Potential impacts of climate change on precipitation

Kevin E. Trenberth
NCAR

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!

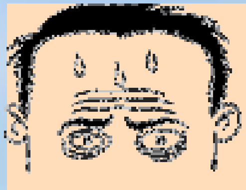
It never rains but it pours!

Global warming: Controlling Heat

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

Evaporation (drying) versus temperature increase.

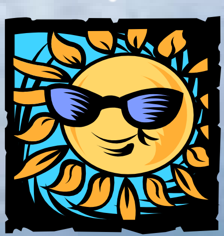
Human body: sweats



Homes: Evaporative coolers (swamp coolers)

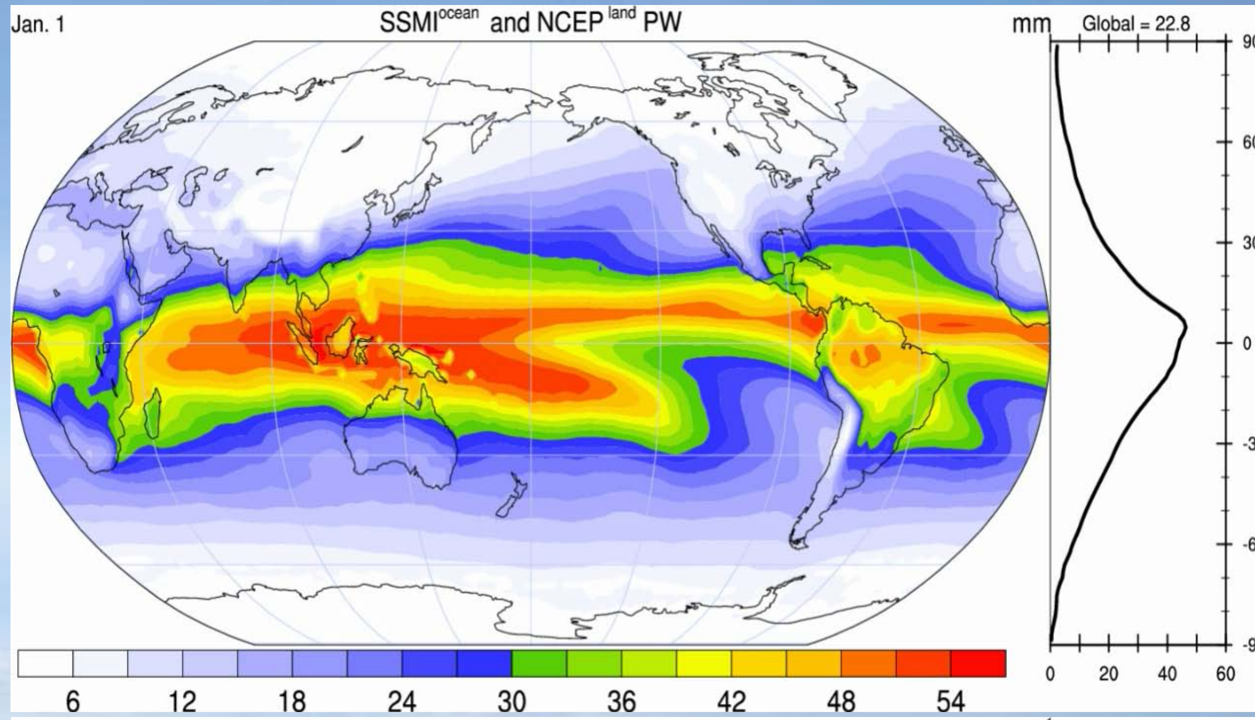
Planet Earth: Evaporation (if moisture available)

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

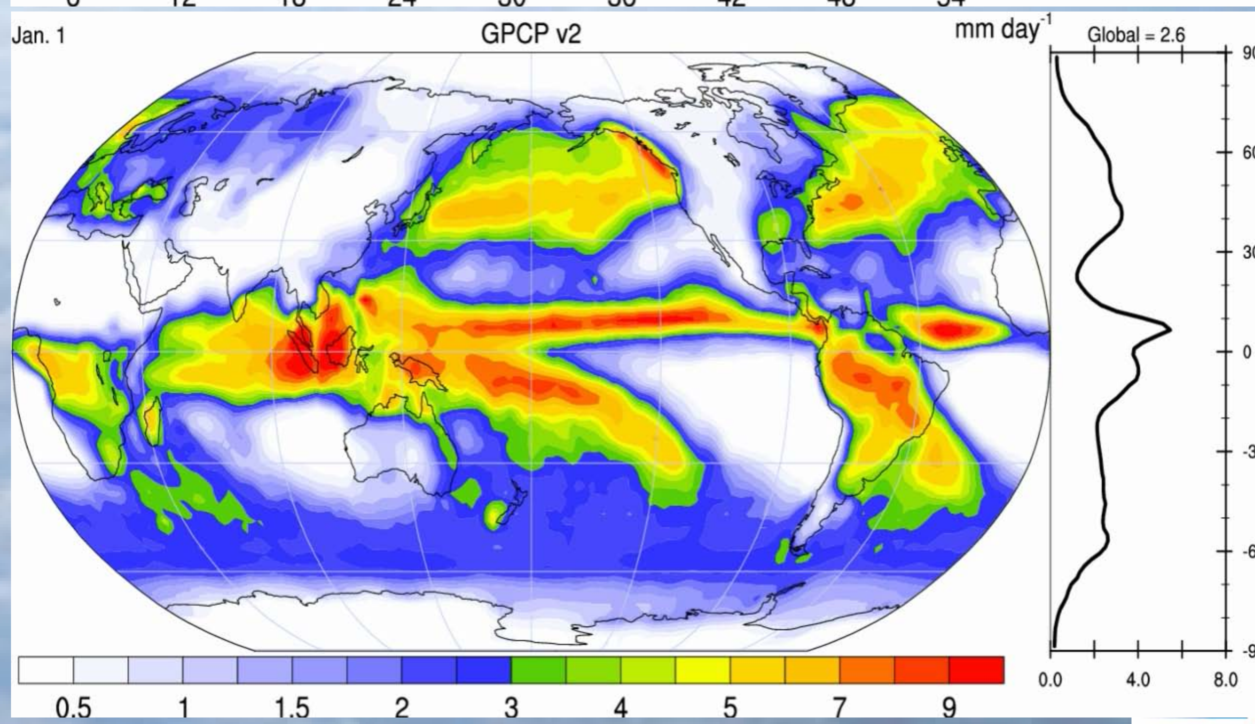


the first thing that happens is that the puddles dry up: before temperature increases.

Precipitable water



Precipitation



How should precipitation change as climate changes?

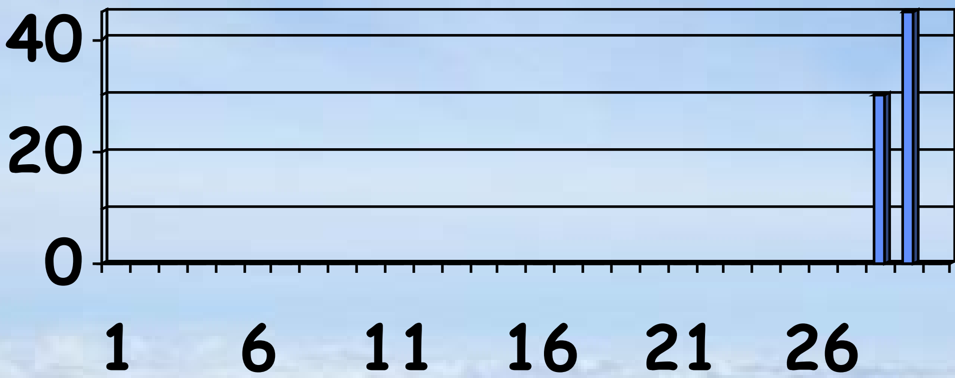
Usually only total **amount** is considered

