# The Global Water Cycle

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# Outline

*First hour*

- Introduction
- The global cycle of energy
- The global water cycle
- Evaporation in the surface layer
- Tropical atmosphere: Heat and moisture balance

*Second hour*

- Variability of the water cycle
- Climate change and water cycle
- Role of water cycle for chemistry

"Water supplies are falling while the demand is dramatically growing at an unsustainable rate. Over the next 20 years, the average supply of water world-wide per person is expected to drop by a third." (K. Matsuura, UNESCO Director-General)

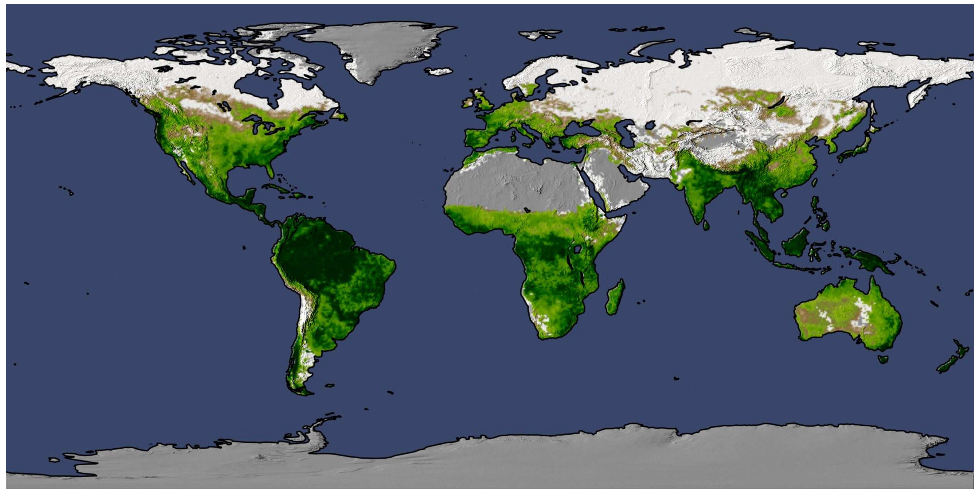
"The poor continue to be the worst affected, with 50% of the population in developing countries exposed to polluted water sources." (World Water Development Report, UN)

WaterYear2003

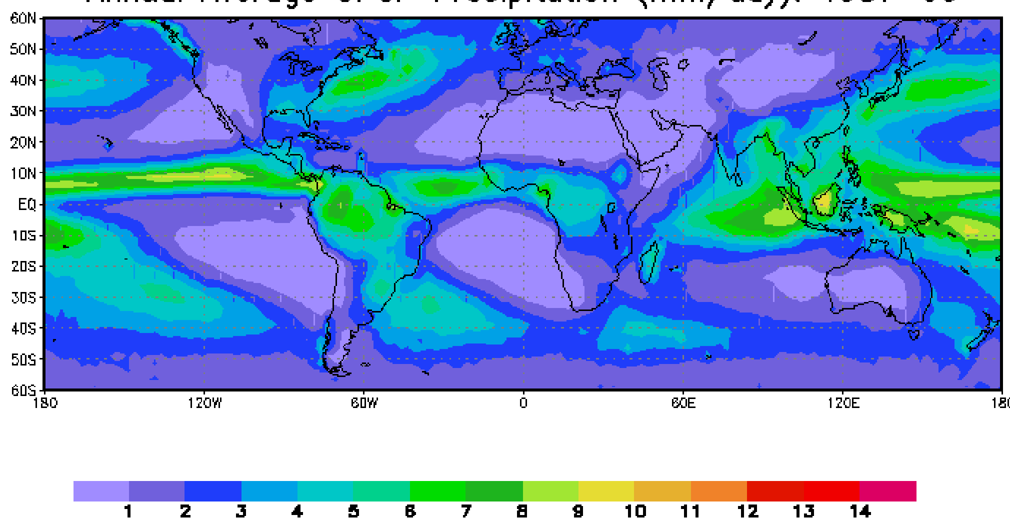

Scientific Challenges…
Image by: Stöckli, Nelson, Hasler
Laboratory for Atmospheres
Goddard Space Flight Center
http://rsd.gsfc.nasa.gov/rsd
USGS
Hurricane Linda west of Mexico
September 9, 1997 17:45 UTC
Data from: NASA, NOAA, USGS

# Life on Earth: Dependence on Freshwater

**Net Primary Production (1980-2000)**

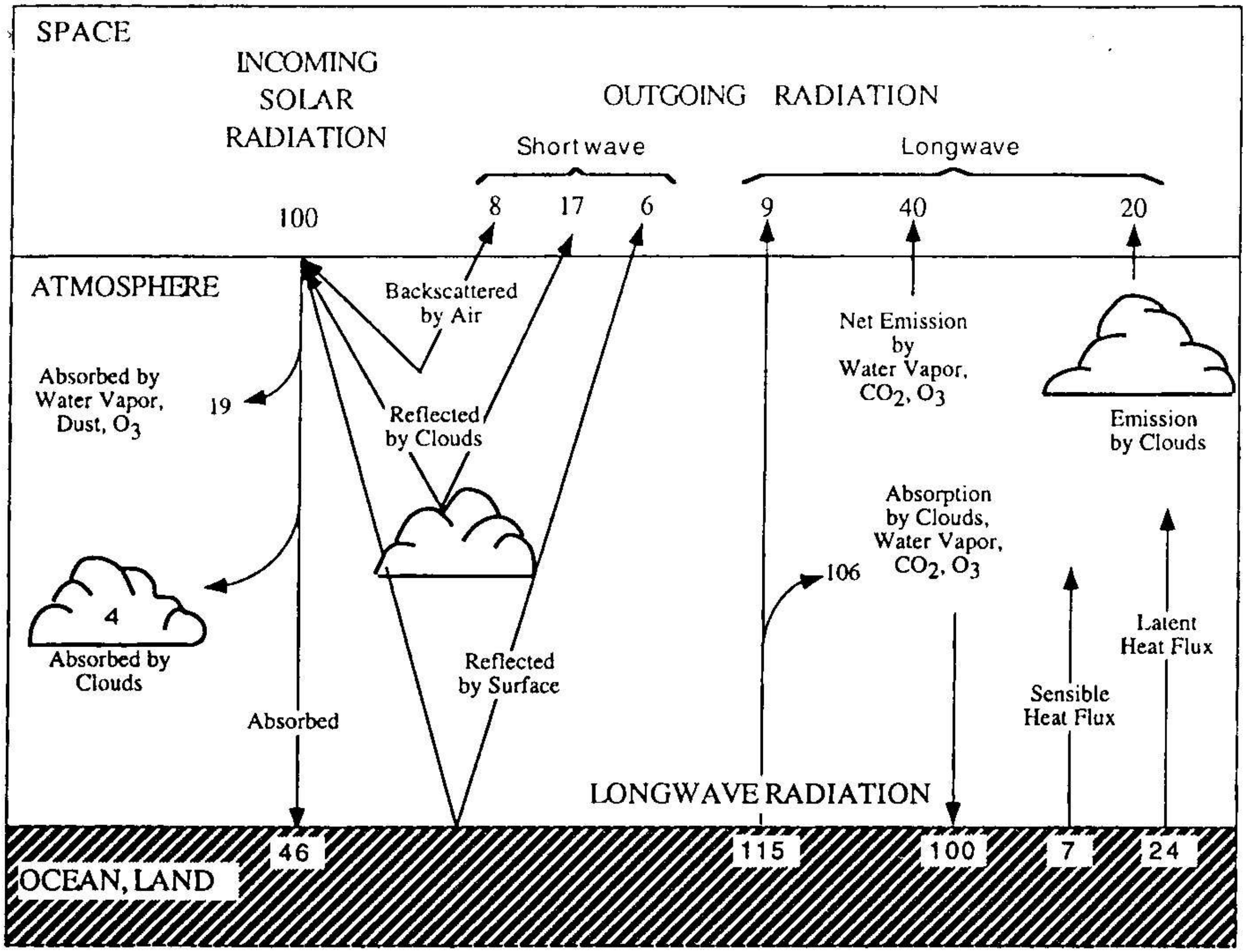


Annual Average GPCP Precipitation (mm/day): 1987–99



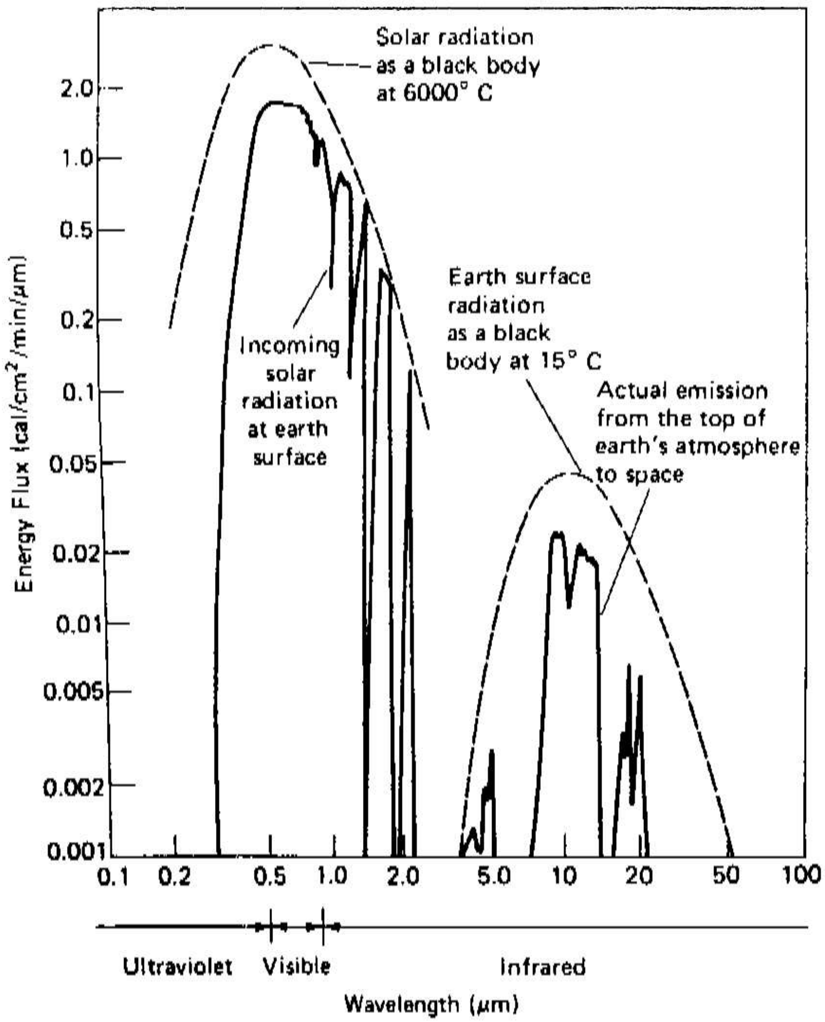

Source: NASA Earth Observatory

# The Global Cycle of Energy: Summary



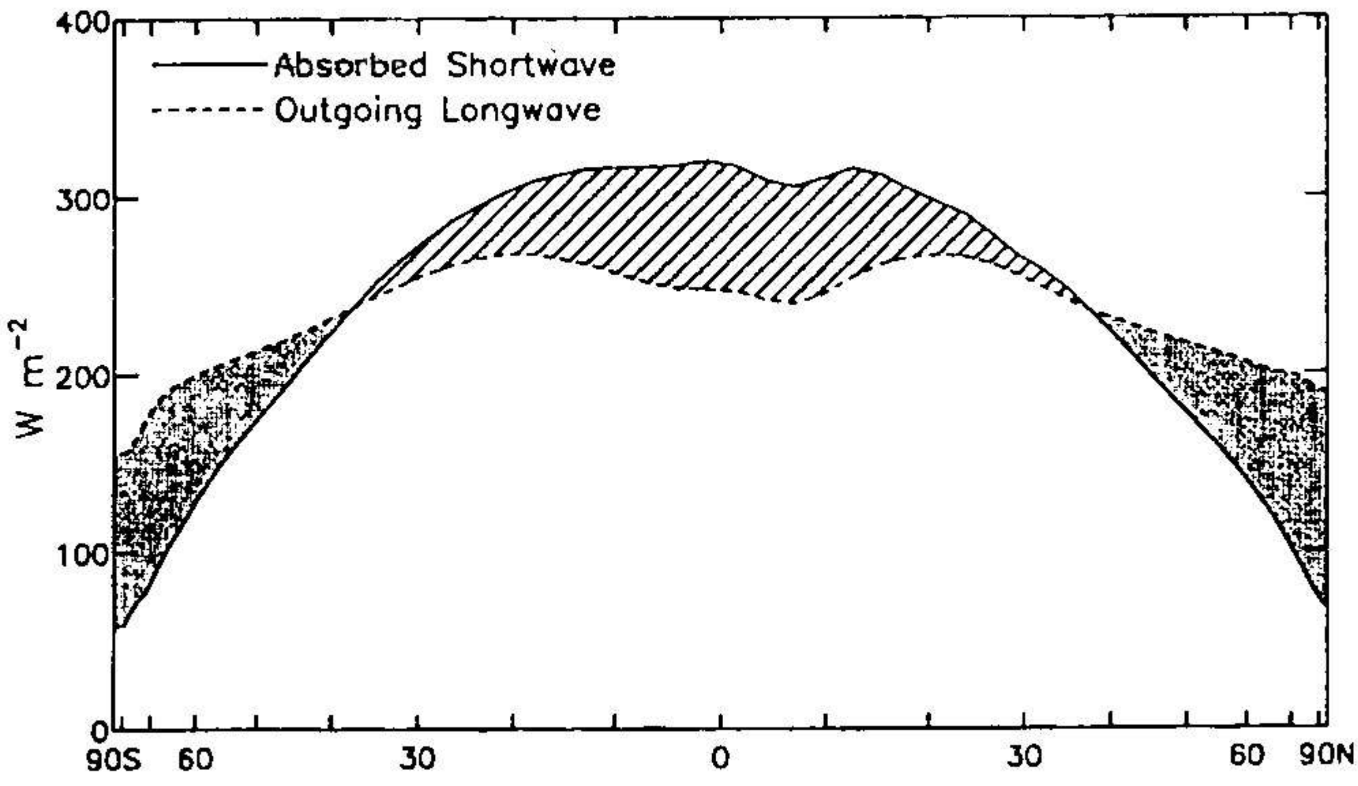

Source: Mitchell (1989)

# The Global Cycle of Energy: Radiation Fluxes at Top and Bottom of the Atmosphere



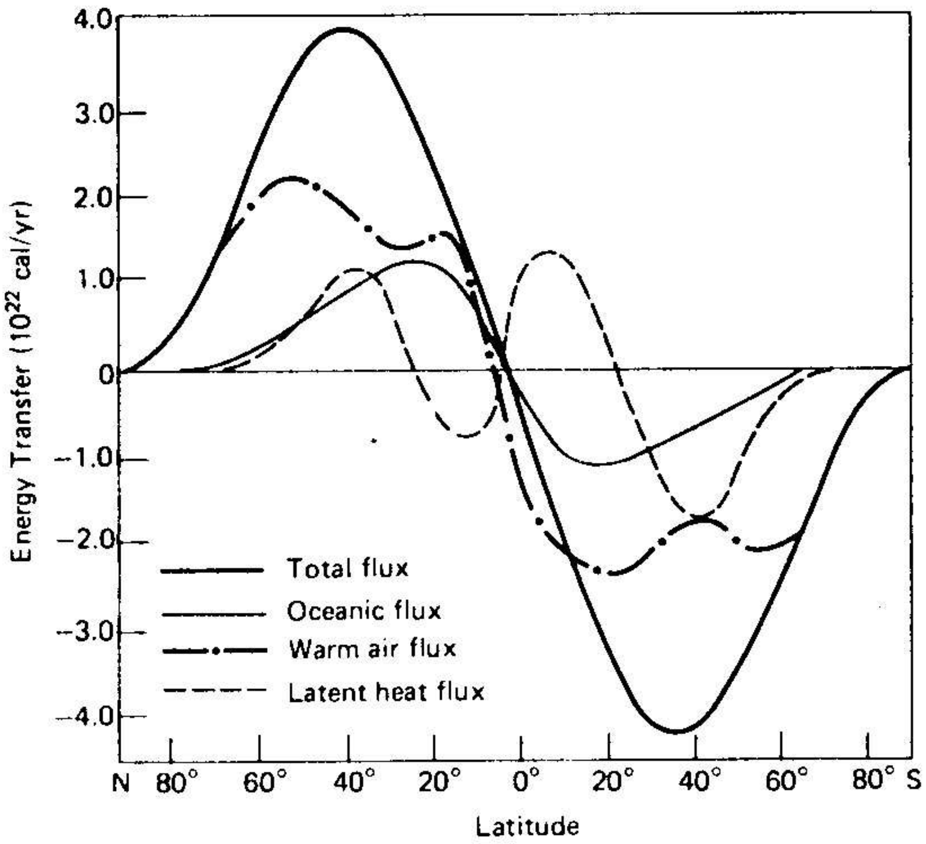

Source: Berner and Berner (1987)

## The Global Cycle of Energy: Radiation at the Top of the Atmosphere




Source: Trenberth and Solomon (1994)

# The Global Cycle of Energy: Poleward Transport of Energy



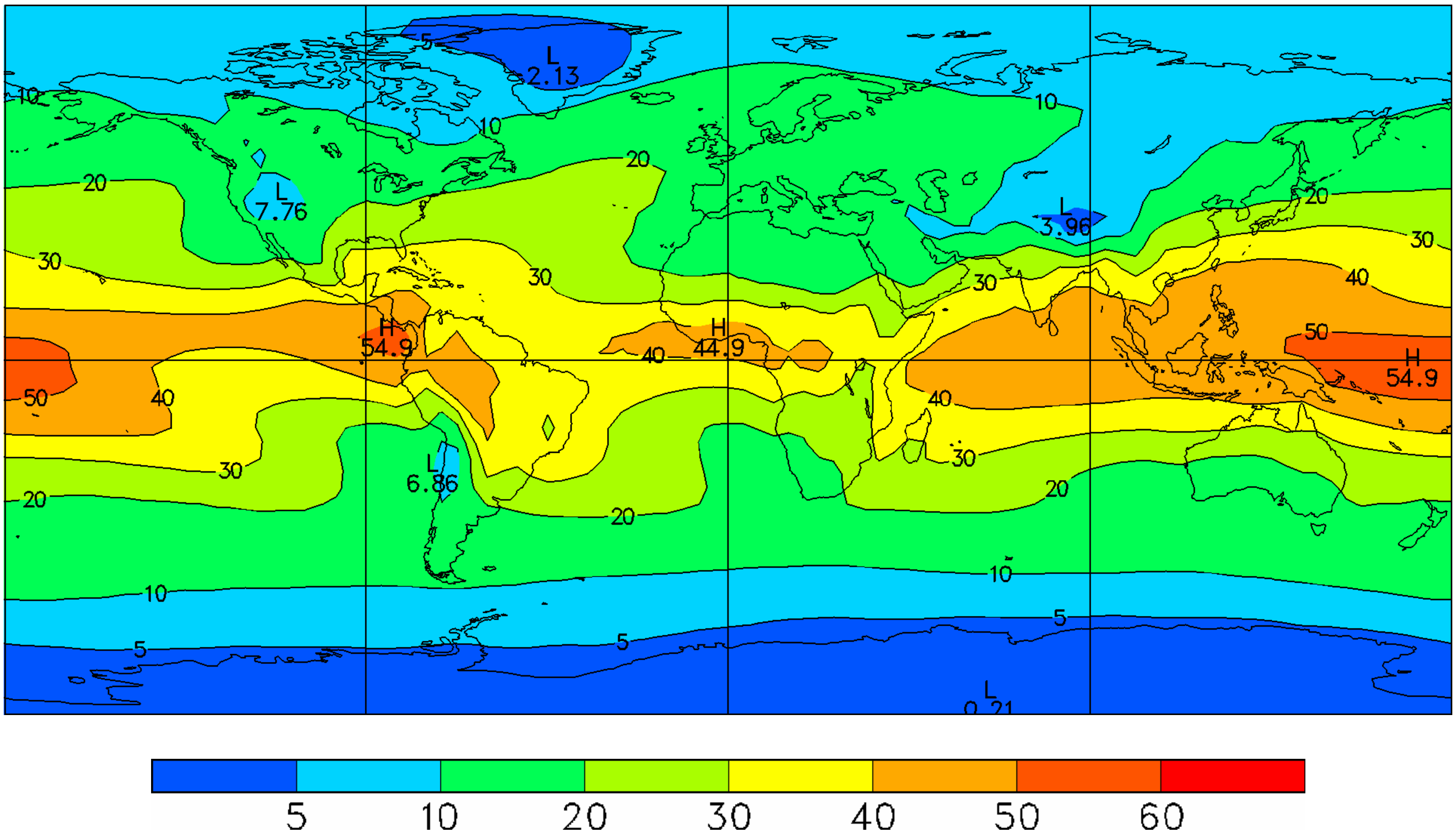

Source: Sellers (1965)

