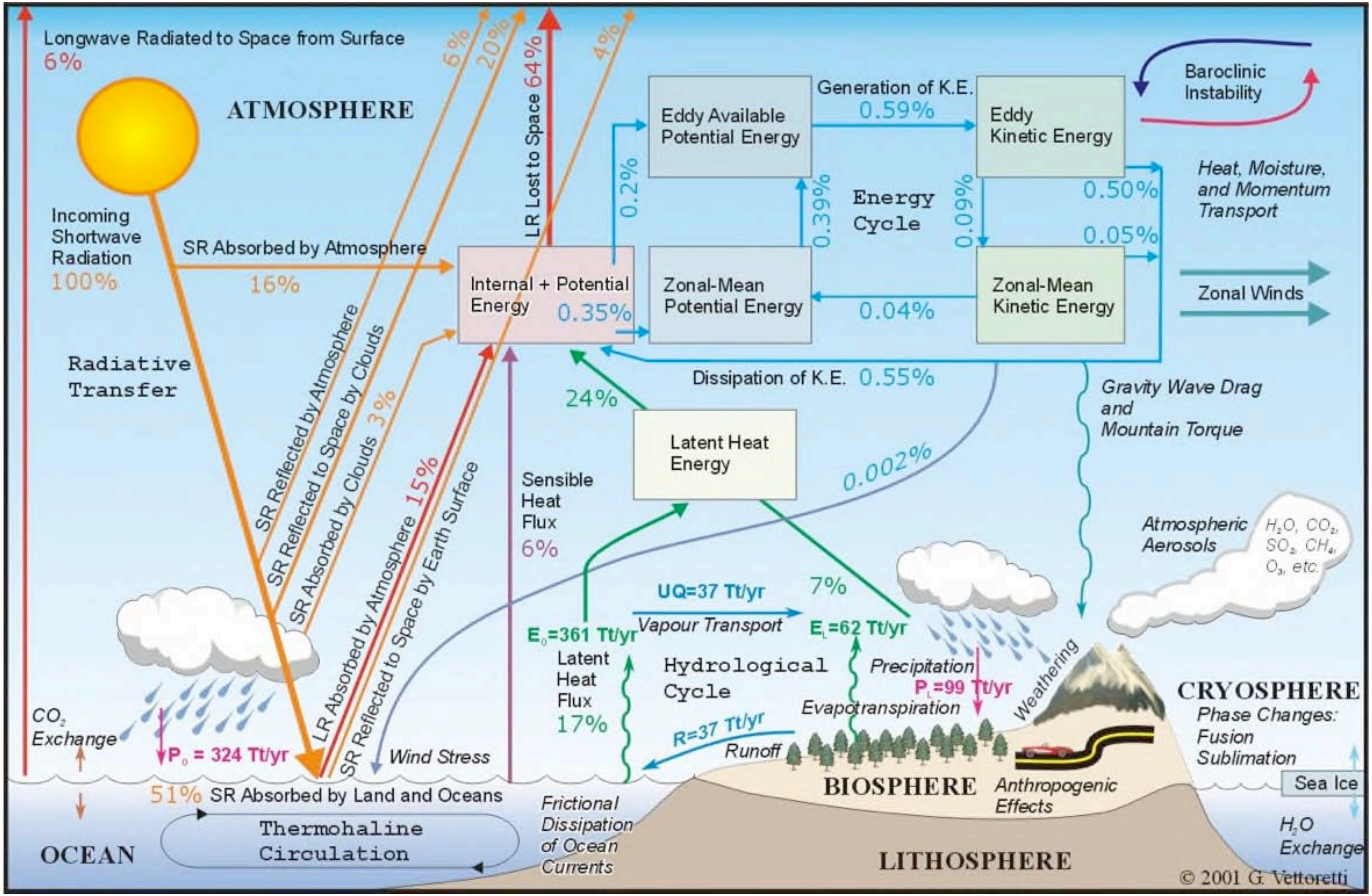
Climate Change:
Forcings, Feedbacks, and Forecasts

Some of these slides are taken from the IPCC's recently released Fourth Assessment.

Beautiful but complicated



Scott Denning already told you about this...

Climate is what you expect.
Weather is what you get.

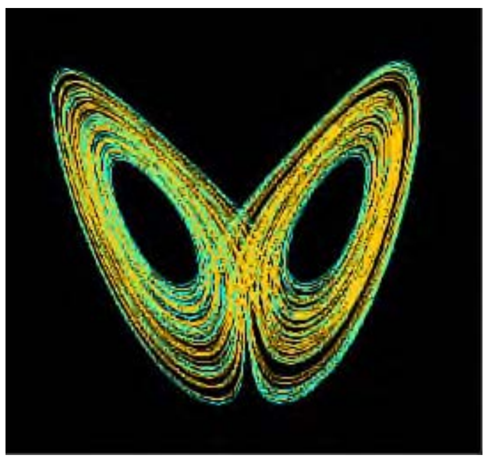
So let's start by asking:

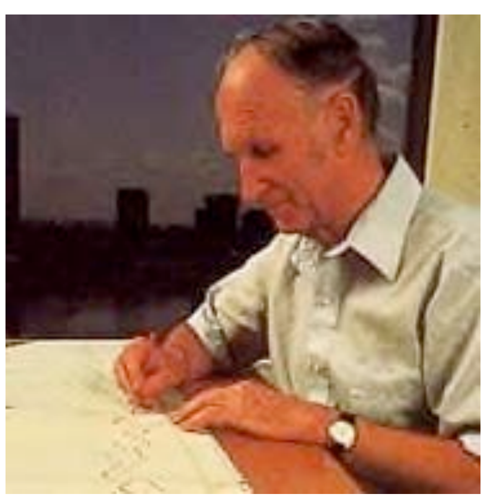
Why can't those turkeys predict the weather?

Small errors in the initial conditions lead to large errors in forecasts.

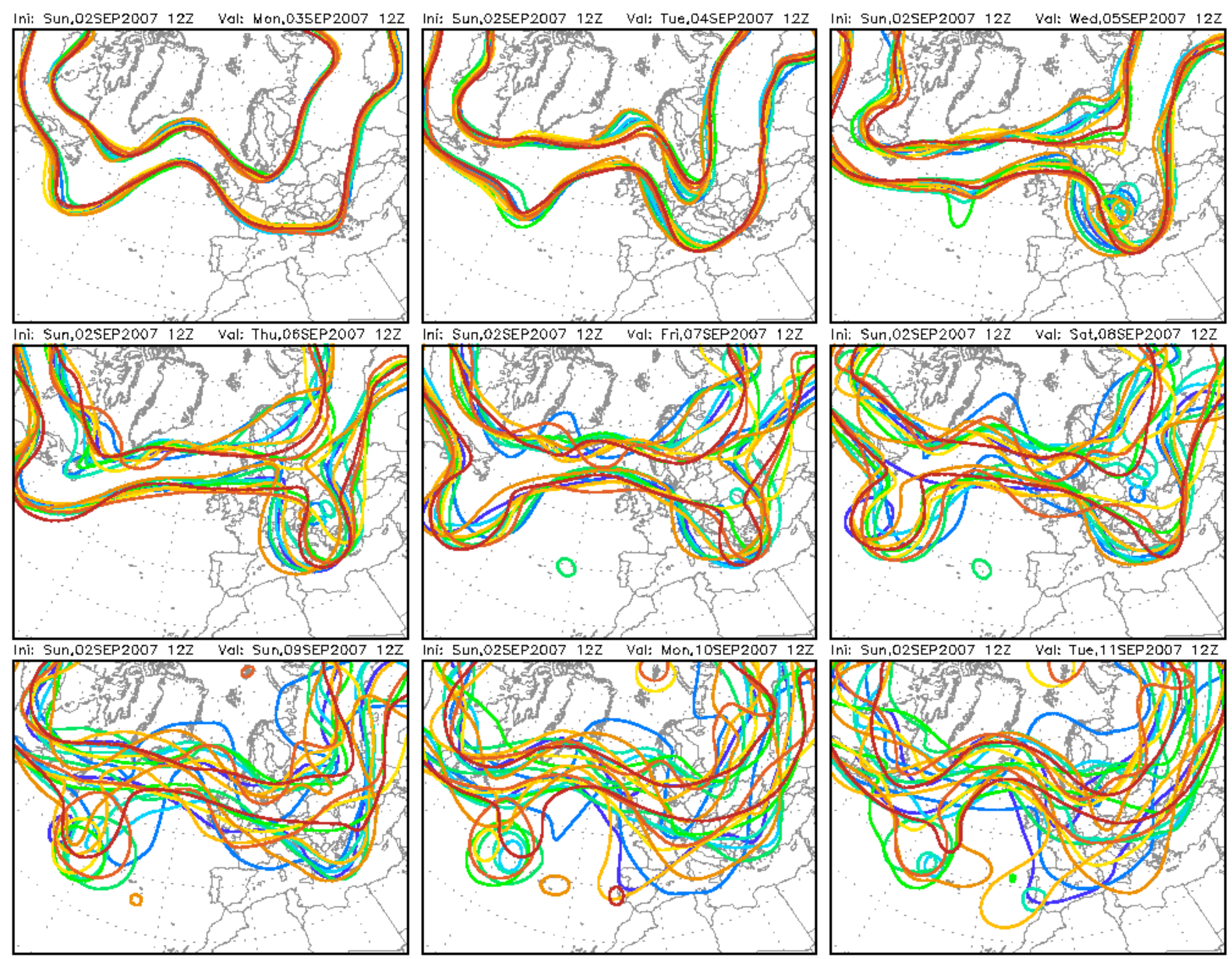
This "*sensitive dependence on initial conditions*" limits the range of useful forecasts to about two weeks.

Limited predictability is a *property of the atmosphere*, and so cannot be eliminated even if we had a perfect forecast model.



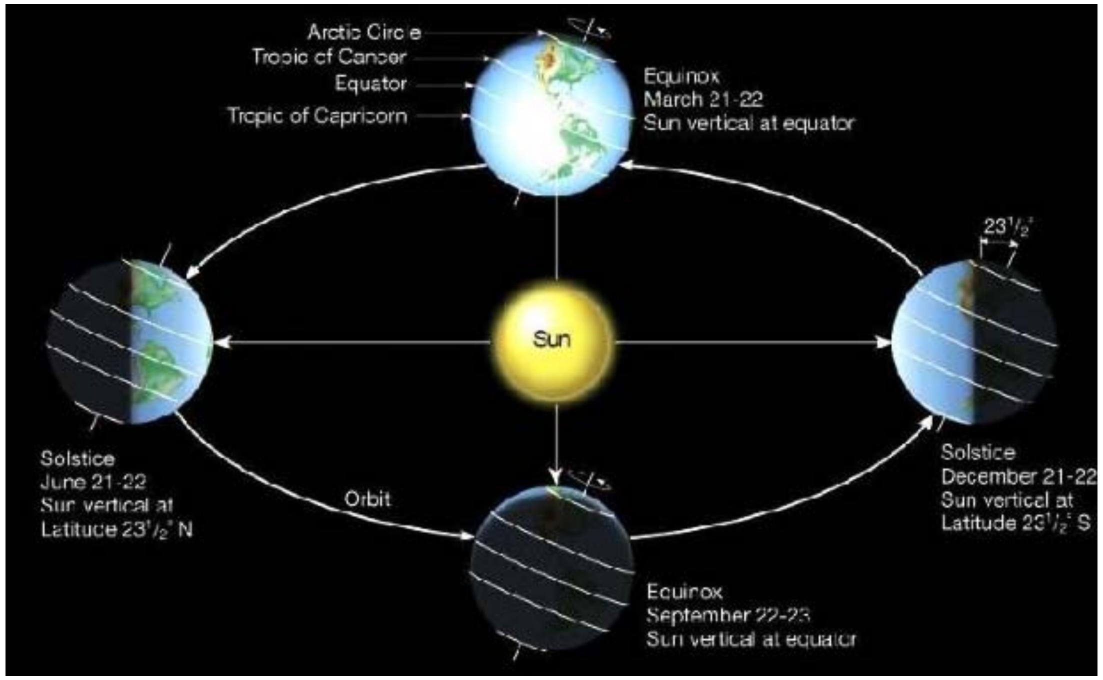


"Dr. Chaos," Ed Lorenz



Climate change can be *forced.*

- Changes in the average weather are often "forced" by changing external influences, e.g.:
  - The day-night cycle
  - The seasonal cycle
  - Ice ages
  - Anthropogenic changes in the composition of the atmosphere



The seasonal cycle

A long-range forecast:
July 2008 will be warmer, in Fort Collins, than January 2008.

This will be a forced change.
The change in the forcing is itself predictable.

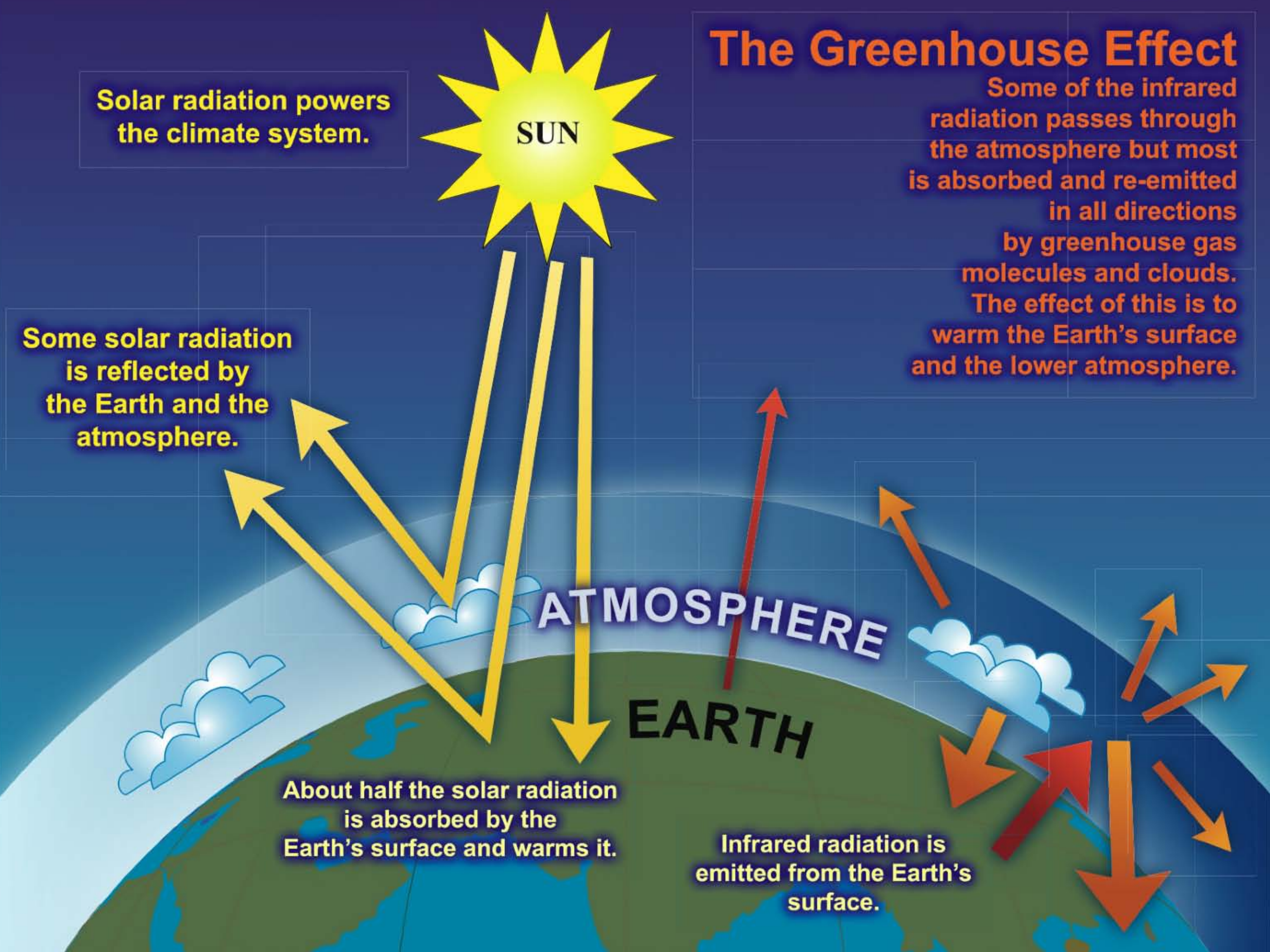
How can we predict climate change, if we can't predict the weather?

