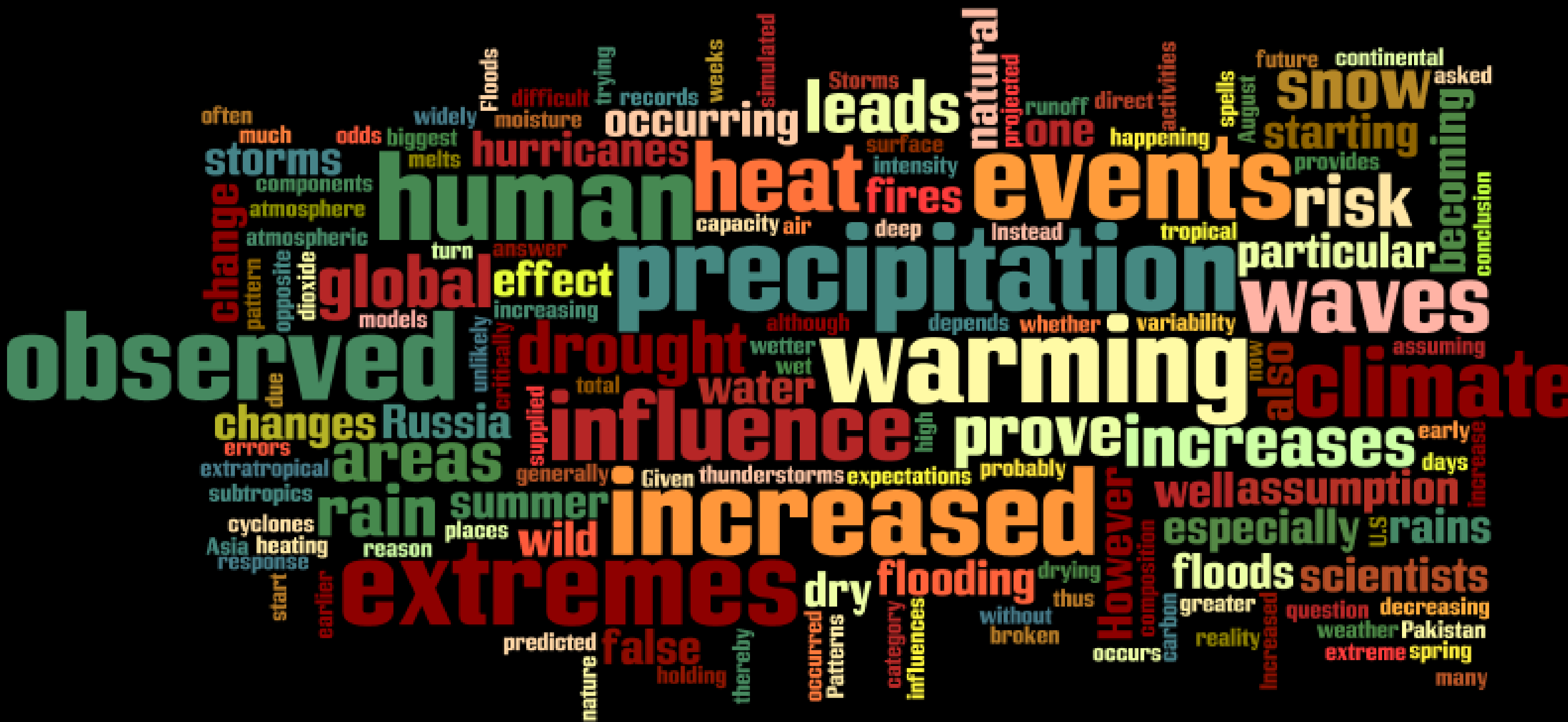
Physical understanding of changes in extremes of precipitation with climate change

Kevin E. Trenberth
NCAR

Summary



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Sayings that describe changes in precipitation with climate change

Sunshine is delicious, rain is refreshing, wind braces us up, snow is exhilarating; there is really no such thing as bad weather, only different kinds of good weather.

John Ruskin

The rich get richer and the poor get poorer!

More bang for the buck!

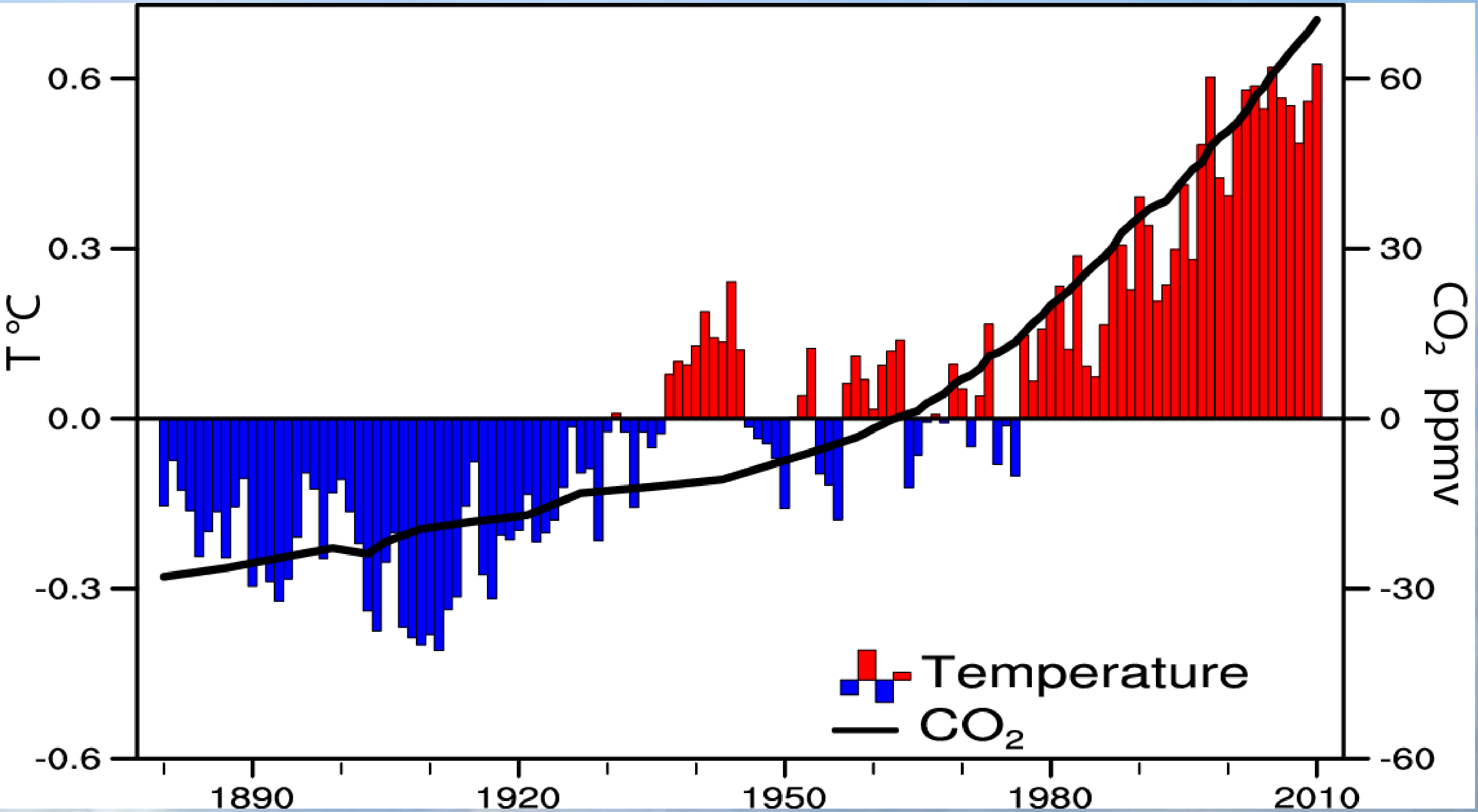
It never rains but it pours!

"Everybody talks about the weather, but nobody does anything about it."
— *Attributed to Mark Twain, 1890s*

"Now humans are doing something about the weather: global warming is contributing to an increased incidence of extreme weather because the environment in which all storms form has changed from human activities."

Kevin Trenberth
USA Today 3 June.

Global temperature and carbon dioxide: anomalies through 2010

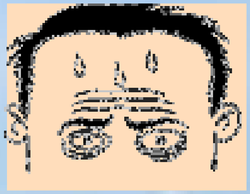


Base period 1900-99; data from NOAA

Global warming: Controlling Heat

The presence of moisture affects the disposition of incoming solar radiation:
Evaporation (drying) versus temperature increase.

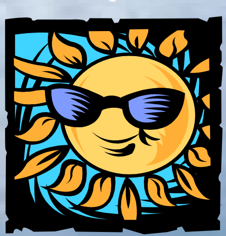
Human body: sweats



Homes: Evaporative coolers (swamp coolers)

Planet Earth: Evaporation (if moisture available)

e.g., When sun comes out after showers,



the first thing that happens is that the puddles dry up: before temperature increases.

Climate change and extreme weather events

Changes in extremes matter most for society and human health

With a warming climate:

- More high temperatures, heat waves
- Wild fires and other consequences
- Fewer cold extremes.

- More extremes in hydrological cycle:
  - Drought
  - Heavy rains, floods
  - Intense storms, hurricanes, tornadoes

Attribution

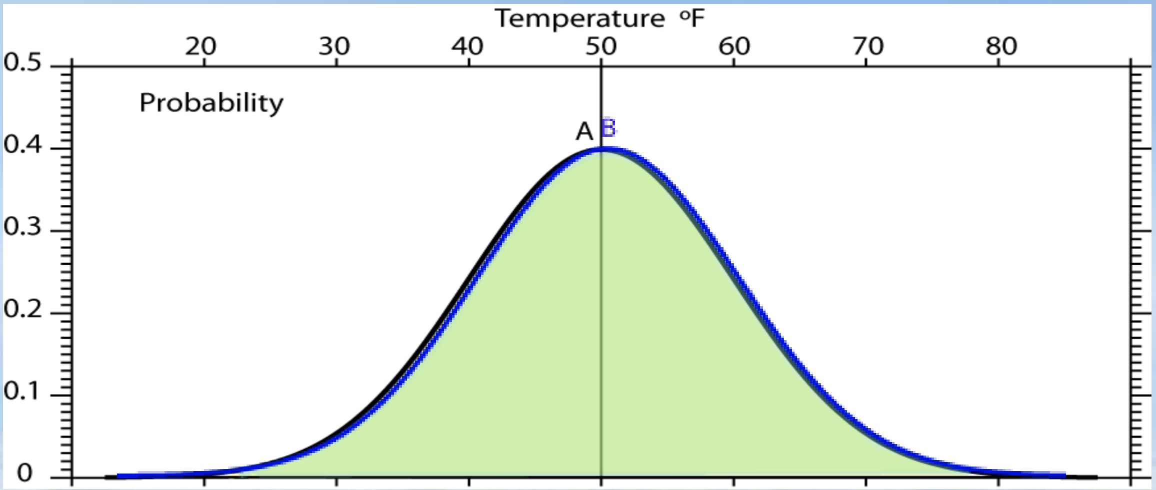
Attribution is difficult as it requires good data and good models to take the signals apart.

1) Documentation of anomalies and how rare they are.
2) Ability to model the event

- Models have difficulty with "blocking"
- Models simulate monsoon rains poorly

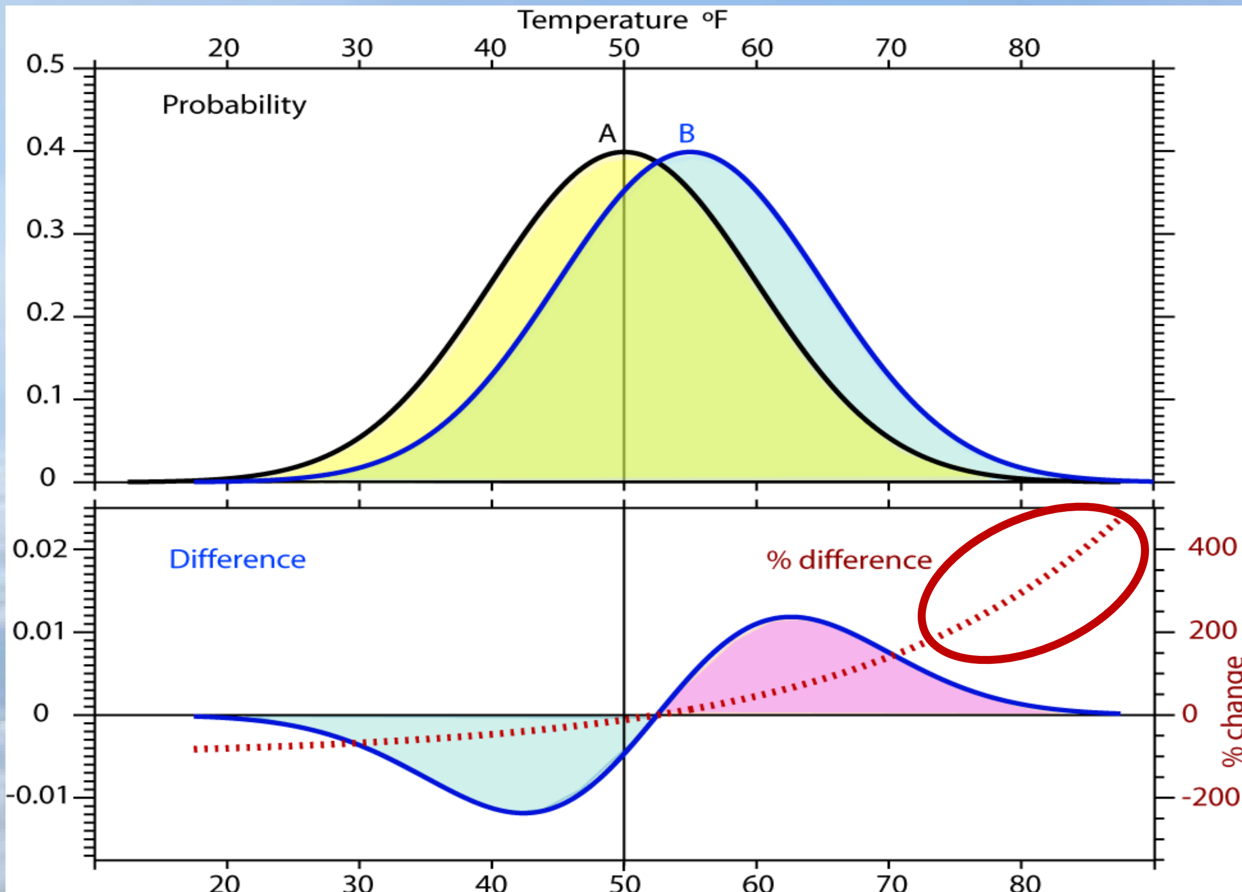
At present all the uncertainties are lumped on the side of natural variability

Reason for focus on extremes



Mean A: 50°F, s.d. 10°F

Reason for focus on extremes



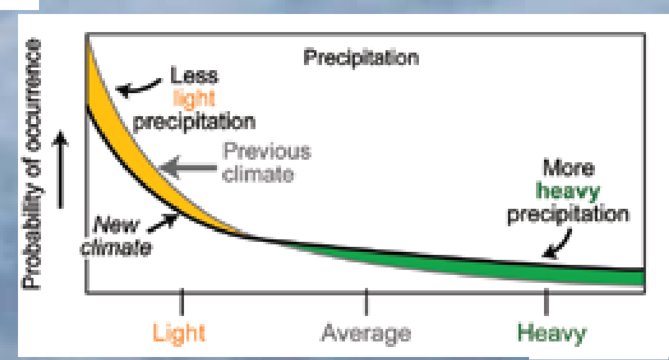
Shift in climate: from A to B

Most of time the values are the same (green).

Biggest changes in extremes: >200%

Mean A: 50°F, s.d. 10°F

Mean B: 55°F, s.d. 10°F



Null hypothesis:

"There is no human influence on climate"

Burden of proof is high. Scientists typically require 95% confidence level (5% significance level)

Type I errors: False positive. Wrongly concluding there is a human influence when there isn't.

Type II errors: False negative. Wrongly concluding there is no human influence, when there is. This kind of error is very common!

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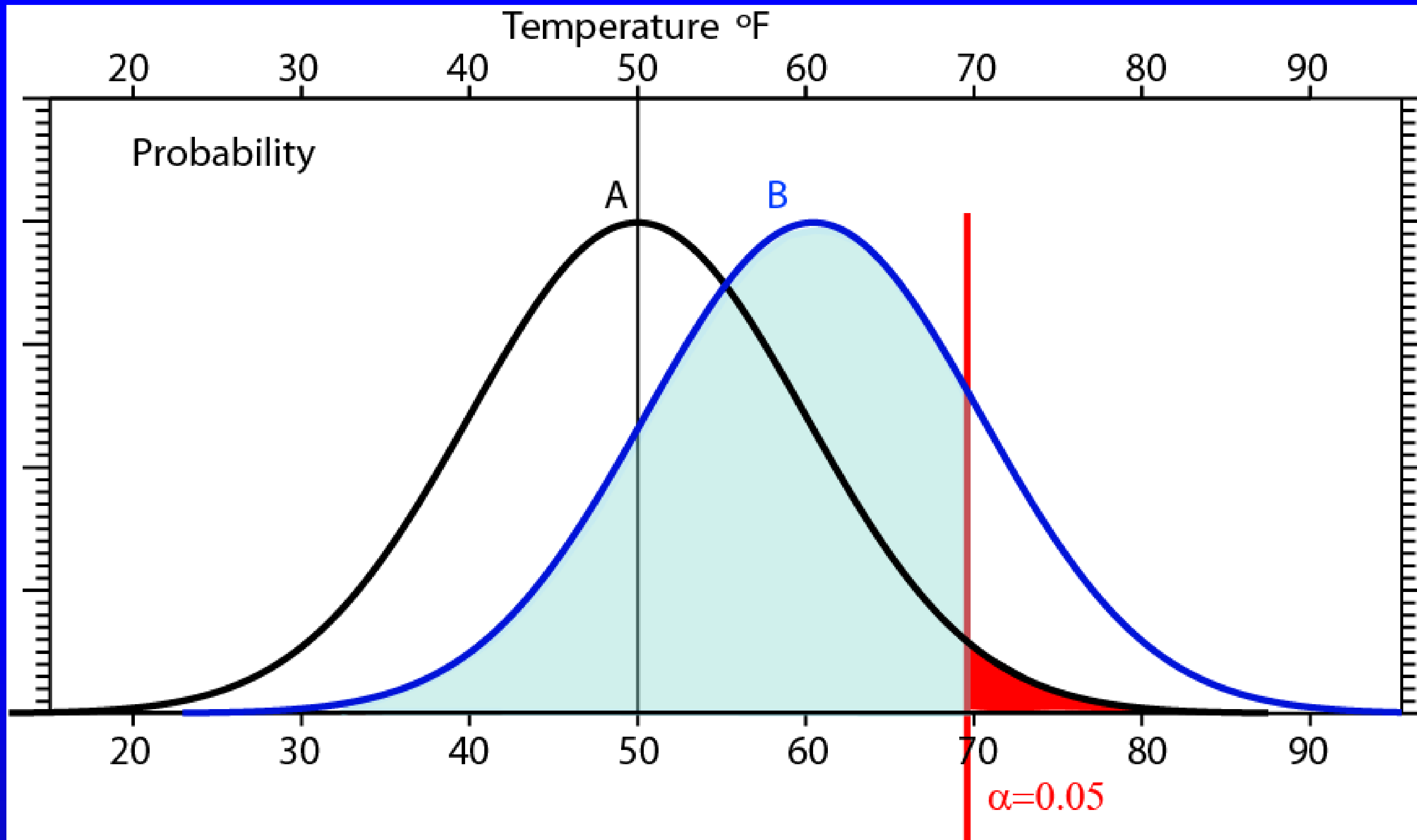

For a 1 standard deviation (10°F) shift in the distribution (due to climate change) from A to B, only values of B to the right of the two tailed 5% significance level (α=0.05 in red) would be considered significant under a null hypothesis of no change. All the values in the blue area of the B distribution would not.

Measured / Perceived	Reality: True	Reality: False
True	Correct ☺	Type I False Positive
False	Type II False Negative	Correct ☺

Null hypothesis:

"There is no human influence on climate"

Was appropriate prior to 2007 (AR4) but IPCC found that global warming is "unequivocal" and "very likely" due to human activities.

So this null hypothesis **no longer appropriate.** If one reverses the null hypothesis "there is a human influence on climate" then it is very hard to prove otherwise at 95% level.

Key difference: the uncertainties fall on the other side!

So these are wrong questions:

"Is it due to global warming?"

"Is it due to natural variability?"

It is always both!

