Climate II

(Winter 2020/2021)

8th lecture:

Climate models

(Structure of climate models, components, climate scenarios: from past to the future)

Gerrit Lohmann, Martin Werner

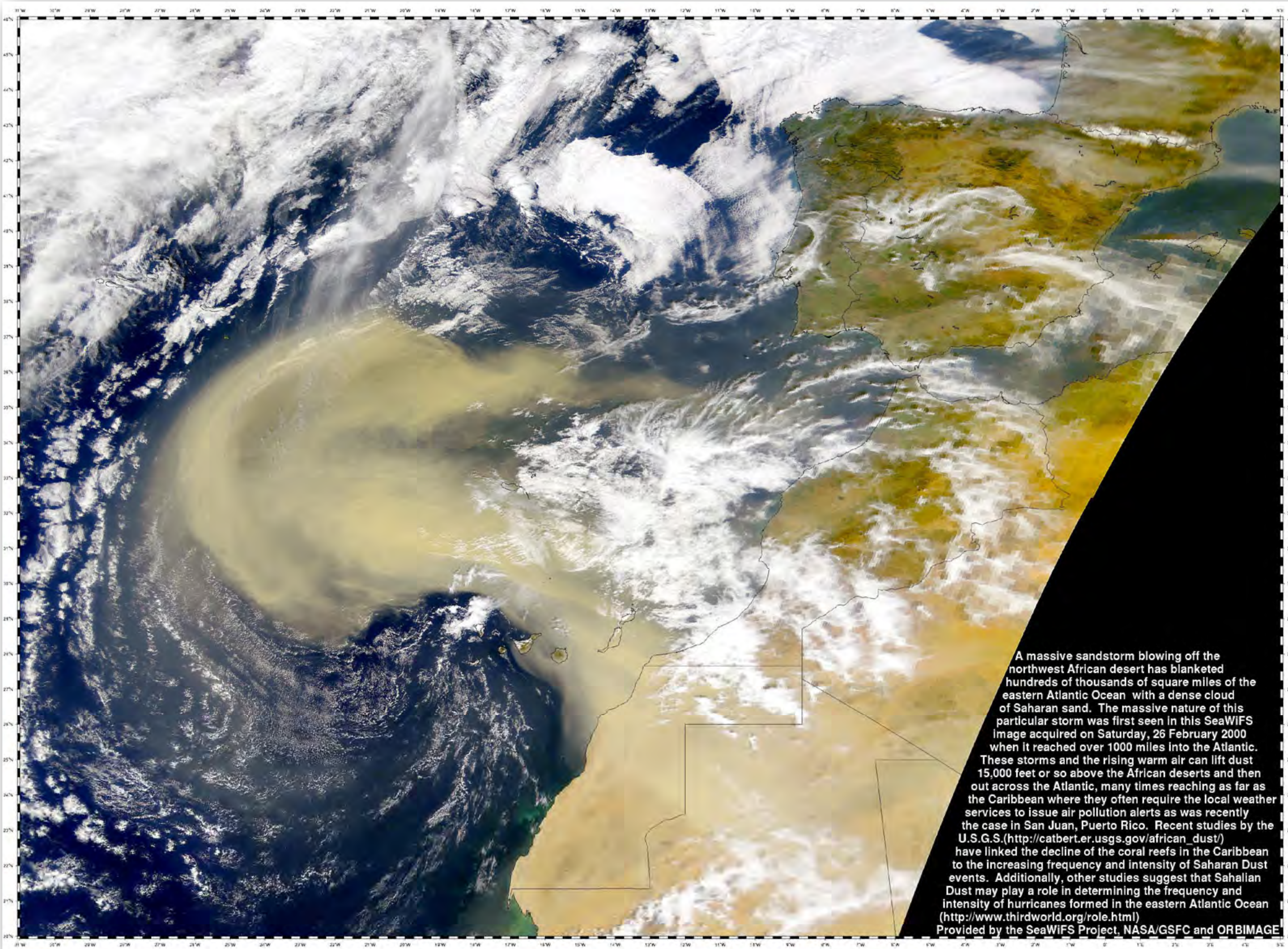
Tuesday, 10:00-11:45

(sometimes shorter, but with some exercises)

https://paleodyn.uni-bremen.de/study/climate2020_21.html

Repetition

Dust in the climate system



Repetition

Dust depositions on glacial-interglacial time scales

Dust–climate couplings over the past 800,000 years from the EPICA Dome C ice core

Vol 452 | 3 April 2008 | doi:10.1038/nature06763

F. Lambert[1,2], B. Delmonte[3], J. R. Petit[4], M. Bigler[1,5], P. R. Kaufmann[1,2], M. A. Hutterli[6], T. F. Stocker[1,2], U. Ruth[7], J. P. Steffensen[5] & V. Maggi[3]

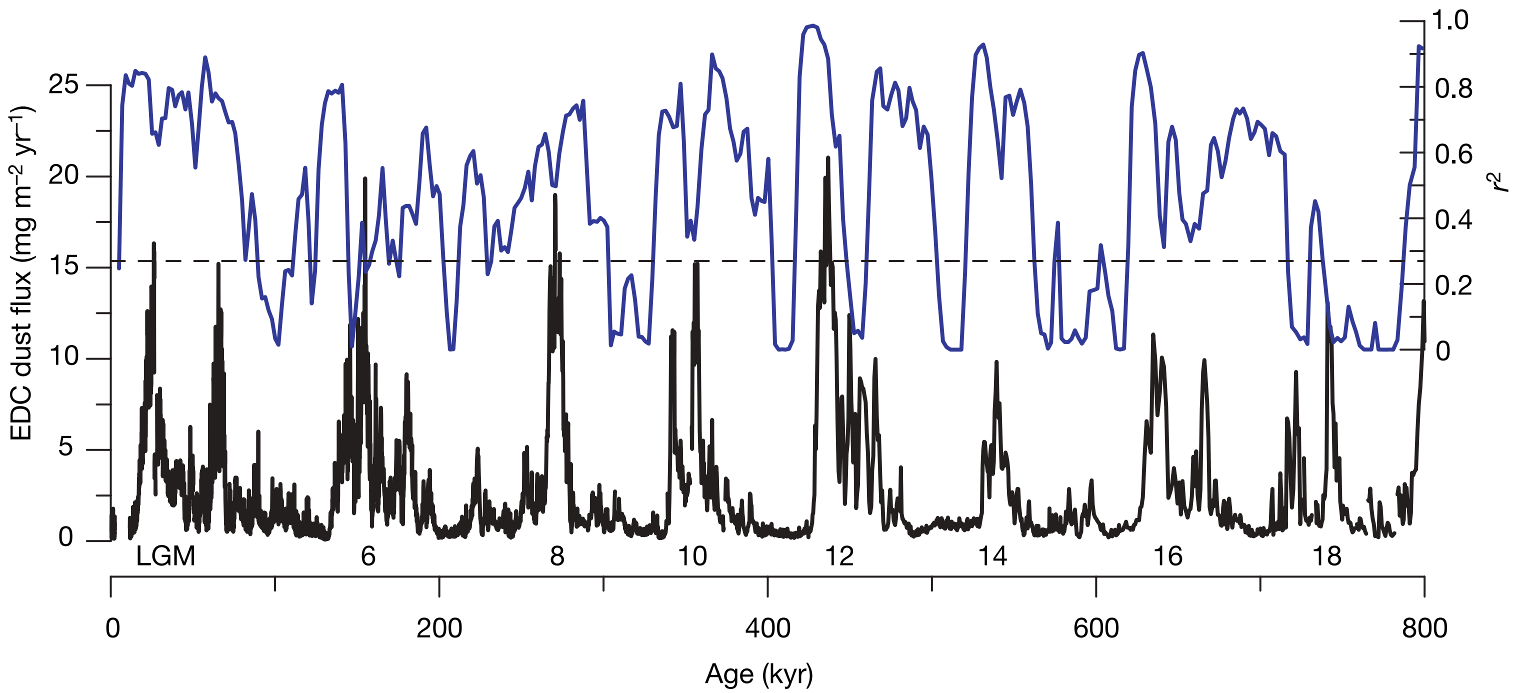


Figure 2 | EDC correlation between dust and temperature. Linear plot of dust flux (black) and the coefficient of determination r^2 (blue) between the high-pass filtered values (18-kyr cut-off) of both the δD and the logarithmic values of dust flux. The correlation was determined using 2-kyr mean values in both records and a gliding 22-kyr window. Correlations (dashed line) are significant at a 95% confidence level. Num marine isotopic glacial stages.

- **strong correlation between dust and temperature changes**

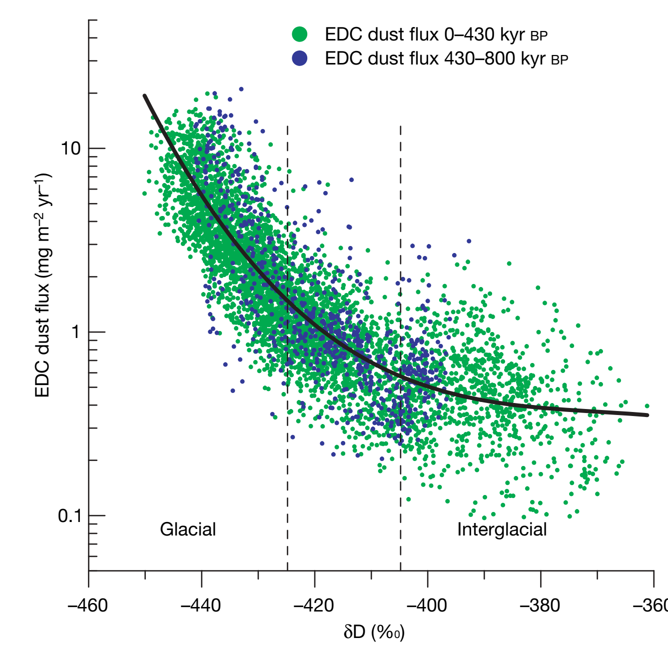


Figure 3 | EDC dust–temperature relationship. Values of δD (ref. 8) are plotted against dust flux (both at 55-cm resolution). Green and blue dots represent data from 0–430 kyr BP and 430–800 kyr BP, respectively. Superposed is a cubic polynomial fit, $\log_{10}(f) = -3.737 \times 10^{-6}(\delta D)^3 - 4.239 \times 10^{-3}(\delta D)^2 - 1.607(\delta D) - 204$, where f is the dust flux (mg m^{-2} yr^{-1}), and δD is in ‰ ($r^2 = 0.73$, $N = 5{,}164$).

