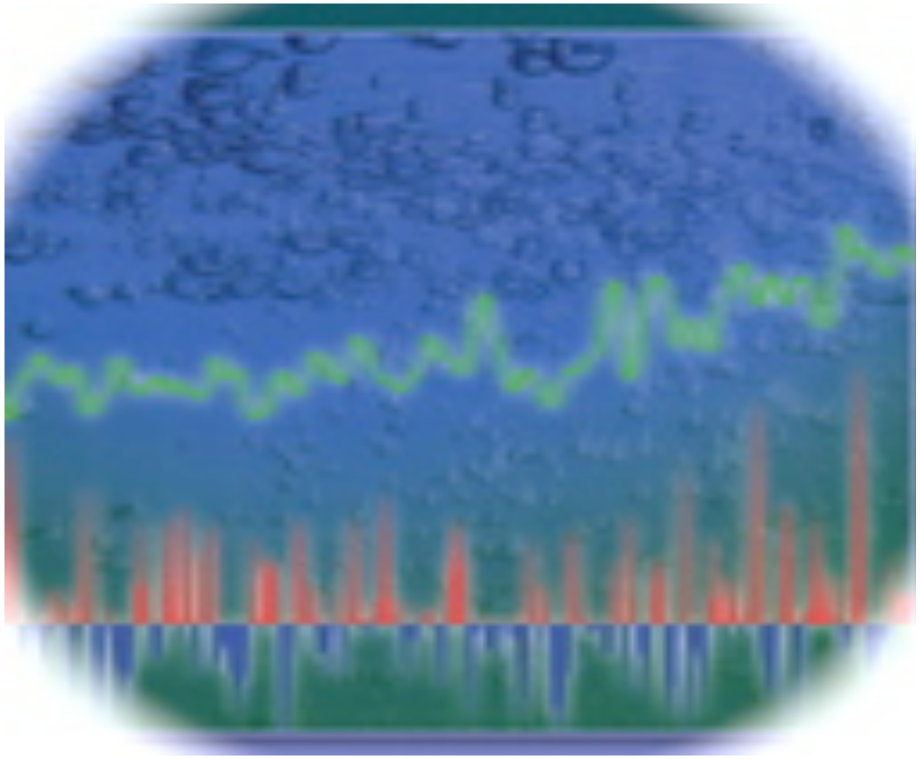
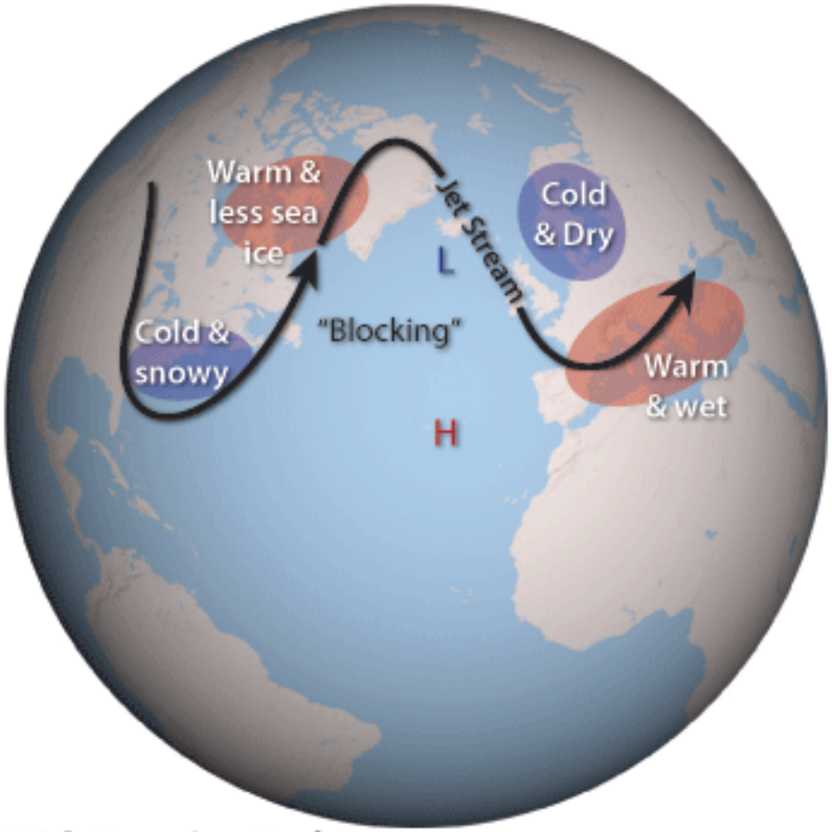
Climate Dynamics:
Why Does Climate Vary?



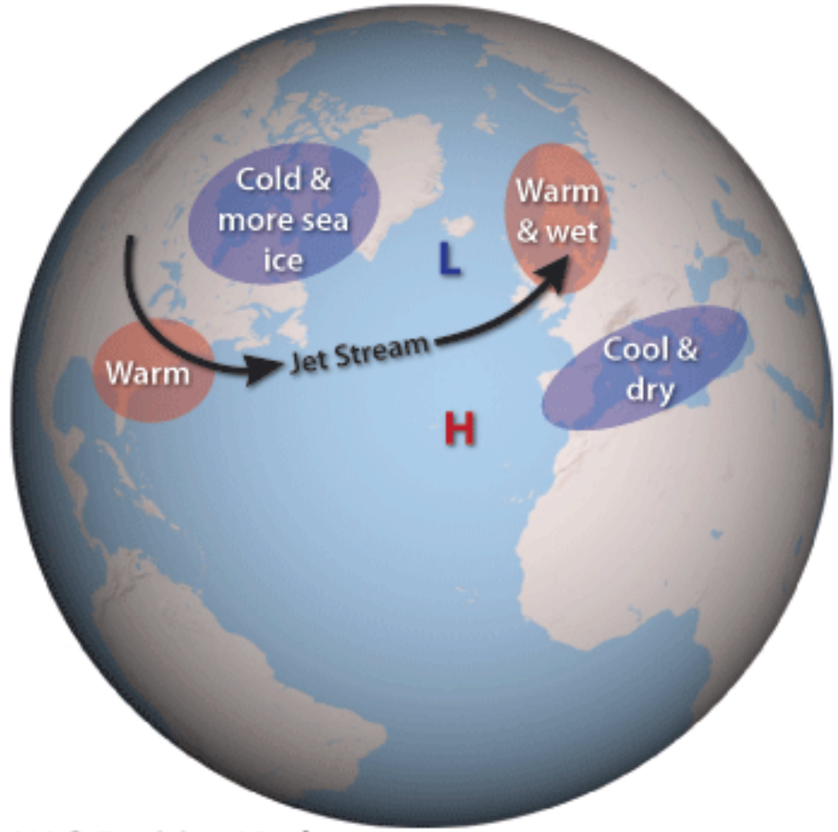
The Recent Global Warming: Observations, Theories, and the Science and Art of Modeling