# The Global Water Cycle: World Water Reserves

| Form of water | Total volume ($km^3$) | Share (%) |
|---|---|---|
| World ocean | 1 338 000 000 | 96.539 |
| Glaciers and permanent snow cover | 24 064 100 | 1.736 |
| Ground water | 23 400 000 | 1.688 |
| Ground ice in zones of permafrost strata | 300 000 | 0.0216 |
| Water in lakes | 176 400 | 0.0127 |
| Soil moisture | 16 500 | 0.0012 |
| Atmospheric water | 12 900 | 0.0009 |
| Marsh water | 11 470 | 0.0008 |
| Water in rivers | 2 120 | 0.0002 |
| Biological water | 1 120 | 0.0001 |
| Total water reserves | 1 385 984 610 | 100.00 |

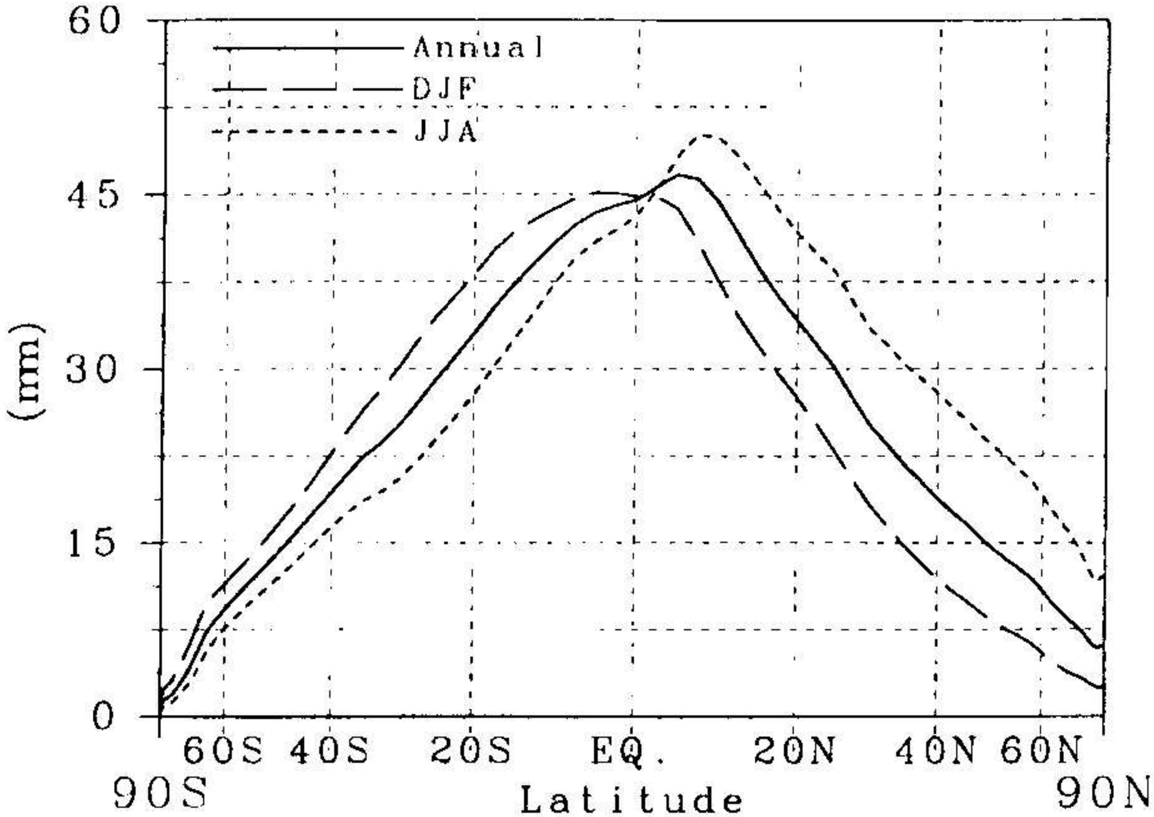
Source: Oki (1999)

# The Global Water Cycle: Water in the Atmosphere



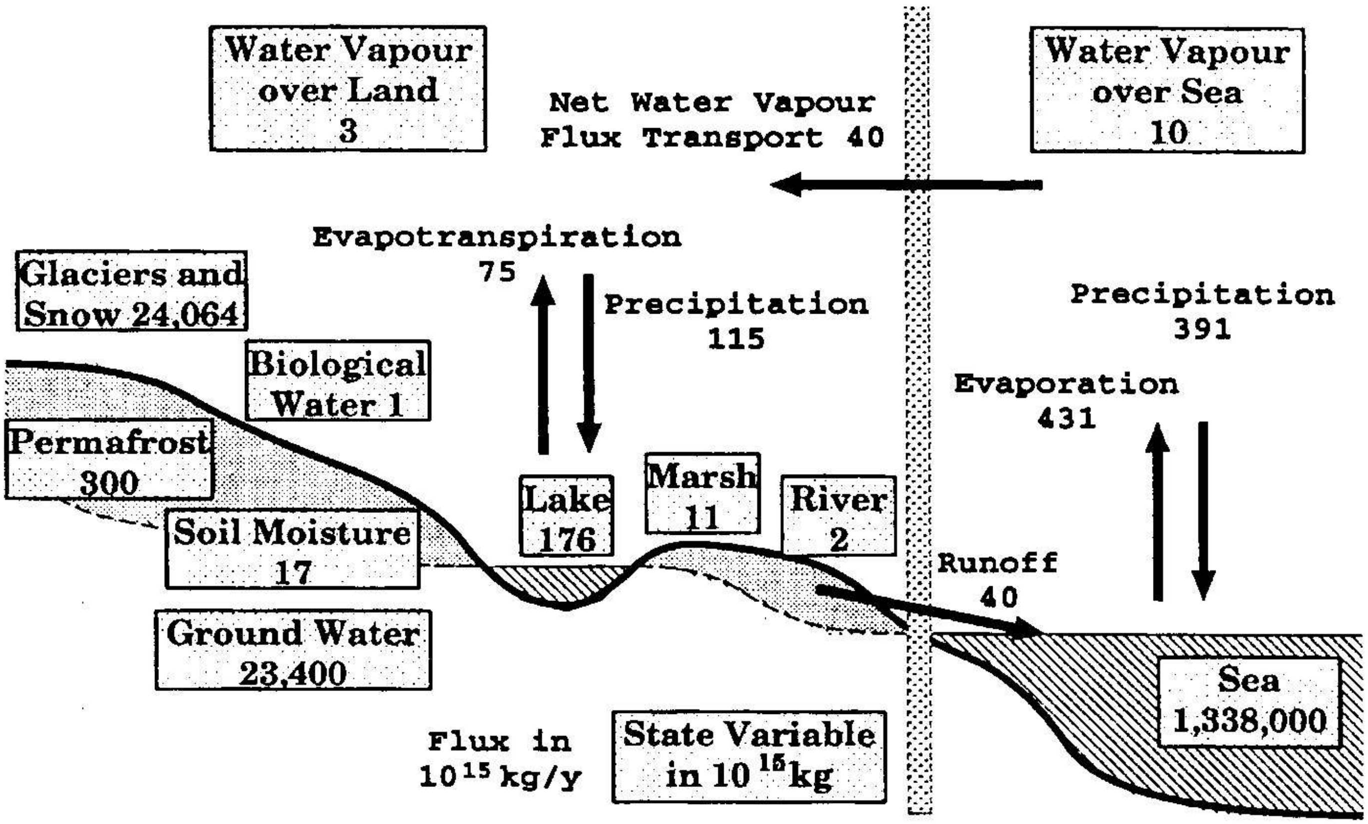

Units: mm

# The Global Water Cycle: Water in the Atmosphere



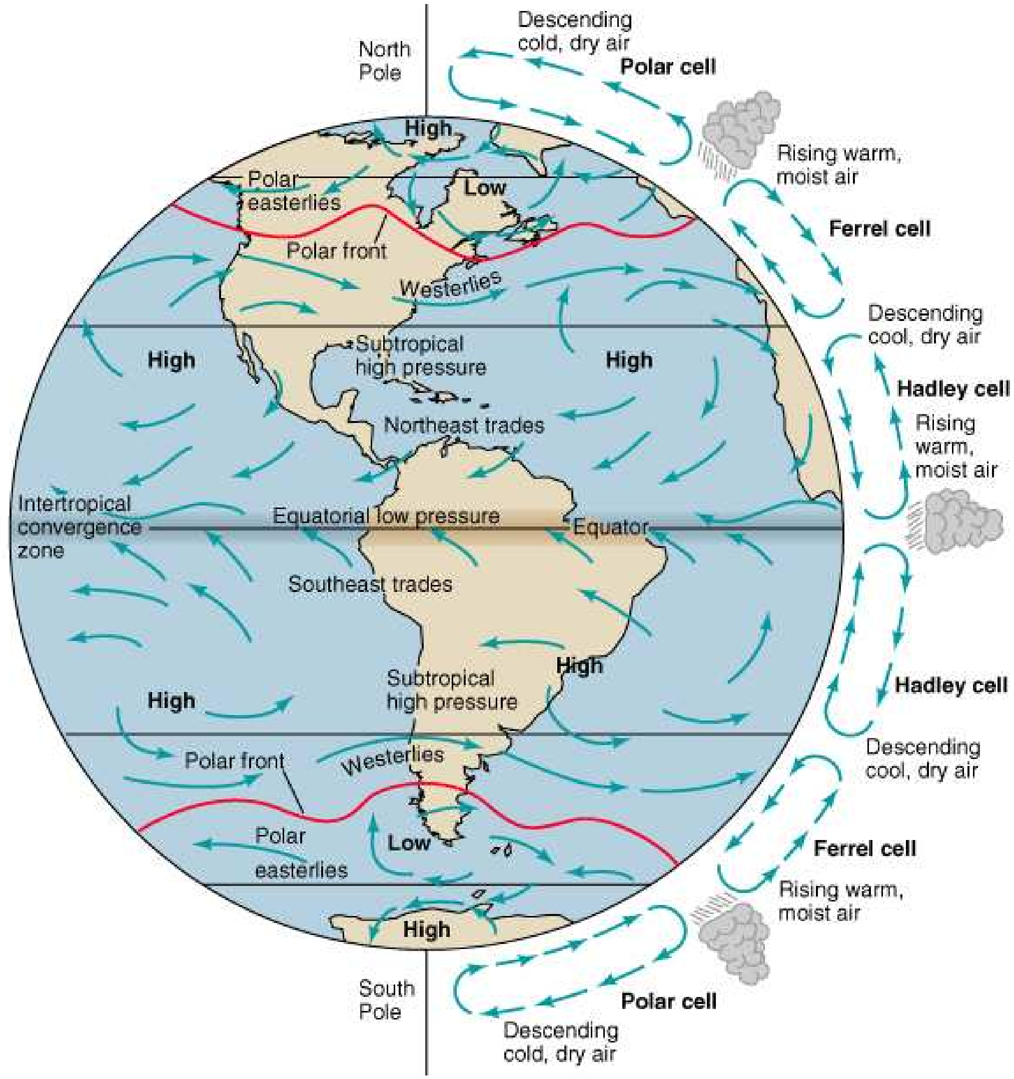

Source: Oki (1999)

# The Global Water Cycle: Summary



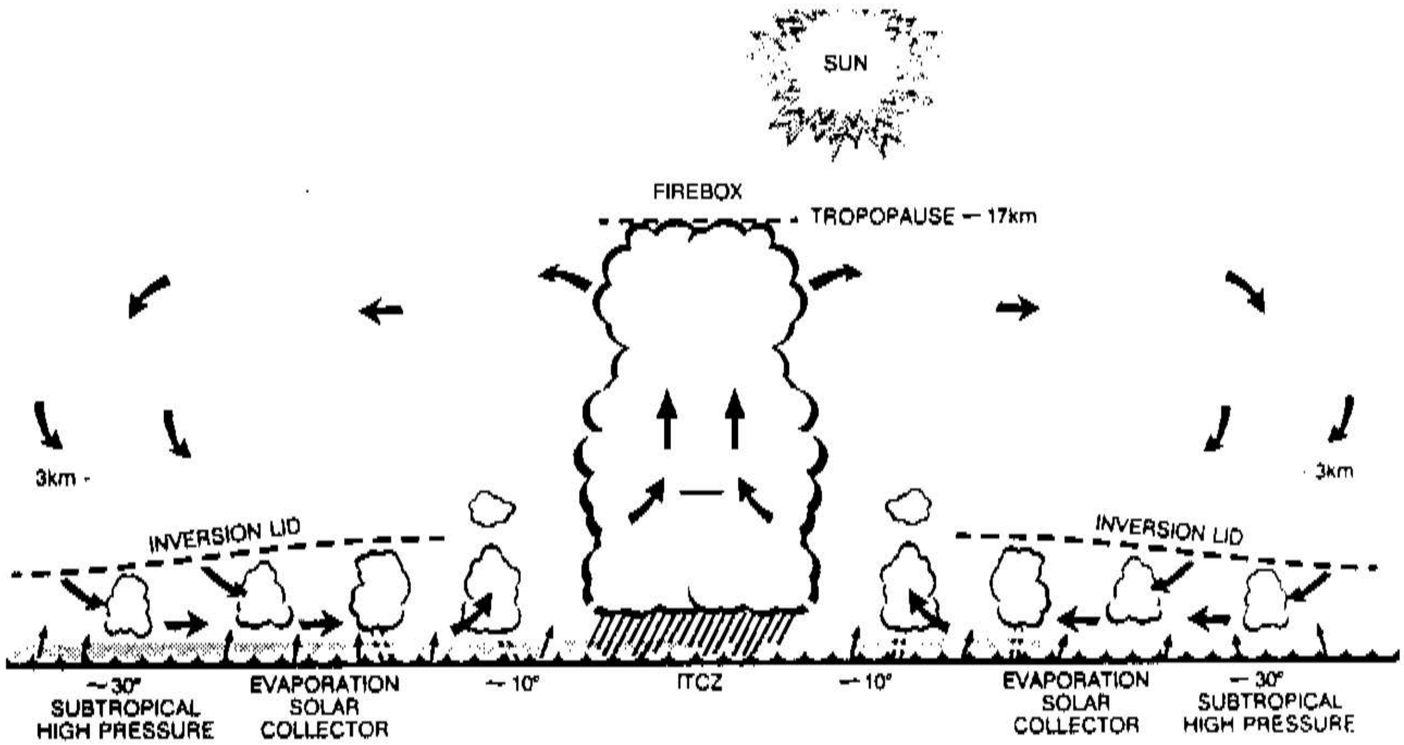

Source: Oki (1999)

# The Global Water Cycle: General Circulation




Source: Univ. of South Dacota (2003)

# The Global Water Cycle: Tropical Circulation

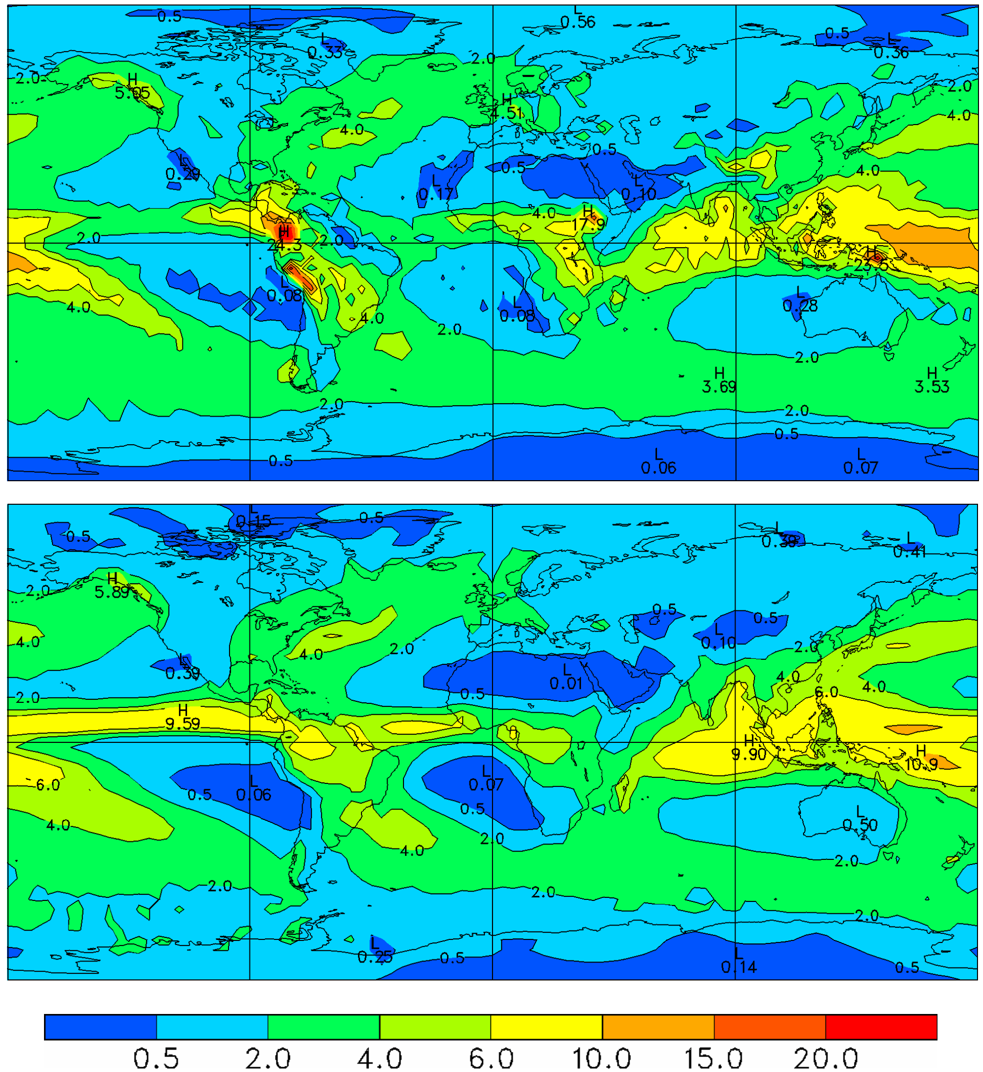



Source: Simpson (1992)