Moreover, natural variability is not a cause: where does the energy perturbation come from to cause the change?

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Some extremes in 2010 of concern

1. The flooding in Pakistan (August) and related earlier flooding in China and India (July)
2. The Russian drought, heat wave and wild fires (which is an event physically related to the Asian flooding via a monsoon circulation and teleconnections)
3. The flooding events in the US, notably the nor-easters in February-March and the "Snowmageddon" record breaking snows in Washington, Philadelphia and Baltimore.
4. Intense heavy rains in Nashville in May (over 20 inches in 2 days)
5. Wettest September ever in Australia, flooding since
6. Flooding in Columbia, drought in Brazil
7. The strong Atlantic hurricane season (19 named storms second after 2005 and tied with 1995 since 1944 when surveillance aircraft began monitoring, and 12 hurricanes). Only one storm made landfall in the US but 3 made landfall in Mexico and hurricane Karl caused extensive flooding in Mexico and Texas. Moisture from Hurricane Karl brought flooding rains to parts of southwest Wisconsin, southern Minnesota, and southeast South Dakota and contributed to Minnesota's wettest September in the 1895-2010 record.
8. Cold outbreaks in Europe and the U.S. (main population centers)

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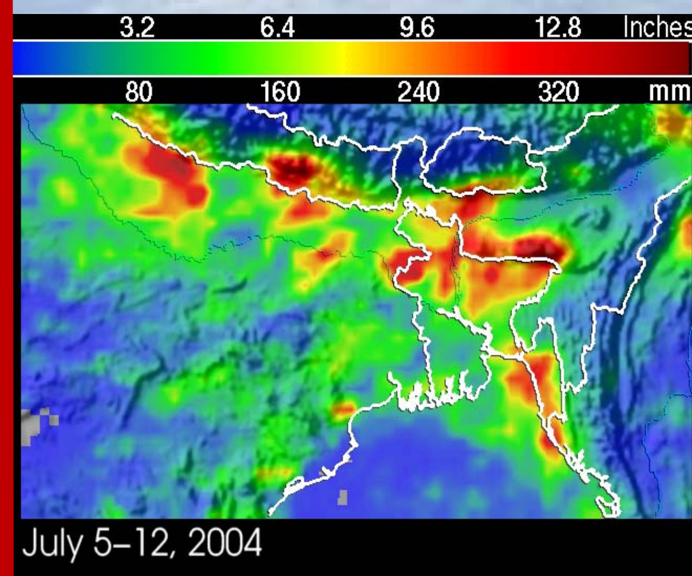
Jul-Aug 2010 **India**

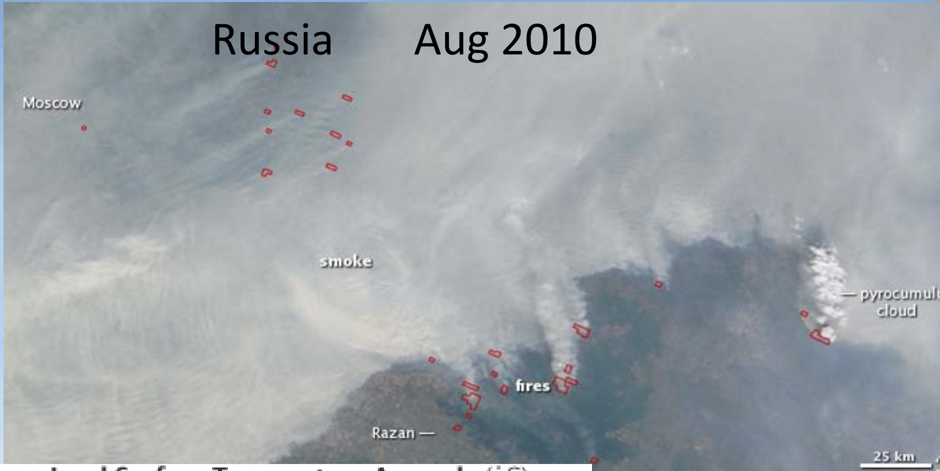
From TRMM satellite

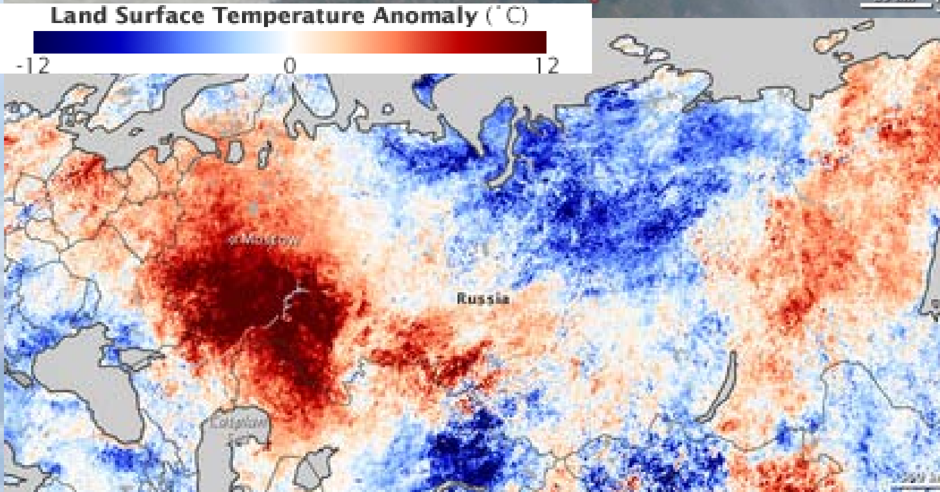


Aug 2010 Pakistan

Russia

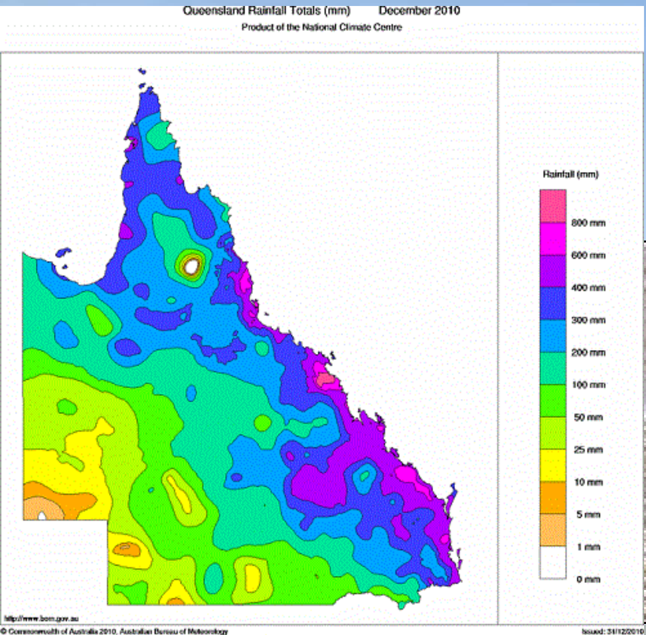
China





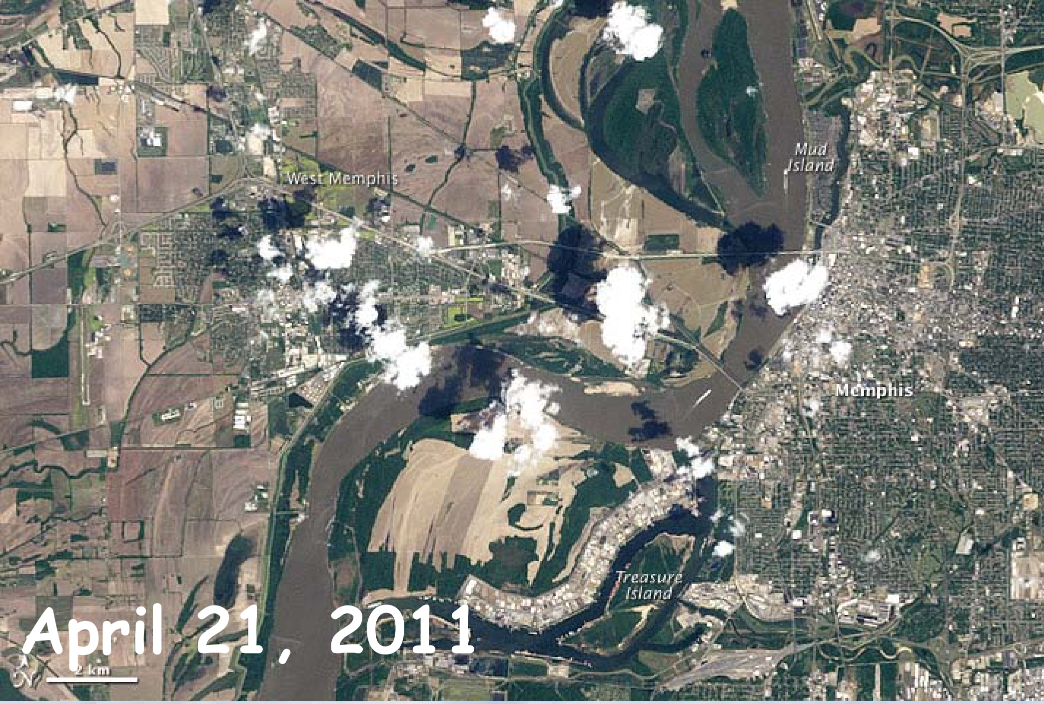
Courtesy NASA

Flooding
Queensland Early Jan 2011



Mississippi River

May 11 (below) and at Memphis



Tornado

Precipitation

Key reference:

Trenberth, K. E., 2011: Changes in precipitation with climate change. *Climate Research*, **47**, 123-138, doi:10.3354/cr00953.

http://www.cgd.ucar.edu/cas/Trenberth/trenberth.papers/SSD%20Trenberth%202nd%20proof.pdf

i.e. on my web site

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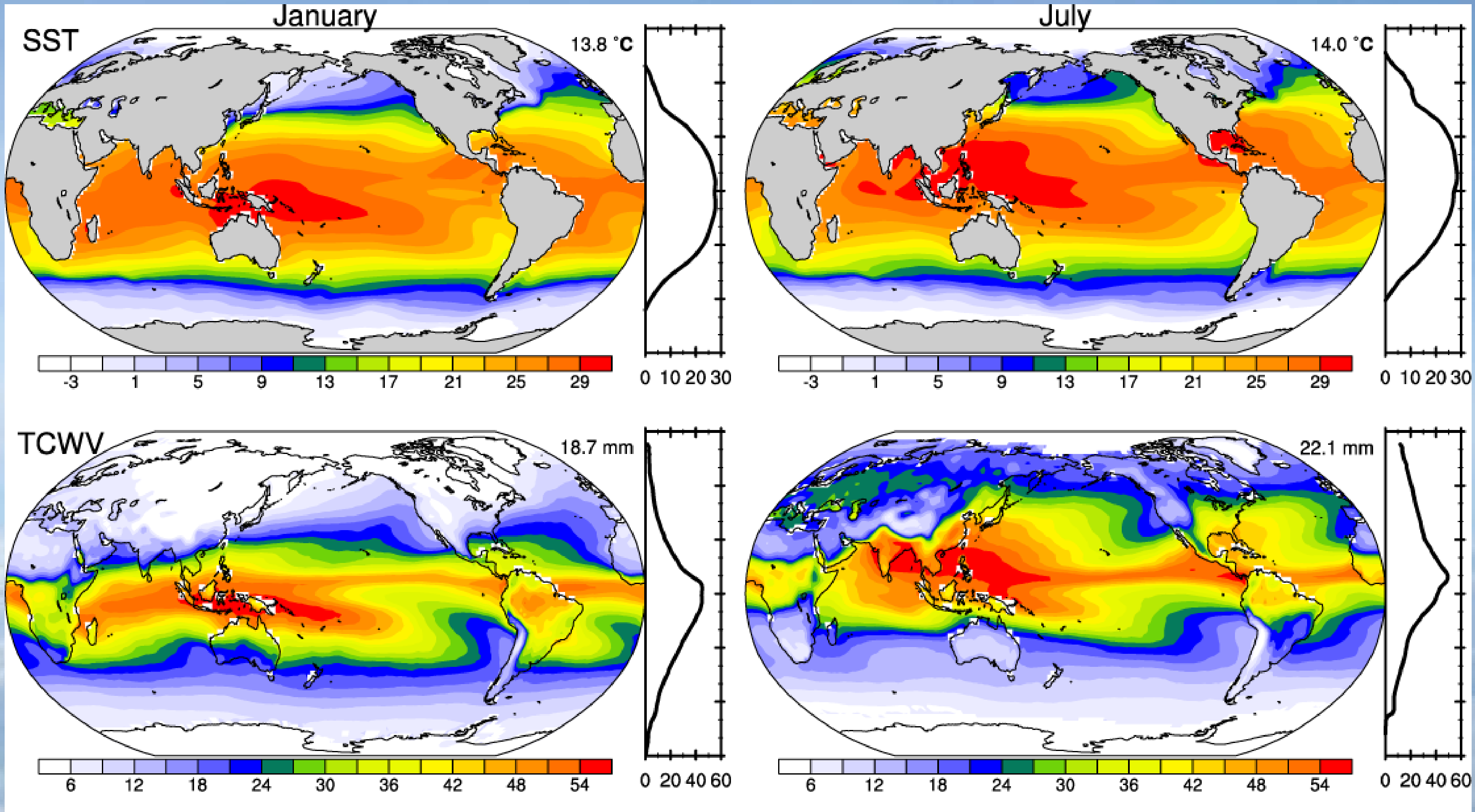
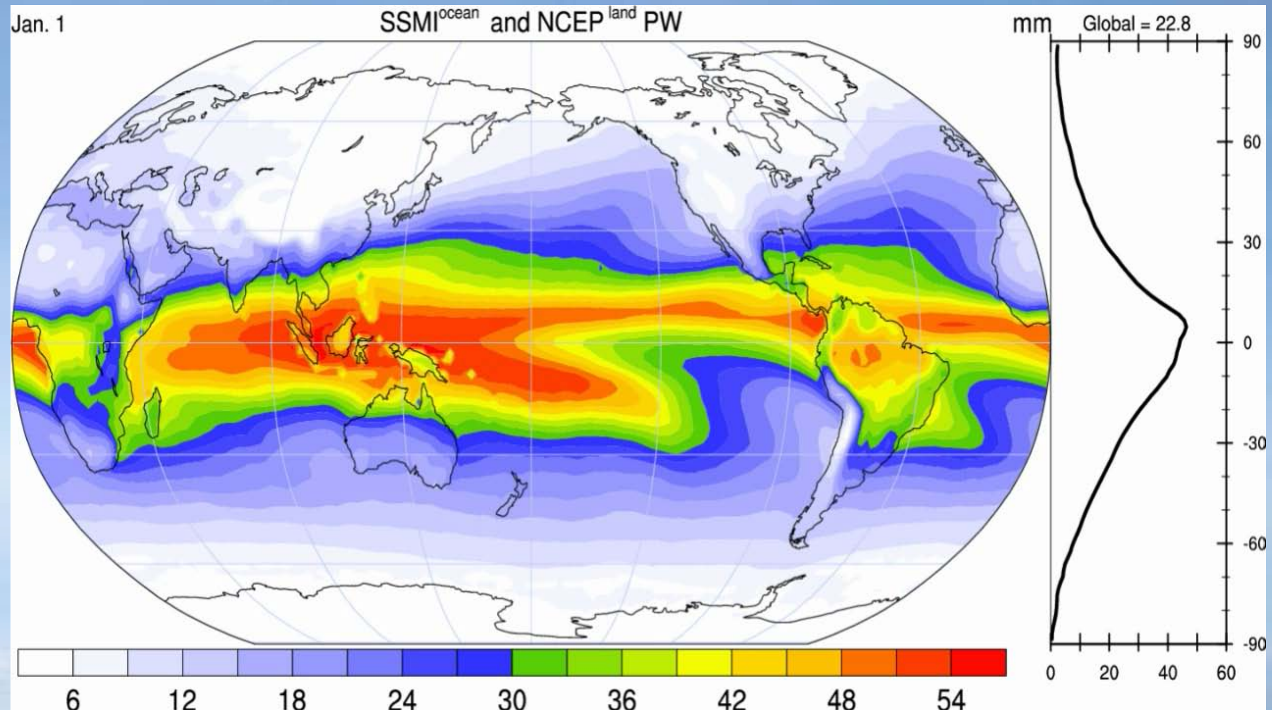
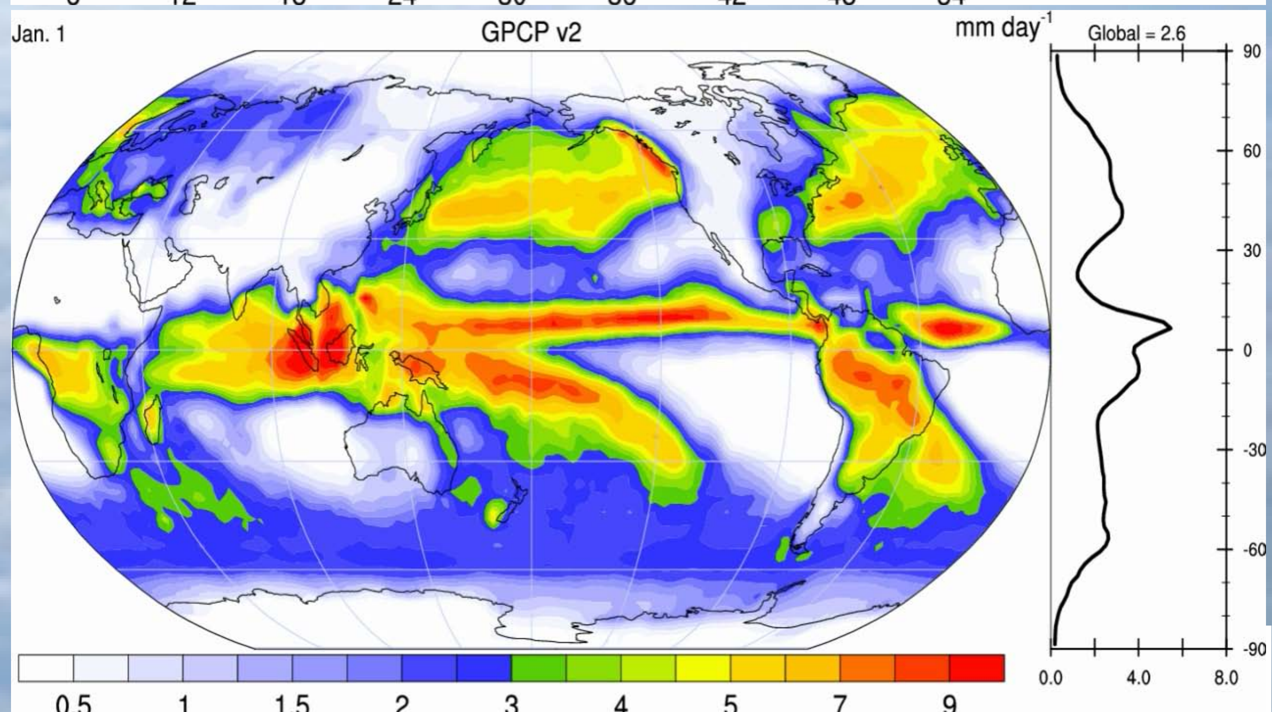


There is a strong relationship between SST and precipitable water, and also with mean precipitation in the tropics.

Precipitable water



Precipitation



How should precipitation change as climate changes?

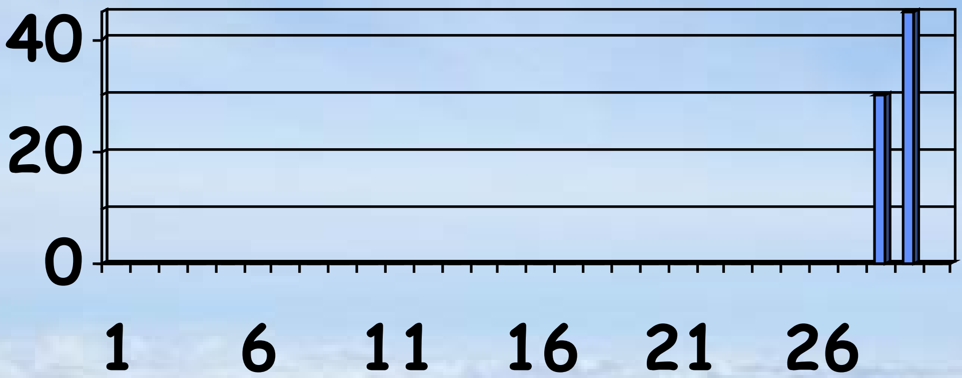
Usually only total **amount** is considered

- But most of the time it does not rain
- The **frequency and duration** (how often)
- The **intensity** (the rate when it does rain)
- The **sequence**
- The **phase**: snow or rain

The intensity and phase affect how much runs off versus how much soaks into the soils.