http://www.esrl.noaa.gov/psd/people/dezheng.sun/lectures/ATOC7500.html

North Atlantic Oscillation

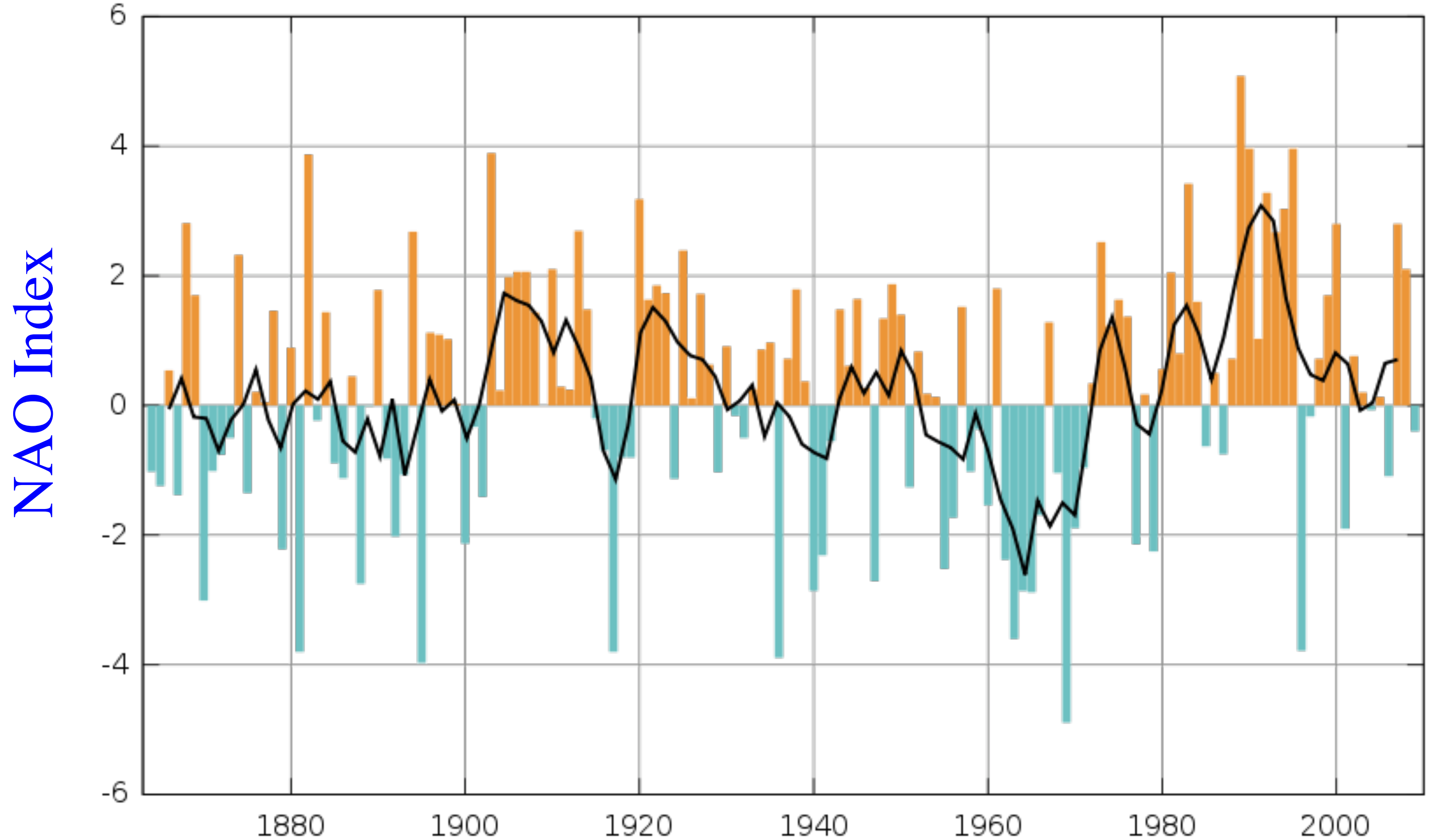


NAO Negative Mode

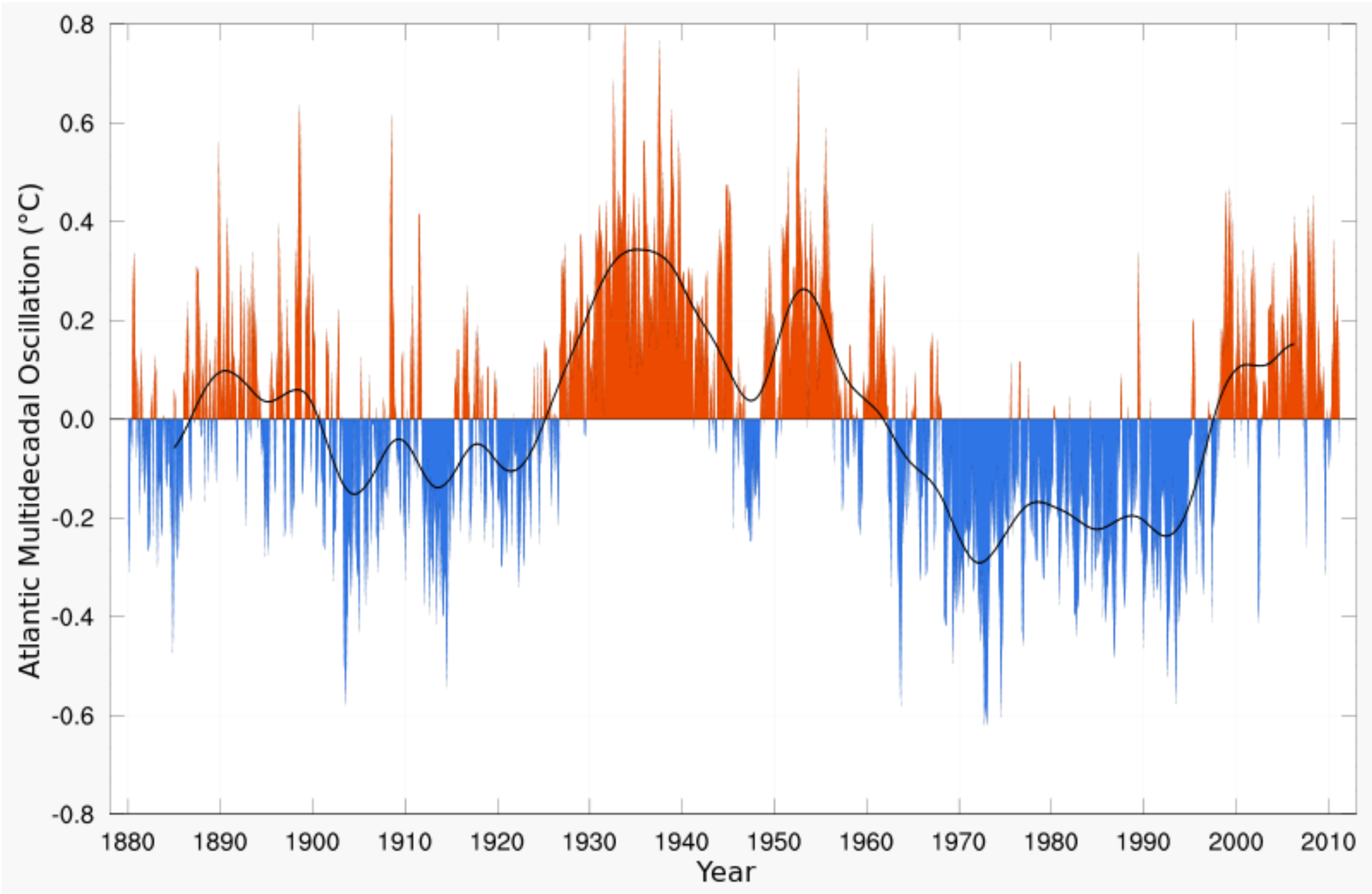


NAO Positive Mode

The North Atlantic Oscillation

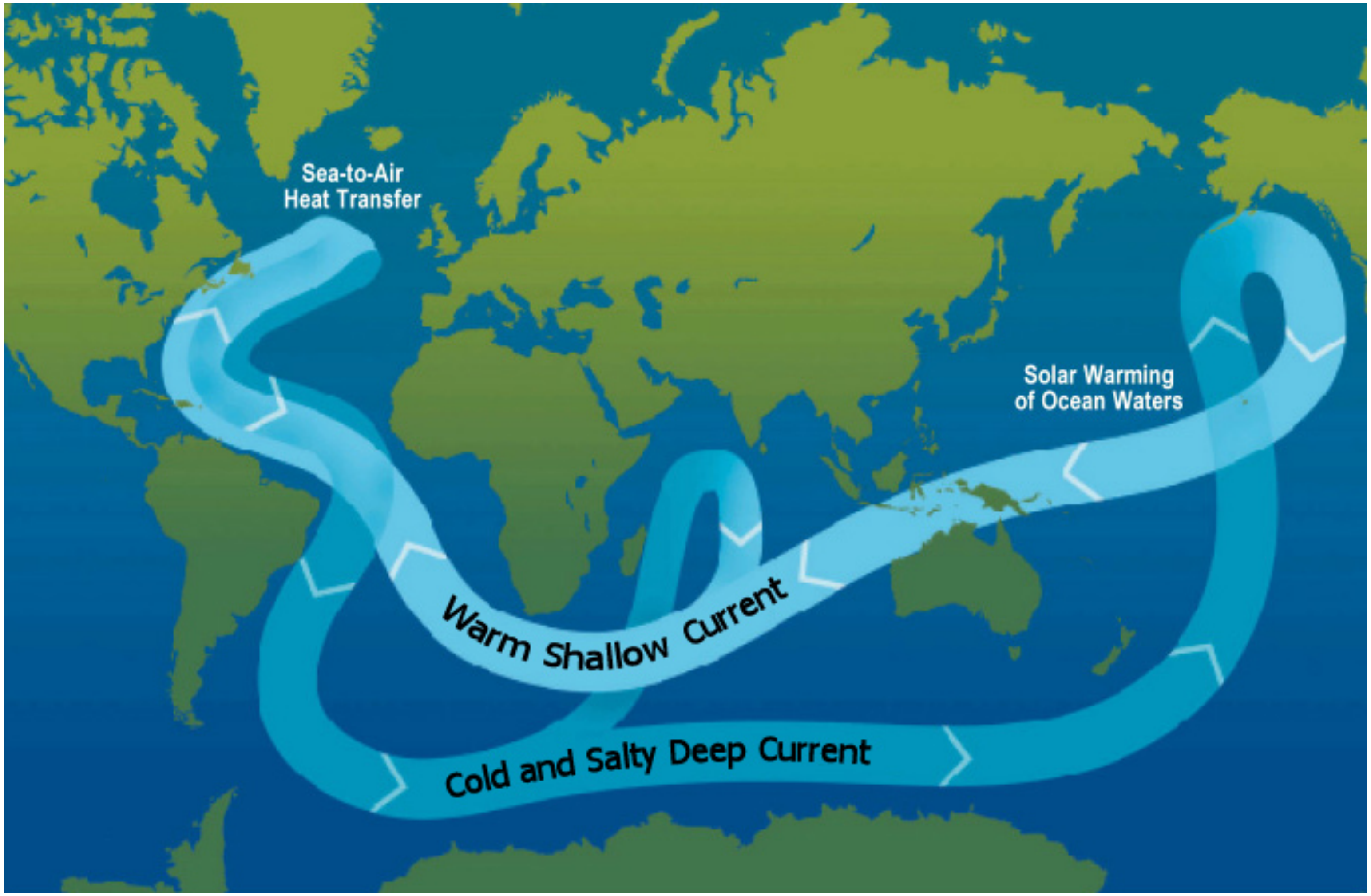


Atlantic Multi-decadal Oscillation

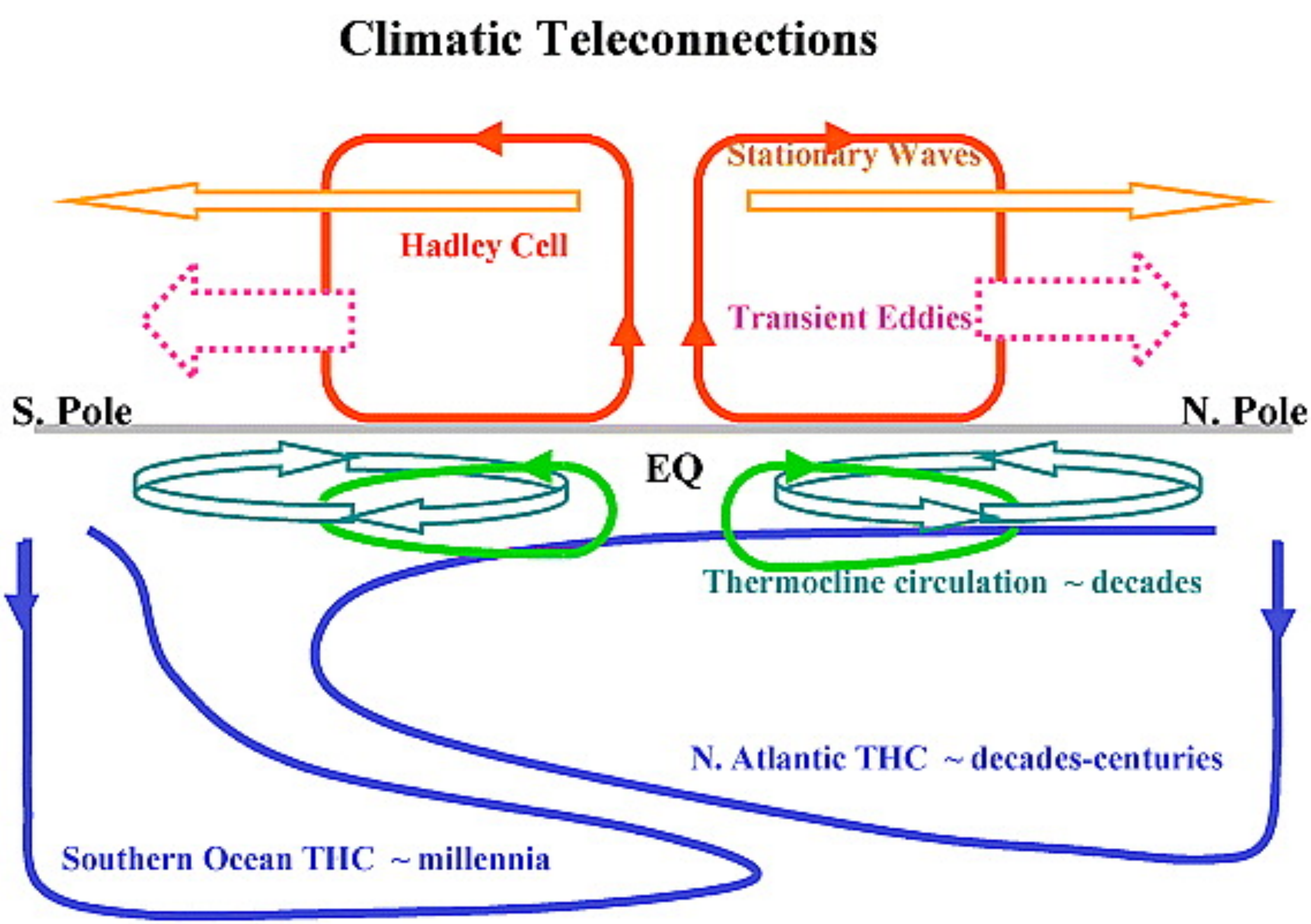


van Oldenborgh et al. 2009

The Global Themohaline Circulation

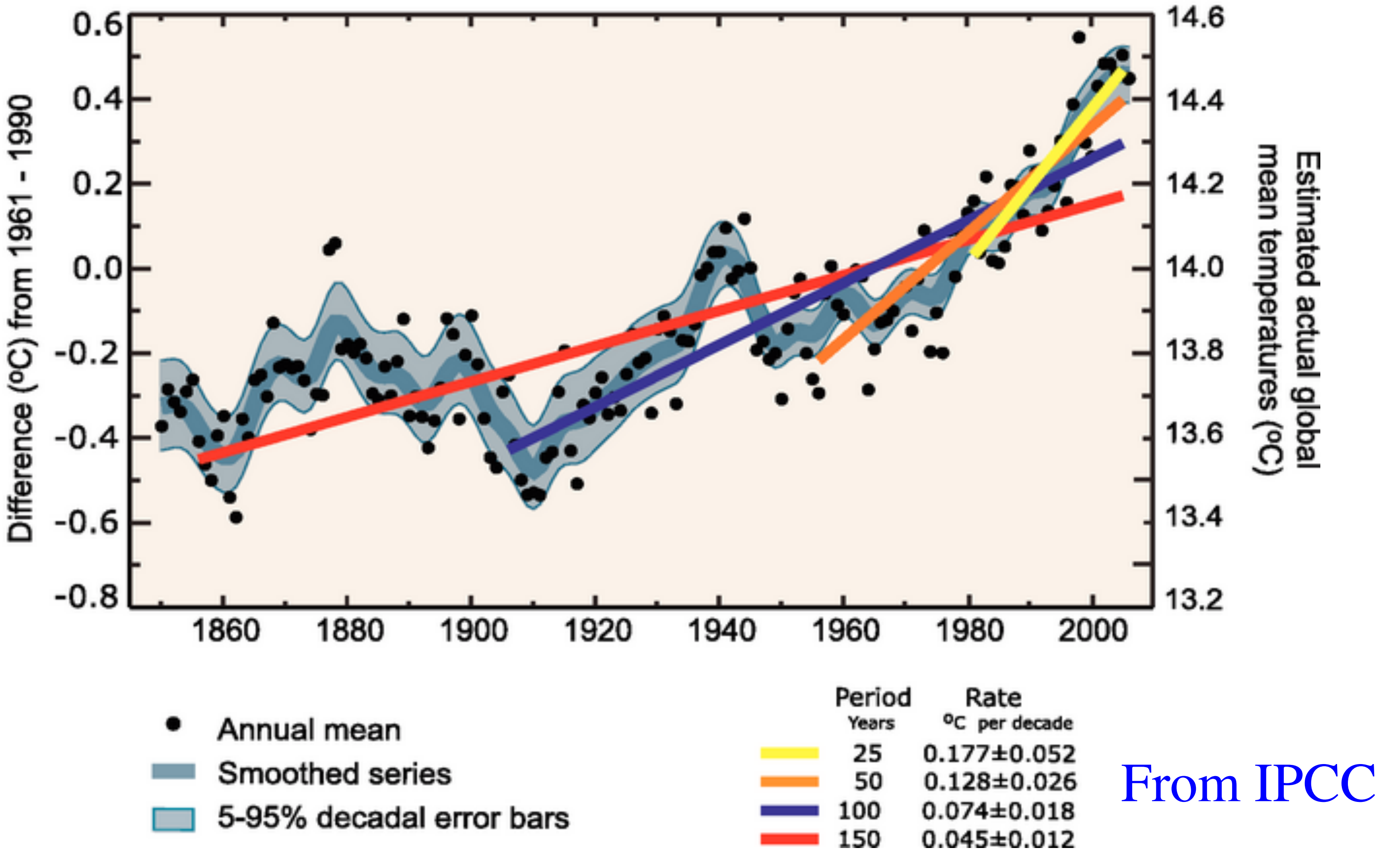


Mechanisms for Tropical-Extratrpical Interacton



The Recent Global Warming

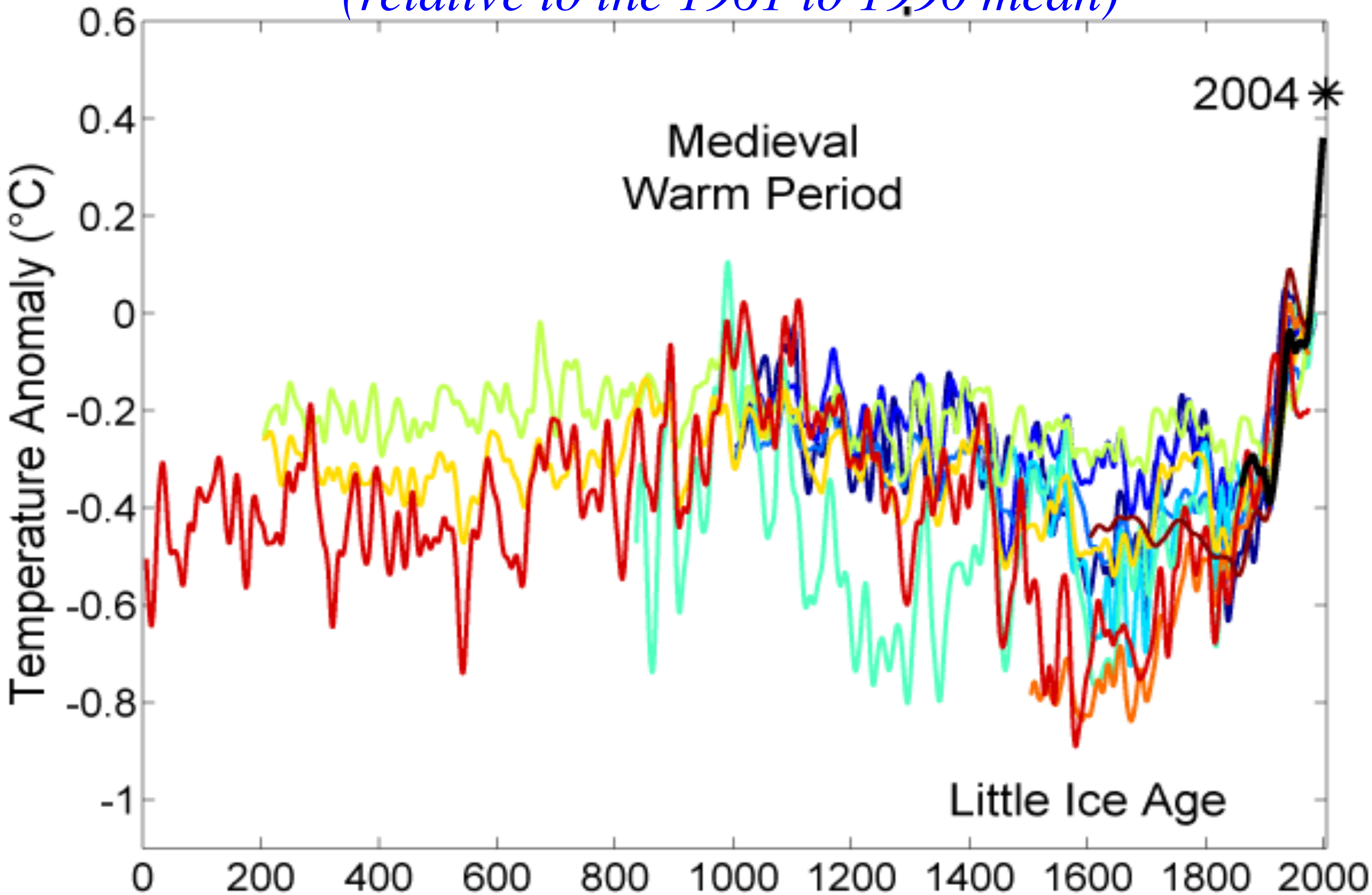
Annual anomalies of global surface air temperature (°C)
(relative to the 1961 to 1990 mean)



From IPCC

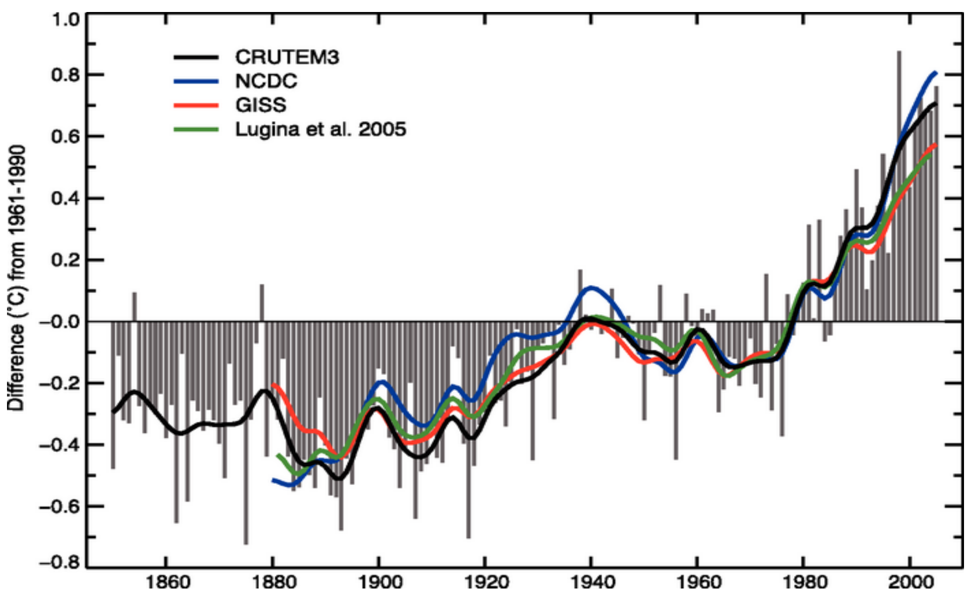
The MCA (MWP) & LIA

Global Surface Temperature over the last 2000 years
(relative to the 1961 to 1990 mean)

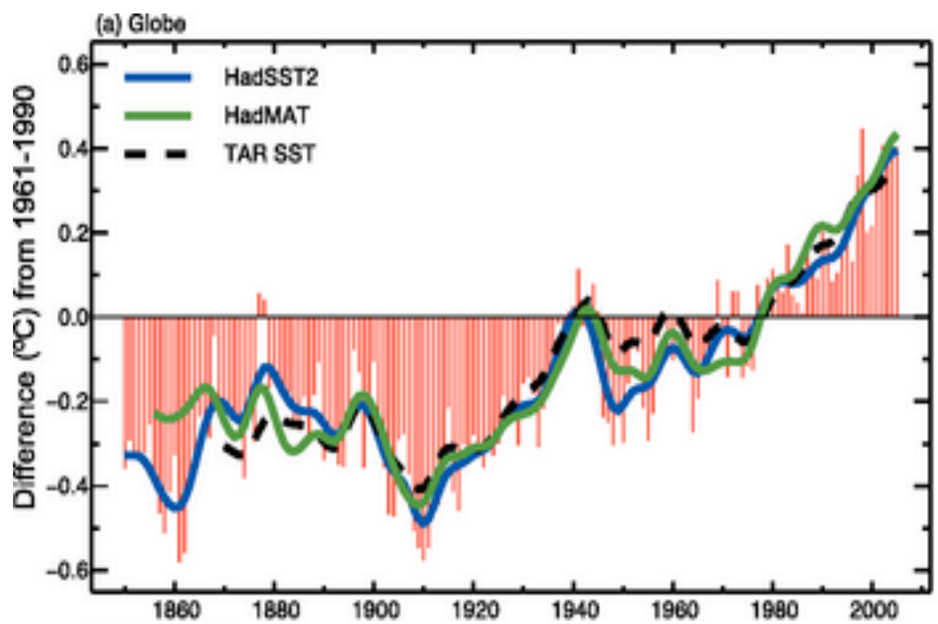


The Recent Global Warming

Annual anomalies of global surface air temperature over land (°C)
(relative to the 1961 to 1990 mean)

