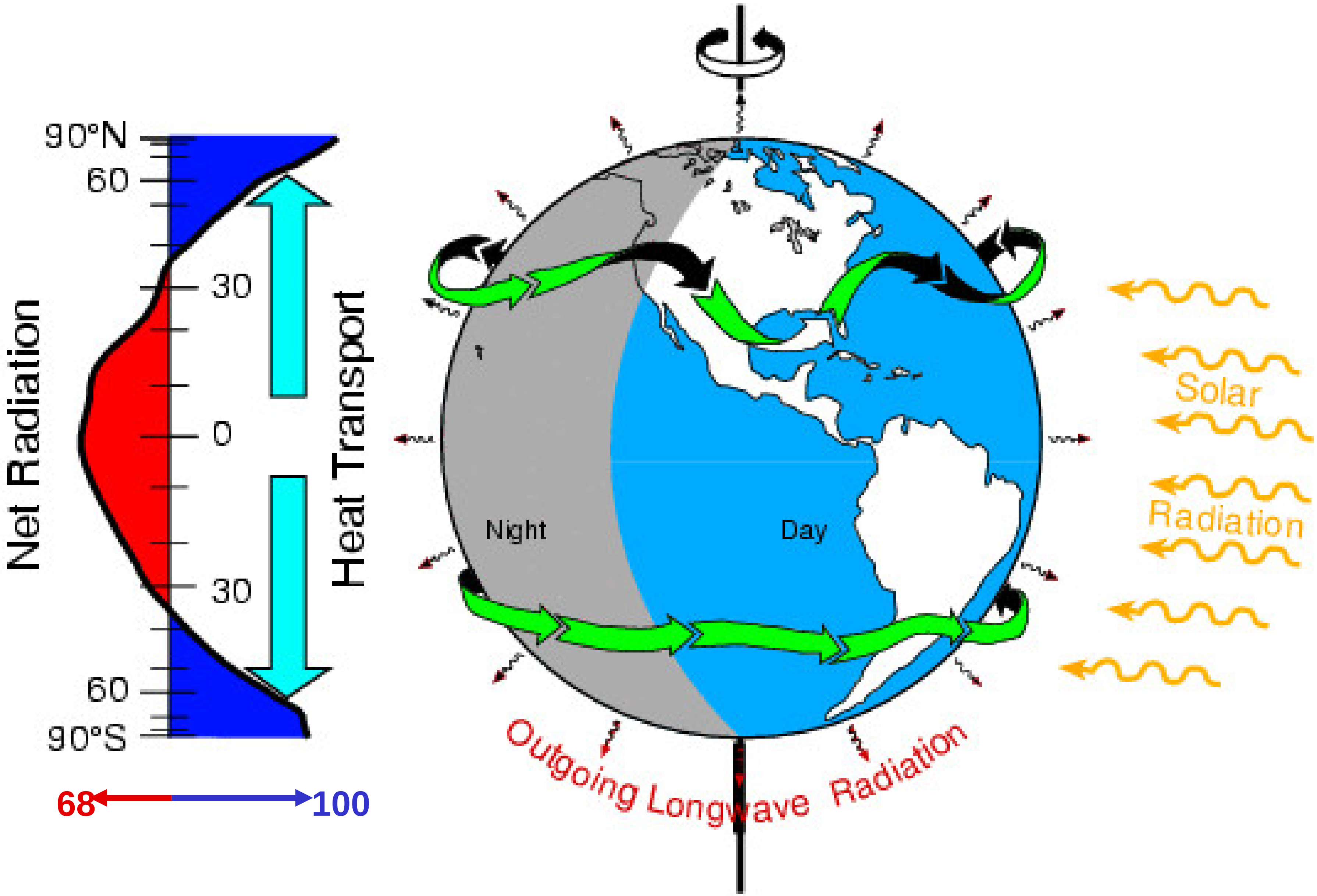
The Earth's Climate System: Variability and change

Kevin E. Trenberth
NCAR

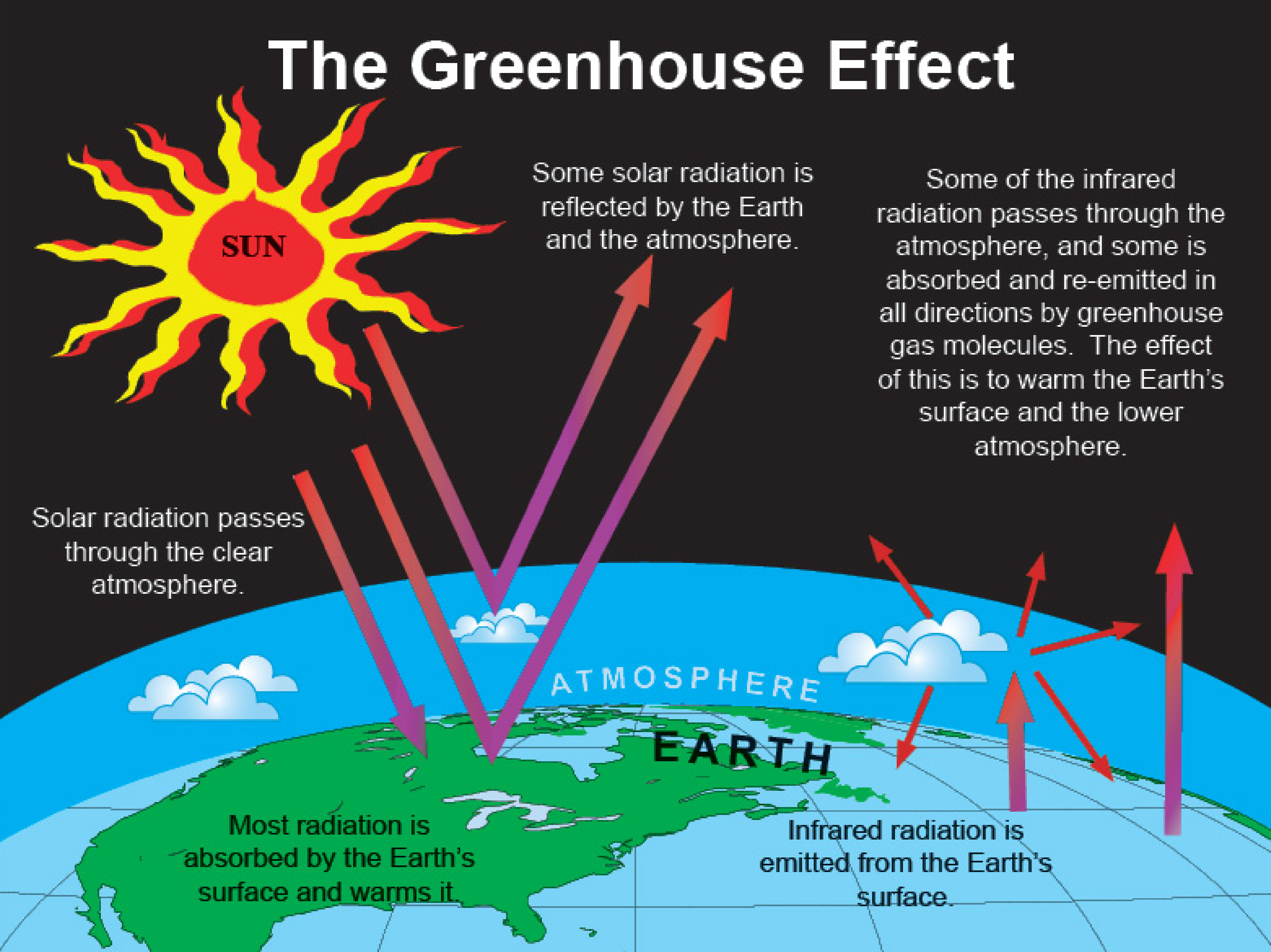


90°N
60
30
0
30
60
90°S
Net Radiation
Heat Transport
68
100
Night
Day
Solar
Radiation
Outgoing Longwave Radiation

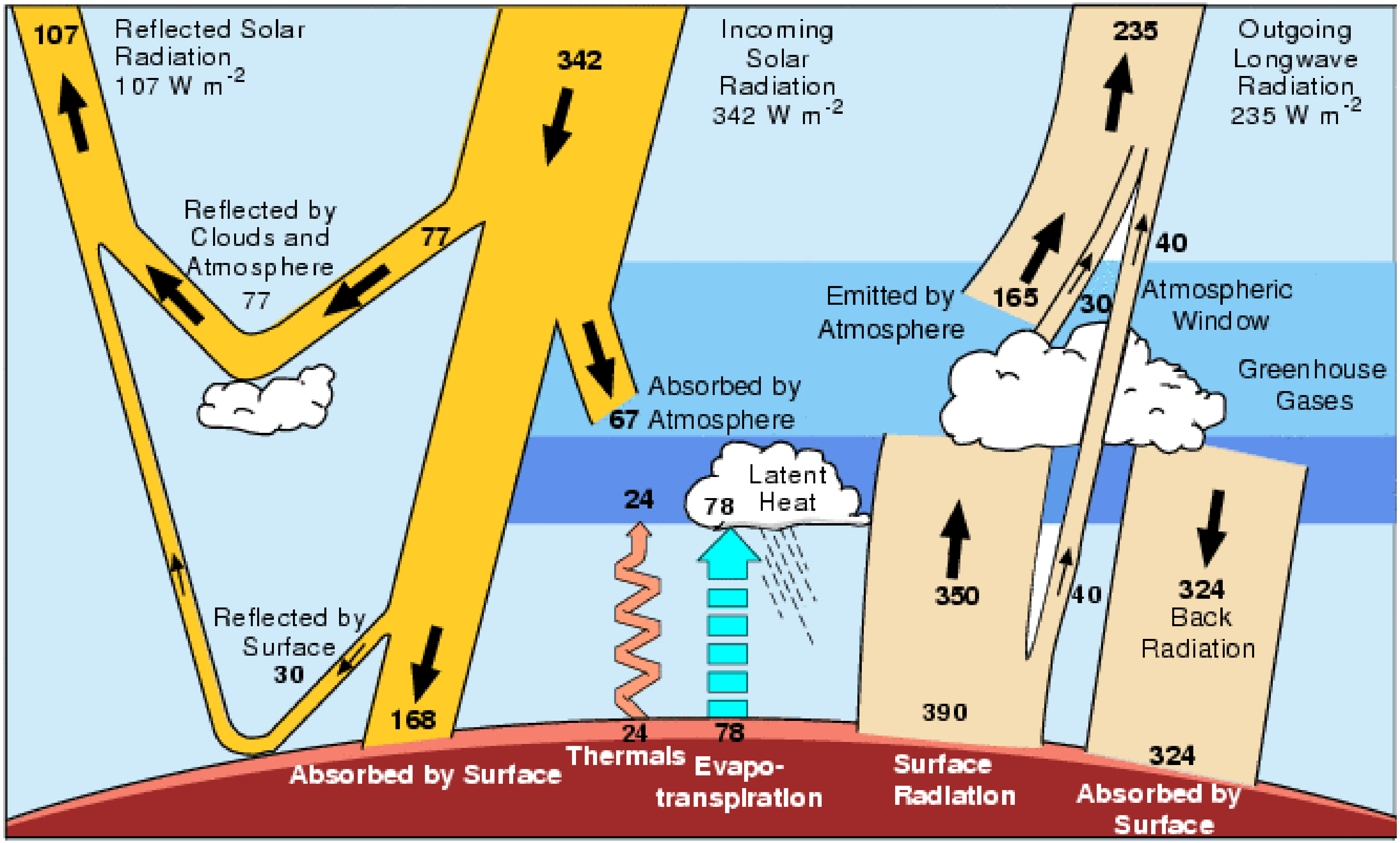
Energy on Earth

The incoming radiant energy is transformed into various forms (internal heat, potential energy, latent energy, and kinetic energy) moved around in various ways primarily by the atmosphere and oceans, stored and sequestered in the ocean, land, and ice components of the climate system, and ultimately radiated back to space as infrared radiation.

An equilibrium climate mandates a balance between the incoming and outgoing radiation and that the flows of energy are systematic. These drive the weather systems in the atmosphere, currents in the ocean, and fundamentally determine the climate. And they can be perturbed, with climate change.


The Greenhouse Effect
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
Some of the infrared radiation passes through the atmosphere, and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.
Solar radiation passes through the clear atmosphere.
ATMOSPHERE
EARTH
Most radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.

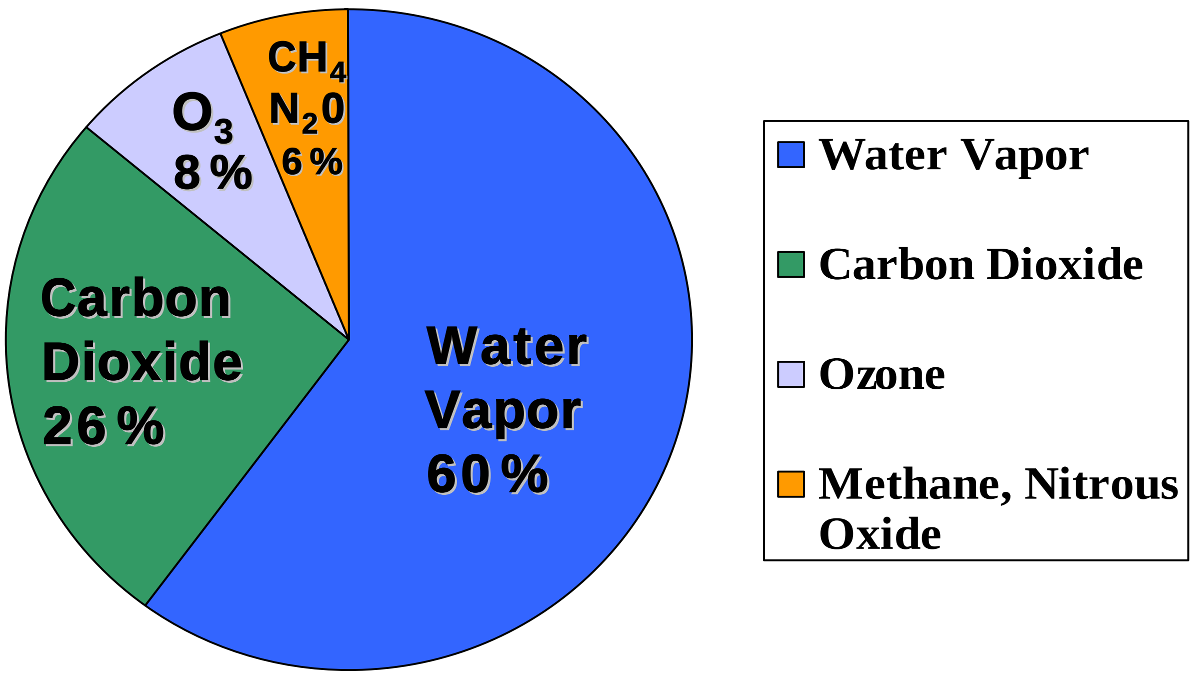
Global Heat Flows



Kiehl and Trenberth 1997

The Earth would be -19°C (-2°F) without atmosphere.
99% of the atmosphere is nitrogen and oxygen which are transparent to radiation