Dust depositions on glacial-interglacial time scales

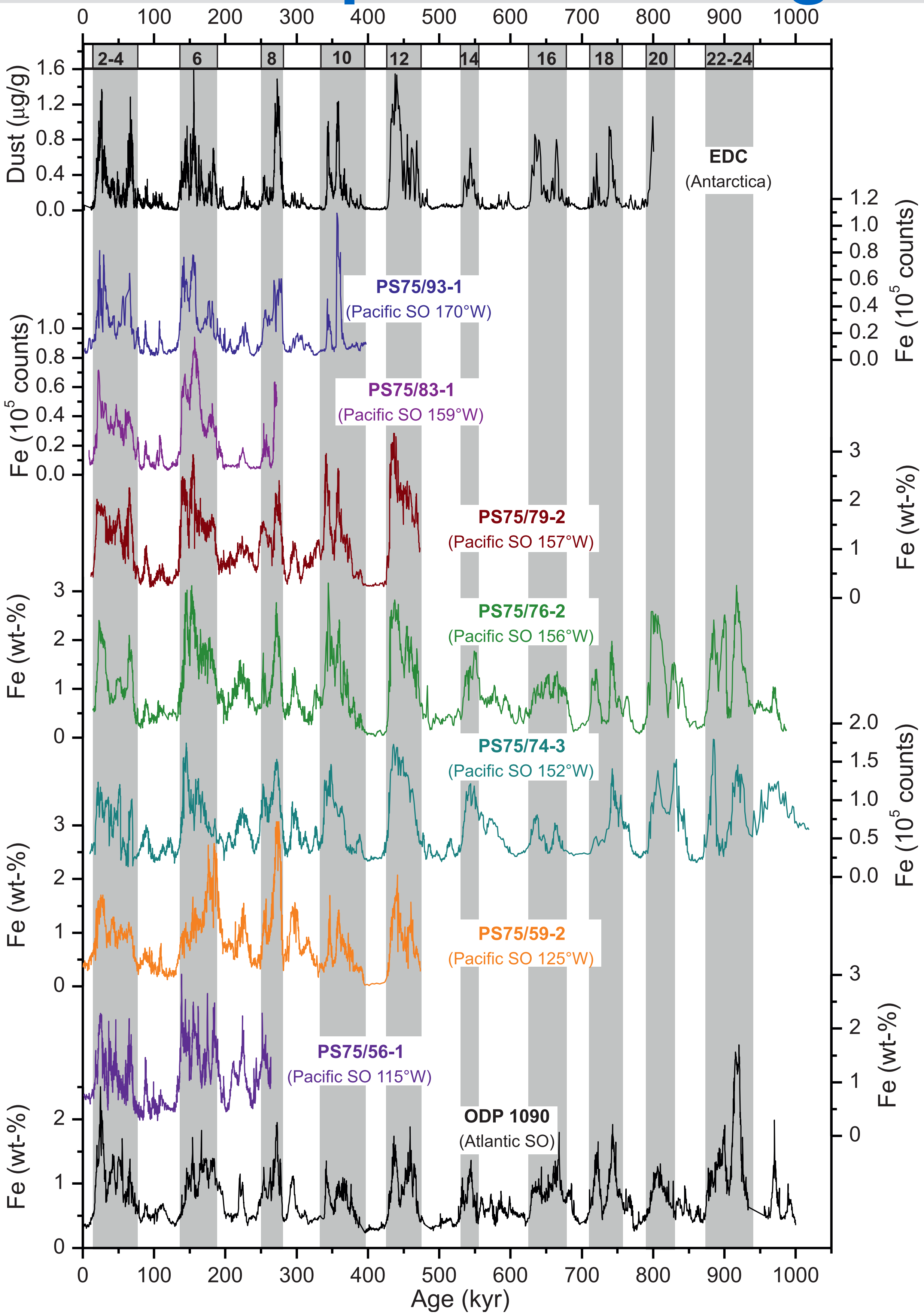


Fig. 2. Iron content fluctuations across the Pacific and Atlantic SO (*7*) compared to dust content changes in the EDC ice core (*1*).

SCIENCE VOL 343 24 JANUARY 2014

Increased Dust Deposition in the Pacific Southern Ocean During Glacial Periods

F. Lamy,[1,2]* R. Gersonde,[1,2] G. Winckler,[3,4] O. Esper,[1] A. Jaeschke,[1,2] G. Kuhn,[1] J. Ullermann,[1] A. Martinez-Garcia,[5] F. Lambert,[6] R. Kilian[7]

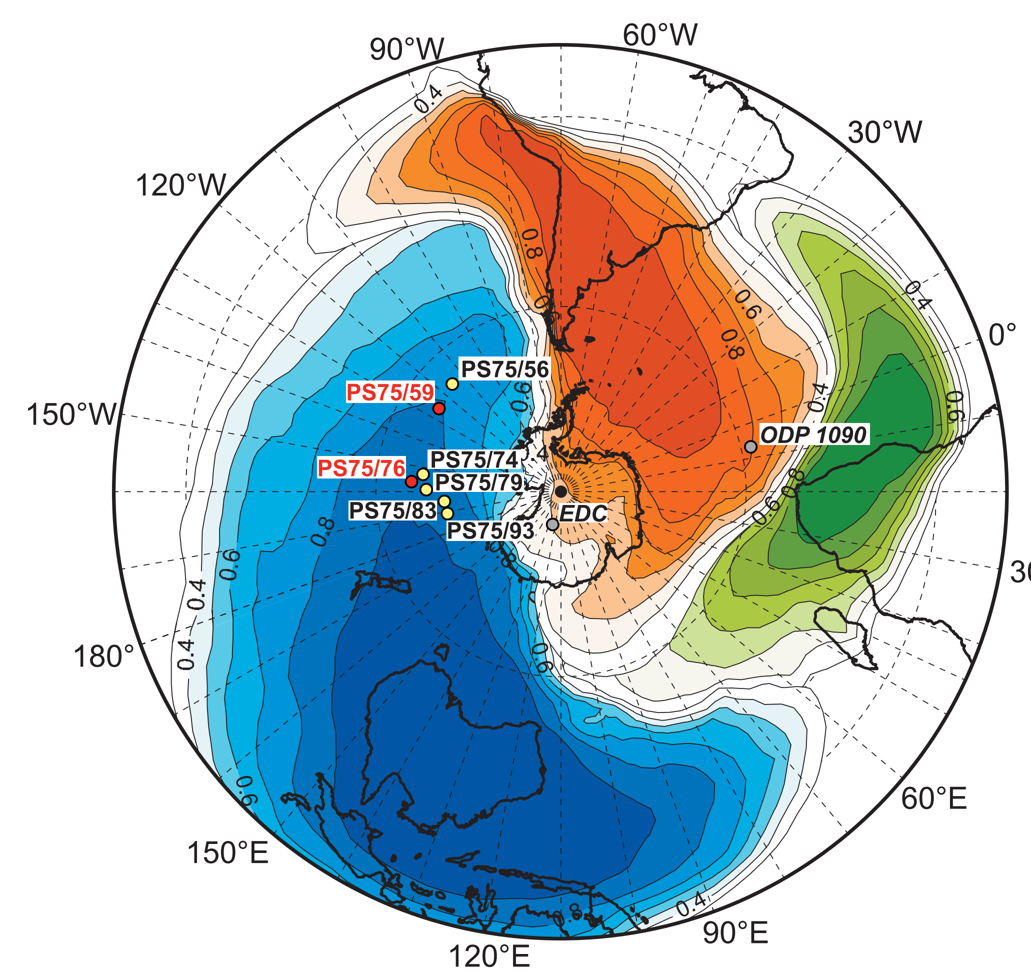
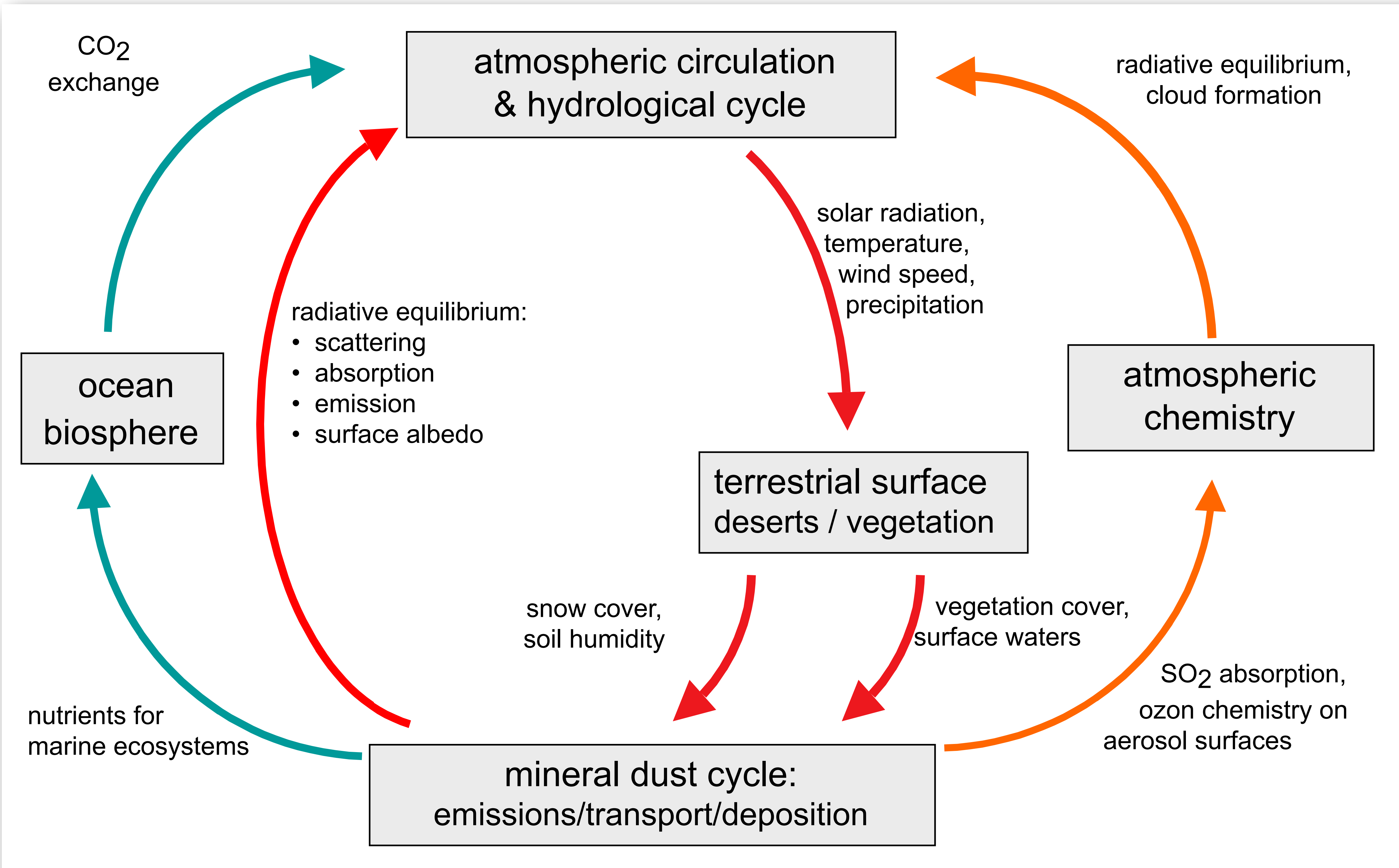


Fig. 1. Map showing the modern relative contributions of the three major dust sources in the Southern Hemisphere (blue, Australia; red, South America; green, South Africa), based on model data (*20*). Red dots mark primary core locations; yellow dots indicate additional cores; gray dots denote location of published reference records (*1*, *4*, *7*).

