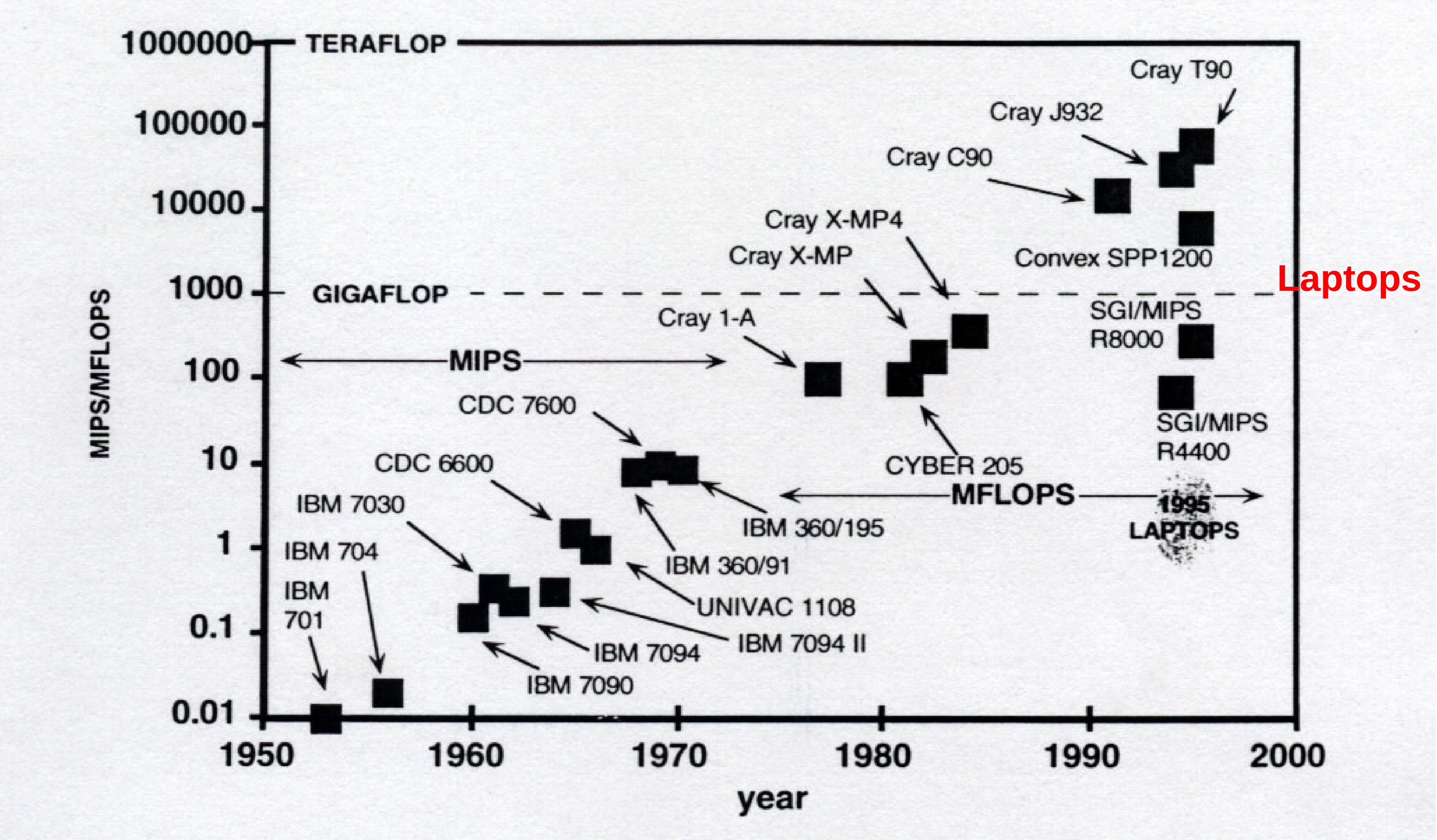
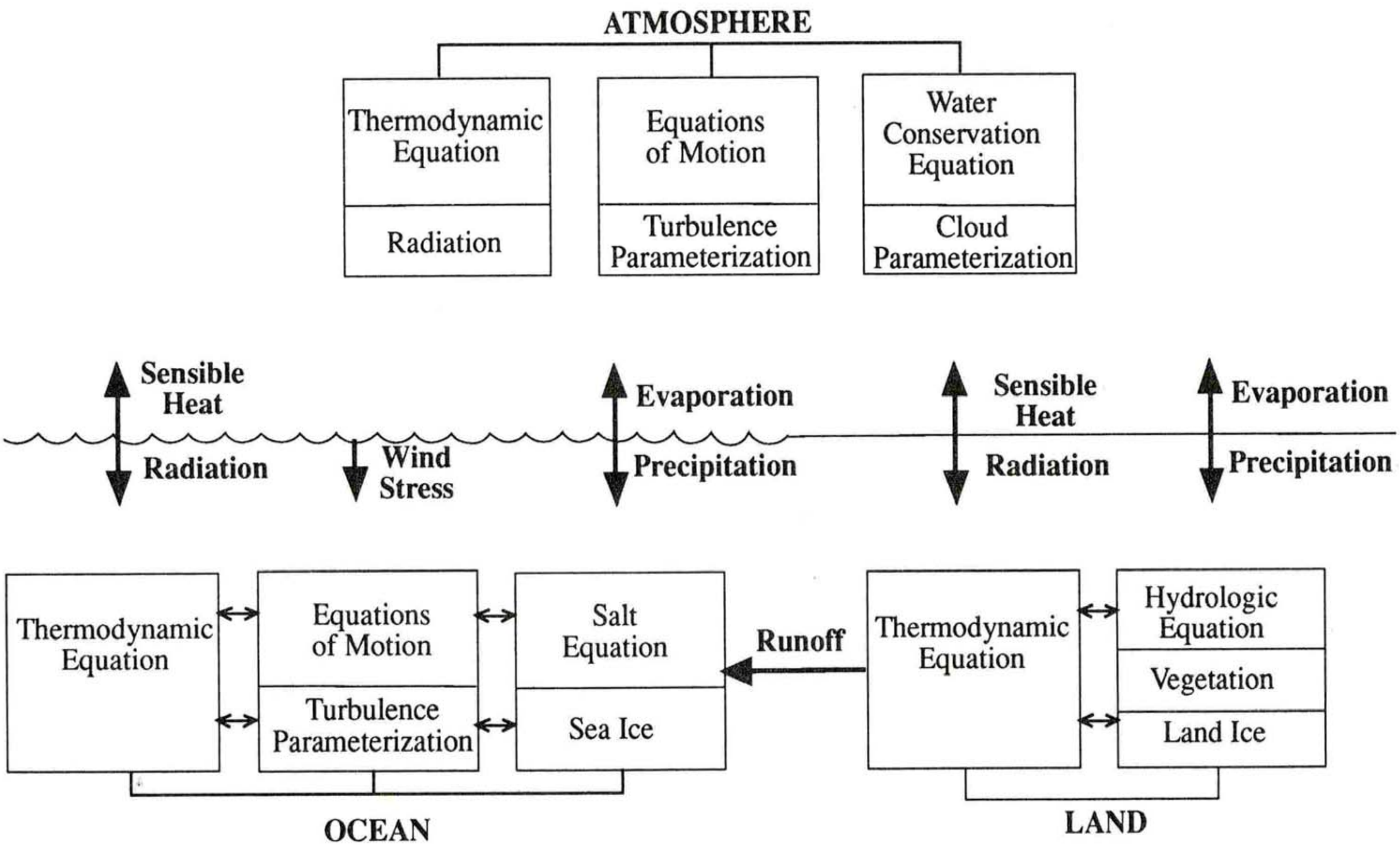
Lectures 14 & 15

Projection of Future Climate Change in the Computer and space Era

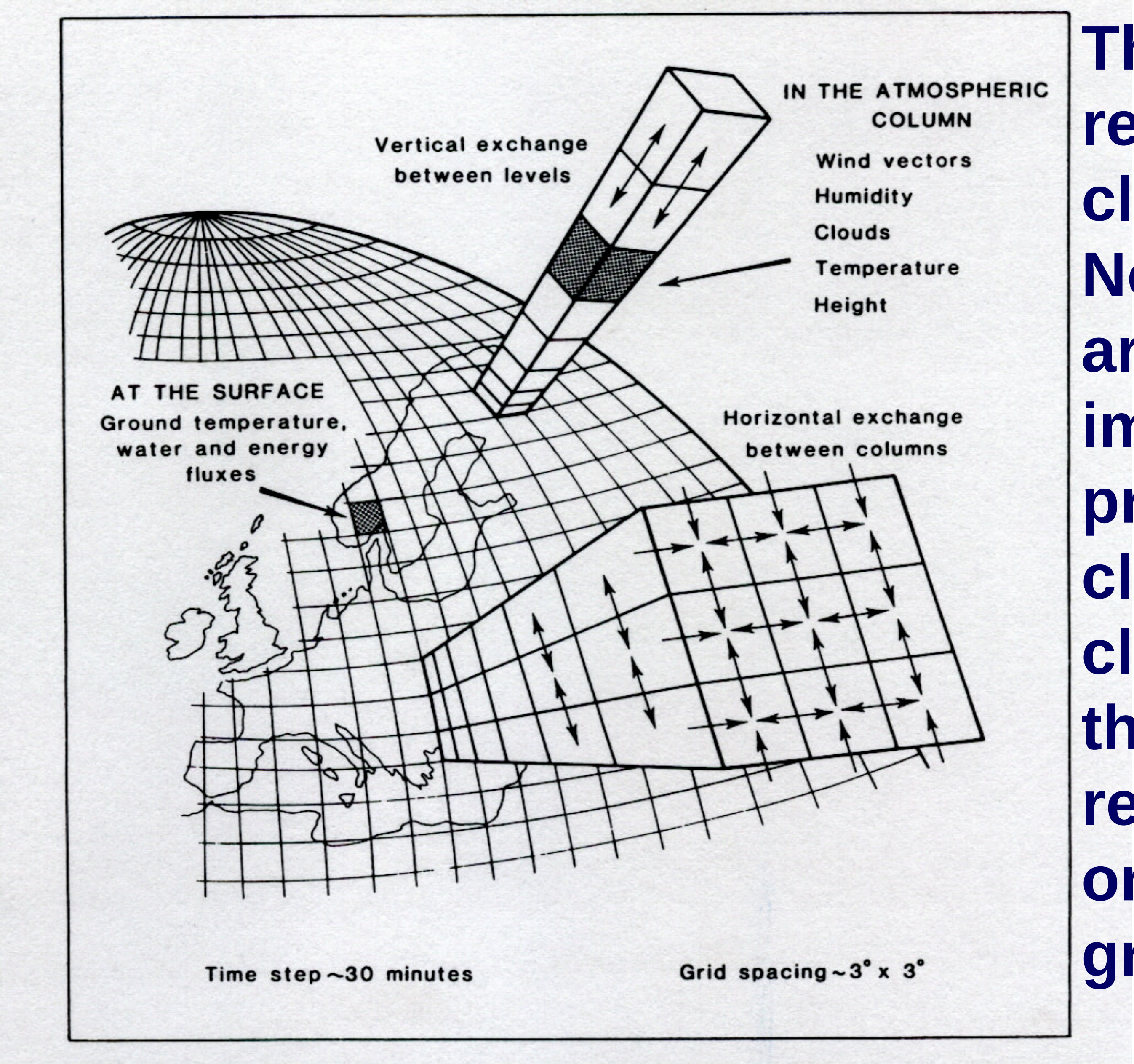
Over the past 50 years, there has been a remarkable increase in computing power, which has facilitated the development of numerical models to study weather and climate. We call these general circulation models (GCMs).



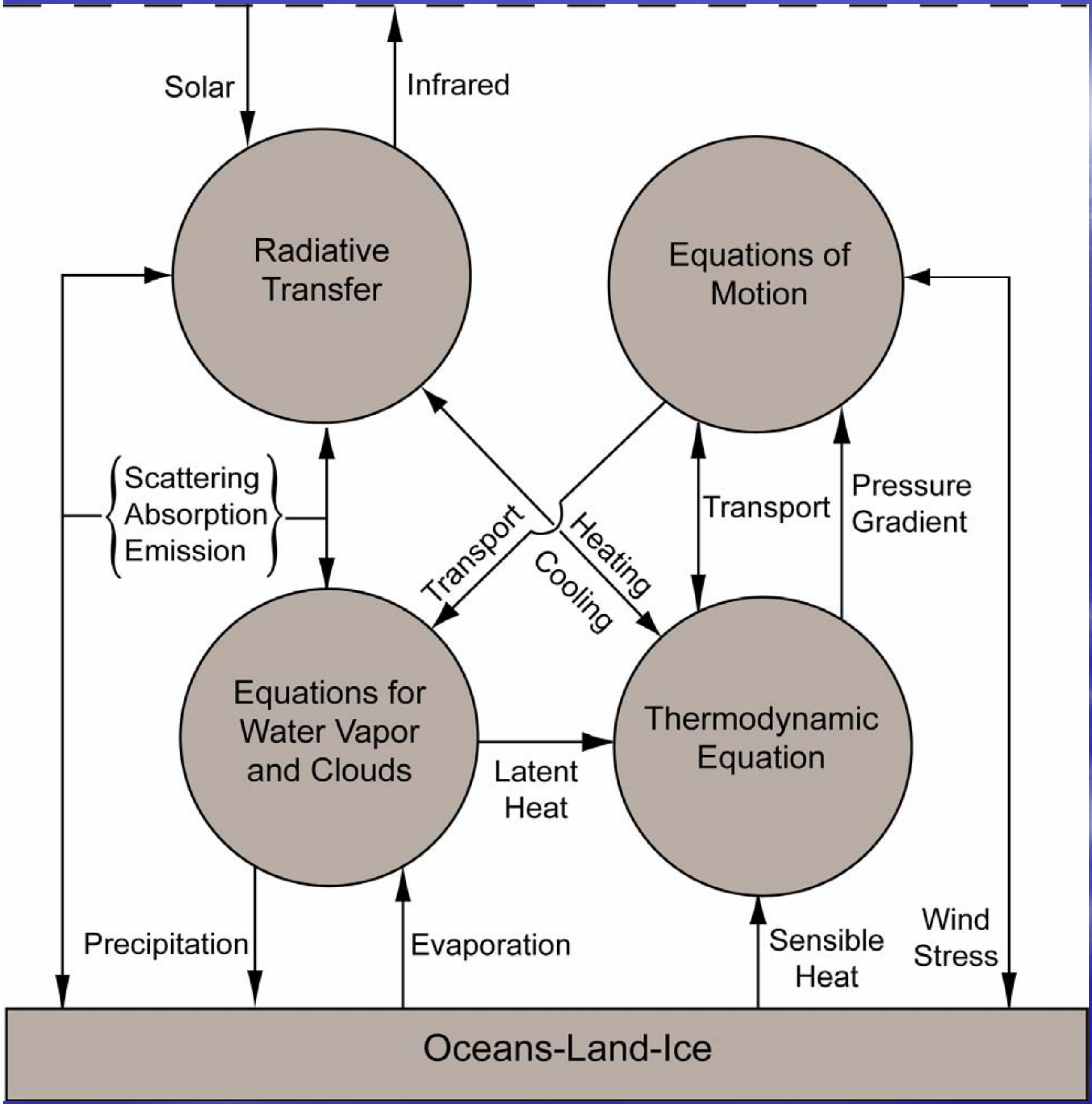
Schematic diagram showing the components of a general circulation model (GCM)



Computational grid of a general circulation model



This is the typical resolution of a climate model. Note that there are many important processes for climate (such as cloud feedback), that cannot be resolved explicitly on such a coarse grid.



