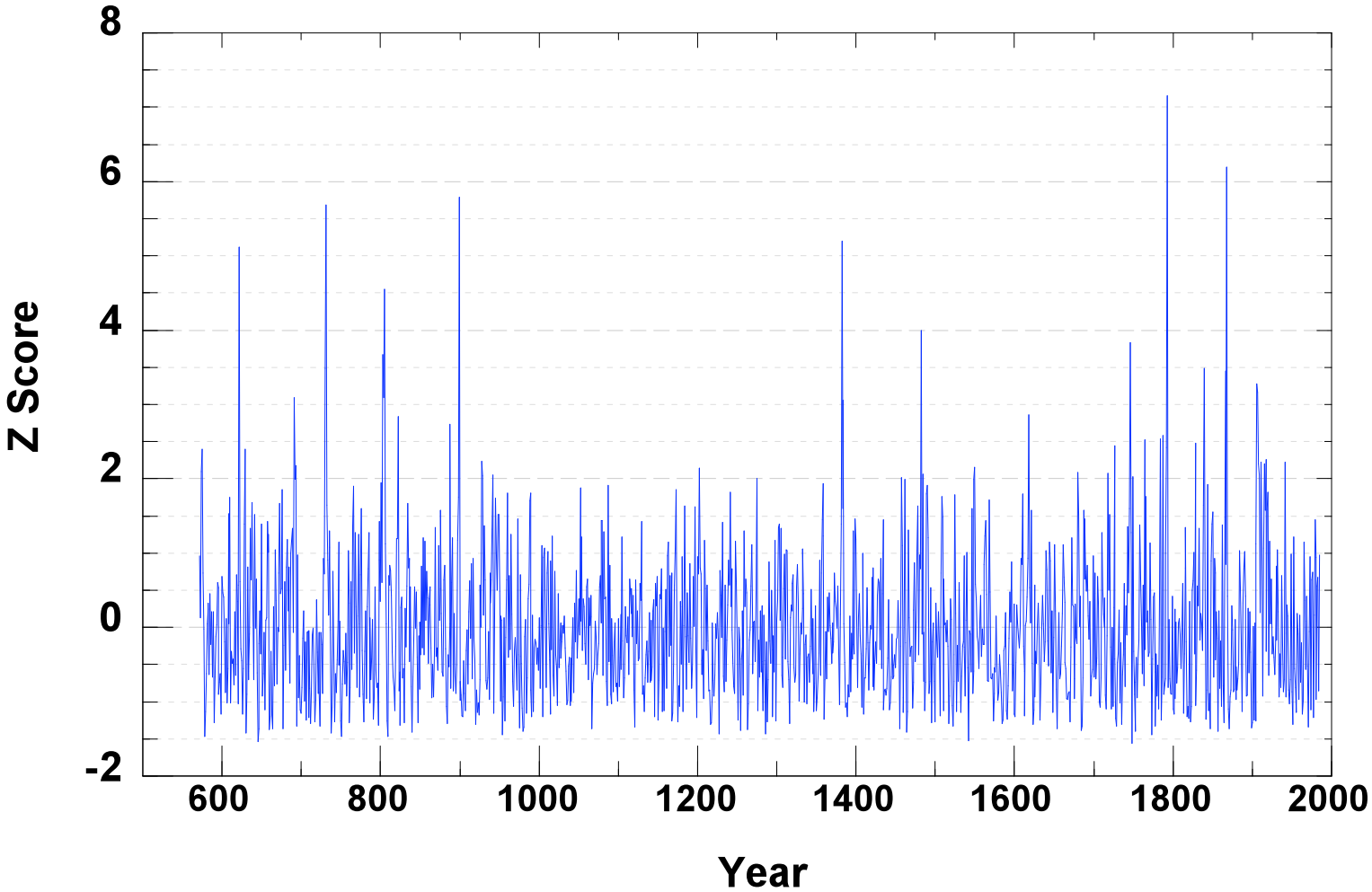
This distribution is constantly evolving in time, as climate evolves

There are many confusing factors in how we understand and communicate these issues

