# The Global Water Cycle

OCN 401
November 12, 2015

# Lecture Outline

1. The Global Water Cycle
   - Processes
   - Reservoirs and Fluxes
   - Composition

2. Models of the Hydrologic Cycle

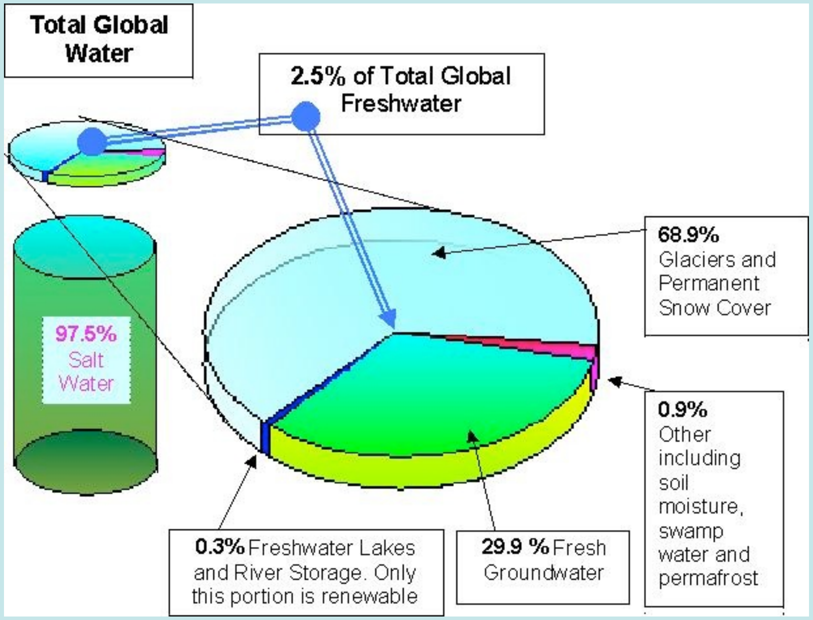
3. The History of the Water Cycle
   - Where did planetary water come from?
   - What happened to the degassed water?
   - What has been the geologic history of sea level?

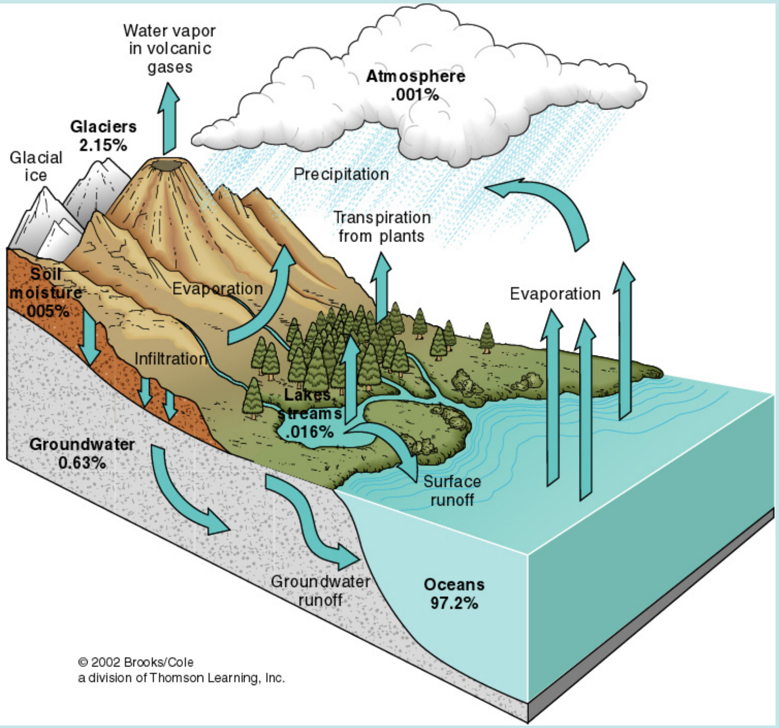
4. The Water Cycle under Scenarios of Future Climate
   - primary productivity
   - socioeconomics

“The annual circulation of $H_2O$ is the largest movement of a chemical substance at the surface of the Earth”

## The distribution of water at the Earth's surface

| | **% of total** |
|---|---|
| Oceans | 97.25 |
| Ice caps and glaciers | 2.05 |
| Groundwater | 0.68 |
| Lakes | 0.01 |
| Soils | 0.005 |
| Atmosphere (as vapor) | 0.001 |
| Rivers | 0.0001 |
| Biosphere | 0.00004 |
| **Total** | **100 %** |





# Origin of water on Earth

Water was delivered to primitive Earth by planetesimals, meteors and comets (Chap. 2) during its accretionary phase, which was largely complete by 3.8 billion years ago (Ga)

Water was released from Earth's crust in volcanic eruptions (degassing), but remained in the atmosphere as long as Earth's surface temperature was >100°C

Once Earth cooled below 100°C, most water condensed to form the oceans

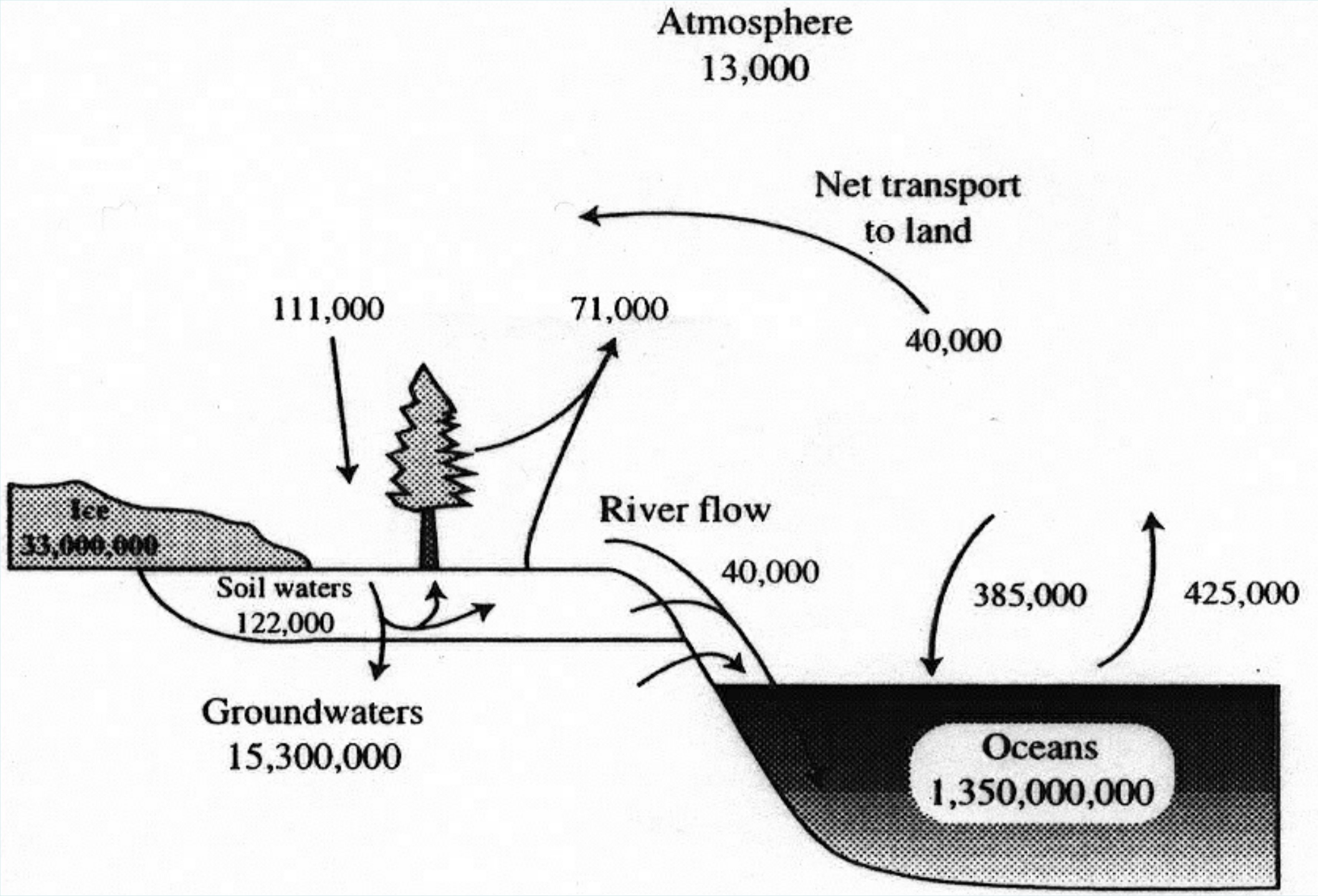
Enough water vapor and $CO_2$ remained in the atmosphere to keep the temperature of Earth's surface above freezing; without this Greenhouse effect the Earth might have remained frozen, like Mars.

There is good evidence of liquid water on Earth at 3.8 bya, and the volume of water has not changed appreciably since then.

# Global water cycle and reservoirs

Units = km$^3$ and km$^3$/yr

1 km$^3$ = 1x 10$^{12}$ L



# The Global Water Cycle: Fluxes and Residence Times

- Using estimates of the reservoir size and the magnitude of fluxes between reservoirs, can calculate the **residence time ($\mathbf{T_r}$)** of water in each reservoir:

  - The $T_r(H_2O)$ of the ocean with respect to the atmosphere:
    $1350 \text{ km}^3 / 0.425 \text{ km}^3/\text{y} = 3{,}176 \text{ y}$

  - The $T_r(H_2O)$ of the ocean with respect to rivers:
    $1350 \text{ km}^3 / 0.04 \text{ km}^3/\text{y} = 33{,}750 \text{ y}$

  - The $T_r(H_2O)$ of soil water with respect to ppt or ET:
    $122 \text{ km}^3 / 71\text{km}^3/\text{y} = 1 \text{ y}$

# “Potential Evapotranspiration”

Average evaporation = 100 cm/yr$^{-1}$
Average precipitation on land = 70cm/yr$^{-1}$
Evaporation + transpiration
returns ~ 70% to atmosphere

Large global differences
Evaporation 4 mm d$^{-1}$ tropics
<1 mmd$^{-1}$ at poles

Tropical rainforests
precipitation > evaporation = river run-off

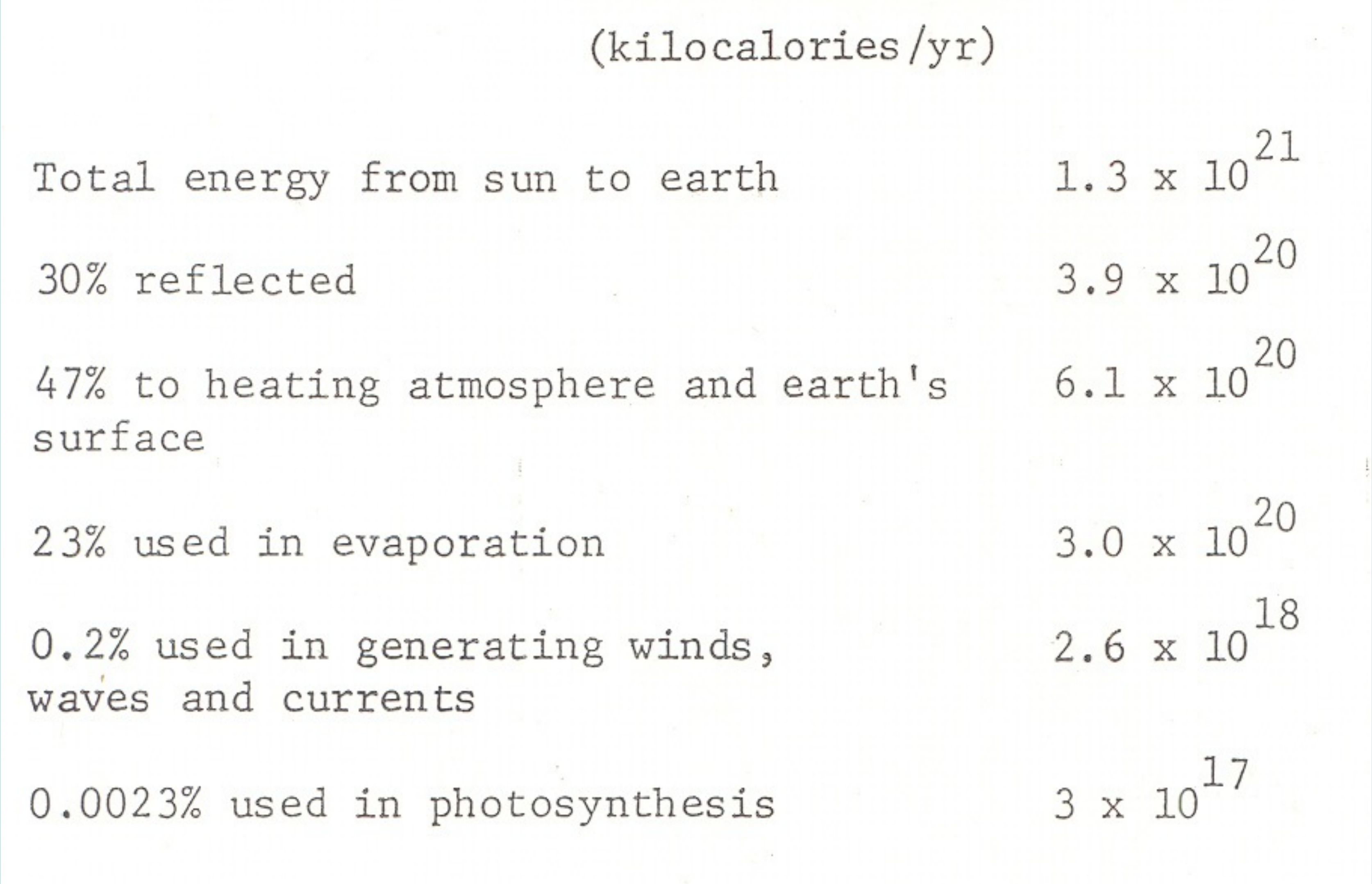
Deserts
precipitation = evaporation - no run off

**Figure 8.7** The water cycle in the Amazonian rain forest. Of the rain that falls, 75% of it returns to the atmosphere to be available again for precipitation, and 25% runs off in river flow.

Most rainfall in the Amazon Basin derives from evapotranspiration within the basin