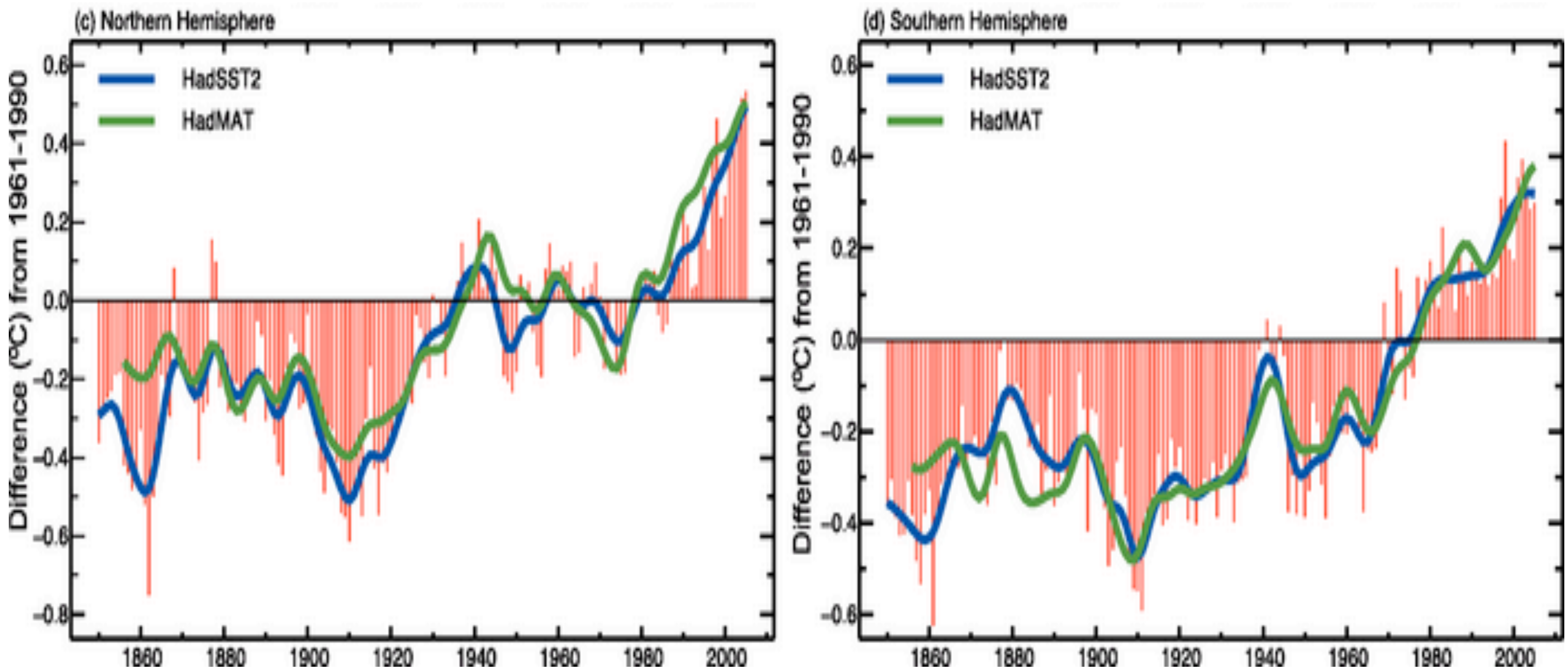


Annual anomalies of global Sea Surface Temperature (°C)
(relative to the 1961 to 1990 mean)



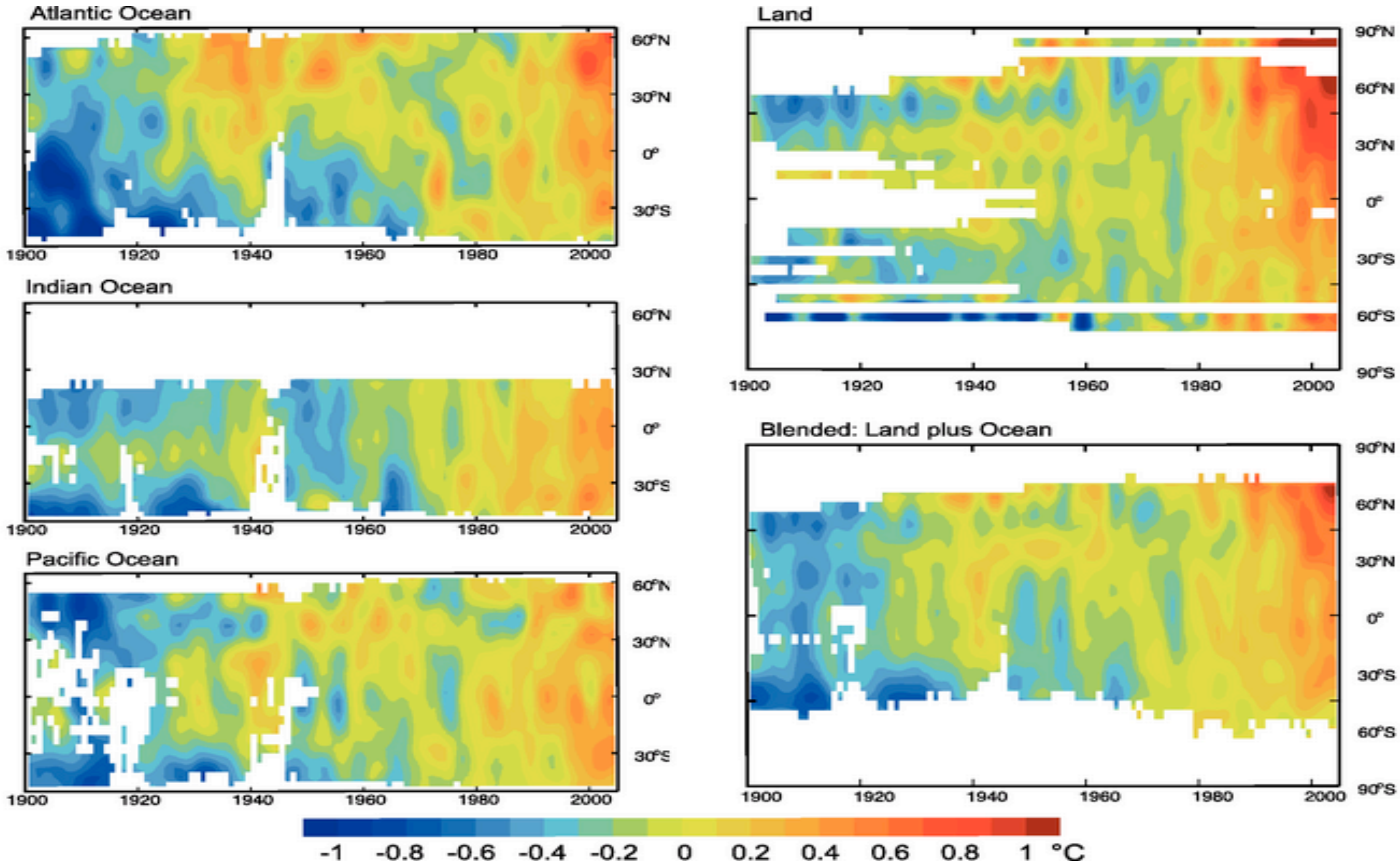
The Recent Global Warming

Annual anomalies of hemispheric Sea Surface Temperature (°C) (relative to the 1961 to 1990 mean)



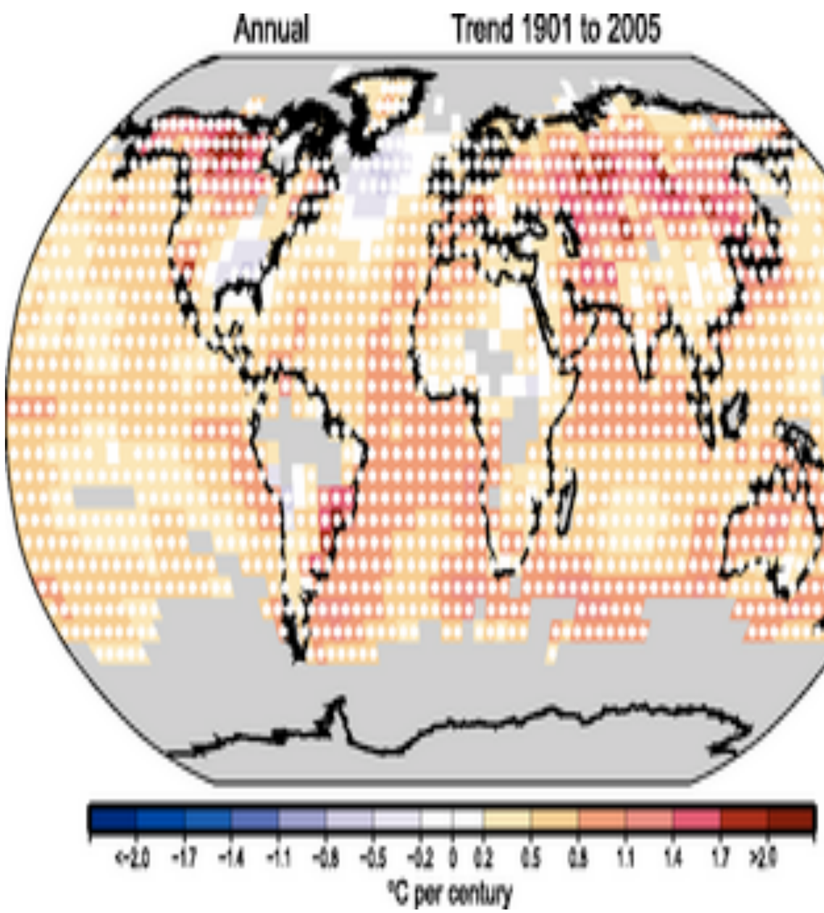
The Recent Global Warming

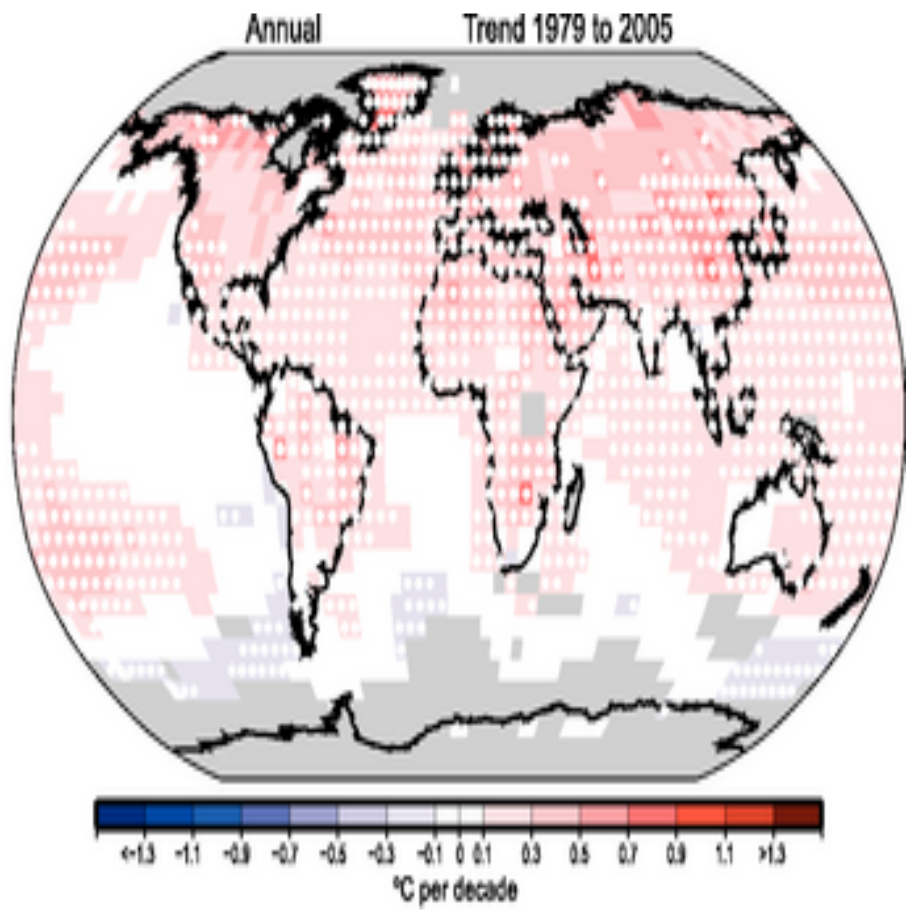
Zonal Mean Temperature Anomalies (°C)



The Recent Global Warming

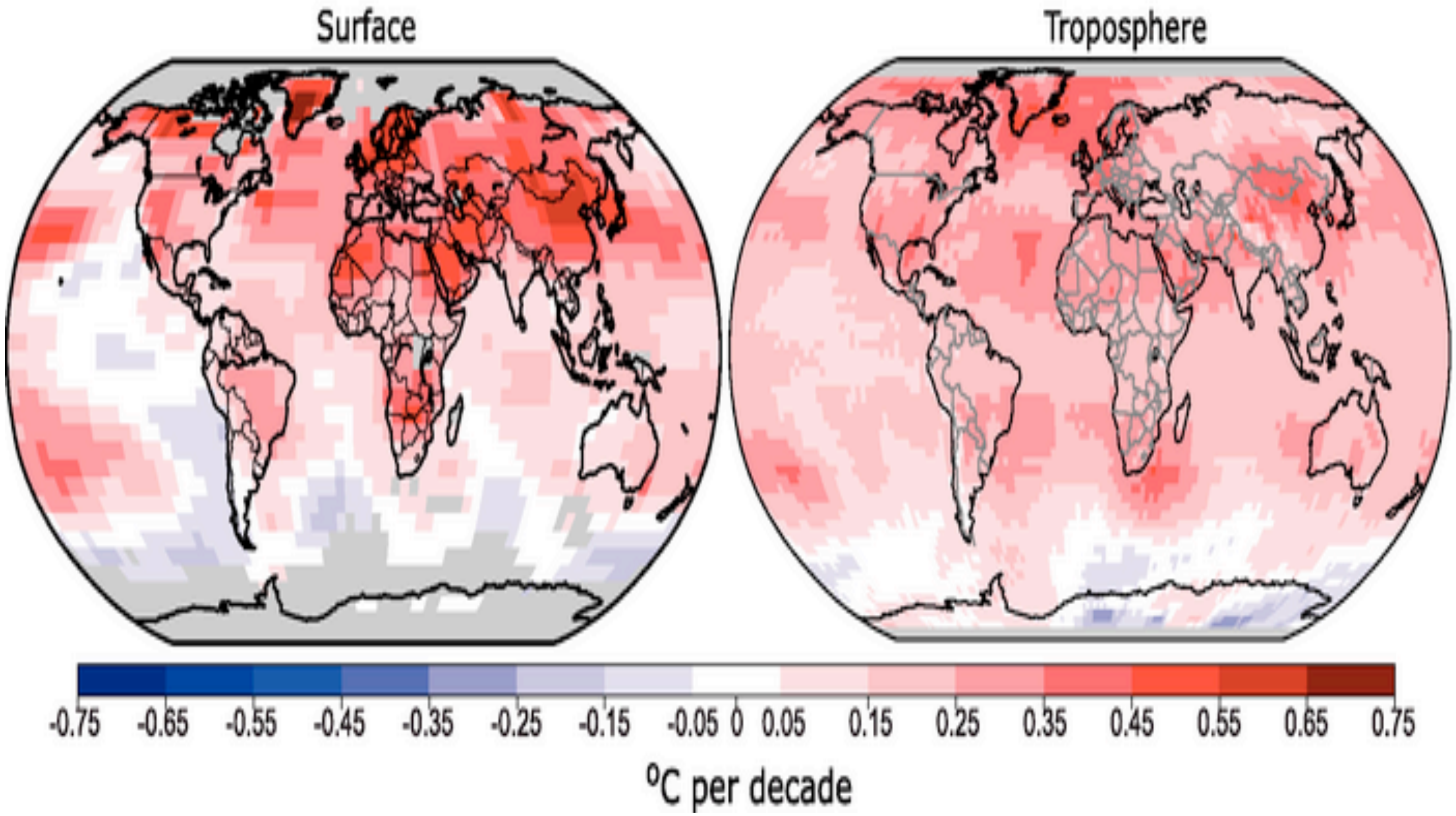
Surface air temperature trends over 1901—2005 and 1979-2005