# The Global Water Cycle: Annual Mean Precipitation

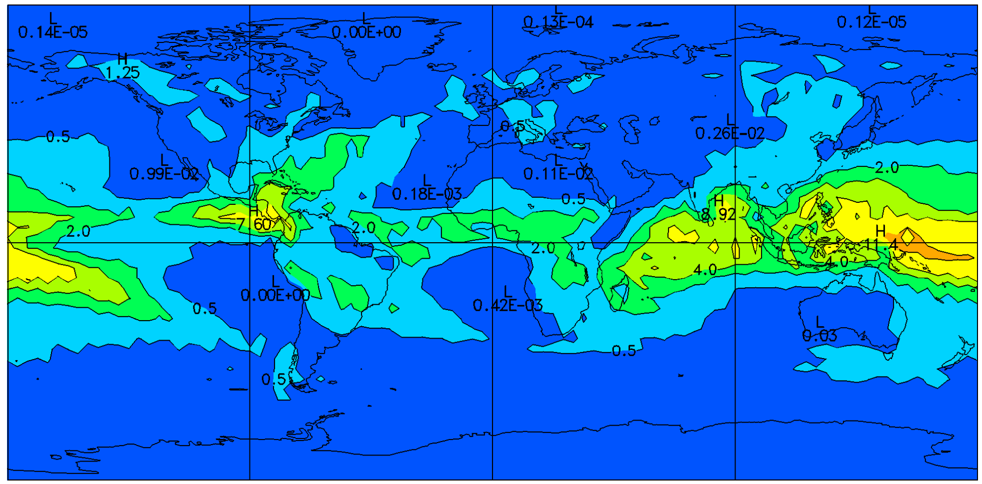
**Experimental**
**CCCma GCM4**

**Observations**
**(Xie and Arkin, 1996)**

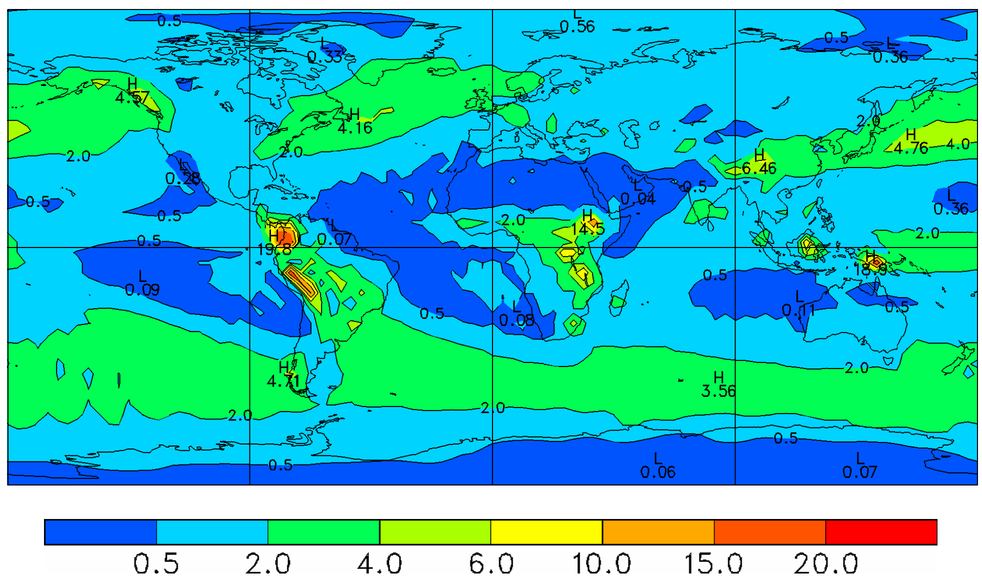



Units: mm/day

# The Global Water Cycle: Sources of Precipitation



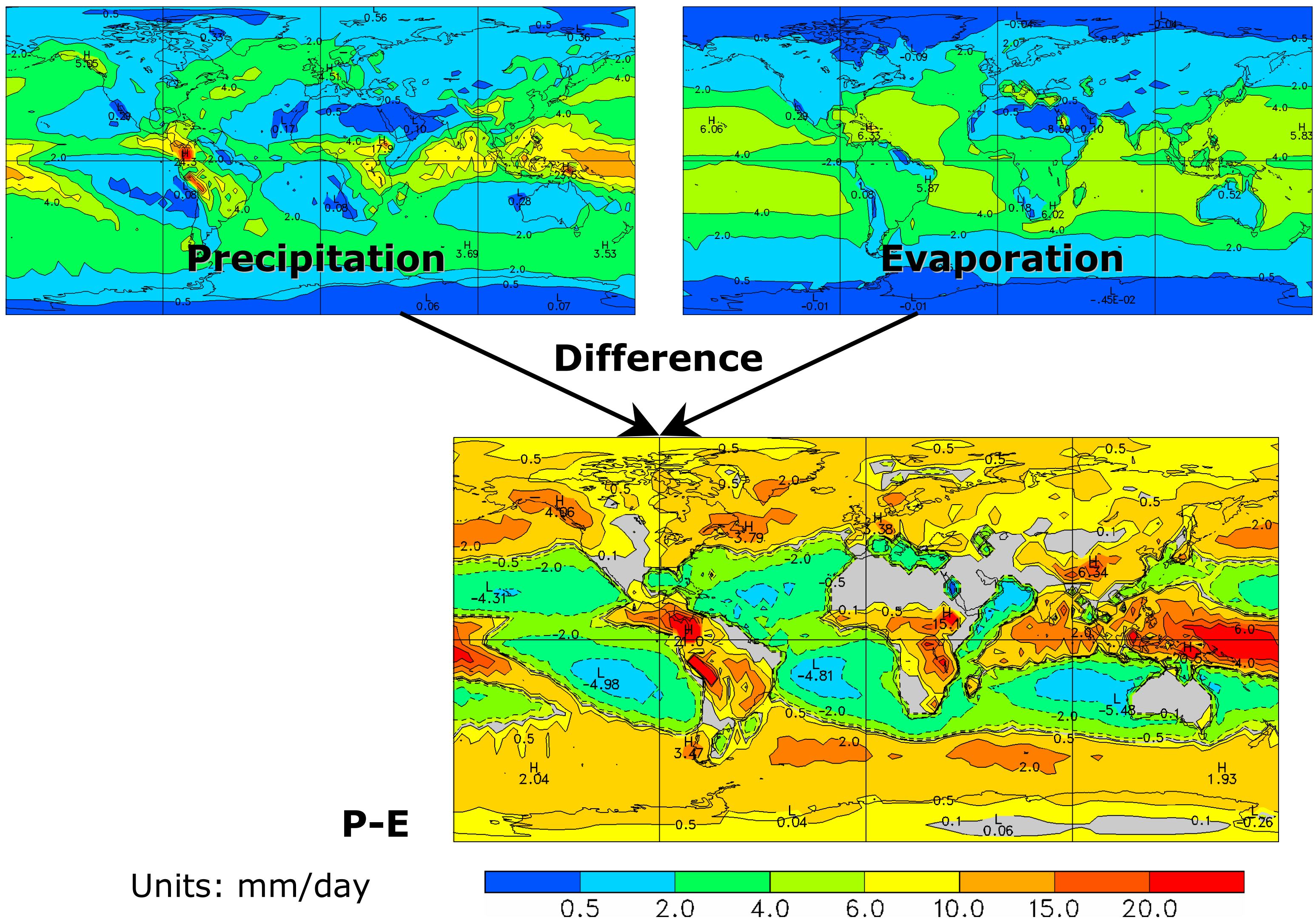
**Convective Clouds**




**Layer Clouds**

Units: mm/day

# The Global Water Cycle: Net Surface Moisture Flux

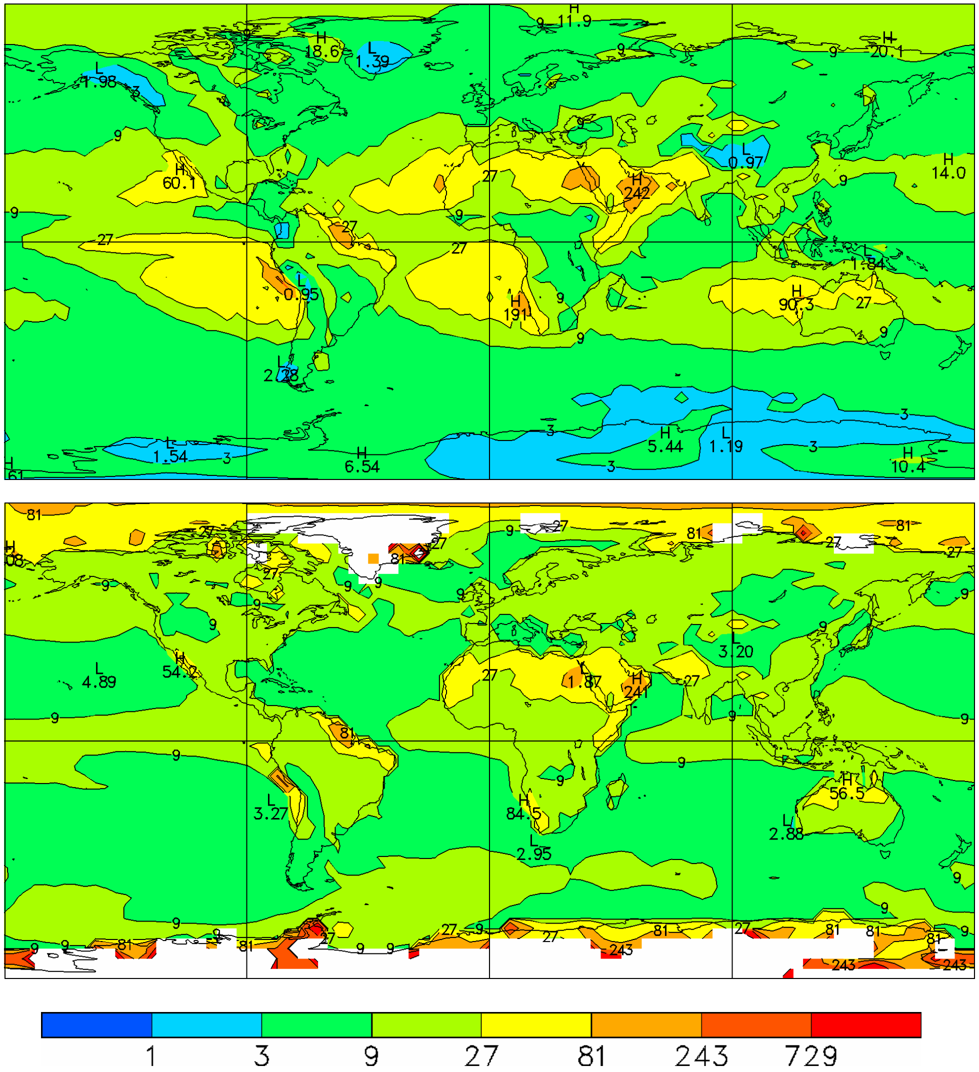


# The Global Water Cycle: Efficiency

$$\tau = \frac{\text{Atm. Water Content}}{\text{Flux at Surface}}$$

**Precipitation**

**Evaporation**




Units: days

# Evaporation in the Surface Layer

$$H = -\rho\, c_p\, u_*\, \Theta_*$$
$$Q = -\rho\, L_v\, u_*\, q_*$$

$$u_* = \frac{k\,U}{\ln\left(\frac{z}{z_0}\right) - \Psi_M\left(\frac{z}{L}\right) + \Psi_M\left(\frac{z_0}{L}\right)}$$

$$\Theta_* = \frac{k\,(\Theta - \Theta_s)\,Pr^{-1}}{\ln\left(\frac{z}{z_t}\right) - \Psi_H\left(\frac{z}{L}\right) + \Psi_H\left(\frac{z_t}{L}\right)}$$

$$q_* = \frac{k\,(q - q_s)\,Pr^{-1}}{\ln\left(\frac{z}{z_q}\right) - \Psi_Q\left(\frac{z}{L}\right) + \Psi_Q\left(\frac{z_q}{L}\right)}$$

Monin-Obukhov length scale:

$$L = \left(\frac{\Theta_v\, u_*^3}{k\, g\, \overline{w'\Theta_v'}}\right)_s$$

Buoyancy flux at surface:

$$\left(\overline{w'\Theta_v'}\right)_s = -u_*\left(\Theta_* + 0.61\,\Theta_{vs}\,q_*\right)$$

# Tropical Atmosphere: Heat and Moisture Balance

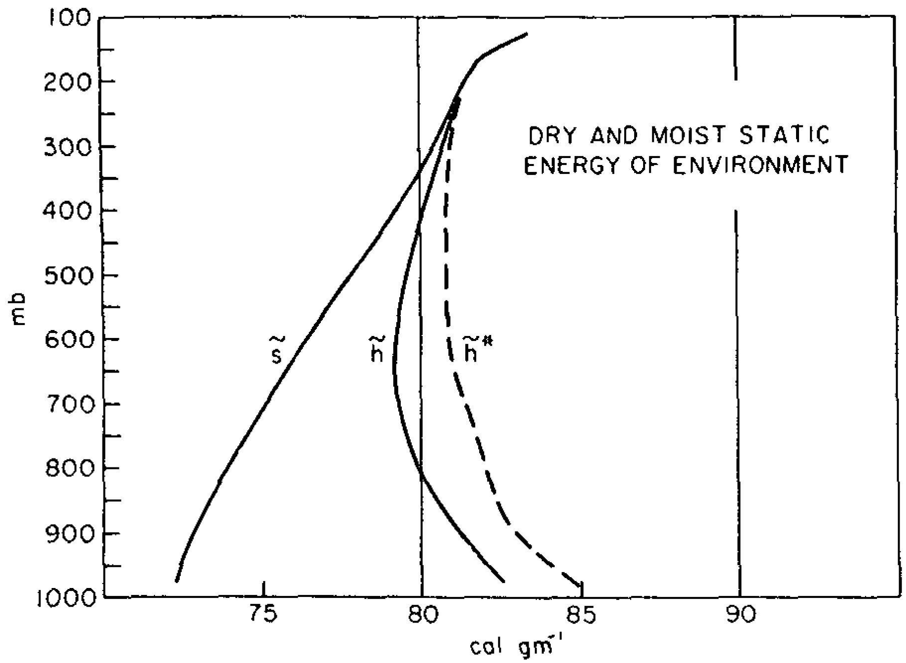
Dry static energy:

$$s \equiv c_p T + gz$$

Moist static energy:

$$h \equiv c_p T + gz + L_v q$$

$$h^* \equiv c_p T + gz + L_v q^*$$




Source: Yanai et al. (1973)

# Tropical Atmosphere: Heat and Moisture Balance

Heat balance:

$$Q_1 \equiv \frac{\partial \bar{s}}{\partial t} + \overline{\nabla \cdot s\mathbf{V}_h} + \frac{\partial \bar{s}\,\bar{\omega}}{\partial p} = Q_R + L_v(c-e) - \frac{\partial}{\partial p}\overline{s'\omega'}$$

eddy vertical transport

radiative heating

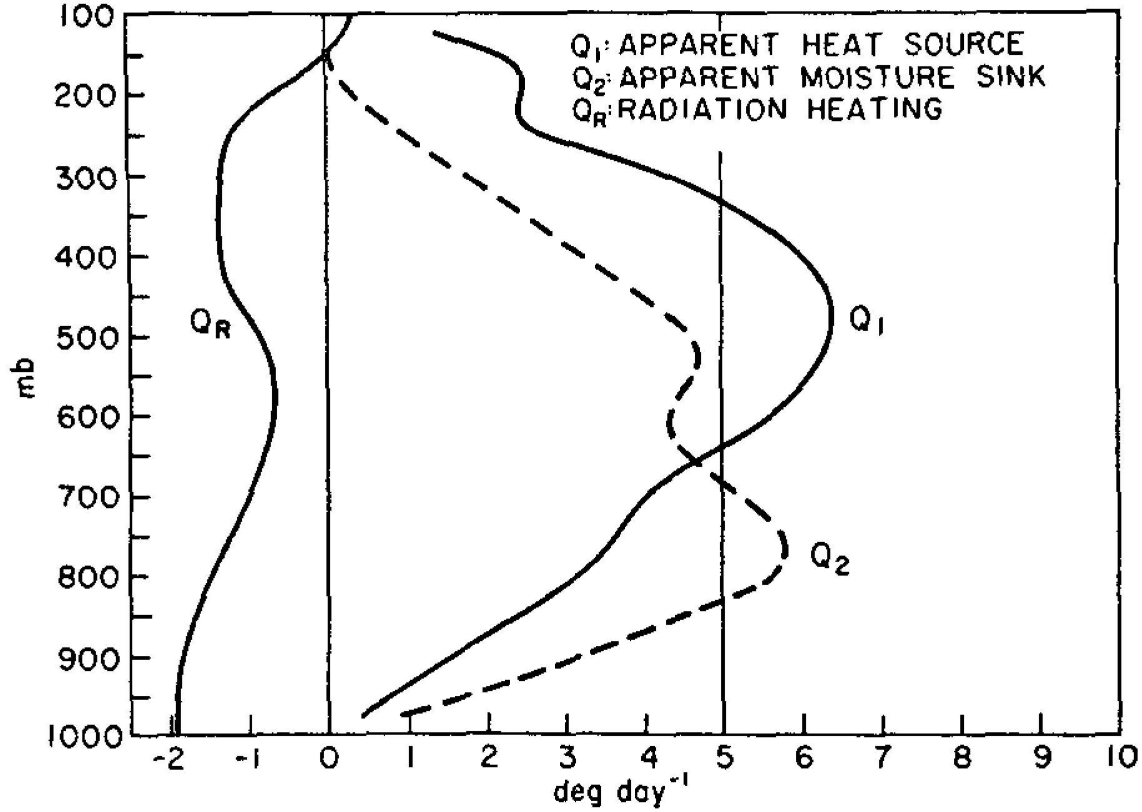
condensation

evaporation

Moisture balance:

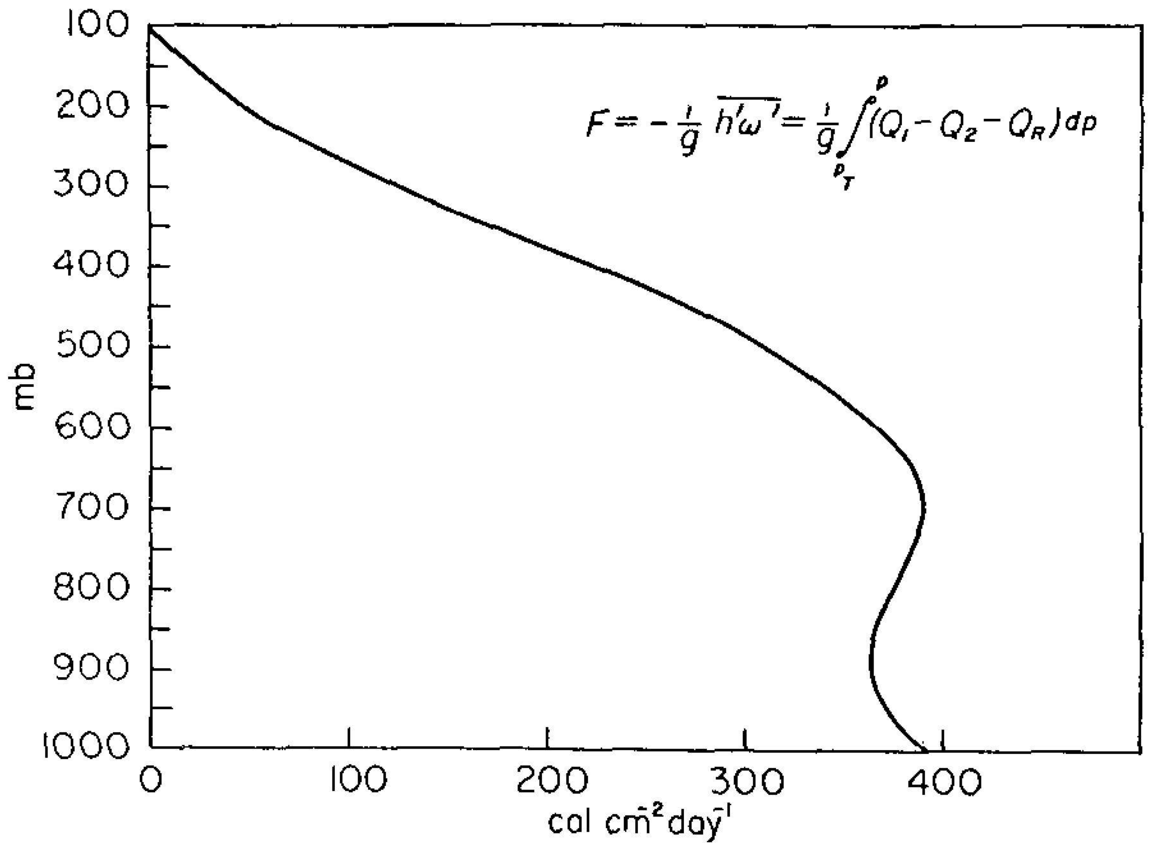
$$Q_2 \equiv -L_v\left(\frac{\partial \bar{q}}{\partial t} + \overline{\nabla \cdot q\mathbf{V}_h} + \frac{\partial \bar{q}\,\bar{\omega}}{\partial p}\right) = L_v(c-e) + L_v\frac{\partial}{\partial p}\overline{q'\omega'}$$

# Tropical Atmosphere: Heat and Moisture Balance



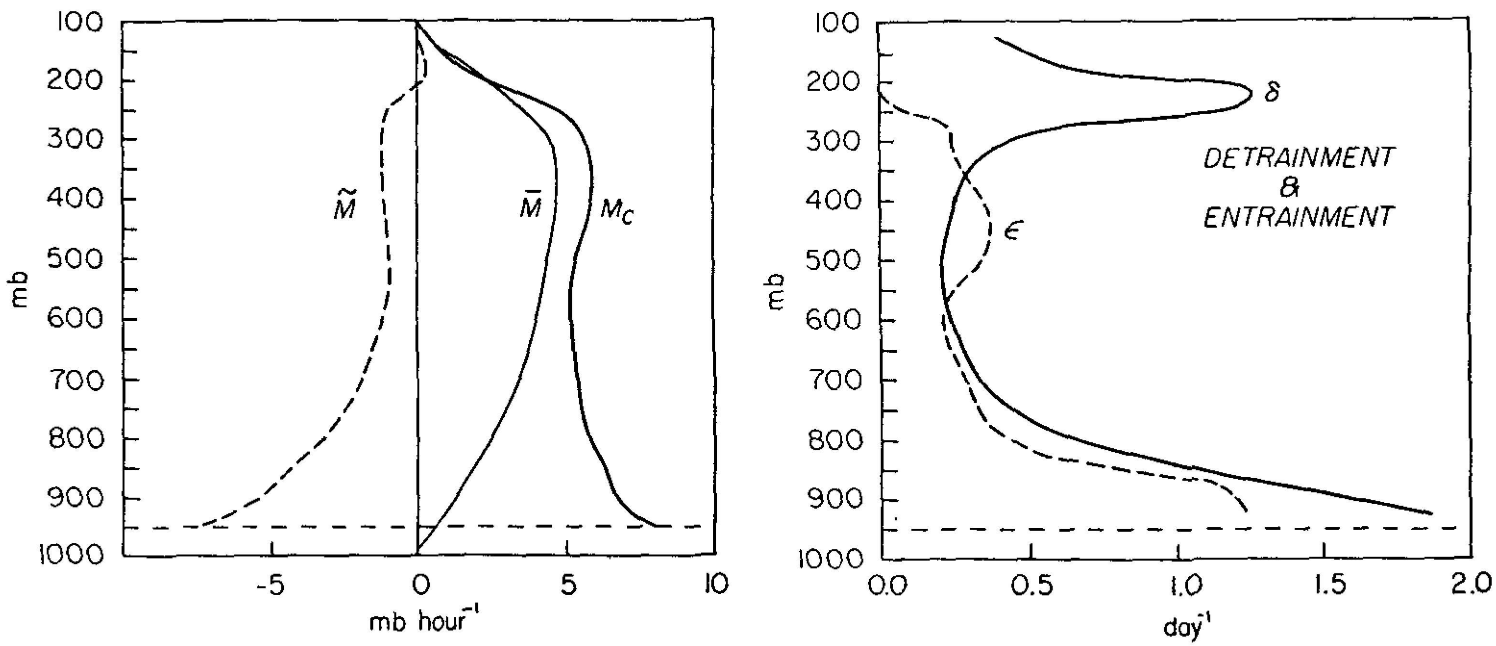

Source: Yanai et al. (1973)

