GLOBAL AND REGIONAL CLIMATE CHANGE

CLIMATE MODELLS AND REGIONAL CLIMATE PROJECTIONS FOR THE 21ST CENTURY

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OUTLINE

I. Global climate change, modelling
II. Historical aspects
III. Regional climate modelling
IV. Joint EU projects on regional climate modelling (PRUDENCE, ENSEMBLES, CECILIA, CORDEX)
V. IPCC – 2007, 2013-2014
VI. SREX - 2012
VII. Progress and findings of IPCC – 2013-2014
VIII. Perspectives for the Polar region
IX. Perspectives for Central Europe

GLOBAL AND REGIONAL CLIMATE CHANGE

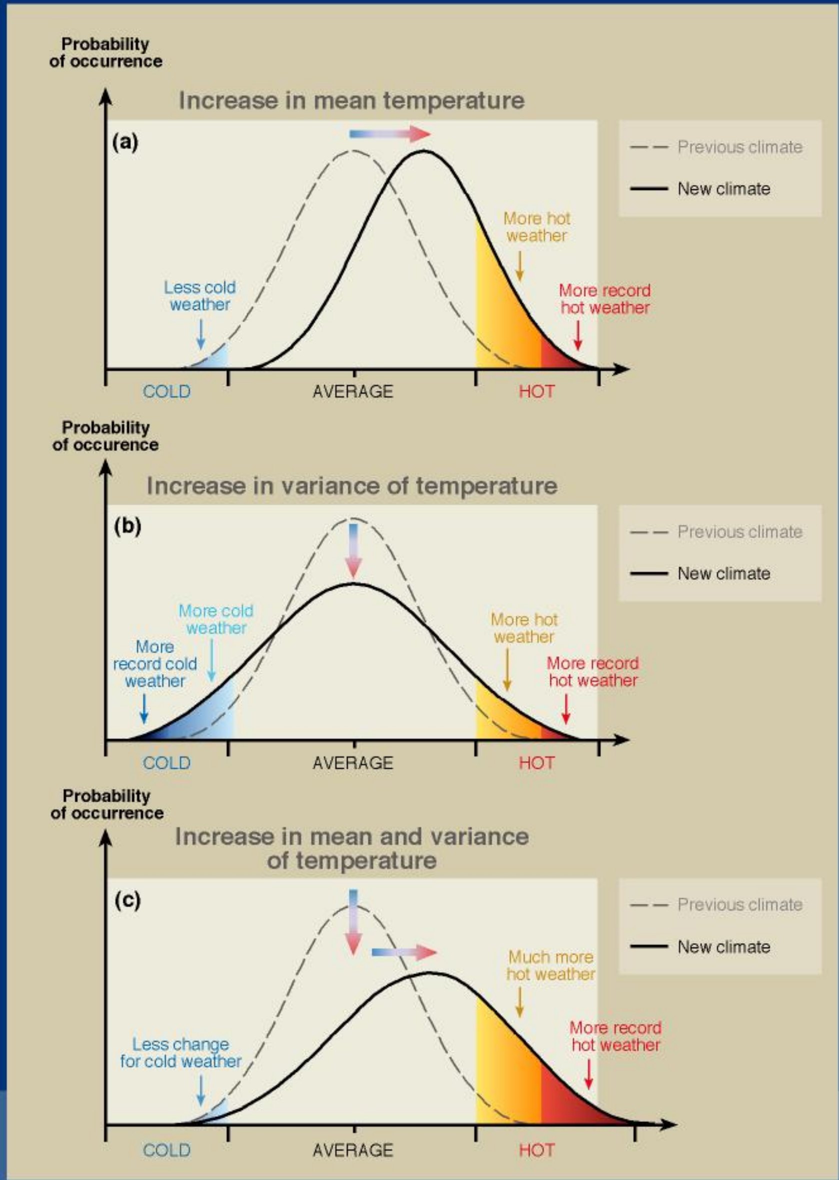
- Judit Bartholy, professor
- Institute of Goography and Earth Science
- Department of Meterorlogy

- Short questions – please interrupt
- Long questions – save until end

What is Climate Change?

- **Climate is the average weather at a given point and time of year, over a long period (typically 30 years).**
- **We expect the weather to change a lot from day to day, but we expect the climate to remain relatively constant.**
- **If the climate doesn't remain constant, we call it climate change.**
- **The key question is what is a significant change – and this depends upon the underlying level of climate variability**
- **Crucial to understand difference between climate change and climate variability…**

Effects on extreme temperatures



SYR - FIGURE 4-1

Key Sources of Information

- The Intergovernmental Panel on Climate Change (IPCC) (www.ipcc.ch)
- IPCC reports supported by >95% of climate scientists
- Fourth and Fifth Assessment Reports (AR4, AR5) published 2007, 2013-2014

Recommended Books

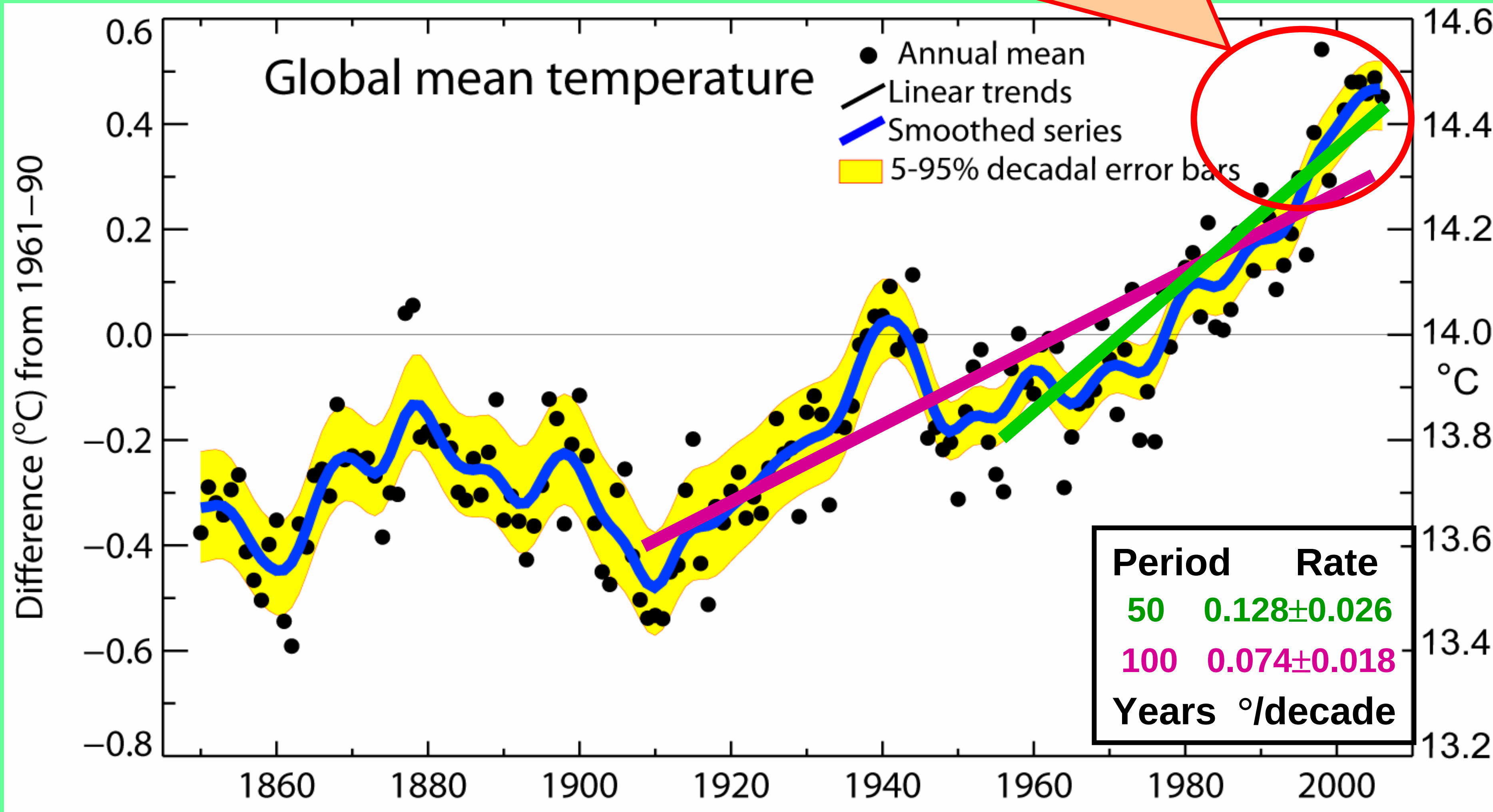
- JT Houghton (2009)
  Global Warming: The Complete Briefing, 4th Ed. Cambridge University Press
  ISBN 0-521-52874-7

- WJ Burroughs (2001)
  Climate Change: A Multidisciplinary Approach. Cambridge University Press
  ISBN 0-521-56771-8

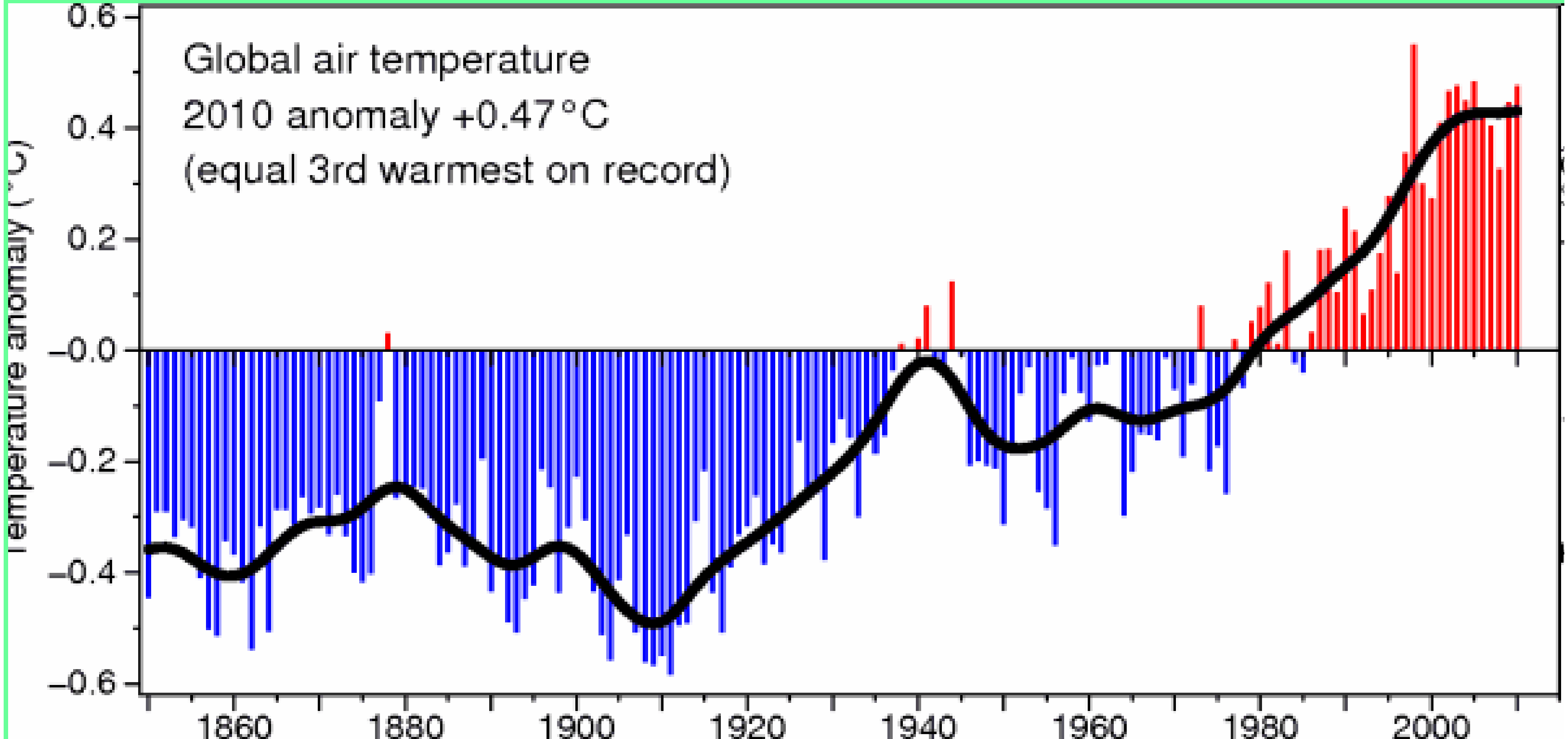
1. Observations of climate change

Global mean temper

Warmest 12 years:
1998,2005,2003,2002,2004,2006, 2001,1997,1995,1999,1990,2000



Global surface temperature 1855-2010

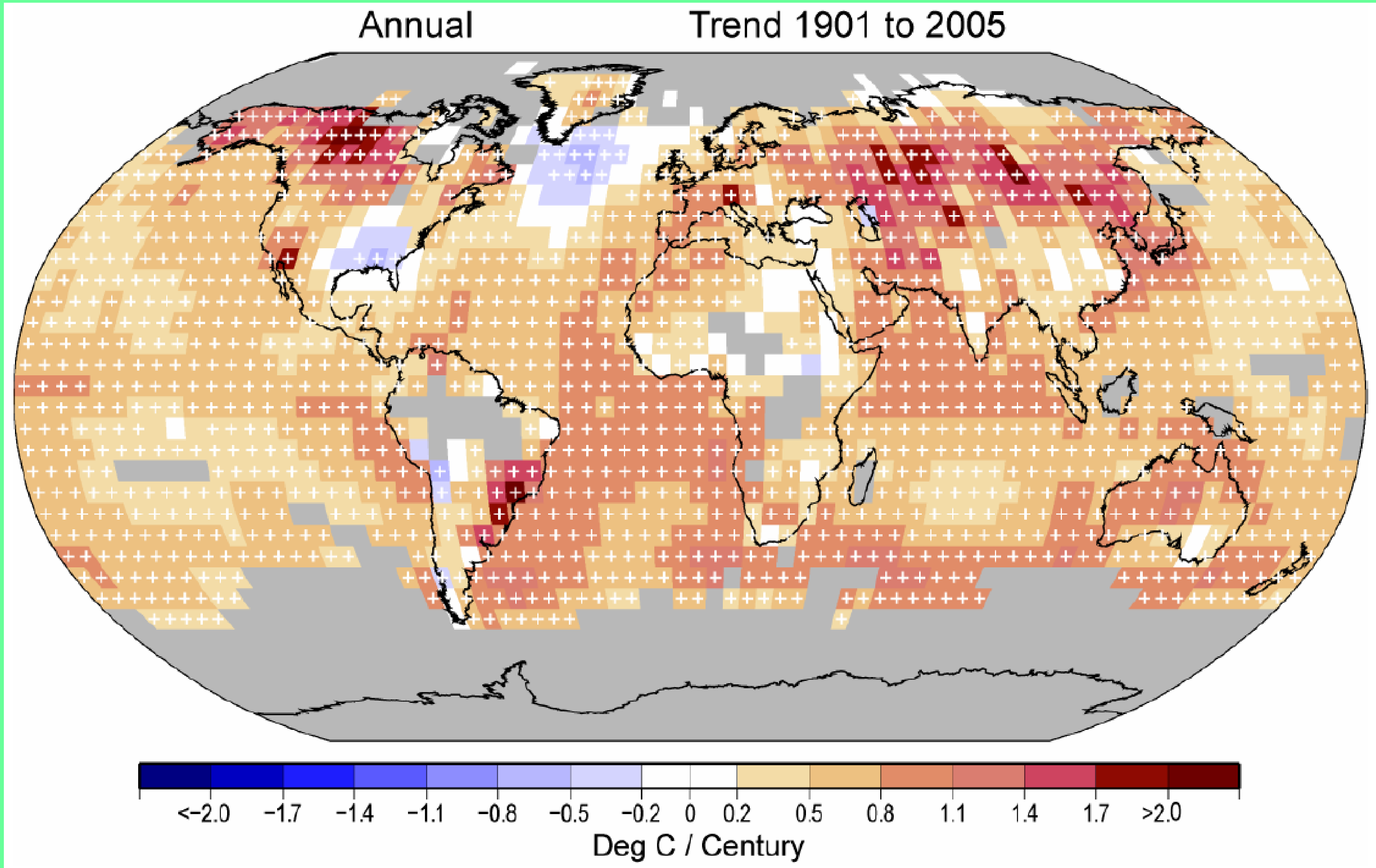


How is this curve calculated?

Possible Problems with station data

- Instrument/human errors
- Changes of instrument/observer or observing technique
- Changes in station surroundings, e.g. urbanisation – this is a common criticism from climate change sceptics
- Some solutions: compare adjacent stations, compare with stations known to be unchanged
- All data in the ‘global’ picture have been carefully checked for these possible artifacts, and where necessary corrected or discarded

Observed surface temperature trend



Trends significant at the 5% level indicated with a '+'. Grey: insufficient data

Other evidence of Climate Change

- Glacier retreat

1875

2004


Portage Glacier AK, 1914 • NOAA

Portage Glacier AK
© 2004 Gary Braasch

c. 1950 • Univ. of Alaska Library

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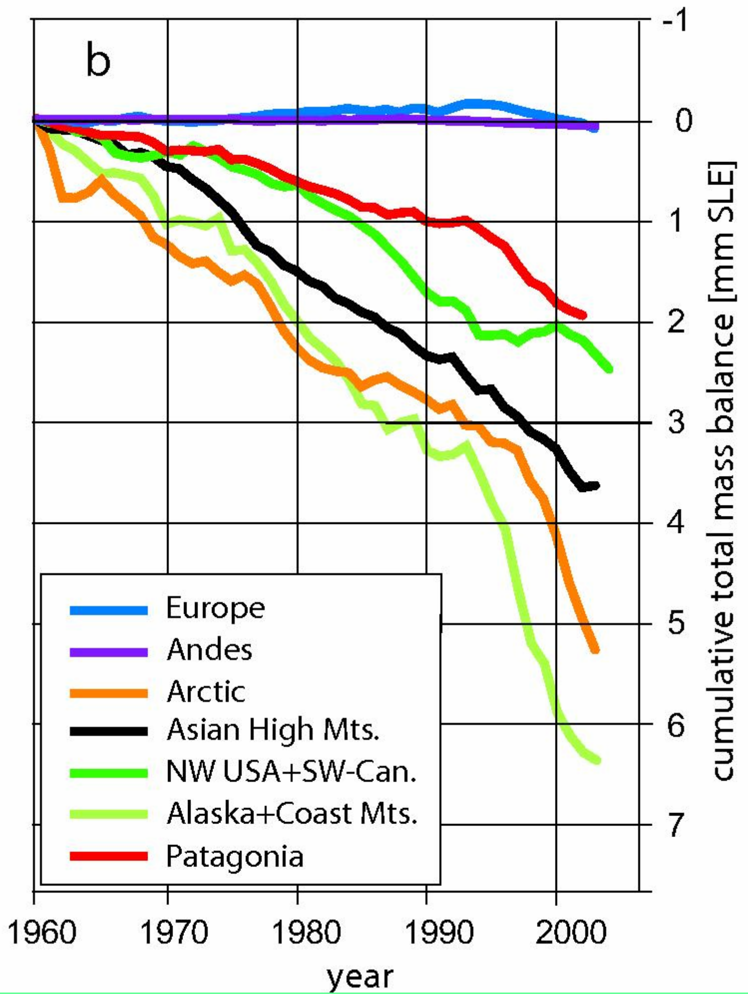
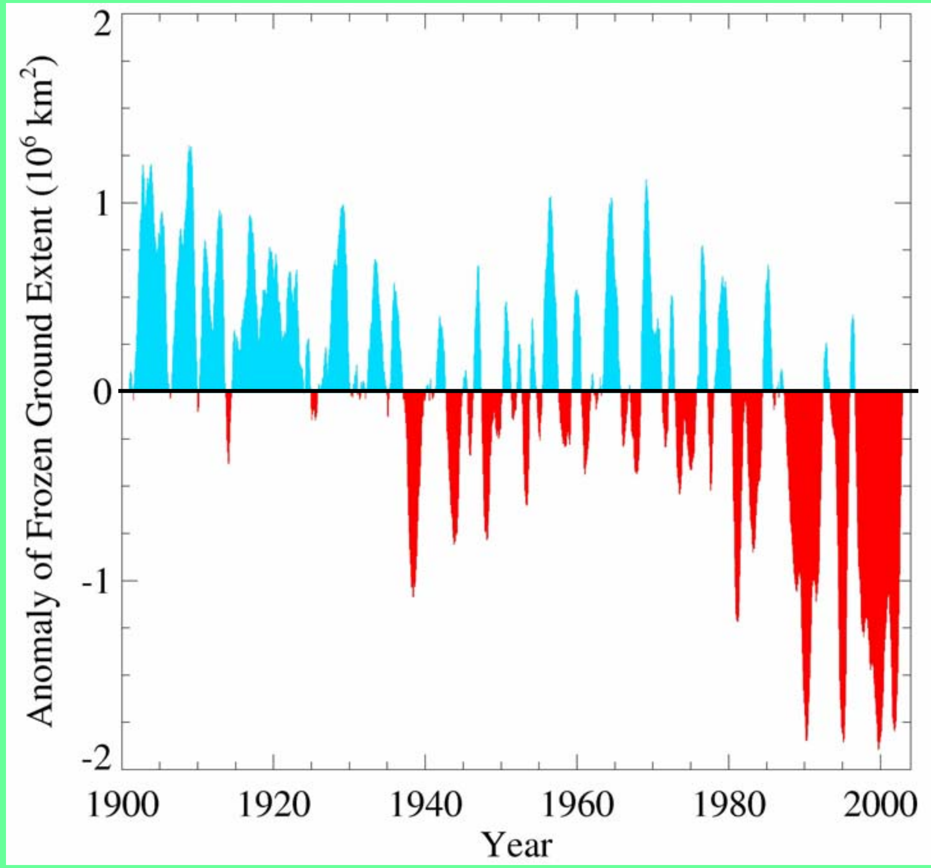
Glaciers and frozen ground are receding

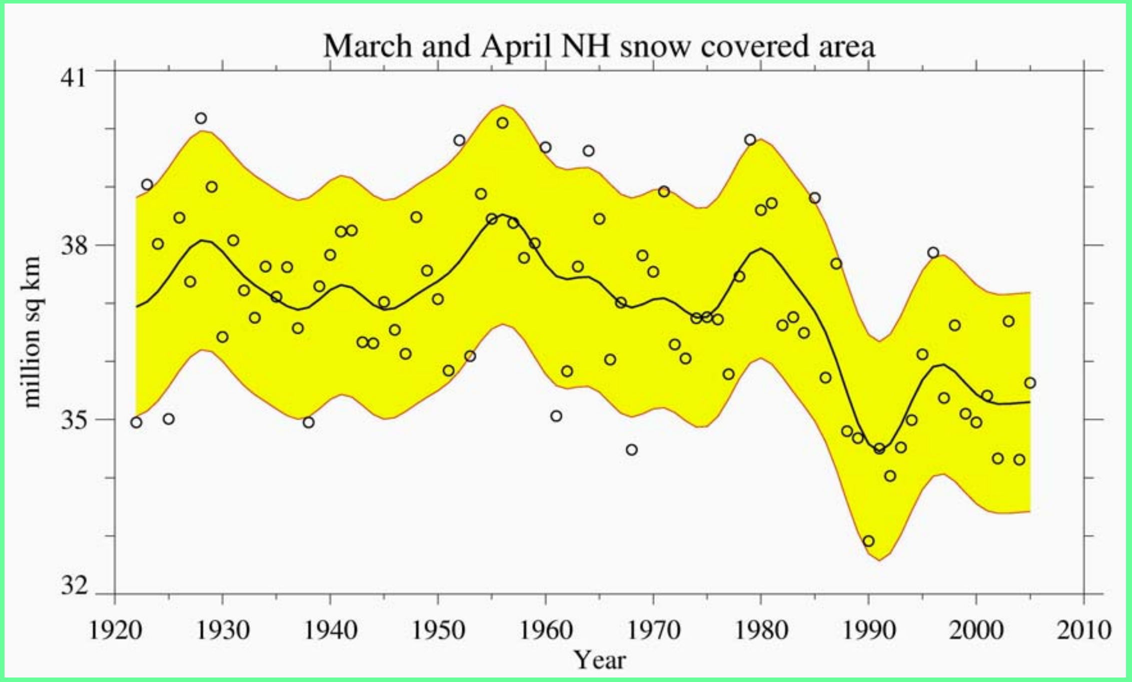


Increased Glacier retreat since the early 1990s

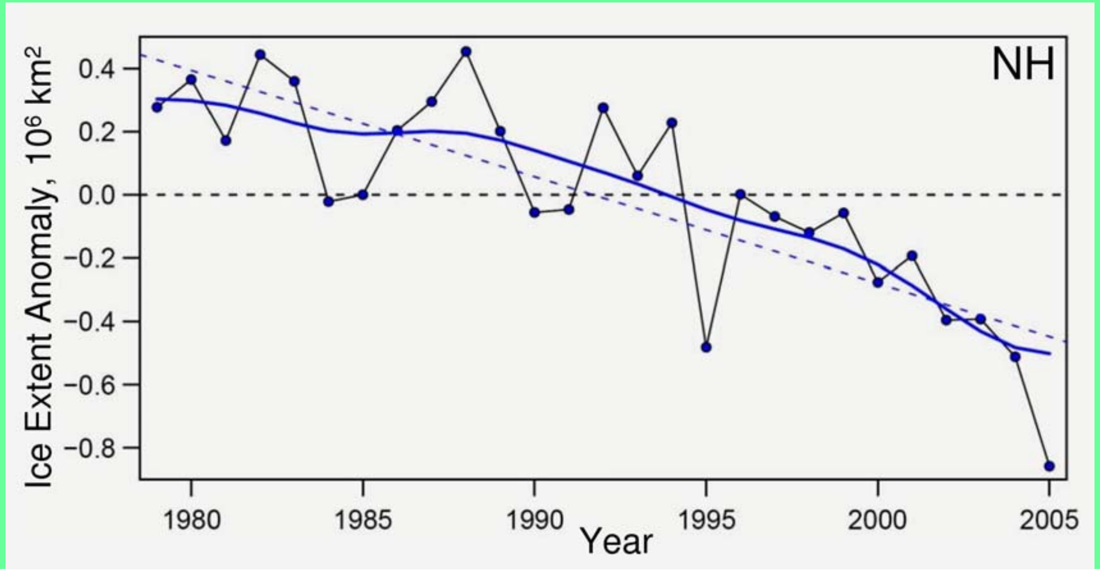


Area of seasonally frozen ground in NH has decreased by 7% from 1901 to 2002

Snow cover and Arctic sea ice are decreasing



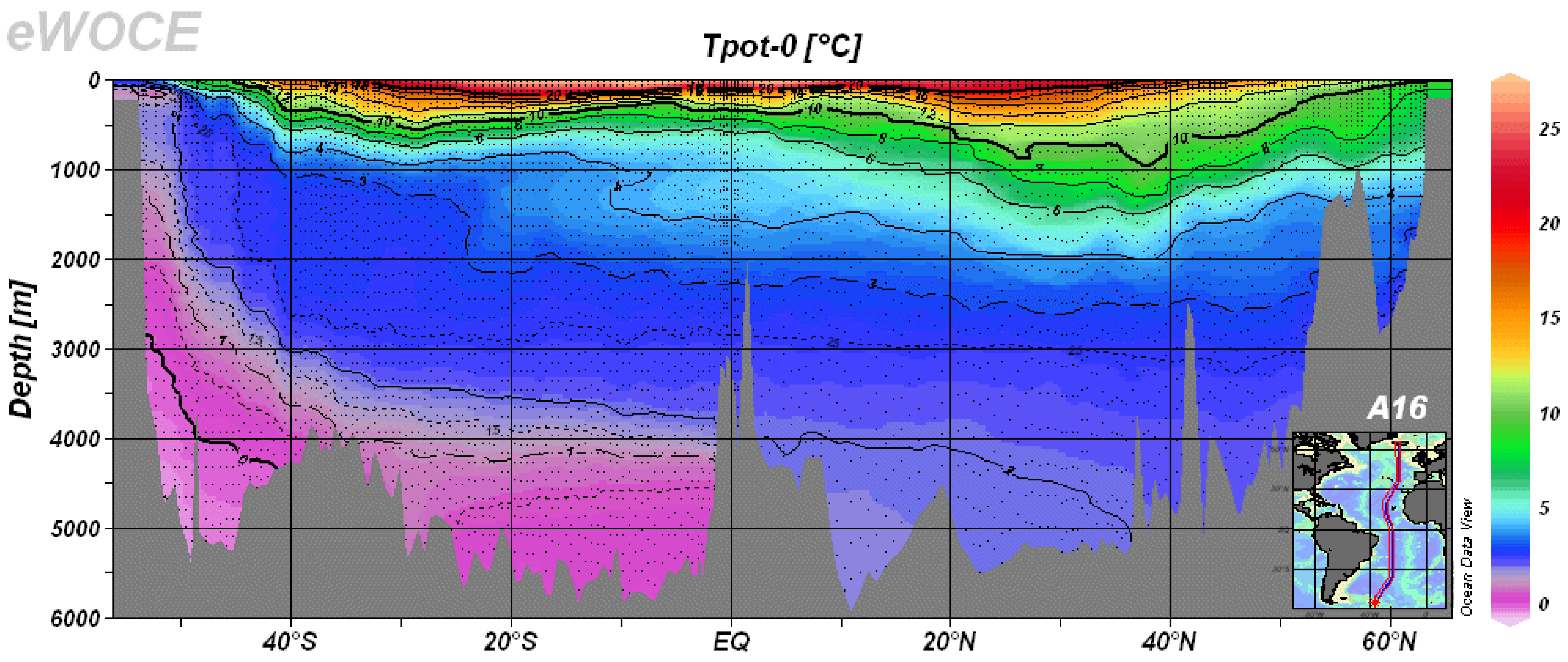
Spring snow cover shows 5% stepwise drop during 1980s



