Changes in precipitation and runoff with a changing climate

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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!

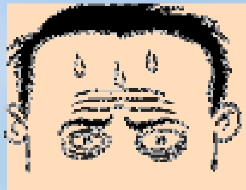
It never rains but it pours!

Global warming: Controlling Heat

The presence of moisture affects the disposition of incoming solar radiation:

Evaporation (drying) versus temperature increase.

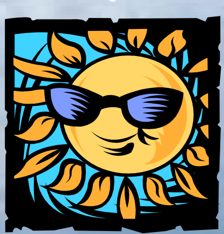
Human body: sweats



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.

How should precipitation change as climate changes?

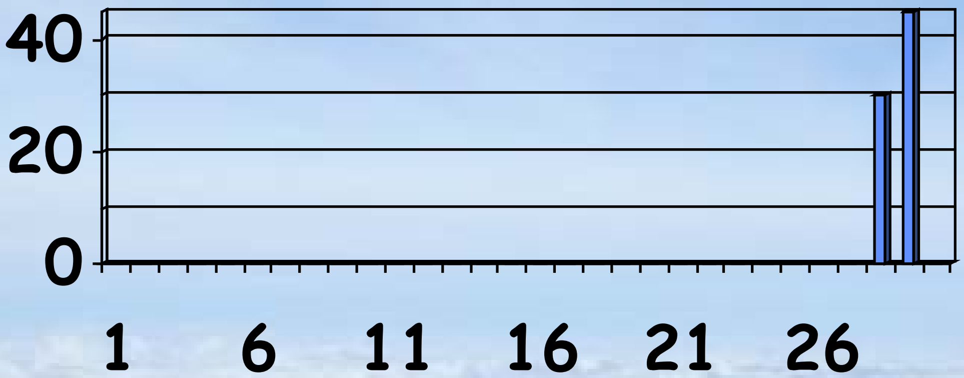
Usually only total **amount** is considered

- 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



drought
wilting plants

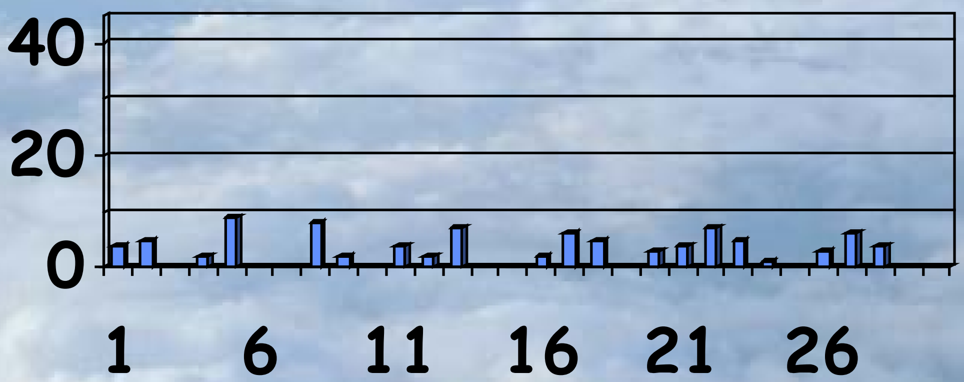
wild fires

local
floods

Monthly
Amount 75 mm

Frequency 6.7%
Intensity 37.5 mm

B

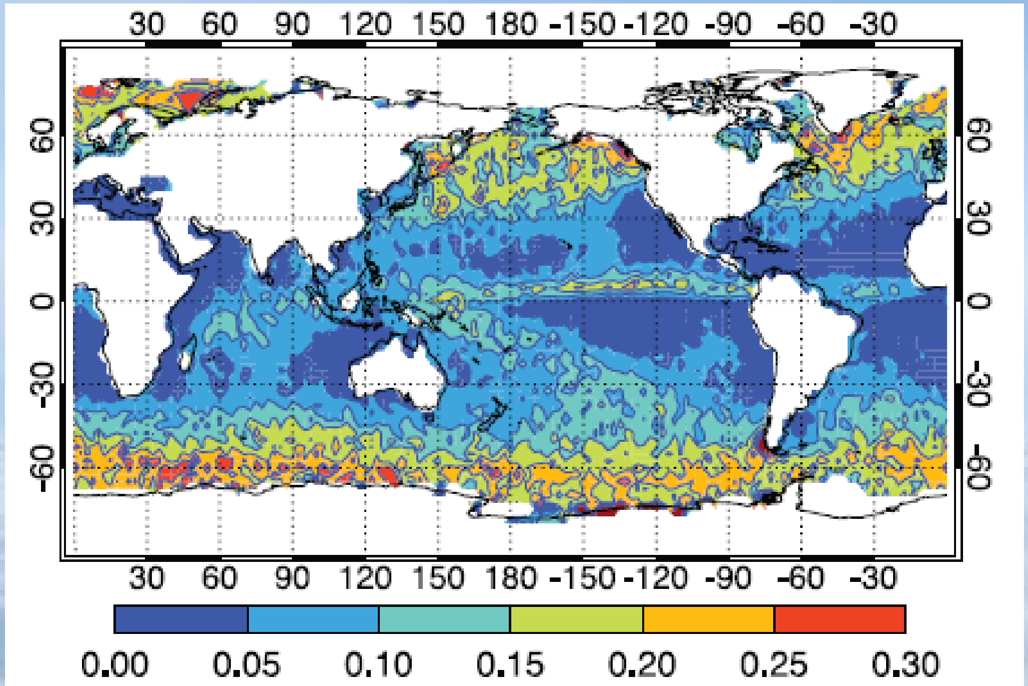


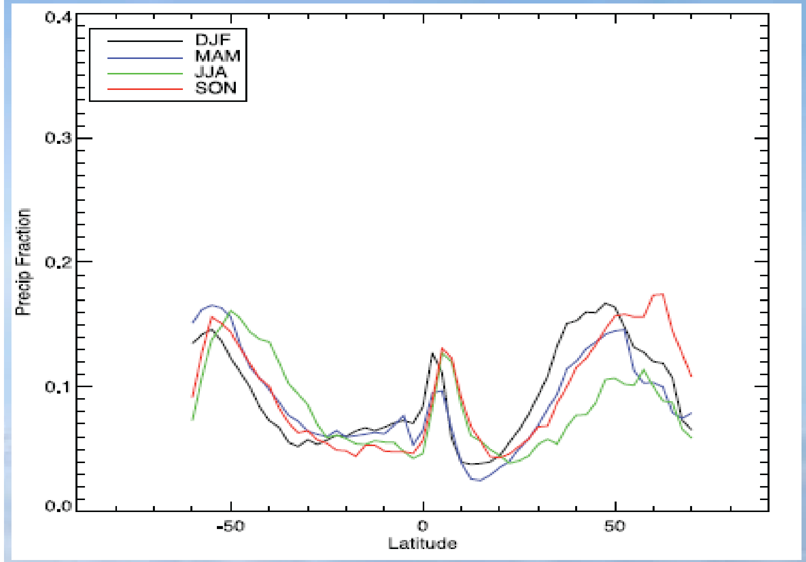
soil moisture replenished
virtually no runoff

Amount 75 mm

Frequency 67%
Intensity 3.75 mm

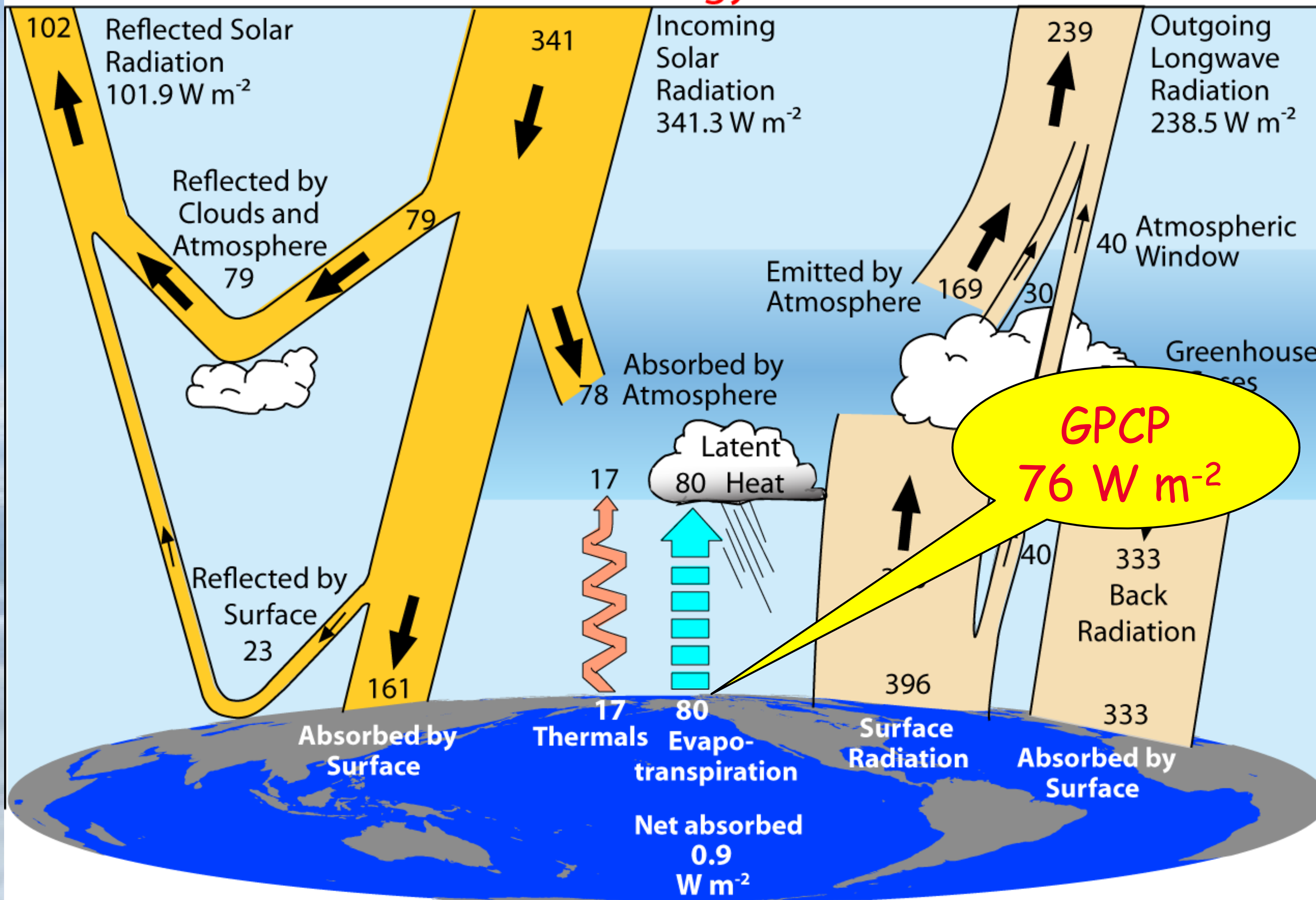
Frequency of precipitation: oceans





Estimated frequency of occurrence (%) of precipitation from Cloudsat observations find precipitation 10.9% of time over oceans (Ellis et al 2009 GRL)