- 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



drought
wilting plants

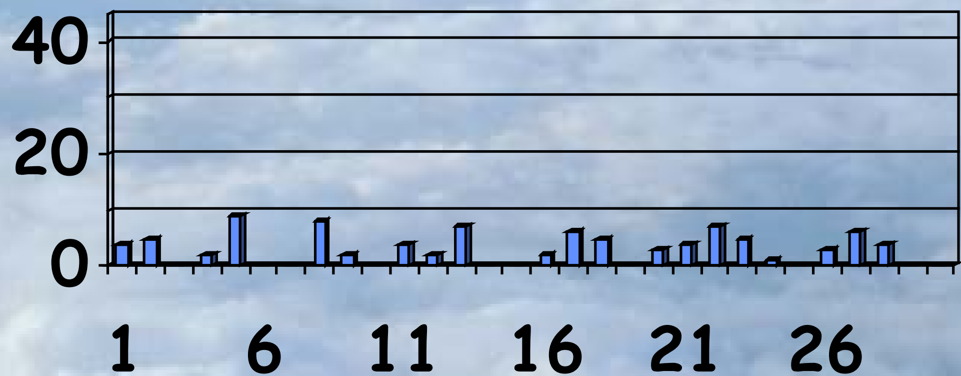
wild fires

local
floods

Monthly Amount 75 mm

Frequency 6.7%
Intensity 37.5 mm

B

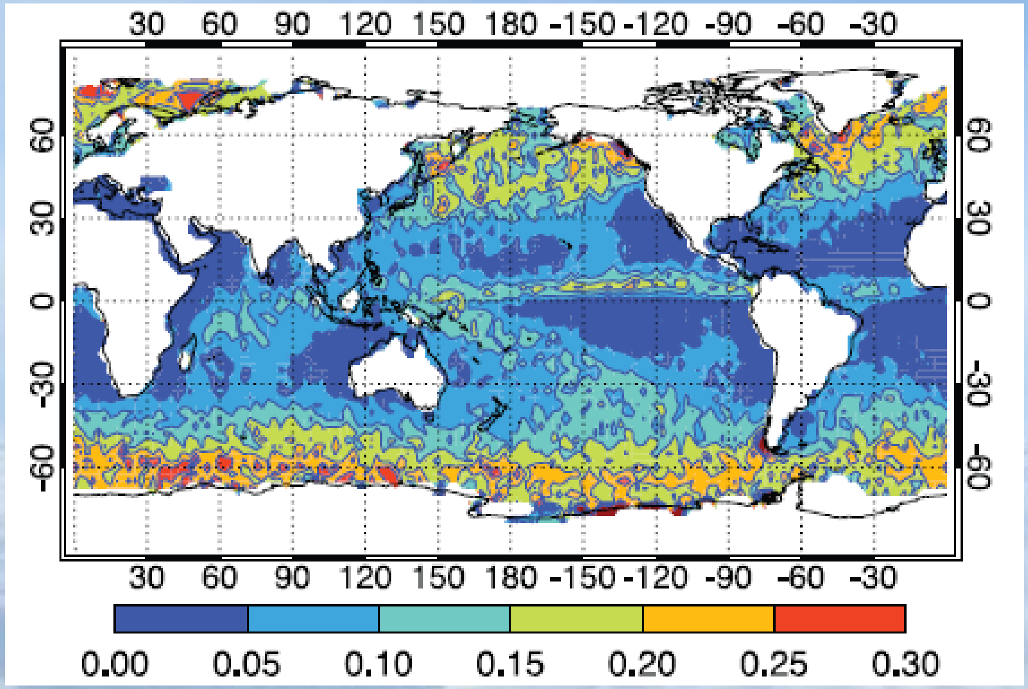


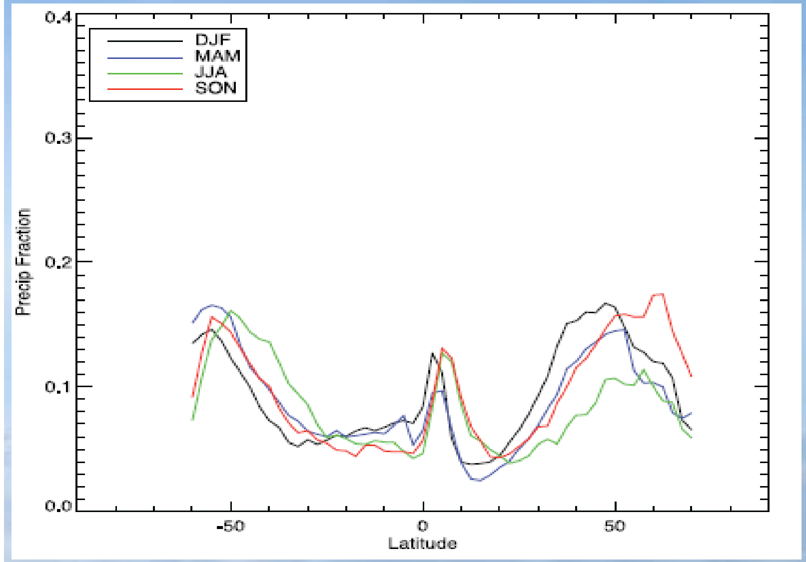
soil moisture replenished
virtually no runoff

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)

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**

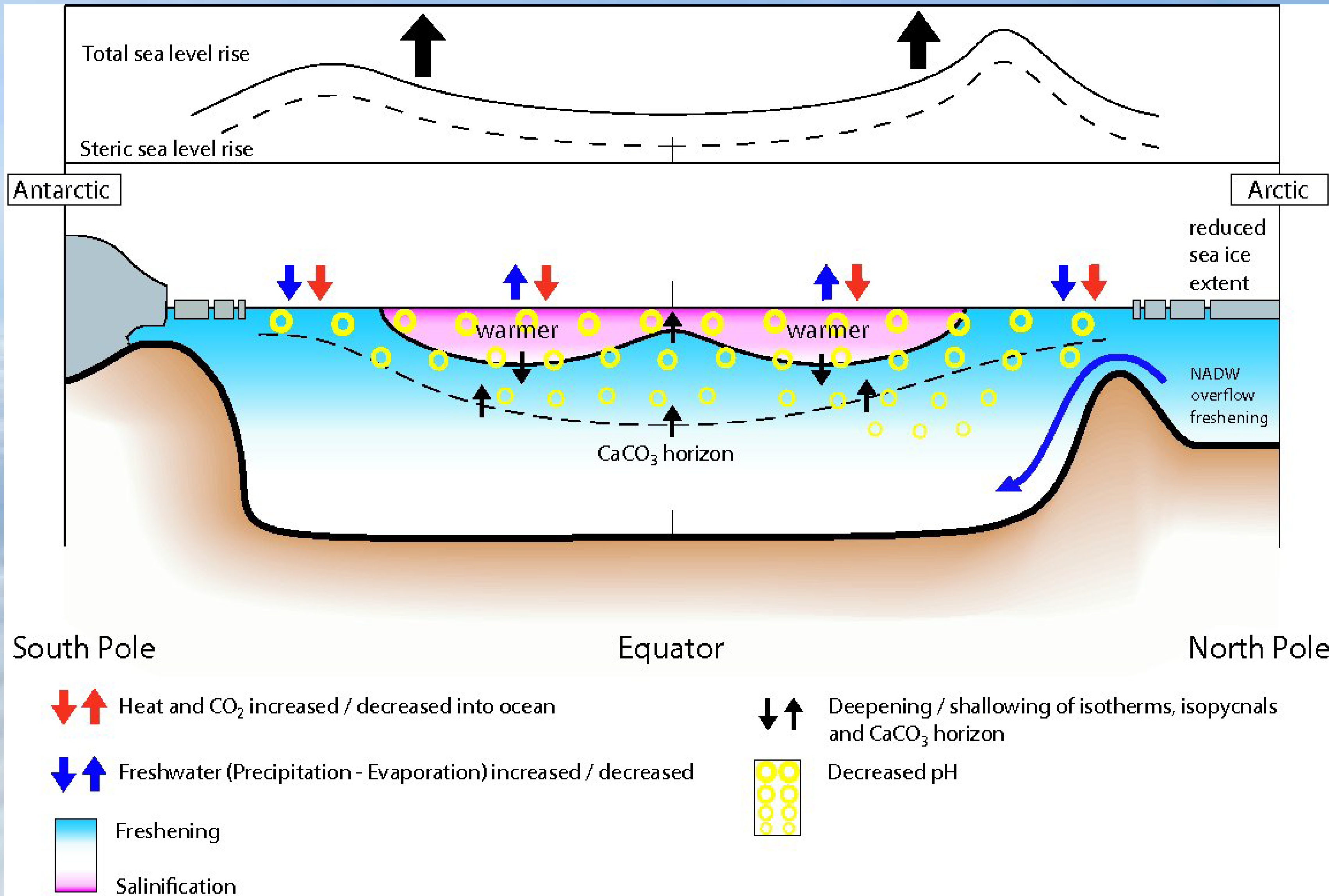
- Can not come from local column.
- Can not come from E.
- Hence has to come from transport by storm-scale circulation into storm.

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.

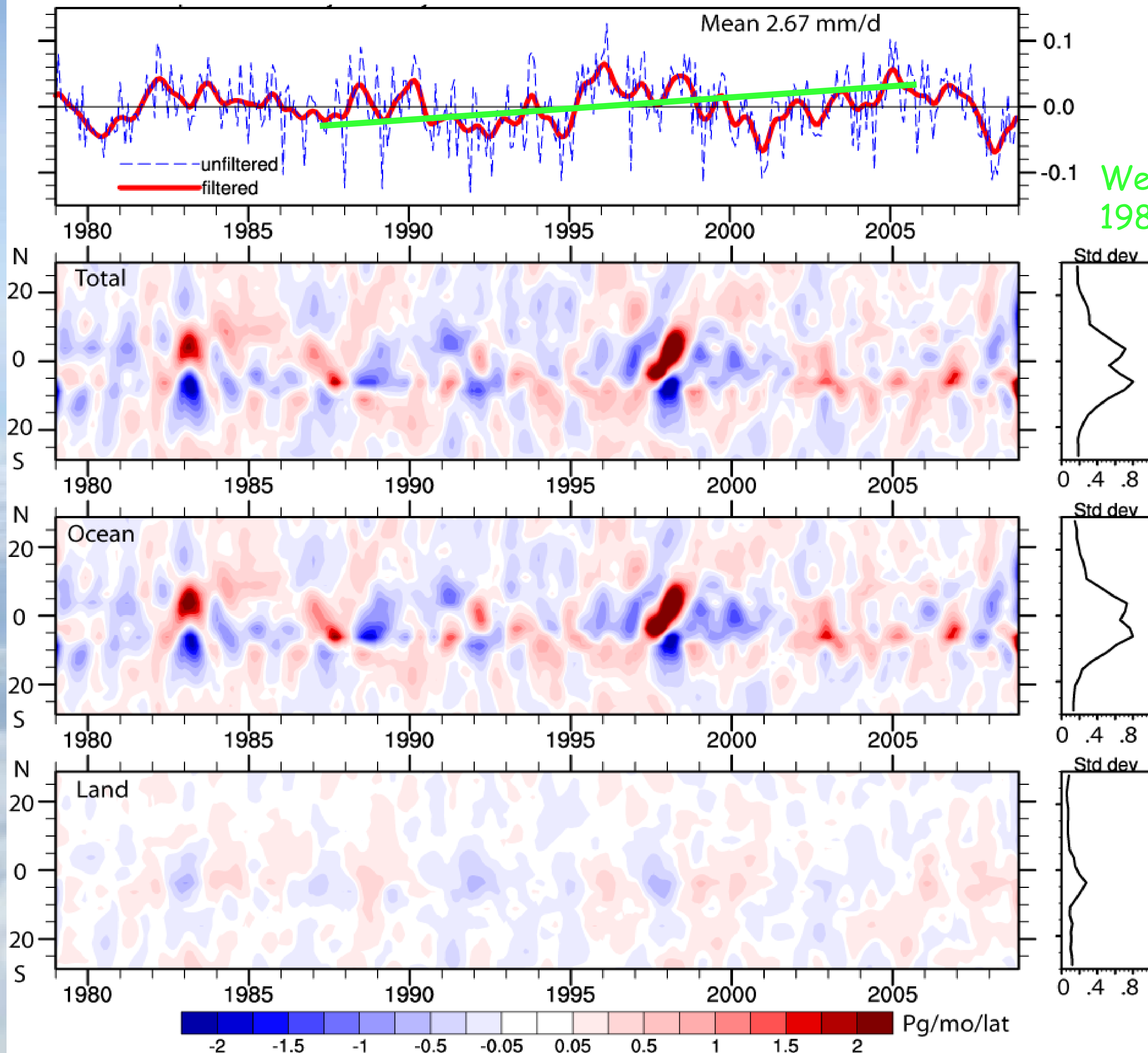
How is precipitation changing?

