Anticipated and Observed Trends in the Global Hydrological Cycle and Storms

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The Looming Water Crisis

- Quite aside from any climate issues, the burgeoning population means increased demand. (2.5B 1950; 6B 2000; 9.3B 2050?)

- 1.2 Billion people have no access to clean drinkable water.
- 2.4 Billion people have no access to sanitation

- By 2050, it is projected that 7B people in 60 countries will face water scarcity.

- In the next 20 years, the per capita supply drops by one third.

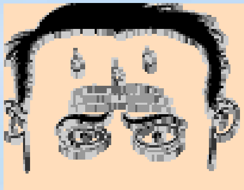
"*World Water Development Report*" United Nations 2003

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.

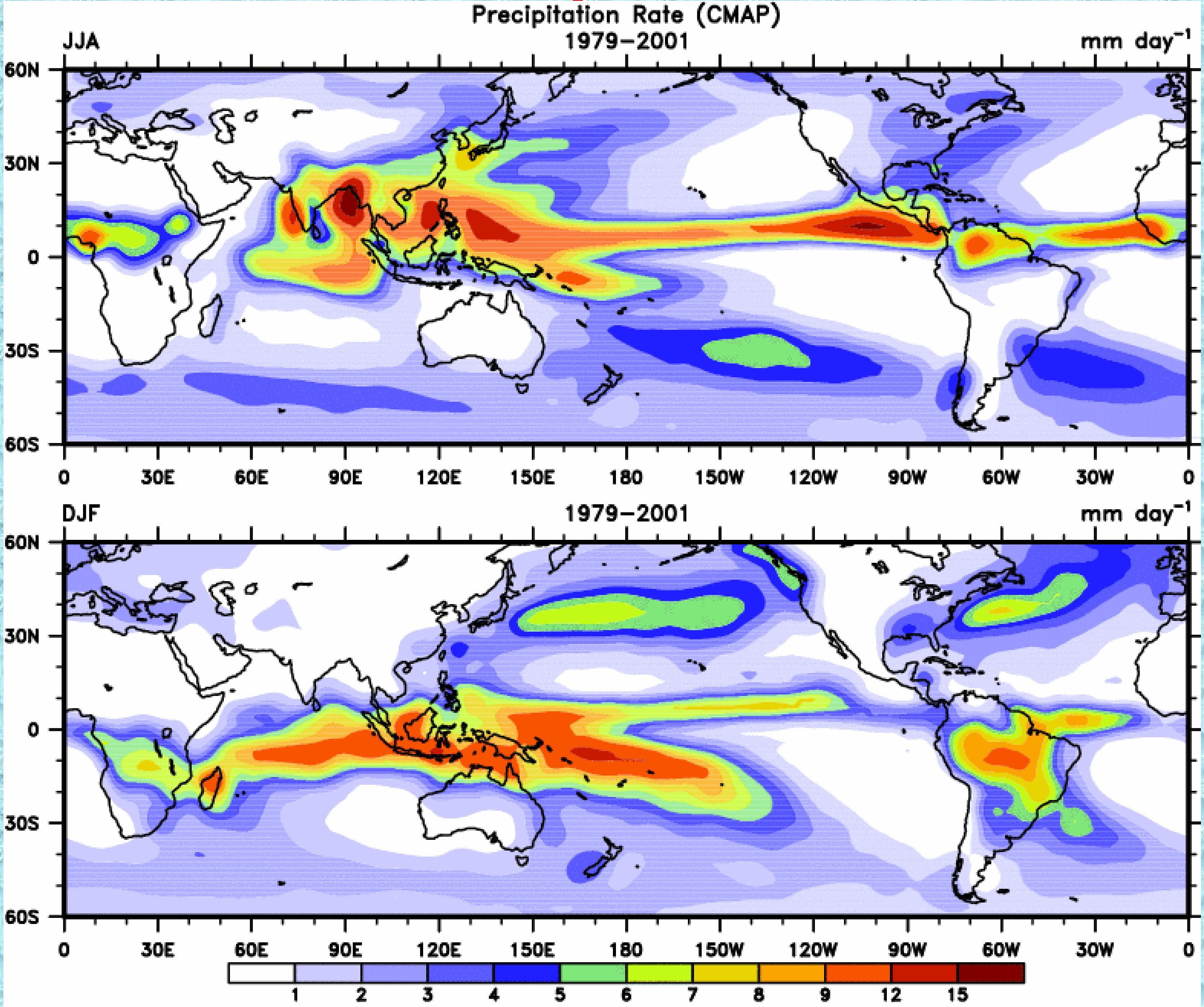
How should rainfall change as climate changes?

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

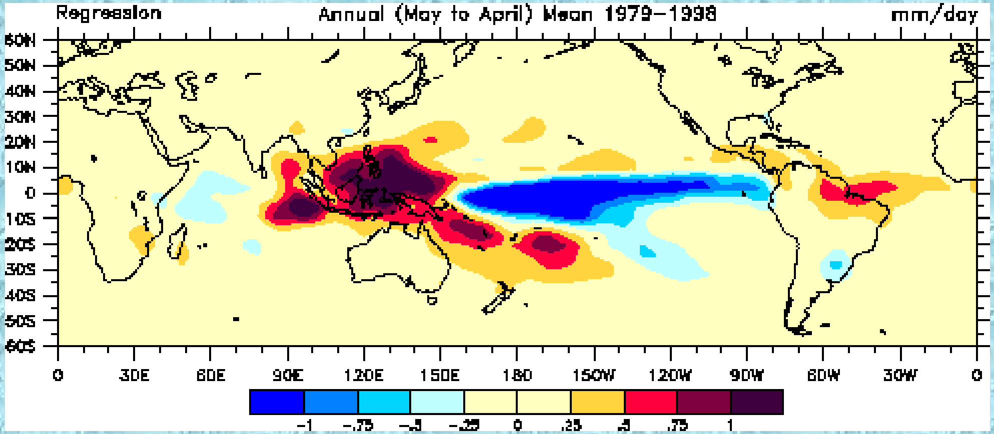
The intensity and phase affect how much runs off versus how much soaks into the soils.

Precipitation

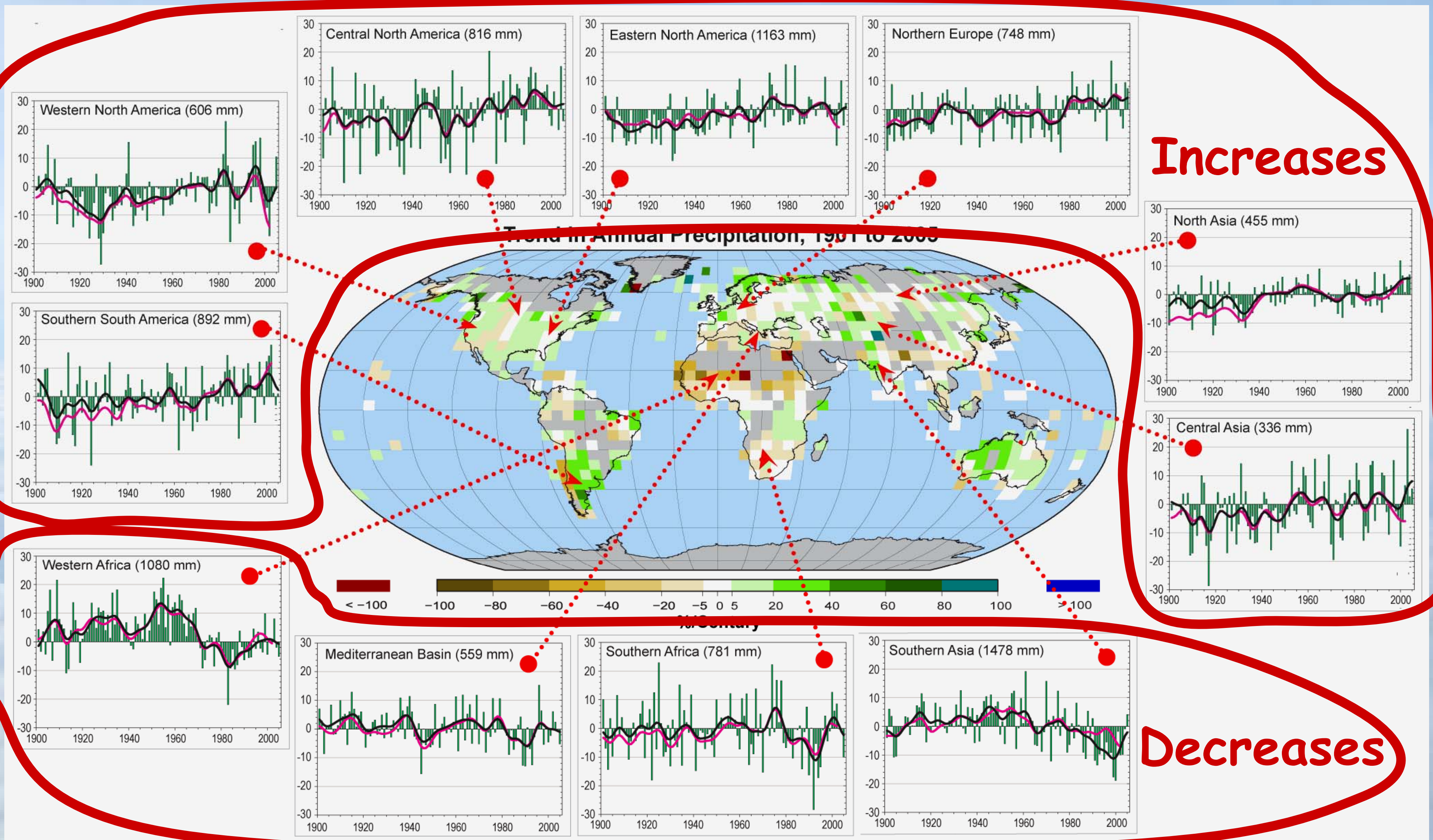


Changes in precipitation depend a lot on the mean

- Precipitation has strong structure with convergence zones
- A small shift creates a dipole: big increases some places, big decreases in others
- This is the first order effect in El Niño



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.

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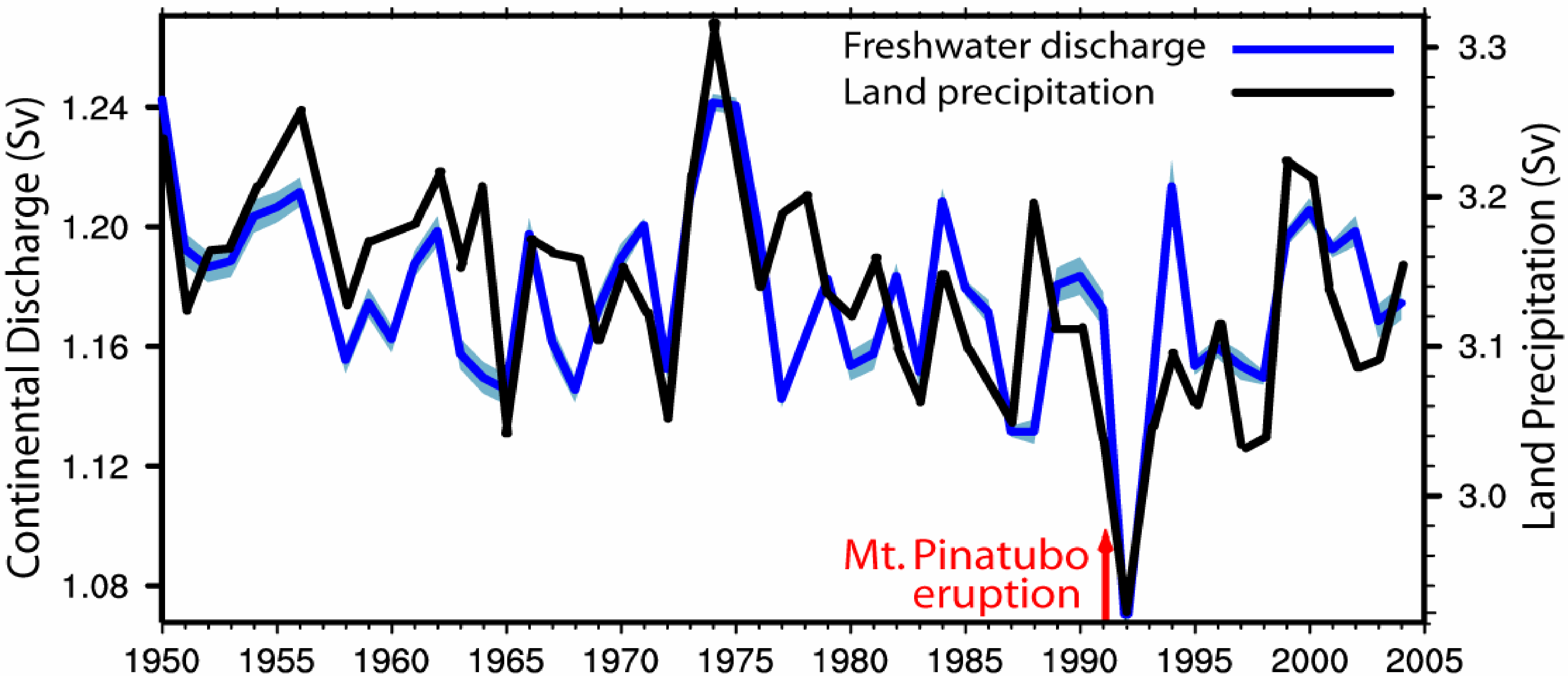
Pinatubo Effect on Hydrological Cycle



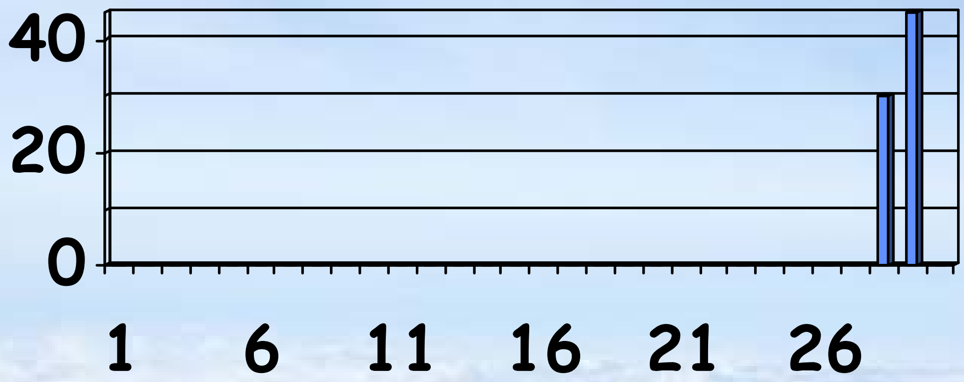
Estimated water year (1 Oct-30 Sep) **land precipitation** and river **discharge** into global oceans based on hindcast from output from CLM3 driven by observed forcings calibrated by observed discharge at 925 rivers.

