GKSS Research Centre, Geesthacht, Germany

Global climate models

Norrköping, October 2010

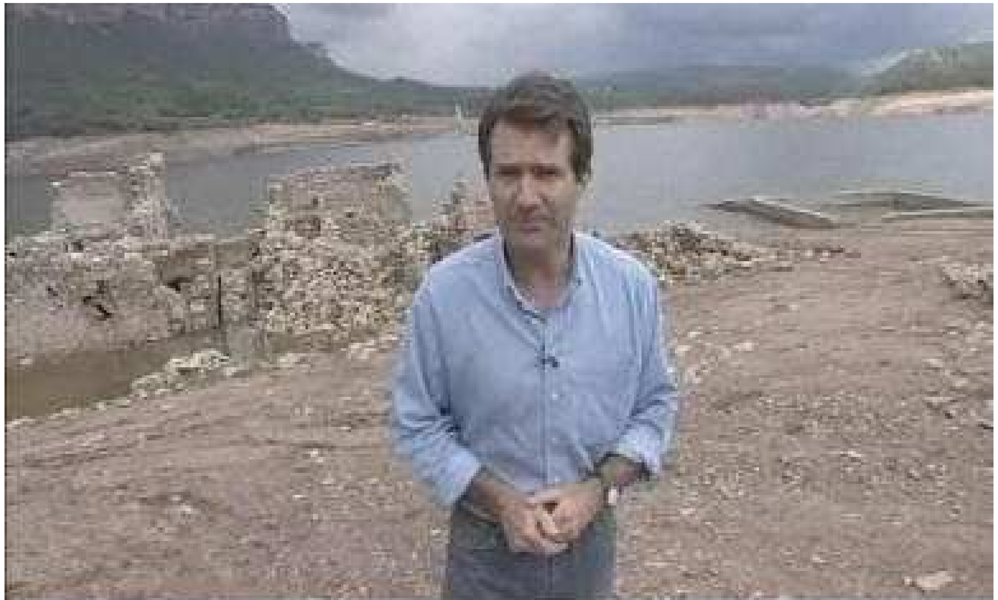
Climate Modelling School

Eduardo Zorita

Stockholm in summer today

Stockholm in summer 20 thousands year ago

May 2008, near Barcelona



October 2009


-How the climate has changed in the past
-External drivers of climate change
-Climate models, climate projections and uncertainties

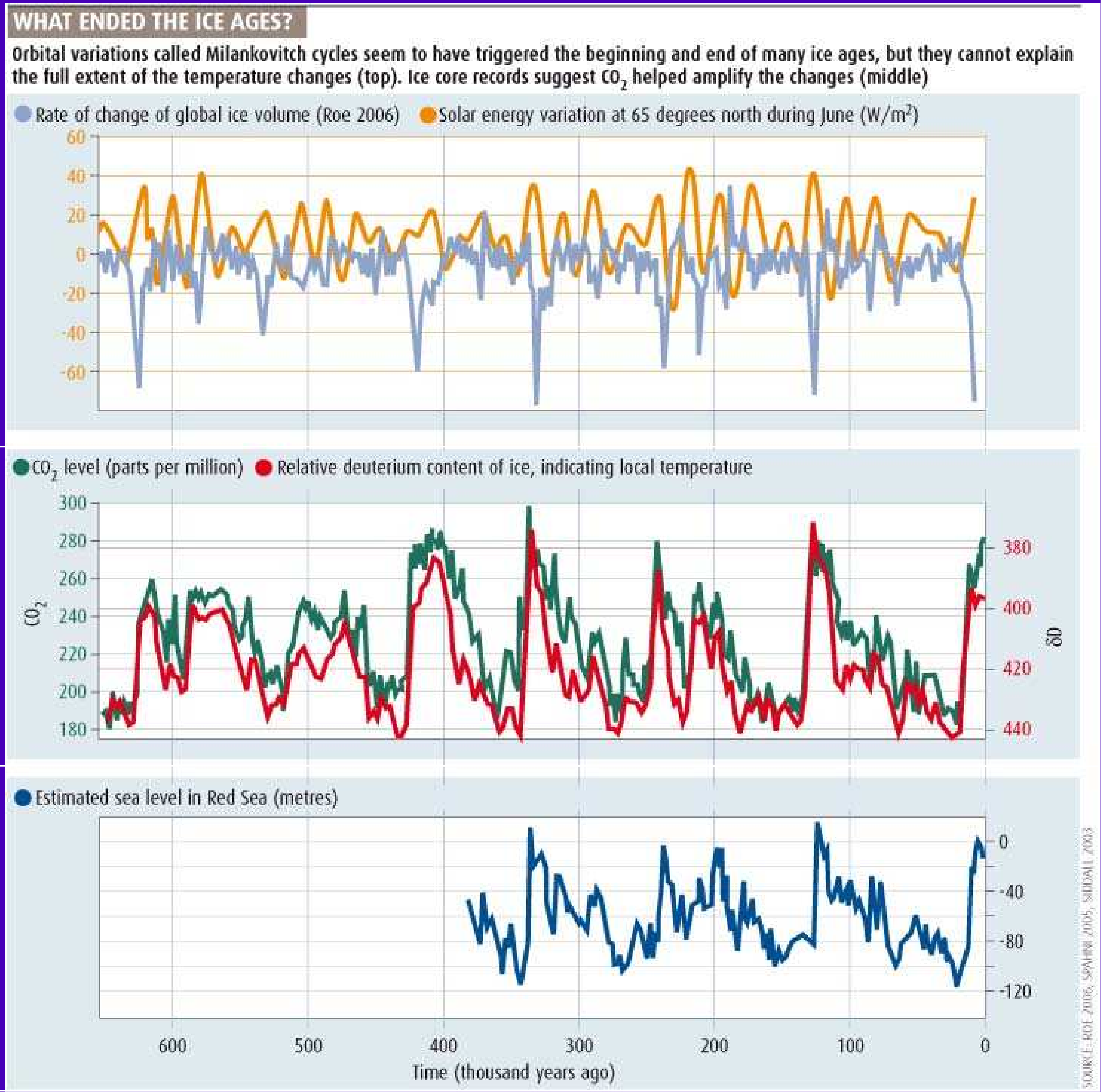
The last million years (almost)

280 ppm

global T ~ 6 K

180 ppm

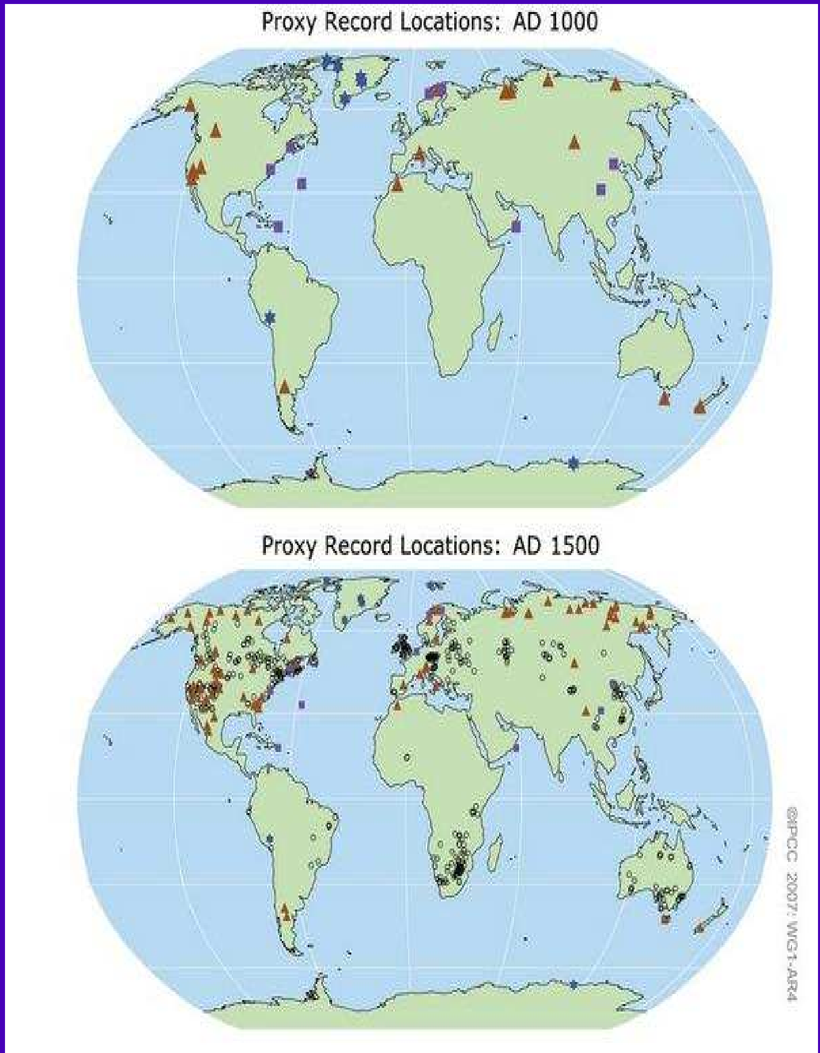
120 meters

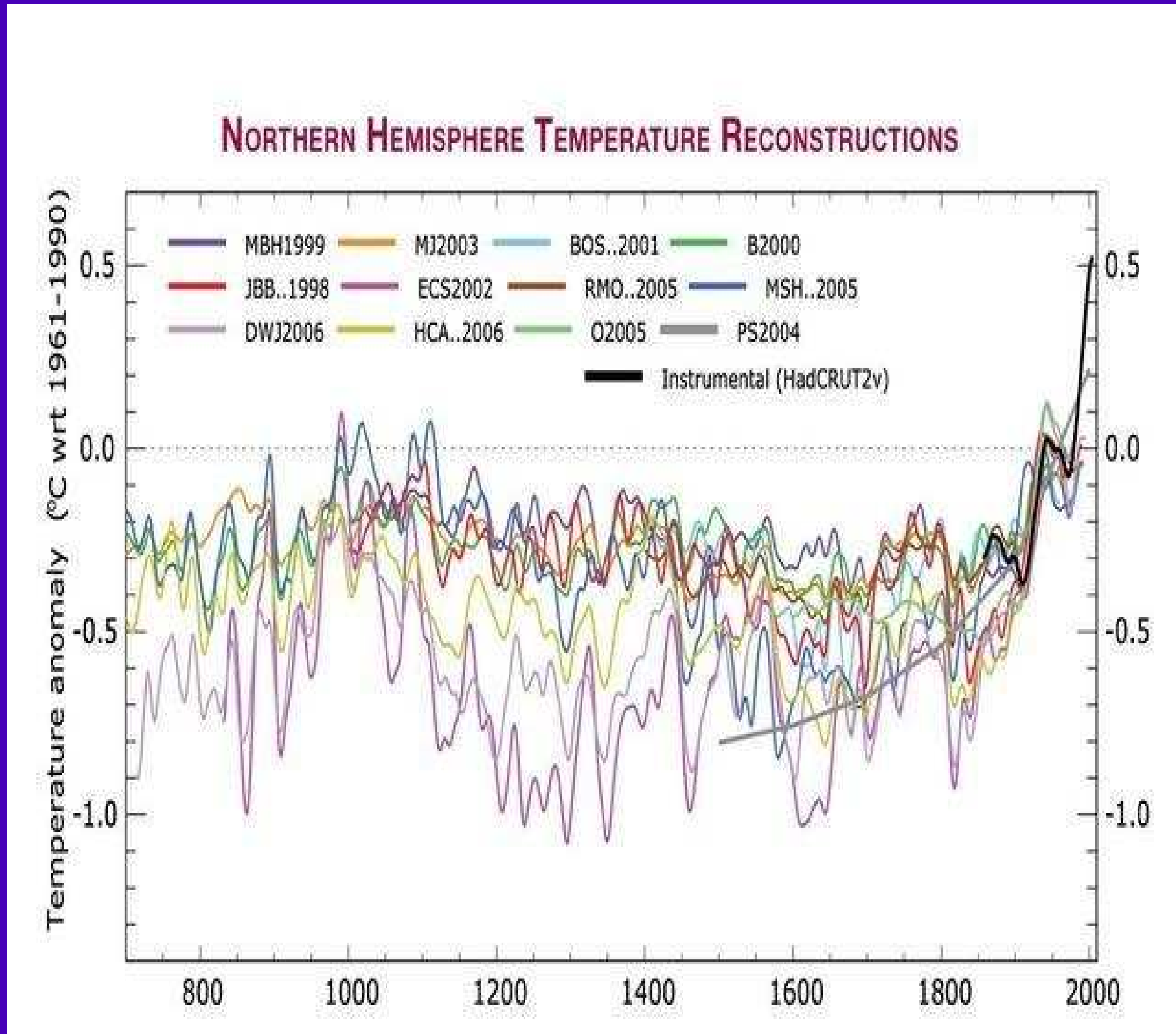


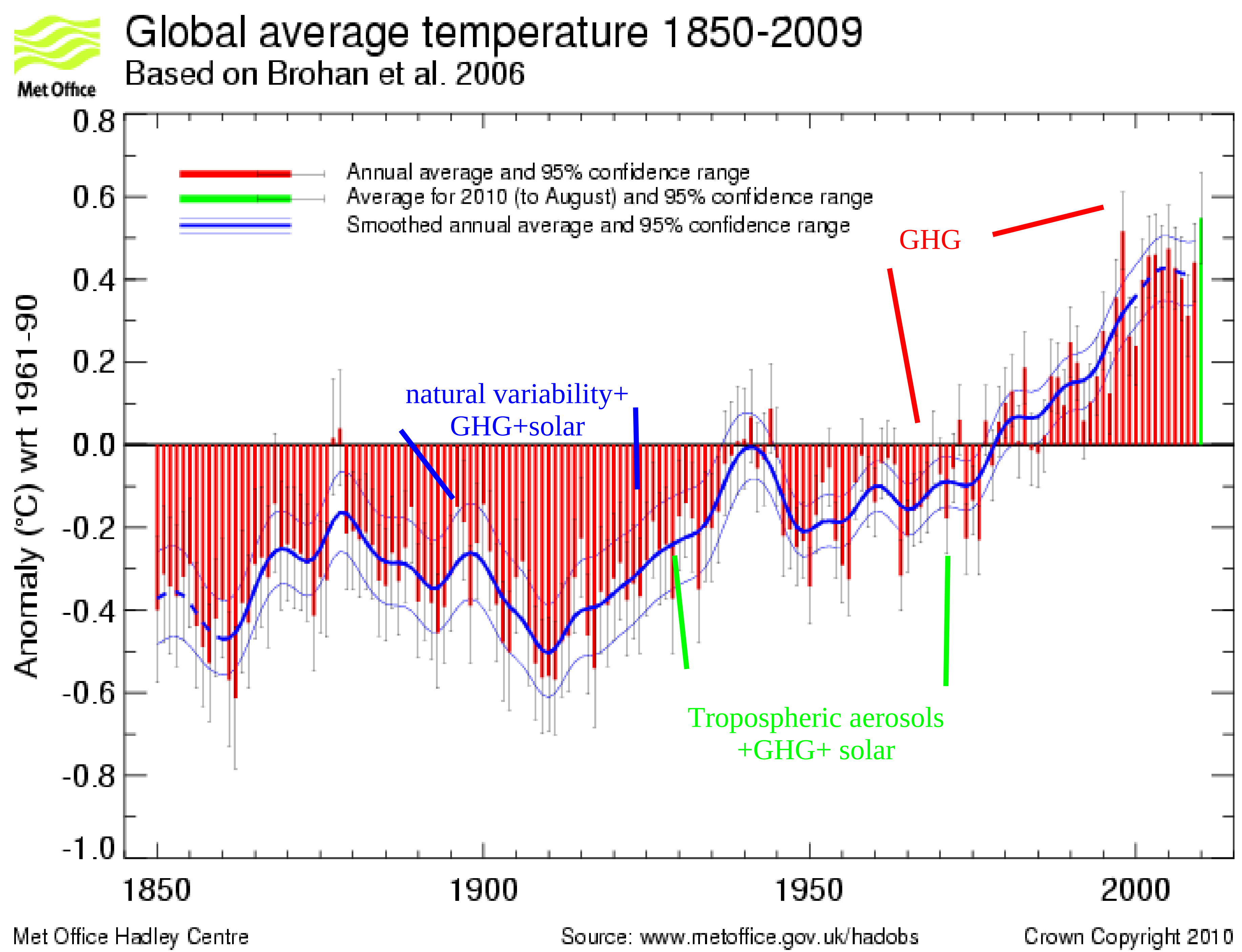
Scotland glacier remnants

Reconstructed Northern Hemisphere temperatures in the past two millennia

Medieval Warm Period ->Little Ice Age ->Recent Warming







Met Office
Global average temperature 1850-2009
Based on Brohan et al. 2006
Annual average and 95% confidence range
Average for 2010 (to August) and 95% confidence range
Smoothed annual average and 95% confidence range
GHG
natural variability+
GHG+solar
Tropospheric aerosols
+GHG+ solar
Anomaly (°C) wrt 1961-90
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
1850
1900
1950
2000
Met Office Hadley Centre
Source: www.metoffice.gov.uk/hadobs
Crown Copyright 2010