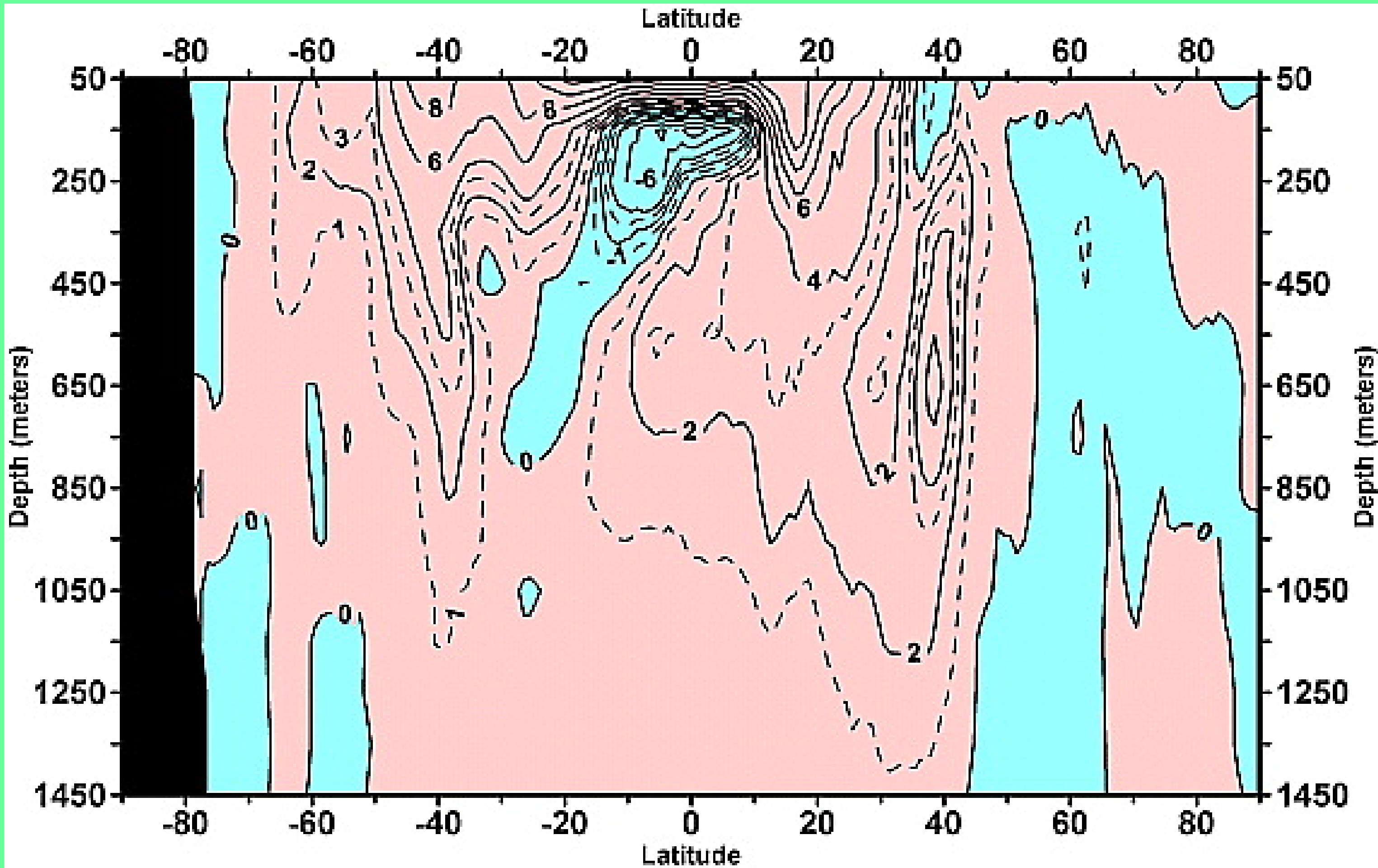
Arctic sea ice area decreased by 2.7% per decade (Summer: -7.4%/decade)

Other evidence of Climate Change

- Ocean heat content has increased
- Temperatures in the Atlantic:

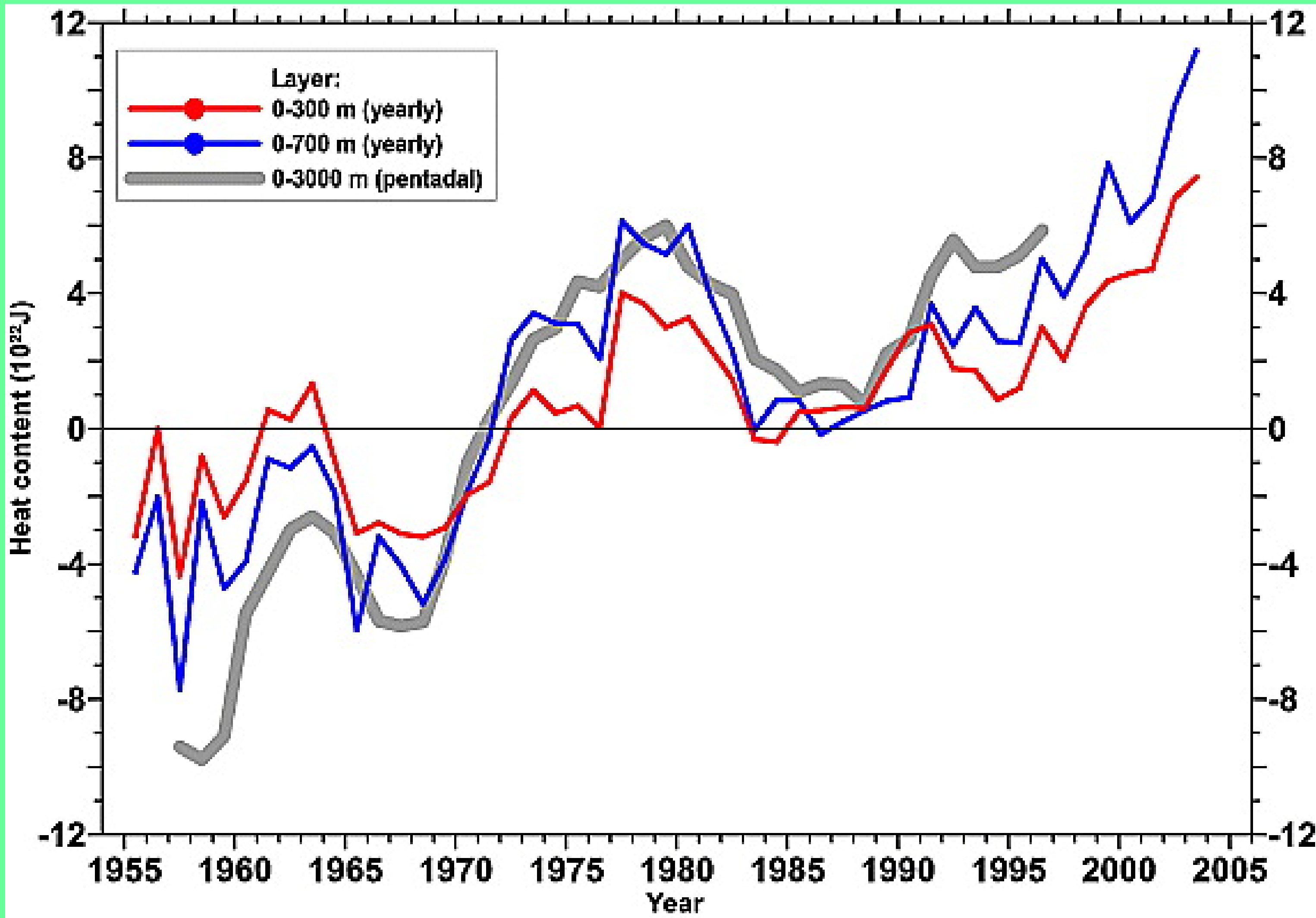


Change in heat content over last 50 years



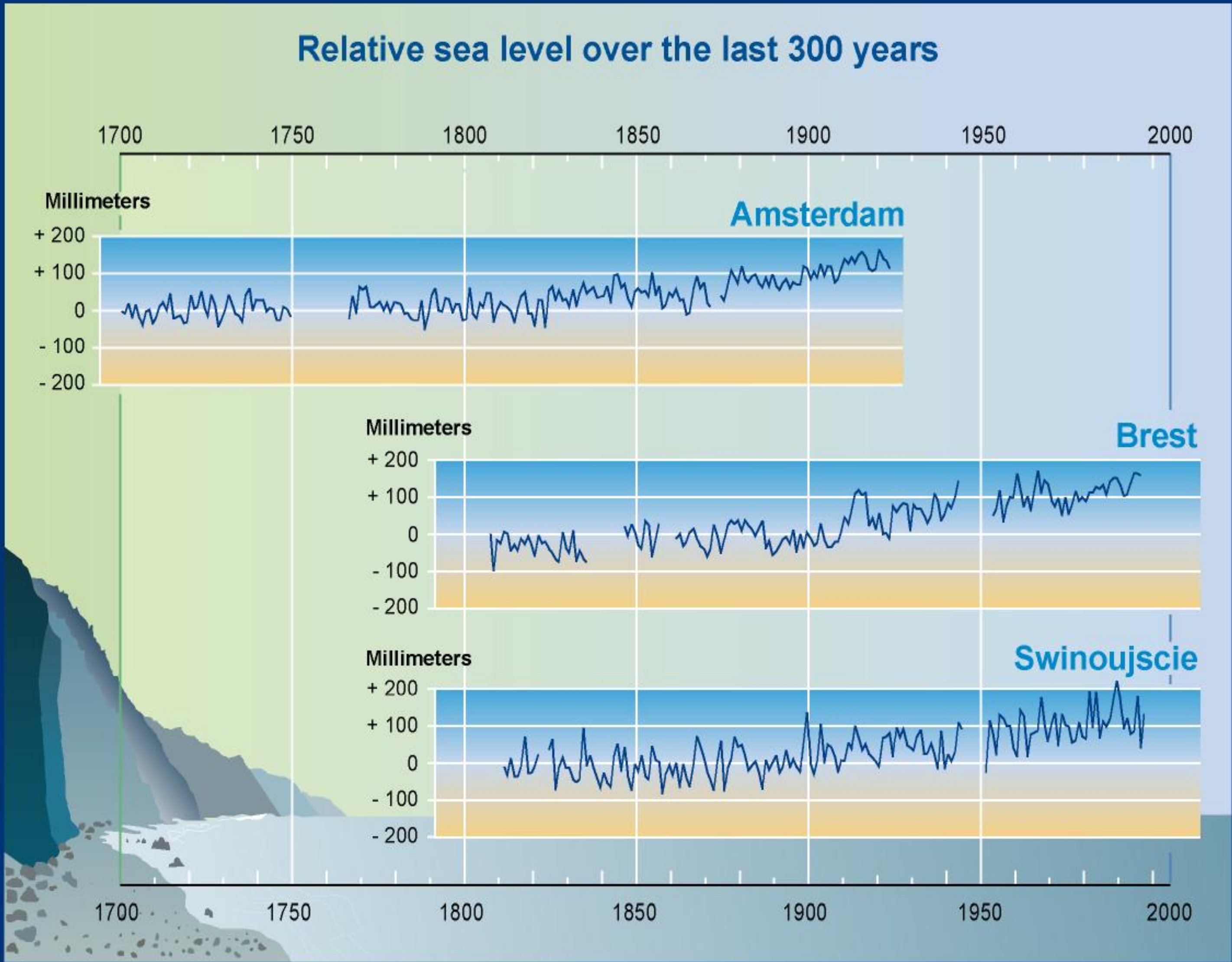
[units: 10^{22} Joules]

Rise in global ocean heat content 1955-2005



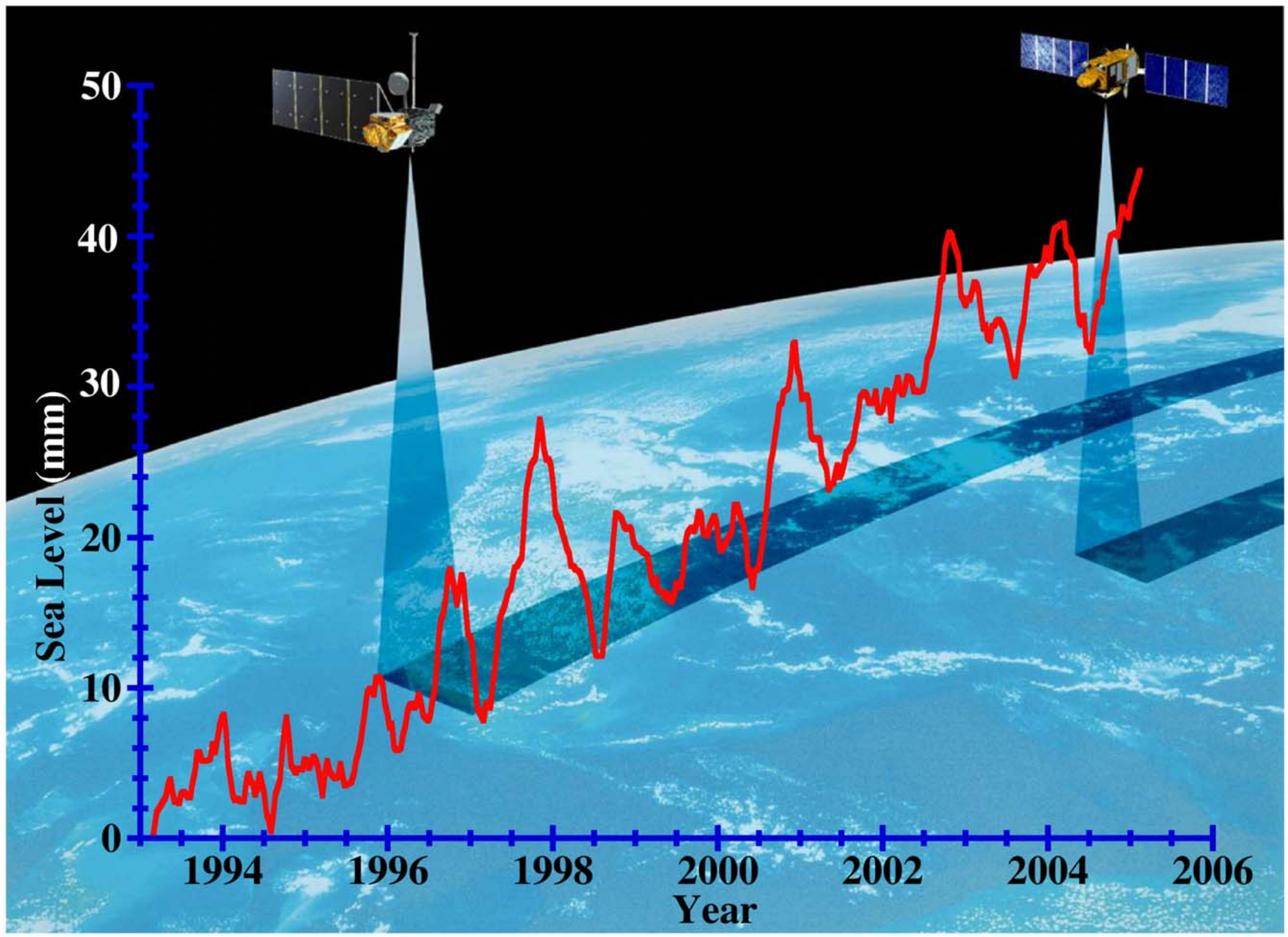
Some ups and downs, but clear overall increase

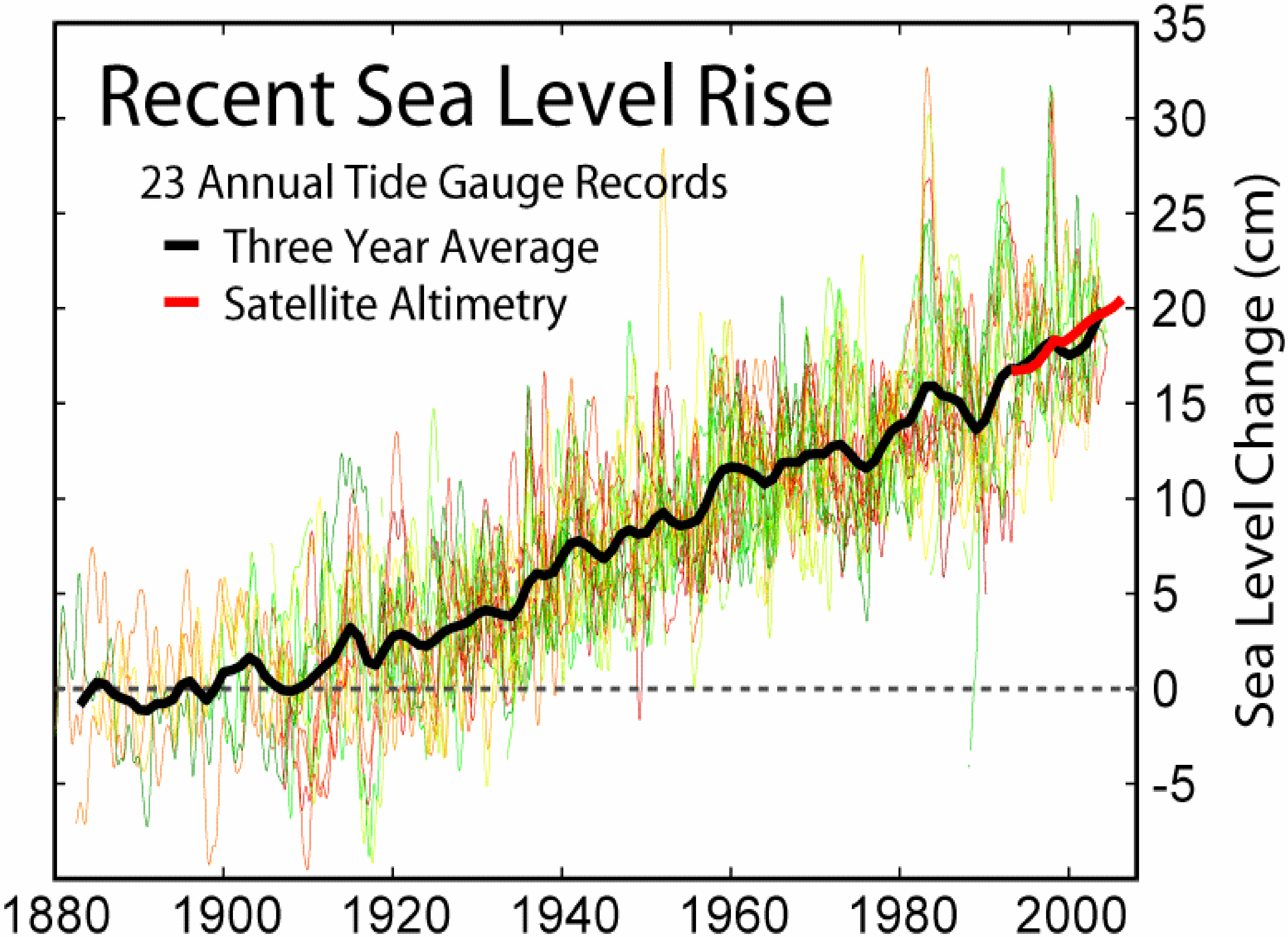
Levitus et al., 2005, GRL



SYR - FIGURE 2-5

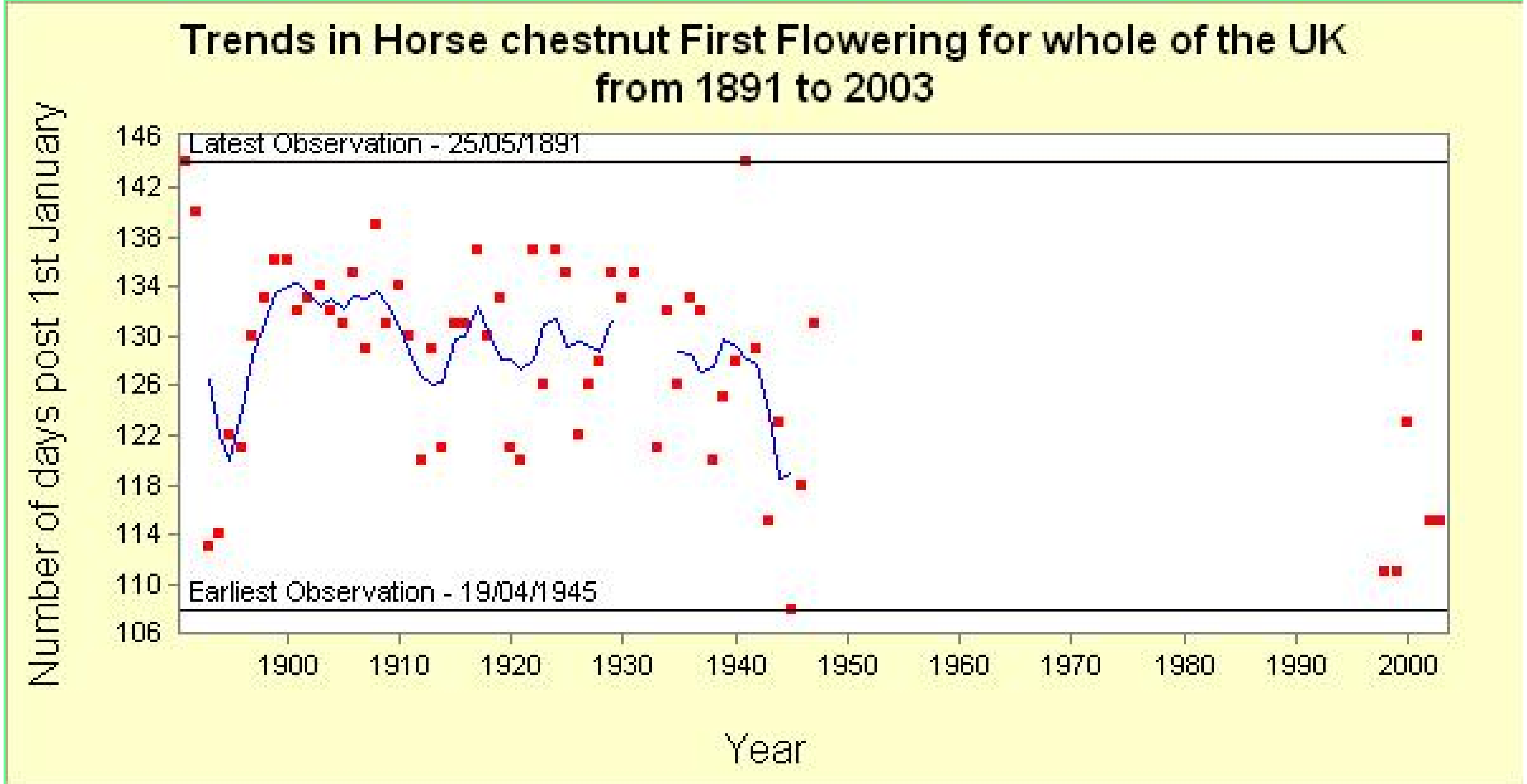
Sea-level from satellites: 4 cm rise in 10 years





Recent Sea Level Rise
23 Annual Tide Gauge Records
Three Year Average
Satellite Altimetry
Sea Level Change (cm)
35
30
25
20
15
10
5
0
-5
1880
1900
1920
1940
1960
1980
2000

Evidence from Phenology (timings of natural events)



www.phenology.org.uk

Direct Observations of Recent Climate Change

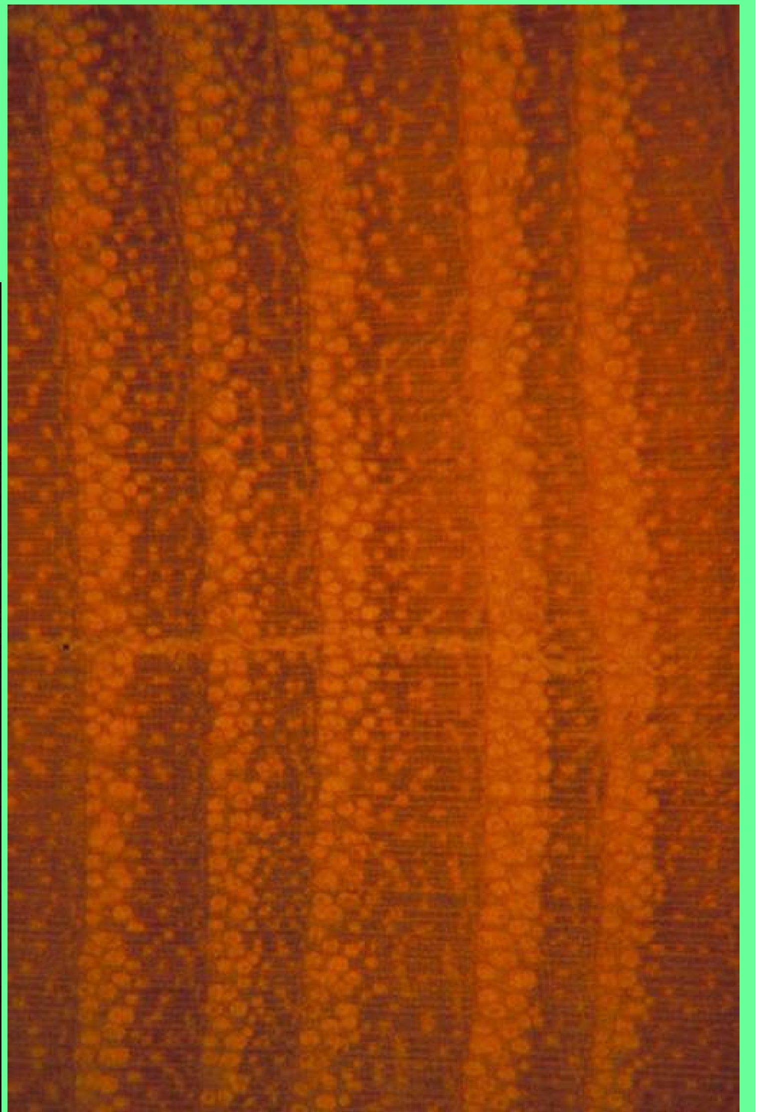
Some aspects of climate have not been observed to change:

- **Tornadoes**
- **Dust-storms**
- **Hail**
- **Lightning**
- **Antarctic sea ice**