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. 2008

Daily Precipitation at 2 stations

A



drought
wilting plants

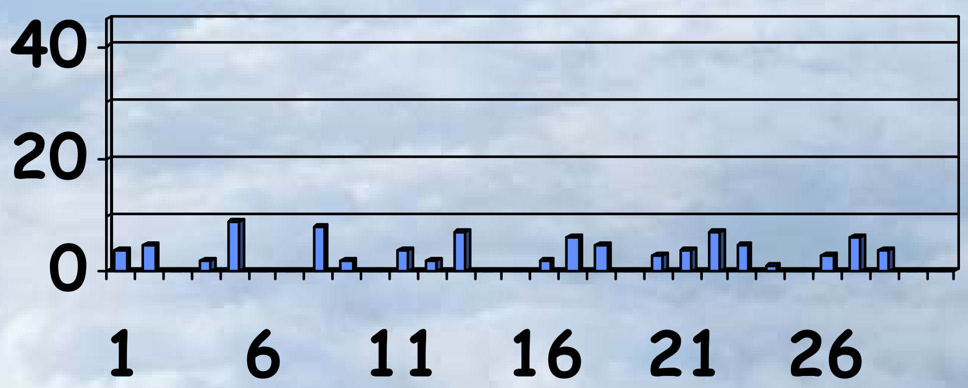
wild fires

local
floods

Monthly
Amount 75 mm

Frequency 6.7%
Intensity 37.5 mm

B



soil moisture replenished
virtually no runoff

Amount 75 mm

Frequency 67%
Intensity 3.75 mm

Why does it rain?

If a parcel of air rises: it expands in the lower air pressure and cools, and therefore may condense moisture, producing a cloud, and ultimately rainfall or snowfall.

Ingredients:

1. A storm of some sort to produce rising air (or orographic uplift):
   storm tracks, etc
2. Microphysics of cloud droplets that matter for condensation and formation of droplets:
   affected by pollution
3. Moisture

Aerosols have multiple effects:

1. **Direct** – cooling
   from sulfate aerosol:
   milky white haze, reflects
2. **Direct** – absorbing
   e.g. black carbon
3. **Indirect** – changes cloud

Indo-Asian Haze transported thousands of kilometers into the equatorial Indian Ocean.

1. **Form cloud condensation nuclei, more droplets, brighter cloud;**
2. **Less rain, longer lasting cloud;**
3. **Absorption in cloud heats and burns off cloud**
4. **Less radiation at surface means less evaporation and less cloud**

Lifetime only a week or so: Very regional in effects

Profound effects at surface:

Short-circuits hydrological cycle

Ramanathan et al 2001

Why does it rain?

Where does the water come from?

Mean global P = E: **2.8 mm/day**
But most of time it does not rain or snow.

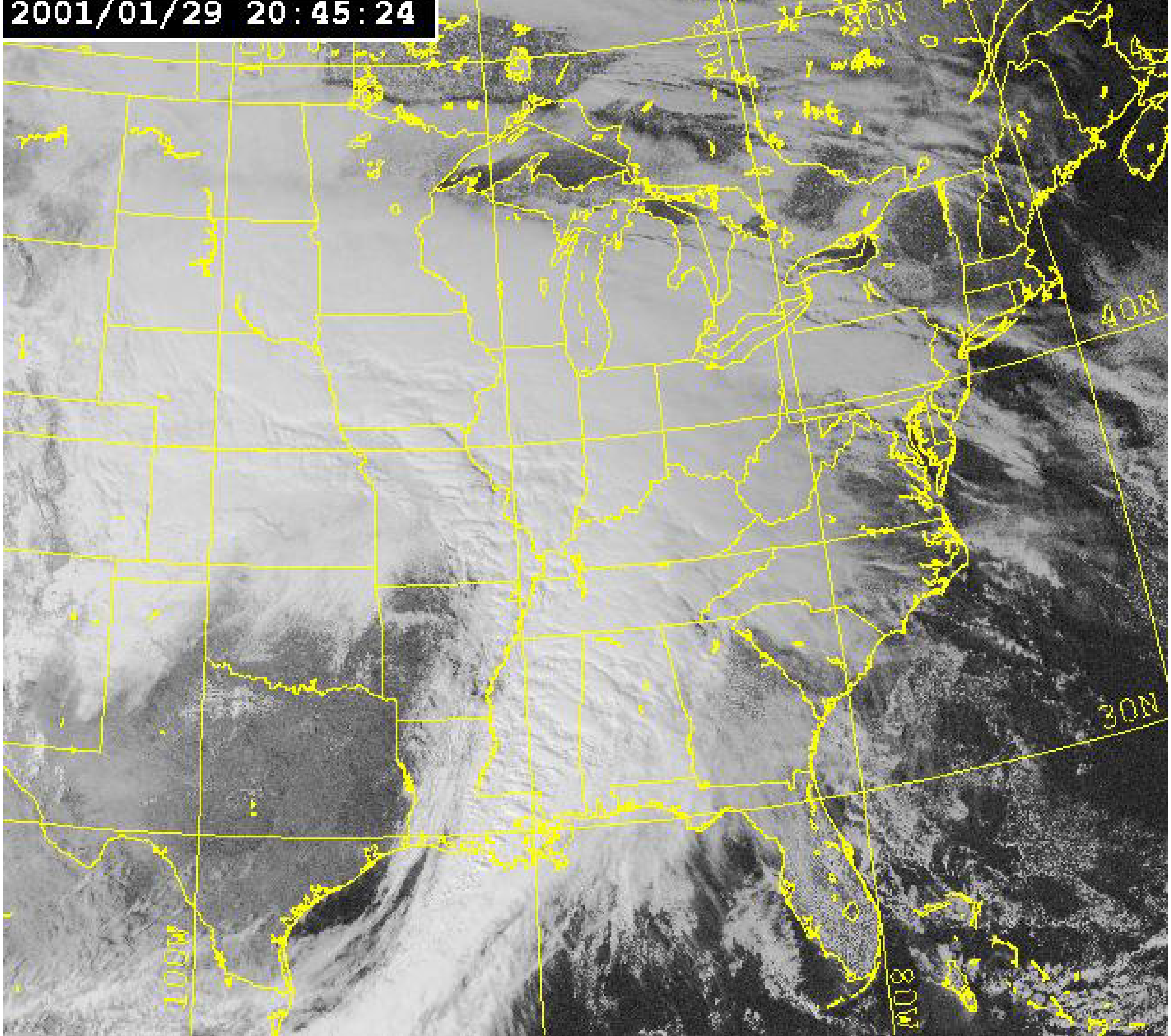
Average rain rate when it does rain is **45 mm/day**
(it rains over about 7% of globe at any time = 1/16)

Precipitable water typically **25 mm**
But only perhaps 30% available ⇒ **7.5 mm**
How can it rain more than this?

Moderate or heavy precipitation:

- Can not come from local column.
- Can not come from E, unless light precipitation.
- 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.


2001/01/29 20:45:24
40N
30N
100W
80W

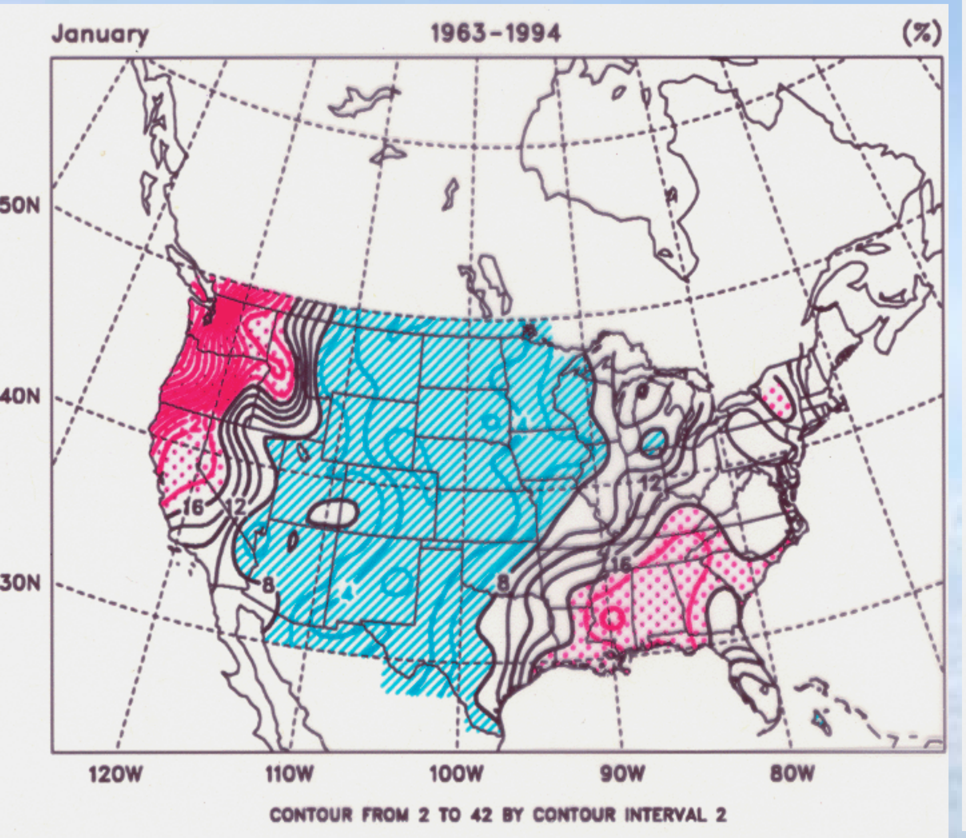
Extratropical Storms

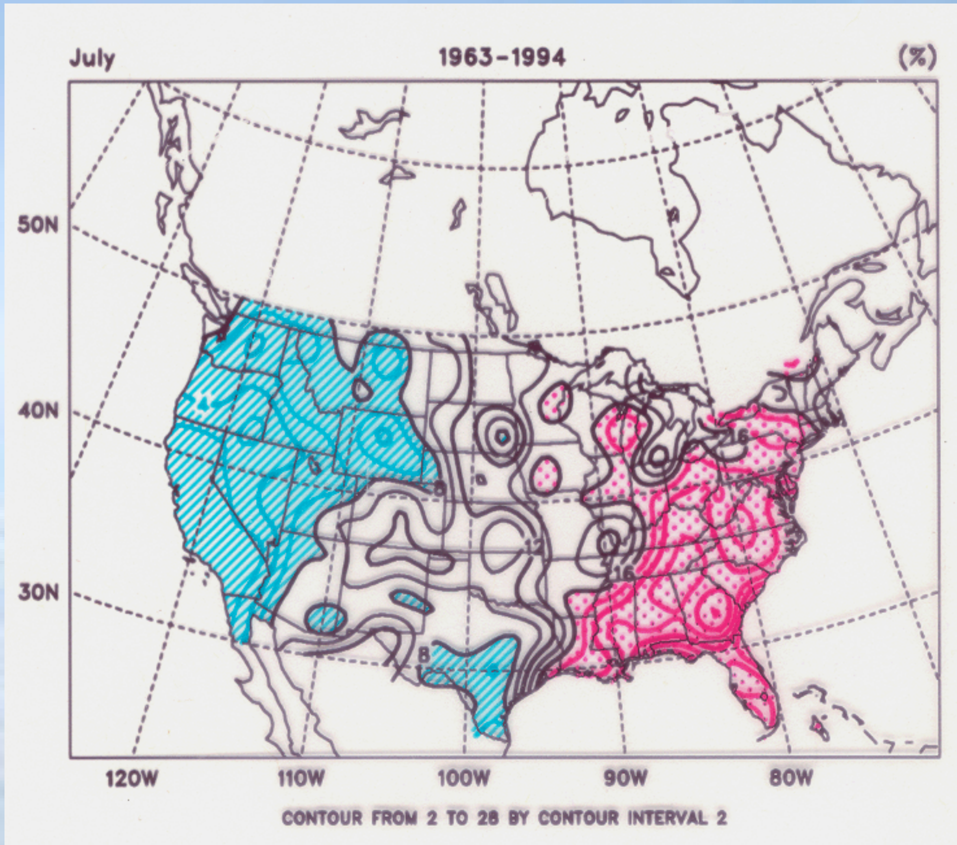
Winds converging into the low, pull cold air from the poles toward the equator, and warm moist air from the equator to the poles.

Where they meet is where we find fronts, bringing widespread precipitation and significant weather, like thunderstorms.

Source: USA TODAY research by Chad Palmer, Graphic by Chuck Rose

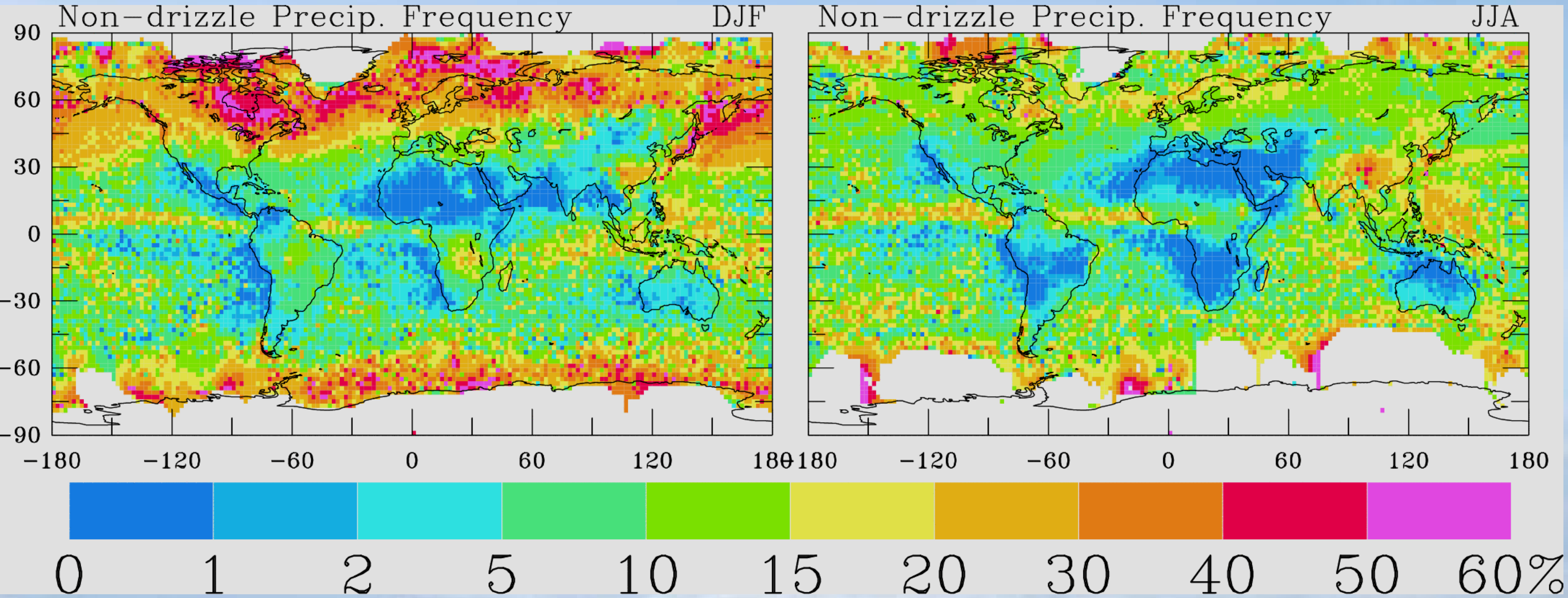
% hours of precipitation > 0.1 mm





Frequency of precipitation for 2°x2.5° grid

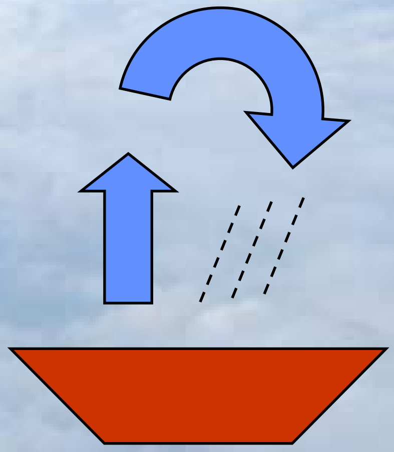
From Trenberth 1998



Estimated frequency of occurrence (%) of non-drizzle precipitation either at time of observation or in the past hour from synops for December-January-February (left) and June-July-August (right). From Dai (2001).