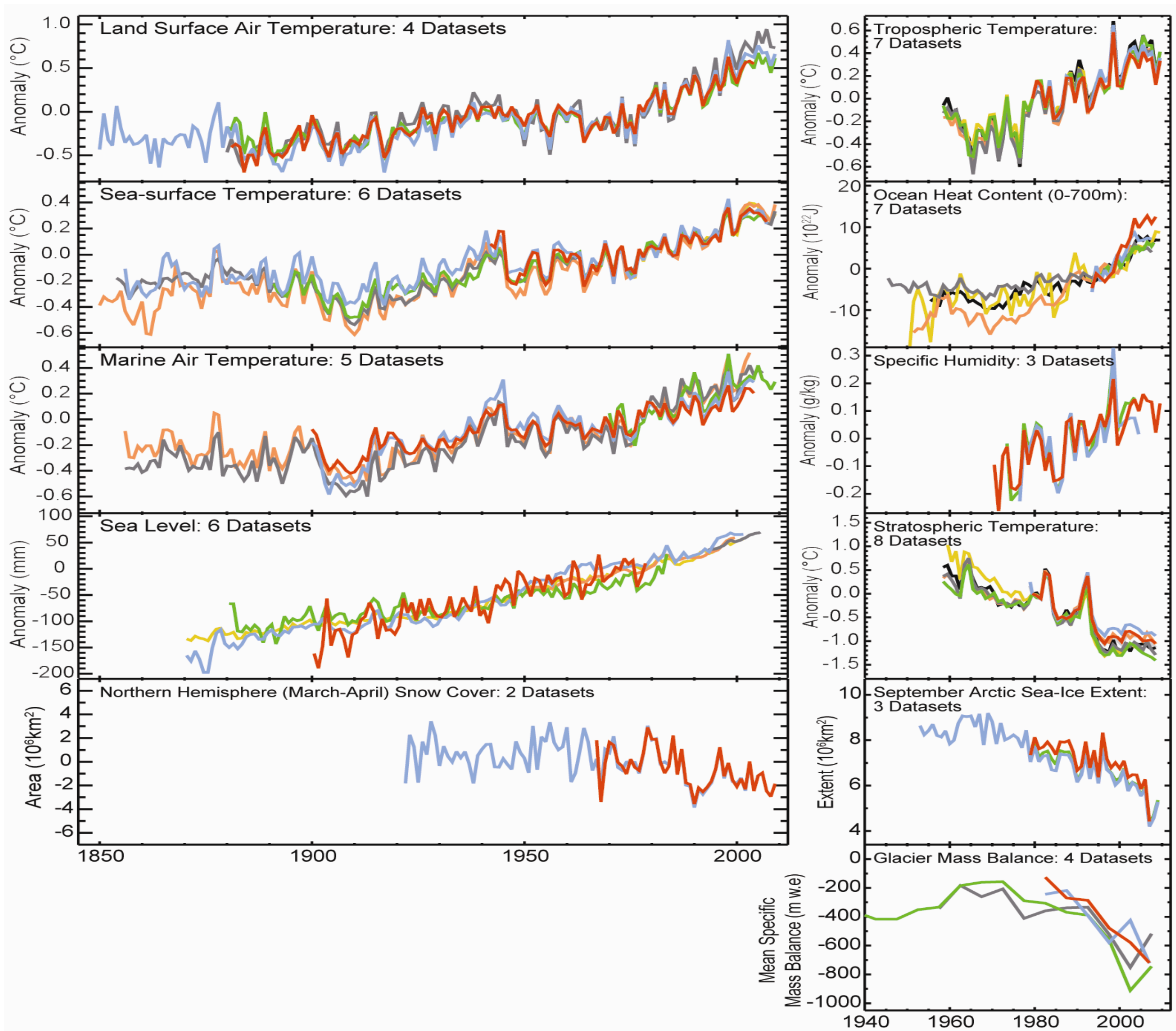


The Recent Global Warming

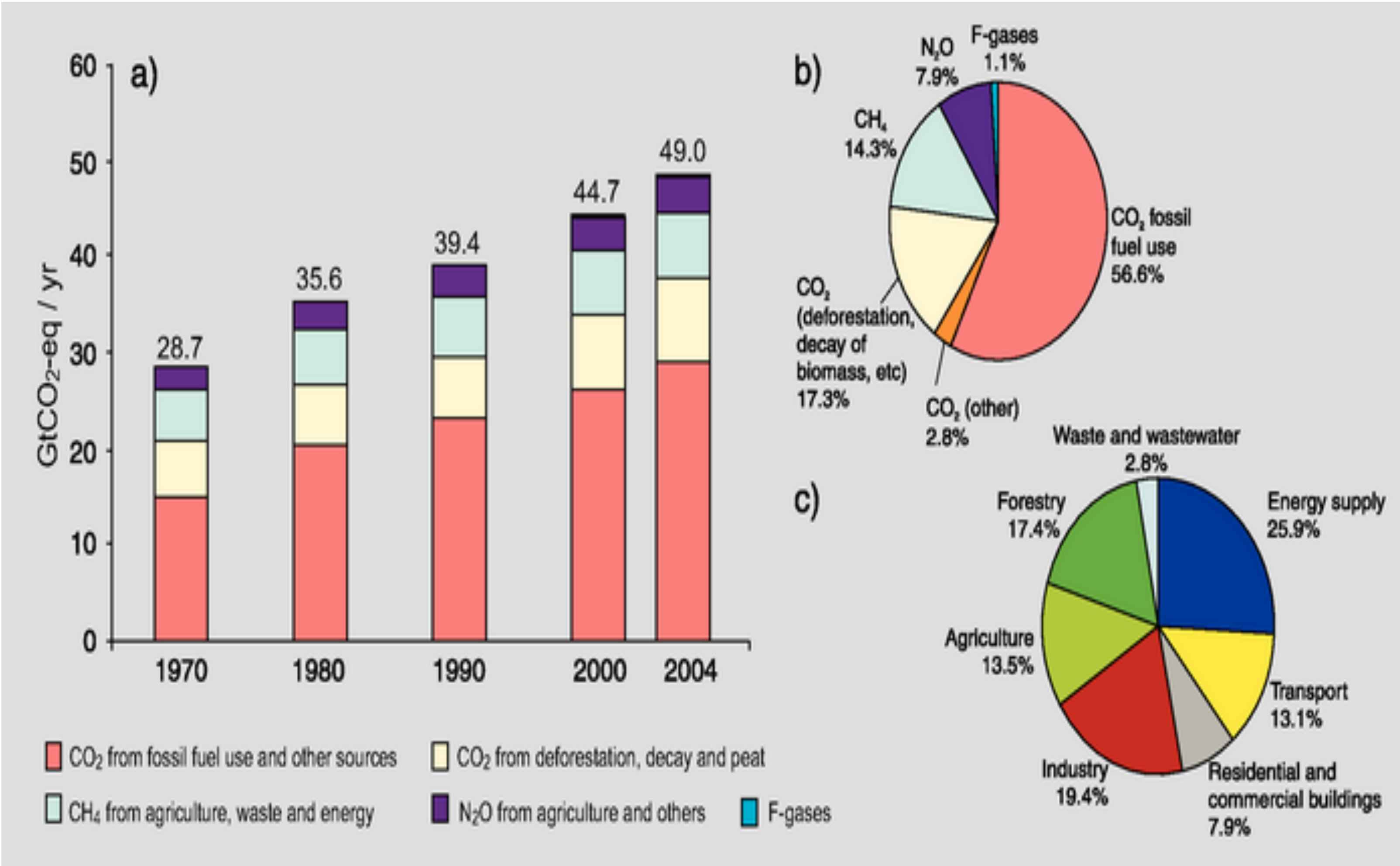
Surface and tropospheric temperature trends over 1979--2005



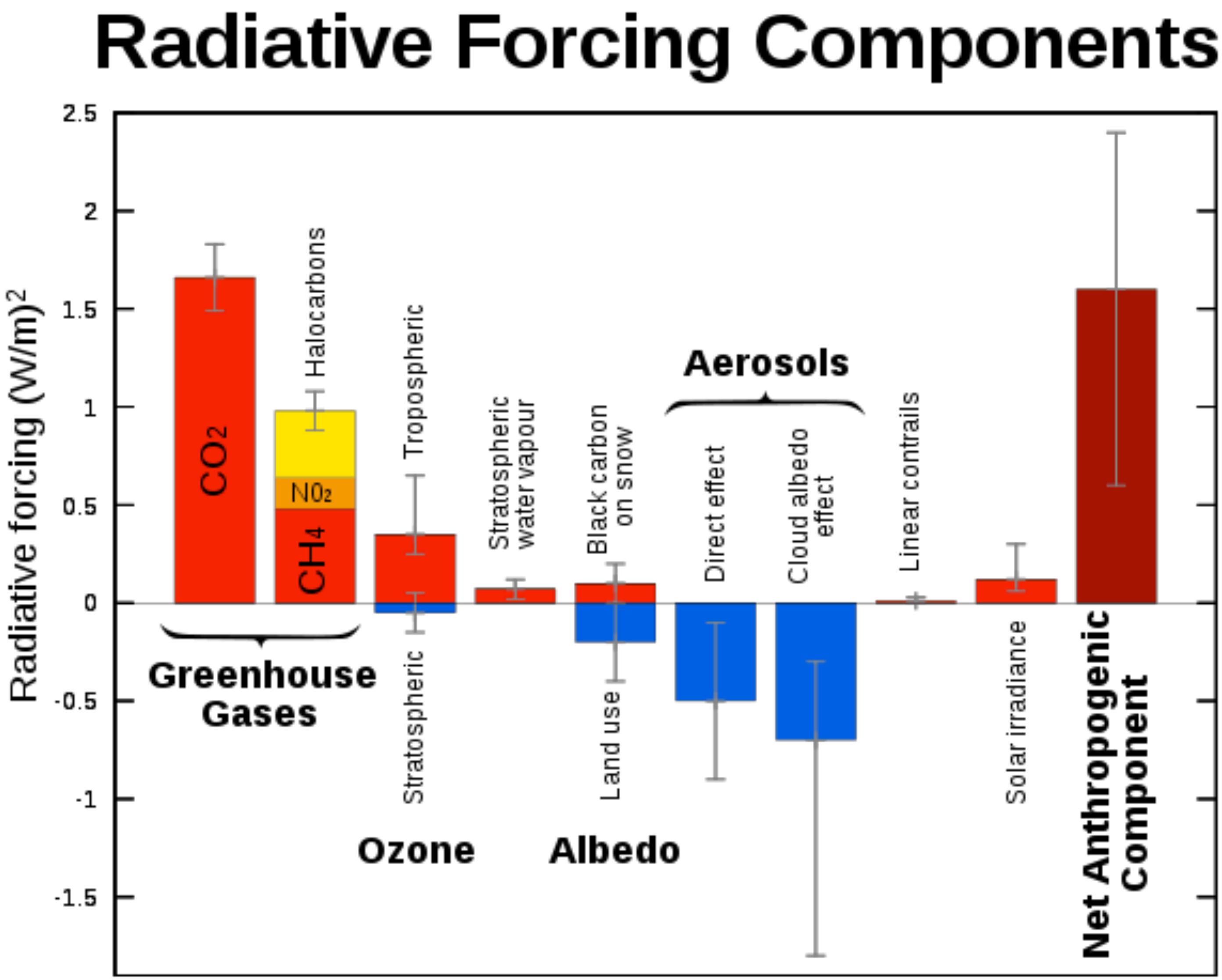
The 11 indicators of global warming



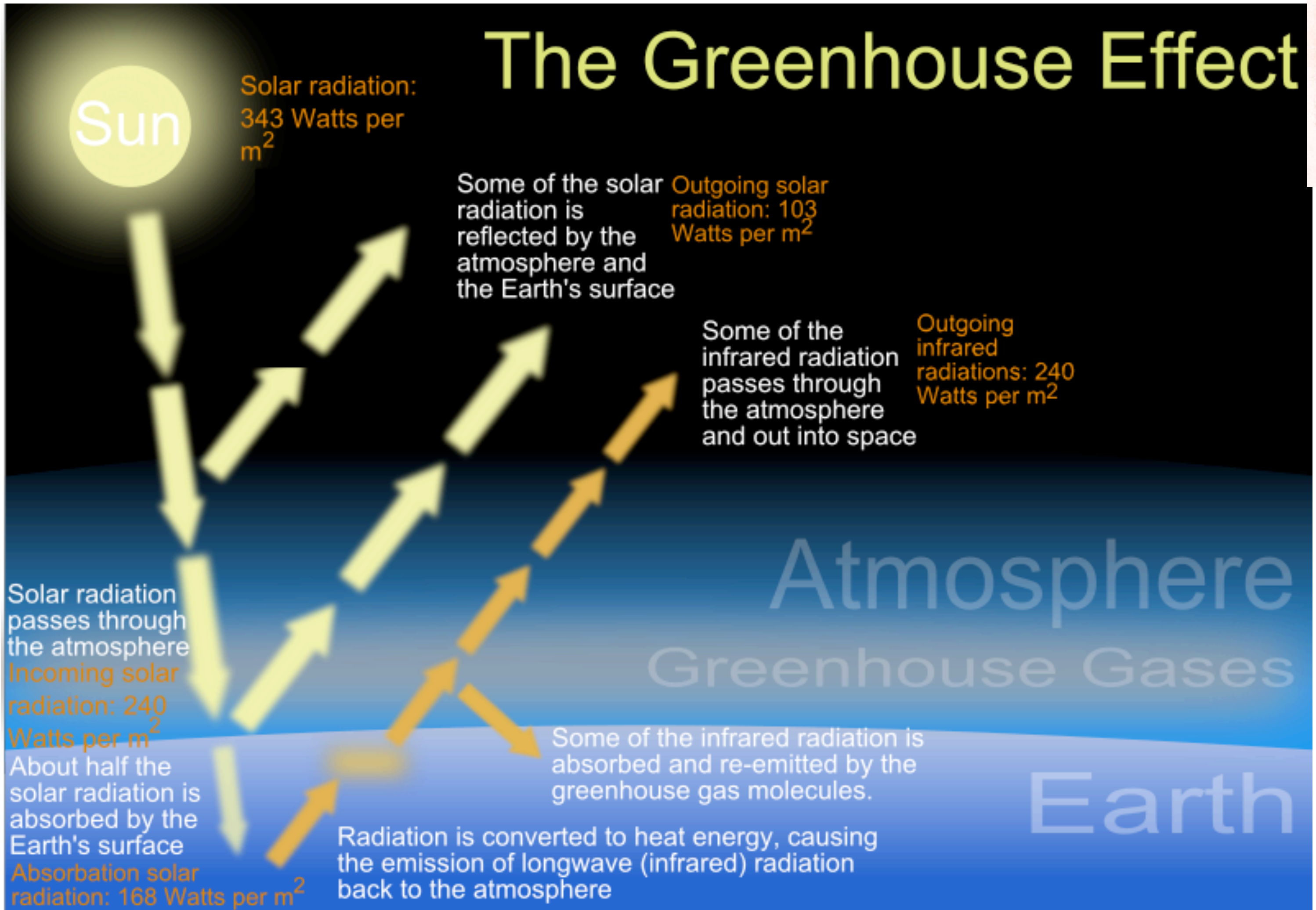
Increases in Greenhouse Gases in the Atmosphere