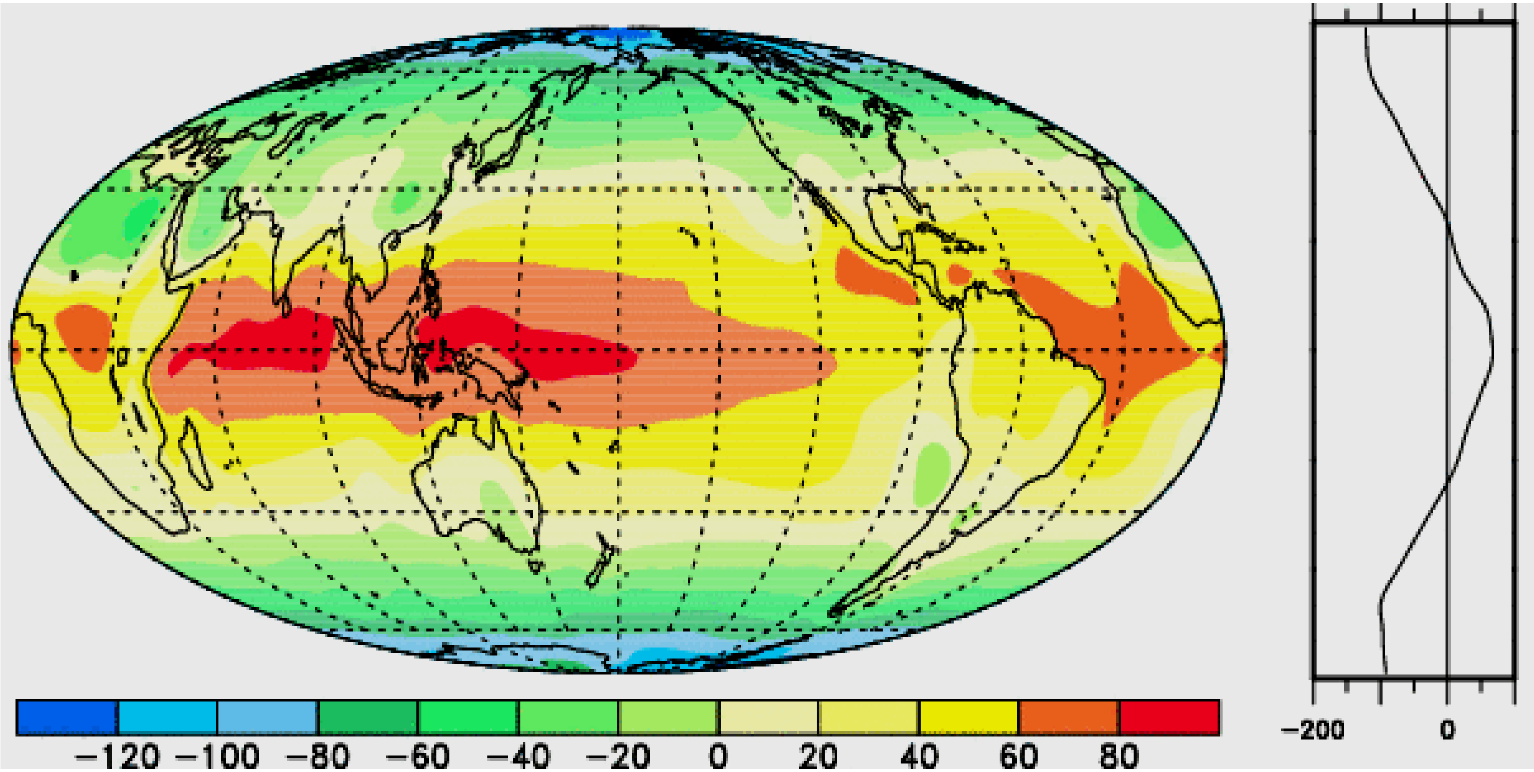
The Natural Greenhouse Effect: clear sky



Clouds also have a greenhouse effect

Kiehl and Trenberth 1997

Net observed radiation TOA



Trenberth & Stepaniak, 2003

The role of the atmosphere in energy

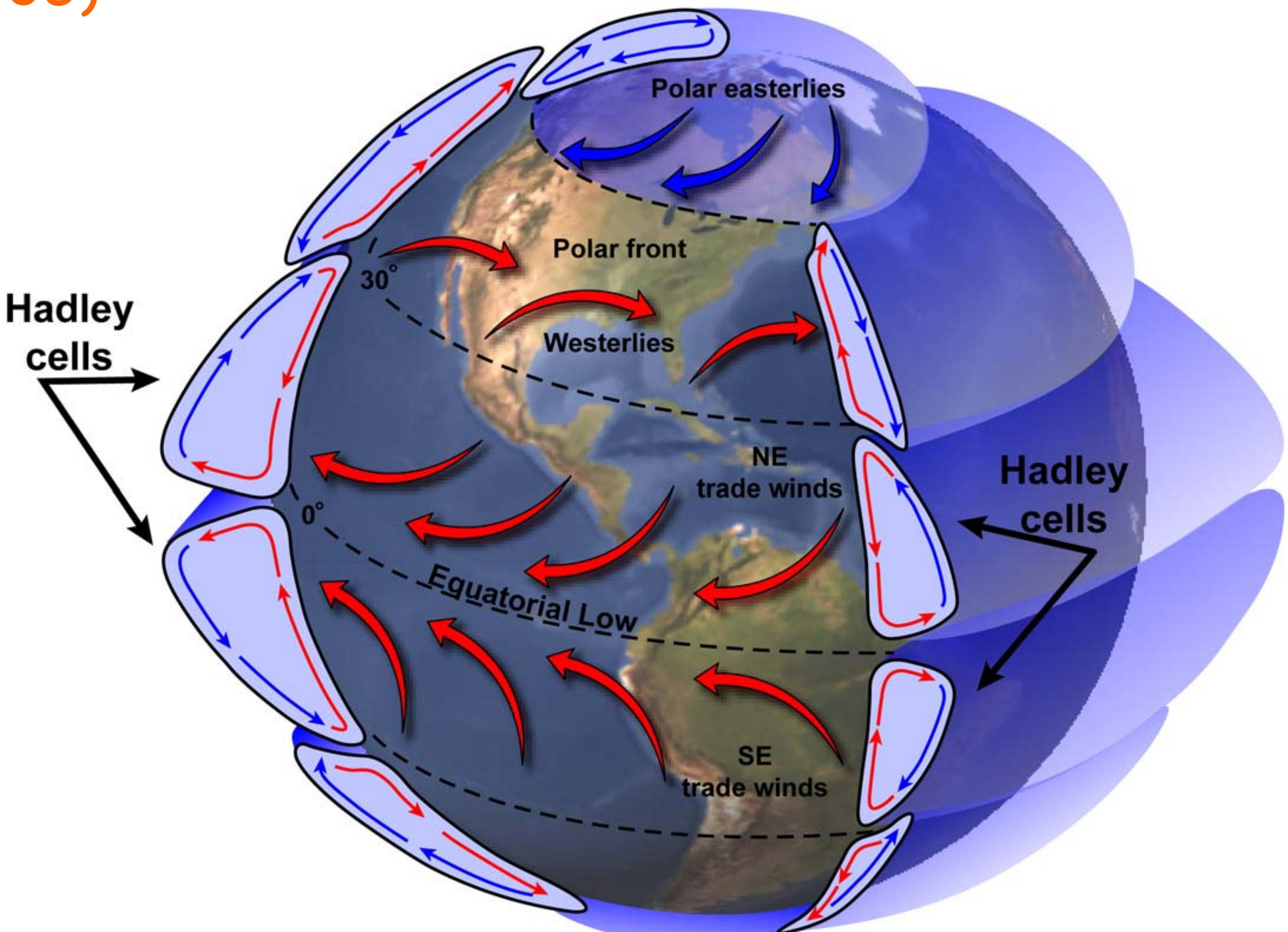
- The atmosphere is the most volatile component of climate system
- Winds in jet streams exceed 100 mph or even 200 mph; winds move energy around.
- Thin envelope around planet 90% within 10 miles of surface 1/400th of the radius of Earth; clouds appear to hug the surface from space.
- The atmosphere does not have much heat capacity

- "Weather" occurs in troposphere (lowest part)
- Weather systems: cyclones, anticyclones, cold and warm fronts tropical storms/hurricanes move heat around: mostly upwards and polewards

George Hadley (1685-1768), English lawyer and scientist.

"I think the cause of the general Trade-winds have not been explained by any of those who have wrote on that subject" (1735)

The overturning Hadley cells are the main way the atmosphere transports energy polewards in low latitudes



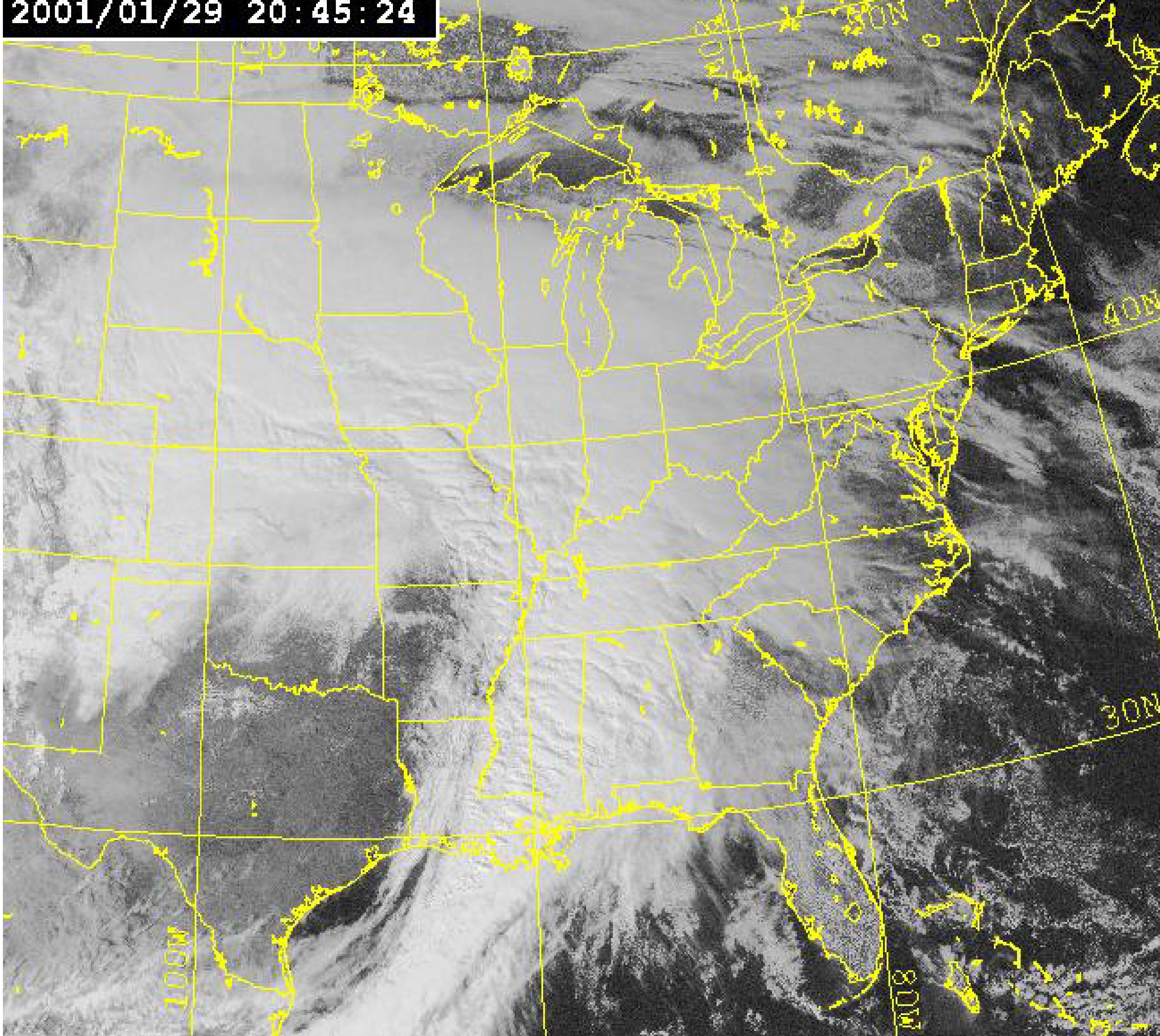
"Extratropical Storms"

Cyclones and anticyclones are the main way of transporting energy polewards in extratropics.

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

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

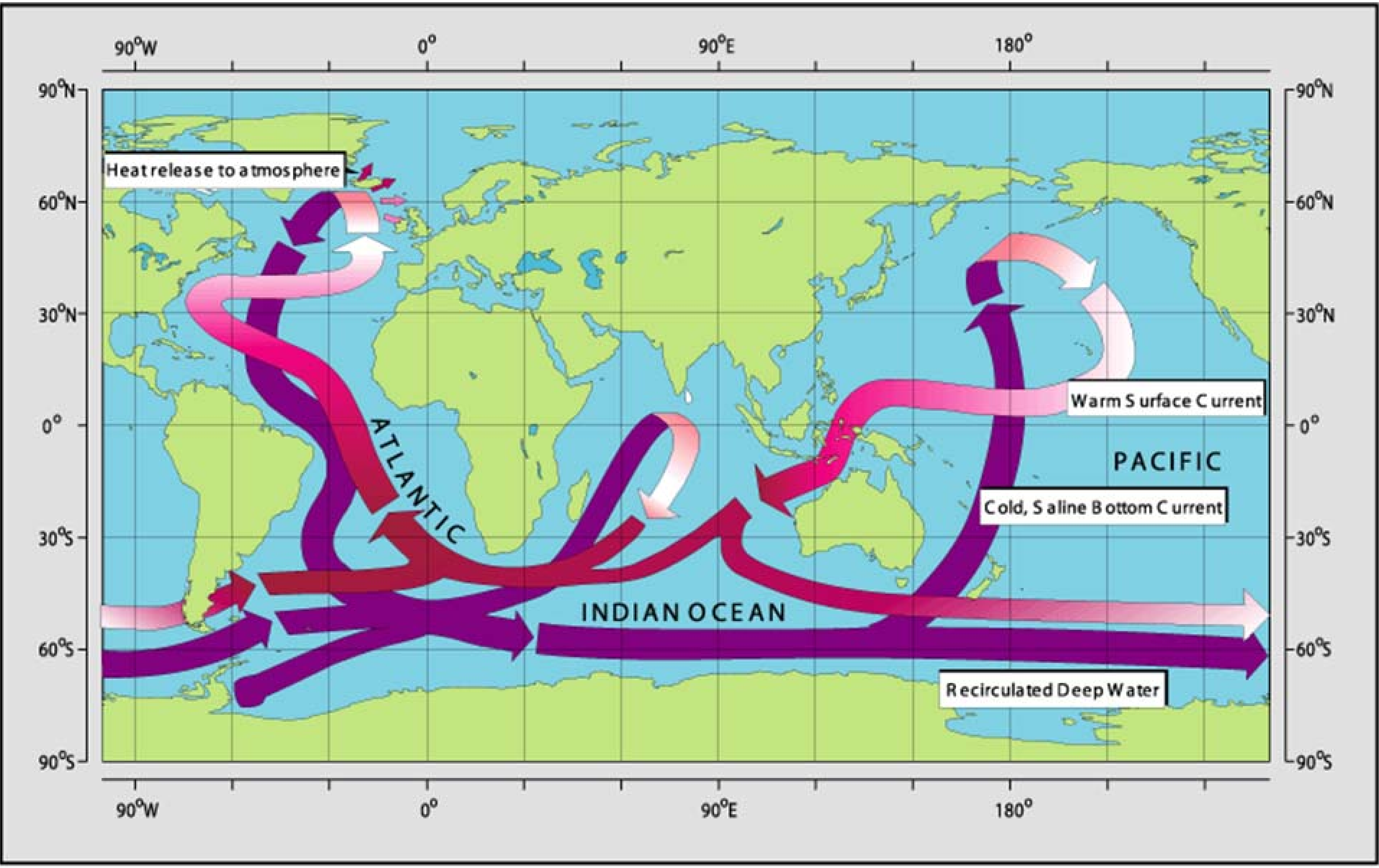
Source: USA TODAY research by Chad Palmer, Graphic by Chuck Rose


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

Role of Oceans

- The oceans cover 70.8% of the Earth's surface.
- The oceans are **wet**: water vapor from the surface provides source for rainfall and thus latent heat energy to the atmosphere.
- The heat capacity of the atmosphere is equivalent to that of 3.5 m of ocean. The oceans slowly adjust to climate changes and can sequester heat for years.
- The ocean is well mixed to about 20 m depth in summer and over 100 m in winter. An overall average of 90 m would delay climate response by 6 years.
- Total ocean: mean depth 3800 m.
- Would add delay of 230 years if rapidly mixed. In reality, the response depends on rate of ventilation of water through the thermocline (vertical mixing).
- Estimate of delay overall is 10 to 100 years.
- The ocean currents redistribute heat, fresh water, and dissolved chemicals around the globe.