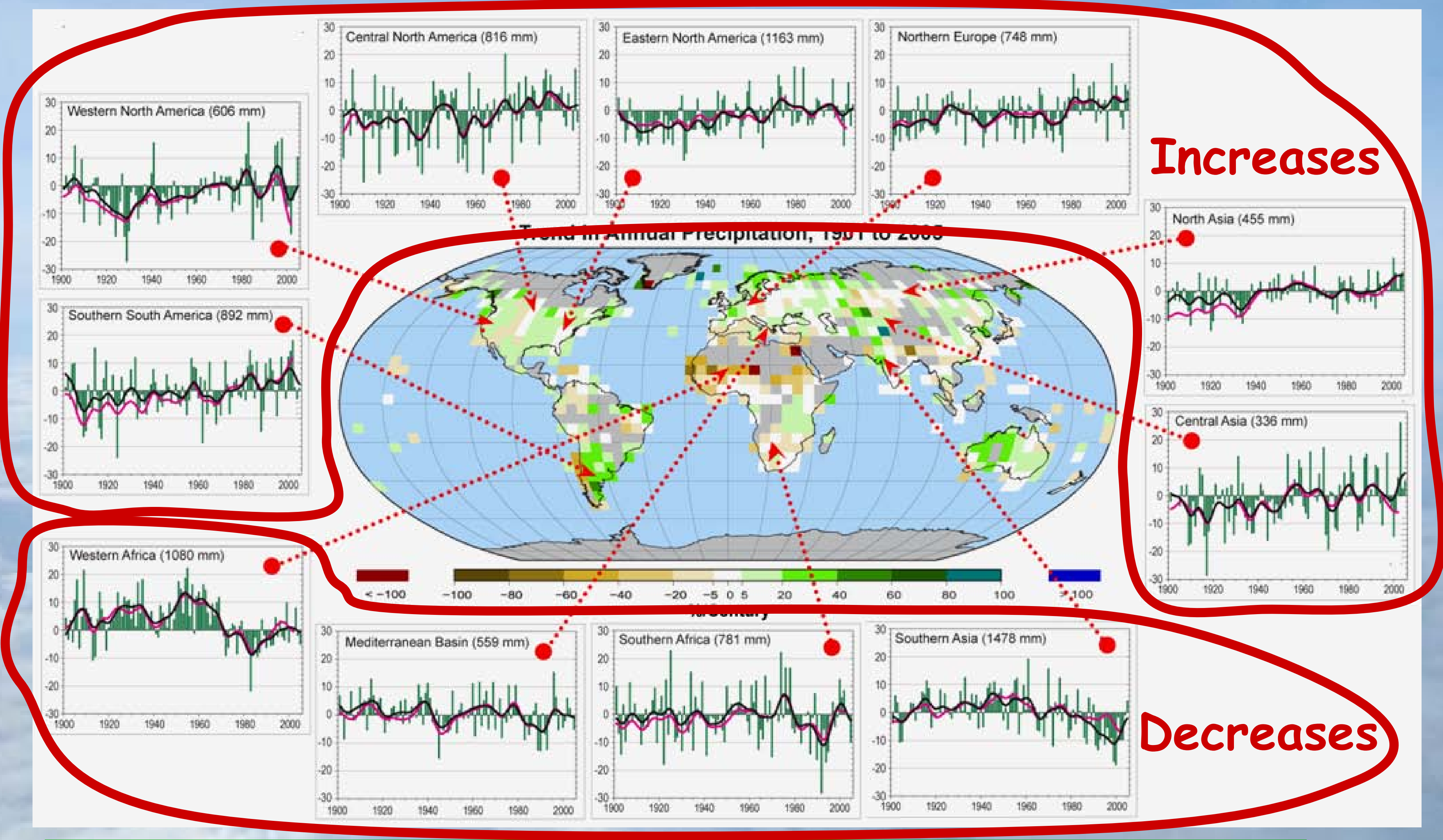
Global Energy Flows W m^{-2}



2000-2005 Trenberth et al 2009

How is precipitation changing?

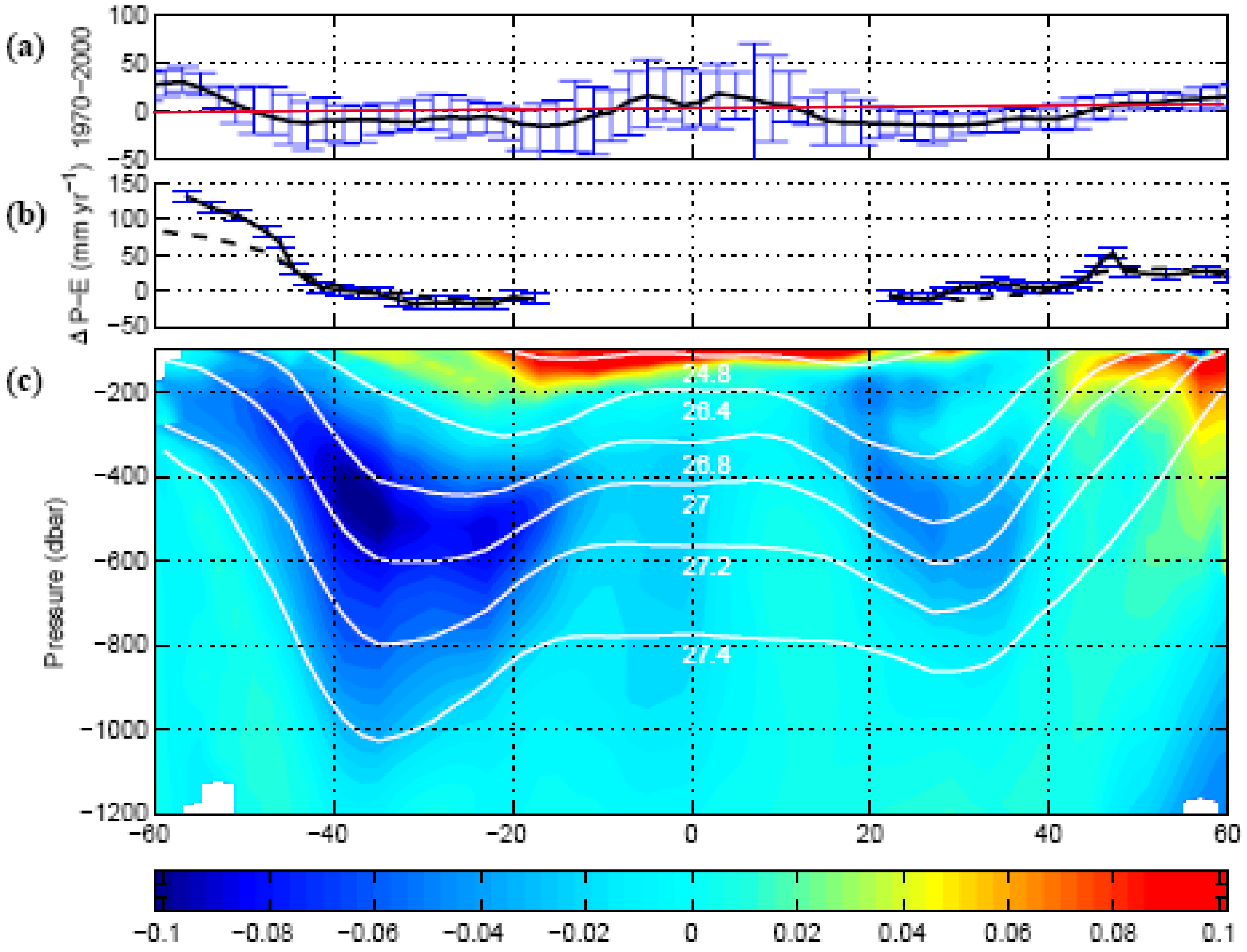
Land precipitation is changing significantly over broad areas



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

IPCC

The ocean as a rain gauge 1970-1995



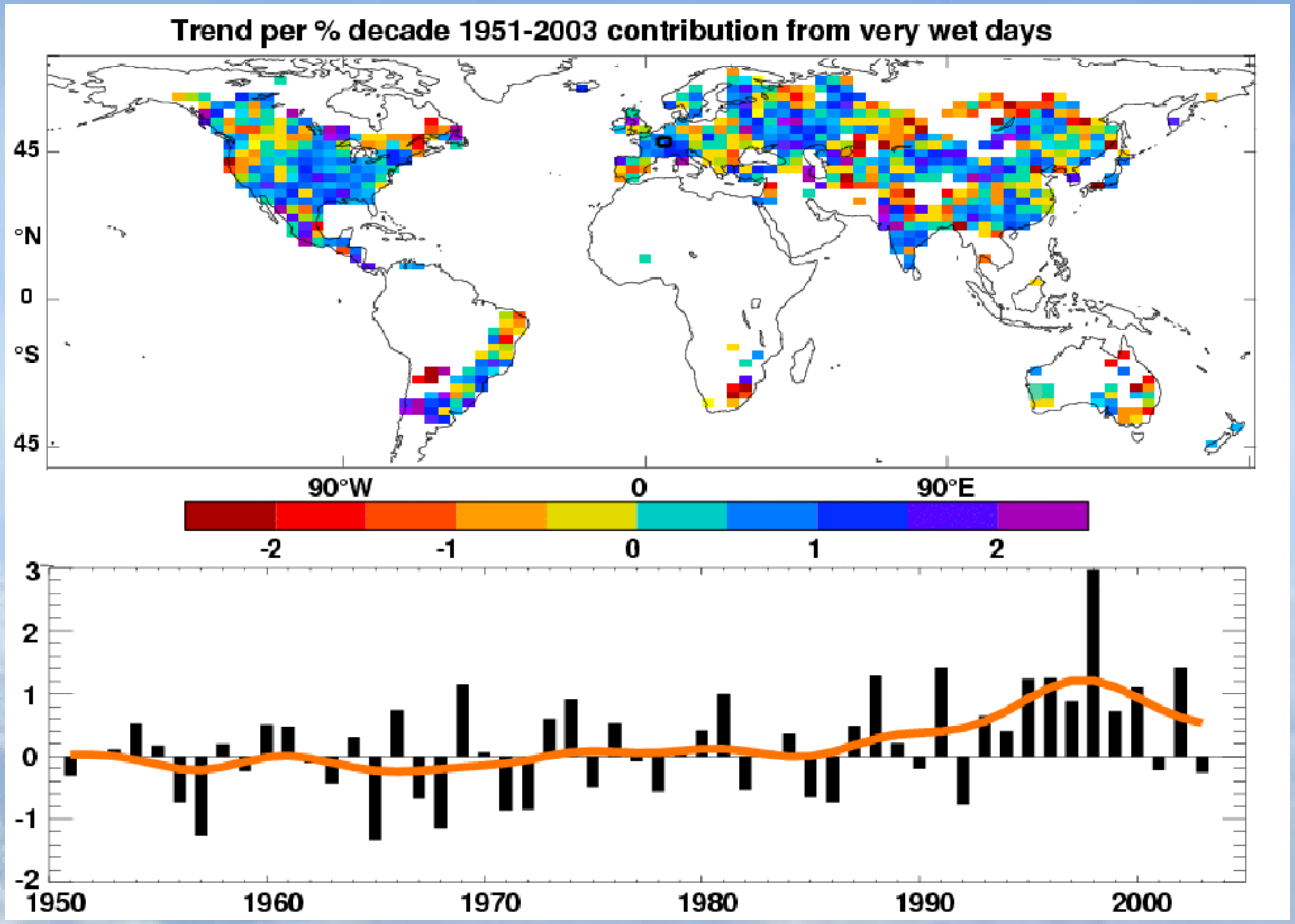
Zonally averaged changes in:

a, P-E using 10 IPCC-class models. Average, 10% -90% range.

b, Difference in P-E (mm/yr) at the ocean surface of each isopycnal layer; running mean, ±2s.d.

c, salinity difference along density layers (psu) where blue is freshening. The top 100 m has been removed to minimize the aliasing of the seasonal signal in the observations.