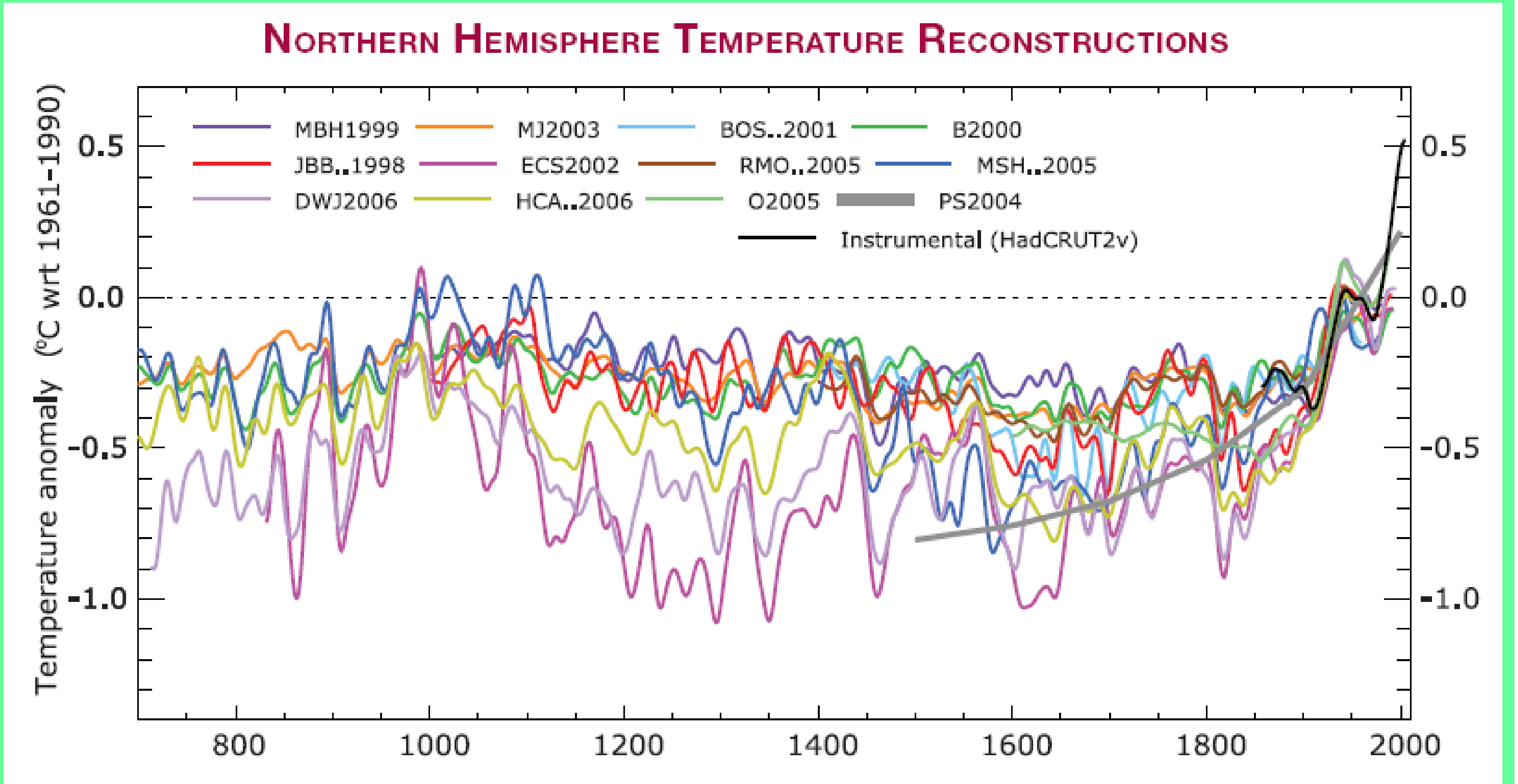
Records further back in time (paleo-data or proxy data)

- E.g. tree rings

Bristlecone Pine (USA) – up to 10000 years old

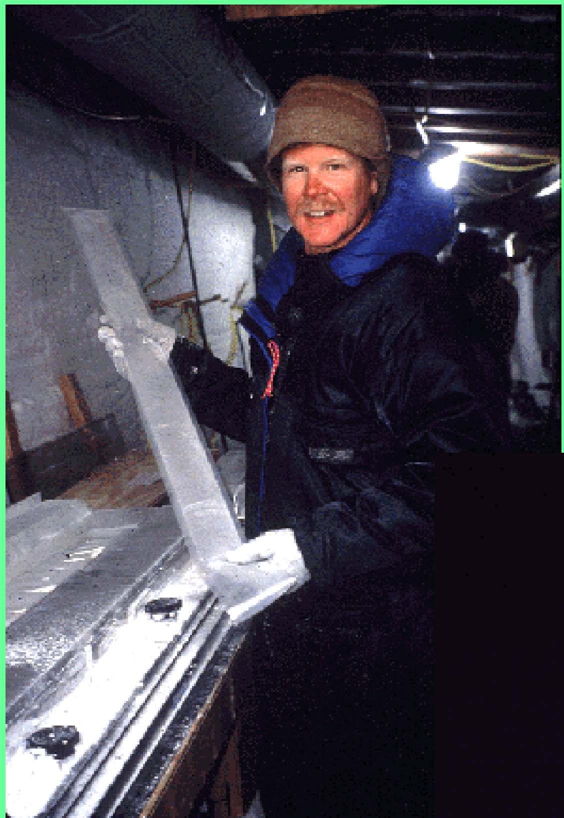


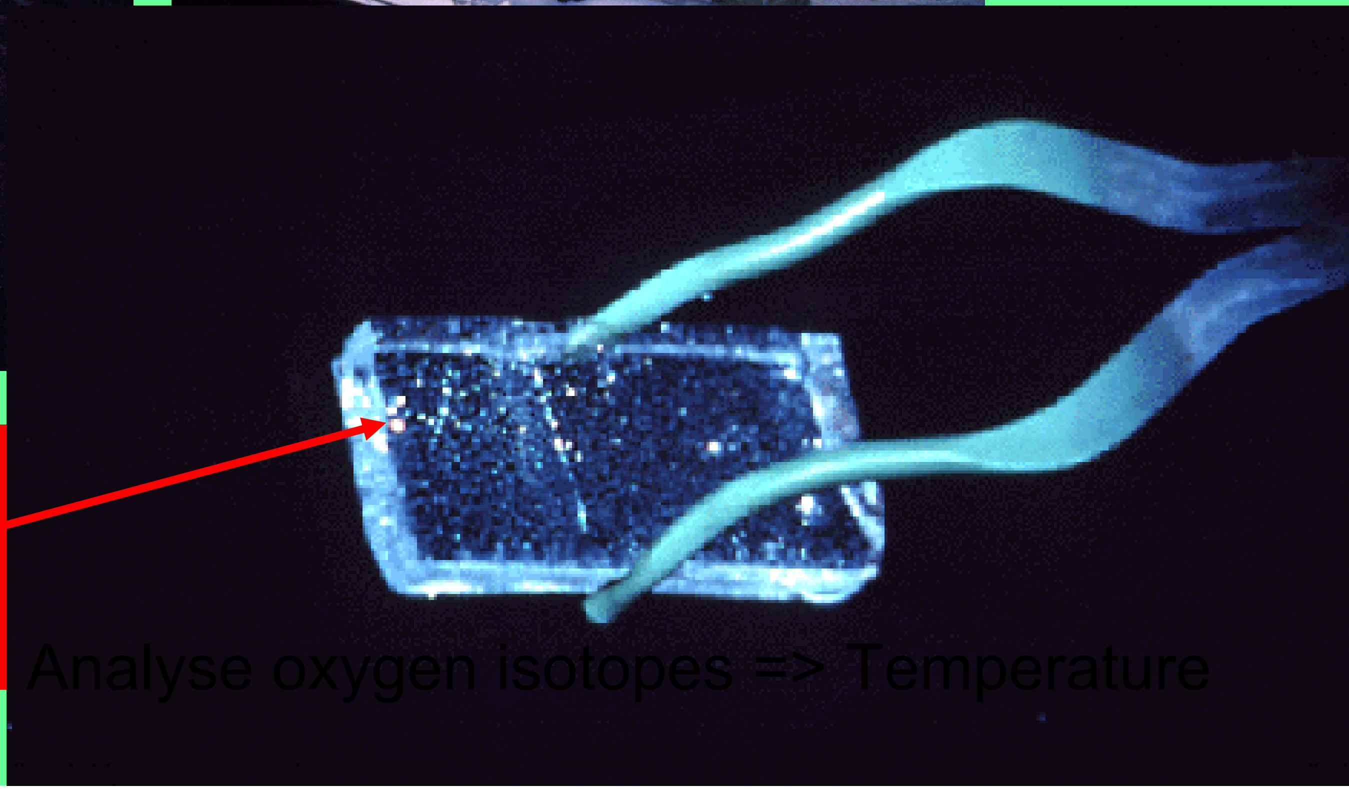
Northern Hemisphere Temperature AD 700-2000
– several different reconstructions from proxy data



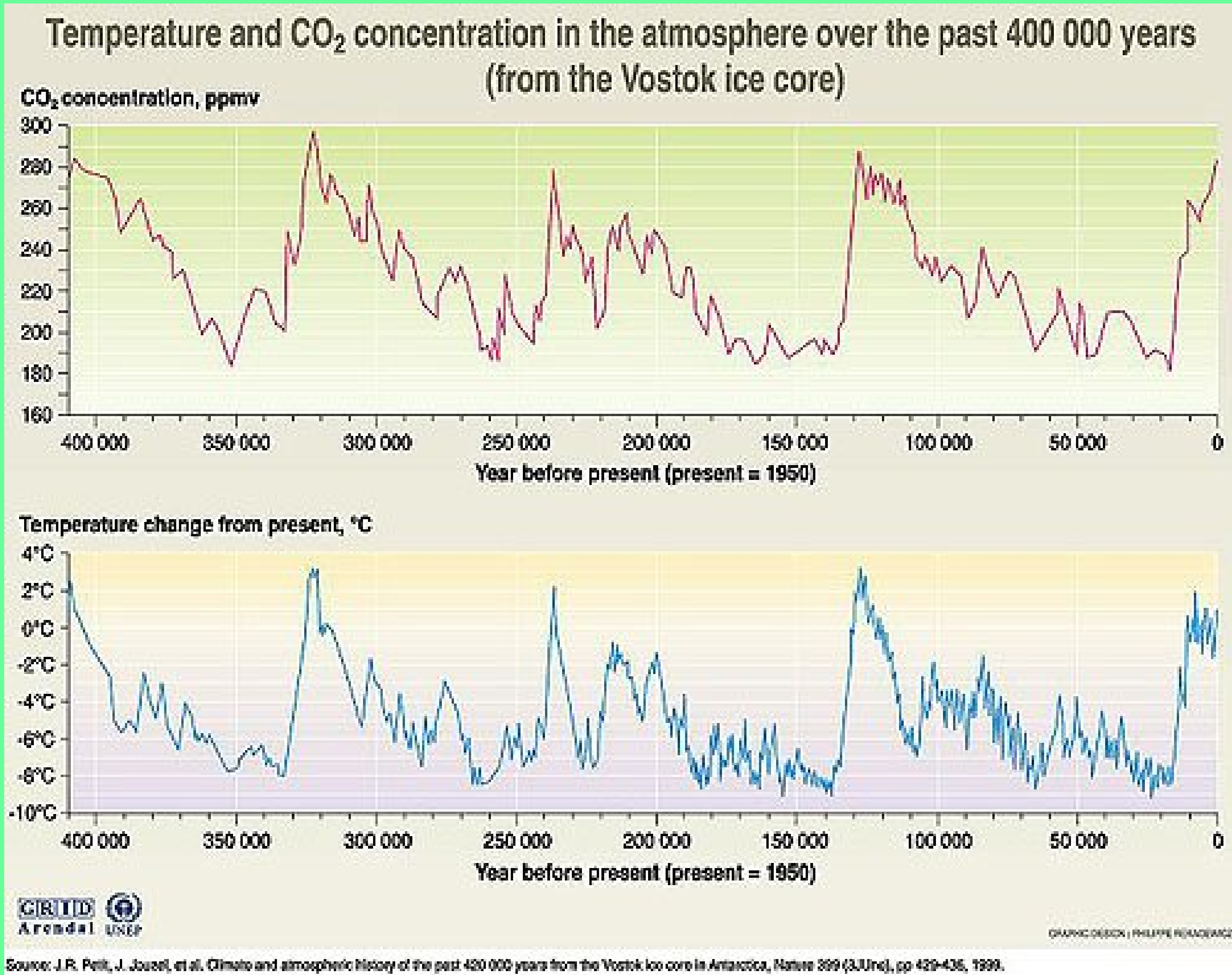
Warming in last 100 years appears exceptional.
But is the uncertainty range (the spread of different reconstructions) large enough?

Ice cores – store past samples of the atmosphere

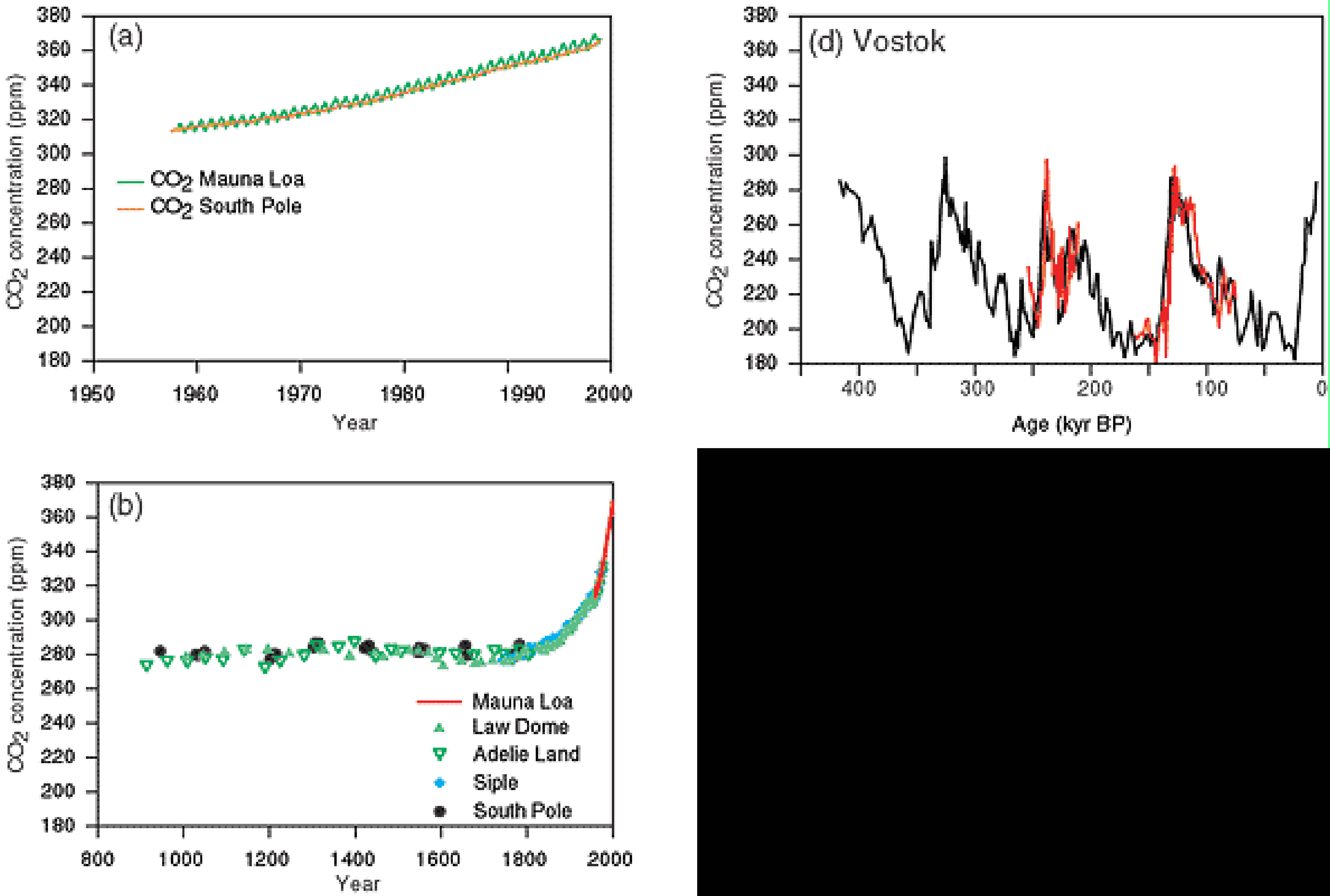




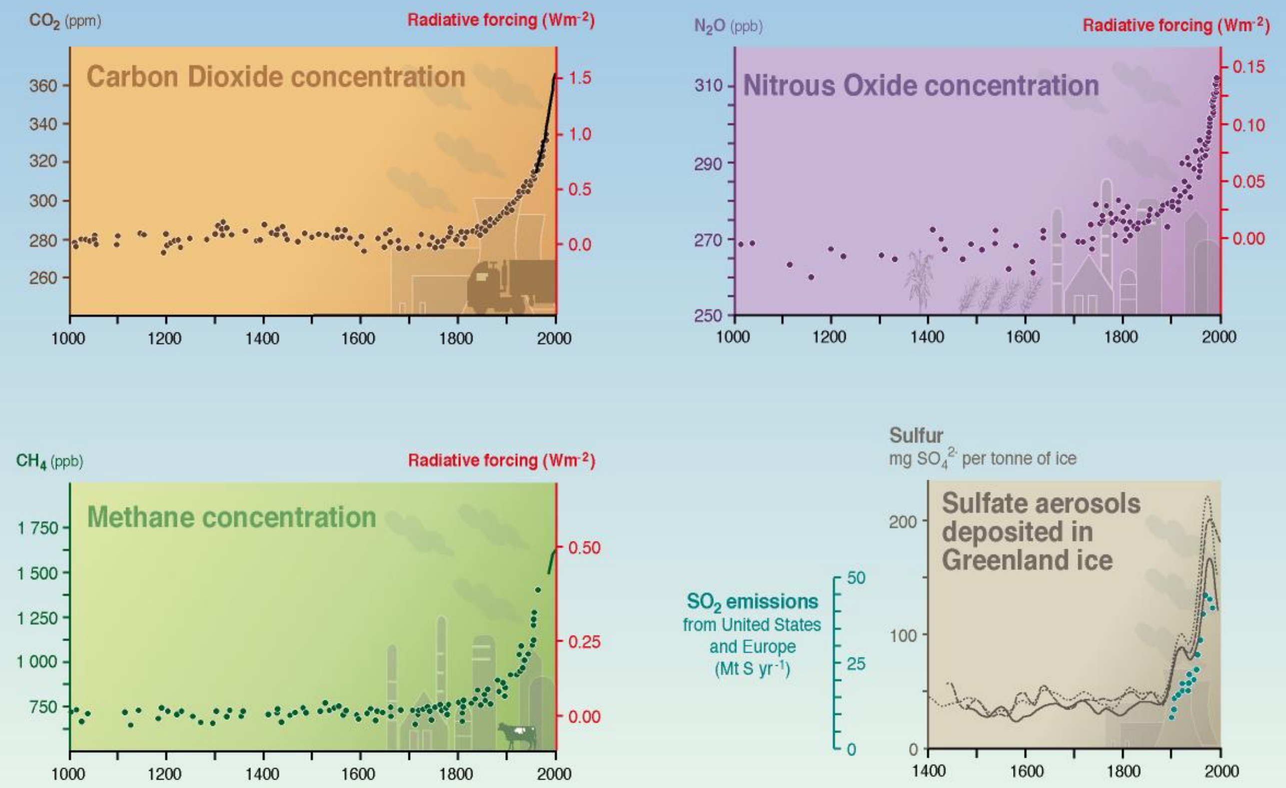
Bubbles of air trapped when ice formed


Temperature and CO2 concentration in the atmosphere over the past 400 000 years
(from the Vostok ice core)
CO2 concentration, ppmv
300
280
260
240
220
200
180
160
400 000
350 000
300 000
250 000
200 000
150 000
100 000
50 000
0
Year before present (present = 1950)
Temperature change from present, °C
4°C
2°C
0°C
-2°C
-4°C
-6°C
-8°C
-10°C
400 000
350 000
300 000
250 000
200 000
150 000
100 000
50 000
0
Year before present (present = 1950)
GRID Arendal
UNEP
Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, Nature 399 (3JUne), pp 429-436, 1999.

Variations in atmospheric CO_2 concentrations on different time-scales

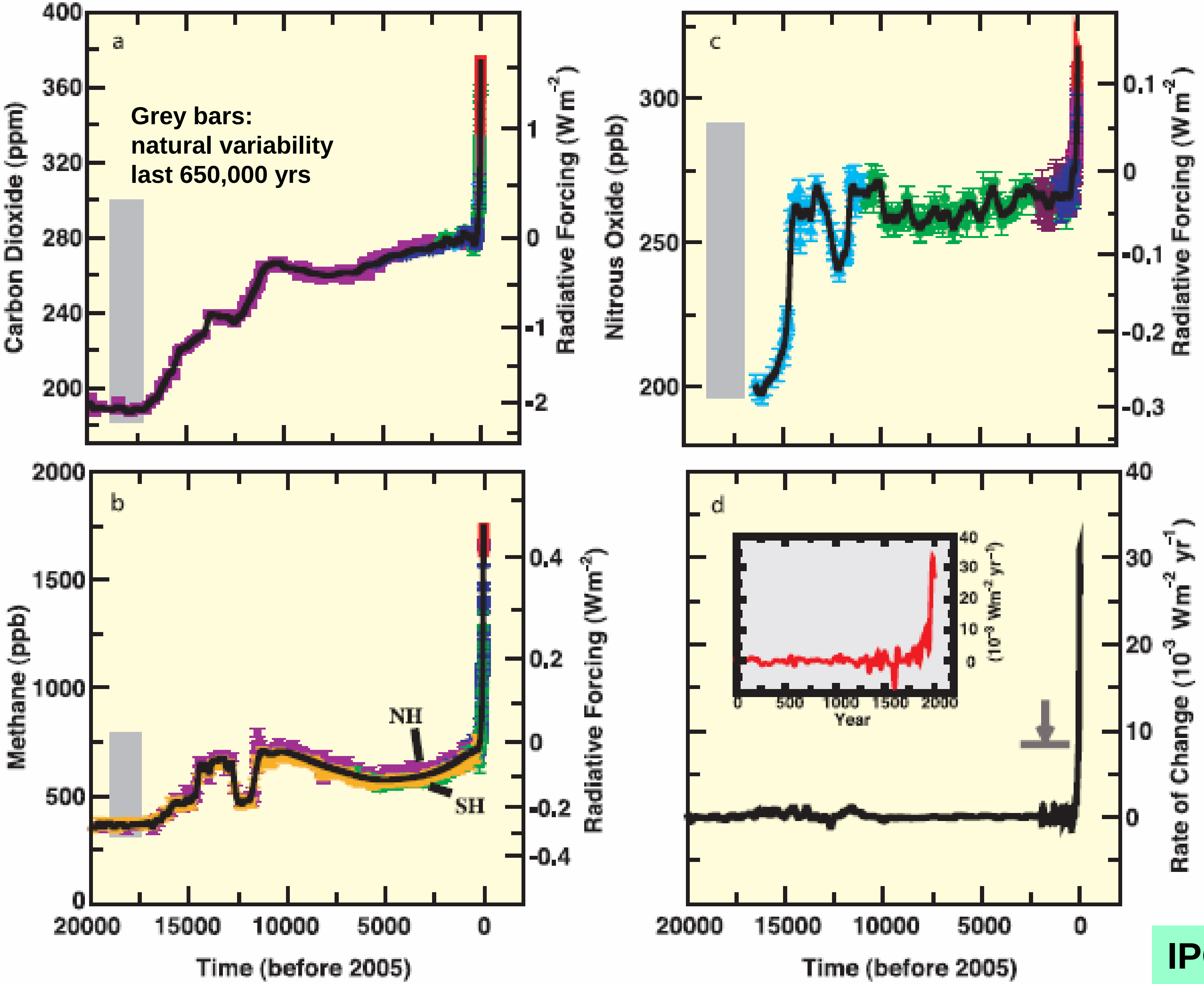


Indicators of the human influence on the atmosphere during the Industrial era



SYR - FIGURE 2-1
WG1 FIGURE SPM-2

Changes in Greenhouse Gases from Ice Core and Modern Data



Rate of change of combined forcing

IPCC report

Summary -- Observations

- Global surface temperatures have risen by about 0.9°C since 1900
- It is likely that this warming is larger than for any century in the last 2000 years, and that the 1990s were the warmest decade in the last millennium.
- The warming differs in different parts of the world, but over the last 25 years, almost everywhere has warmed, and very few places have cooled.
- Other changes have occurred, e.g.:
  - Sea level has risen by about 40 cm,
  - Ocean heat content has increased,
  - Almost all mountain glaciers have retreated
- Coincident with this global warming, levels of CO_2 (and other ‘greenhouse’ gases) have dramatically increased, to levels higher than those experienced for maybe millions of years.

How we can have informations on climate future???

CLIMATE MODELLING

an overview

Key Questions

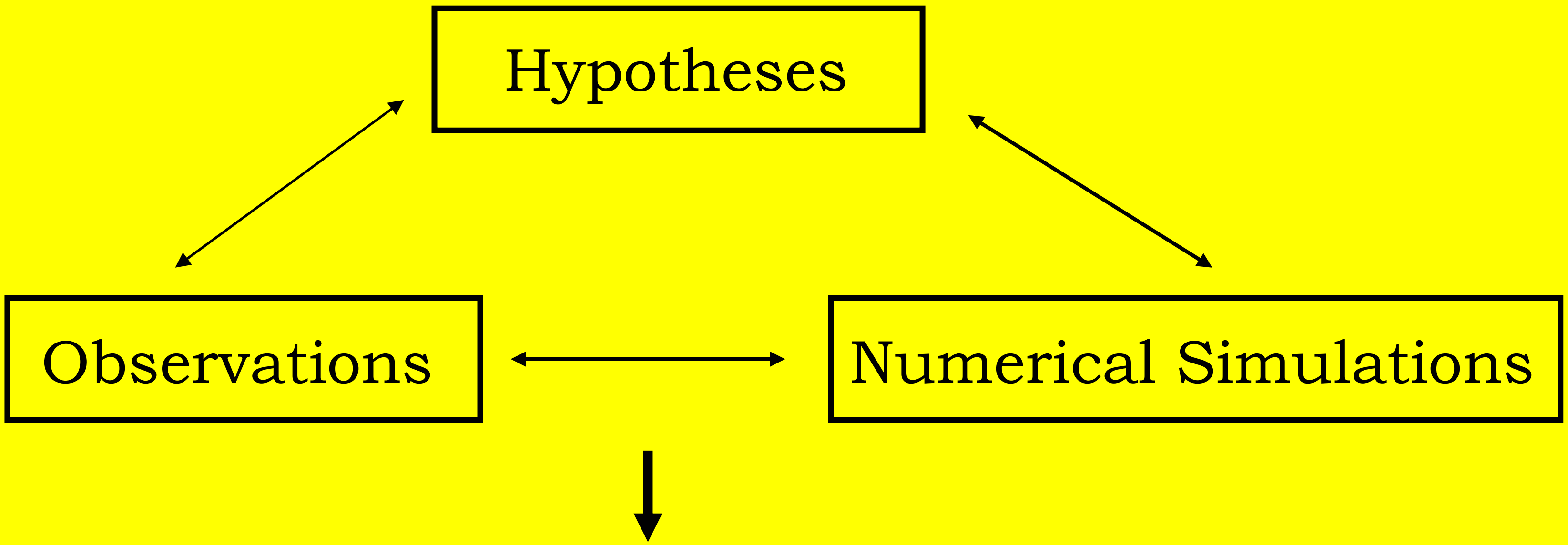
- What is a climate model?
- Why use them?
- What types of climate models are there?

What is a climate model?

- A mathematical representation of the many processes that make up our climate.

- Requires:
  - Knowledge of the **physical laws** that govern climate
  - **Mathematical expressions** for those laws
  - **Numerical methods** to solve the mathematical expressions on a computer (if needed)
  - A computer of **adequate size** to carry out the calculations

Why Numerical climate simulations ?