Causes of external climate variations

Main climate forcings in the period 7000BP to present are:

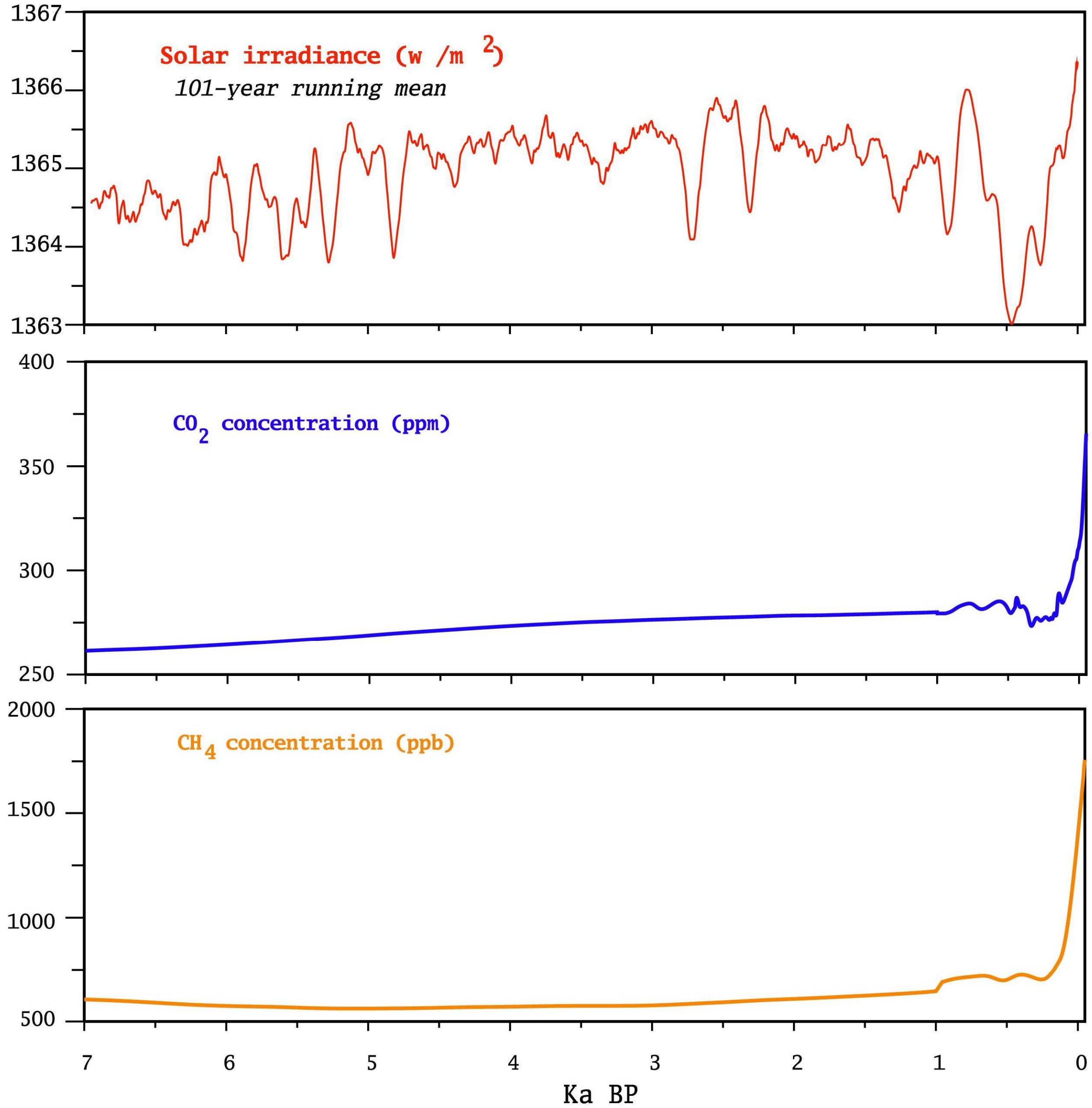
-*Orbital forcing*, due to slow changes in the Earth's orbital parameters. The precession of the perihelion (period ca. 19000 years), obliquity (period ca. 40000 years) and eccentricity (period ca. 100000 years). This forcing can be accurately calculated.

-*CO2 and CH4 concentrations.* Derived from the concentrations in air bubbles trapped in ice cores

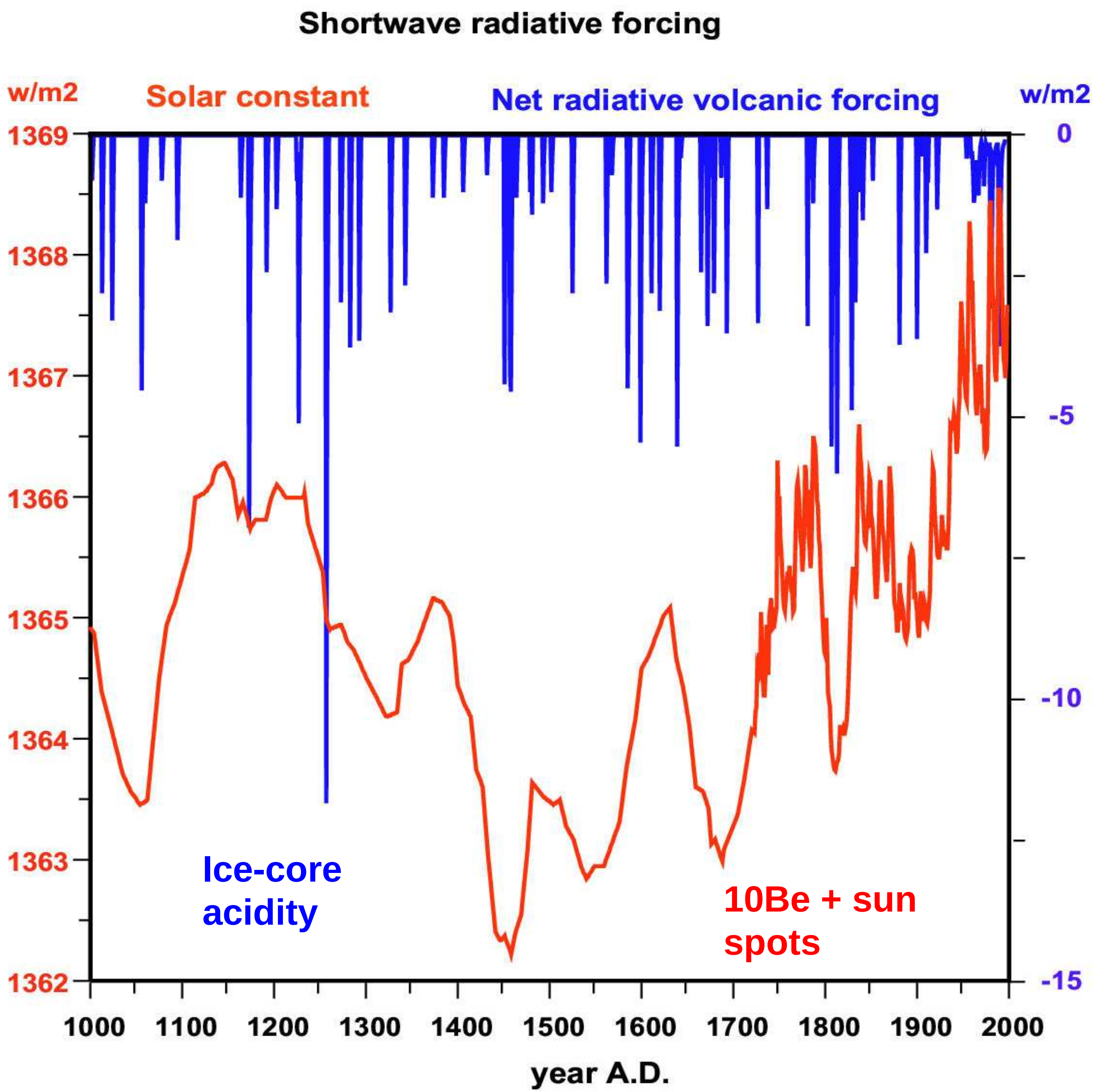
-*Intrinsic solar irradiance*, caused by internal solar dynamics. Derived from concentrations of the isotopes C14 and Be10 in ice cores. Produced by cosmic rays, their production rate is modulated by the solar open magnetic field

-*Volcanic forcing, caused by the production of stratospheric aerosols from sulphate volcanic eruptions*

External forcings

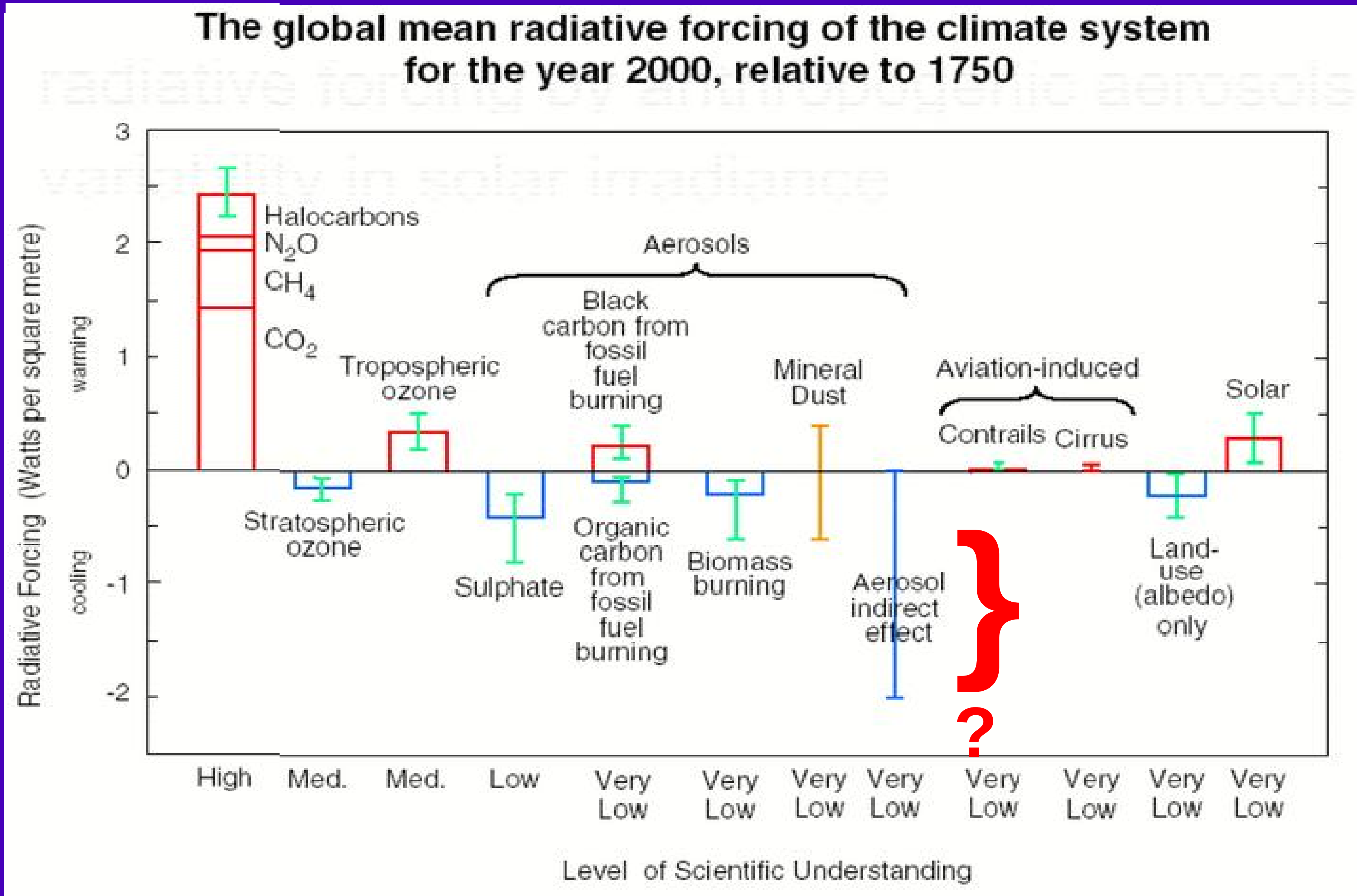


Derived from C14 concentrations in tree rings, Weber and Crowley (2004), and from Be10 in ice cores, Crowley (2000).



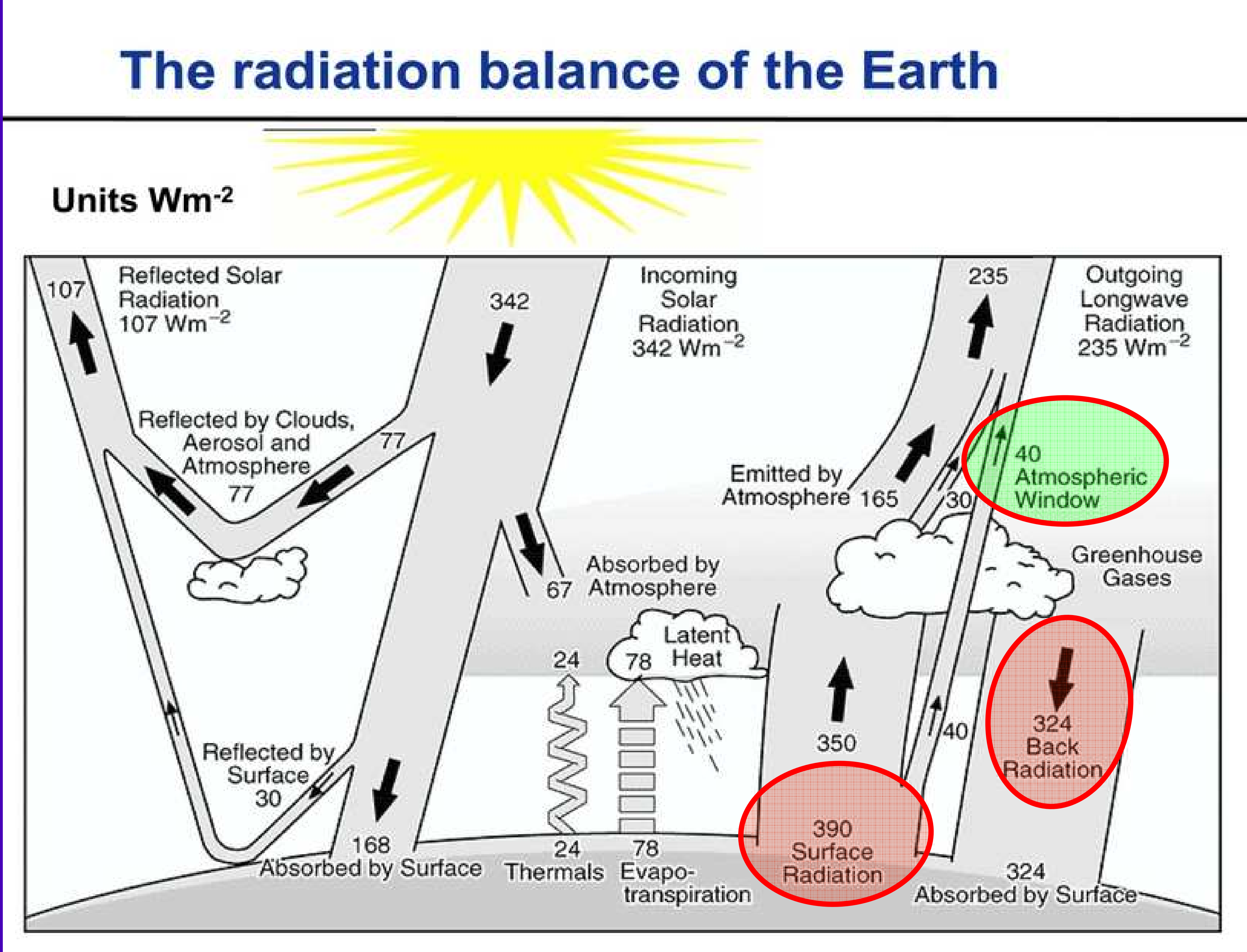
Shortwave radiative forcing
w/m2
Solar constant
Net radiative volcanic forcing
w/m2
1369
1368
1367
1366
1365
1364
1363
1362
0
-5
-10
-15
Ice-core acidity
10Be + sun spots
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
year A.D.