Daily Precipitation at 2 stations

A



Monthly Amount 75 mm

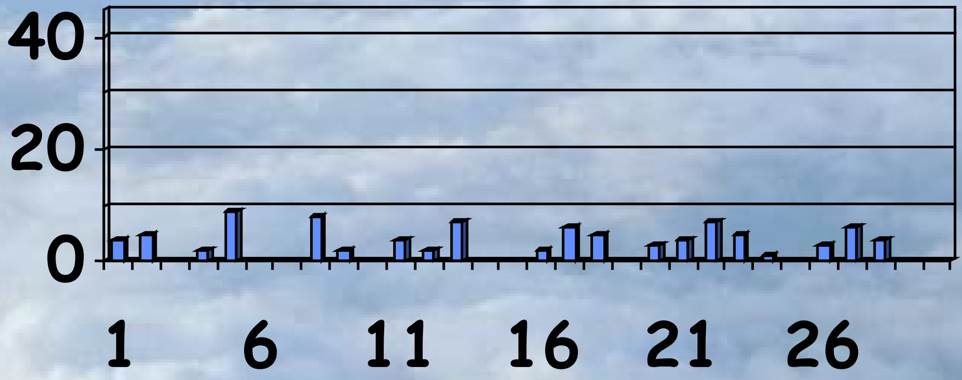
Frequency 6.7%
Intensity 37.5 mm

drought
wilting plants

wild fires

local
floods

B



Amount 75 mm

Frequency 67%
Intensity 3.75 mm

soil moisture replenished
virtually no runoff

Most precipitation comes from moisture convergence by weather systems

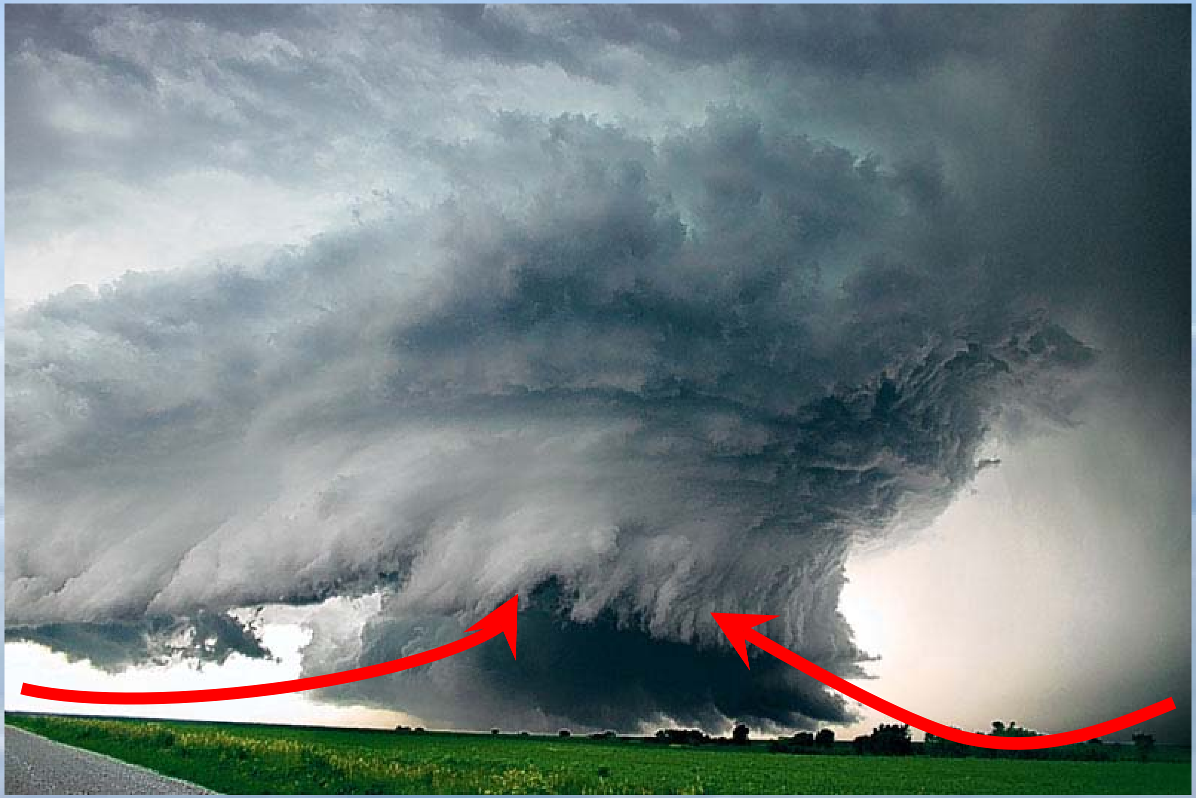
The intermittent nature of precipitation (average frequency over oceans is 11%) means that **moderate or heavy precipitation**

- Can not come from local column.
- Can not come from E.
- Hence has to come from transport by storm-scale circulation into storm.

On average, rain producing systems (e.g., extratropical cyclones; thunderstorms) reach out and grab moisture from distance about 3 to 5 times radius of precipitating area.

Most precipitation comes from moisture convergence by weather systems

Rain comes from moisture convergence by low level winds:

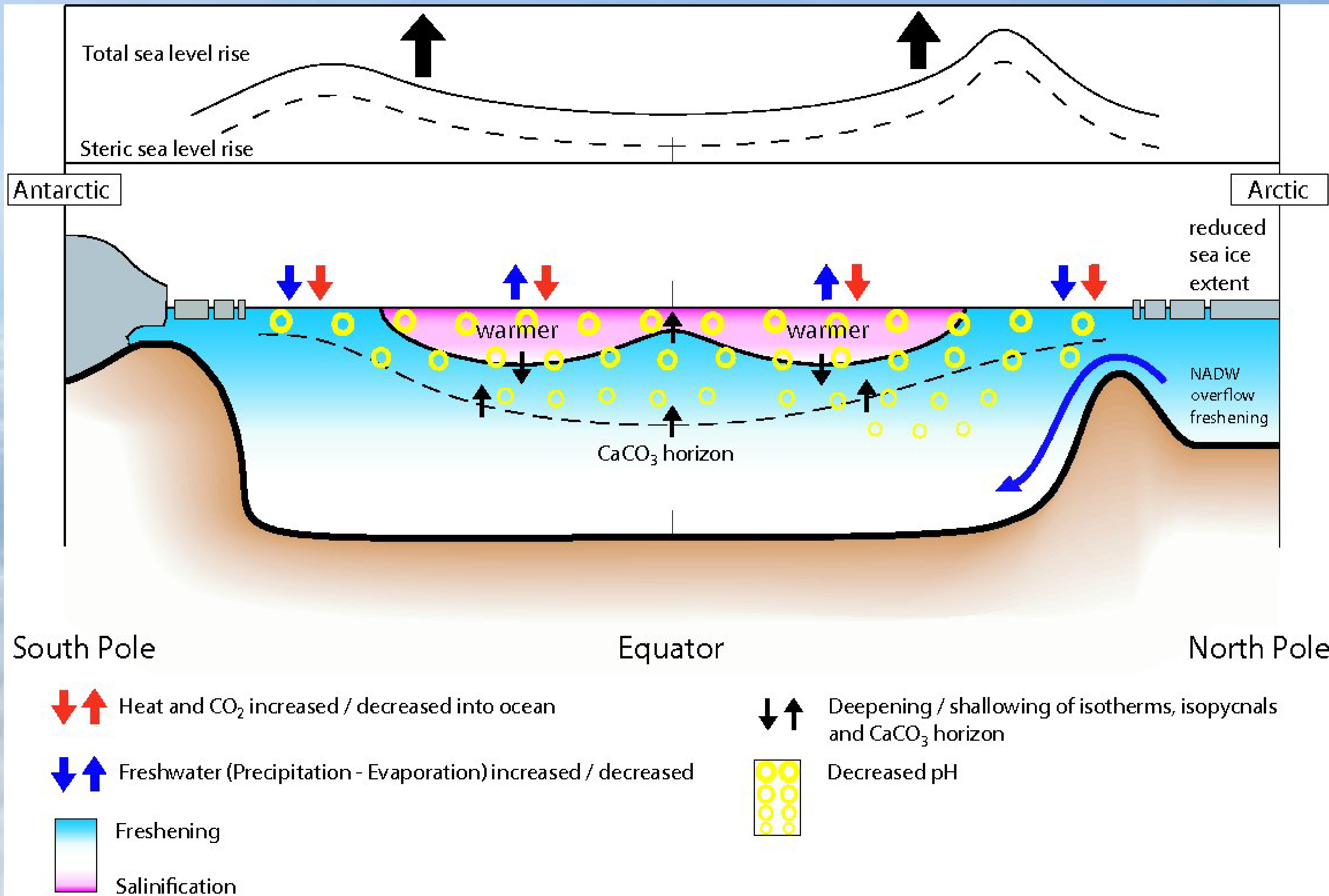


More moisture means heavier rains

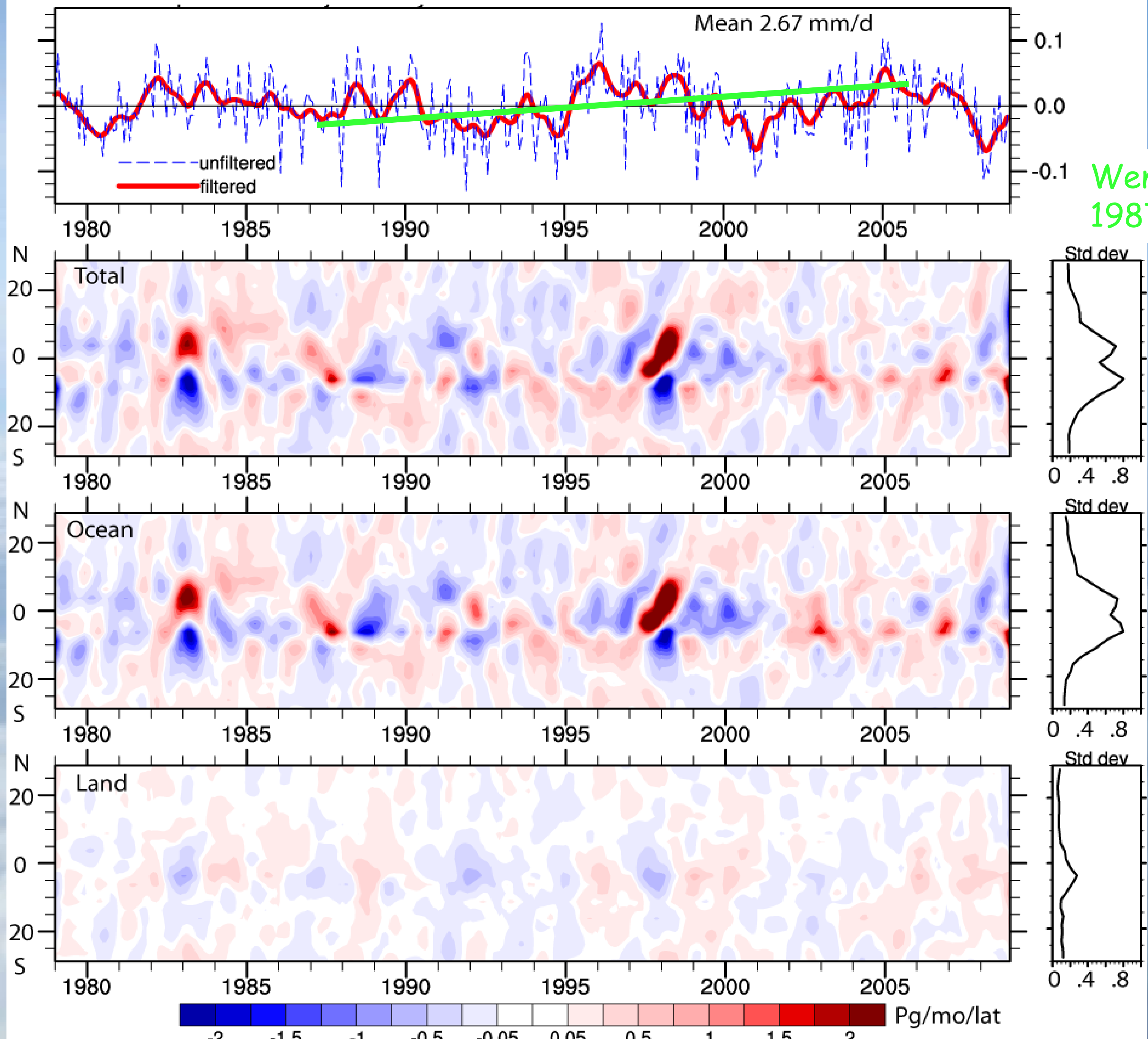
How is precipitation changing?

Changes in ocean state

from 1950-1960's to 1990-2000's (IPCC 2007 Figure 5.18)