Principal components of the physical and mathematical definitions and interactions of a general circulation model (GCM) for climate simulations, particularly in reference to radiative transfer in the Earth-atmosphere system.

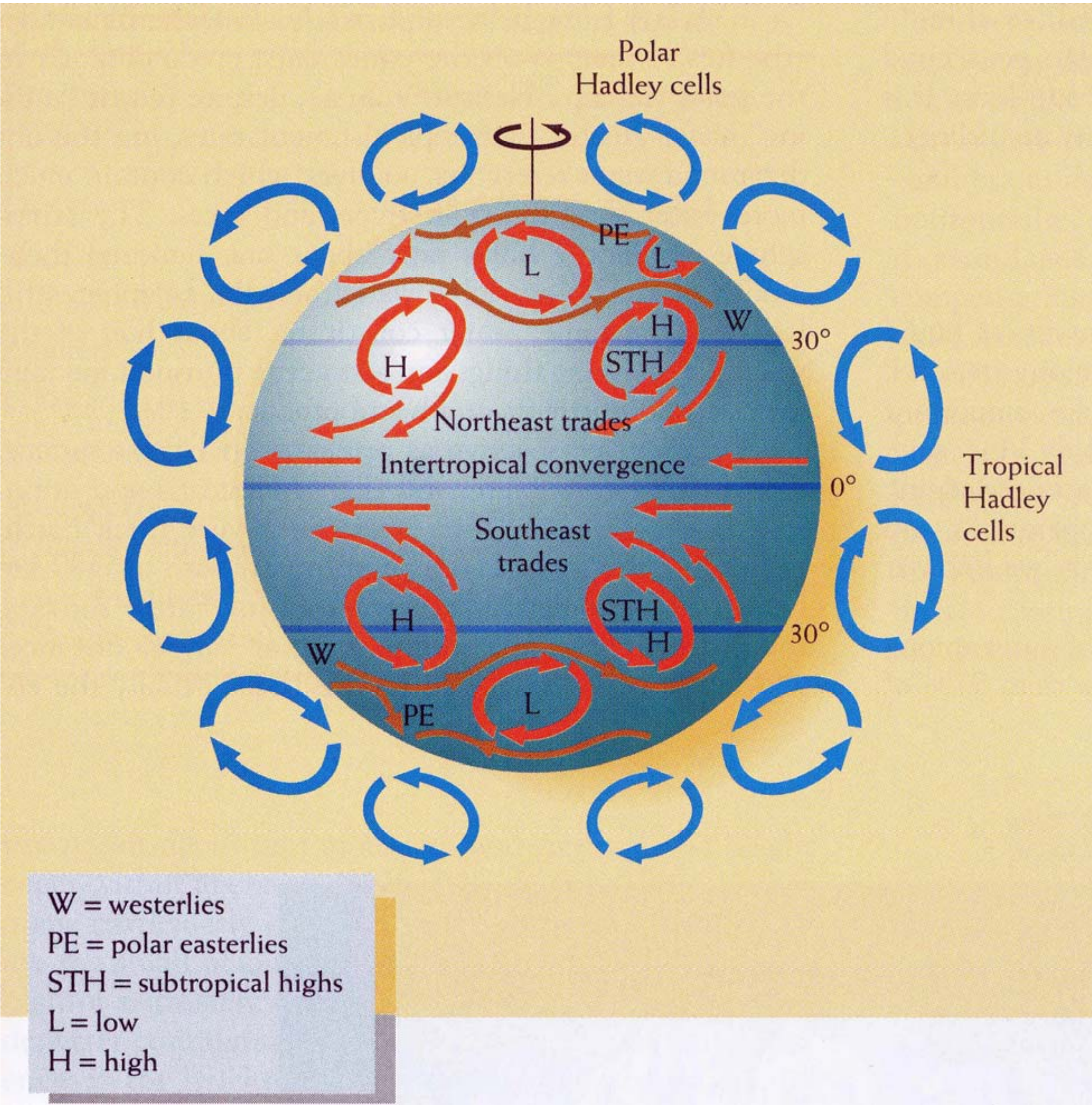
Weather vs Climate

Weather is the short-time-scale (< a few days) evolution of the of the atmosphere.

Climate is the statistics of weather. It refers to the mean (or average) weather and the deviation from the mean during a particular period (e.g., 30 yrs).

Weather prediction. The evolution of the state variables of the atmosphere is governed by nonlinear dynamics (referred to as “chaos”, or the butterfly effects), and is inherently unpredictable beyond a certain period of time, say about 2 weeks.

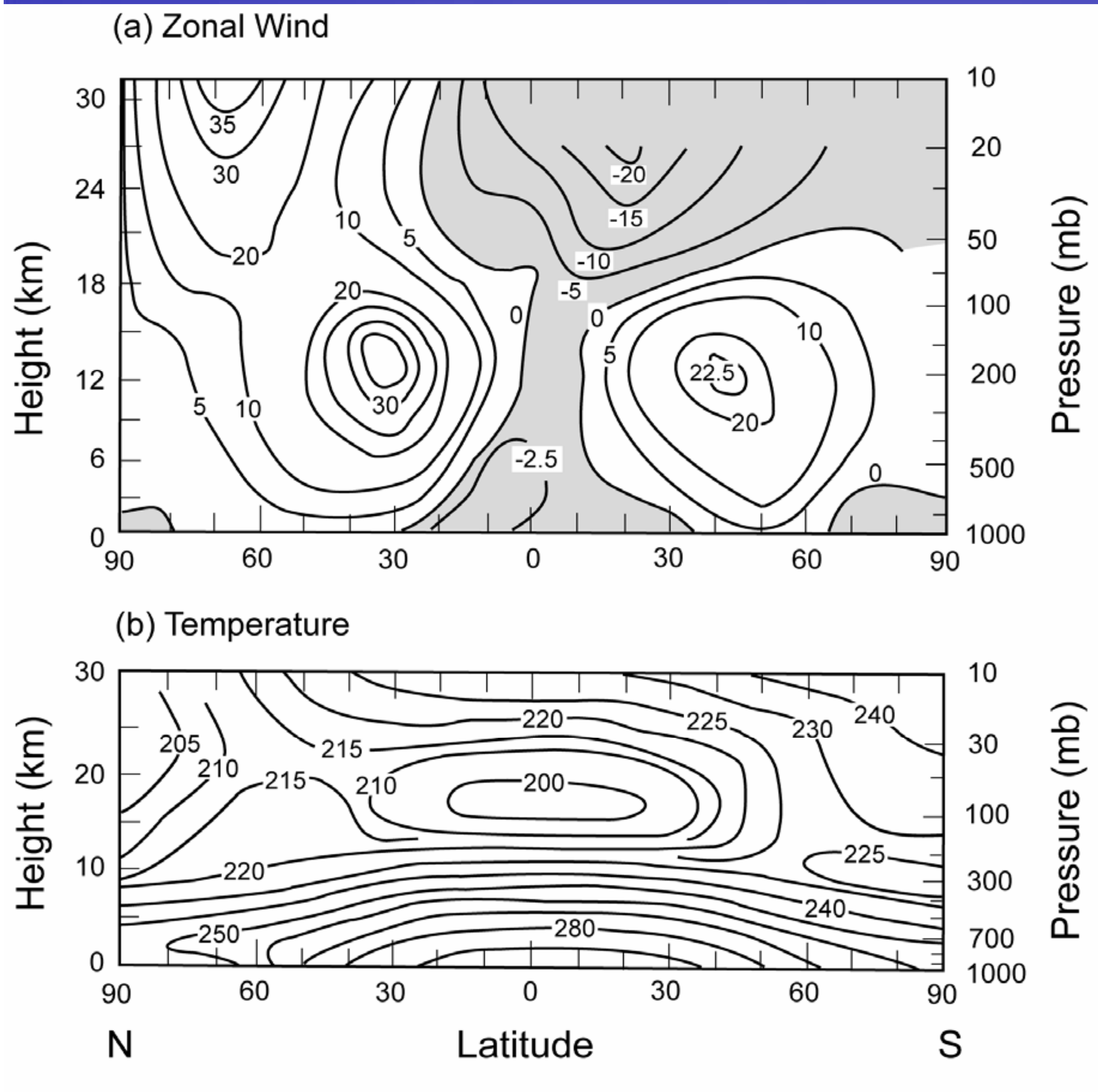
Climate prediction. It is possible to project the statistics of weather in terms of mean and variance.



On the Earth's surface, the diagrams refer to surface winds. The transient highs (H) and lows (L) we see on daily weather maps are primarily lower atmospheric features, whereas the Hadley circulation can extend vertically as much as 20 km.

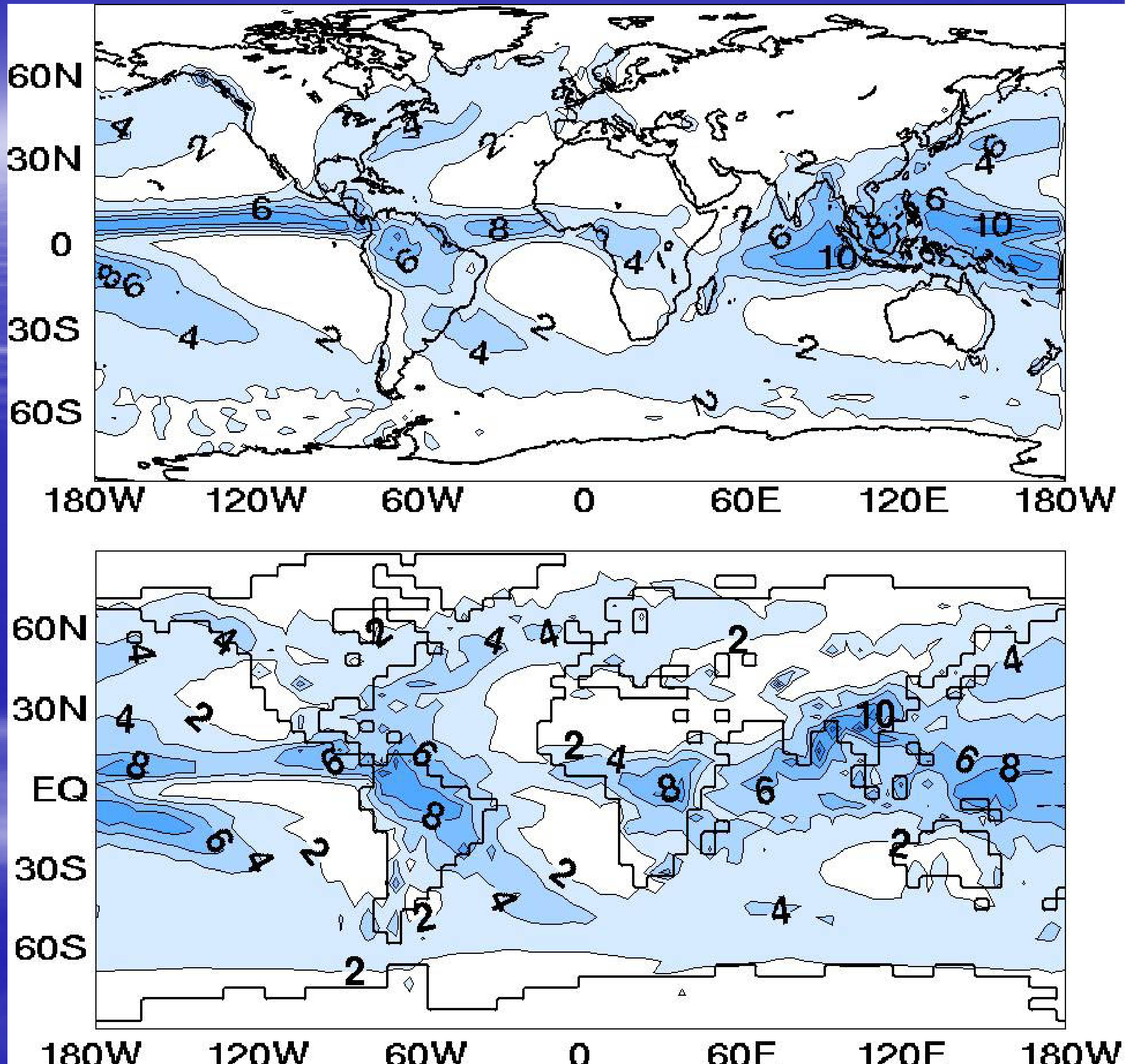
The west-to-east direction is referred to as the zonal direction.