Helm et al. 2009



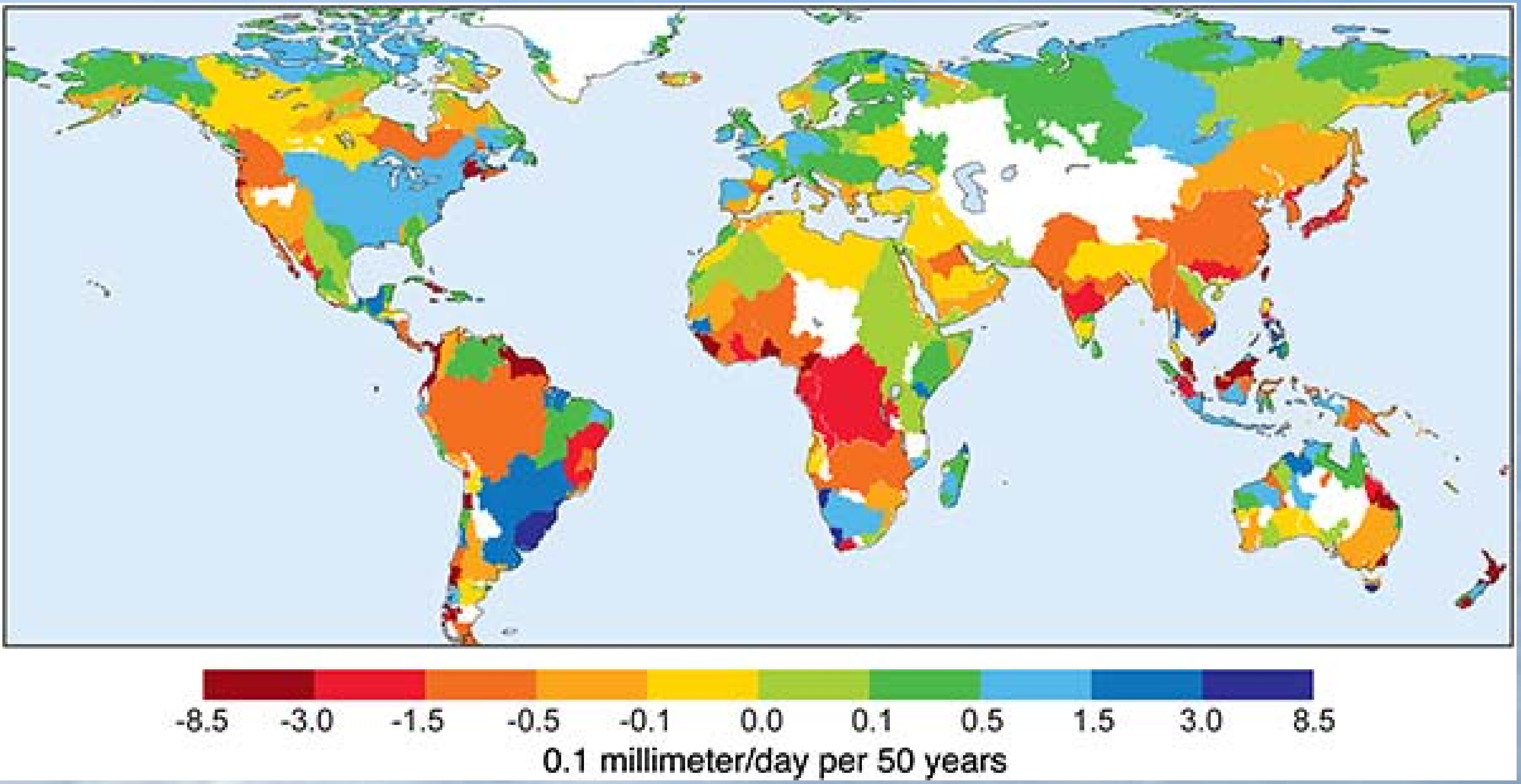
Precipitation

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.

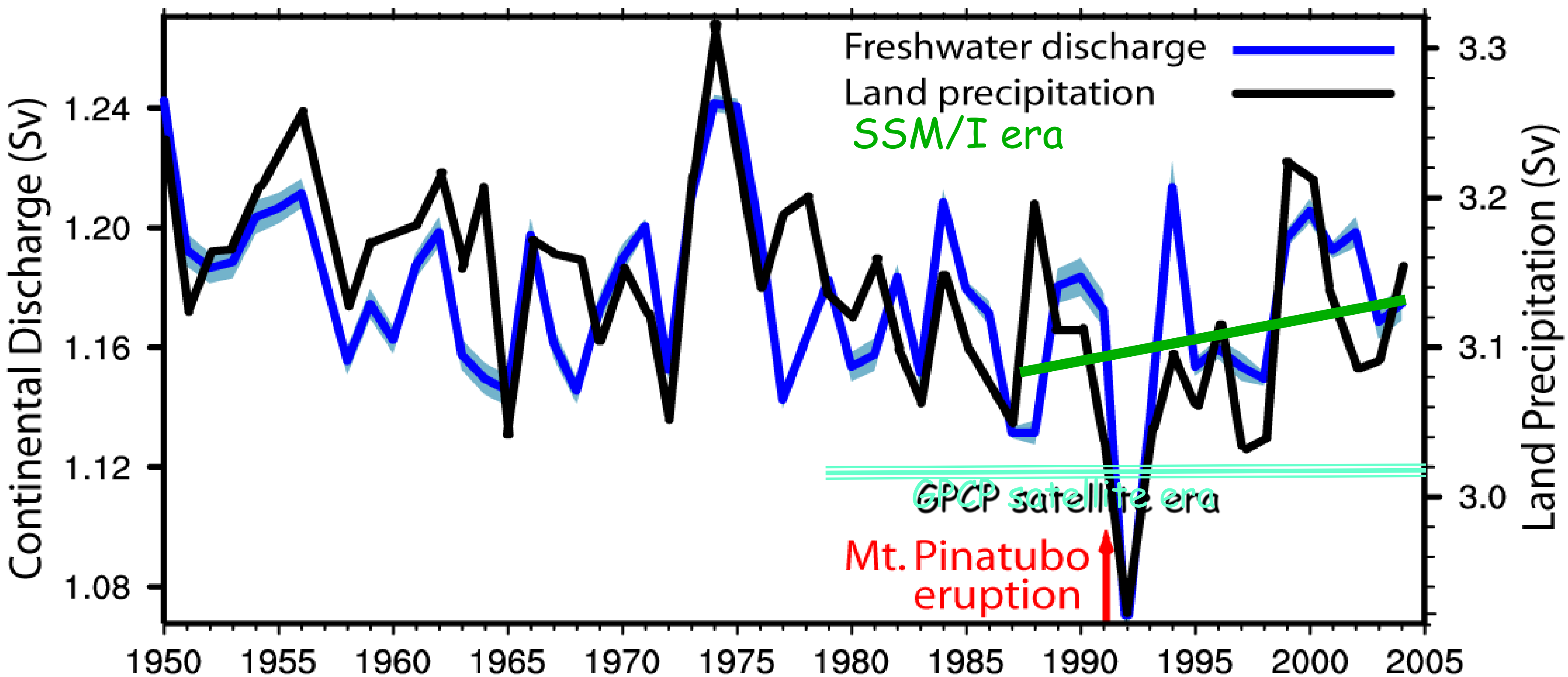
Trends 1948-2004 in runoff by river basin



Based on river discharge into ocean

Dai et al.2009

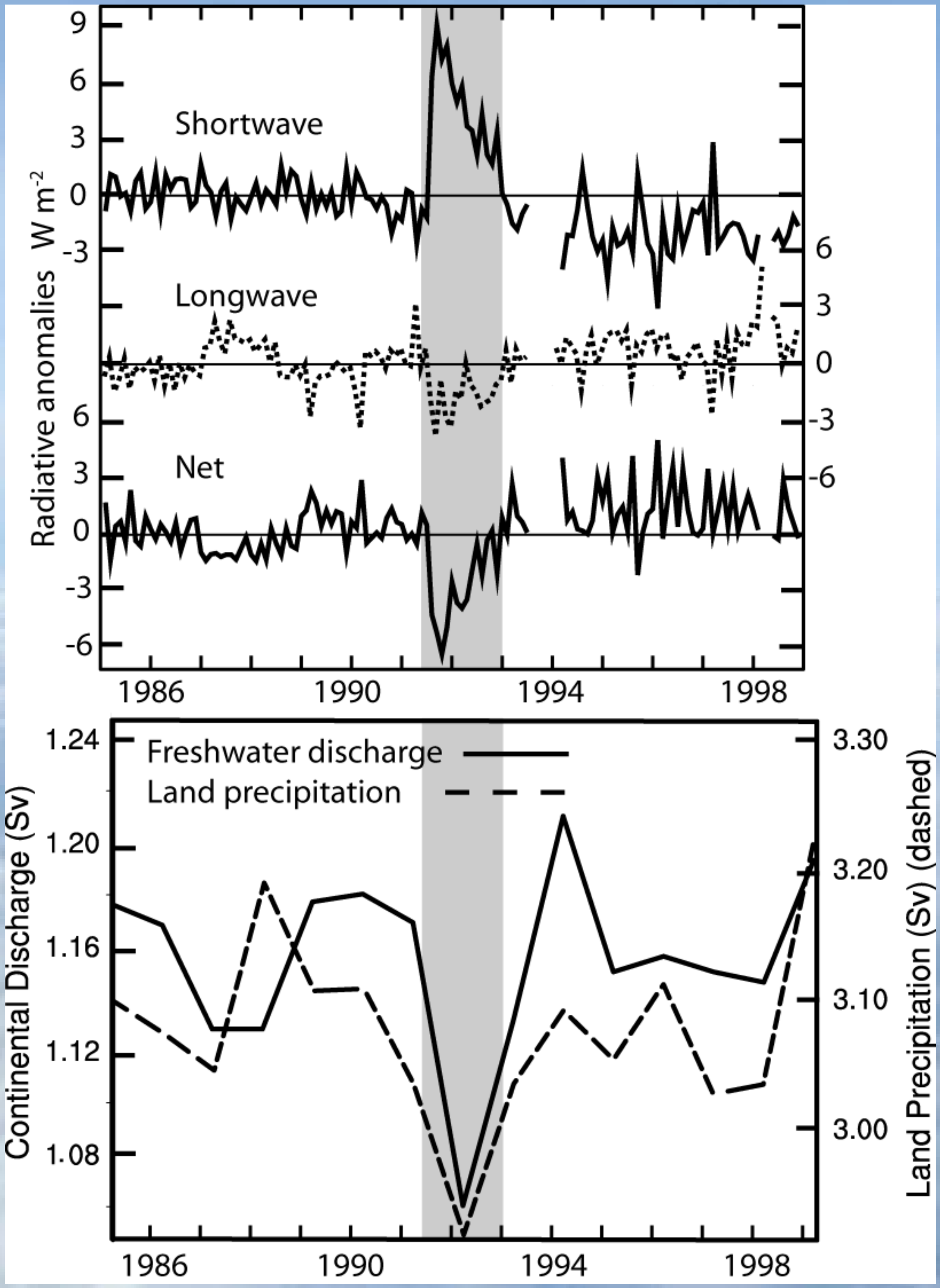
Pinatubo Effect on Hydrological Cycle



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



Mount Pinatubo in June 1991 had a pronounced effect on land precipitation and runoff (3.6σ).