Importance of ET implies long-term implications of deforestation for this region

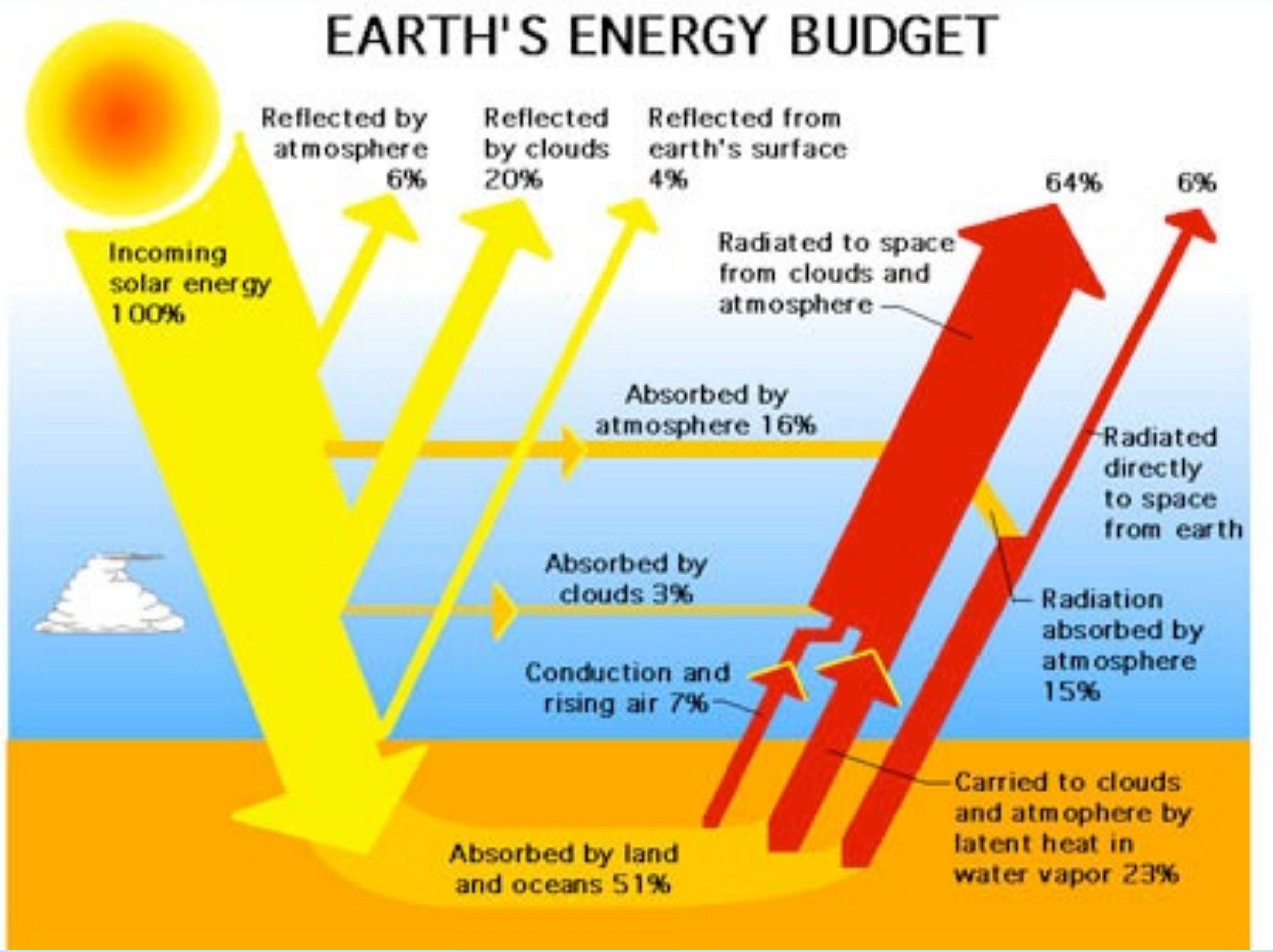
# Solar Energy Budget



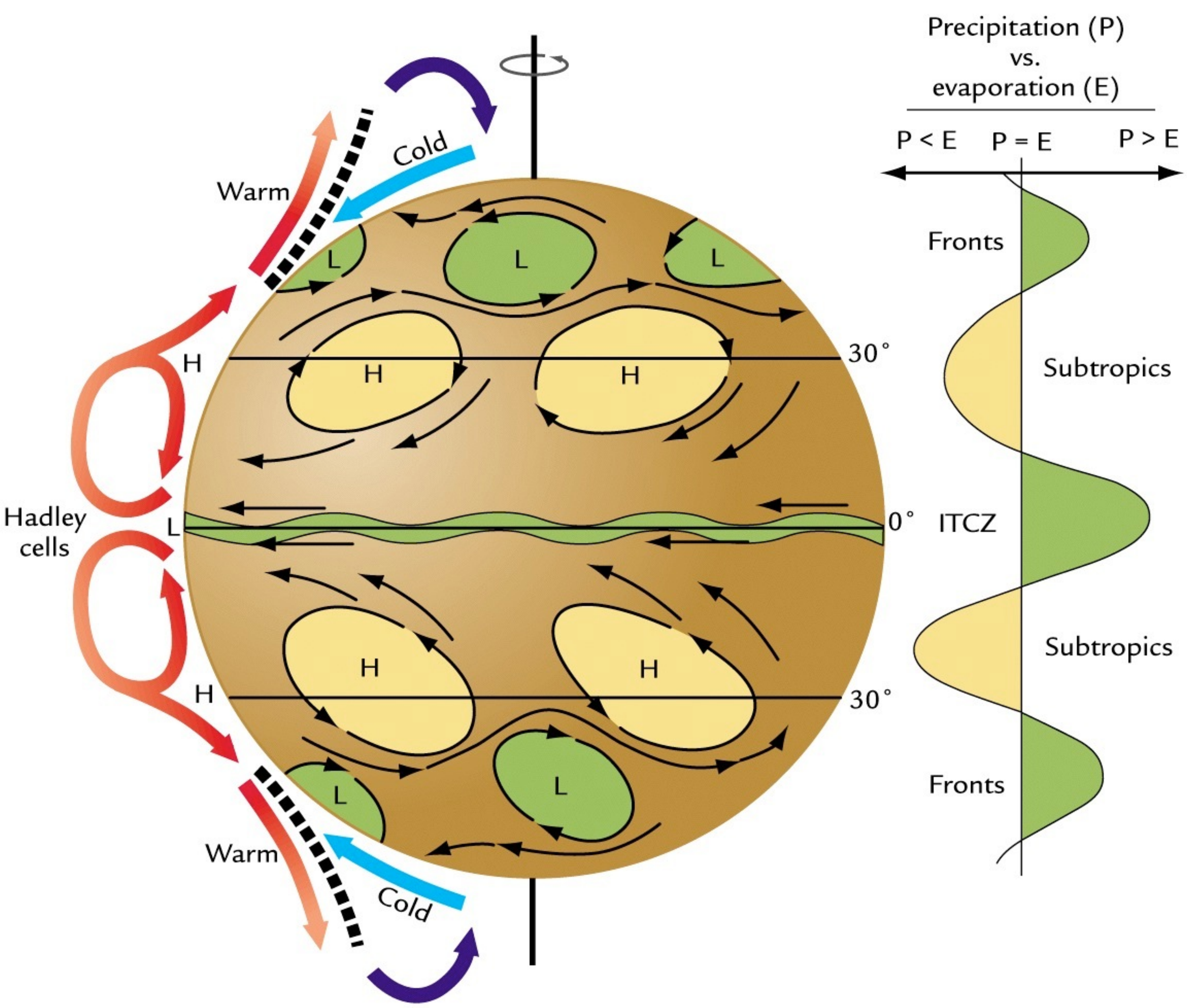
| | (kilocalories/yr) |
|---|---|
| Total energy from sun to earth | $1.3 \times 10^{21}$ |
| 30% reflected | $3.9 \times 10^{20}$ |
| 47% to heating atmosphere and earth's surface | $6.1 \times 10^{20}$ |
| 23% used in evaporation | $3.0 \times 10^{20}$ |
| 0.2% used in generating winds, waves and currents | $2.6 \times 10^{18}$ |
| 0.0023% used in photosynthesis | $3 \times 10^{17}$ |

70% of the sun’s energy is absorbed at the Earth’s surface, where it drives the hydrologic cycle.

# Solar Energy Budget



# Three-cell model of atmospheric circulation

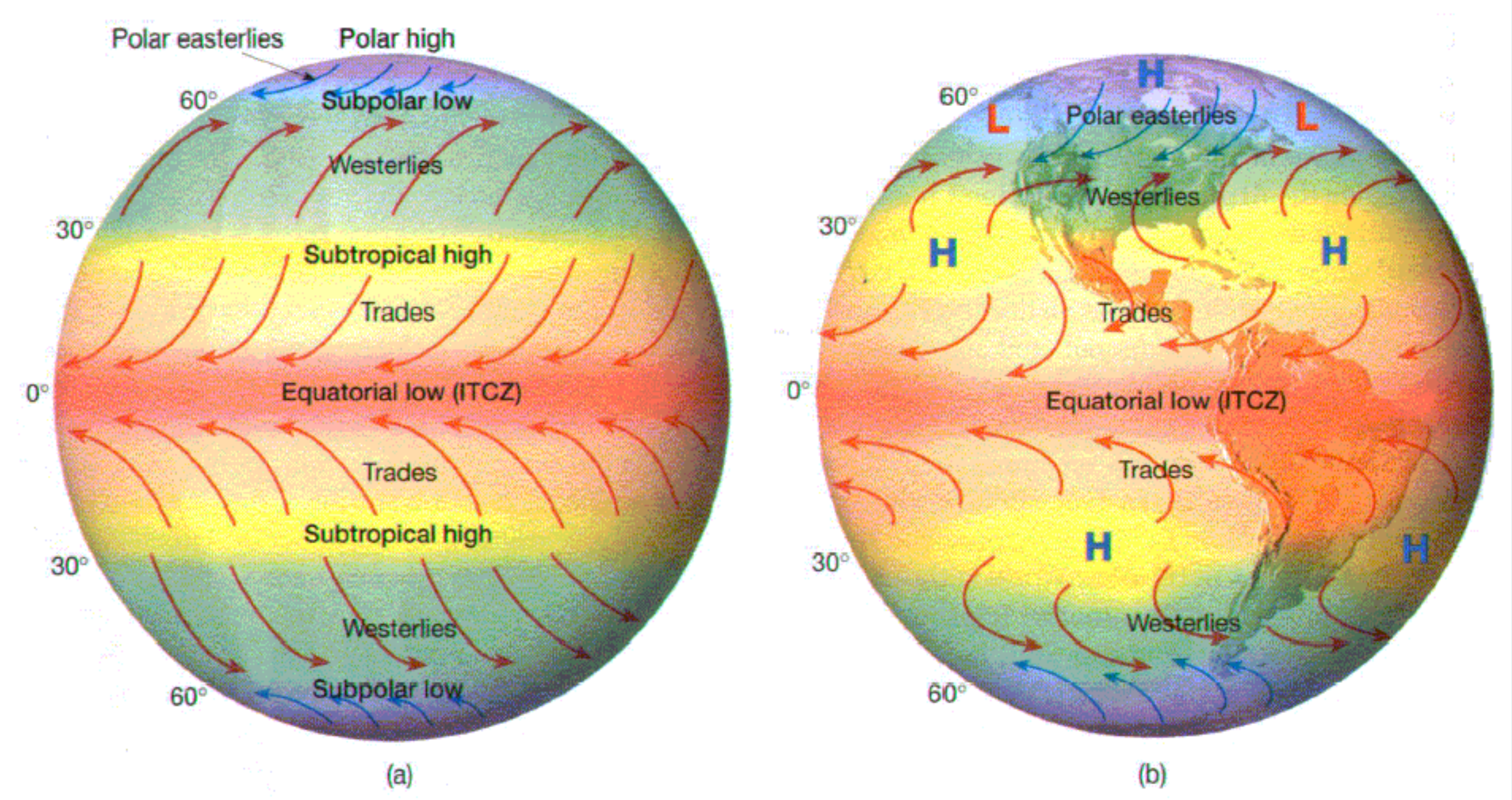


(1) **Polar cells**

**(2) Midlatitude cells**

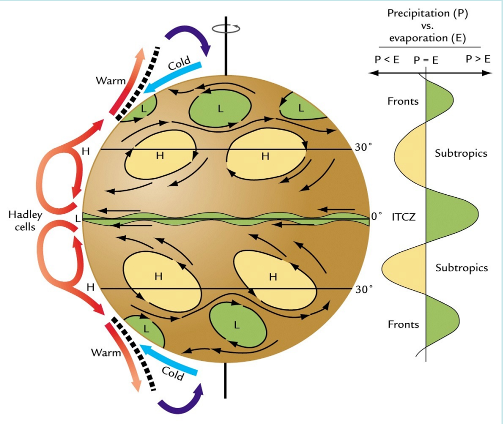
**(3) Hadley cells**

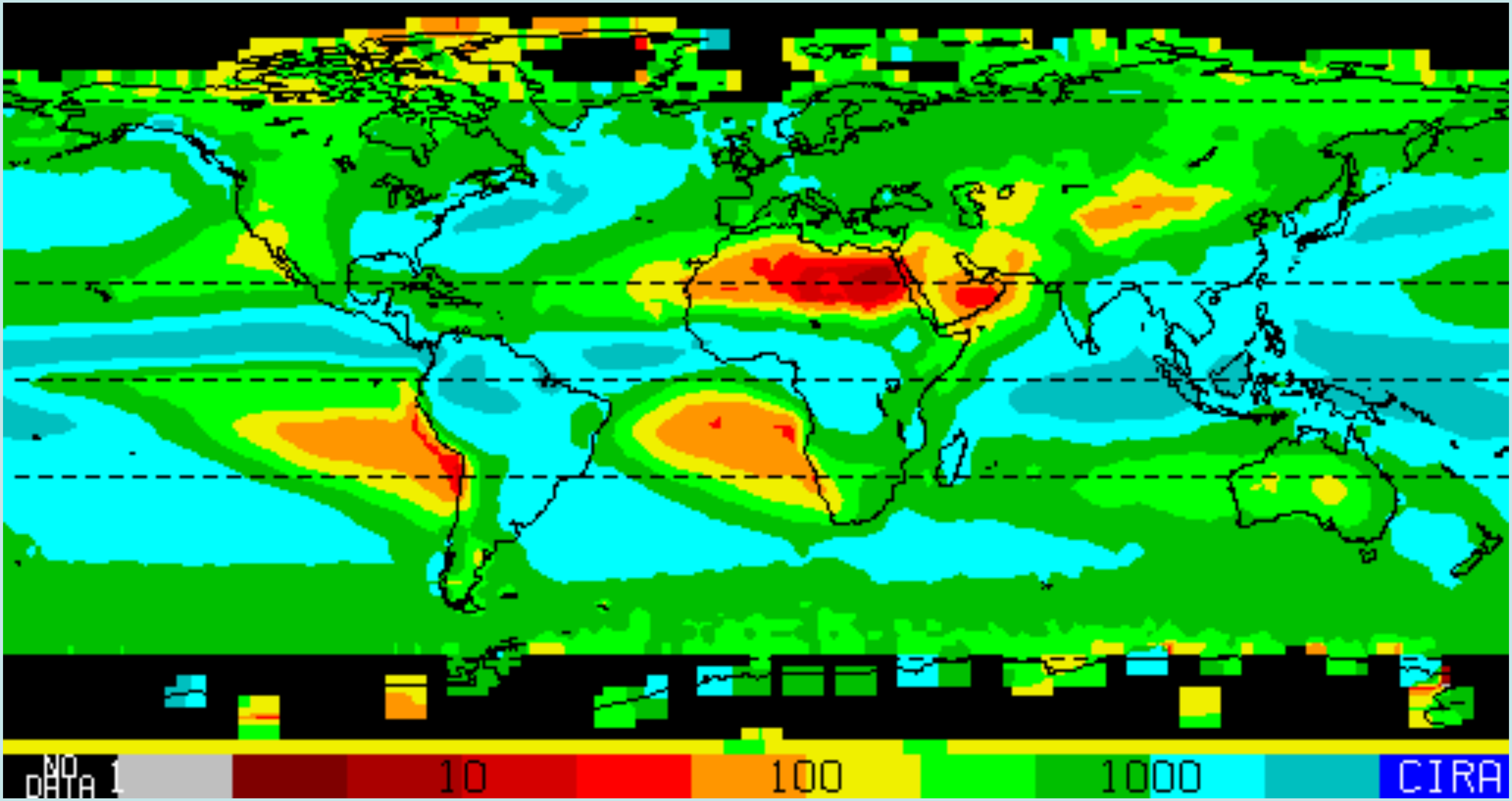
# Idealized vs. actual zonal pressure belts



**Non-uniform surface = uneven heating**
**Unstable windflow = eddies**
**Sun doesn't remain over the equator year-round = 23.5N-23.5S**

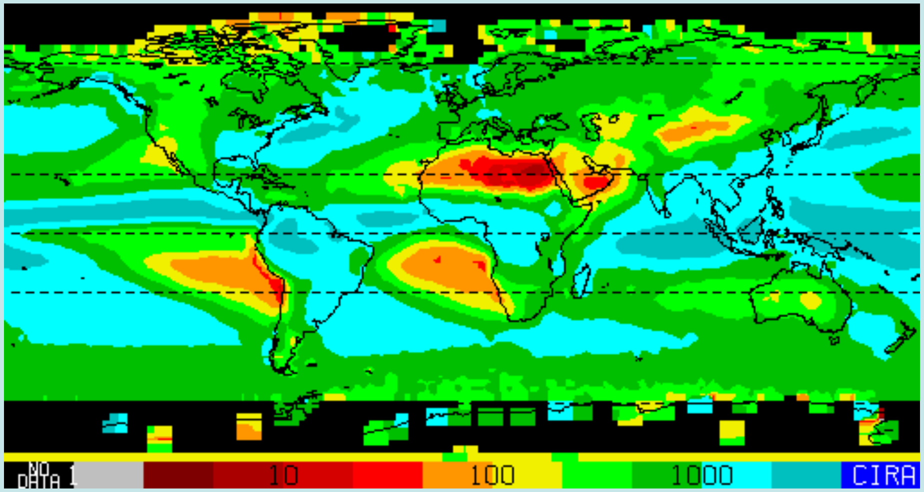
# Movement of $H_2O$ through the atmosphere determines the distribution of rainfall; global average precip ~943mm





Eastern continental margins tend to be wet, western margins dry

…why?



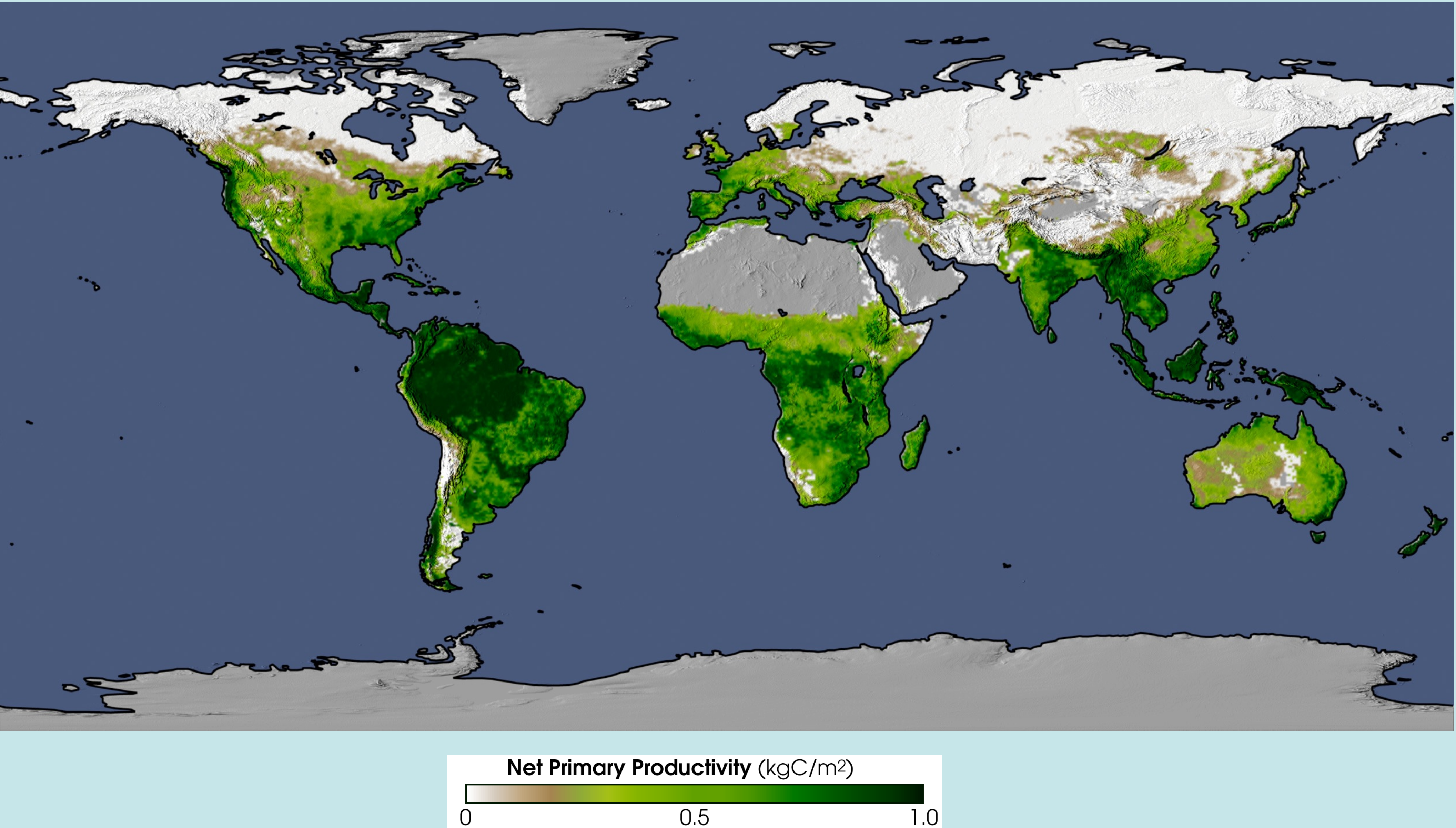
Primary source of water vapor is evaporation from warm tropical & subtropical oceans

In tropics & subtropics, winds are primarily from the east (Trades), carrying moist ocean air toward eastern margins of continents

On east side of continents, heating by land or flow over elevation causes air to rise, forming clouds and precipitation

Air flowing over the west side of the continents and adjoining eastern oceans has already been depleted of much of its water vapor & precipitation potential; e.g., Taiwan, Madagascar.