The great ocean conveyer: of heat and salts



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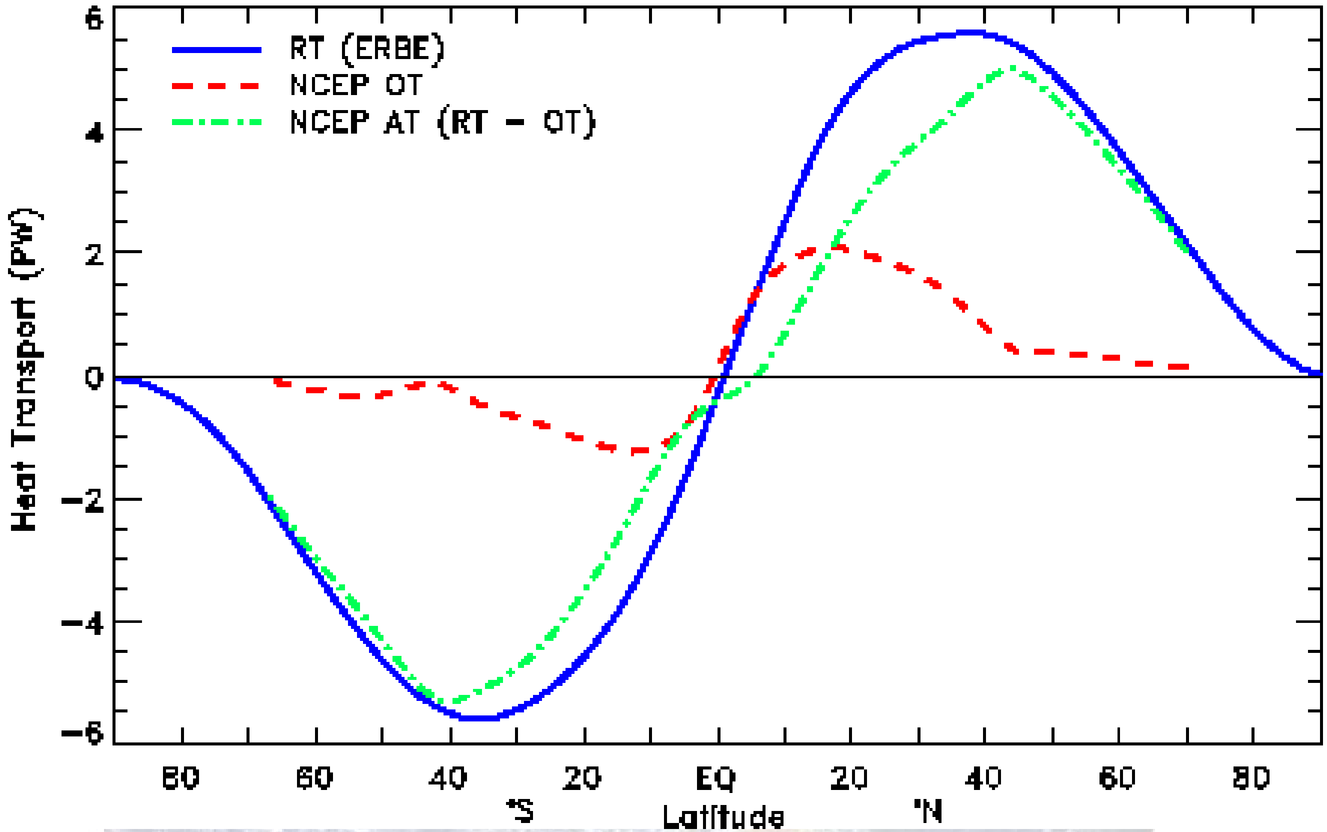

Trenberth and Caron, J. Clim. 2001

OCEAN-ATMOSPHERE TRANSPORTS

The latest best estimate of the partitioning of meridional transports by the atmosphere and ocean.

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Role of Land

- Heat penetration into land with annual cycle is ~2 m.
- Heat capacity of land is much less than water:
  - Specific heat of land 4½ less than sea water
  - For moist soil maybe factor of 2
- Land plays lesser role than oceans in storing heat.

Consequently:

- Surface air temperature changes over land are large and occur much faster than over the oceans.
- Land has enormous variety of features: topography, soils, vegetation, slopes, water capacity.
- Land systems are highly heterogeneous and on small spatial scales.
- Changes in soil moisture affect disposition of heat: rise in temperature versus evaporation.
- Changes in land and vegetation affect climate through albedo, roughness and evapotranspiration.

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Kansas 2001
Irrigation circles:
Corn, sorghum green,
Wheat gold

The Role of Ice

Major ice sheets, e.g., Antarctica and Greenland. Penetration of heat occurs primarily through conduction.

⇒ The mass involved in changes from year to year is small but important on century time scales.

Unlike land, ice melts ⇒ changes in sea level on longer time-scales.

Ice volumes: 28,000,000 km^3 water is in ice sheets, ice caps and glaciers.

Most is in the Antarctic ice sheet which, if melted, would increase sea level by ~65 m, vs Greenland 7 m and the other glaciers and ice caps 0.35 m.

In Arctic: sea ice ~ 3-4 m thick

Around Antarctic: ~ 1-2 m thick

Ice is bright: reflects the solar radiation ⇒ ice-albedo feedback

Ice ↑ ⇒ radiation reflected ⇒ cooler ⇒ Ice ↑

The West Antarctic Ice Sheet (WAIS) partly grounded below sea level.

⇒ Warming could alter grounding of the ice sheet, making it float, and vulnerable to rapid (i.e. centuries) disintegration.

⇒ rise in sea level of 4-6 m.

May be irreversible if collapse begins.

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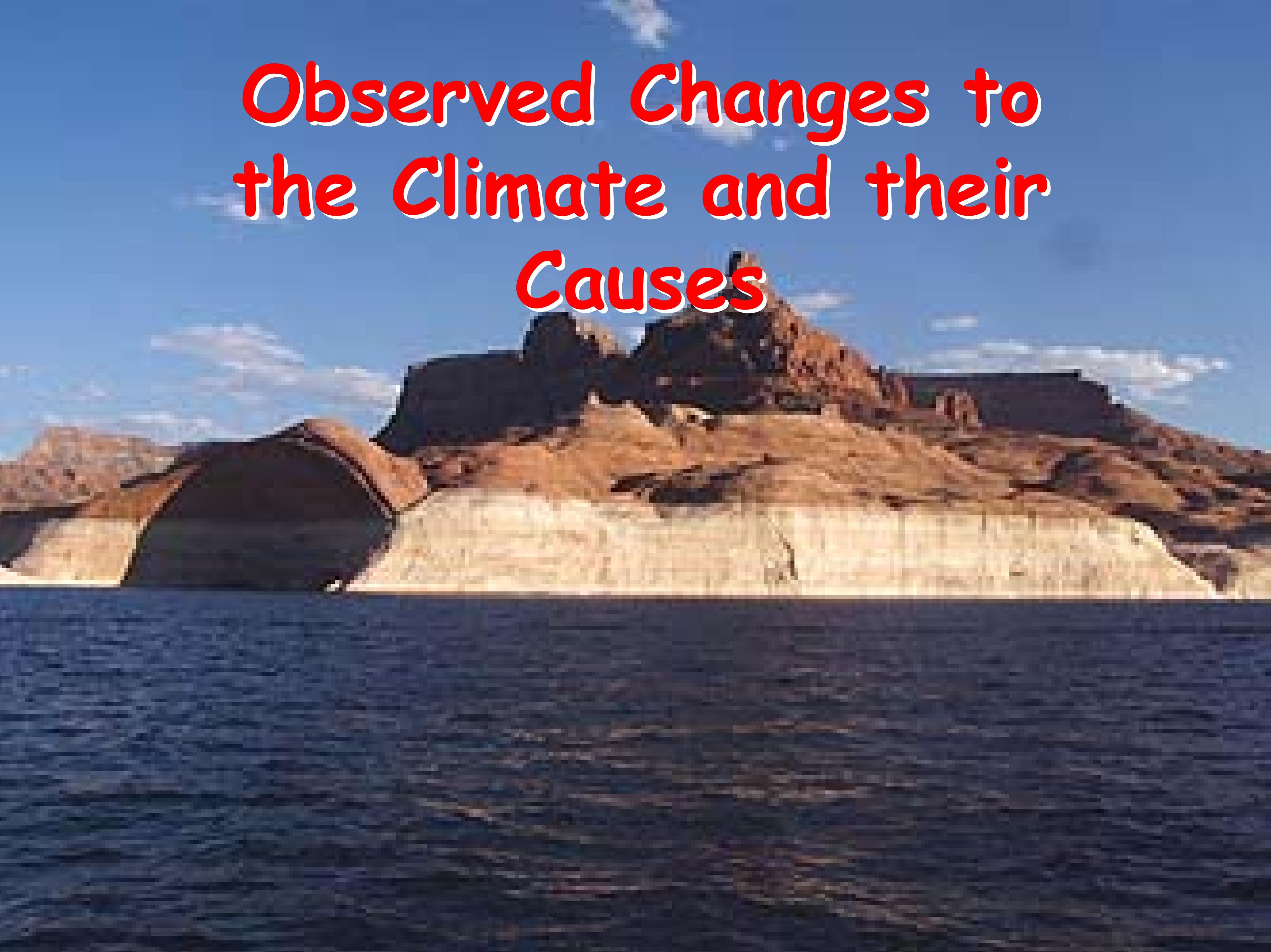
Observed Changes to the Climate and their Causes



Some human-induced environmental changes relevant to climate

- Changes in land use (e.g. farming, building cities)
- Storage and use of water (dams, reservoirs, irrigation)
- Combustion of fossil fuels
  - Generation of heat
  - Generation of particulate pollution (e.g., soot, smoke)
  - Generation of gaseous pollution → particulates (e.g., sulfur dioxide, nitrogen dioxide; get oxidized to form sulfate, nitrate)
  - Generates carbon dioxide
- Generation of other greenhouse gases

  Methane, Nitrous oxide, Chlorofluorocarbons, Ozone

Especially via biomass burning, landfills, rice paddies agriculture, animal husbandry, fossil fuel use, leaky fuel lines, and industry

Changes the composition of the atmosphere

Most important are the gases with long lifetimes

Like CO_2 > 100 years

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The incoming energy from the sun is 342 W m^{-2}:
but this is the annual global mean:
It amounts to 175 PetaWatts =175,000,000 billion Watts.
About **120 PW** is absorbed.

The biggest power plants in existence are 1000 MegaWatts and we normally think of units of
1 KiloWatt = 1 bar heater; or 100 W = light bulb.

So the energy from the sun is 120 million of these power stations. It shows:

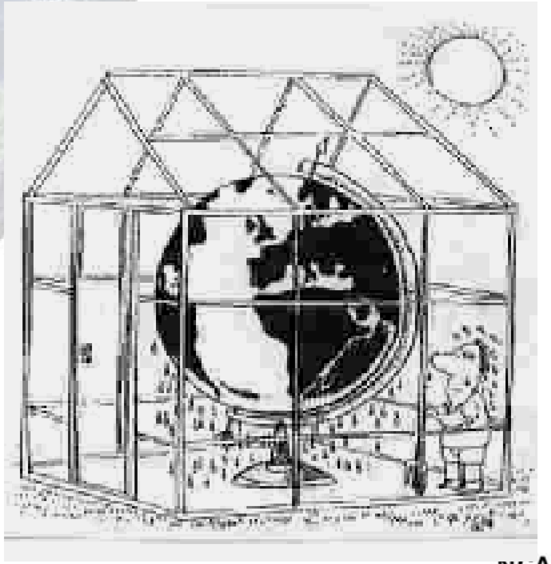
1) **Direct human influences are tiny vs nature.**
2) **The main way human activities can affect climate is through interference with the natural flows of energy such as by changing the composition of the atmosphere**

The enhanced greenhouse effect

CO_2 has increased >33%

If CO_2 were suddenly doubled then:

- atmosphere must warm up to restore balance via radiation to space
- In absence of other changes: warming is 1.2°C
- Feedbacks cause complications
- Best estimate is warming of 2.9°C so feedbacks roughly double change
- Real world changes complex and more gradual



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Climate

The atmosphere is a "global commons." Air over one place is typically half way round the world a week later, as shown by manned balloon flights.

The atmosphere is a dumping ground for all nations for pollution of all sorts. Some lasts a long time and is shared with all. **One consequence is global warming!**

Global Warming is happening

Since 1970, rise in:

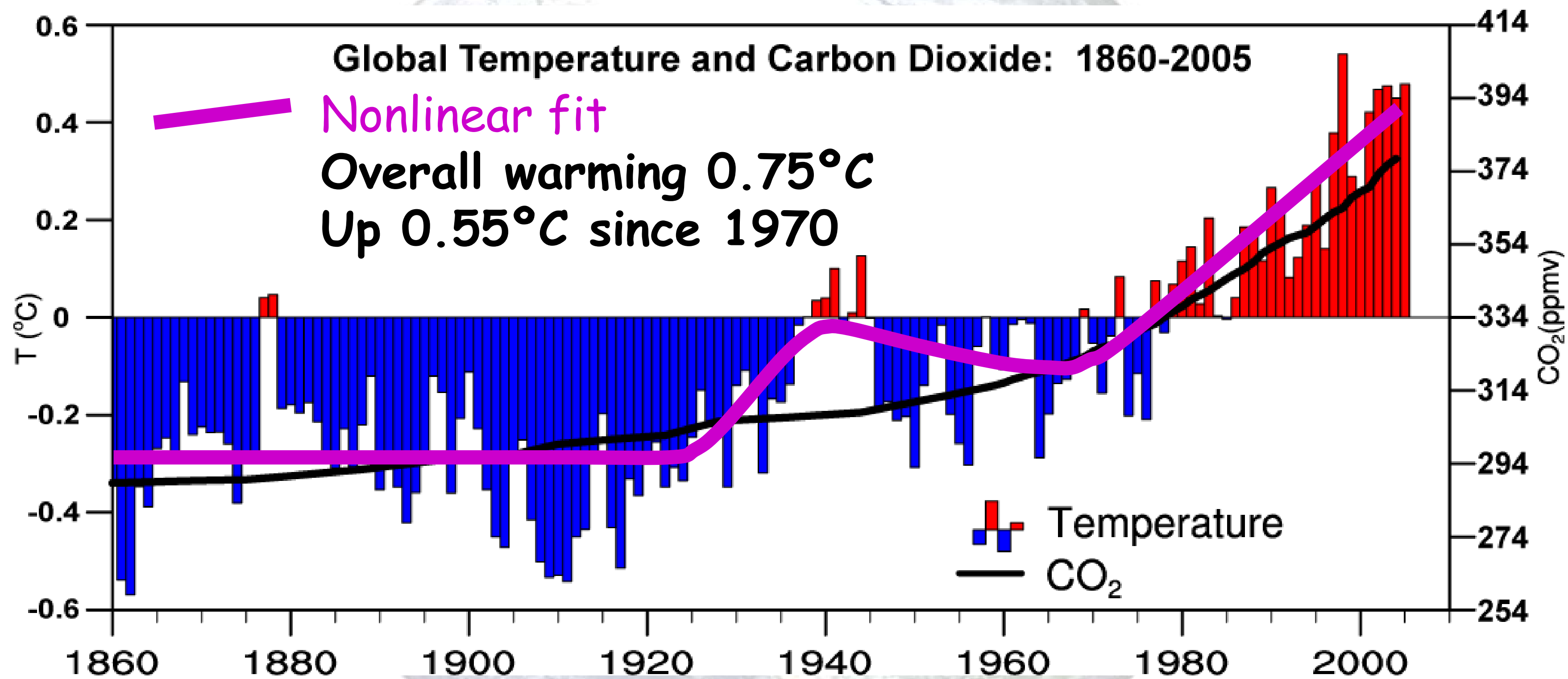
- Carbon Dioxide
- Global temperatures
- Global SSTs
- Global sea level
- Tropical SSTs
- Water vapor
- Rainfall intensity
- Precipitation extratropics
- Hurricane intensity
- Drought

Decrease in:

Snow extent

Arctic sea ice

Variations of the Earth's surface temperature



Annual mean departures from the 1961-90 average for global temperatures, mean 14.0°C, and carbon dioxide concentrations from ice cores and Mauna Loa (1958 on), mean 333.7 ppmv. Updated from Karl and Trenberth 2003.