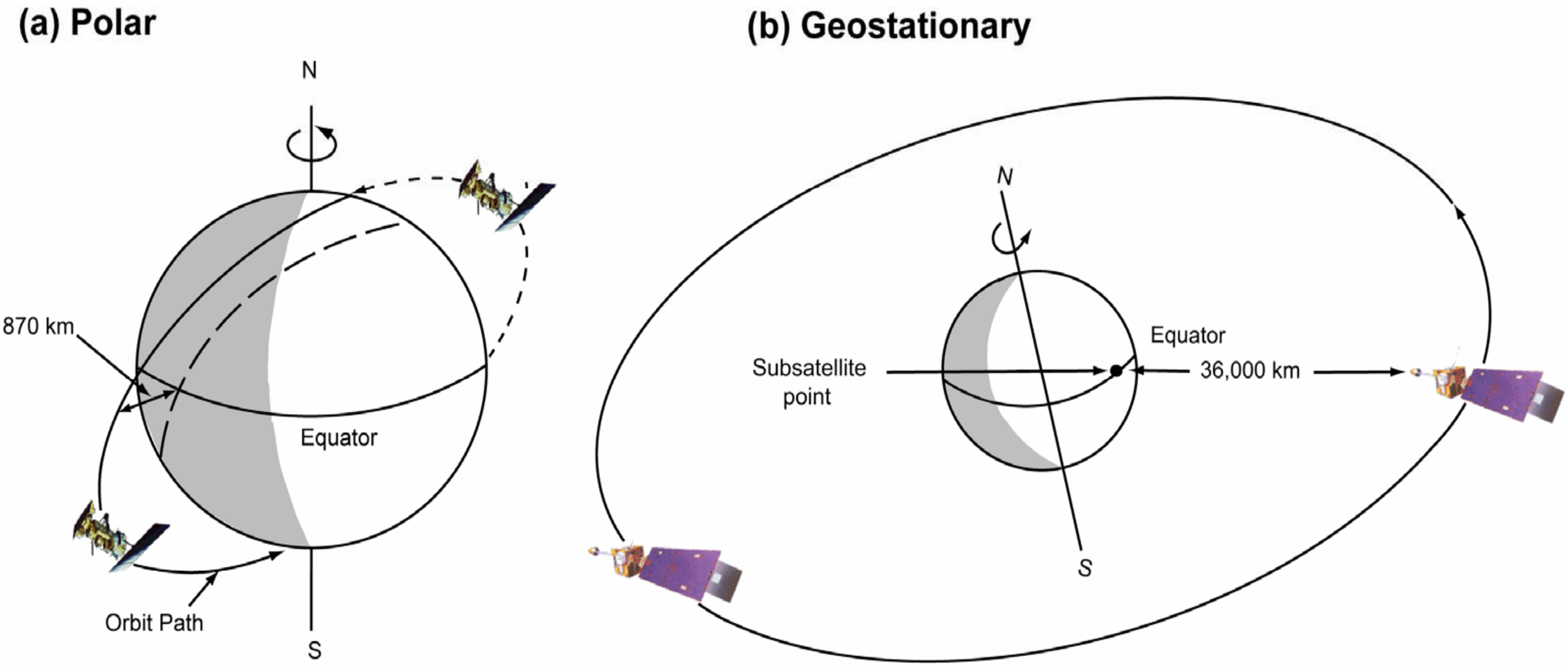
The south-to-north direction is referred to as the meridional direction.



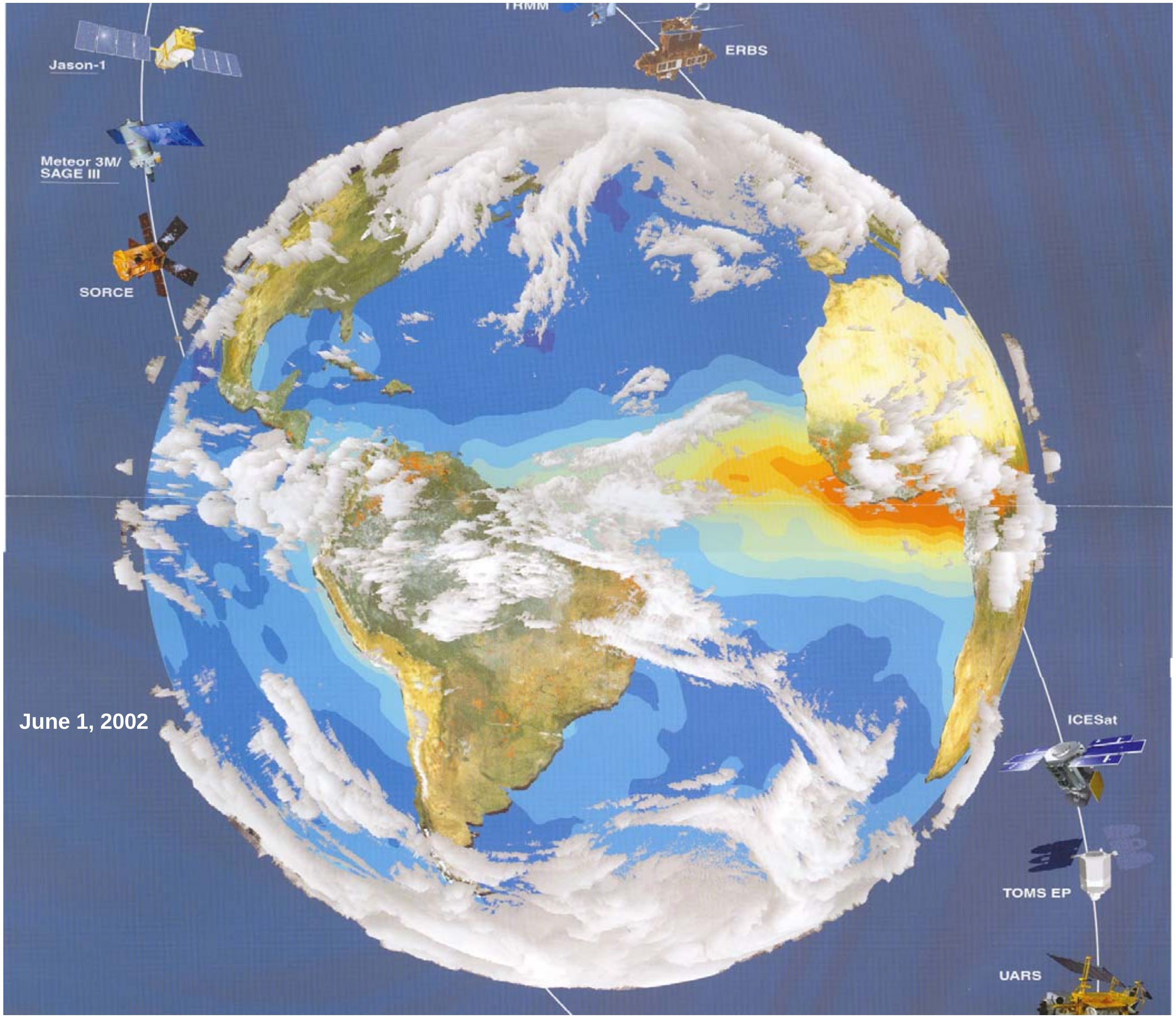
Observed (a) zonal mean wind (m/sec) and (b) temperature (K) in height (pressure)-latitude cross section for December, January, and February. Negative regions of winds are shaded (data taken from Newell et al., 1974).

Observed (top) and simulated (bottom) annual mean precipitation rates



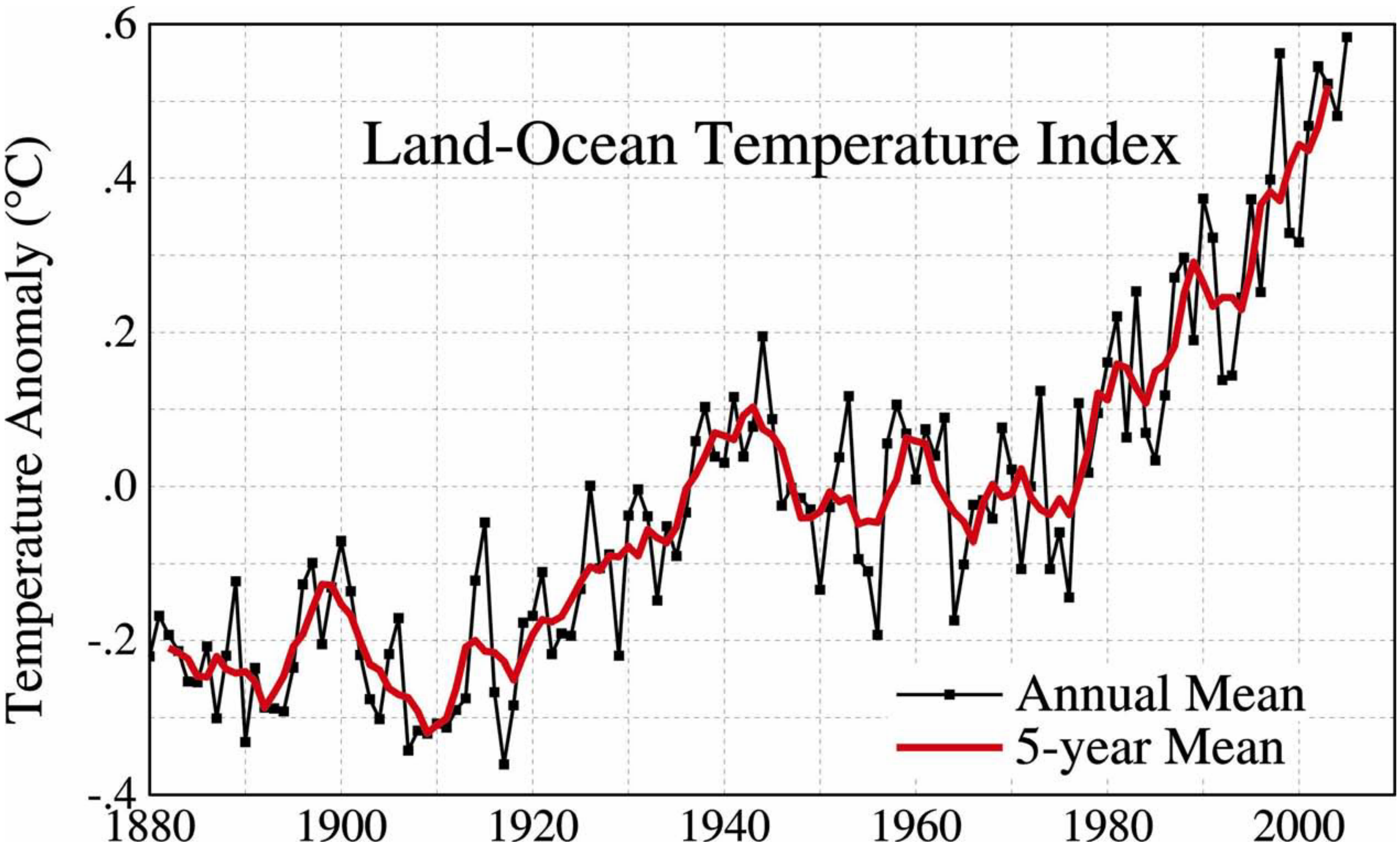


(a) Polar and (b) geostationary orbits for NOAA satellites. The polar orbit rotates one degree per day to make it synchronous with the sun. The geostationary satellite stays continuously above one spot on Earth.