- **Understanding of cause and effect**
- Predictive skill: our main tool to make predictions for the future

Important climate model components

- Radiation
  - as it drives the system each climate model needs some description of the exchange of **shortwave and longwave radiation**
- Dynamics
  - the **movement of energy** in the system both in the horizontal and vertical (winds, ocean currents, convection, bottom water formation)
- Surface processes
  - the exchange of energy and water at the ocean, **sea-ice** and **land surface**, including albedo, emissivity, etc.
- Chemistry
  - chemical **composition** of the atmosphere, land and oceans as well as exchanges between them (e.g., carbon exchanges)

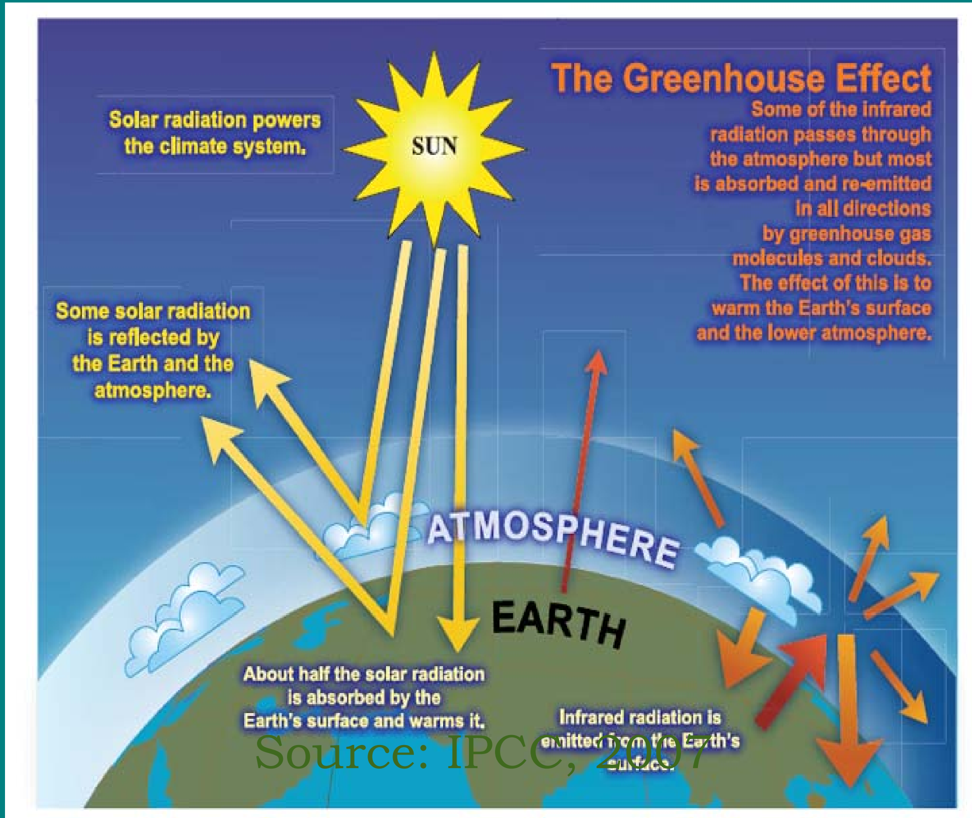
Model resolution

- Depending on our question we need to decide how to divide the Earth in our model and how often we need to calculate the state of the system.
  - Choices in space are 0-d (point), 1-d (e.g., 1 vertical column), 2-d (1 vertical layer, latitude and longitude), and 3-d (many layers, lat and lon)

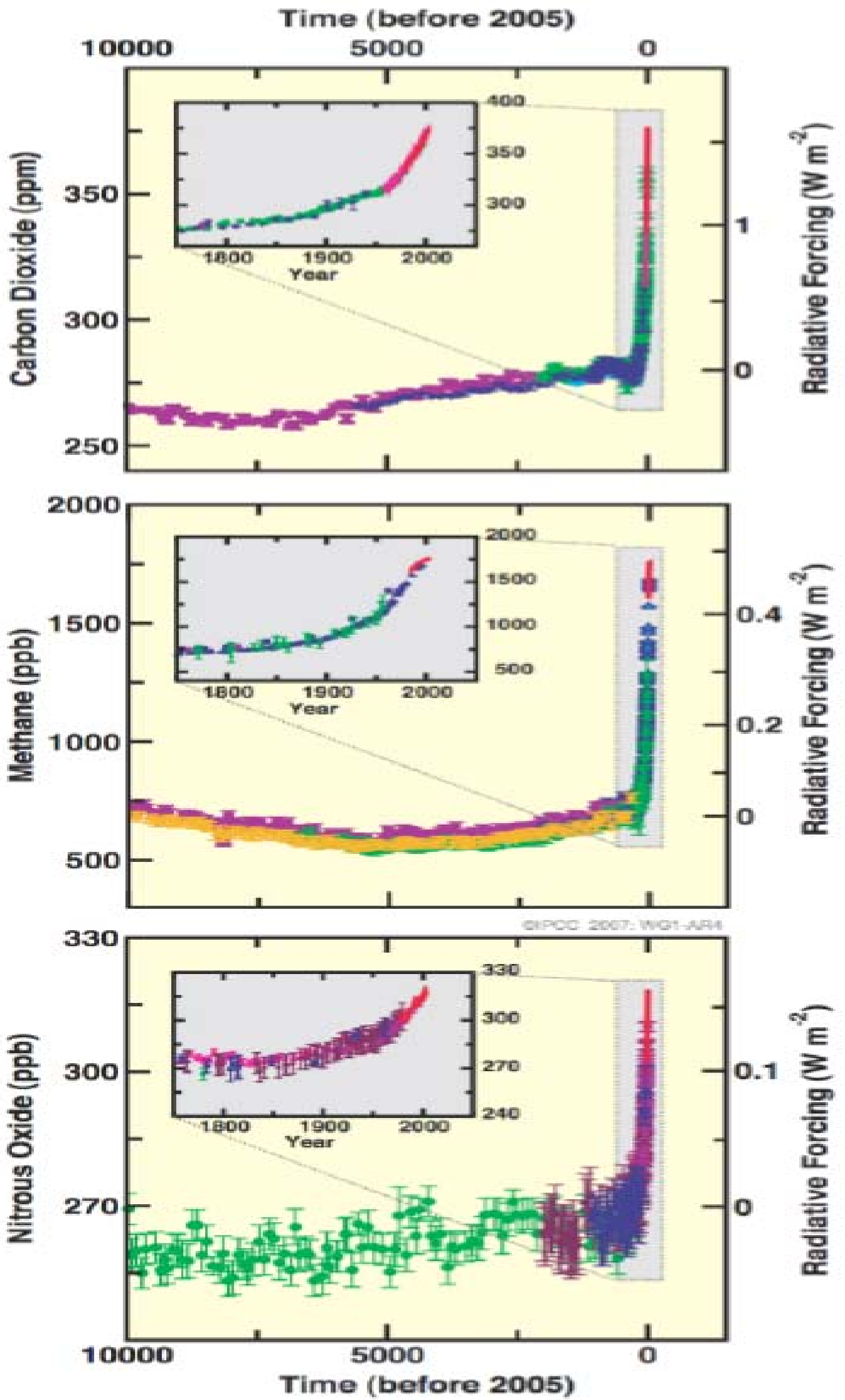
  Examples:
  - A global **energy balance model** treats the Earth as one point and has **no time** resolution
  - Weather forecast models calculate the weather every few minutes, every 10 km.

The Greenhouse Effect
How does it work?

- The atmosphere contains gases that **absorb the infrared radiation** emitted from the surface and then re-emit it from the atmosphere in all directions.
- Some of this radiation will therefore be emitted downwards and be an **additional source of energy** at the surface, which leads to a warming at the surface!



Source: IPCC, 2007



Concentration changes of the greenhouse gases of the atmosphere in the last 10 000 years.

Based on ice score and directly measured data.

Forrás: IPCC, 2007

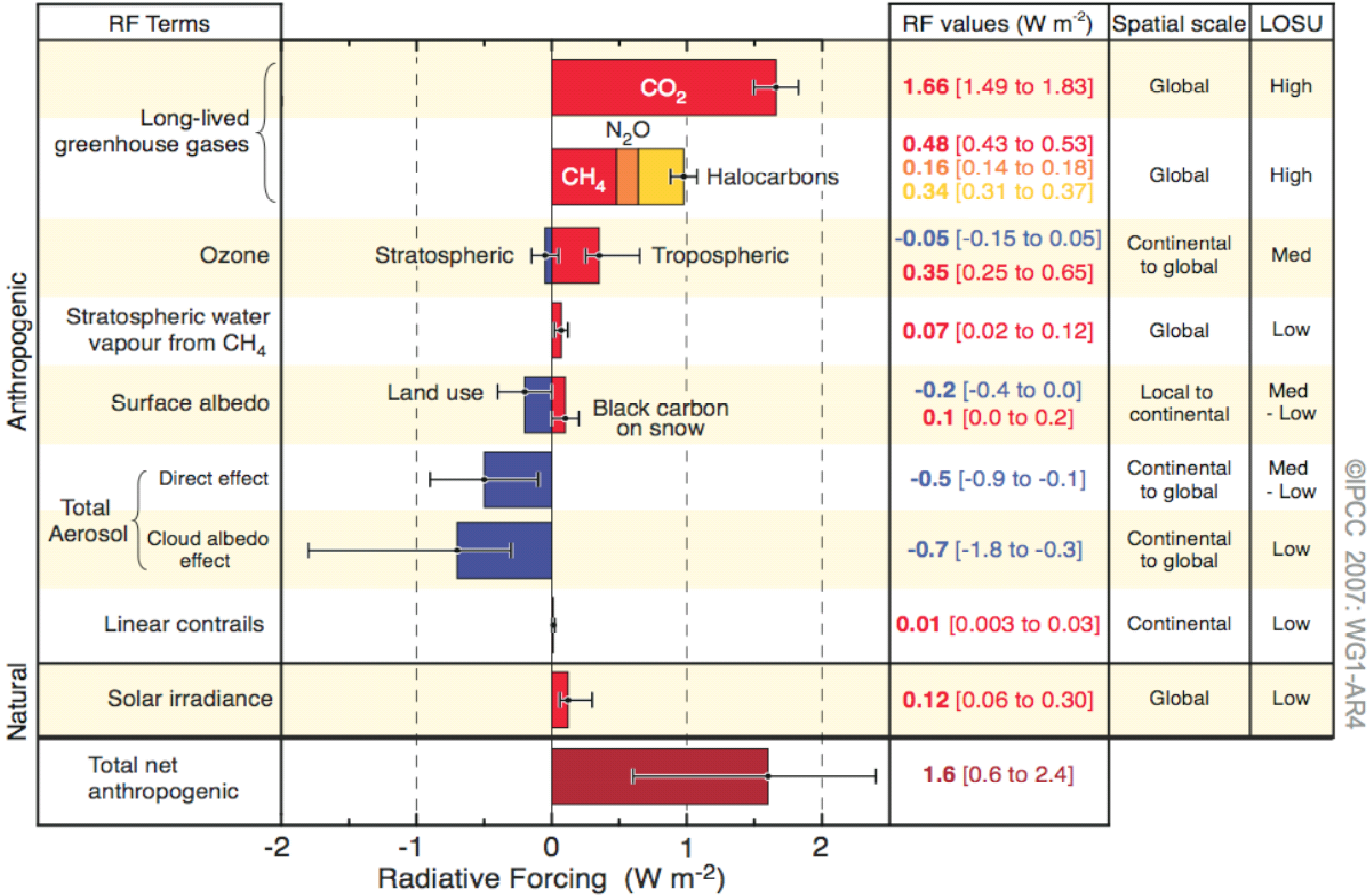
What is Radiative Forcing?

Definition:

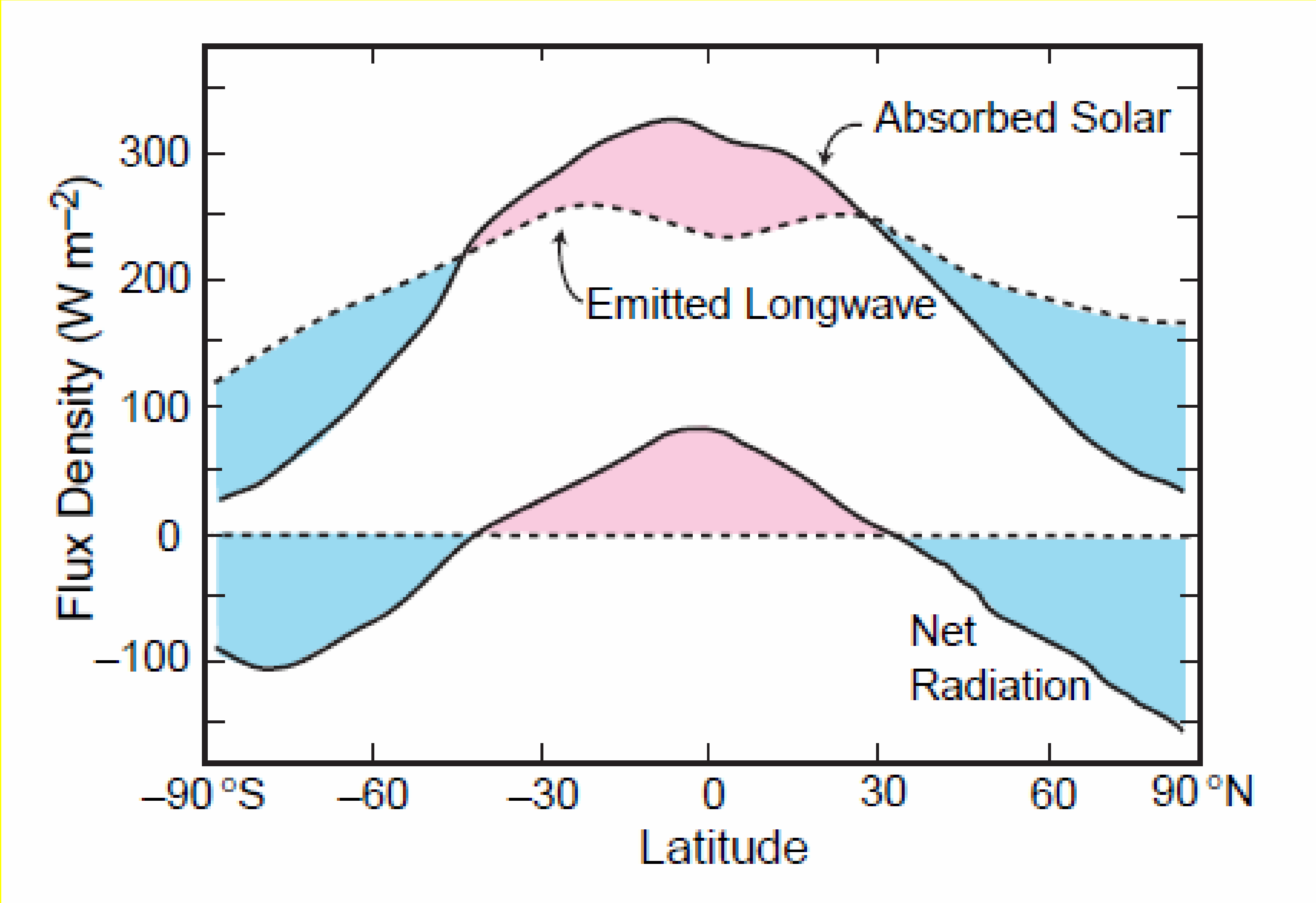
Radiative forcing is a measure of the influence a factor (think CO2) has in **altering the balance of incoming and outgoing energy** in the Earth-Atmosphere system.

In report -IPCC 2007 radiative forcing values are for changes relative to preindustrial conditions defined at 1750 and are expressed in watts per square meter (W/m2).

Estimated changes of the components of the radiative forcing (for 2005)

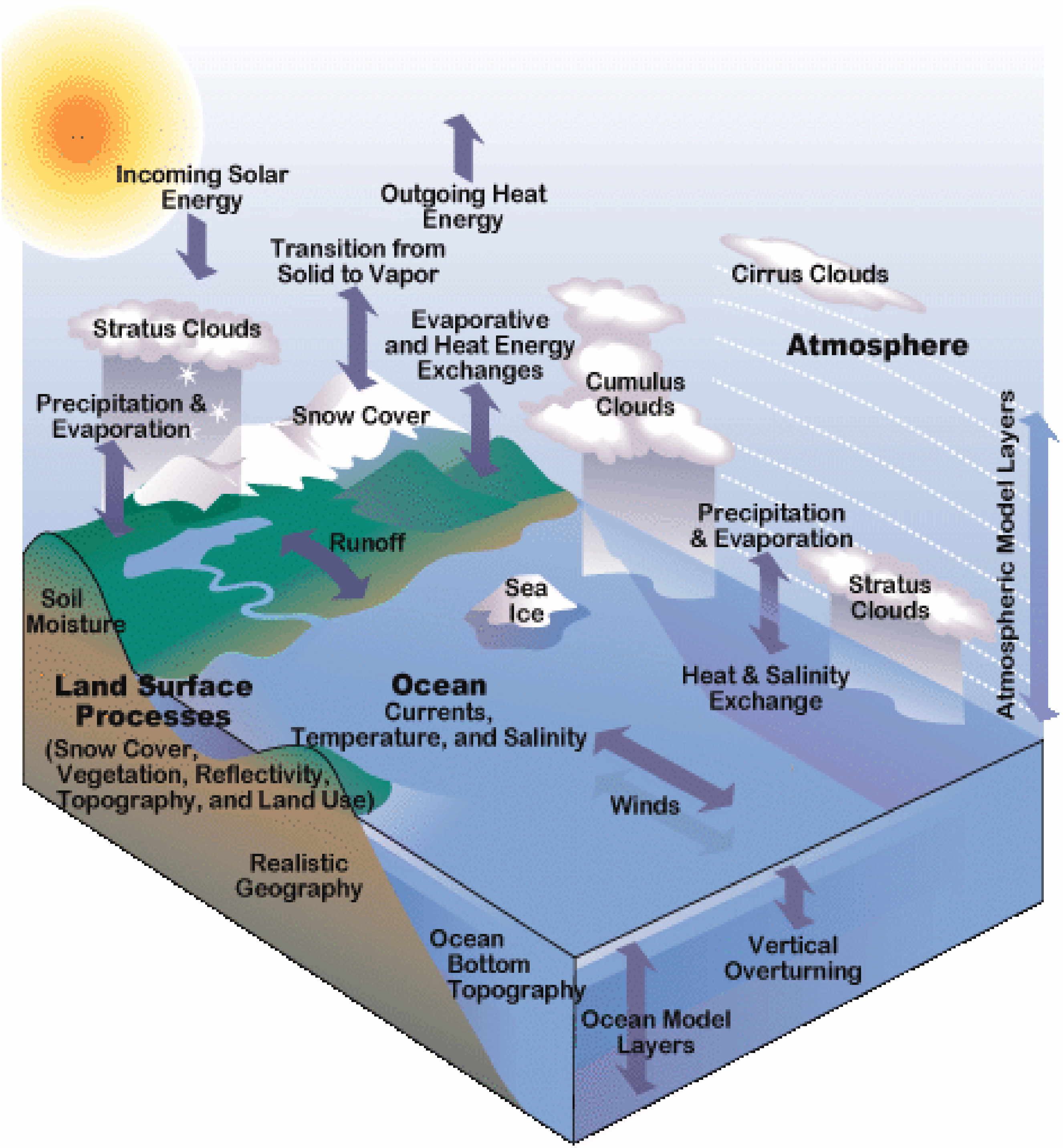


Imbalance of the net radiative balance as a function of latitude



Net warming in the tropics and a net cooling toward the poles

That's why it is warmer in the tropics than at the poles……….



General circulation models

All processes should be included

Atmospheric model Component

$$\frac{du}{dt} - \left(f + u\frac{\tan\phi}{a}\right)v = -\frac{1}{a\cos\phi}\frac{1}{\rho}\frac{\partial p}{\partial\lambda} + F_\lambda$$

E-W wind (zonal)

$$\frac{dv}{dt} + \left(f + u\frac{\tan\phi}{a}\right)u = -\frac{1}{\rho a}\frac{\partial p}{\partial\phi} + F_\phi$$

N-S wind (merid)

$$g = -\frac{1}{\rho}\frac{\partial p}{\partial z}$$

Vertical balance

$$\frac{\partial\rho}{\partial t} = -\frac{1}{a\cos\phi}\left[\frac{\partial}{\partial\lambda}(\rho u) + \frac{\partial}{\partial\phi}(\rho v\cos\phi)\right] - \frac{\partial}{\partial z}(\rho w)$$

Mass

$$c_p\frac{dT}{dt} - \frac{1}{\rho}\frac{dp}{dt} = Q$$

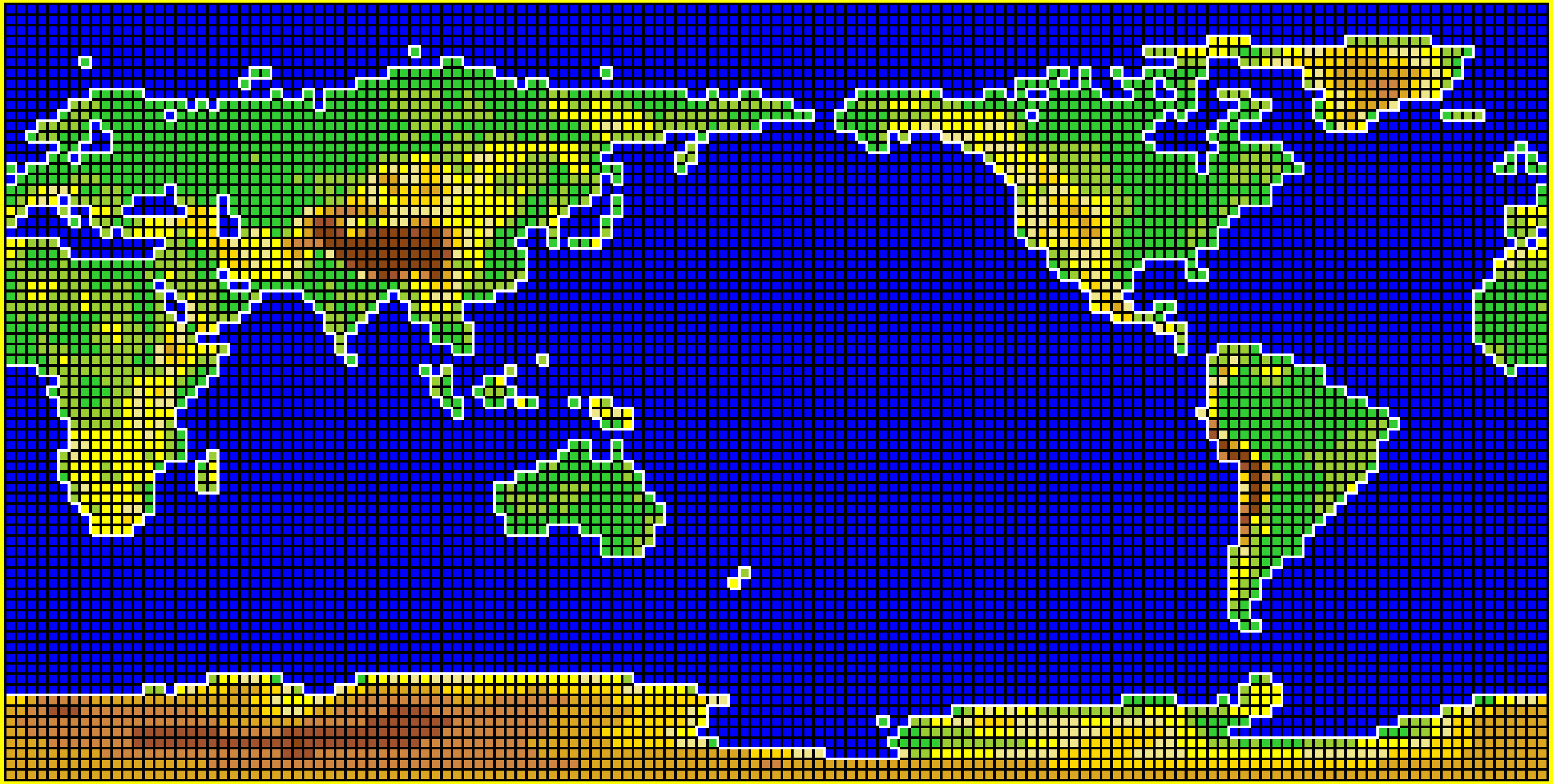
Temperature

$$p = \rho RT$$

Ideal Gas

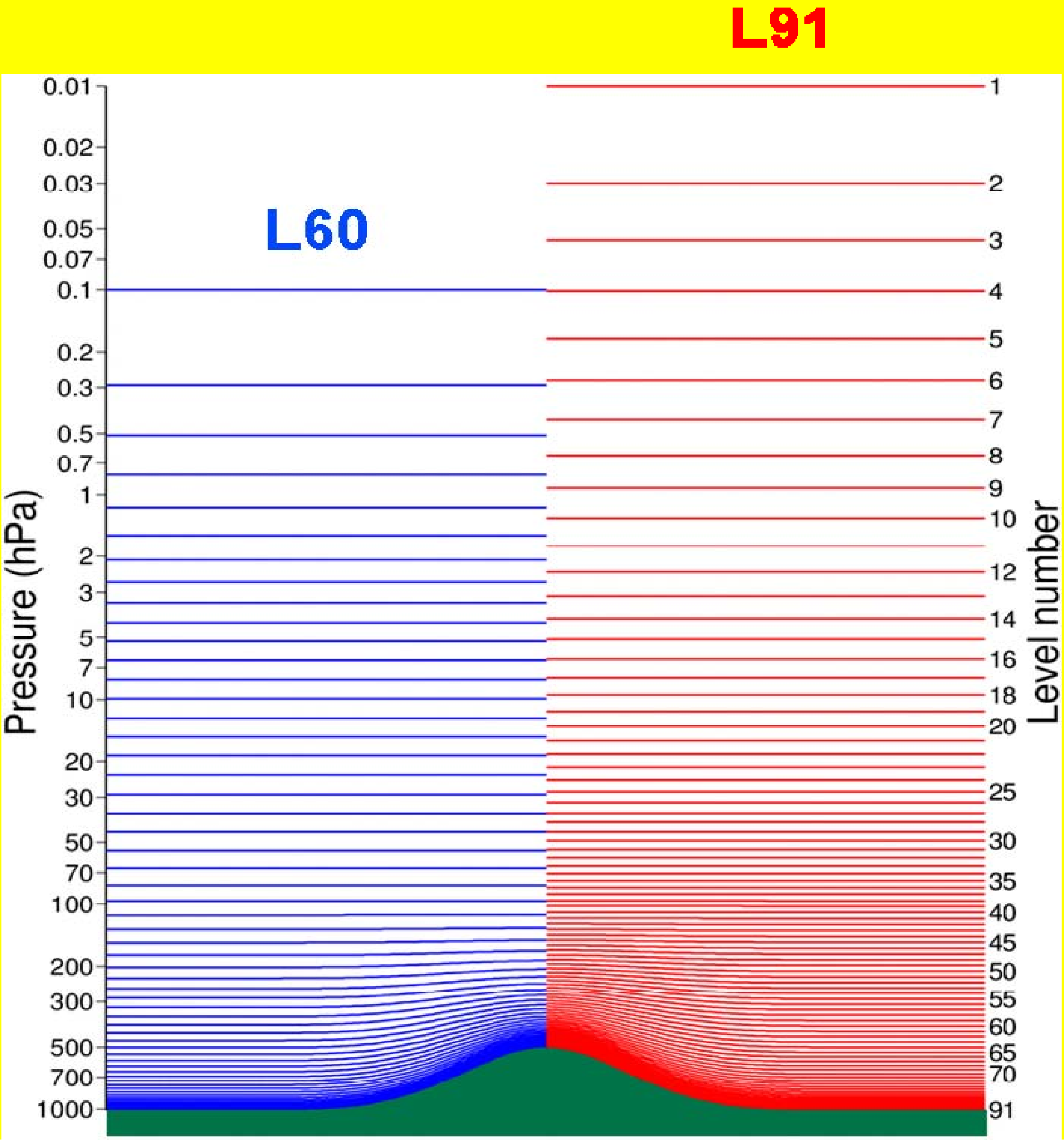
6 equations for 6 unknowns (u,v,w,T,p,ρ) –
Moisture often added as 7th equation