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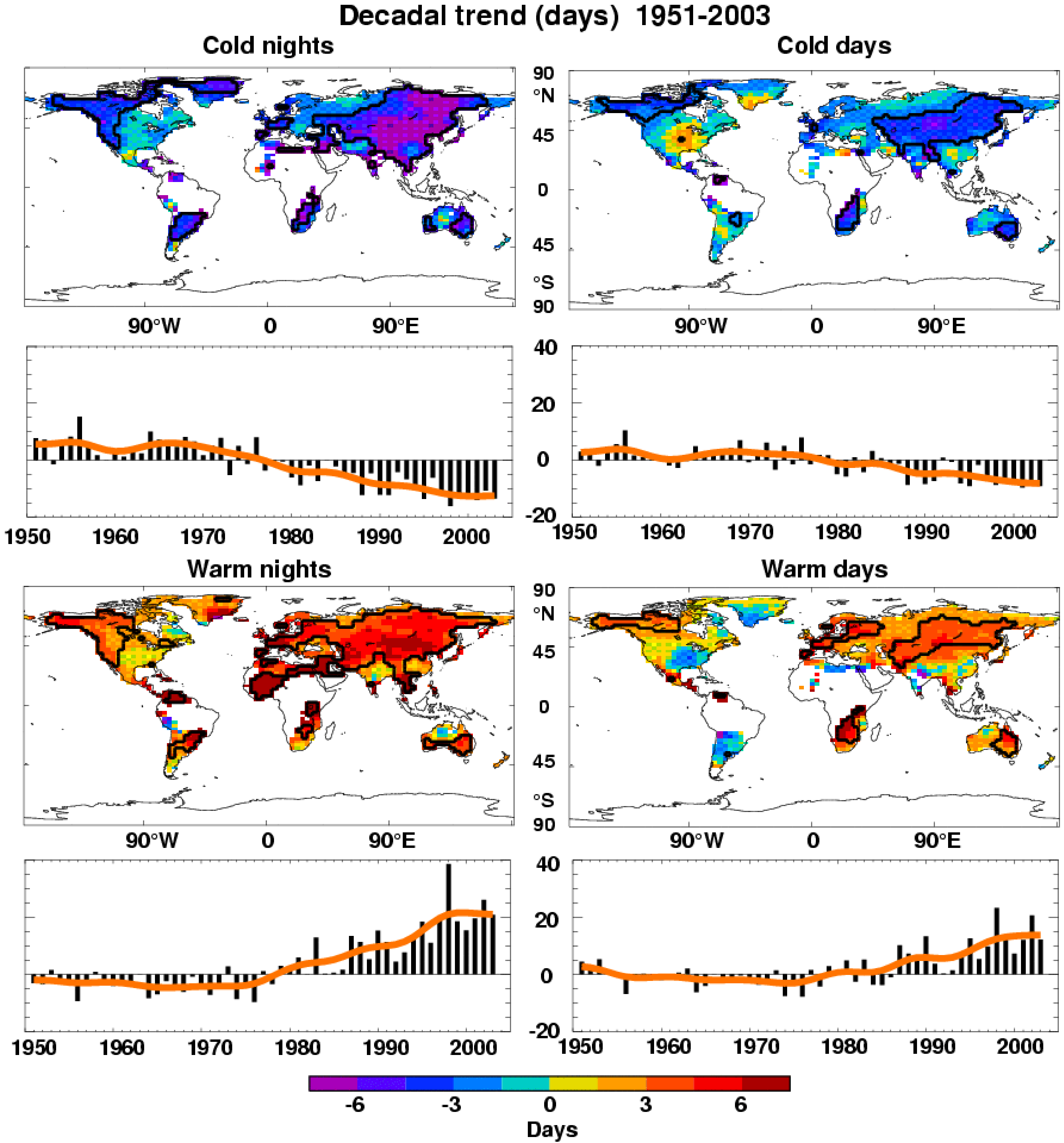
Heat Waves

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



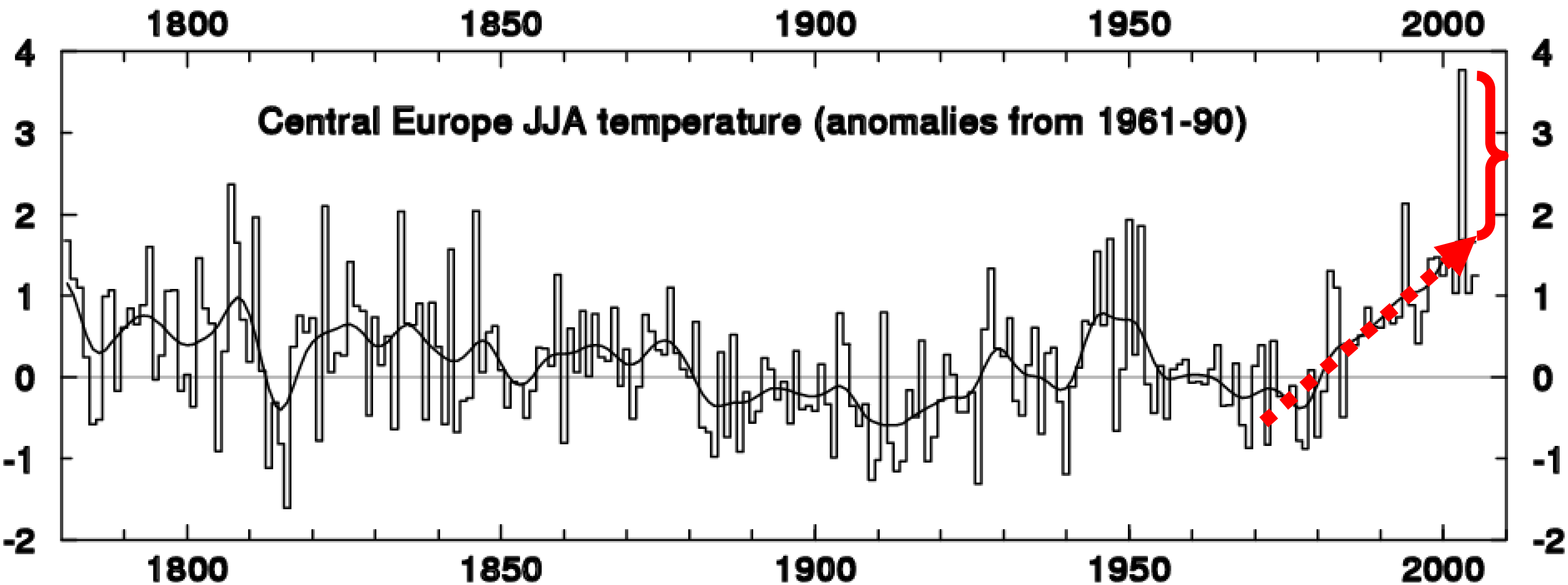
Extremes of temperature are changing!

Observed trends (days) per decade for 1951 to 2003

From Alexander et al. (2006)

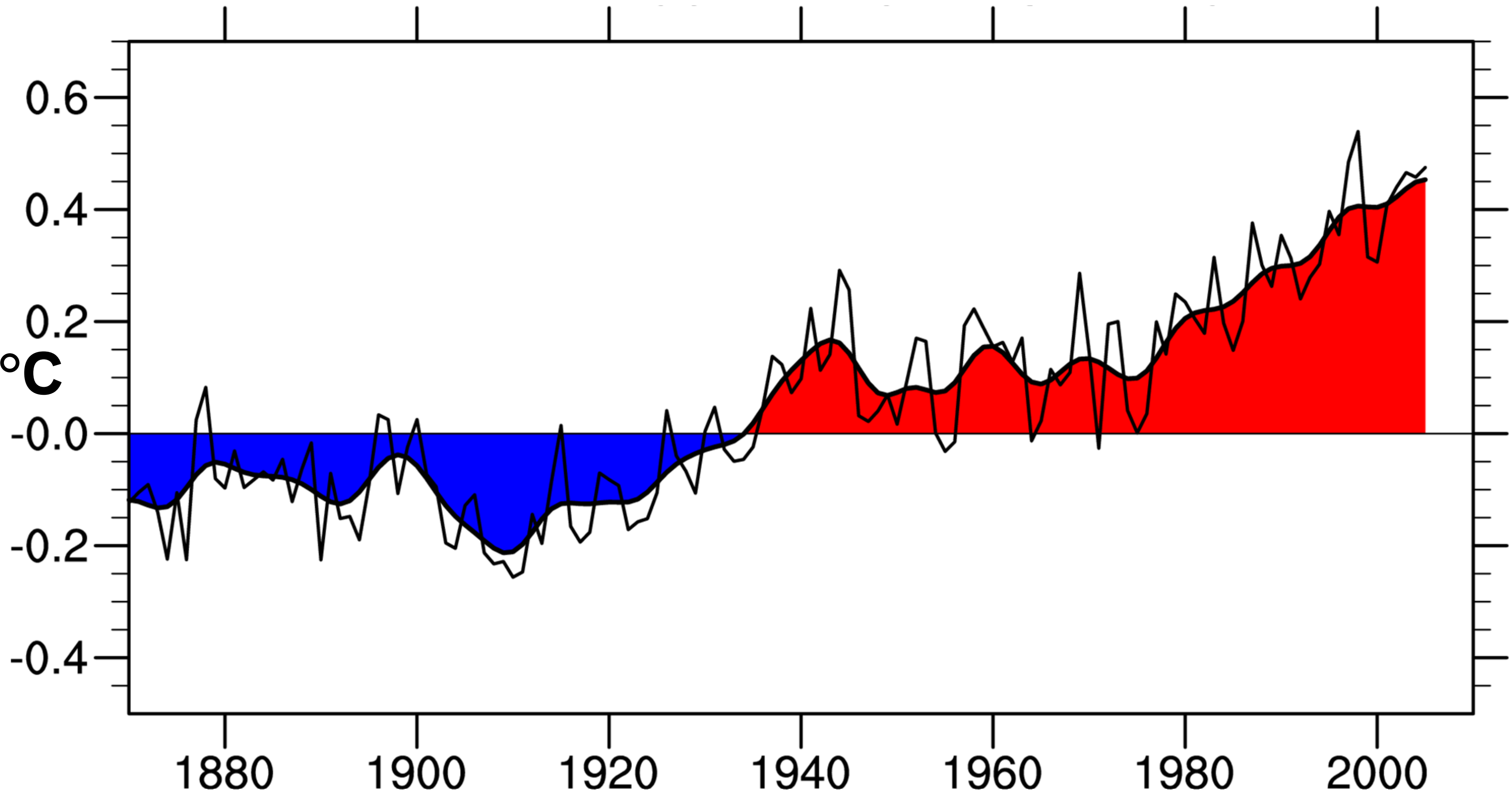
Europe summer temperatures

Exceptional heat wave and drought of 2003 was a major extreme made more likely by global warming: 30K deaths

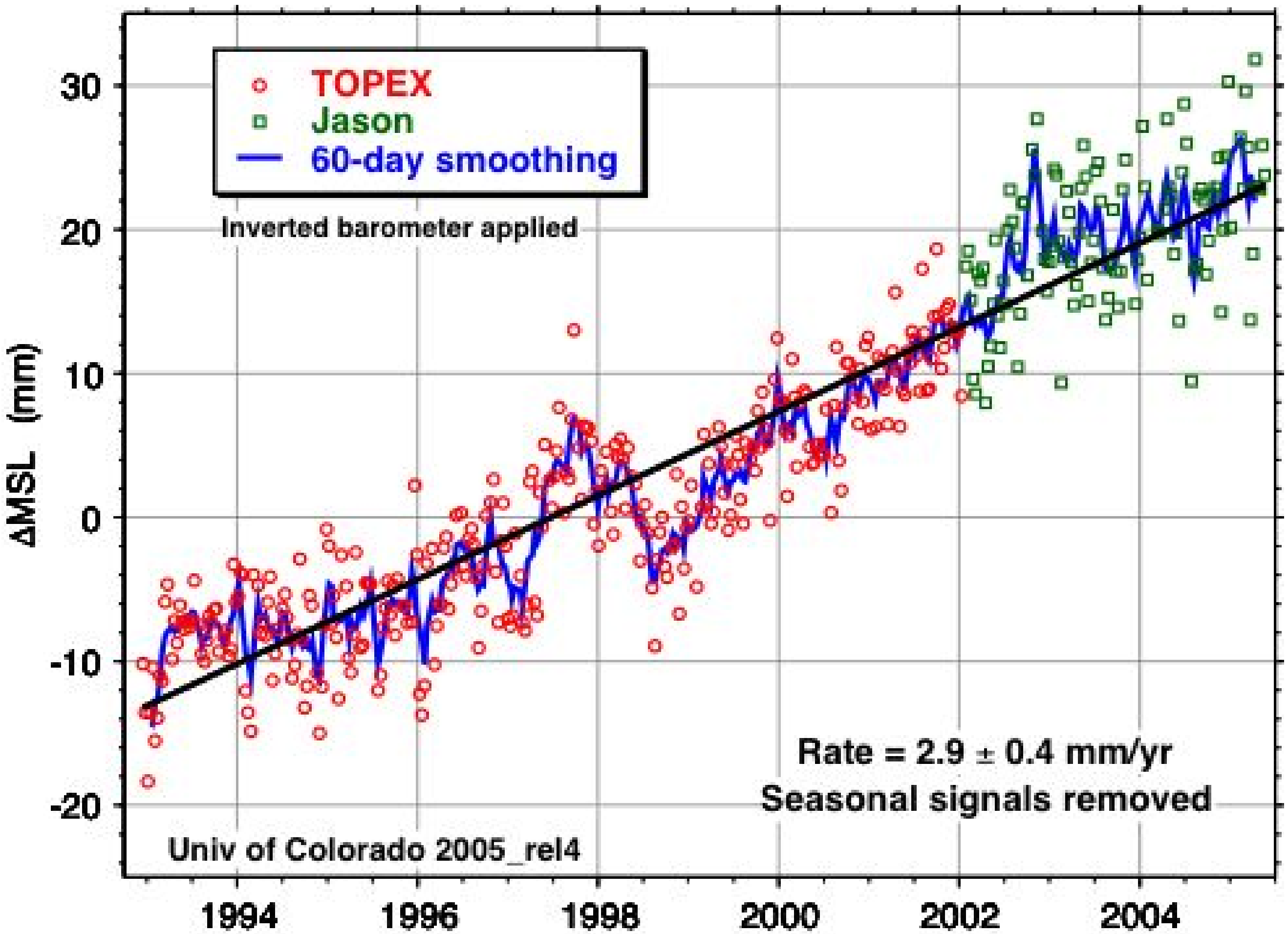


From P. Jones

Global Sea Surface Temperature: base 1901-70



Sea level is rising:
from ocean expansion and melting glaciers

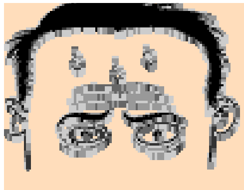


Since 1993 Global sea level has risen 37 mm (1.46 inches)

- 60% from expansion as ocean temperatures rise,
- 40% from melting glaciers

Steve Nerem

Controlling Heat



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.