We have estimated of the annual mean **recycling ratio** of the percentage precipitation coming from evaporation within a length scale of 1000 km (625 miles) globally as about 20%;

Mississippi basin:
recycling of local moisture is 3 times more important in summer vs winter for rain.



(adapted from Trenberth 1999).

Note: models generally do recycling incorrectly

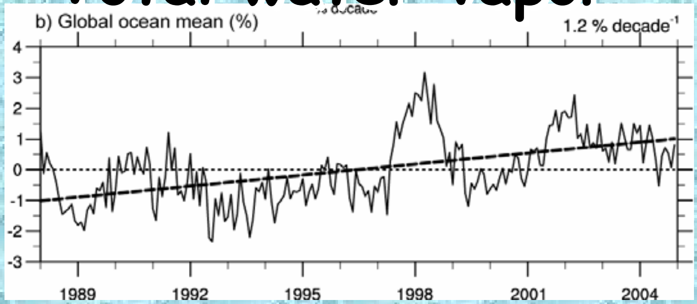
Air holds more water vapor at higher temperatures

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



How should precipitation P change as the climate changes?

- With increased GHGs: increased **surface** heating evaporation E⇑ and P⇑
- With increased aerosols, E⇓ and P⇓
- **Net global effect is small and complex**

- Warming and T⇑ means water vapor ⇑ as observed
- Because precipitation comes from storms gathering up available moisture, **rain and snow intensity ⇑** : **widely observed**
- But this must reduce lifetime and frequency of storms
- Result: **wet areas get wetter, dry areas drier**

How should precipitation P change as the climate changes?

- "**The rich get richer and the poor get poorer**". More water vapor plus moisture transports from divergence regions (subtropics) to convergence zones. Result: **wet areas get wetter, dry areas drier** (Neelin, Chou)
- "**Upped ante**" precip decreases on edges of convergence zones as it takes more instability to trigger convection: more intense rains and upward motion but broader downward motion. (Neelin, Chou)
- "**More bang for the buck**": The moisture and energy transport is a physical constraint, and with increased moisture, the winds can be less to achieve the same transport. Hence the divergent circulation weakens. (Soden, Held, et al)

Heat waves and wild fires

Impacts on human health and mortality, economic impacts, ecosystem and wildlife impacts

Global warming

⇓

Heating ↑

⇓

Temperature ↑ & Evaporation ↑

⇓

water holding capacity ↑

⇓

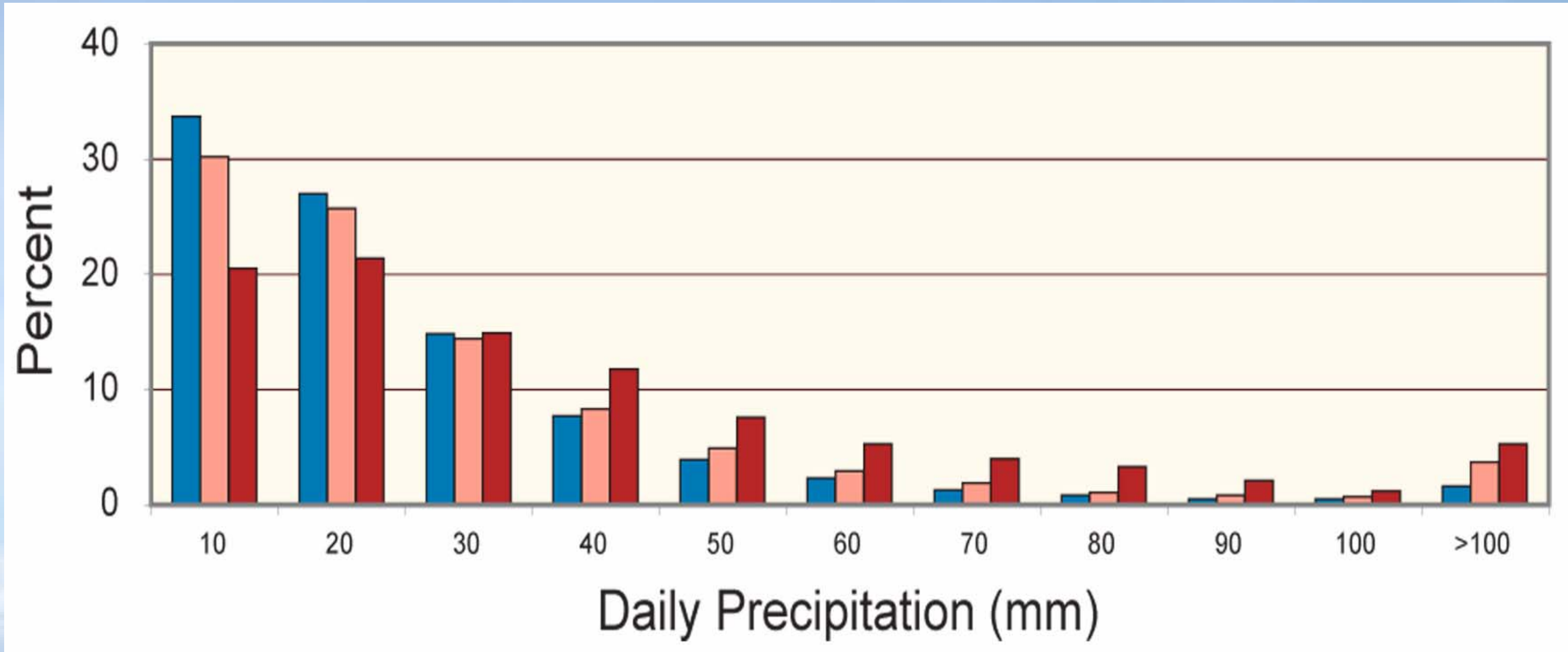
atmospheric moisture ↑

⇓ ⇓

greenhouse effect ↑ & rain intensity ↑

⇓

&



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.

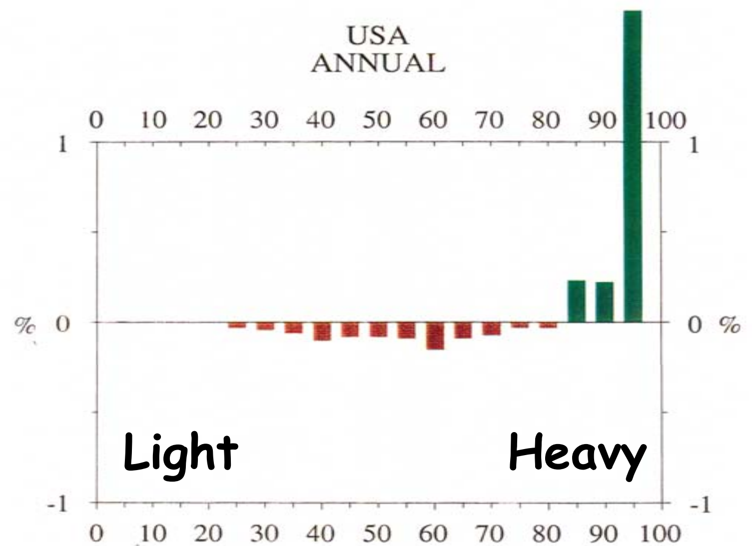
Karl and Trenberth 2003

Changes in U.S. precipitation 1900 to 2002

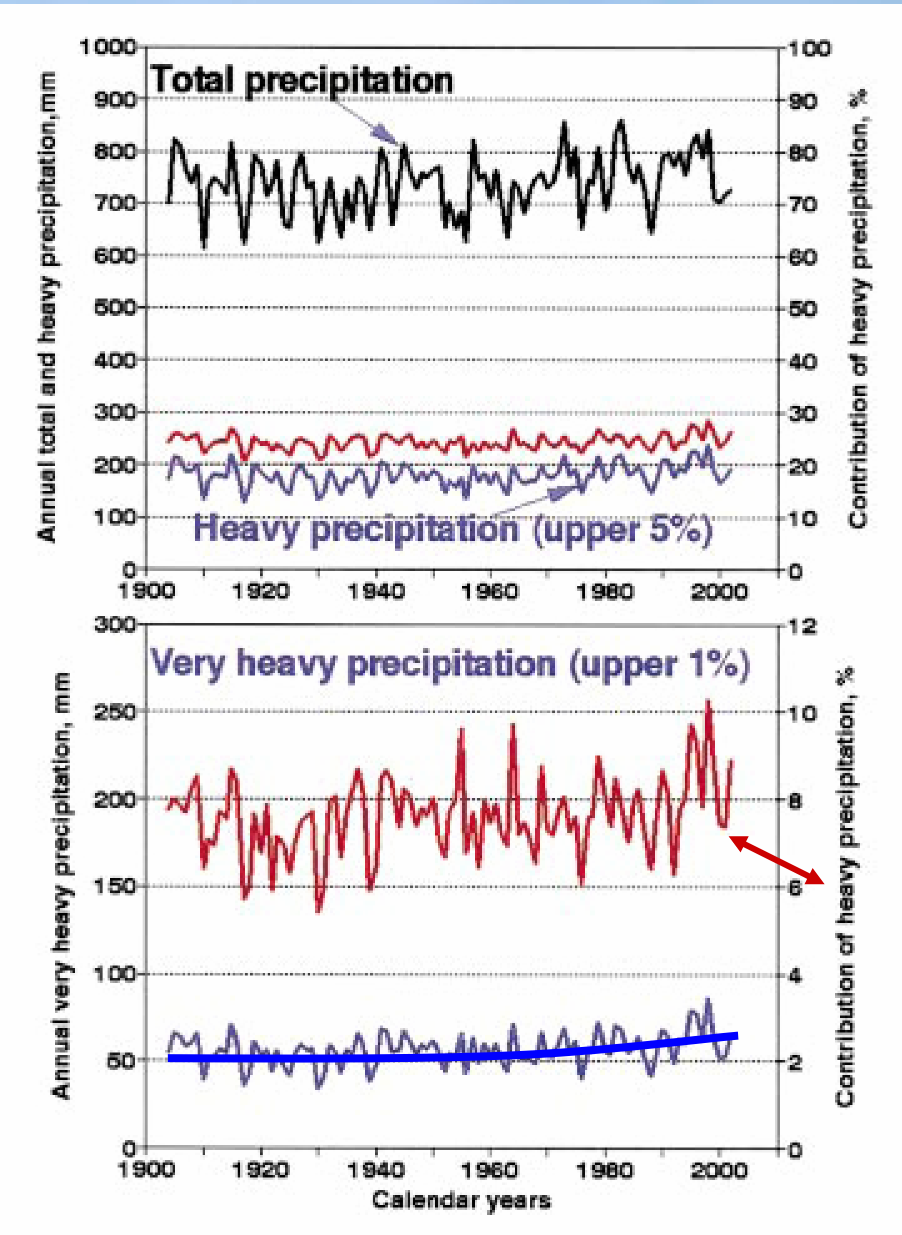
Changes in total, heavy, and very heavy precipitation over contiguous U.S.

Linear trends are up and significant at 1%: 7, 14, 20% /century

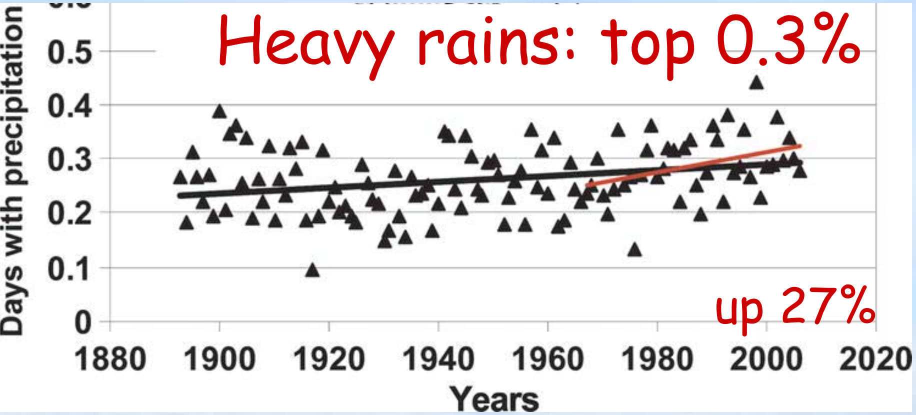
Groisman et al 2004
Karl et al 2003

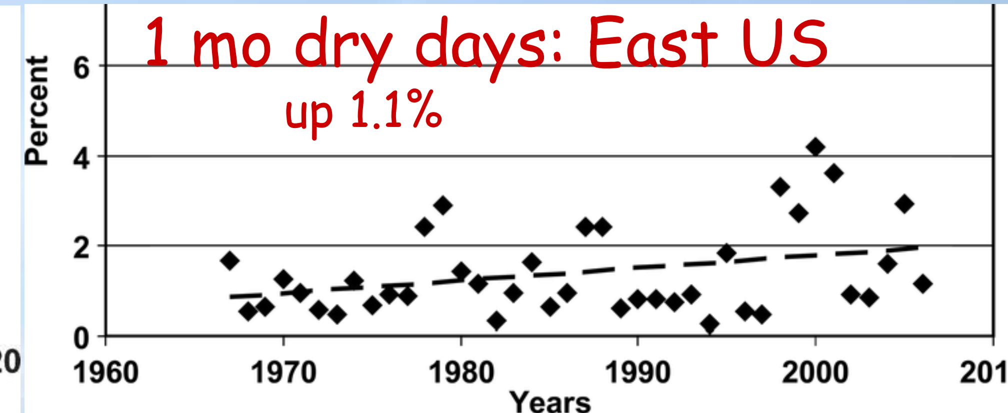


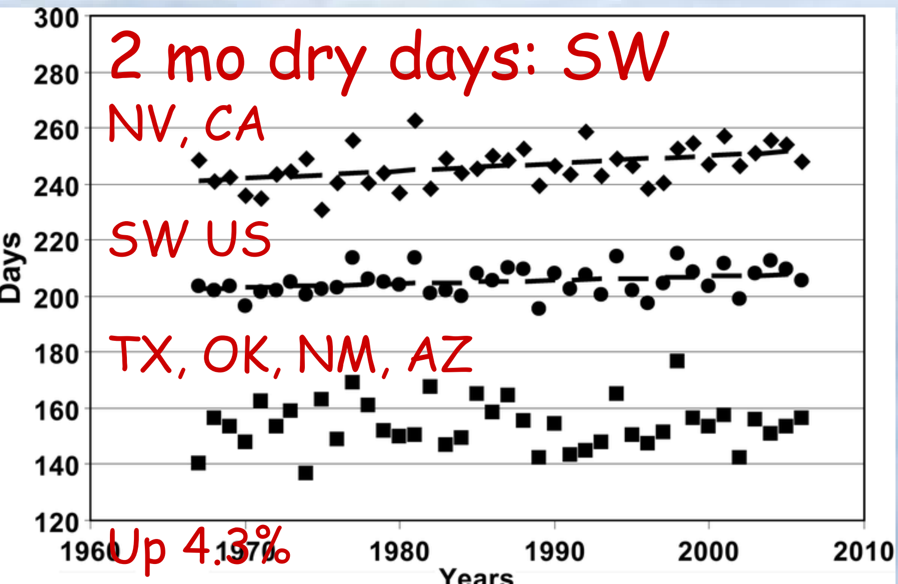
Percentiles

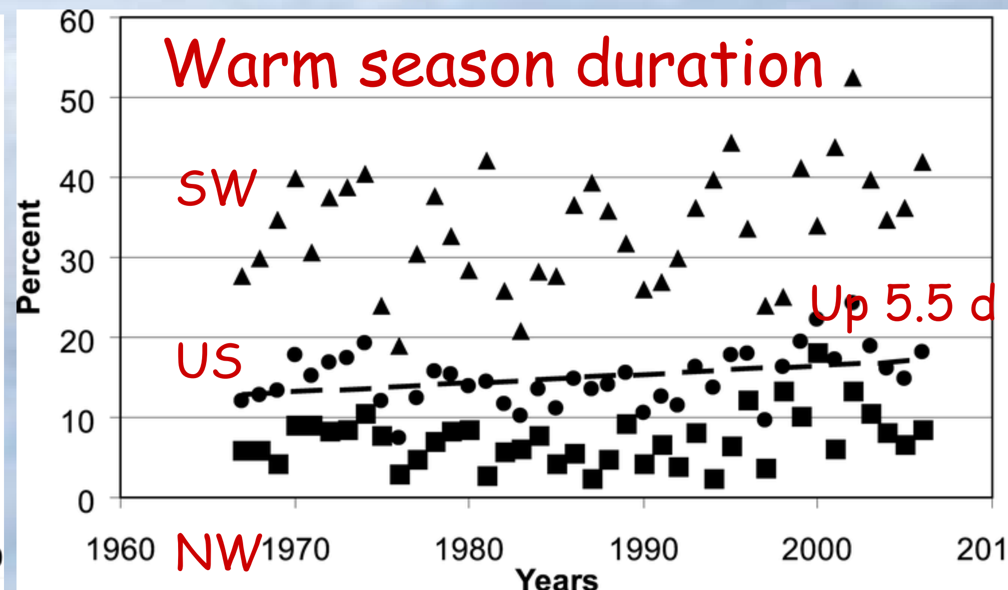


Increases in extremes in U.S.