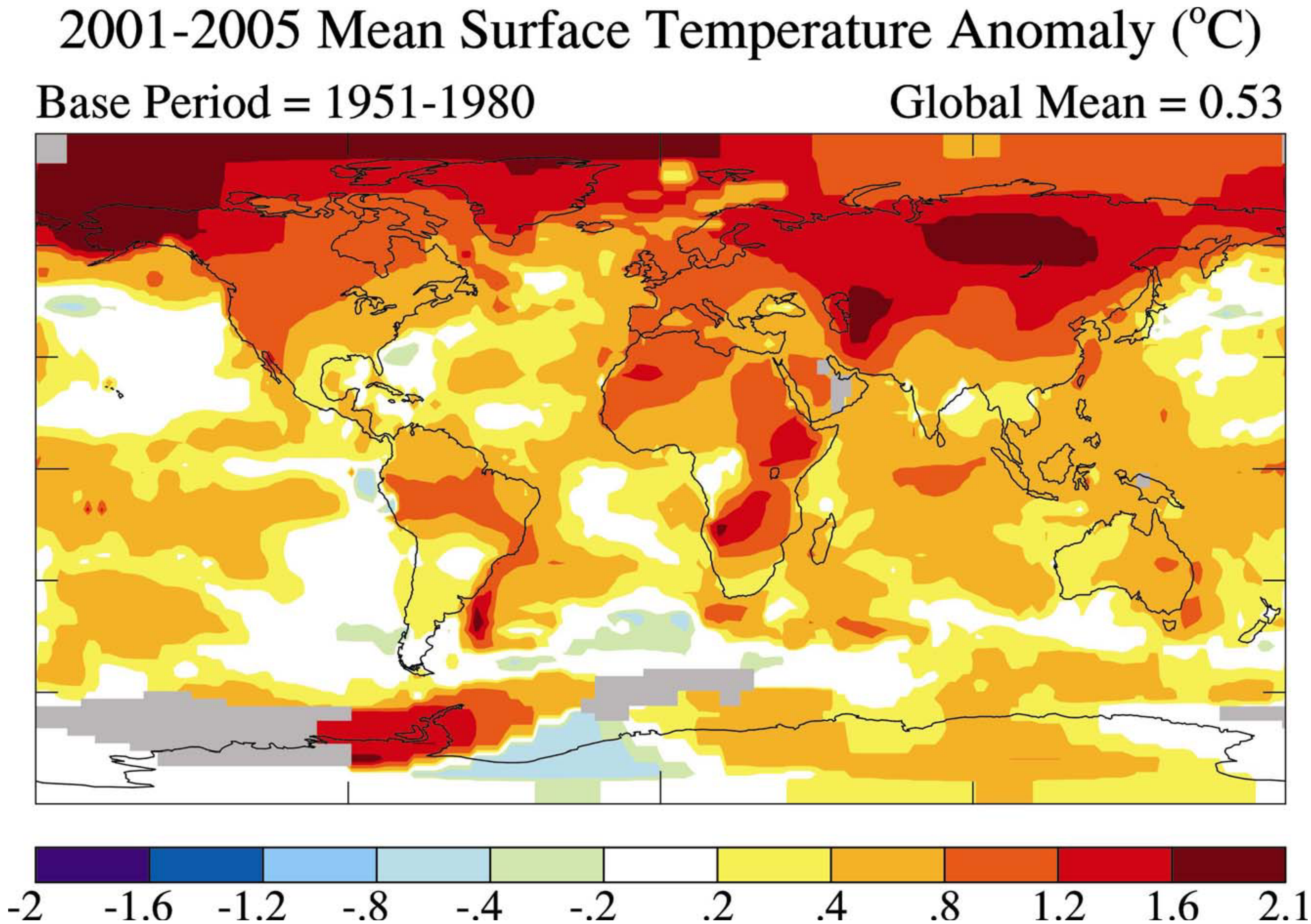


Climate data from satellites temperature, humidity, clouds, precipitation, radiation budget, ozone, aerosols, land and ocean surfaces, and greenhouse gases.

Projection to the future? (globe and regions)



Global mean surface temperature change based on surface air measurements over land and SSTs over ocean. *Source:* Update of Hansen et al., *JGR,* 106, 23947, 2001; Reynolds and Smith, *J. Climate,* 7, 1994;Rayner et al., *JGR,* 108, 2003 (afterJames E.Hansen 2006).



(After James E. Hansen 2006)

Global Climate Models

- Because we do not have future data to check and verify climate models, they must be built solely on our knowledge of the present historical climate conditions [temperature, precipitation, mean circulation patterns (winds), cloud distributions (cloud cover, type, particle size), radiation budgets at the top of the atmosphere, etc.], a process referred to as tuning.
- It is essential that the computer models for climate studies be based upon well-established physical principles.

Climate Sensitivity and Feedback

- Climate forcing, ΔF, with units of W / m^2 (e.g., increase in greenhouse gases)
- Climate change response (e.g, global mean surface temperature), ΔT, in ºC
- A measure of climate sensitivity

$$\Delta T \;/\; \Delta F = \lambda_R$$

- Feedback: A process that change the sensitivity of the climate response

CLIMATE FEEDBACKS

If the climate's response to an increase in greenhouse gases were simply to increase its temperature to compensate for the increase in greenhouse trapping of infrared radiation, the climate change problem would be quite simple. Unfortunately, there are climate feedbacks that come into play, influencing the climate's response. The main climate feedbacks are:

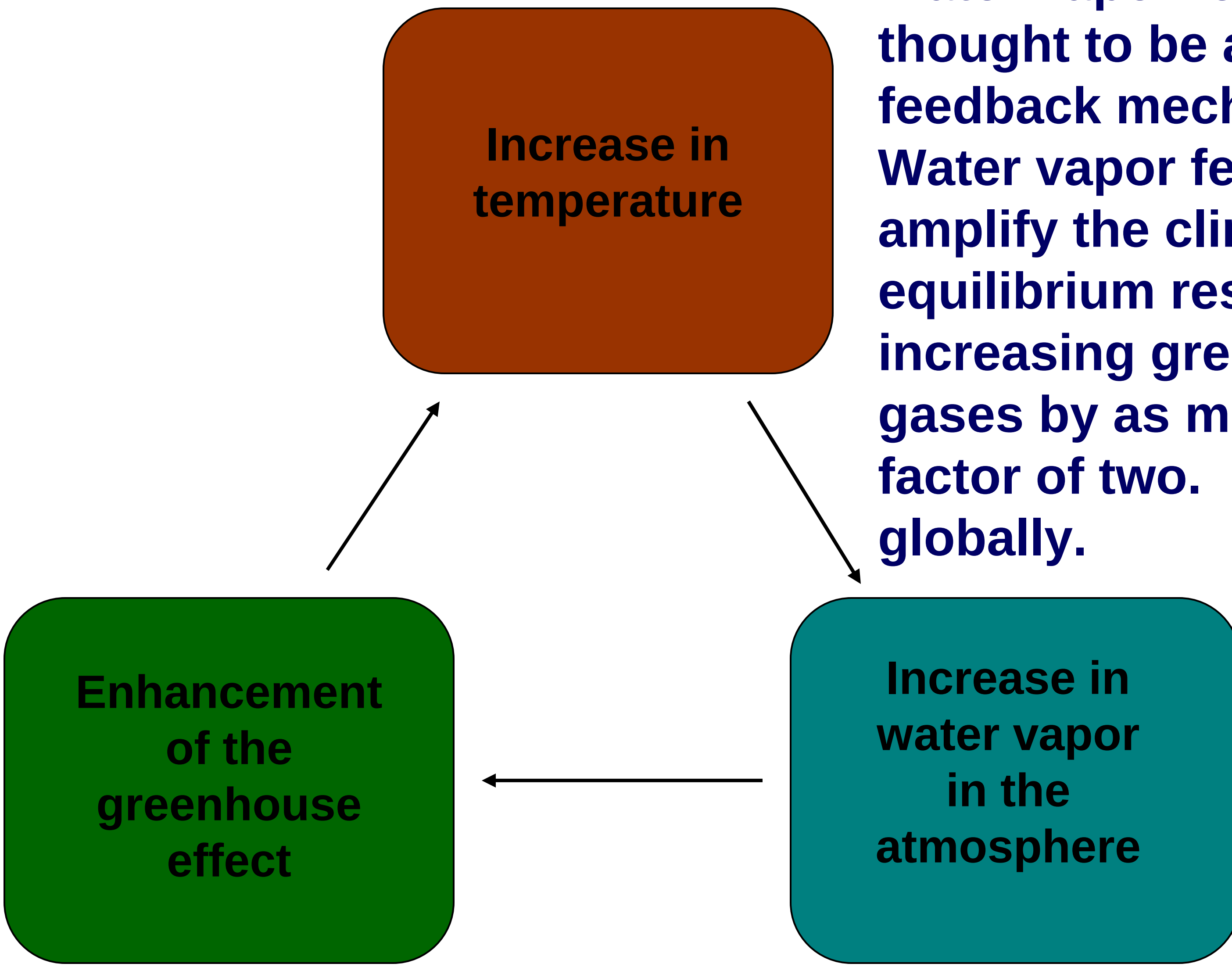
(1) Water vapor feedback

(2) Surface albedo feedback

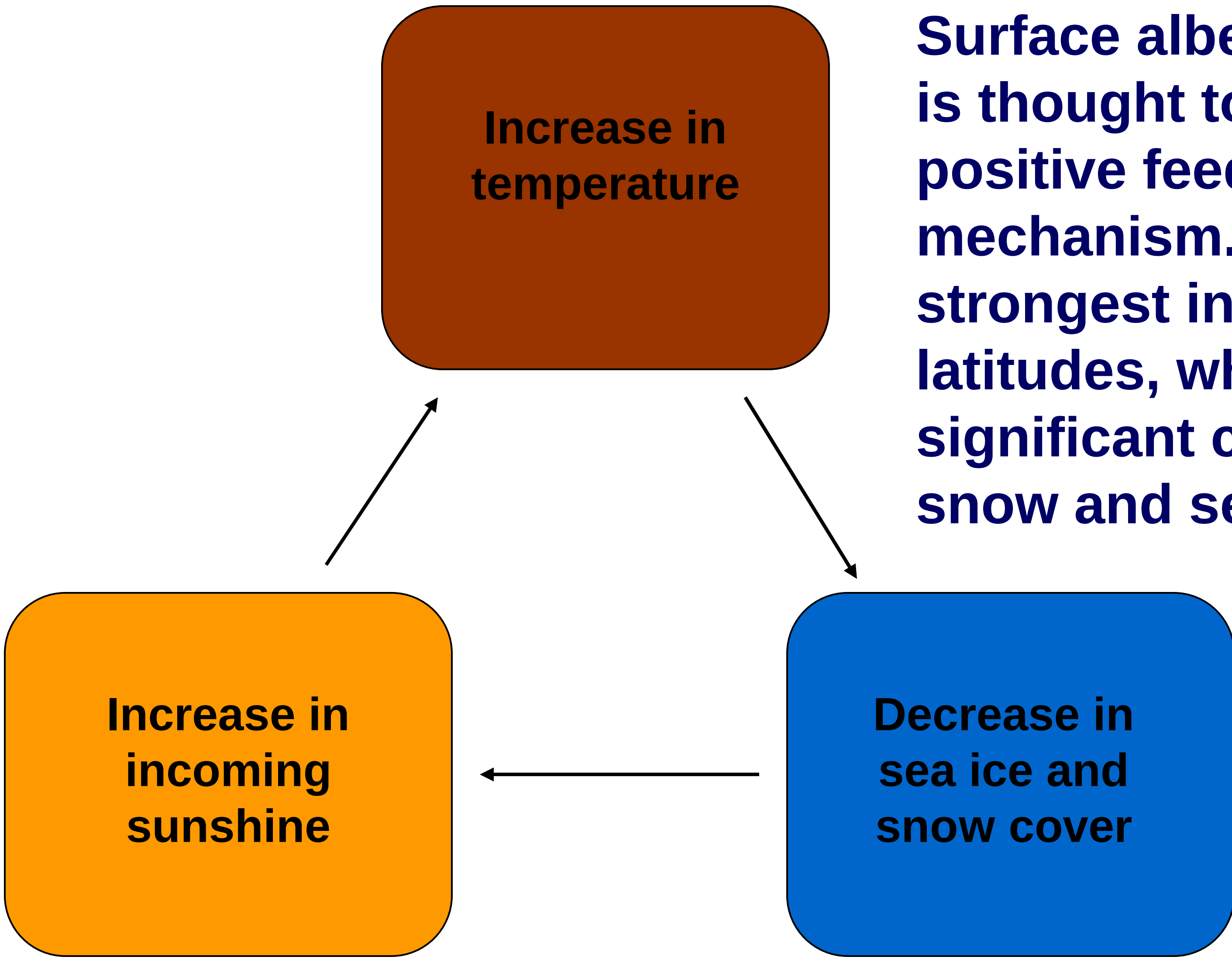
(3) Cloud feedback

WATER VAPOR FEEDBACK

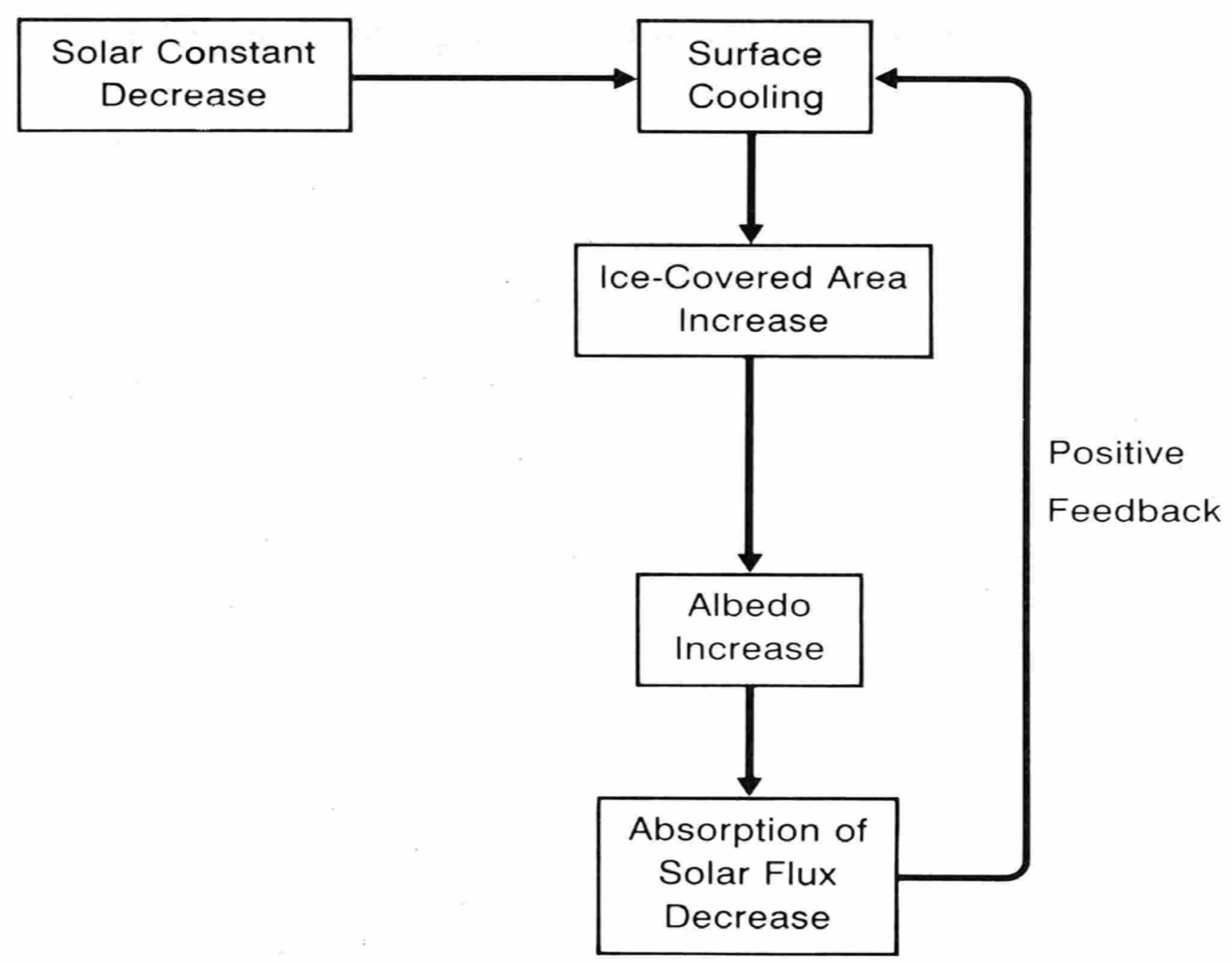
Water vapor feedback is thought to be a positive feedback mechanism. Water vapor feedback might amplify the climate’s equilibrium response to increasing greenhouse gases by as much as a factor of two. It acts globally.