External forcings of 20th century climate change (without volcanoes)

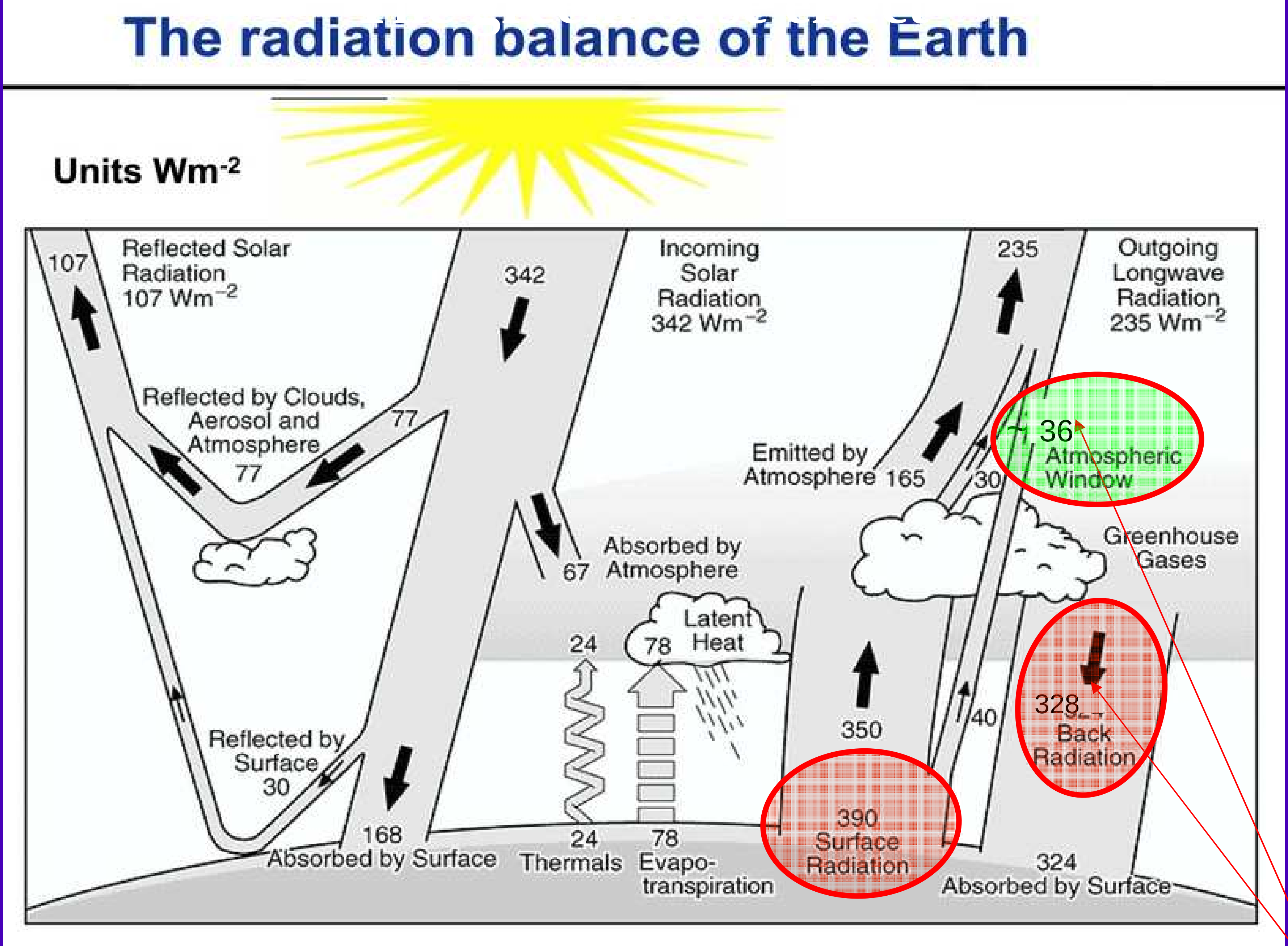


Total anthropogenic forcing in 2100 : 6.7 (4.2-9.1) w/m2

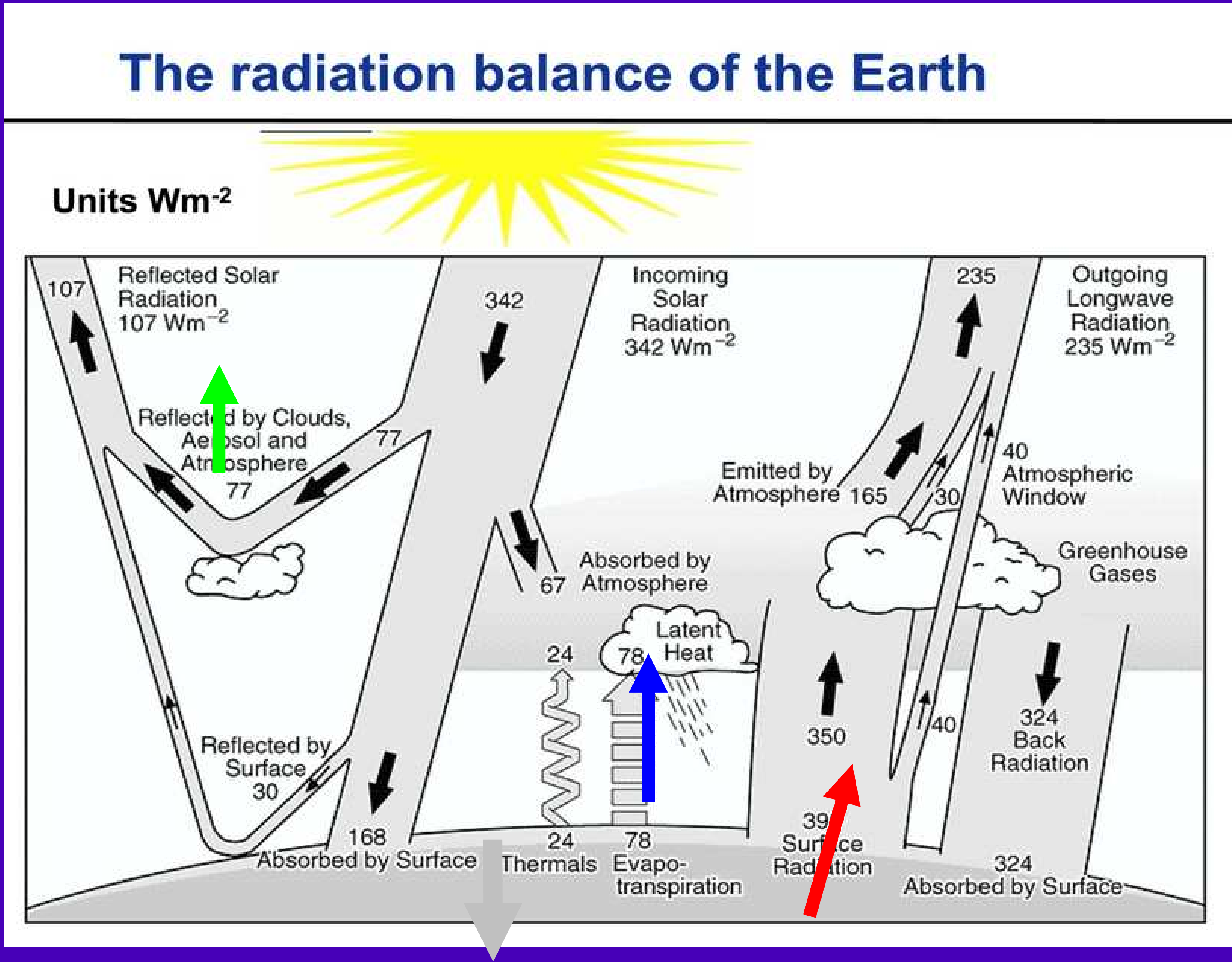
The greenhouse effect



The greenhouse effect



The Earth has multiple ways to react, and to simulate this reaction is difficult



-Increase surface temperature

-Increase evaporation

-Increase cloudiness

-Increase ocean heat-storage

All simultaneously

Some important climate feedbacks (+,-,uncertain)

Black-body: increased temperatures increase the outward long-wave emission

Water vapor feedback: Warmer ocean temperatures increase evaporation -> atmospheric humidity -> water vapor greenhouse forcing

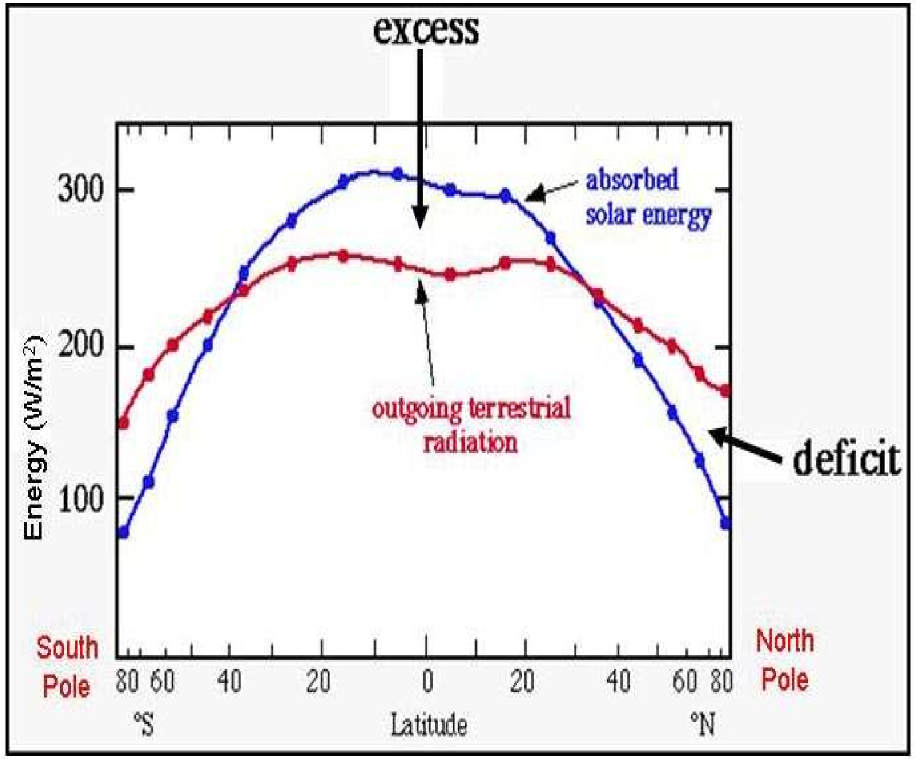
Cloud feedback: warmer temperatures change cloud cover -> short wave and long wave radiation forcing . Sign depends on cloud type, cloud location

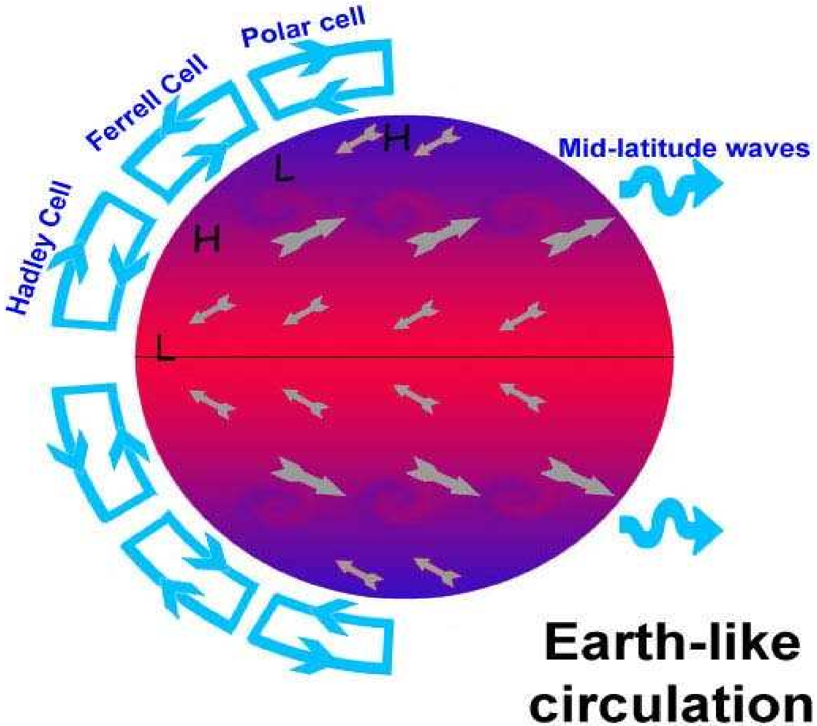
Surface albedo: warmer temperatures melt snow and ice -> albedo decrease

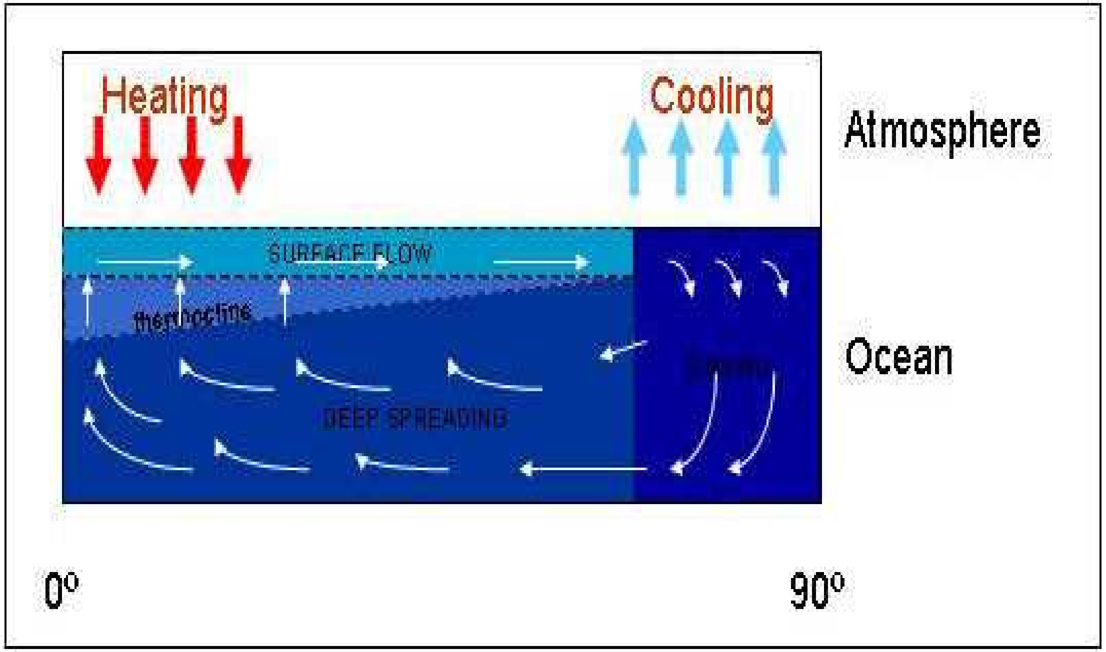
Lapse-rate feedback: decreased vertical temperature profile decrease the atmospheric greenhouse gas forcing

Many other feedbacks involve vegetation, soil moisture, oceanic circulation, carbon cycle, etc