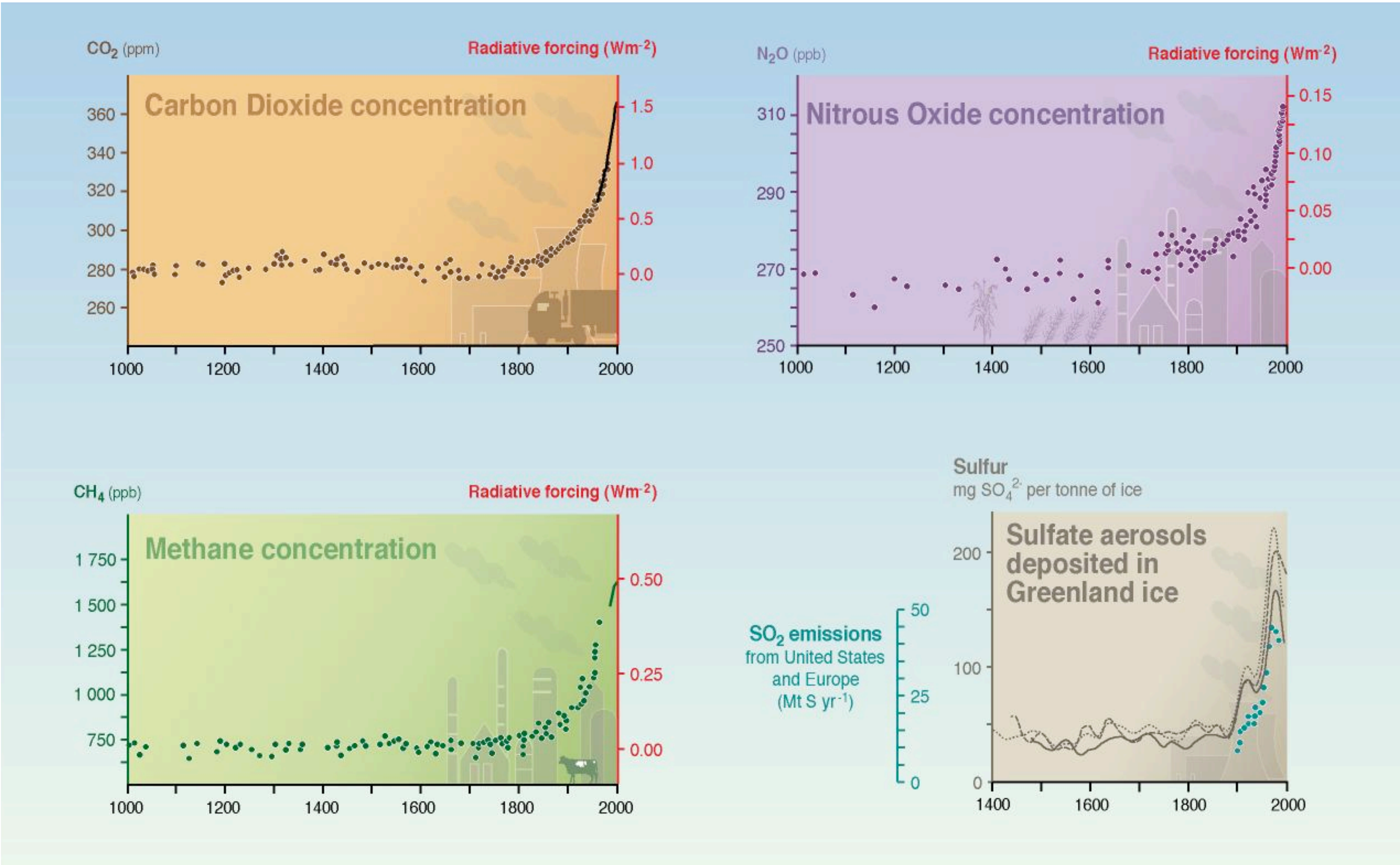
- **Day-to-day changes are due to weather systems growing, moving, dying, etc. -- This is simply the atmosphere going about its business.**
- **The predictability of such weather changes is limited, to about 2 weeks, by sensitive dependence on initial conditions.**
- **Changes in climate can arise from changes in *forcing* by "external" influences.**
- **If the external forcings can be predicted, and if they are strong enough, then the resulting climate change can also be predicted.**

So, we need to talk about forcings.

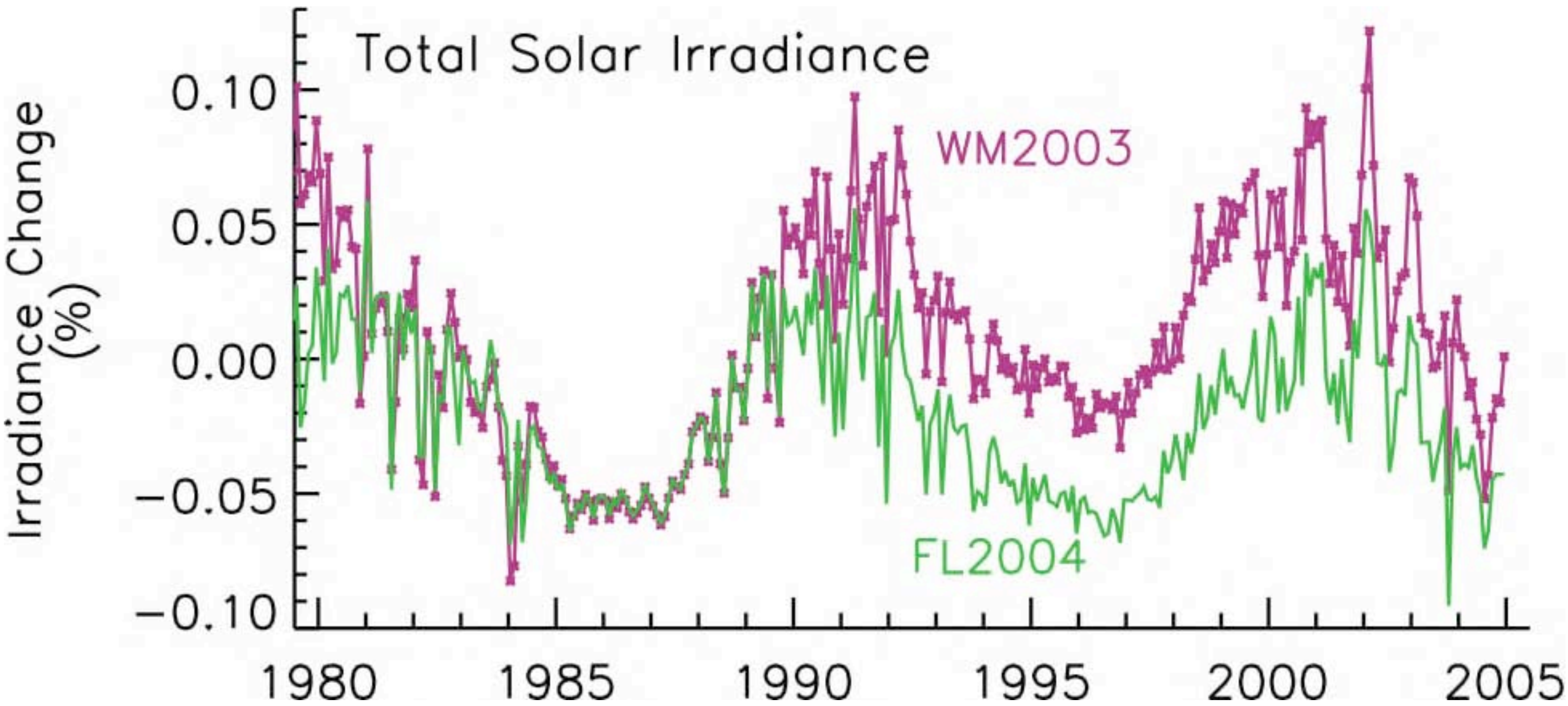
Kinds of Forcings

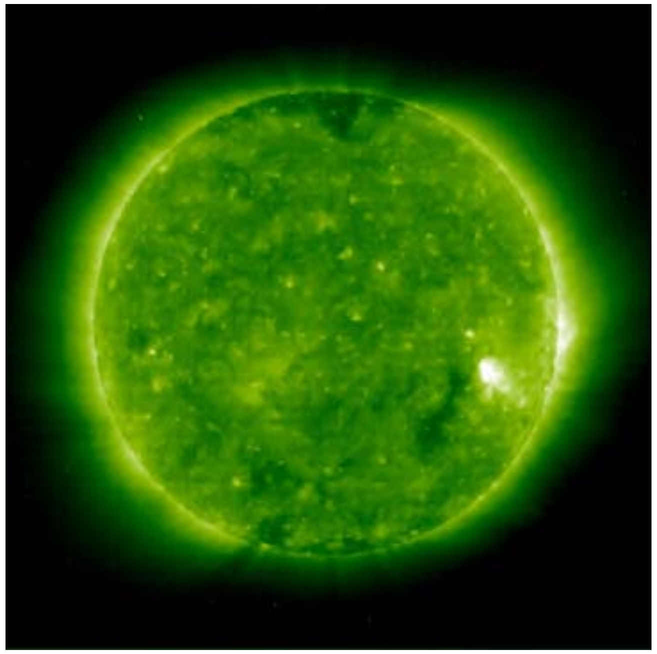
- **Anthropogenic changes in the gaseous composition of the atmosphere**
- **Anthropogenic changes in atmospheric aerosols**
- **Changes in land use**
- **Volcanic eruptions**
- **Changes in solar output**
- **Changes in the Earth's orbital parameters (on very long time scales)**

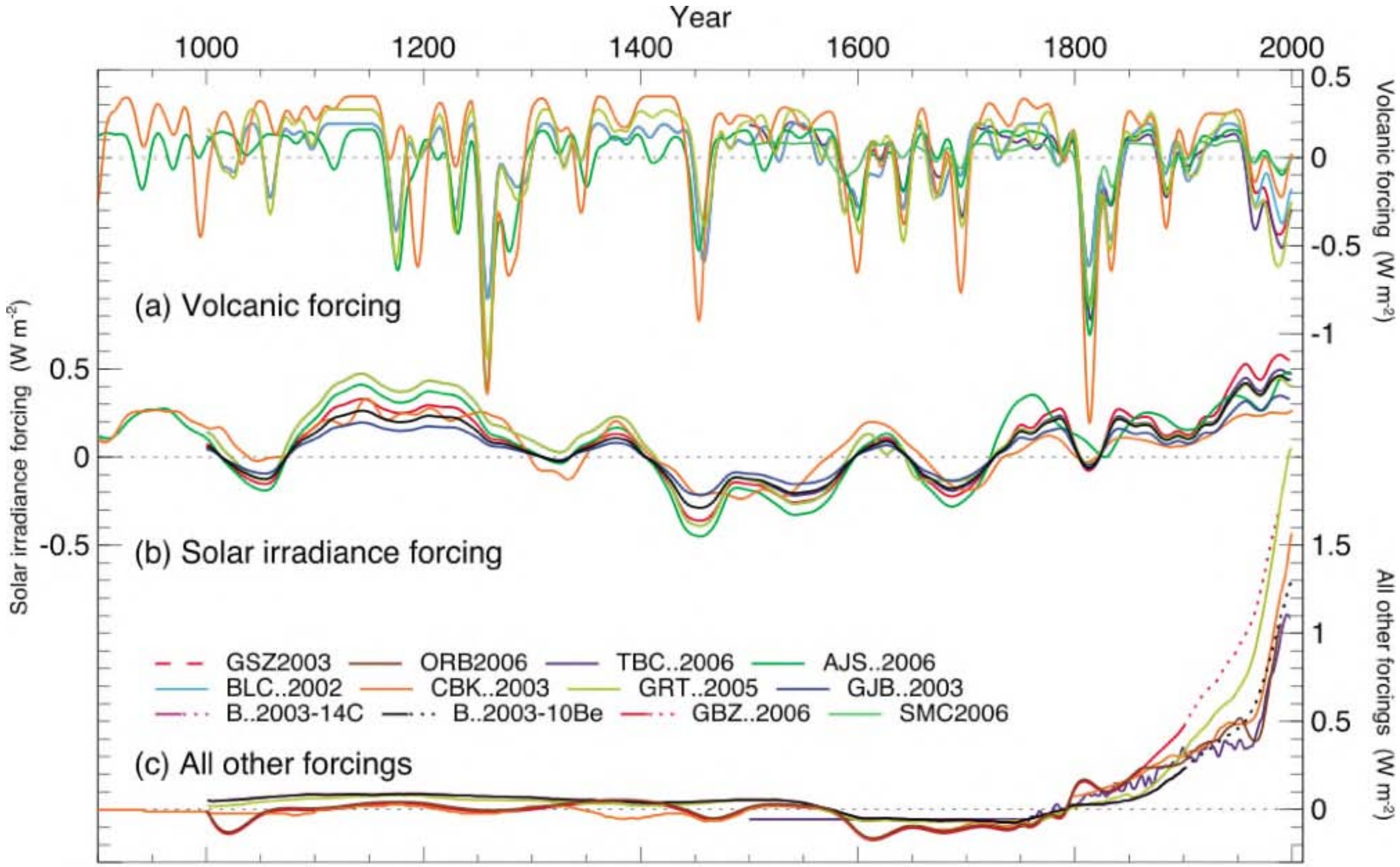

The Greenhouse Effect
Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth's surface and the lower atmosphere.
Solar radiation powers the climate system.
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
ATMOSPHERE
EARTH
About half the solar radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.