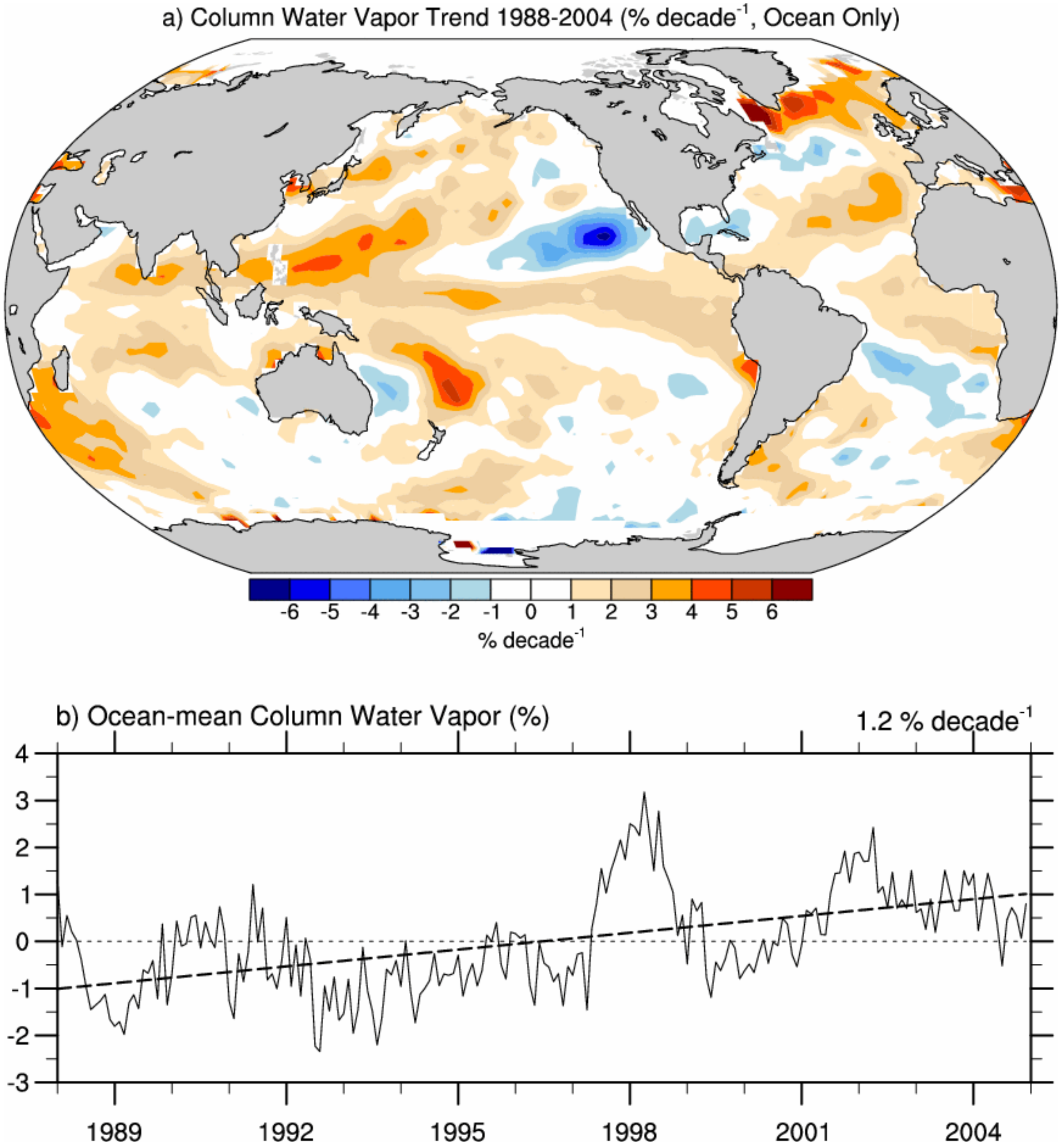
Water Holding Capacity

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.

Observations show that this is happening at the surface and in lower atmosphere:

This means more moisture available for storms.

Total column water vapor is increasing:



Best estimate of linear trends for global ocean 1.3±0.3% per decade

Sig. at >99%

Trenberth et al 2005

Global warming

⇓

Heating ↑

⇓

Temperature ↑ & Evaporation ↑

⇓

water holding capacity ↑

⇓

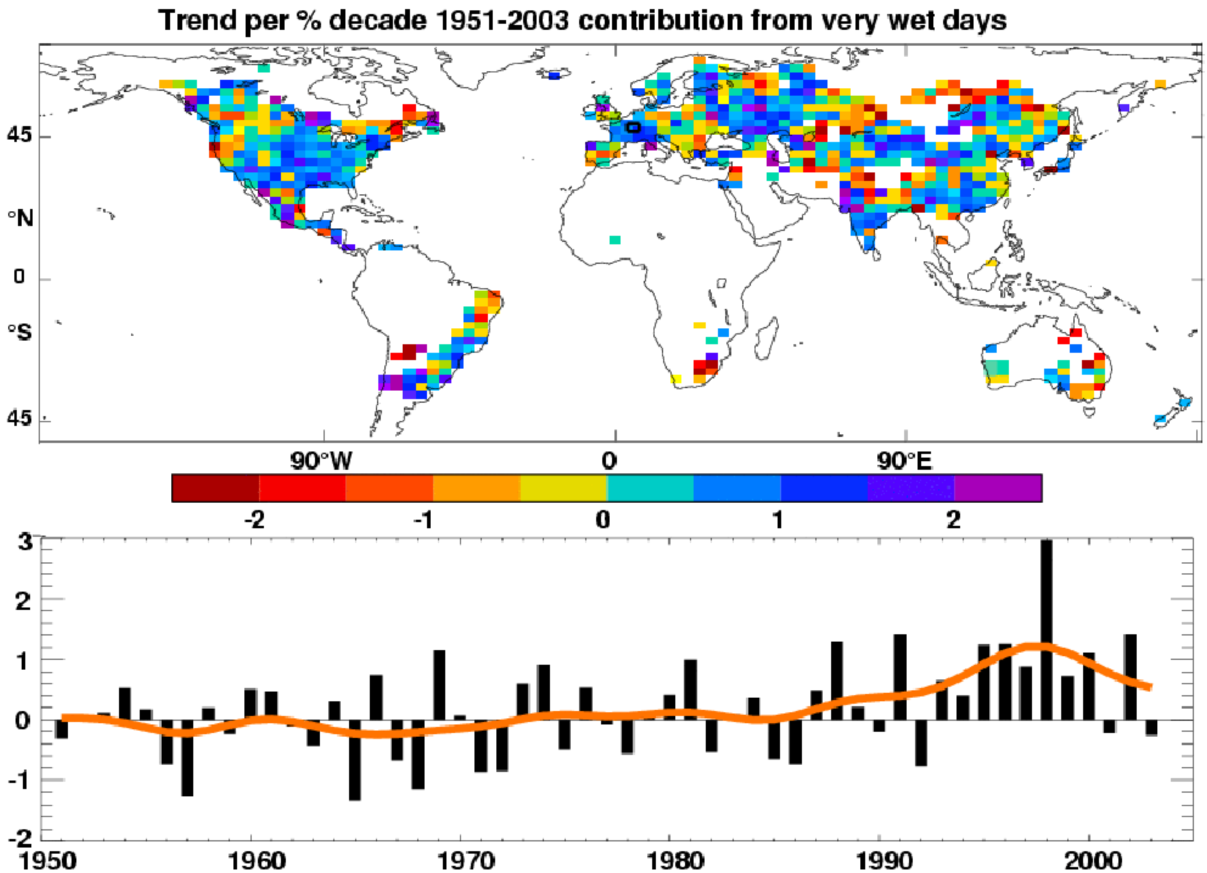
atmospheric moisture ↑

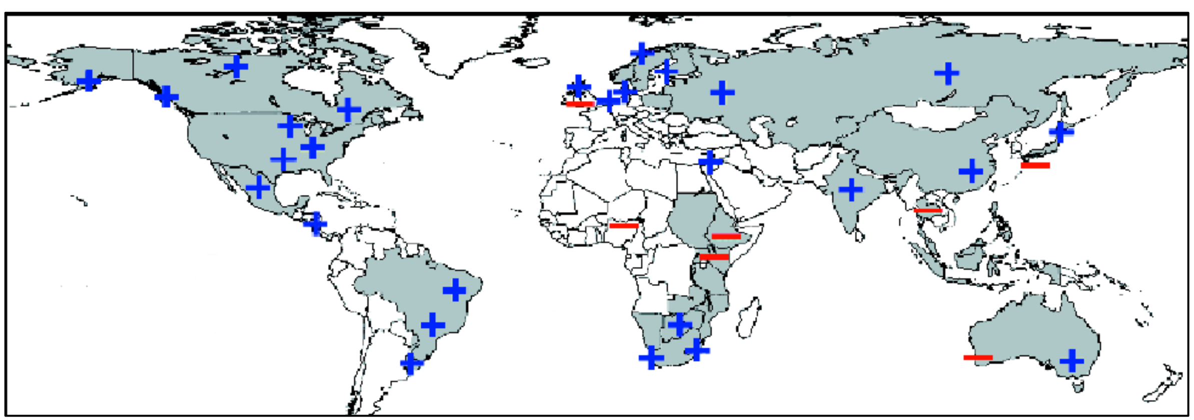
⇓ ⇓

greenhouse effect ↑ & rain intensity ↑

⇓

&





Precipitation

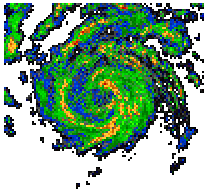
Observed trends (%) per decade for 1951–2003 contribution to total annual from **very wet days** > 95th %ile.

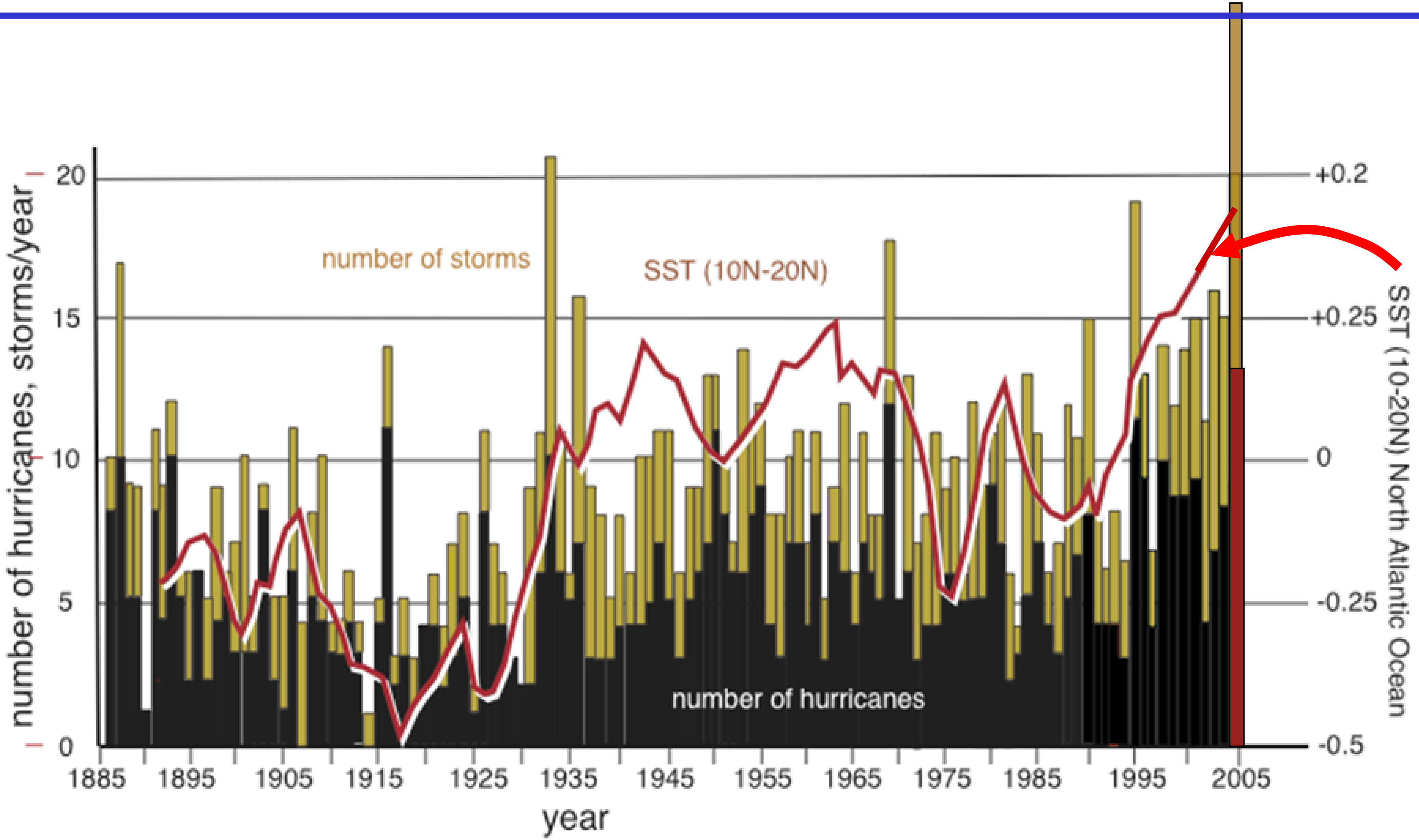
Alexander et al 2006

Regions where recent decades heavy precip >> mean precip

updated from Groisman et al. (2005a).

Changes in **hurricanes** in the North Atlantic Ocean





Evidence for reality of climate change

Glaciers melting

1909

Toboggan Glacier Alaska

2000

1858 1974

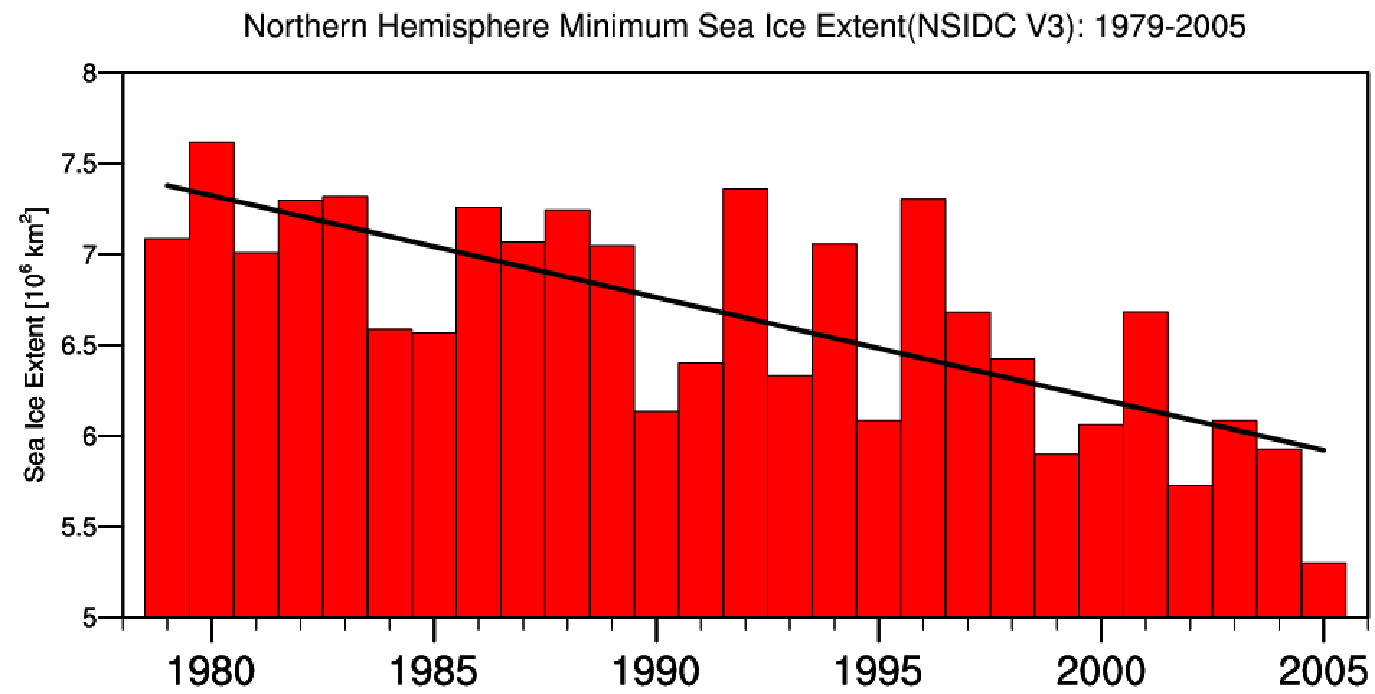
Grindelwald Glacier

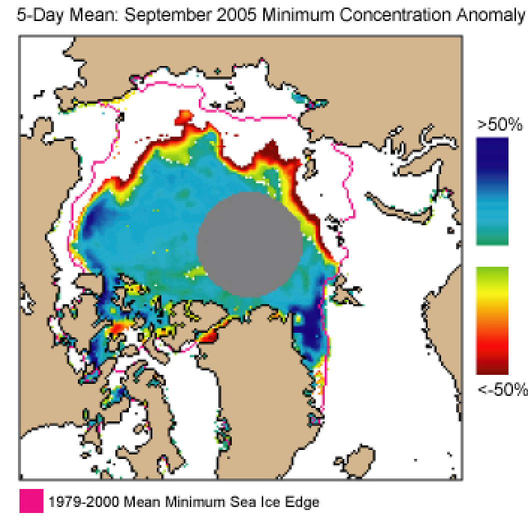
A. Circa 1900
Photo Source: Munich Society for Environmental Research