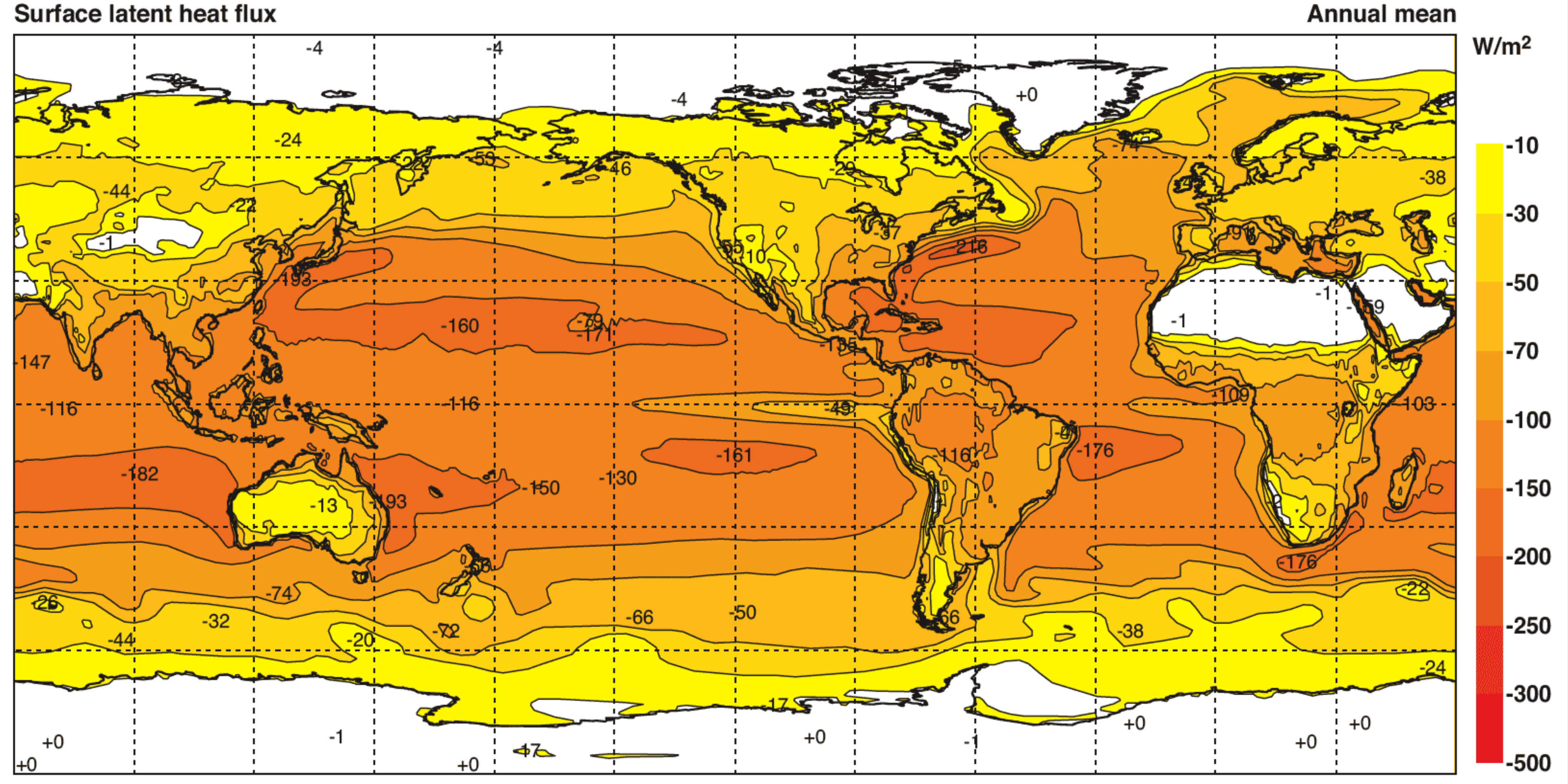
# The availability of $H_2O$ on land is the single most important factor for plant growth. Net Primary Production (NPP) reflects rainfall



Evaporation of water is an important mechanism for transporting excess heat from the tropics to the poles through latent heat of evaporation

Atmosphere transports ~ 50% of the excess heat from the tropics towards the poles

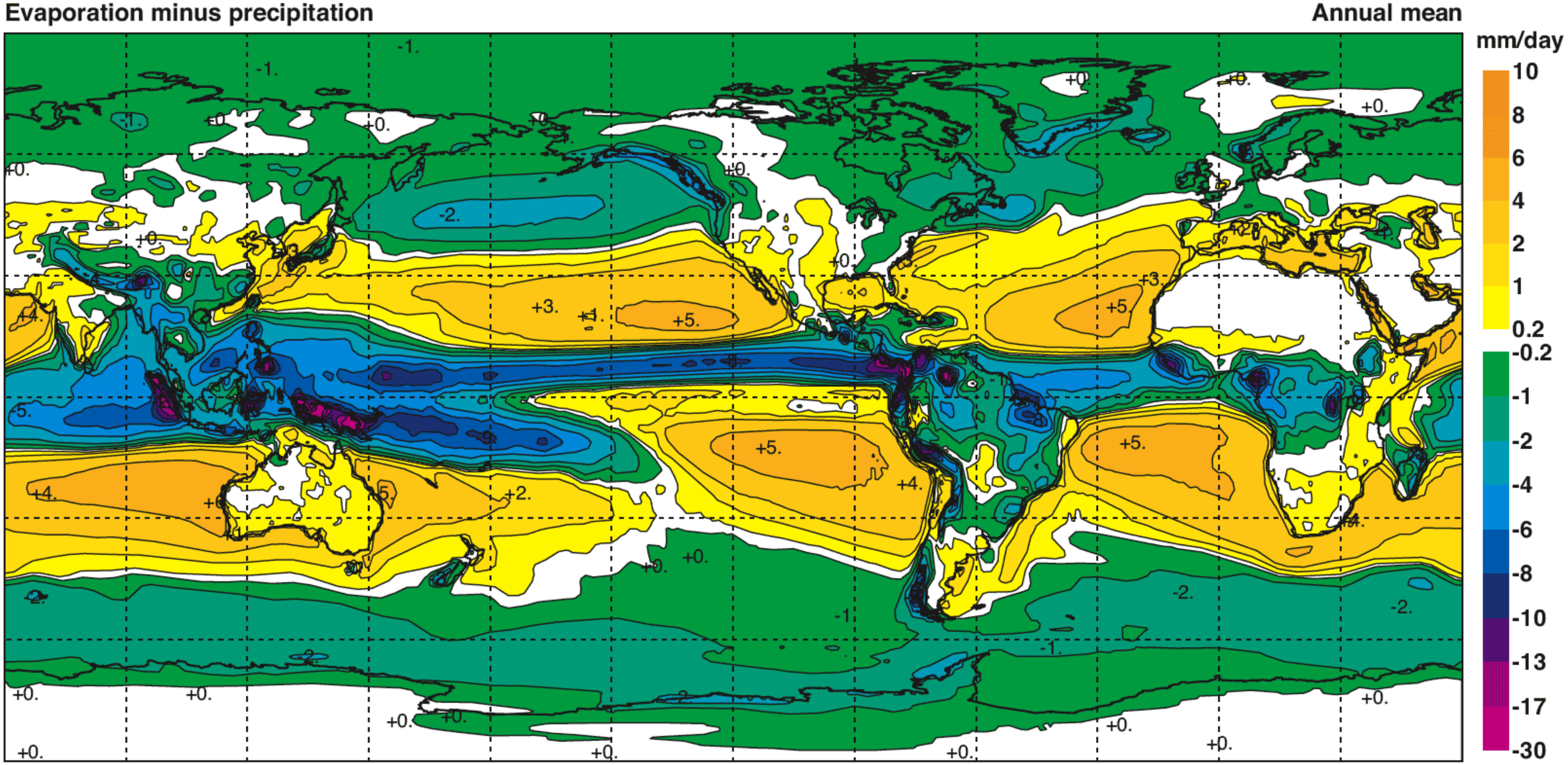
Winds drive surface circulation of the ocean



Surface latent heat flux

Annual mean

# Net evaporation from the surface ocean affects surface water salinity in the ocean and increases surface water density controlling thermohaline circulation of ocean



# Surface water salinity in the Atlantic Ocean

The maxima in evaporation-precipitation results in the highest surface water salinities in the mid-latitudes around 30 N and 30S

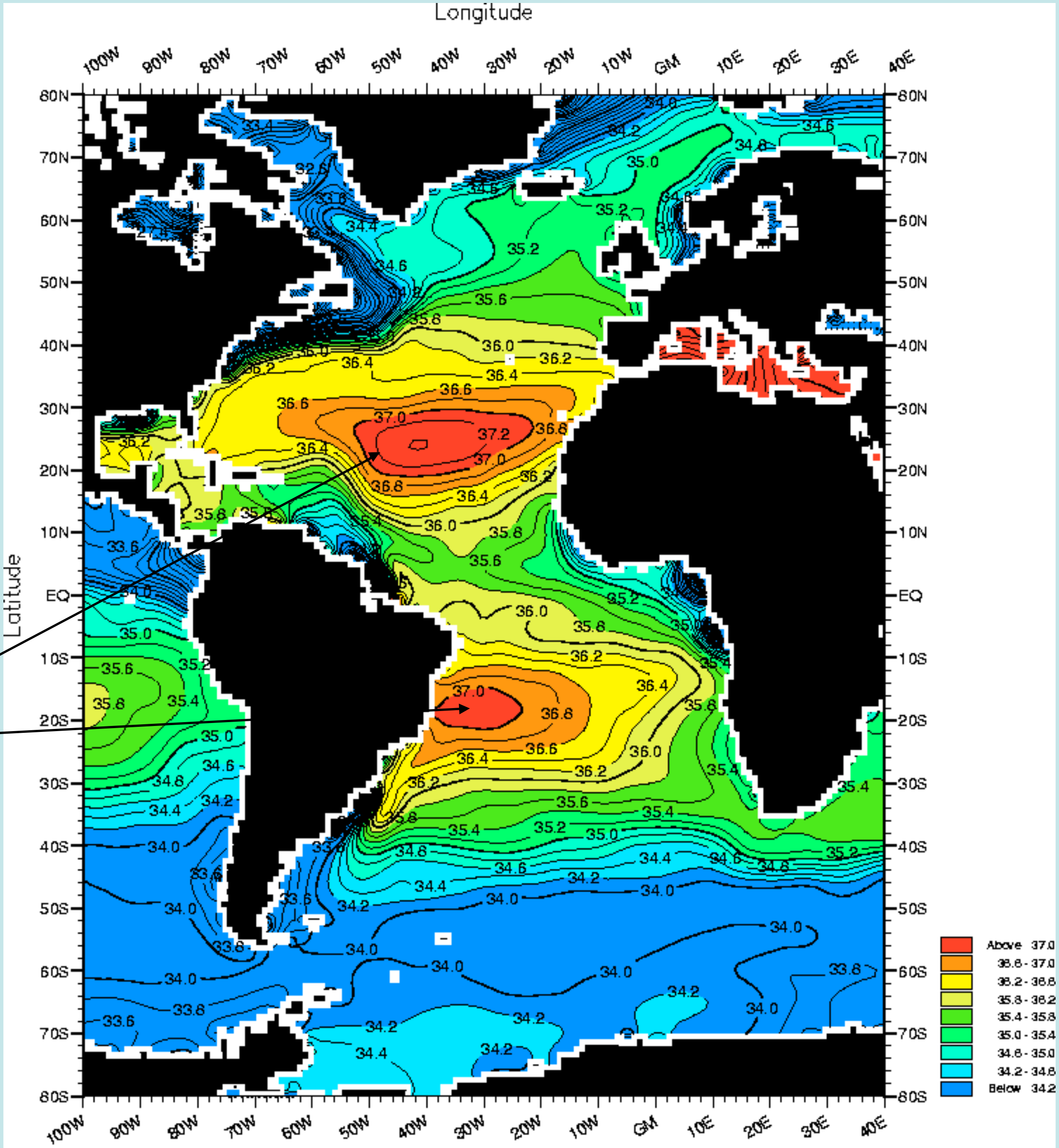
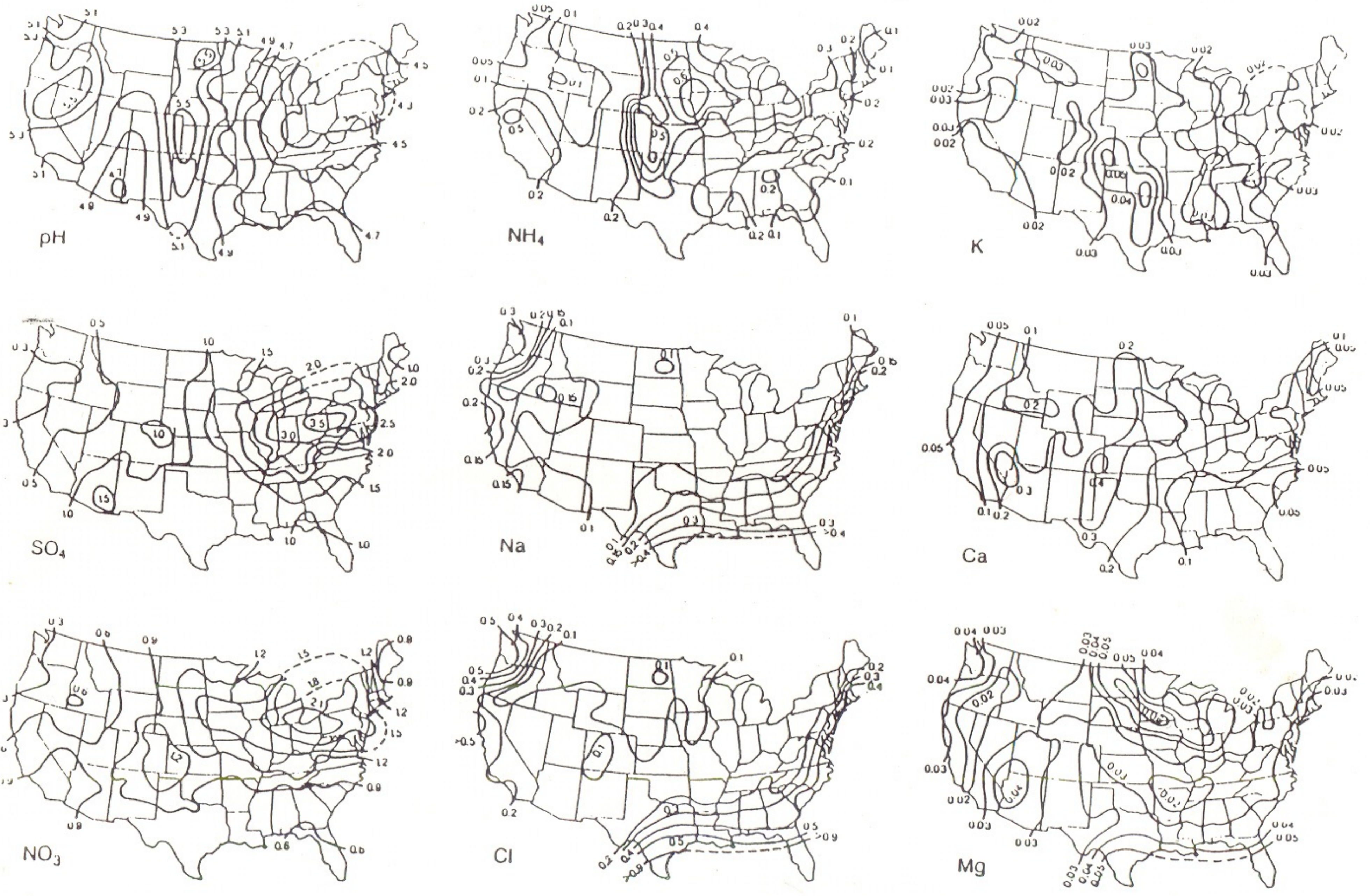