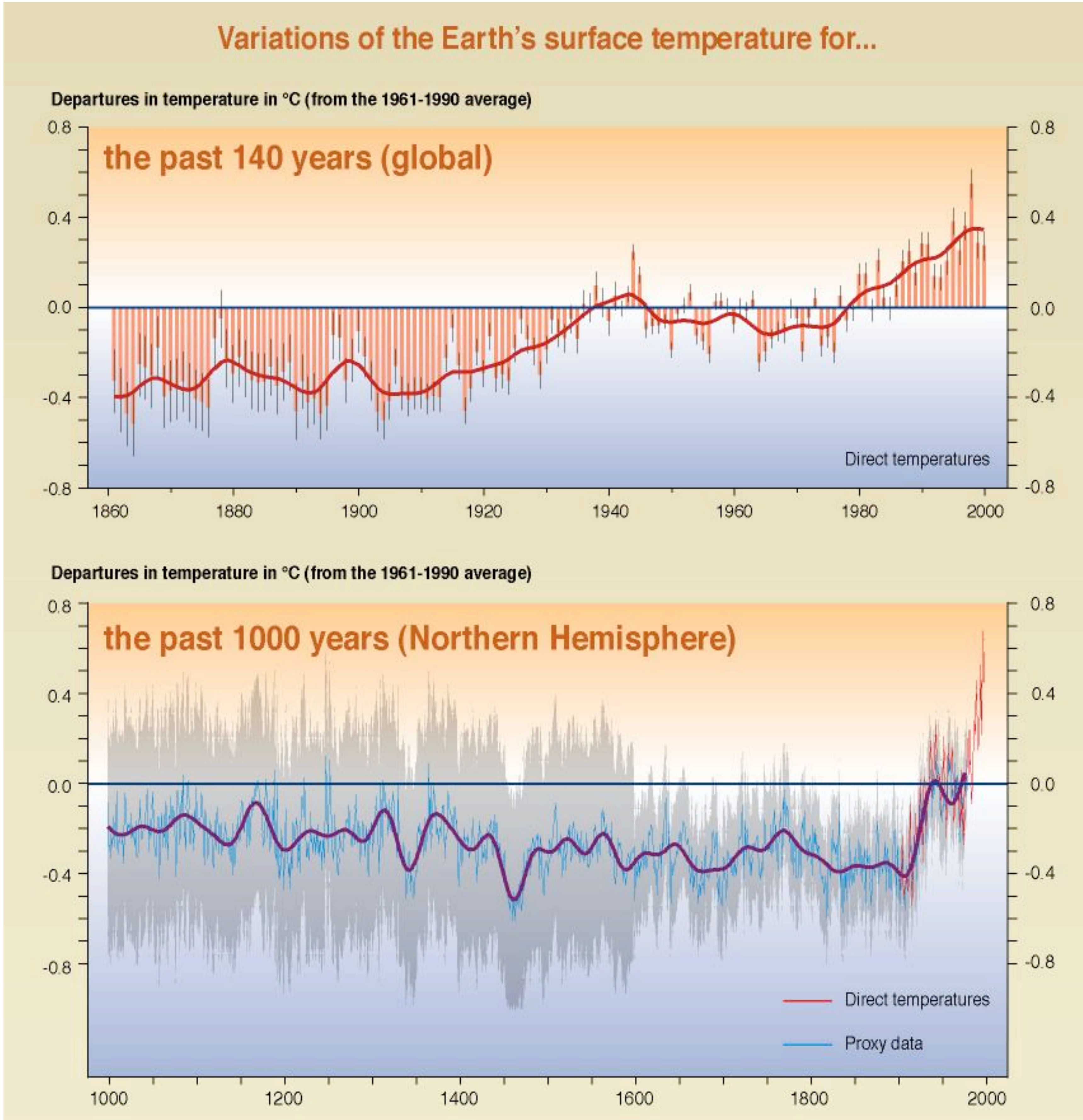
Here "*radiative forcing*" refers to the effects of a perturbation on the radiation at the top of the atmosphere.

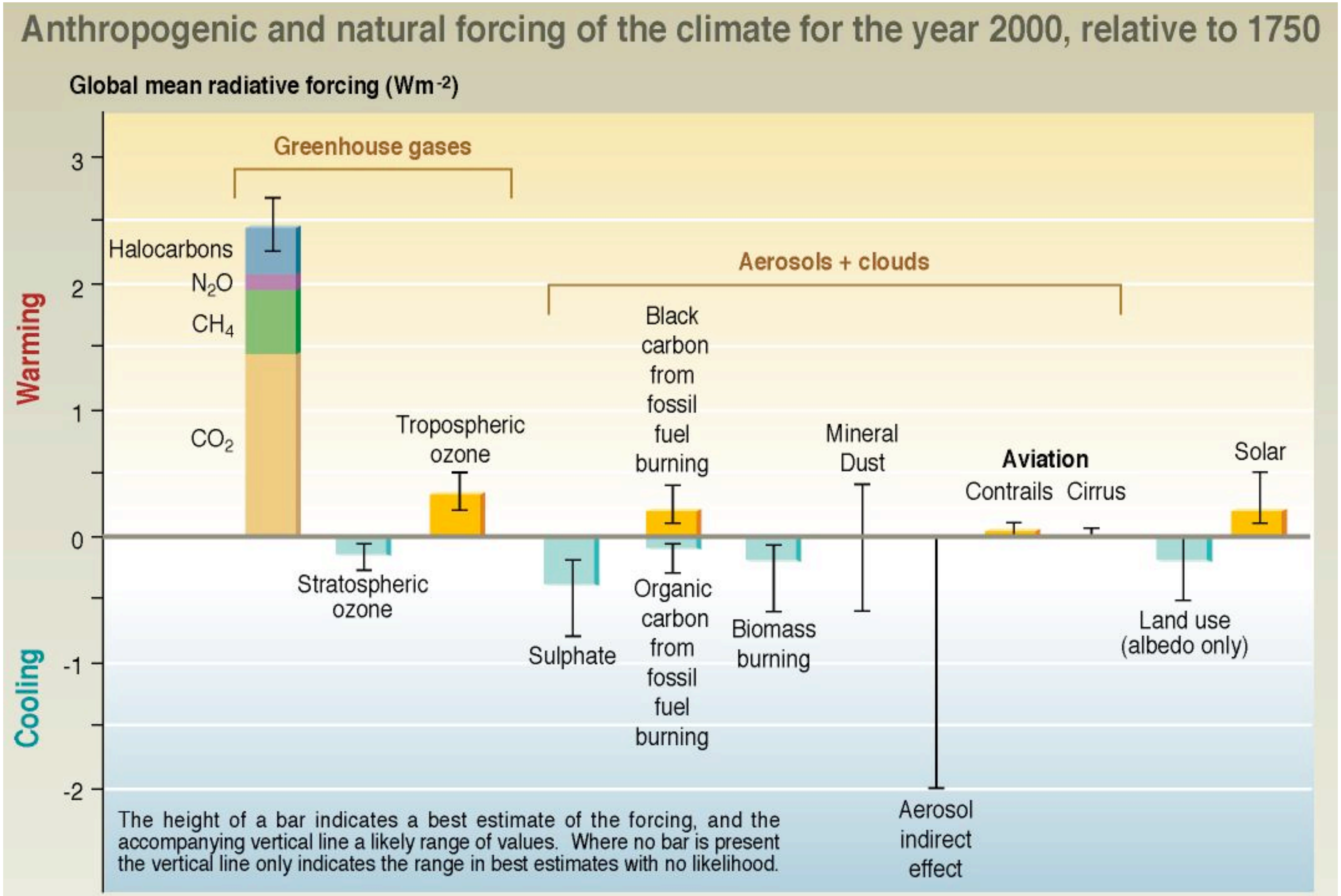

Total Solar Irradiance
WM2003
FL2004
Irradiance Change
(%)
0.10
0.05
0.00
−0.05
−0.10
1980
1985
1990
1995
2000
2005





Year
1000
1200
1400
1600
1800
2000
0.5
0
-0.5
-1
Volcanic forcing (W m^{-2})
(a) Volcanic forcing
Solar irradiance forcing (W m^{-2})
0.5
0
-0.5
(b) Solar irradiance forcing
GSZ2003
ORB2006
TBC..2006
AJS..2006
BLC..2002
CBK..2003
GRT..2005
GJB..2003
B..2003-14C
B..2003-10Be
GBZ..2006
SMC2006
(c) All other forcings
1.5
1
0.5
0
All other forcings (W m^{-2})

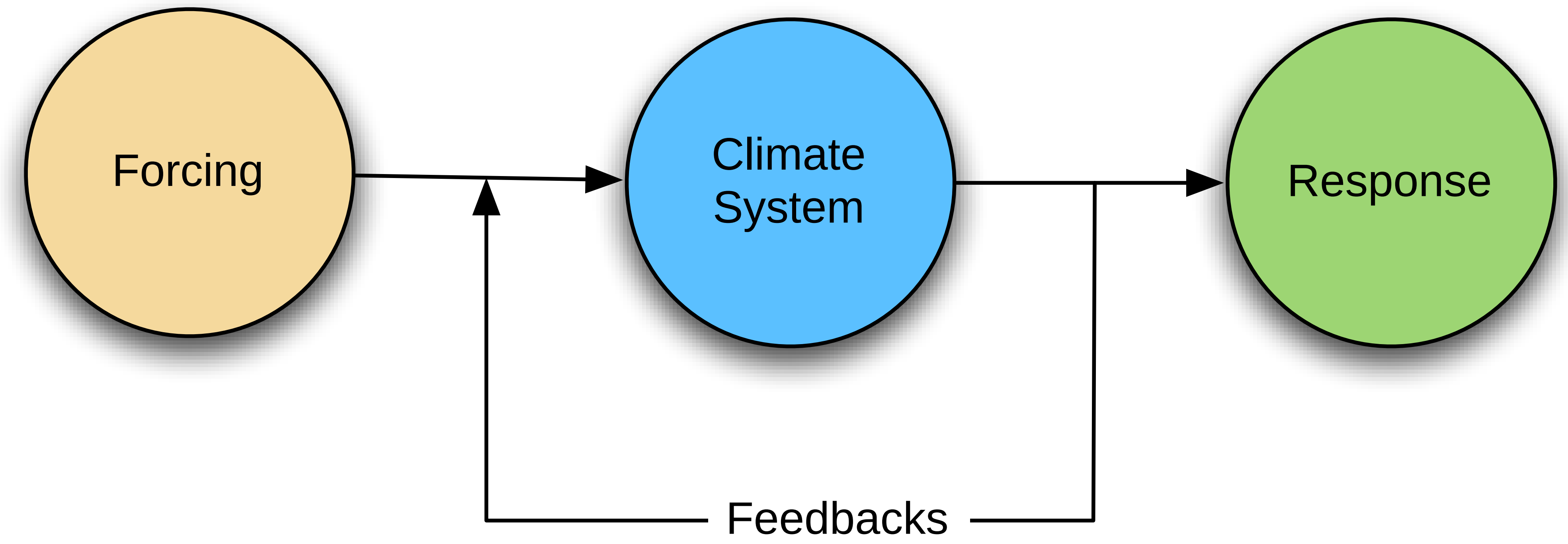

Variations of the Earth's surface temperature for...
Departures in temperature in °C (from the 1961-1990 average)
the past 140 years (global)
Direct temperatures
0.8
0.4
0.0
-0.4
-0.8
1860
1880
1900
1920
1940
1960
1980
2000
Departures in temperature in °C (from the 1961-1990 average)
the past 1000 years (Northern Hemisphere)
Direct temperatures
Proxy data
1000
1200
1400
1600
1800
2000



Anthropogenic and natural forcing of the climate for the year 2000, relative to 1750
Global mean radiative forcing (Wm-2)
Warming
Cooling
3
2
1
0
-1
-2
Greenhouse gases
Halocarbons
N2O
CH4
CO2
Aerosols + clouds
Tropospheric ozone
Stratospheric ozone
Black carbon from fossil fuel burning
Organic carbon from fossil fuel burning
Sulphate
Biomass burning
Mineral Dust
Aerosol indirect effect
Aviation
Contrails
Cirrus
Land use (albedo only)
Solar
The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates with no likelihood.

Feedbacks

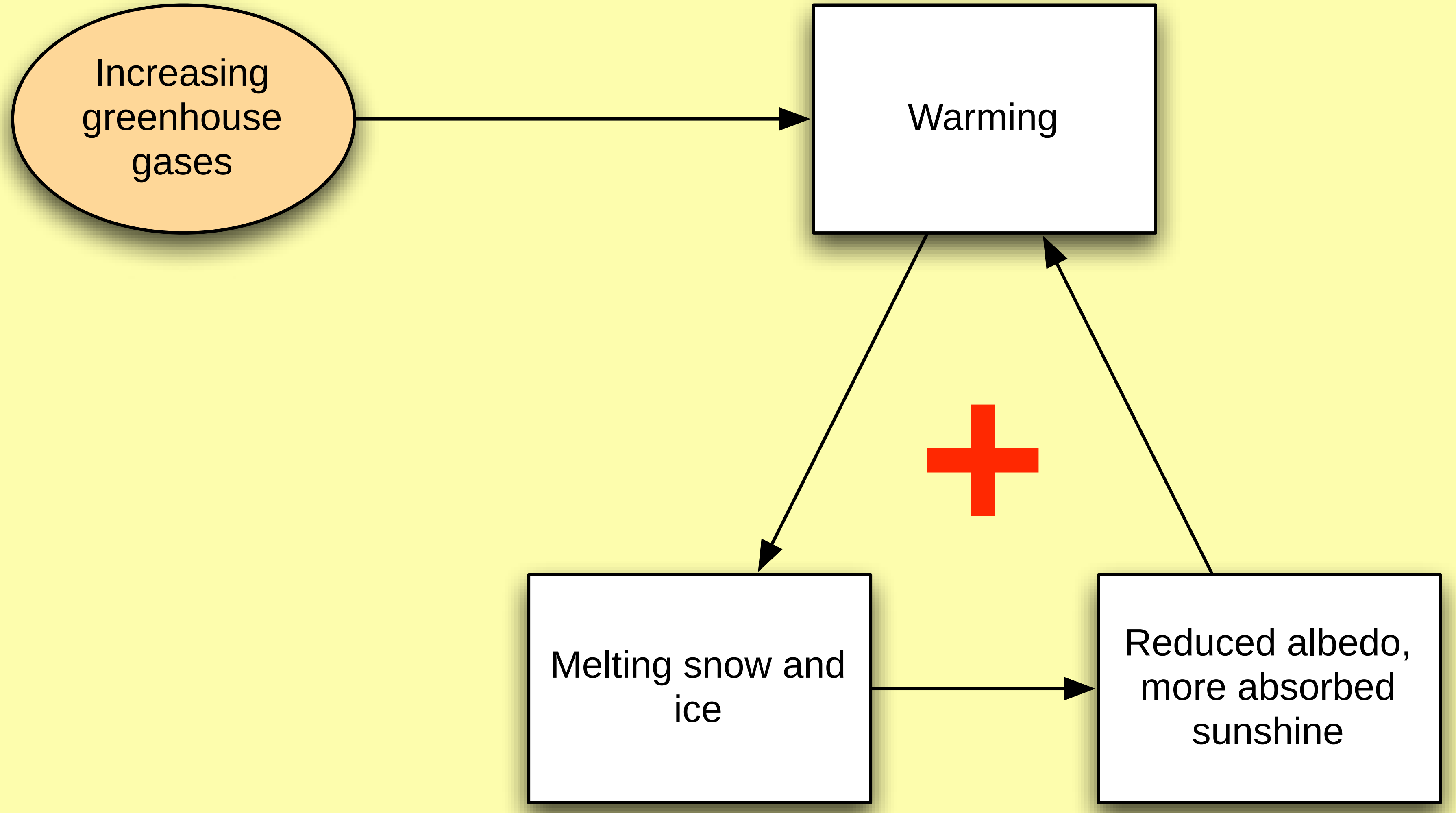
What Is Feedback?