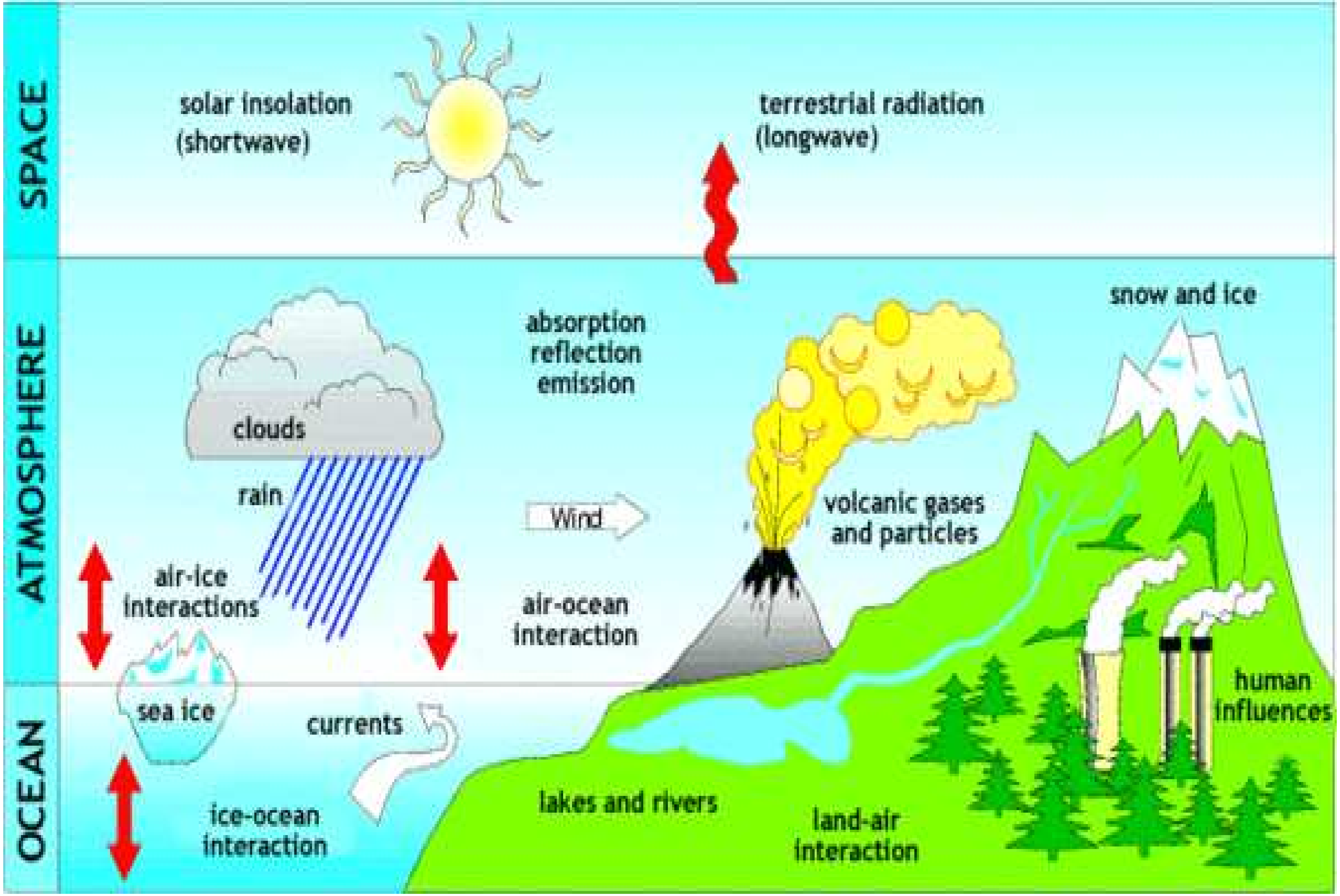
The climate as a heat machine







The complexity of the climate system



Primitive Equations

$$\frac{du}{dt} - 2\Omega \sin\theta v - \frac{uv\tan\theta}{a} + \frac{uw}{a} = -\frac{1}{a\cos\theta}\frac{\partial\Phi}{\partial\lambda} + F_\lambda$$

$$\frac{dv}{dt} + 2\Omega \sin\theta u - \frac{u^2\tan\theta}{a} + \frac{vw}{a} = -\frac{1}{a}\frac{\partial\Phi}{\partial\theta} + F_\theta$$

Newtons 2nd law

F =m a

$$\frac{\partial\Phi}{\partial p} = -\frac{RT}{p}$$

Equation state ~ PV=nRT

$$\frac{dT}{dt} = \frac{\alpha\omega}{c_p} + \dot{Q}$$

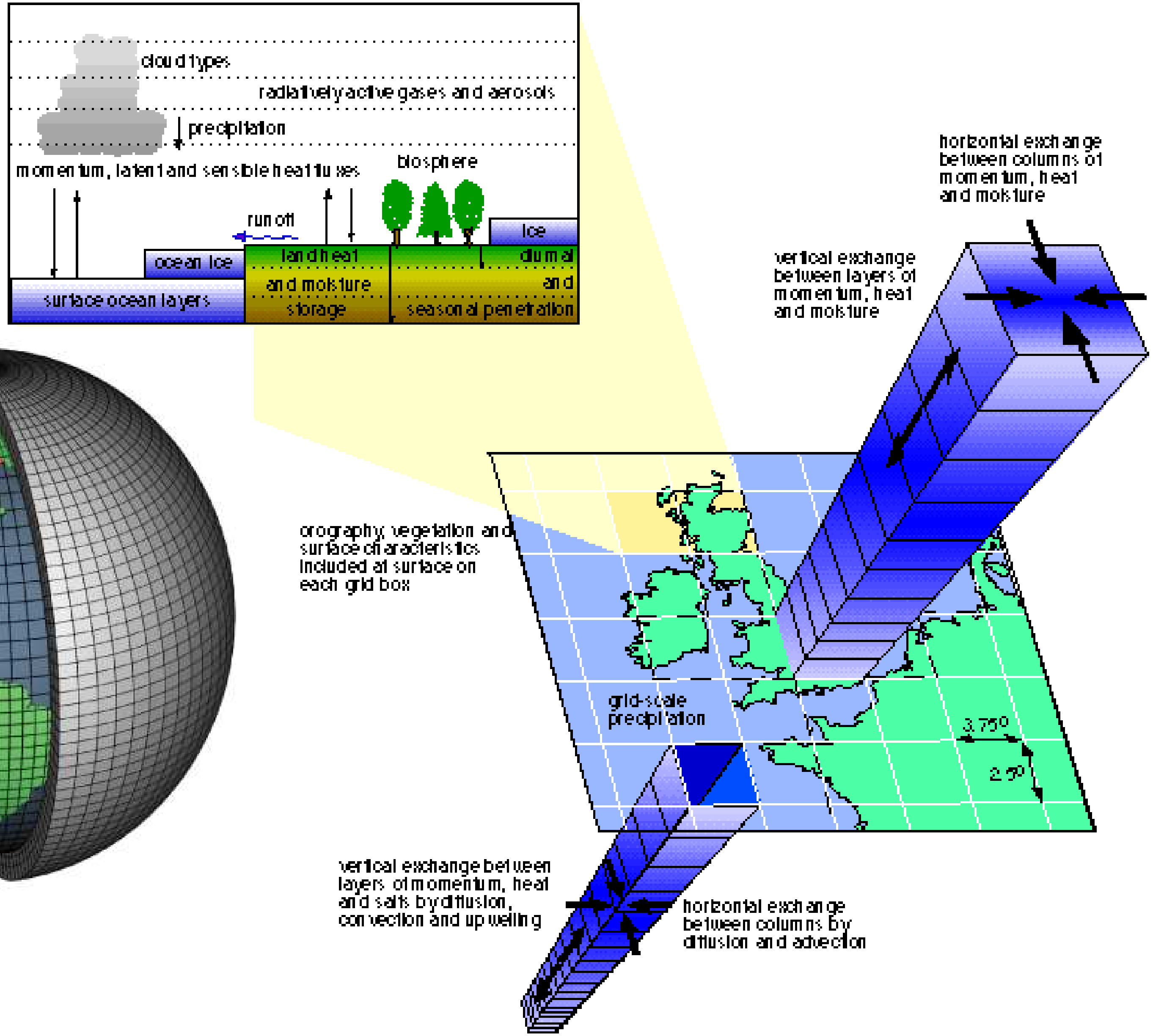
Conservation of energy

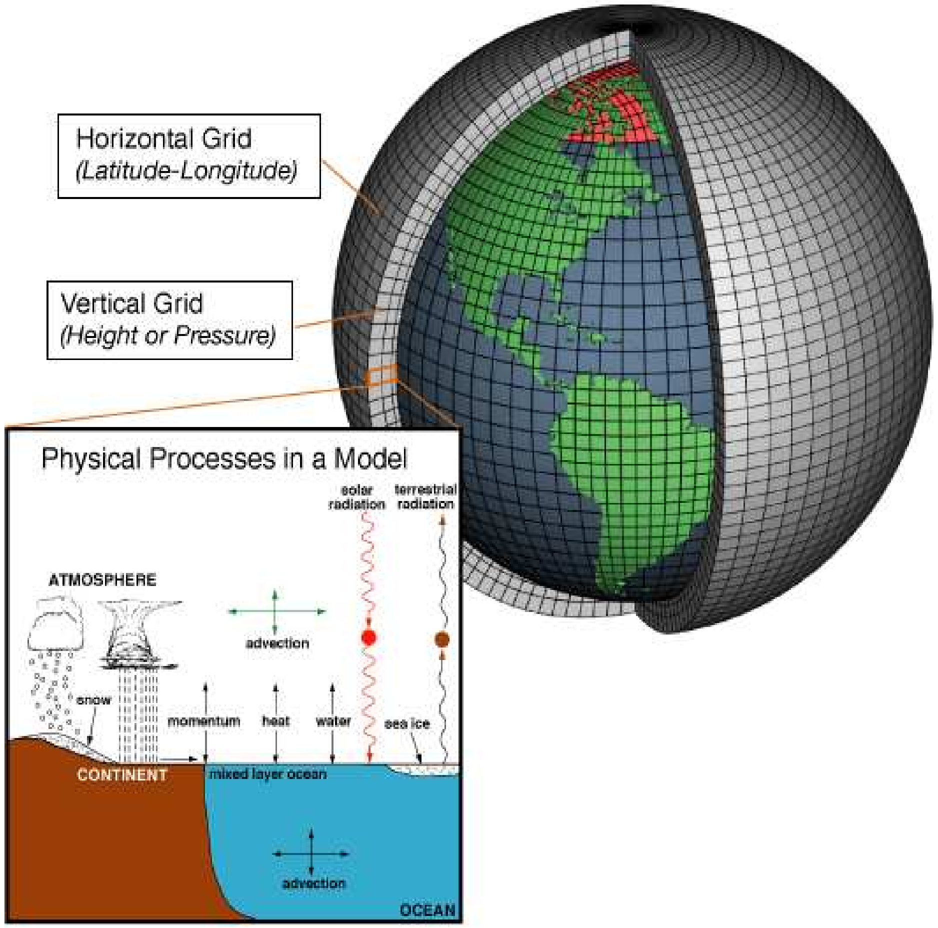
$$\frac{\partial\omega}{\partial p} = -\nabla\cdot\vec{v}$$

Conservation of mass

Structure of a General Circulation Model

Present complex climate models do not simulate changes in land-ice sheets (e.g. Greenland melting)





courtesy D. Vinner, CRU

Climate models

Always work in progress....

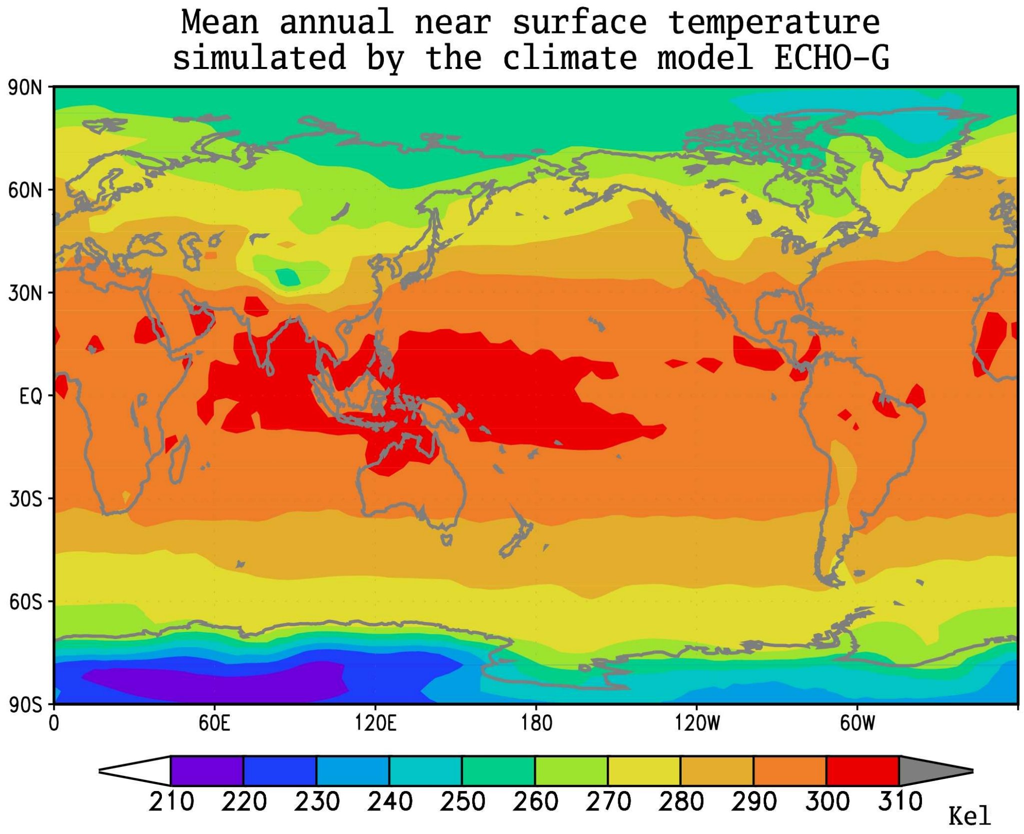
View from
German Climate Computing Centre,
Hamburg

What is (in) a climate model?

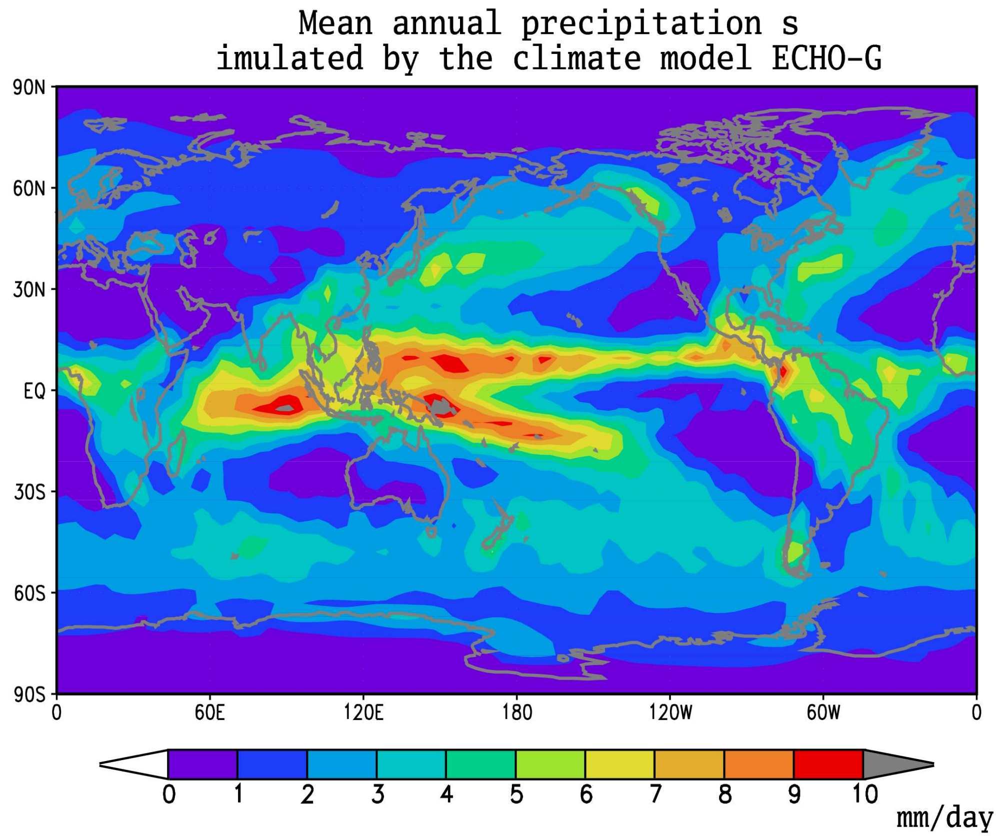
A computer program (0.5 mill pages) that was written to represent:
-air flows from high pressure to low pressure
-the Earth is round and rotates
-hot air is lighter than cold air
-solar radiation is absorbed and reflected by all materials
-infrared radiation is absorbed and emitted by all materials
-water vapor condenses below certain relative humidity threshold, clouds are formed. And it may rain

-Warm water warms the air, warm air warms the water surface
-Rain makes sea water fresher, evaporation makes seawater saltier

-water masses flow from high pressure to low pressure
-winds exert a drag on ocean surface. currents arise
-warm water is lighter than cold water
-salt water is heavier than fresh water