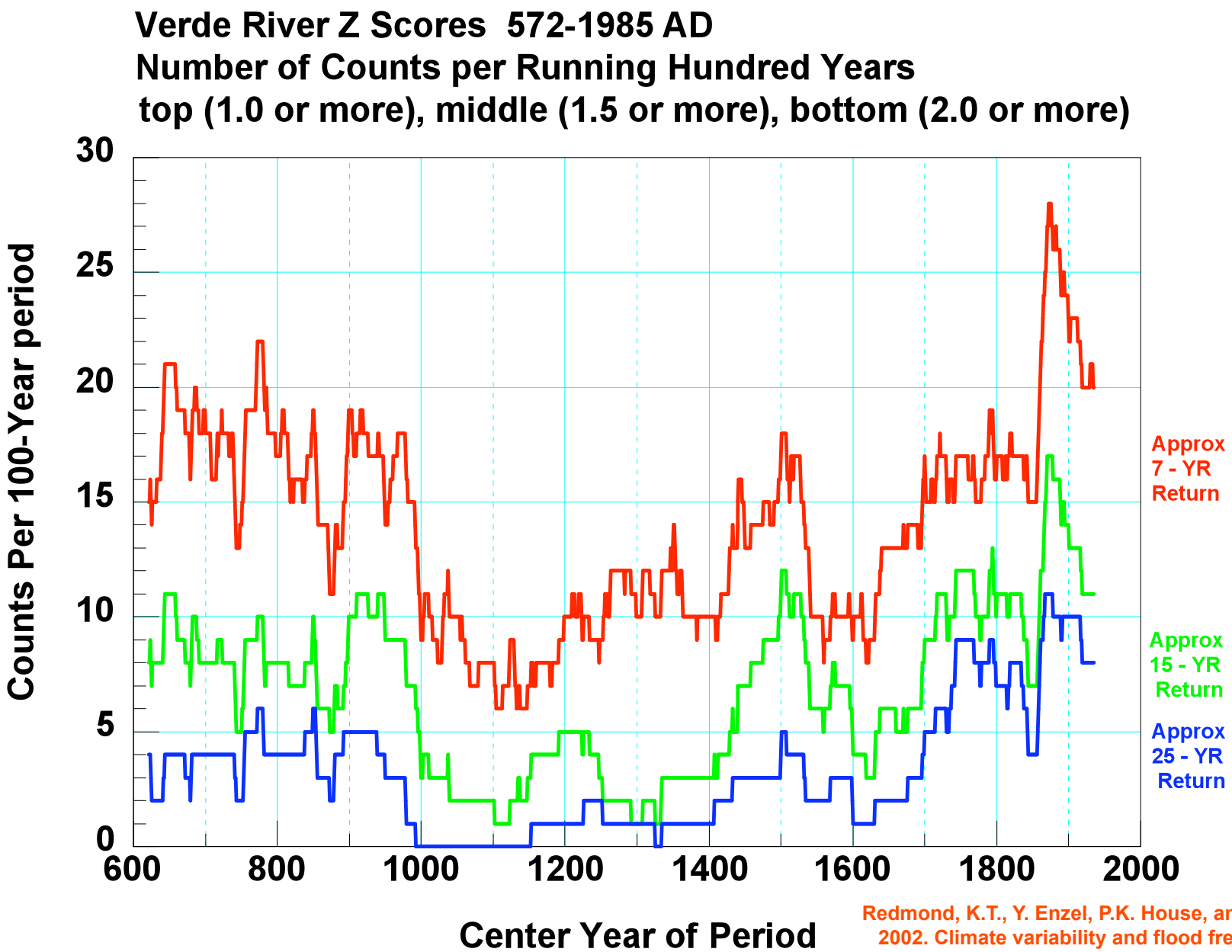
- Intensities versus totals
- How to describe rates
- Integrals versus differentials
- Many issues of terminology
  - Likelihood of 500-year storm varies hour by hour or day by day
  - "Officer, I couldn't have been going 80 miles per hour …
    - … I've only been on the freeway 15 minutes!"

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.



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.” *

Corollary:

There are no true climatic “normals”.

* 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"

The "present future" will slowly depart from its "prior future"

Stationarity slowly but progressively becoming a less valid assumption

How much until this departure is "significant" ?
(not so much in statistical terms, but in practical terms)

Major question looming: How do we adjust all the statistics of the past to reflect the expected future?