# Tropical Atmosphere: Heat and Moisture Balance




Source: Yanai et al. (1973)

# Tropical Atmosphere: Heat and Moisture Balance: Role of Convection

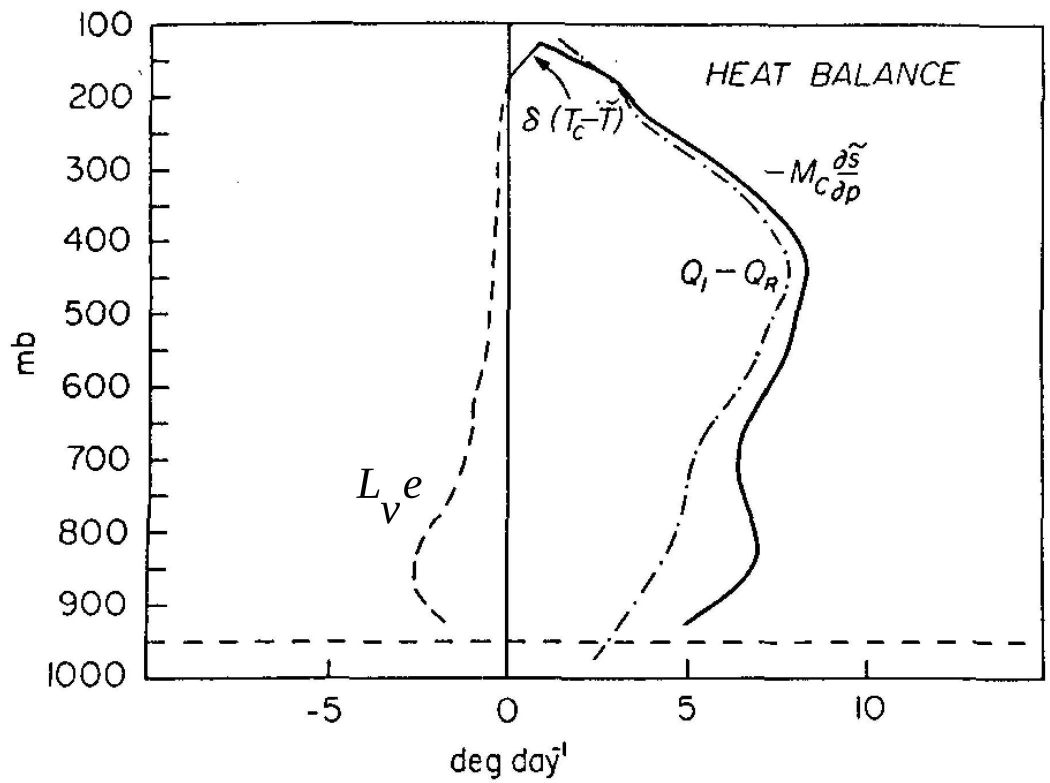



$$Q_1 - Q_R = -M_c \frac{\partial \tilde{s}}{\partial p} - L_v e$$

$$-Q_2 / L_v = -M_c \frac{\partial \tilde{q}}{\partial p} + \delta\left(q_c - \tilde{q} + l\right)$$

Source: Yanai et al. (1973)

# Tropical Atmosphere: Heat and Moisture Balance: Role of Convection

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Source: Yanai et al. (1973)

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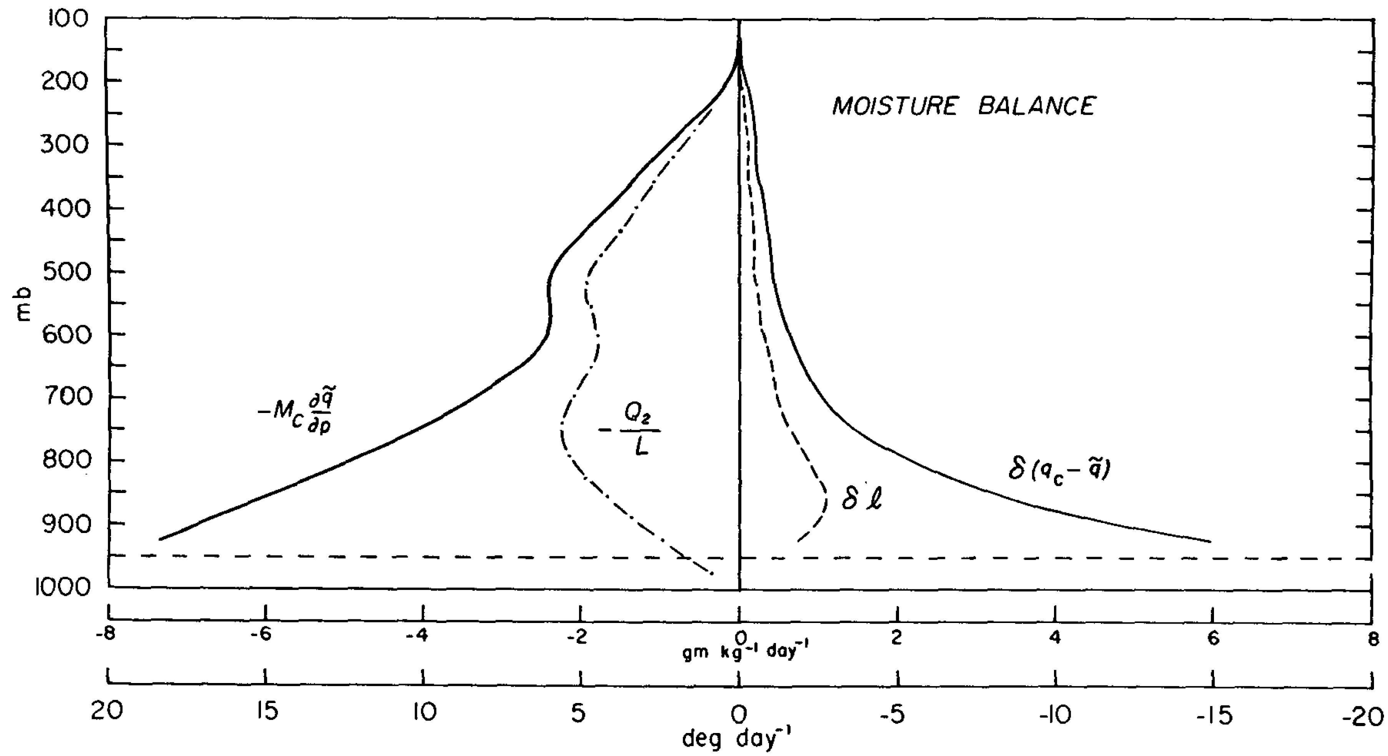
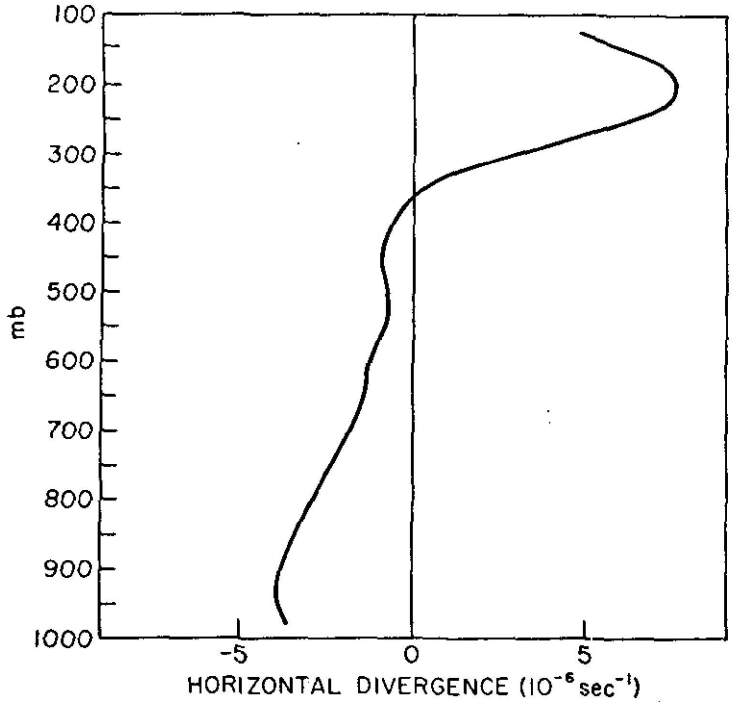
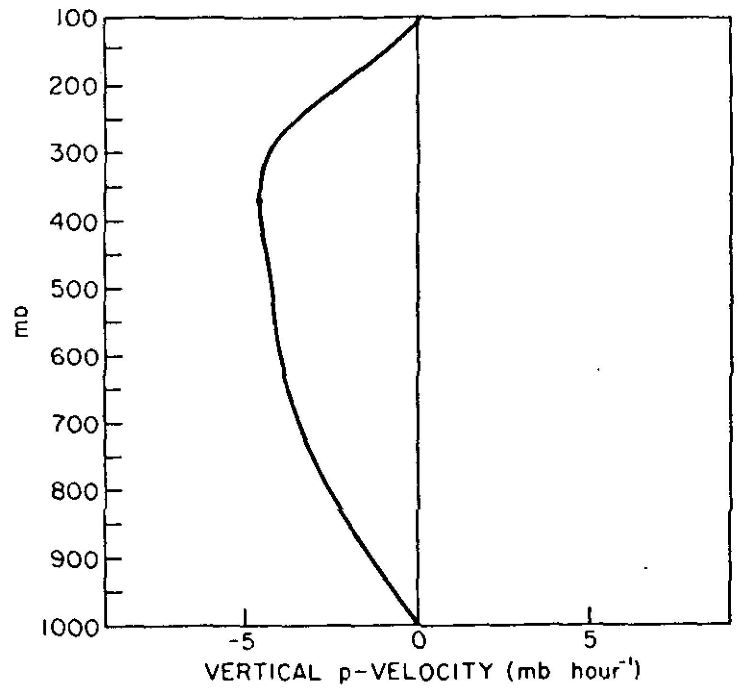



$$-Q_2 / L_v = -M_c \frac{\partial \tilde{q}}{\partial p} + \delta\left(q_c - \tilde{q} + l\right)$$

Source: Yanai et al. (1973)

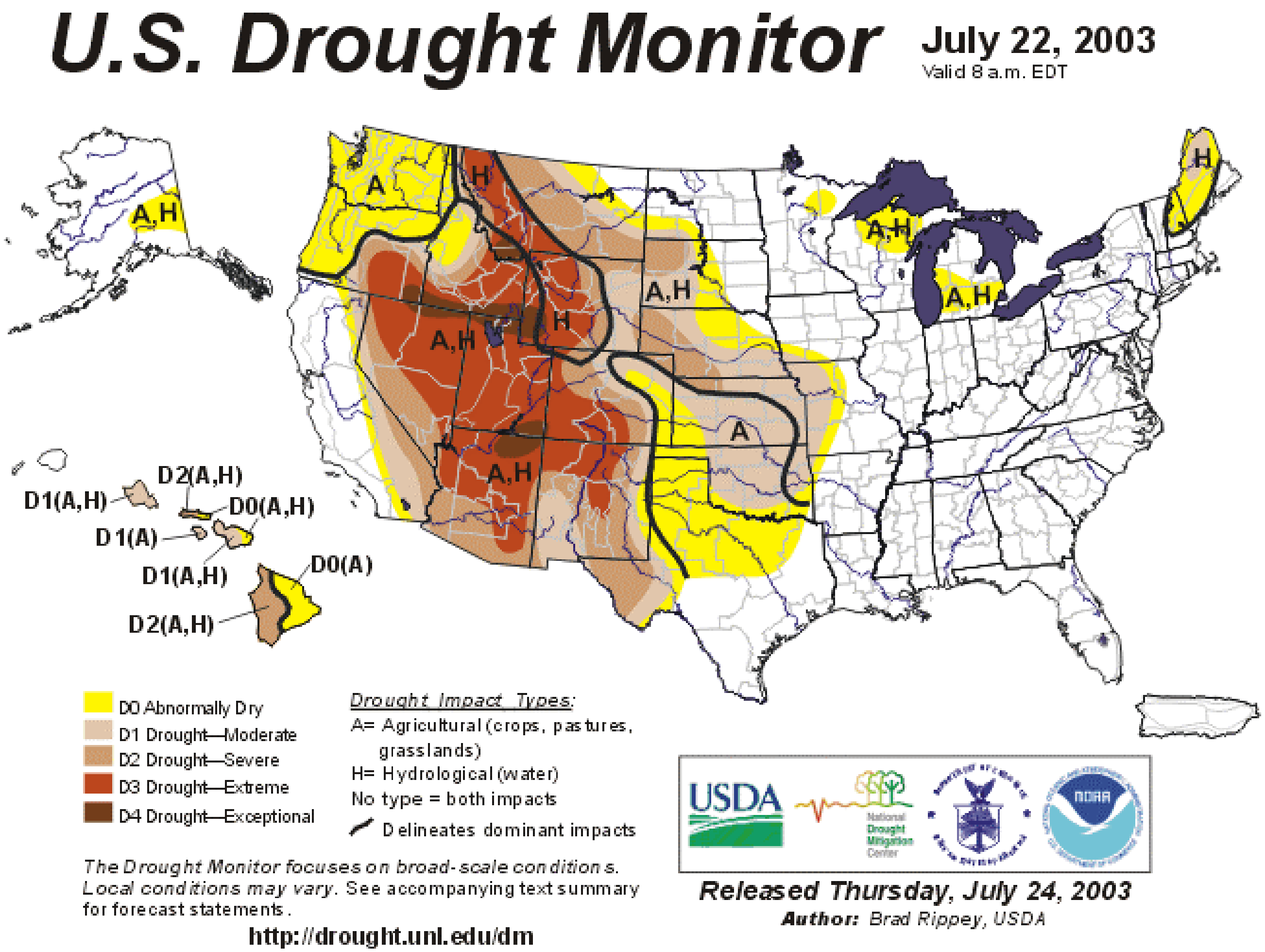
# Tropical Atmosphere: Heat and Moisture Balance: Role of Convection



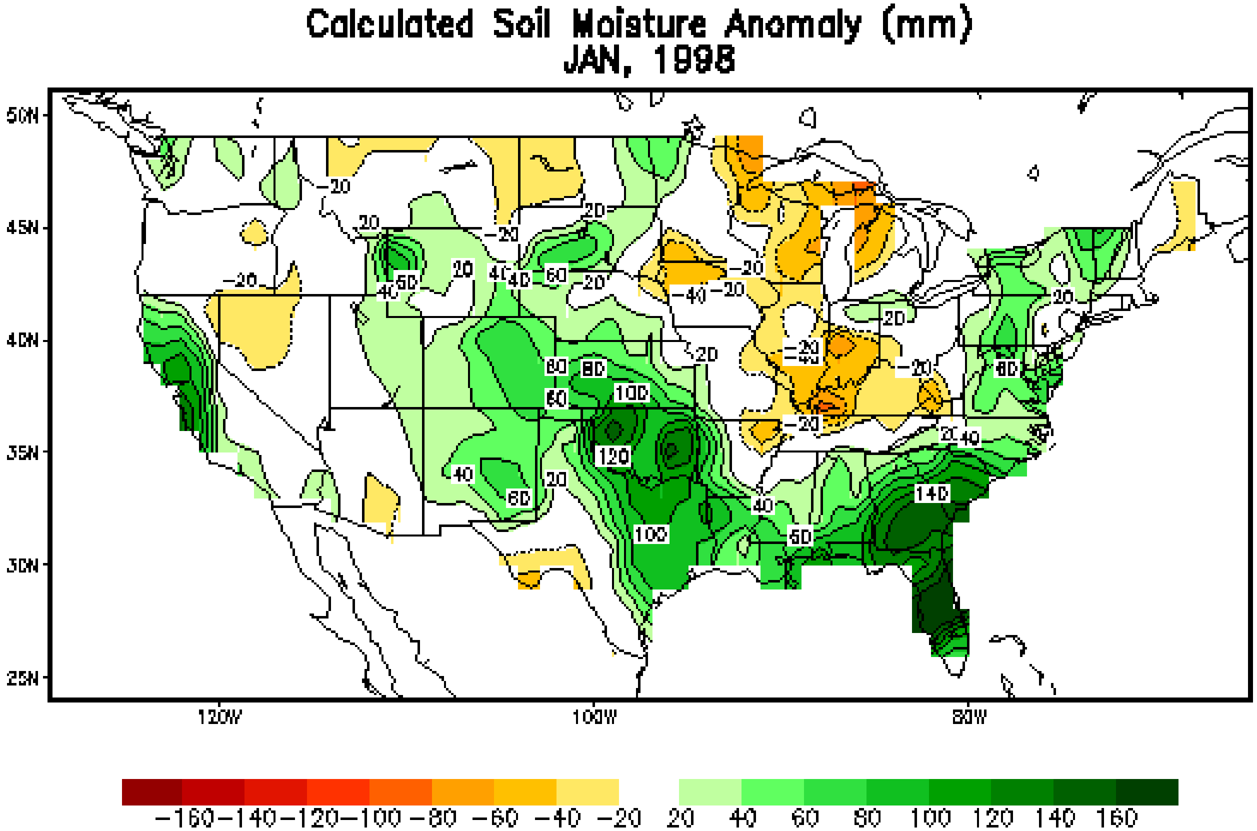




Source: Yanai et al. (1973)

# Variability of the Water Cycle: A Snapshot

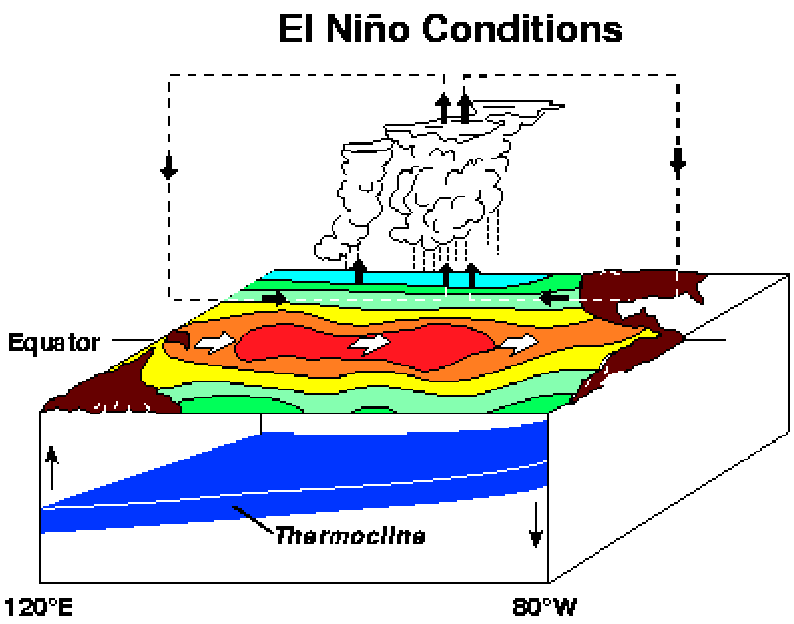


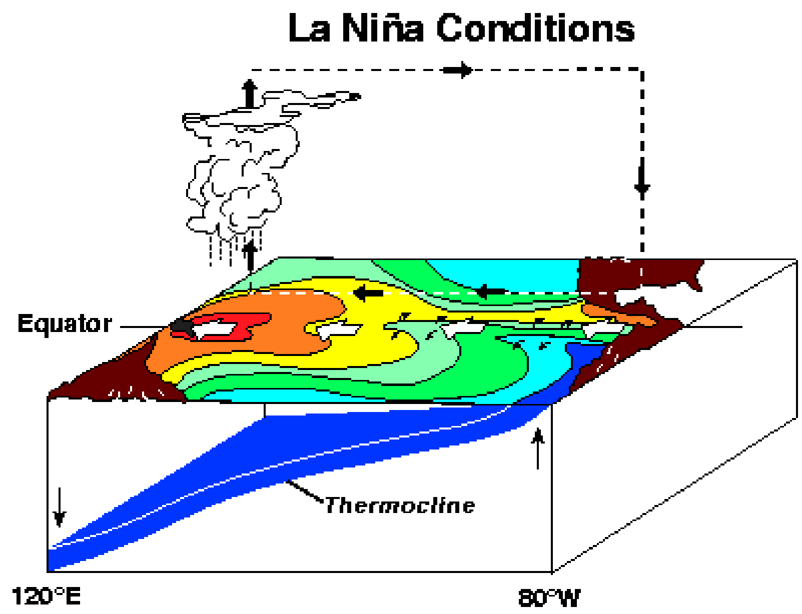
# Variability of the Water Cycle: Regional Variations