Atmospheric models - dicing up the world



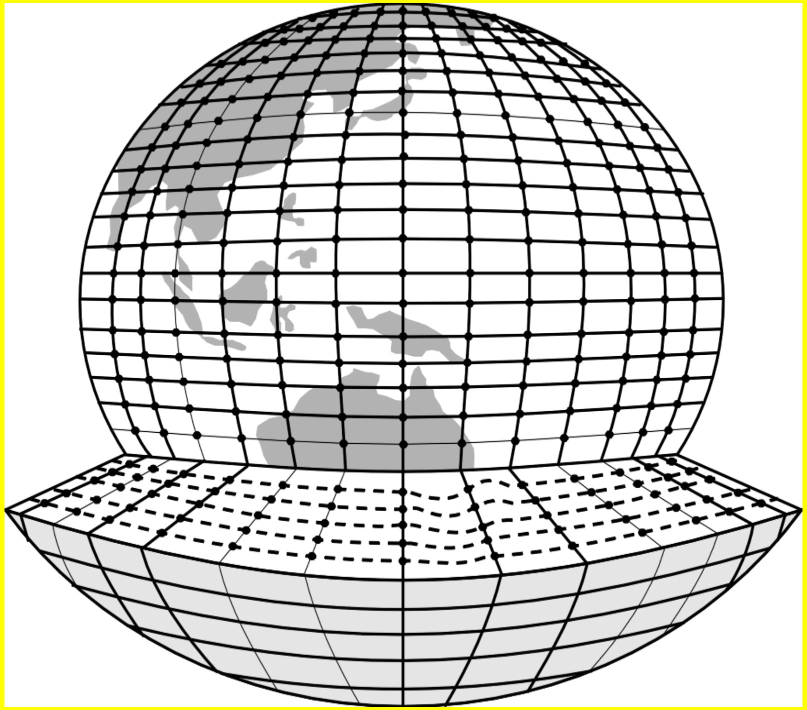
2.5 deg x 2.5 deg grid

Atmospheric models - dicing up the world



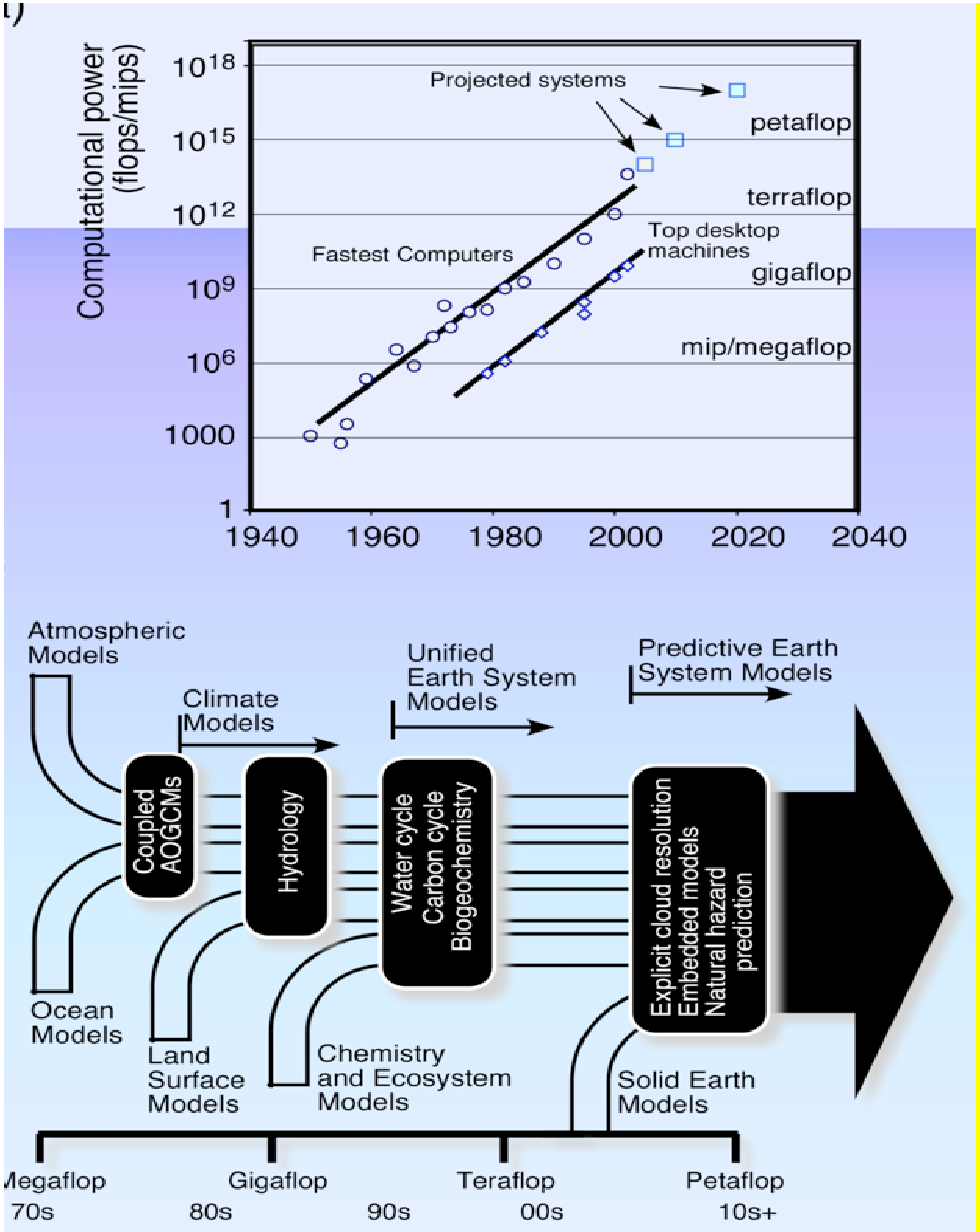
Vertical levels

Atmospheric models – computing capacity



How many calculations does an atmospheric model have to perform:

- **2.5 x 2.5 degrees (~ 250 km x 250 km) -> about 10,000 grid**
- **30 layers in the vertical -> about 300,000 grid boxes**
- **At least 7 unknowns -> about 2.1 million variables**
- **Assume 20 calculations (low estimate) for each variable -> about 42 million calculations per time-step**
- **Time step of 30 minutes -> about 2 billion calculations per day**
- **100 years of simulation -> 73 trillion calculations**



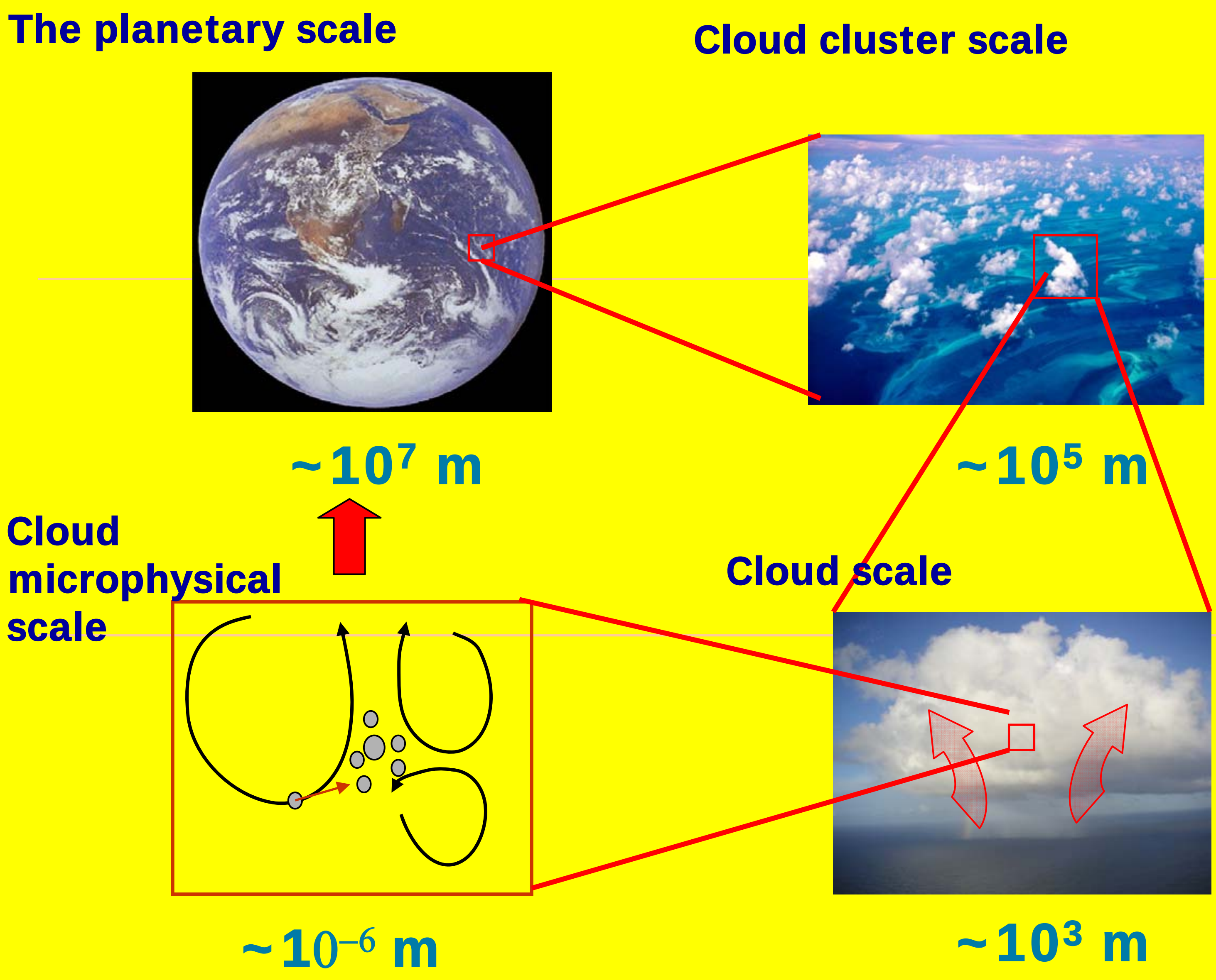
Climate Computing

Climate modelling requires the use of the most powerful supercomputers **on Earth, and even with those we have to simplify the models.**

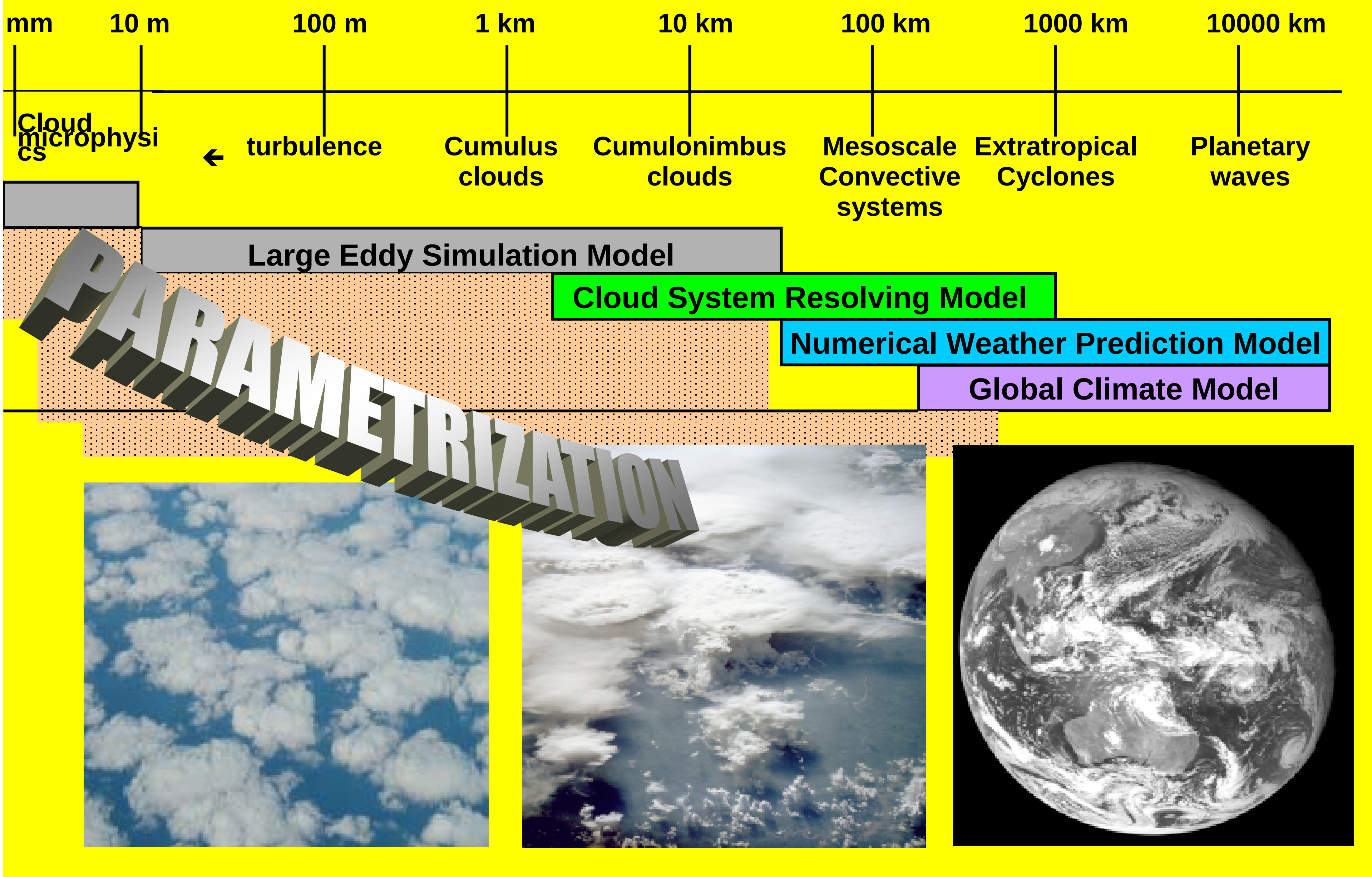
Climate modelling is therefore limited by the computer capabilities **and will be for the foreseeable future.**

McGuffie and Henderson-Sellers, 2005

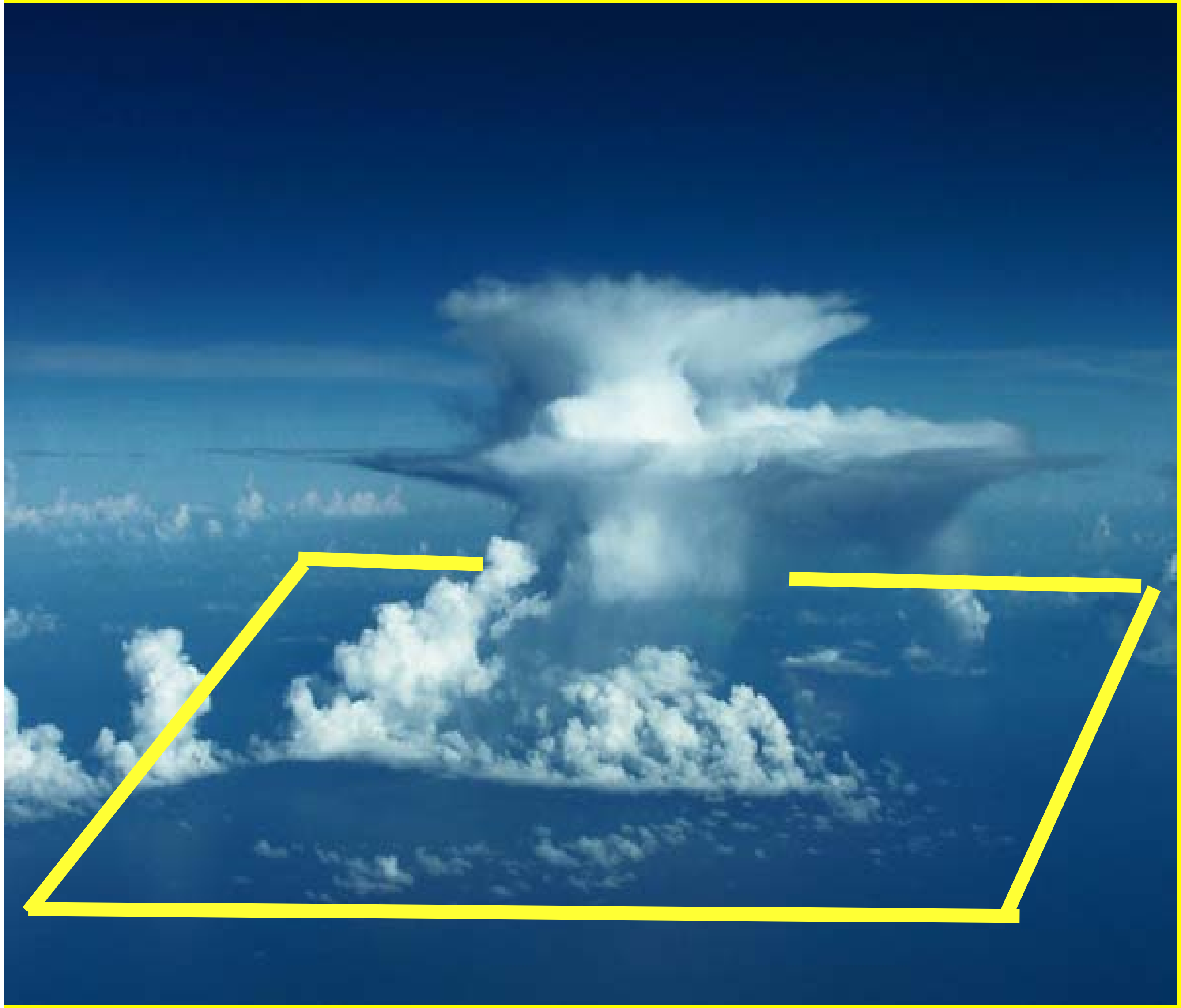
The climate system : A truly multiscale problem



No single model can include all relevant processes



Parametrization

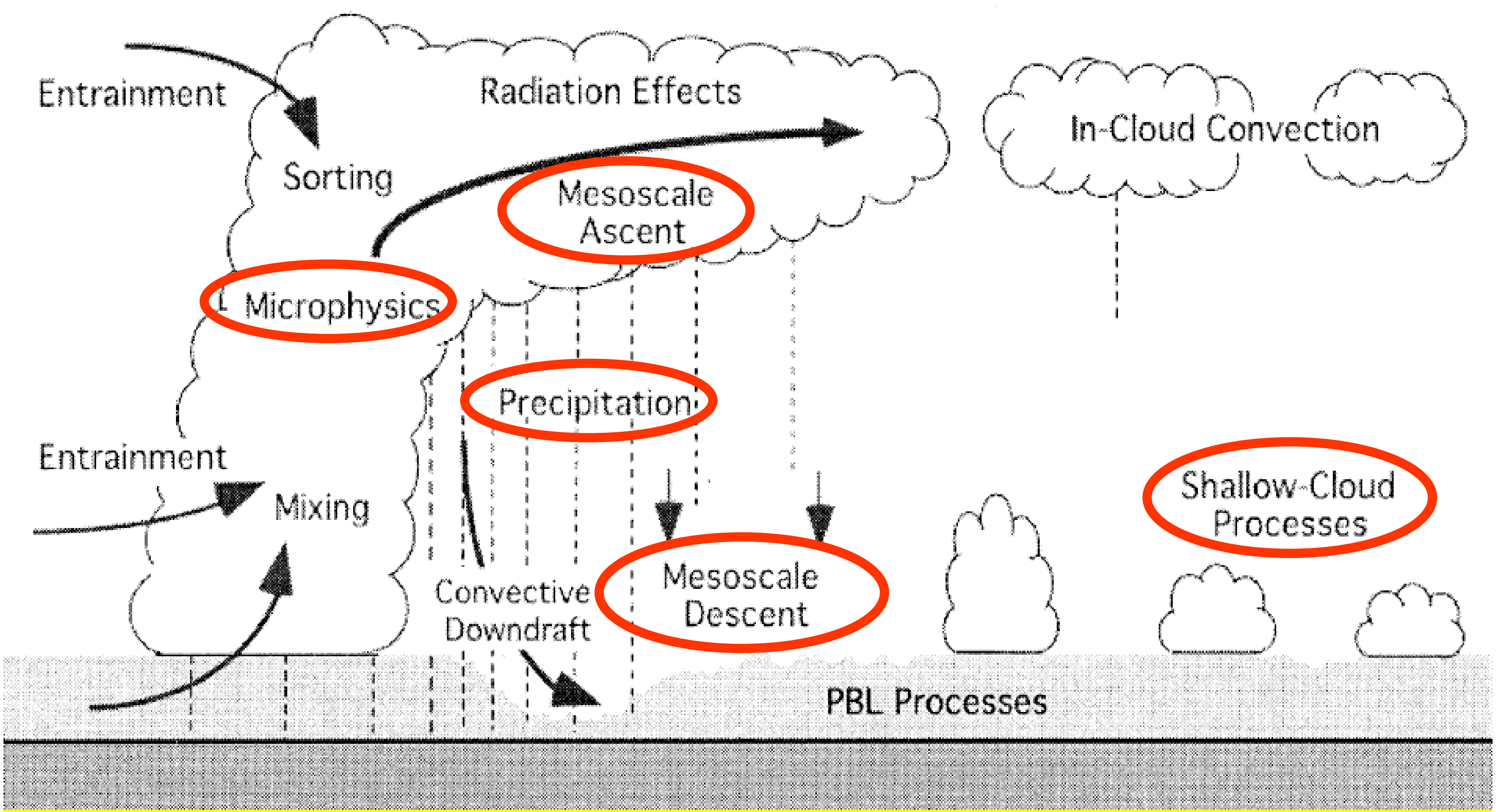


The size of one grid-box is limited by computational capability

Processes that act on scales smaller than our grid box will be excluded from the solutions.

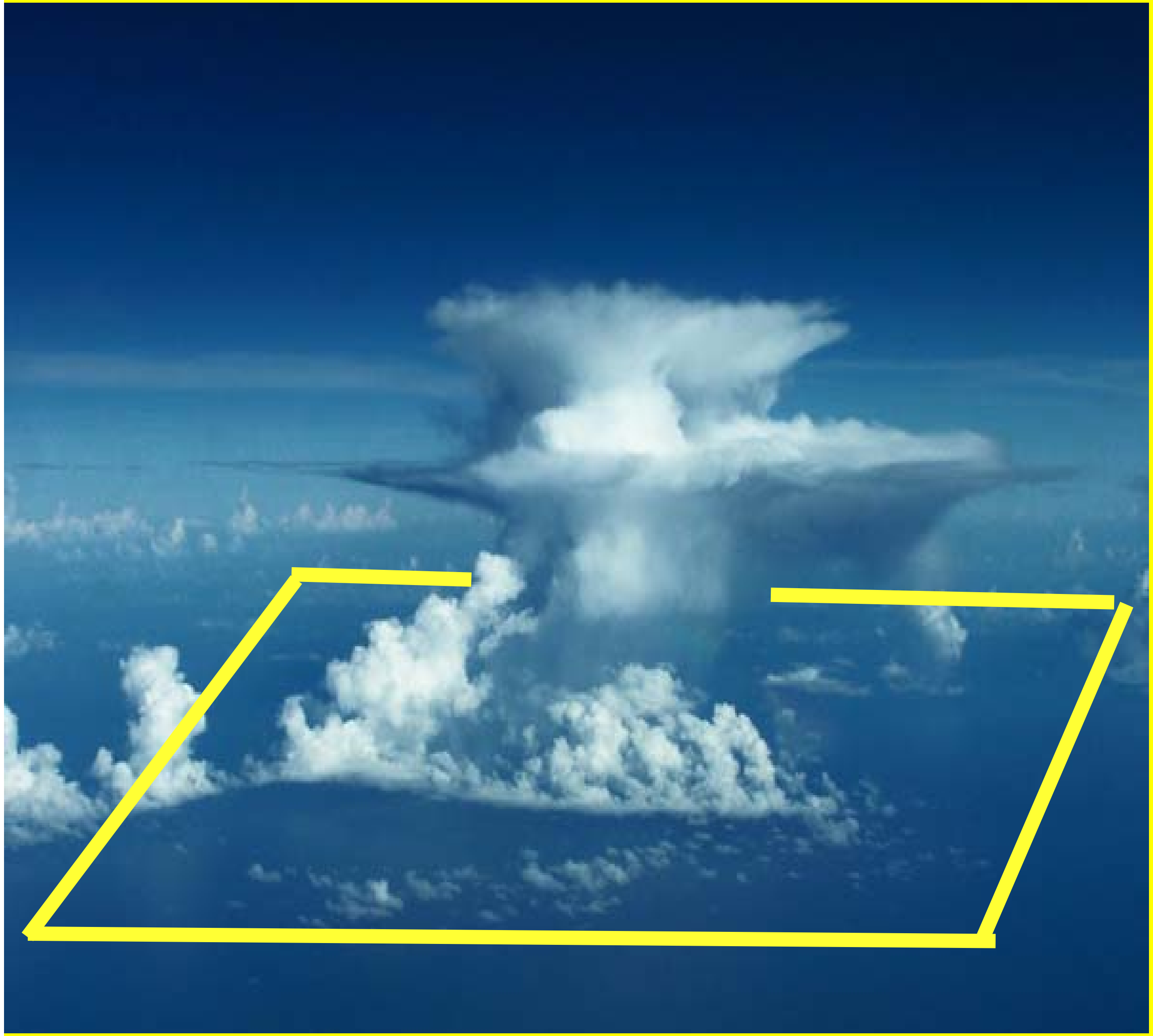
We need to include them using parametrization (a largely statistical description of what goes on "inside" the box).

Parametrization



Examples for processes that need to be parametrized in the atmosphere

Parametrization

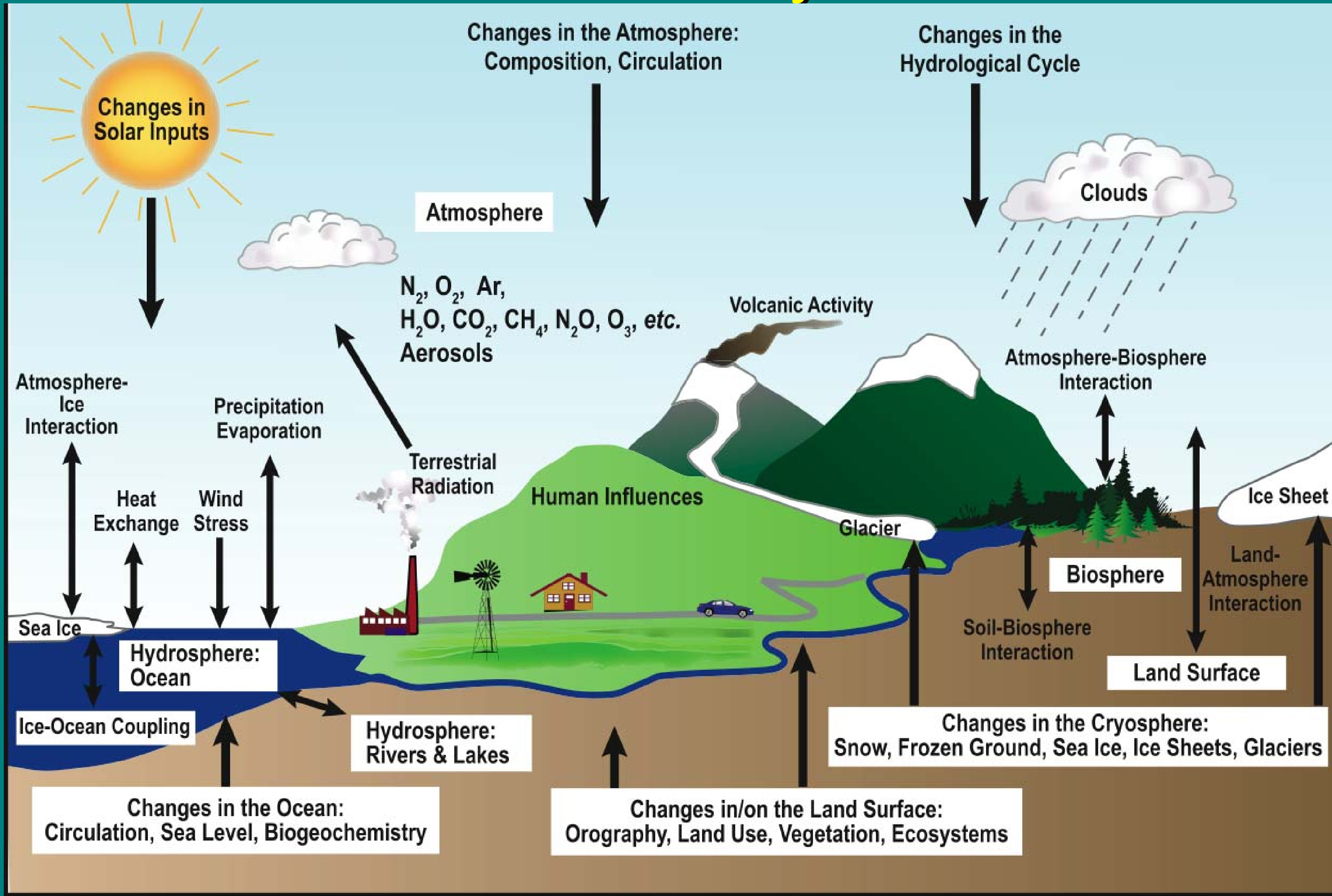


As parametrizations are simplifications of the actual physical laws,

their (necessary) use is an additional source of model uncertainty.