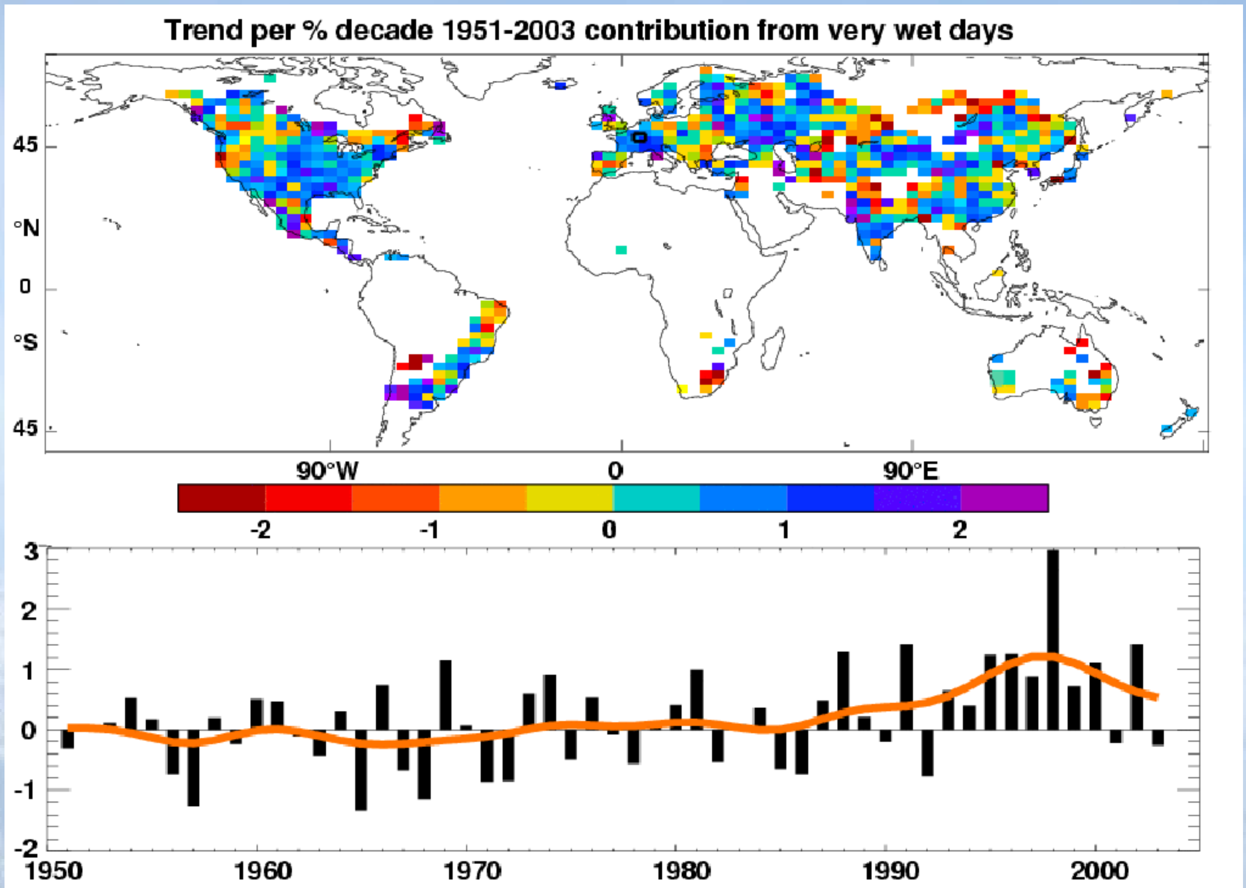


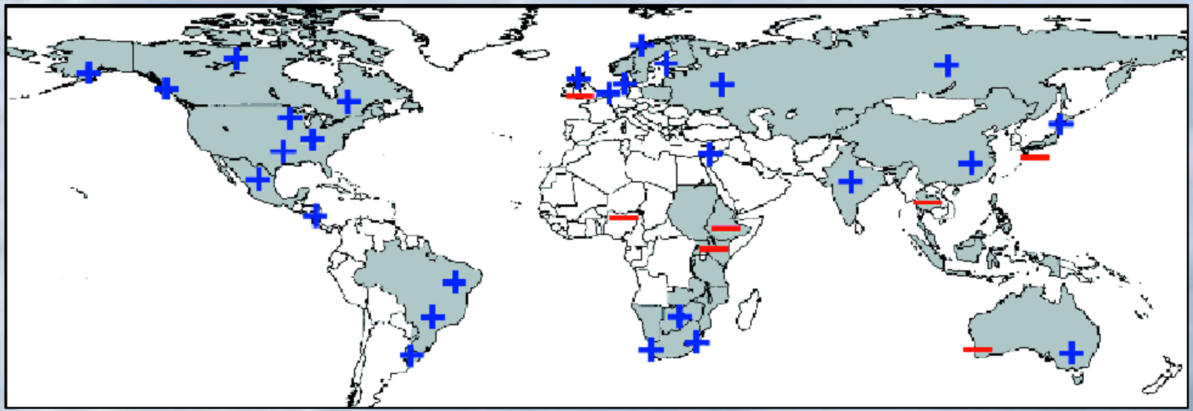






Per 40 years 1967-2006 Groisman, Knight 08





Precipitation

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

Alexander et al 2006

Regions where recent decades heavy precip >> mean precip

updated from Groisman et al. (2005a).

Extensive Flooding in Europe, August 2002

Danube
Budapest,
Hungary

Mueglitz River
near Dresden
E. Germany

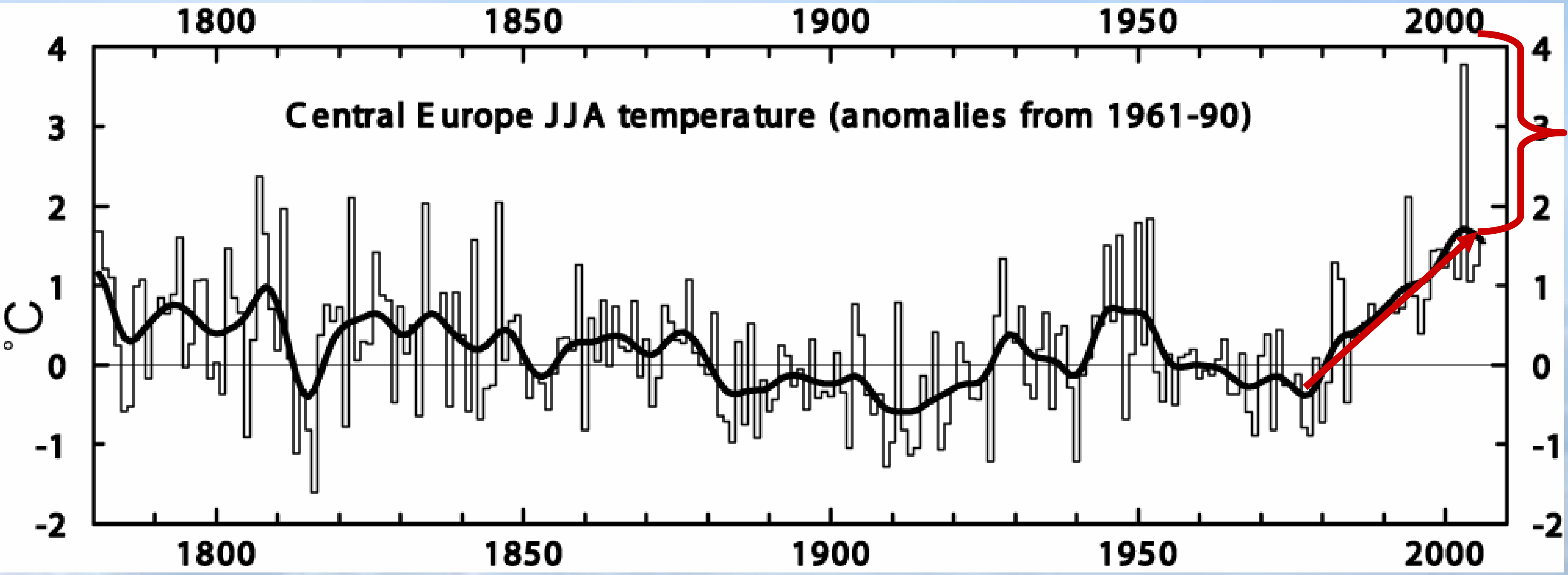
Flooded Art Gallery
Dresden
E. Germany

Kamp River
near Vienna
Austria

Kralupy, Czech Rep.

Havel/Prague, Czech Rep.

Heat waves are increasing: an example



Extreme Heat Wave
Summer 2003
Europe
30,000 deaths

Trend plus variability?

IPCC

Flood damages:

1. Local and national authorities work to prevent floods (e.g., Corp of Engineers, Bureau of Reclamation, Councils)
   Build ditches, culverts, drains, levees
   Can backfire!

2. Deforestation in many countries:
   Leads to faster runoff, exacerbates flooding

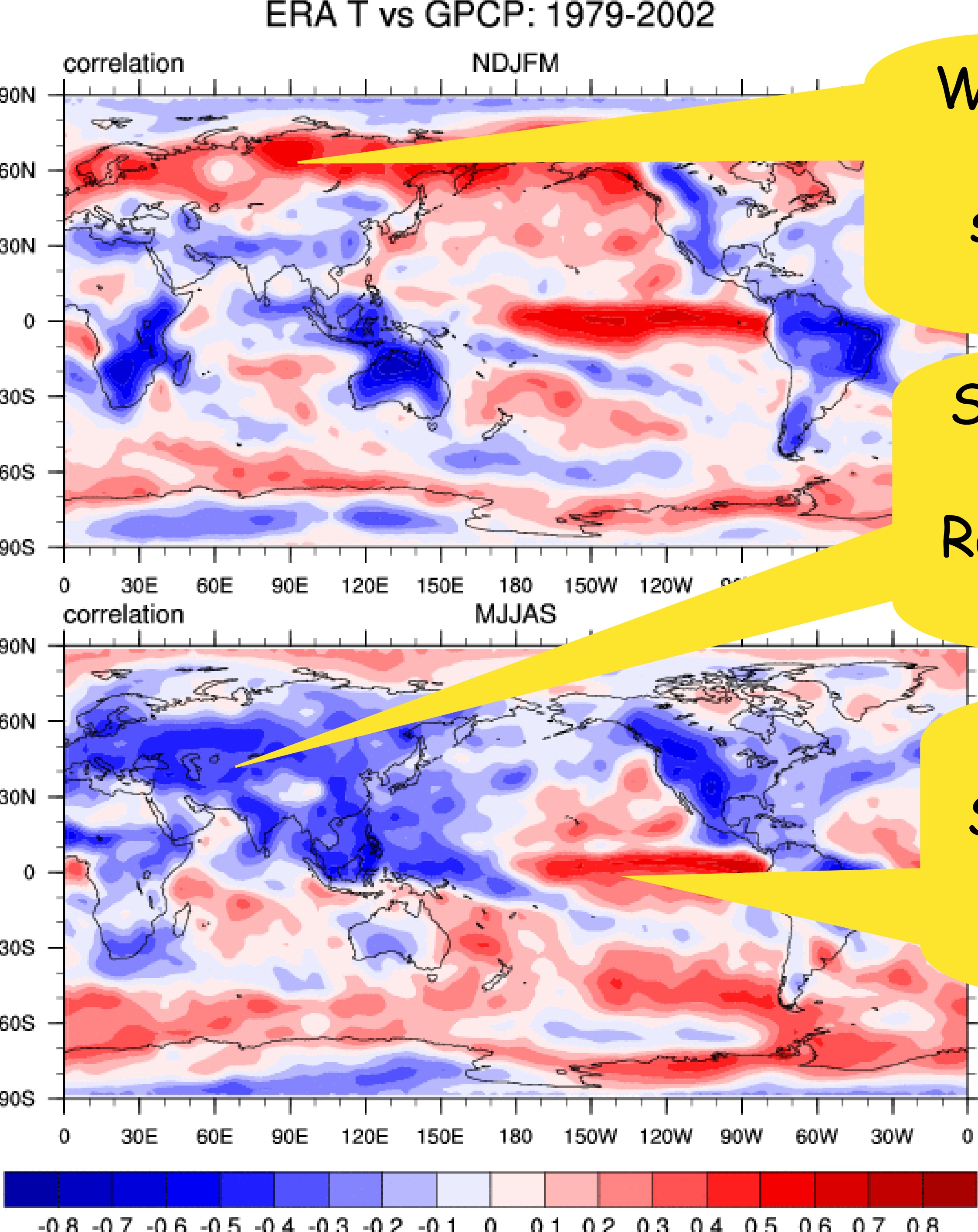
3. Increased vulnerability to flooding through settling in flood plains and coastal regions
   Increases losses.

Flooding statistics NOT useful for determining weather part of flooding!

Drought:

3 kinds of drought

1. Meteorological: absence of rain
2. Agricultural: absence of soil moisture
3. Hydrological: absence of water in rivers, lakes and reservoirs



Winter high lats: air can't hold moisture in cold, storms warm and moist southerlies.