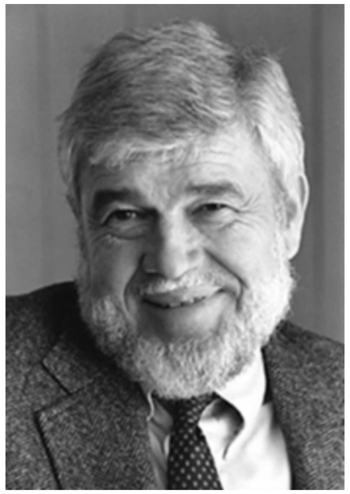
Repetition

Dust in the climate system



Repetition

LGM dust cycle: fertilisation of the marine biosphere



John Martin

The Iron Hypothesis

Figure 1. In the equatorial Pacific Ocean and Gulf of Alaska, phytoplankton populations are relatively low (purple shaded areas on map), despite adequate sunlight and nutrients. John Martin set out to prove that a lack of dissolved iron in the water in these areas keeps populations of marine algae lower than normal.

- **Dust contains iron which is a key micro-nutrient in the Southern Ocean**

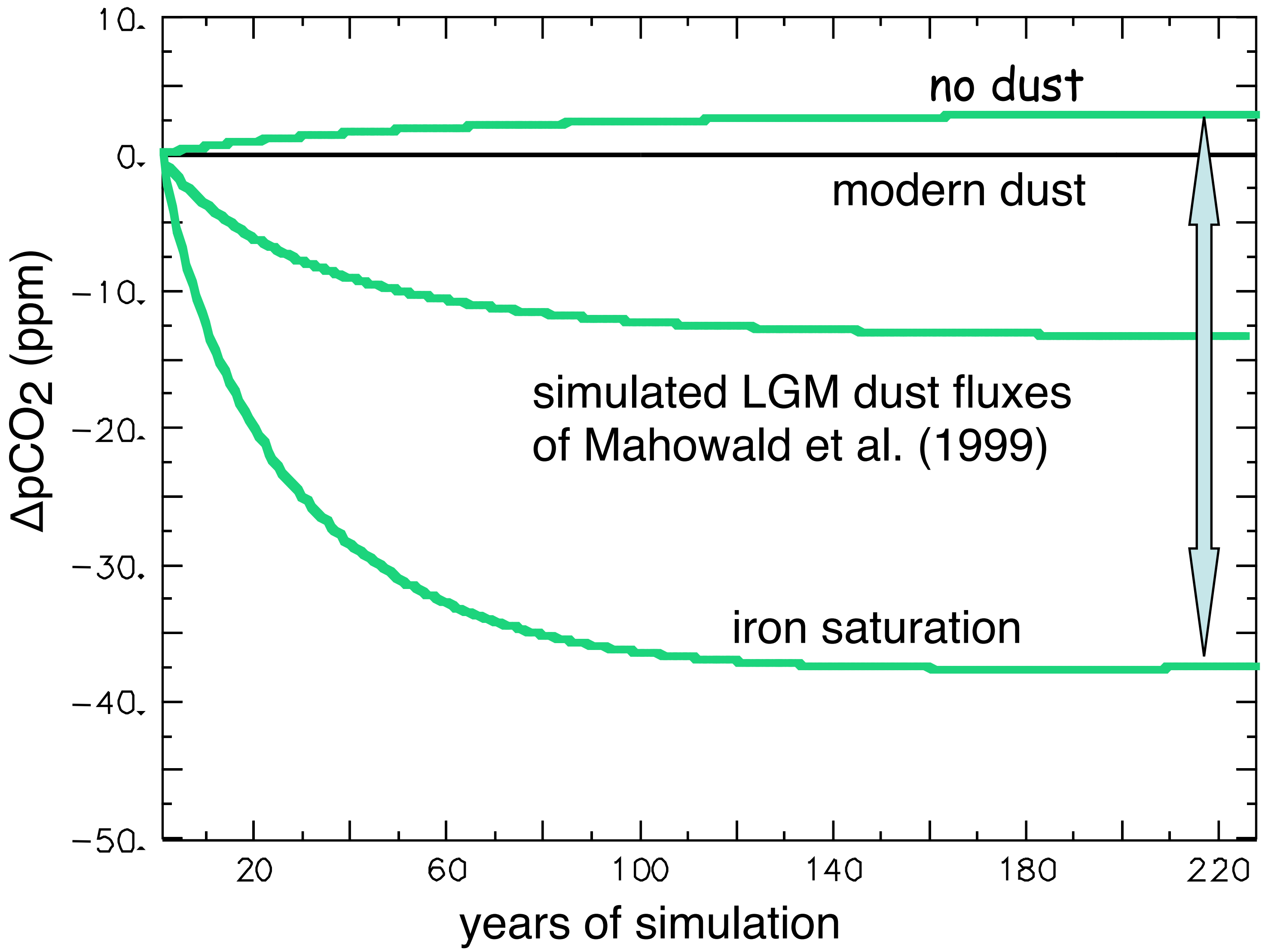
(http://www.palomar.edu/oceanography/iron.htm)

Repetition

LGM dust cycle: fertilisation of the marine biosphere

Ocean Carbon Cycle: Sensitivity Studies for different LGM conditions

- Hypothesis of Martin (1988) : Iron Fertilisation of the Glacial Ocean



- increased LGM iron deposition:
  -15 ppm

- mechanisms
  - export of organic material
  - export of $CaCO_3$
    (change of alkalinity)

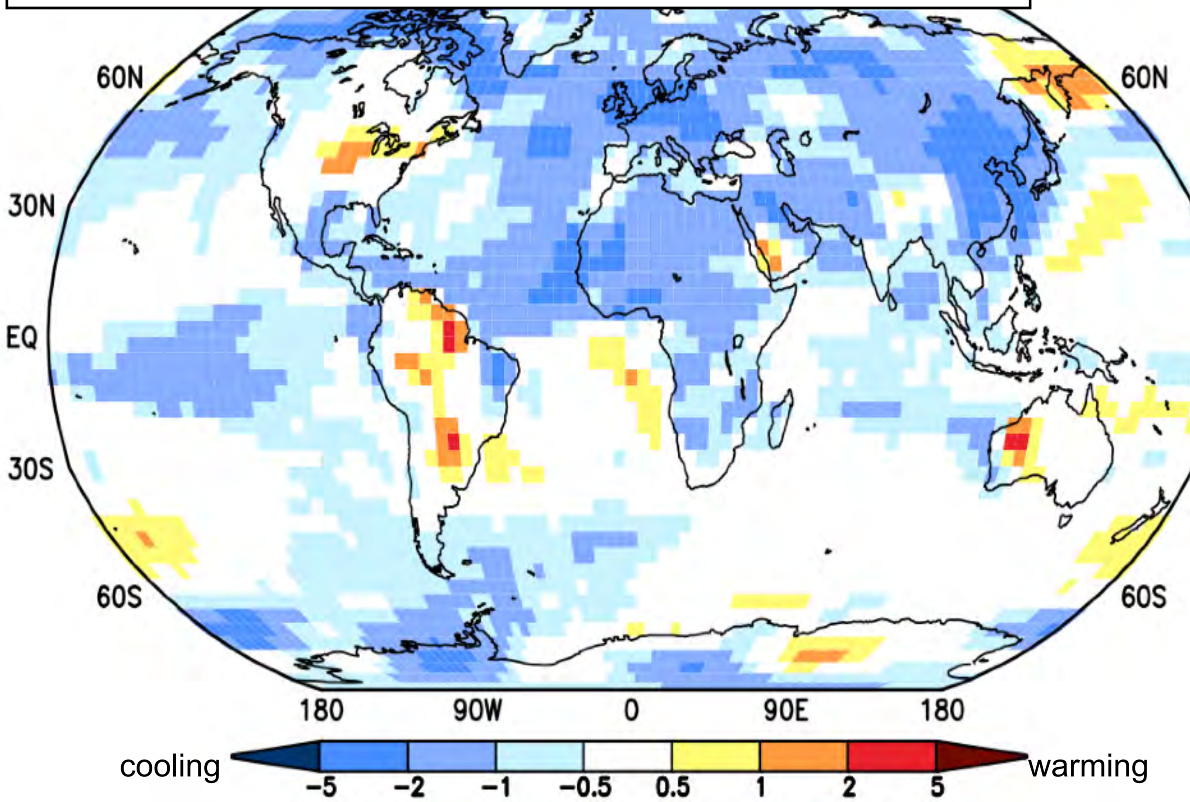
- sensitivity
  no dust deposition: +3 ppm
  iron saturation: -39 ppm

(Quelle: Bopp et al.., 2003)

Repetition

Changes of the LGM radiative budget by dust

LGM temperature changes by dust radiative forcing [K]



optical properties of mineral aerosols:

- **only aerosol particles between 0.3 - 4 μm have been considered**
- **uniform mineralogy: 98% clay, 2% hematite, intern mixing**
- **refractive indices based on Sokolik und Toon (1999)**

Zonal changes of radiative forcing and temperature:

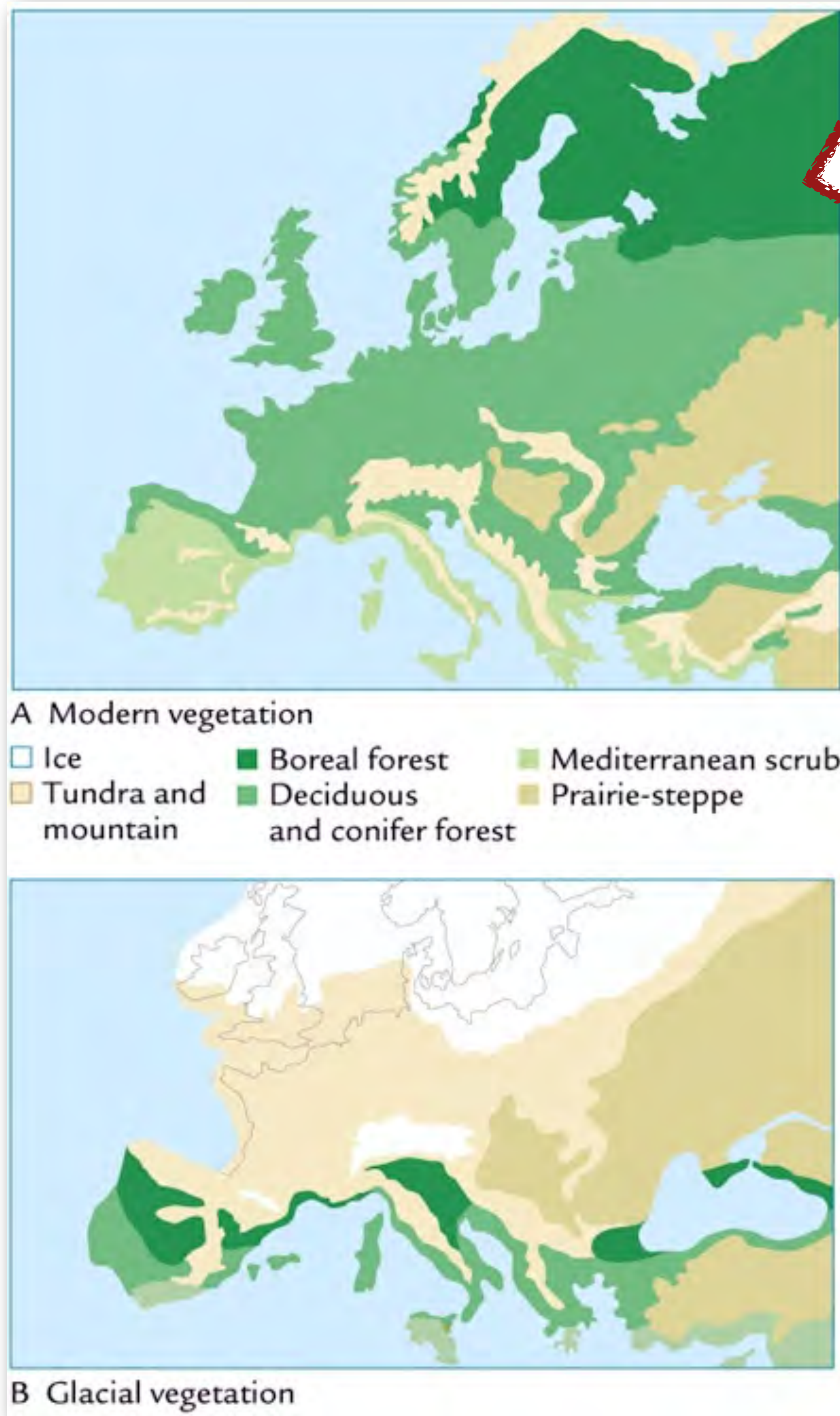
	Claquin et al. [2003]	ECHAM5-HAM		
	TOA forcing [W/m^2]	TOA forcing [W/m^2]	Δ T_{surf} [K] (by dust)	Δ T_{surf} [K] (CO_2, albedo*, ice)
Global	***-1***	***-1.4***	***-0.6***	***-4.3***
90°N-45°N	-0.3	-0.6	-1.1	-14.6
45°N-45°S	-1.6	-1.8	-0.5	-1.7
45°S-90°S	+0.2	-0.8	-0.4	-6.3

(*change of albedo by dust deposition has been neglected)

- **largest radiative cooling effect near the source regions (between 45°S und 45°N)**
- **no *linear* relation between radiative effect and temperature changes**
- **feedback processes of radiative changes to the dust cycle (emission/transport/deposition) are relatively small**

Repetition

LGM climate of North America and Europe



remember LGM lecture!

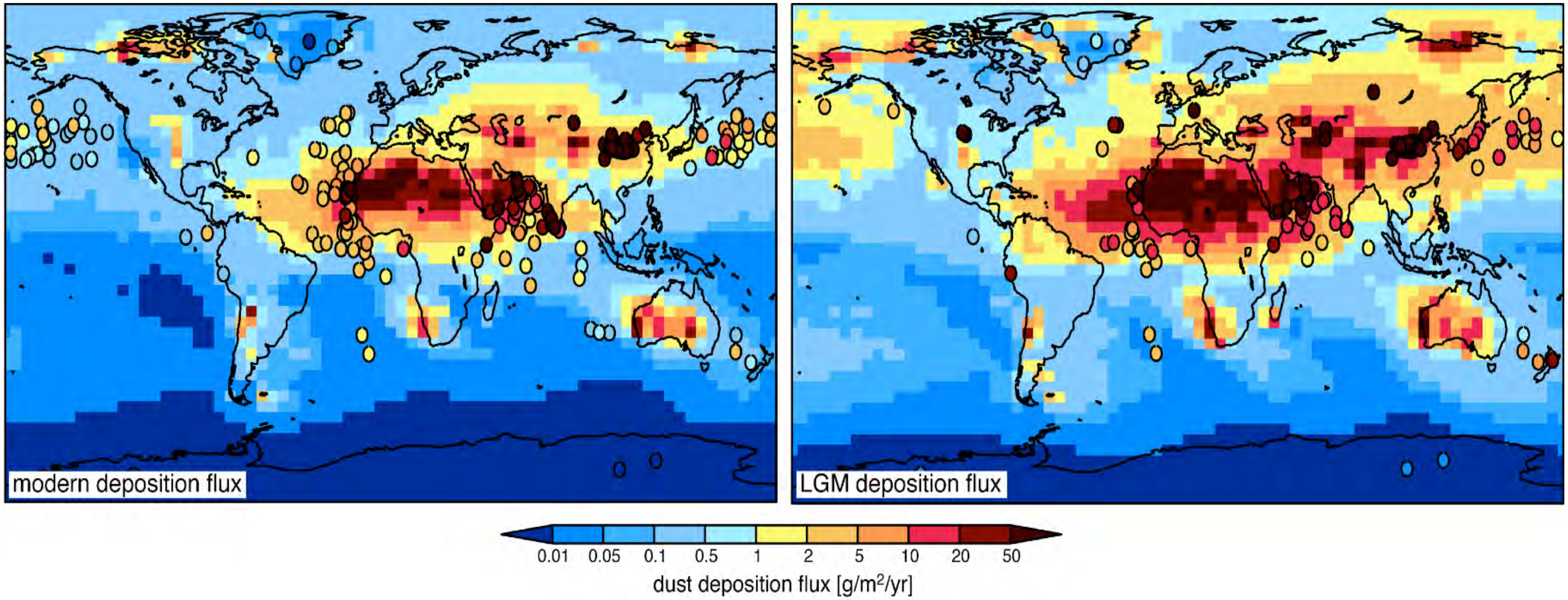
[from: Ruddiman, 2008]

Repetition

Modern and LGM dust deposition fluxes

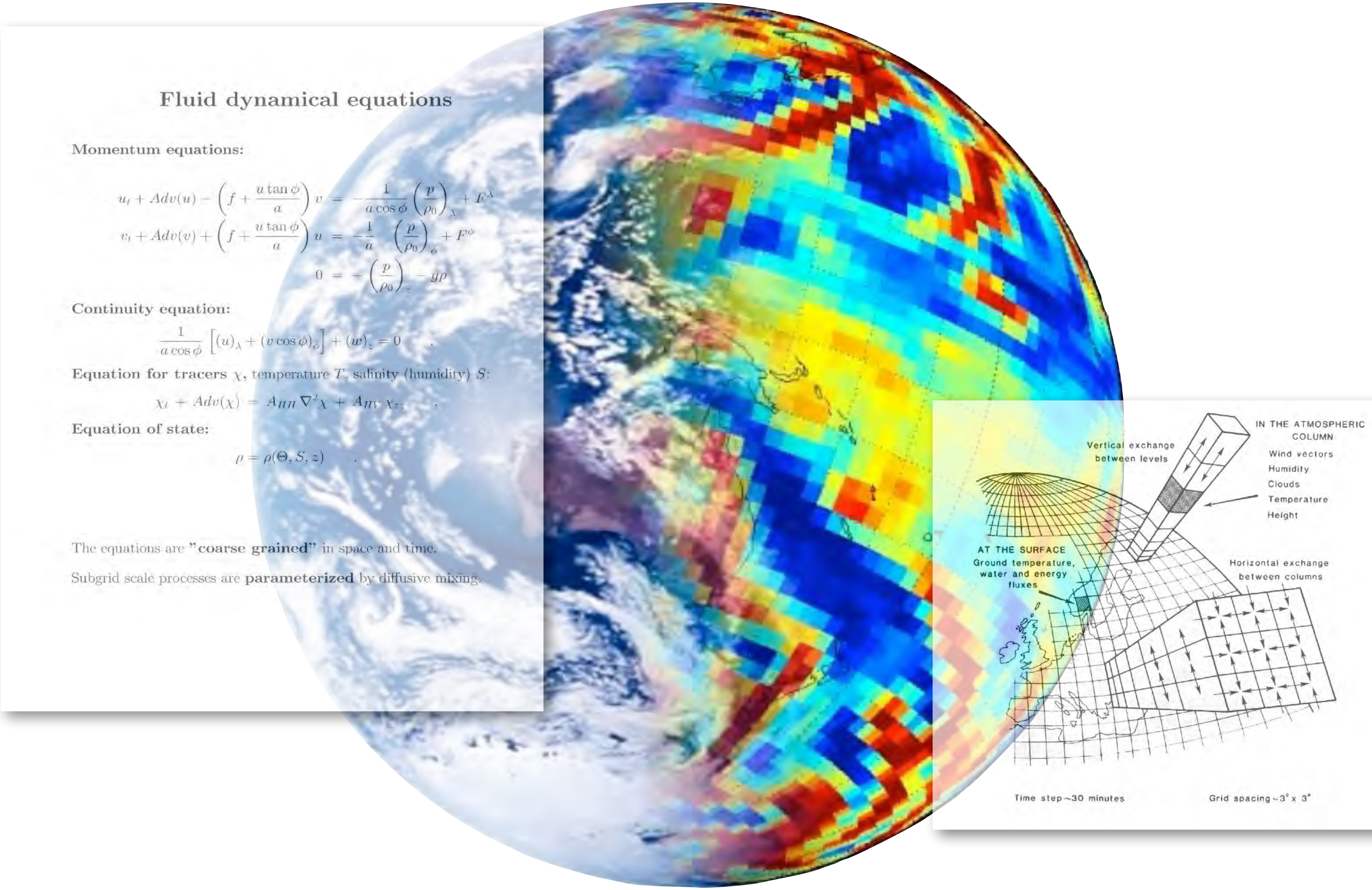
simulation: ECHAM-4 GCM climatology (modern and LGM, respectively)

reconstructions: DIRTMAP Datenbank



(DIRTMAP: Dust Indicator and Records of Terrestrial and Marine Paleoenvironments)