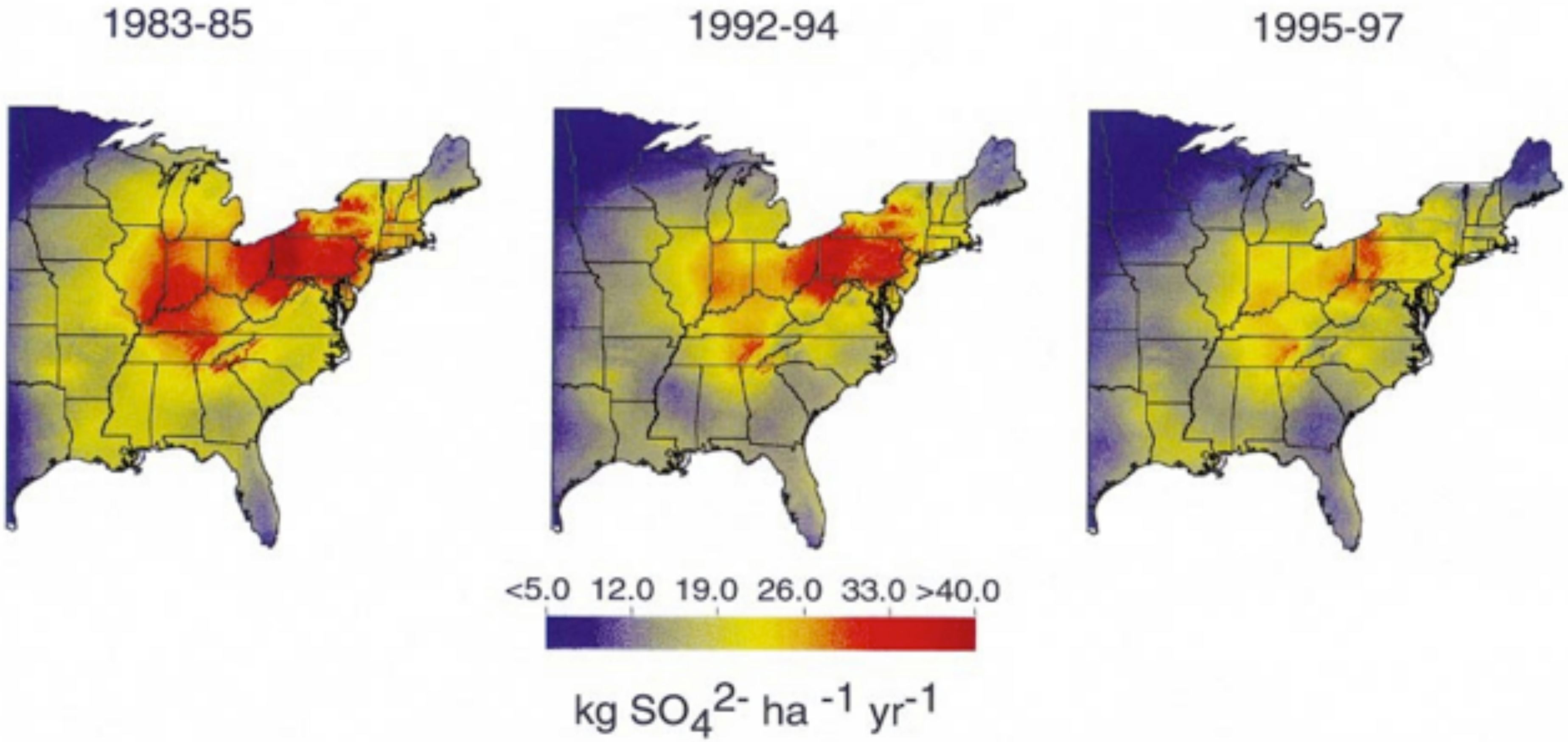
Fig. A2-1. Annual mean salinity (PSS) at the surface.

Minimum Value= 3.57 Maximum Value= 39.76 Contour Interval: 0.20

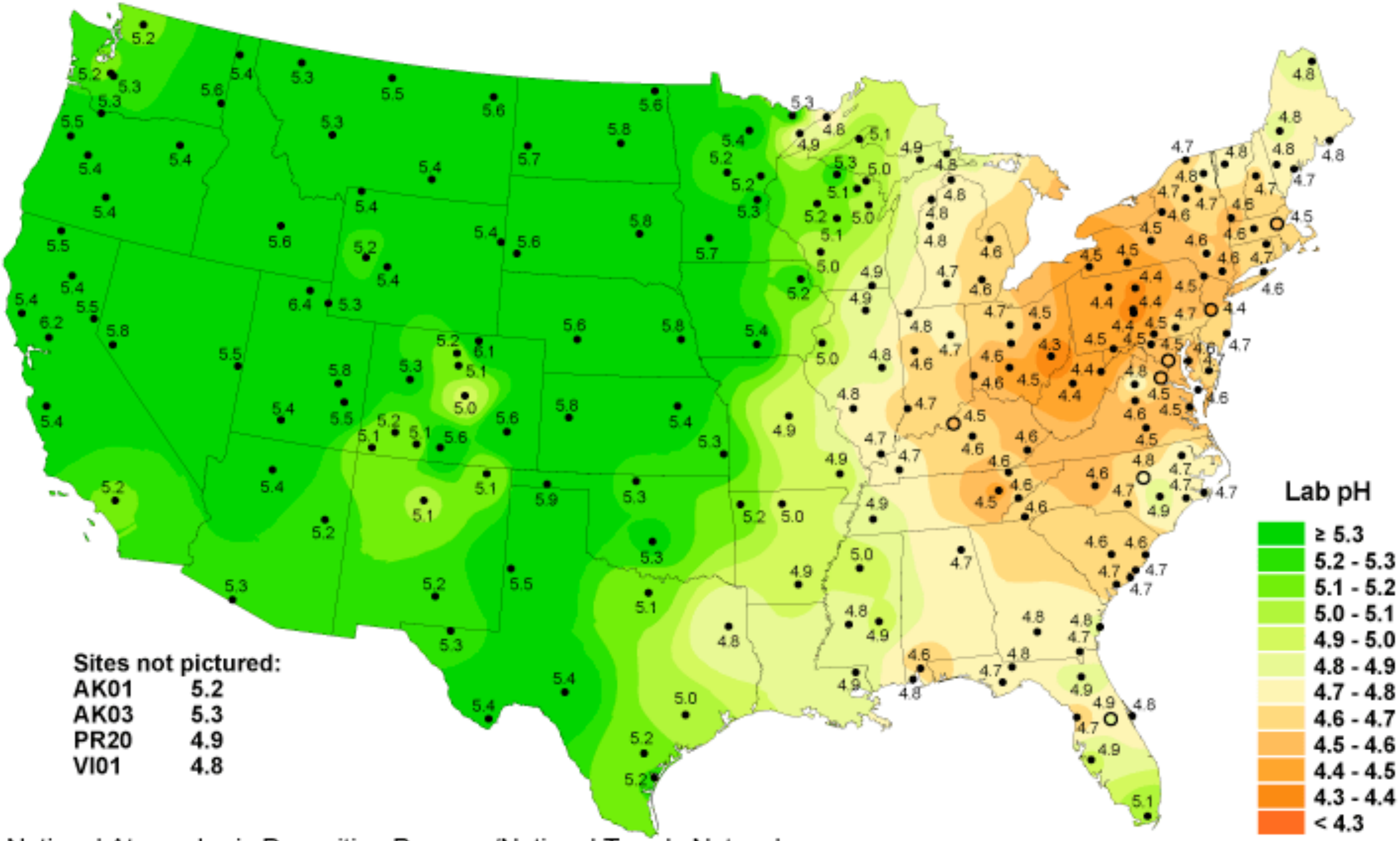
# Composition of precipitation over the continental U.S. --oceanic sources as well as land-based ones



# Sulfate Wet Deposition



# Hydrogen ion concentration as pH from measurements made at the Central Analytical Laboratory, 2006

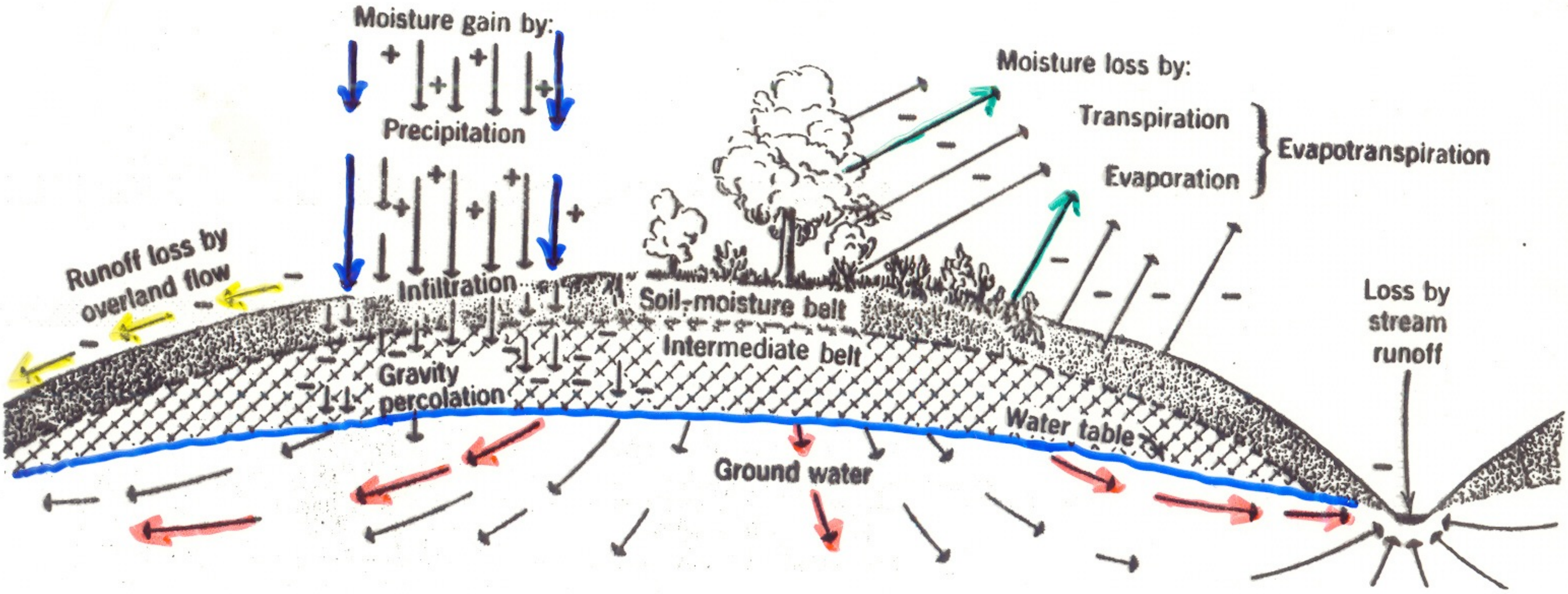


**Sites not pictured:**

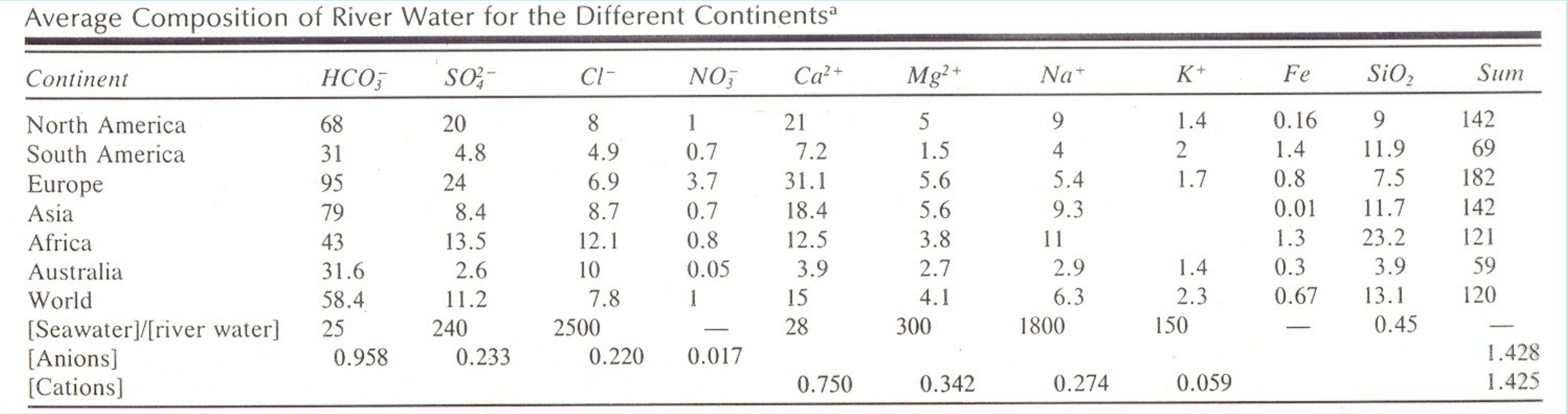
| | |
|---|---|
| AK01 | 5.2 |
| AK03 | 5.3 |
| PR20 | 4.9 |
| VI01 | 4.8 |

National Atmospheric Deposition Program/National Trends Network
http://nadp.sws.uiuc.edu

# Pathways of Precipitation once arriving at Earth's Surface

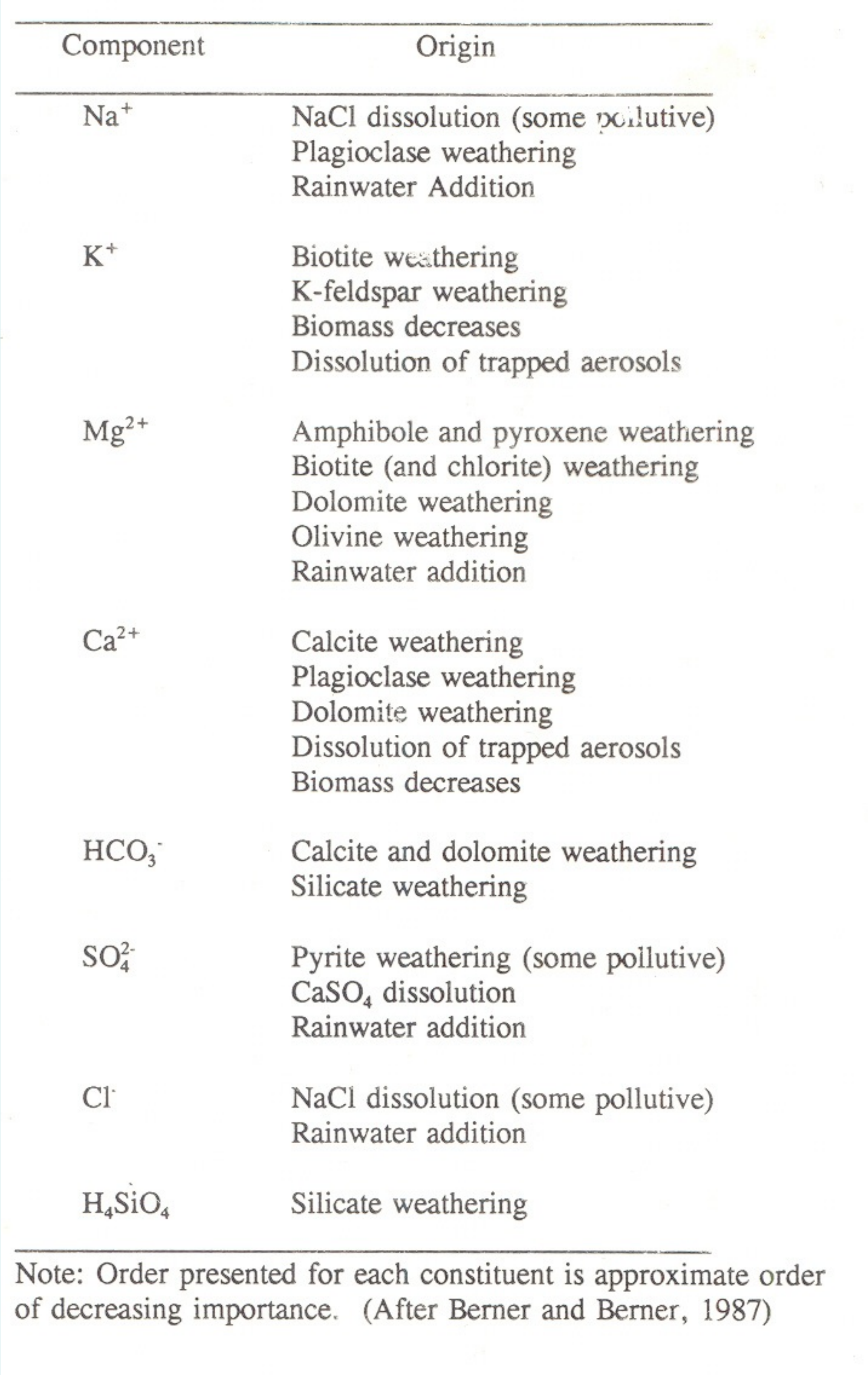


# Interaction of Rainwater with Rocks and Soils at Earth's Surface Alters its Composition



Average Composition of River Water for the Different Continents[a]

| *Continent* | $HCO_3^-$ | $SO_4^{2-}$ | $Cl^-$ | $NO_3^-$ | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+$ | $K^+$ | *Fe* | $SiO_2$ | *Sum* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| North America | 68 | 20 | 8 | 1 | 21 | 5 | 9 | 1.4 | 0.16 | 9 | 142 |
| South America | 31 | 4.8 | 4.9 | 0.7 | 7.2 | 1.5 | 4 | 2 | 1.4 | 11.9 | 69 |
| Europe | 95 | 24 | 6.9 | 3.7 | 31.1 | 5.6 | 5.4 | 1.7 | 0.8 | 7.5 | 182 |
| Asia | 79 | 8.4 | 8.7 | 0.7 | 18.4 | 5.6 | 9.3 |  | 0.01 | 11.7 | 142 |
| Africa | 43 | 13.5 | 12.1 | 0.8 | 12.5 | 3.8 | 11 |  | 1.3 | 23.2 | 121 |
| Australia | 31.6 | 2.6 | 10 | 0.05 | 3.9 | 2.7 | 2.9 | 1.4 | 0.3 | 3.9 | 59 |
| World | 58.4 | 11.2 | 7.8 | 1 | 15 | 4.1 | 6.3 | 2.3 | 0.67 | 13.1 | 120 |
| [Seawater]/[river water] | 25 | 240 | 2500 | — | 28 | 300 | 1800 | 150 | — | 0.45 | — |
| [Anions] | 0.958 | 0.233 | 0.220 | 0.017 |  |  |  |  |  |  | 1.428 |
| [Cations] |  |  |  |  | 0.750 | 0.342 | 0.274 | 0.059 |  |  | 1.425 |