Added Radiative Forcing



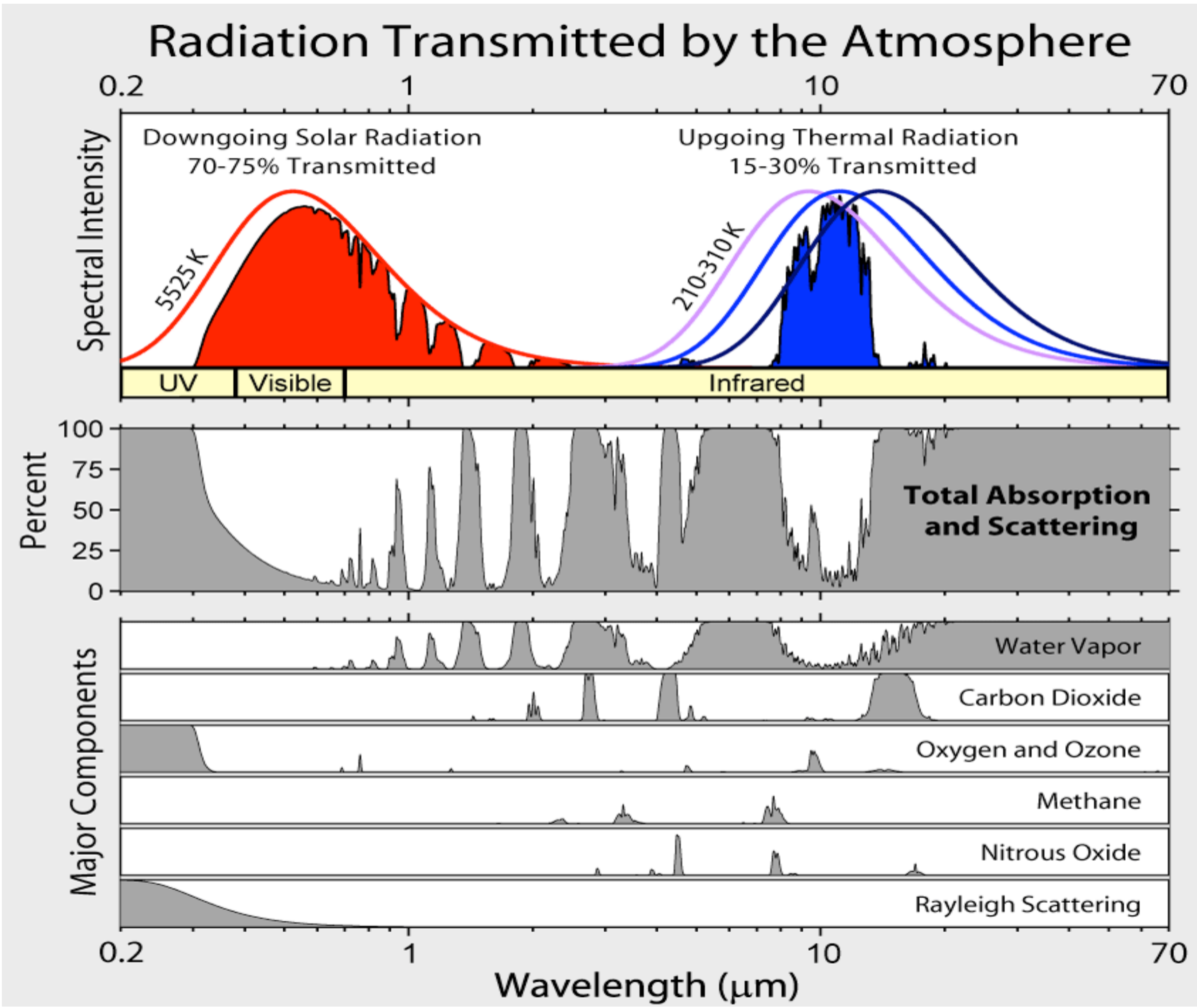
The Greenhouse Effect



Joseph Fourier

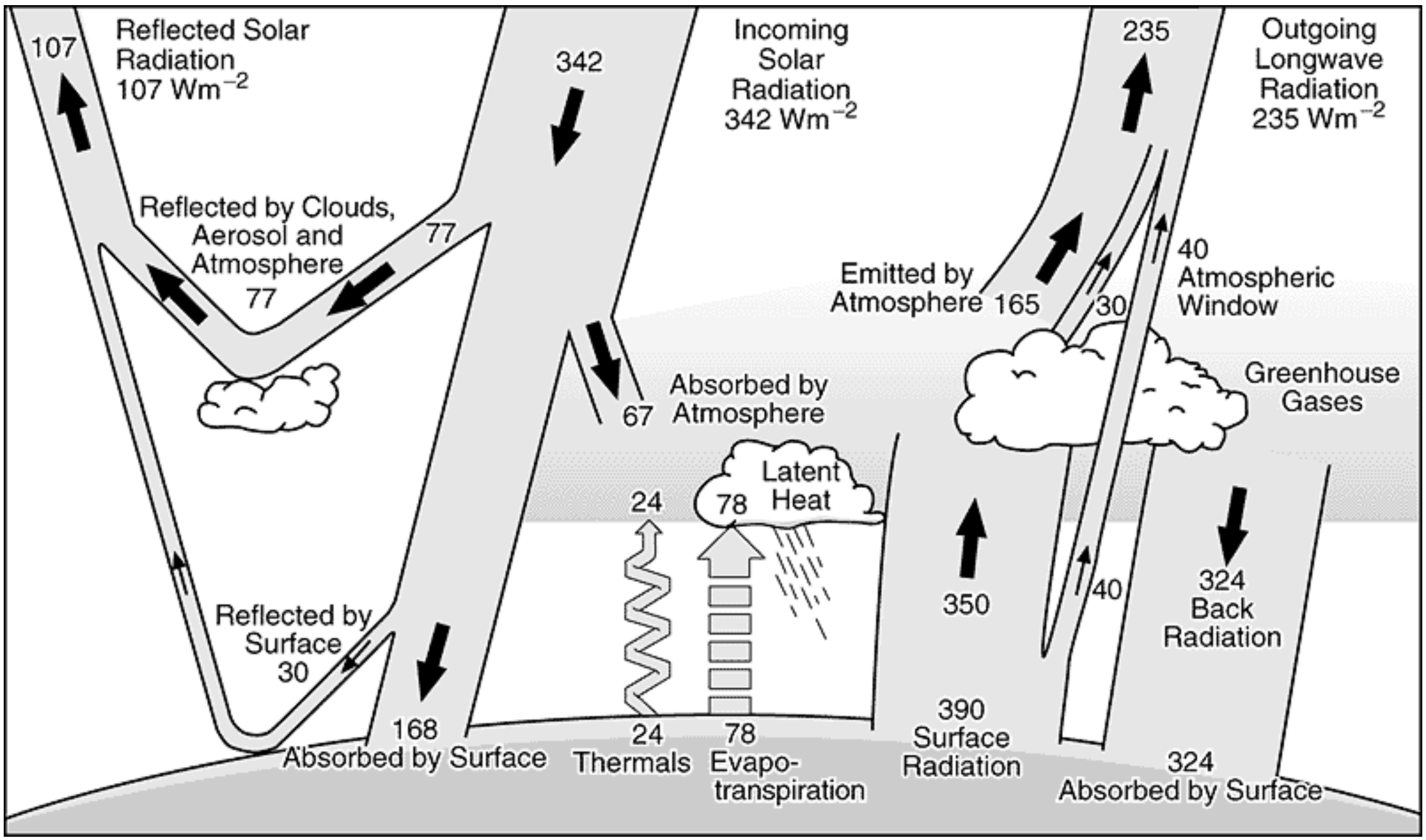
From IPCC

Major Greenhouse Gases In The Atmosphere

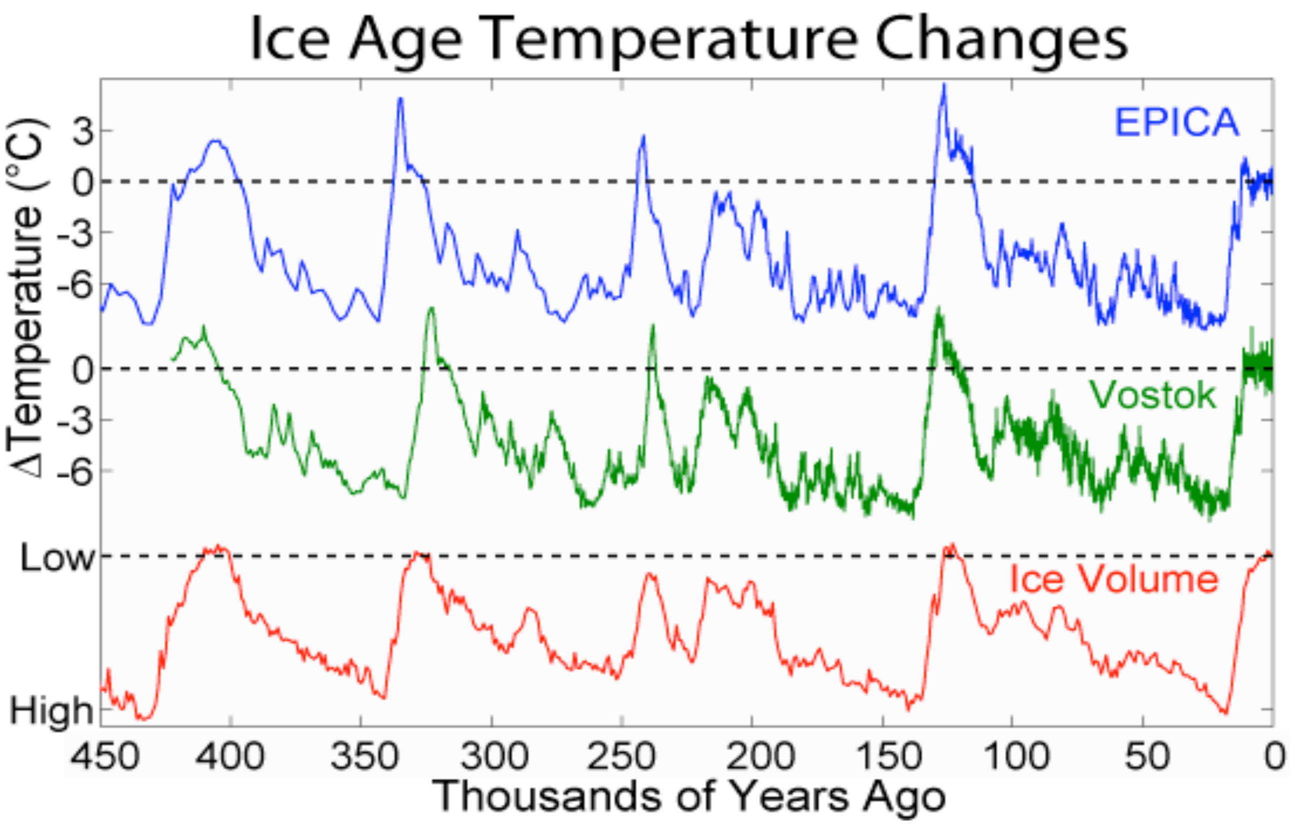


From MODTRAN

The Energy Balance of the Climate System



CO2: A Cause of the Ice Age?



Svante Arrhenius

½ $CO_2 \rightarrow -4\ ^oC$

$2XCO_2 \rightarrow +4^oC$

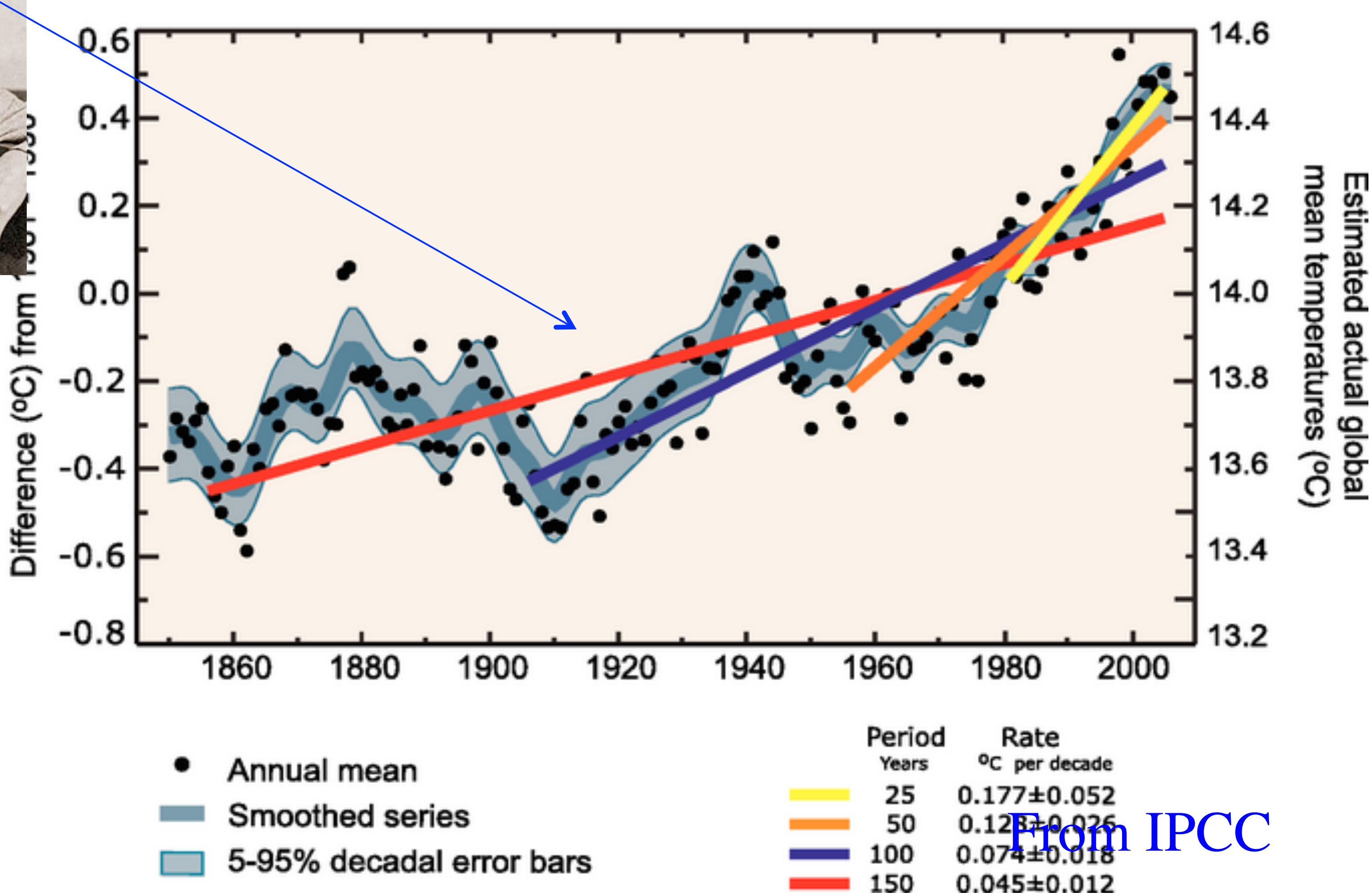
From IPCC

The Decadal Warming of 1930s

CO2?

Guy Callendar

$2XCO_2 \rightarrow 2\ ^oC$

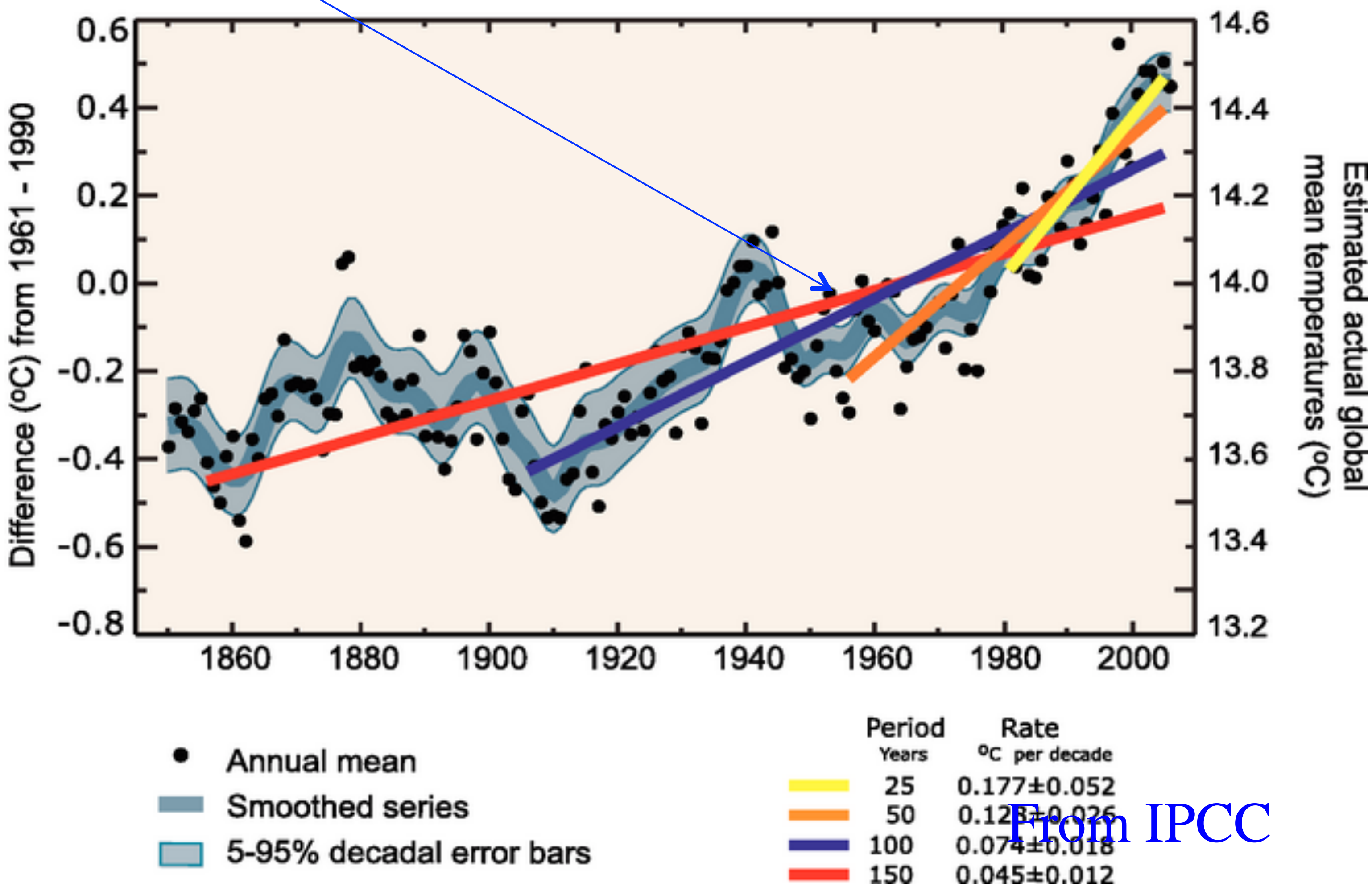


From IPCC

The Revival of CO2 Theory in 1950-60s

Bert Bolin

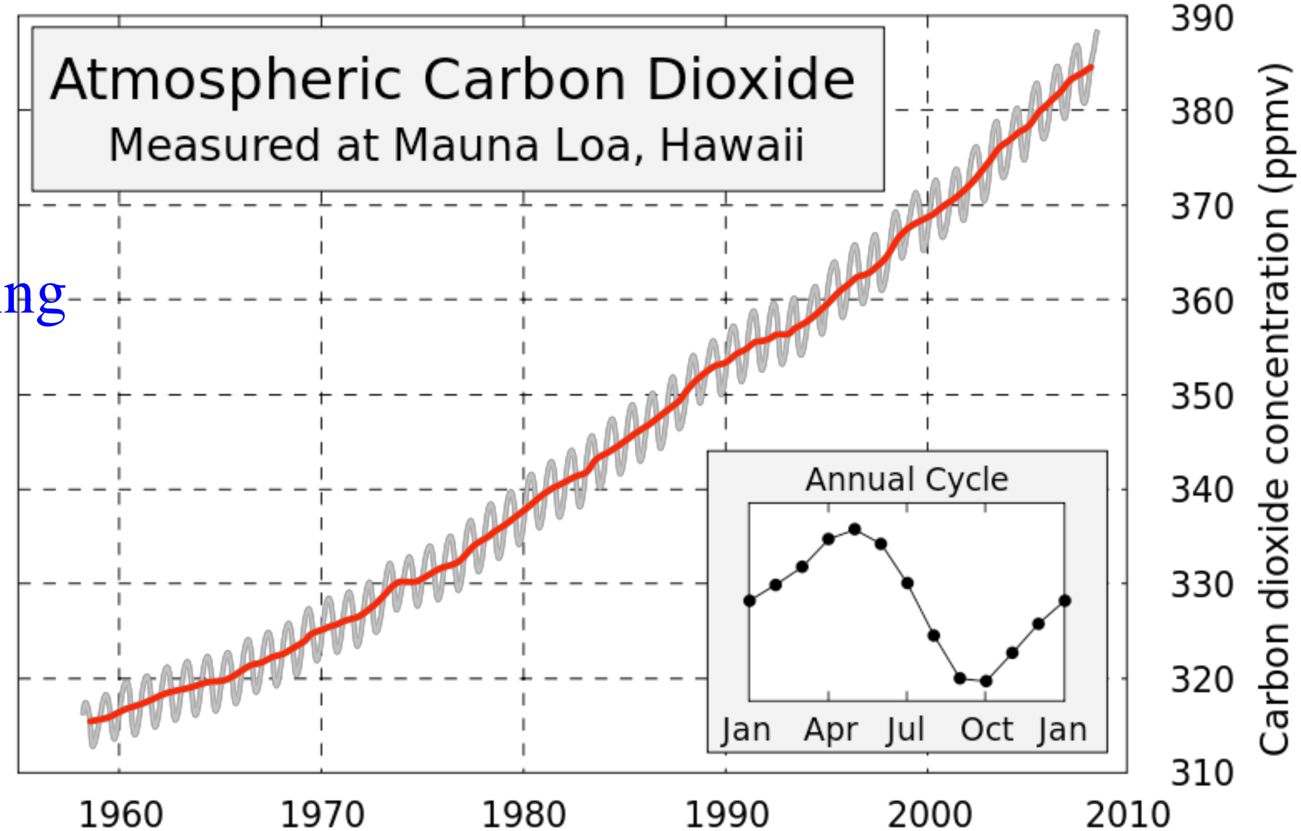
CO2?