Source: NOAA

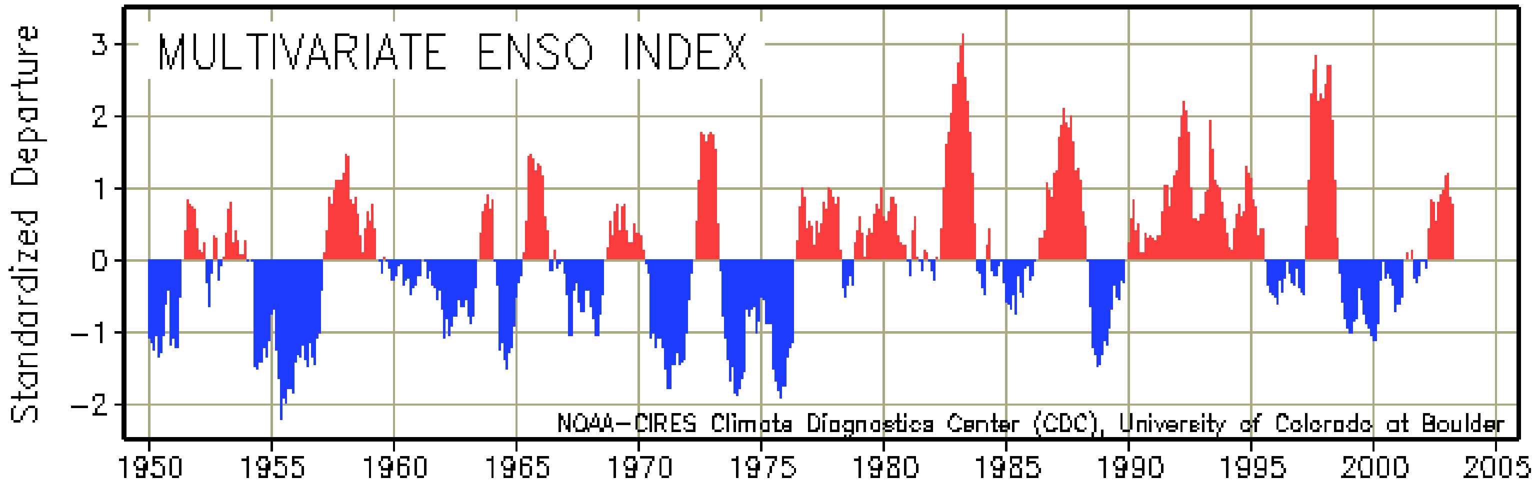
# Variability of the Water Cycle: ENSO




Source: NOAA

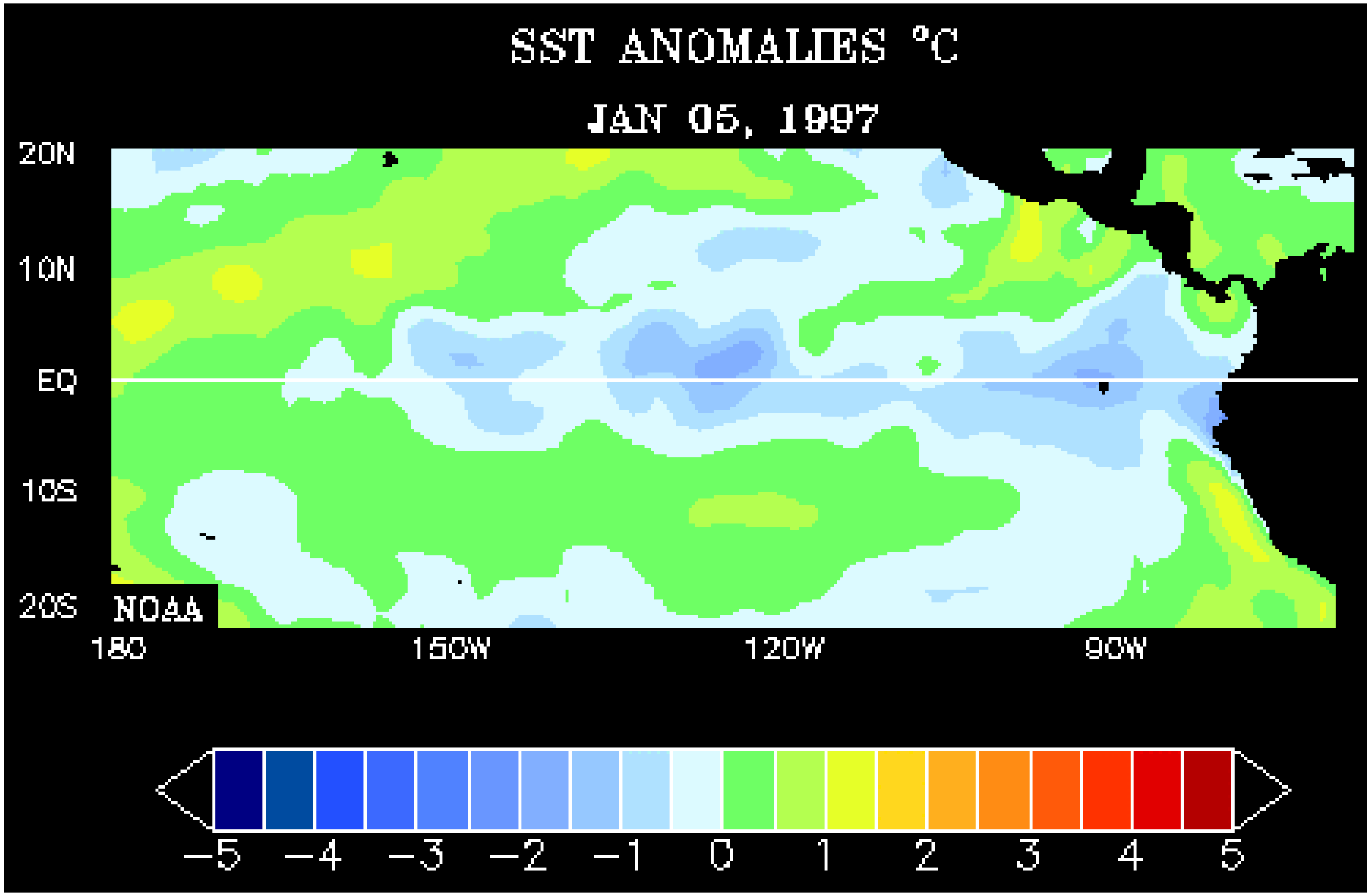
# Variability of the Water Cycle: ENSO Index




**Commonly used indices:**

- **Southern Oscillation Index (SOI): Difference in sea-level pressure between Tahiti and Darwin, Australia**
- **Nino 3: Anomalous sea-surface temperature within the region bounded by 5N-5S and 150W-190W.**

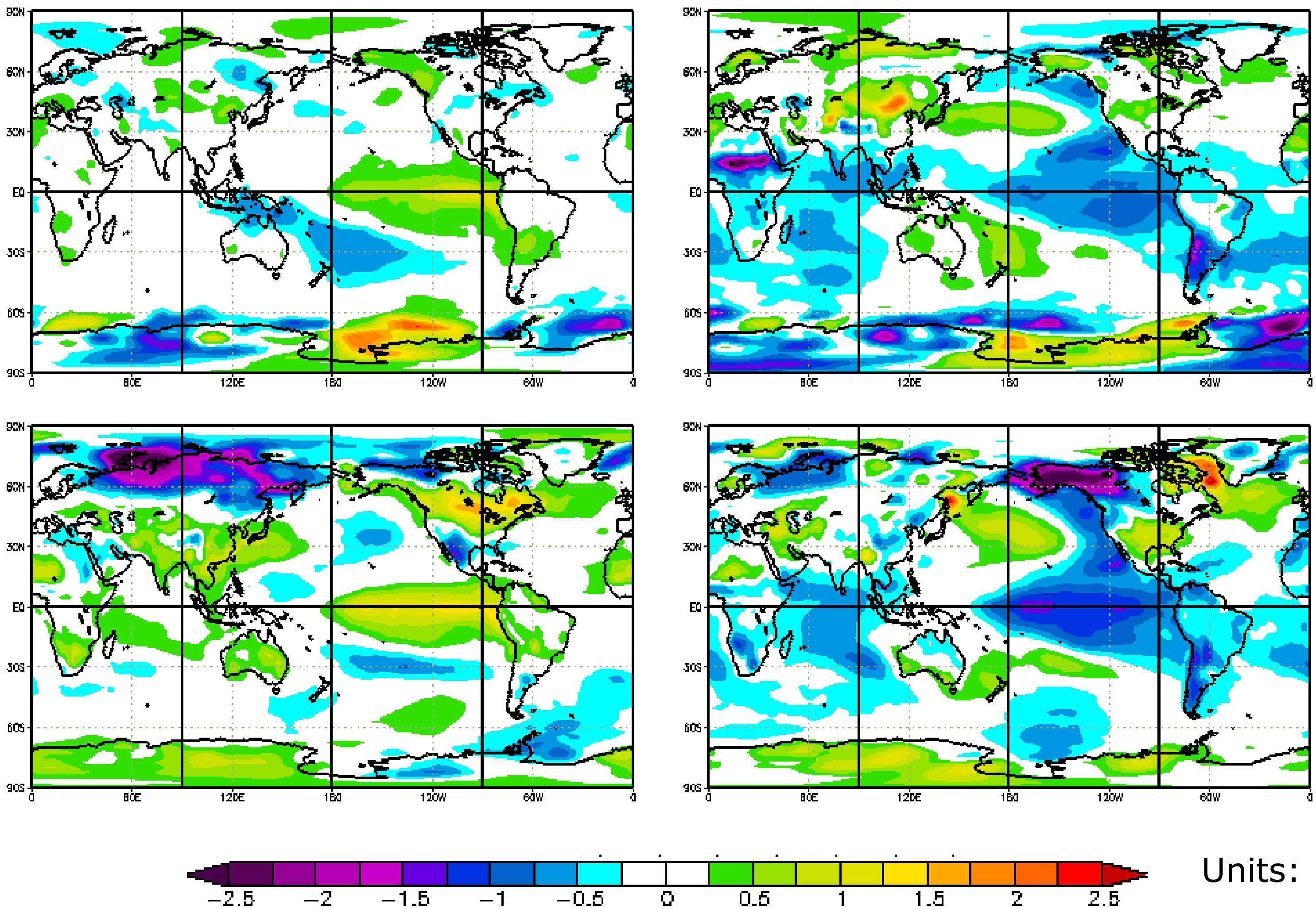
## Variability of the Water Cycle: El Nino in 1997



# Variability of the Water Cycle: Temperature Change

El Nino

La Nina

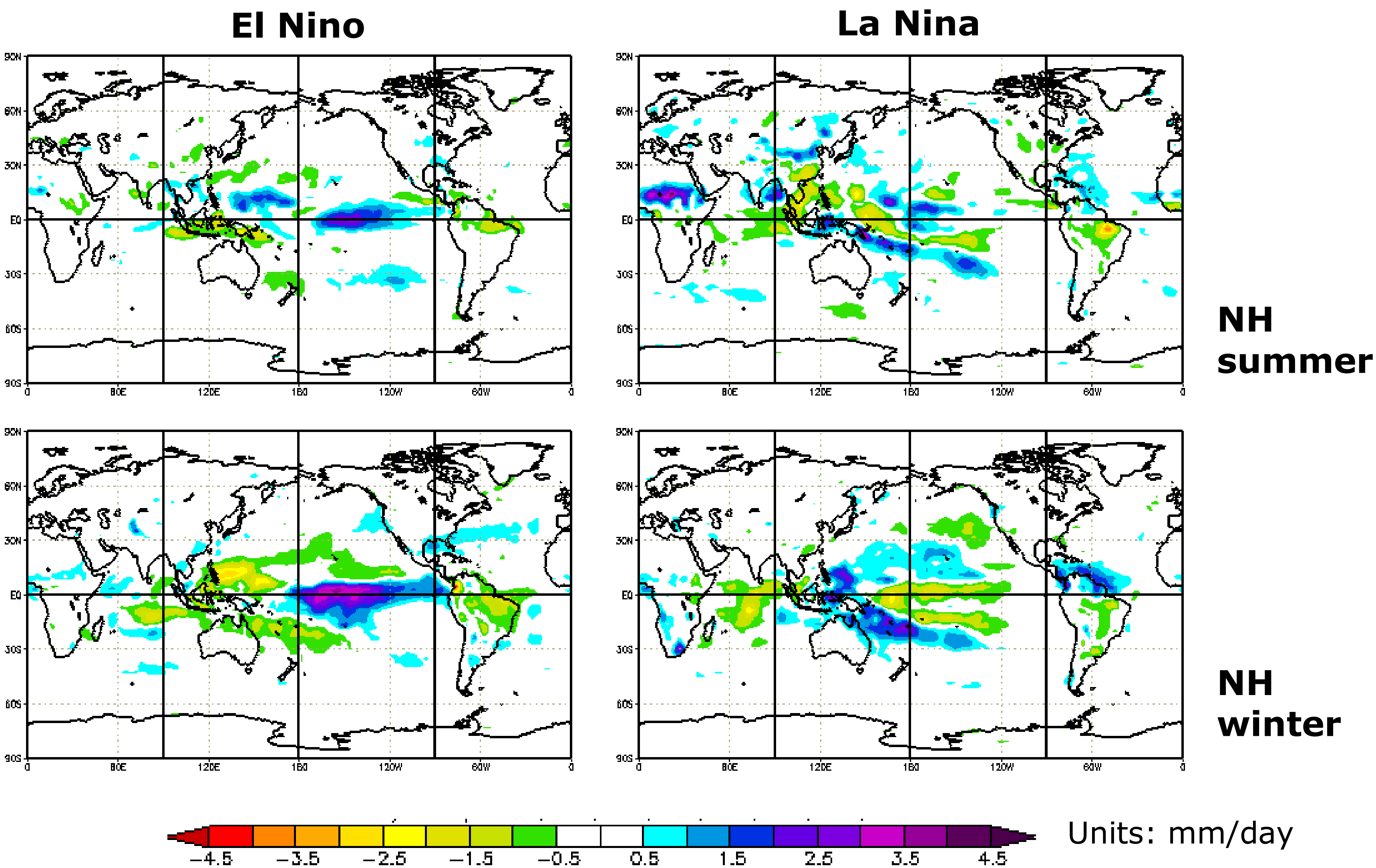



NH summer

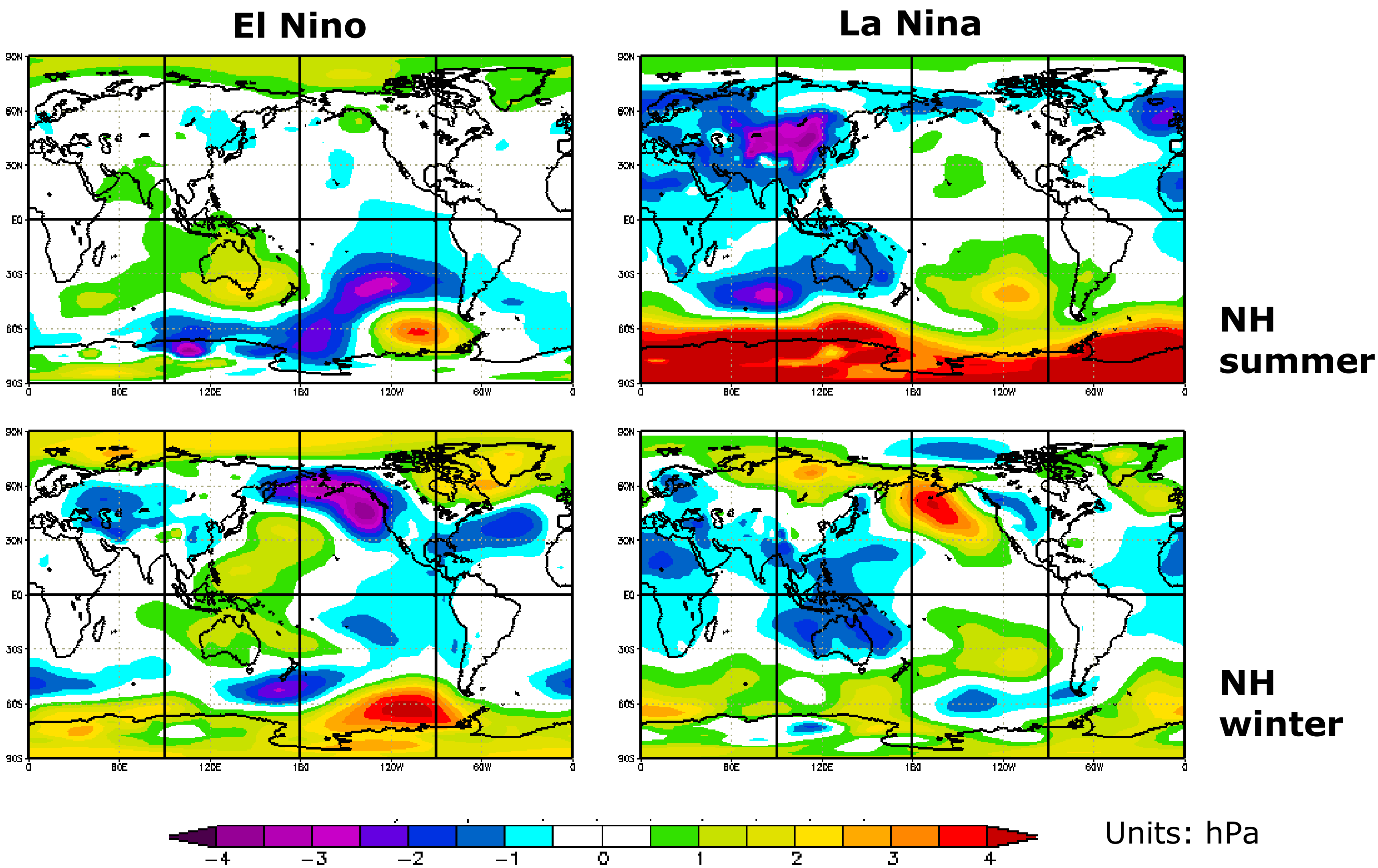
NH winter

Units: Kelvin

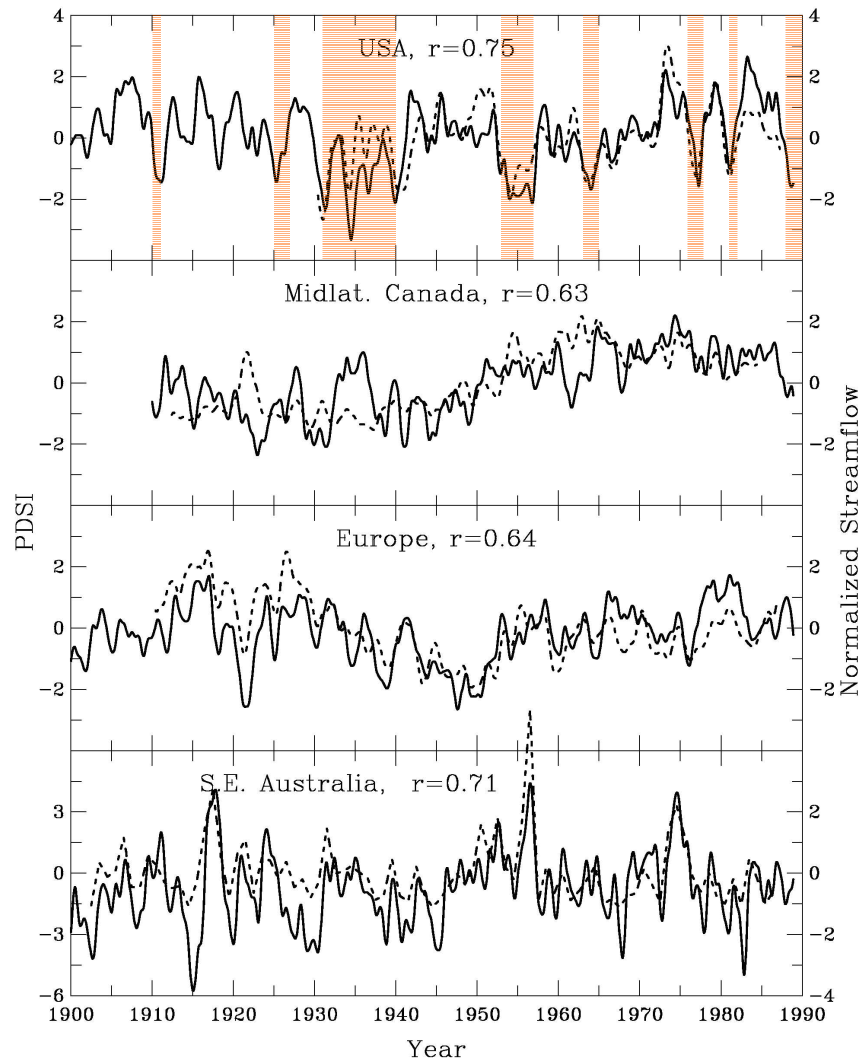
# Variability of the Water Cycle: Precipitation Change