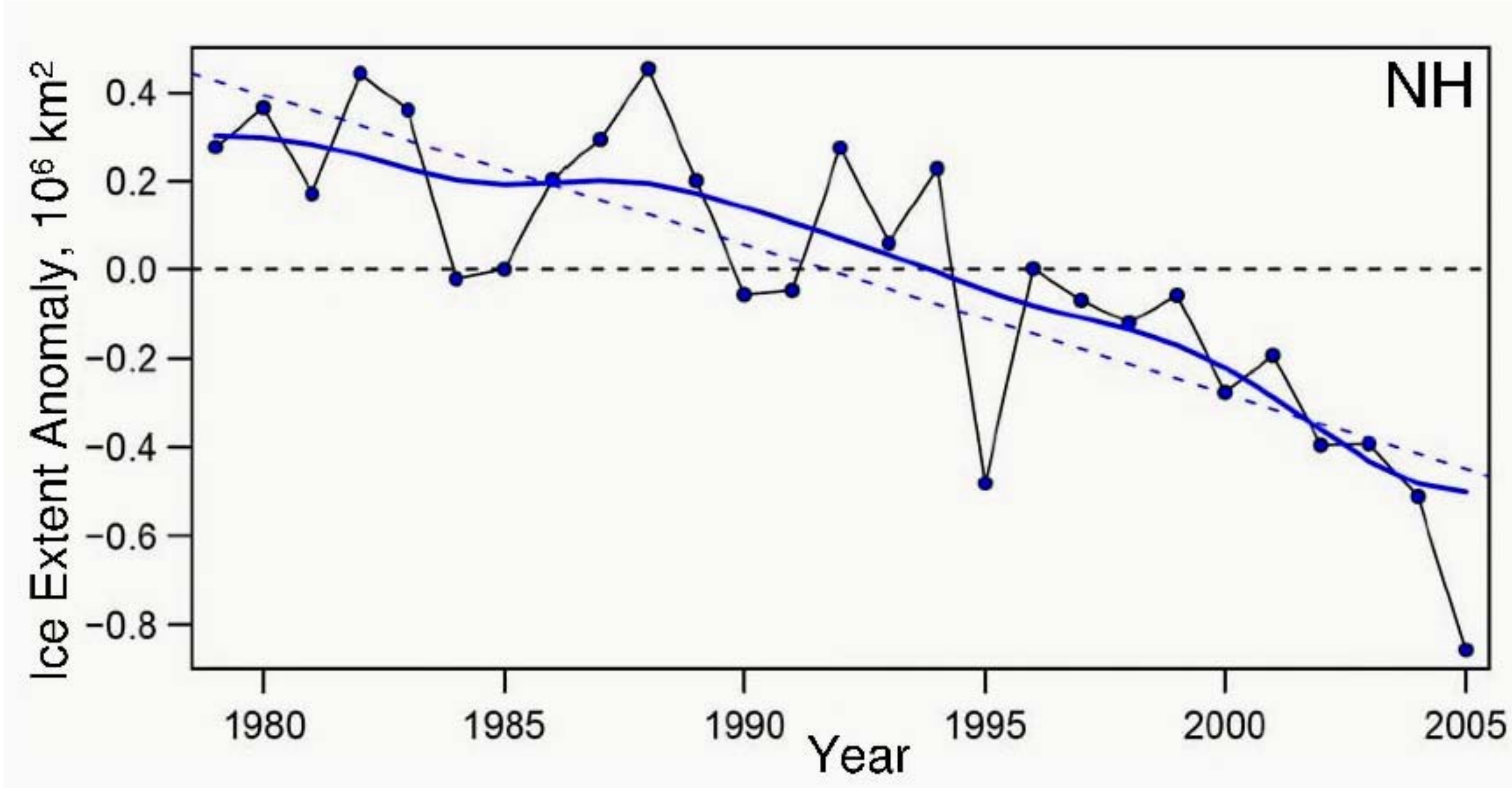


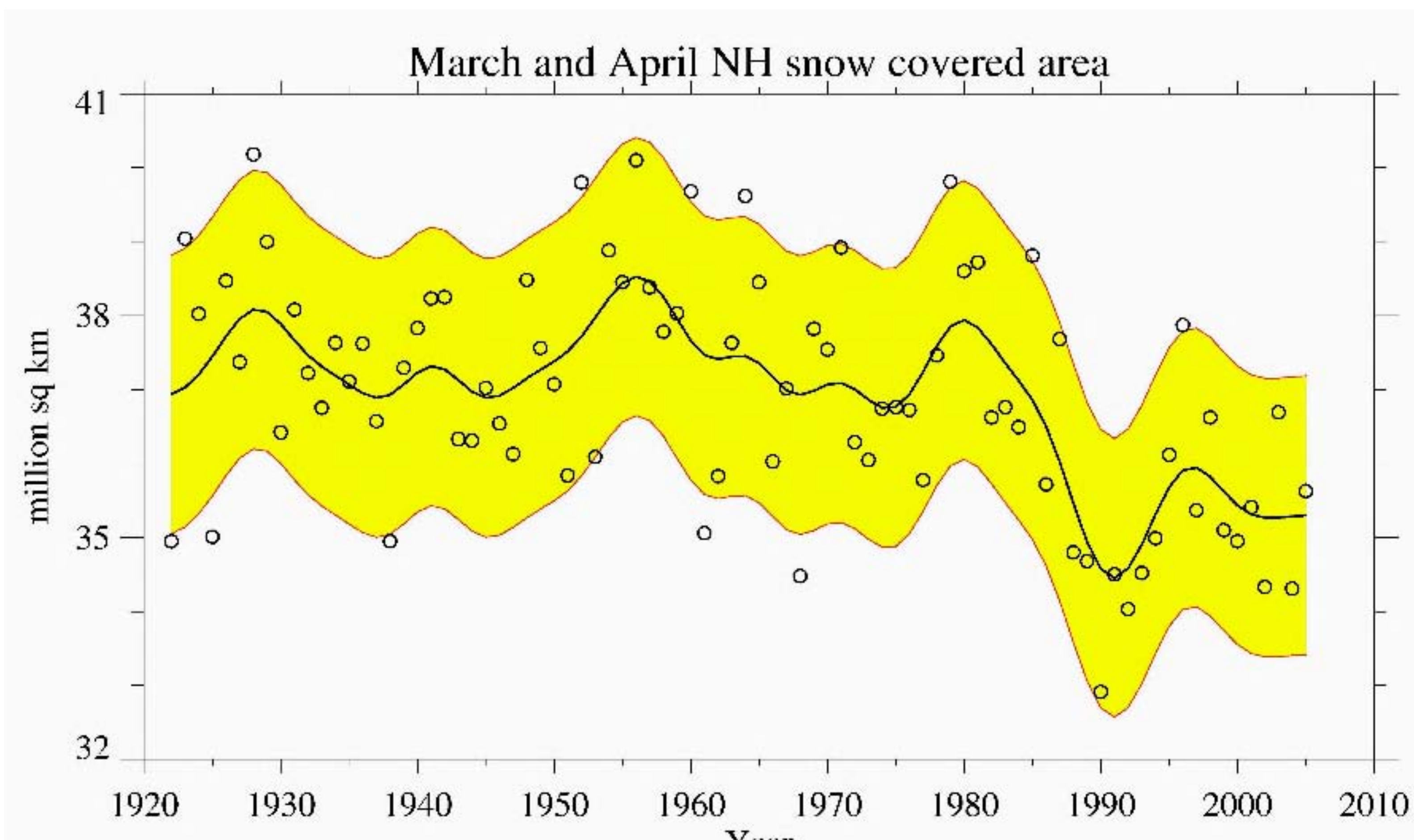
Kinds of Feedbacks

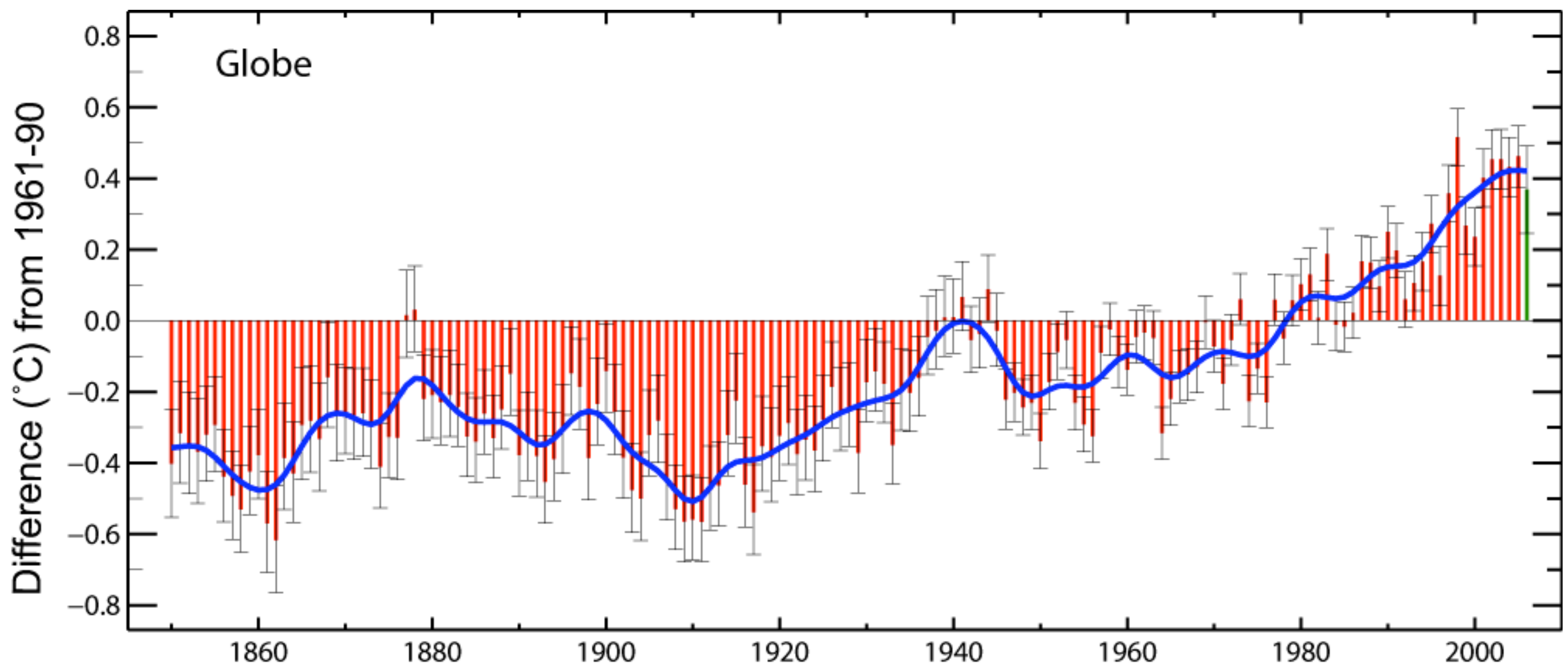
- Albedo Feedback
- Water vapor feedback
- Lapse-rate feedback
- Cloud feedback(s)

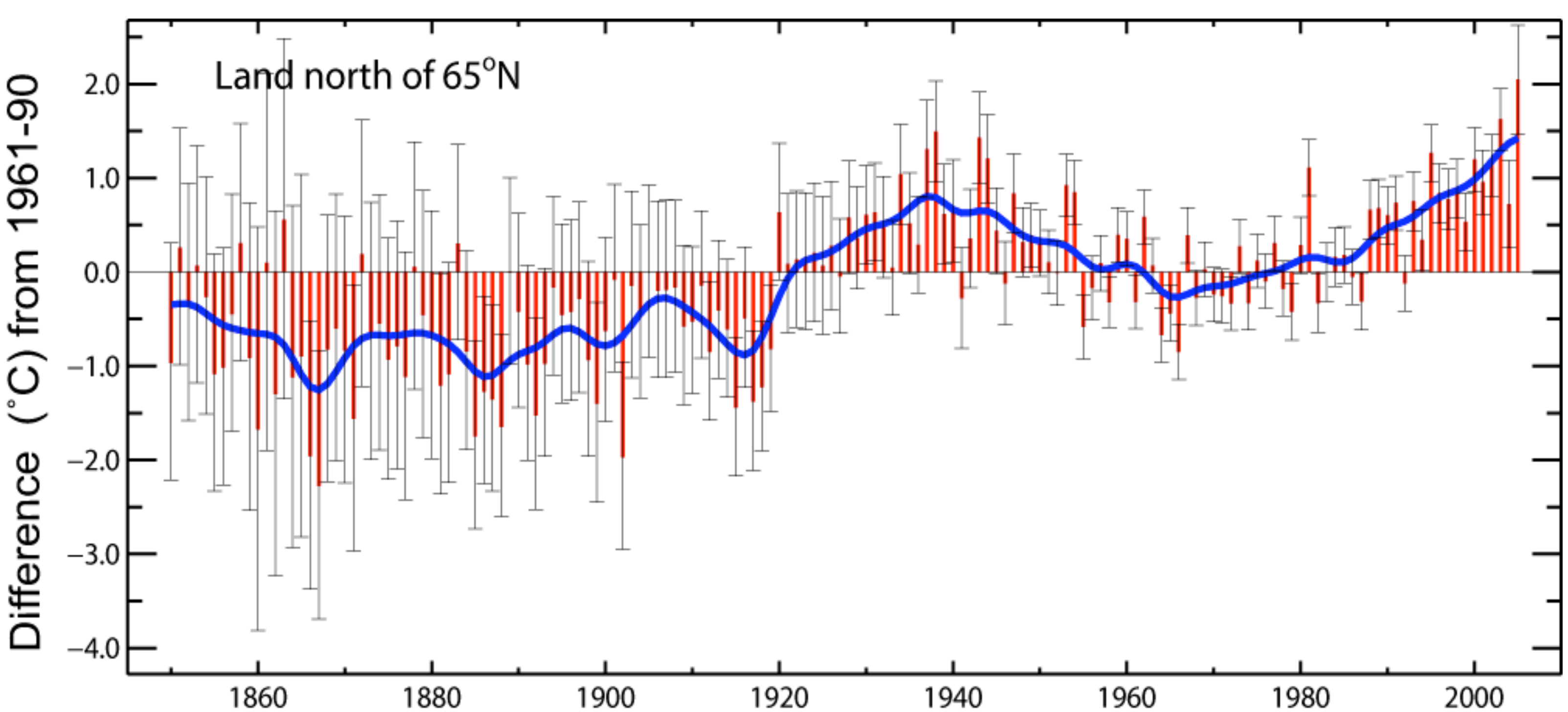
Albedo Feedback




NH
Ice Extent Anomaly, 10^6 km^2
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
1980
1985
1990
1995
2000
2005
Year


March and April NH snow covered area
million sq km
41
38
35
32
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