Example of output of a climate model

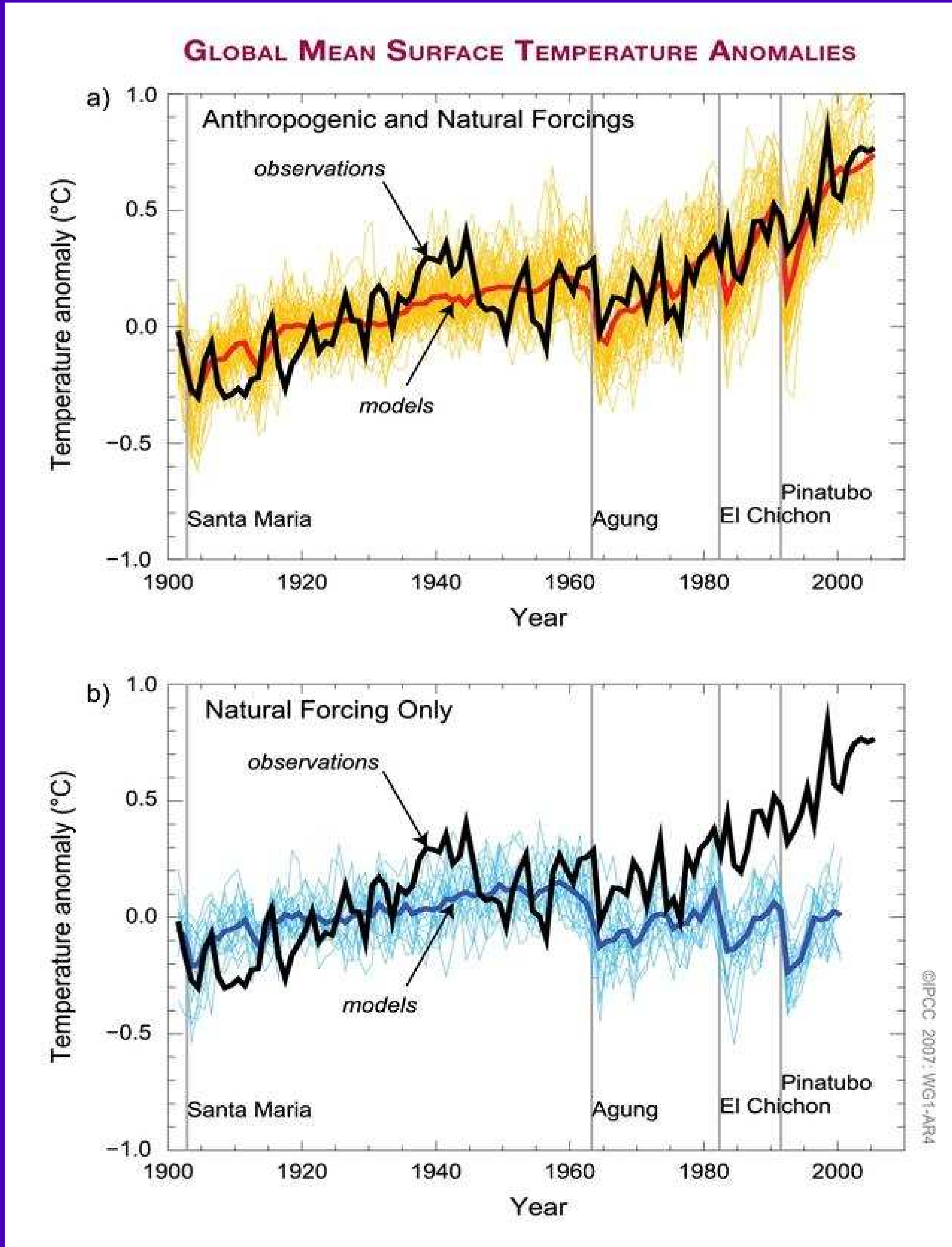


Complete output is similar to that of a weather prediction model:

3-d T, 3-d wind, 3-d moisture,

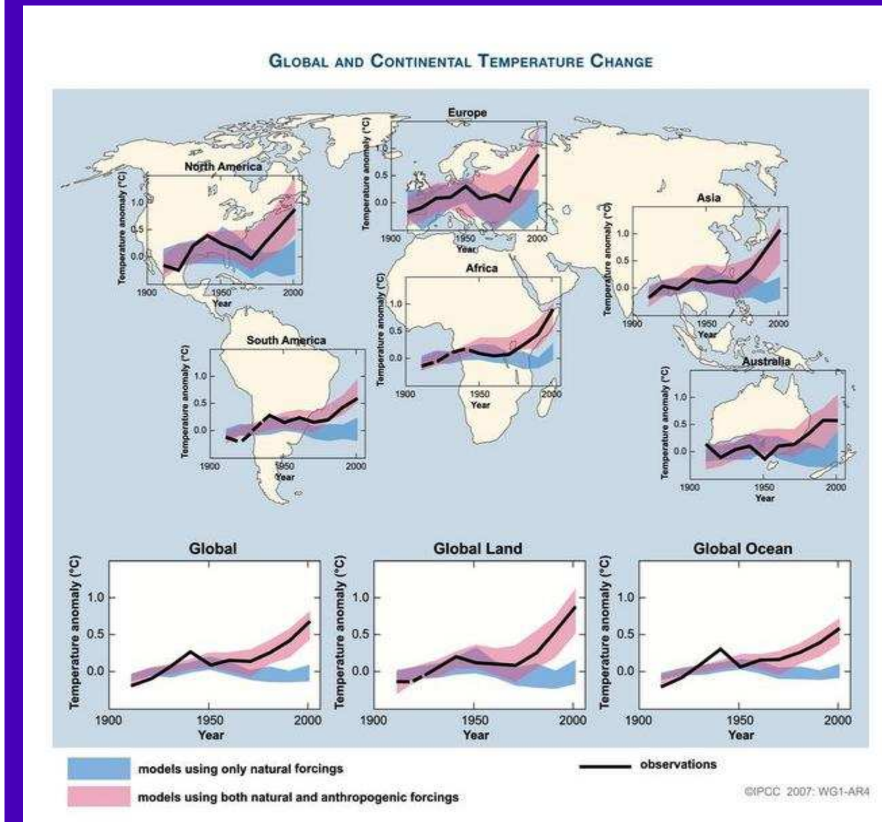
3-d cloudiness, precipitation,

A very complete,global , huge data set



Climate models replicate the observed global T evolution using observed forcings

-Uncertainty in aerolsol forcing
-Different climate model sensitivity



Some numbers of climate models

- Spectral (spherical harmonics) or finite differences schemes

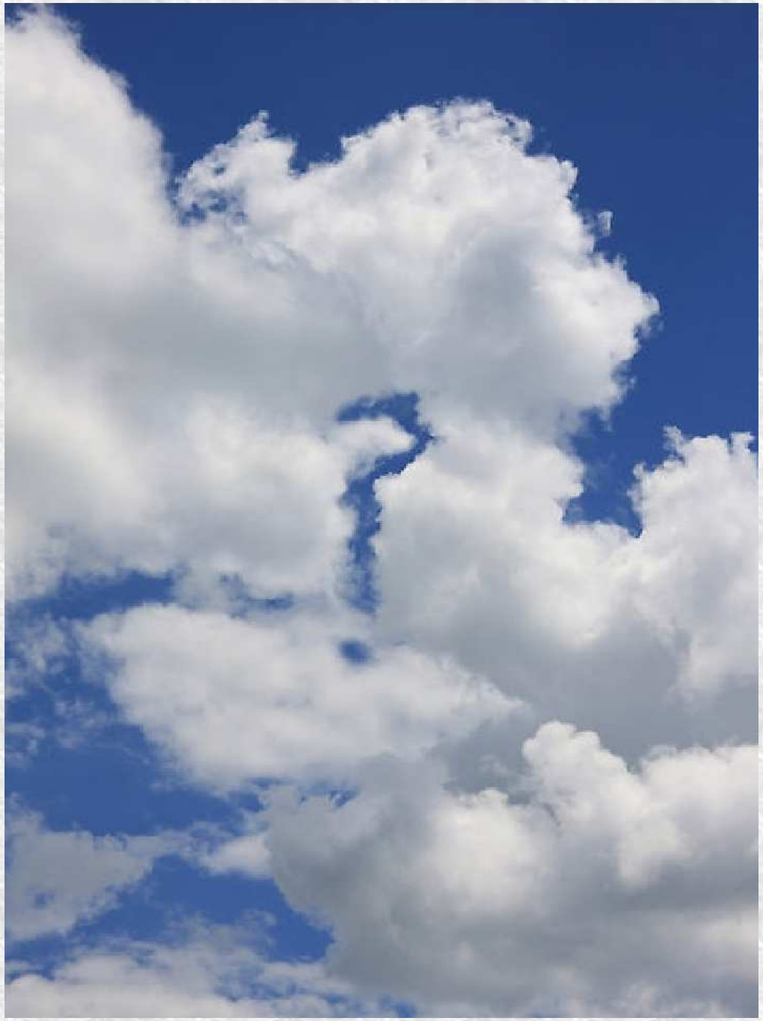
-Fortran code – with some pieces of C code- ~ $5x10^5$ lines

-On non-massive parallel machines (10^1 nodes), 1 model -year takes ~ 4 hours

-Size of model output ~ 1 GB per model-year

-Typical length of simulations: 100-1000 years

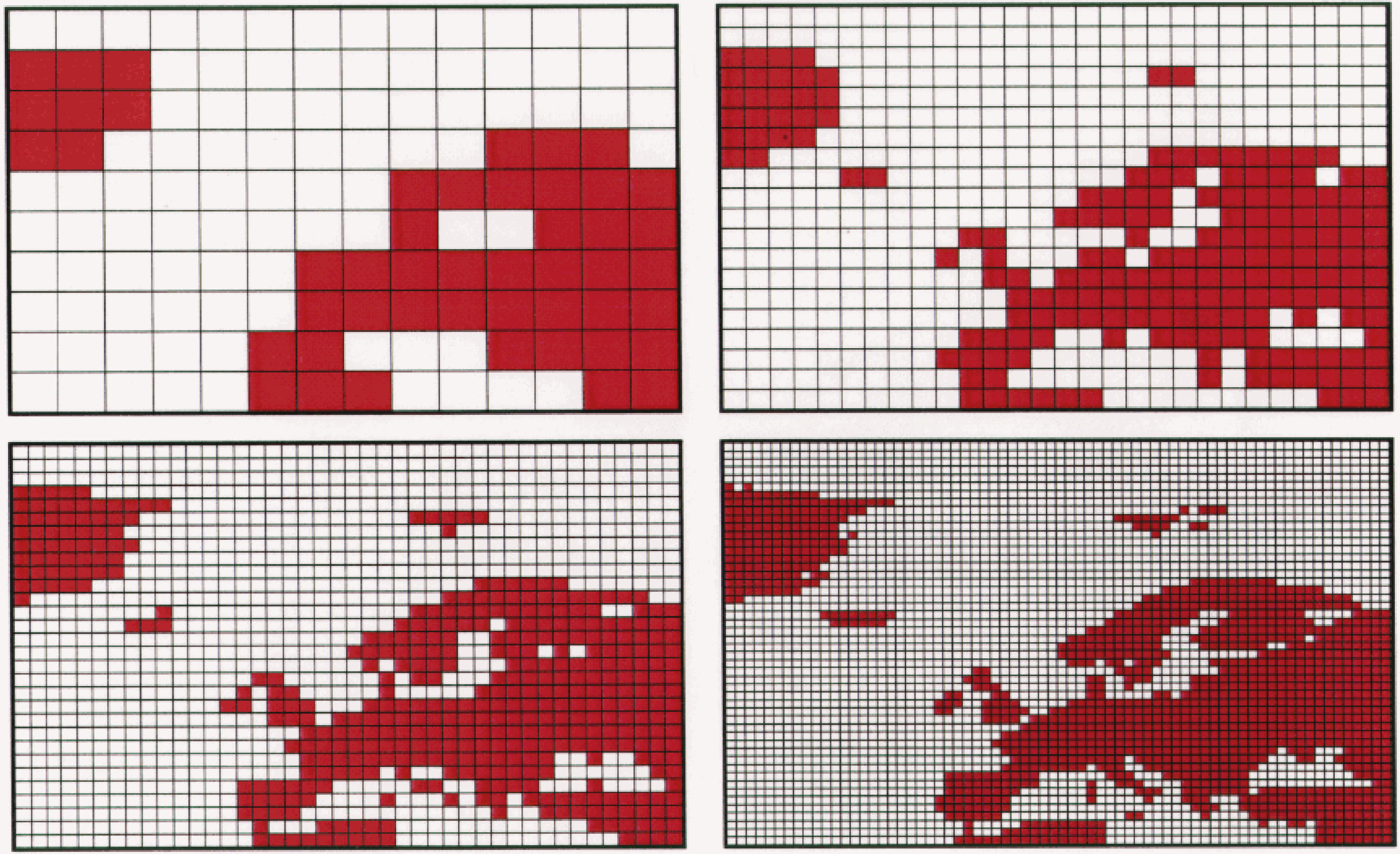
Where do the limitations of climate models lie ?