# Variability of the Water Cycle: SL Pressure Change

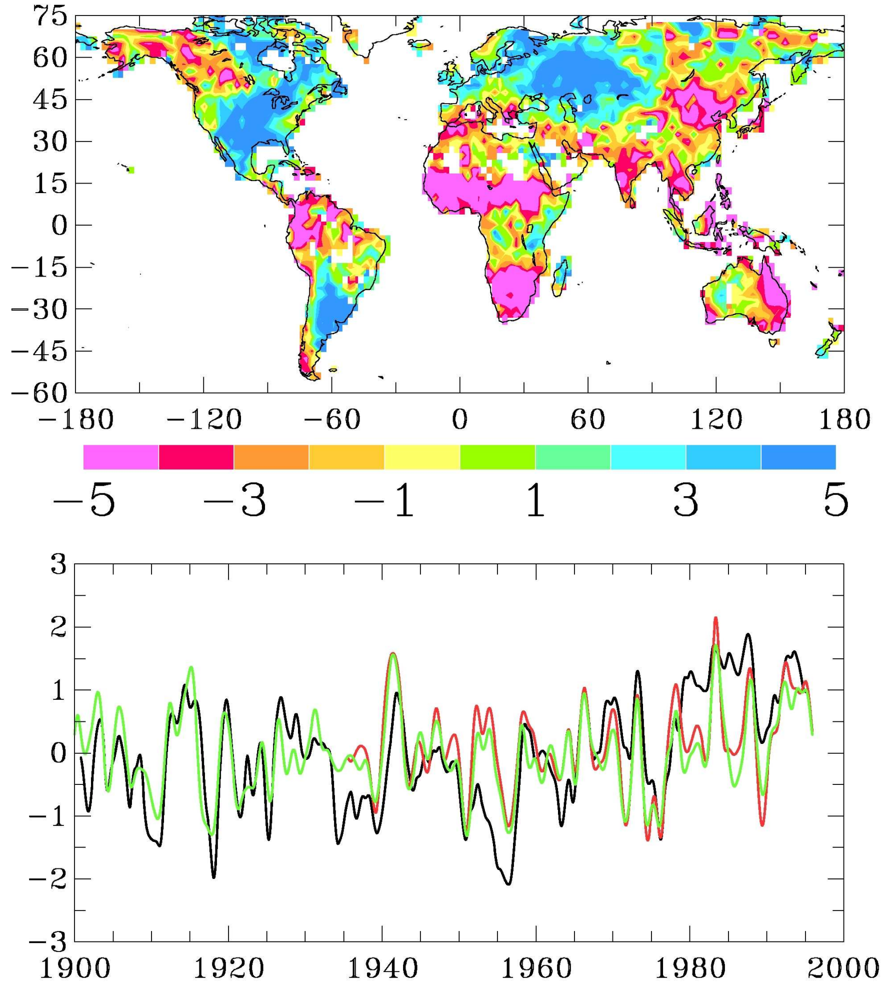


# Variability of the Water Cycle: Drought cycles



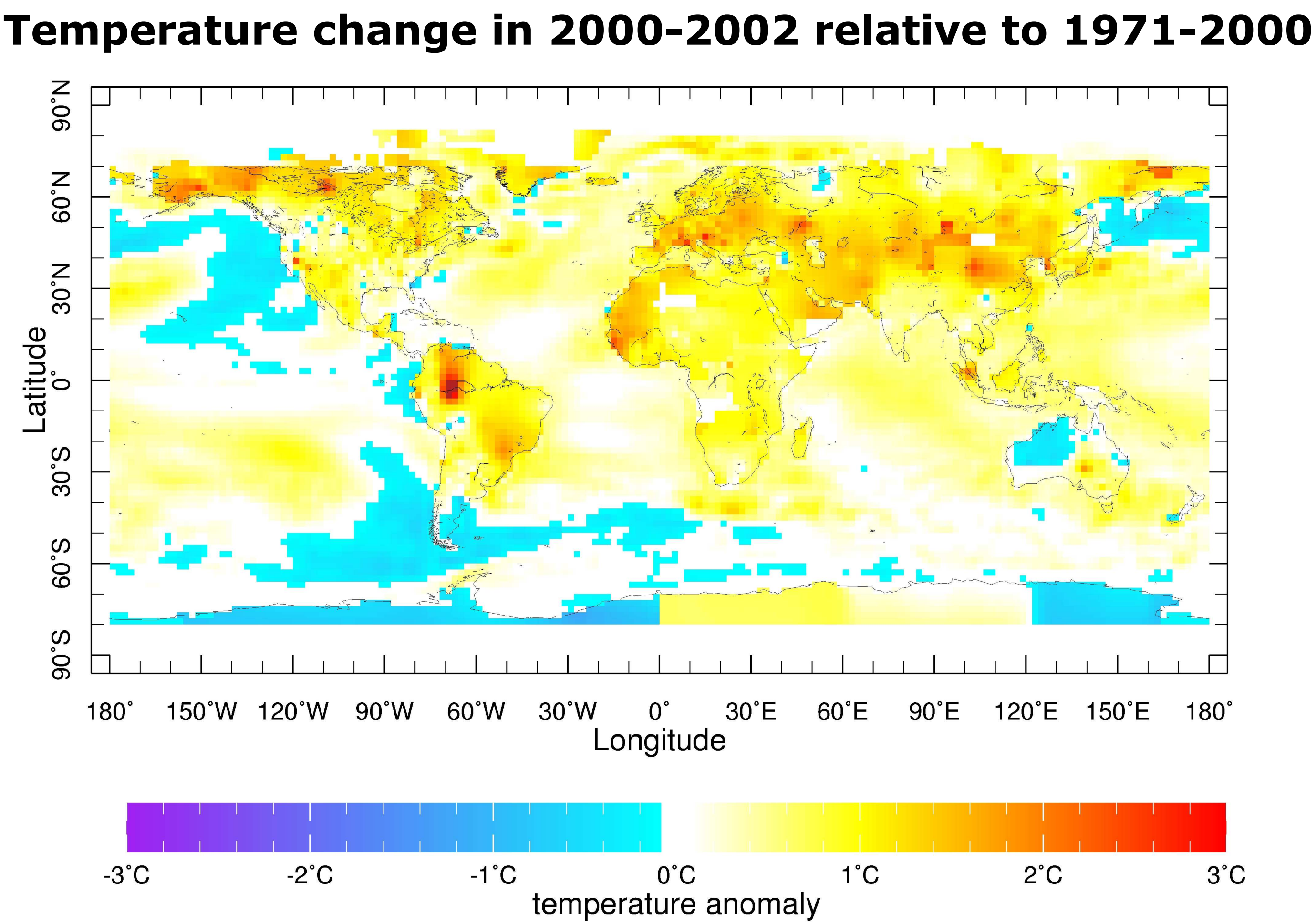

Source: Dai
and Trenberth (1998)

# Variability of the Water Cycle: Drought cycles



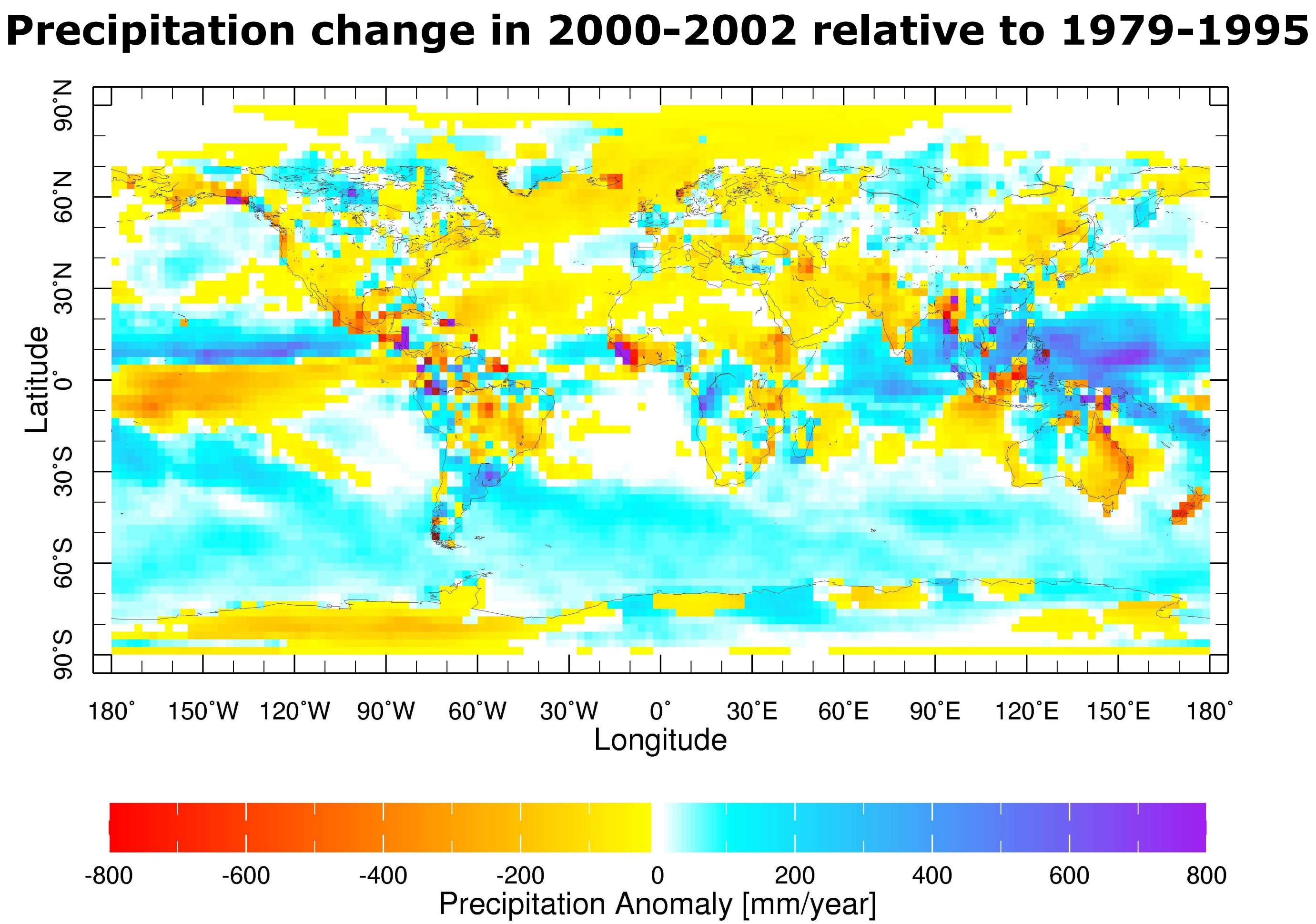

Source: Dai and Trenberth (1998)

# Variability of the Water Cycle: Recent Years



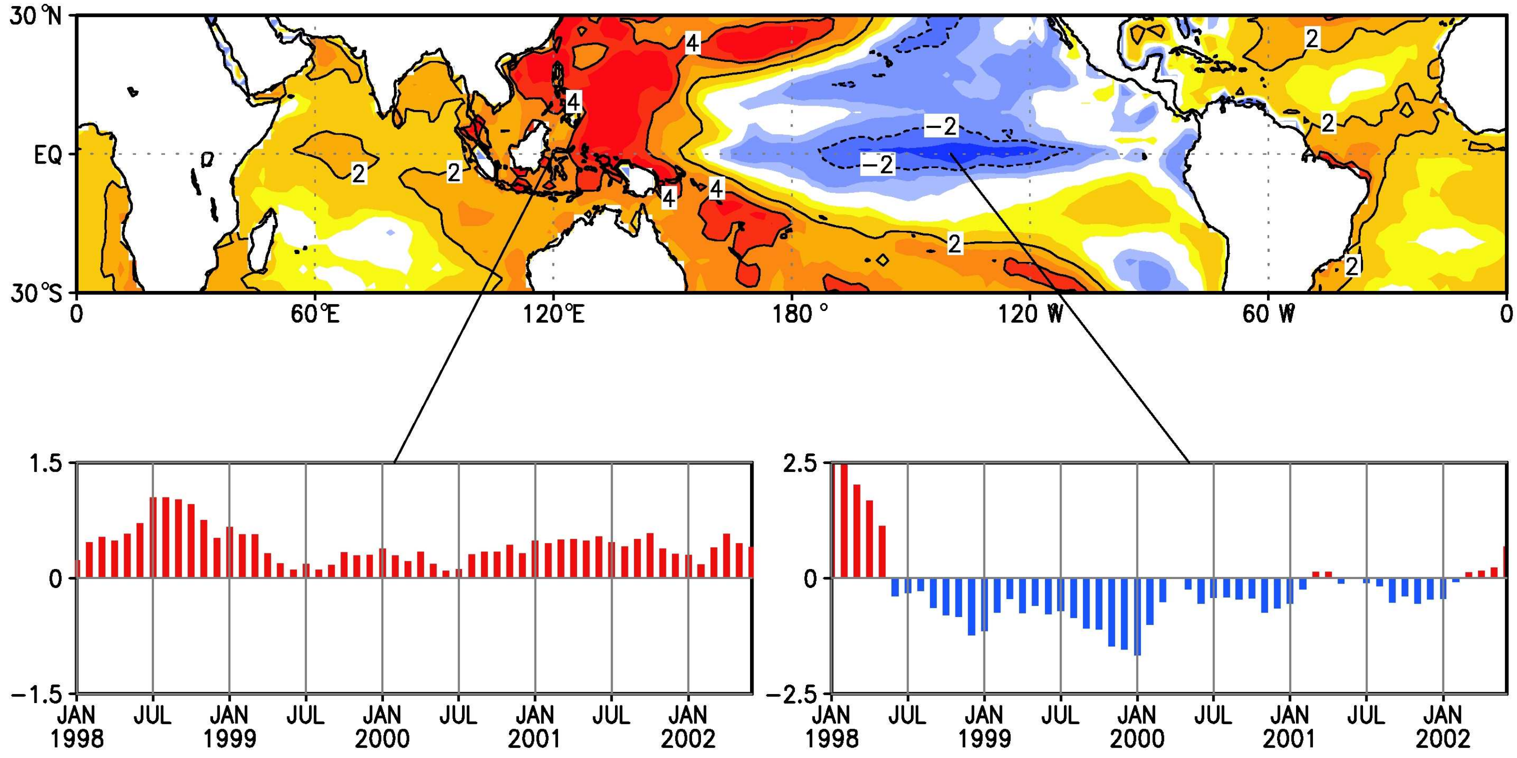

Source: NOAA NCEP CPC CAMS

# Variability of the Water Cycle: Recent Years



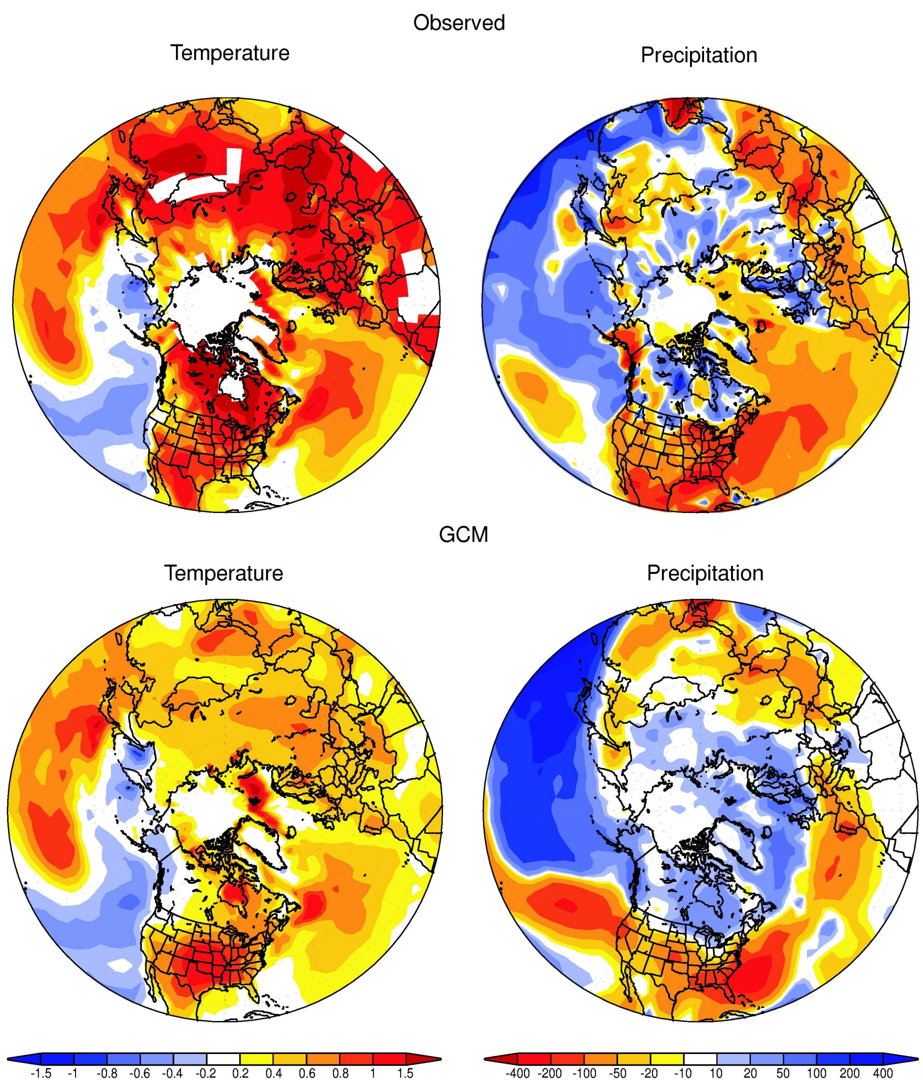

Source: NOAA NCEP CPC CAMS_OPI

# Variability of the Water Cycle: Role of the Ocean



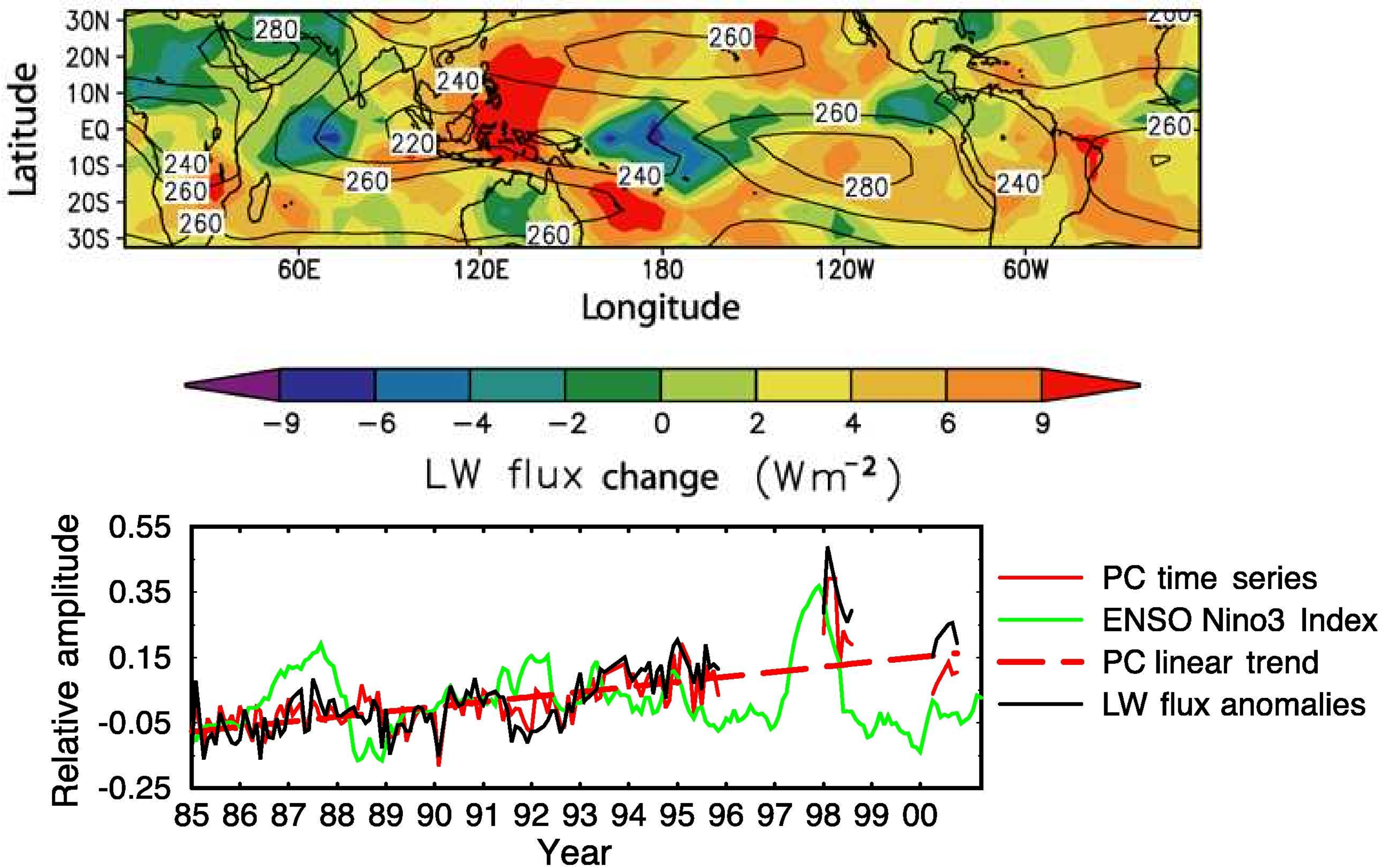

Source: Hoerling and Kumar (2003)