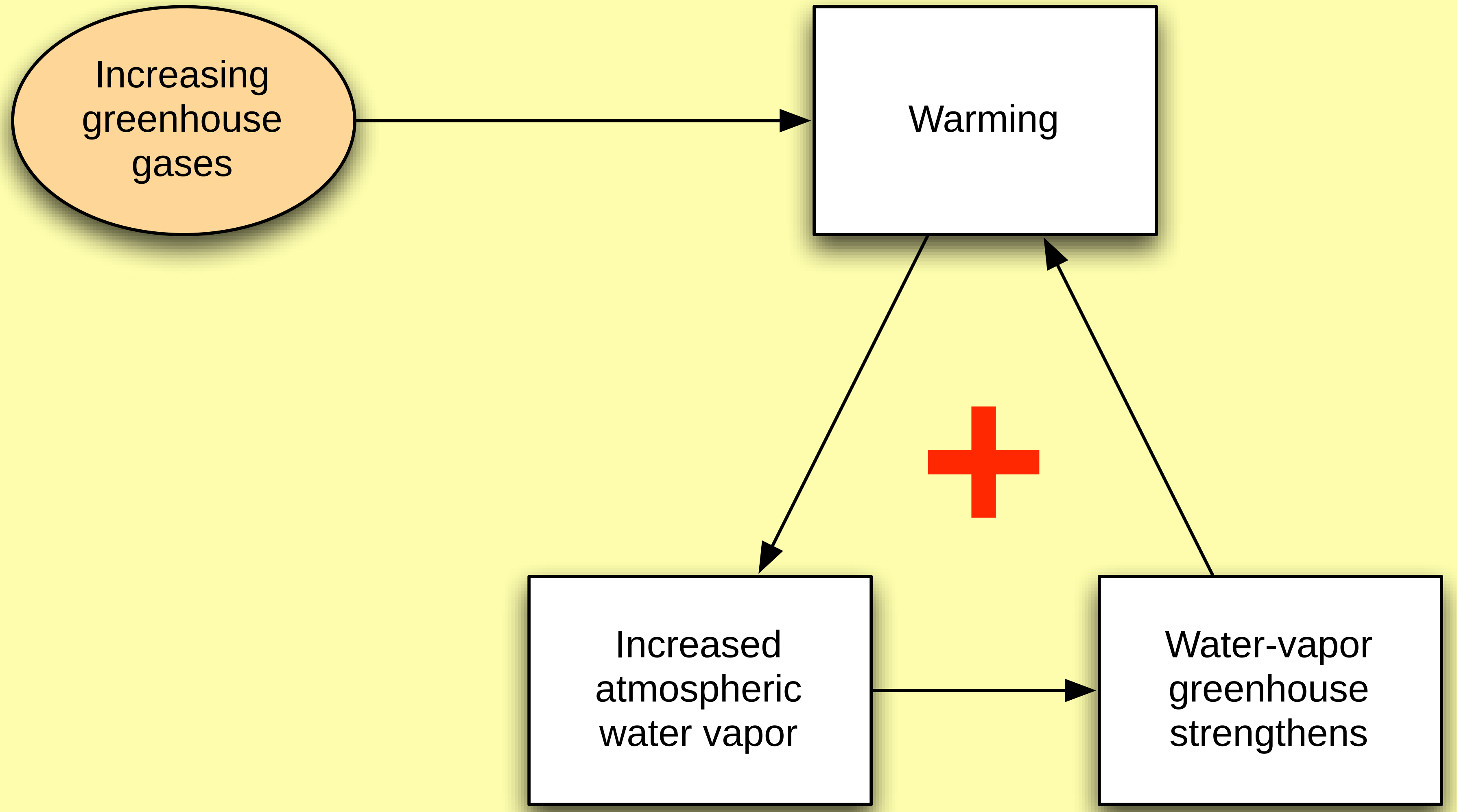




Warming in the Arctic is roughly double that for the whole Earth.

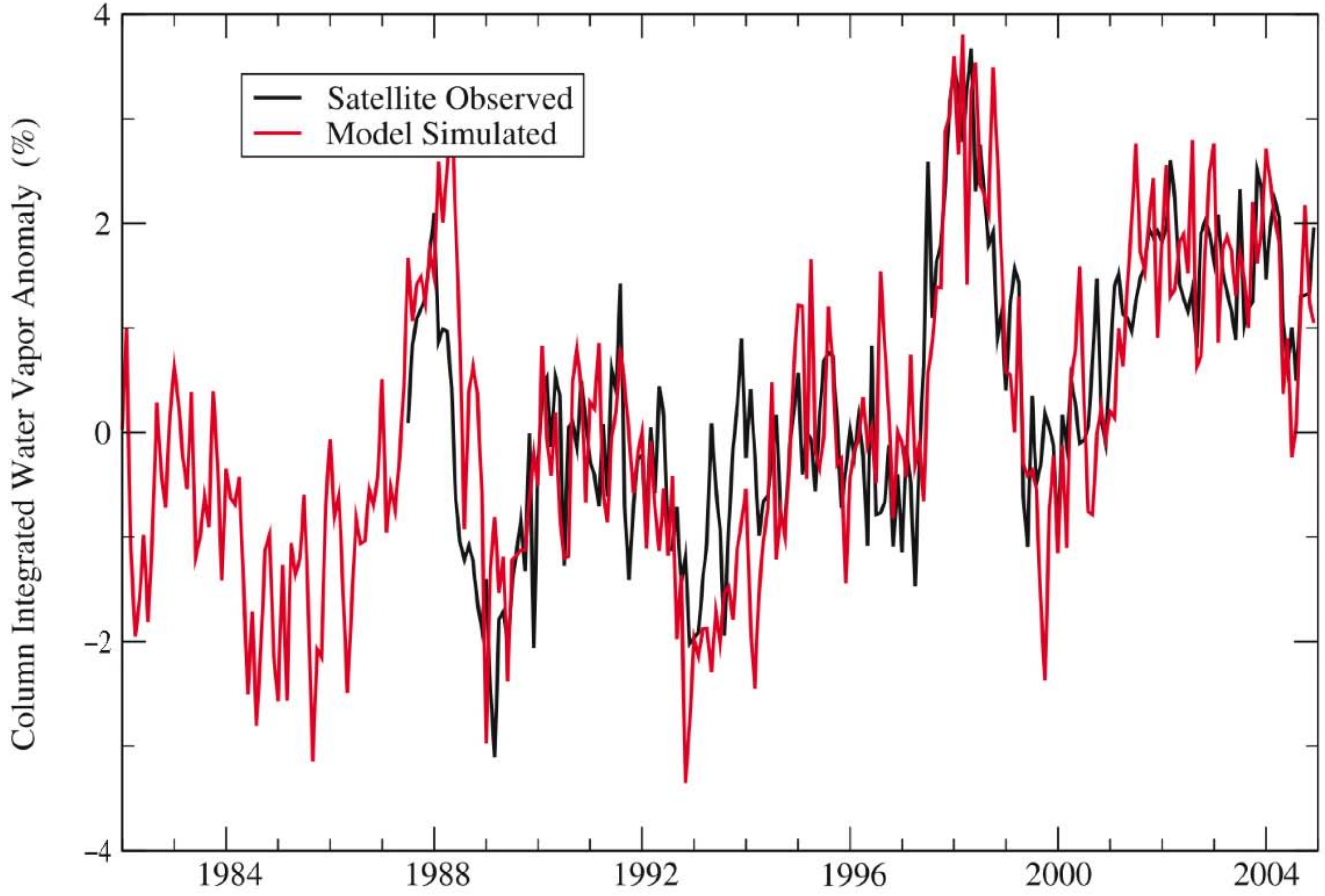
Note different scales

Water Vapor Feedback

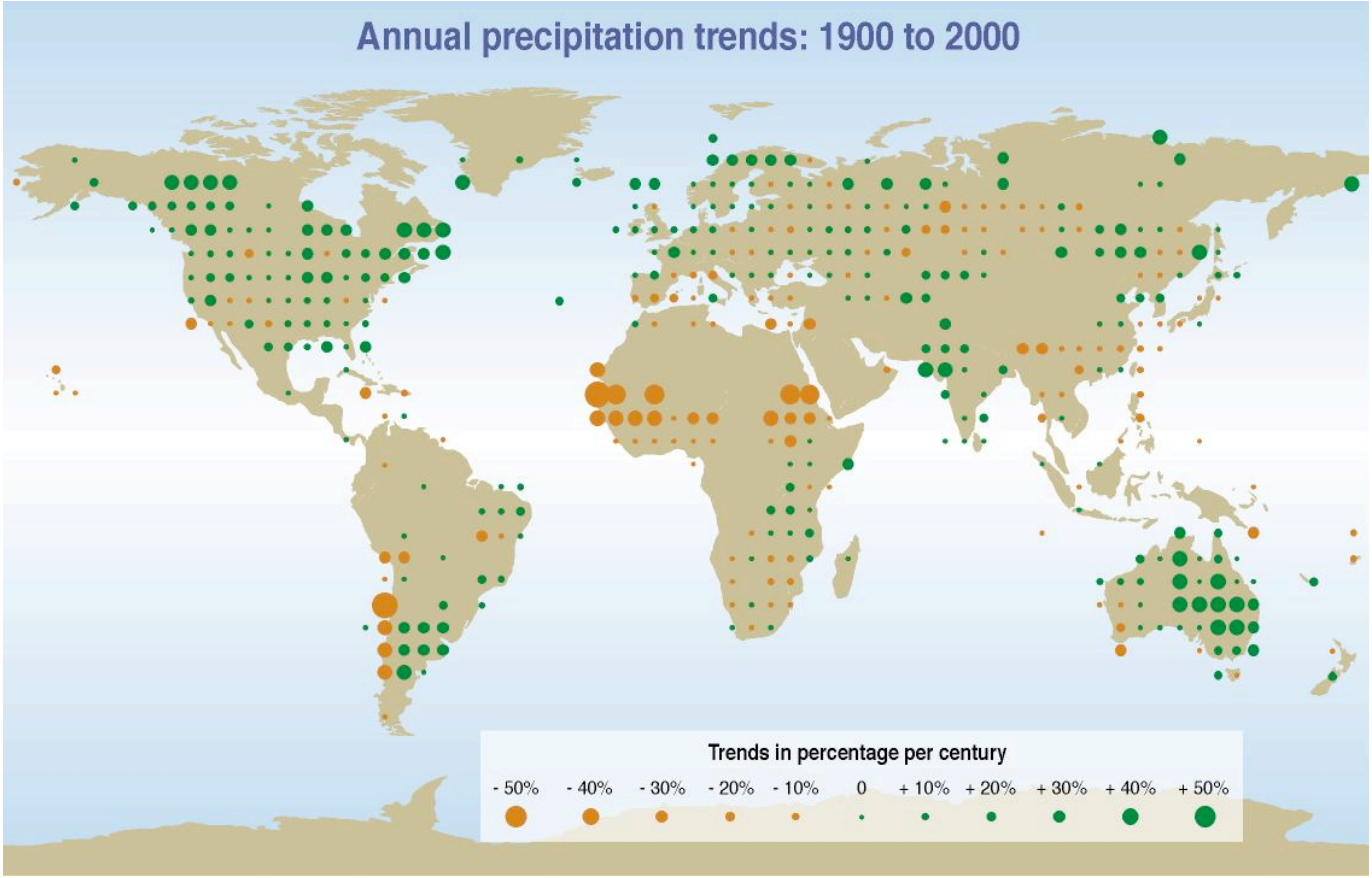


As water vapor increases, precipitation and evaporation also increase.

Changes in Water Vapor

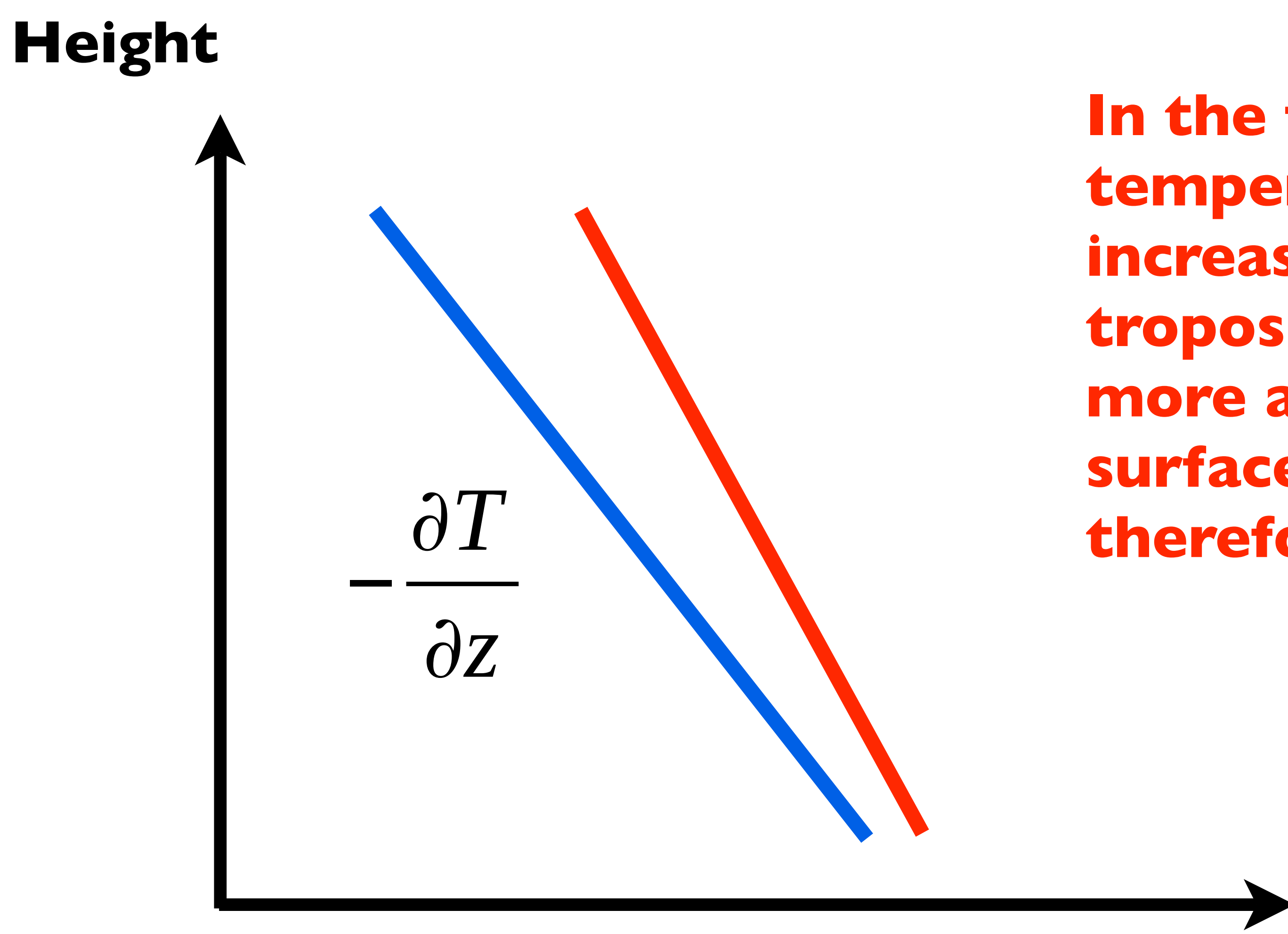


To produce the red curve, a global atmospheric model was forced with the observed sea-surface temperatures for the years shown.