Changes in ocean state

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

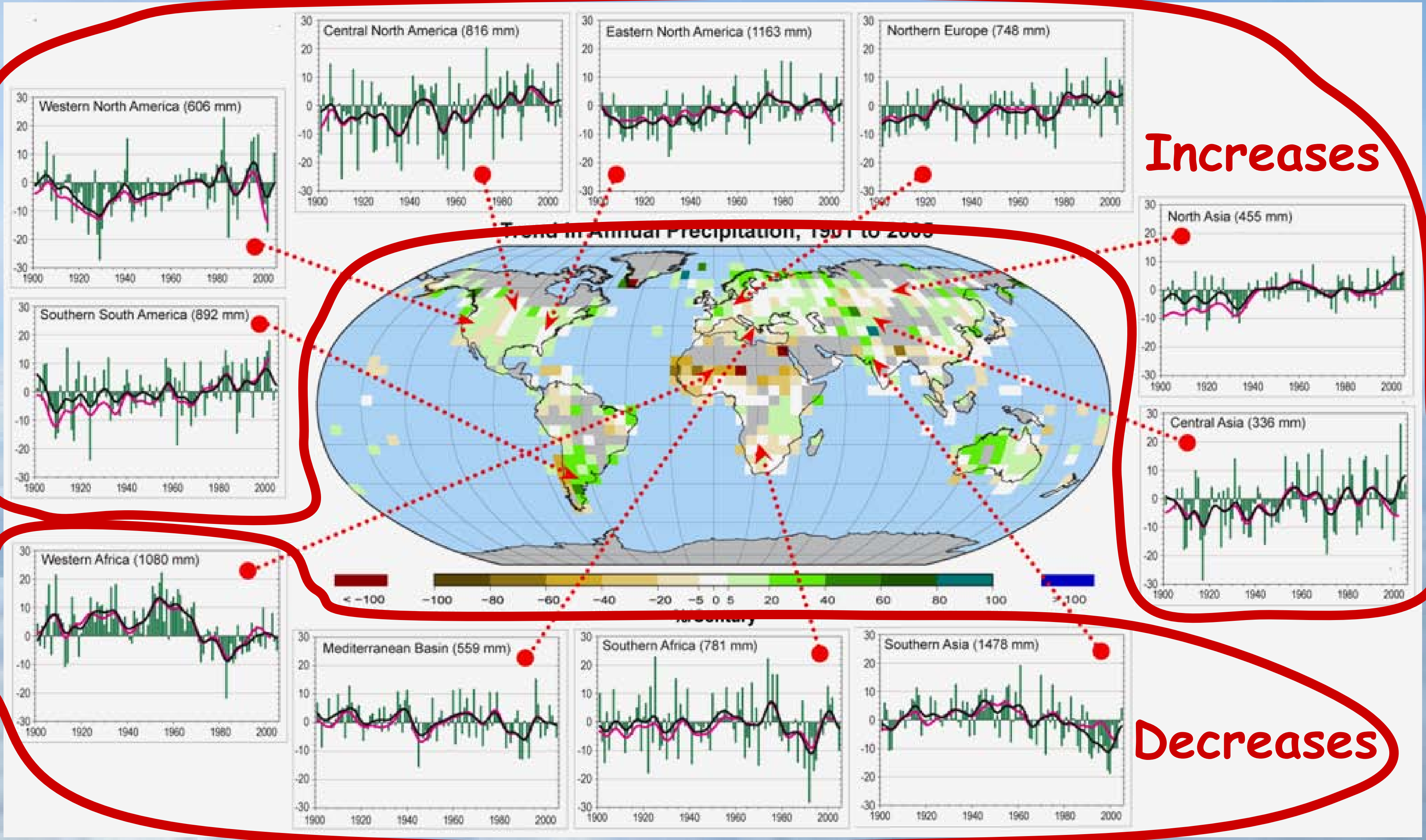


GPCP Global precipitation 1979-2008



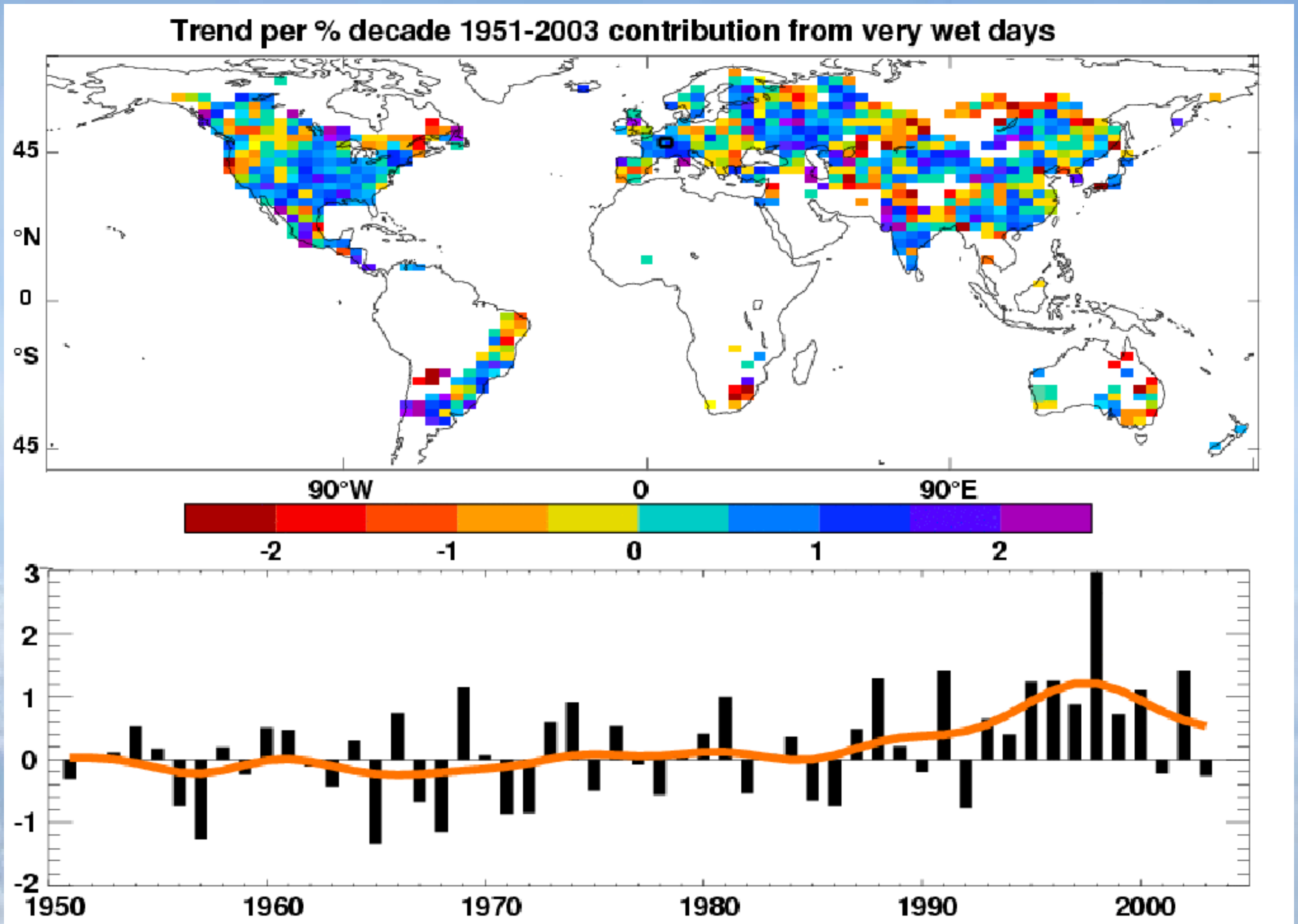
Wentz 2007:
1987-2006

Land 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



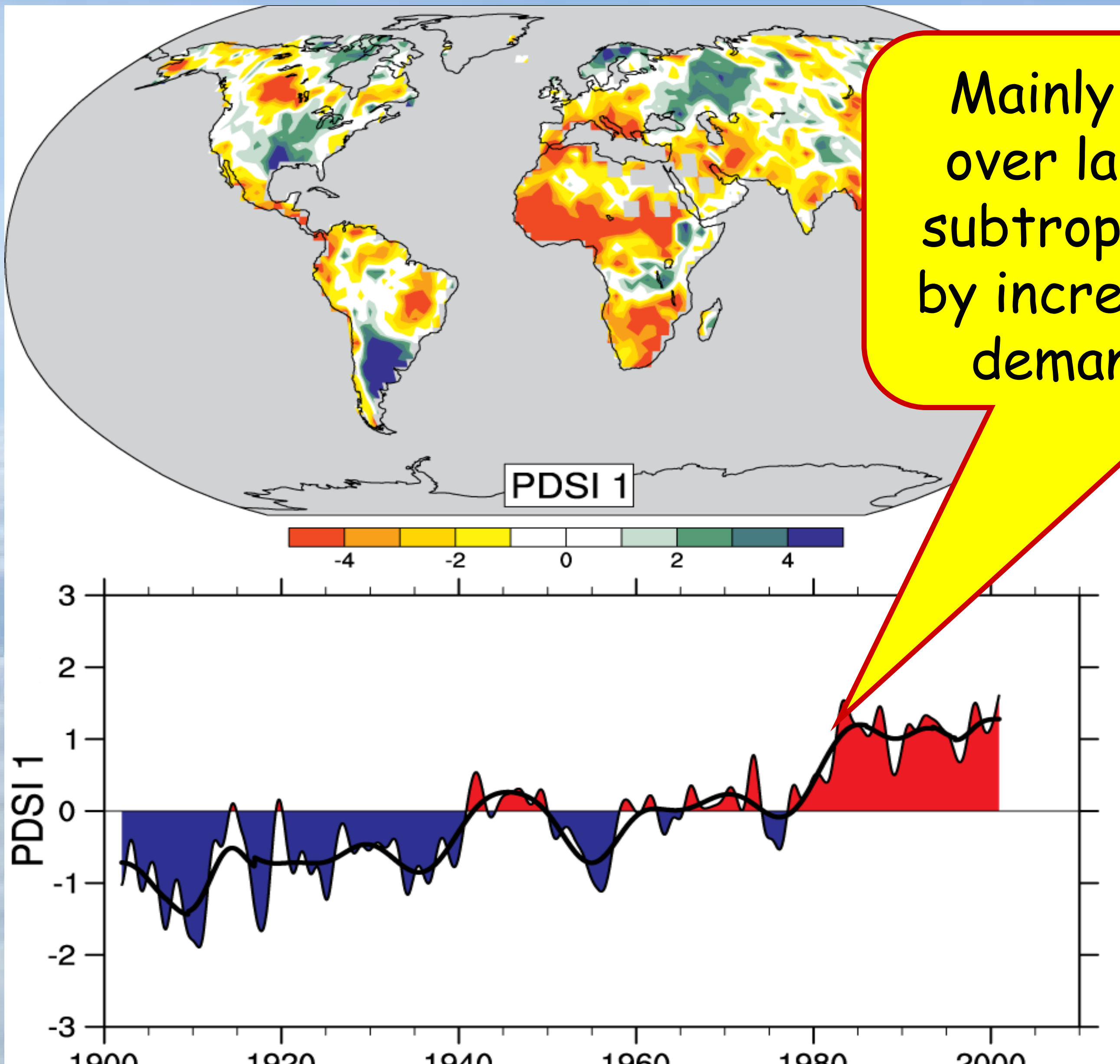
Precipitation

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.