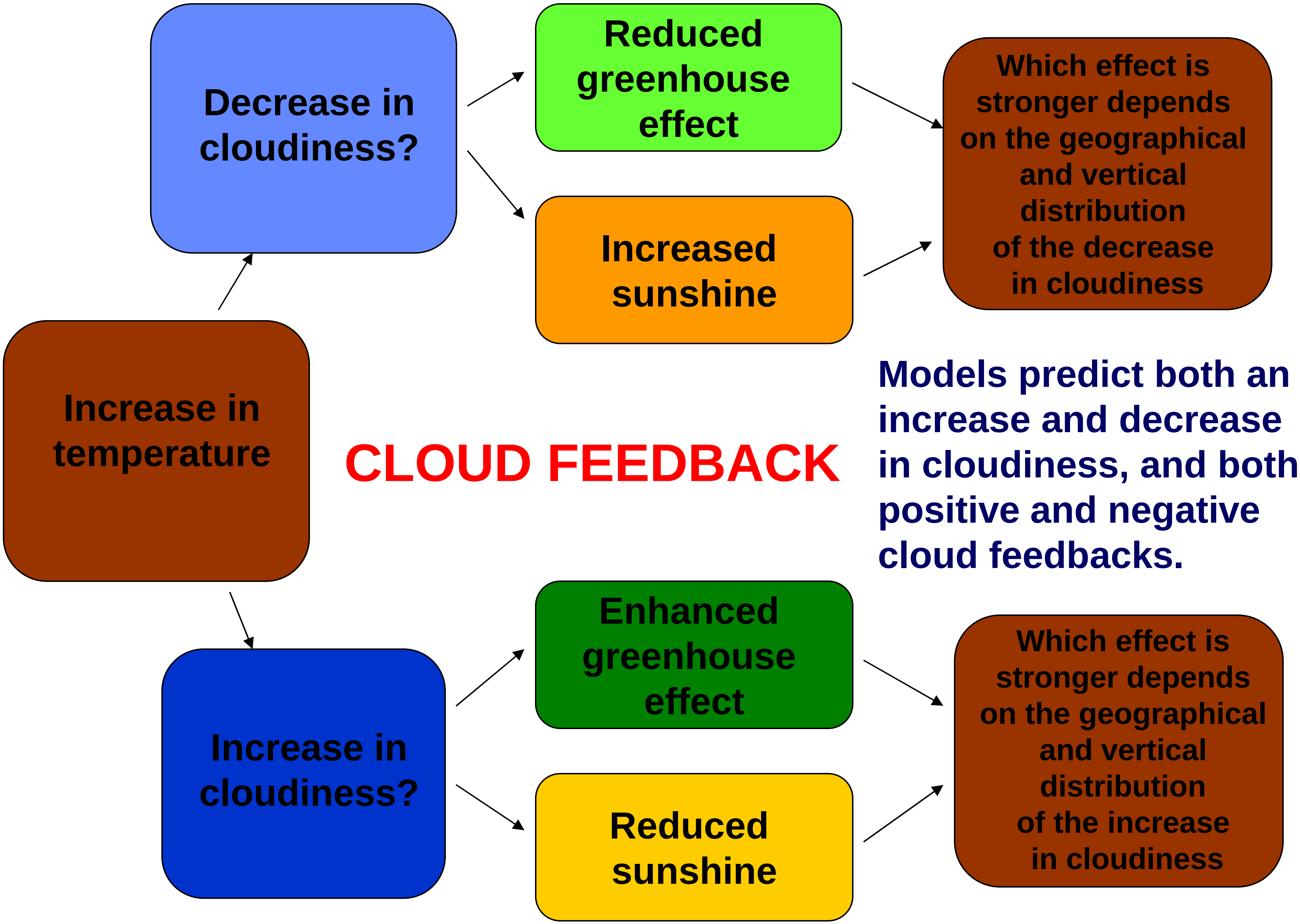
SURFACE ALBEDO FEEDBACK



Surface albedo feedback is thought to be a positive feedback mechanism. Its effect is strongest in mid to high latitudes, where there is significant coverage of snow and sea ice.



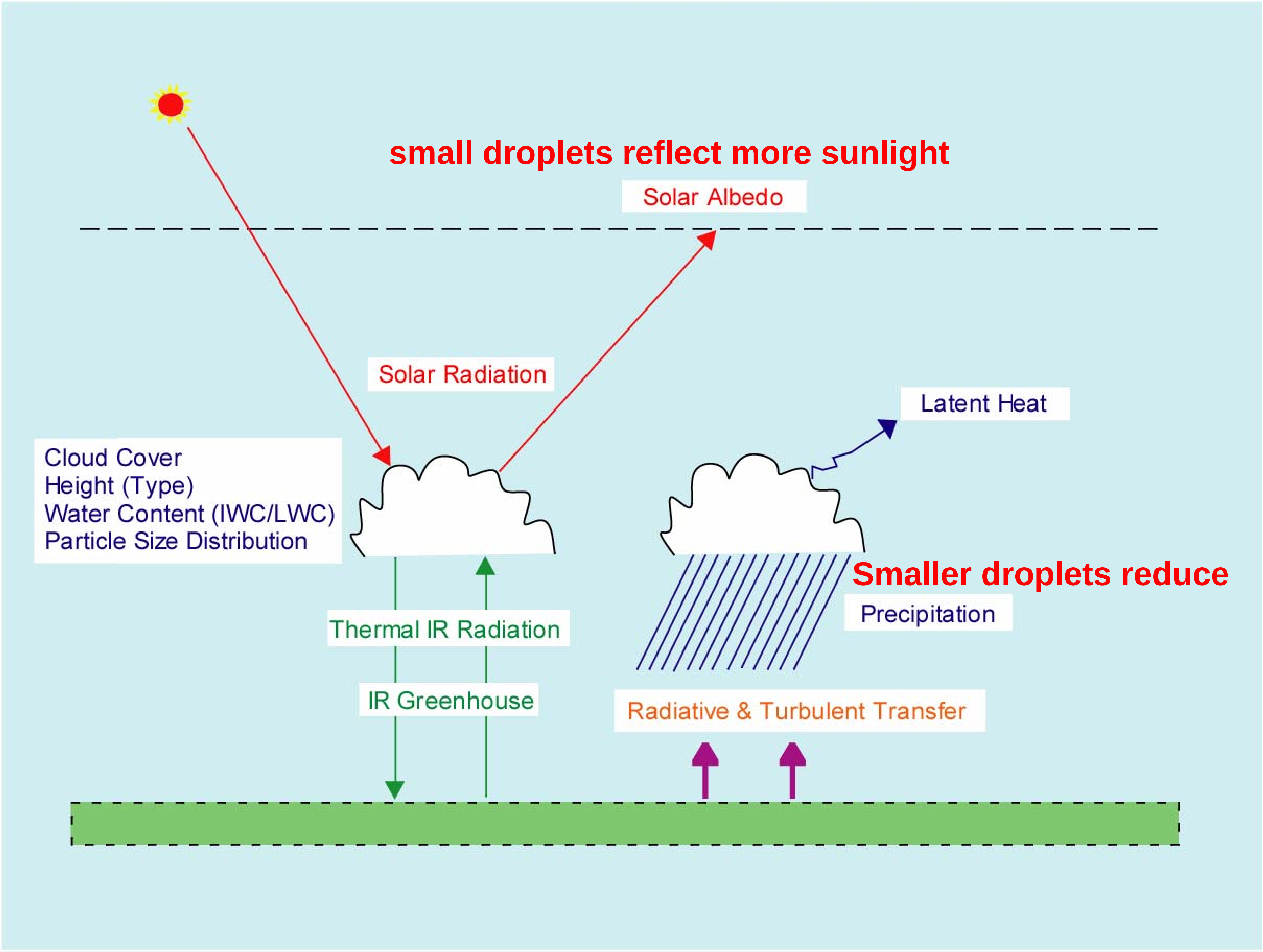
An illustration of the ice-albedo feedback due to the radiative perturbations of the solar constant.


Decrease in cloudiness?
Reduced greenhouse effect
Increased sunshine
Which effect is stronger depends on the geographical and vertical distribution of the decrease in cloudiness
Increase in temperature
CLOUD FEEDBACK
Models predict both an increase and decrease in cloudiness, and both positive and negative cloud feedbacks.
Increase in cloudiness?
Enhanced greenhouse effect
Reduced sunshine
Which effect is stronger depends on the geographical and vertical distribution of the increase in cloudiness

To understand how cloud feedback might work, you have to understand some facts about clouds:

(1) Clouds absorb radiation in the infrared, and therefore have a greenhouse effect on the climate. If you put a cloud high in the atmosphere, it will have a stronger greenhouse effect than if you put it low in the atmosphere.

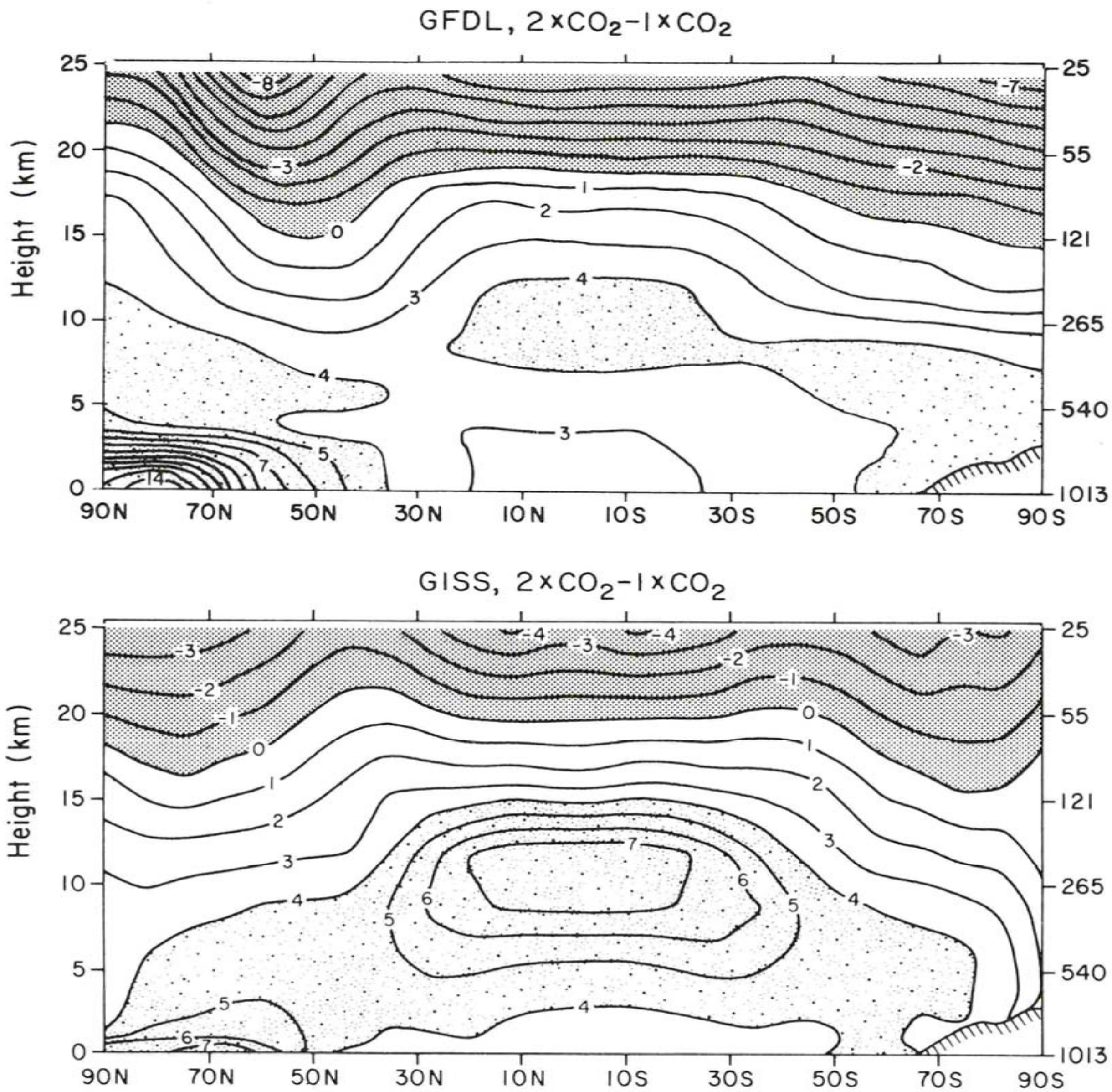
(2) Clouds reflect sunshine back to space. So more clouds means less sunshine for earth. If you put a cloud high in the atmosphere, it will reflect about the same amount of sunshine as if you put a cloud low in the atmosphere.