Climate models



Fluid dynamical equations

Momentum equations:

$$u_t + Adv(u) - \left(f + \frac{u\tan\phi}{a}\right) v = -\frac{1}{a\cos\phi}\left(\frac{p}{\rho_0}\right)_\lambda + F^\lambda$$
$$v_t + Adv(v) + \left(f + \frac{u\tan\phi}{a}\right) u = -\frac{1}{a}\left(\frac{p}{\rho_0}\right)_\phi + F^\phi$$
$$0 = -\left(\frac{p}{\rho_0}\right)_z - g\rho$$

Continuity equation:

$$\frac{1}{a\cos\phi}\left[(u)_\lambda + (v\cos\phi)_\phi\right] + (w)_z = 0 \quad .$$

Equation for tracers χ, temperature T, salinity (humidity) S:

$$\chi_t + Adv(\chi) = A_{HH}\nabla^2\chi + A_{HV}\chi_{zz} \quad .$$

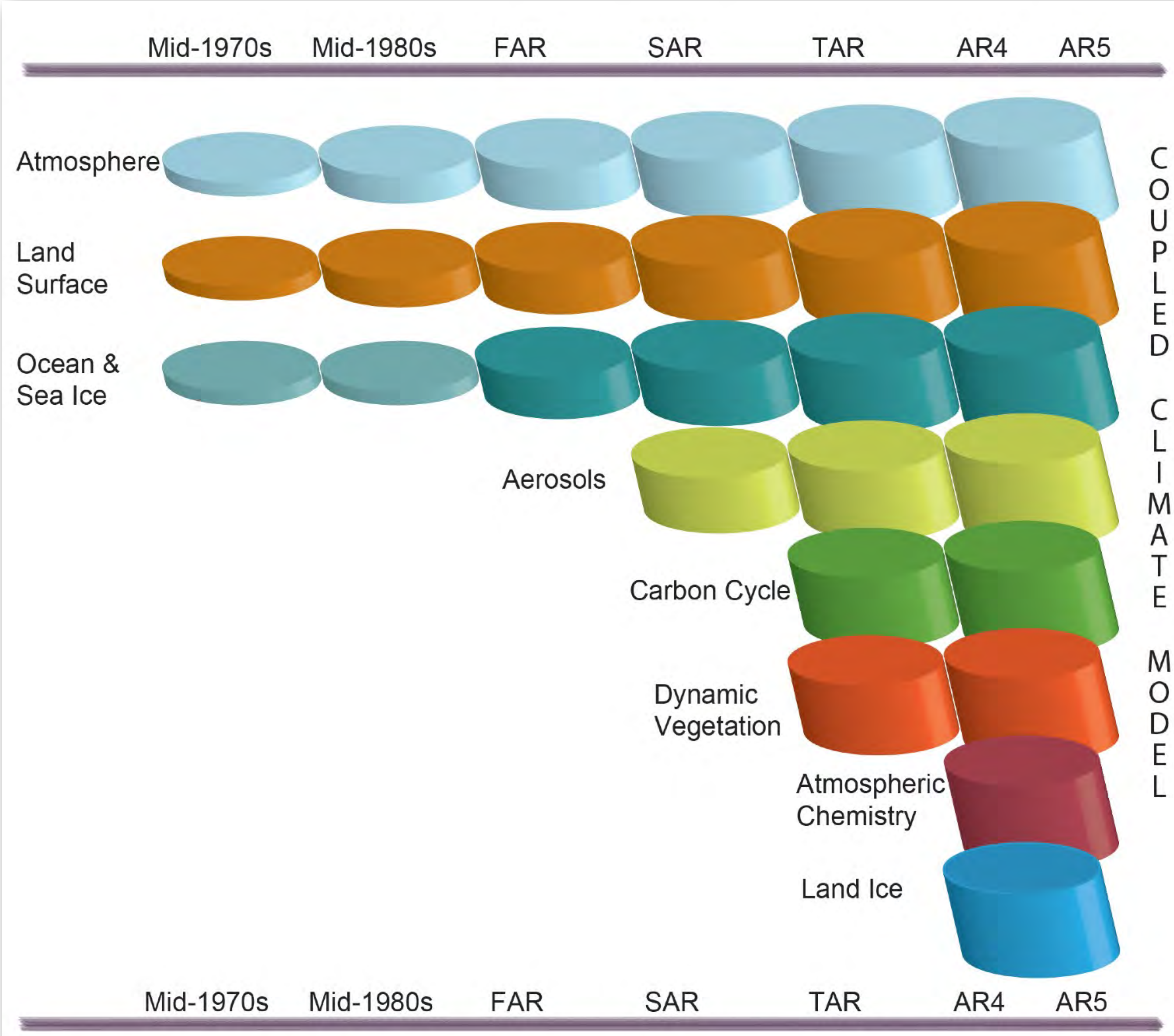
Equation of state:

$$\rho = \rho(\Theta, S, z) \quad .$$

The equations are **"coarse grained"** in space and time.

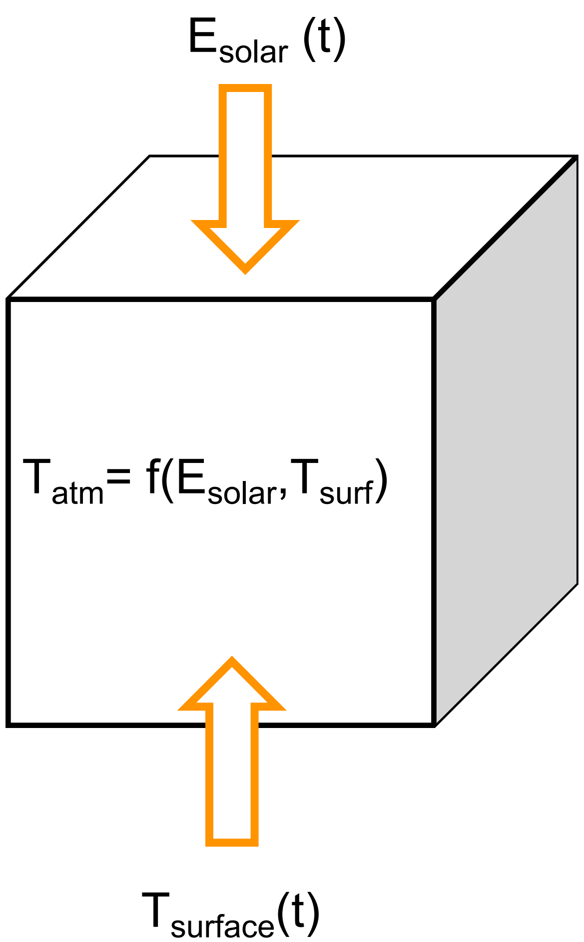
Subgrid scale processes are **parameterized** by diffusive mixing.

Historical development of climate models



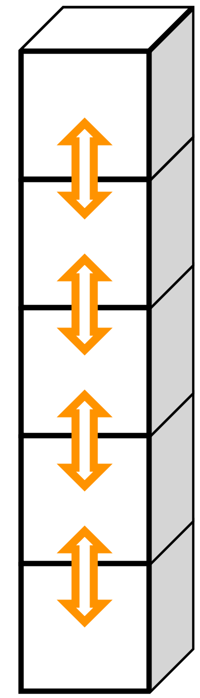
[IPCC, AR5, 2013, Fig. 1.10]

Different types of climate models



Box Model

Example:
mean temperature of the atmosphere as a function of solar energy input and mean surface temperature