This is a *very big* challenge / opportunity for Applied Climatology

A growth industry

Methodology
Application of that methodology
Acceptance of that methodology

Concluding thoughts

Wet hydrologic extremes on short time scales exhibit heavy tails

We may be underestimating the size and frequency of rare events

Climate history exhibits non-stationarity
This has been understood and appreciated for many years

Floods and droughts, in some circumstances, could both increase
(not discussed before this point)

Can climate become “more extreme” everywhere ?
What exactly does this mean ?

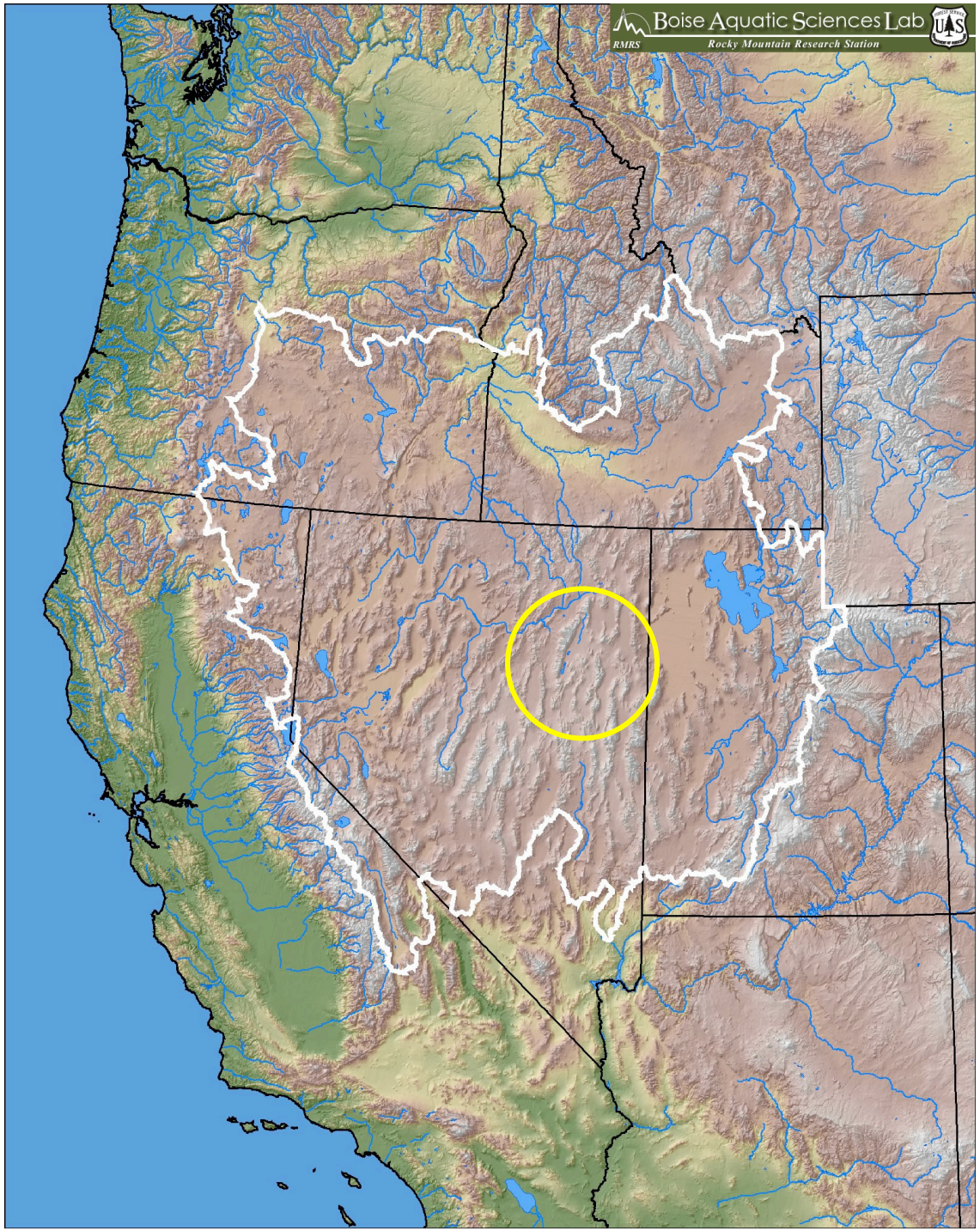
Fixed-magnitude extremes seem to be increasing in frequency