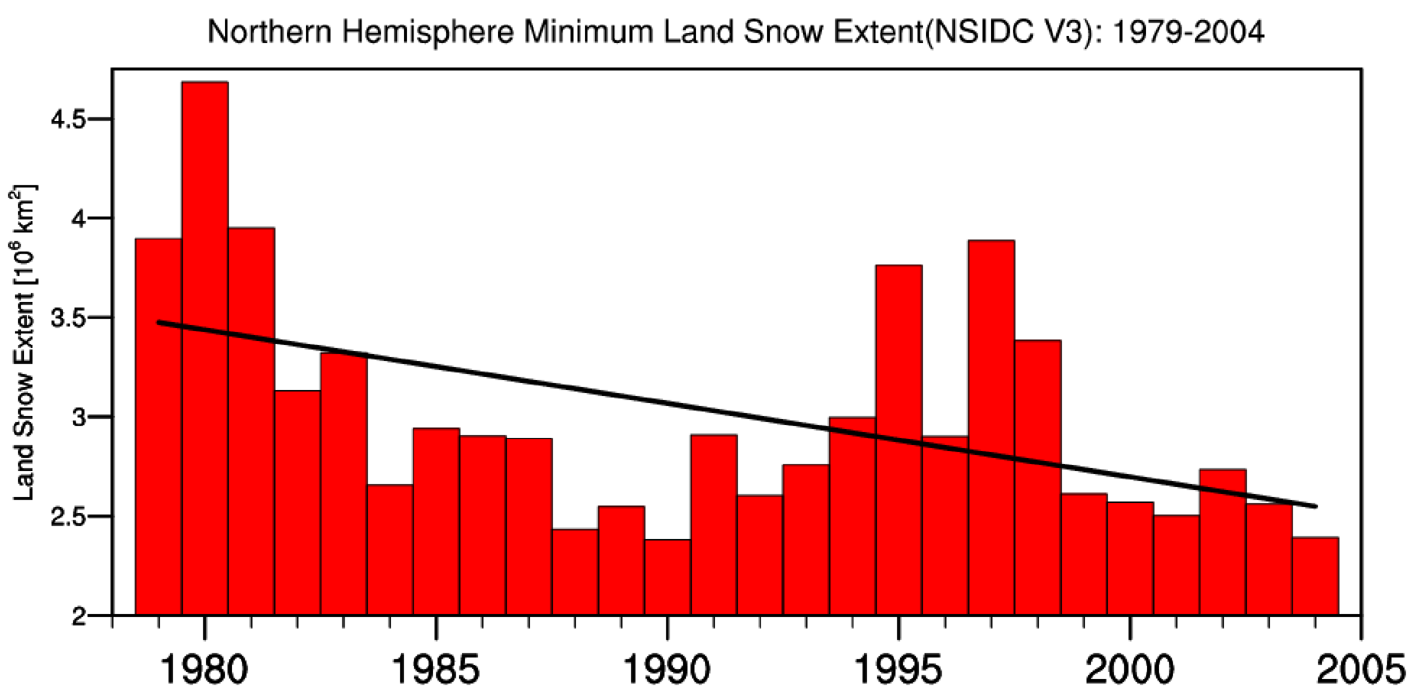
B. Recent

1900 2003

Alpine glacier, Austria



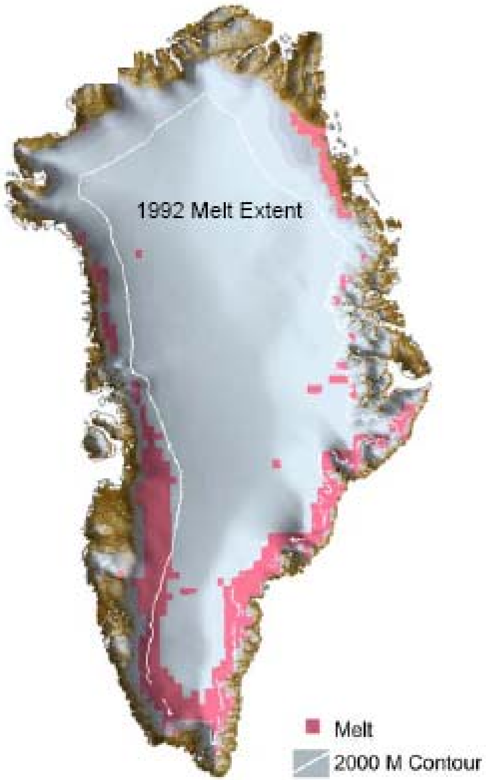


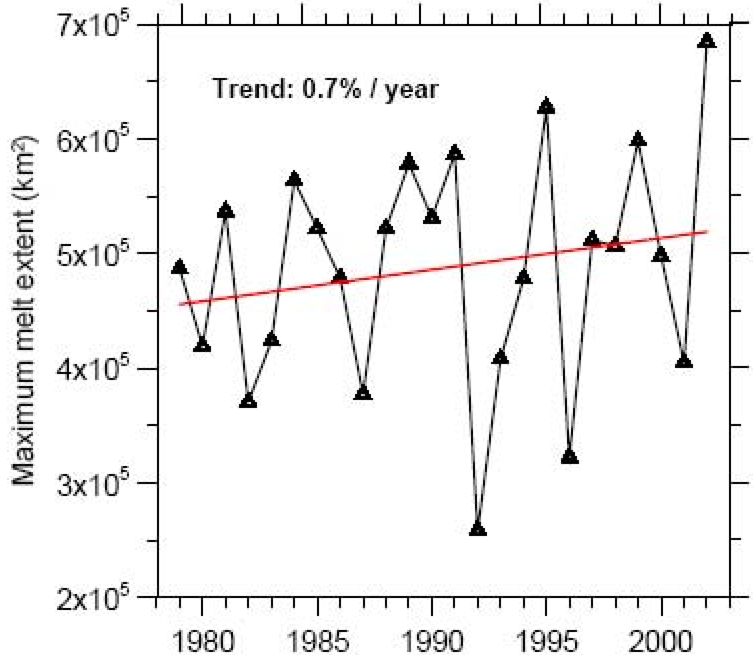


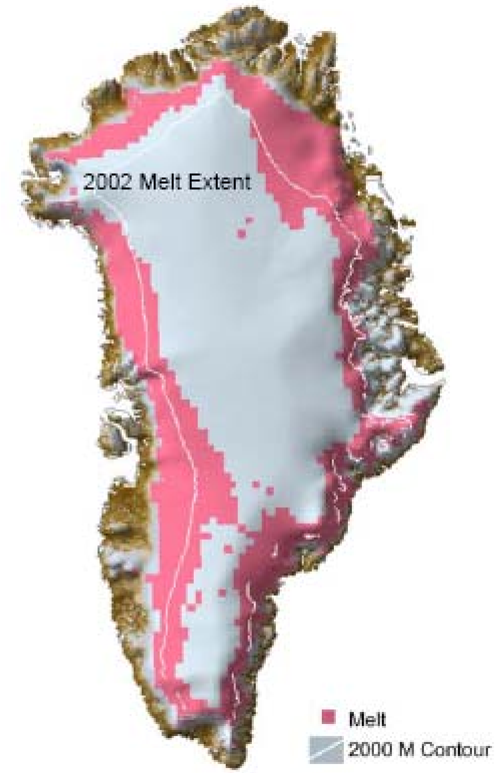
Declines in sea ice and snow cover

Runoff from earlier snow melt about 1-2 weeks earlier

Response of the Greenland Ice Sheet to Climatic Forcing







Greenland ice sheet melt area increased on average by 16% from 1979 to 2002.
The smallest melt extent was observed after the Mt. Pinatubo eruption in 1992

University of Colorado

Konrad Steffen and Russell Huff, University of Colorado at Boulder

CIRES

Surface melt on Greenland

Melt descending into a moulin: a vertical shaft carrying water to the base of the ice sheet.

Braithwaite
Univ. Manchester

SNOW PACK: In many land and 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**

Wildfire, near Denver CO: 2002

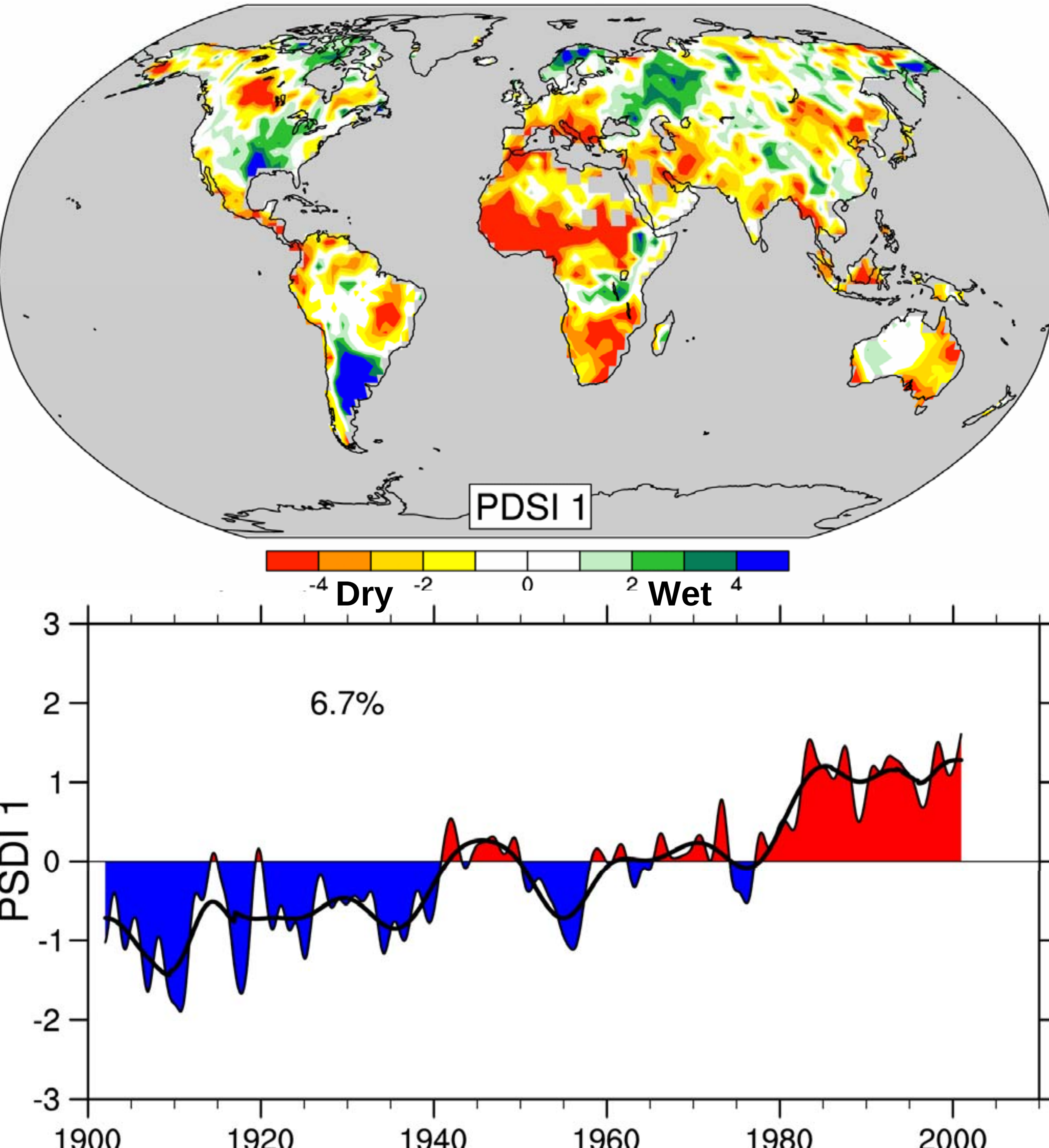
Drought:

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



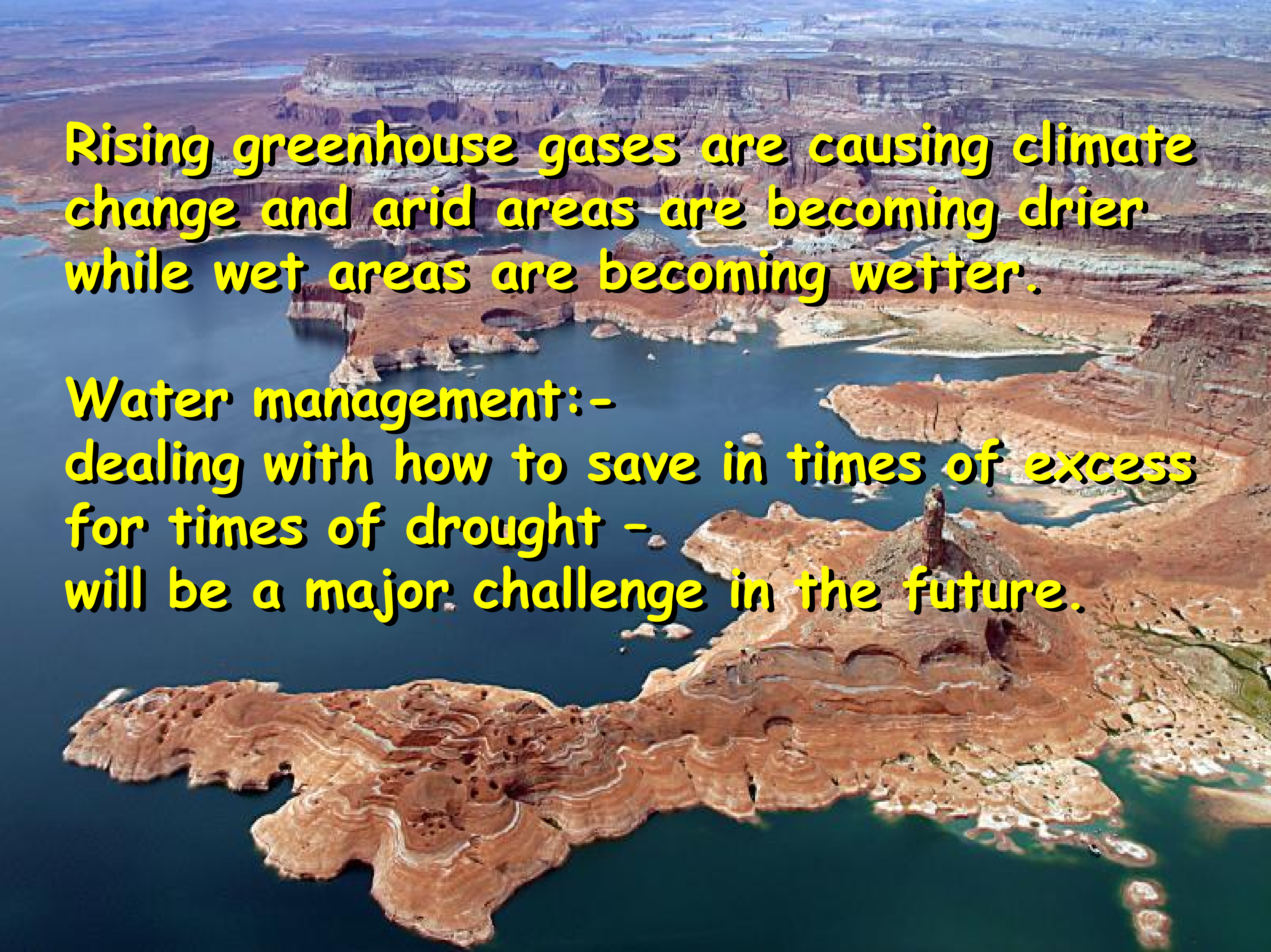
Palmer Drought Severity Index

PDSI

Dominant pattern:

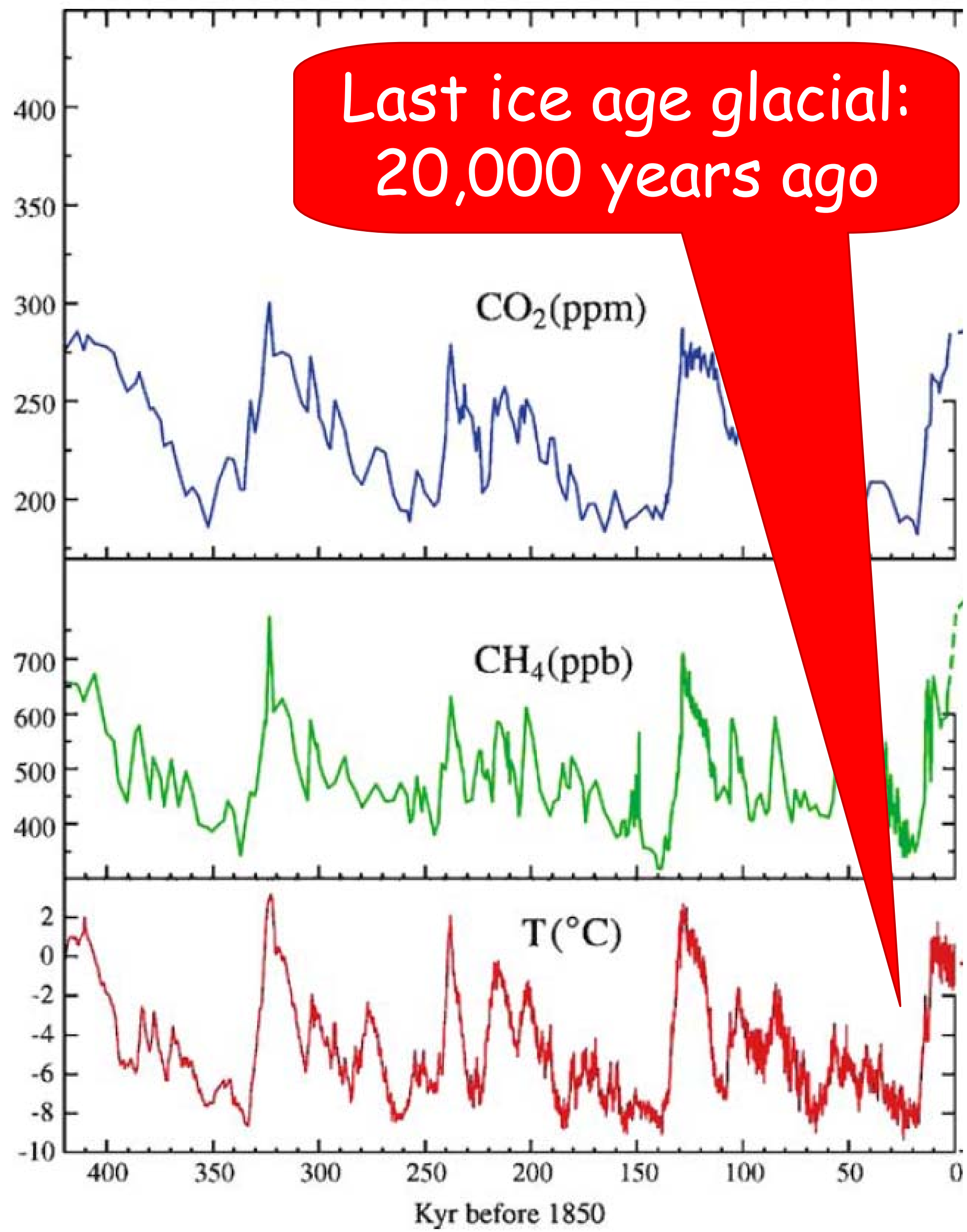
Upward trend.

Dai et al 2004

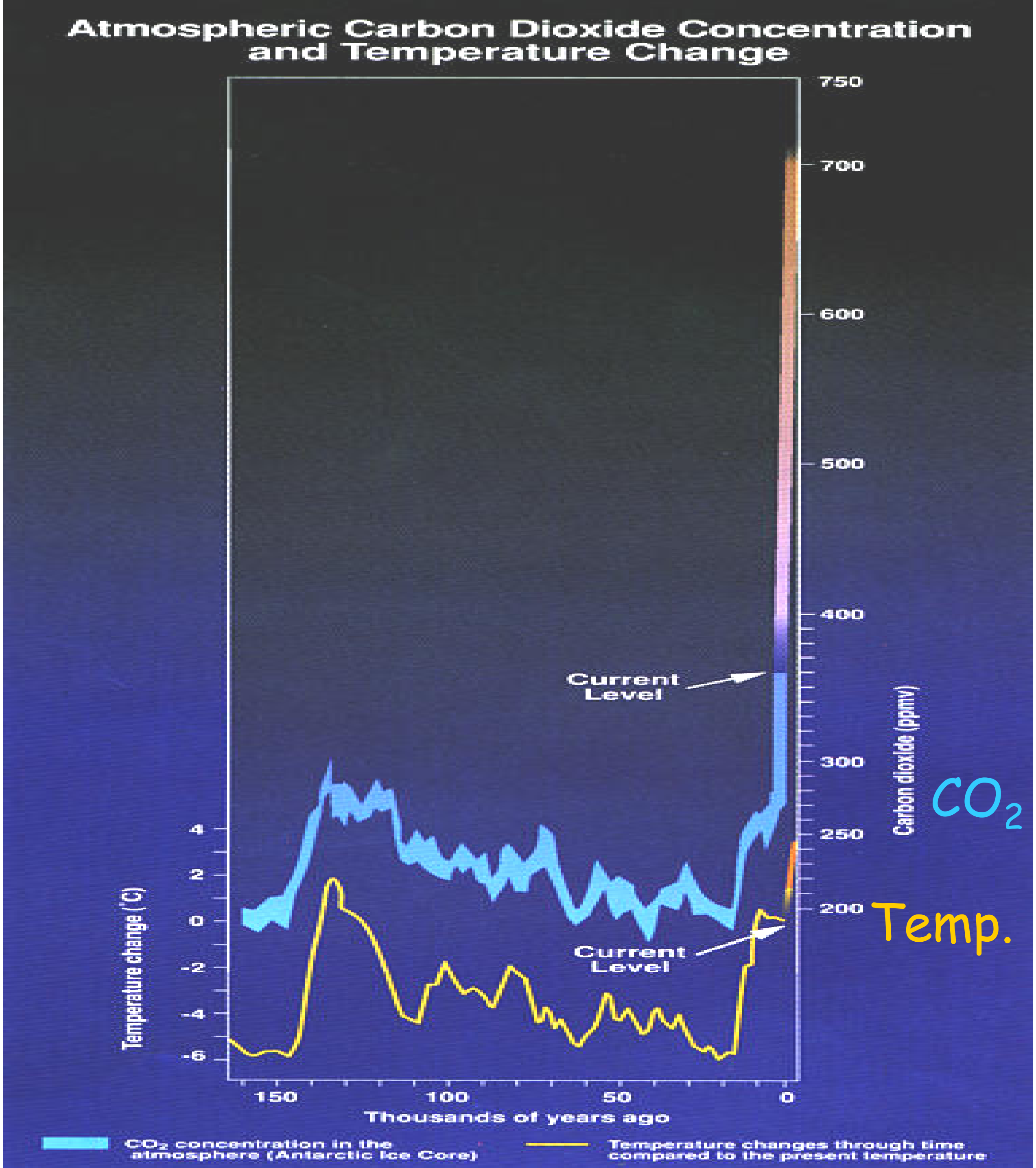


Rising greenhouse gases are causing climate change and arid areas are becoming drier while wet areas are becoming wetter.

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

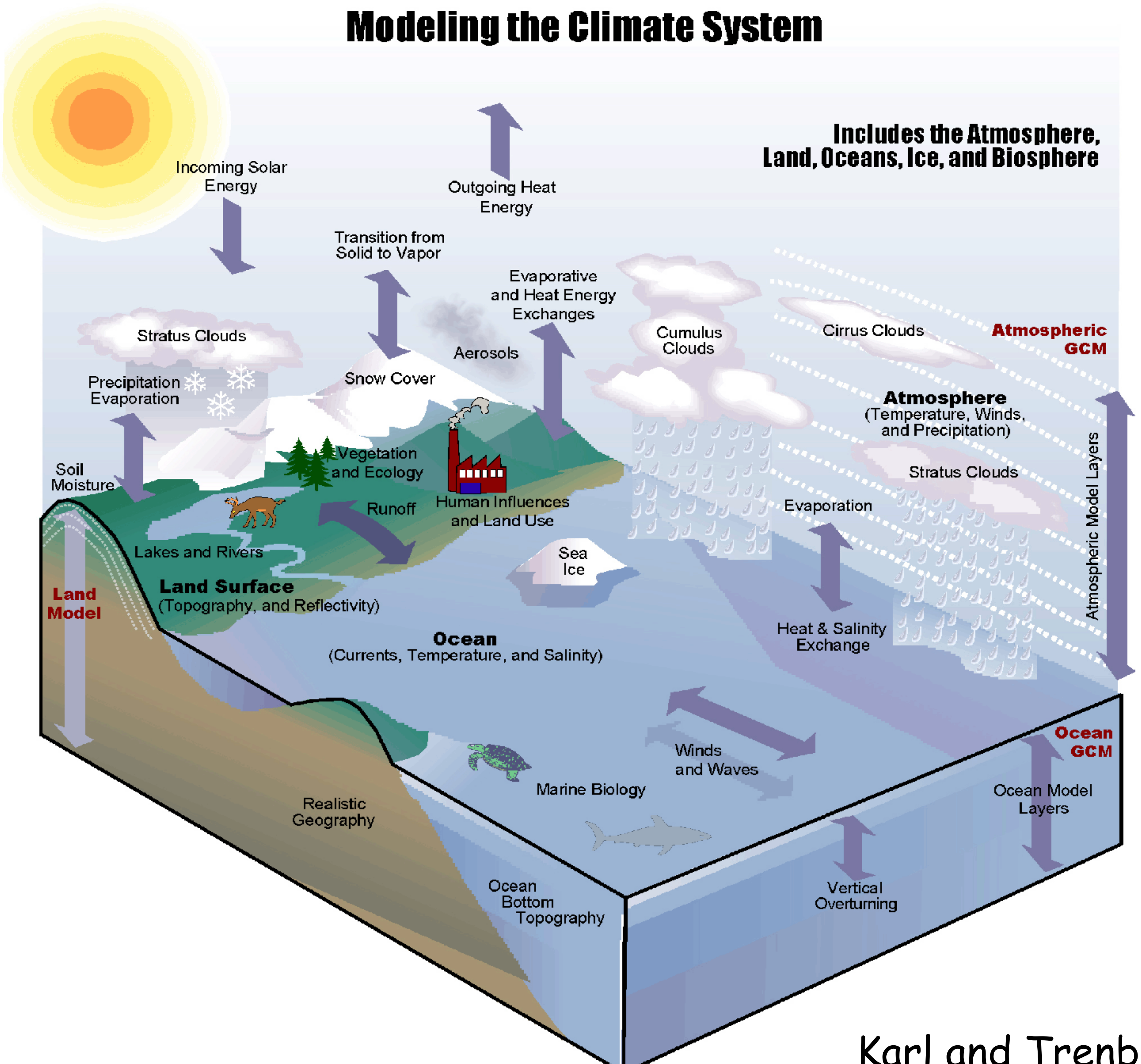


Last ice age glacial:
20,000 years ago
400
350
300
250
200
CO_2(ppm)
700
600
500
400
CH_4(ppb)
2
0
-2
-4
-6
-8
-10
T(°C)
400
350
300
250
200
150
100
50
0
Kyr before 1850



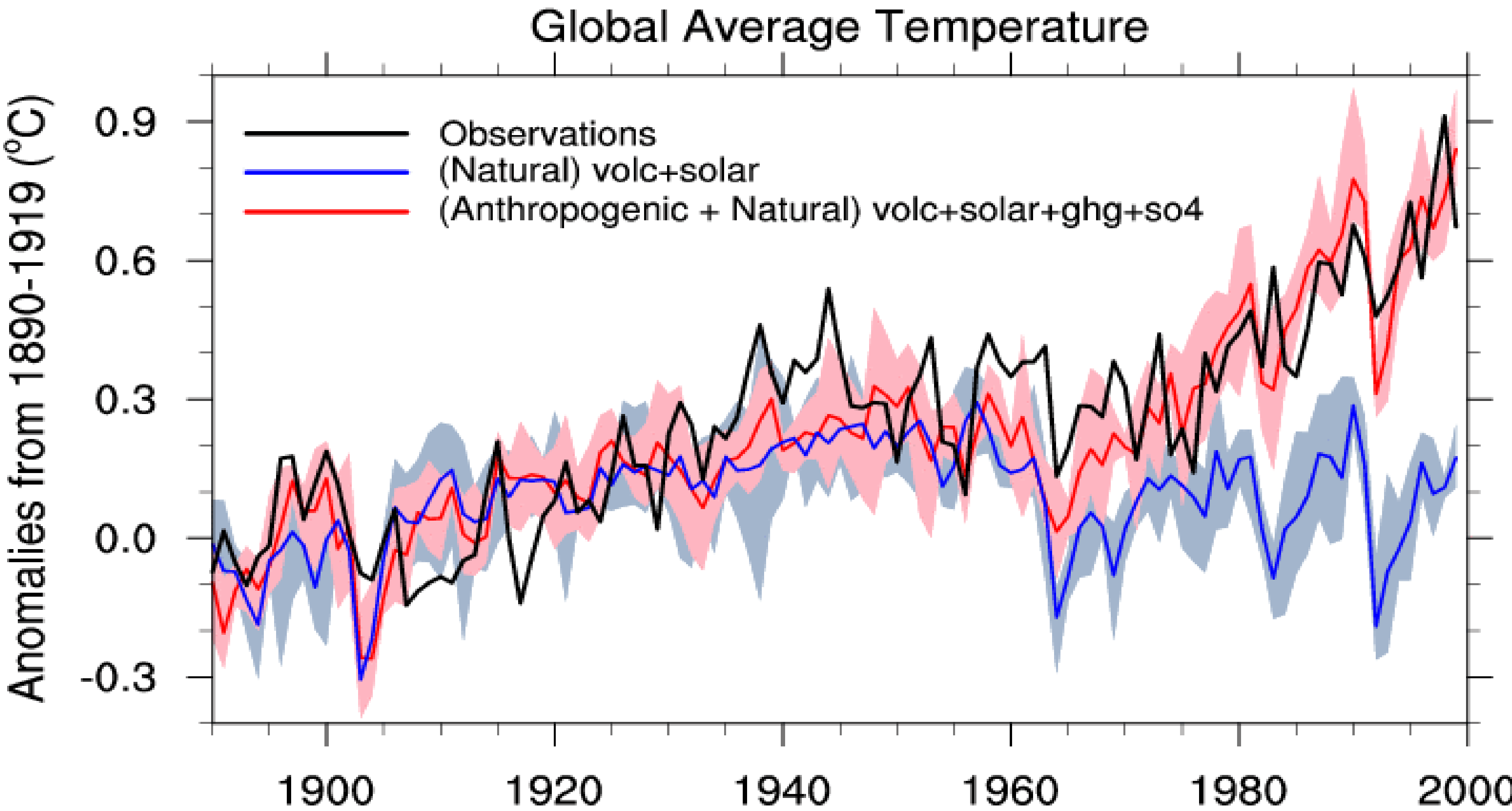
Atmospheric Carbon Dioxide Concentration and Temperature Change
750
700
600
500
400
300
250
200
Carbon dioxide (ppmv)
Current Level
Current Level
4
2
0
-2
-4
-6
Temperature change (°C)
150
100
50
0
Thousands of years ago
CO_2 concentration in the atmosphere (Antarctic Ice Core)
Temperature changes through time compared to the present temperature
CO_2
Temp.