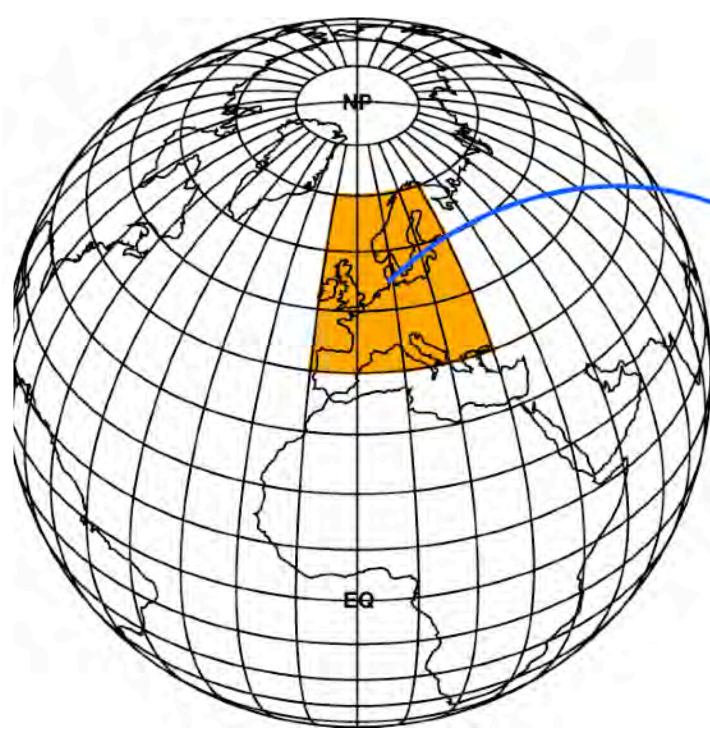


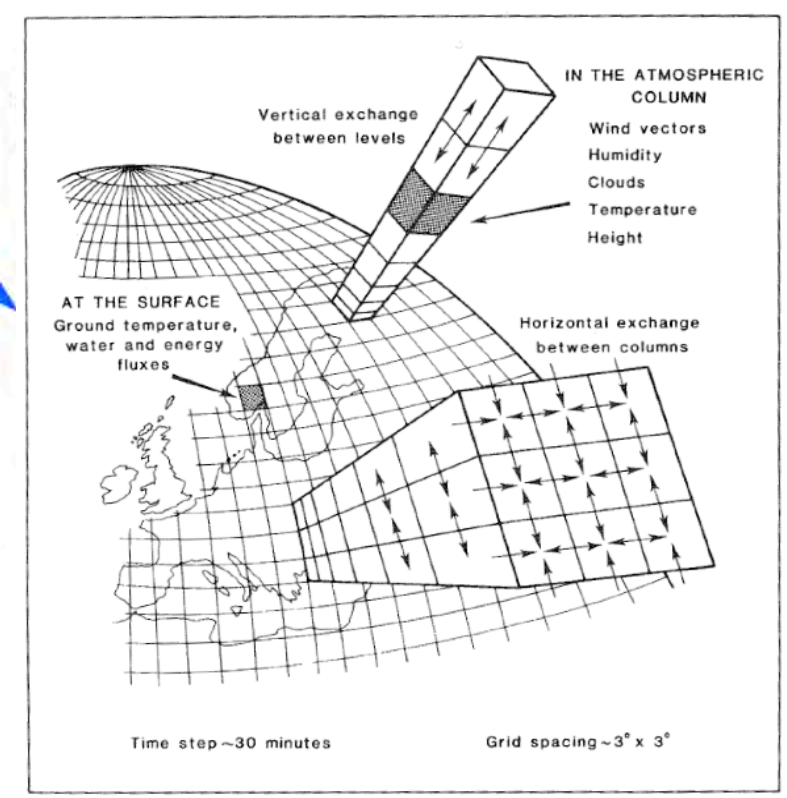
Column Model

Example:
vertical diffusion of smoke in the atmosphere

General Circulation Model

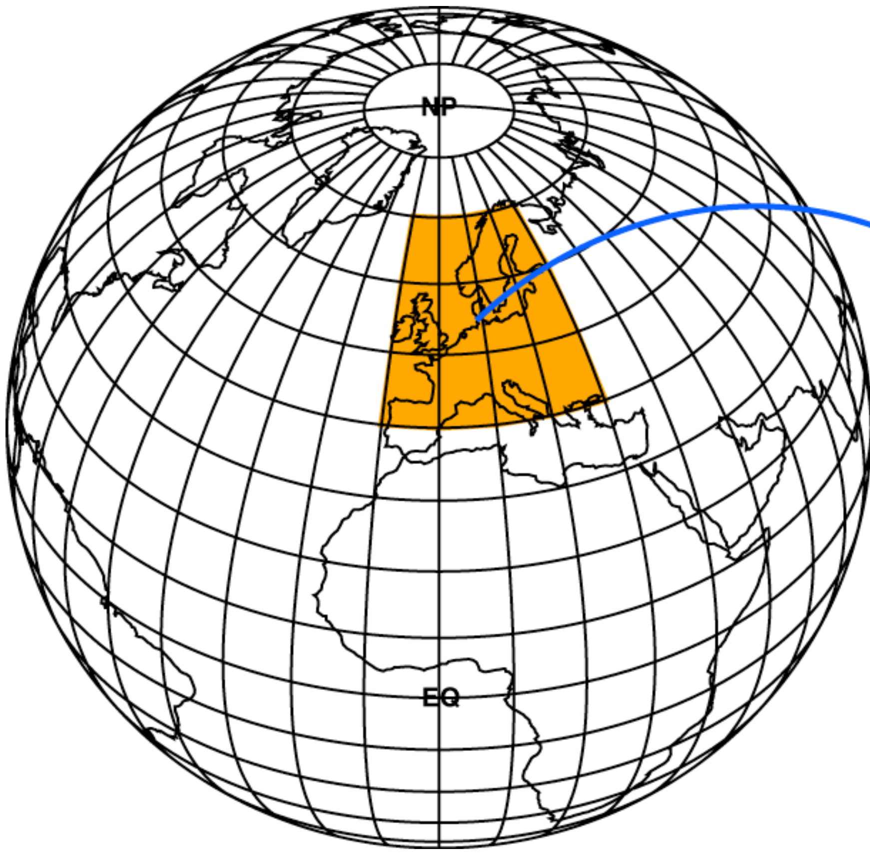
Example:
climate change scenario for the next 100 years

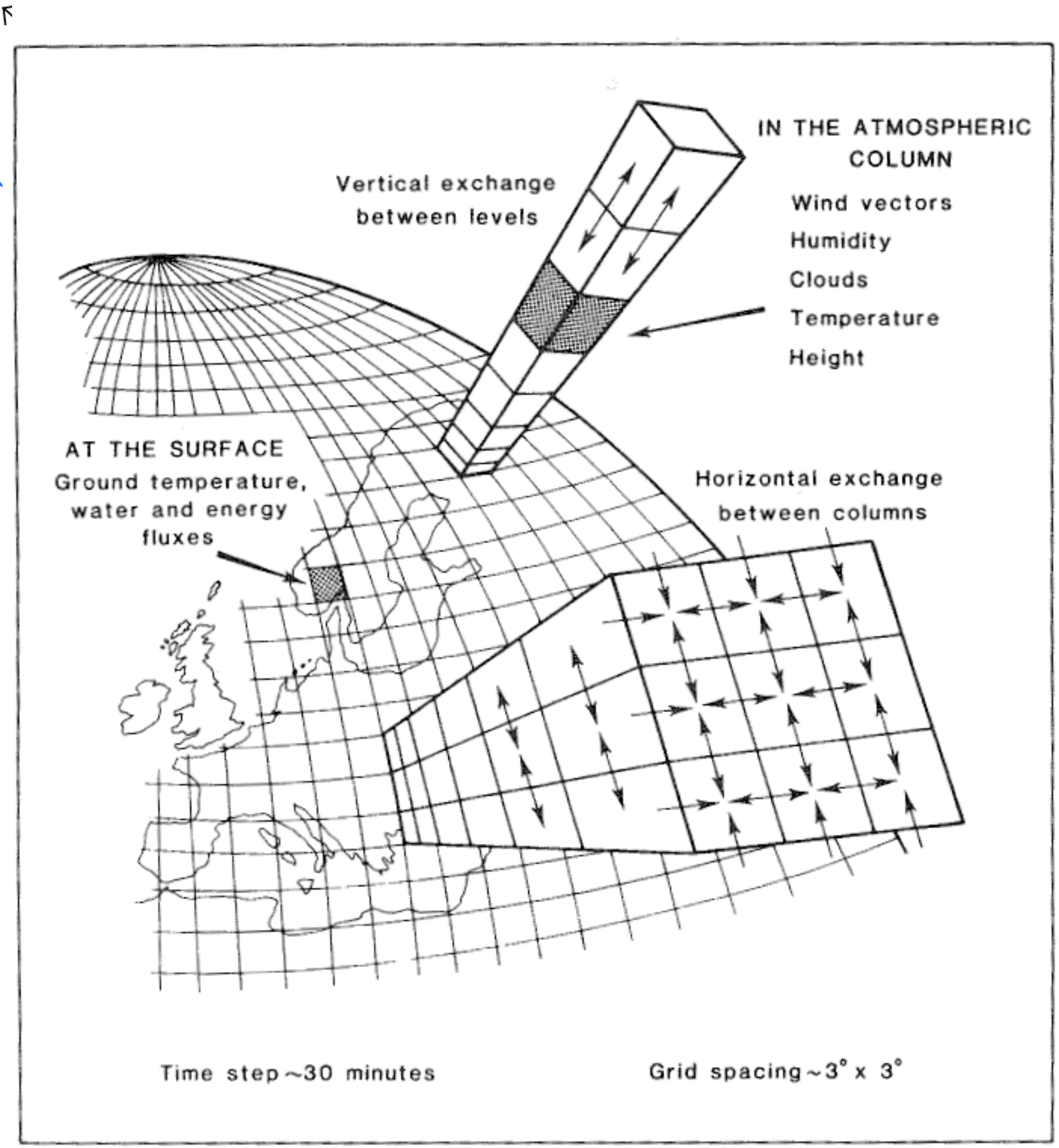




[McGuffie & Henderson-Sellers, A Climate Modelling Primer]

General Circulation Model (GCM)





- GCM: General Circulation Model
  - *Physical model of the atmosphere (AGCM) and the ocean (OGCM)*
- CM: Climate Model
- ESM: Earth System Model
  - *GCM plus different add-ons (e.g. C-cycle)*
- The evolution of the climate model terminology (GCM, CM, ESM) has not been straight-forward and various authors use the terms in different ways

[McGuffie & Henderson-Sellers, A Climate Modelling Primer]

Atmosphere models

- the basic equations that describe the physical state of the atmosphere are the so-called *fundamental equations* which contain *6 state variables*
    - *two horizontal wind components (u- & v-component)*
    - *one vertical wind component (w-component)*
    - *pressure* p
    - *temperature* T
    - *density* ρ
- sometimes, a 7th unknown is included to the set of fundamental equations
    - *moisture* q

Fundamental equations of an atmosphere model

- for the atmosphere exist *6 state variables*
  - two horizontal wind components (u- & v-component)
  - one vertical wind component (w-component)
  - pressure
  - temperature
  - density
  - (moisture)

=> the fundamental equations are sufficient to determine the state of the atmosphere

(1) Conservation of Energy

$$\frac{DI}{Dt} = -p\frac{d\rho^{-1}}{dt} + Q$$

(2) Conservation of Momentum

$$\frac{D\mathbf{v}}{Dt} = -2\mathbf{\Omega} \times \mathbf{v} - \rho^{-1}\nabla p + \mathbf{g} + \mathbf{F}$$