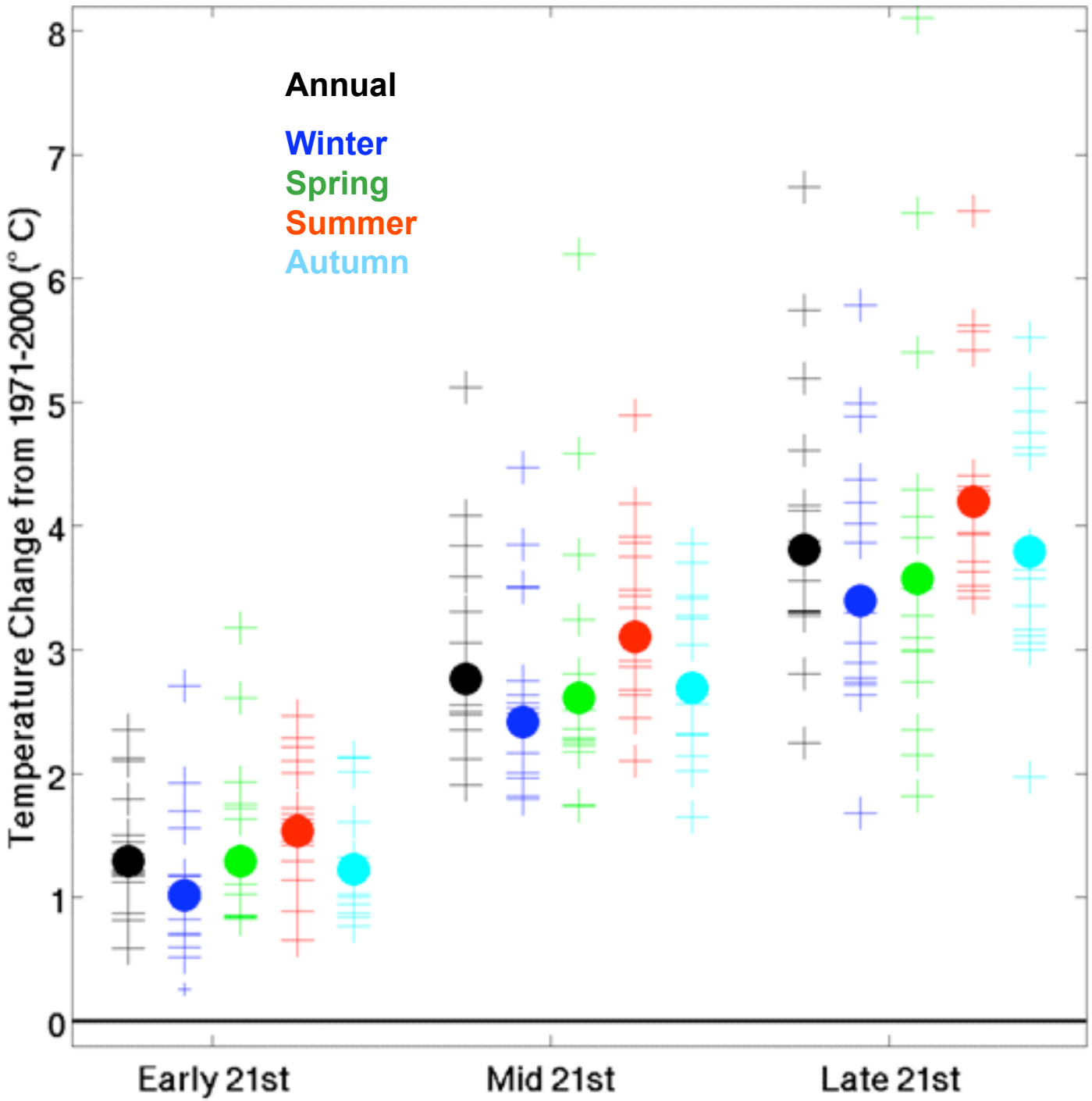
General expectation that upper percentiles will increase in magnitude

Consistent observations very badly needed (example: accumulations)
Data quality issues can have major effects on interpretation

Thank You !
Many Glacier, Nov 2006. NPS.