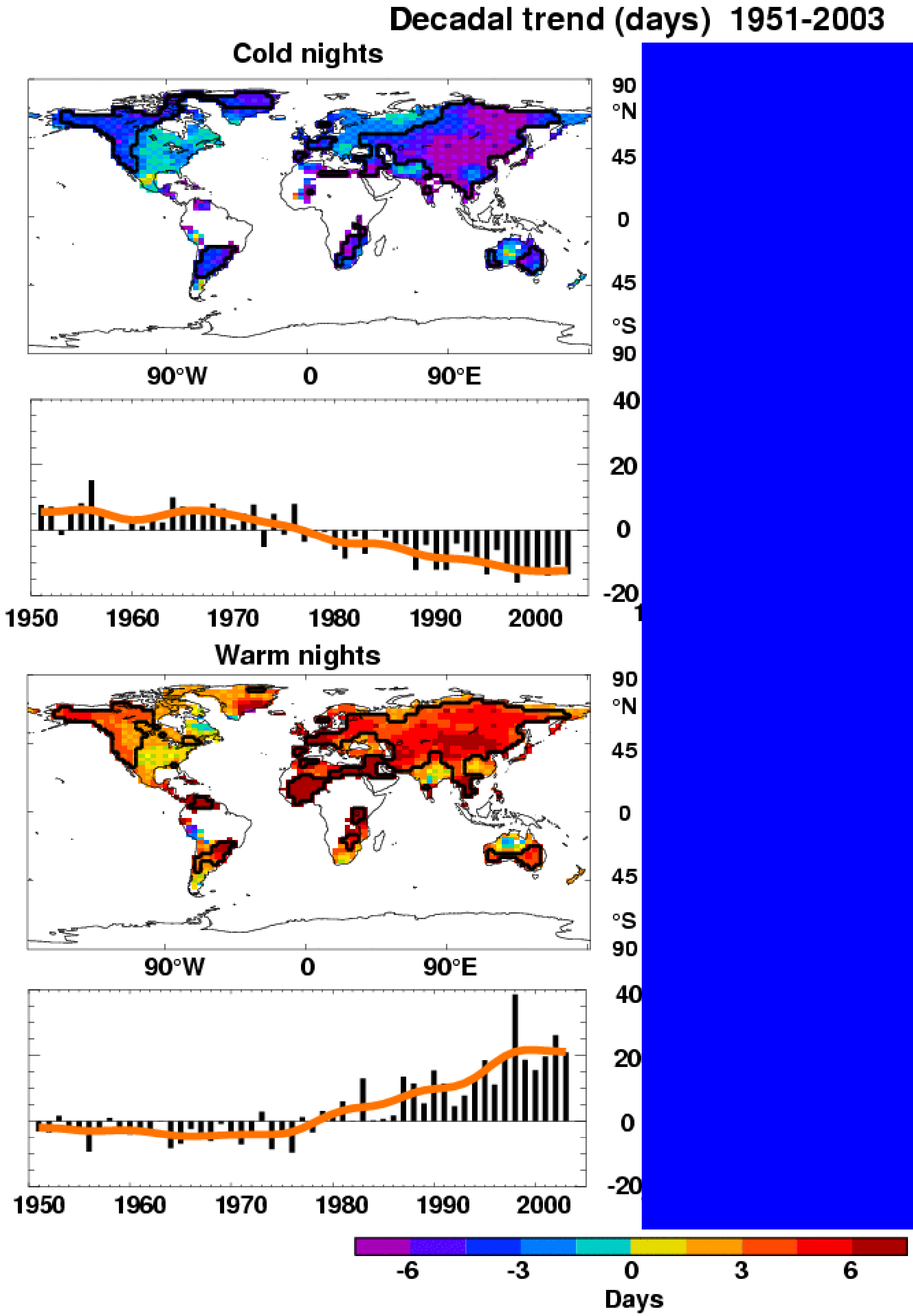
Summer land: hot and dry or cool and wet
Rain and cloud cool and **air condition** the planet!

May-September

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

Positive: hot and wet or cool and dry (as in El Nino region).

Trenberth and Shea 2005



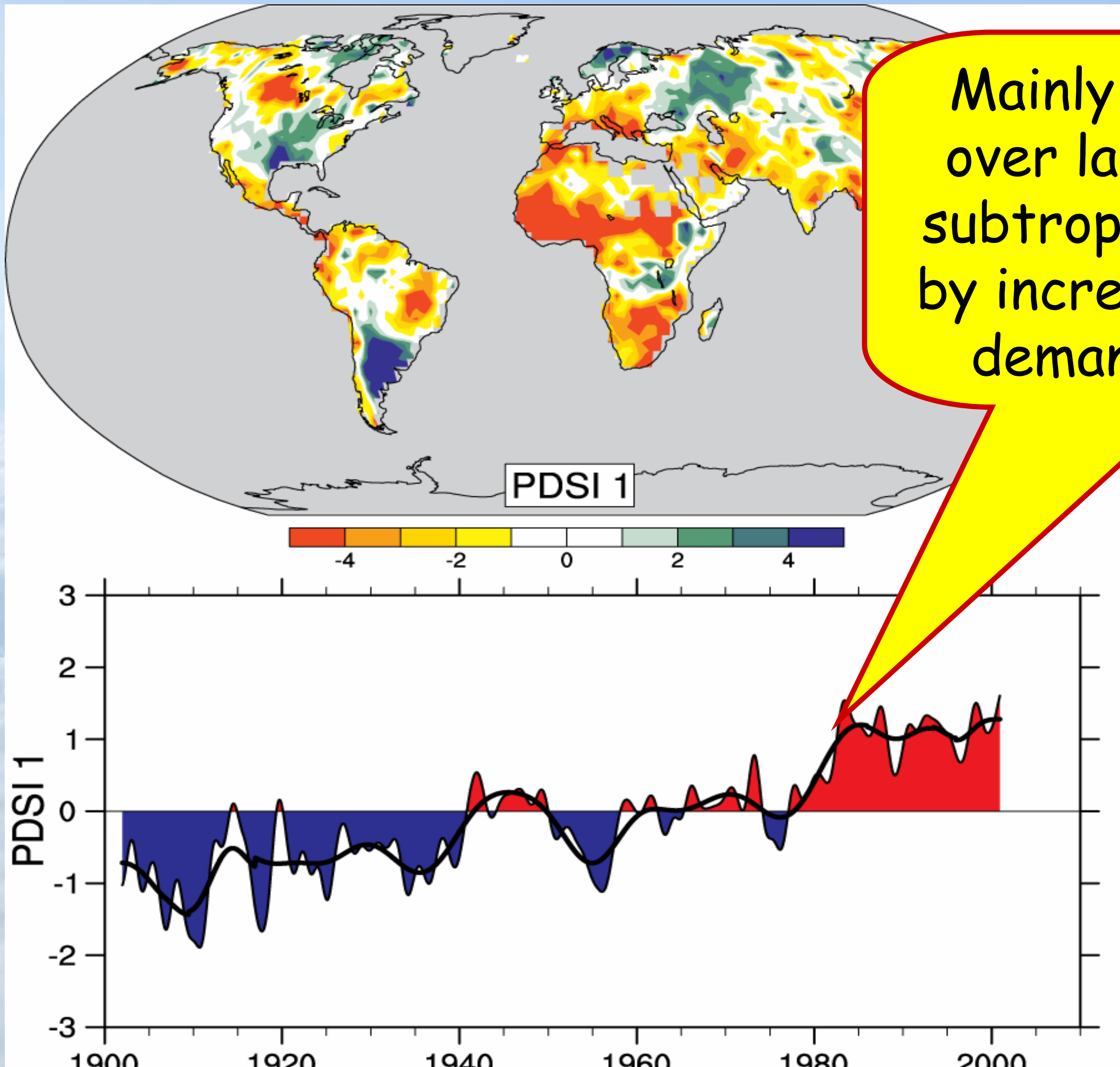
Extremes of temperature are changing!

Observed trends (days) per decade for 1951 to 2003:

5th or 95th percentiles

From Alexander et al. (2006) and IPCC

Drought is increasing most places



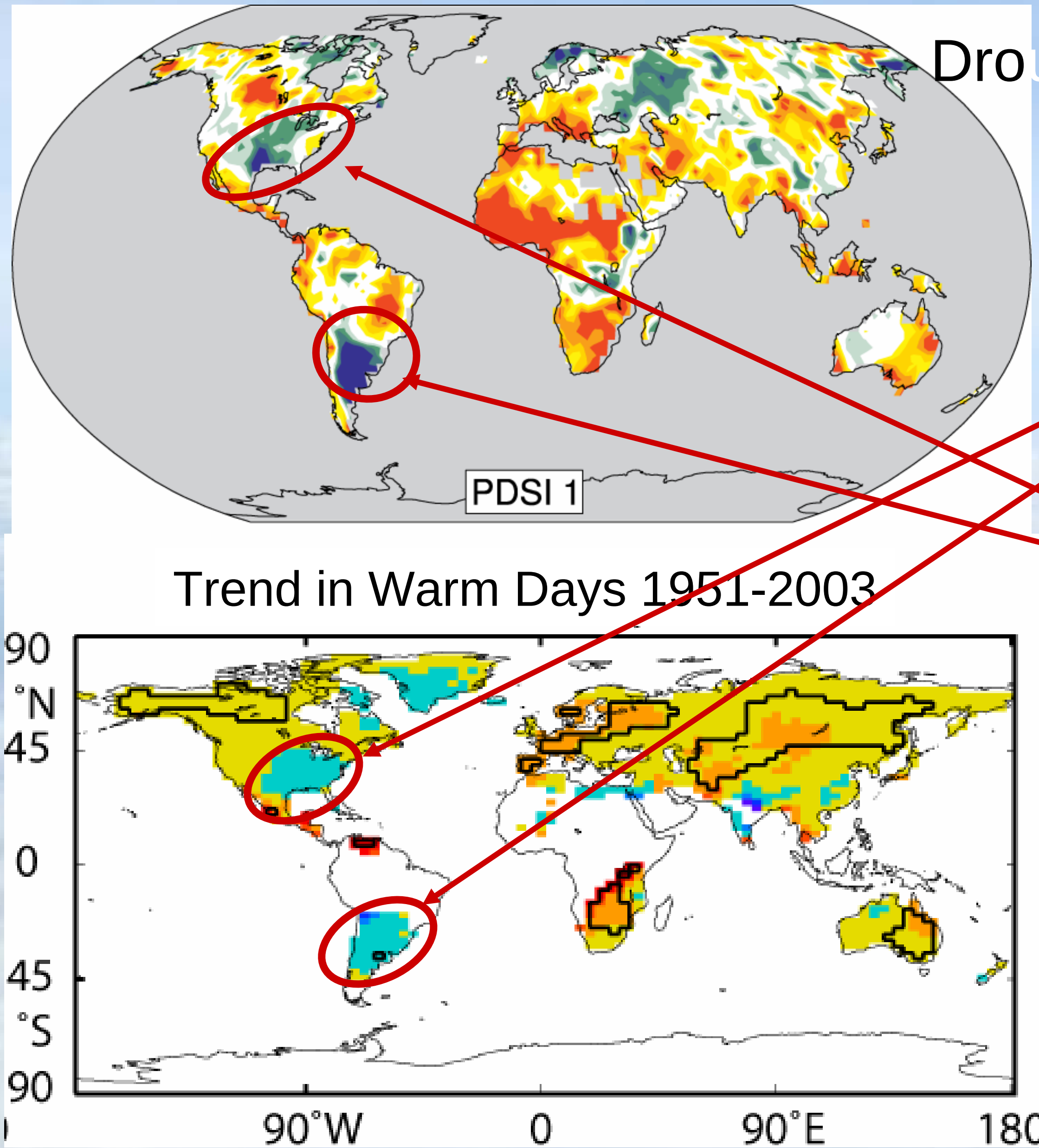
Mainly decrease in rain over land in tropics and subtropics, but enhanced by increased atmospheric demand with warming

Severity Index (PDSI) for 1900 to 2002.

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

IPCC 2007

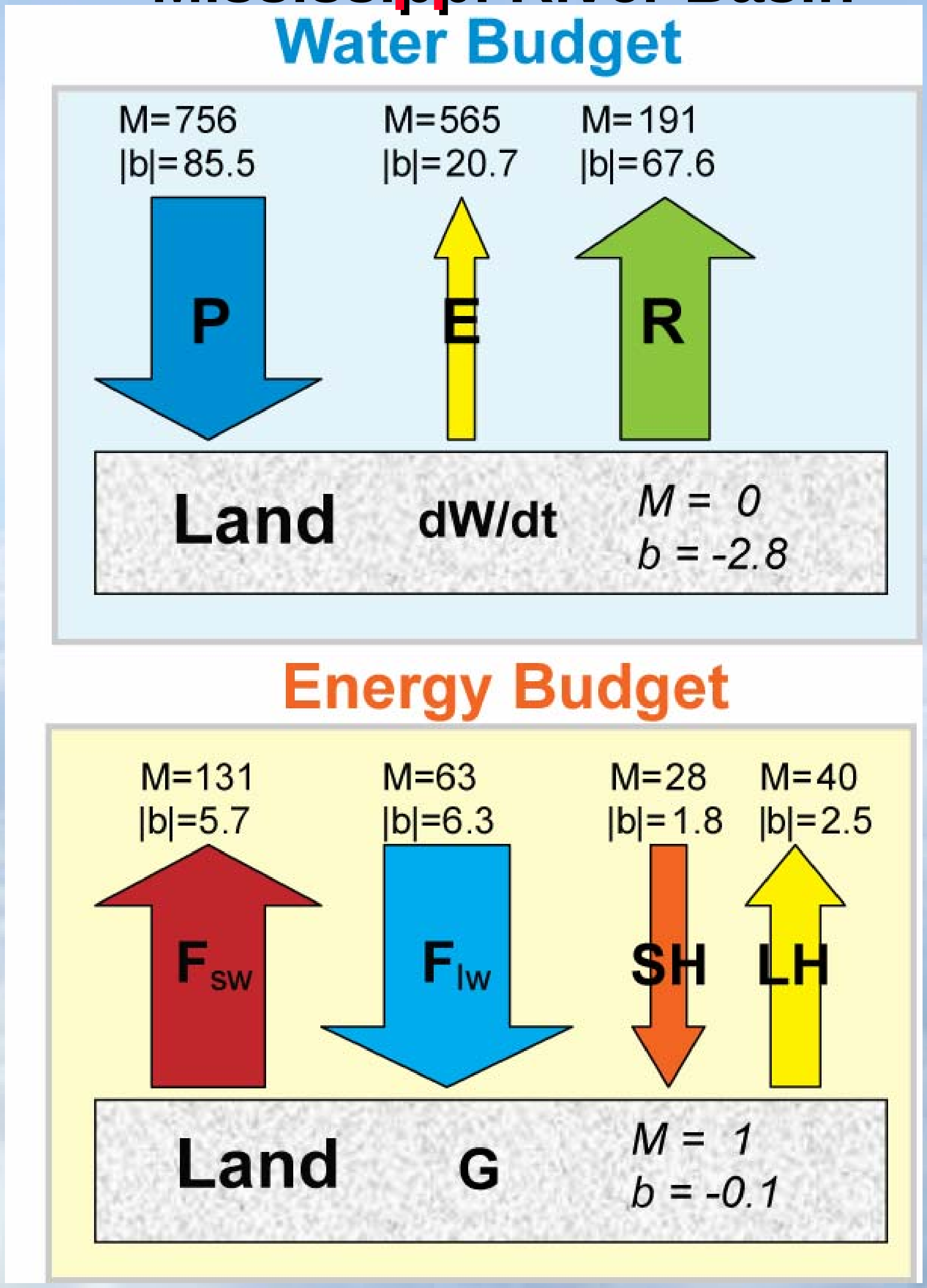
Increases in rainfall and cloud counter warming



Absence of warming by day coincides with wetter and cloudier conditions

IPCC 2007

Mississippi River Basin



TRENDS: 1948 to 2004

M is the long-term annual (water-year) mean in mm for water components; W m^{-2} for energy components

b: annual linear trend 1948-2004 mm/century for water W m^{-2}/century for energy (proportional to arrow shaft width).

The downward arrow means that the flux increases the trend of *dW/dt* or *G*.

So it has become cloudier and wetter, with less solar radiation, but with increased ET and diminished SH (change in Bowen ratio).