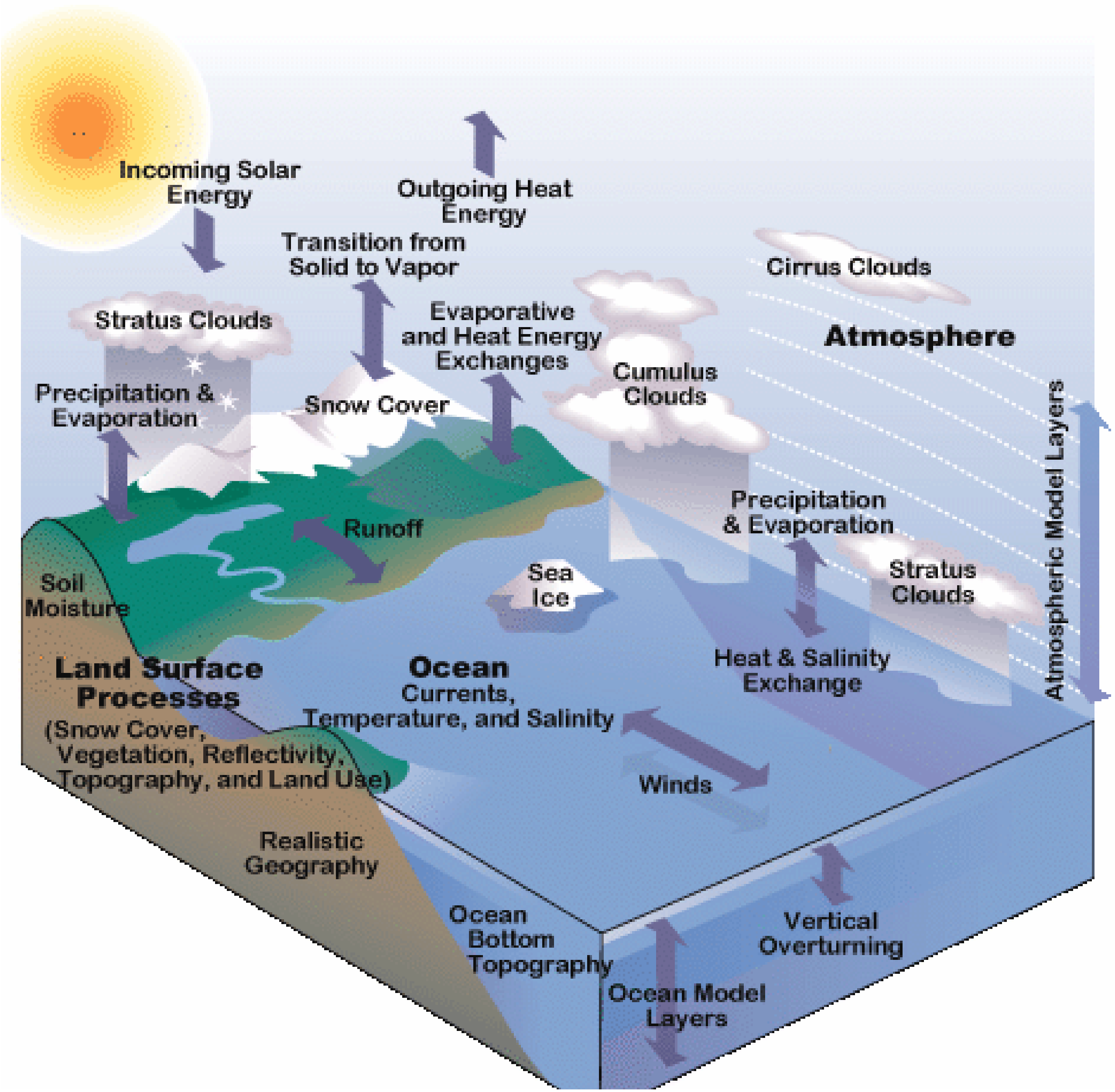
Model Structure

The Climate System



How do we simulate this?

Climate Processes



- **Radiative transfer: solar & terrestrial**
- **Phase transition of water**
- **Convective mixing**
- **Cloud microphysics**
- **Evapotranspiration**
- **Movement of heat and water in soils**

Starting Point: Fundamental Laws of Physics

1. Conservation of Mass

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \left(\vec{V}\rho\right) - \frac{\partial (w\rho)}{\partial z}$$

2. First Law of Thermodynamics

$$\frac{\partial \rho\theta}{\partial t} = -\nabla \cdot \left(\vec{V}\rho\theta\right) - \frac{\partial w\rho\theta}{\partial z} + \frac{\rho}{C_p}\frac{T}{\theta}\dot{H}$$

3. Newton's Second Law

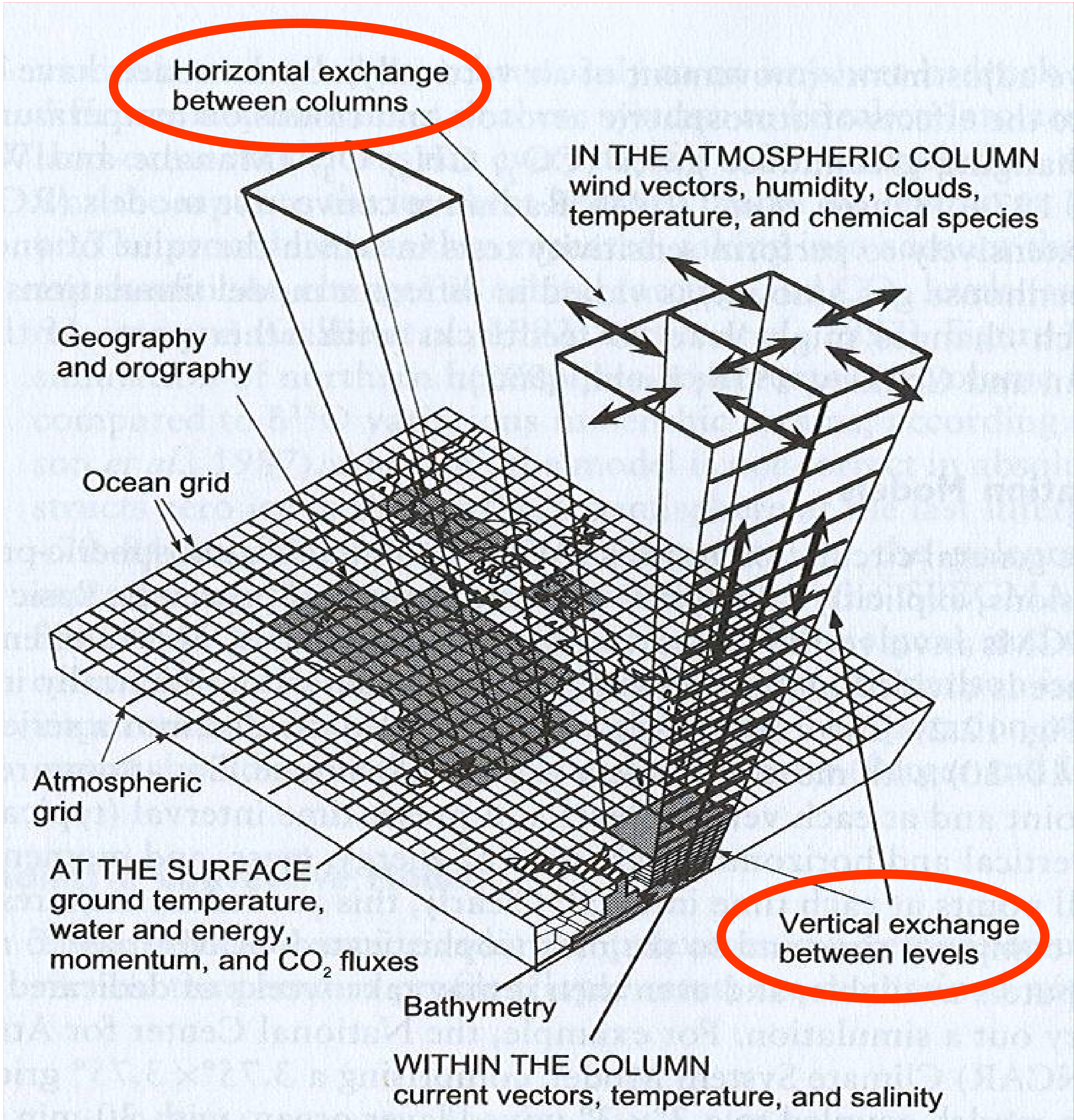
$$\frac{d_a \vec{V}_{a,3}}{dt} = \sum (Forces/mass)$$

But - these are complex differential equations!

How can we use them?

By solving them on a grid.

Plus conservation of water vapor, chemical species, …



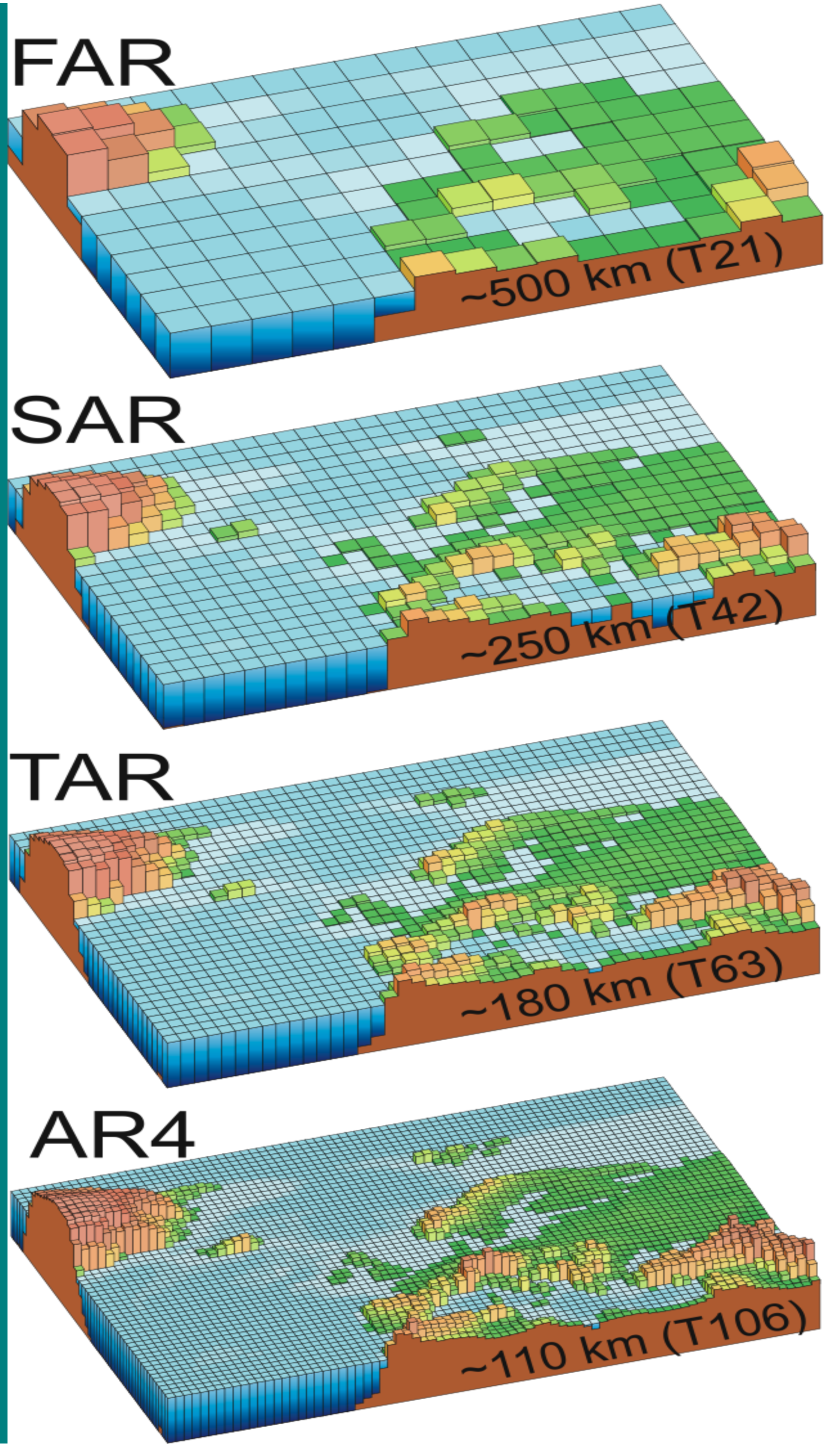
Global Climate Models: Structure

Solving the equations on geographical grid.

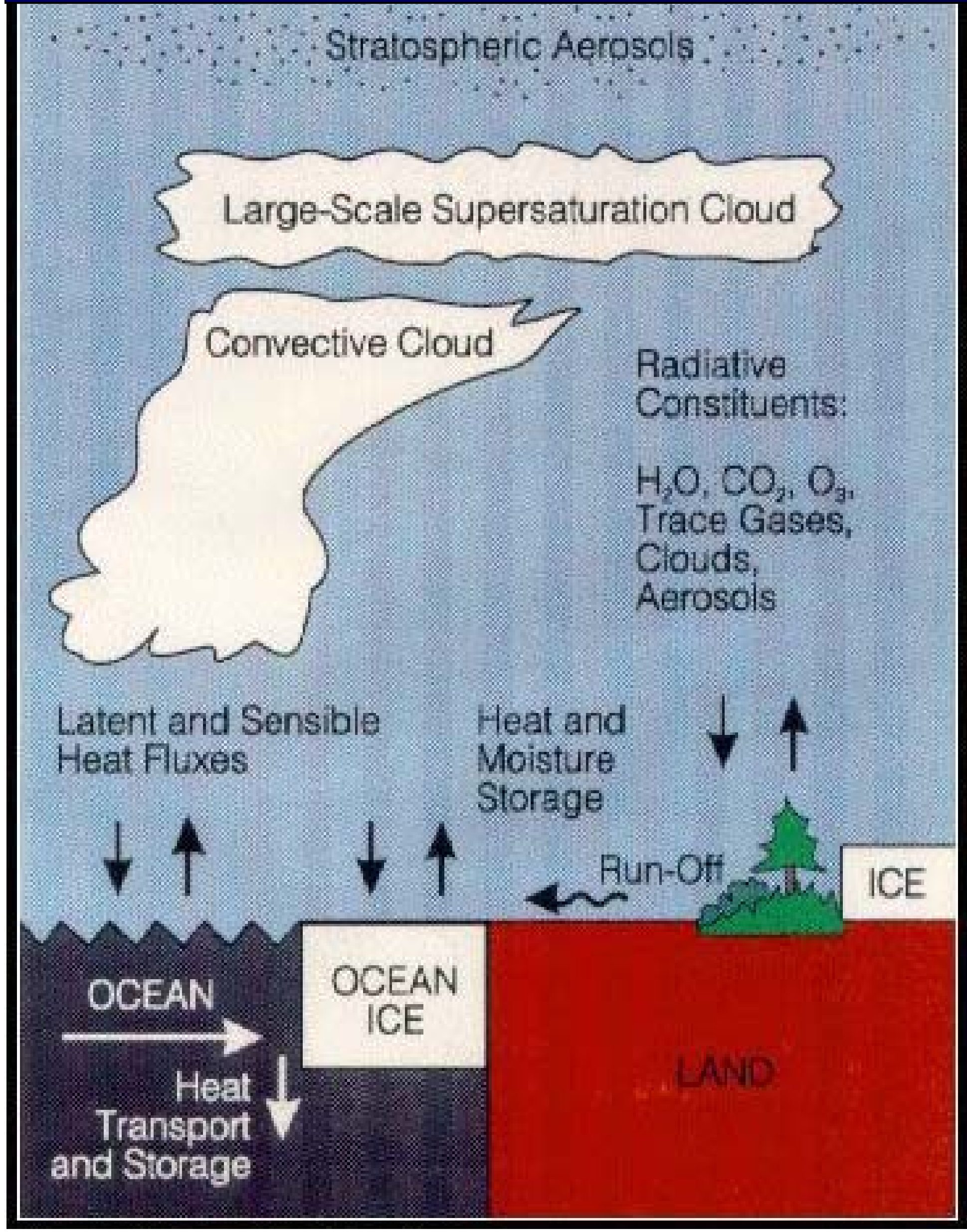
Resolution Increases over Time

Computing demand increases inversely with *cube* of horizontal resolution.

Increased computing power has allowed increased resolution

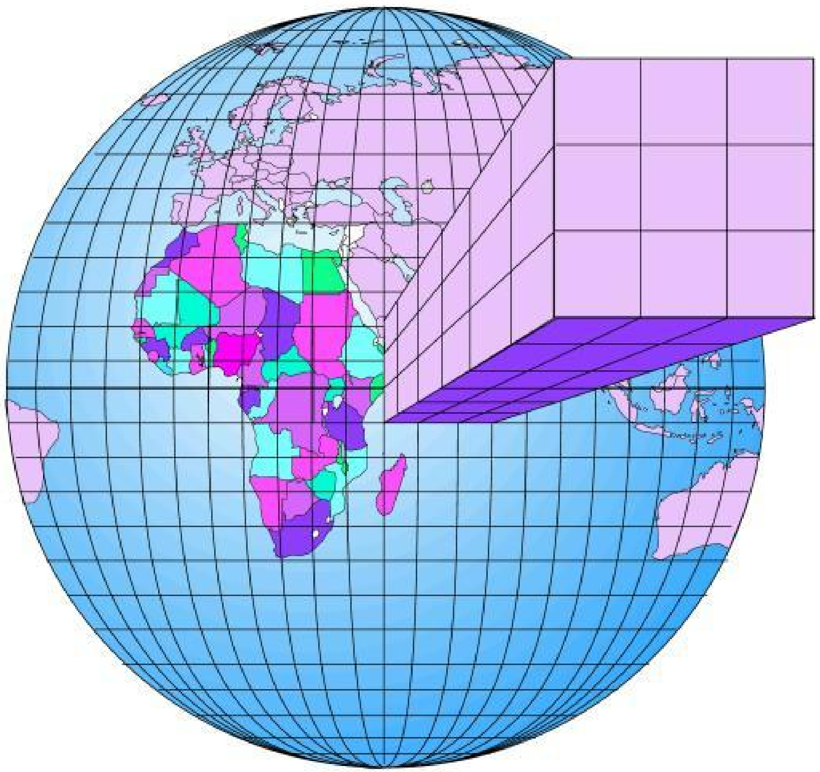


Physical Processes Simulated by GCMs



- Seasonal and Diurnal Cycles
- Latent and Sensible Heat Fluxes
- Clouds and Convection
- Planetary Boundary Layer
- Greenhouse Gases
- Aerosols
- Sea Ice
- Ground Hydrology
- Ocean Heat Transport
- *Ocean Circulation*
- *Dynamic Vegetation*
- *Dynamic Ice Sheets*
- *Carbon Cycle Chemistry*

Modern climate models



- <u>**Forcing:**</u> **solar irradiance, volcanic aerosols, greenhouse gases, …**
- <u>**Predict:**</u> **T, p, wind, clouds, water vapor, soil moisture, ocean current, salinity, sea ice, …**
- <u>**Very high spatial resolution:**</u>
  <1 deg lat/lon resolution
  ~50 atm, ~30 ocn, ~10 soil layers

==> 6.5 million grid boxes

- <u>**Very small time steps**</u> **(~minutes)**
- <u>**Ensemble runs**</u> **multiple experiments)**

Model experiments (e.g. 1800-2100) take weeks to months on supercomputers

Model Evaluation

How Are Models Evaluated?

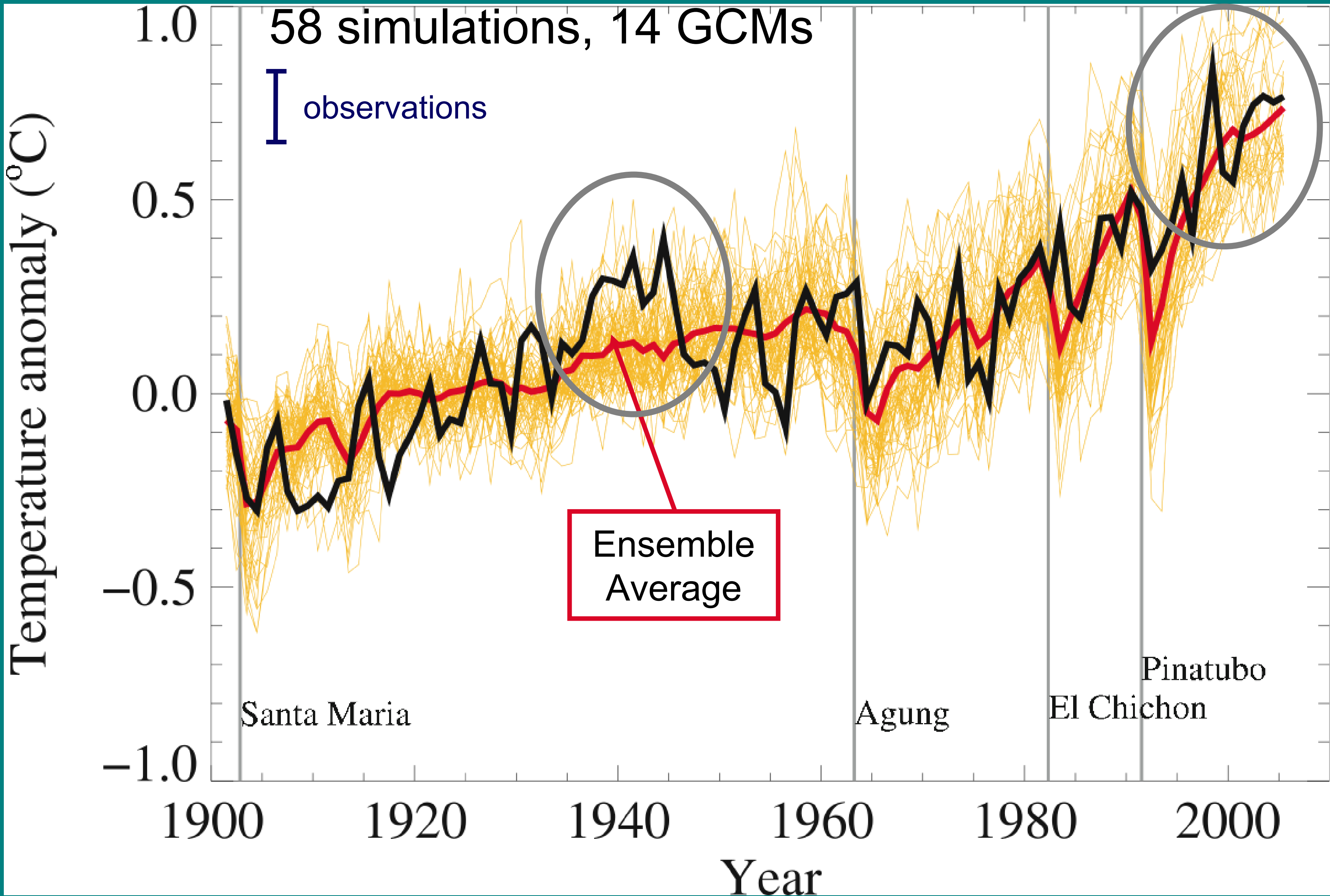
- Testing against observations (present and past)
- Comparison with other models
- Metrics of reliability
- Comparison with numerical weather prediction

What Limits Evaluation?

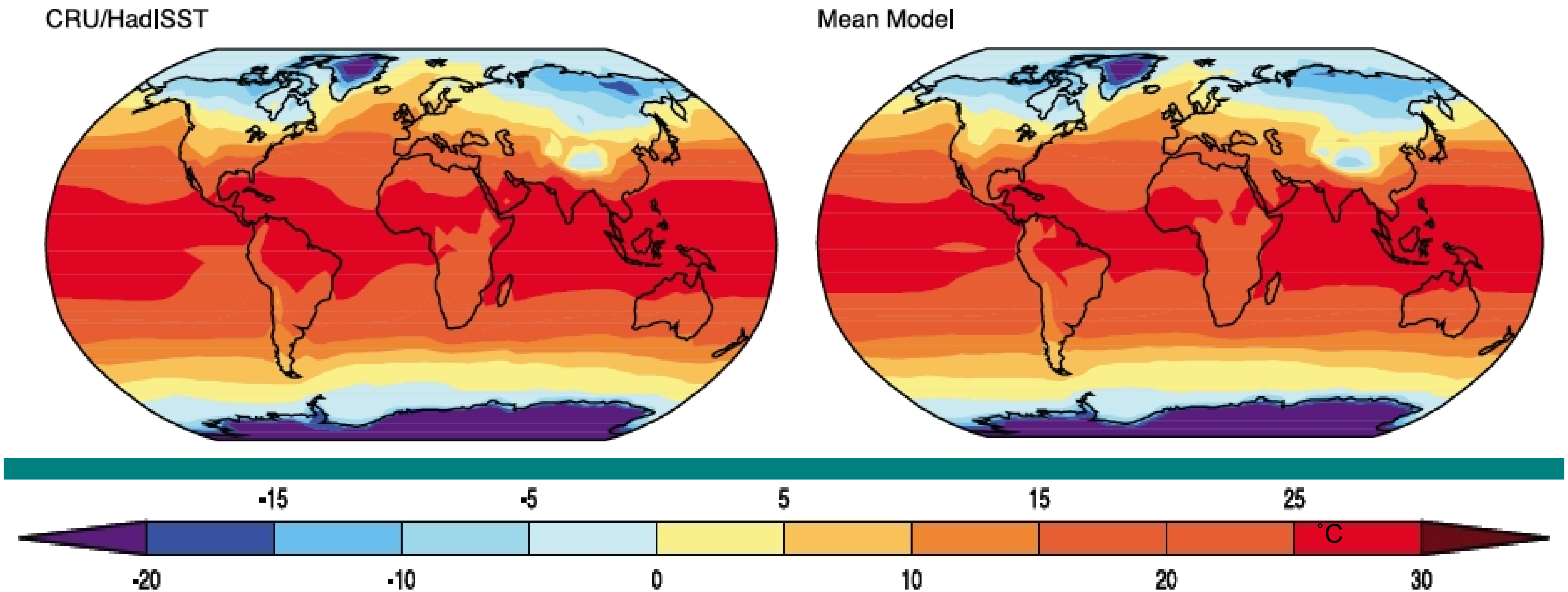
- **Unforced (internal) variability**
- **Availability of Observations**
- **Accuracy of Observations**
- **Accuracy of Boundary Conditions (Forcing)**

These help us to determine the "goodness of simulations".