From IPCC

The Revival of CO2 Theory in 1950-60s: The Keeling Measurements

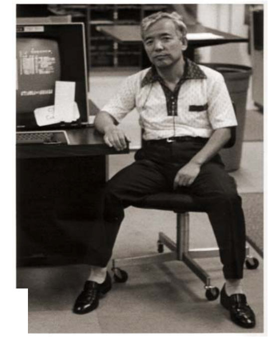
Charles Keeling



From IPCC

The Dawn of Modern Era of Modeling Climate Change

Manabe's Radiative Convective Model



S. Manabe

Manabe's 1D R-C mo

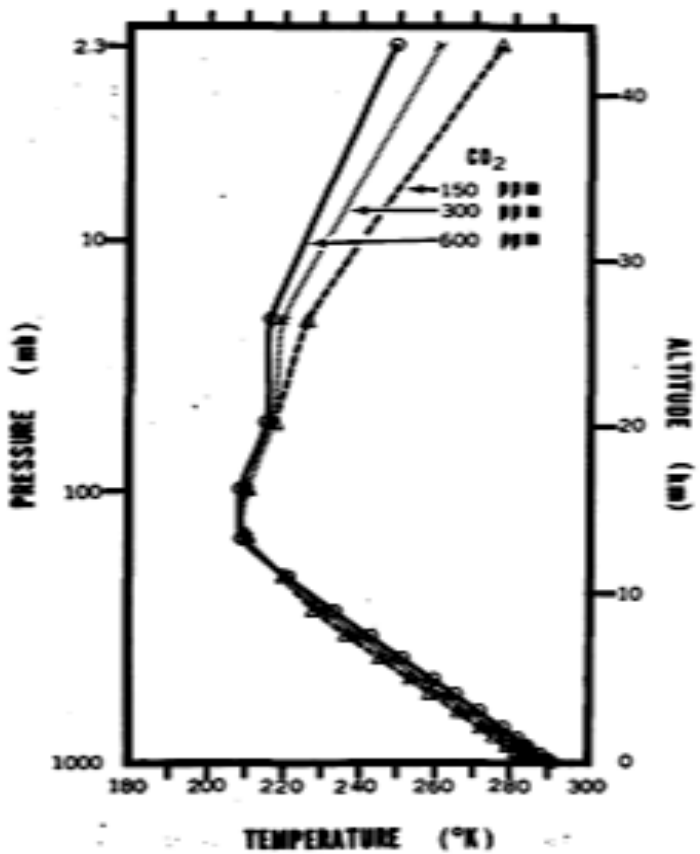


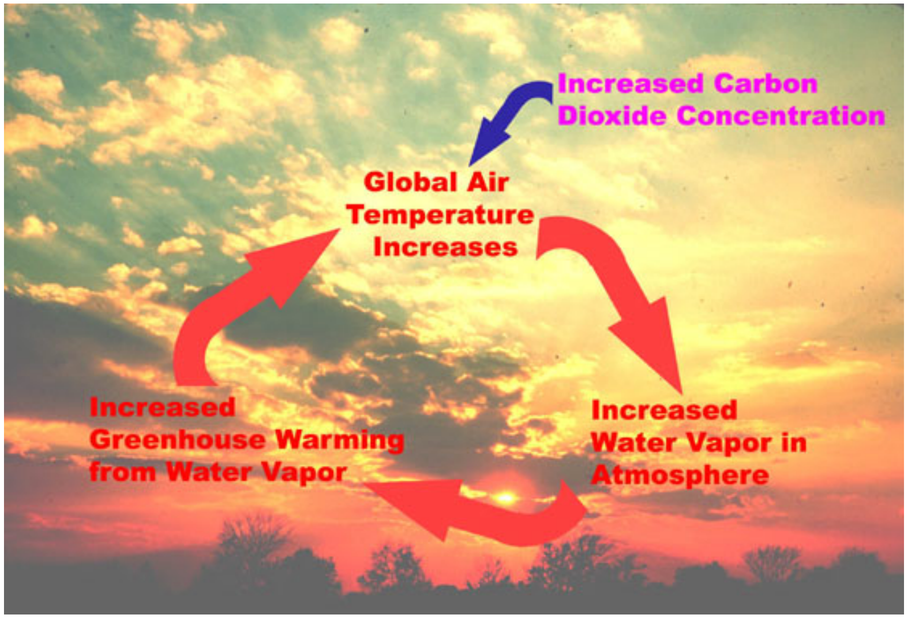
FIG. 16. Vertical distributions of temperature in radiative convective equilibrium for various values of CO_2 content.

TABLE 5. Change of equilibrium temperature of the earth's surface corresponding to various changes of CO_2 content of the atmosphere.

Change of CO_2 content (ppm)	Fixed absolute humidity		Fixed relative humidity	
	Average cloudiness	Clear	Average cloudiness	Clear
300→150	−1.25	−1.30	−2.28	−2.80
300→600	+1.33	+1.36	+2.36	2.92

Manabe and Wetherald 1967

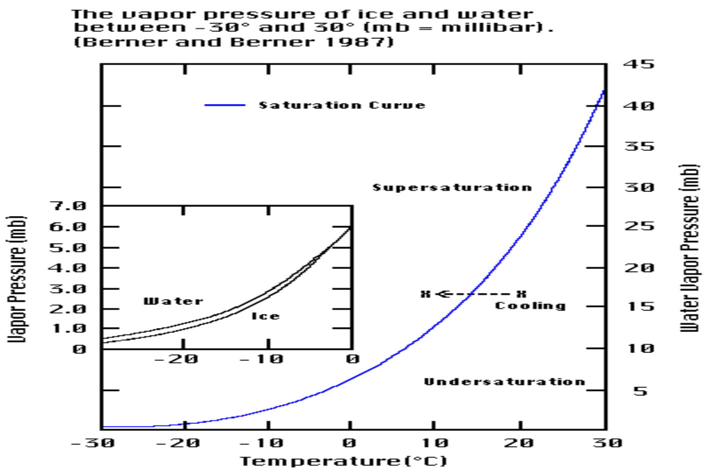
The Water Vapor Feedback
Implied by a Constant RH



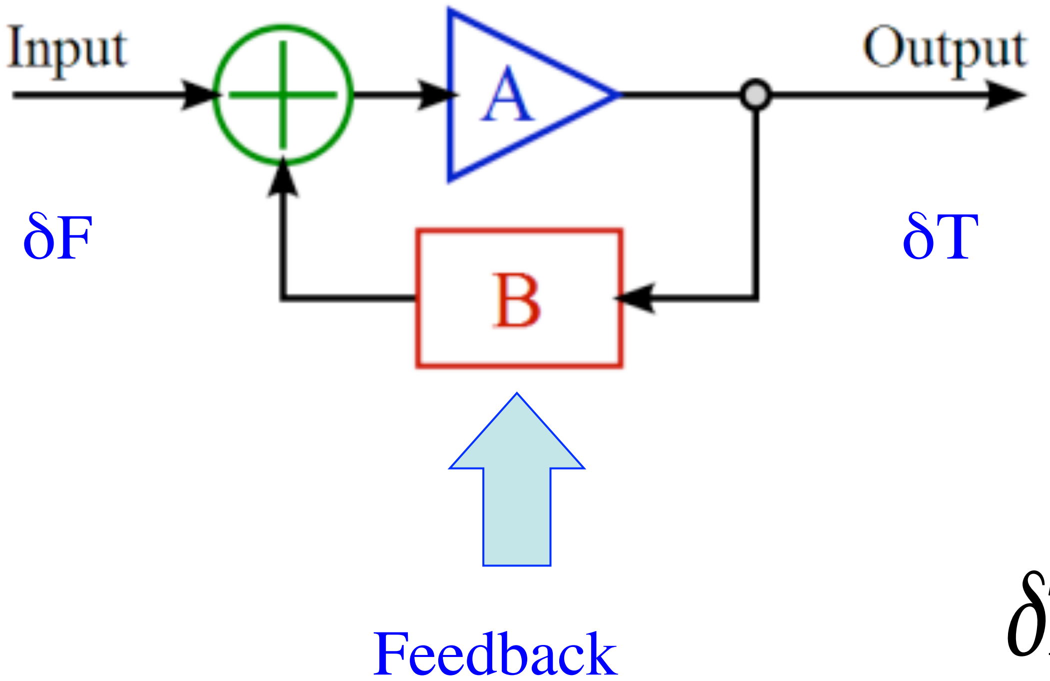
$$q = RH \bullet q_s$$

$$q_s = \varepsilon \frac{e_s}{p - e_s} \approx \varepsilon \frac{e_s}{p}$$

$$e_s \approx 6.1094 \exp\left(\frac{17.625T}{T+243.04}\right)$$



Feedback and Climate Sensitivity



$$F(T,\lambda) = 0$$

$$\delta T = \frac{\frac{\partial F}{\partial \lambda}\delta\lambda}{\frac{\partial F}{\partial T}} = \frac{dF}{4\sigma T^3(1-f)}$$

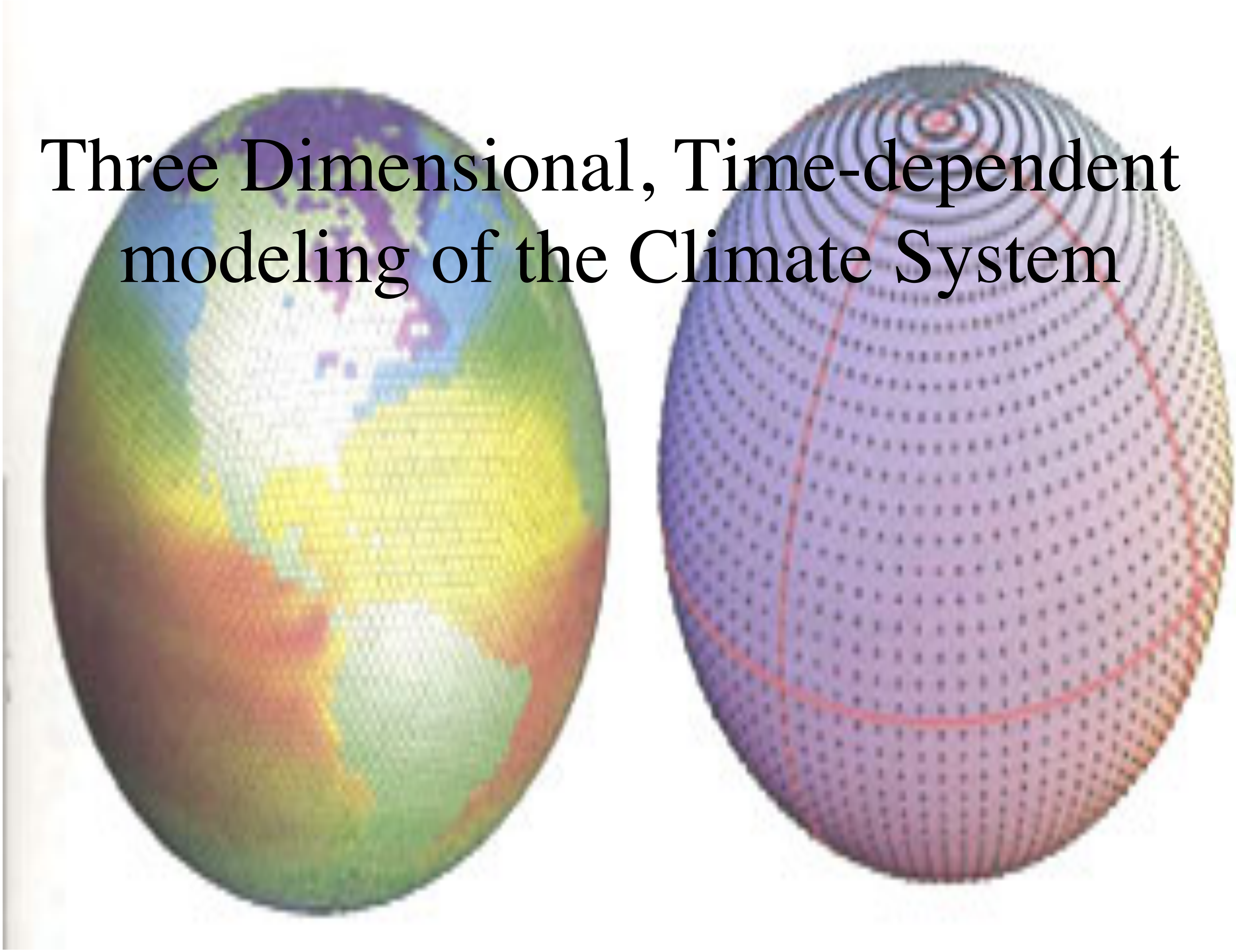
Some Key Feedbacks

$$F(T,\lambda) = 0$$

$$\delta T = \frac{dF}{4\sigma T^3 (1 - \sum_i f_i)}$$

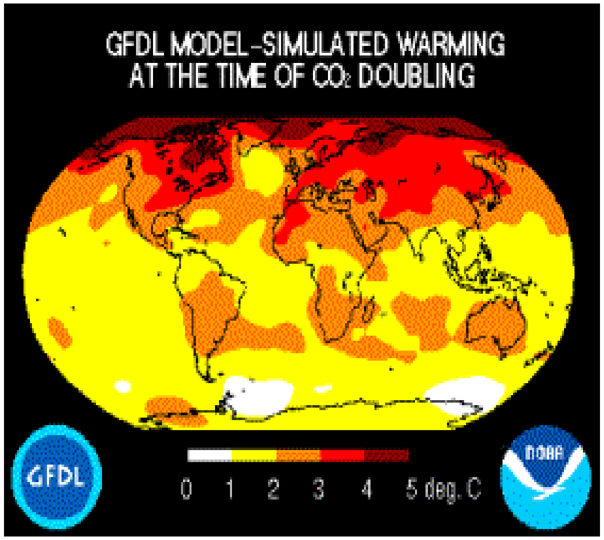
Process
Water Vapor
Lapse rate
Cloud albedo
Cloud greenhouse effect
Ice/snow albedo