Ocean precipitation was also slightly below normal, and the global values are lowest on record.

Drought and heat waves

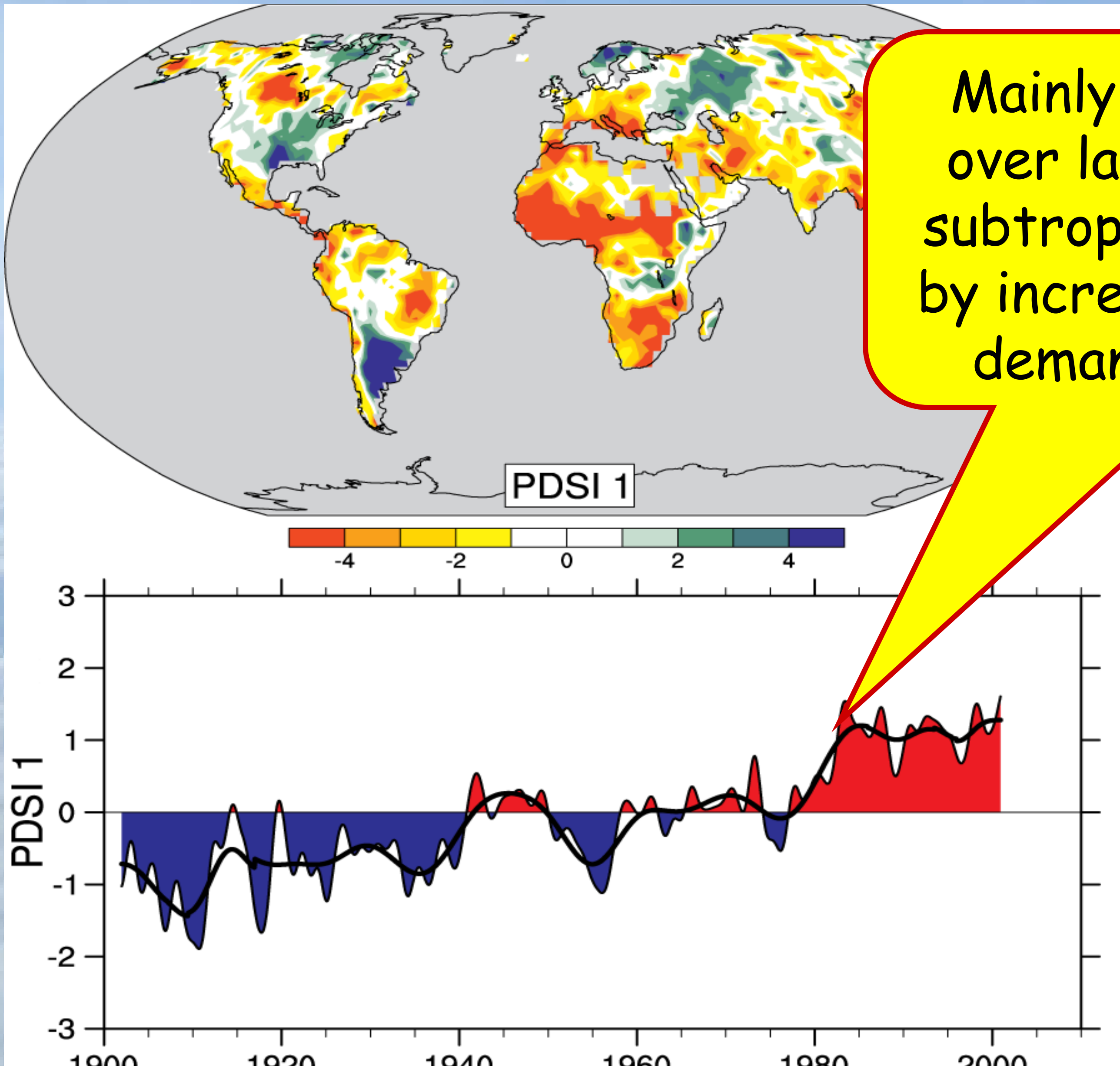
3 kinds of drought

1. Meteorological: absence of rain

2. Agricultural: absence of soil moisture

3. Hydrological: absence of water in rivers, lakes and reservoirs

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

Most precipitation comes from moisture convergence by weather systems

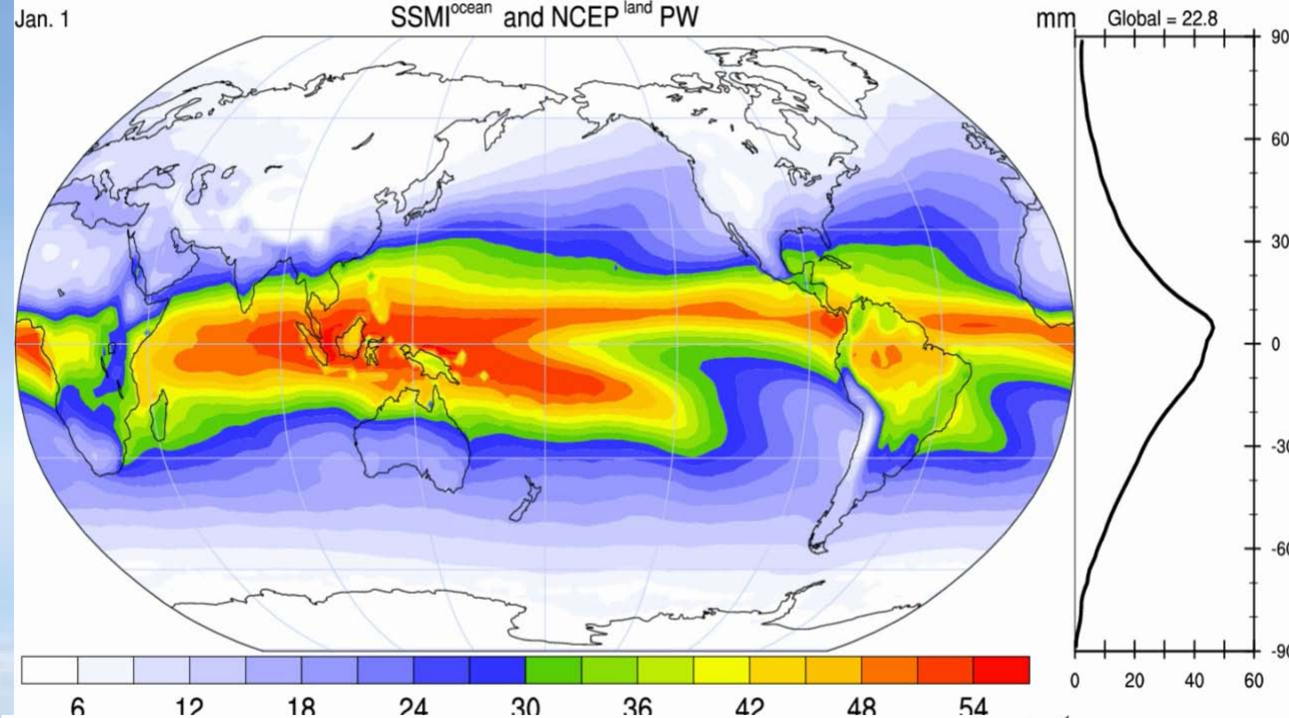
The intermittent nature of precipitation (average frequency over oceans is 11%) means that **moderate or heavy precipitation**

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

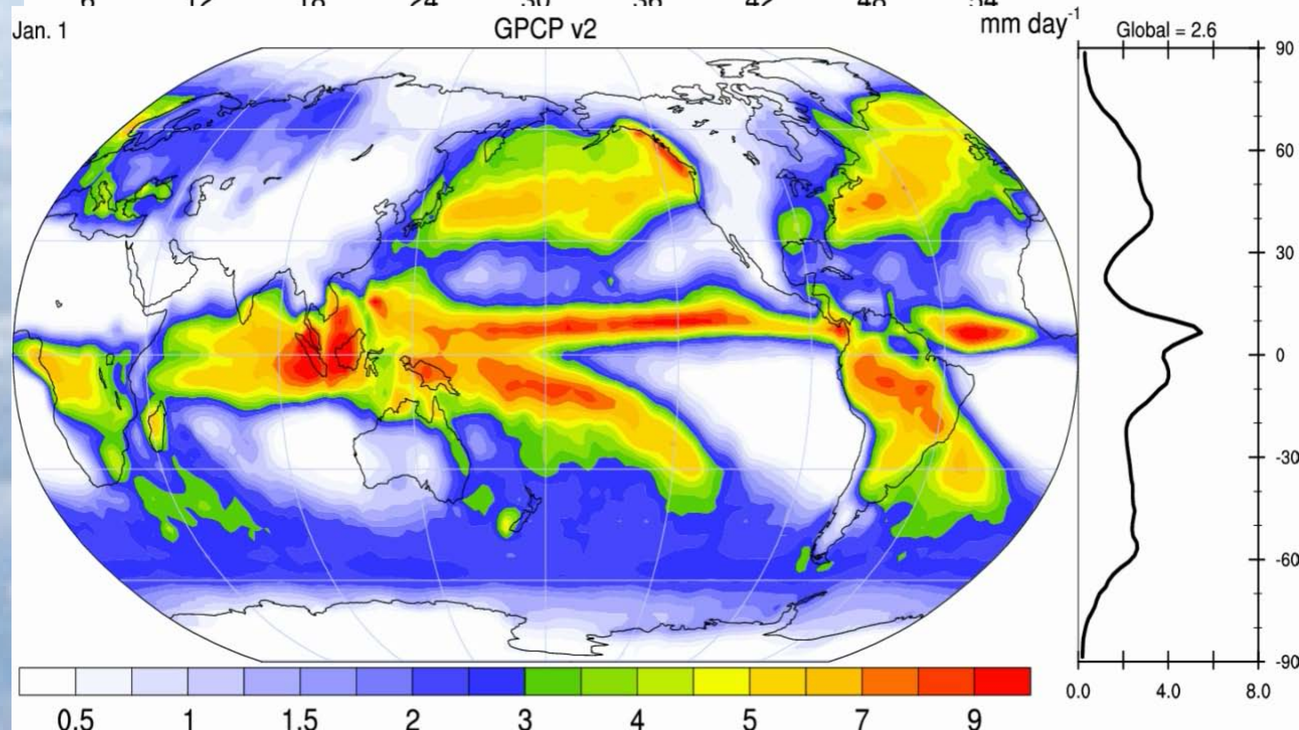
On average, rain producing systems (e.g., extratropical cyclones; thunderstorms) reach out and grab moisture from distance about 3 to 5 times radius of precipitating area.