European part of the land-sea mask for different T-model resolutions

a) T21

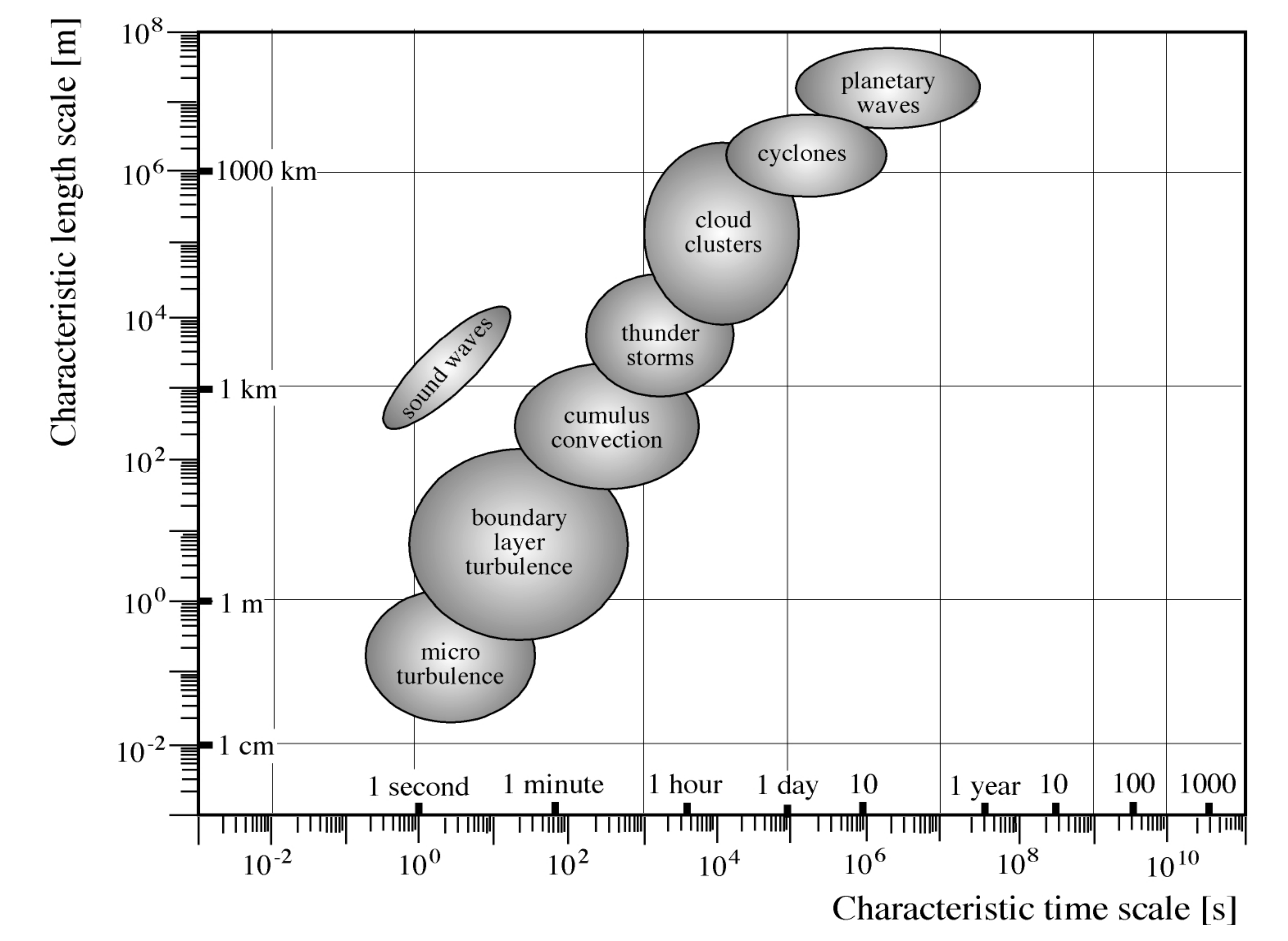
b) T42



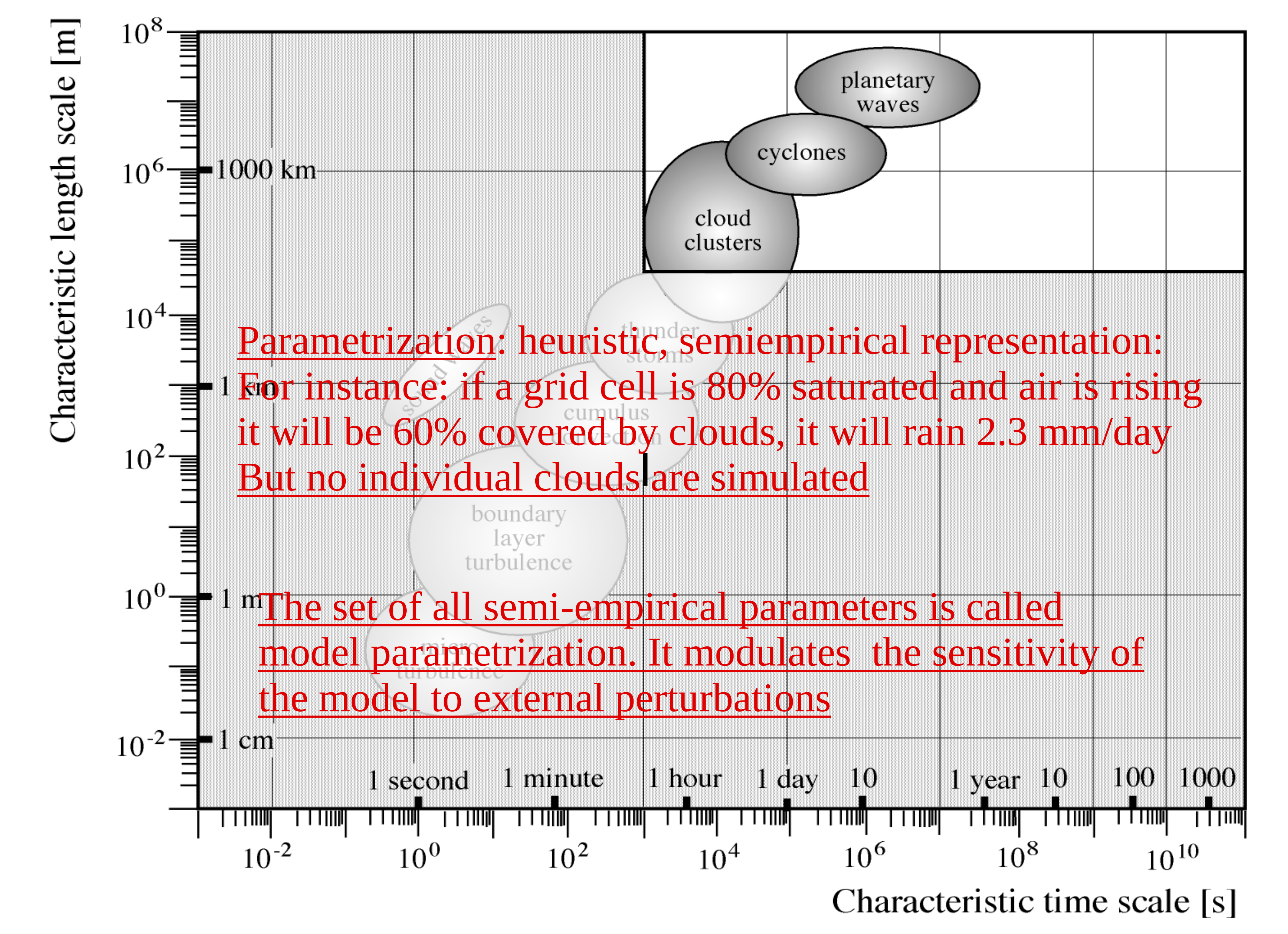
c) T63

d) T106

Dynamical atmospheric processes



Dynamical atmospheric processes <u>represented in a global climate model</u>



<u>Parametrization</u>: heuristic, semiempirical representation:
For instance: if a grid cell is 80% saturated and air is rising
it will be 60% covered by clouds, it will rain 2.3 mm/day
<u>But no individual clouds are simulated</u>

<u>The set of all semi-empirical parameters is called model parametrization. It modulates the sensitivity of the model to external perturbations</u>

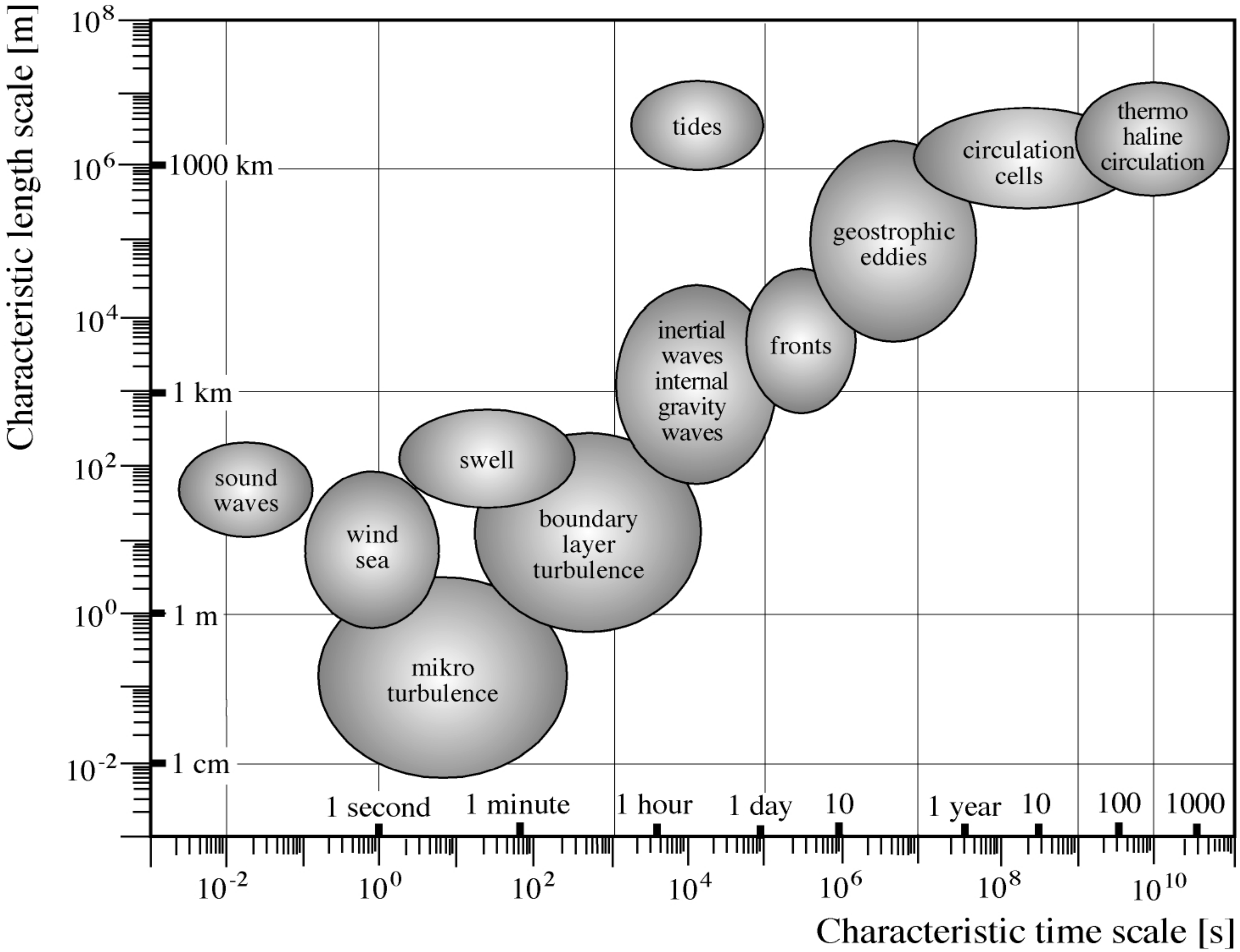
Important examples of parametrizations in a climate model (atmospheric sub-model)

Table I. Some model parameters perturbed by Murphy *et al.* (2004).

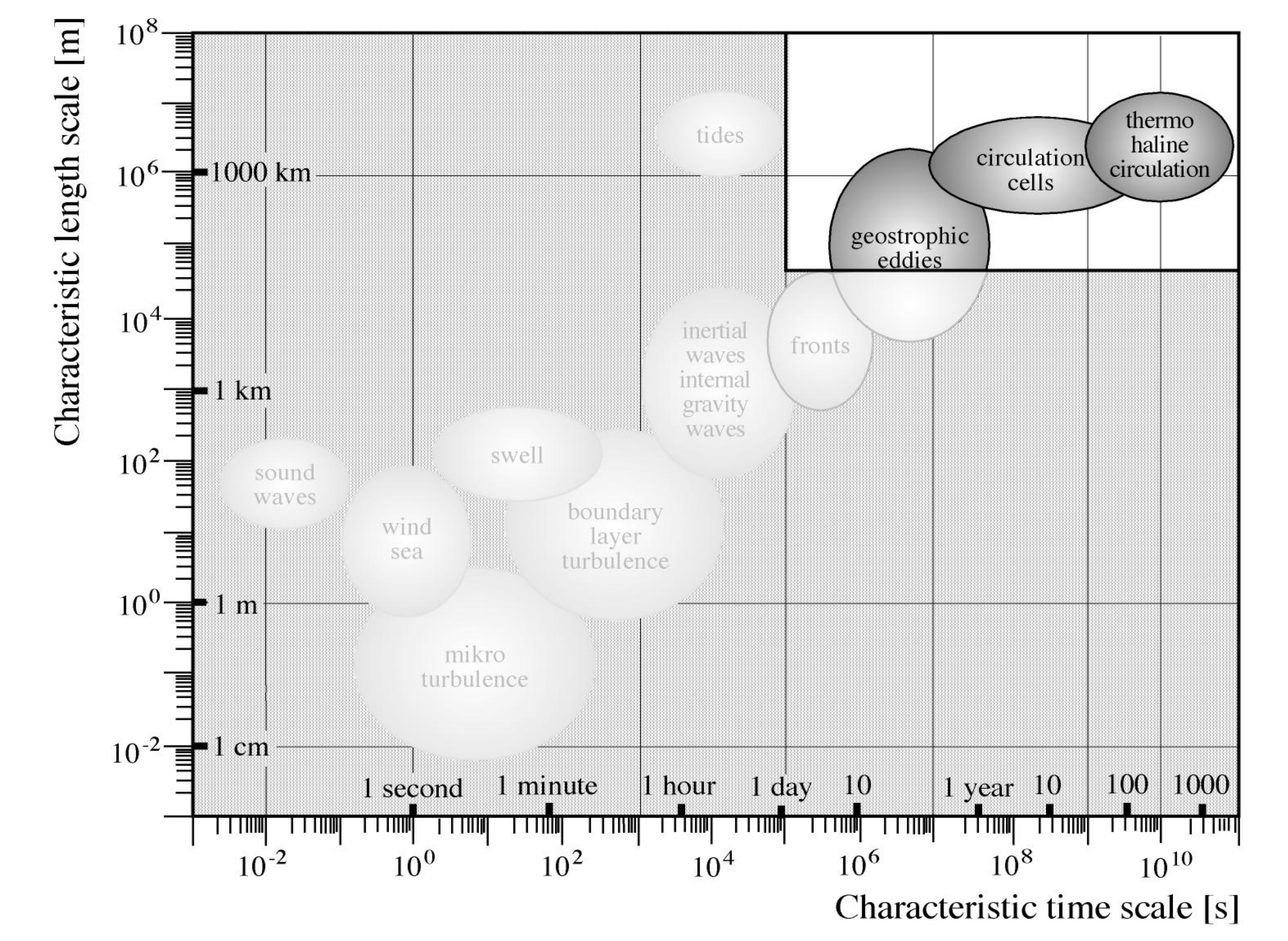
Parameter	Physical process	Values used		
		Low	Middle	High
Droplet to rain conversion rate (s^{-1})	Cloud	0.5×10^{-4}	1.0×10^{-4}	4.0×10^{-4}
Relative humidity for cloud formation	Cloud	0.6	0.7	0.9
Cloud fraction at saturation (free trop.)	Cloud	0.5	0.7	0.8
Entrainment rate coefficient	Convection	0.6	3.0	9.0
Time-scale for destruction of CAPE (h)	Convection	1.0	2.0	4.0
Effective radius of ice particles (μm)	Radiation	25	30	40
Diffusion e-folding time (h)	Dynamics	6	12	24
Roughness length parameter (Charnock)	Boundary	0.012	0.016	0.020
Stomatal conductance dependent on CO_2	Land	Off	–	On
Ocean-to-ice heat diffusion coefficient (m^2 s^{-1})	Sea ice	2.5×10^{-5}	1.0×10^{-4}	3.8×10^{-4}

A representative list of the model parameters perturbed by Murphy *et al.* (2004) together with the physical process they are associated with and the perturbed values used.

Dynamical oceanic processes



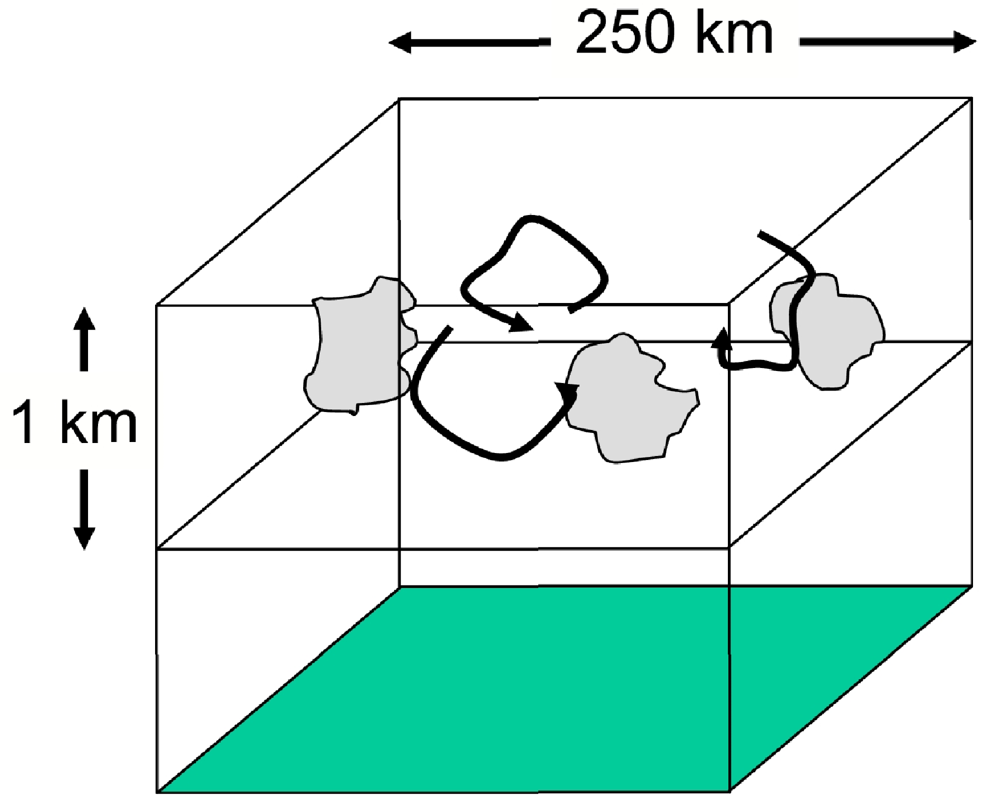
Dynamical oceanic processes represented in a global climate model



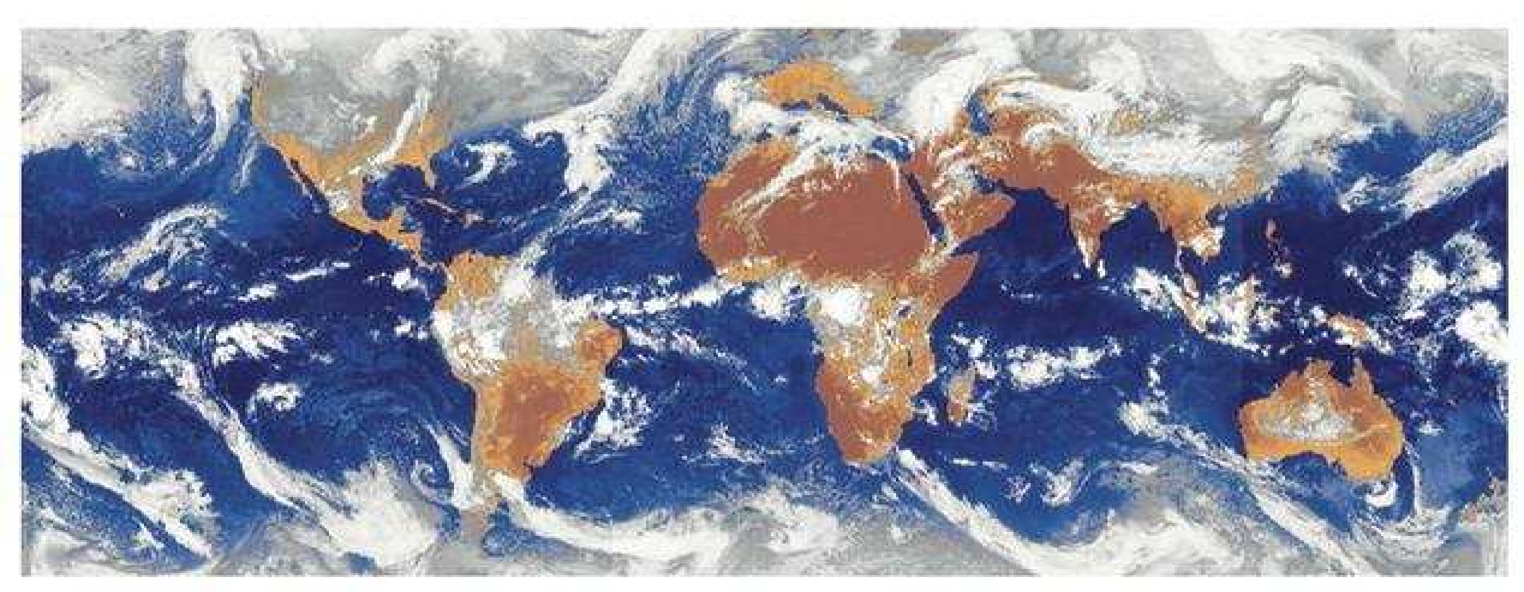
Major consequence of limited resolution : clouds