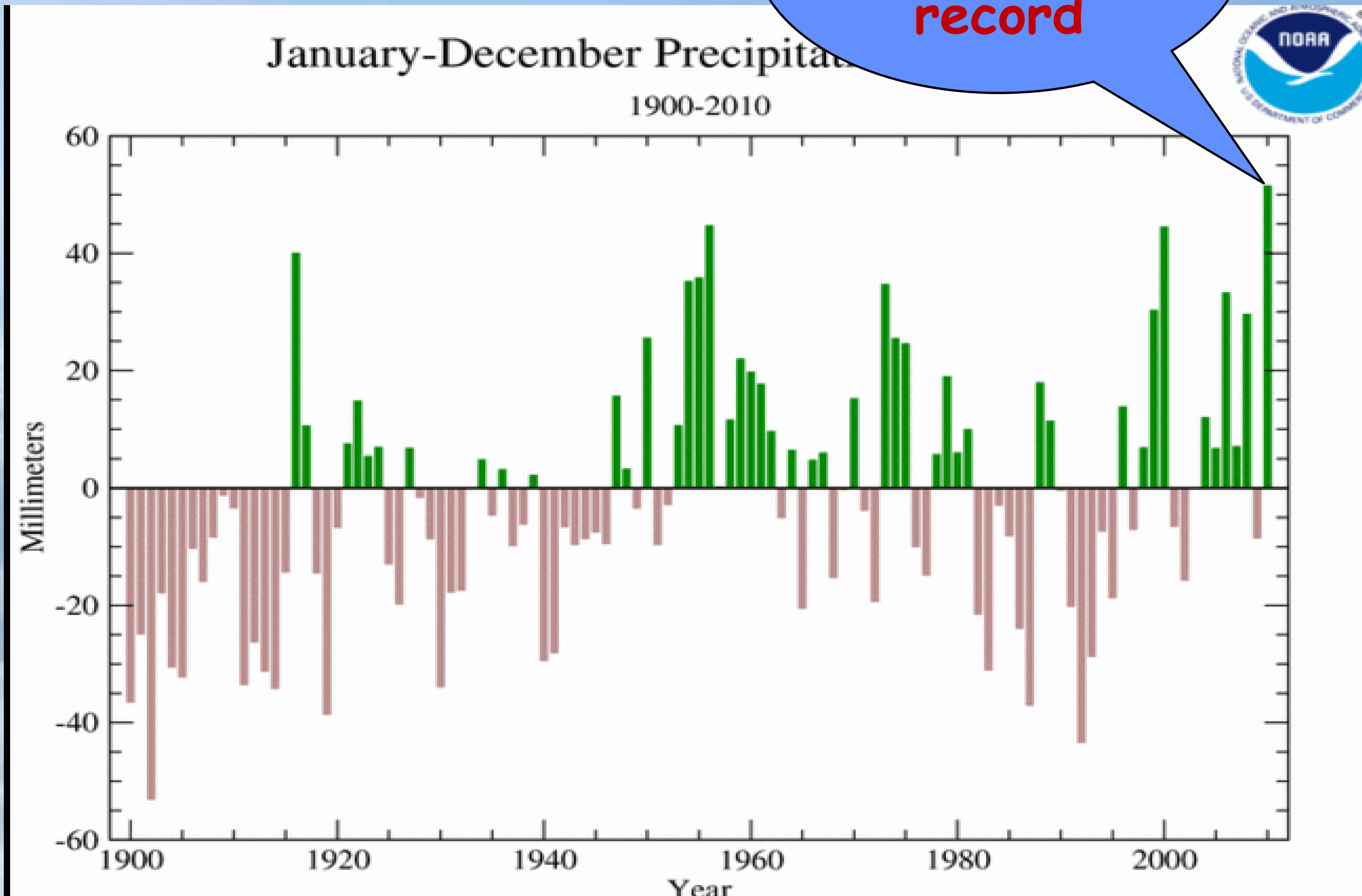


GPCP Global precipitation 1979-2008

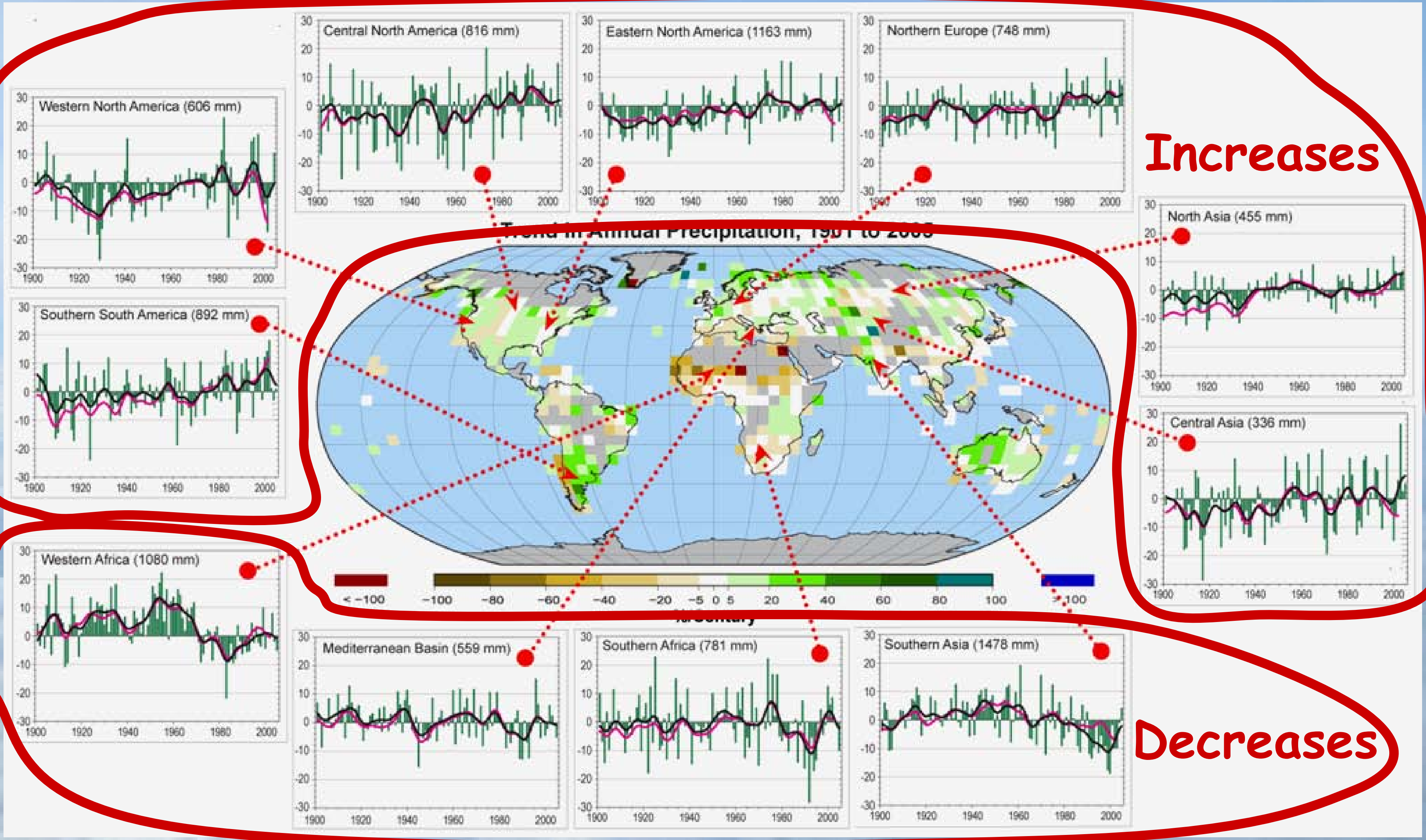


Wentz 2007:
1987-2006

Land: Annual mean pre… …alies

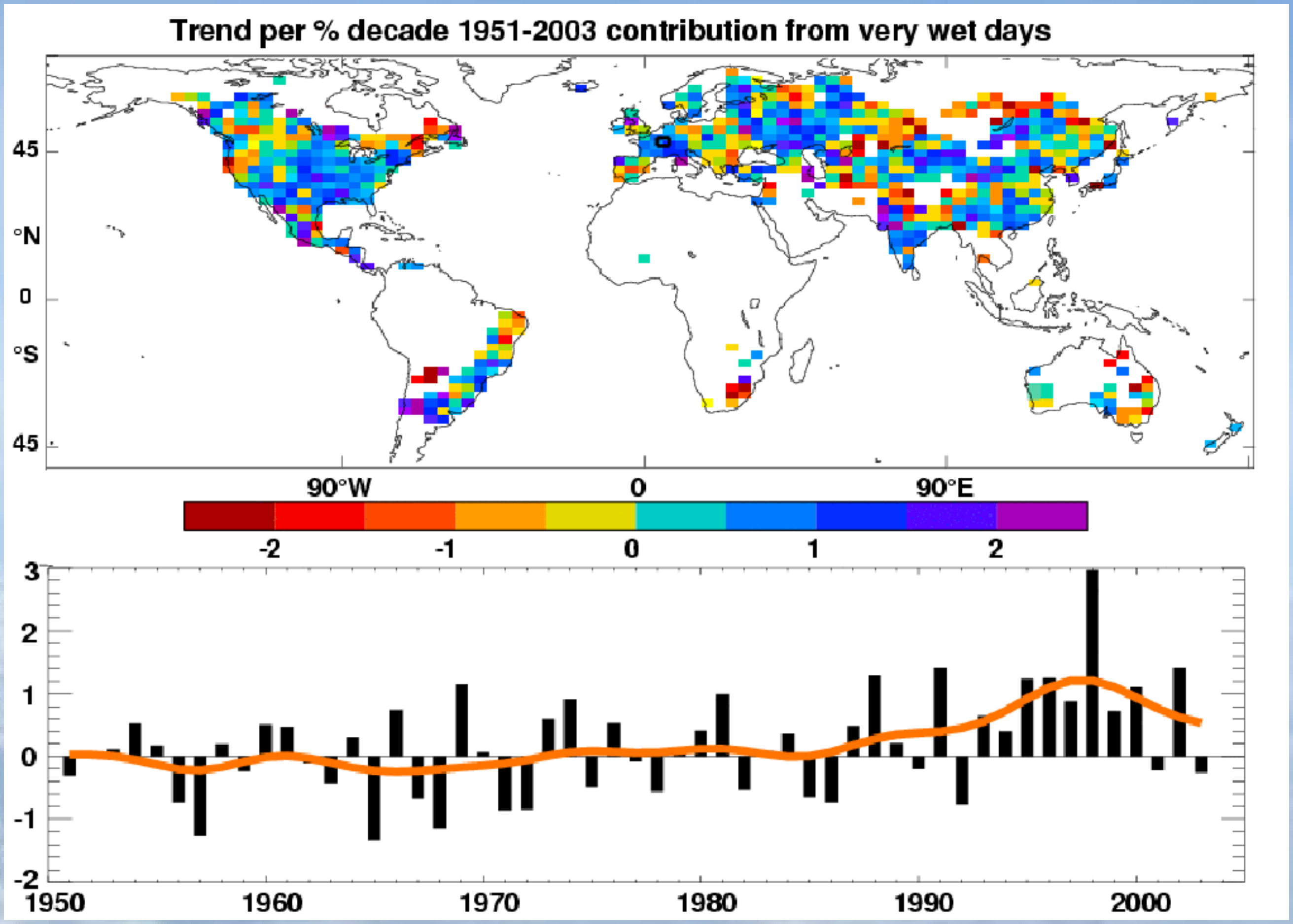


Land precipitation is changing significantly over broad areas



Smoothed annual anomalies for precipitation (%) over land from 1900 to 2005; other regions are dominated by variability.

IPCC



Precipitation

Observed trends (%) per decade for 1951-2003 contribution to total annual from **very wet days** > 95th %ile.

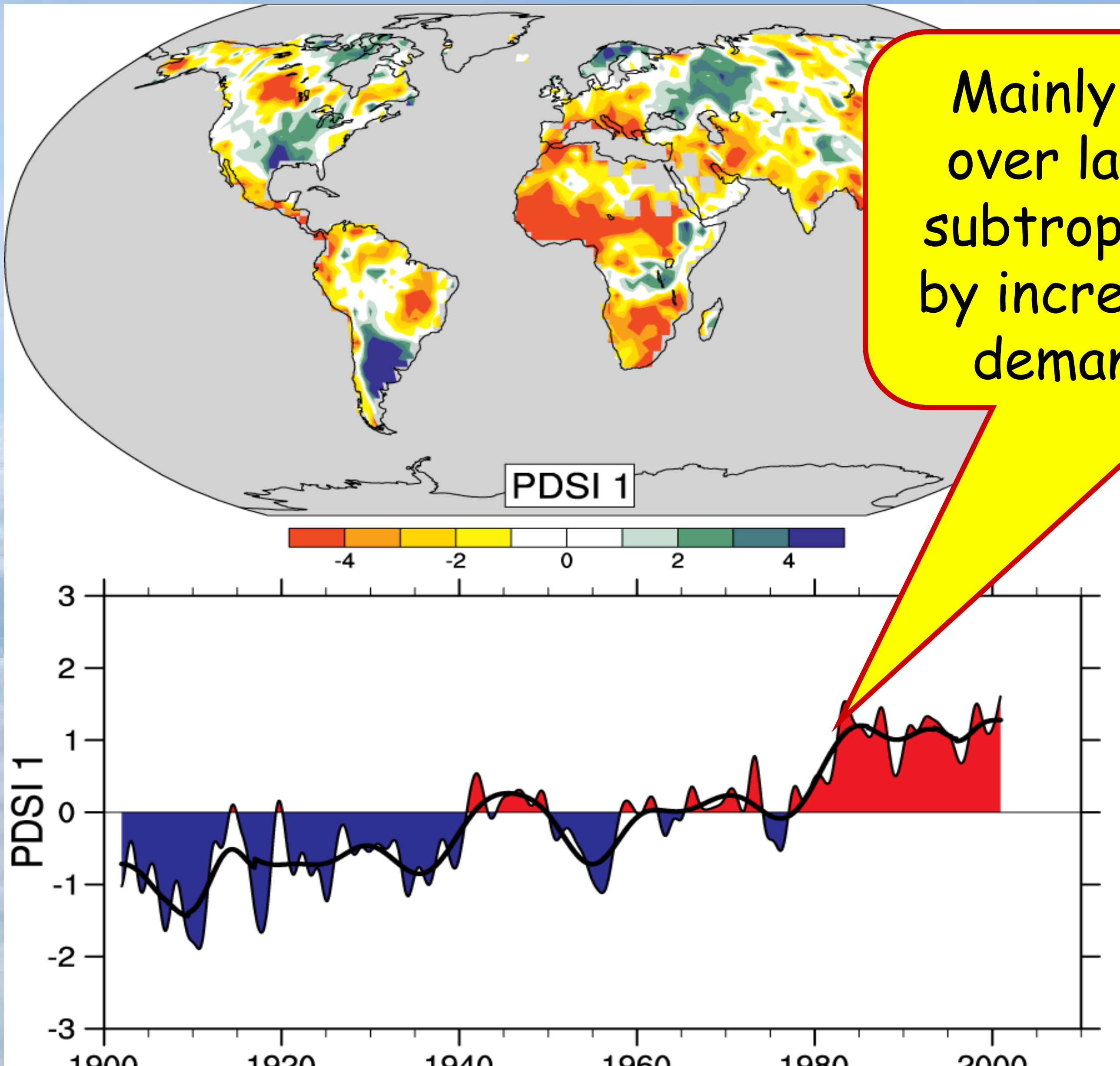
Alexander et al 2006
IPCC AR4

Heavy precipitation days are increasing even in places where precipitation is decreasing.

Enhanced Drying over Land Under Global Warming

- Increased longwave radiative heating provides additional energy for surface evaporation
- Higher air temperatures increase atmospheric demand for water vapor
- Reduced precipitation frequency can lead to longer dry spells and increased drought
- Larger warming over land than over ocean leads to larger increases in potential evaporation over land than ocean, which can lead to increased water stress over land.

Drought is increasing most places



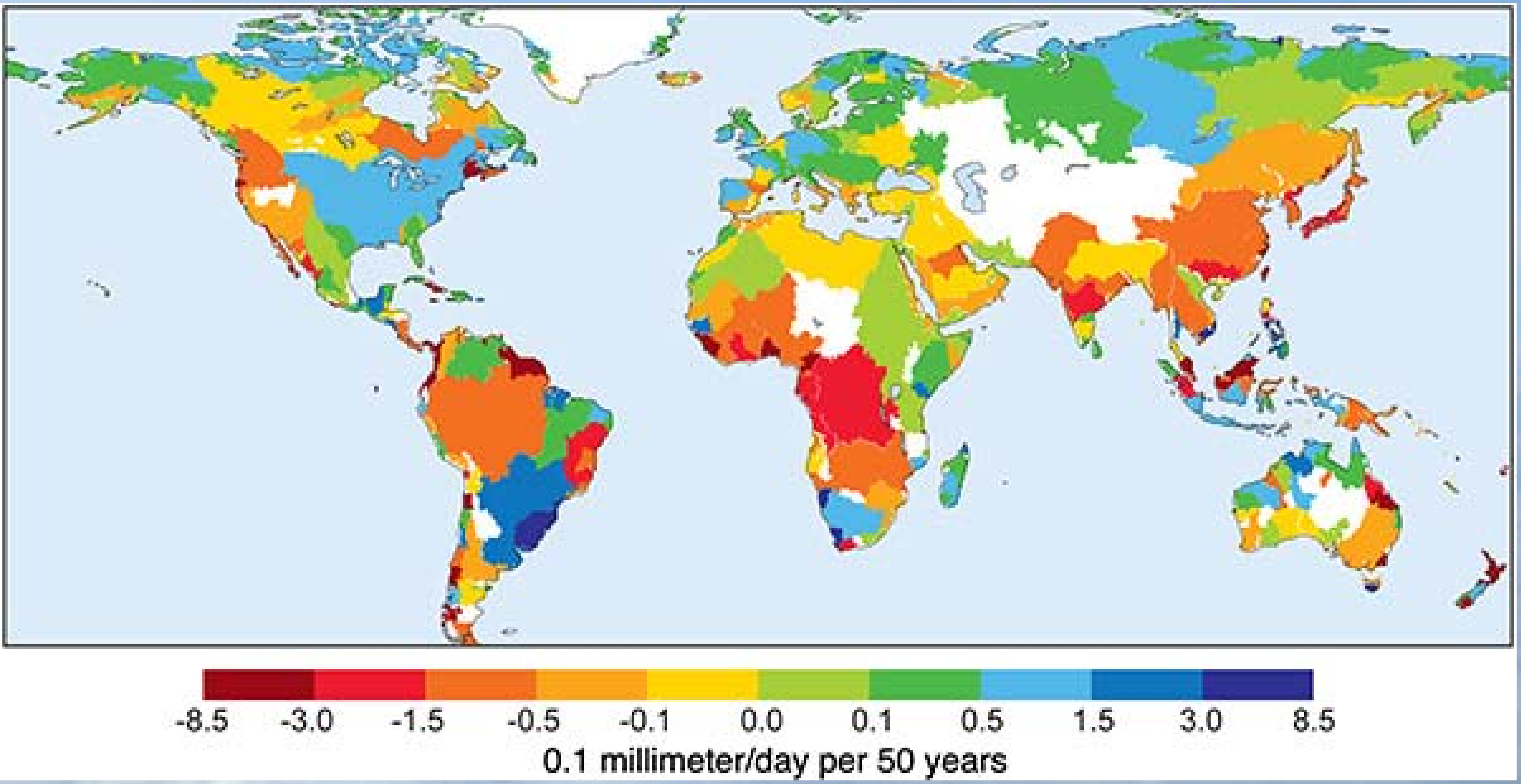
Mainly decrease in rain over land in tropics and subtropics, but enhanced by increased atmospheric demand with warming

Severity Index (PDSI) for 1900 to 2002.

The time series (below) accounts for most of the trend in PDSI.

Dai et al 2004
IPCC 2007

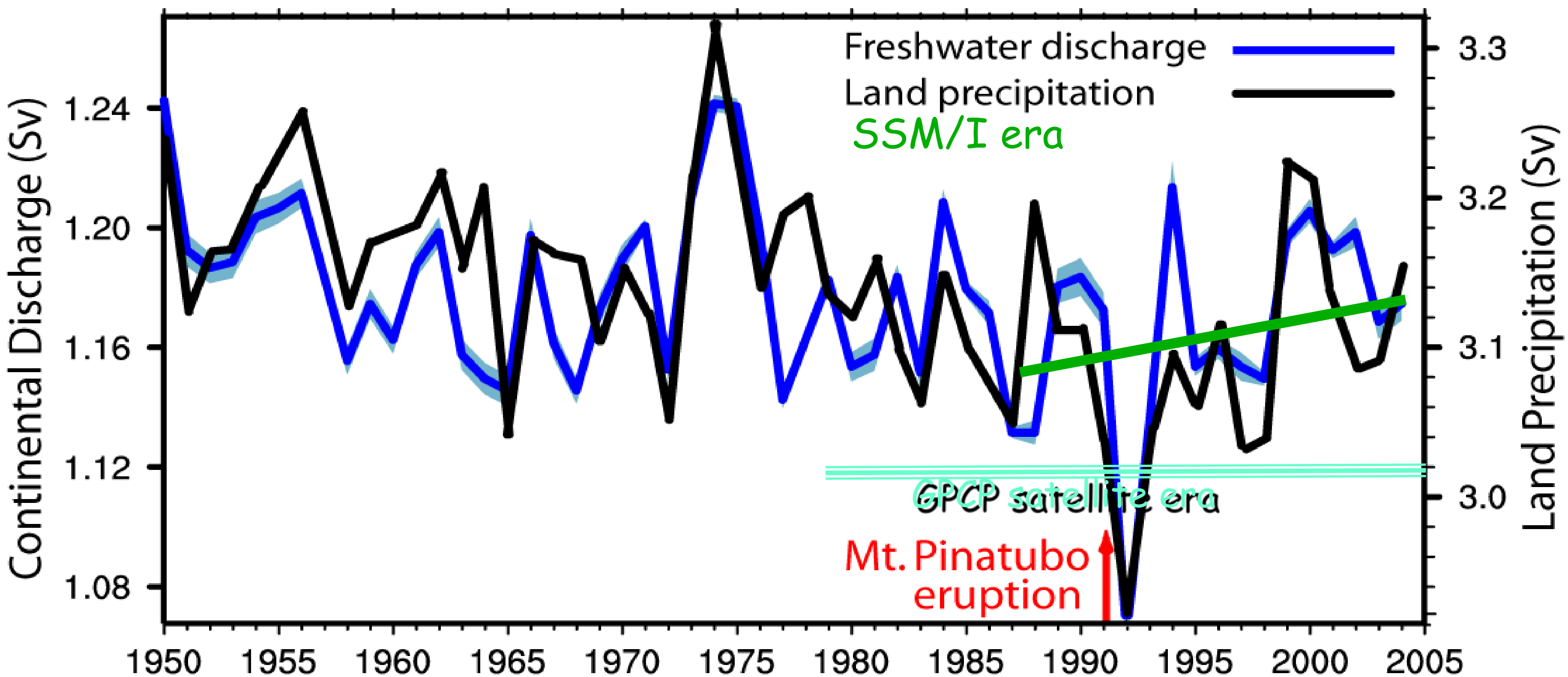
Trends 1948-2004 in runoff by river basin



Based on river discharge into ocean

Dai et al.2009

Pinatubo Effect on Hydrological Cycle



Estimated water year (1 Oct-30 Sep) **land precipitation** and river **discharge** into global oceans based on hindcast from output from CLM3 driven by observed forcings calibrated by observed discharge at 925 rivers.

Note: 1) effects of Pinatubo; 2) downward trend (contrast to Labat et al (2004) and Gedney et al (2006) owing to more data and improved missing data infilling)

Trenberth and Dai 2007; Dai et al. 2009

Geoengineering:

One proposed solution to global warming:

- Emulate a volcano: Pinatubo
- Cut down on incoming solar radiation
- Is the cure worse than the disease?

Factors in Changes in Precipitation

It never rains but it pours!

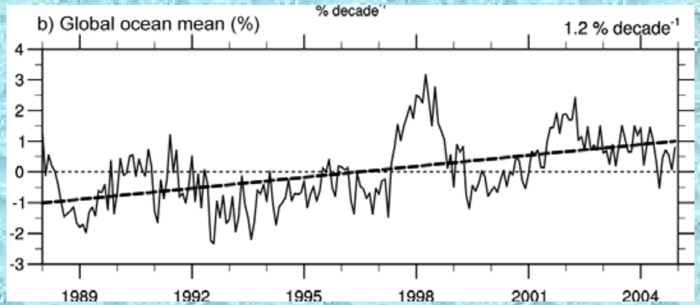
Air holds more water vapor at higher temperatures

A basic physical law tells us that the water holding capacity of the atmosphere goes up at about 7% per degree Celsius increase in temperature. (4% per °F)

Observations show that this is happening at the surface and in lower atmosphere: 0.55°C since 1970 over global oceans and 4% more water vapor.

This means more moisture available for storms and an enhanced greenhouse effect.

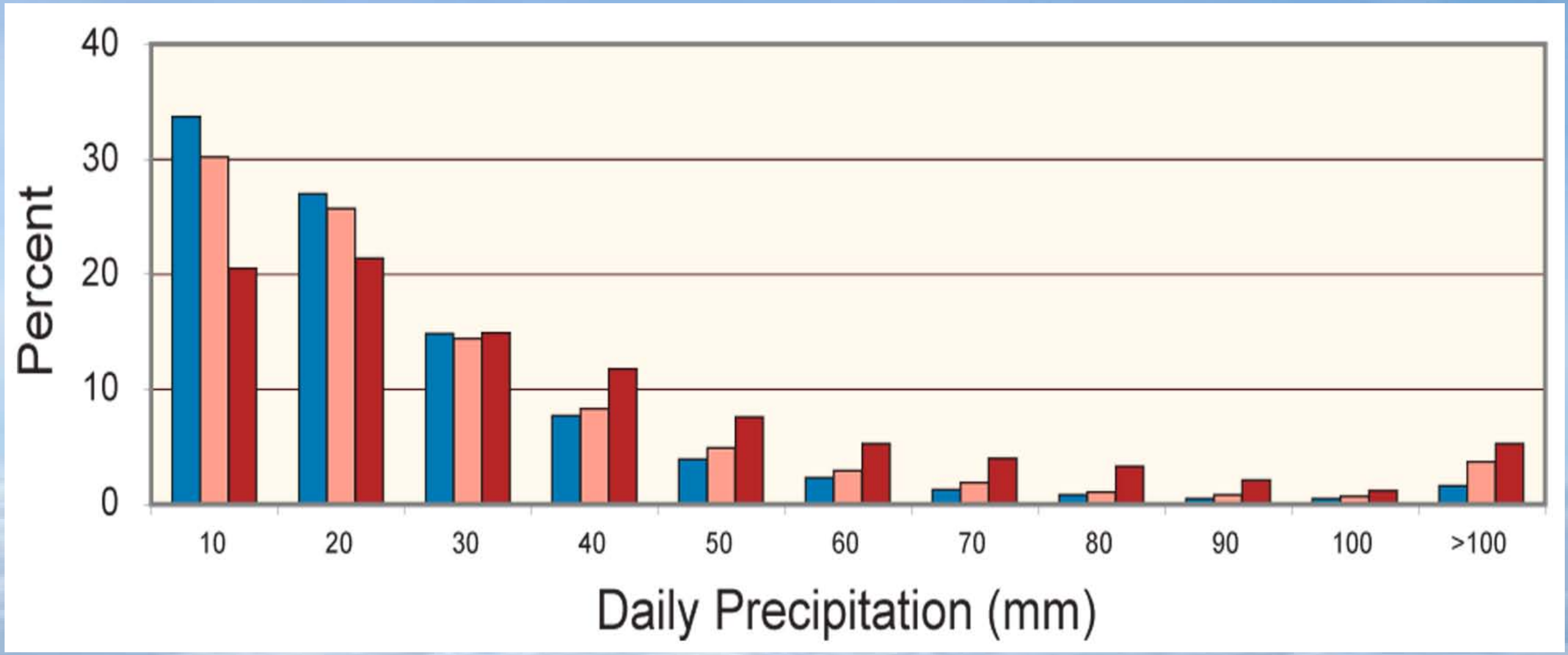
Total water vapor



More intense rains (or snow) but longer dry spells

Trenberth et al 2003

Higher temperatures: heavier precipitation



Percent of total seasonal precipitation for stations with 230mm±5mm falling into 10mm daily intervals based on seasonal mean temperature. Blue bar -3°C to 19°C, pink bar 19°C to 29°C, dark red bar 29°C to 35°C, based on 51, 37 and 12 stations.