Drought is increasing most places



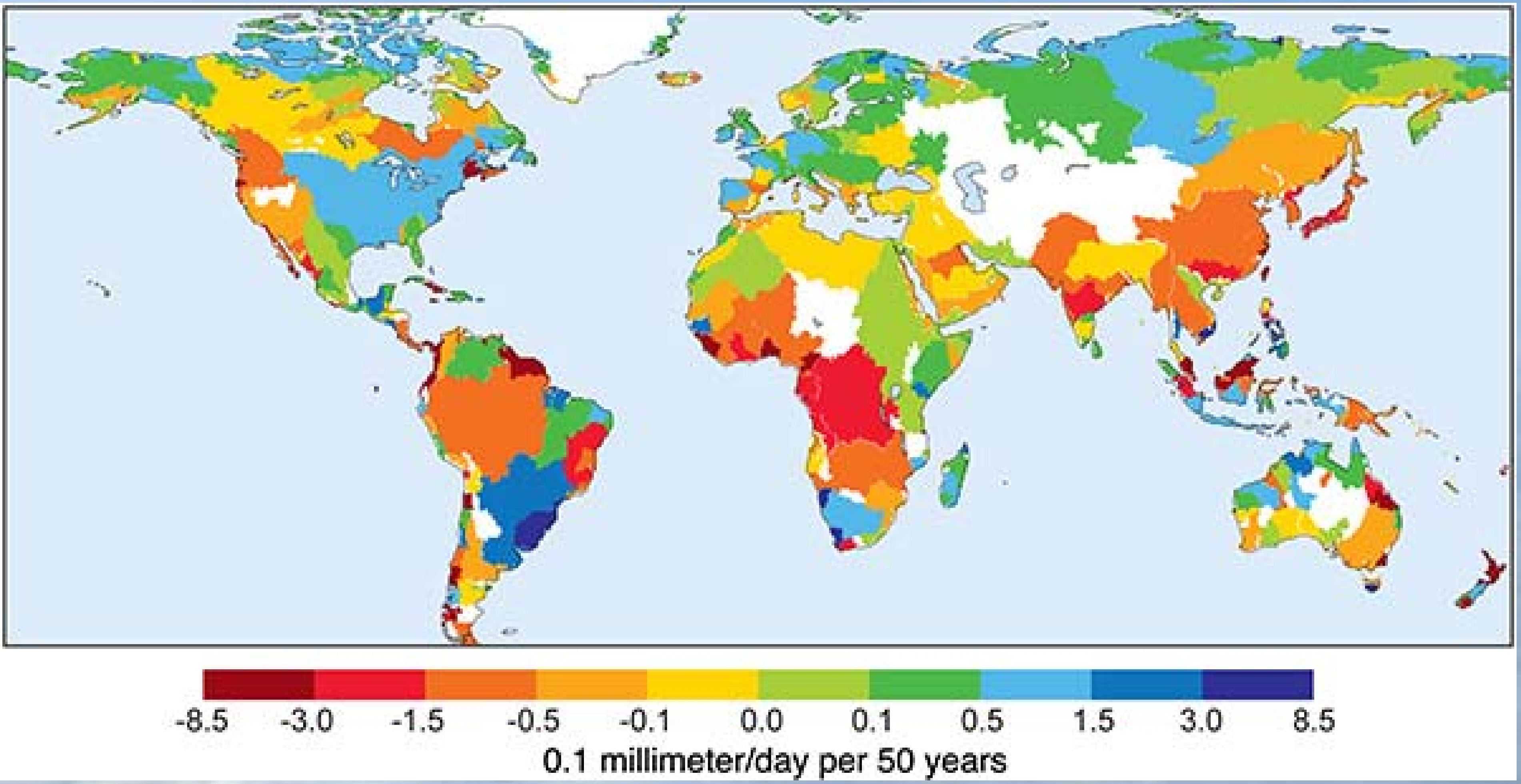
Mainly decrease in rain over land in tropics and subtropics, but enhanced by increased atmospheric demand with warming

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

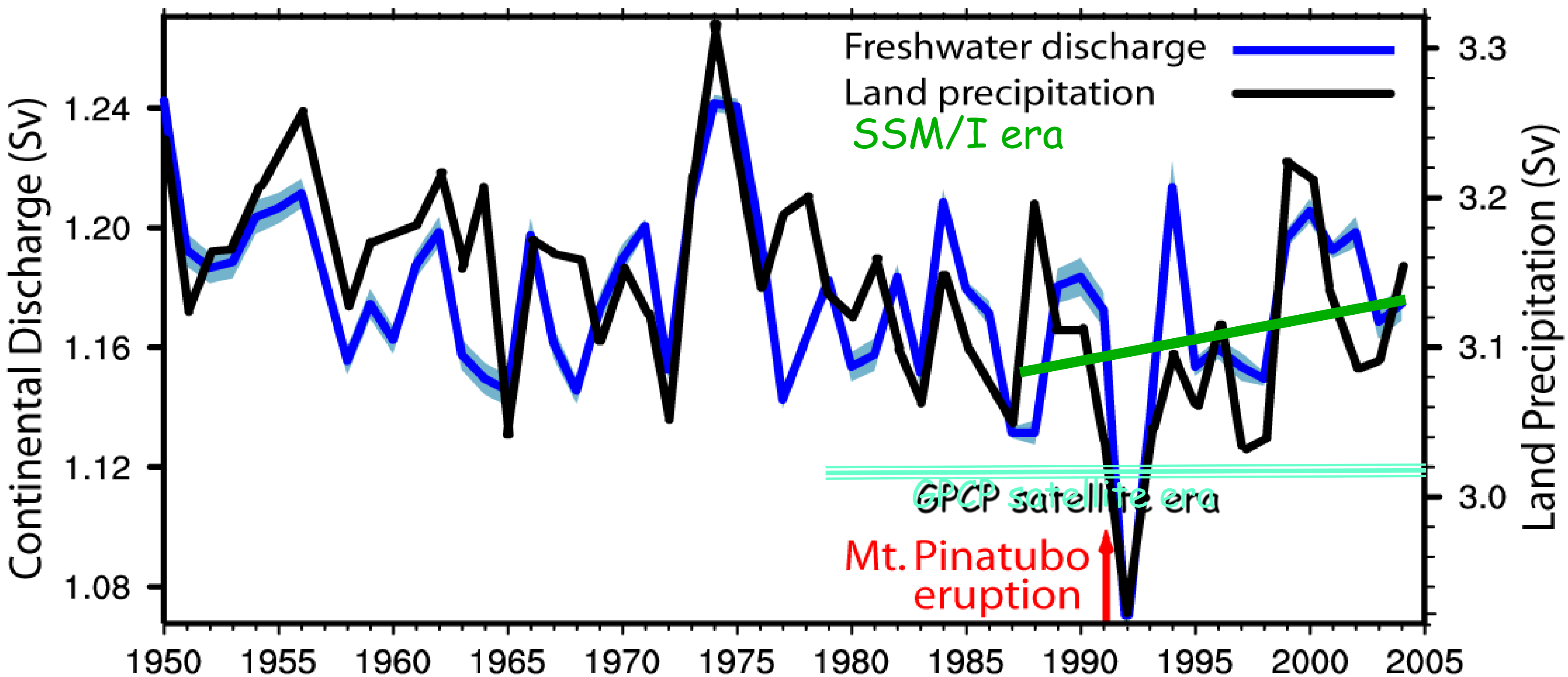
Trends 1948-2004 in runoff by river basin



Based on river discharge into ocean

Dai et al.2009

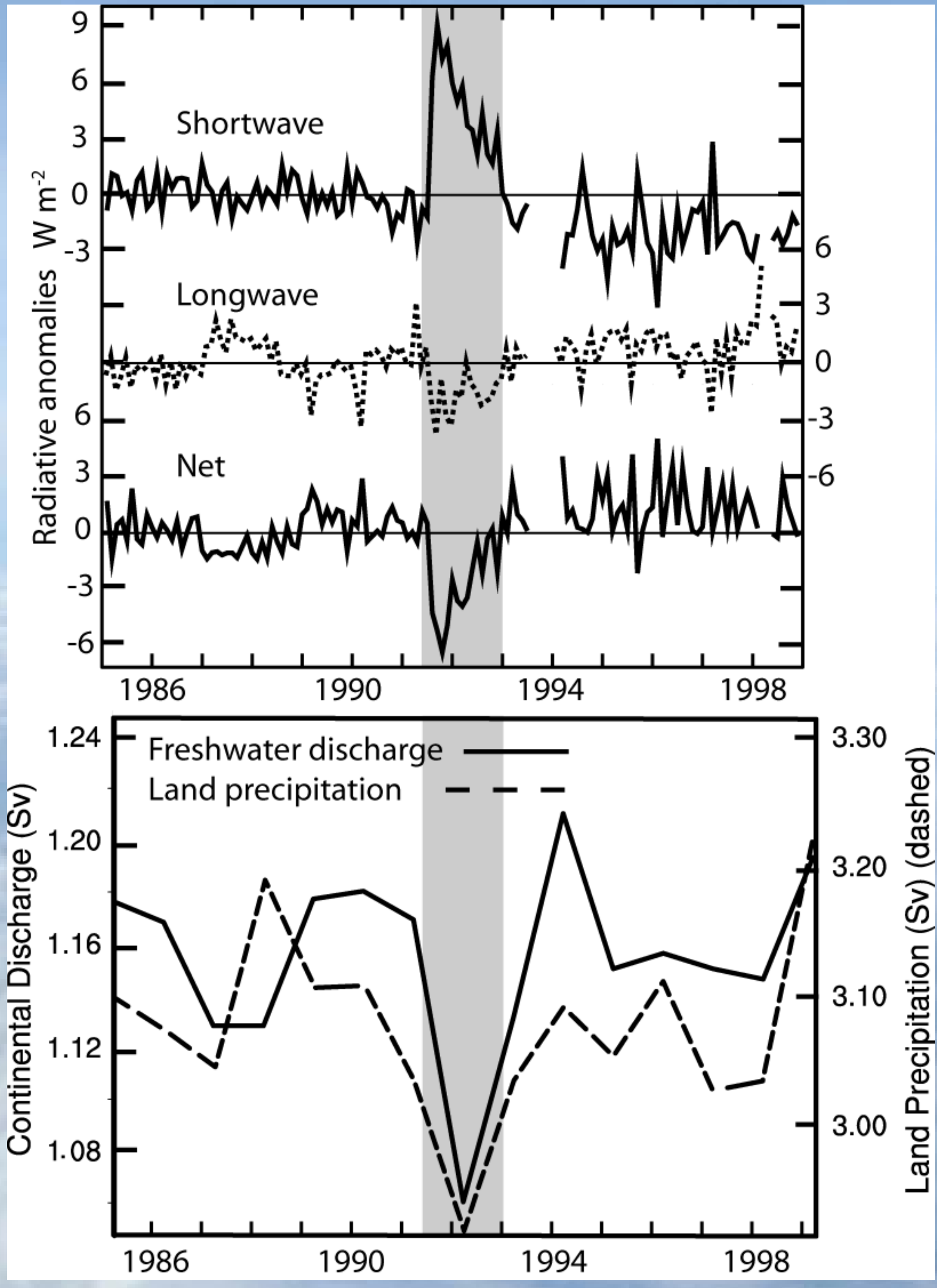
Pinatubo Effect on Hydrological Cycle



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



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.