Double click

Precipitable water



Precipitation



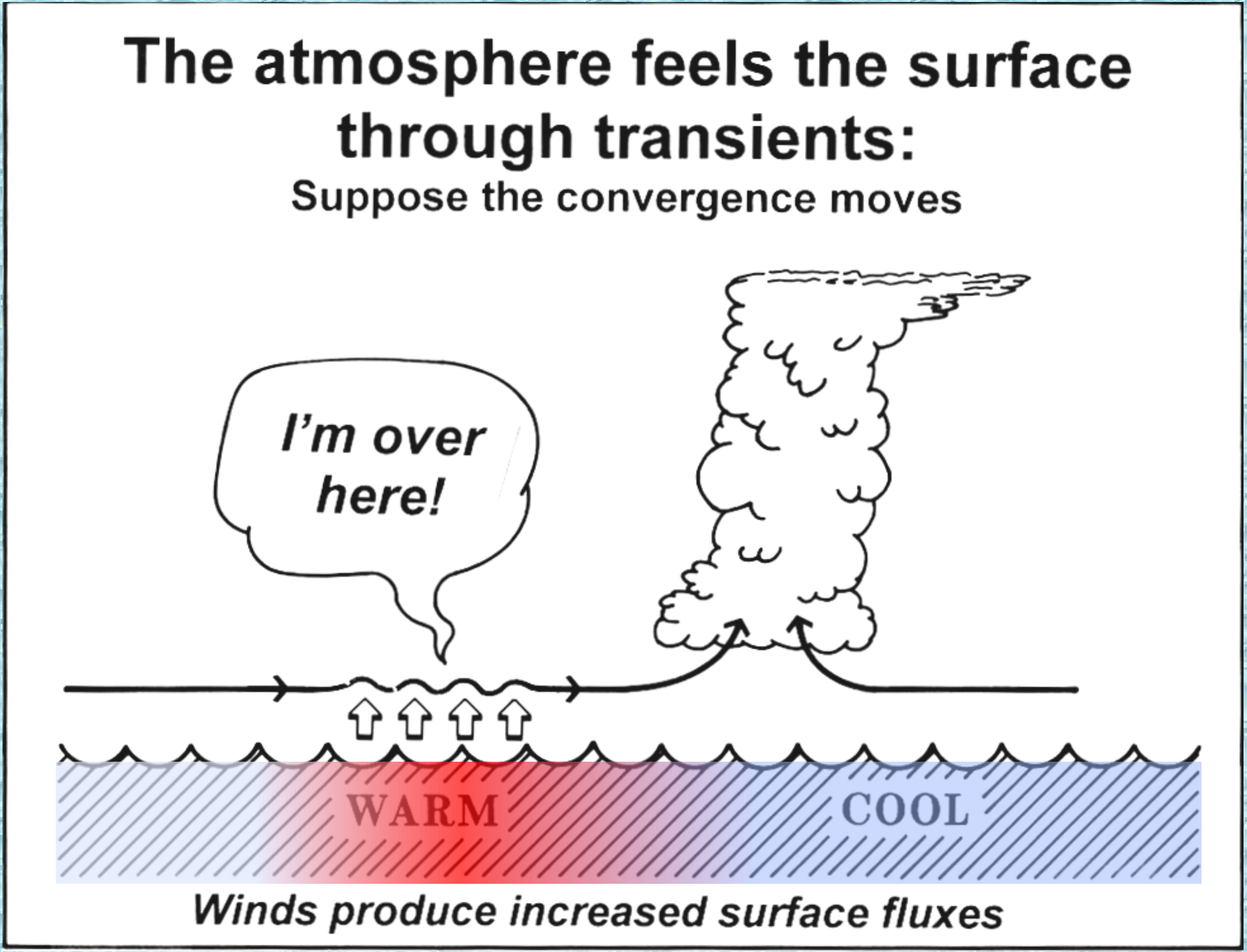
Factors in Changes in Precipitation

There are holes in the sky
Where the rain comes in
But they're ever so small
That's why rain is thin

Spike Milligan

It never rains but it pours!

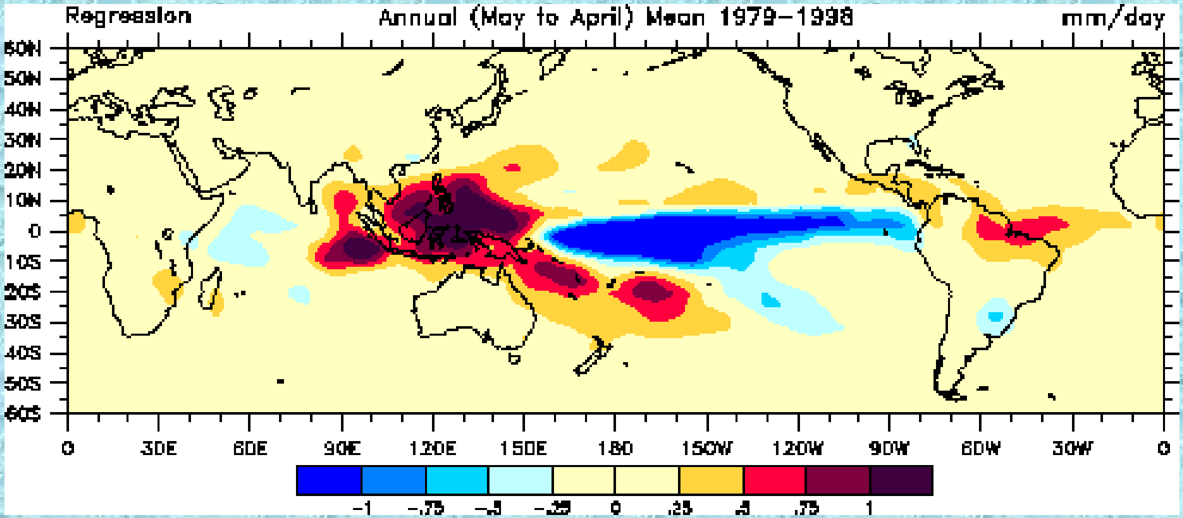
Precipitation prefers high SSTs



- SST changes moist static stability and alters surface pressure gradients and thus winds
- Convergence preferred near warmest waters

Changes in precipitation depend on the mean

- Precipitation has **strong structure:** 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



- Changes in SST with climate change create shifts in convergence zones and winds (pressure gradients) that dominate patterns of precipitation changes

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.
- With increased aerosols, E⇓ and P⇓
- **Net global effect is small and complex**
- Models suggest E⇑ and P⇑ 2-3% per °C.

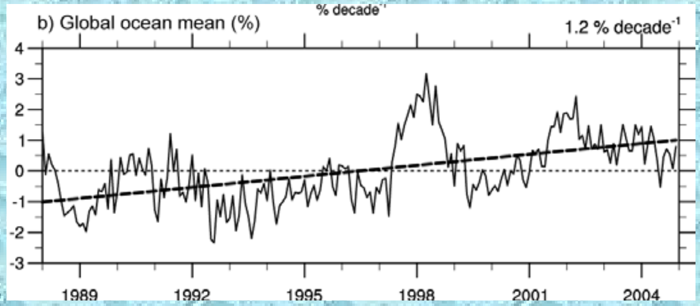
Air holds more water vapor at higher temperatures

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.

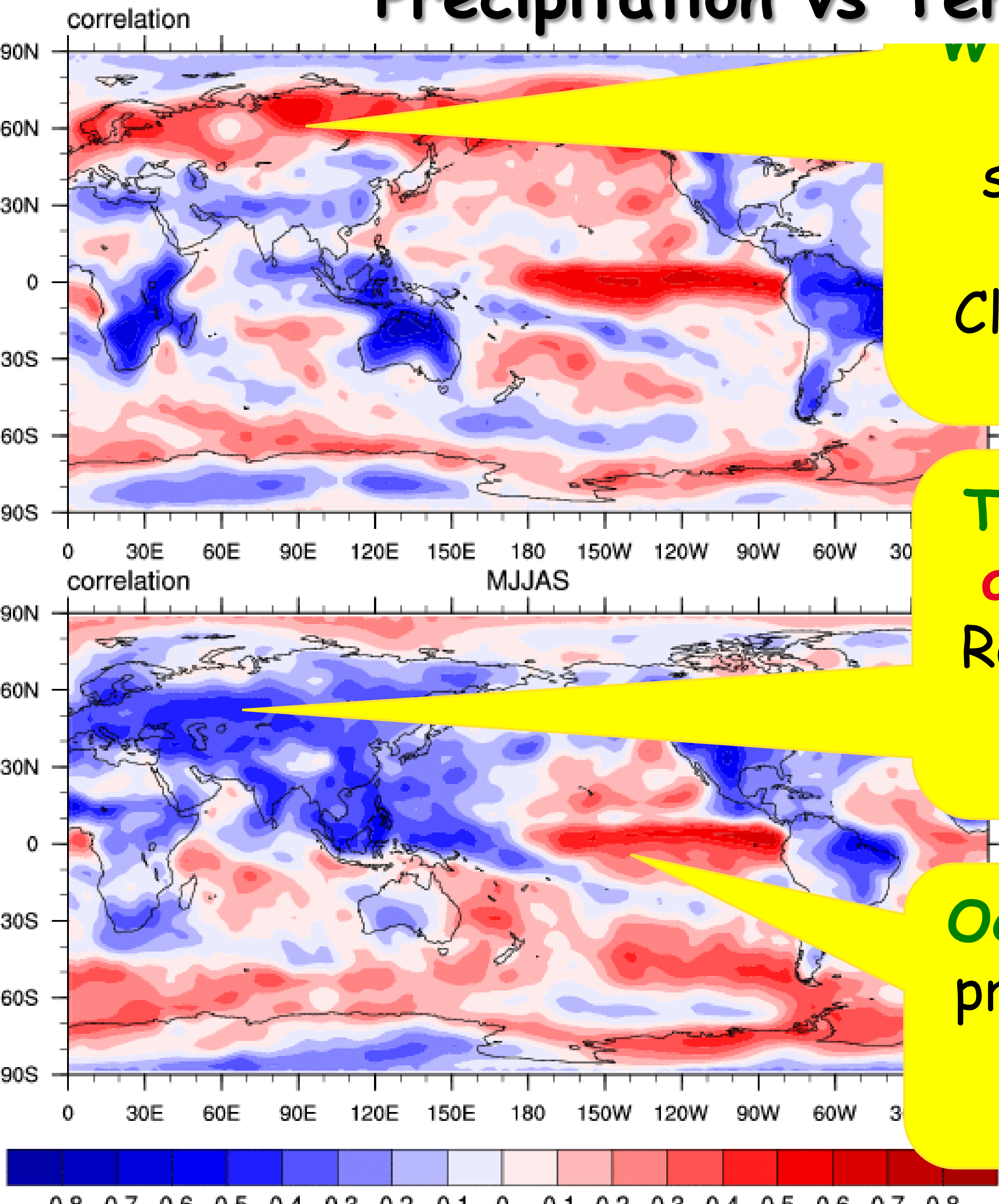
Total water vapor



More intense rains (or snow) but longer dry spells

Trenberth et al 2003

Precipitation vs Temperature

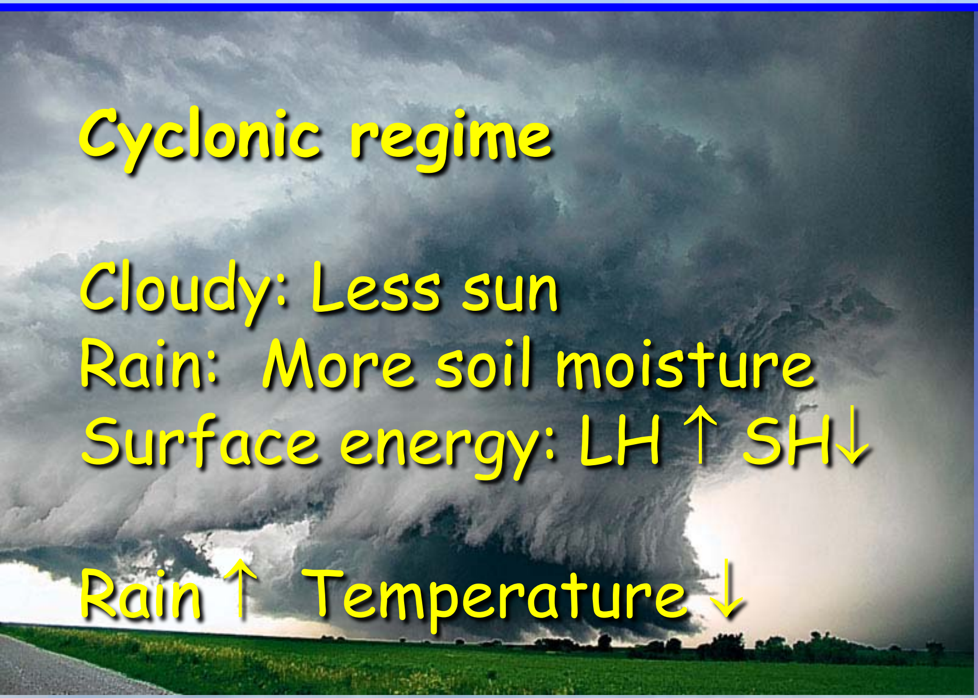


Winter high lats: air can't hold moisture in cold; storms: warm and moist southerlies.
Clausius-Clapeyron effect
T⇒P