GCM Simulations of Global T



Time Average Surface Temperature (1980-1999)

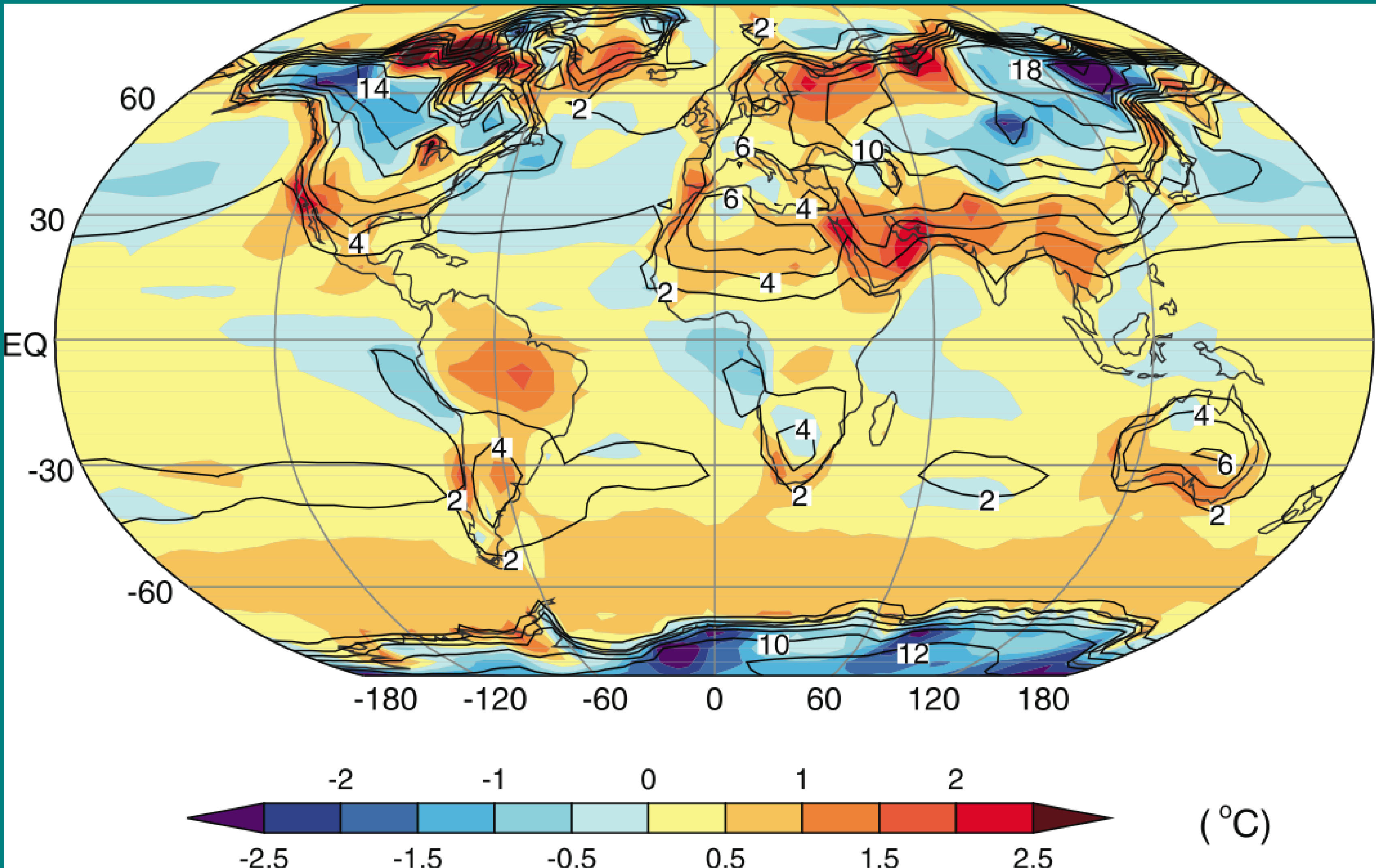


Mean Model: Average of 23 GCMs

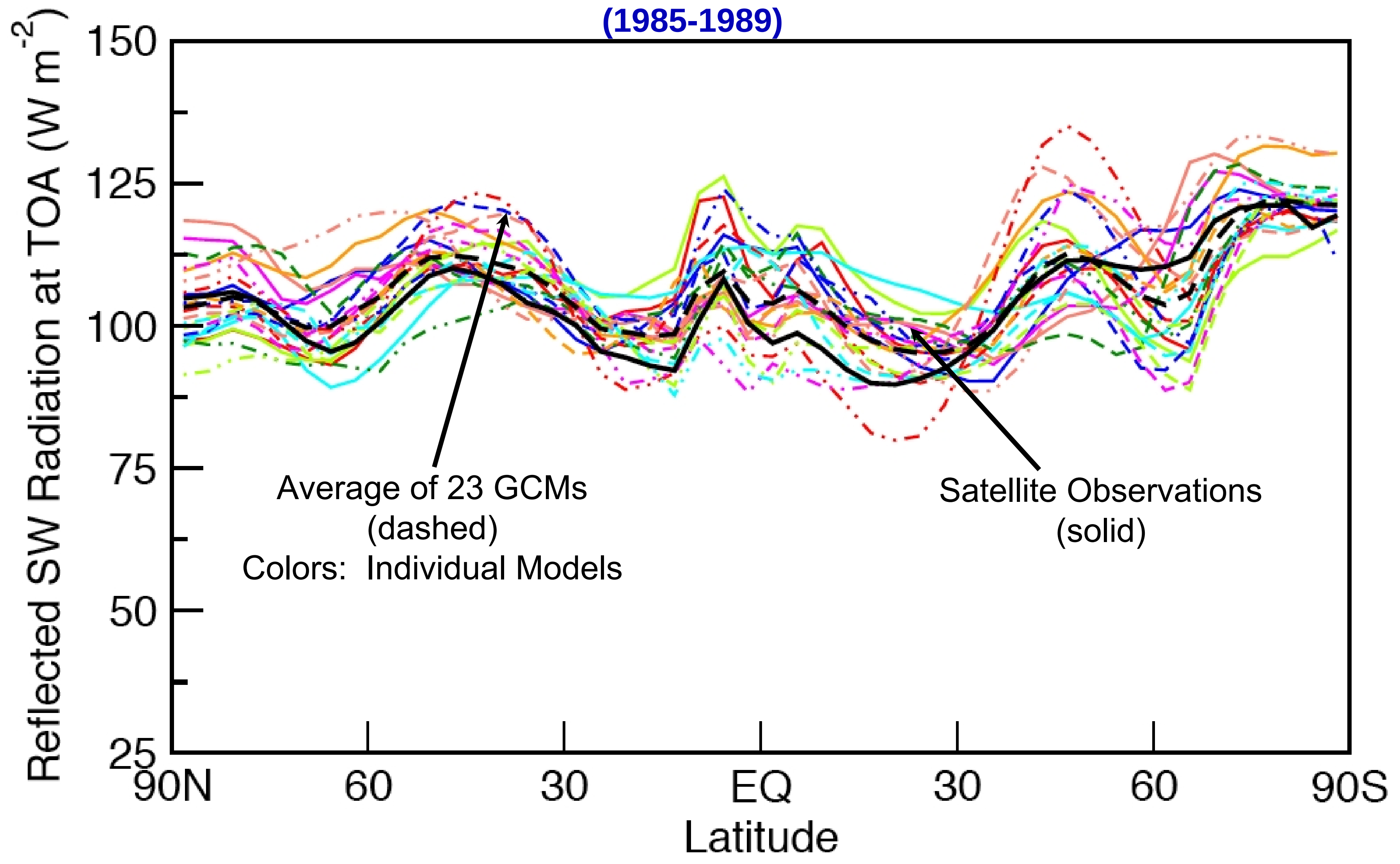
Annual Variability (Seasons)

Lines: Observed Standard Deviation (of monthly means)

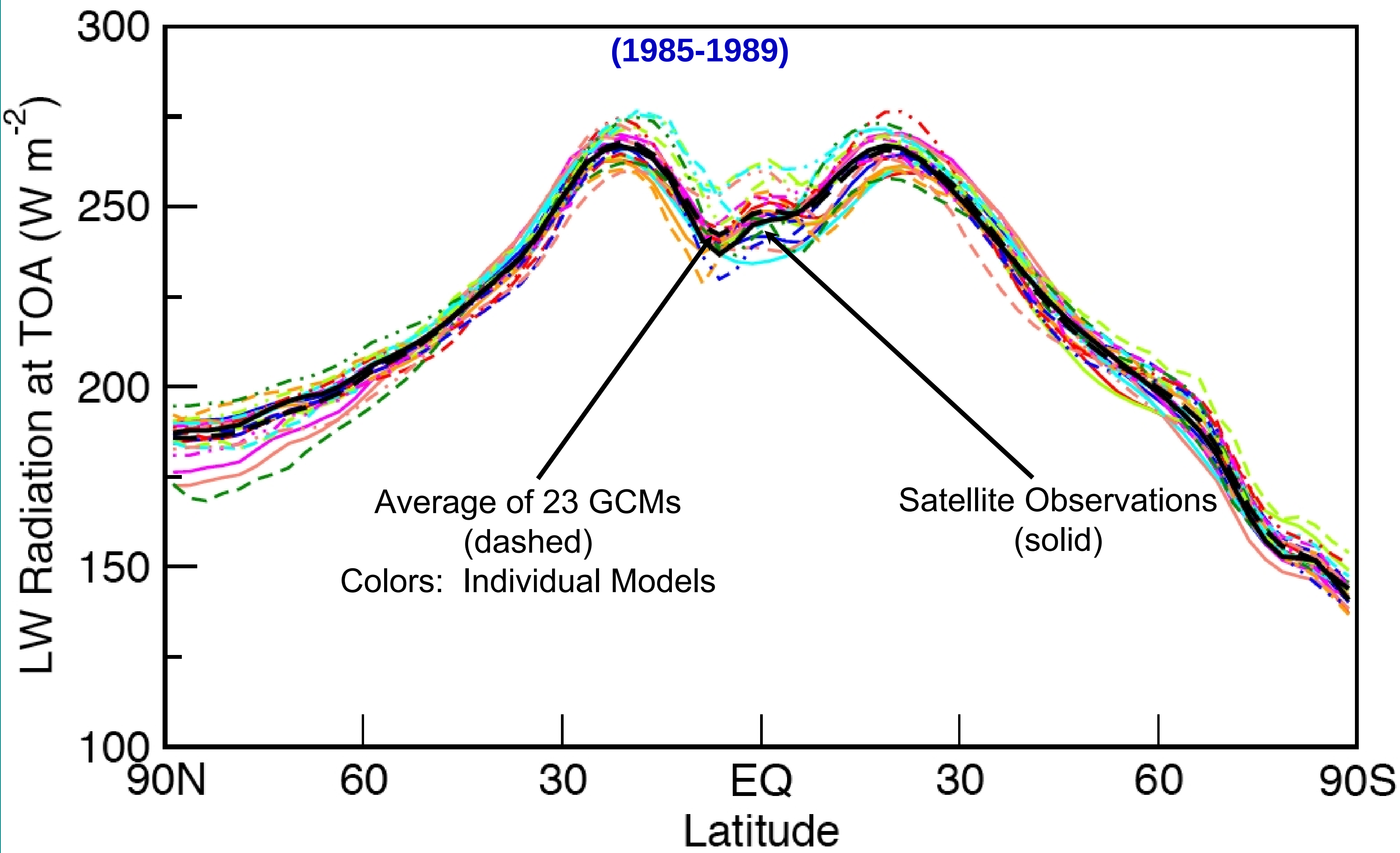
Colors: Ensemble mean - observations



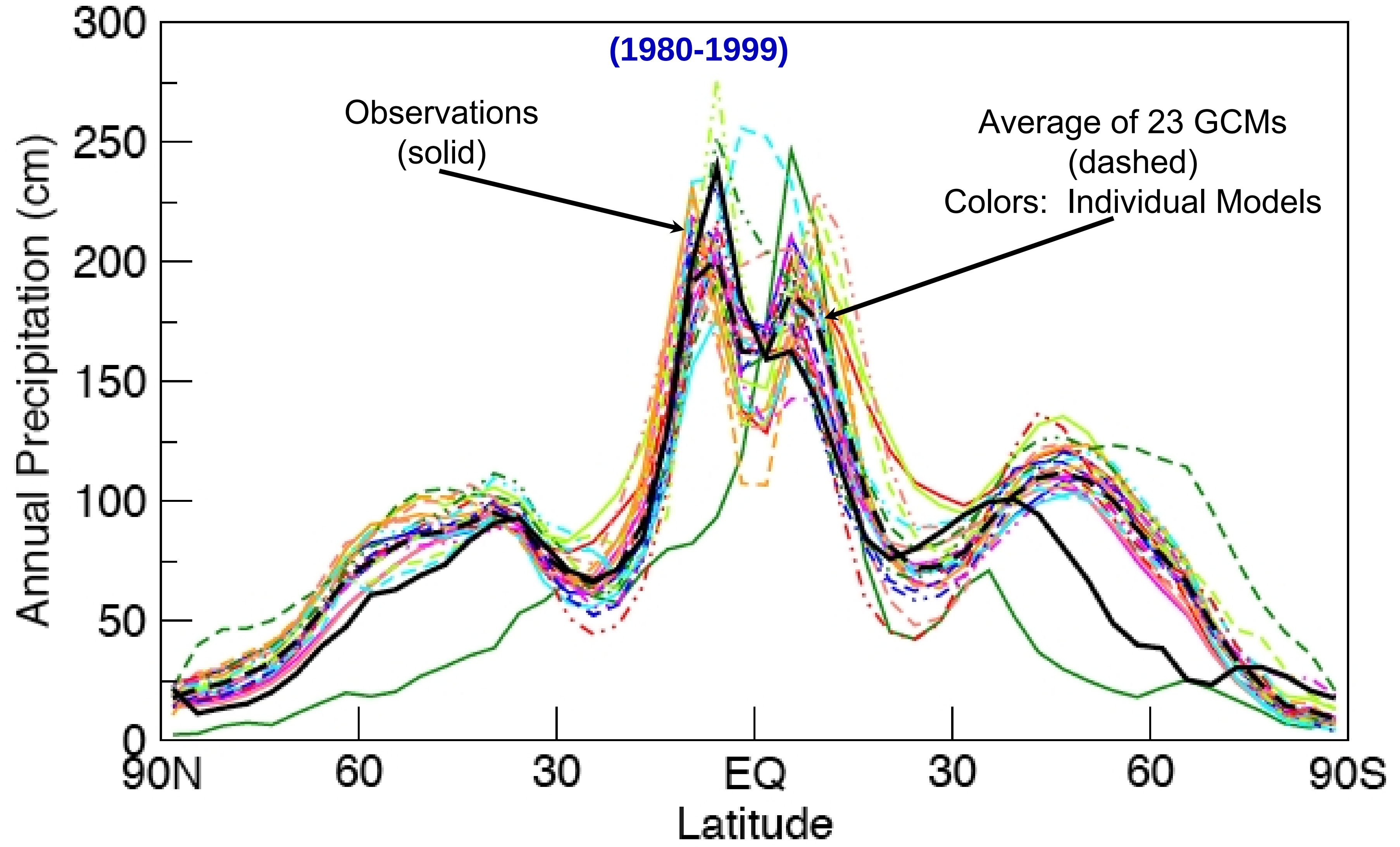
Mean Reflected Solar Radiation



Mean Emitted Infrared Radiation



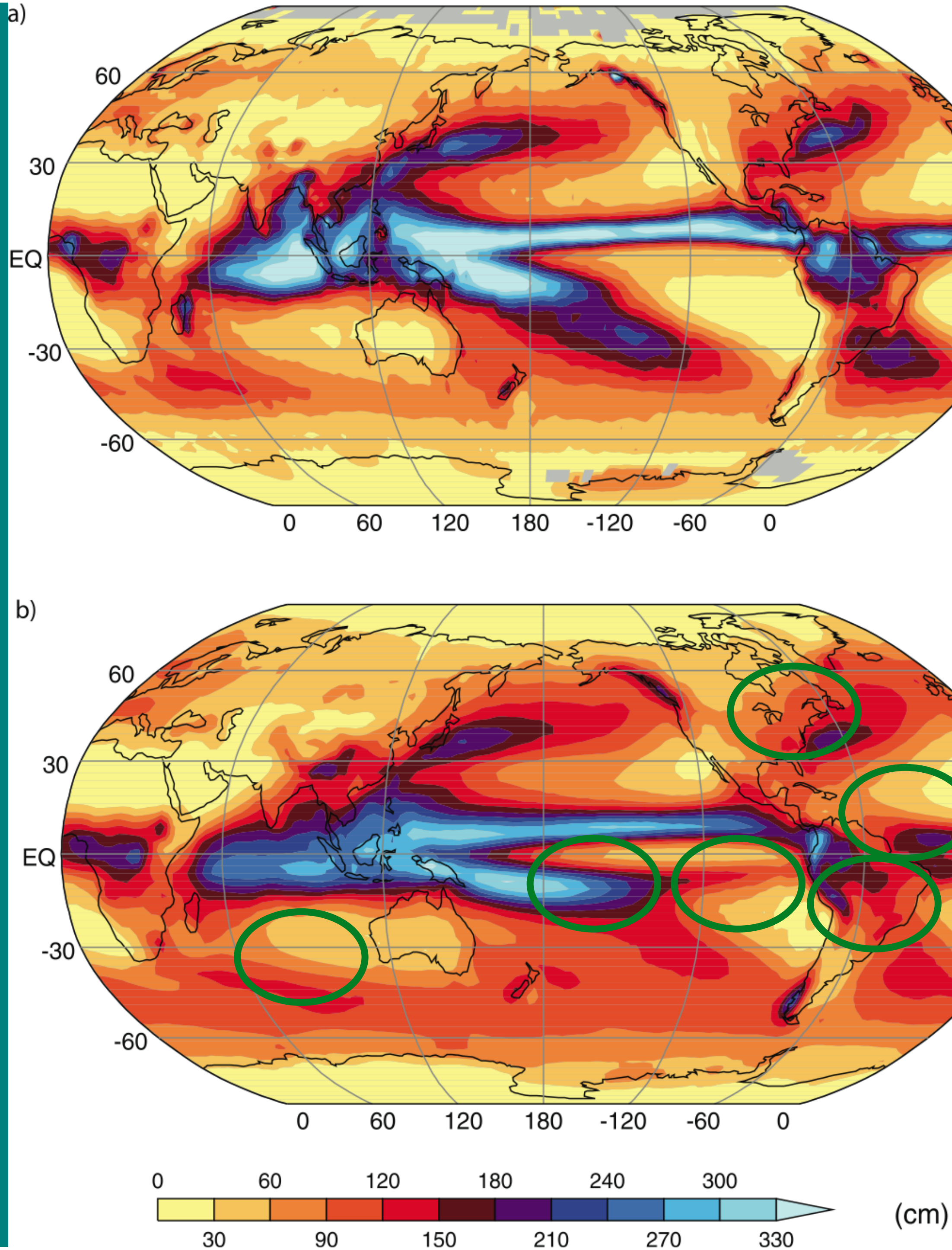
Zonal Average Precipitation



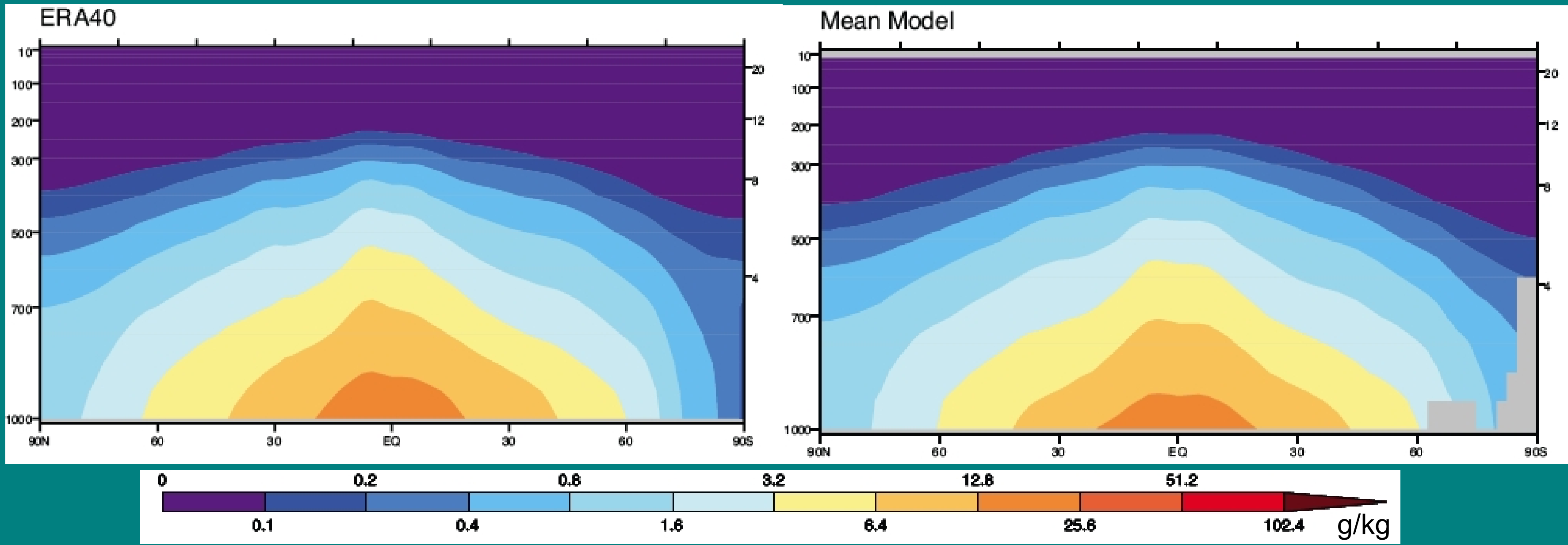
Annual Mean Precipitation (1980-1999)

Observations

Average of 23 GCMs



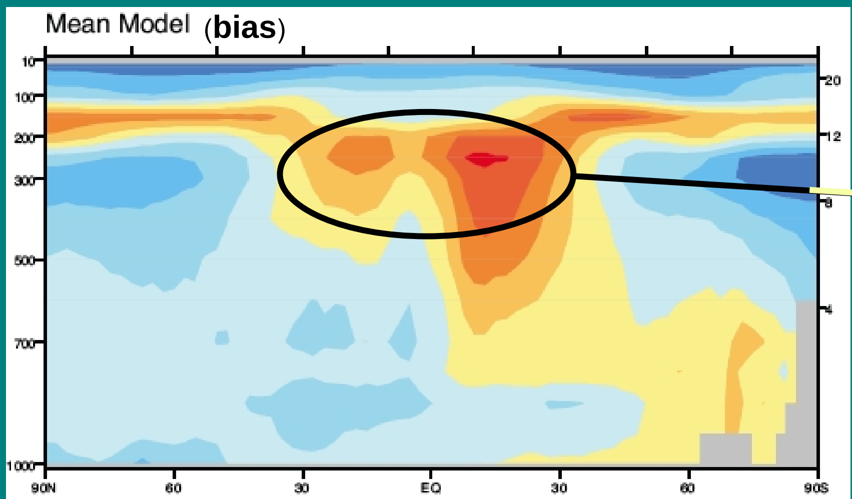
Atmospheric Specific Humidity (1980-1999)



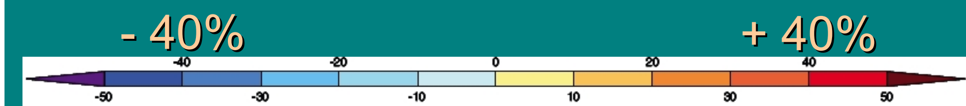
Mean Model: Average of 20 GCMs

Vertical Axes: Left - Pressure (millibars)

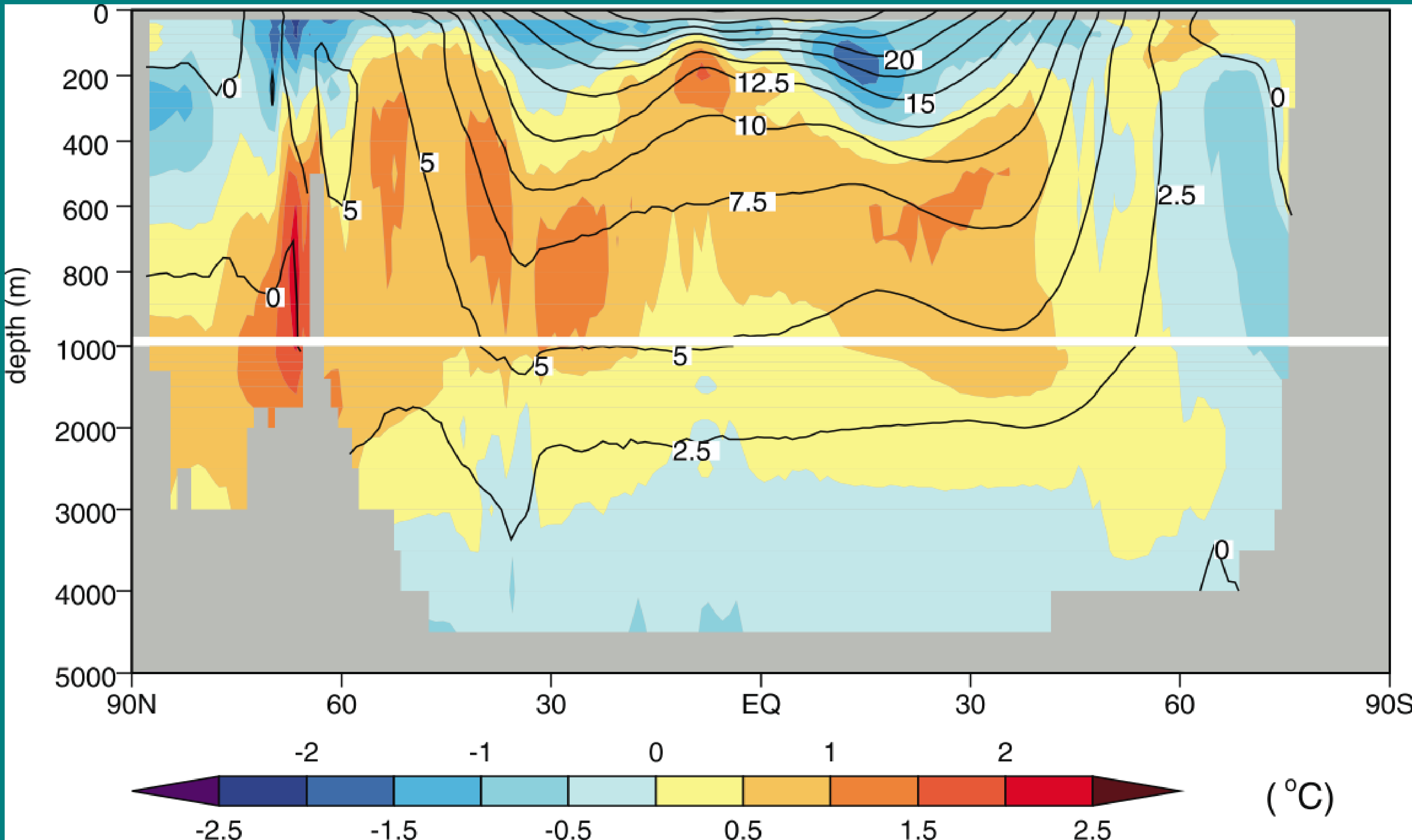
Right - Elevation (km)



Moist bias in tropical troposphere

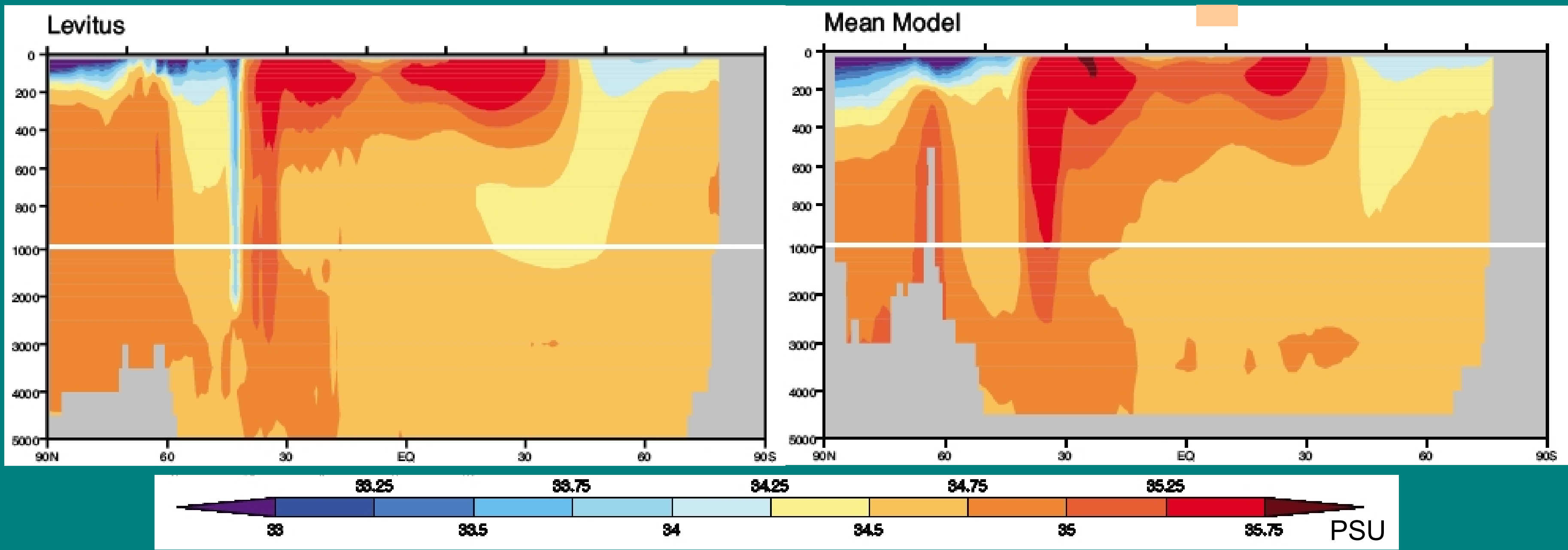


Ocean Temperature (1957-1990)



Mean Model: Average of 18 GCMs

Ocean Salinity (1957-1990)