(3) Conservation of Mass

$$\frac{D\rho}{Dt} = -\rho\nabla \cdot \mathbf{v} + C - E$$

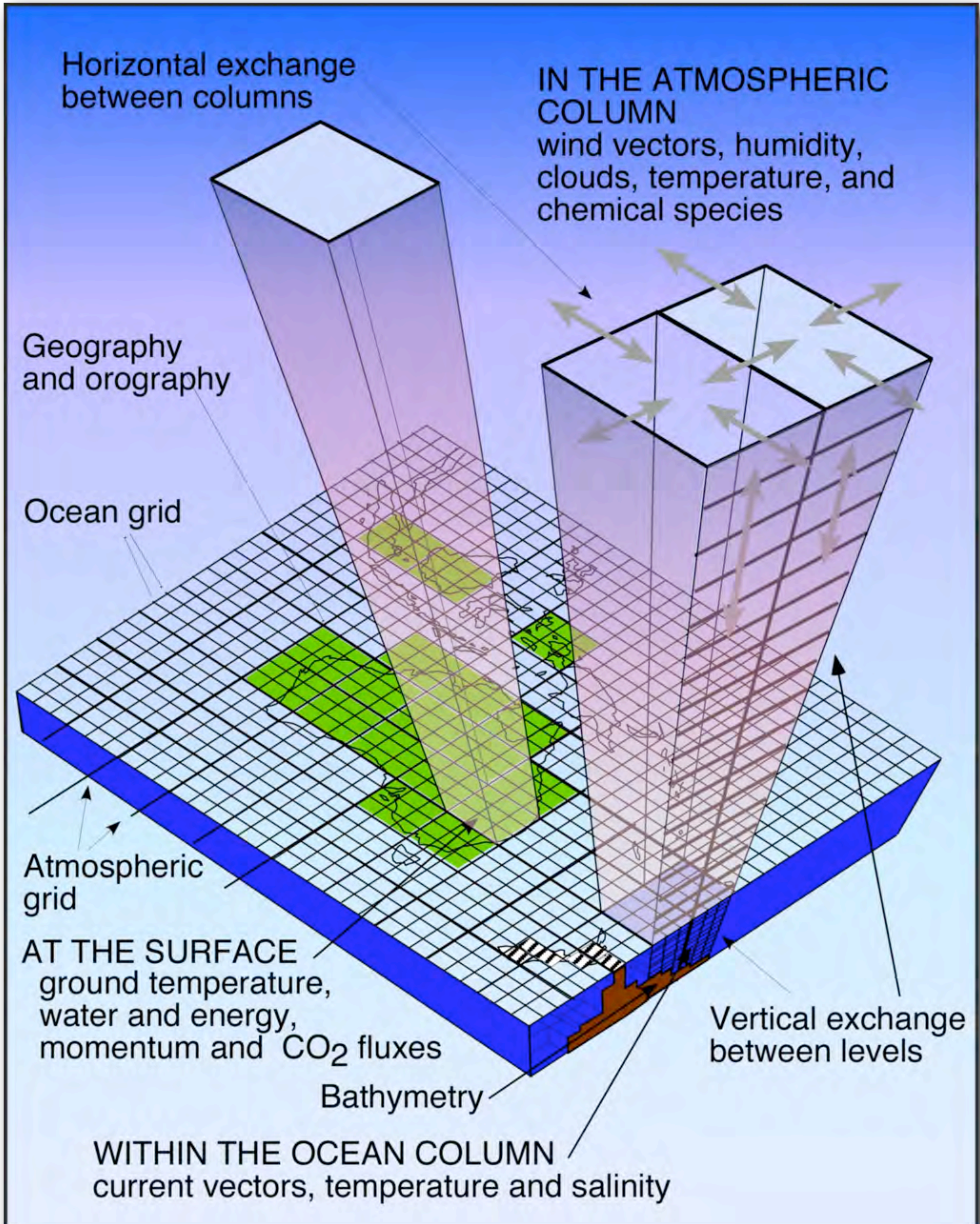
(4) Hydrostatic Balance

$$dp = -\rho g dz$$

(5) Ideal Gas Law

$$p = \rho RT$$

Atmosphere models: The challenge of discretizing



[McGuffie & Henderson-Sellers, A Climate Modelling Primer, 2005]

Atmosphere models: Horizontal discretizing

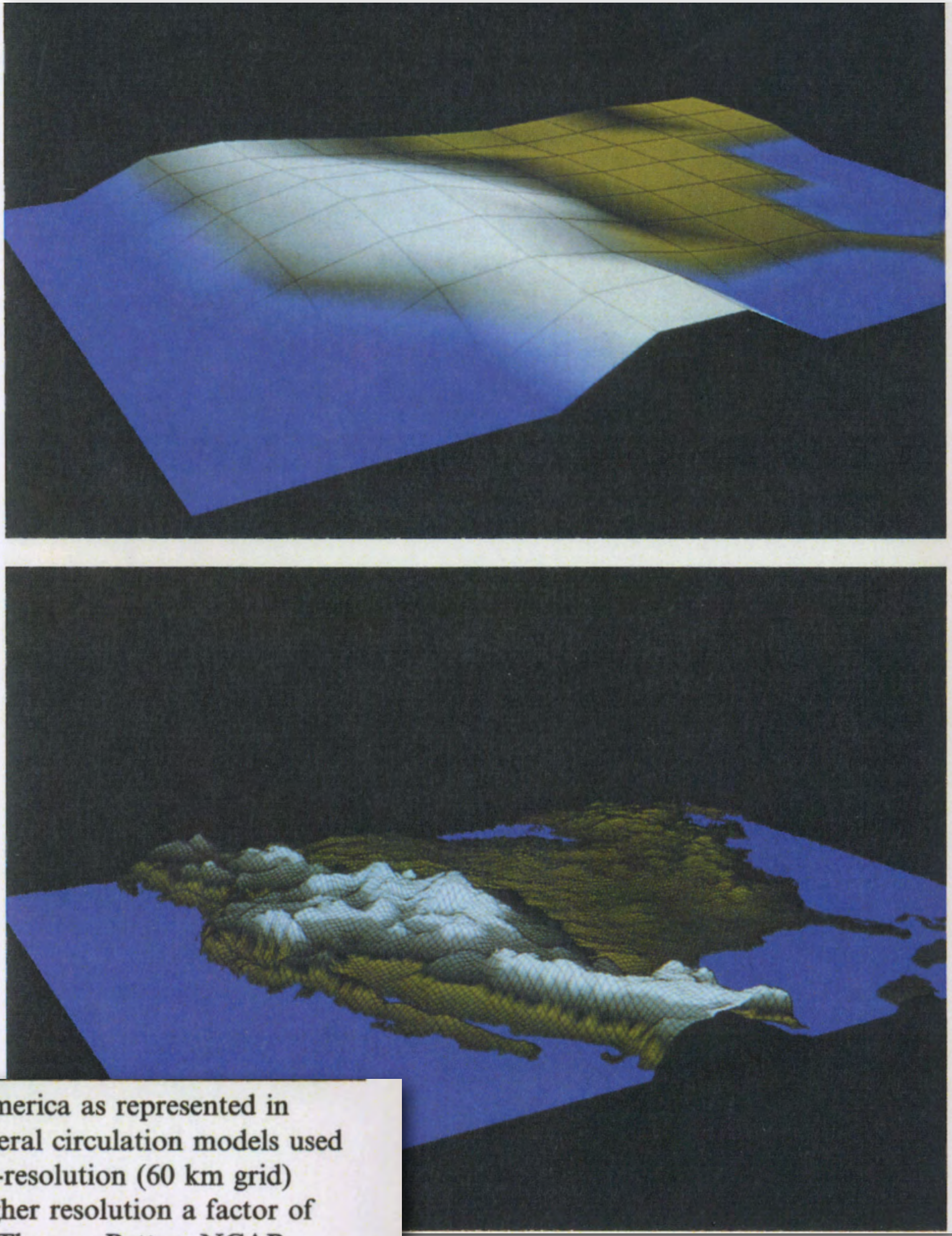


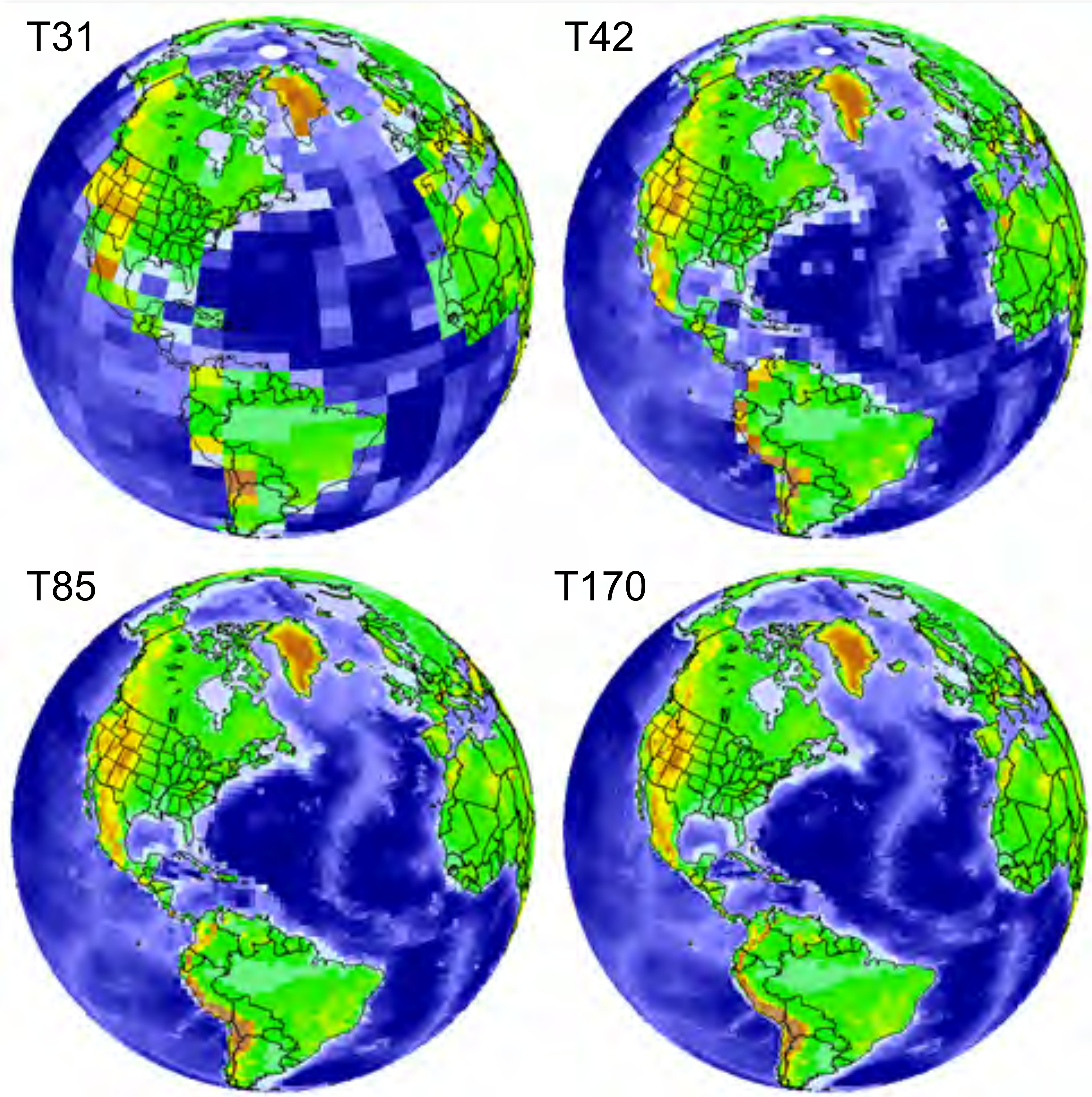
Plate 10 Schematic depiction of the topography over North America as represented in most coarse-resolution (480 km grid) atmospheric general circulation models used for climate simulation in the past (above) and in high-resolution (60 km grid) global operational forecast models (below). At the higher resolution a factor of 500 times the computing power is required. Courtesy Thomas Bettge, NCAR. *Chapters 9 and 23.*

[Trenberth, Climate System Modeling, 1993]

Horizontal resolution of atmosphere models

T31:
96 x 48 grid points
=> grid size:
~ 3.8° x 3.8°

T42:
128 x 64 grid points
=> grid size:
~ 2.8° x 2.8°



[NCAR ACM Colloquim, 2006]

T85:
256 x 128 grid points
=> grid size:
~ 1.4° x 1.4°

T170:
512 x 256 grid points
=> grid size:
~ 0.7° x 0.7°

Atmosphere models: Vertical discretizing

Sigma Coordinate (Simplest Form):