small droplets reflect more sunlight
Solar Albedo
Solar Radiation
Latent Heat
Cloud Cover
Height (Type)
Water Content (IWC/LWC)
Particle Size Distribution
Smaller droplets reduce
Precipitation
Thermal IR Radiation
IR Greenhouse
Radiative & Turbulent Transfer

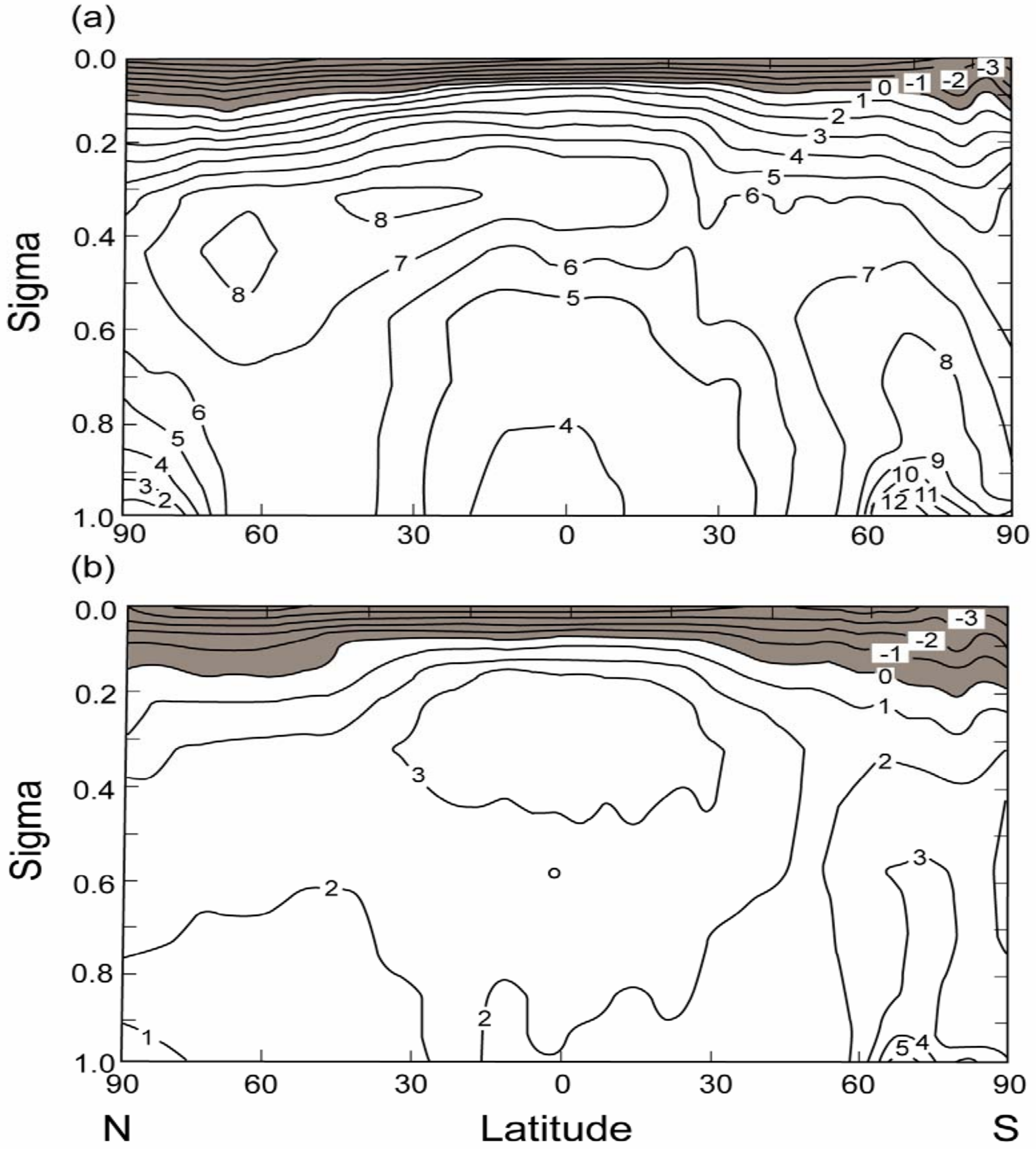
Transient vs Equilibrium climate response

Transient response refers to the evolution of the climate system as it responds to external forcing, such as an increase in greenhouse gases.

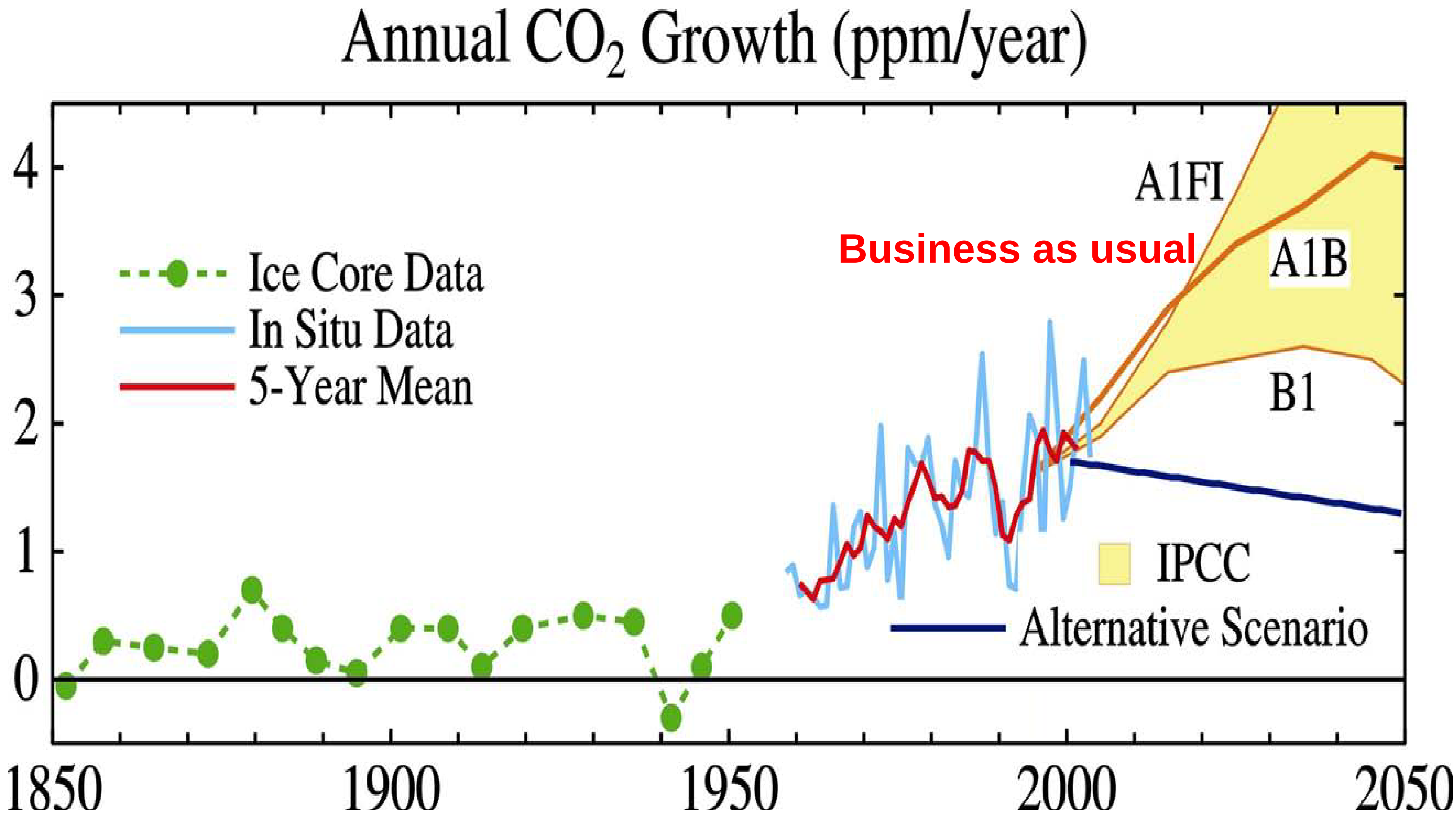
Equilibrium response refers to the final state of the climate system after it has adjusted to the external forcing. The magnitude of the equilibrium response compared to the magnitude of the forcing is referred to as the climate sensitivity.



Contour plot of the zonally averaged change in air temperature during DJF resulting from a CO_2 doubling in two models that each give a global-average surface temperature increase of 4°C. Cooling and warming greater than 4°C are shaded. [Top panel, Wetherald and Manabe (1986); bottom panel, Hansen *et al.* (1984), as printed in Schlesinger and Mitchell (1987).



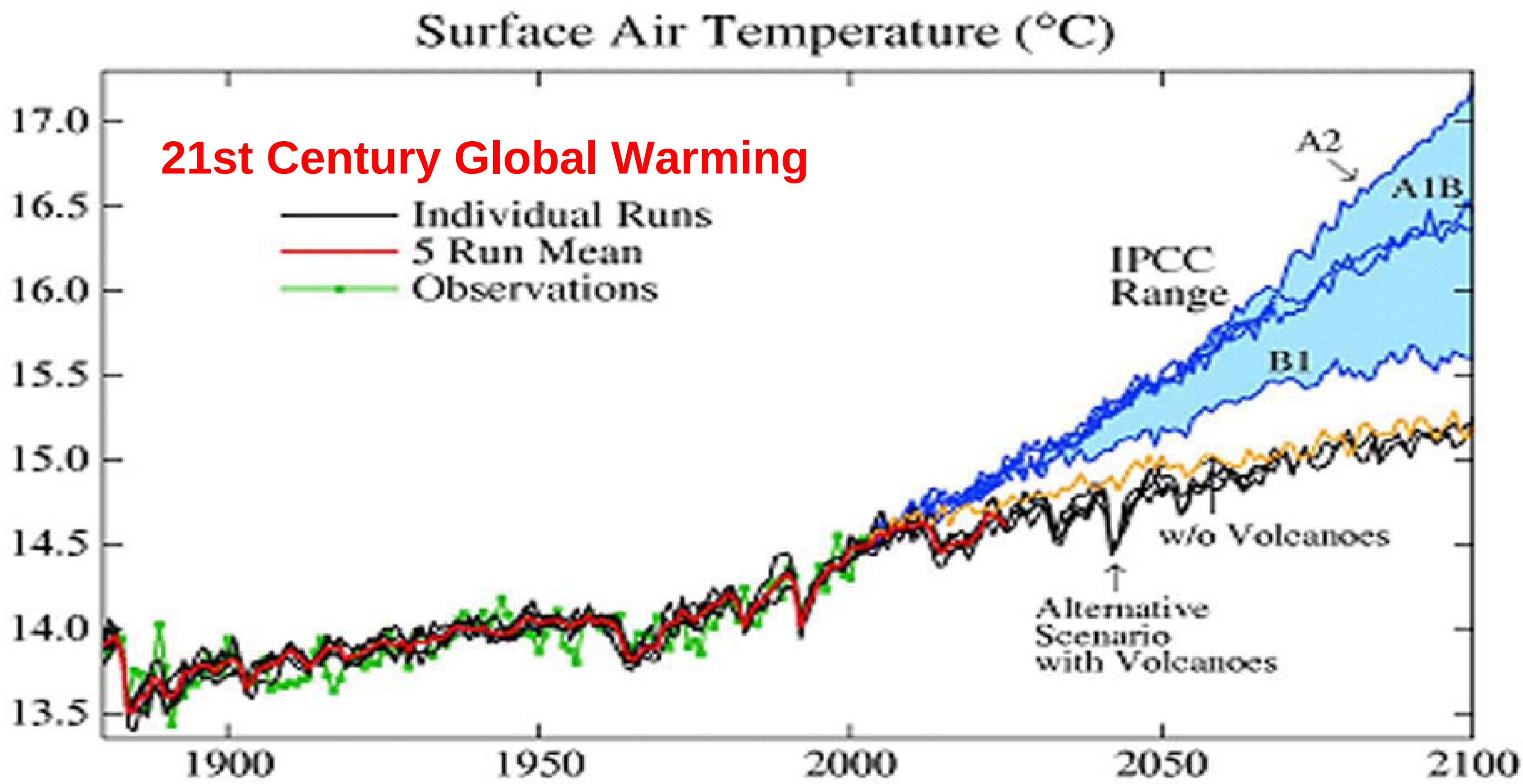
Height (σ-coordinate)-latitude cross section of equilibrium temperature changes in a 10-year summer simulation of doubling CO_2. Contours in every 1 K and reductions are shaded. (a) cloud parameterization using an RH method; and (b) an interactive cloud water prognostic equation and radiative transfer feedback (data taken from Senior and Mitchell, 1993).



Growth rate of atmospheric CO2 (ppm/year).