As temperatures and e_s increase, more precipitation falls in heavy (over 40mm/day) to extreme (over 100mm/day) daily amounts.

Karl and Trenberth 2003

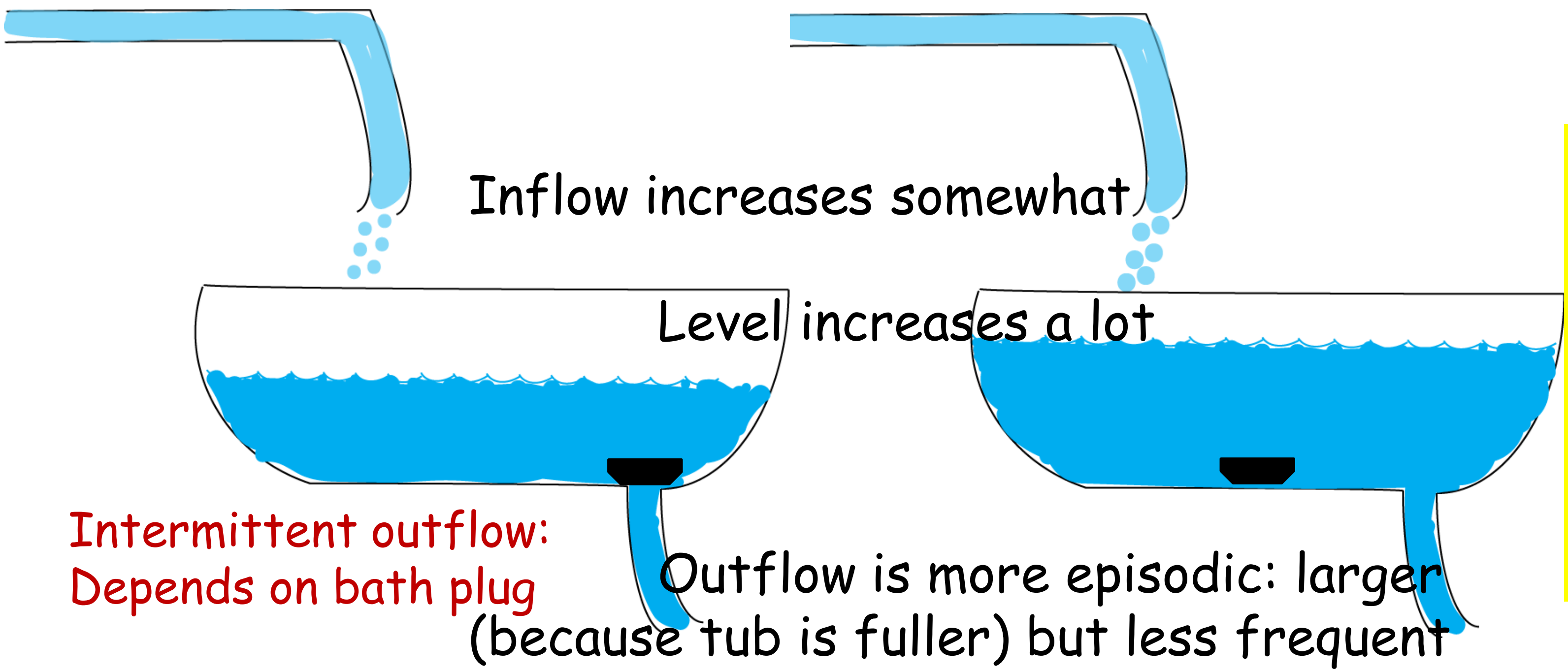
How should precipitation P change as the climate changes?

- With increased GHGs: increased **surface** heating evaporation E⇑ and P⇑
- **Clausius Clapeyron:** water holding capacity of atmosphere goes up about 7% per °C. (4% per °F)
- With increased aerosols, E⇓ and P⇓
- **Net global effect is small and complex**
- Models suggest E⇑ and P⇑ 2-3% per °C.

Bathtub analogy

Before warming

After warming

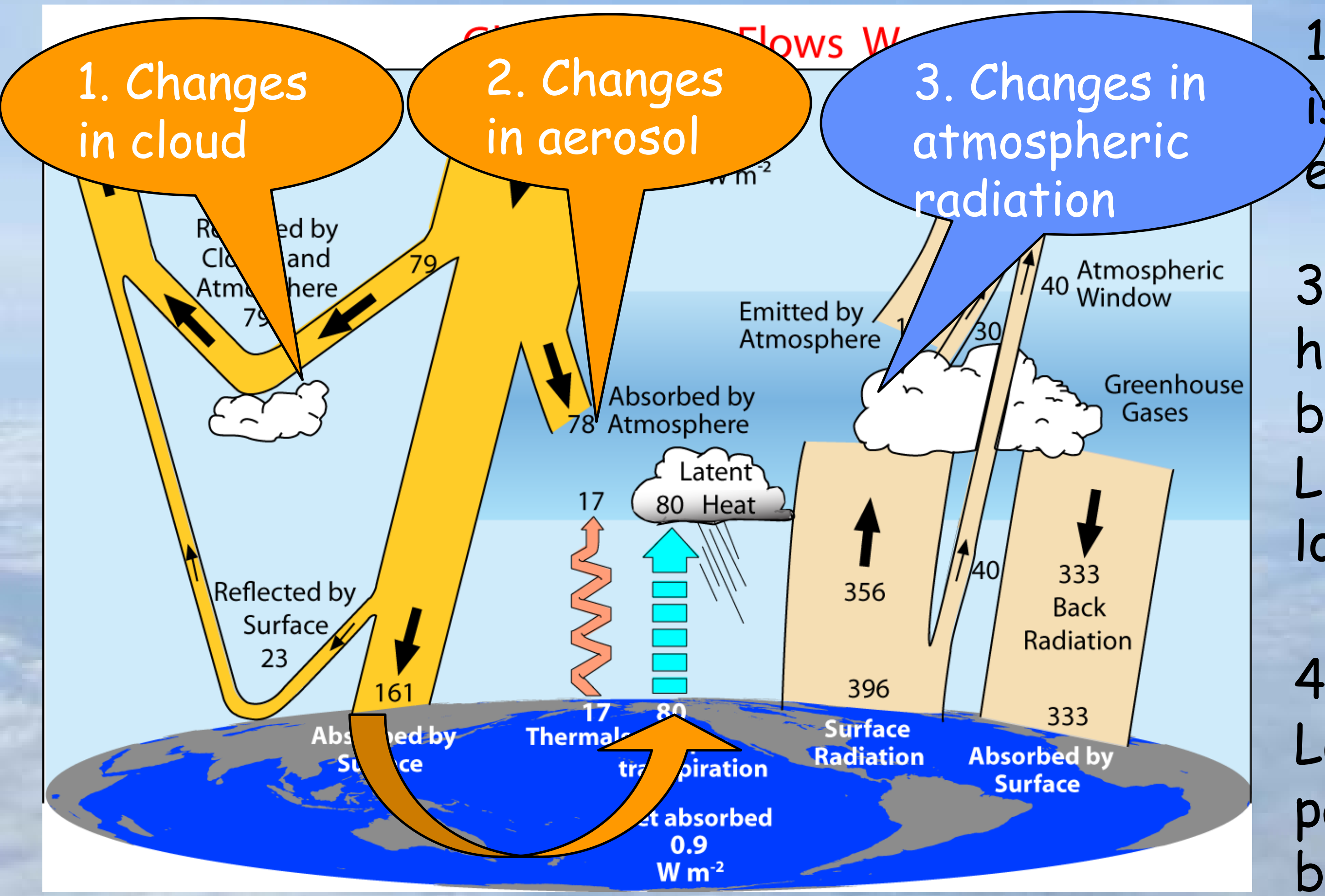


Evaporation

Atmosphere Moisture

Precipitation

Controls on the changes in net precipitation



1.+2. Evaporation is limited by energy available

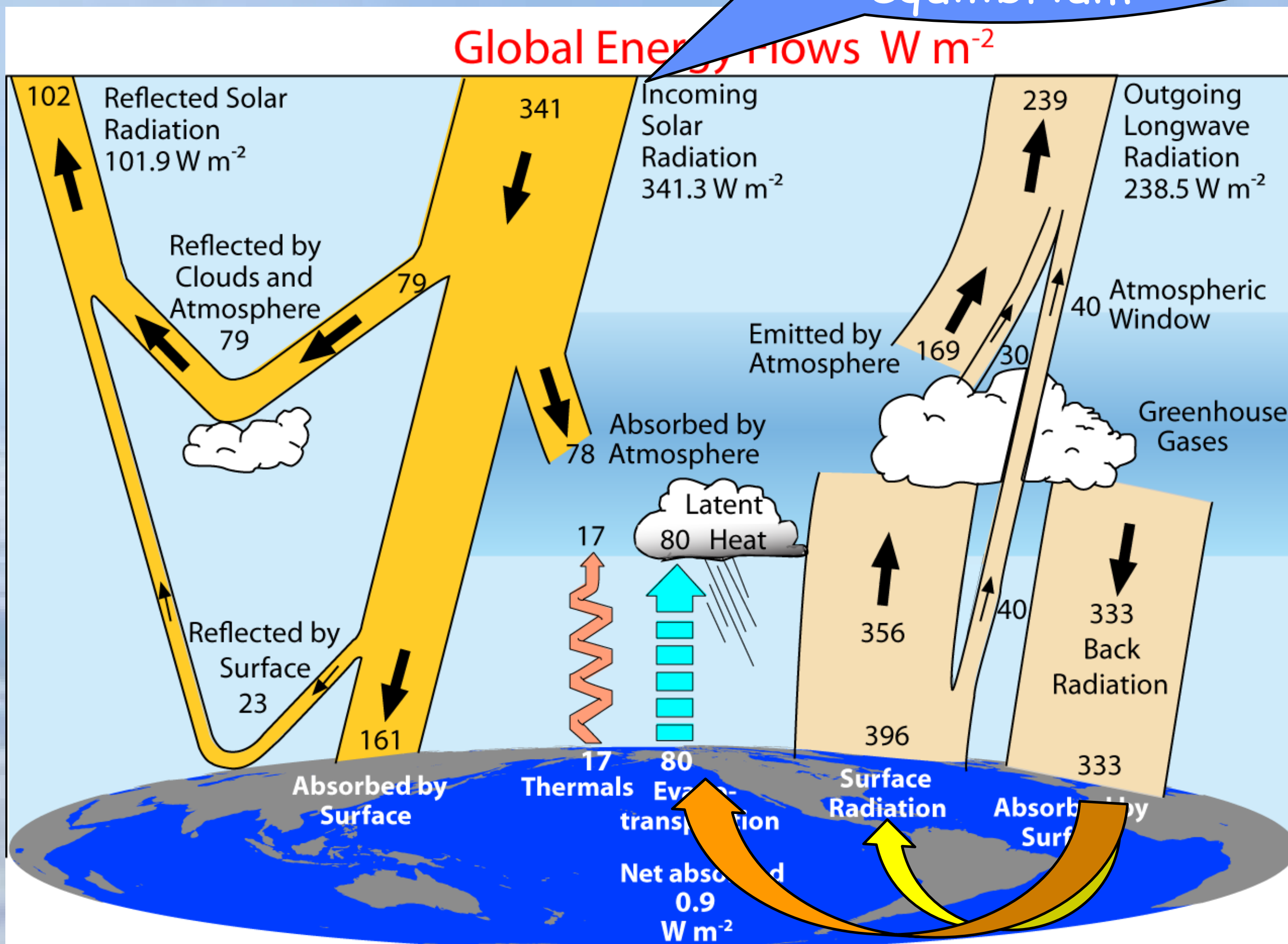
3. Latent heating has to be mostly balanced by net LW radiative losses (SH small)

4. Over land: Latent heating is partly balanced by sensible heat

2000-2005 Trenberth et al 2009

Controls on t… …ecipitation

TOA radiation does not change (much) in equilibrium



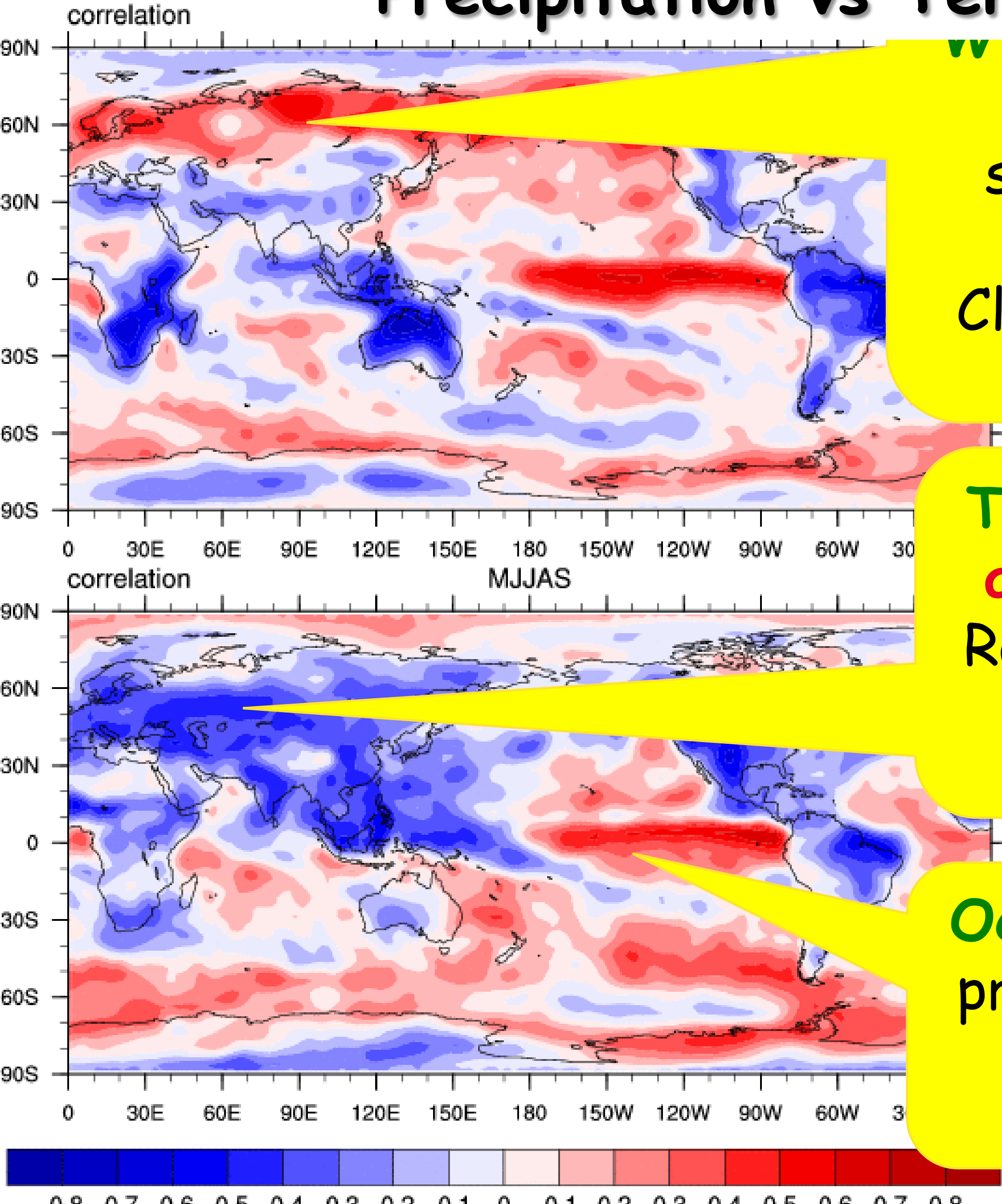
If the only change in climate is from increased GHGs: then SW does not change (until ice melts and if clouds change), and so OLR must end up the same.

But downwelling and net LW↓ increases and so other terms must change: mainly evaporative cooling.

Transient response may differ from equilibrium (see Andrews et al. 09)
Land responds faster. Radiative properties partly control rate of increase of precipitation.: Stephens and Ellis 2008

2000-2005 Trenberth et al 2009

Precipitation vs Temperature

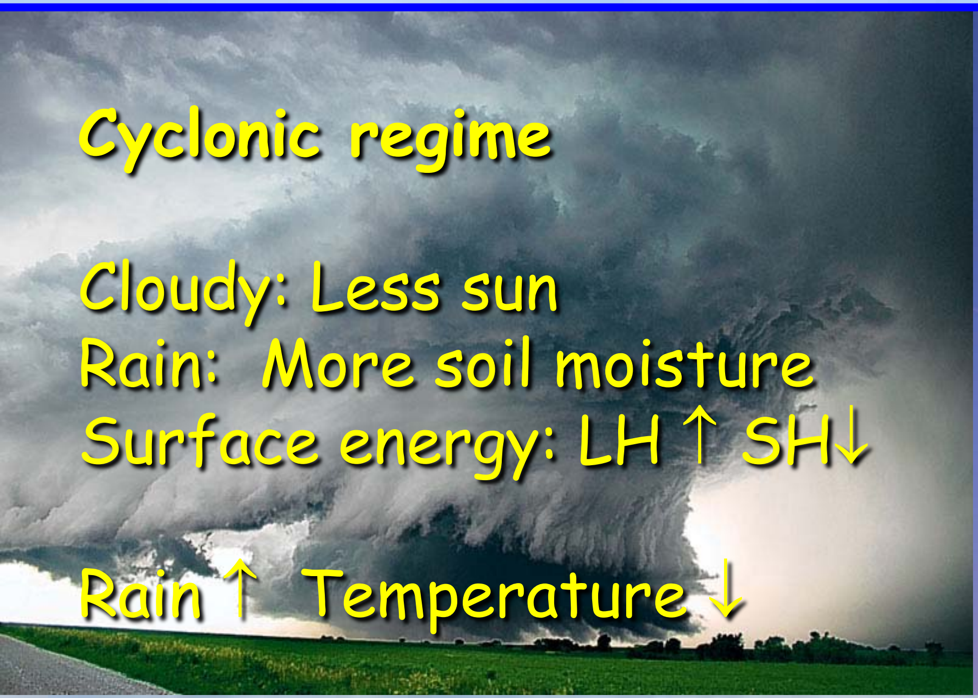


Winter high lats: air can't hold moisture in cold; storms: warm and moist southerlies.
Clausius-Clapeyron effect
T⇒P

Tropics/summer land: **hot and dry** or **cool and wet**
Rain and cloud cool and **air condition** the planet!
P⇒T

Oceans: El Nino high SSTs produce rain, ocean forces atmosphere
SST⇒P

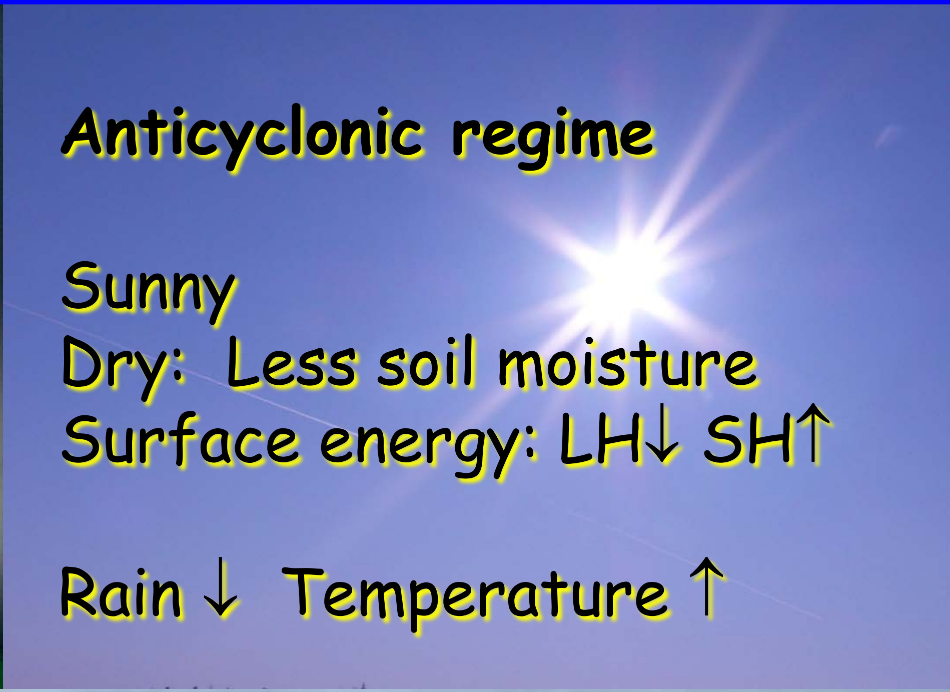
Temperature vs Precipitation



Cyclonic regime

Cloudy: Less sun
Rain: More soil moisture
Surface energy: LH ↑ SH↓

Rain ↑ Temperature ↓



Anticyclonic regime

Sunny
Dry: Less soil moisture
Surface energy: LH↓ SH↑

Rain ↓ Temperature ↑

Summer: Land

Strong negative correlations

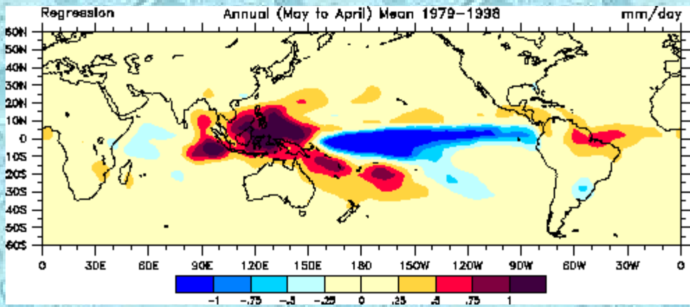
Does **not** apply to oceans

Air holds more water vapor at higher temperatures

- The **C-C effect** is important over oceans (abundant moisture) and over land at mid to high latitudes in winter.
- "**The rich get richer and the poor get poorer**". More moisture transports from divergence regions (subtropics) to convergence zones. Result: **wet areas get wetter, dry areas drier** (Neelin, Chou)
- But increases in moist static energy and **gross moist instability** enables **stronger convection and more intense rains**. **Hadley circulation** becomes deeper.
- Hence it **changes winds** and convergence: **narrower zones**.