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

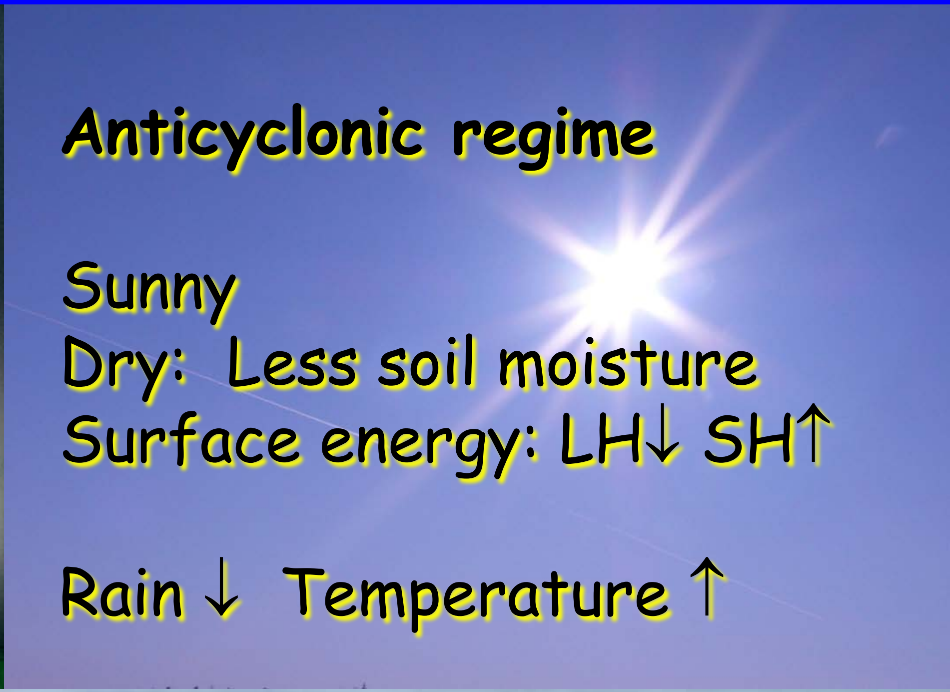
Temperature vs Precipitation



Cyclonic regime

Cloudy: Less sun
Rain: More soil moisture
Surface energy: LH $\uparrow$ SH $\downarrow$

Rain $\uparrow$ Temperature $\downarrow$



Anticyclonic regime

Sunny
Dry: Less soil moisture
Surface energy: LH $\downarrow$ SH $\uparrow$

Rain $\downarrow$ Temperature $\uparrow$

Summer: Land

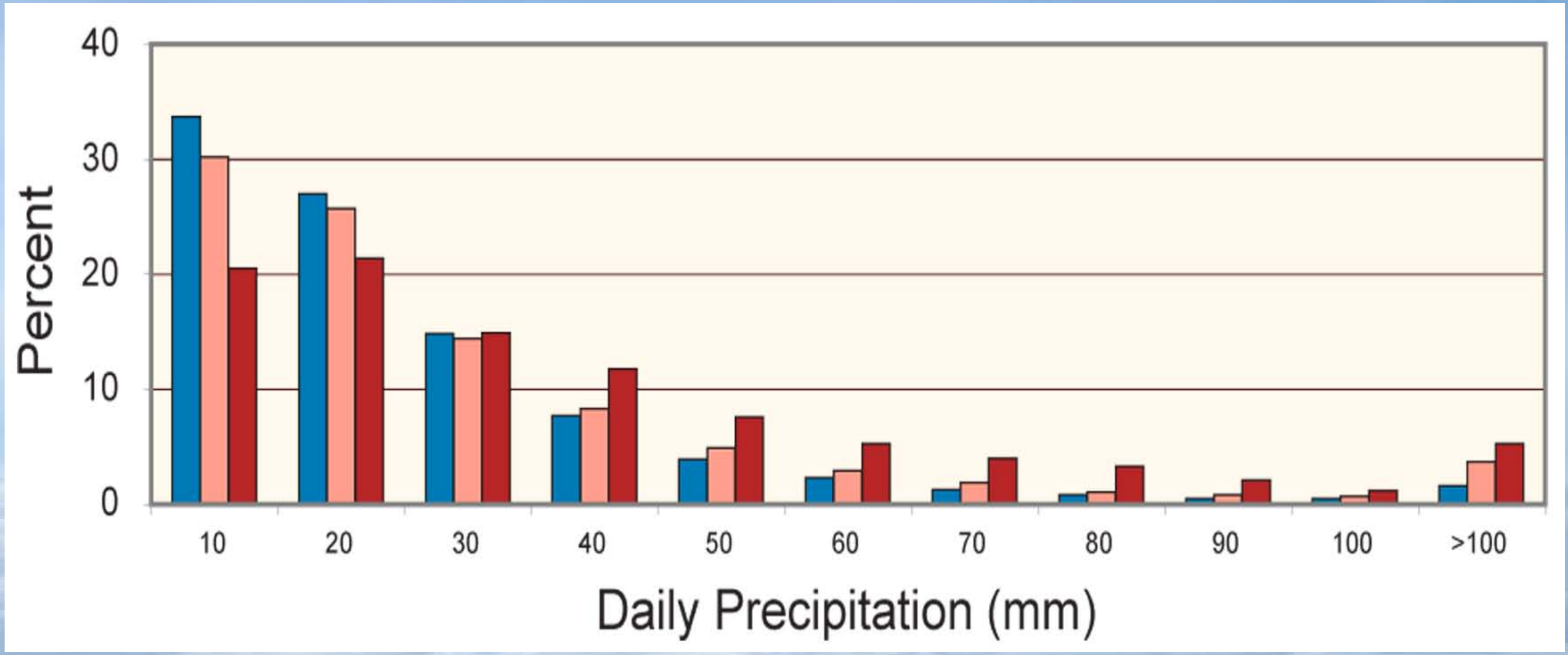
Strong negative correlations

Does **not** apply to oceans

Supply of moisture over land is critical

- Over **land in summer** and over **tropical continents**, the strong negative correlations between temperature and precipitation suggest factors other than C-C are critical: the **supply of moisture**.
- There is a strong diurnal cycle (that is not well simulated by most models).
- In these regimes, convection plays a dominant role
- Recycling is more important in summer and advection of moisture from afar is less likely to occur.
- Monsoons play a key role where active.
- Given the right synoptic situation and diurnal cycle, severe convection and **intense rains** can occur.

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

Air holds more water vapor at higher temperatures

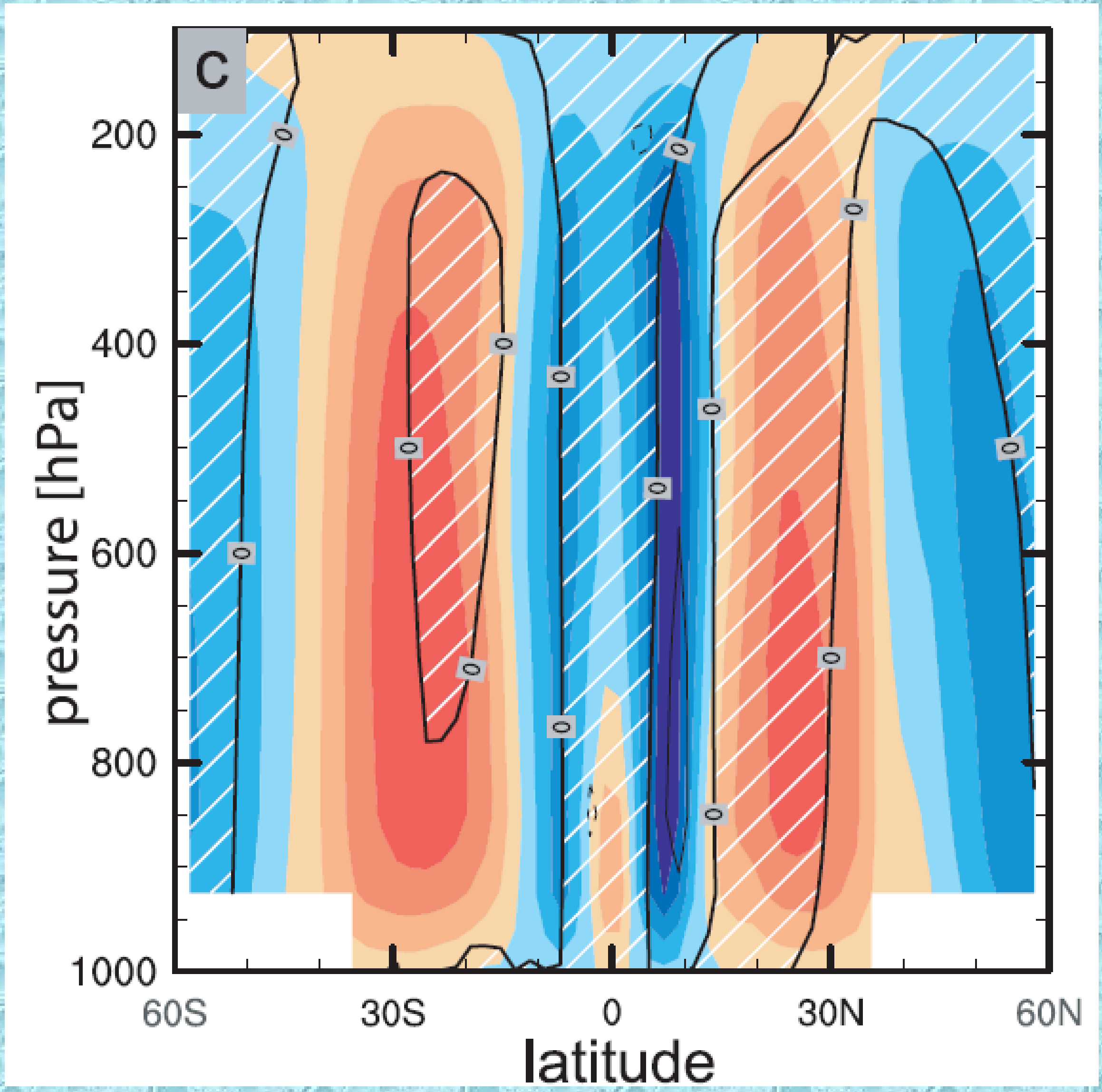
- The **C-C effect** is important over oceans (abundant moisture) and over land at mid to high latitudes in winter.
- "**The rich get richer and the poor get poorer**". More moisture transports from divergence regions (subtropics) to convergence zones. Result: **wet areas get wetter, dry areas drier** (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.**
- "**Upped ante**" precip decreases on edges of convergence zones as it takes more instability to trigger convection. (Neelin, Chou)

Model ω changes

Oceans

Mean vertical motion and changes in circulation (increased upward motion is given by white hatching):

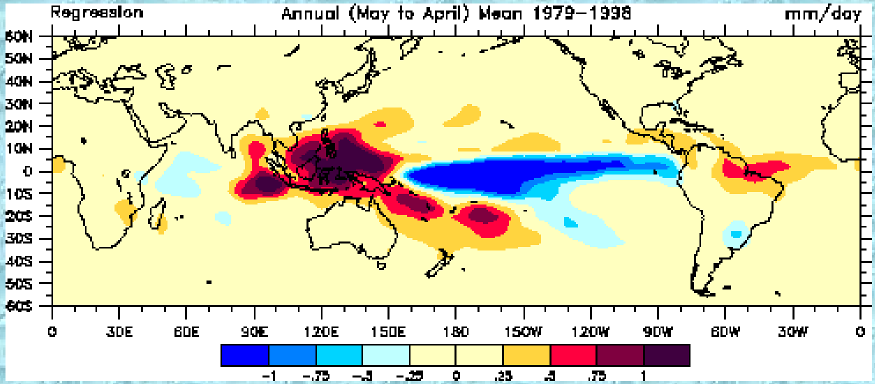
Narrower upward Hadley circulation, widening of tropics



AR4 models A1B
2090s vs 2010s
Richter and Xie 2008

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



SNOW PACK: In many mountain areas, contributions of **global warming** include:

- 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**

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!