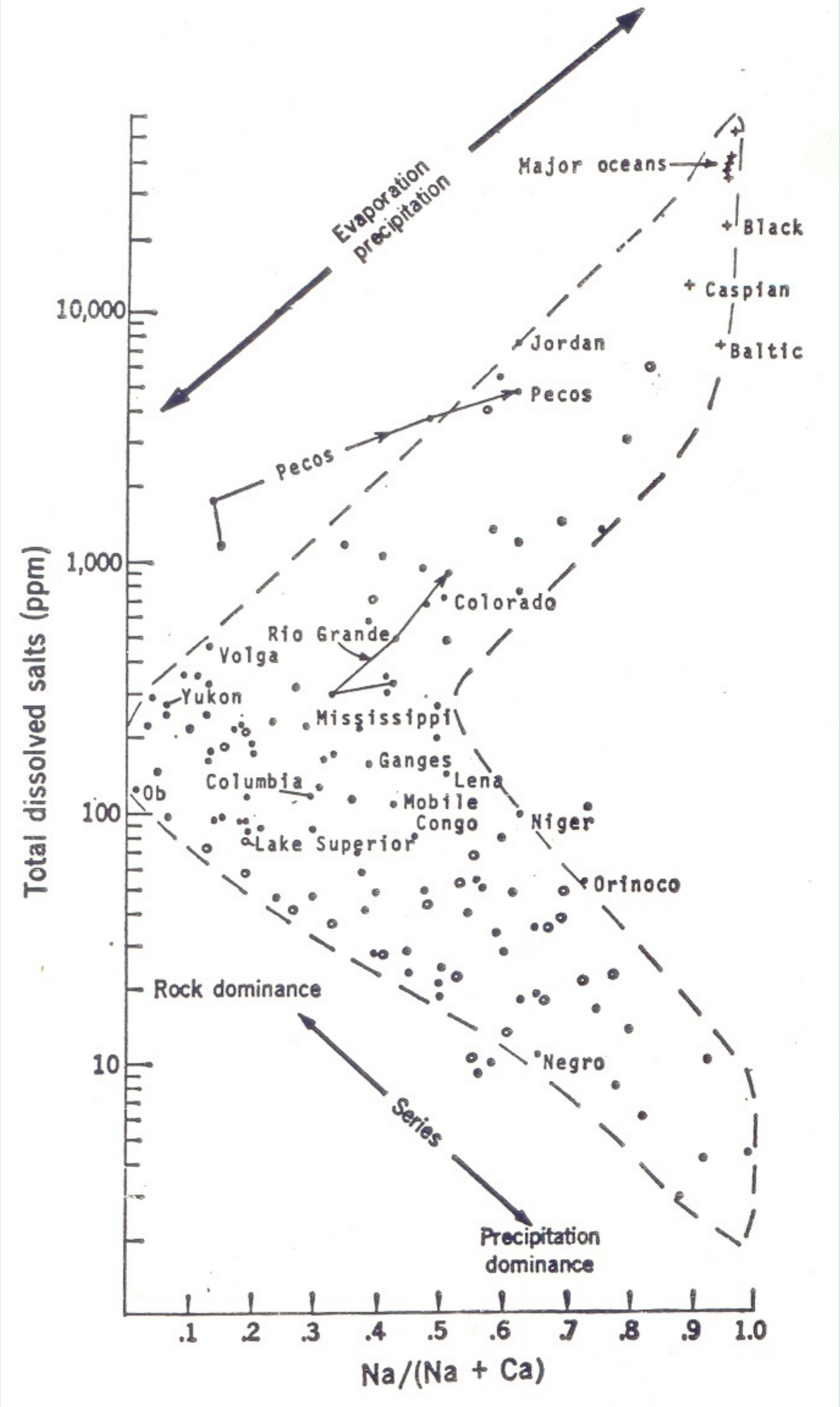


| Component | Origin |
|---|---|
| $Na^+$ | NaCl dissolution (some pollutive) |
| | Plagioclase weathering |
| | Rainwater Addition |
| $K^+$ | Biotite weathering |
| | K-feldspar weathering |
| | Biomass decreases |
| | Dissolution of trapped aerosols |
| $Mg^{2+}$ | Amphibole and pyroxene weathering |
| | Biotite (and chlorite) weathering |
| | Dolomite weathering |
| | Olivine weathering |
| | Rainwater addition |
| $Ca^{2+}$ | Calcite weathering |
| | Plagioclase weathering |
| | Dolomite weathering |
| | Dissolution of trapped aerosols |
| | Biomass decreases |
| $HCO_3^-$ | Calcite and dolomite weathering |
| | Silicate weathering |
| $SO_4^{2-}$ | Pyrite weathering (some pollutive) |
| | $CaSO_4$ dissolution |
| | Rainwater addition |
| $Cl^-$ | NaCl dissolution (some pollutive) |
| | Rainwater addition |
| $H_4SiO_4$ | Silicate weathering |

Note: Order presented for each constituent is approximate order of decreasing importance. (After Berner and Berner, 1987)

Precipitation > evaporation,
= runoff,
the main transporter of
physical and chemical
weathering to the sea

Gibbs (1970) classification of global rivers by composition, linking river TDS to the dominant processes controlling addition of ions to rivers.



# thinking about the global water cycle on a geologic time scale…

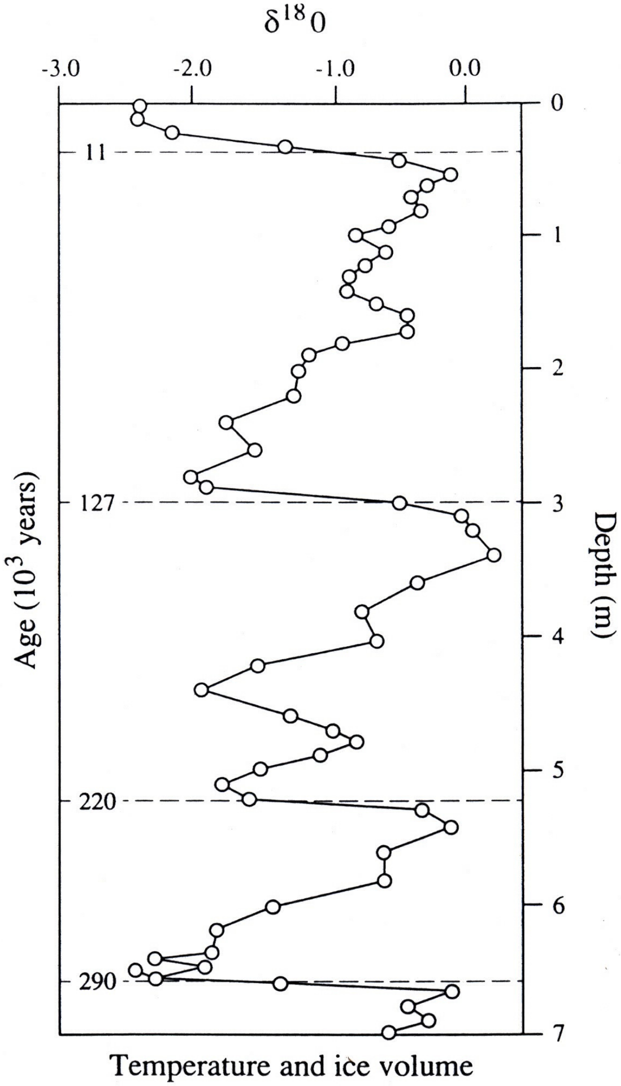


**Figure 9.23** Changes in the $\delta^{18}O$ in sedimentary carbonates of the Caribbean Sea during the last 300,000 years. Enrichment of $\delta^{18}O$ during the last glacial epoch (20,000 ybp) is associated with lower sea levels and a greater proportion of $H_2^{18}O$ in seawater. From Broecker (1973).

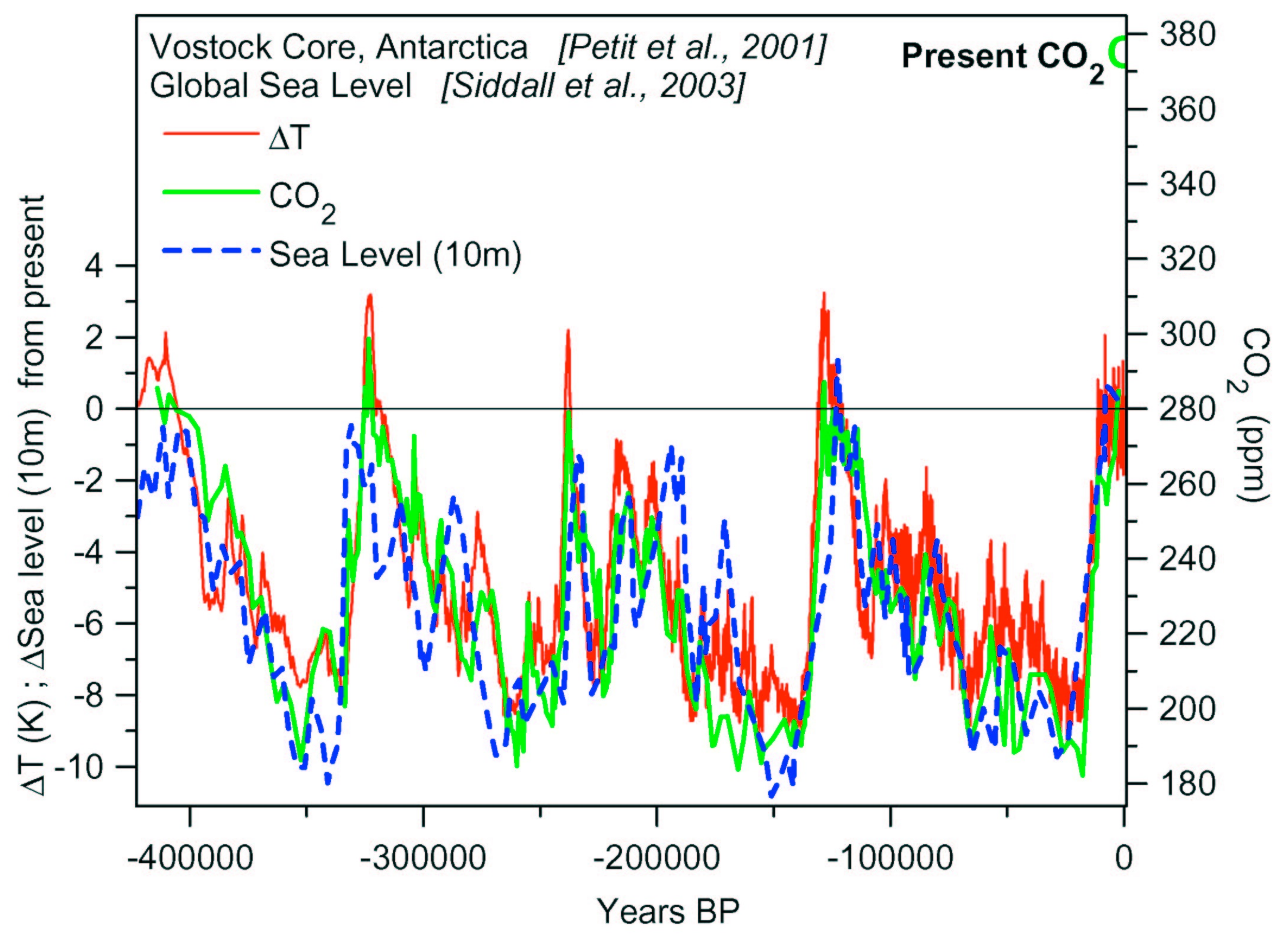
Carbonate precipitation study

$$Ca^{2+} + 2HCO_3^- \text{-->} CaCO_{3(s)} + H_2O + CO_2$$

Preferential evaporation for $^{16}O$ leads to glacial enrichment, and subsequent oceanic enrichment in $^{18}O$

The geologic record shows large changes in ocean volume, as evidenced by del $^{18}O$ of marine carbonates, that accompanied repeated glaciation during the Pleistocene Epoch

During the last peak glaciation (18,000 ybp) 42,000,000 km$^3$ of seawater was trapped in polar ice caps, or 3% of oceans volume, and this lowered sea level by 120 m relative to the present day



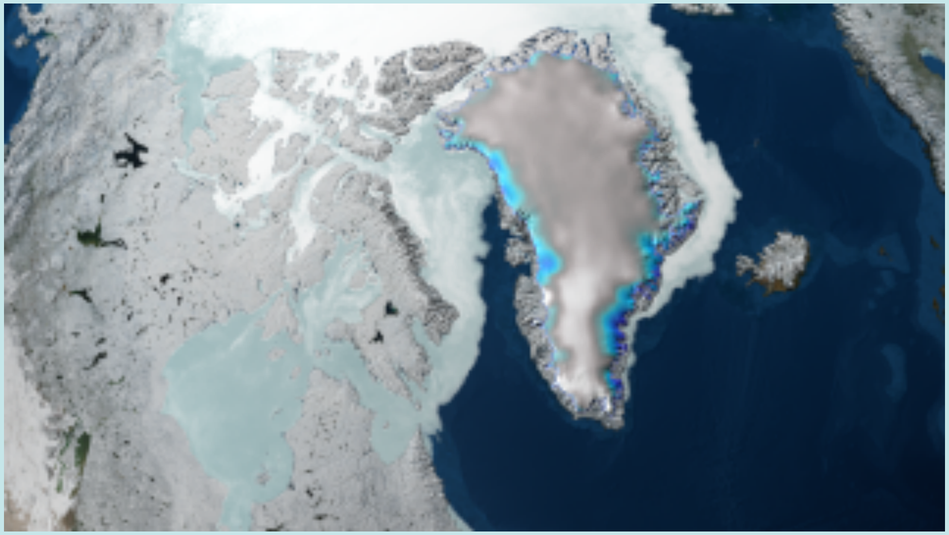
Continental glaciations thus represent a major disruption in the Earth's hydrologic cycle, or a loss of steady state conditions

18,000 ybp estimate total ppt was 14% lower than at present, deserts expanded,  NPP and terrestrial biomass were lower,

Erosion of exposed continental shelf sediments during glacials increased nutrient flux to the ocean, and possibly Fe leading to higher NPP