DISCARDS


Boise Aquatic Sciences Lab
RMRS
Rocky Mountain Research Station



East Central Nevada

Projected Temperature Changes (C)

15 Models

IPCC A1B

Early 21st

2011-2040

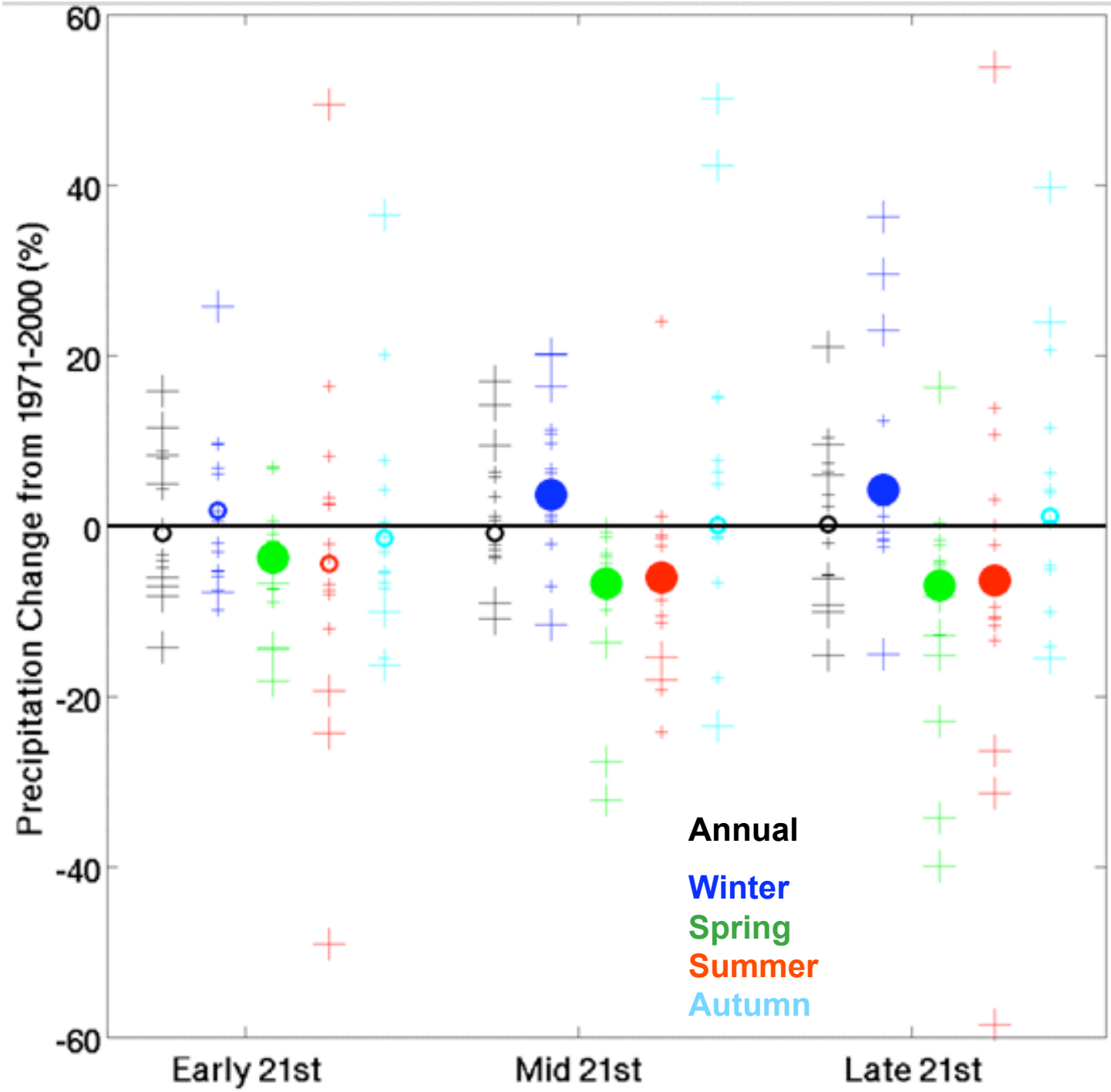
Middle 21st

2041-2070

Late 21st

2071-2100

John Abatzoglou



East Central Nevada

Projected Precipitation Changes (%)

15 Models

IPCC A1B

Early 21st

2011-2040

Middle 21st

2041-2070

Late 21st

2071-2100

John Abatzoglou