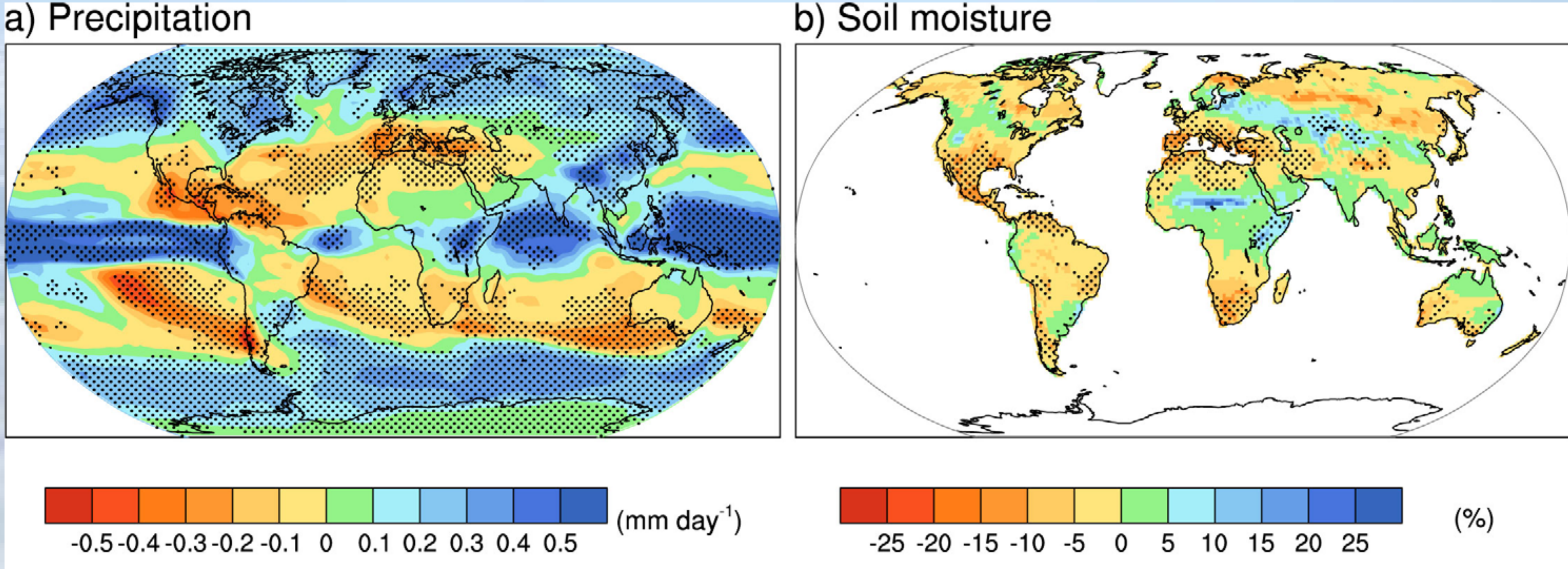
Qian et al 2007

SNOW PACK: In Colorado, as in many mountain areas, **global warming** contributes to:

- more **precipitation** falls as **rain** rather than **snow,** especially in the fall and spring.
- **snow melt** occurs faster and sooner in the spring
- **snow pack** is therefore less as summer arrives
- **soil moisture** is less, and **recycling** is less
- **global warming** means more drying and heat stress
- the risk of **drought** increases substantially in summer
- along with **heat waves** and **wildfires**

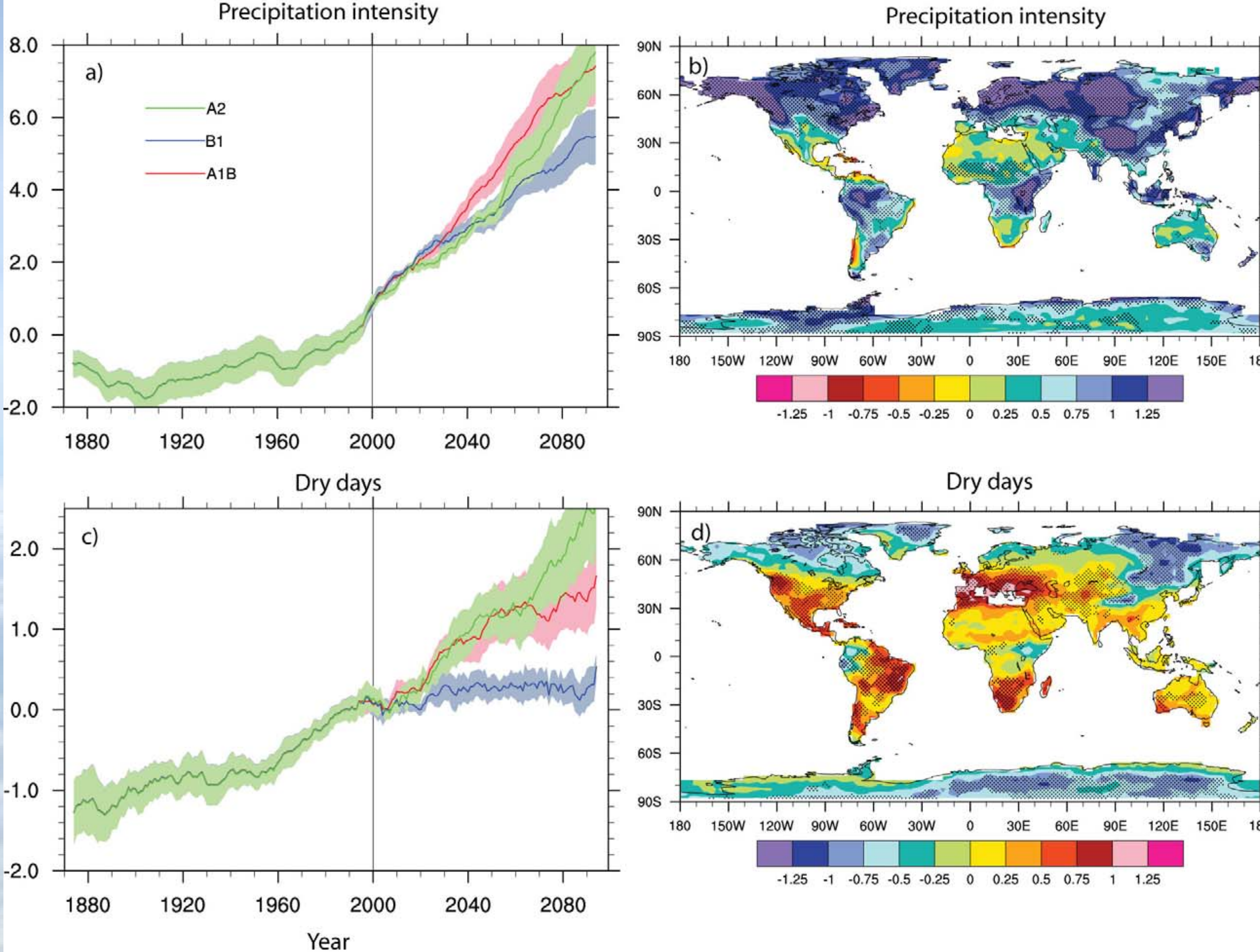
"Rich get richer, poor get poorer"

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



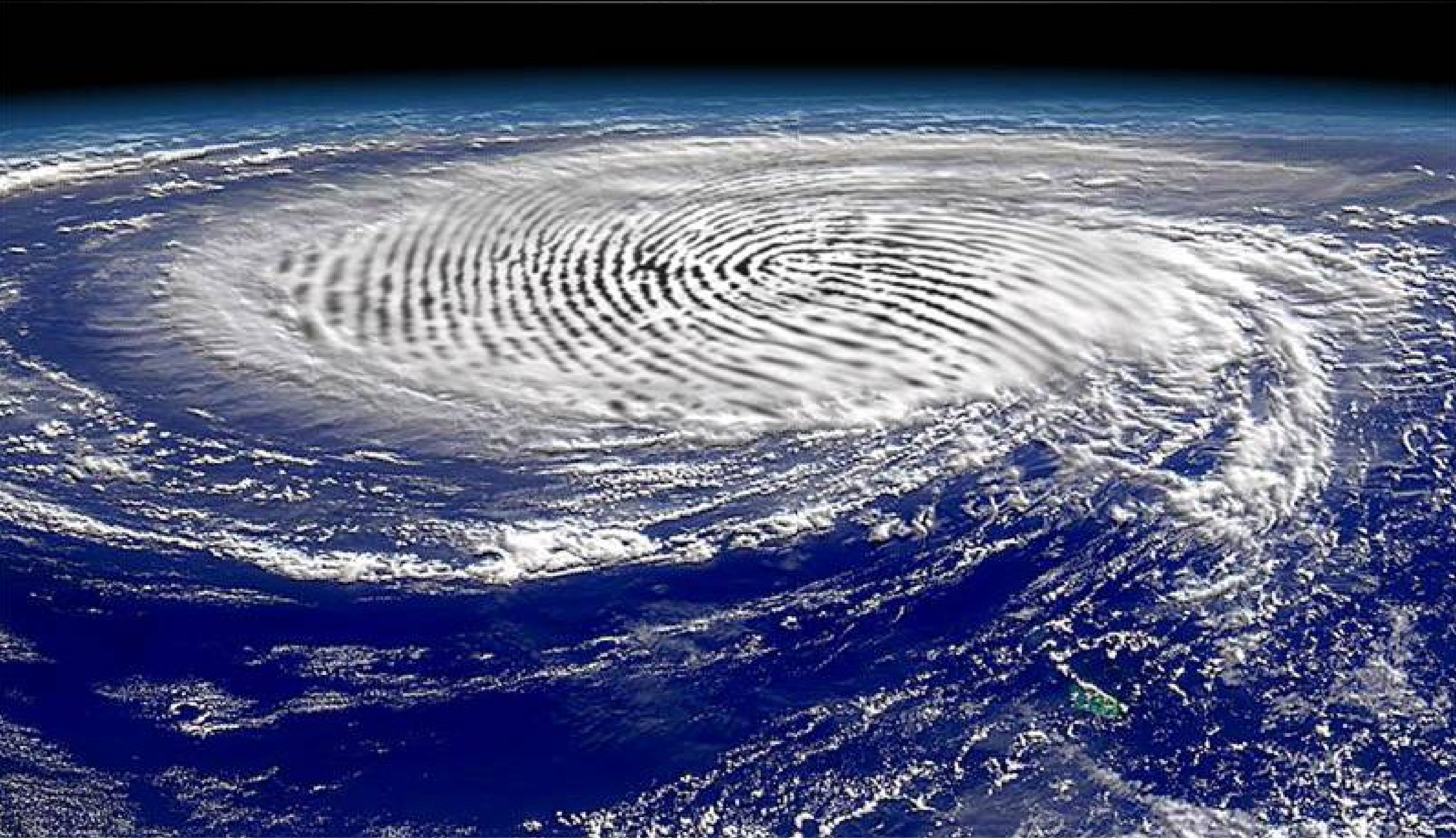
2090-2100

IPCC

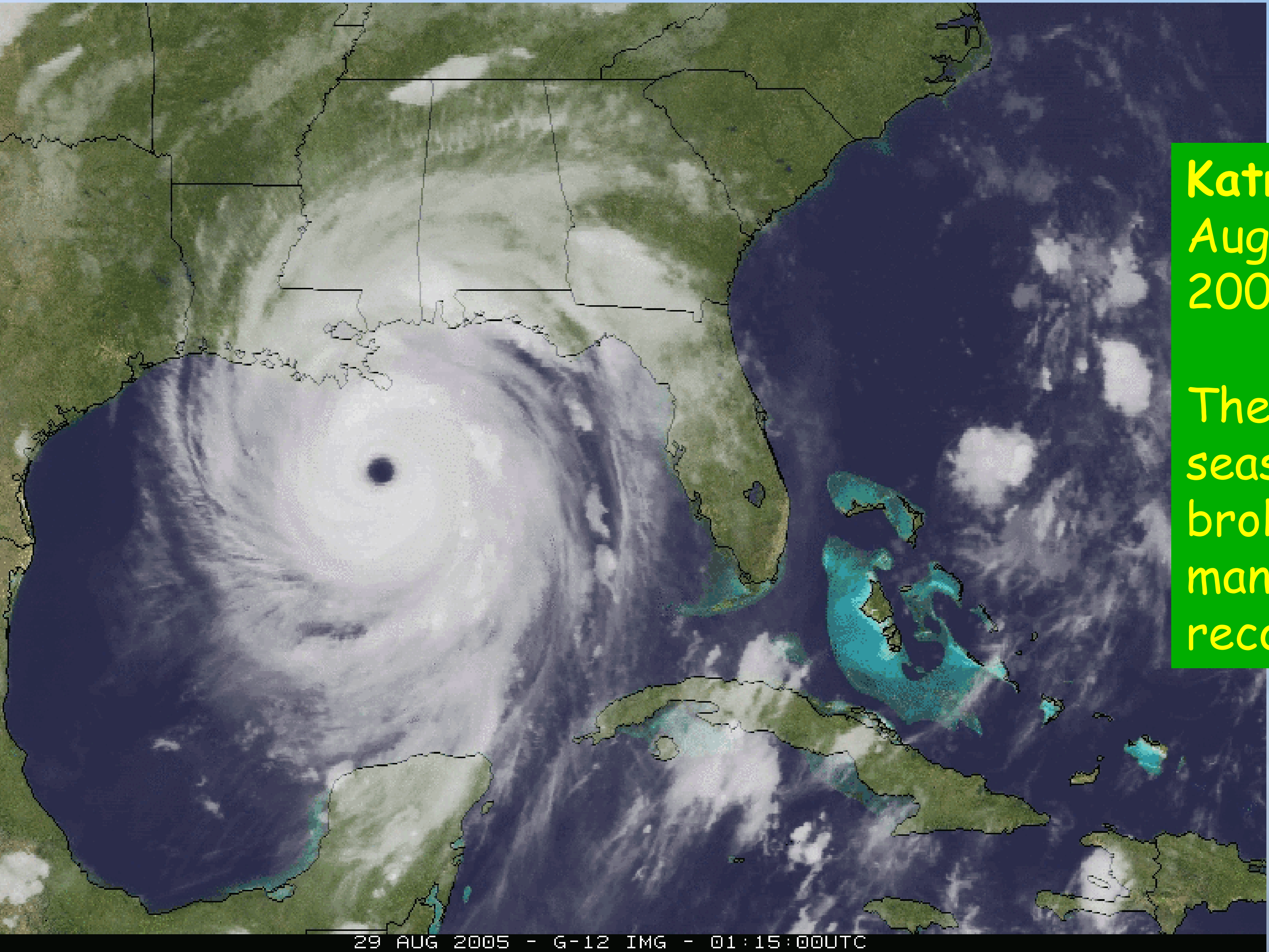


(Tebaldi , C., J.M. Arblaster, K. Hayhoe, and G.A. Meehl, 2006: Going to the extremes: An intercomparison of model-simulated historical and future changes in extreme events. *Clim. Change*.)

Are hurricanes changing with global warming?