--possibly creating a positive feedback on lowering $P_{CO2}$

# Melting of glaciers and ice shelves could raise sea levels by 60-80m



Glacier melt increasing sea level, but major effect is thermal expansion

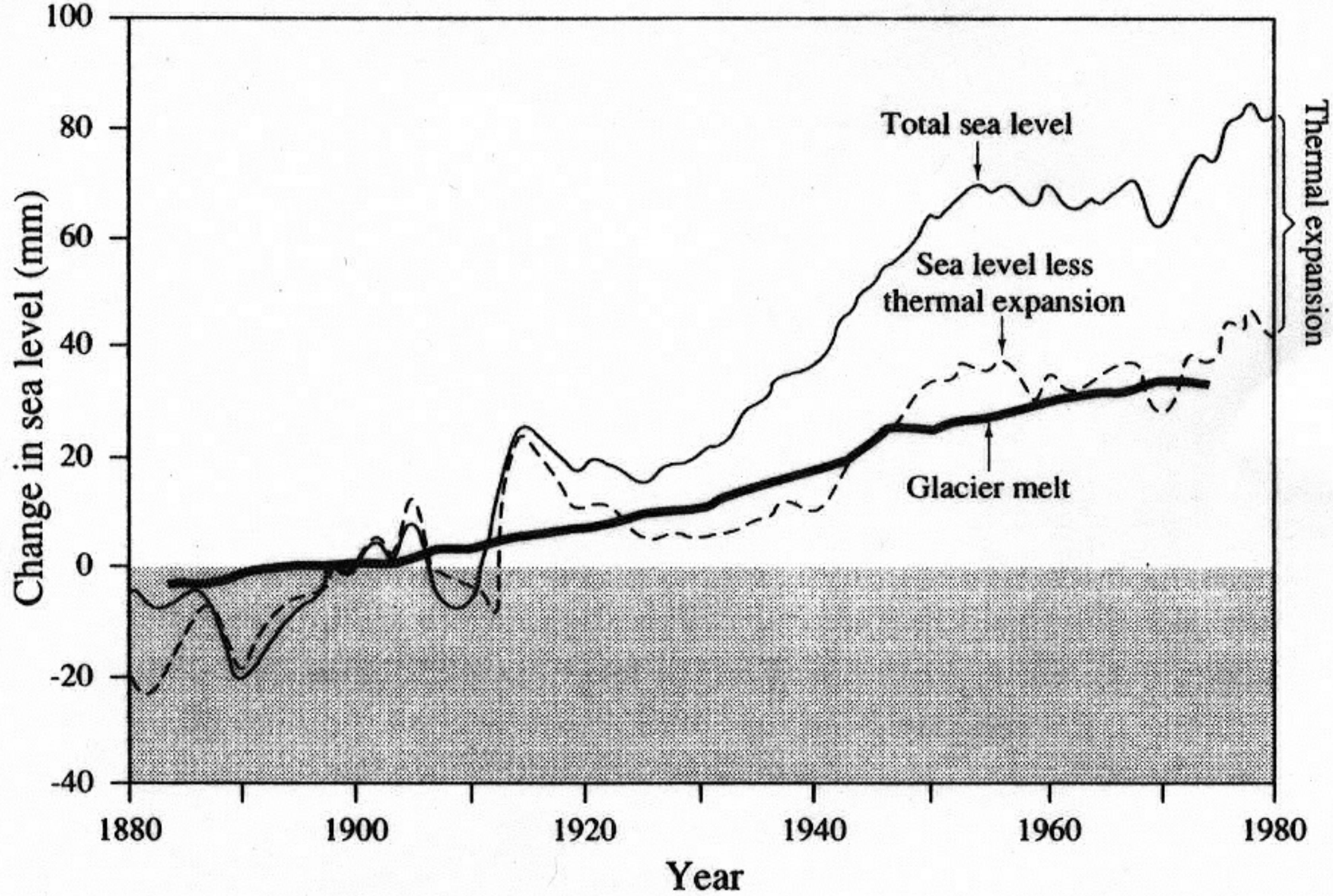
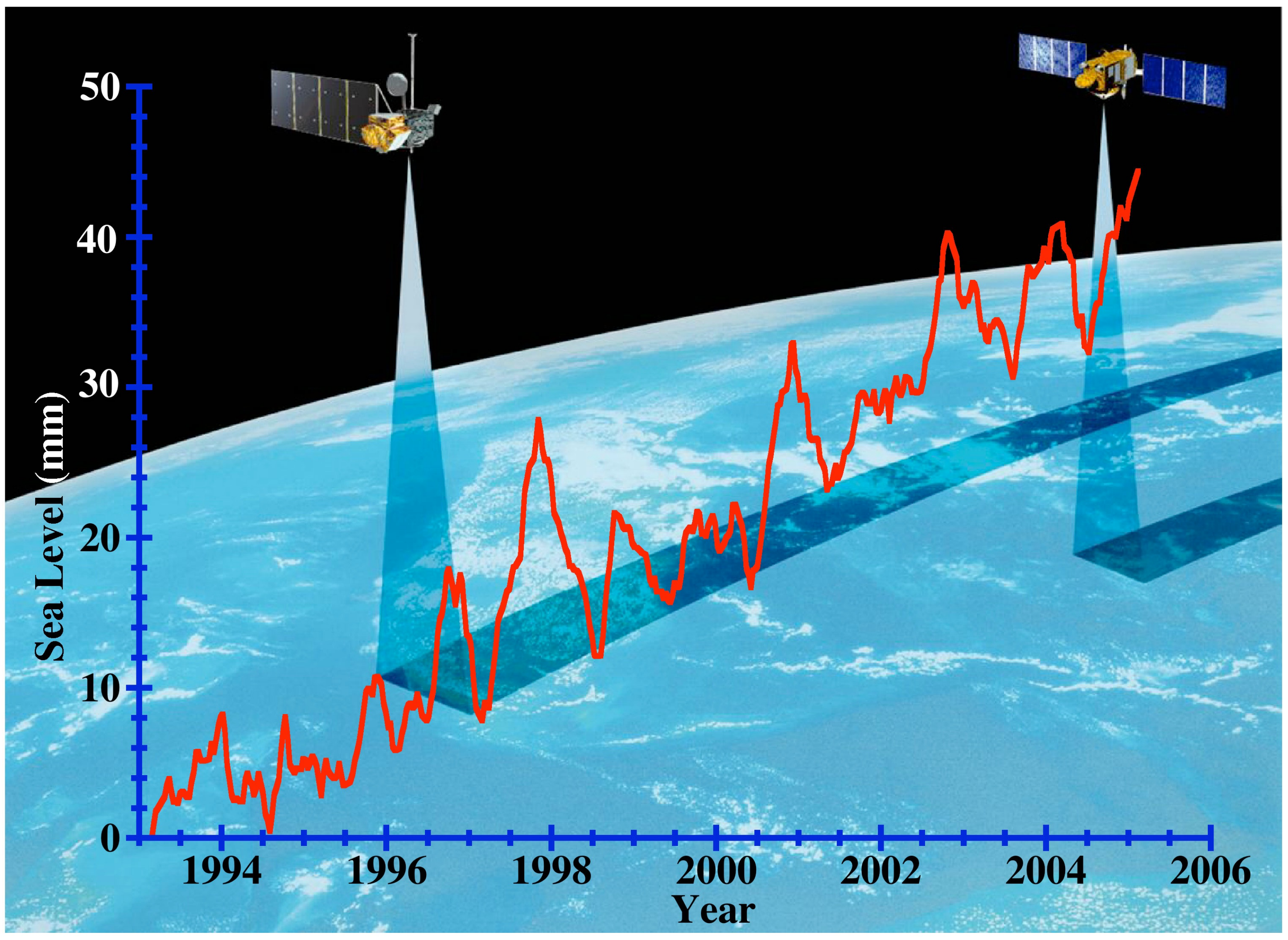


**Figure 10.3** Changes in sea level during the last century (Gornitz et al. 1982), indicating the proportion due to thermal expansion of the oceans and that due to melting of glaciers. From Jacobs (1986), after Meier (1984). Copyright 1984 by the AAAS.

# Satellite altimetry can also be used to estimate sea level rise



# modeling the global water cycle to consider scenarios of future climate…

# Models of the Hydrologic Cycle

Watershed models follow the fate of water received in ppt, and calculate runoff after subtraction of loss due to plant uptake.

- The soil is defined as a collection of small boxes, in which annual input and output of water must be equal.
- Water entering the soil in excess of its holding capacity is routed to the next lower soil layer, or to the next downslope unit via subsurface flow.

Such models can be coupled to models of soil chemistry to predict the loss of elements in runoff.

Continental scale models have been developed to assess the contribution of continental land areas to the global hydrologic cycle; coupled to GCMs, which are driven by climate, such models can predict global biogeochemical phenomena.

Models can be constructed that predict water movement on regional scales
These can be coupled to global climate models

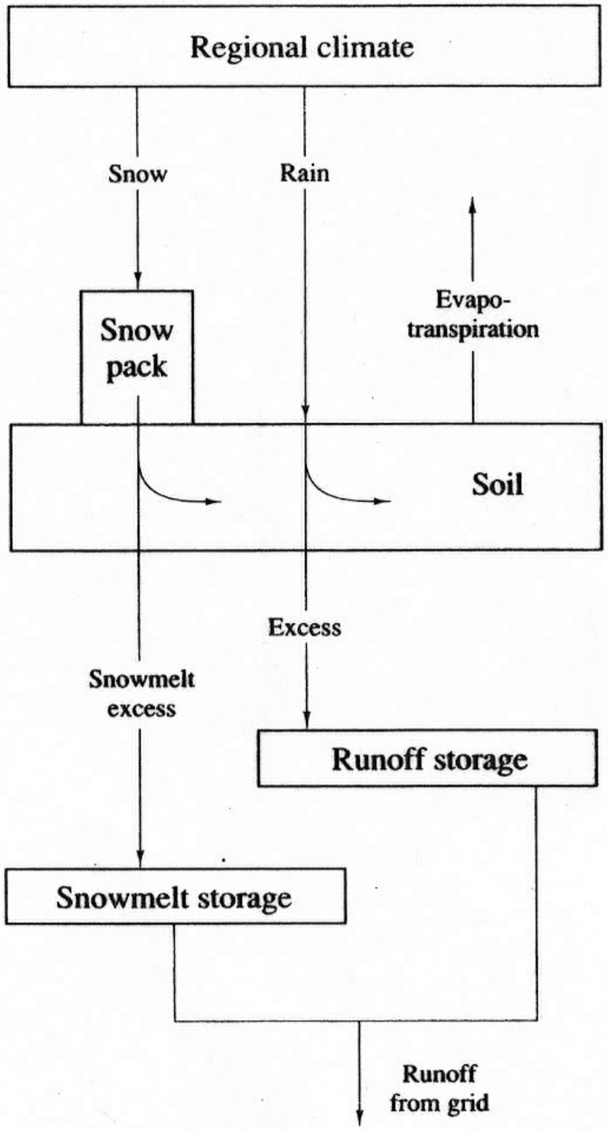


**Figure 10.2** Components of a model for the hydrologic cycle of South America. From Vörösmarty et al. (1989).

Most models predict a more humid world in response to global warming, with increased rates of water movement through the hydrologic cycle: enhanced evaporation, precipitation, runoff

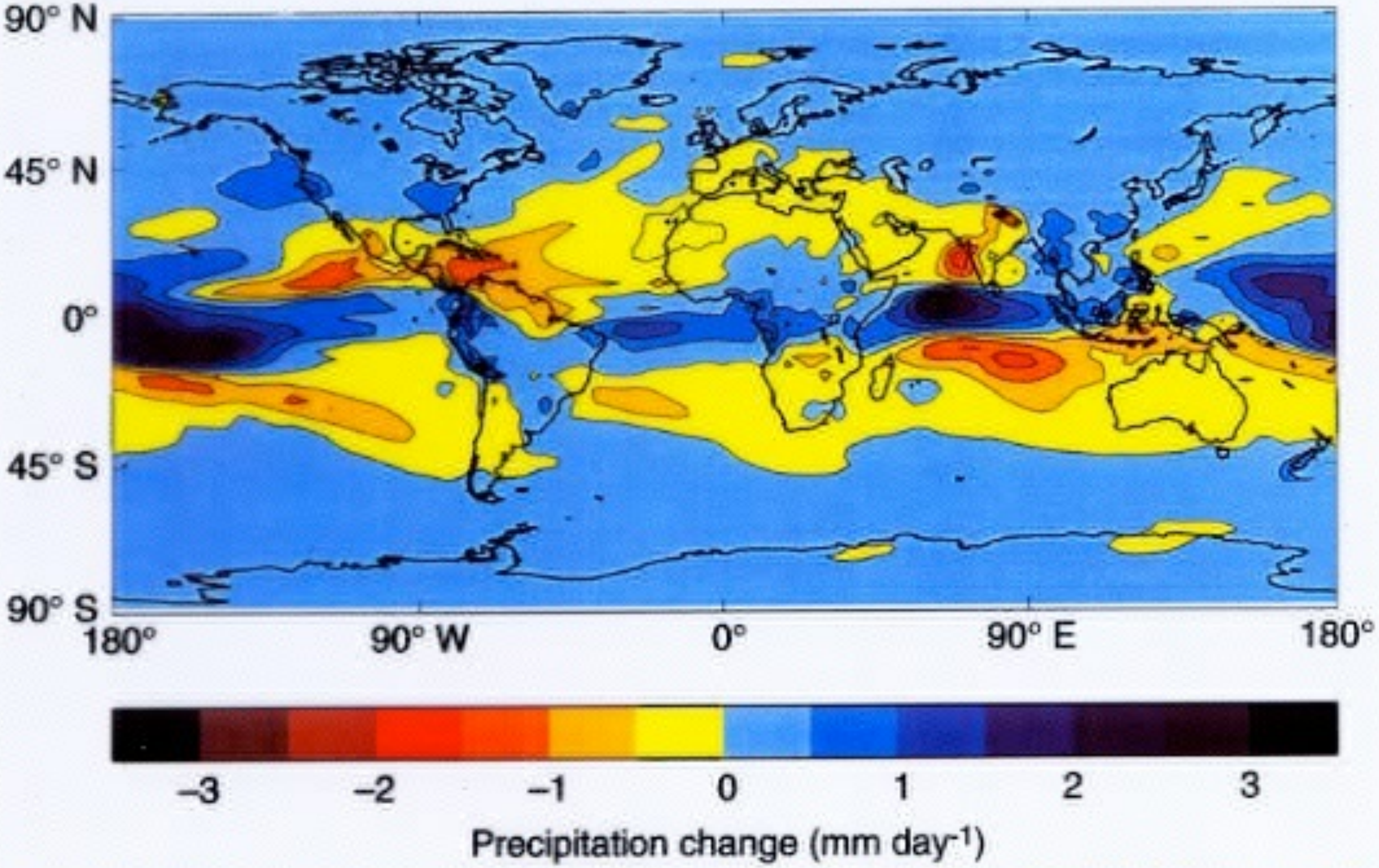
Not all land areas would be equally affected, with higher latitudes being disproportionately affected.

Evidence consistent with this global warming effect on the hydrologic cycle includes:

- increased water vapor in the stratosphere
- increases in rainfall over mid-latitudes in N. hemisphere
- decrease in precipitation over N. Africa
- greater runoff from land

## Observed change in annual precipitation for the 2050s

The change in annual precipitation for the 2050s compared with the present day, when the climate model is driven with an increase in greenhouse gas concentrations equivalent to about 1 percent increase per year in $CO_2$. This illustration shows the average of four model runs with different starting conditions.



Source: R. Nicholls, Middlesex University in the U.K. Meteorological Office. 1997. *Climate Change and Its Impacts: A Global Perspective*. Brittanic Crown Copyright.

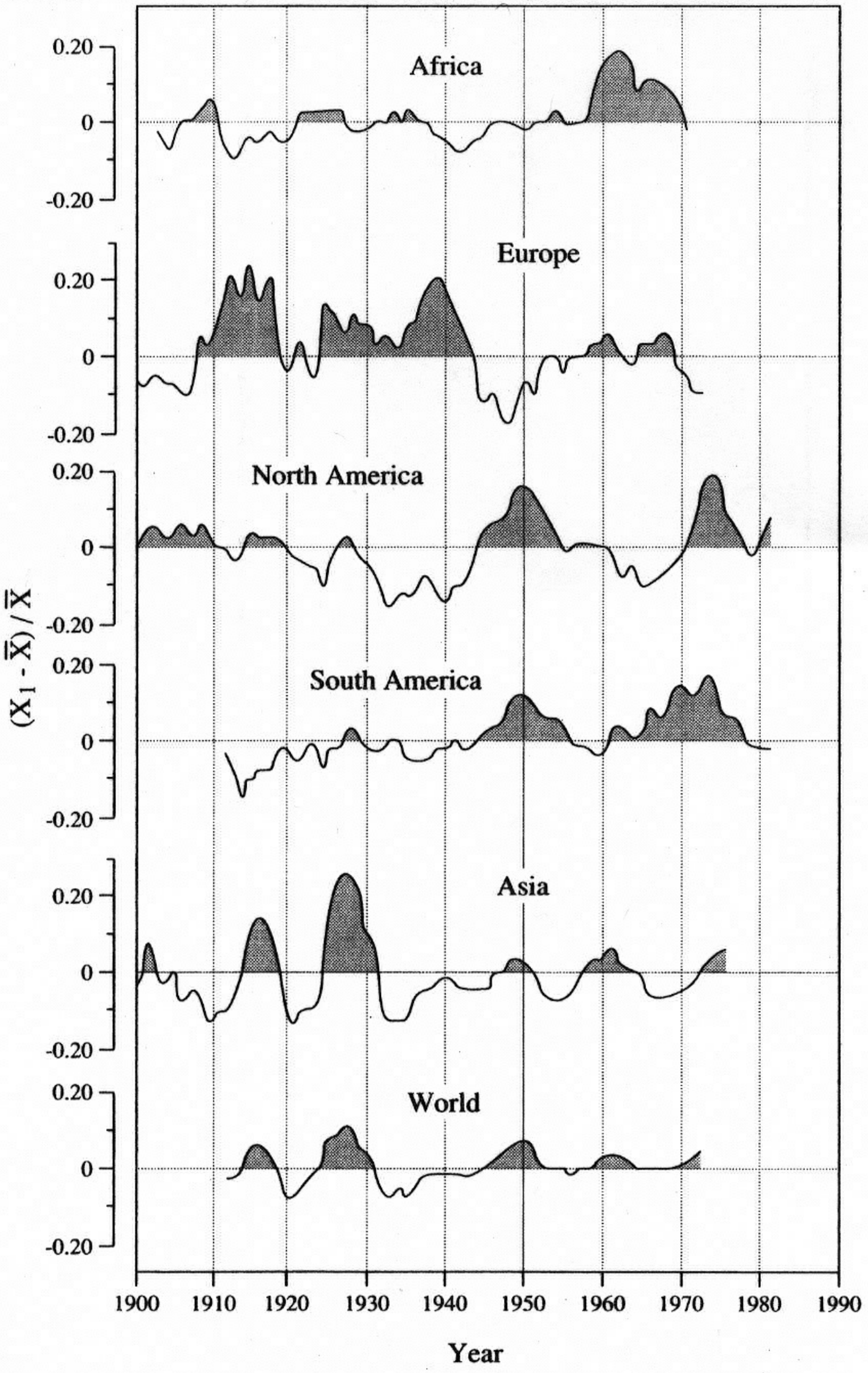


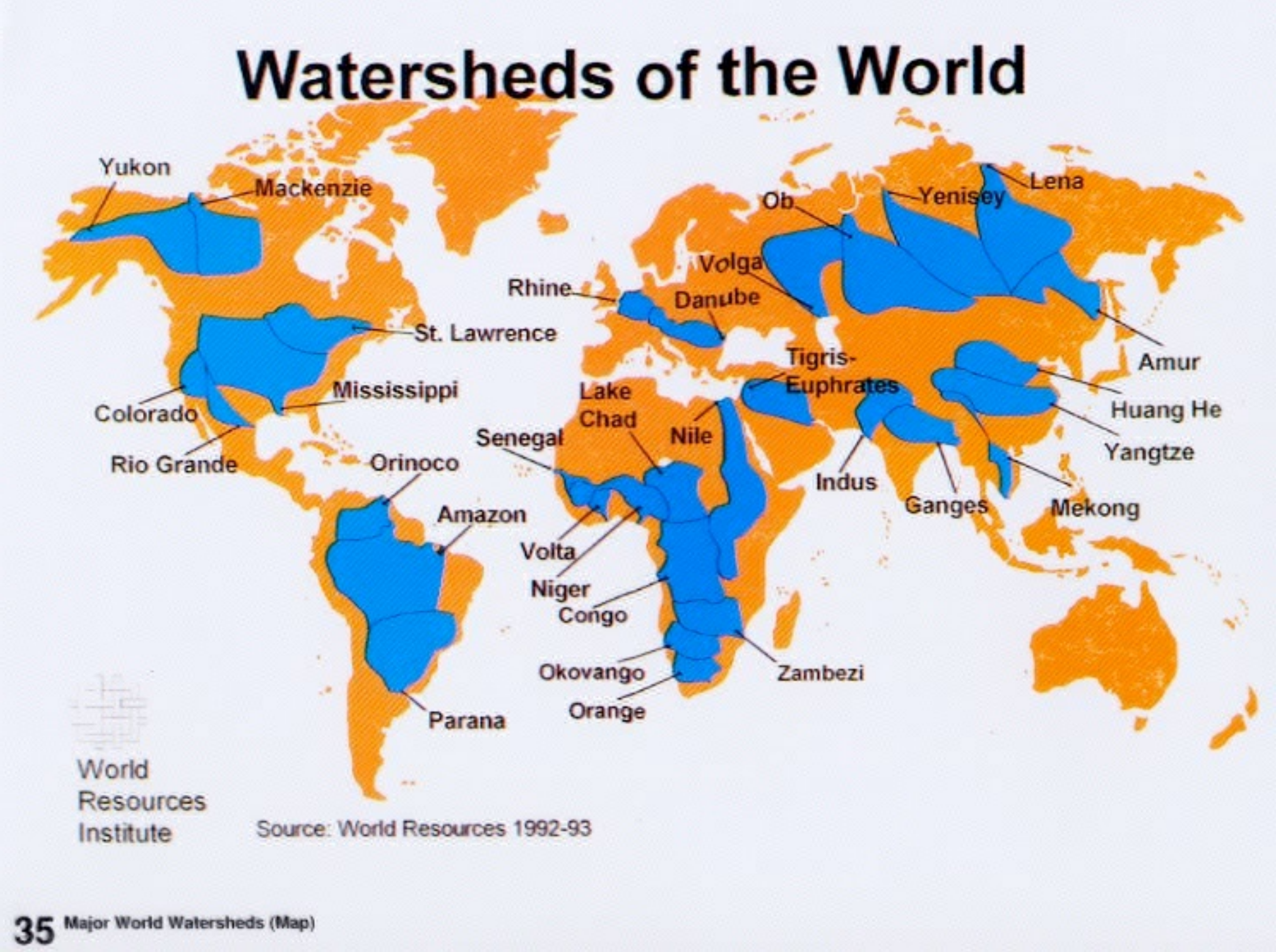
**Figure 10.4** A comparison of fluctuations in riverflow draining various continents and averaged for the world. Variation is expressed as the difference between an annual value and the long-term mean, as a fraction of the long-term mean. From Probst and Tardy (1987).