Three Dimensional, Time-dependent modeling of the Climate System



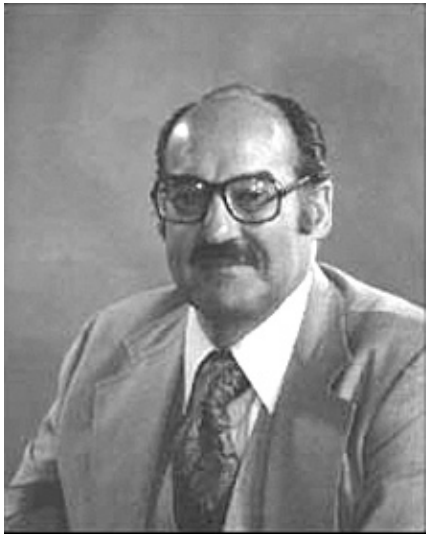
A Little History of 3-D Modeling

- Manabe's 3D GCM



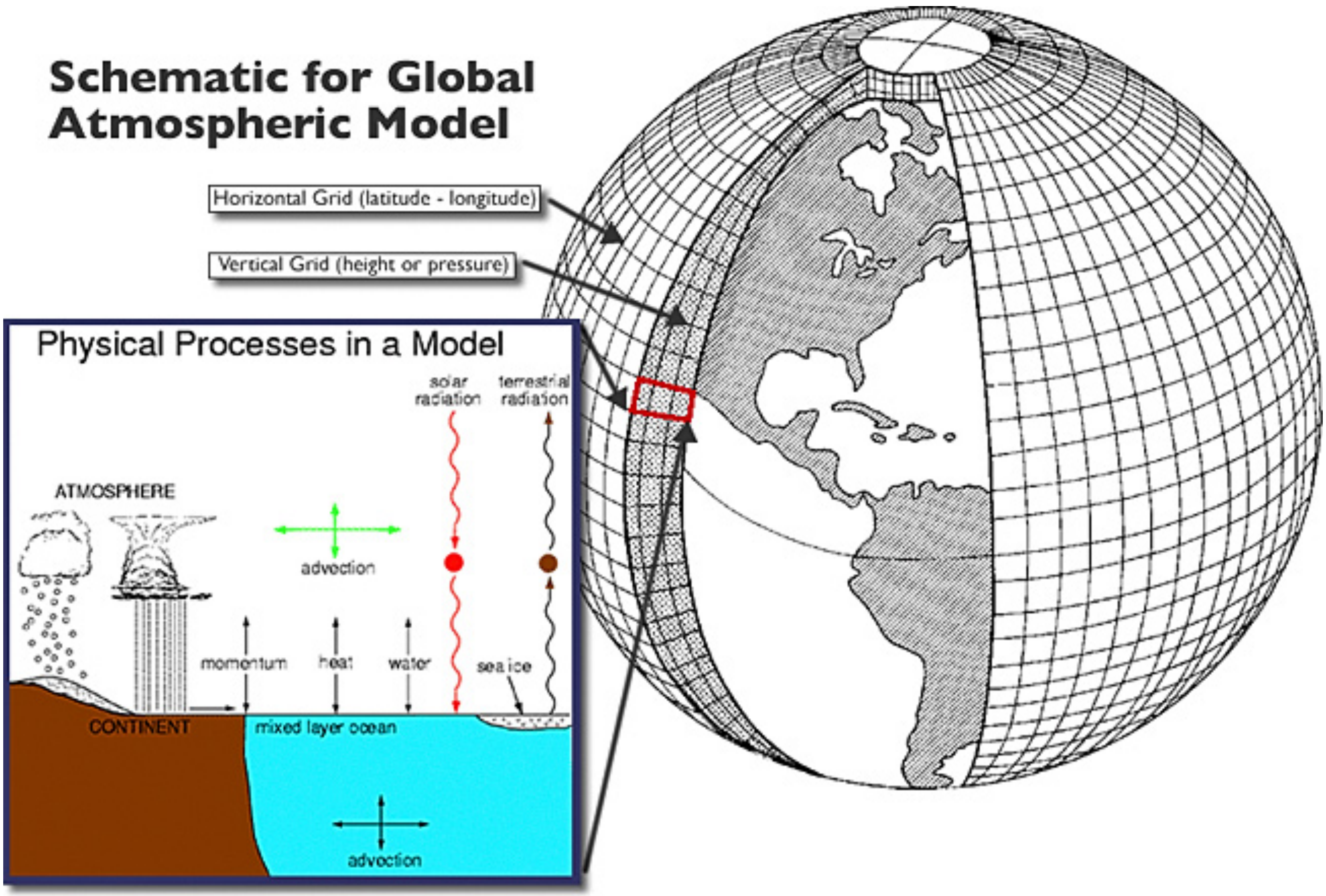
- Syukuro Manabe

Geophysical Fluid Dynamics Laboratory (GFDL)

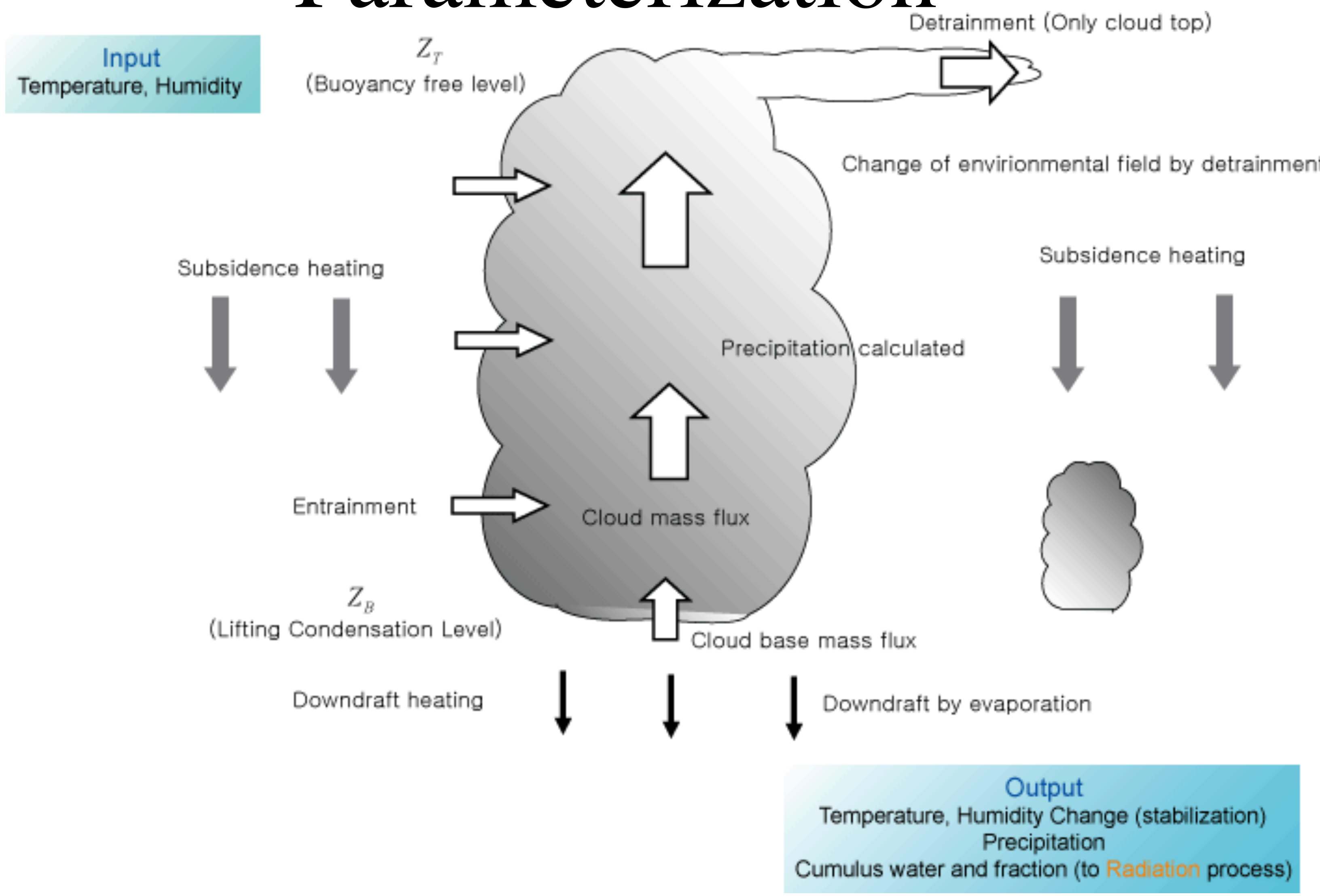


Joseph Smagorinsky

Some basic concepts: Discretization



Some basic concepts: Parameterization



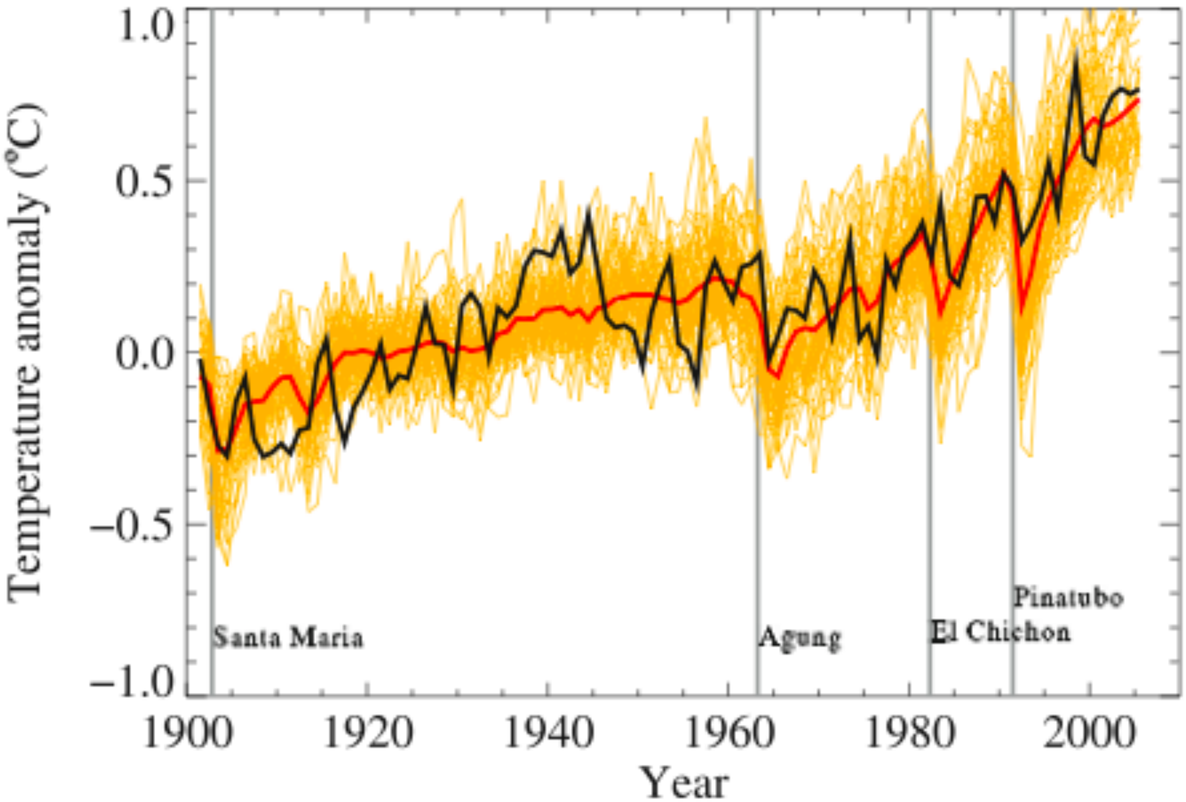
The Basic Equations

- The equation for the motions in the atmosphere and ocean: the Navier-Stokes Equation (Newton's second law)
- The continuity equation (mass conservation)
- The equation of state for air and sea water
- The energy conservation equation: the first law of thermodynamics
- The budget equation for water vapor, salt, CO_2, etc.

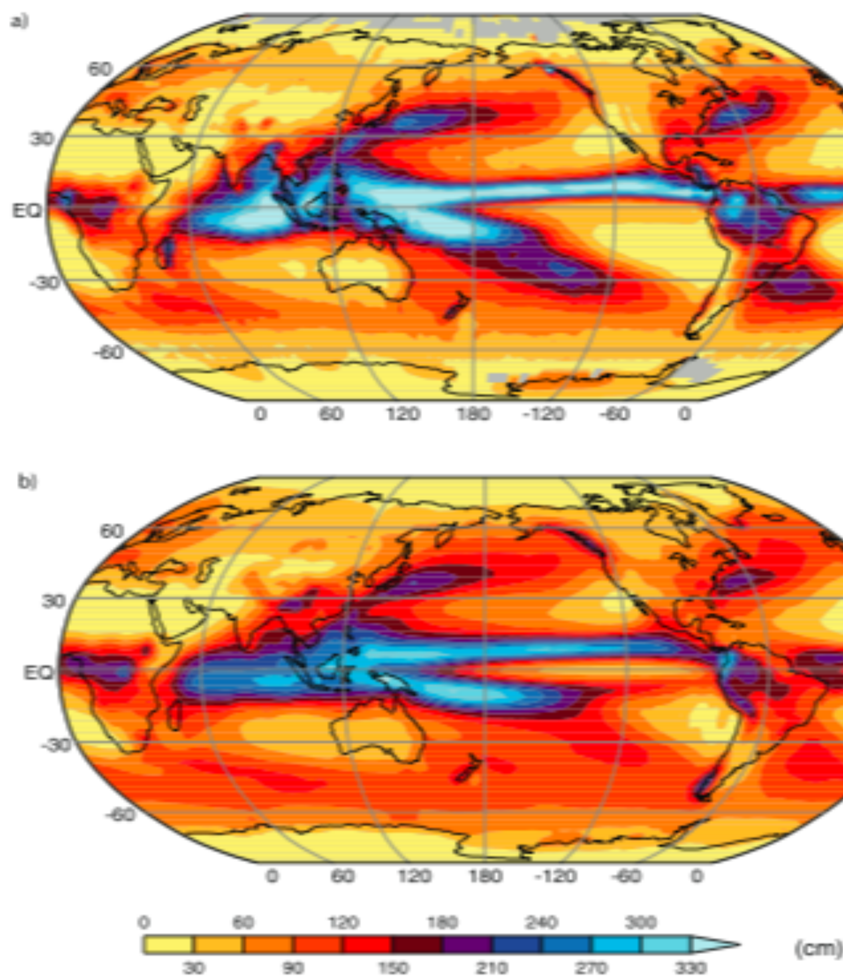
Some approximations still in use

- The flow is incompressible
- The flow is **Boussinesq**
- The flow is hydrostatic

Successes and Challenges: Simulation of global mean temperature variations



Successes and Challenges: Simulation of the rainfall distribution



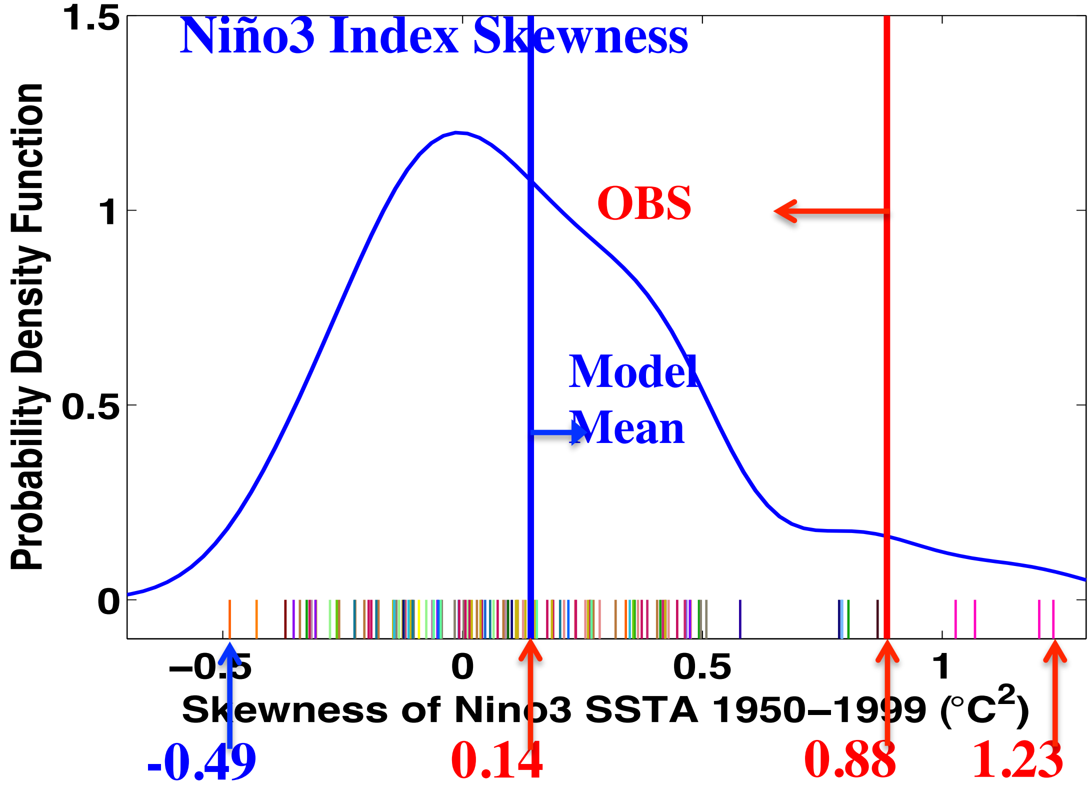
Some Key Feedbacks

$$F(T, \lambda) = 0$$

$$\delta T = \frac{dF}{4\sigma T^3 (1 - \sum_i f_i)}$$

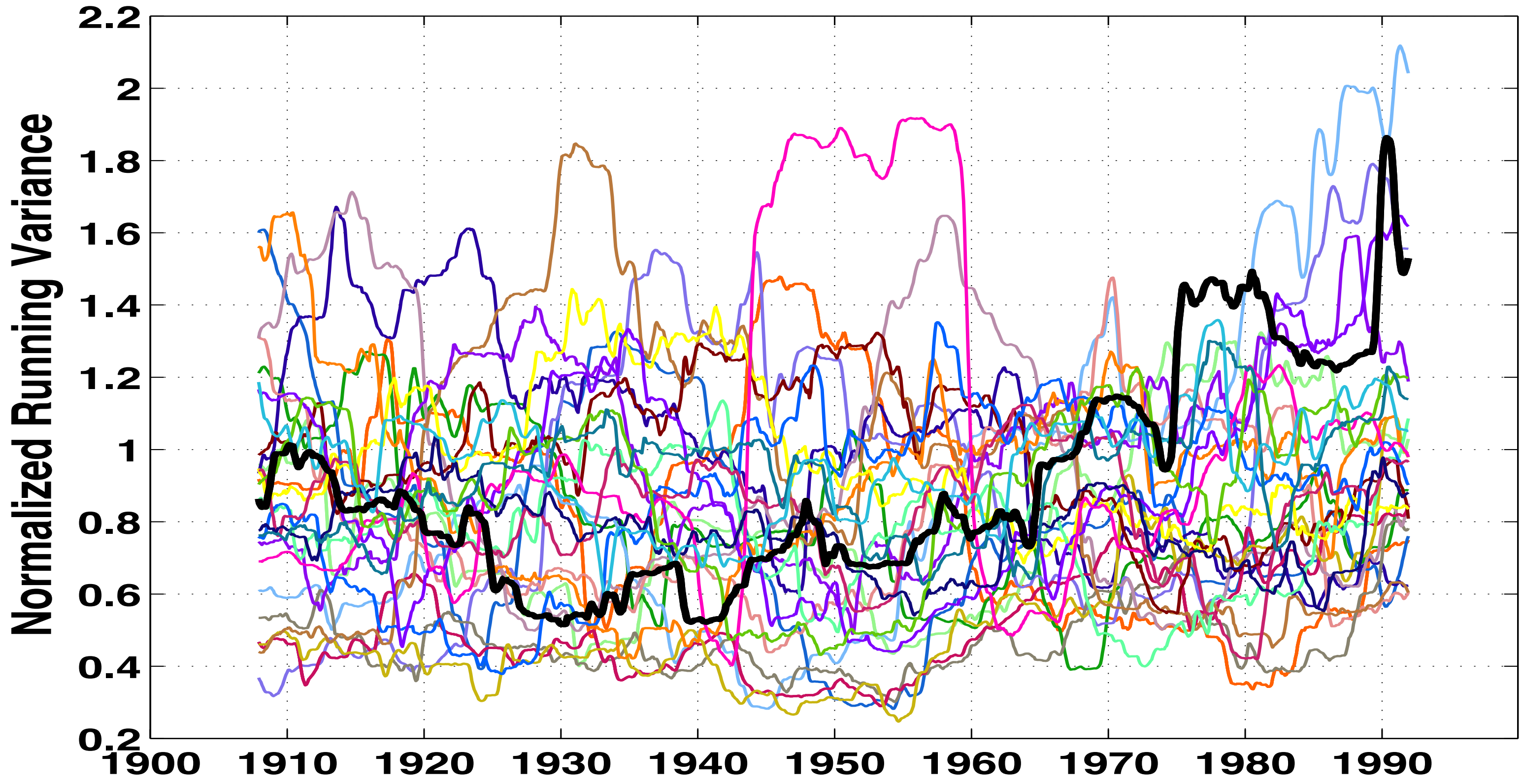
Process	Sign	Confidence level
Water Vapor	+	High
Lapse rate	-	High
Water Vapor plus Lapse rate	+	High
Cloud albedo	?	
Cloud greenhouse effect	?	
Ice albedo	+	Certain