*Source: Hansen and Sato, PNAS, **101**, 16109, 2004.*

IPCC: Intergovernmental Panel on Climate Change



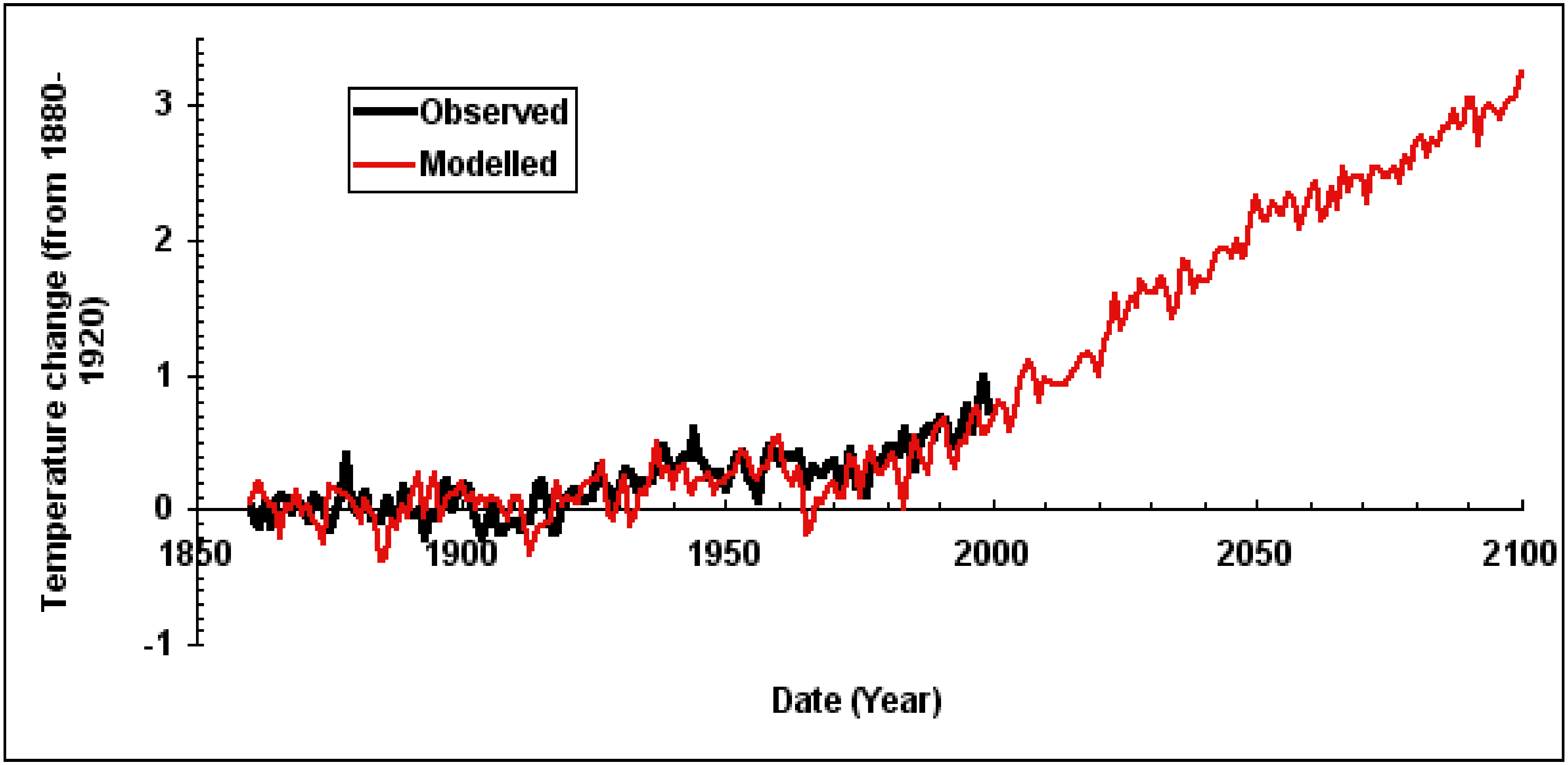
Climate Simulations for IPCC 2007 Report

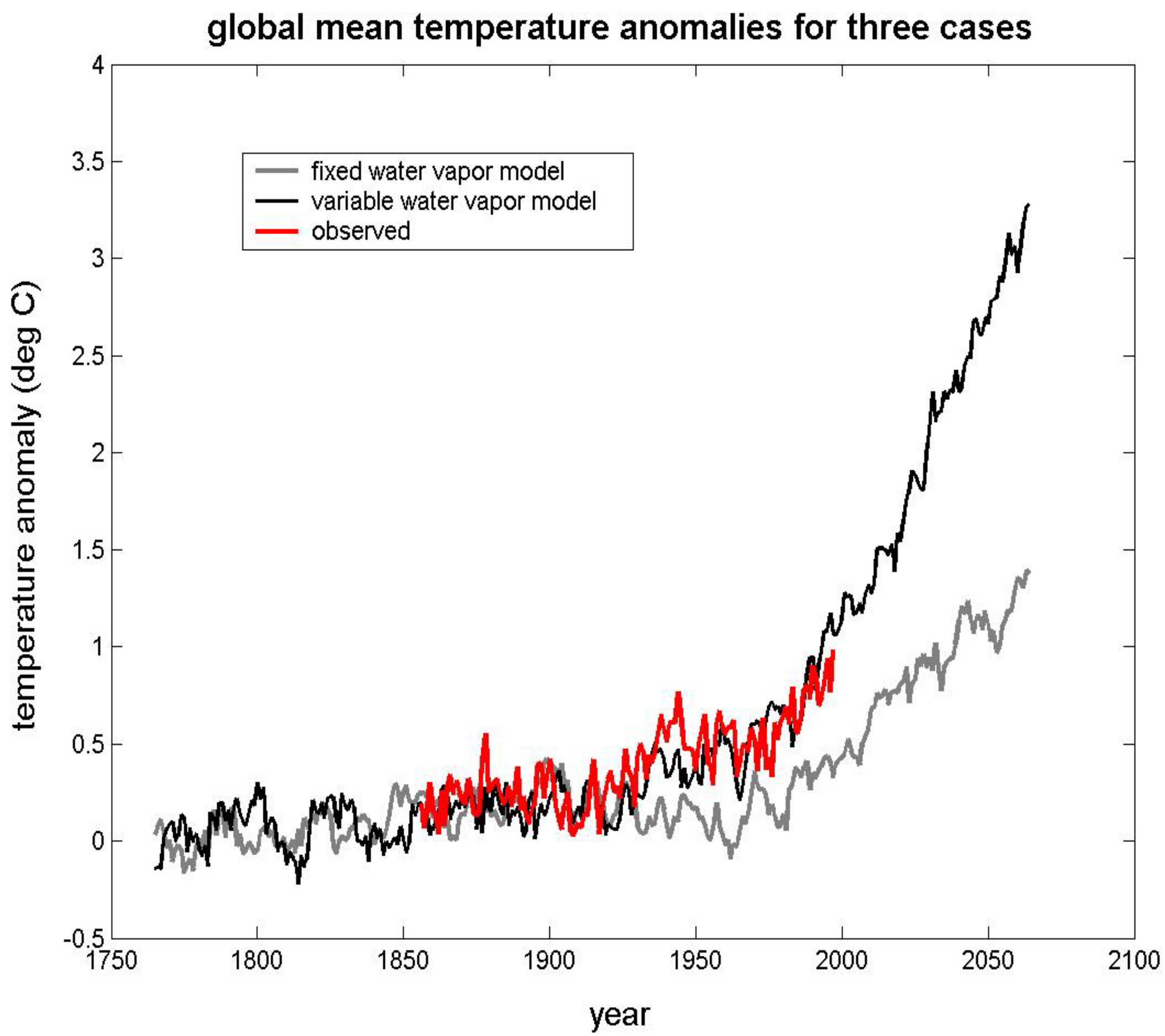
- **Climate Model Sensitivity ~ 2.7ºC for 2xCO_2**
 (consistent with paleoclimate data & other models)
- **Simulations Consistent with 1880-2003 Observations**
(key test = ocean heat storage)
- **Simulated Global Warming < 1ºC in Alternative Scenario**

Conclusion: Warming < 1ºC if additional forcing ~ 1.5 W/m2

Source: **Hansen et al.,** ***to be submitted to J. Geophys. Res.***

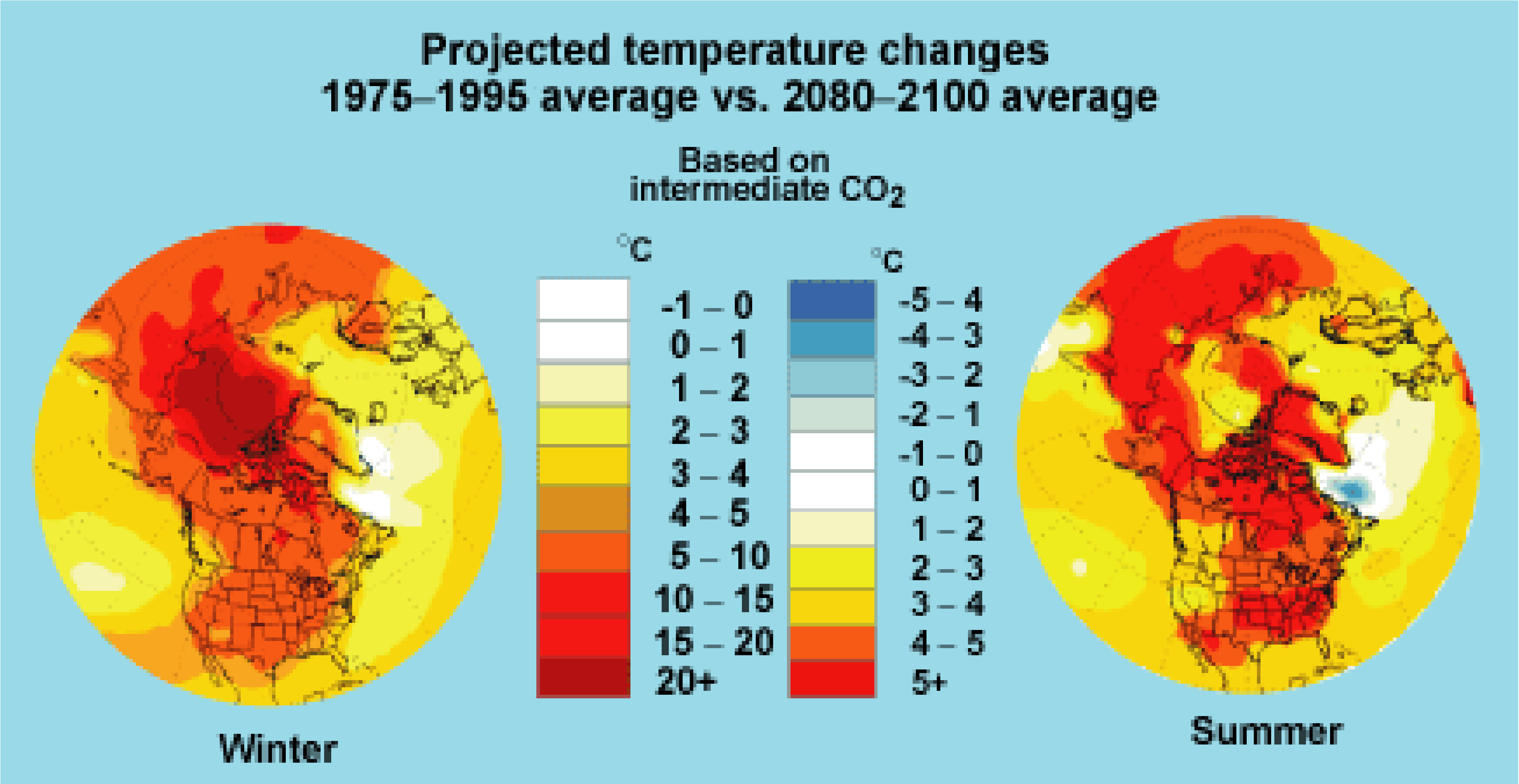
When our best guess of the observed increase in greenhouse gases and sulfate aerosols is imposed on a general circulation model, the model simulates the warming trend over the past century quite well. Note that the warming trend over the next century is projected to dwarf that of the past century. This particular model was developed at the Hadley Centre in the U.K.



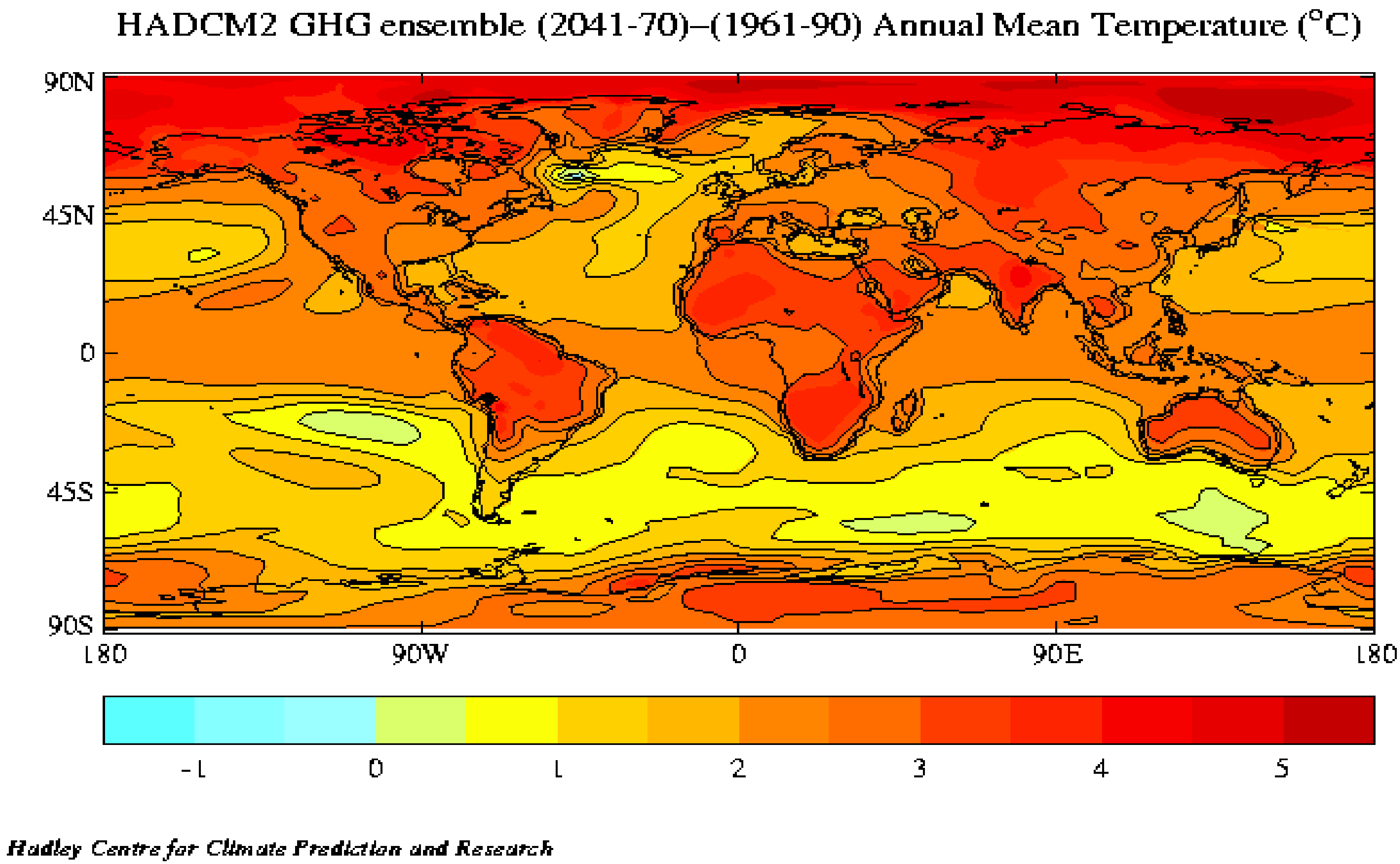


An example of how transient climate change experiments can help us learn about the climate system (Princeton-GFDL model)