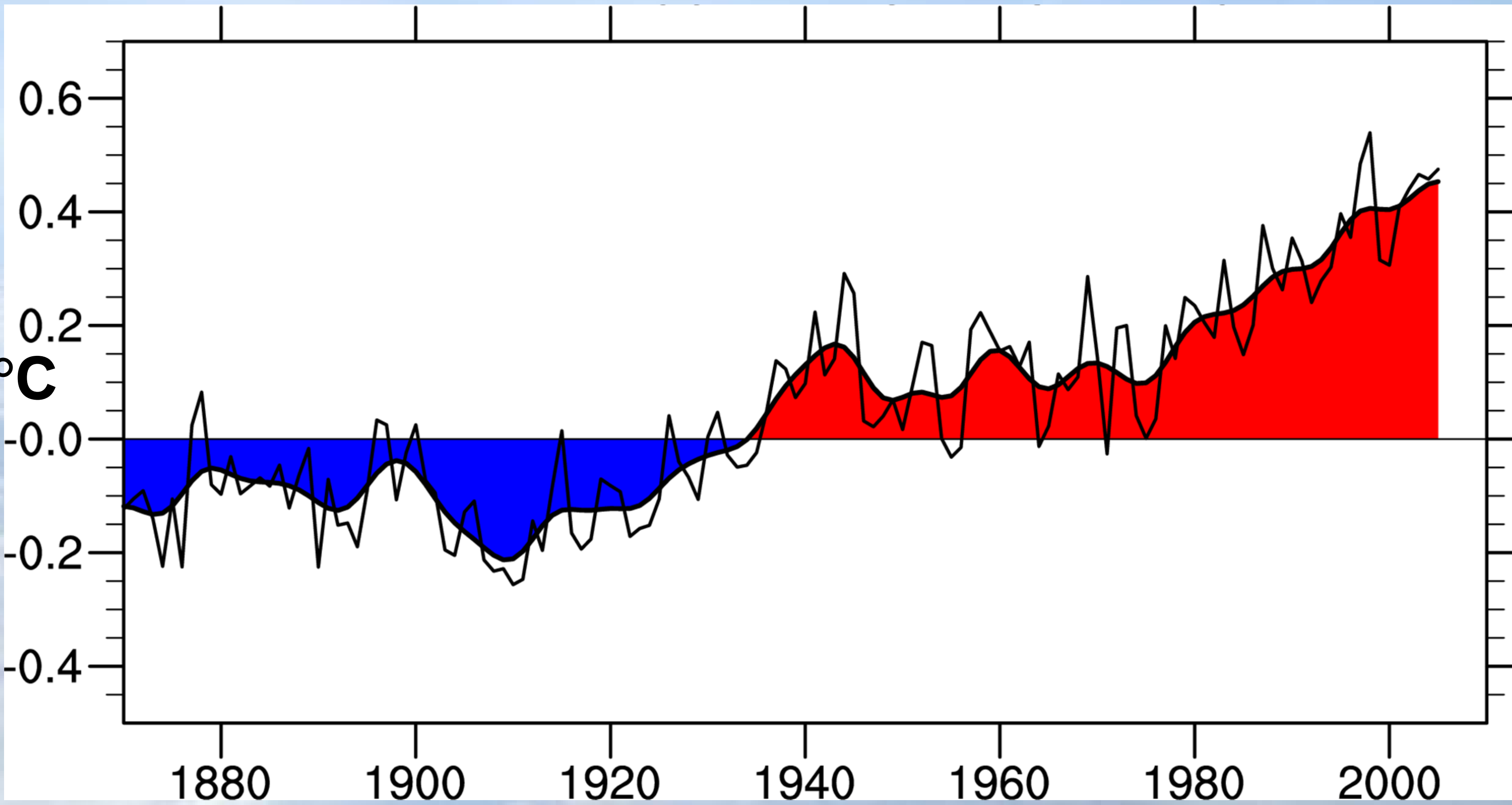
North Atlantic hurricanes have increased with SSTs

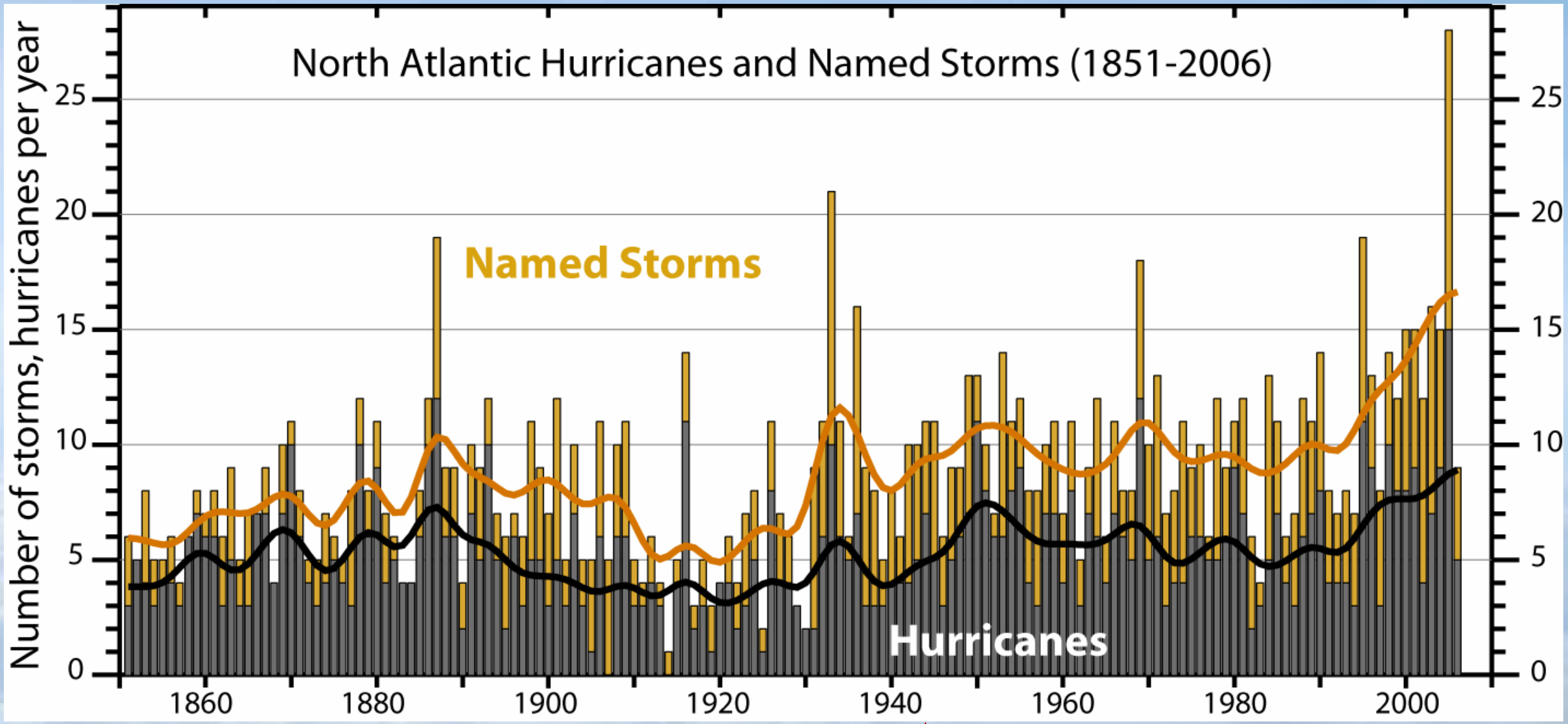


Katrina
August 2005

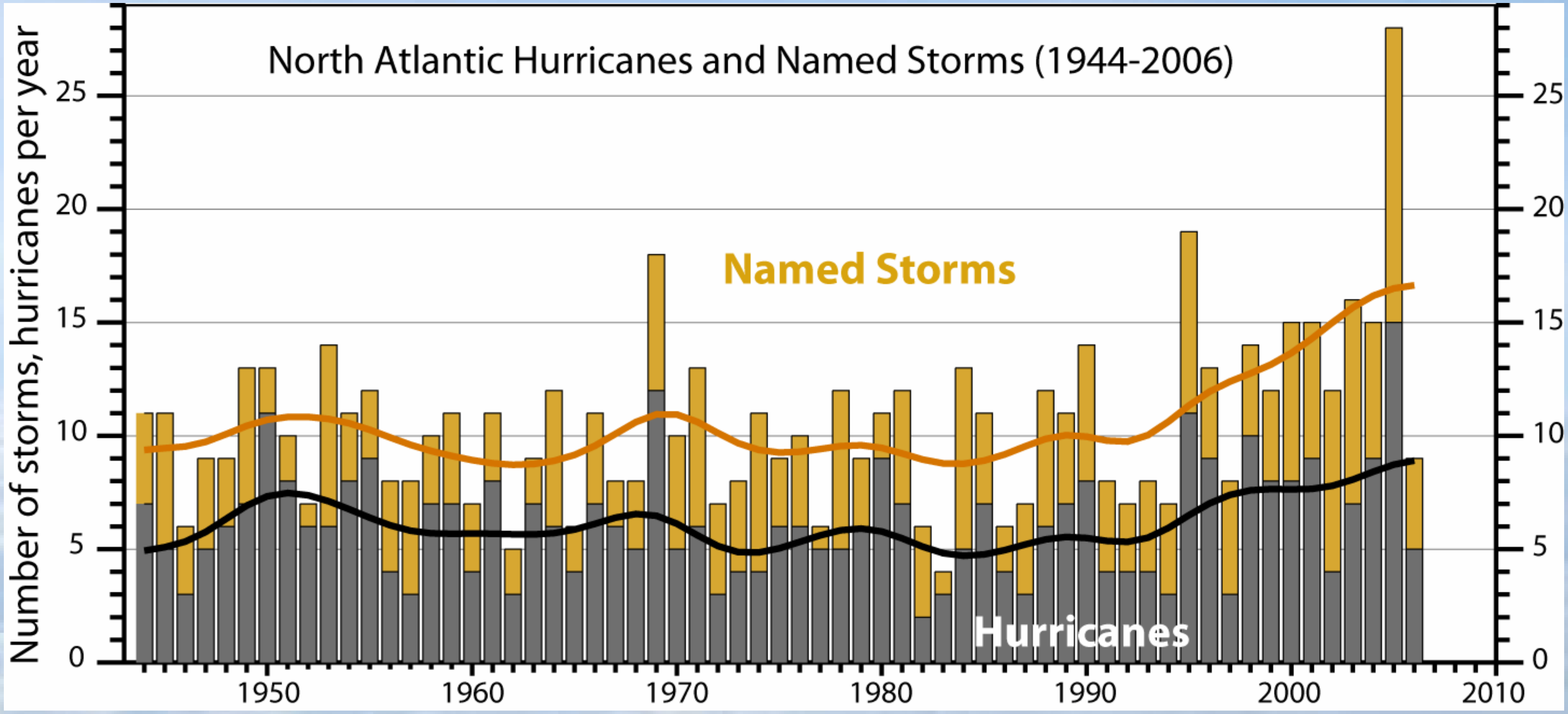
The 2005 season broke many records

Global SSTs are increasing: base period 1901-70

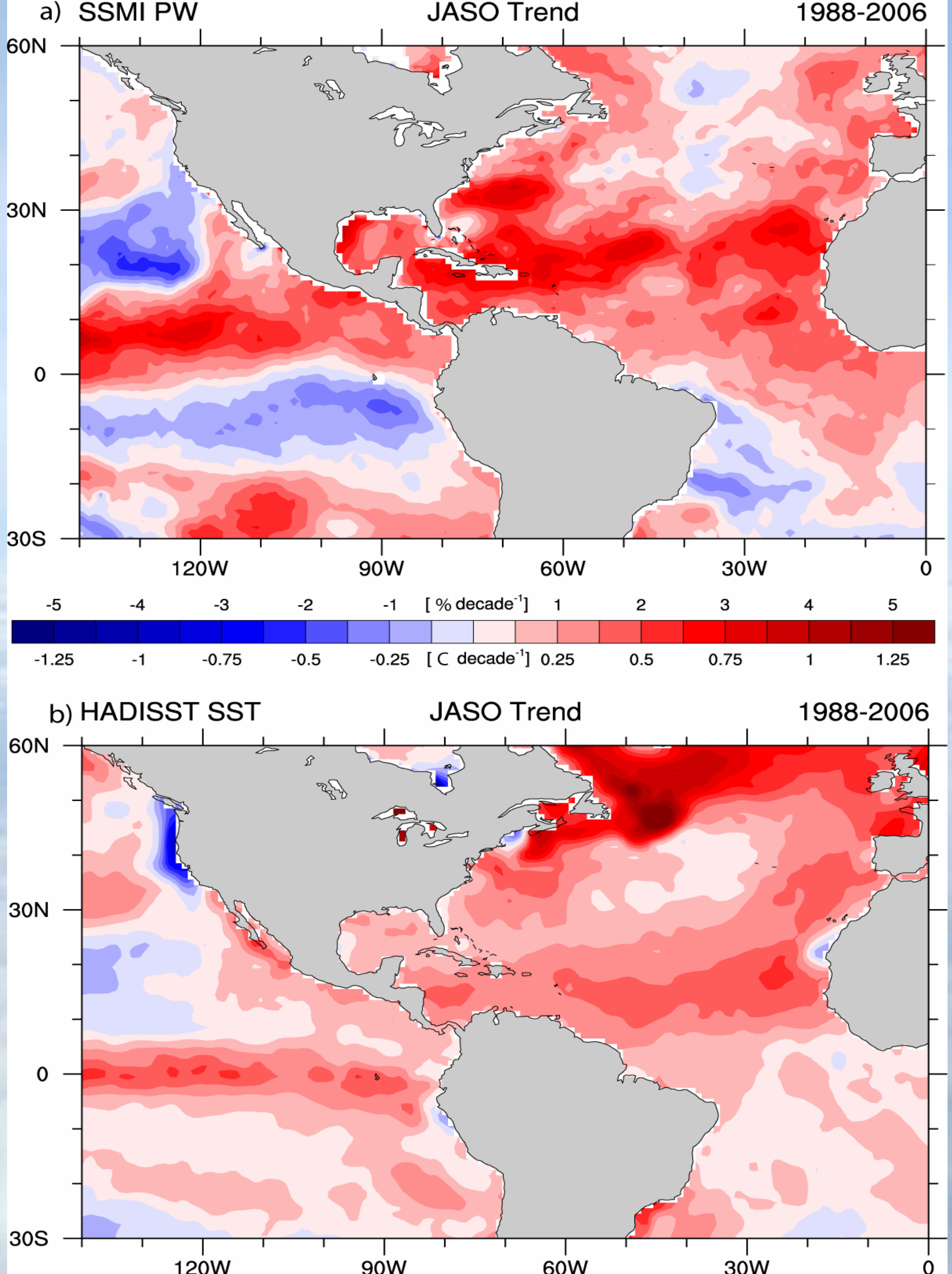




The record of numbers of named storms and hurricanes for the Atlantic from 1850 to 2006 based on the best track data.



The record of numbers of named storms and hurricanes for the Atlantic from 1944 to 2006 based on the best track data.