3. ENSO Statistics in CMIP5

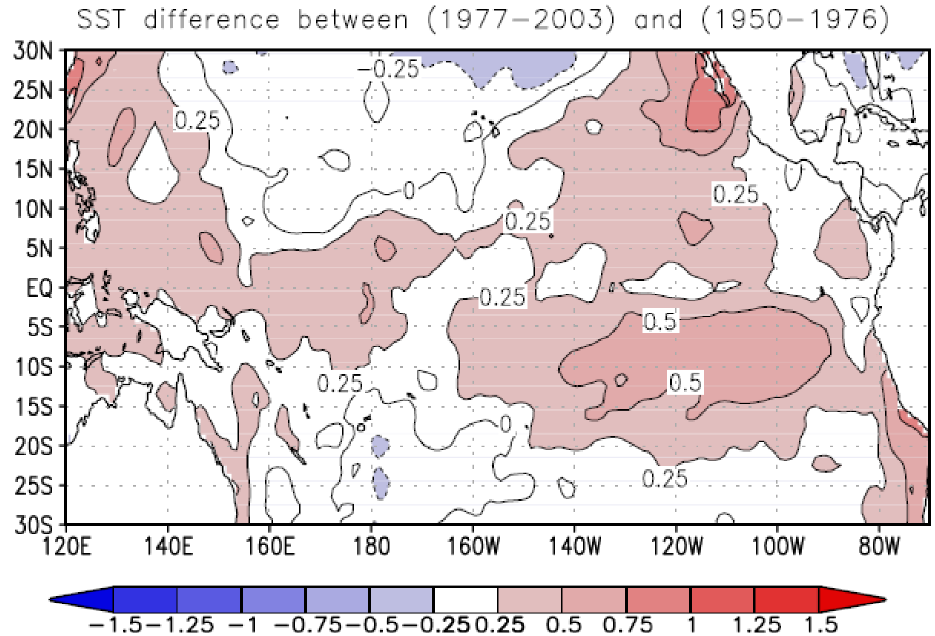


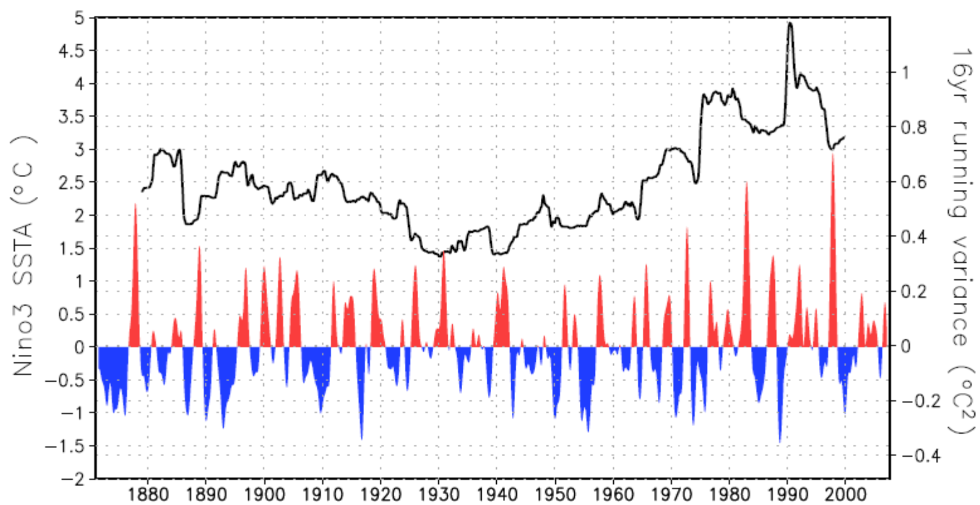
3. ENSO Statistics in CMIP5

Normalized Running Variance

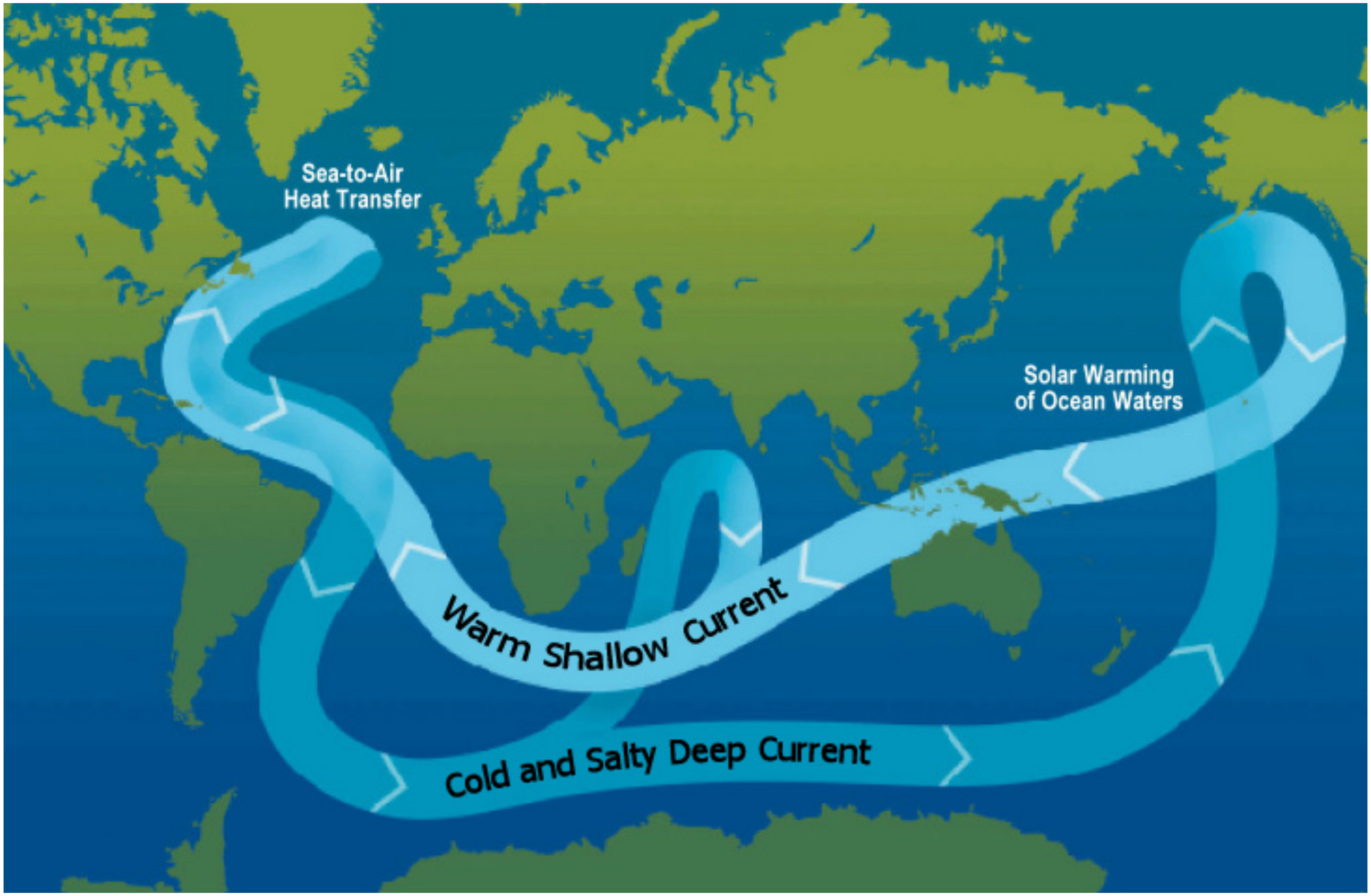


A Cause or A Consequence?



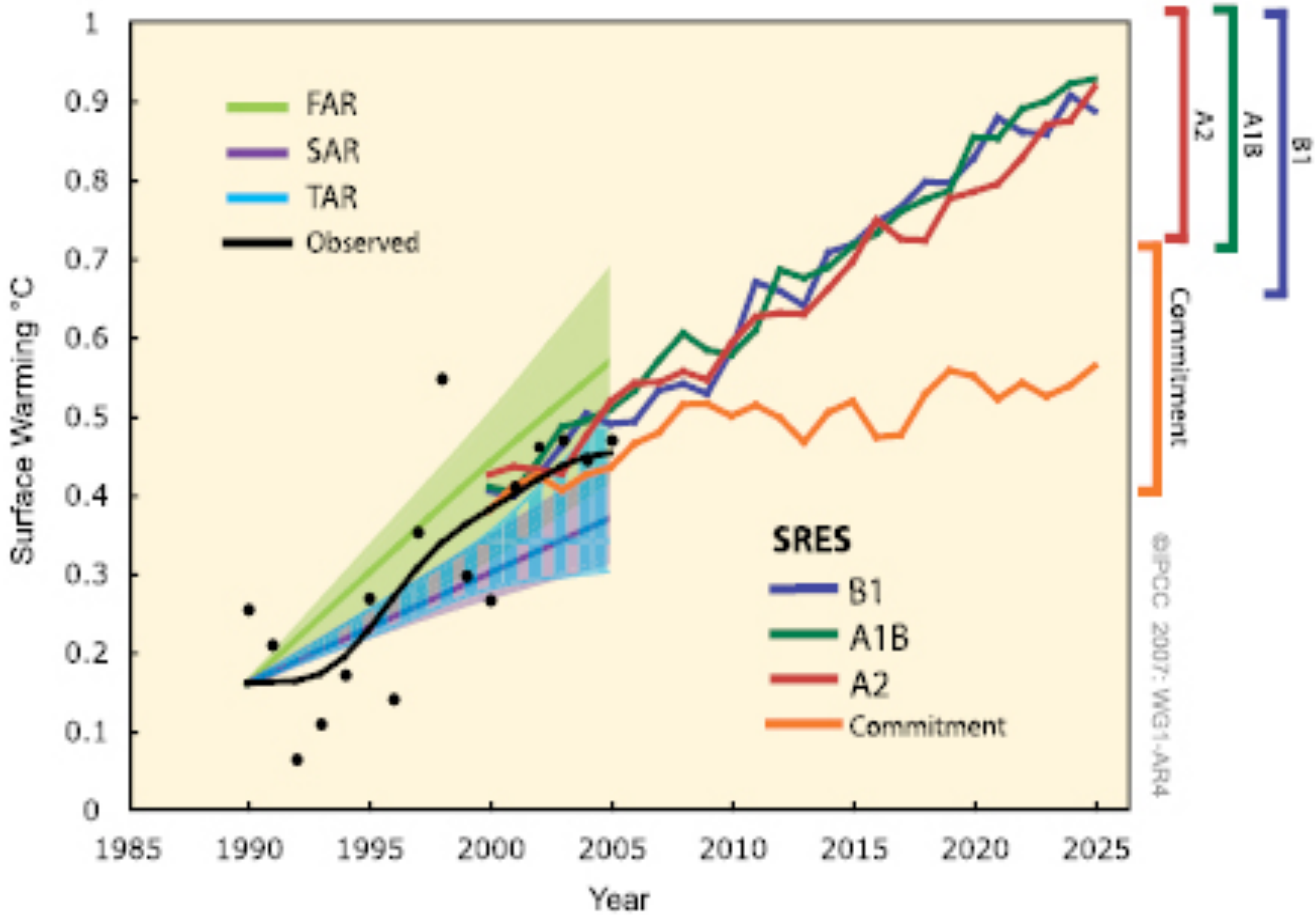


Themohaline Circulation Variability



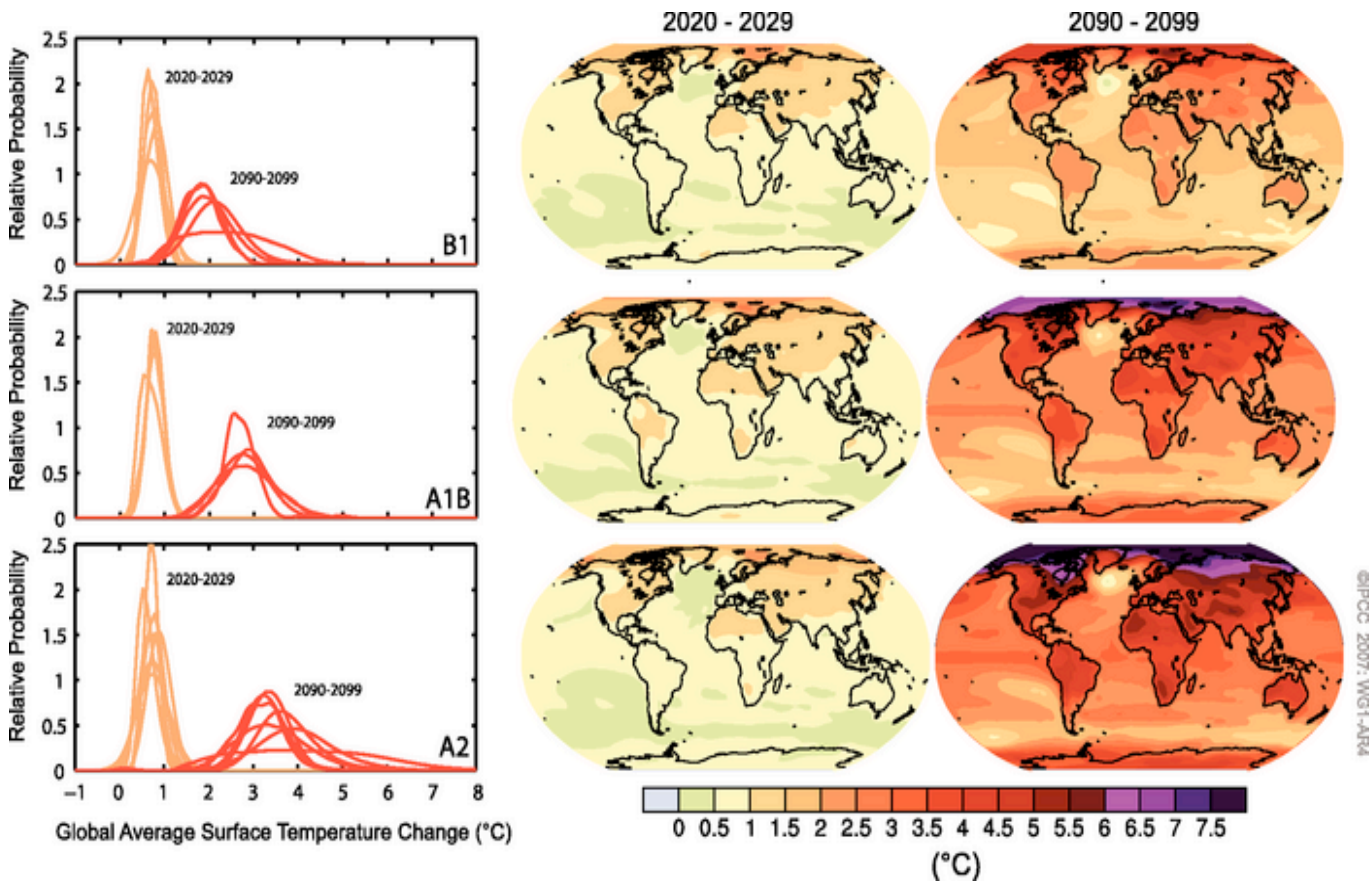
Future Volcanic Activities

Projections of Future Climate Change



Projections of Future Climate Change

relative to the period 1980 to 1999



A Poem By Robert Frost

Some say the world will end in fire,

Some say in ice.

From what I've tasted of desire

I hold with those who favor fire.

But if it had to perish twice,

I think I know enough of hate

To say that for destruction ice

Is also great

And would suffice.