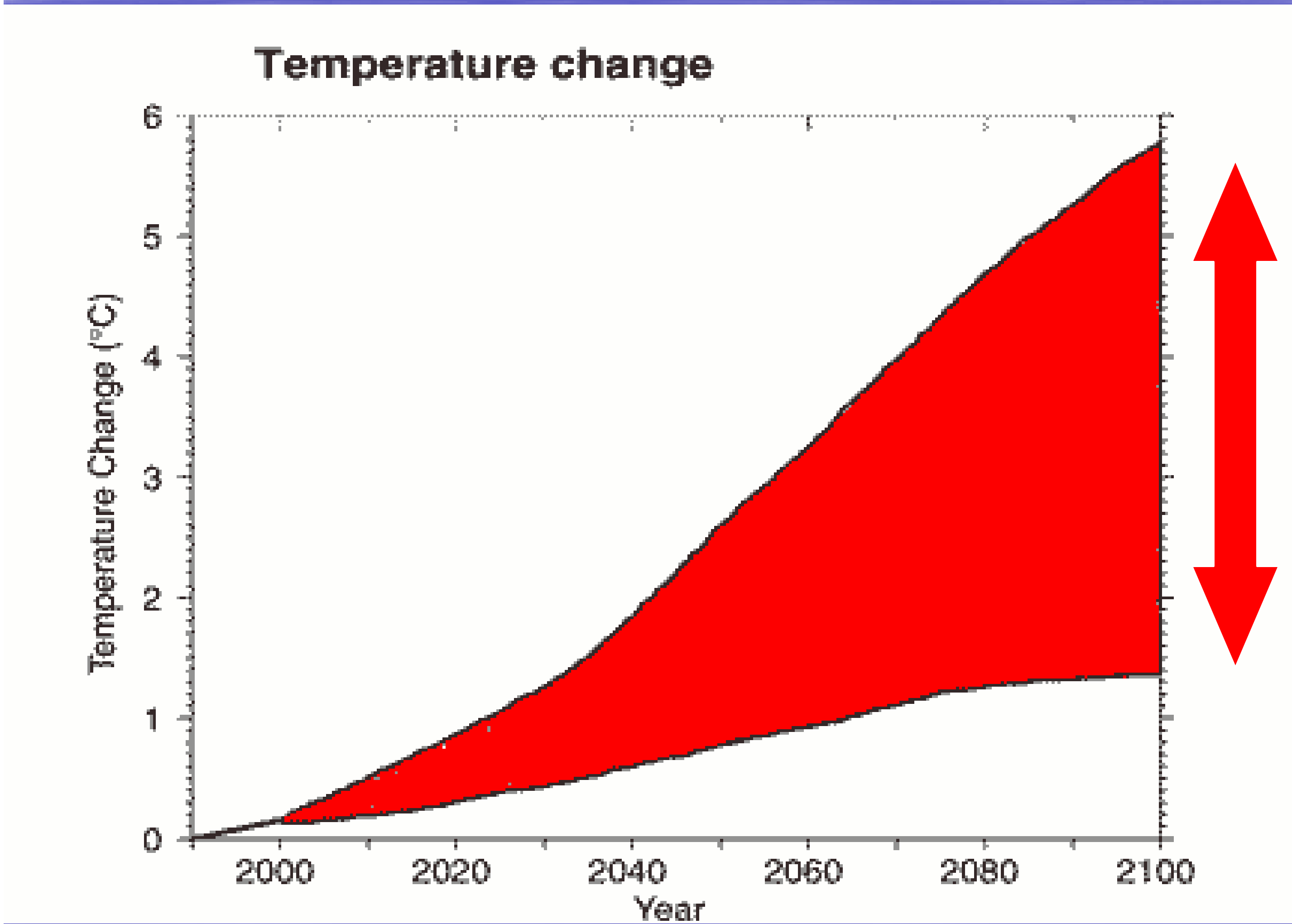
In transient climate change experiments, we can examine not only global mean temperature, but also the simulated geographical distribution of the climate change (an example from a simulation done with the Canadian Climate Model).



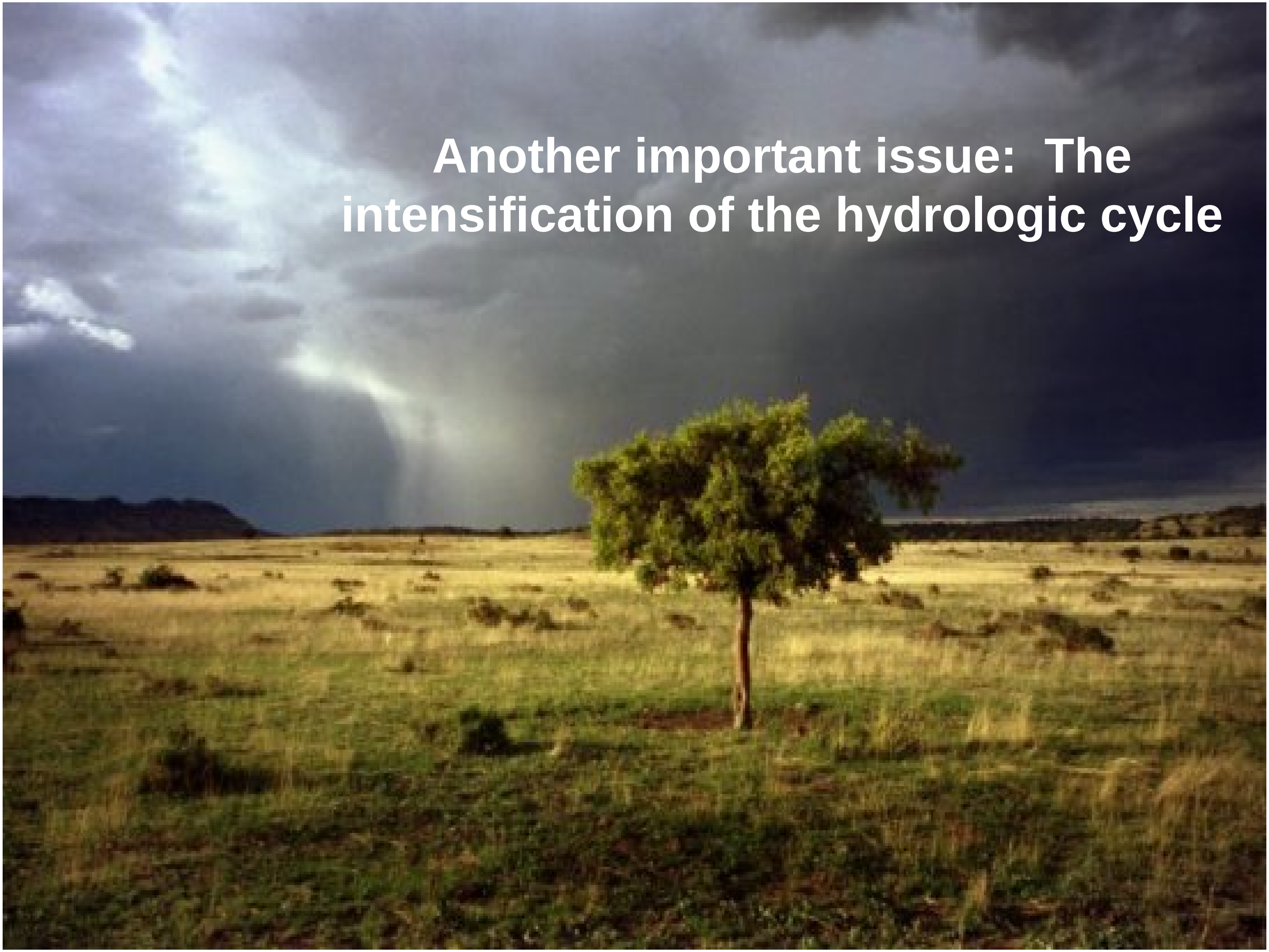
Here is an example of the temperature increase projected by the Hadley Centre model. On the regional scale, climate models tend to differ significantly.



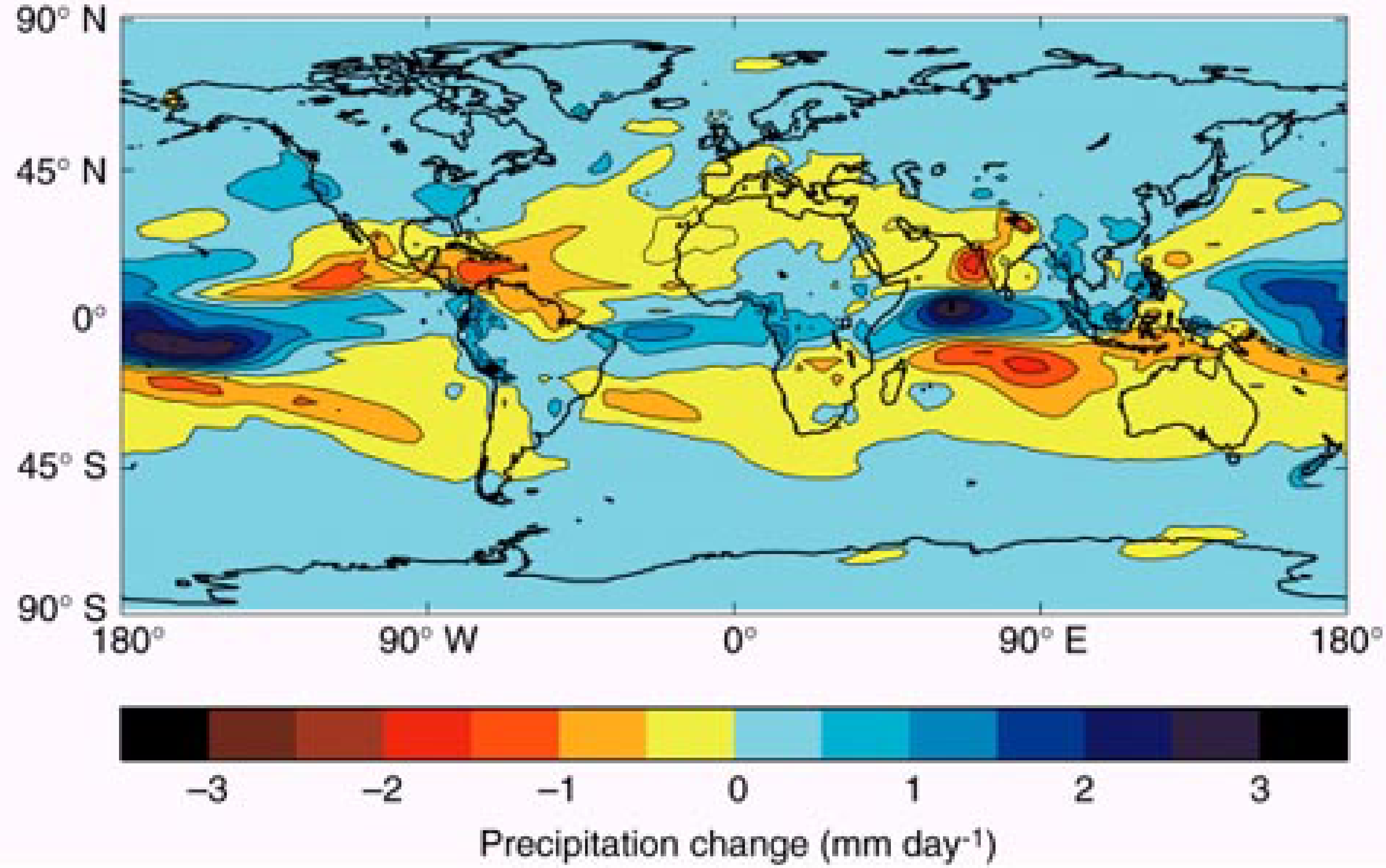
Uncertainty about the future: This plot shows the upper and lower limits of the warming over the coming century predicted by current GCM simulations.



This range is due to two factors: (1) uncertainty in emissions scenarios and (2) different model sensitivities (i.e. different simulations of climate feedbacks).


Another important issue: The
intensification of the hydrologic cycle

Precipitation for the 2050s



The projected 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 a 1% increase per year in CO_2.

The Met Office - Hadley Centre for Climate Prediction and Research.

Uncertainties (understanding and reduction of)

- Model vs Model
  - Models for the understanding of physical processes (feedbacks, physical parameterizations)
  - Models for the projection of future climates (due to increases in greenhouse gases and aerosols)
- Model vs Observation
  - Required data to assist the construction of climate models
  - Long term observations of key climate parameters