Precipitation in models

A challenge:

Amount: distribution:
double ITCZ

Frequency: too often

Intensity: too low

Runoff: not correct

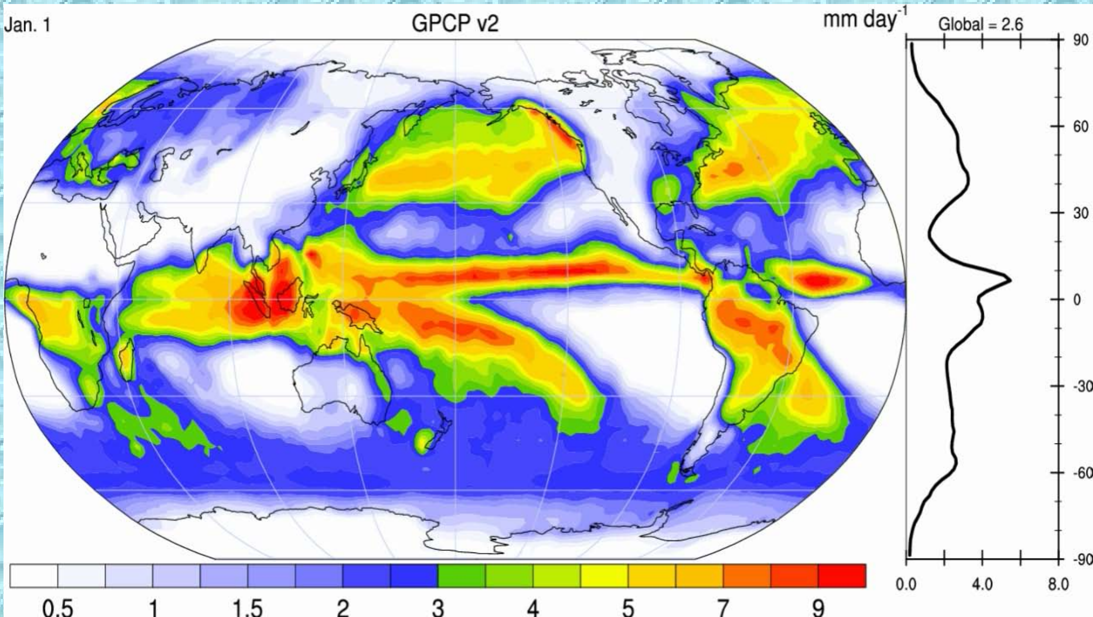
Recycling: too large

Diurnal cycle: poor

Lifetime: too short
(moisture)

Issues:

Tropical transients too weak
Hurricanes
MJOs
Easterly waves

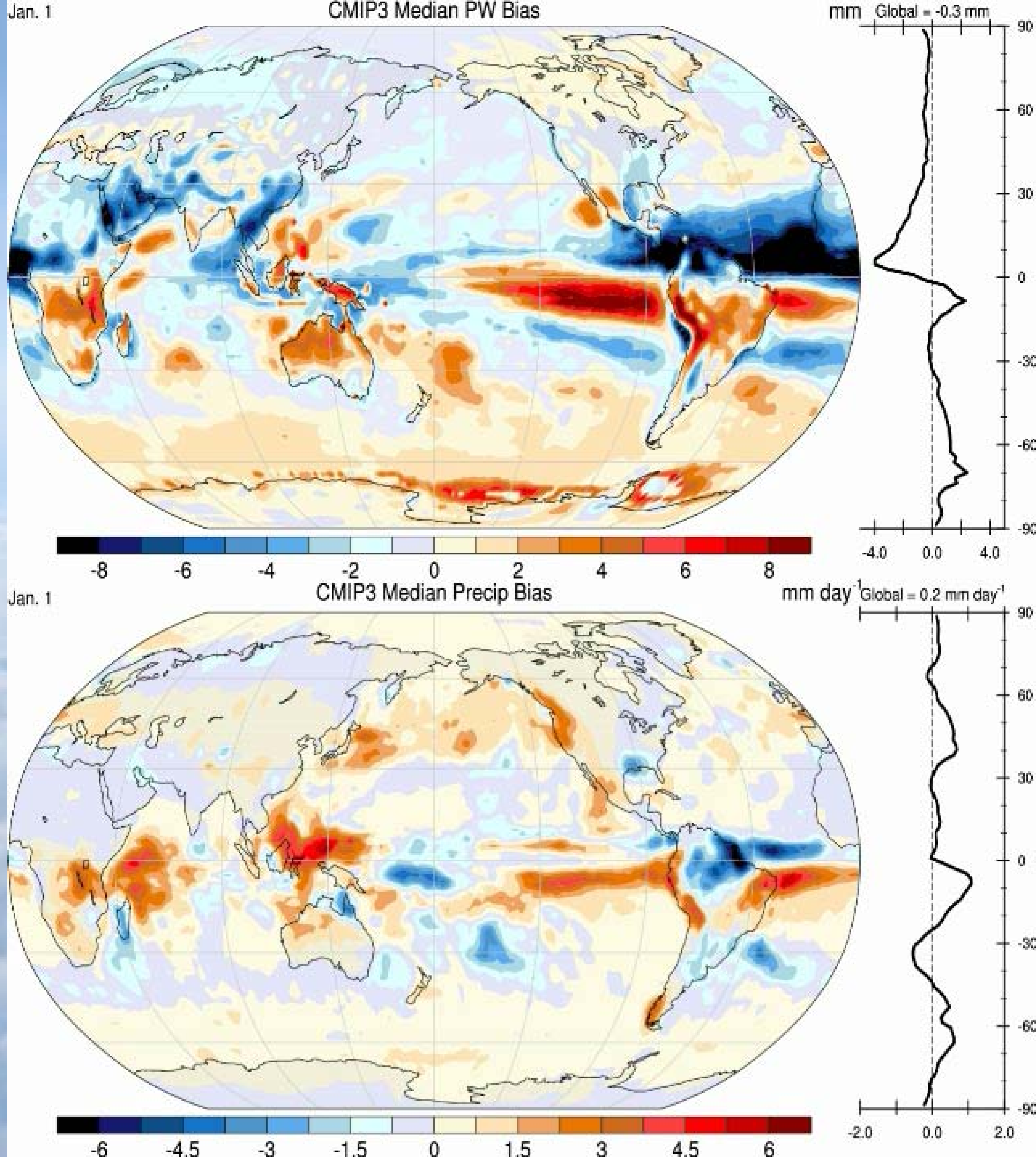


Median model bias

double click

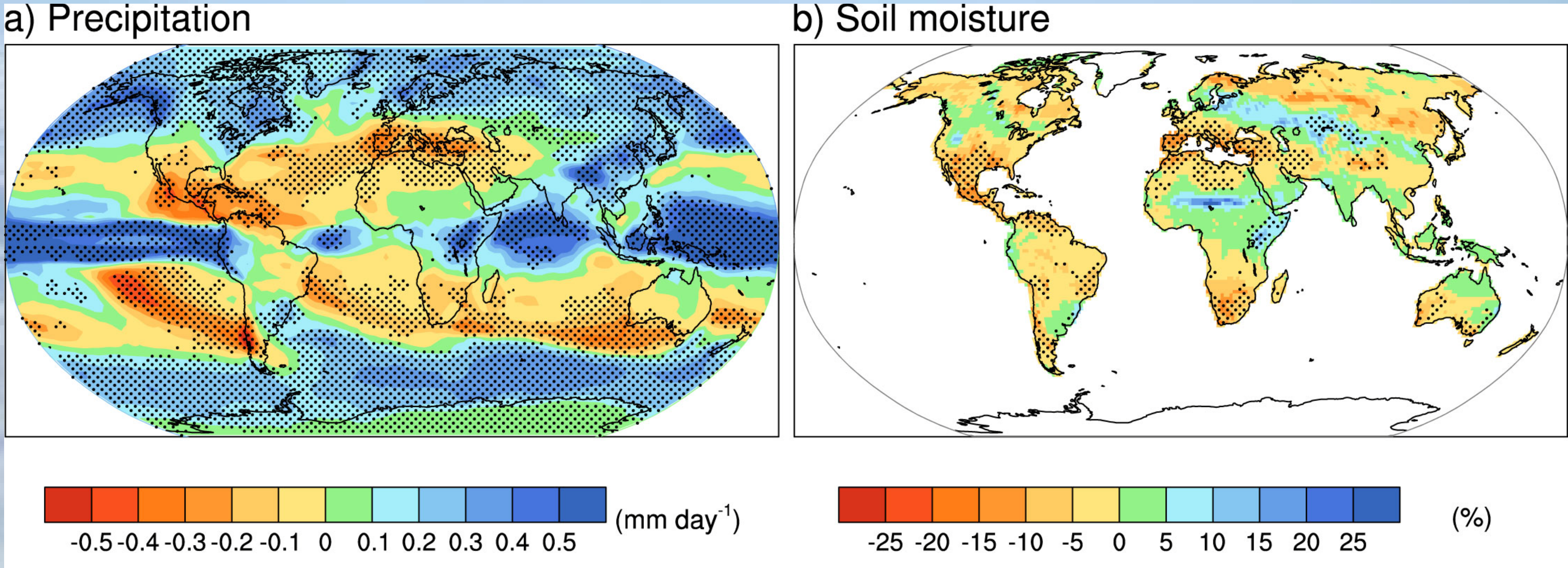
Precipitable water

Precipitation



"Rich get richer, poor get poorer"