# Variability of the Water Cycle: Role of the Ocean



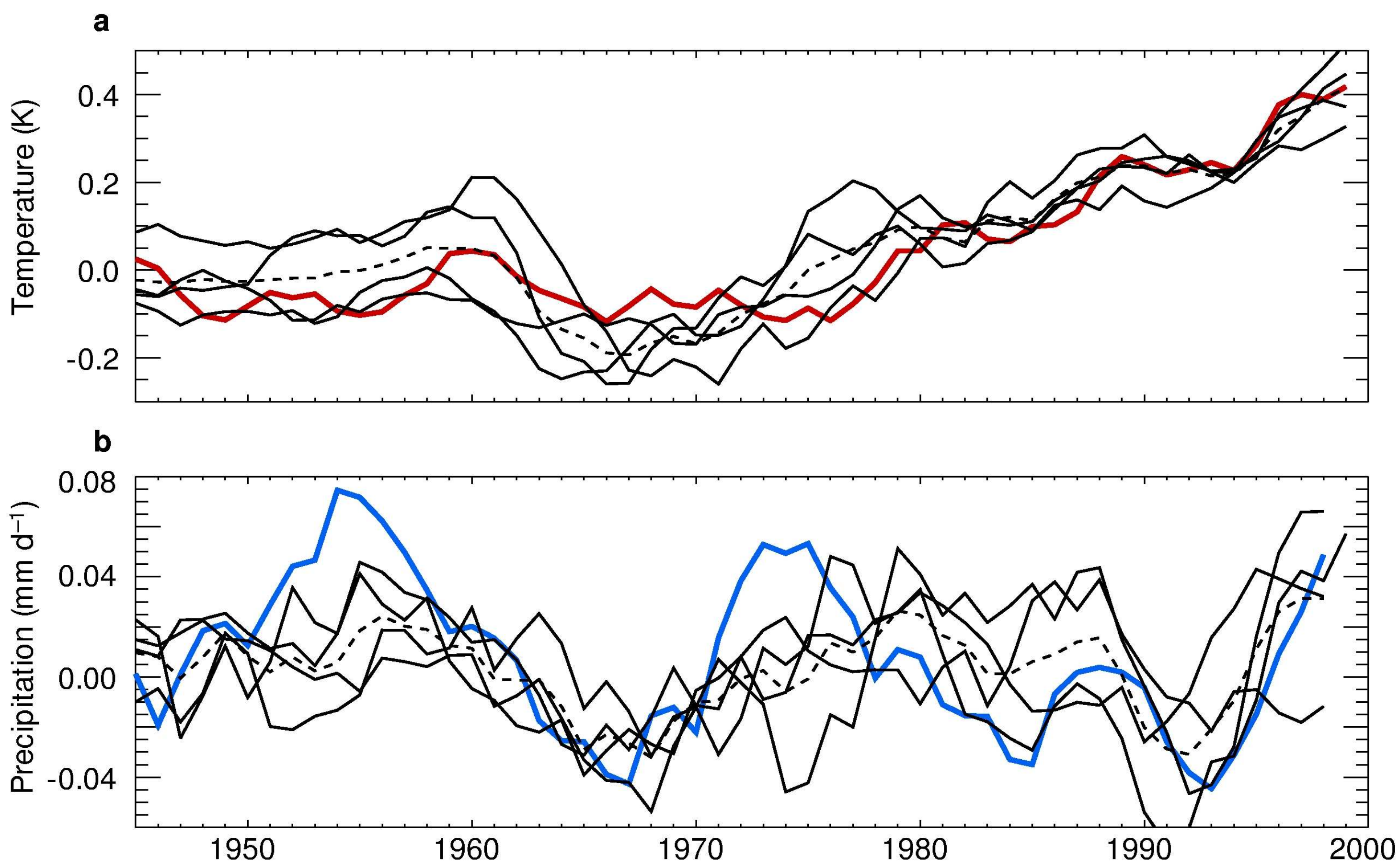

Source: Hoerling and Kumar (2003)

# Variability of the Water Cycle: Role of the Ocean



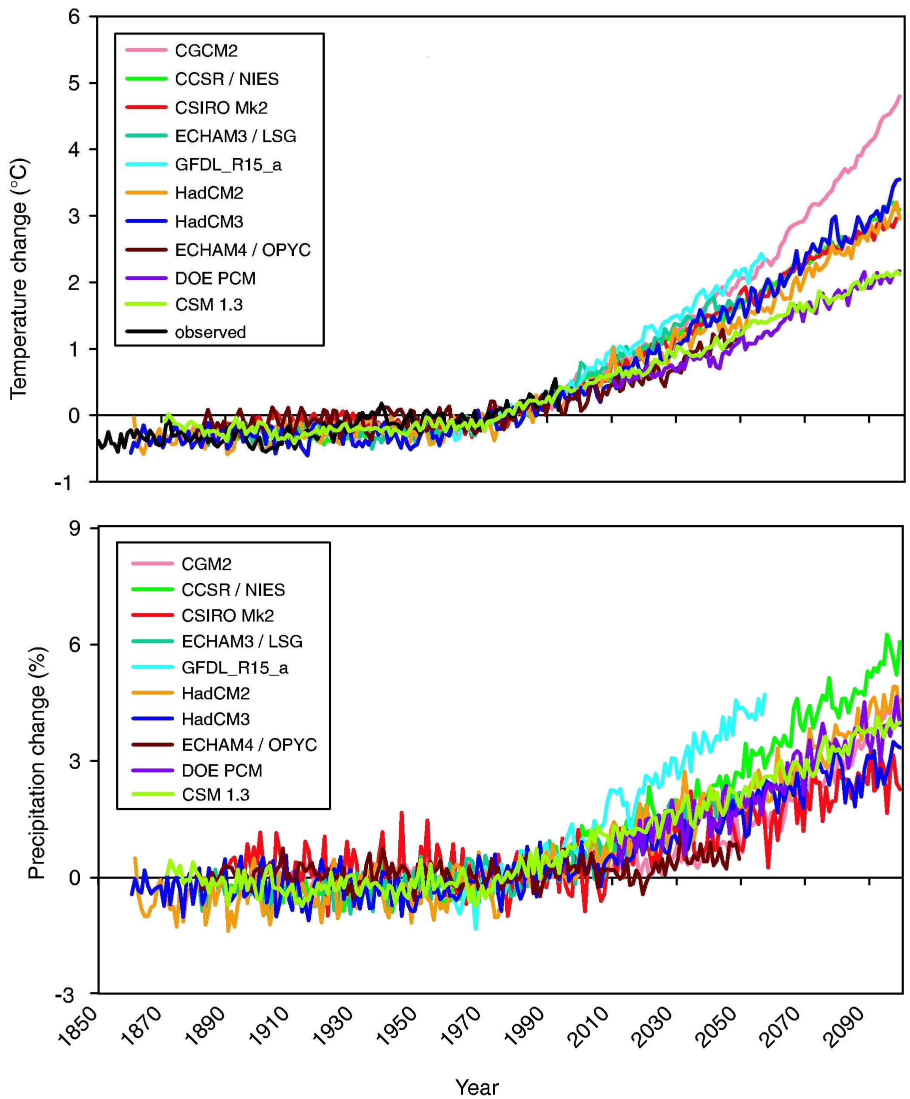

Source: Chen et al. (2002)

# Climate Change and Water Cycle: The Last 50 Years



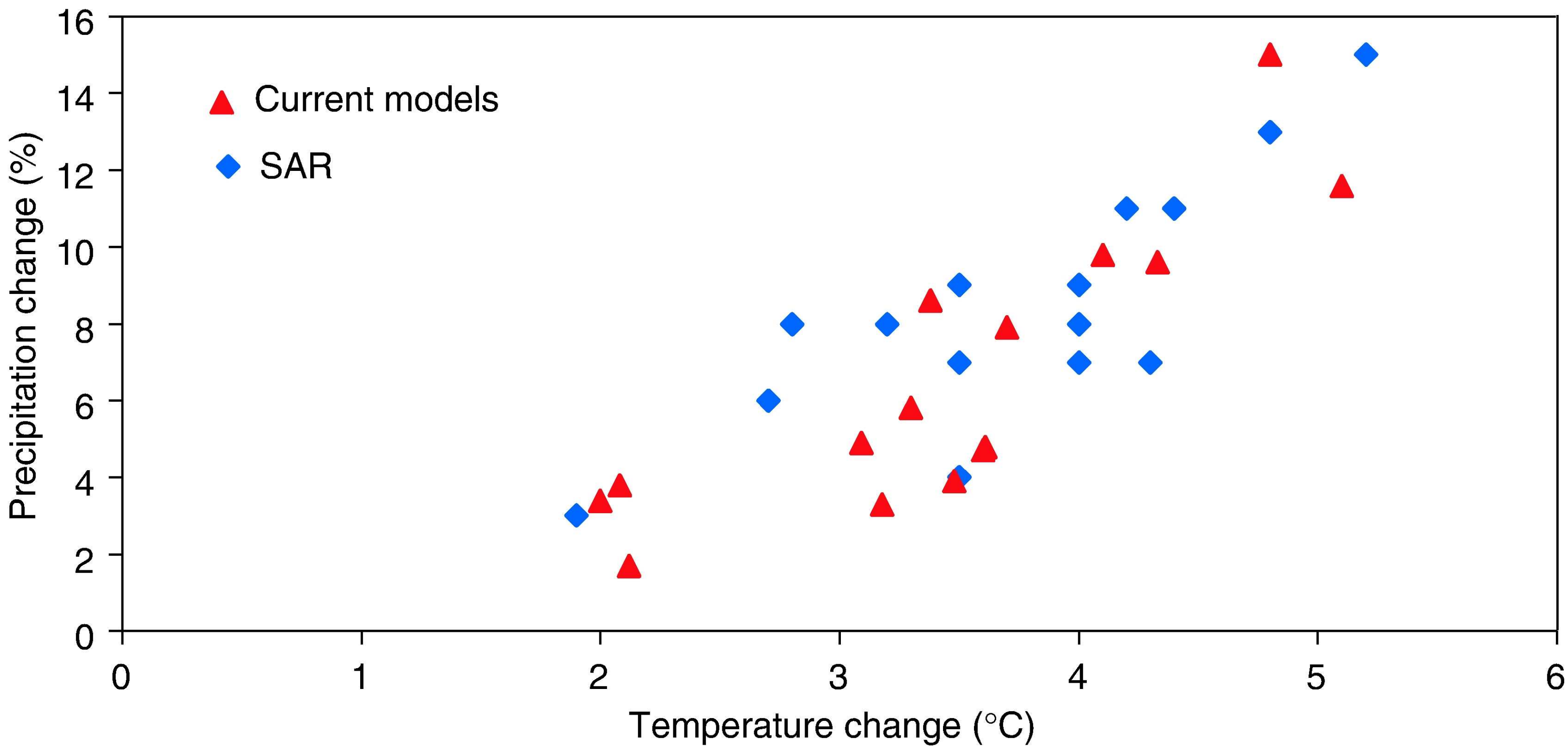

Source: P. Stott, The Met Office

# Climate Change and Water Cycle: Projections




Source: IPCC, TAR (2001)

# Climate Change and Water Cycle: Precipitation vs. Temperature Change




Source: IPCC, TAR (2001)

## Climate Change and Water Cycle:
## Why Does Precipitation Change Differently?

Surface energy budget :

- net shortwave radiative flux
- latent heat flux
- melting and freezing of soil moisture, ice, snow

$$C_e \frac{\partial T_s}{\partial t} = S + L + L_v E + H + L_f (m_f + m_s) + A$$

- storage
- net longwave radiative flux
- sensible heat flux
- oceanic transport

Average surface energy budget :

$$S + L + L_v E + H + A = 0$$

## Climate Change and Water Cycle:
## Why Does Precipitation Change Differently?

Difference equation between surface energy budgets:

$$\delta S + \delta L + L_v \delta E + \delta H = \delta N = 0$$

Greenhouse effect:

$$\delta L = \delta G - 4\sigma T_s^3 \delta T_s$$

Steady state:

$$\delta P = -\delta E$$

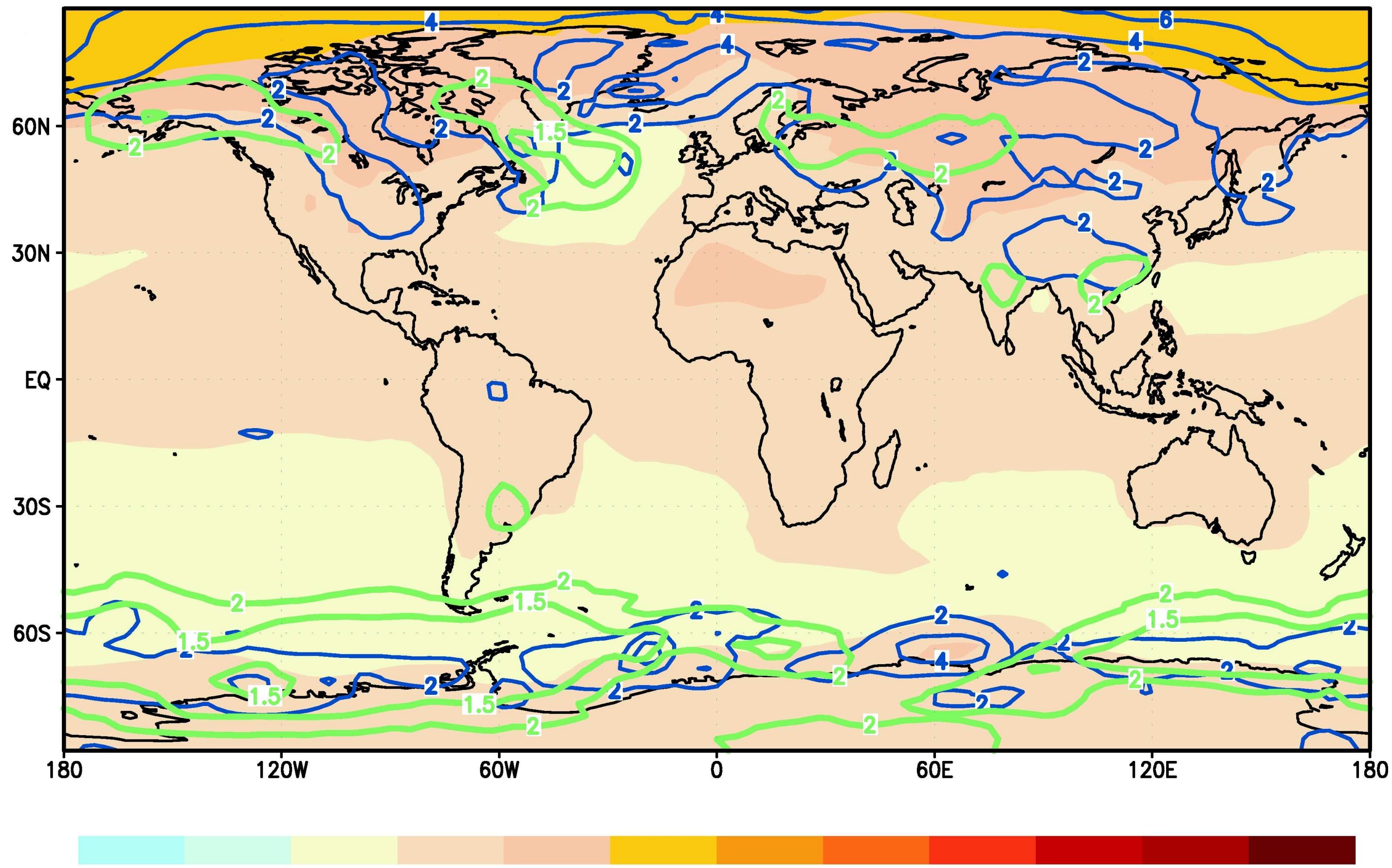
$$\Rightarrow L_v \delta P = \delta G - 4\sigma T_s^3 \delta T_s + \delta S + \delta H$$

## Climate Change and Water Cycle: Why Does Precipitation Change Differently?

| | NCAR | GFDL | GISS | CCC |
|---|---|---|---|---|
| $\delta L$ | 4.2 | 4.9 | 4.1 | 3.8 |
| $\delta S$ | 1.3 | 1.5 | 2.9 | -2.4 |
| $\delta H$ | 2.7 | 0.6 | 3.3 | 1.6 |
| $\delta N$ | 1.0 | -0.1 | -0.1 | 0.0 |
| $L_v \delta E$ | -7.1 | -7.1 | -10.4 | -3.0 |

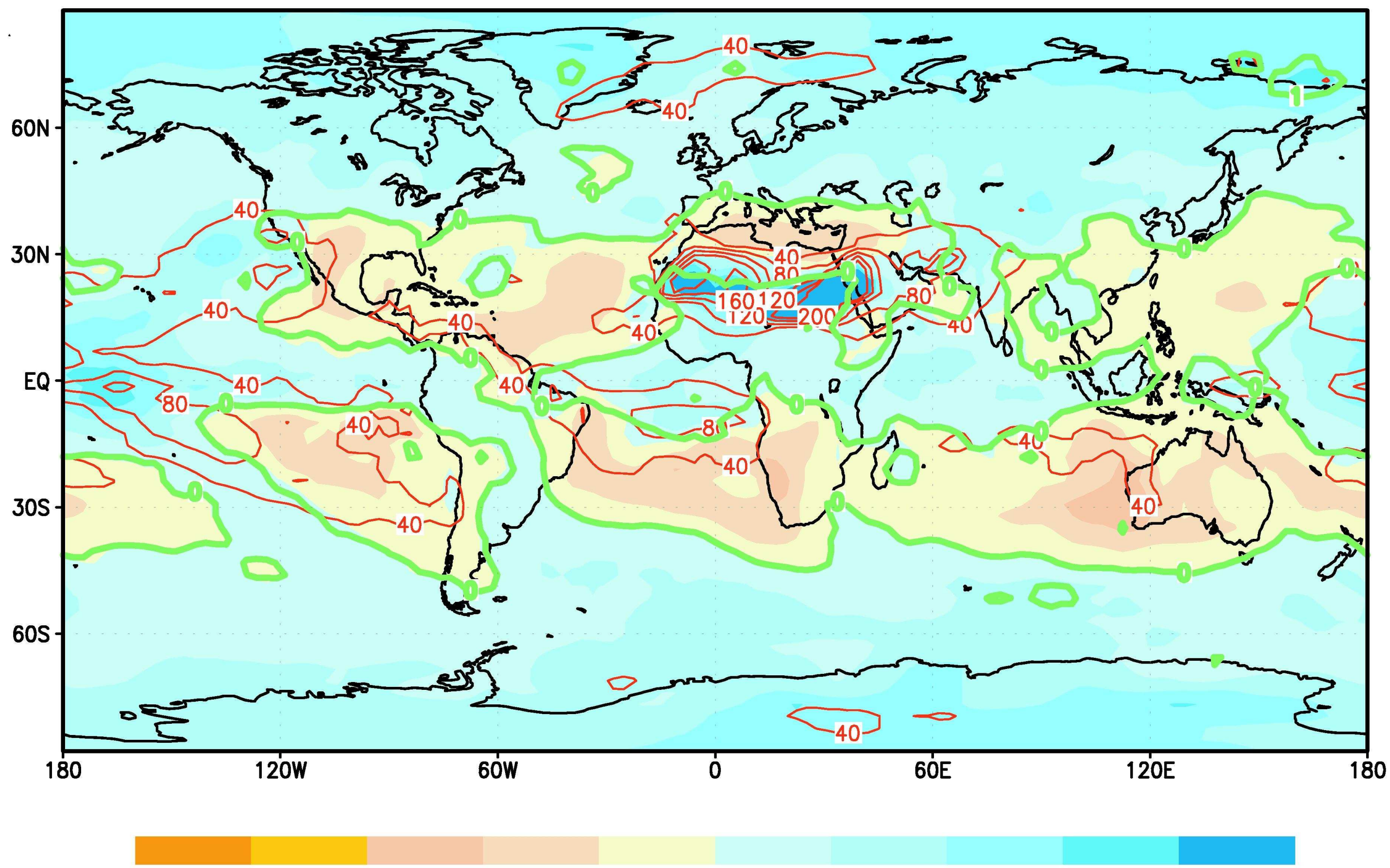
Source: Boer (1993)