- grid boxes are typically 250 km wide and 1 km high
- processes important for cloud formation happen at much smaller scales
- it is very difficult to represent effects of clouds and small scale processes only in terms of grid box mean properties

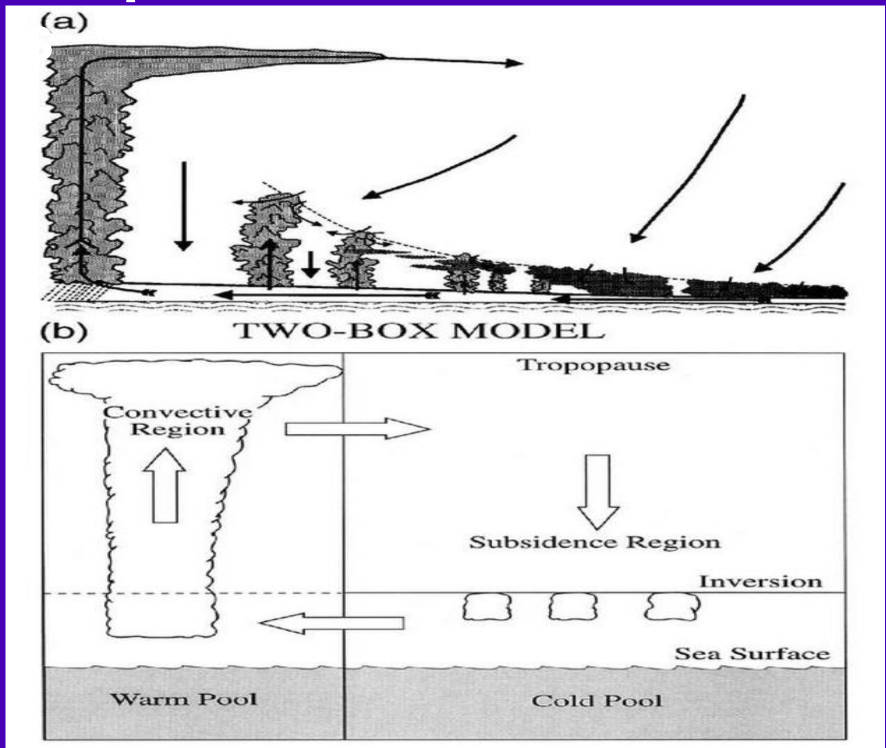
clouds and small-scale circulations



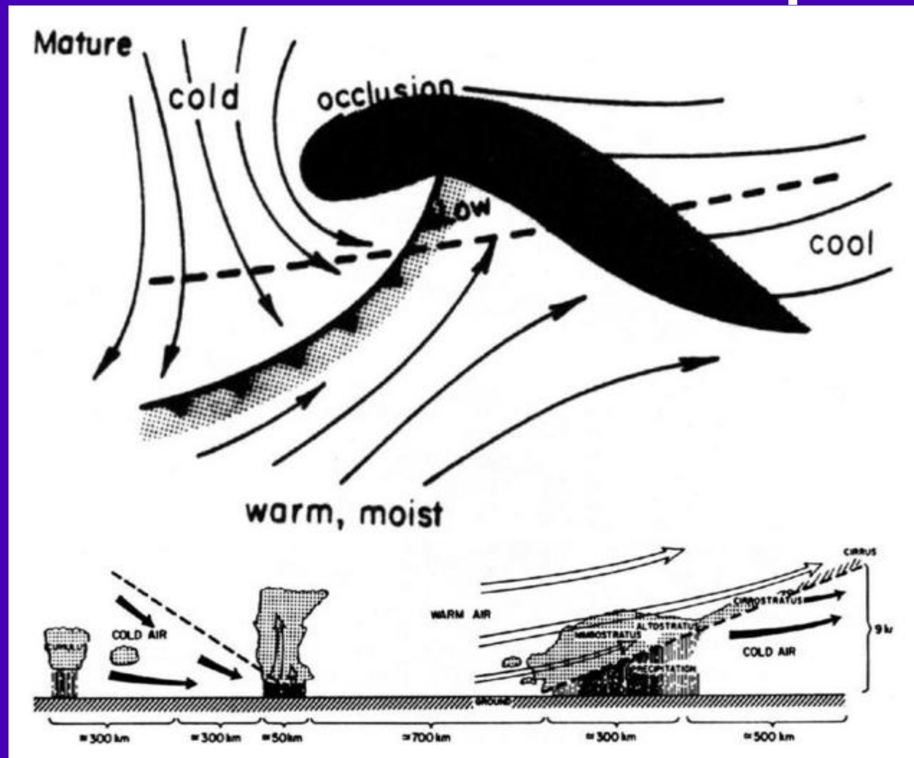
About 65% of the Earth surface is covered by clouds at any time



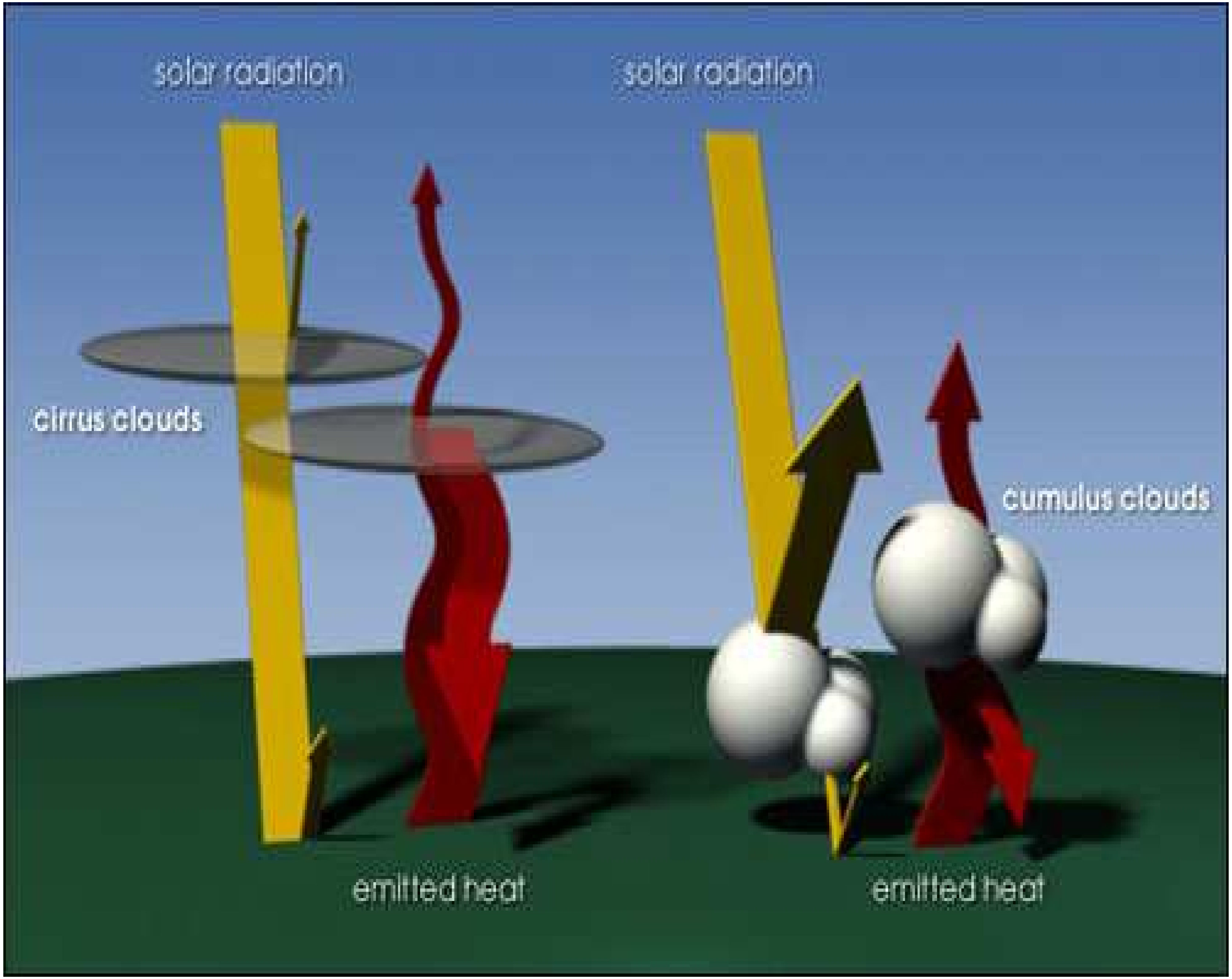
Tropic



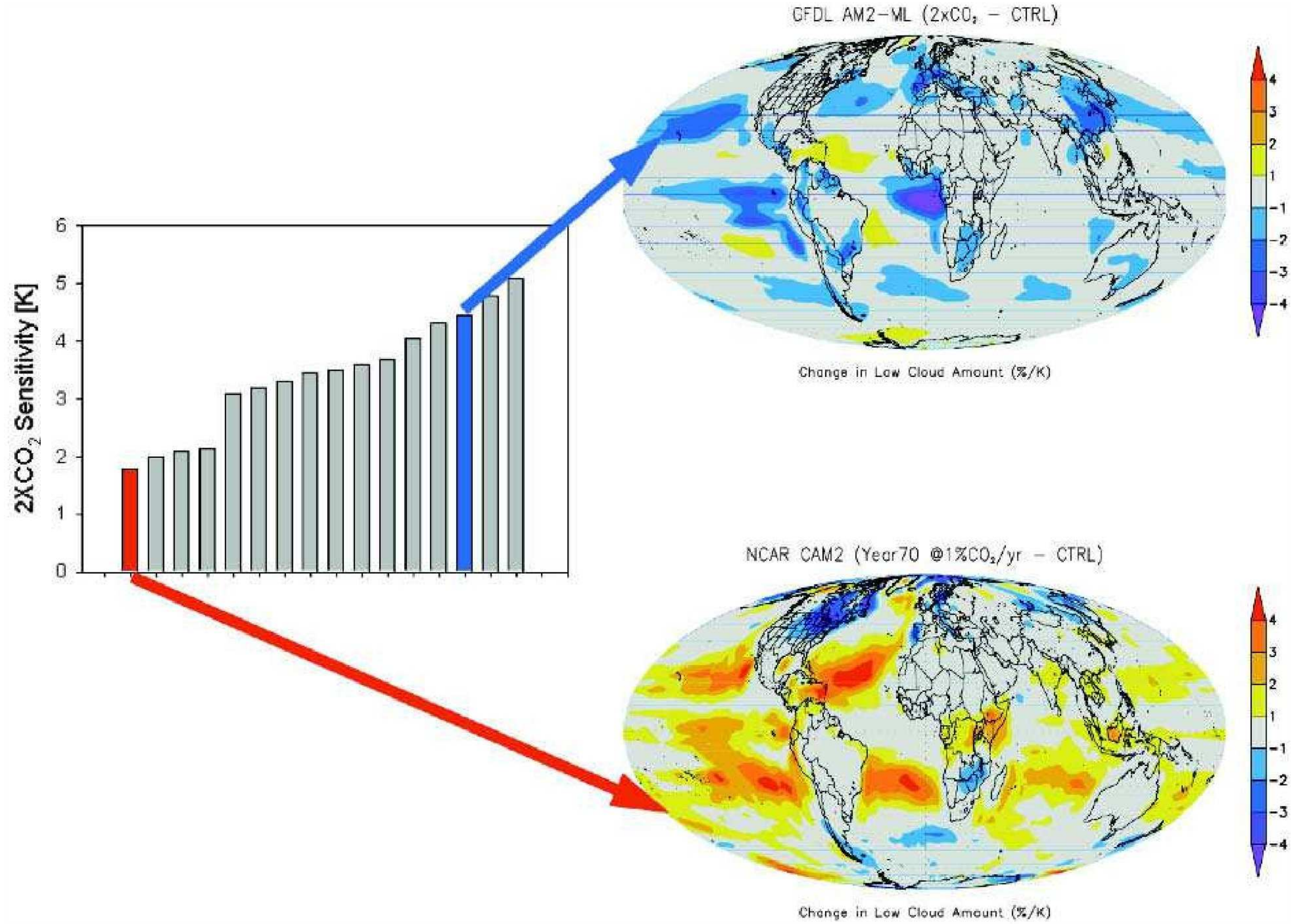
Extratropics



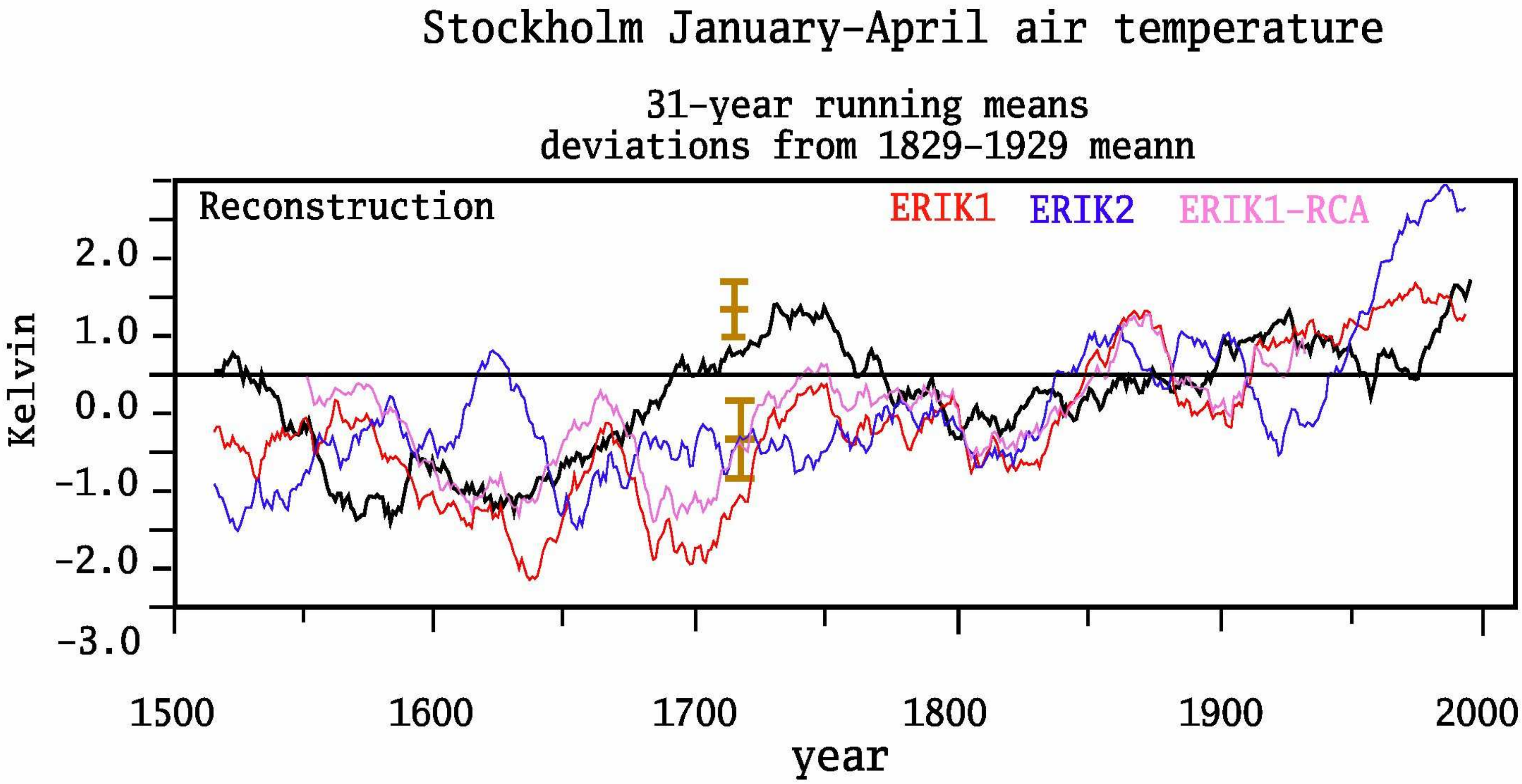
Types of clouds and its radiative properties