Trenberth and Dai 2007

Geoengineering:

One proposed solution to global warming:

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

Geoengineering

Indications are that

1) climate models over-estimate the cooling with volcanoes (overestimate the benefits)
2) Climate models under-estimate the changes in precipitation and the hydrological cycle (underestimate the bad side effects)
3) Costs are high and go on forever
4) There is not an adequate observing system to tell if the effects are doing what they are supposed to, or saying just what is happening.
5) Holding out false hope of a magic pill solution works against taking seriously needed actions.
6) Who is to make decisions for all of humanity when there are potentially bad side effects that hurt some more than others? (Ethical issues)

NCAR

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!

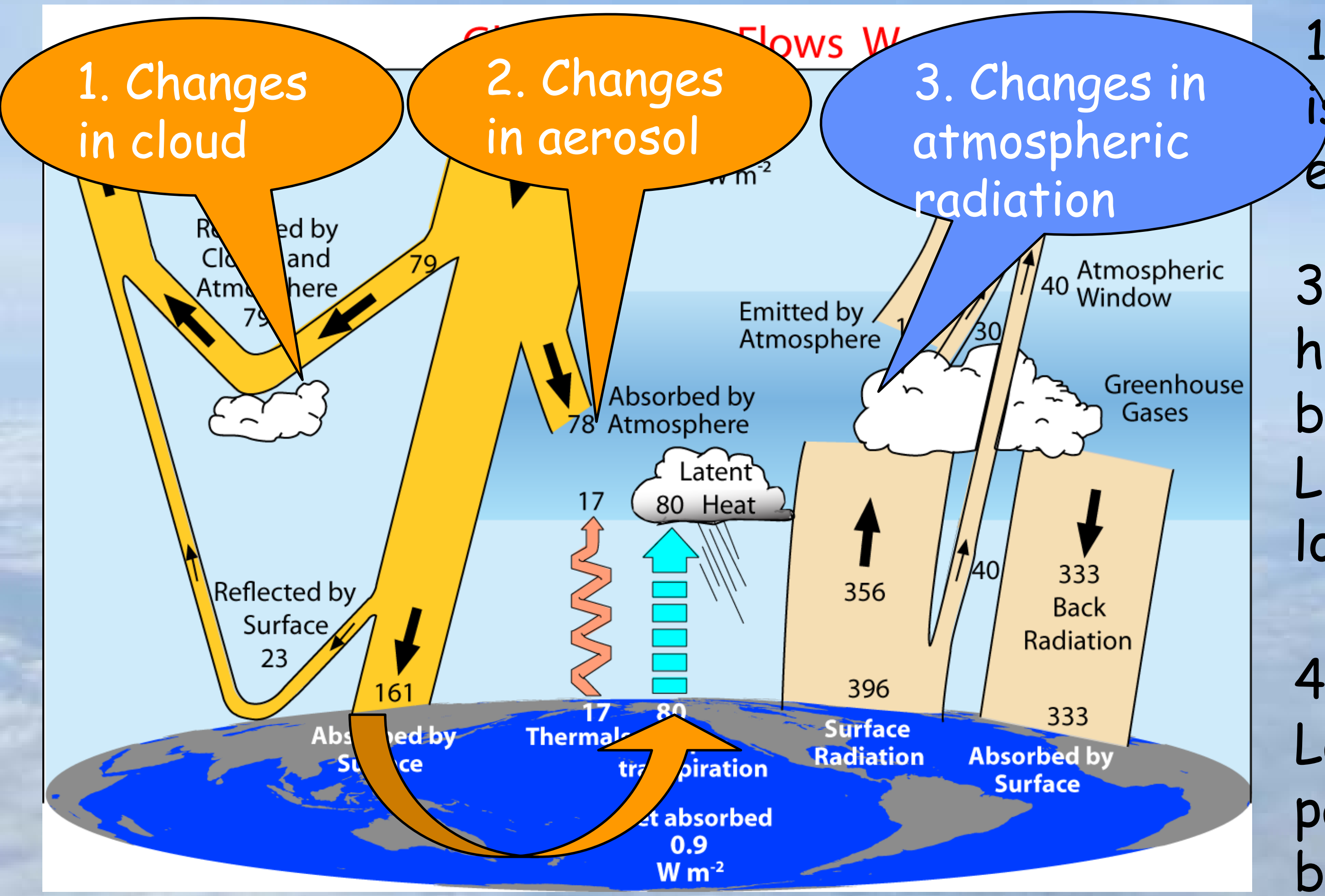
Factors in Changes in Precipitation

It never rains but it pours!

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.

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

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

Aerosol indirect effects

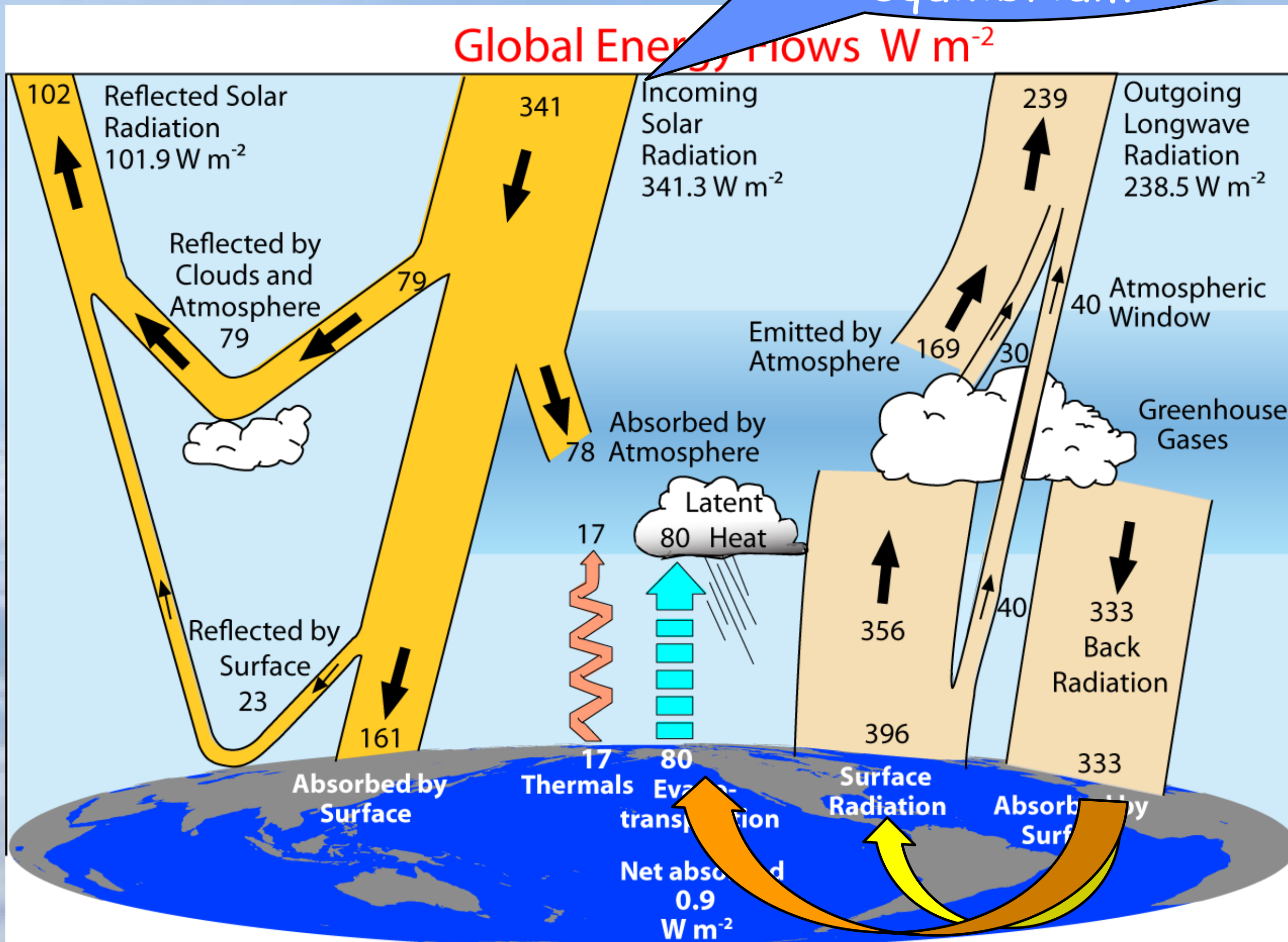
Table 1. Overview of the different aerosol indirect effects and range of the radiative budget perturbation at the top-of-the atmosphere (F_{TOA}) [W m^{-2}], at the surface (F_{SFC}) and the likely sign of the change in global mean surface precipitation (P) as estimated from Fig. 2 and from the literature cited in the text.

Effect	Cloud type	Description	F_{TOA}	F_{SFC}	P
Indirect aerosol effect for clouds with fixed water amounts (cloud albedo or Twomey effect)	All clouds	The more numerous smaller cloud particles reflect more solar radiation	−0.5 to −1.9	similar to F_{TOA}	n/a
Indirect aerosol effect with varying water amounts (cloud lifetime effect)	All clouds	Smaller cloud particles decrease the precipitation efficiency thereby prolonging cloud lifetime	−0.3 to −1.4	similar to F_{TOA}	decrease
Semi-direct effect	All clouds	Absorption of solar radiation by soot may cause evaporation of cloud particles	+0.1 to −0.5	larger than F_{TOA}	decrease
Thermodynamic effect	Mixed-phase clouds	Smaller cloud droplets delay the onset of freezing	?	?	increase or decrease
Glaciation indirect effect	Mixed-phase clouds	More ice nuclei increase the precipitation efficiency	?	?	increase
Riming indirect effect	Mixed-phase clouds	Smaller cloud droplets decrease the riming efficiency	?	?	decrease
Surface energy budget effect	All clouds	Increased aerosol and cloud optical thickness decrease the net surface solar radiation	n/a	−1.8 to −4	decrease

Lohmann and Feichter 2005

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

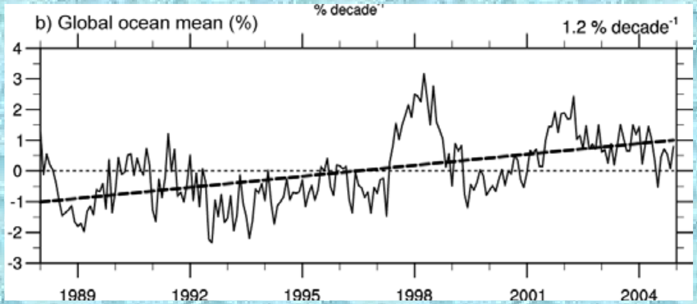
Air holds more water vapor at higher temperatures

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.