Cyclical pattern of historical runoff reveals a dampening for world mean due to variance in continental cycles

Recent increases in water vapor, precipitation, and streamflow are consistent with predicted changes due to a global warming

--but some of this may be from reduced evapotranspiration due to reduced vegetation in some regions

# Revisiting Regional Variability



# The Global Water Cycle: Regional Variability

- Global averages obscure substantial regional differences in the hydrologic cycle.
  - Evaporation from the oceans ranges from 4 mm/d in the tropics to <1 mm/d at the poles.
  - Net evaporative loss at tropical latitudes accounts for the higher salinity of tropical oceans.
  - The relative balance of ppt and evap differs strongly between regions.

- Sources of water contributing to precipitation differ greatly regionally.
  - Most rainfall over the oceans is derived from seawater.
  - Most rainfall in the Amazon Basin derives from evapotranspiration within the basin, and long-range atmospheric transport; importance of ET implies long-term implications of deforestation for this region.

# Facts and figures from the World Water Council

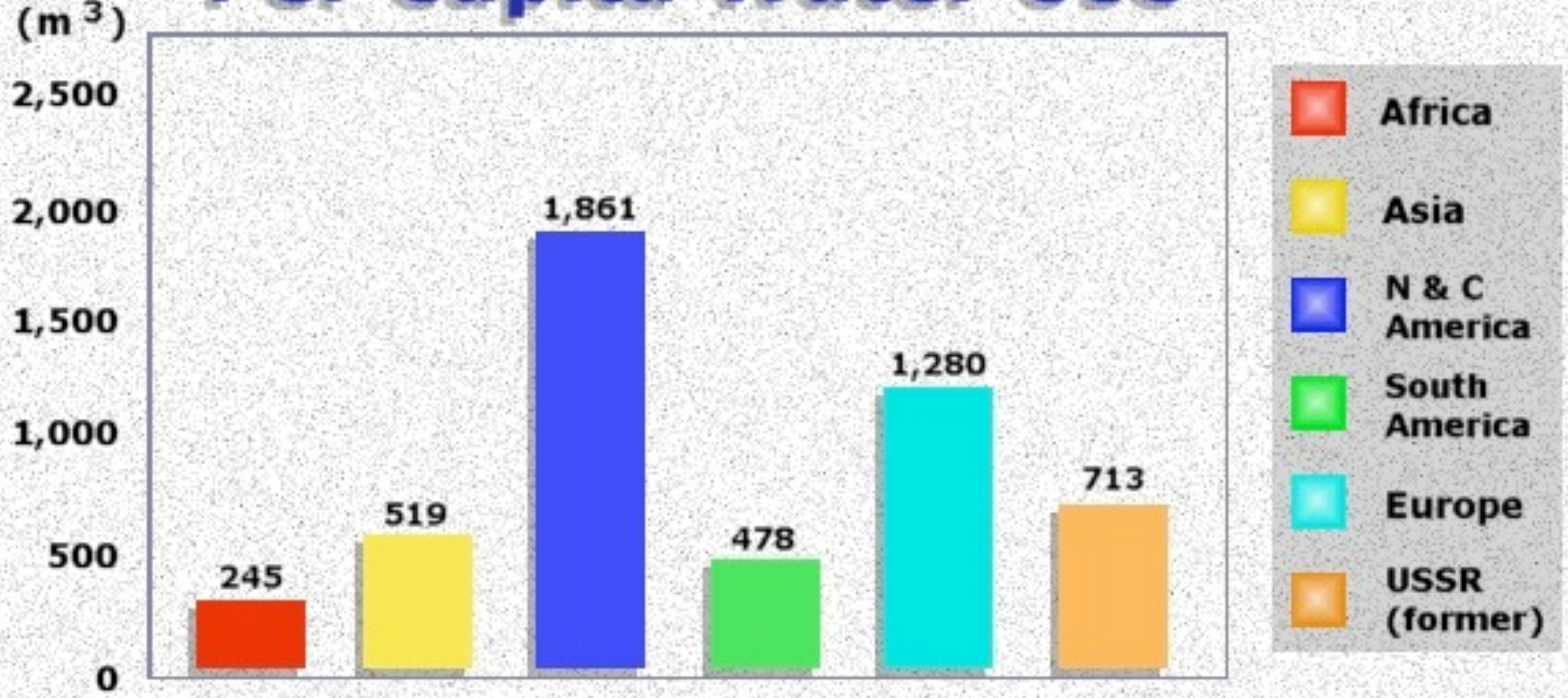
44,000 $km^3$ Quantity of water from rivers or aquifers to ocean

10,000-12,000 $km^3$ available for human consumption

4,000 $km^3$ global water withdrawals

2,000 $km^3$ global water consumption

# Per Capita Water Use



*Taken from: Belyaev, V., Institute of Geography, U.S.S.R. National Academy of Sciences, Moscow. (1987)*

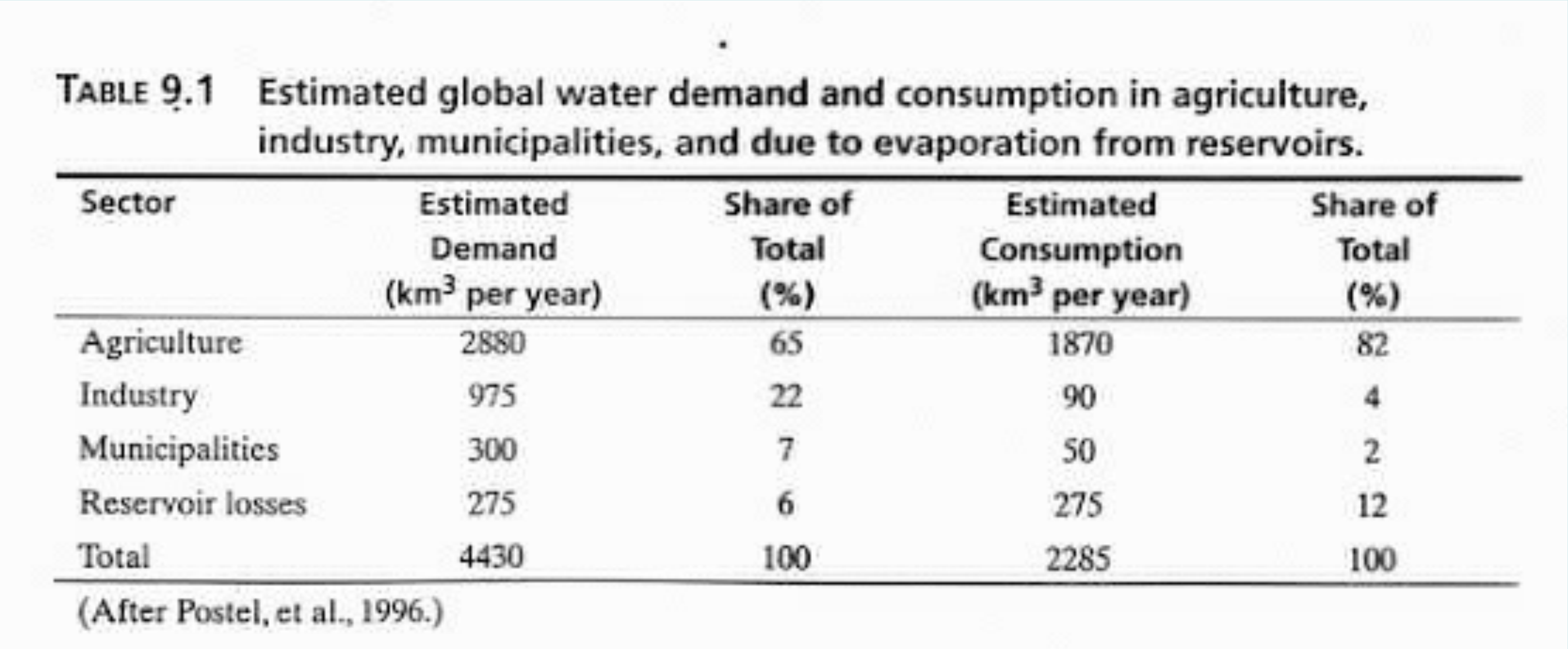
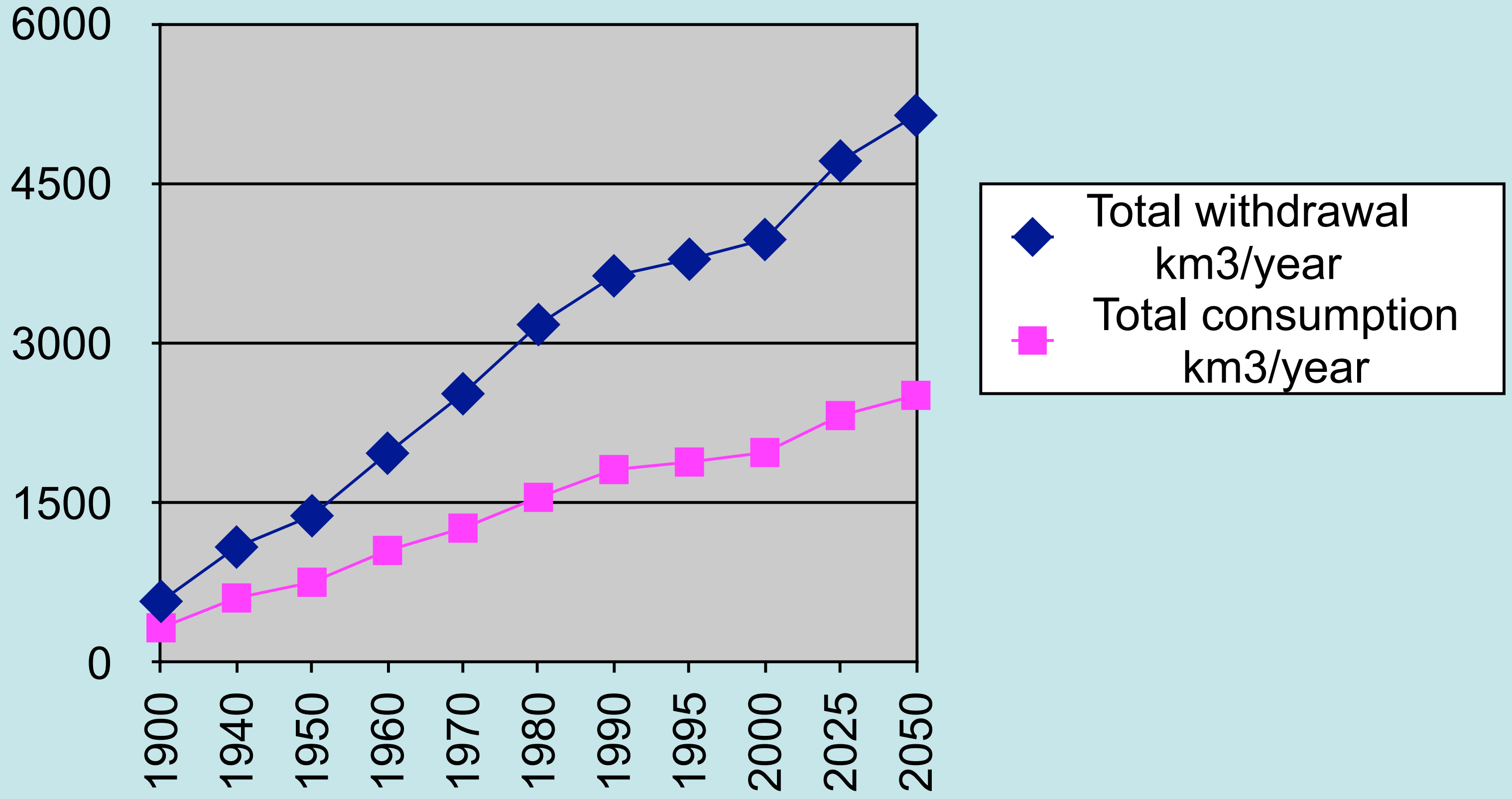


TABLE 9.1 Estimated global water demand and consumption in agriculture, industry, municipalities, and due to evaporation from reservoirs.

| Sector | Estimated Demand ($km^3$ per year) | Share of Total (%) | Estimated Consumption ($km^3$ per year) | Share of Total (%) |
|---|---|---|---|---|
| Agriculture | 2880 | 65 | 1870 | 82 |
| Industry | 975 | 22 | 90 | 4 |
| Municipalities | 300 | 7 | 50 | 2 |
| Reservoir losses | 275 | 6 | 275 | 12 |
| Total | 4430 | 100 | 2285 | 100 |

(After Postel, et al., 1996.)

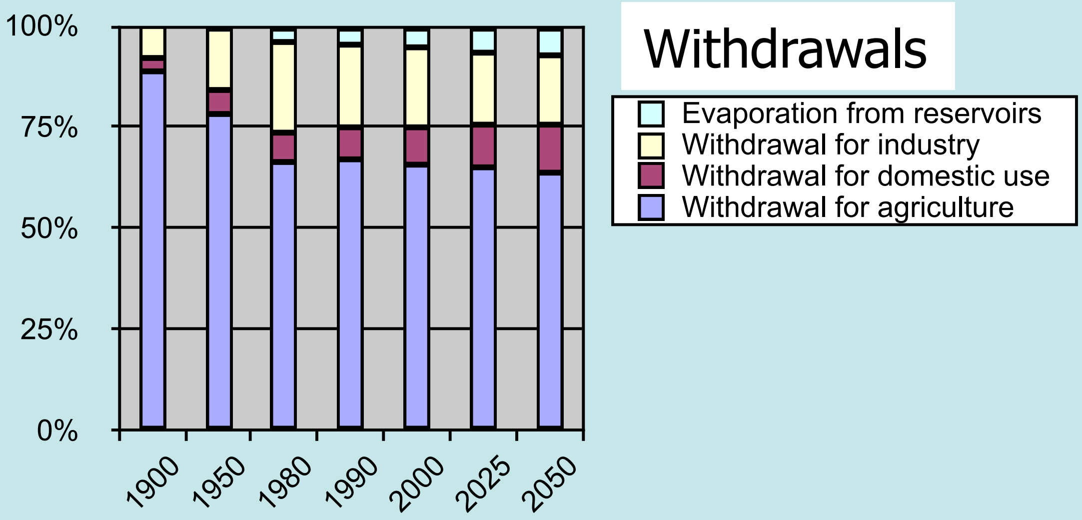
# Total withdrawals and consumption

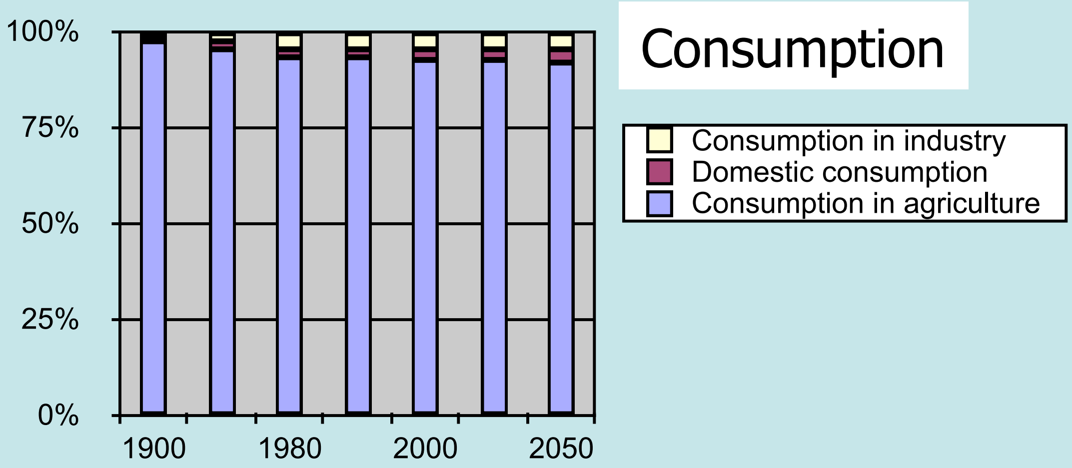


Source: Shiklomanov, 1999 http://webworld.unesco.org/water/ihp/db/shiklomanov/index.shtml