Clouds: the known unknown
largest source of uncertainty in climate projections



Uncertainty due to the unknown initial conditions



Sources of uncertainty in climate projections

Structural uncertainty: Is the climate model 'correct'

Use many *good* climate models

Parametrical uncertainty : is the parametrization correct

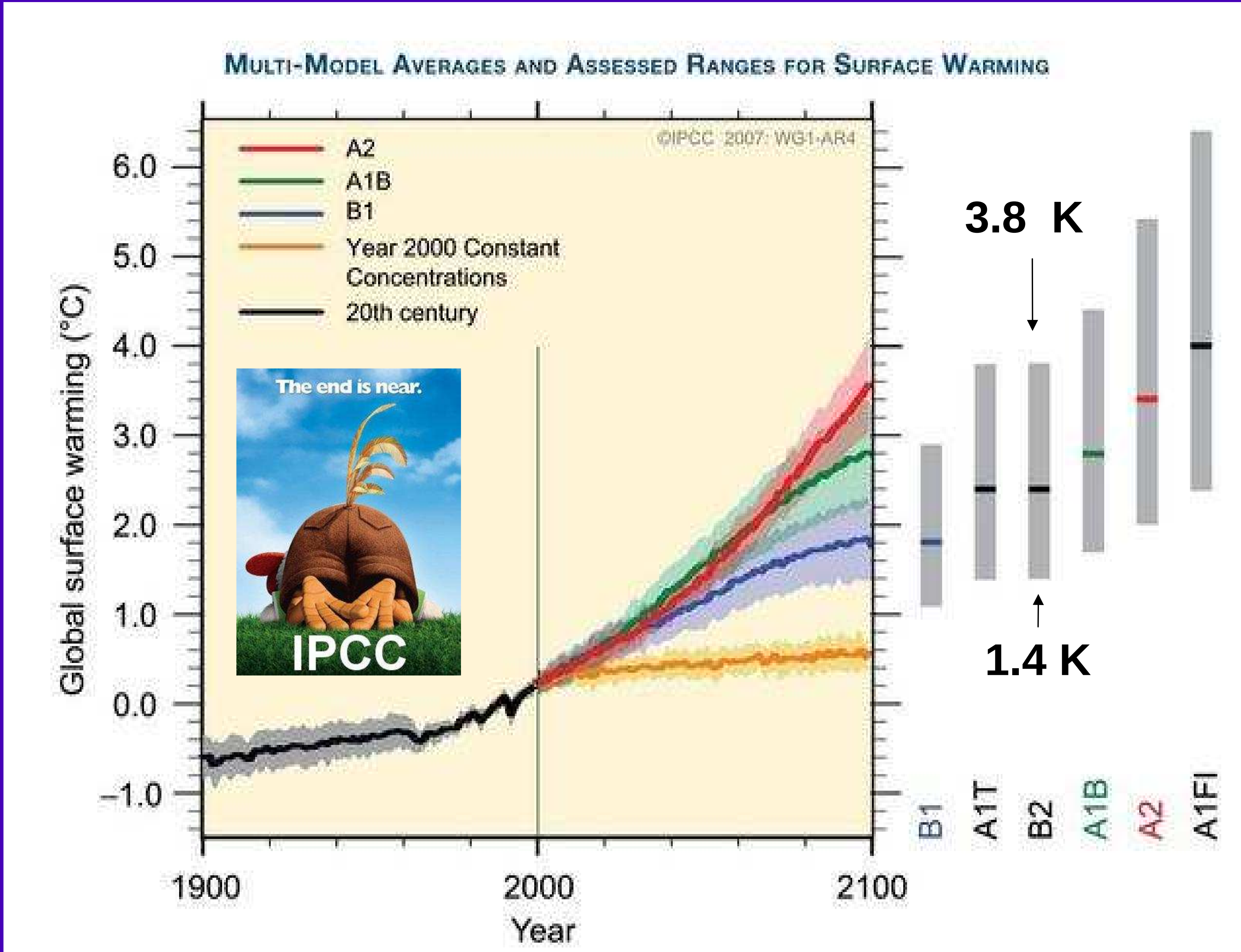
Use many *good* different parametrizations

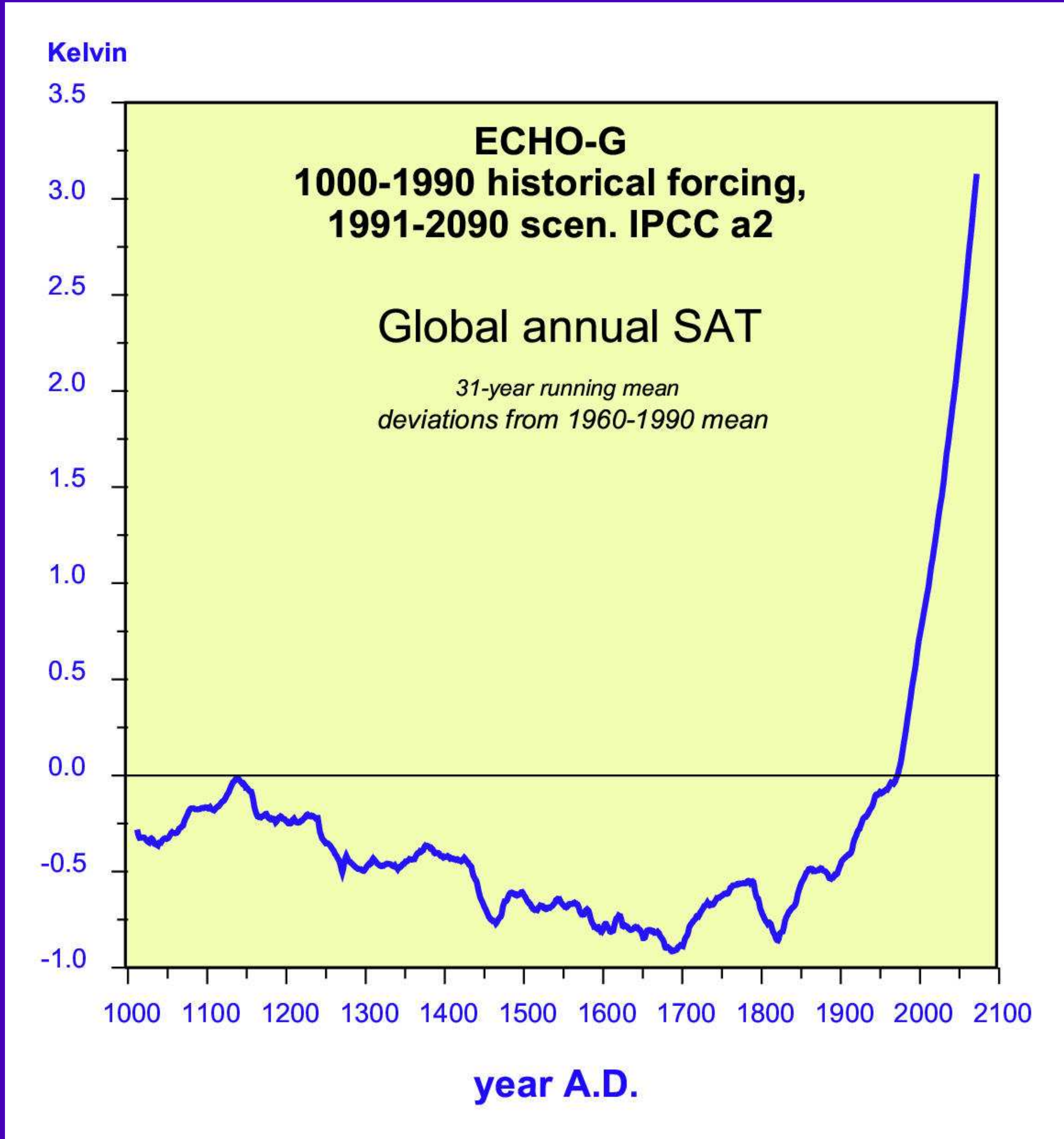
Uncertainty in the initial conditions

Use many different initial conditions

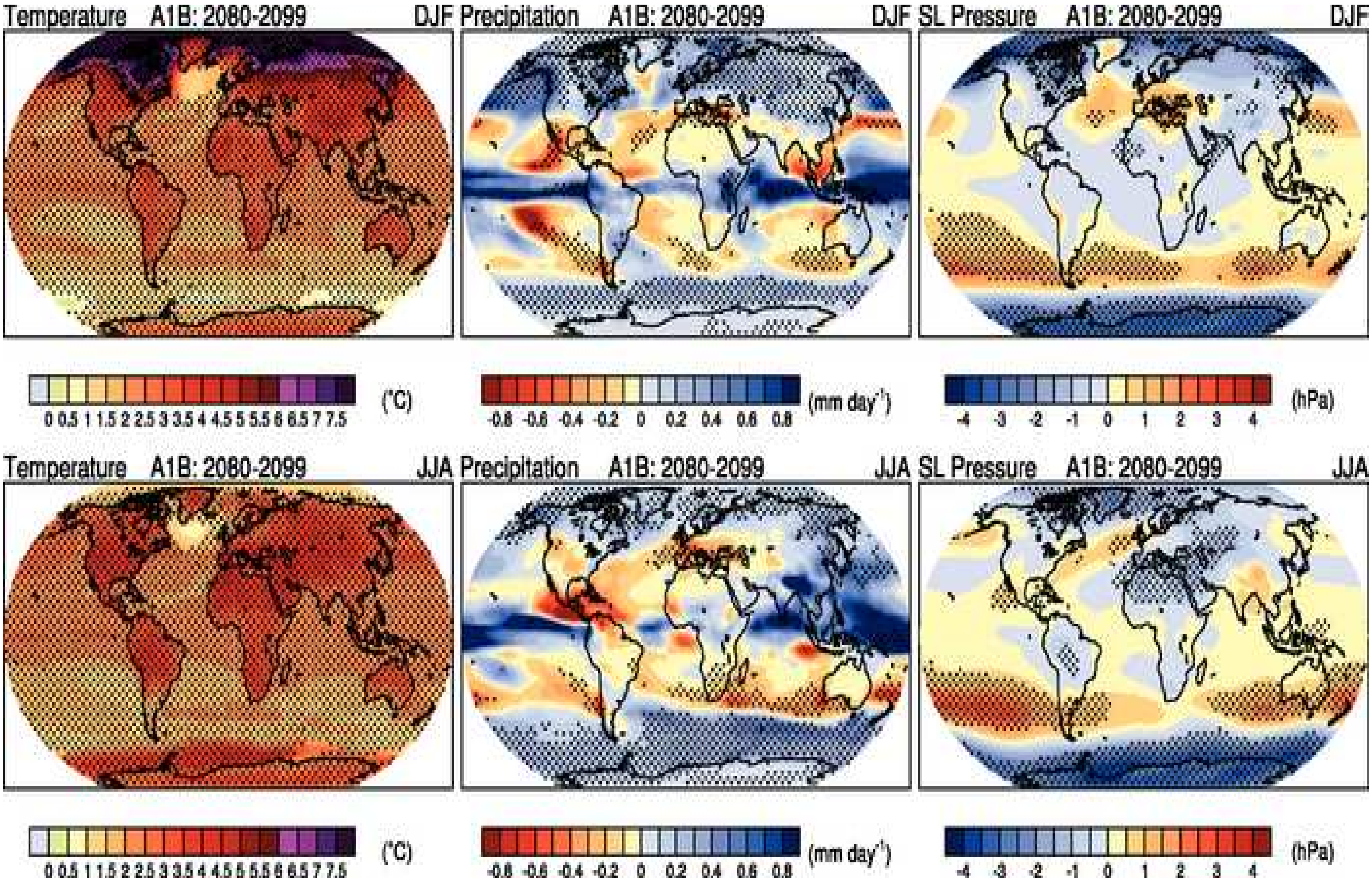
Ensemble of simulations

Climate projections:assuming scenarios for future emissions



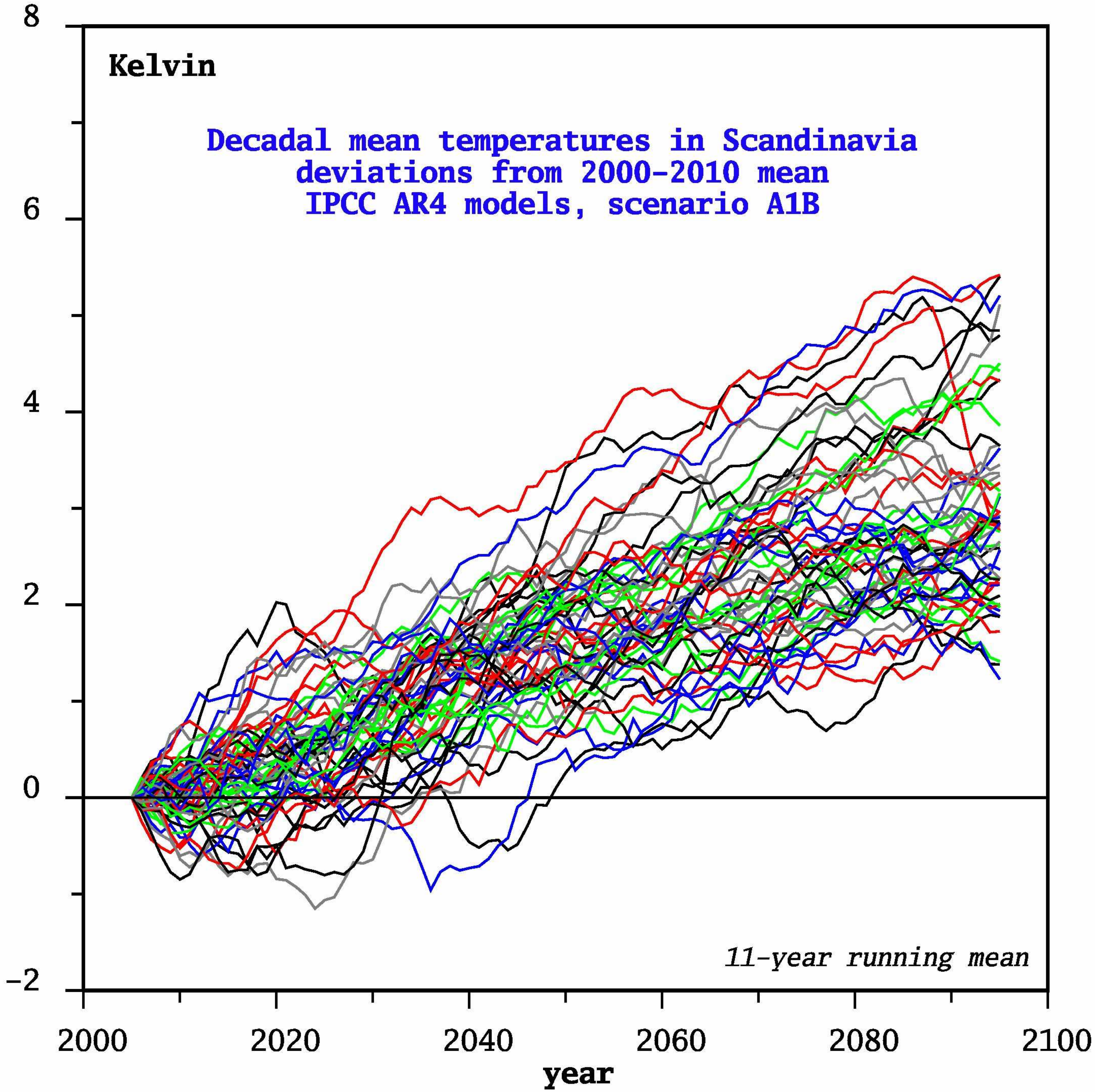

Kelvin
ECHO-G
1000-1990 historical forcing,
1991-2090 scen. IPCC a2
Global annual SAT
31-year running mean
deviations from 1960-1990 mean
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
year A.D.

Essential IPCC climate projections



Surface temperature: Stronger warming in winter, high latitudes and over the continents

Precipitation: increase at high latitudes, decreases in the subtropics, more uncertain



Kelvin
Decadal mean temperatures in Scandinavia
deviations from 2000-2010 mean
IPCC AR4 models, scenario A1B
11-year running mean
8
6
4
2
0
-2
2000
2020
2040
2060
2080
2100
year

Estimating uncertainty...

~~Certainty~~

UnCertainty

small scale, precipitation

Large-scale, temperature


KEY
DARS
KEY