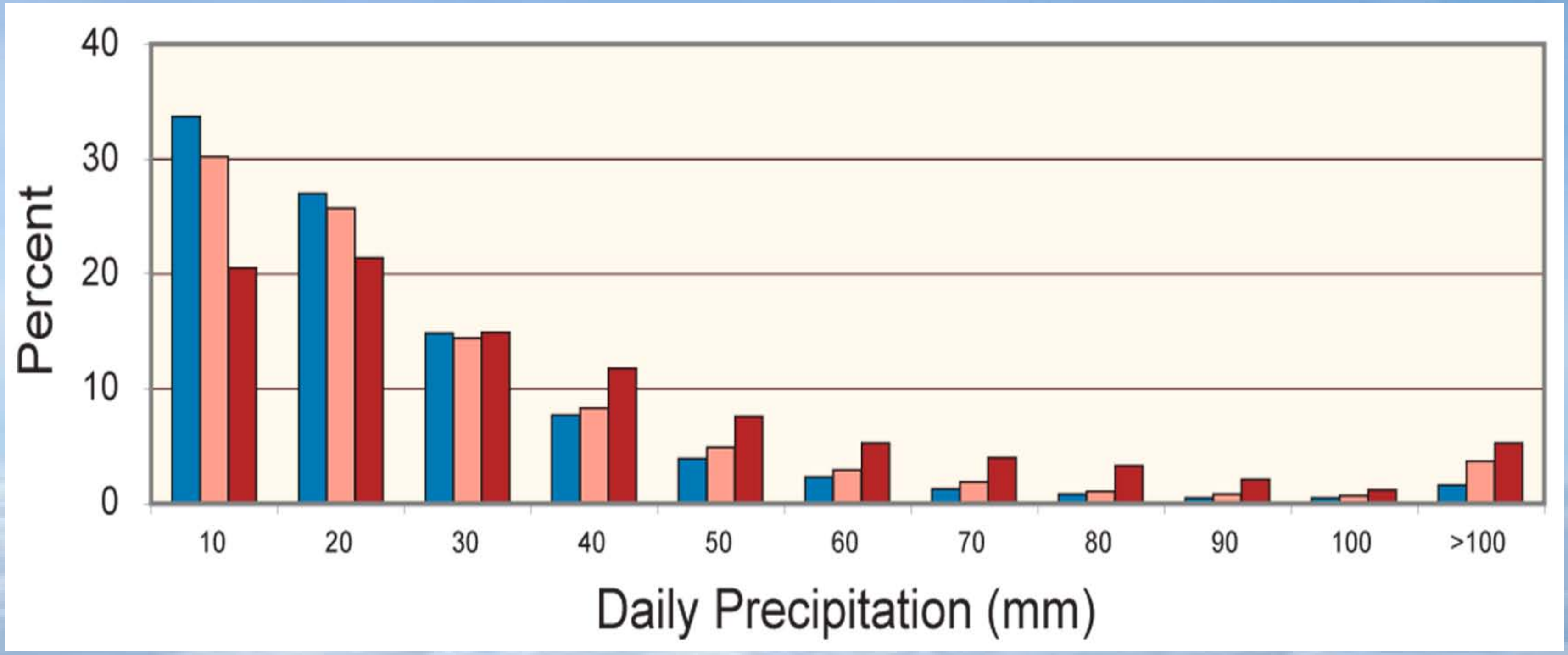
Total water vapor



More intense rains (or snow) but longer dry spells

Trenberth et al 2003

Higher temperatures: heavier precipitation

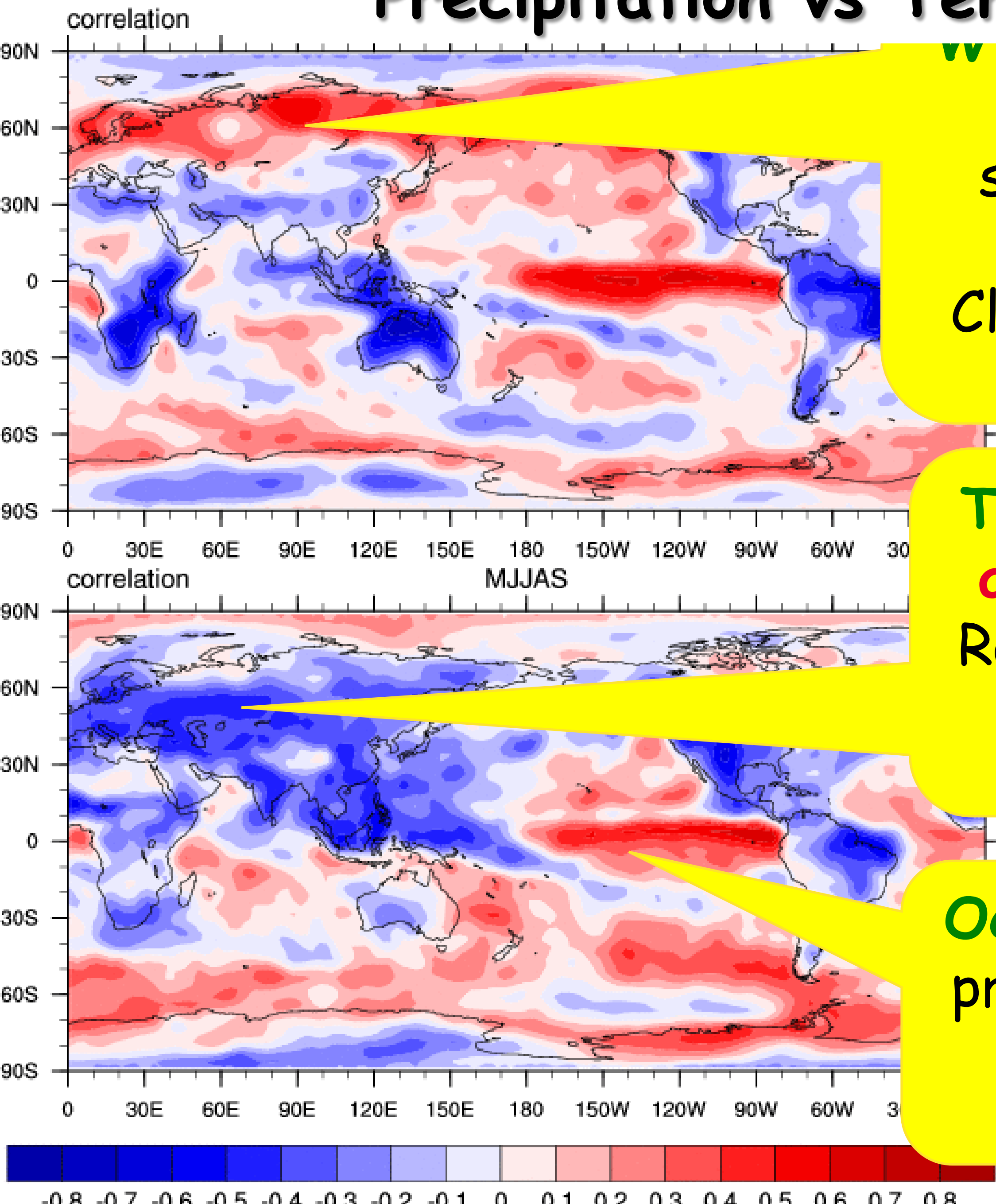


Percent of total seasonal precipitation for stations with 230mm±5mm falling into 10mm daily intervals based on seasonal mean temperature. Blue bar -3°C to 19°C, pink bar 19°C to 29°C, dark red bar 29°C to 35°C, based on 51, 37 and 12 stations.

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

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

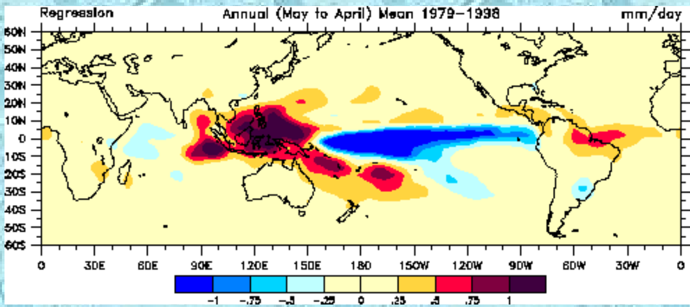
Does **not** apply to oceans

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.**
- "**Upped ante**" precip decreases on edges of convergence zones as it takes more instability to trigger convection. (Neelin, Chou)

How else should precipitation P change as the climate changes?

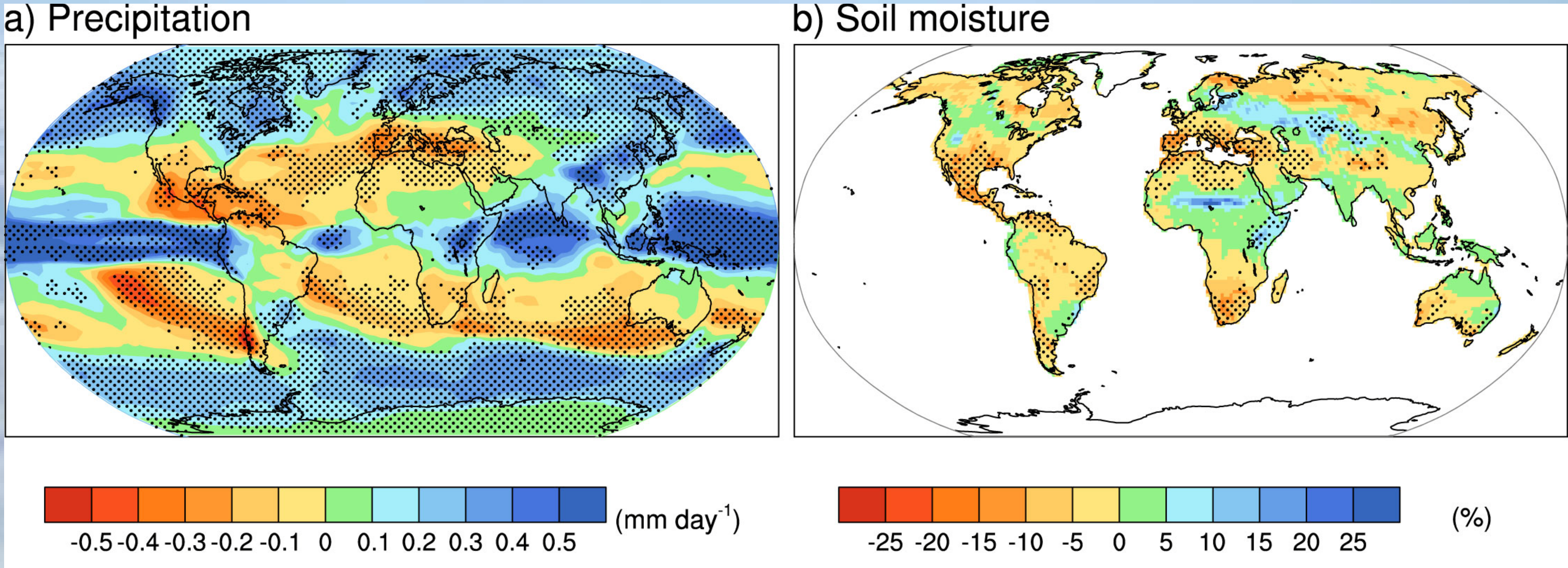
- "**More bang for the buck**": With increased moisture, the winds can be less to achieve the same transport. Hence the divergent circulation weakens. (Soden & Held)
- Changes in characteristics: **more intense less frequent rains** (Trenberth et al)