Annual precipitation trends: 1900 to 2000
Trends in percentage per century
- 50%
- 40%
- 30%
- 20%
- 10%
0
+ 10%
+ 20%
+ 30%
+ 40%
+ 50%

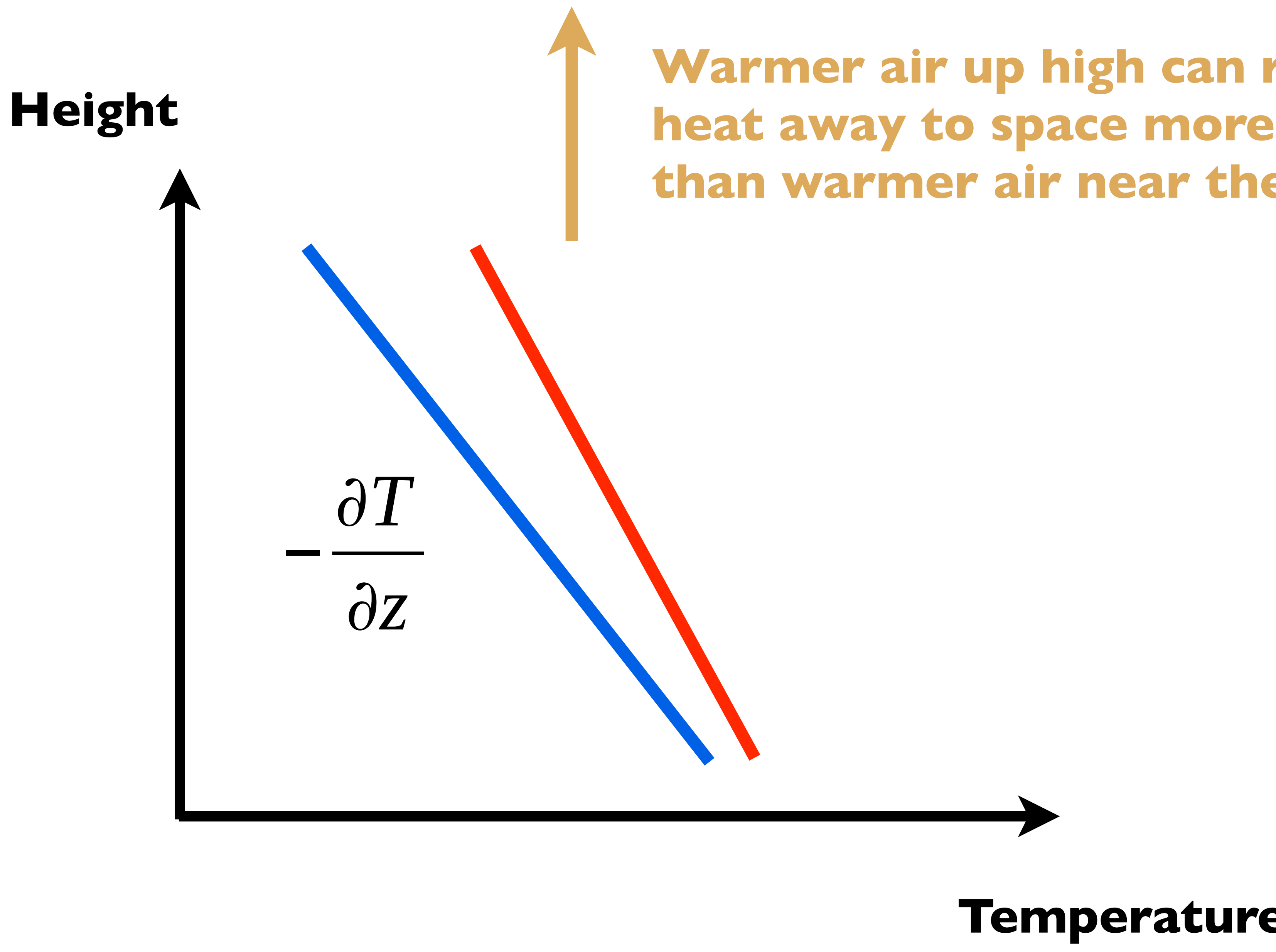
What is the “lapse rate?”

The “lapse rate” is the rate at which temperature decreases upward.



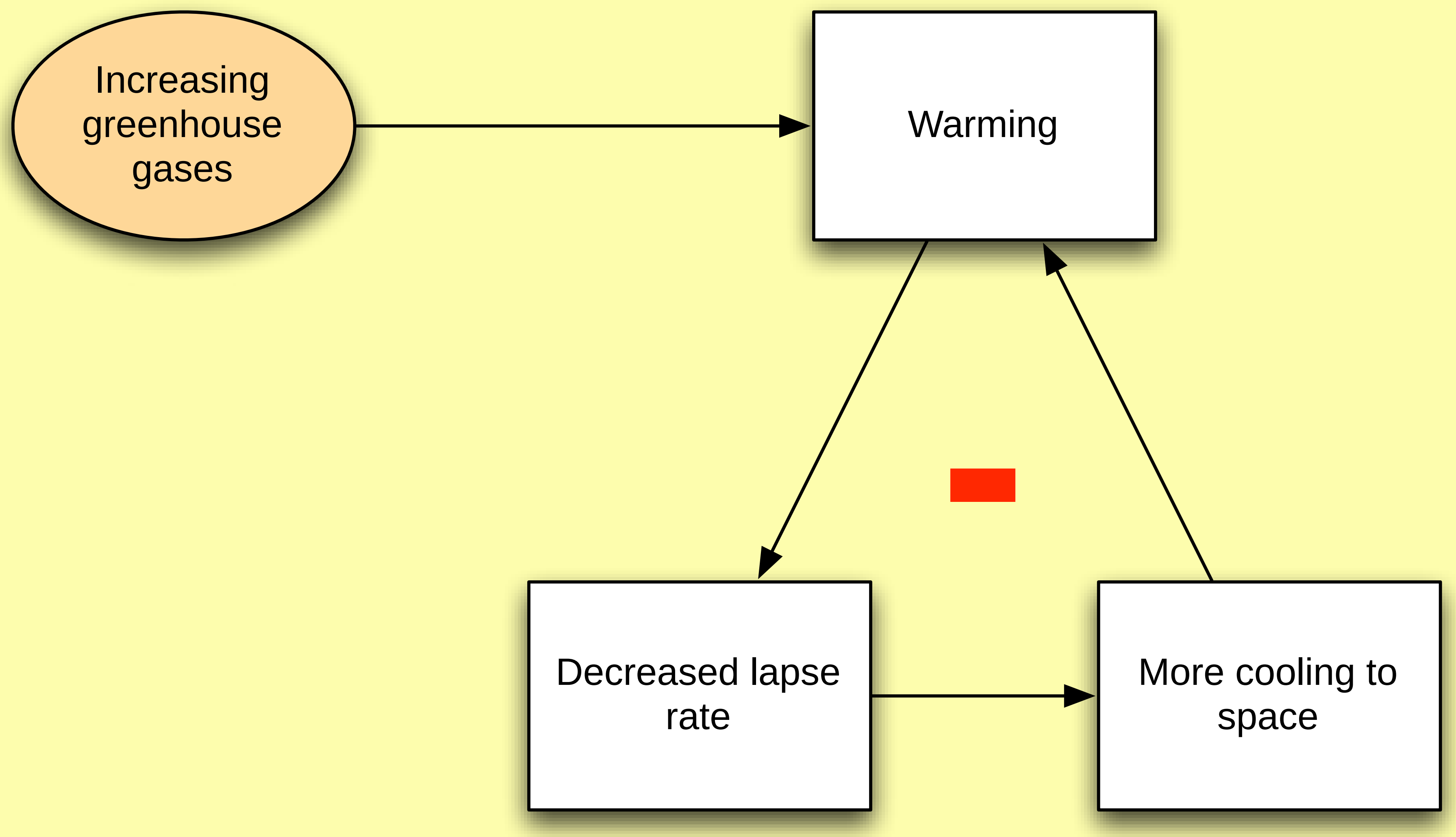
In the future climate, the temperature is predicted to increase throughout the troposphere, but it increases more aloft than near the surface. The lapse rate is, therefore, said to decrease.

How the lapse rate can feed back:



Warmer air up high can radiate heat away to space more easily than warmer air near the ground.

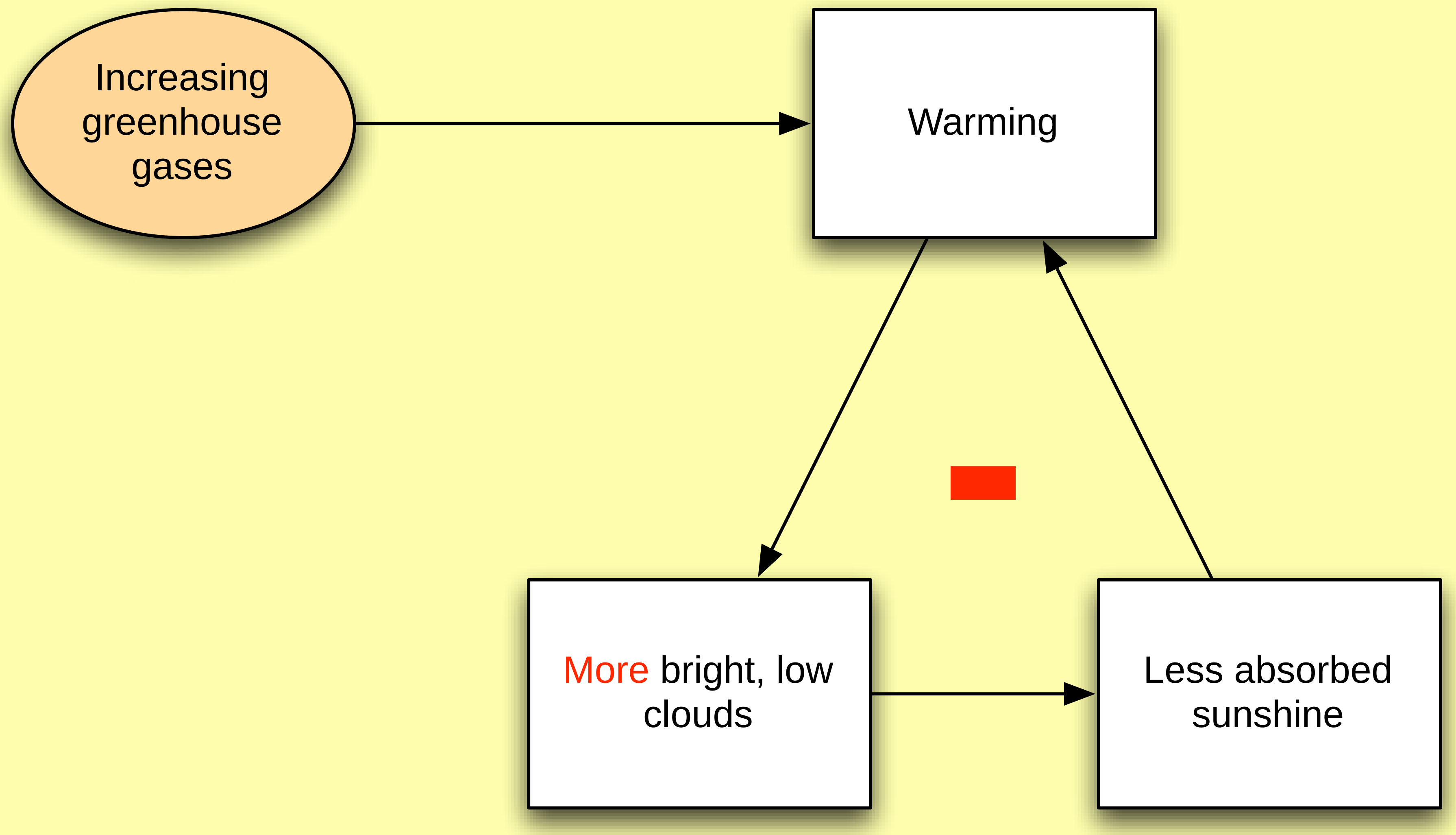
Lapse-Rate Feedback



Cloud Feedback(s)

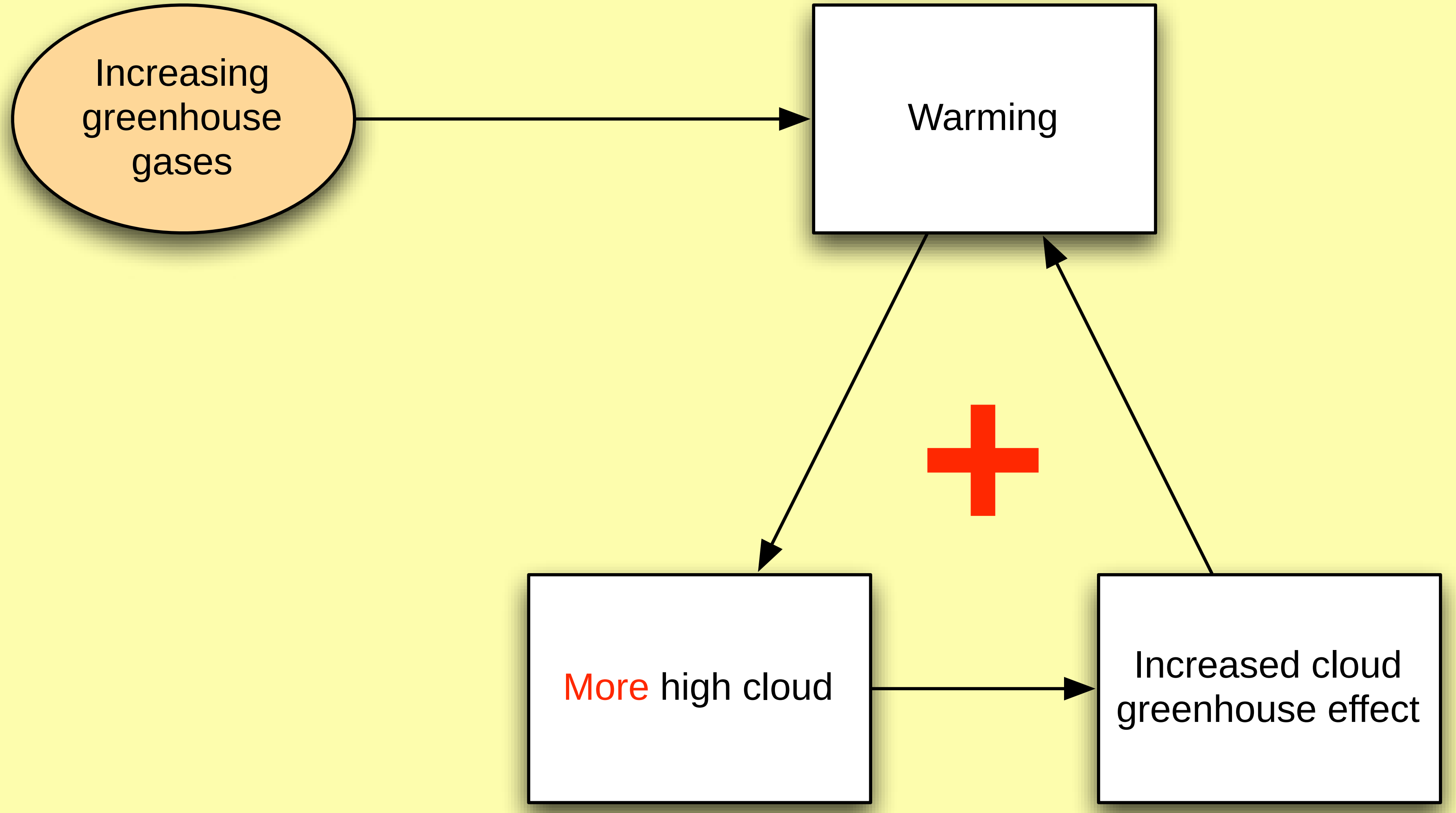
- Cloud amount
- Cloud top height
- Cloud optical properties

Low-Cloud Feedback



Note: This feedback can be either positive or negative.