Future projections by D.Zimmer, based on the evolution of business as usual

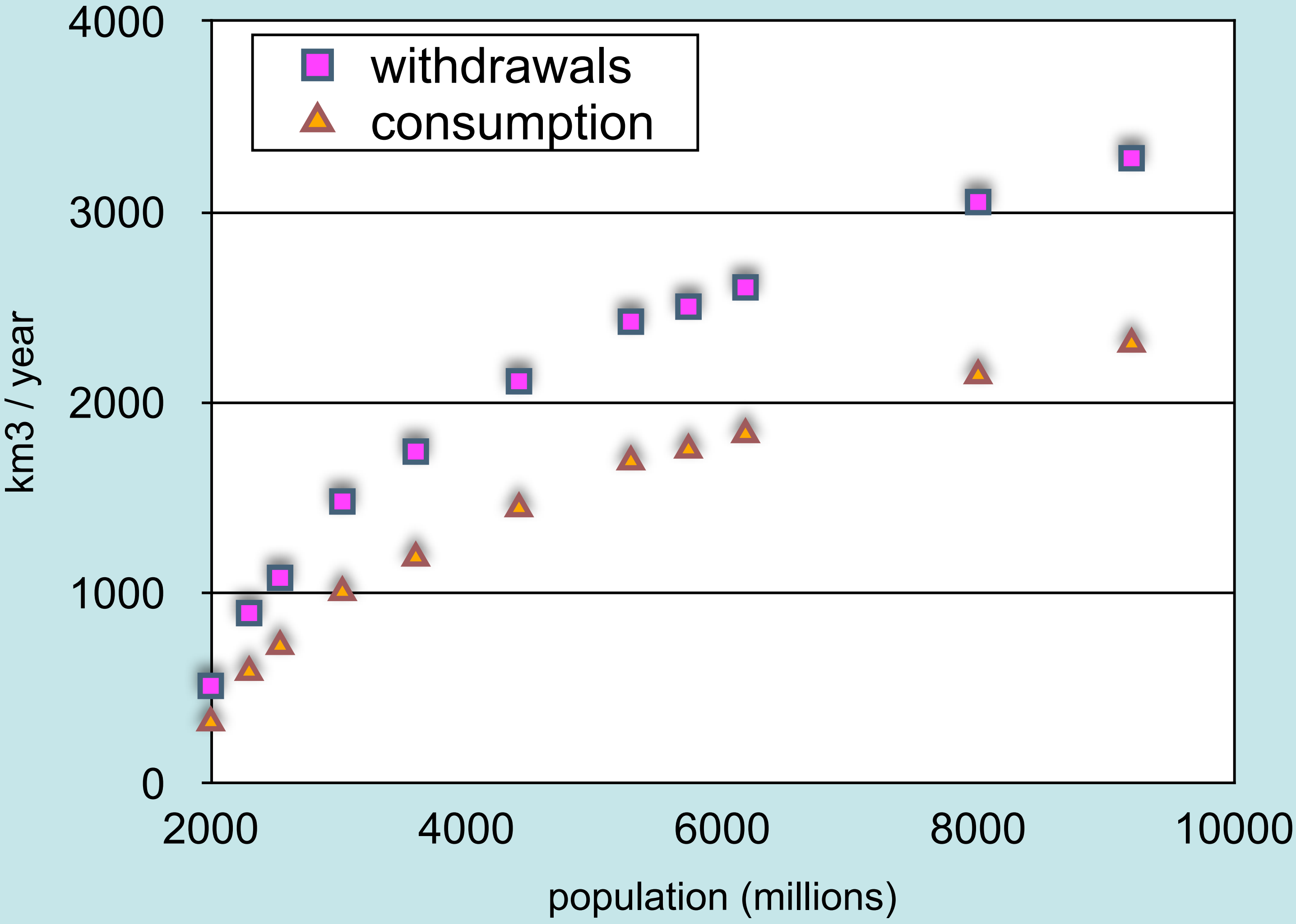
# Breakdown of water withdrawals and consumption by sector





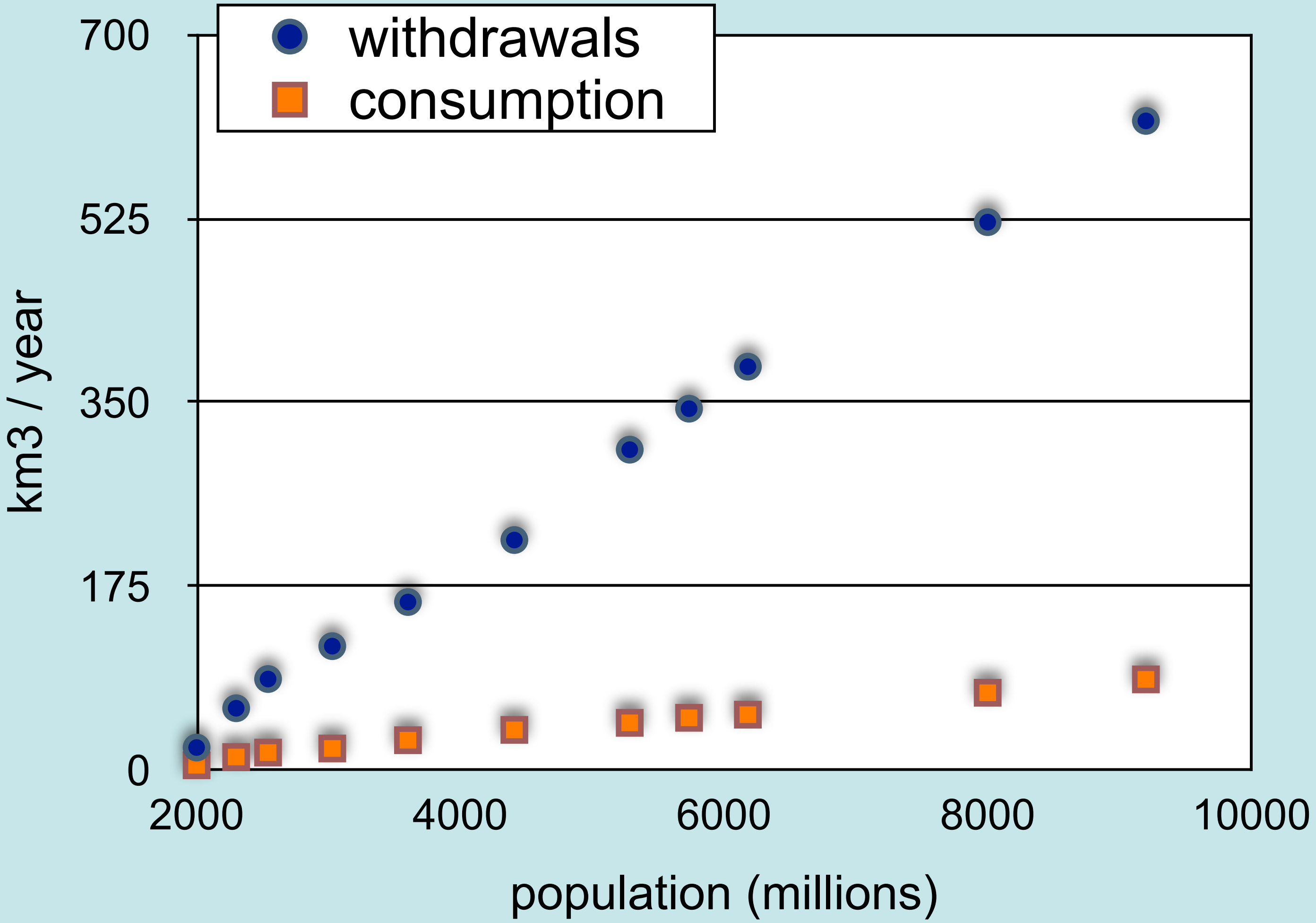
Source: Shiklomanov, 1999, future projections by D.Zimmer

# Water withdrawals and consumption for agriculture use



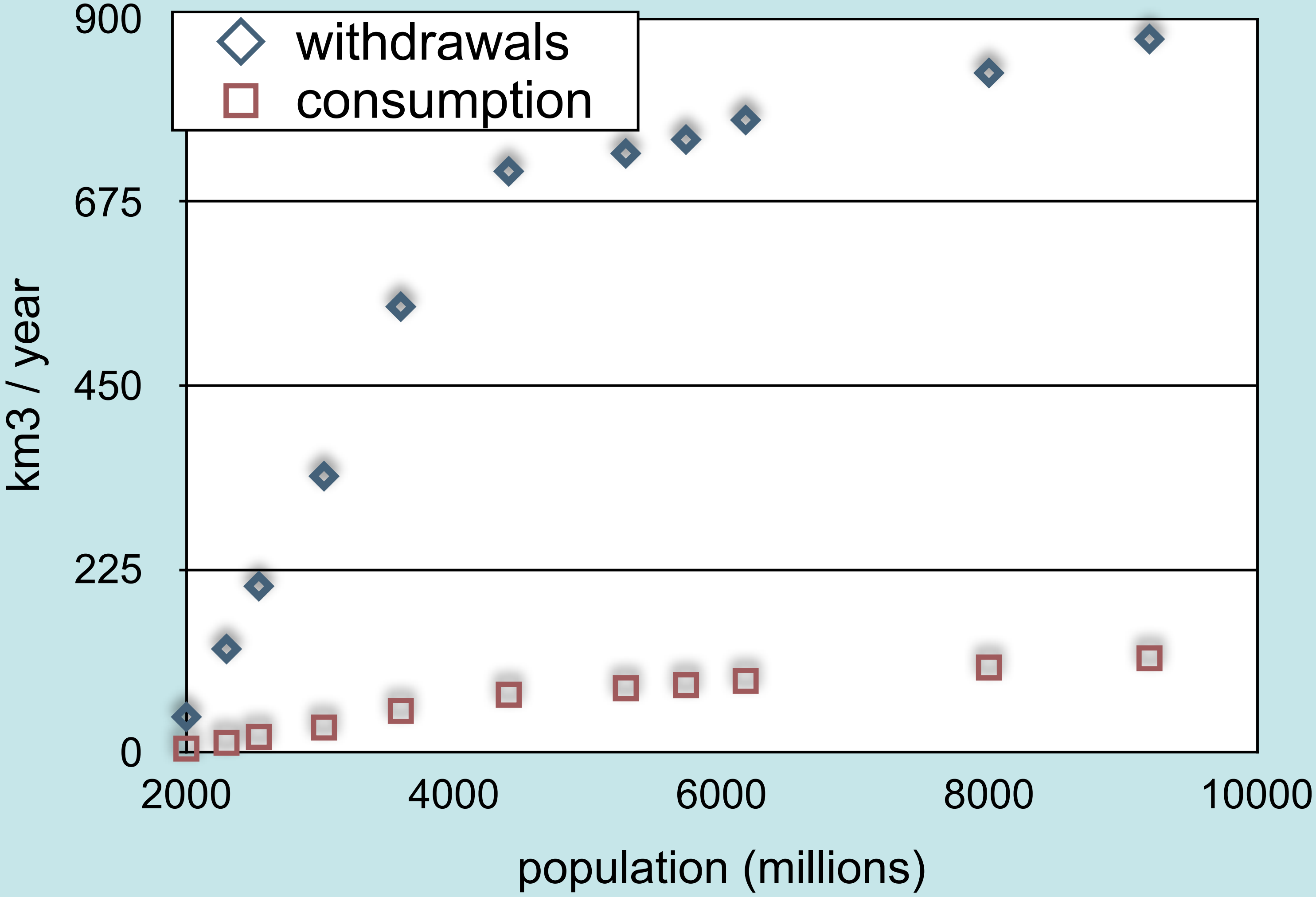
Source: Shiklomanov, 1999, future projections by D.Zimmer

# Water withdrawals and consumption for domestic use



Source: Shiklomanov, 1999, future projections by D.Zimmer

# Water withdrawals and consumption for industrial use



Source: Shiklomanov, 1999, future projections by D.Zimmer

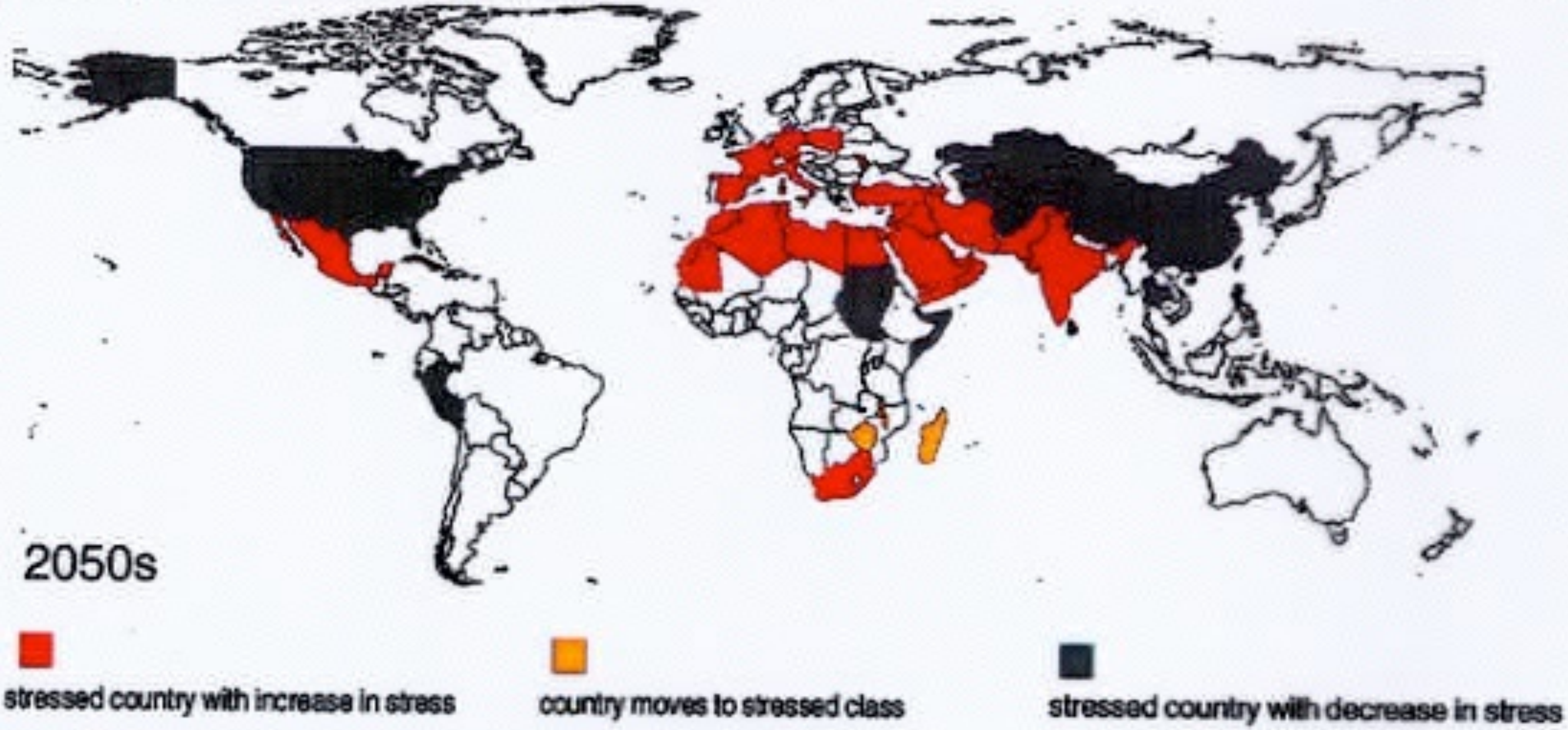
# Figures

| | **1900** | **1950** | **1980** | **1990** | **2000** | **2025** | **2050** |
|---|---|---|---|---|---|---|---|
| Population (million) | 2000 | 2542 | 4410 | 5285 | 6181 | 8000 | 9200 |
| Irrigated areas M ha | 47.3 | 101 | 198 | 243 | 264 | 307 | 331 |
| Withdrawal for agriculture km3/yr | 513 | 1080 | 2112 | 2425 | 2605 | 3053 | 3283 |
| Consumption in agriculture km3/yr | 321 | 722 | 1445 | 1691 | 1834 | 2143 | 2309 |
| Ratio consumption/withdrawal | 63% | 67% | 68% | 70% | 70% | 70% | 70% |
| Withdrawal for domestic use km3/yr | 21.5 | 86.7 | 219 | 305 | 384 | 522 | 618 |
| Domestic consumption km3/yr | 4.6 | 16.7 | 38.3 | 45 | 52.8 | 73.6 | 86.4 |
| Ratio consumption/withdrawal | 21% | 19% | 17% | 15% | 14% | 14% | 14% |
| Withdrawal for industry km3/yr | 44 | 204 | 713 | 735 | 776 | 834 | 875 |
| Consumption in industry km3/yr | 5 | 19 | 71 | 79 | 88 | 104 | 116 |
| Ratio consumption/withdrawal | 11% | 9% | 10% | 11% | 11% | 13% | 13% |
| Reservoir evaporation km3 | 0.3 | 11.1 | 131 | 167 | 208 | 302 | 362 |
| Total withdrawals km3/yr | **579** | **1382** | **3175** | **3632** | **3973** | **4710** | **5138** |
| Total consumption km3/yr | **330** | **758** | **1554** | **1815** | **1975** | **2321** | **2511** |

Source: Shiklomanov, 1999, future projections by D.Zimmer

## Change in water stress

Change in water stress, due to climate change, in countries using more than 20 percent of their potential water resources.



*Source:* N. Arnell and R. King, University of Southampton in the U.K. Meteorological Office. 1997. *Climate Change and Its Impacts: A Global Perspective.* Brittanic Crown Copyright.

# Lecture Summary

The global hydrologic cycle consists of various reservoirs of water on the Earth's surface, and fluxes between these reservoirs allow calculation of water residence time for each reservoir.

The origin of water and its distribution into vapor vs. liquid occurred very early in Earth's history.

Evidence for changes in sea level indicates fluctuations of ocean volume as a function of global climate.

Global warming can significantly affect the global hydrologic cycle.

# Changes in NPP 1982-1989