- 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

Model predictions
"Rich get richer, poor get poorer"

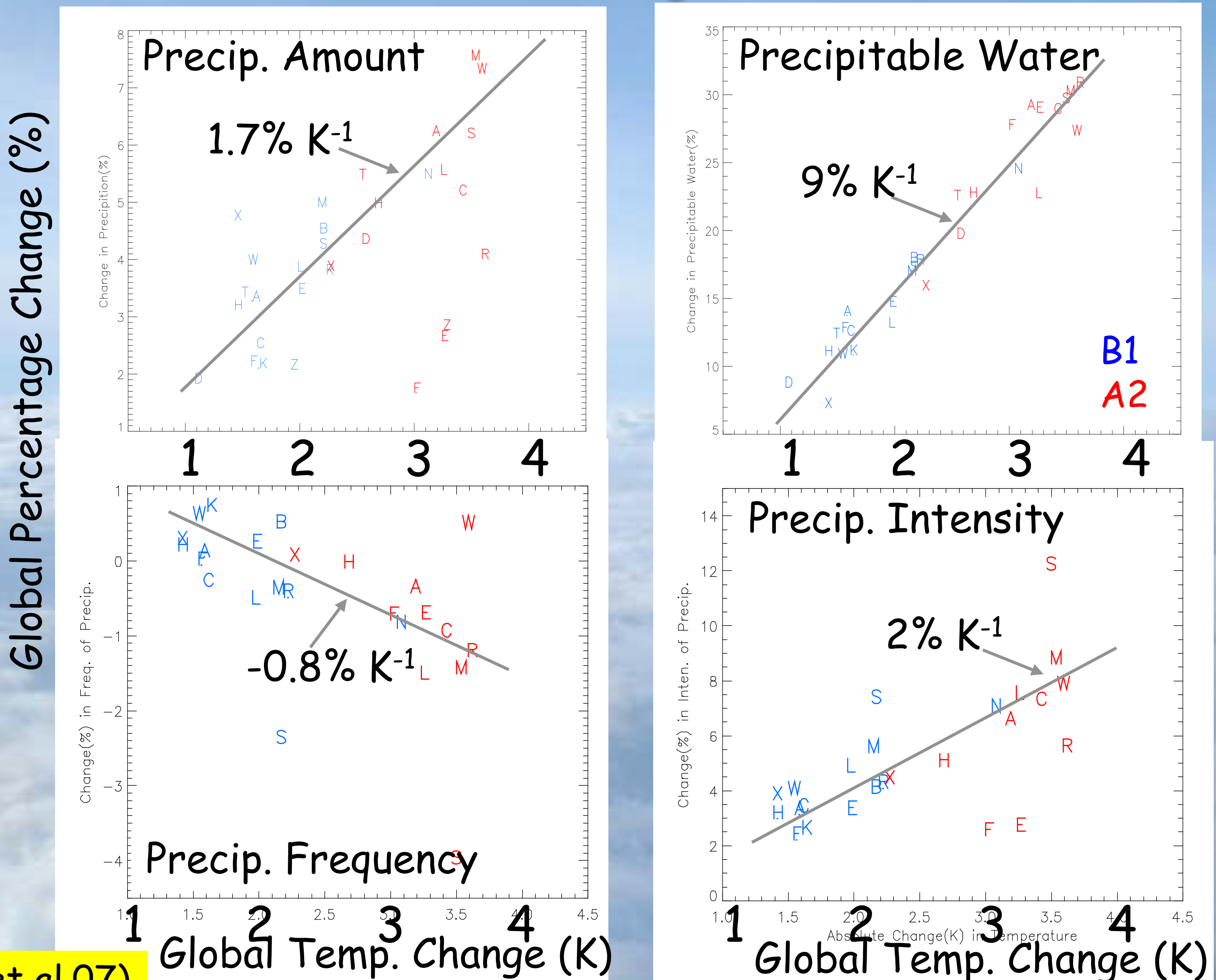
Projections: Combined effects of increased precipitation intensity and more dry days contribute to lower soil moisture



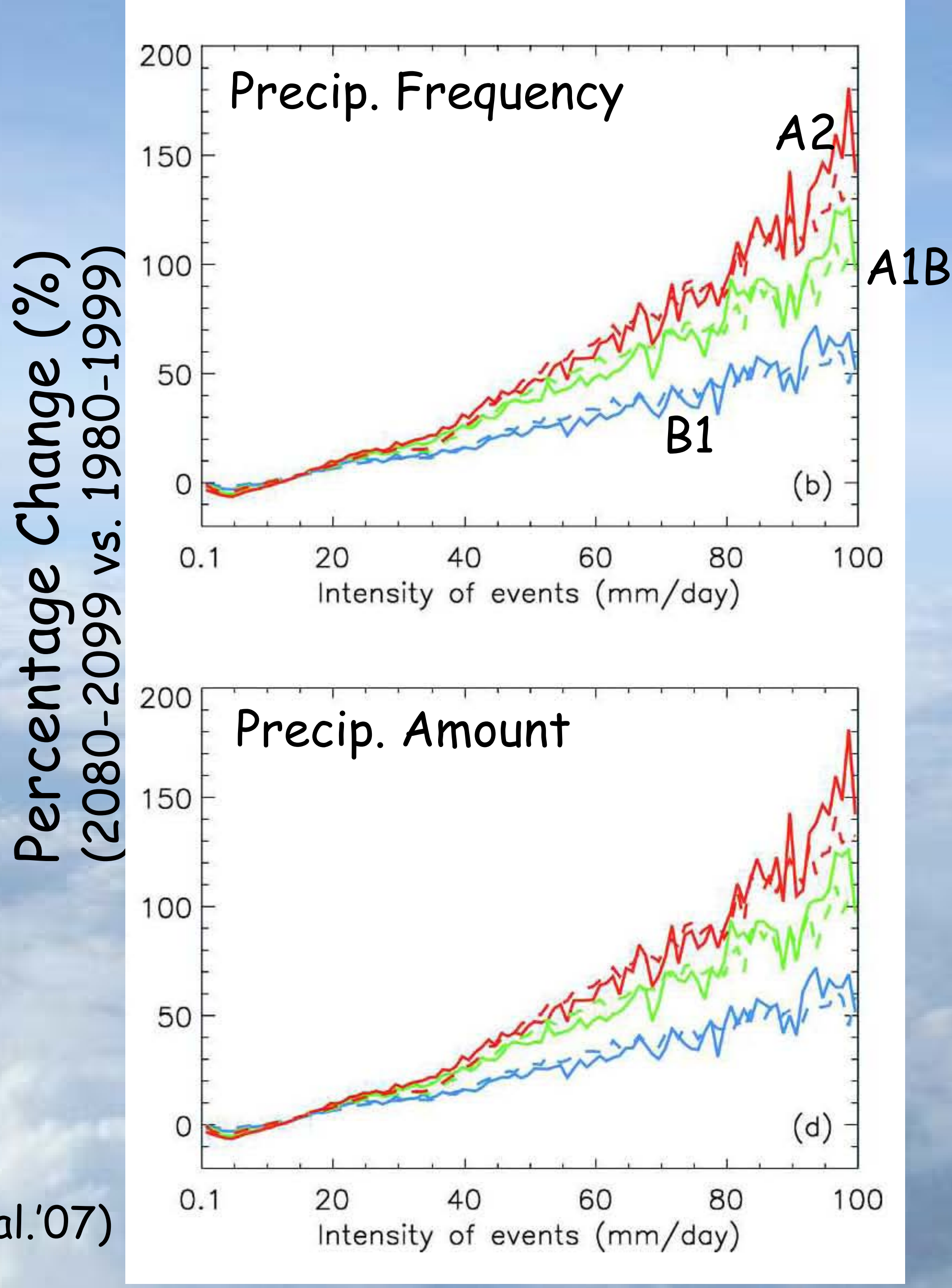
2090-2100

IPCC

IPCC AR4 Model Predicted Changes: 1980-99 vs. 2080-99



(Sun et al.07)



There is higher frequency of more intense events contributing to the total amount. The % change is over 100% for A1B and A2.