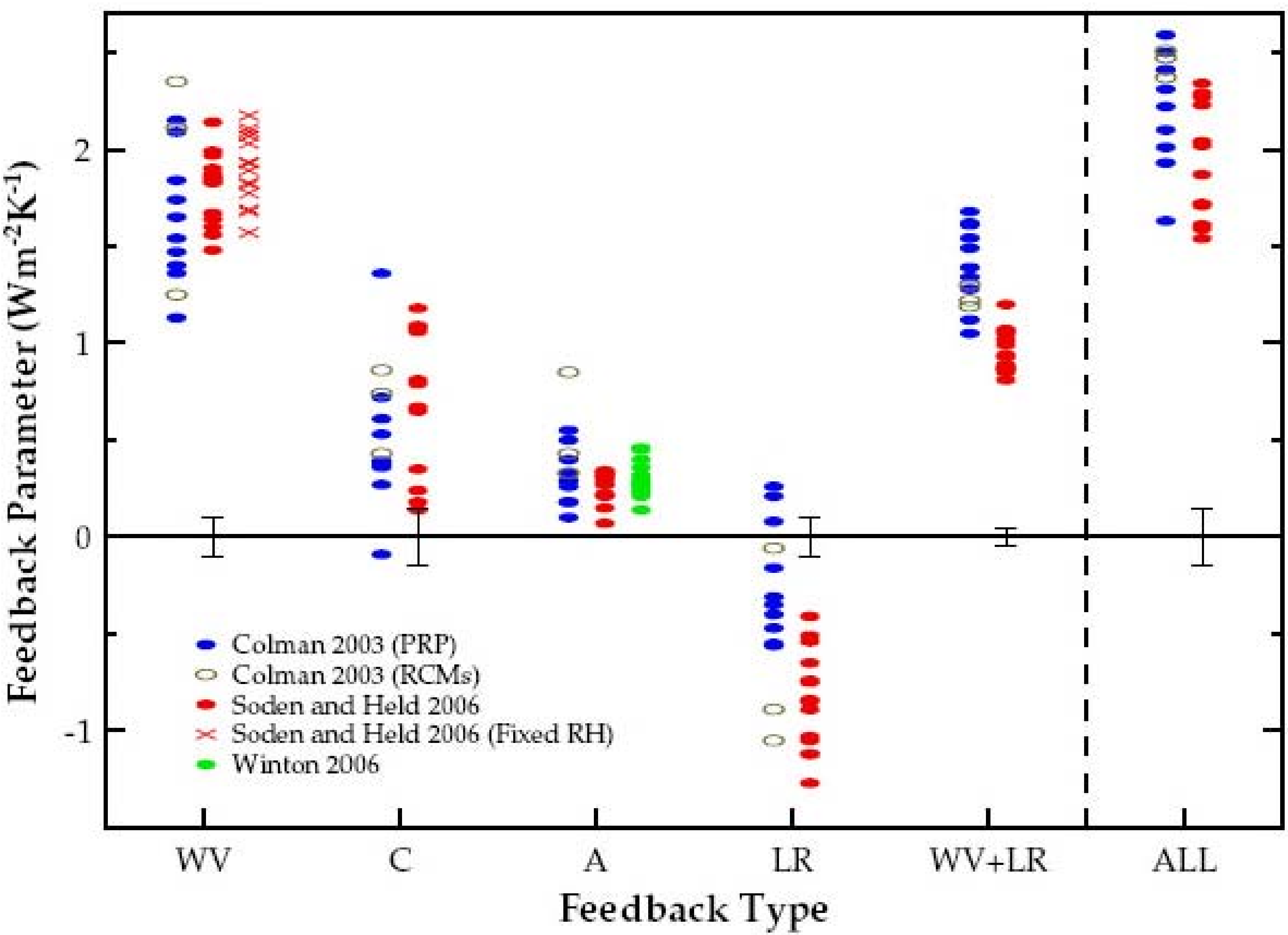
High-Cloud Feedback



Note: This feedback can be either positive or negative.


So, let’s see what we’ve got...

Feedbacks in Real Climate Change Simulations



The Bottom Line:

The positive feedbacks are stronger than the negative feedbacks.

The combined effect of all feedbacks is to increase the warming by about a factor of two.

Forecasts

First, a reality check:
Can we “predict” past changes?

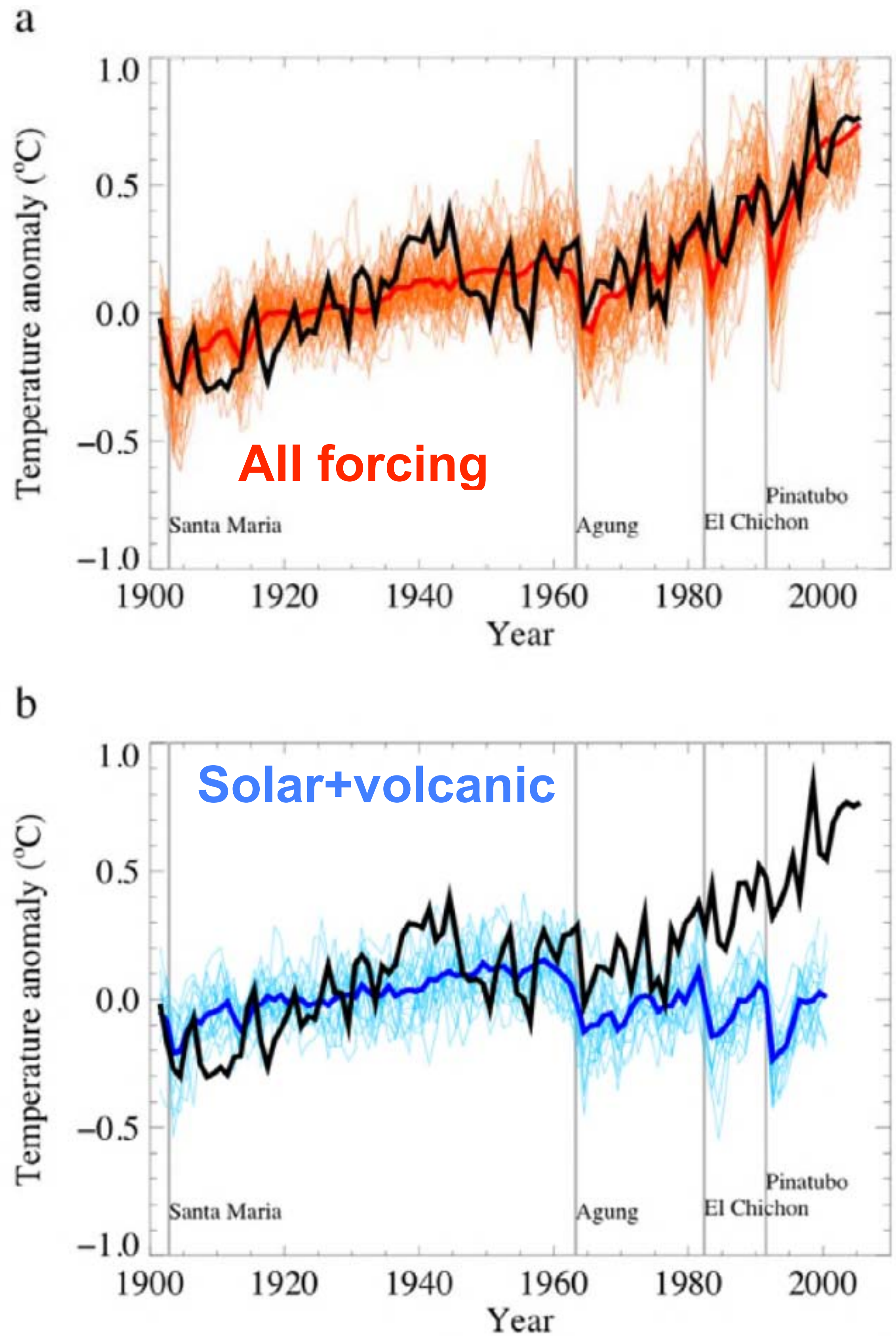
The climate of the 20th century

The observed changes are shown by the black curves.

Results from about 20 models are shown in red (upper panel) and blue (lower panel).

However, these results are not completely convincing, because:

- **Many of the prescribed forcing components are uncertain,**
- **The forcings have not been "standardized," and**
- **Inspection of the model results shows that model-sensitivity is inversely correlated with the strength of the forcing used.**



IPCC

Warming of ~3 K for doubling CO_2
Rising sea level ~ 1 m in 21st century
Stronger storms
More droughts

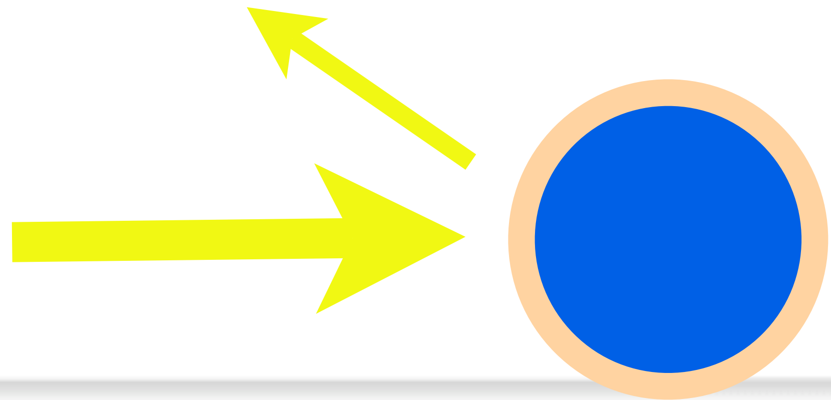
All based on simulations with complicated computer models.

But before we get to that...

Climate Modeling
On the Back of an Envelope

Warning:
The next two slides have equations.

Increasing CO_2 Perturbs the Earth's Radiation Budget



$$(1-\alpha)S\pi a^2 = \varepsilon(\sigma T_S^4)4\pi a^2$$

$$(1-\alpha)S = 4\varepsilon(\sigma T_S^4)$$

$$0 = 4(\Delta\varepsilon)(\sigma T_S^4) + 4\varepsilon(4\sigma T_S^3 \Delta T_S)$$

Assumptions: 1) Only CO_2 is perturbed; 2) No feedbacks.

$$\Delta T_S = -\frac{T_S}{4}\frac{\Delta\varepsilon}{\varepsilon}$$

Let's put in some numbers:

$$\Delta T_S = -\frac{T_S}{4}\frac{\Delta\varepsilon}{\varepsilon}$$

$$\varepsilon(\sigma T_S^4) = 240 \quad W m^{-2}$$

$$(\Delta\varepsilon)(\sigma T_S^4) = -4 \quad W m^{-2}$$

$$\therefore \frac{\Delta\varepsilon}{\varepsilon} = -\frac{4}{240}$$

~2%

$$T_S = 288 \quad K$$

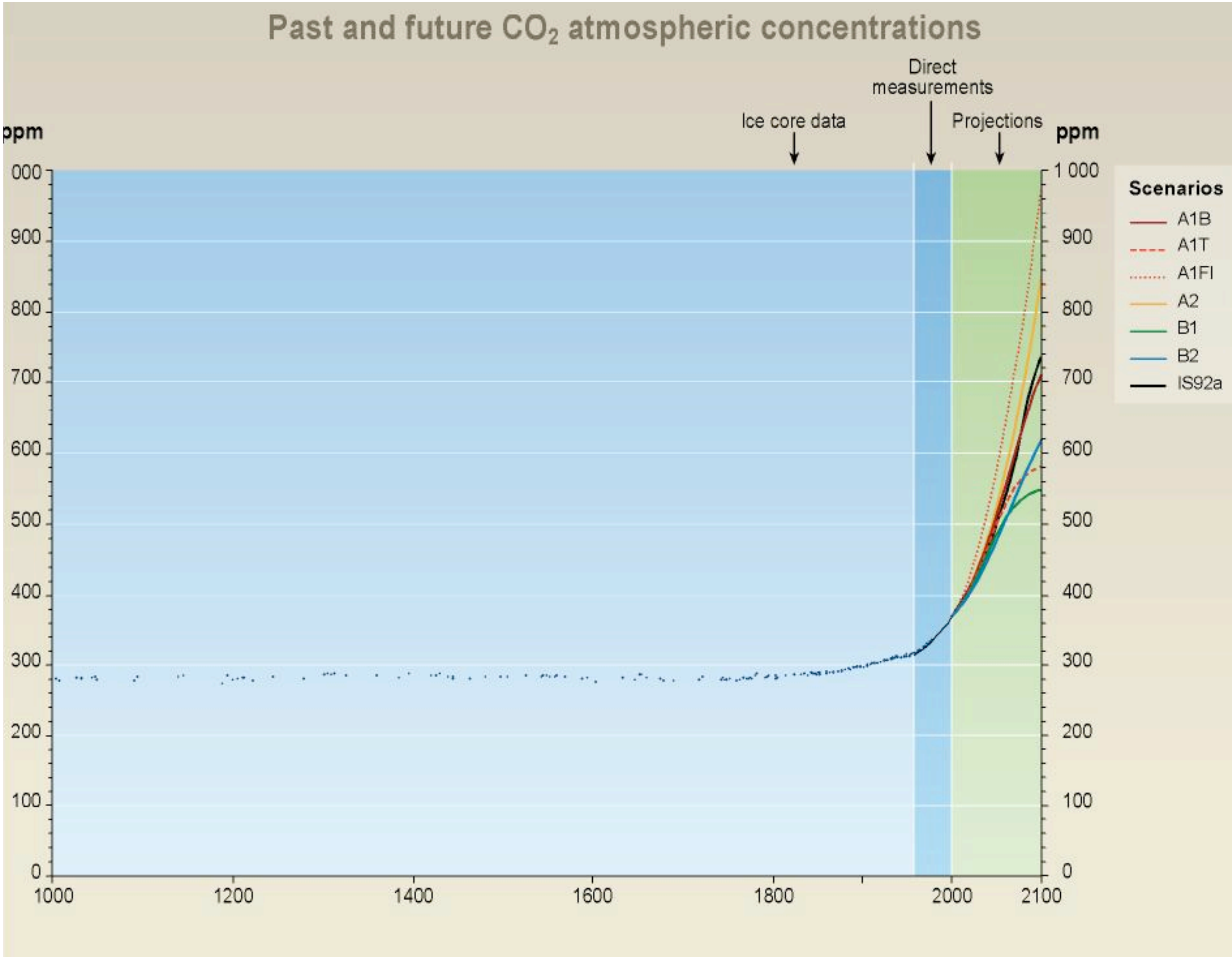
$$\Delta T_S = -\frac{288 \quad K}{4}\left(-\frac{4}{240}\right) = 1.2 \quad K$$