How else should precipitation P change as the climate changes?

- "**More bang for the buck**": With increased moisture, the winds can be less to achieve the same transport. Hence the divergent circulation weakens. (Soden & Held)
- Changes in characteristics: **more intense less frequent rains** (Trenberth et al)
- Changed winds **change SSTs**: ITCZ, storm tracks **move**: dipoles Example: ENSO



- **Type**: snow to rain
- Snow pack **melts** sooner, runoff earlier, summer soil moisture less, risk of summer drought, wildfires increases

Precipitation in models:
"all models are wrong, some are useful"

A challenge:

Amount: distribution:
double ITCZ

Frequency: too often

Intensity: too low

Runoff: not correct

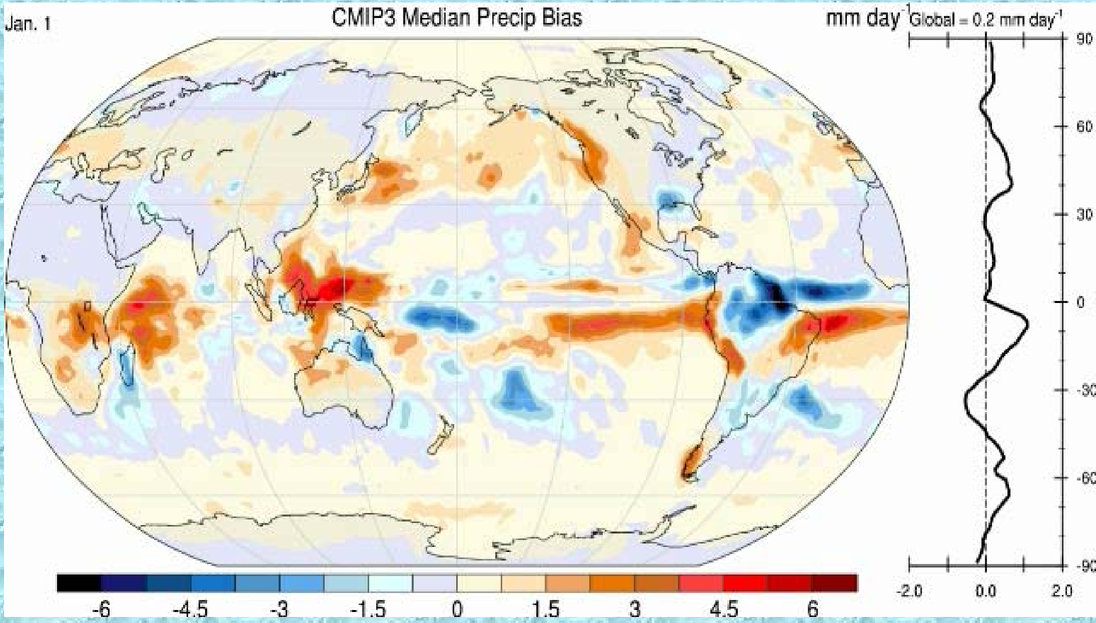
Recycling: too large

Diurnal cycle: poor

Lifetime: too short
(moisture)

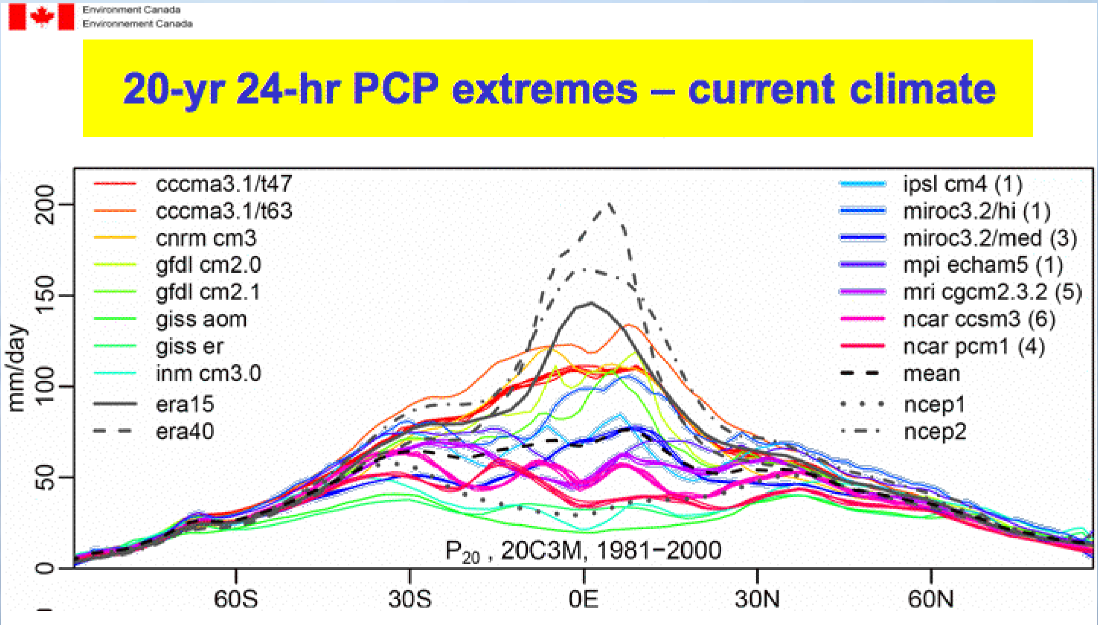
Issues:

Tropical transients too weak
- Hurricanes
- MJOs
- Easterly waves



All models are wrong, some are useful!

There are many analyses of models, but models are demonstrably poor at many aspects of the hydrological cycle.

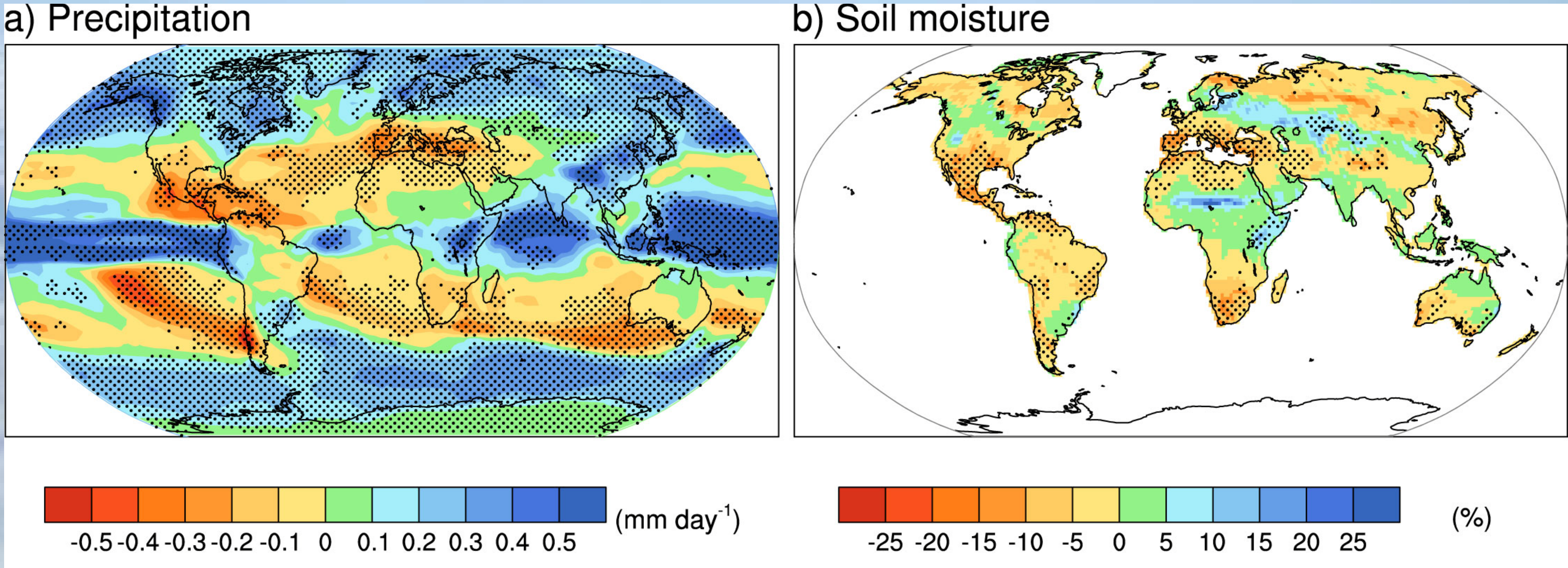


Courtesy Francis Zwiers

Model predictions

"Rich get richer, poor get poorer"

Projections: Combined effects of increased precipitation intensity and more dry days contribute to lower soil moisture



2090-2100

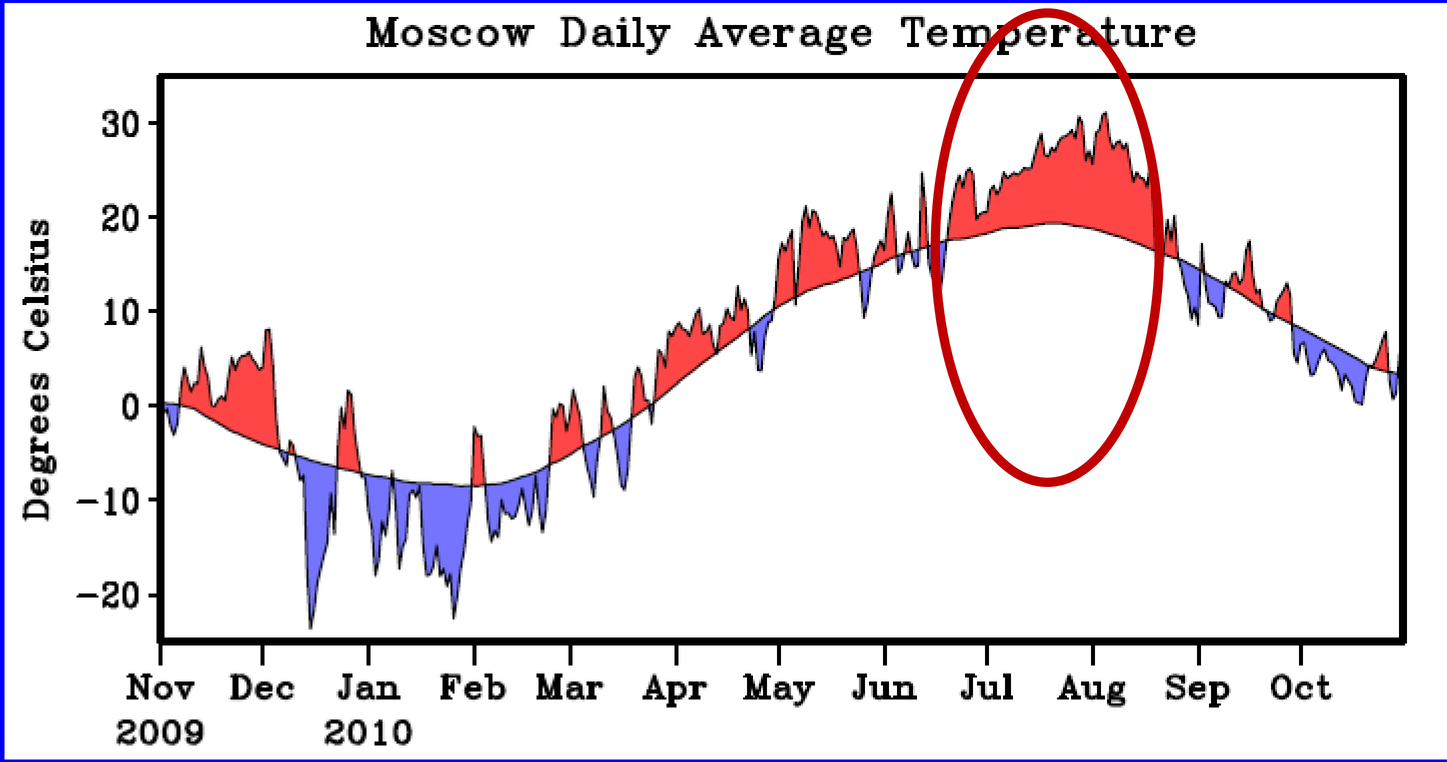
IPCC

Russian heat wave attribution

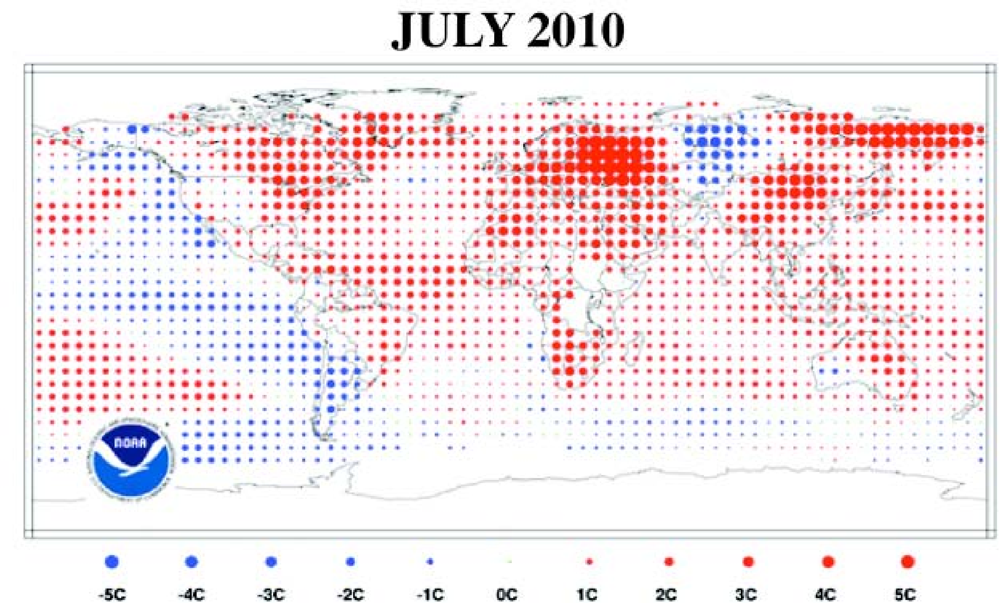
Train of causation /evidence

There is a climate event, with observational evidence:

1) Record high temperatures in Russia, heat waves, wild fires, over a month
2) High SSTs in tropical Indian Ocean, western Pacific
3) Arctic sea ice loss: near record low
4) High precipitation, flooding in Pakistan, India, China: SE Asia
   - Distribution linked to La Nina