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



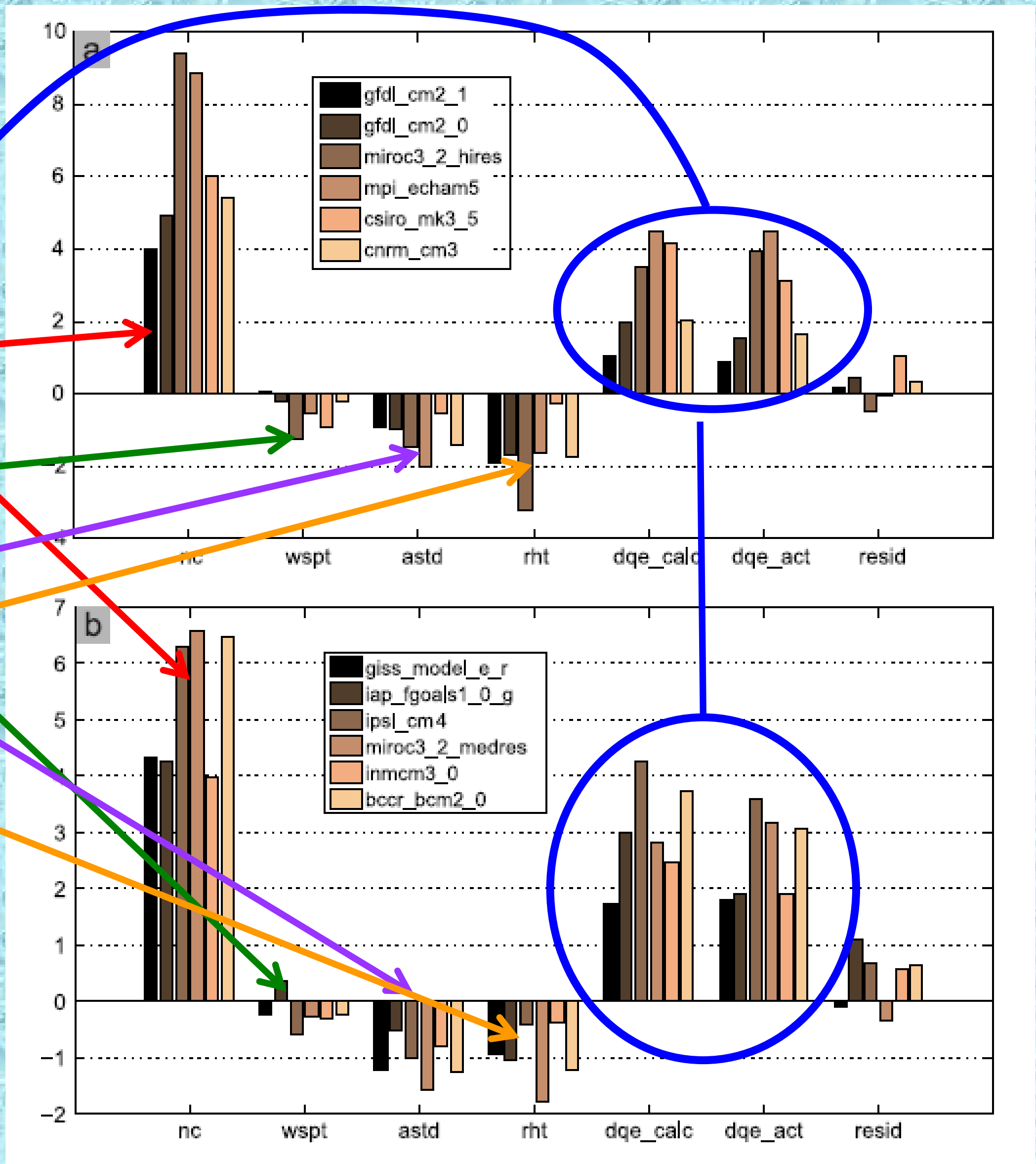
2090-2100

IPCC

Model precipitation changes

Oceans

- 2-3% per K increase in E and P
- C-C effect 4-6%
- Sfc wind speed ↓ 0.01m/s
- Sea-air T diff↓ 0.05K
- Sfc RH ↑ 0.2%



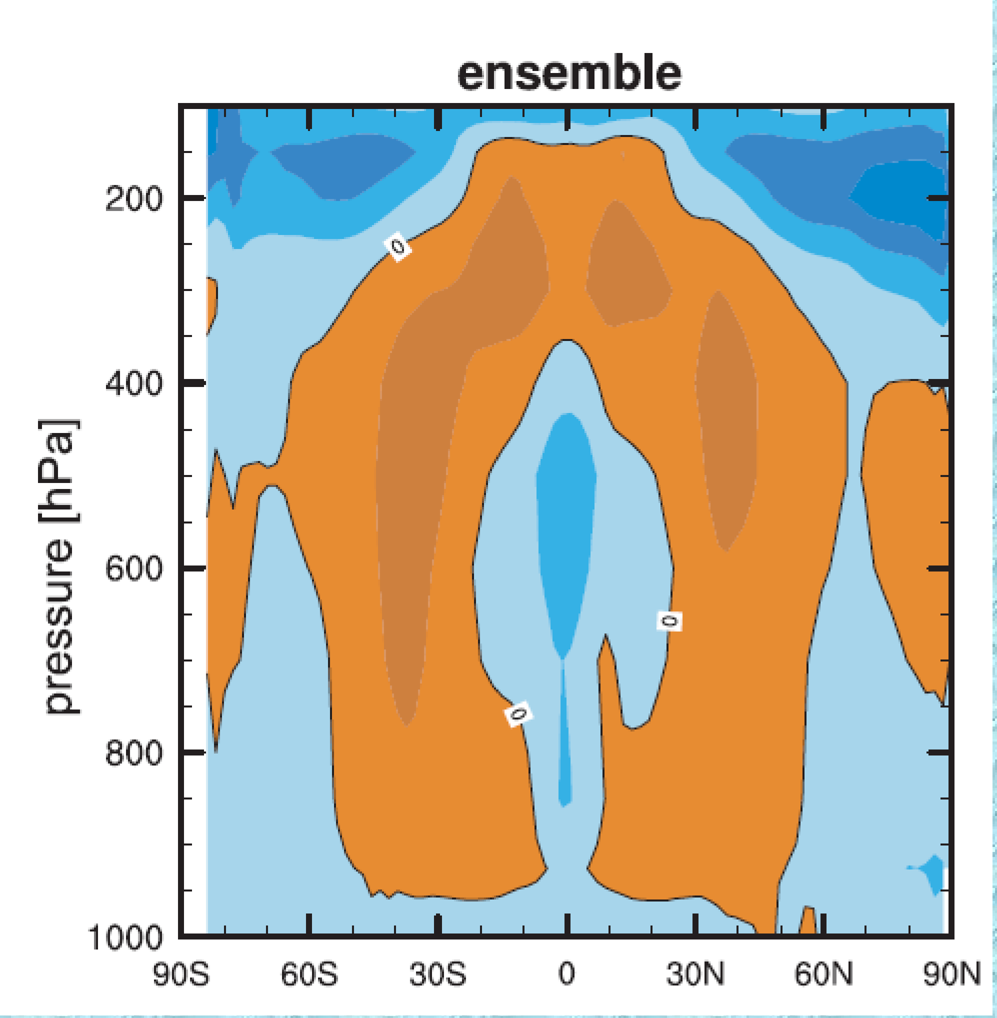
AR4 models A1B
2046 to 2101
Richter and Xie 2008

Model RH changes

Oceans

Contour interval 2%

- Reflects changes in circulation
- Drying in increased subsidence does not penetrate to surface;
- Some advective changes



AR4 models A1B
2046 to 2101
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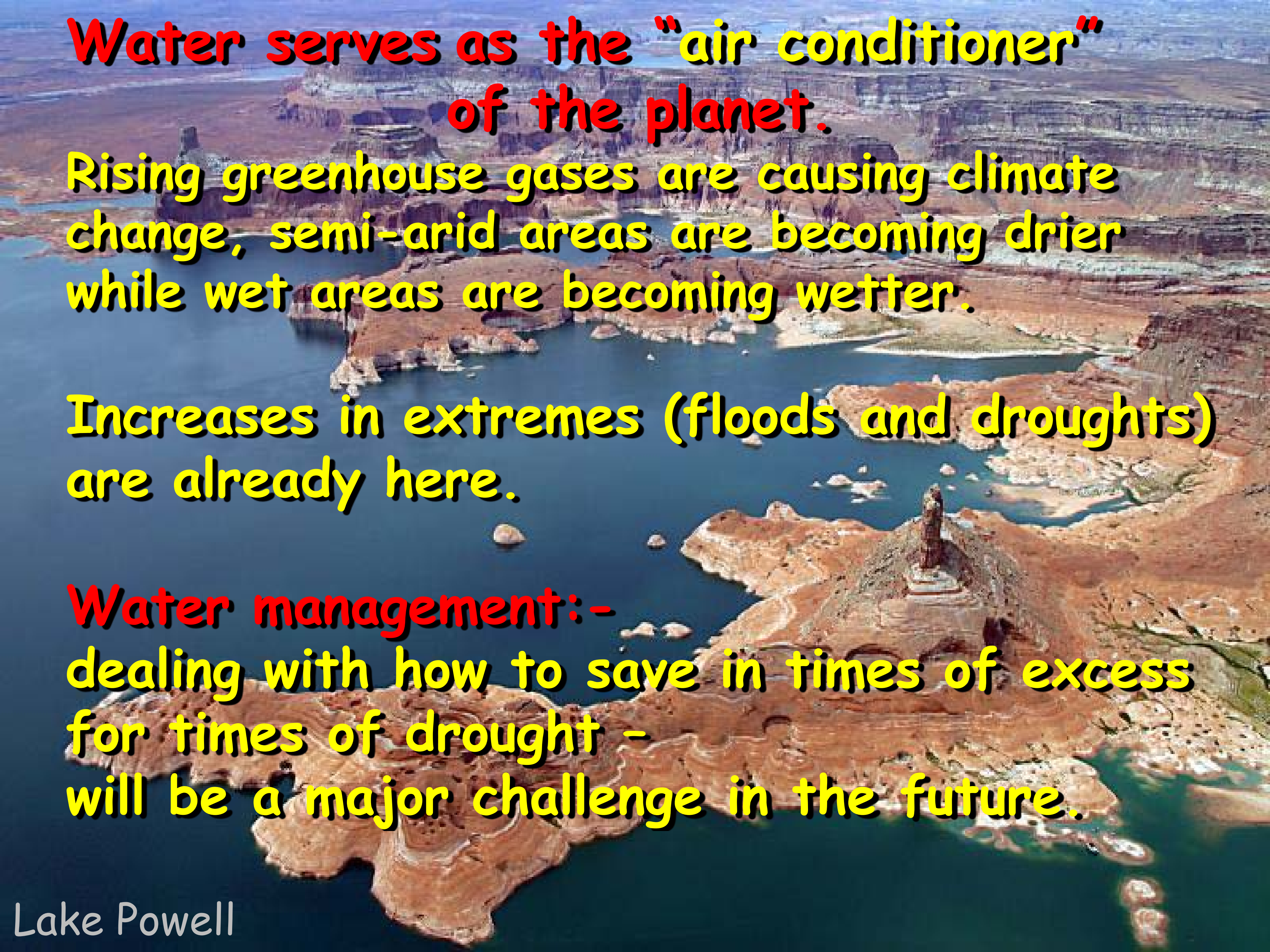
Water serves as the "air conditioner" of the planet.
Rising greenhouse gases are causing climate change, semi-arid areas are becoming drier while wet areas are becoming wetter.
Increases in extremes (floods and droughts) are already here.
Water management:-
dealing with how to save in times of excess for times of drought –
will be a major challenge in the future.
Lake Powell

Prospects for increases in extreme weather events