~0.5%

Lessons Learned

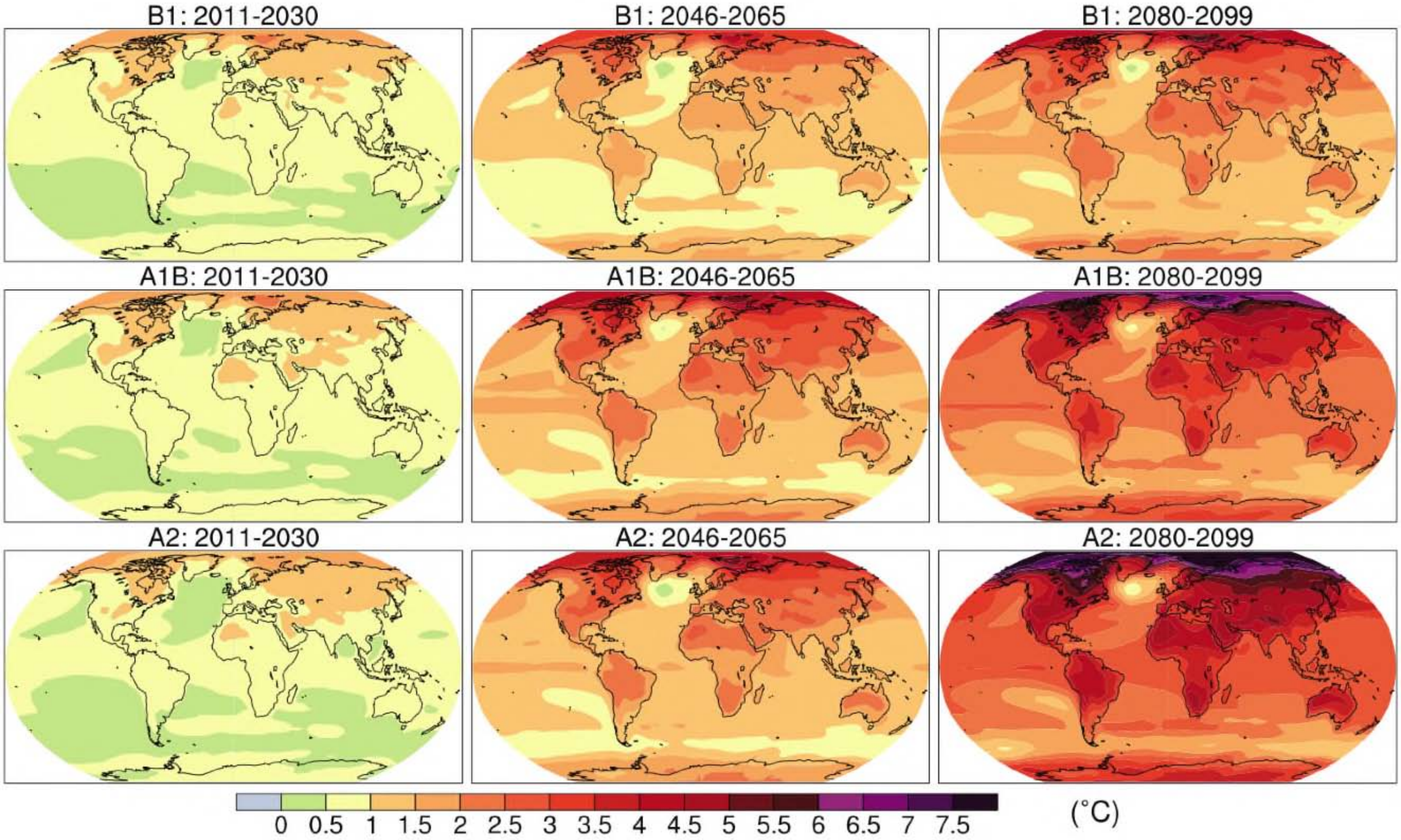
- We don’t need no stinking computer models!
- Feedbacks are important.


IPCC, Paris,
Early 2007

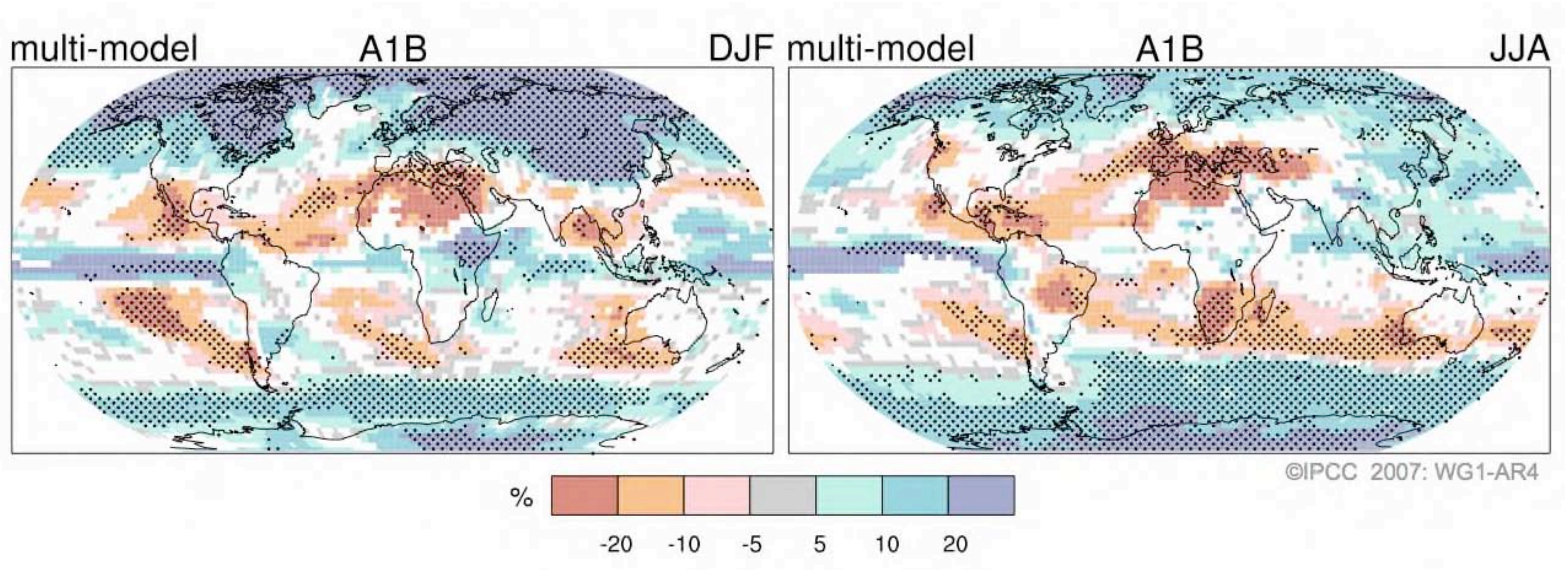


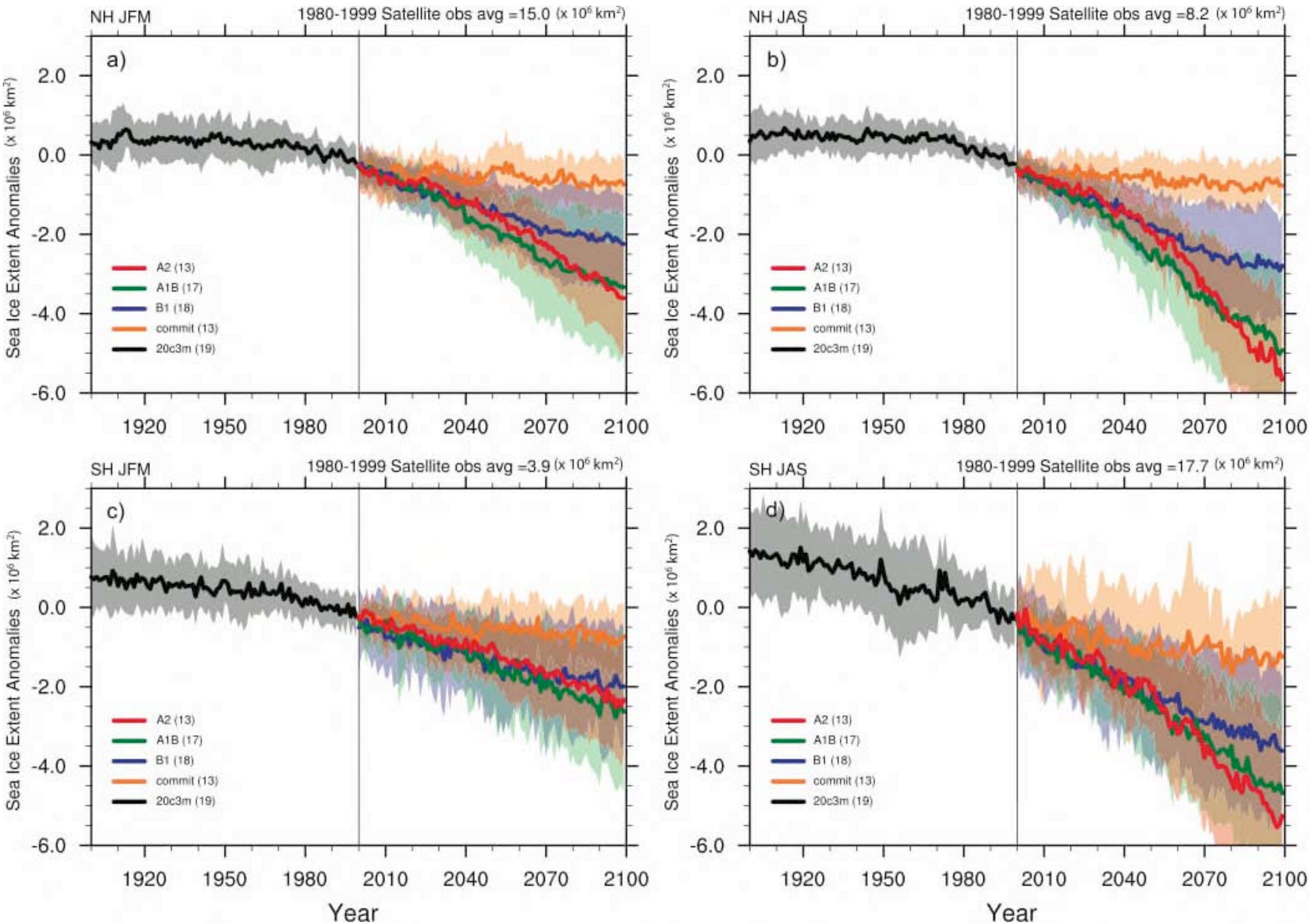
Past and future CO_2 atmospheric concentrations
Direct measurements
Ice core data
Projections
ppm
ppm
000
900
800
700
600
500
400
300
200
100
0
1 000
900
800
700
600
500
400
300
200
100
0
1000
1200
1400
1600
1800
2000
2100
Scenarios
A1B
A1T
A1FI
A2
B1
B2
IS92a

Predicted Warming

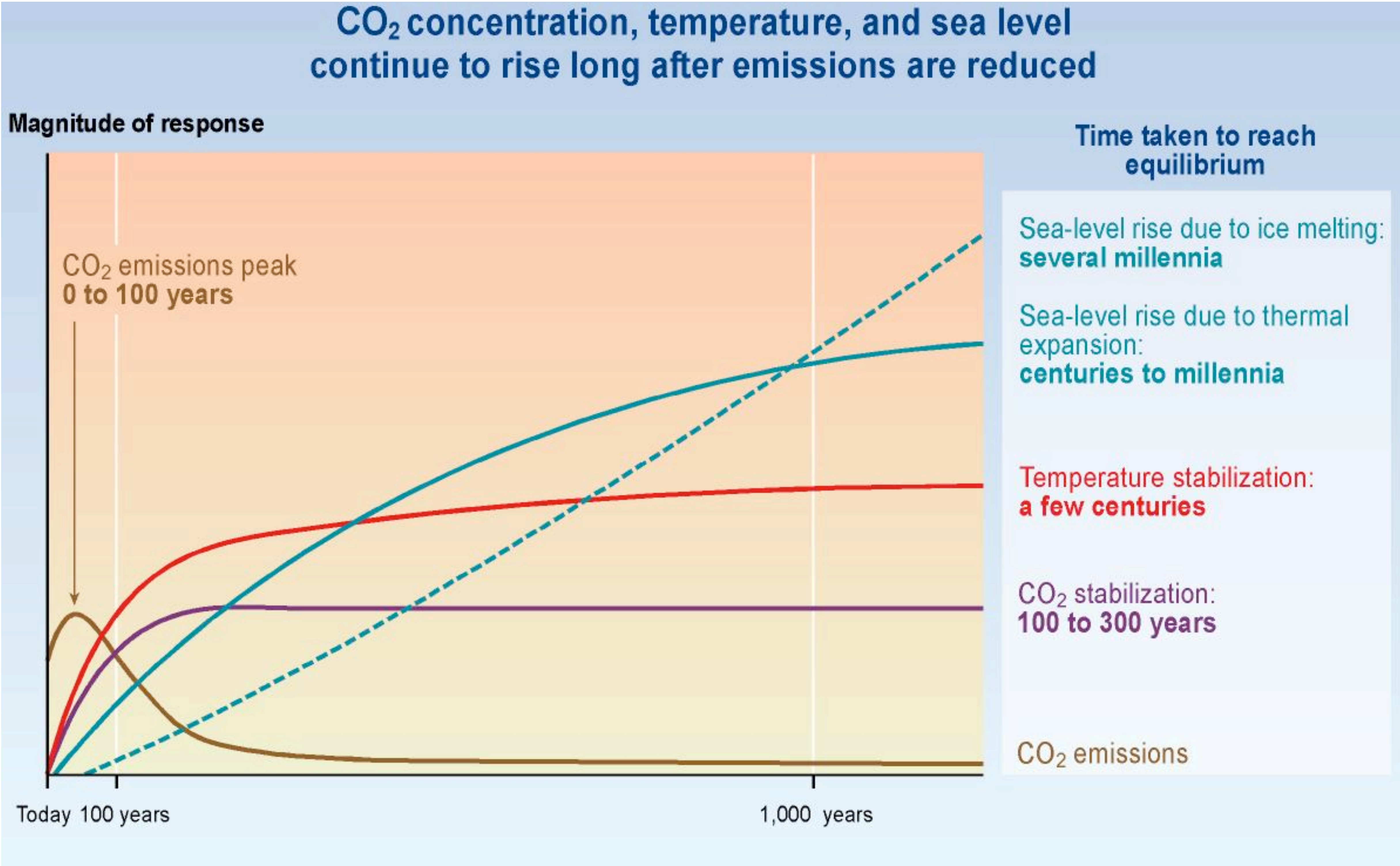


Predicted Precipitation Changes





NH JFM
1980-1999 Satellite obs avg =15.0 (x 10^6 km^2)
a)
Sea Ice Extent Anomalies (x 10^6 km^2)
A2 (13)
A1B (17)
B1 (18)
commit (13)
20c3m (19)
NH JAS
1980-1999 Satellite obs avg =8.2 (x 10^6 km^2)
b)
SH JFM
1980-1999 Satellite obs avg =3.9 (x 10^6 km^2)
c)
SH JAS
1980-1999 Satellite obs avg =17.7 (x 10^6 km^2)
d)
Year


CO_2 concentration, temperature, and sea level
continue to rise long after emissions are reduced
Magnitude of response
Time taken to reach equilibrium
Sea-level rise due to ice melting:
several millennia
Sea-level rise due to thermal expansion:
centuries to millennia
Temperature stabilization:
a few centuries
CO_2 stabilization:
100 to 300 years
CO_2 emissions
CO_2 emissions peak
0 to 100 years
Today
100 years
1,000 years

Conclusions

- Long-term climate change can be predicted when it is due to predictable changes in external forcing.
- Feedbacks are expected to amplify the response to the forcing.
- A simple estimate of surface temperature change due to increasing CO_2 (without feedbacks) can be made on the back of an envelope.
- Predictions for the 21st century show warming of the troposphere especially in the Arctic, an increase in precipitation extremes, a decrease in snow and ice cover, and an increase in sea level.

Recommended Reading

- **Climate Change 2007 - The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC**
- **“Chaos: The Making of a New Science,” by James Gleick**
- **“The Two-Mile Time Machine: Ice Cores, Abrupt Climate Change, and Our Future,” by Richard Alley**