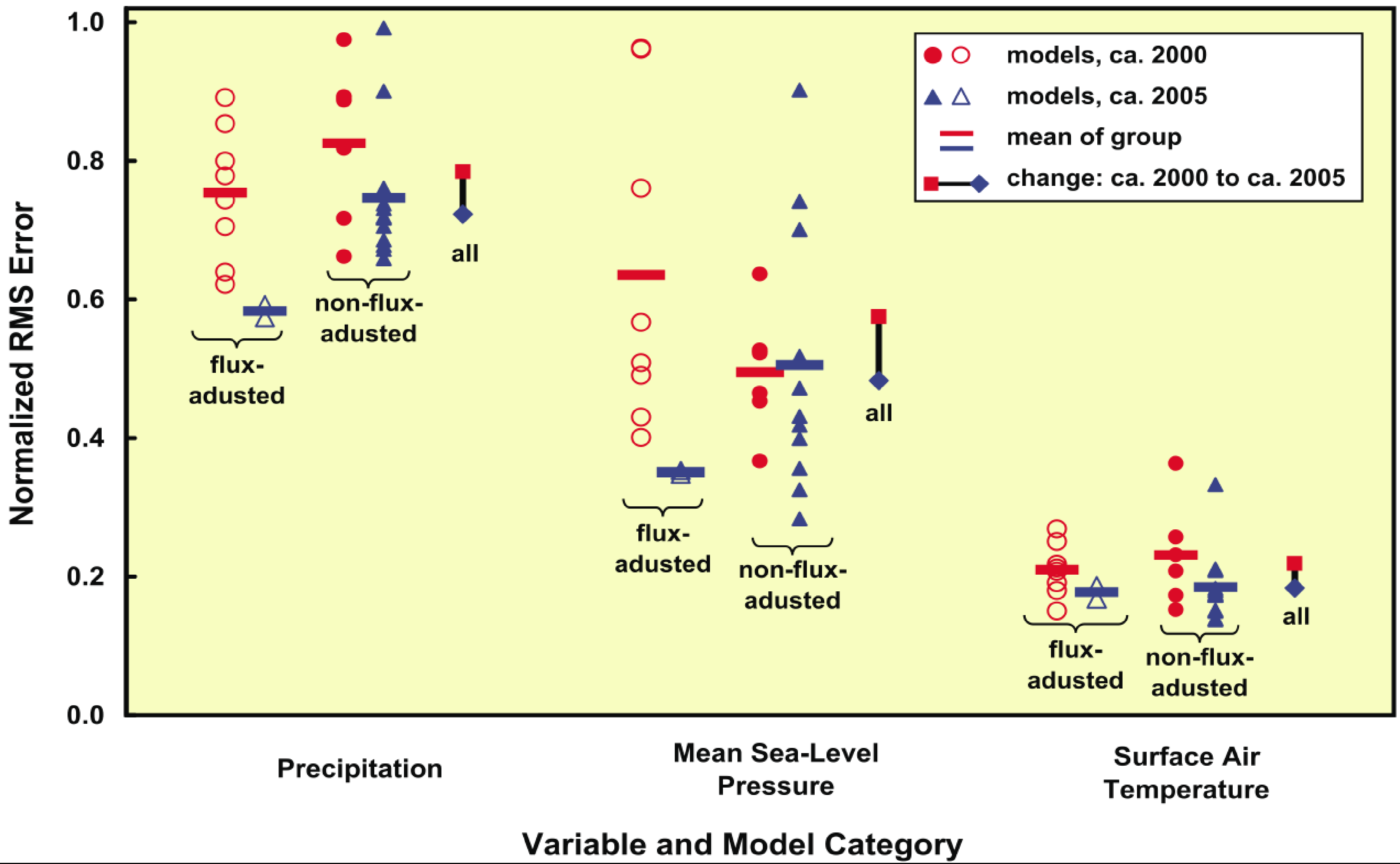
Vertical Axes: Depth (m)

Mean Model: Average of 18 GCMs

PSU = "practical salinity units"

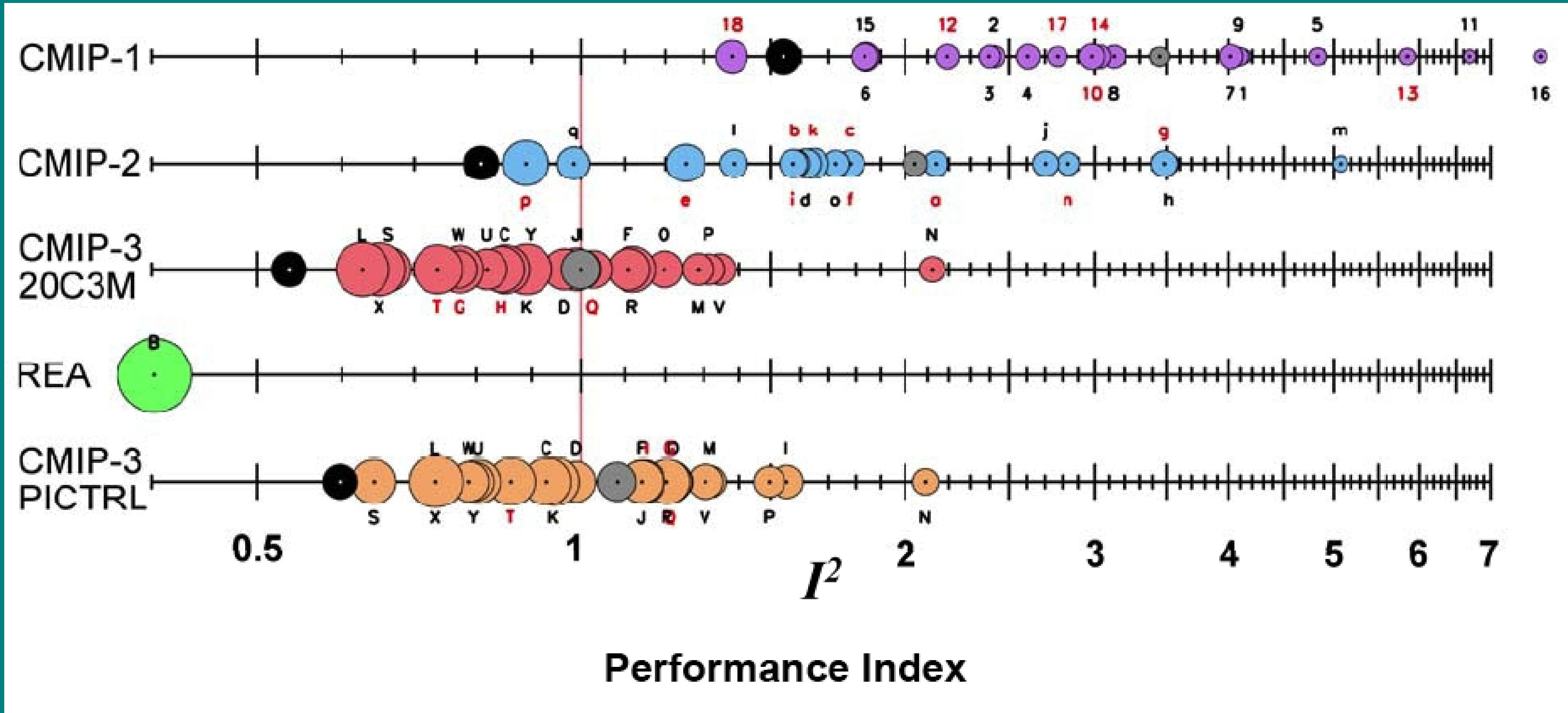
- based on conductivity of electricity in water
- PSU = 35 ⇒ water is 3.5% salt

Are Models Improving? - 1



“Normalized” = RMS error / observed space-time variability

Are Models Improving? - 2



"Performance Index" combines error estimates of

Sea level pressure **Temperature** **Winds**

Humidity **Precipitation** **Snow/Ice**

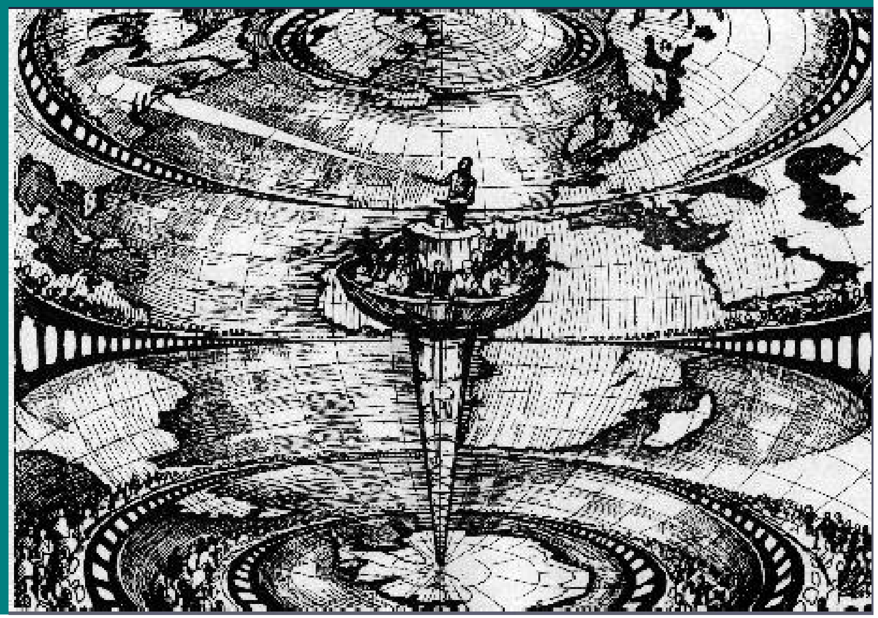
Ocean salinity **Heat flux**

(Reichler and Kim, 2007)

Historical aspects

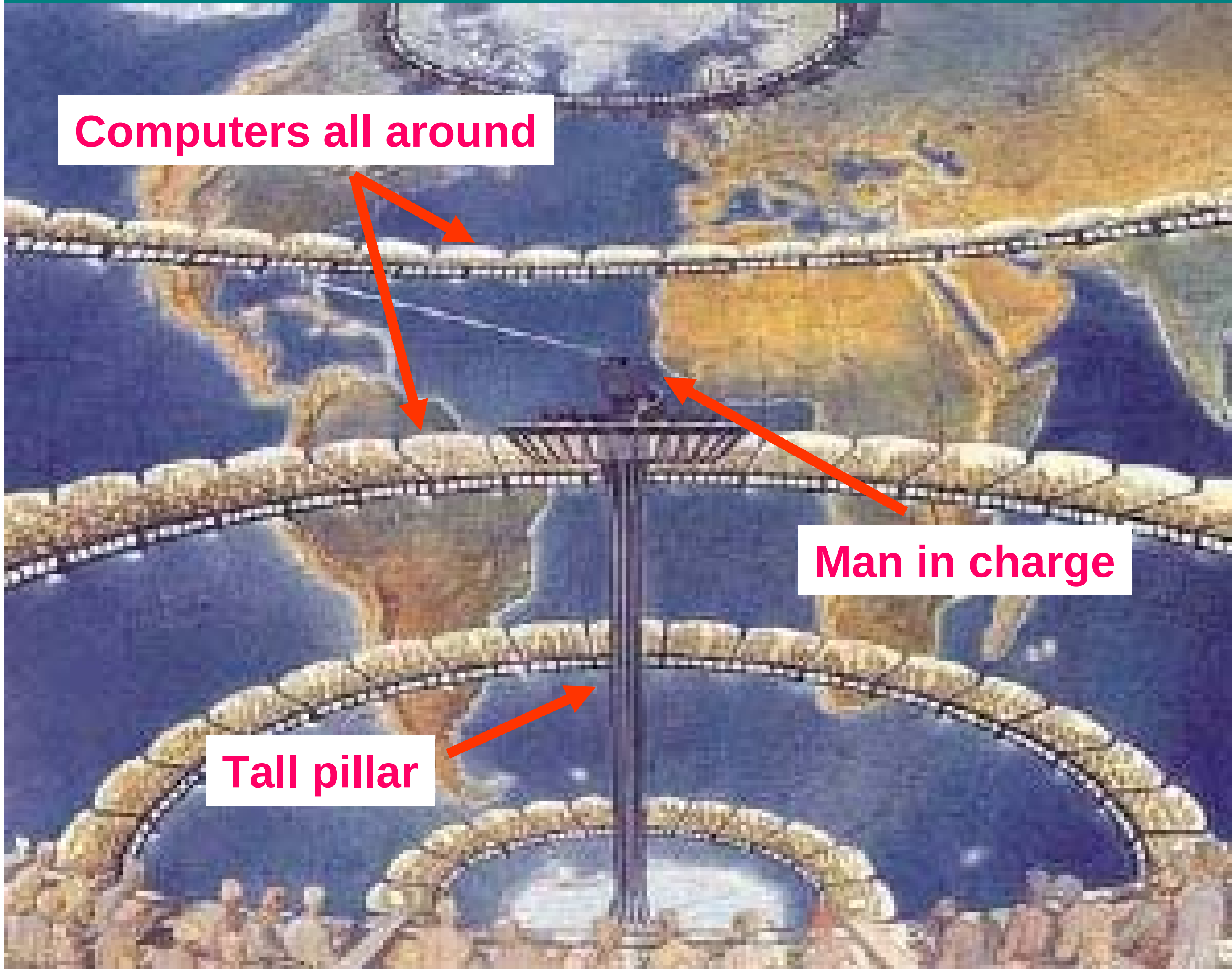
L. F. Richardson, 1931

Lewis Fry Richardson



- **L.F. Richardson started with the basics of the Numerical Weather Prediction**
- **First experiment (1921)**
- **„The equations are complicated, because the atmosphere is complicated by itself."**

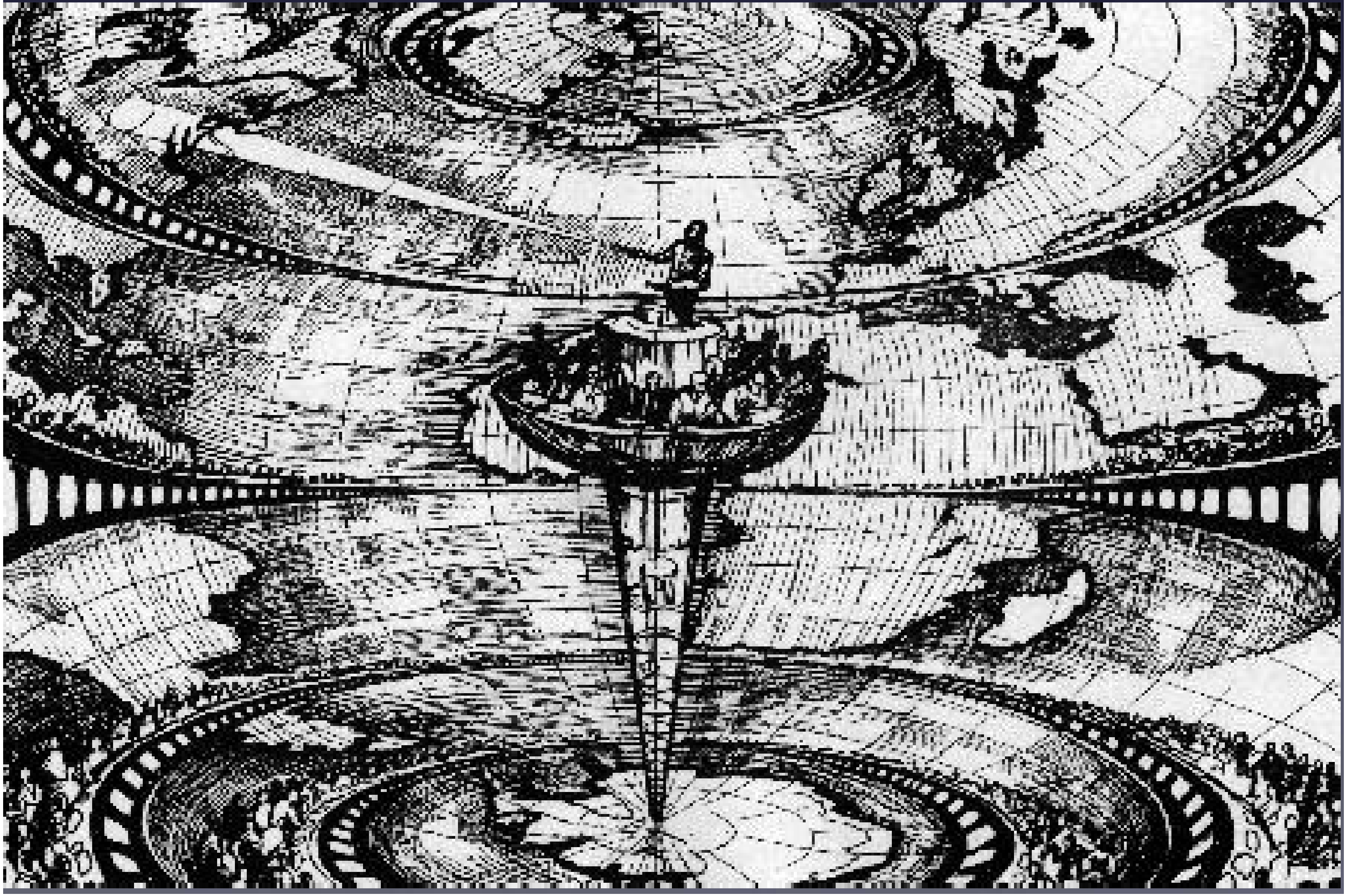
Weather Prediction by Numerical Process
Lewis Fry Richardson's dream - 1922



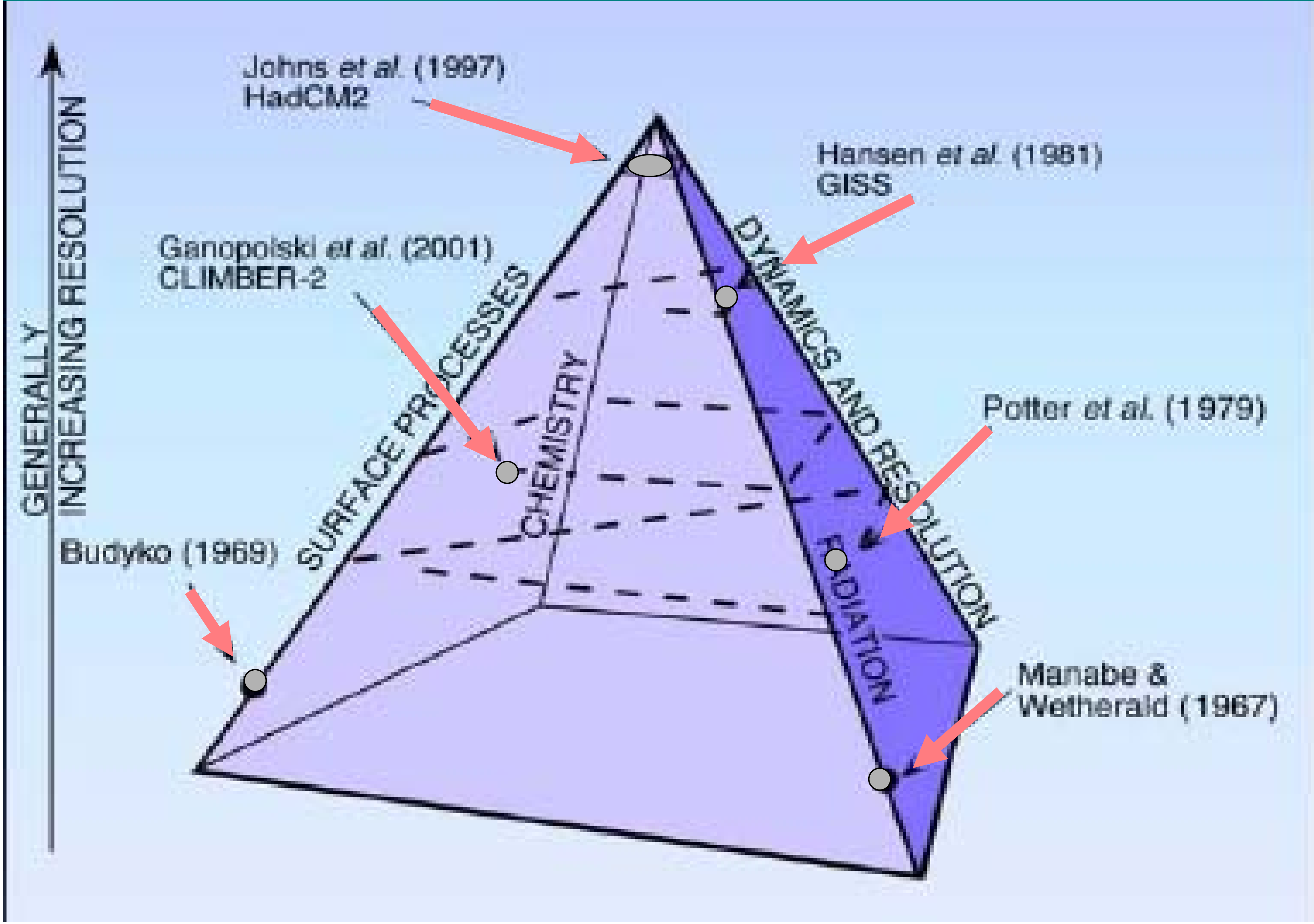
Forcasting fabric:

- Like a large theater hall
- Sphere shape building
- On the walls a map of the globe
- Chief meteorologist

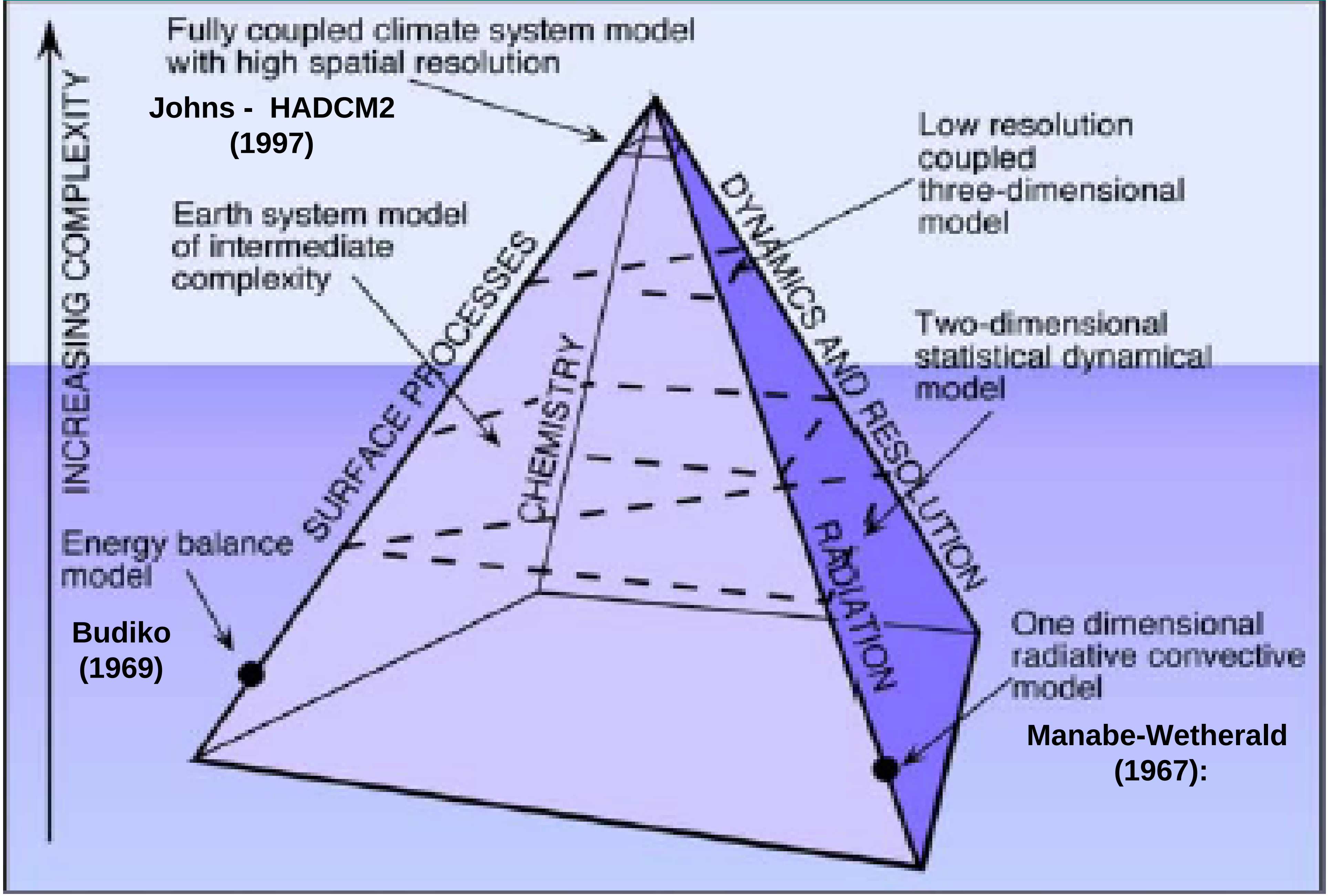
"Forcasting fabric"



The pyramid of climate modells



The pyramid of climate modells



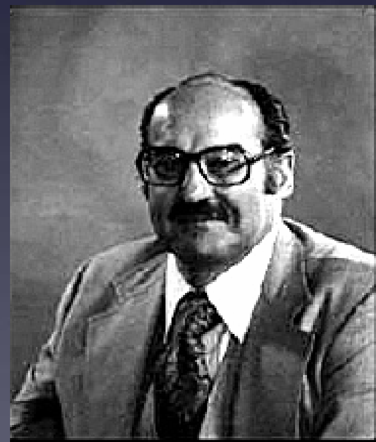
Climate modells - 1940's, 1950's

Forties and Fifties

In 1952 Bert Bolin concluded that "there is very little hope for the possibility of deducing a theory for the general circulation of the atmosphere from the complete hydrodynamic and thermodynamic equations.

Already Von Neuman had started working on numerical computations of the atmosphere

Smagorinsky



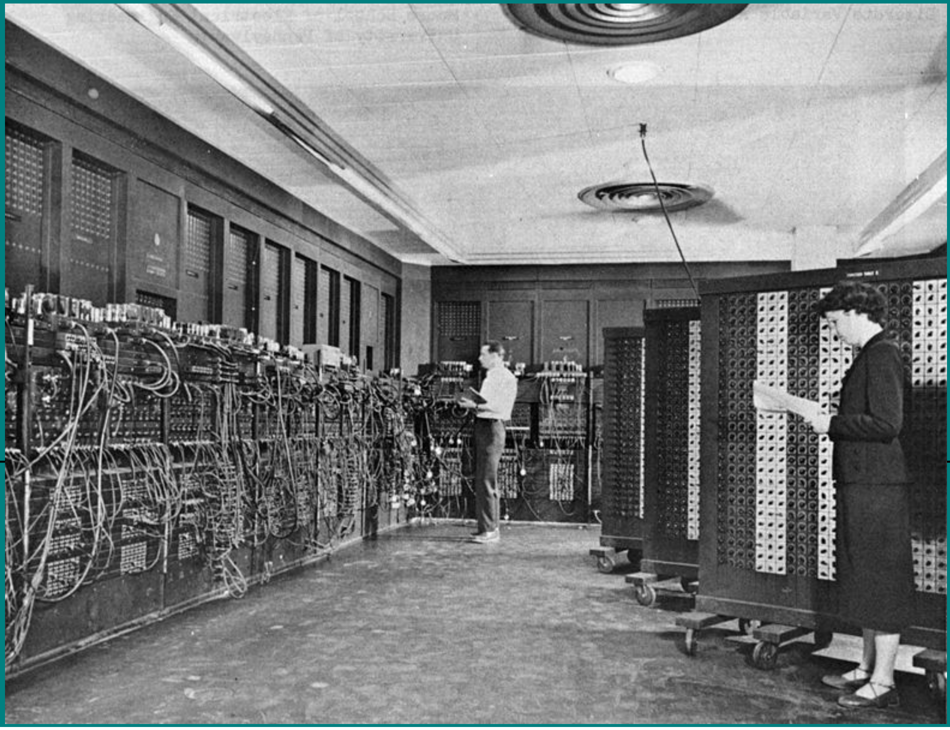
Charney

"the machine will give a greater scope to the making and testing of physical hypotheses"

by 1949, results were looking fairly realistic.

The development history of climate modells

- Neumann János
- First computers
  ENIAC, EDVAC



The development history of climate modells

- Programer as a new job
- Dependence from computer capacity
- Larger and larger models

Plan

- 5 x ½ hour 'lectures':

  0900-0930 Observations of climate change

  0930-1000 Greenhouse effect and human influence on climate

  1000-1030 Natural climate variability

  1030-1100 Break

  1100-1130 Modelling the climate system

  1130-1200 Future climate

  1200-1215 Questions and discussion