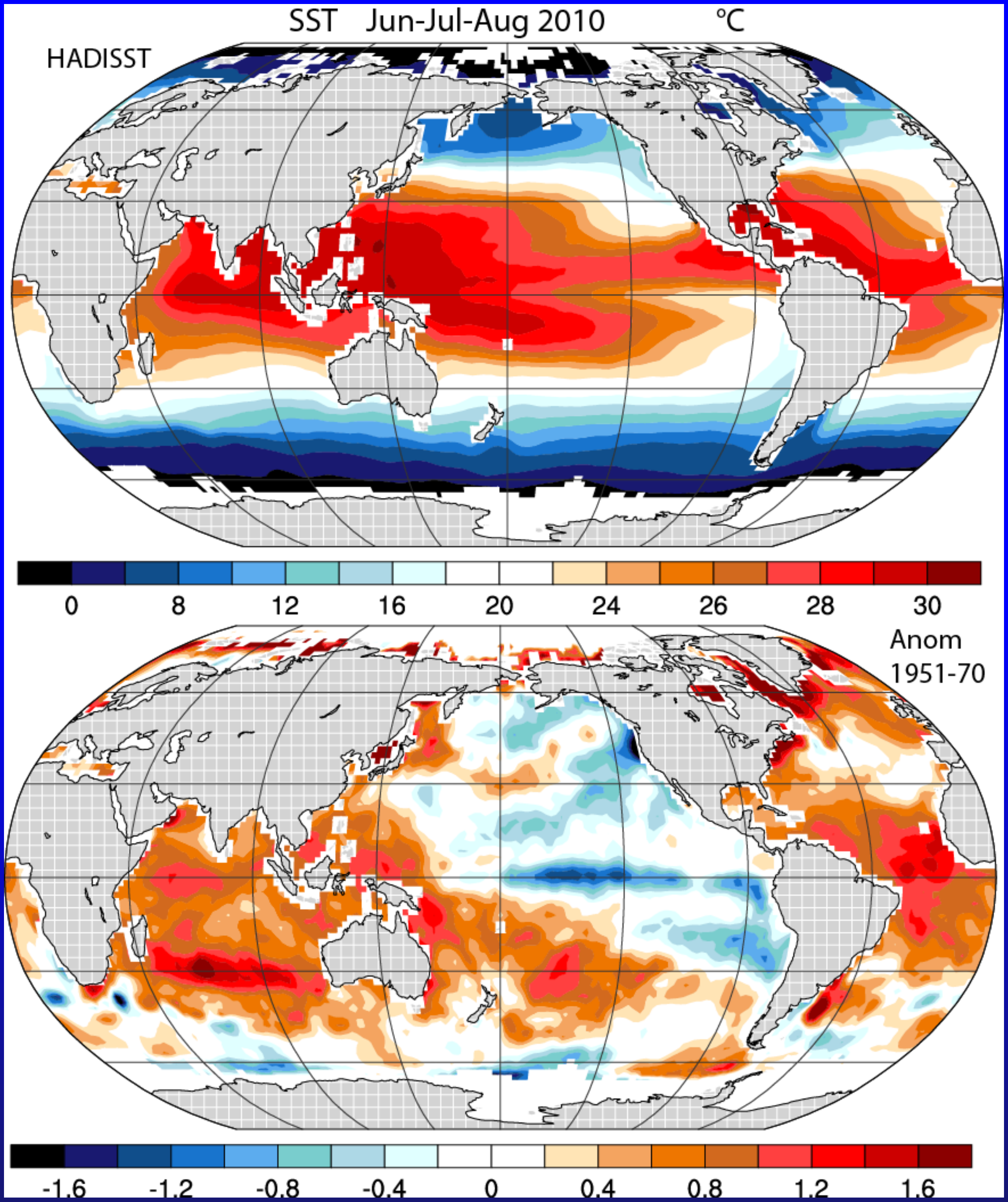


Temperatures



From Dole et al 2011

NCAR

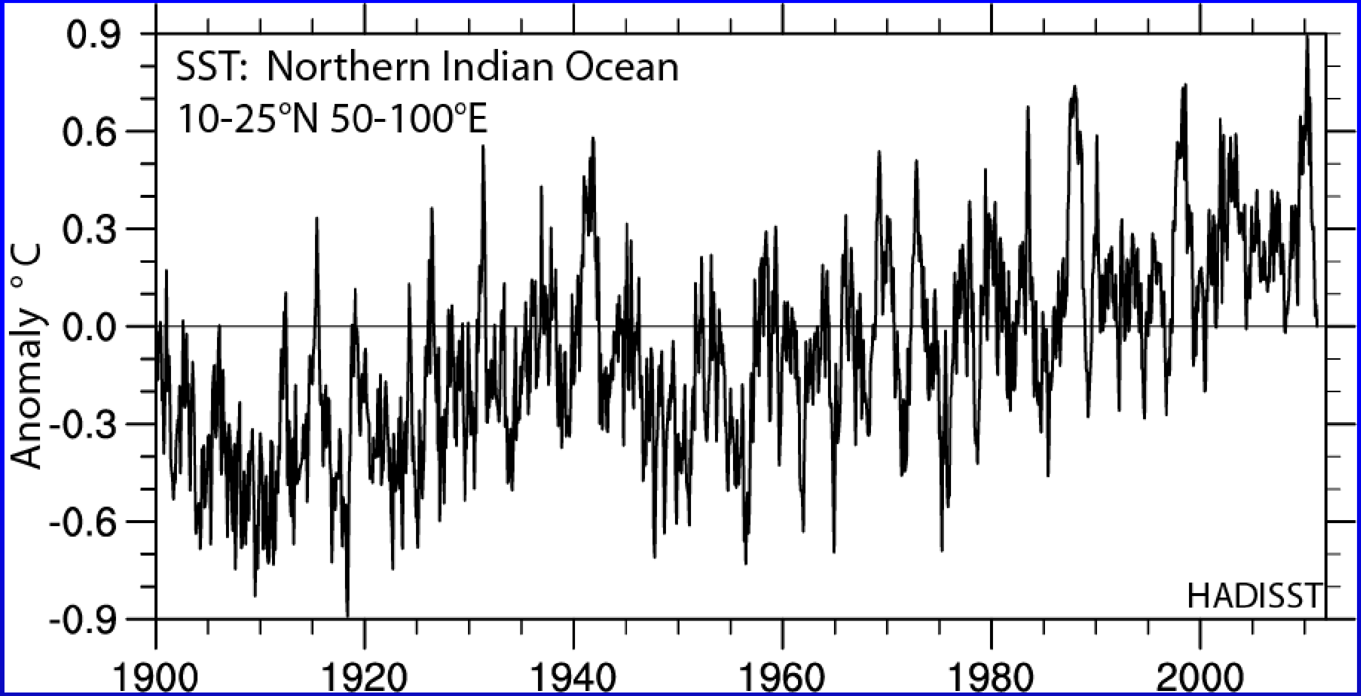


SSTs

Positive anomalies on top of normally high SSTs have extra impact owing to C-C

Northern Indian Ocean

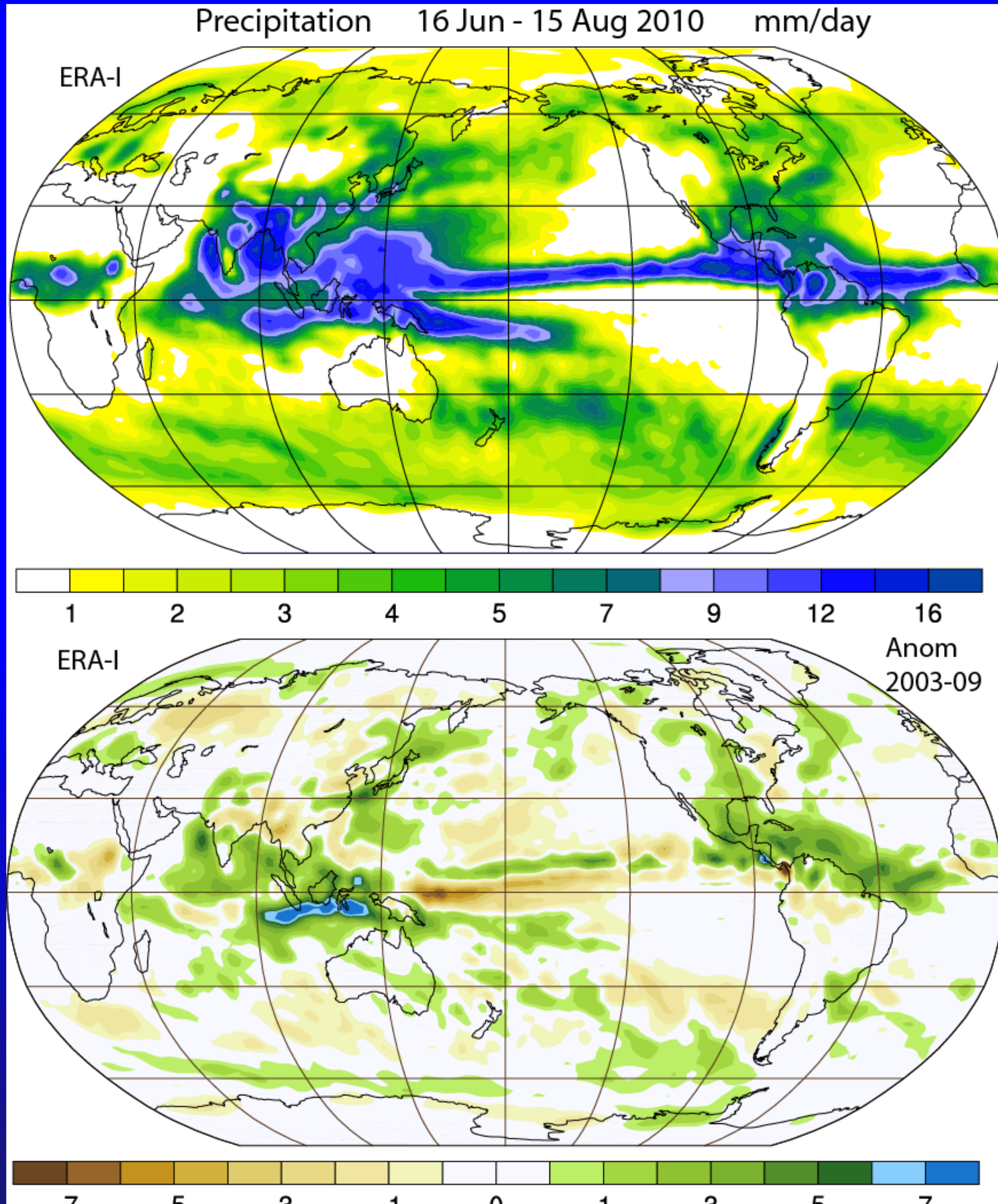
Incl: Bay of Bengal and Arabian Sea



May 2010 highest on record (30.4°C) and anomaly 0.9°C (2.9 σ)

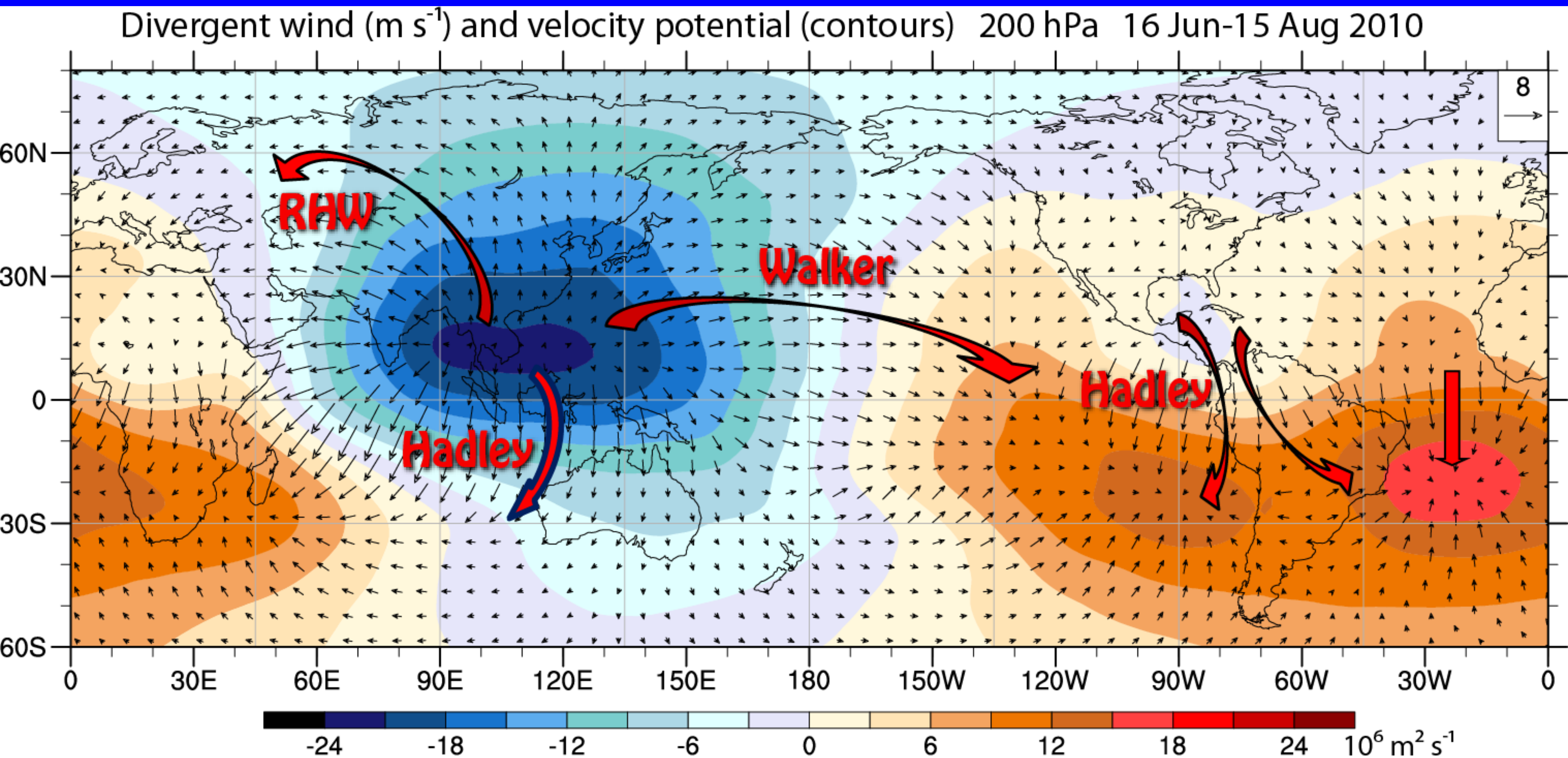
(base period 1960-89)

NCAR



Precipitation

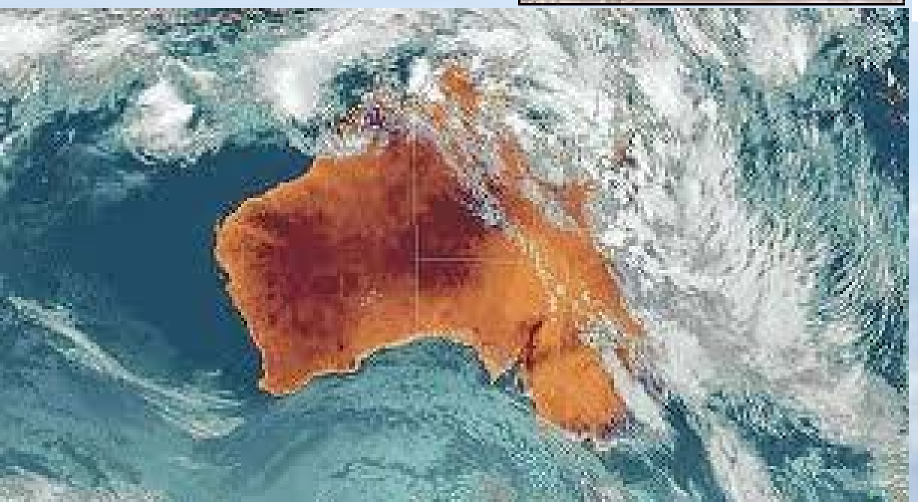
ERA-I

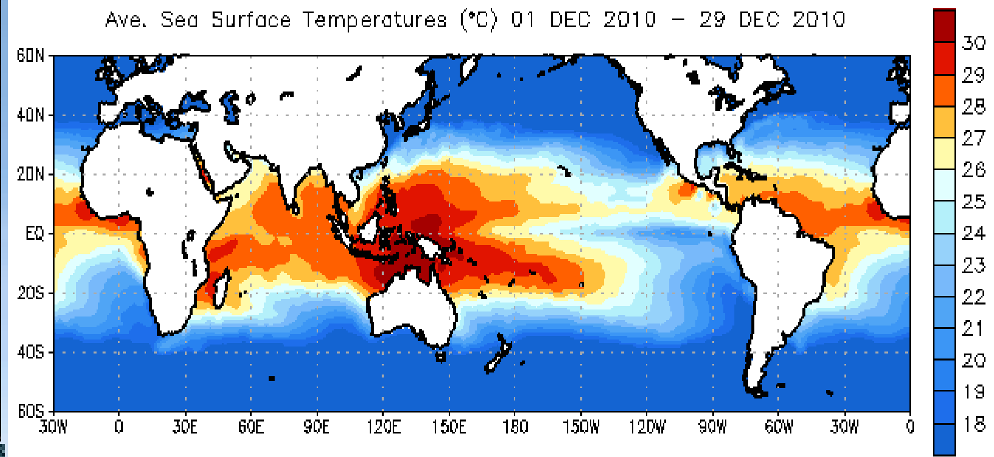


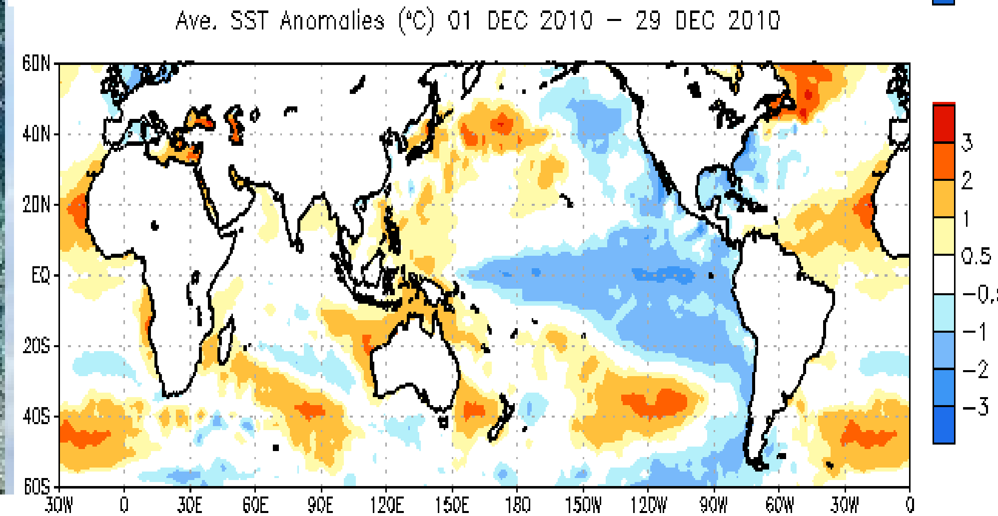
Record high SSTs in Caribbean and Gulf of Mexico Aug 2010
Record flooding in Columbia, 2nd highest activity in Atlantic tropical storms: 19 named, 12 hurricanes, 4 cat 4 or 5.
Drought in Brazil.

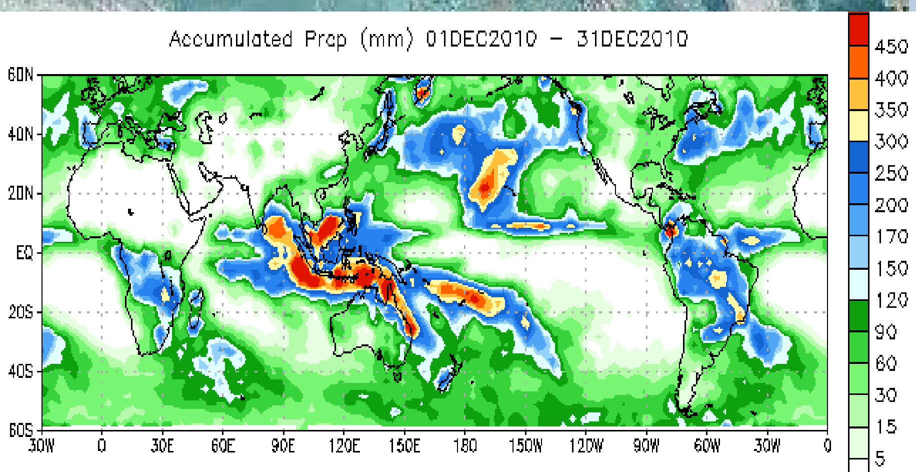
Flooding
Queensland
Early Jan 2011

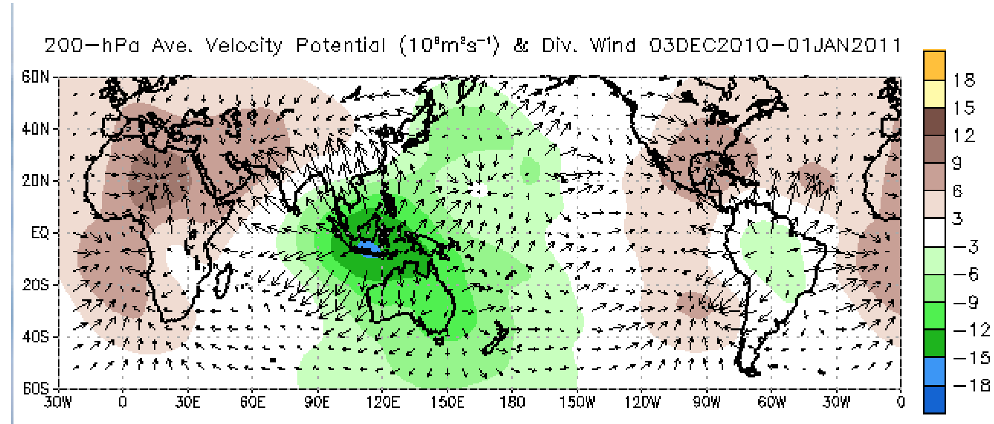
La Niña











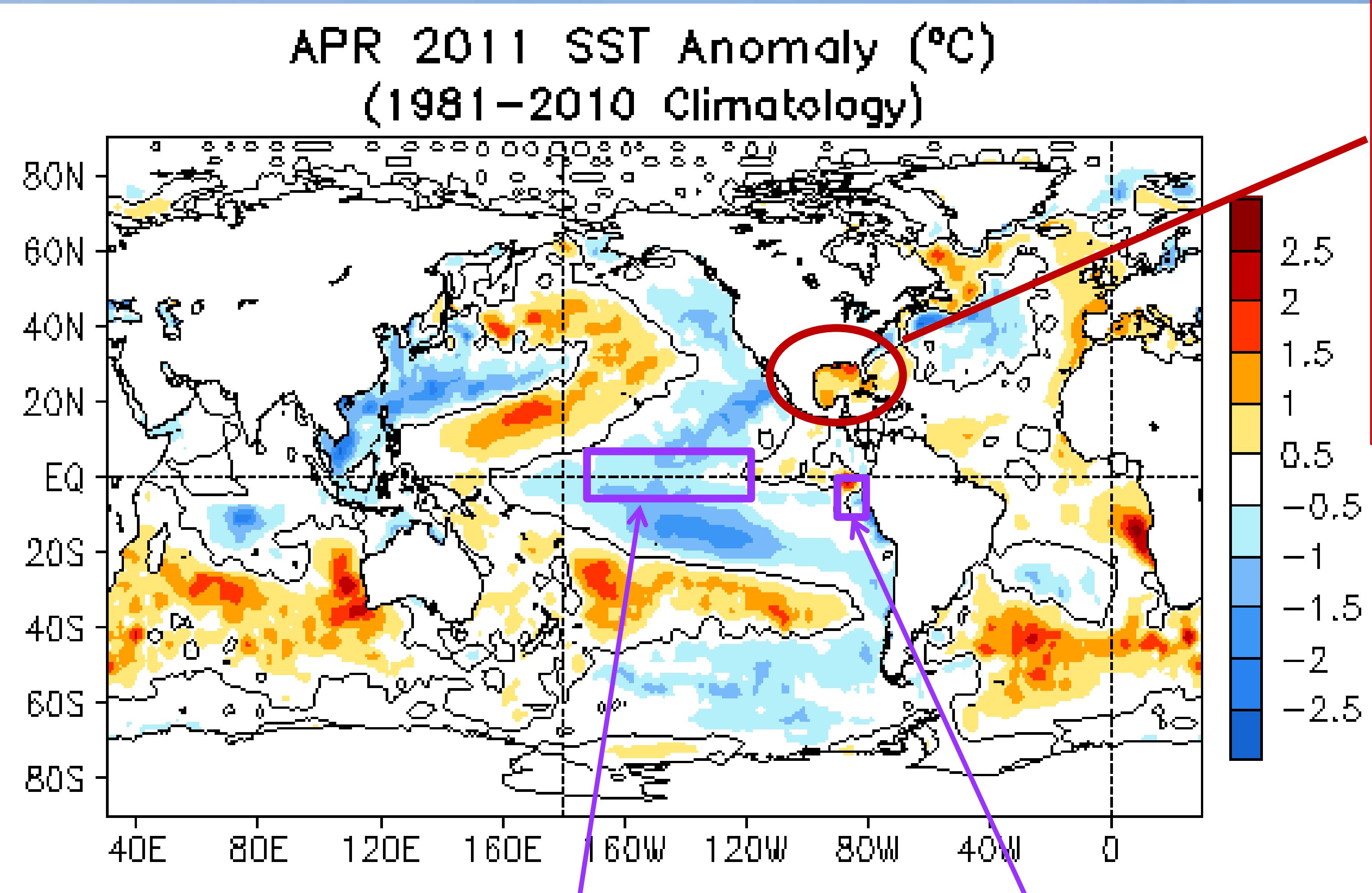
Flooding on the Mississippi:

There were multiple "1-in-500 year" or "1-in-100 year flood events within a few years of each other in parts of the Basin…

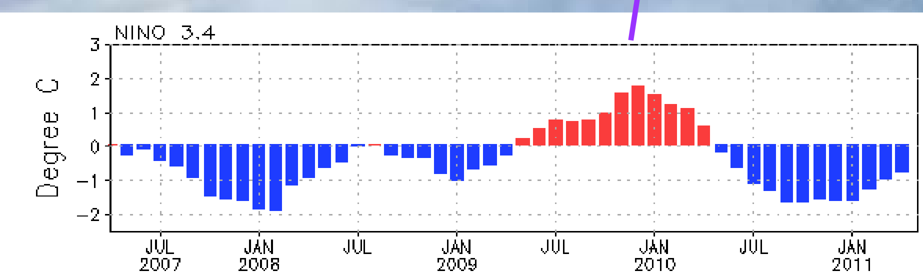
1993
Then again in **2008**.
And now: **2011**

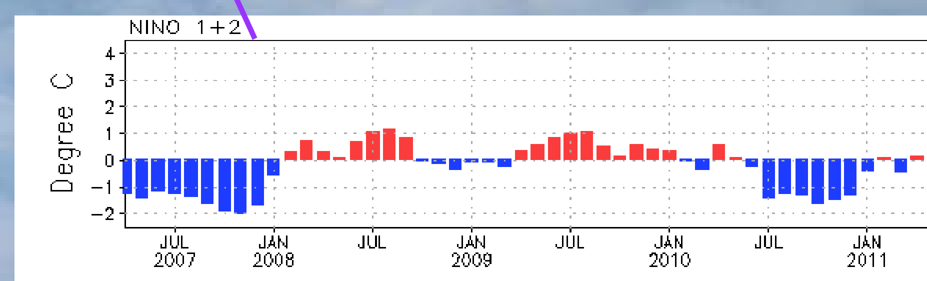
AP 2000; NYT 2011

Peter Gleick



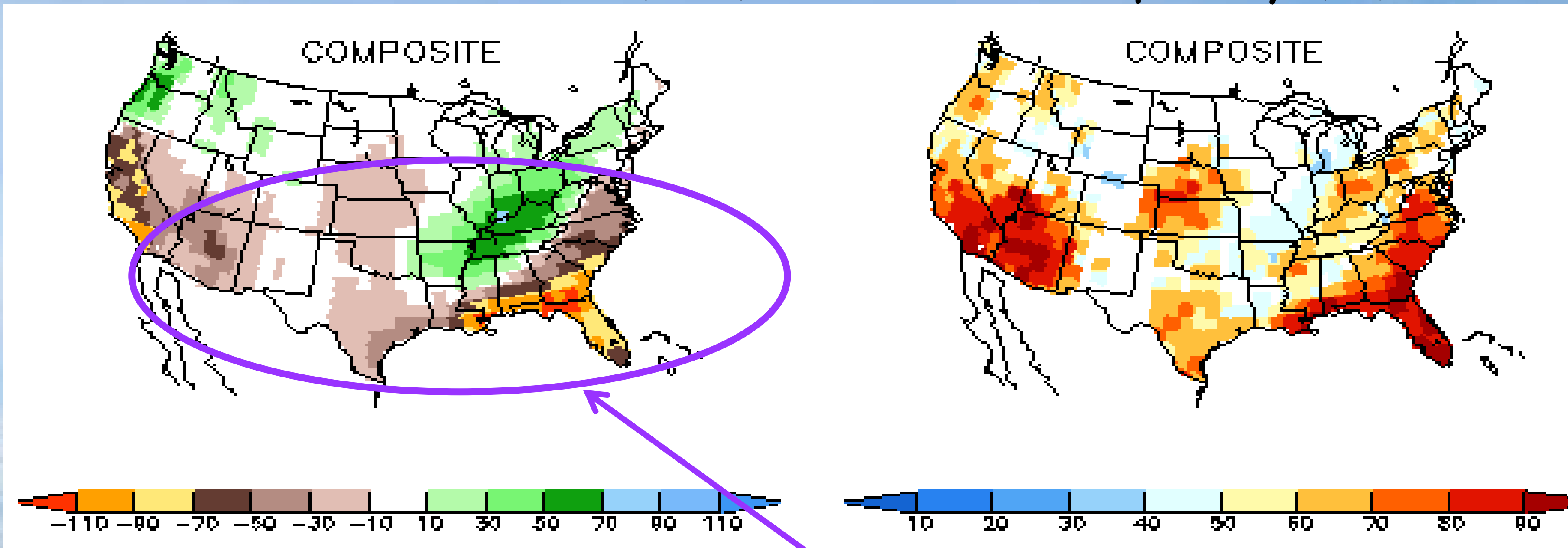
SSTs in Gulf 0.5 to 1.5°C above 1981-2010 values: ~1.5°C above pre-1970 values

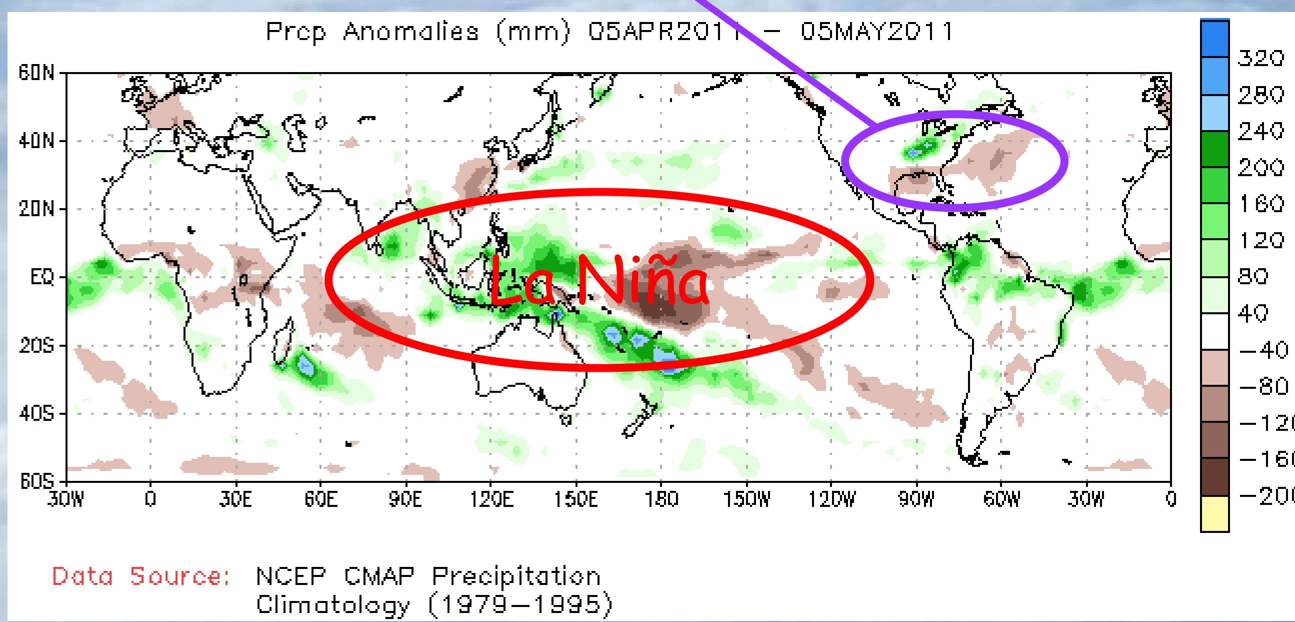




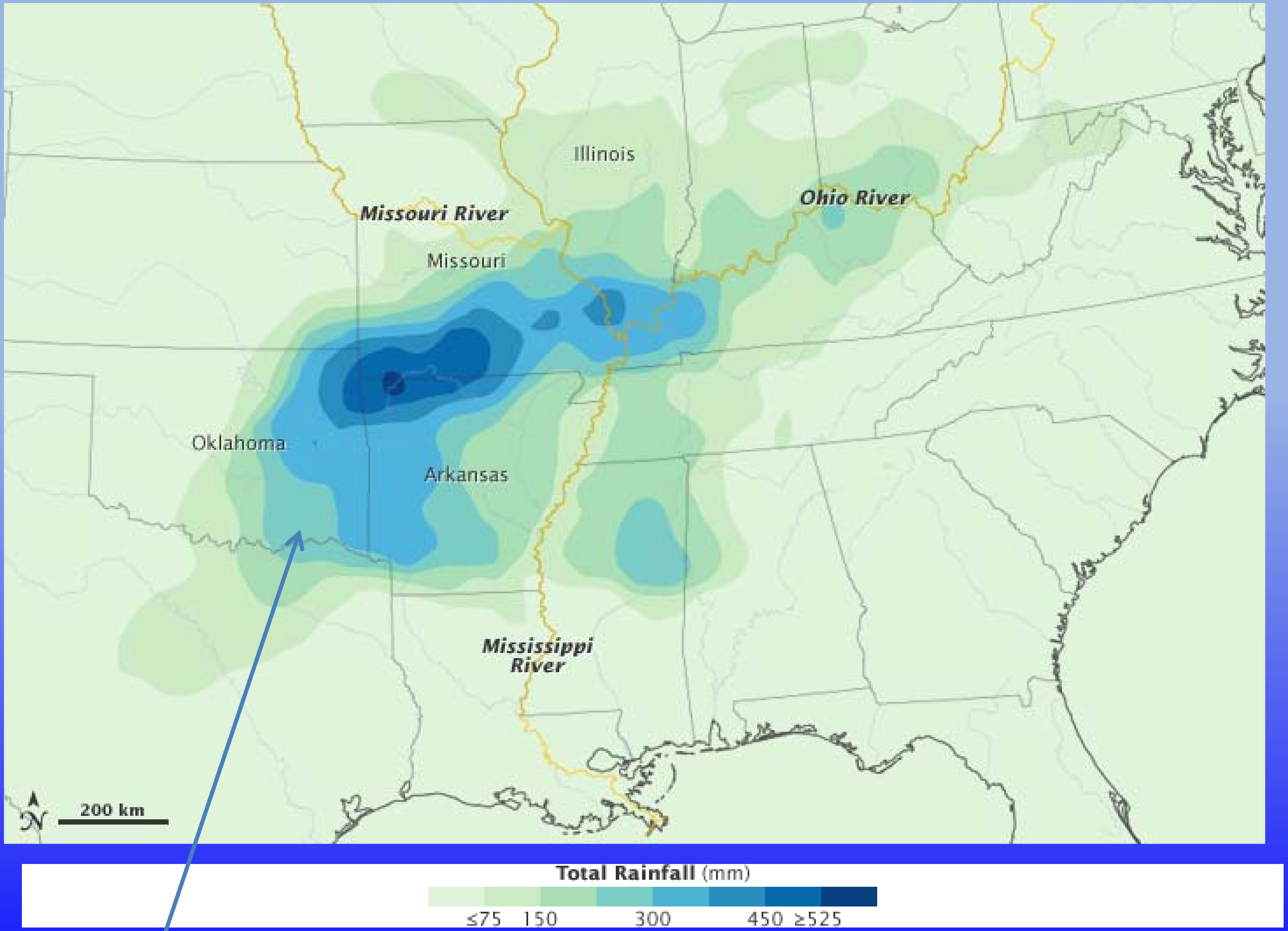
La Nina precipitation anomalies for JFM

anomalies (mm)   frequency (%)

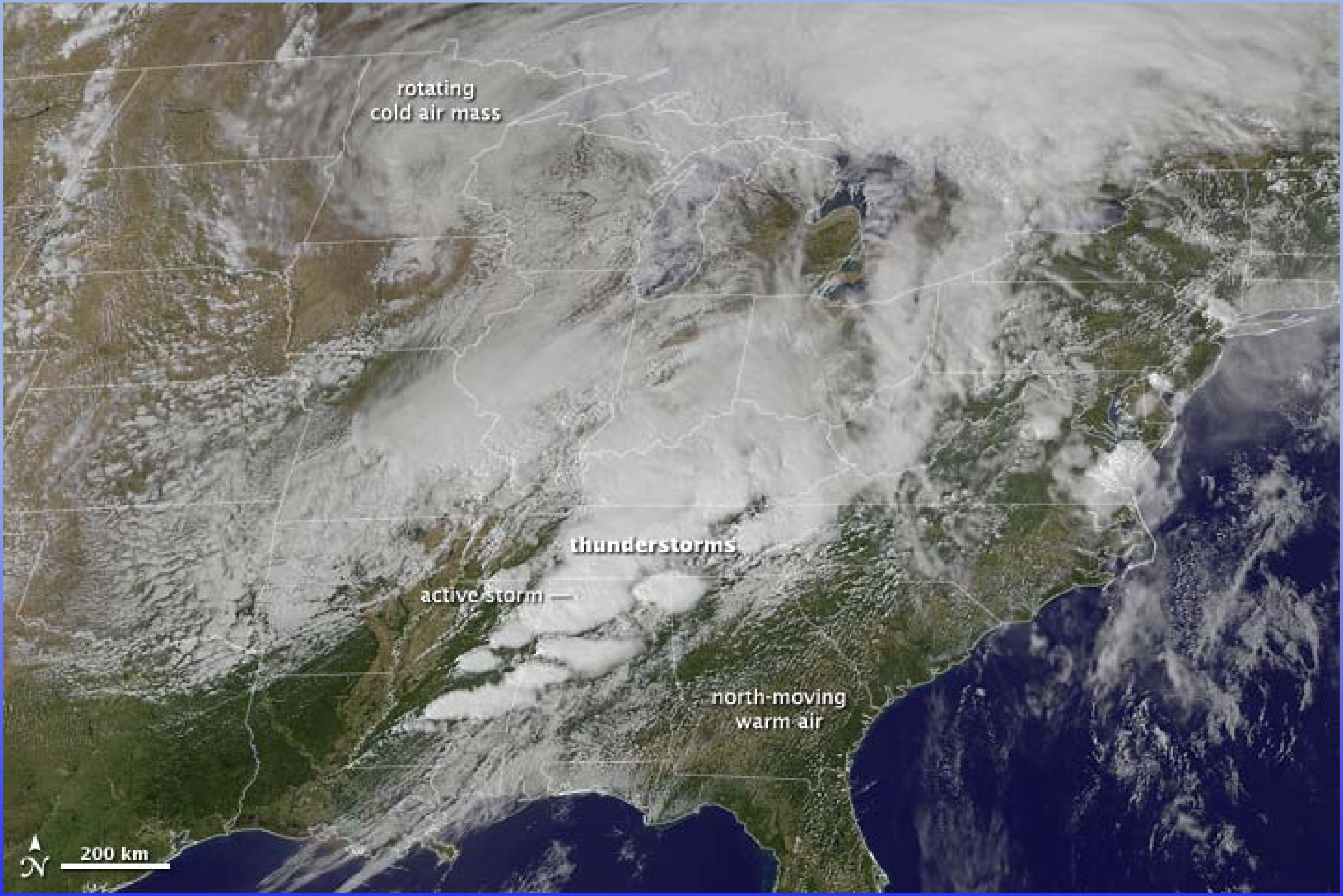




19-25 April 2011



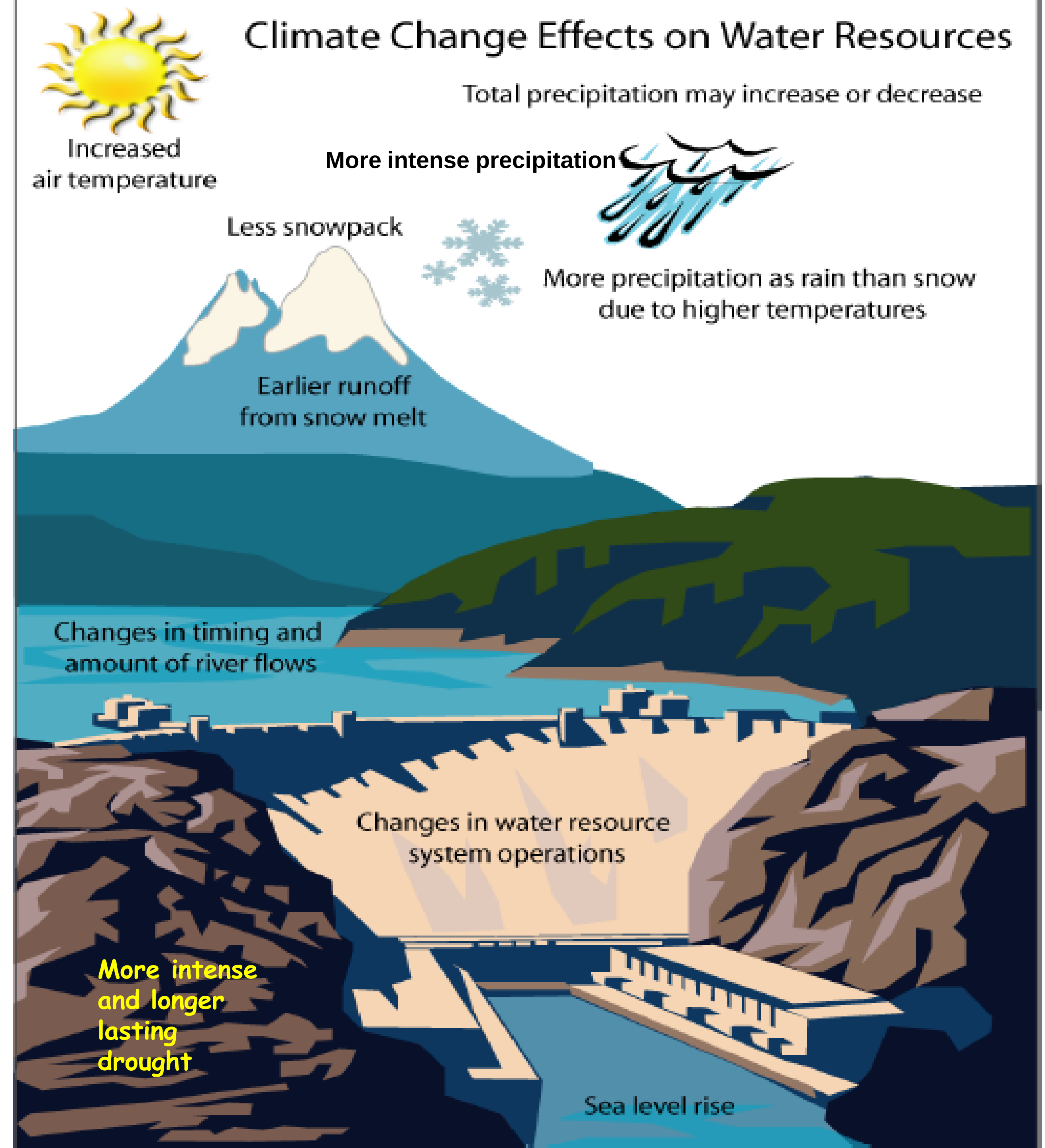
10 inches


rotating
cold air mass
thunderstorms
active storm
north-moving
warm air
N
200 km

The environment in which all storms form has changed owing to human activities.

Global warming has increased temperatures, and directly related to that, is an increase in the water holding of the atmosphere.

Over the ocean, where there are no water limitations, observations confirm that the amount of water vapor in the atmosphere has increased by about 4%, consistent with a 1°F warming of sea surface temperatures (SSTs) since about the 1970s.



Adapted from Peter Gleick

Prospects for increases in extreme weather events