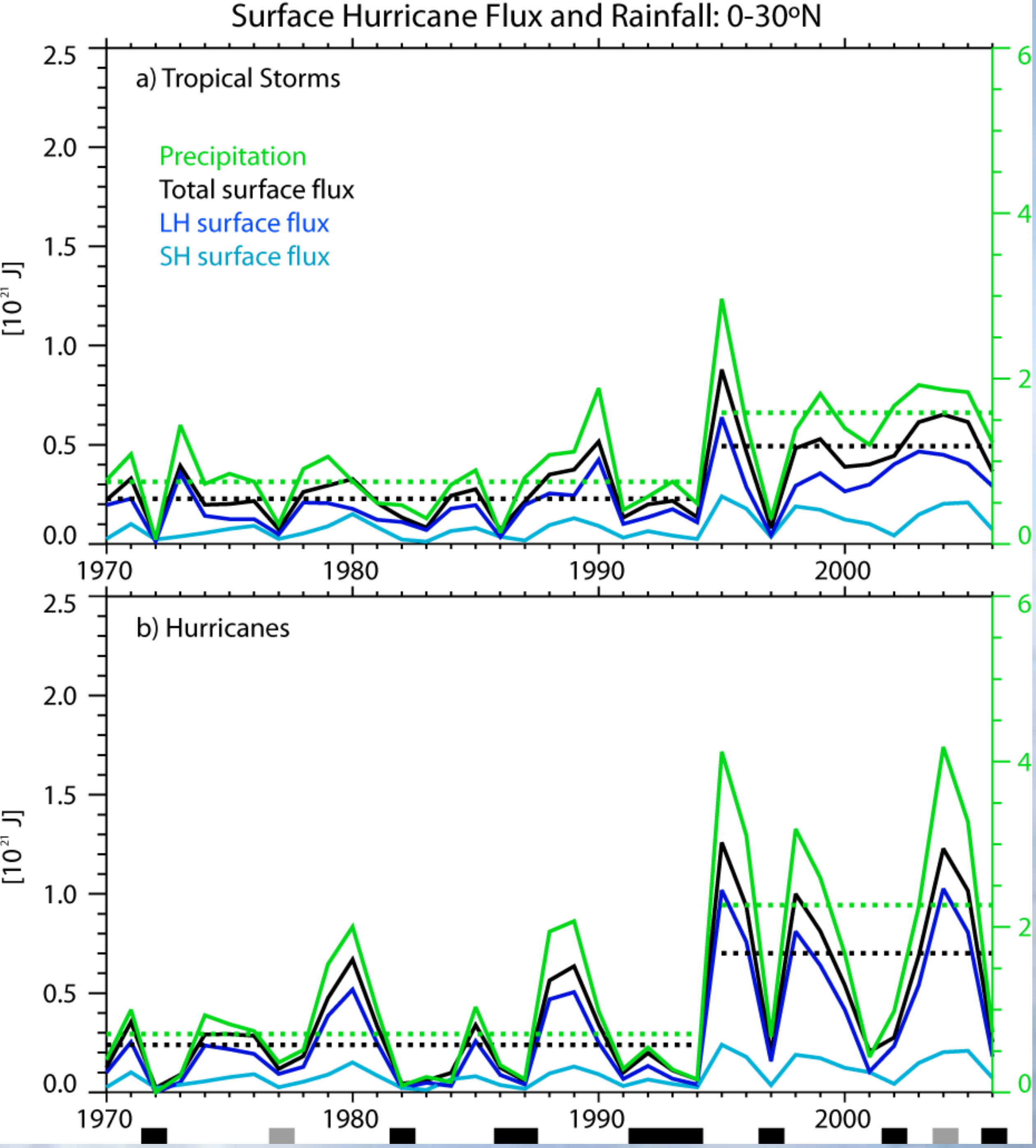


Precip Water

Atlantic
JASO
Linear trends

SSTs

Higher SSTs and
Higher water vapor



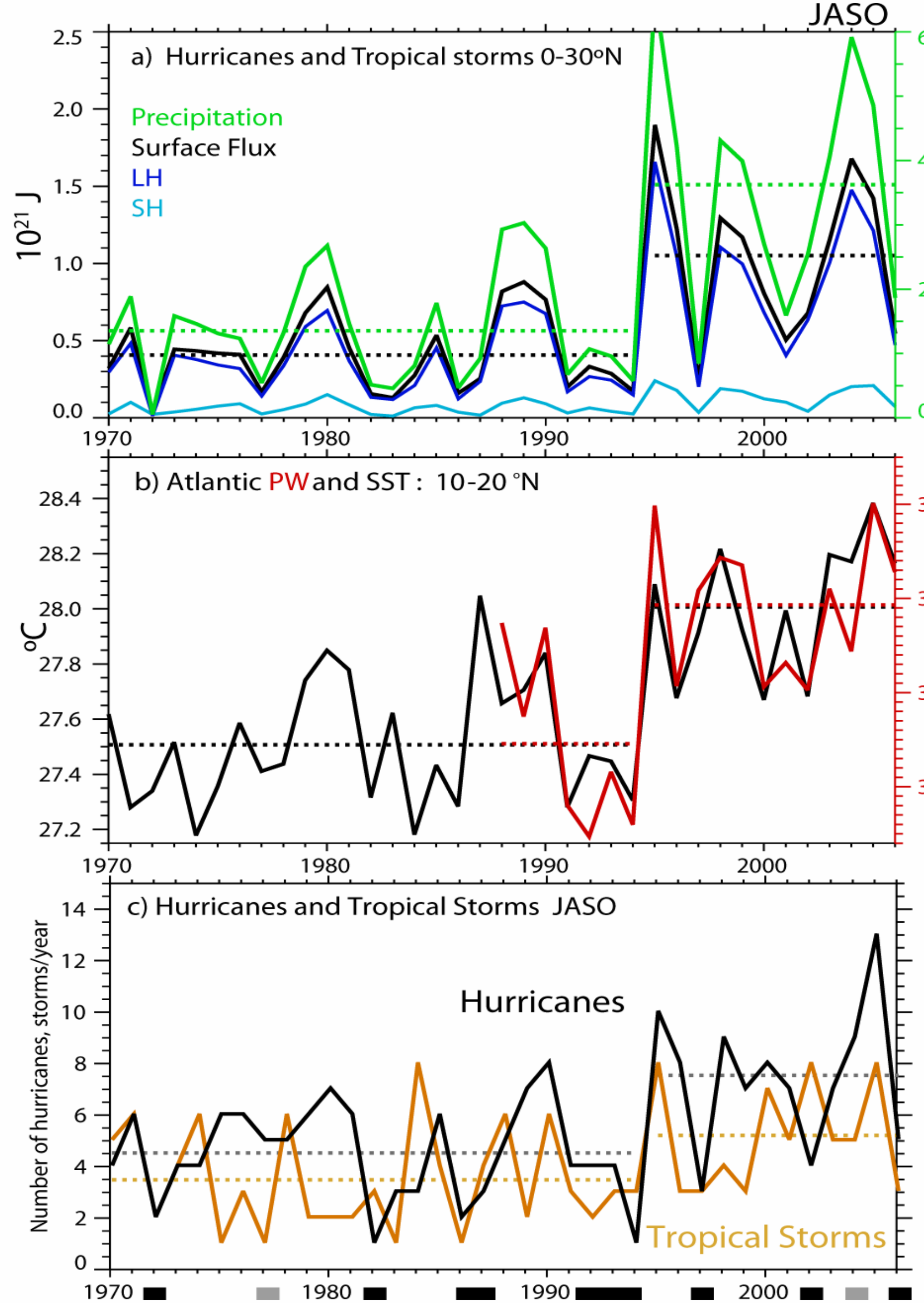
JASO

Time series

Named TS

Hurricanes

EN events



JASO

Atlantic time series

Fluxes

Precip water

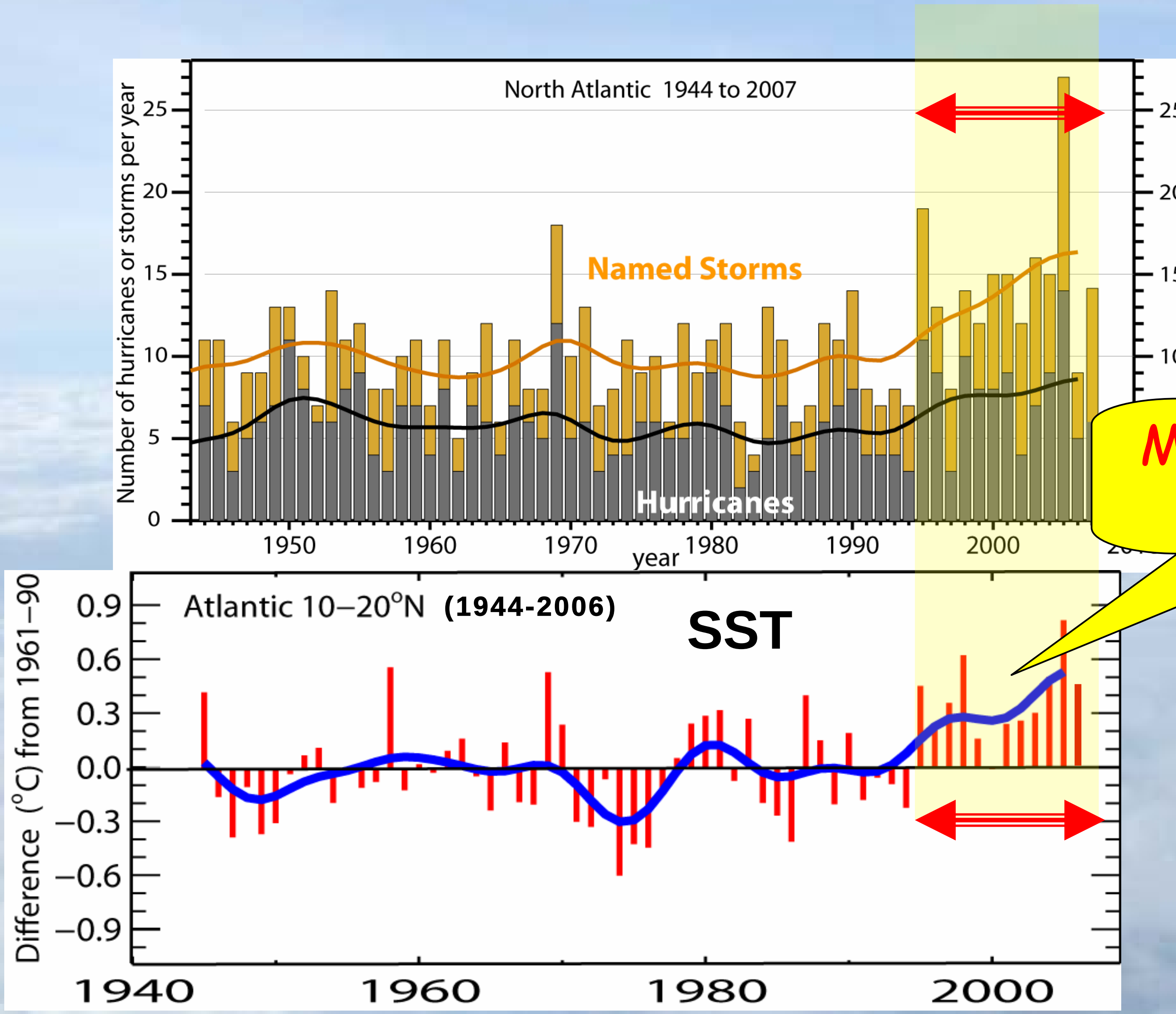
SST

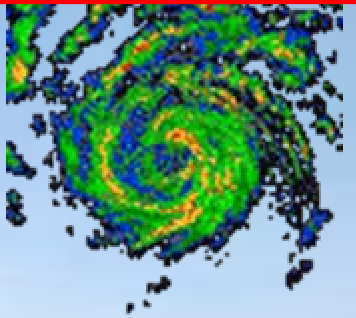
Numbers:

TS

Hurricanes

North Atlantic hurricanes have increased with SSTs





Marked increase after 1994

N. Atlantic hurricane record best

Global number and percentage of intense hurricanes is increasing

IPCC

Climate changes in both rainfall and temperature should be considered together.

"It's not the heat it's the humidity!"

Comfort depends upon both.

Water serves as the "air conditioner" of the planet.

There appear to be prospects for increases in extremes:

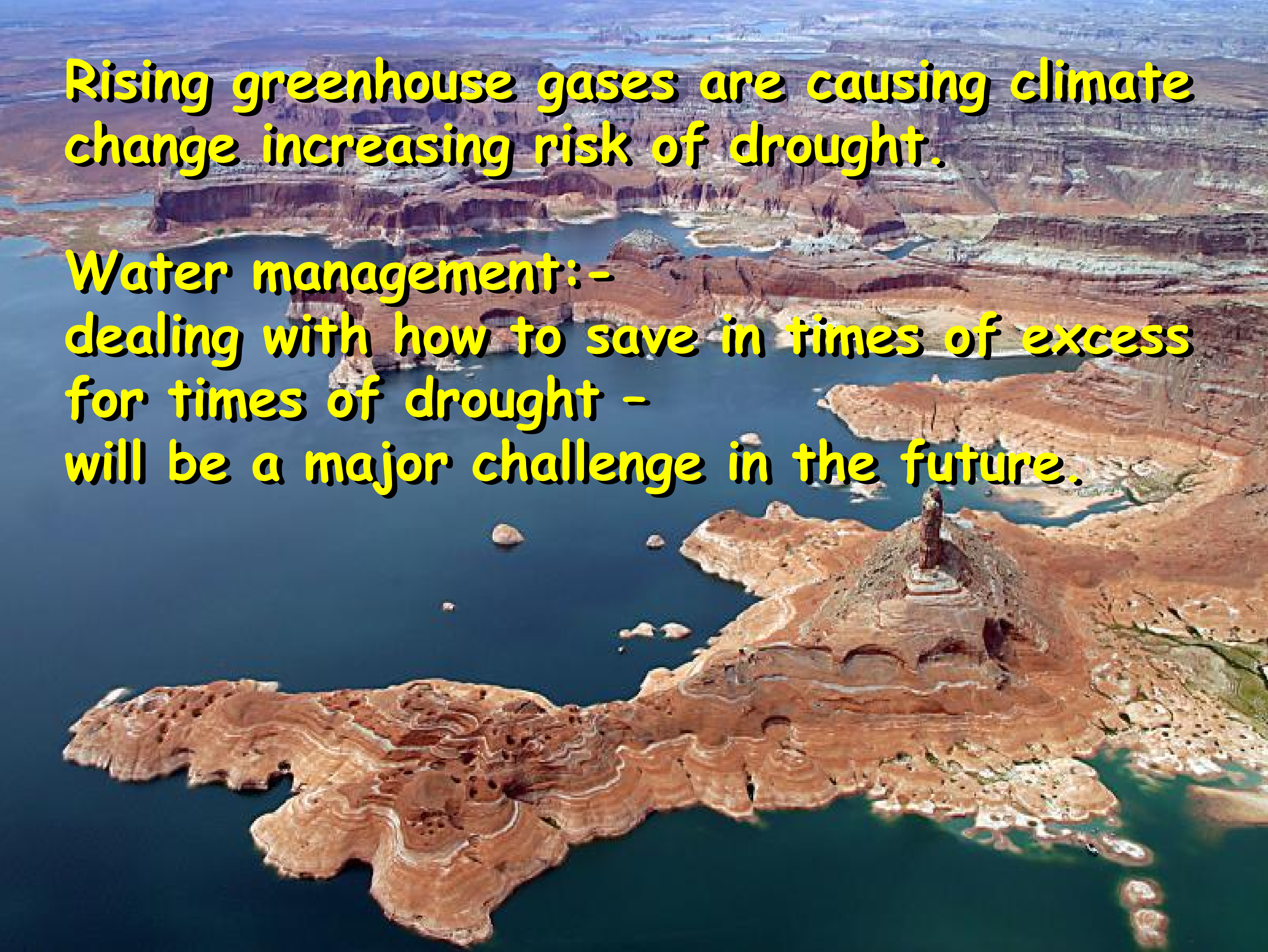
More floods and droughts: both have adverse impacts.

Water management will be a key issue:

How to save excesses in floods for times of drought?

Rising greenhouse gases are causing climate change increasing risk of drought.

Water management:-
dealing with how to save in times of excess for times of drought –
will be a major challenge in the future.



Prospects for increases in extreme weather events