# Climate Change and Water Cycle: Temperature Change 2021-2050 vs. 1961-1990



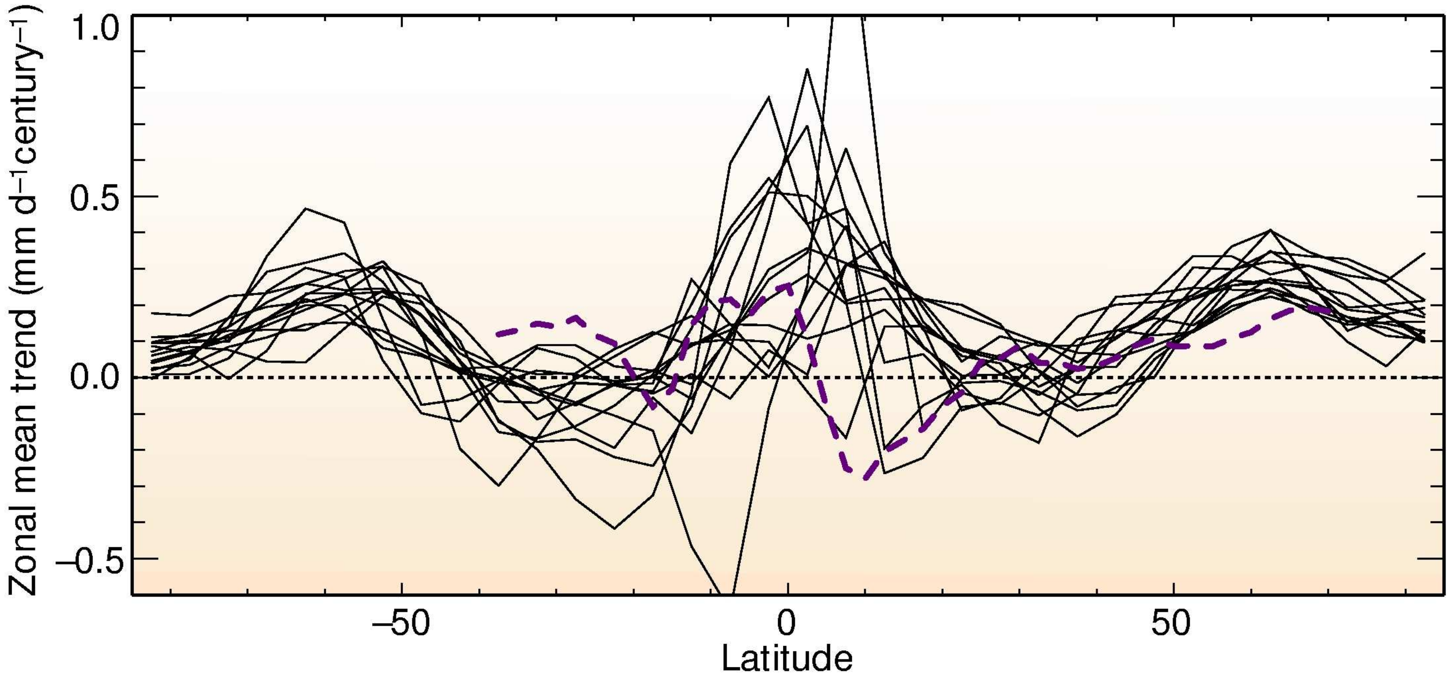

Source: IPCC, TAR (2001)

# Climate Change and Water Cycle: Precipitation Change 2021-2050 vs. 1961-1990




Source: IPCC, TAR (2001)

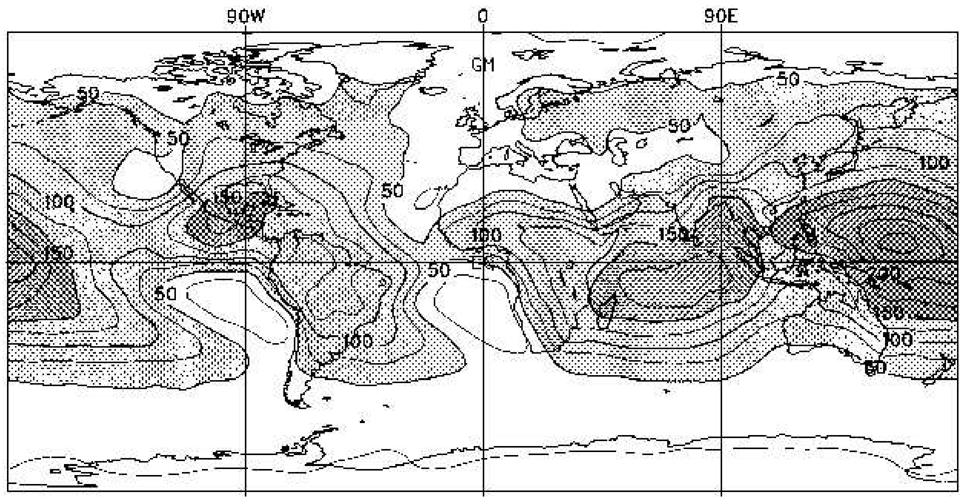
# Climate Change and Water Cycle: Zonal Mean Precipitation Trends



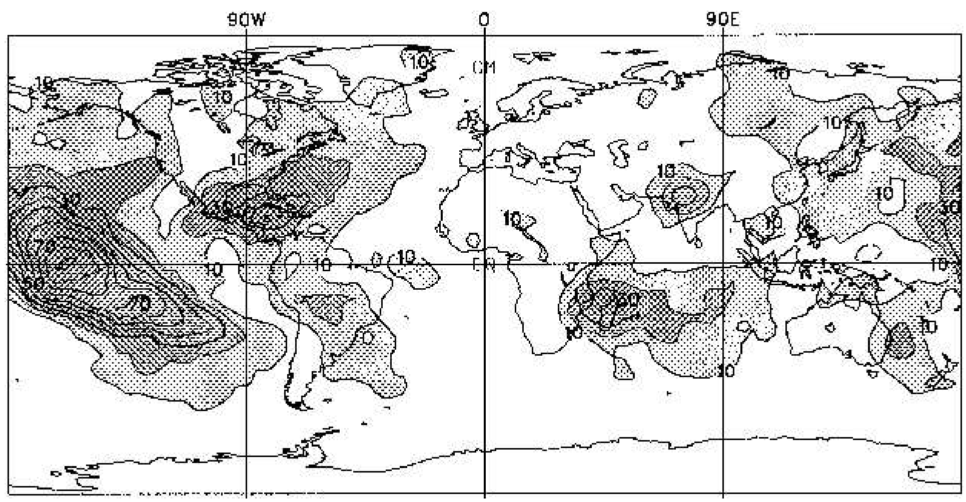

Source: Allen and Ingram (2002)

# Climate Change and Water Cycle: Extremes

**20-year return value for precipitation for 1975-1995**



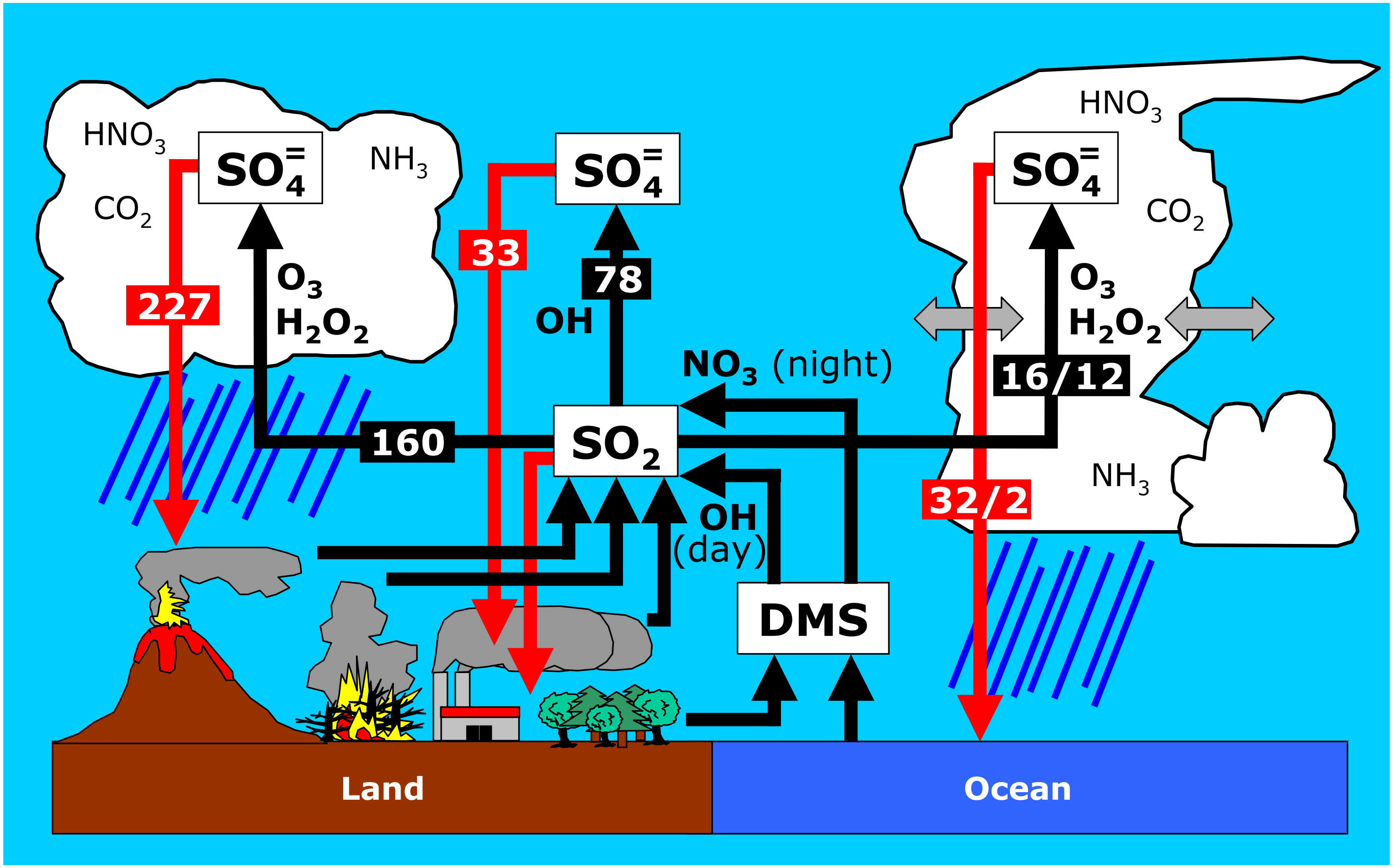

**Change from 1975-1995 to 2080-2100**




Units: mm/day

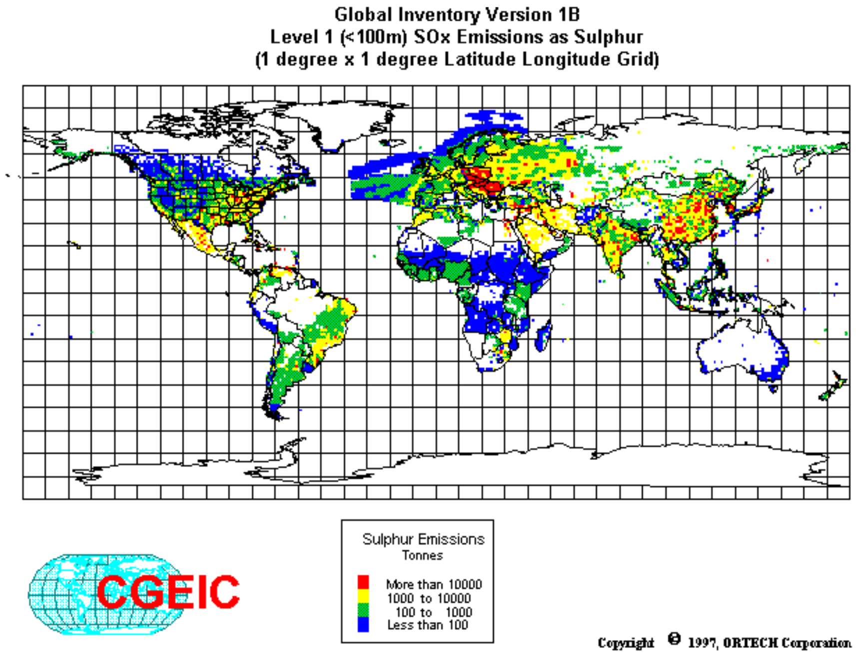
Source: Kharin and Zwiers (2000)

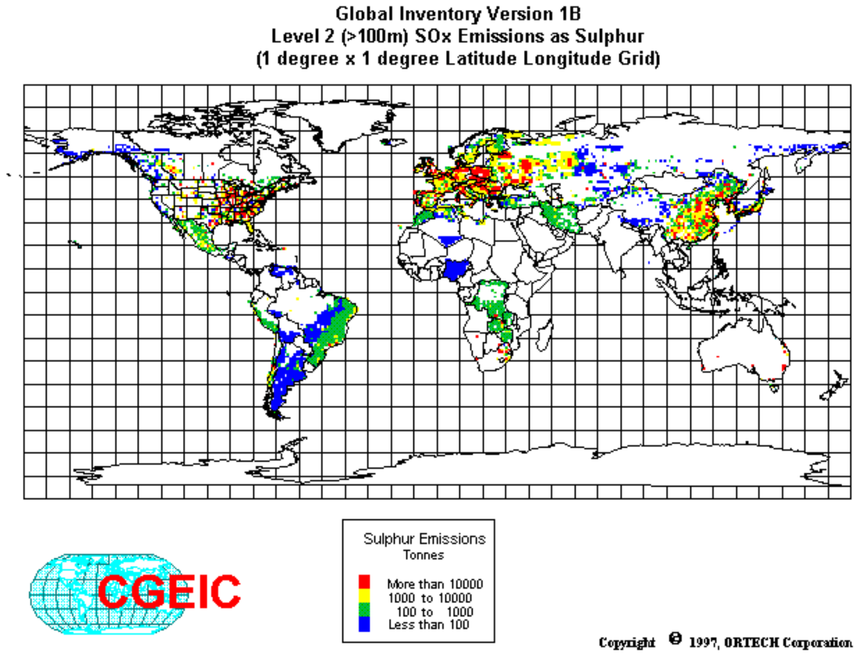
# Role of Water Cycle for Chemistry: Sulphur Cycle



# Role of Water Cycle for Chemistry: Sulphur Cycle

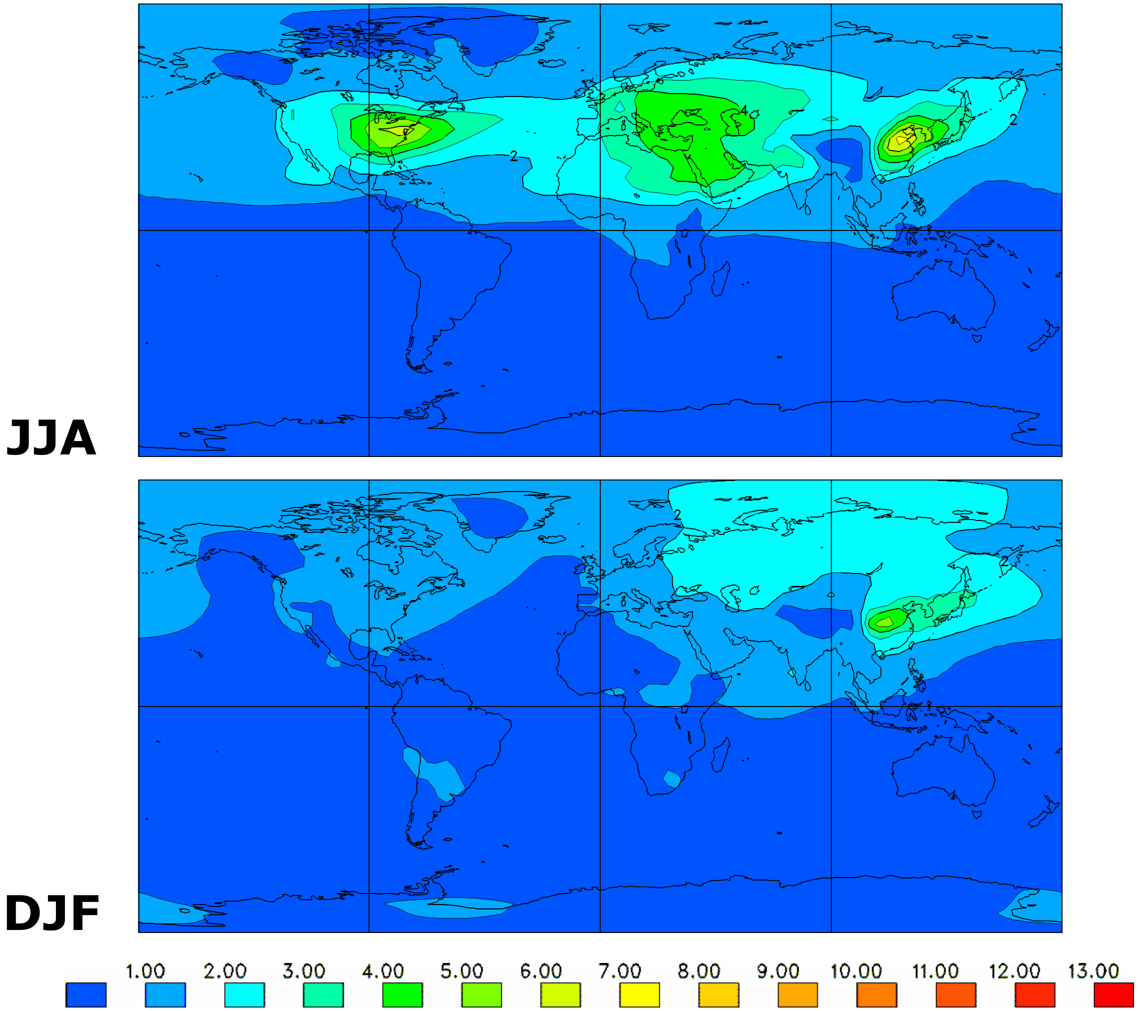
## $SO_2$ emissions



# Role of Water Cycle for Chemistry: Sulphur Cycle

**$SO_4^{=}$ burden (in µgS/m²)**

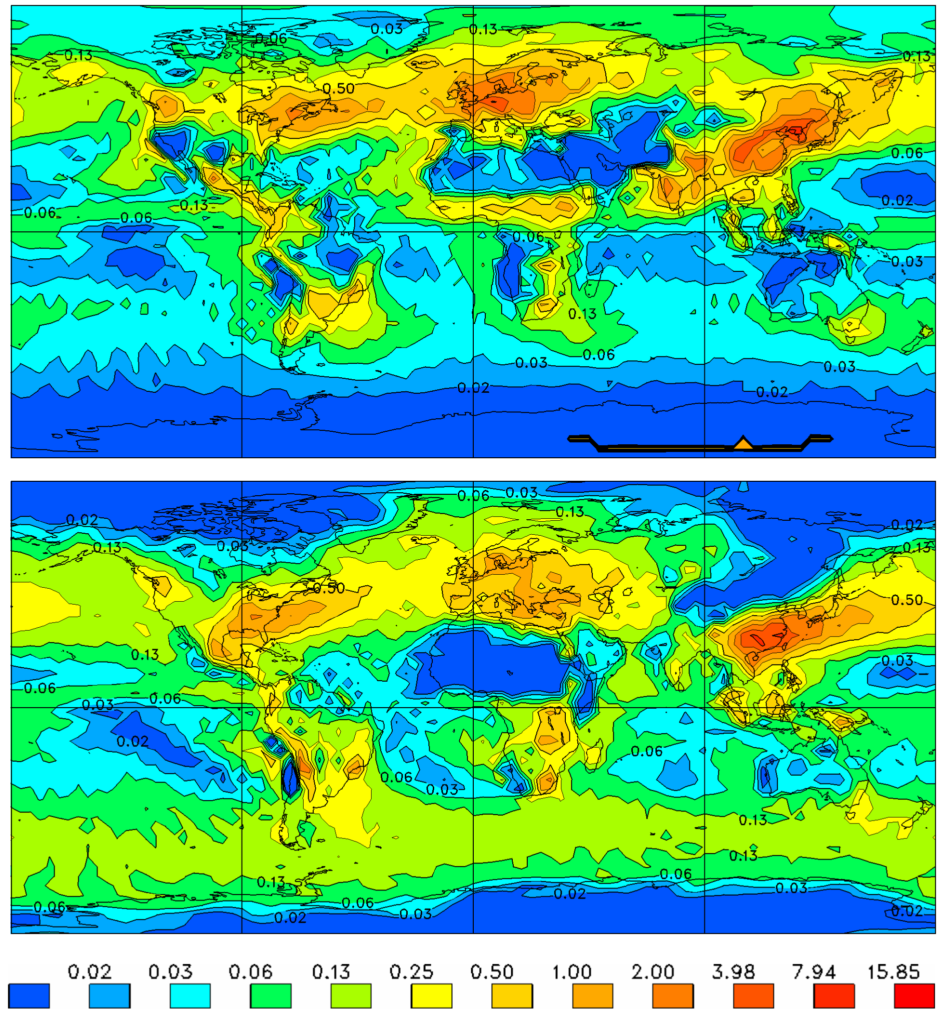


# Role of Water Cycle for Chemistry: Sulphur Cycle

**$SO_4^{=}$ wet deposition (in $mS/m^2/day$)**

JJA

DJF



# Role of Water Cycle for Chemistry: Sulphur Cycle

| Simulation | Process | Change in $SO_4^=$ burden† (in %) | Mean $SO_4^=$ lifetime‡ (in days) | Change in $SO_2$ burden (in %) |
|---|---|---|---|---|
| DCWD | Wet Deposition in Deep Convection | +116 | 12.8 | -1 |
| DCIP | Oxidation in Deep Convection | -2 | 6.1 | -1 |
| LCWD | Wet Deposition in Stratiform Clouds | +303 | 22.8 | +1 |
| LCIP | Oxidation in Stratiform Clouds | +10 | 8.1 | +134 |
| SCIP | Oxidation in Shallow Convection | -0.4 | 5.6 | +2 |
| DD | Dry Deposition of $SO_4^=$ | +10 | 6.2 | +0.1 |
| GP | Gas Phase Production of $SO_4^=$ | -26 | 4.5 | +51 |

†relative to simulation GCM4
‡mean $SO_4^=$ lifetime in GCM4 is 5.6 days