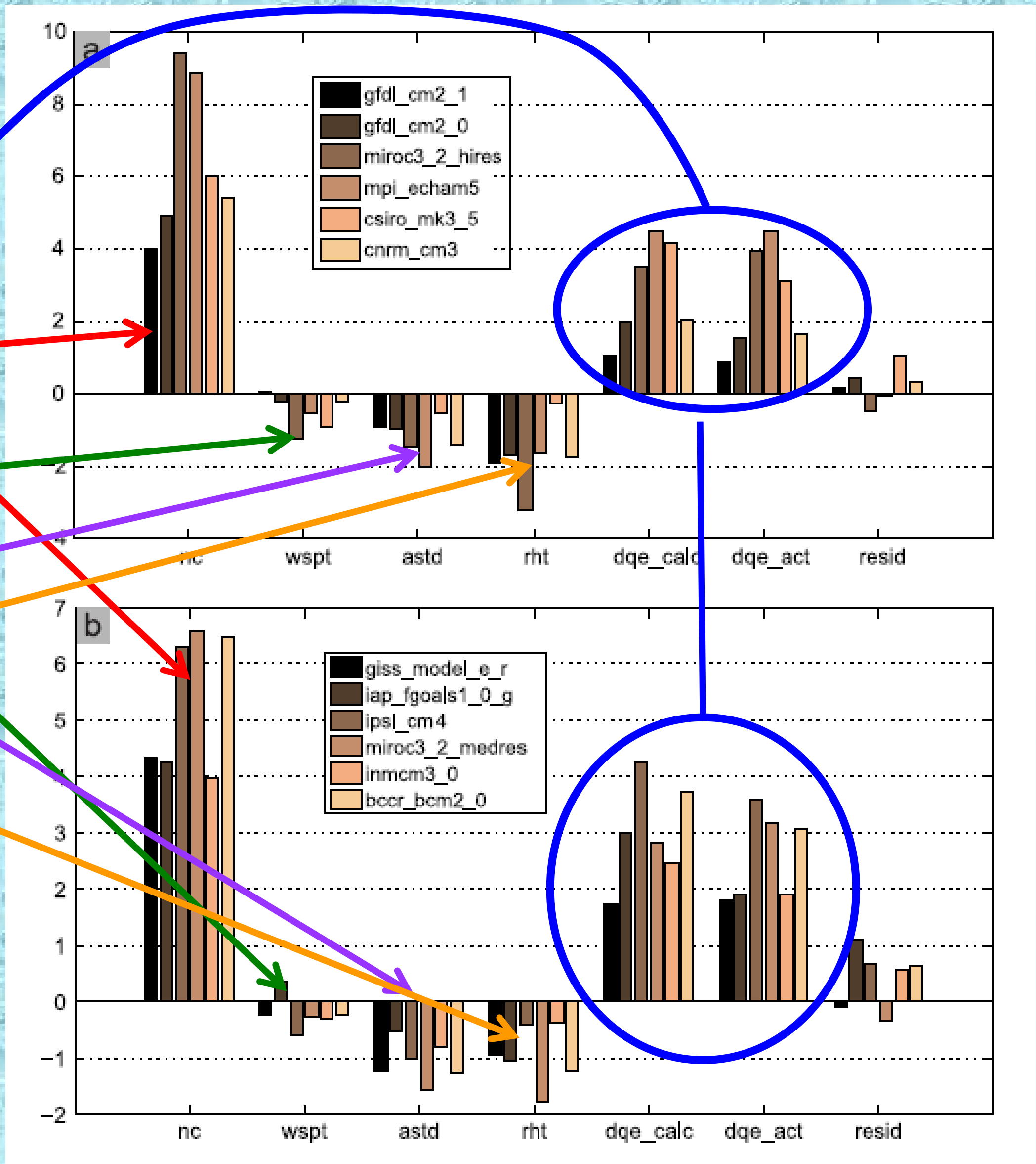
(Sun et al.'07)

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
Also: Trenberth 1998
Stephens and Ellis 2008
Allan and Ingram 2002



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

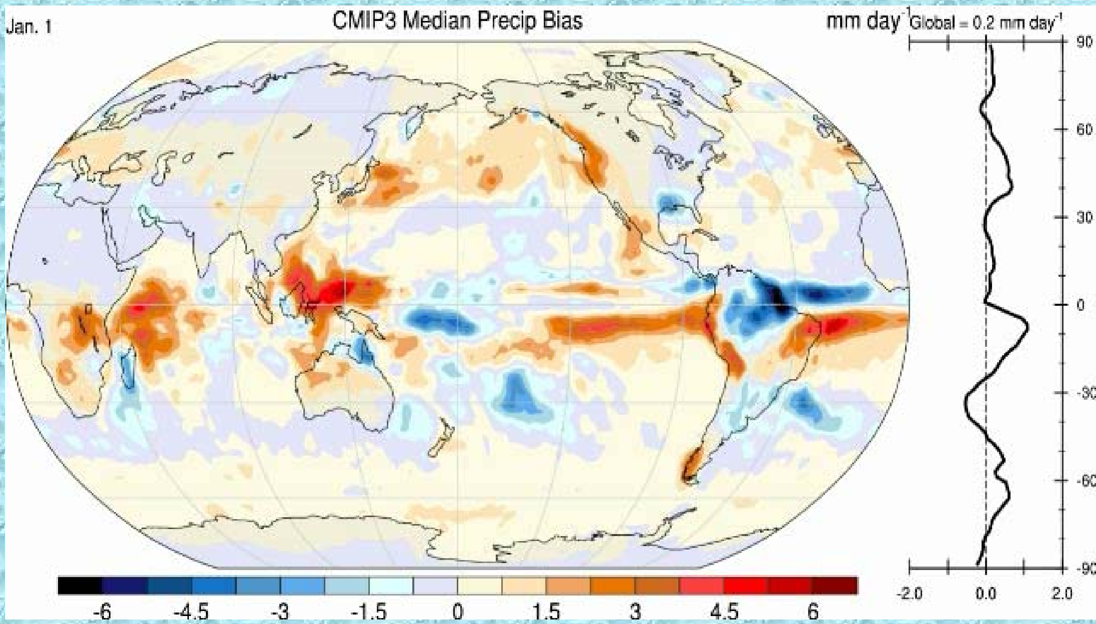
Recycling: too large

Diurnal cycle: poor

Lifetime: too short
(moisture)

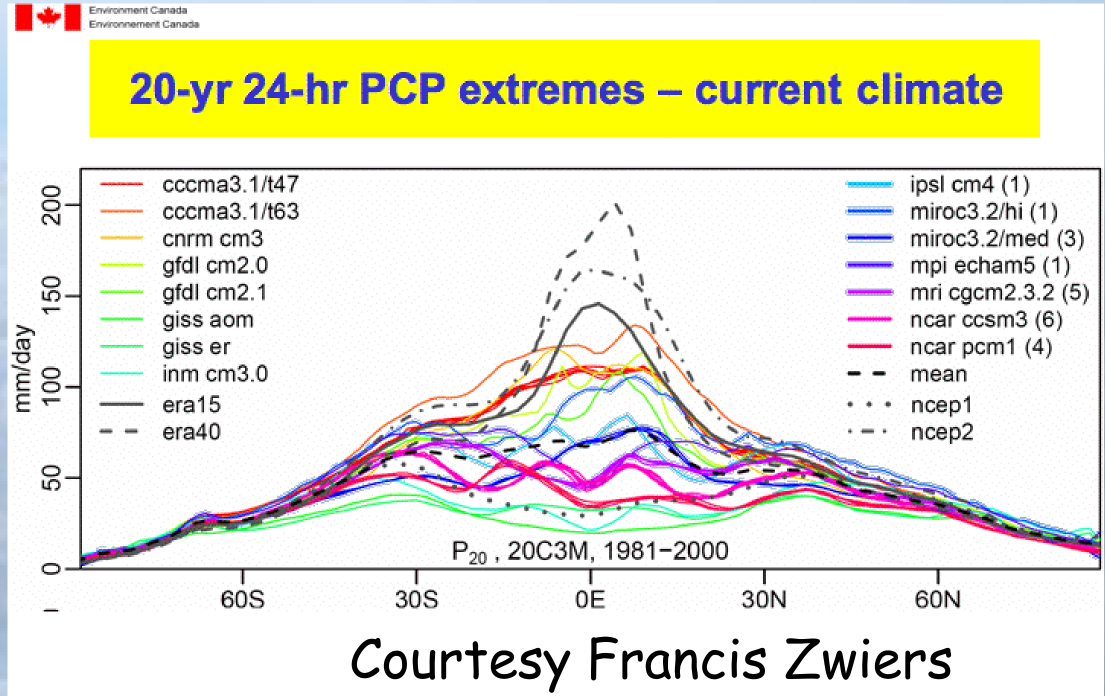
Issues:

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.

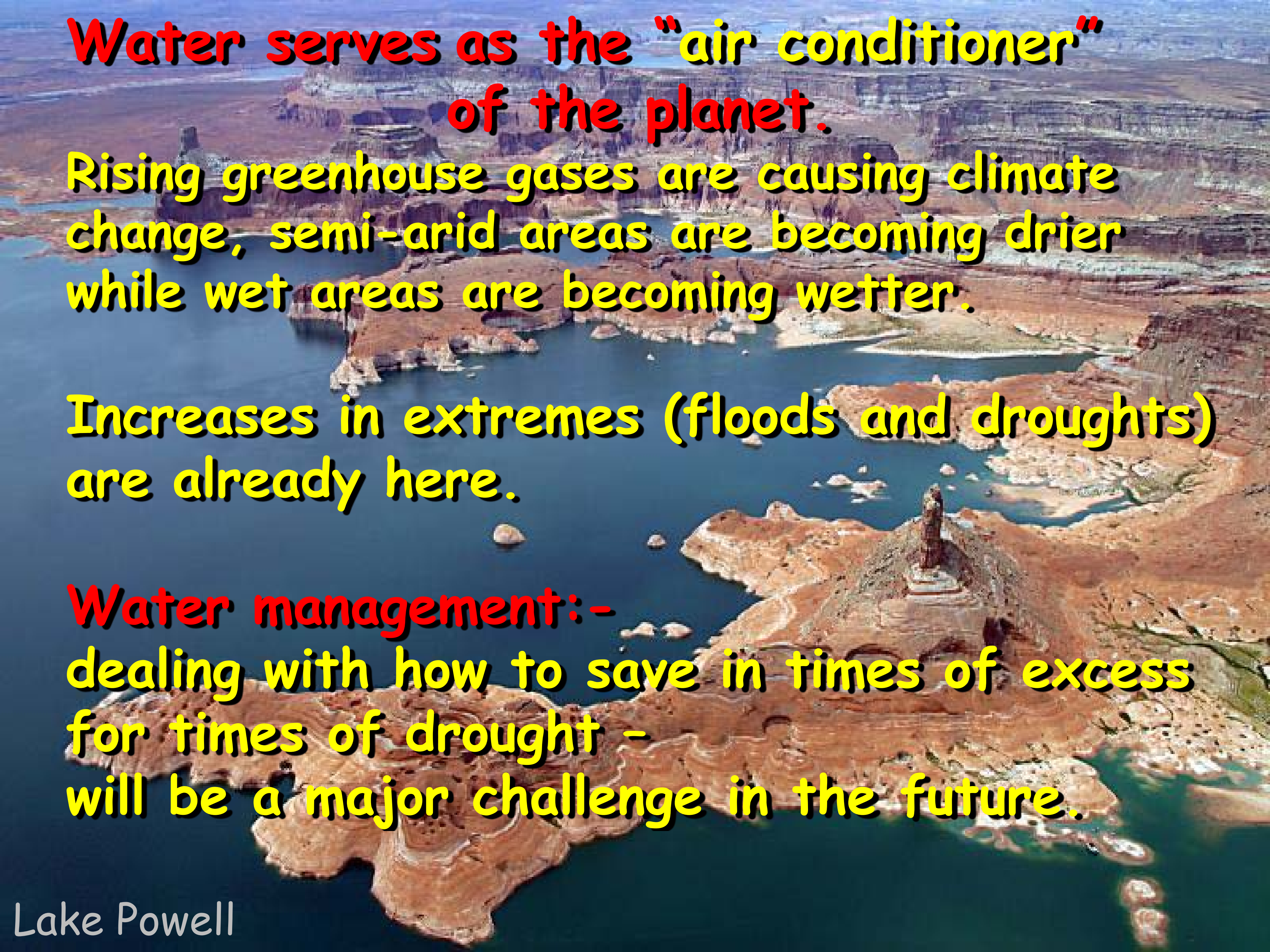


Water serves as the "air conditioner" of the planet.

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