Modeling the Climate System

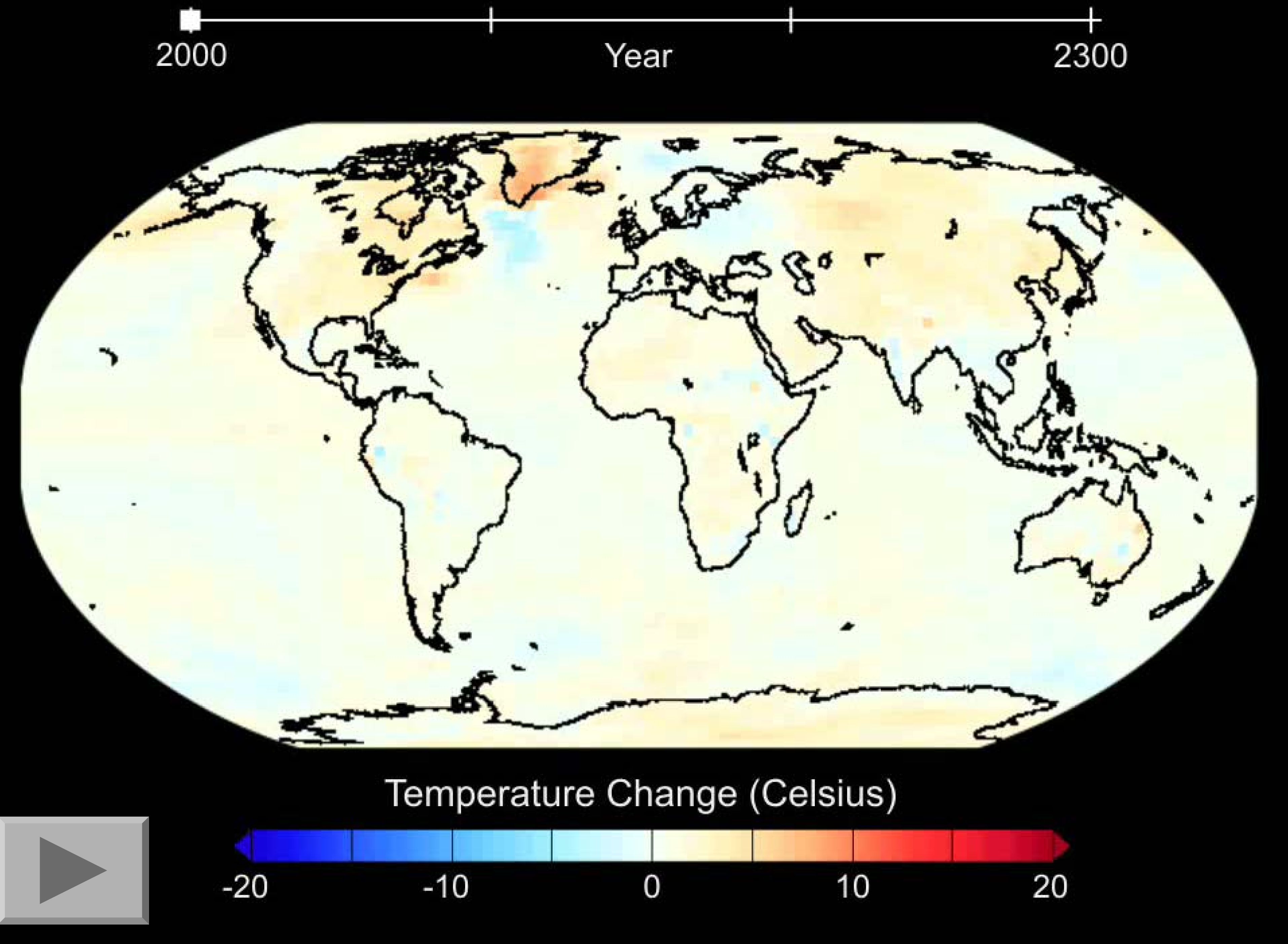


Karl and Trenberth 2003

Natural forcings do not account for observed 20th century warming after 1970

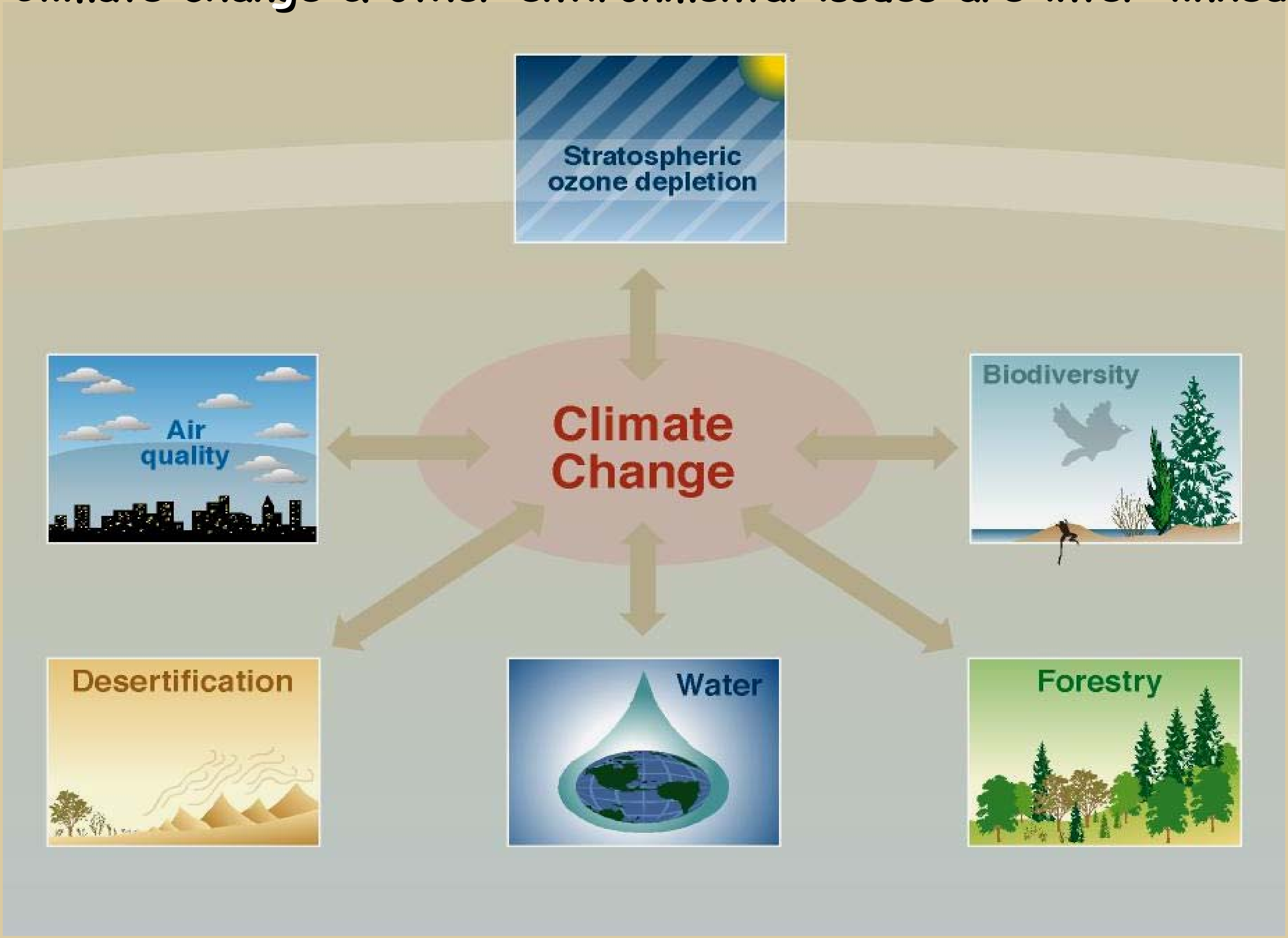


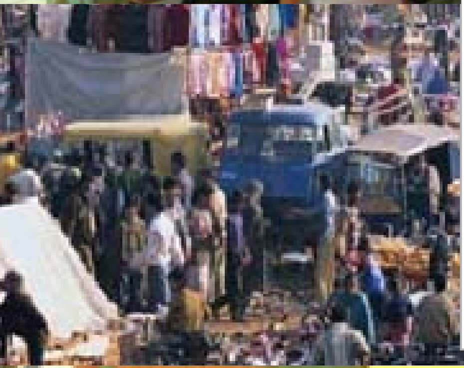
Meehl et al, 2004: J. Climate.

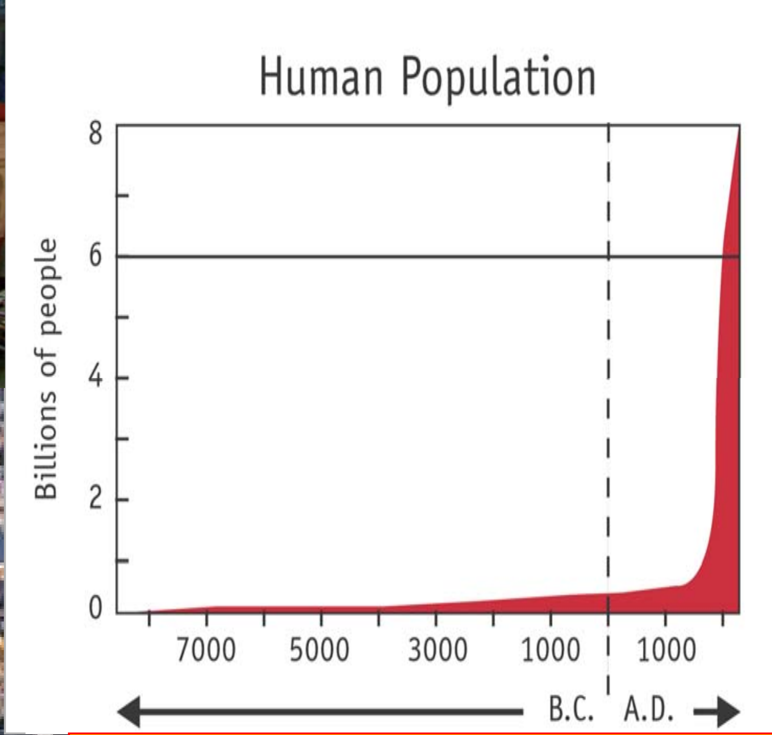


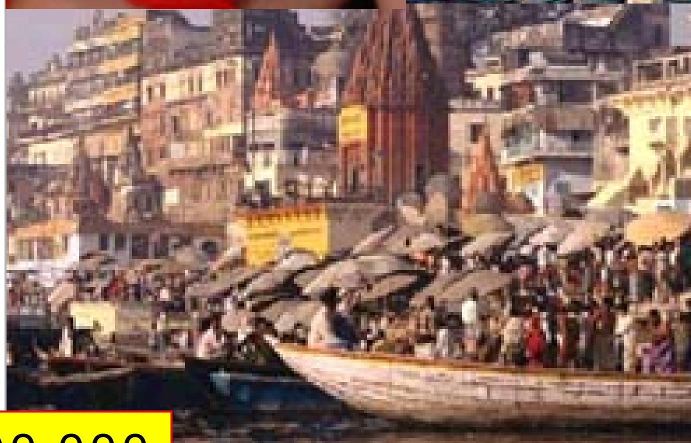
2000
Year
2300
Temperature Change (Celsius)
-20
-10
0
10
20

Climate change & other environmental issues are inter-linked

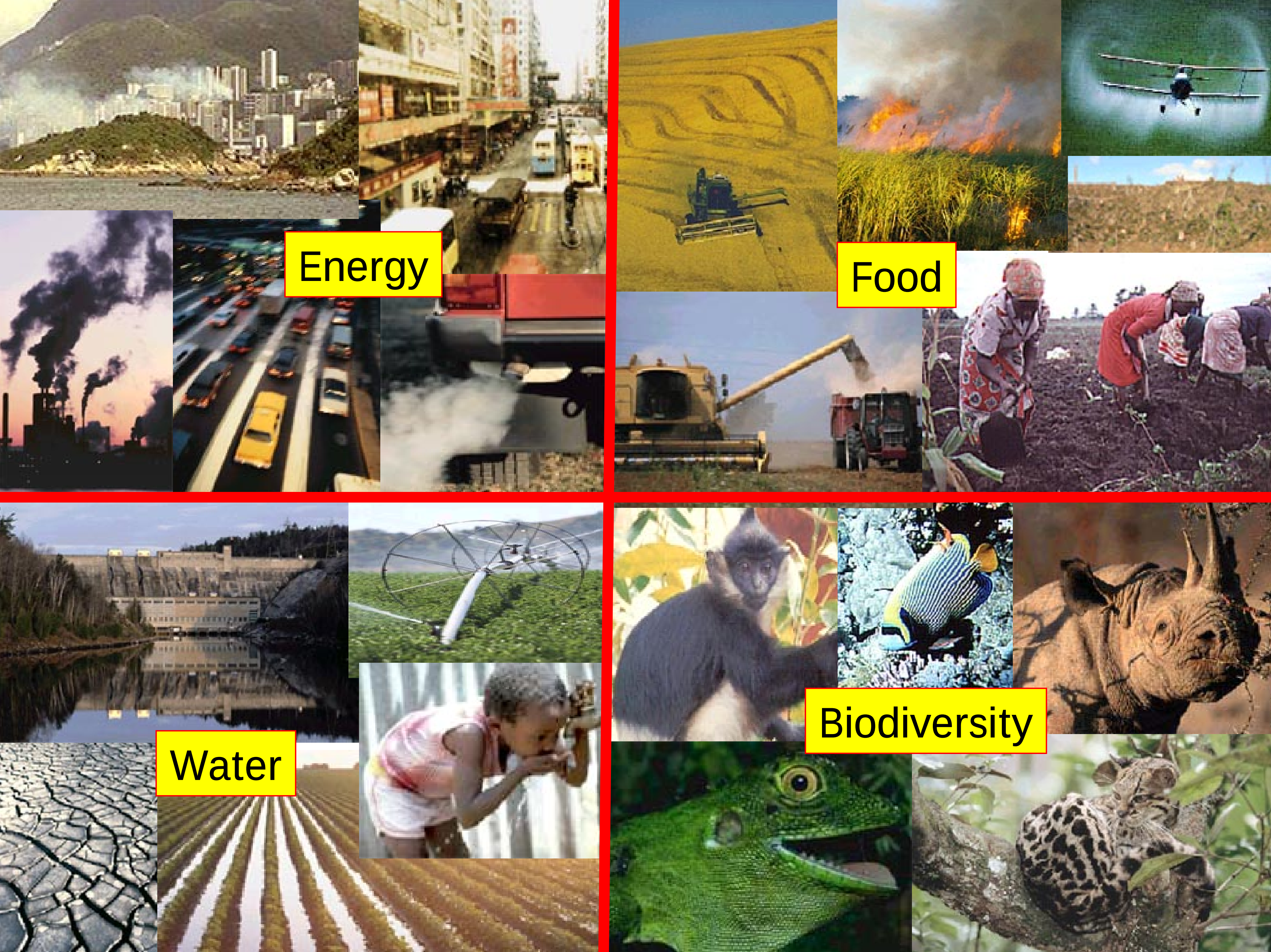








World Population 6,640,000,000


Energy
Food
Water
Biodiversity

Agricultural Lands | Coastal Zones | Forest Lands | Freshwater Systems | Arid Lands Grasslands

Food and Fiber Production

Provision of Clean and Sufficient Water

Maintenance of Biodiversity

Maintenance of Human Health

Storage and cycling of Carbon, Nitrogen, Phosphorus

Climate change will affect the ability of ecological systems to provide essential ecological goods and services

Food production needs to double to meet the needs of an additional 3 billion people in the next 30 years

Climate change is projected to decrease agricultural productivity in the tropics and sub-tropics

Wood fuel is the only source of fuel for one third of the world's population

Wood demand will double in next 50 years

Climate change is projected to increase forest productivity, but forest management will become more difficult, due to an increase in pests and fires

Climate change is projected to decrease water availability in many arid and semi-arid regions

One third of the world's population is now subject to water scarcity

The population facing water scarcity will more than double over the next 30 years

Estimated 10-15% of the world's species could become extinct over the next 30 years

Biodiversity underlies all ecological goods and services

Climate change will exacerbate the loss of biodiversity

The Challenge: Sustainable Management of an Ever-Changing Planet

Global warming actions

There are uncertainties about how climate will change.
But climate will change.
And it could be very disruptive.
There will be substantial costs incurred;
-often by innocent people and countries

The issue is directly linked to

- fossil fuel energy use.
- security (foreign oil imports).
- sustainability.

Oil supplies will be exceeded by demand sooner or later and long before we run out.

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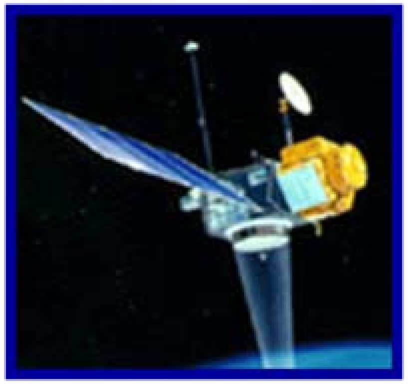
The **challenge** is to better determine the **heat budget** at the **surface of the Earth** on a continuing basis:
Provides for changes in **heat storage of oceans**, glacier and ice sheet melt, changes in SSTs and associated changes in atmospheric circulation, some aspects of which should be **predictable** on decadal time scales.

We need a better observing system!



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The parable of the frog

A frog placed in a pot of hot water, immediately jumps out to save himself.

But a frog placed in a pot of cold water that is slowly brought to the boil, remains in the pot and dies!

Is this a parable for global warming?