Define new coordinate variable s as

$$\sigma = p / p_{surf}$$

=> at surface: $\sigma = 1$

at top of atmosphere: $\sigma = 0$

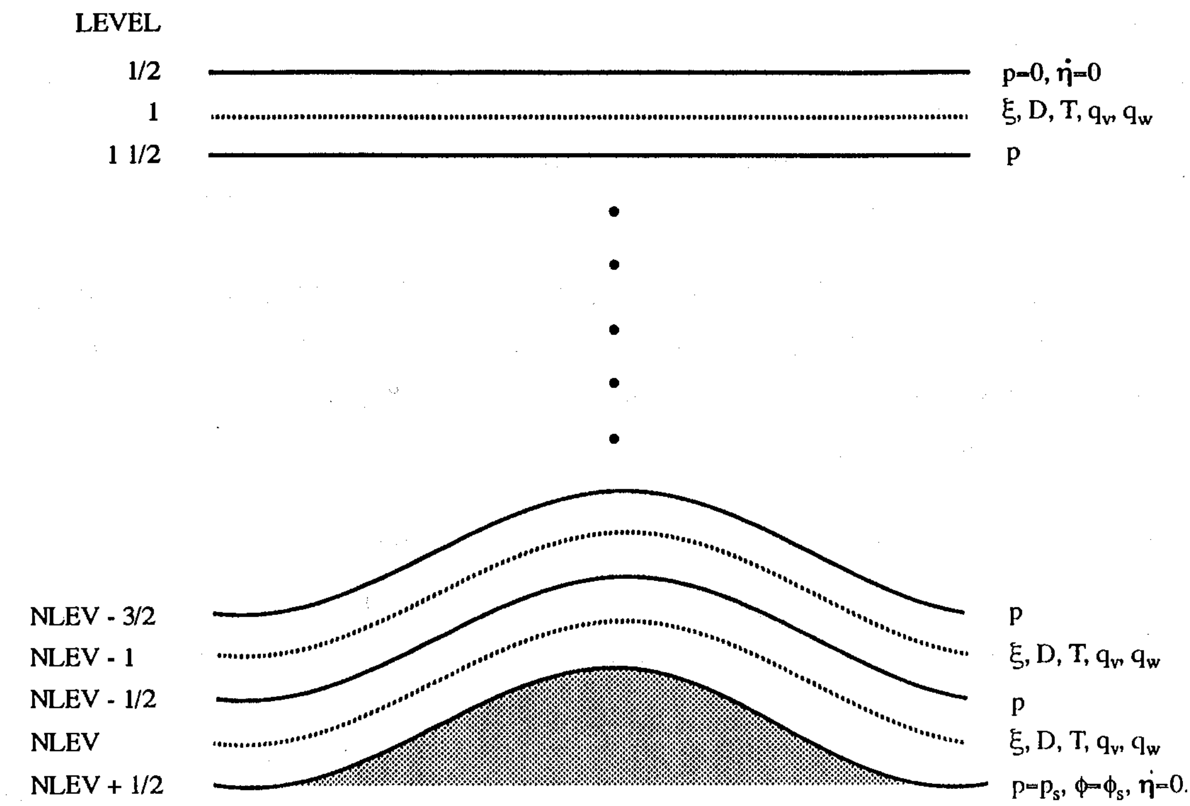


Figure 3 Vertical distribution of variables

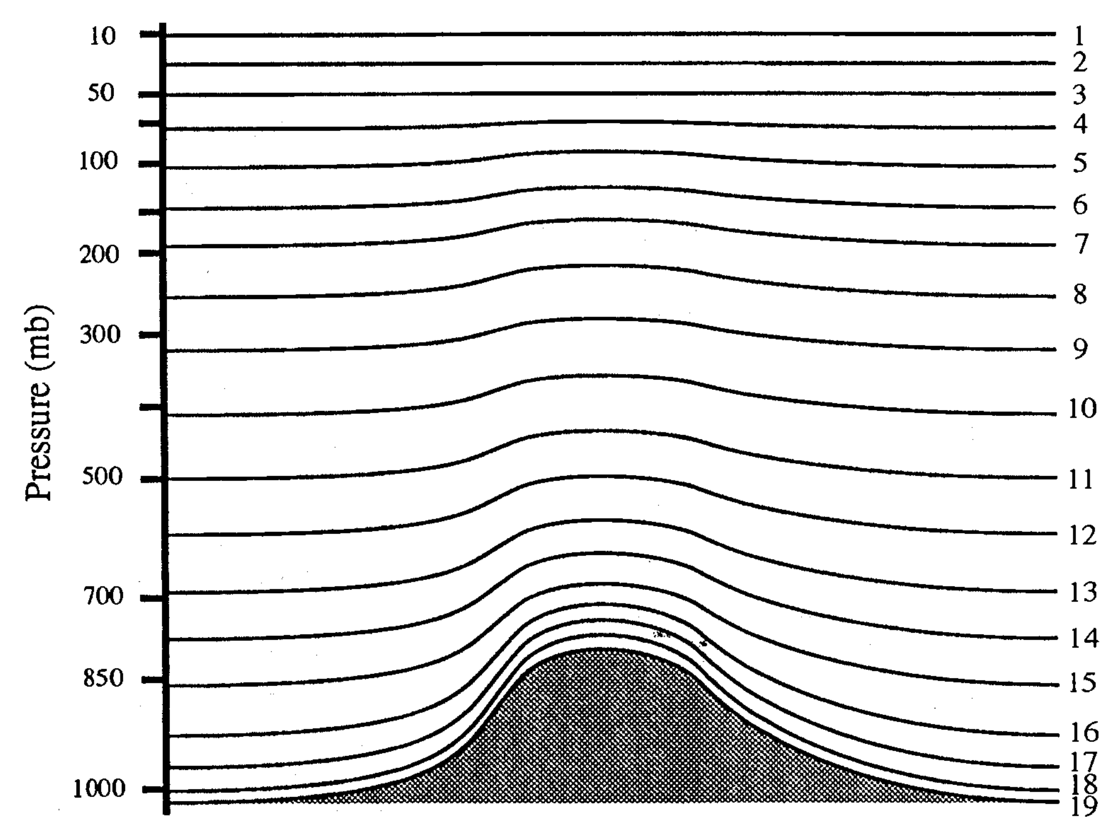


Figure 4 Distribution of full-level pressures in the 19-level ECHAM3 model

[MPI Meteorology Hamburg, The ECHAM3 AGCM, Tech. Report No. 6, 1993]

Temporal discretizing

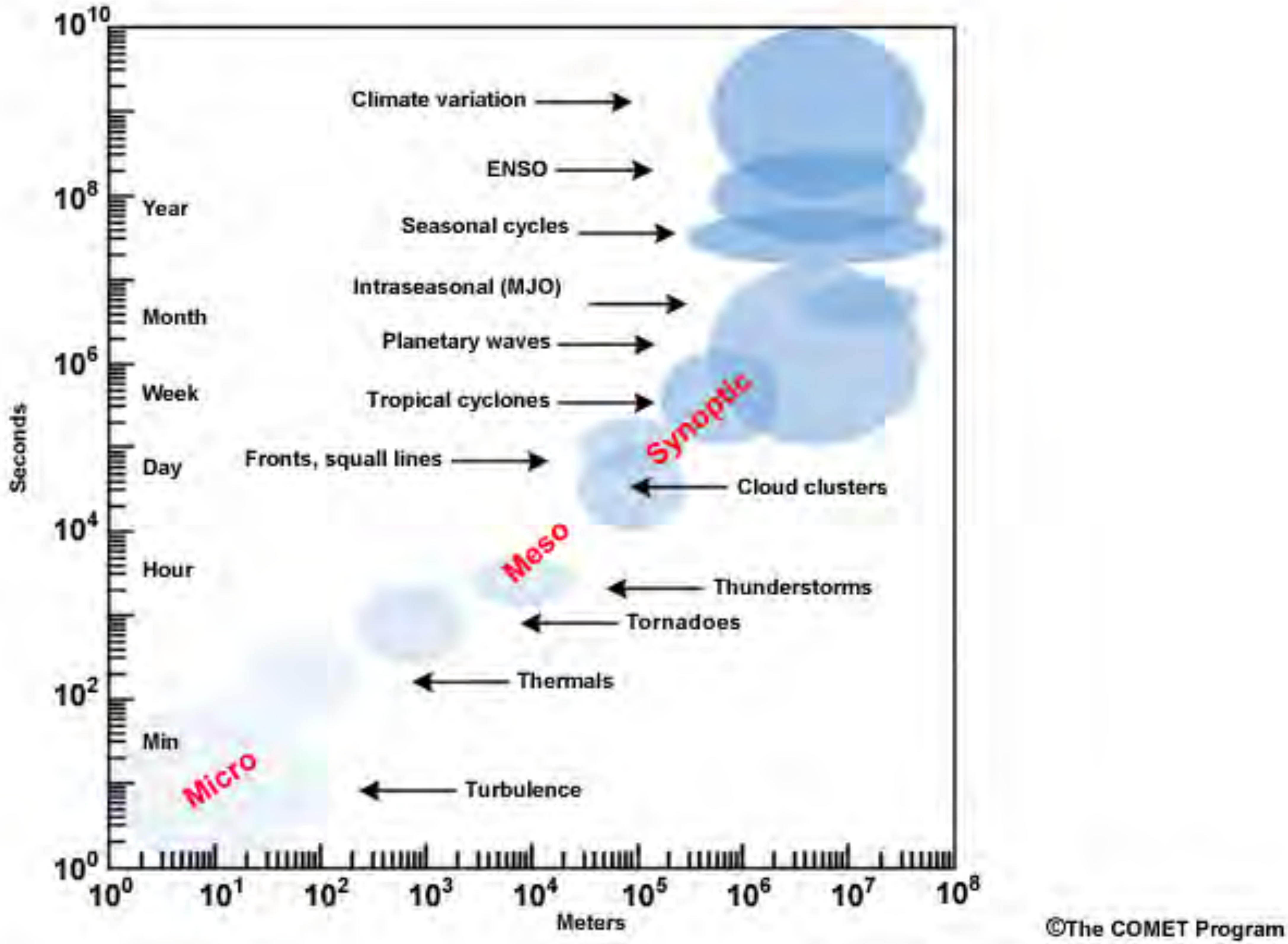
- *Relation between spatial grid size and model time step:*
  The time step must be short enough that the maximum speed of propagation of information does not permit any transfer from one grid point to another *within* one time step

$$\Delta t \leq \Delta x / c \qquad (\, c = \text{propagation velocity})$$

- Example: ECHAM atmosphere GCM

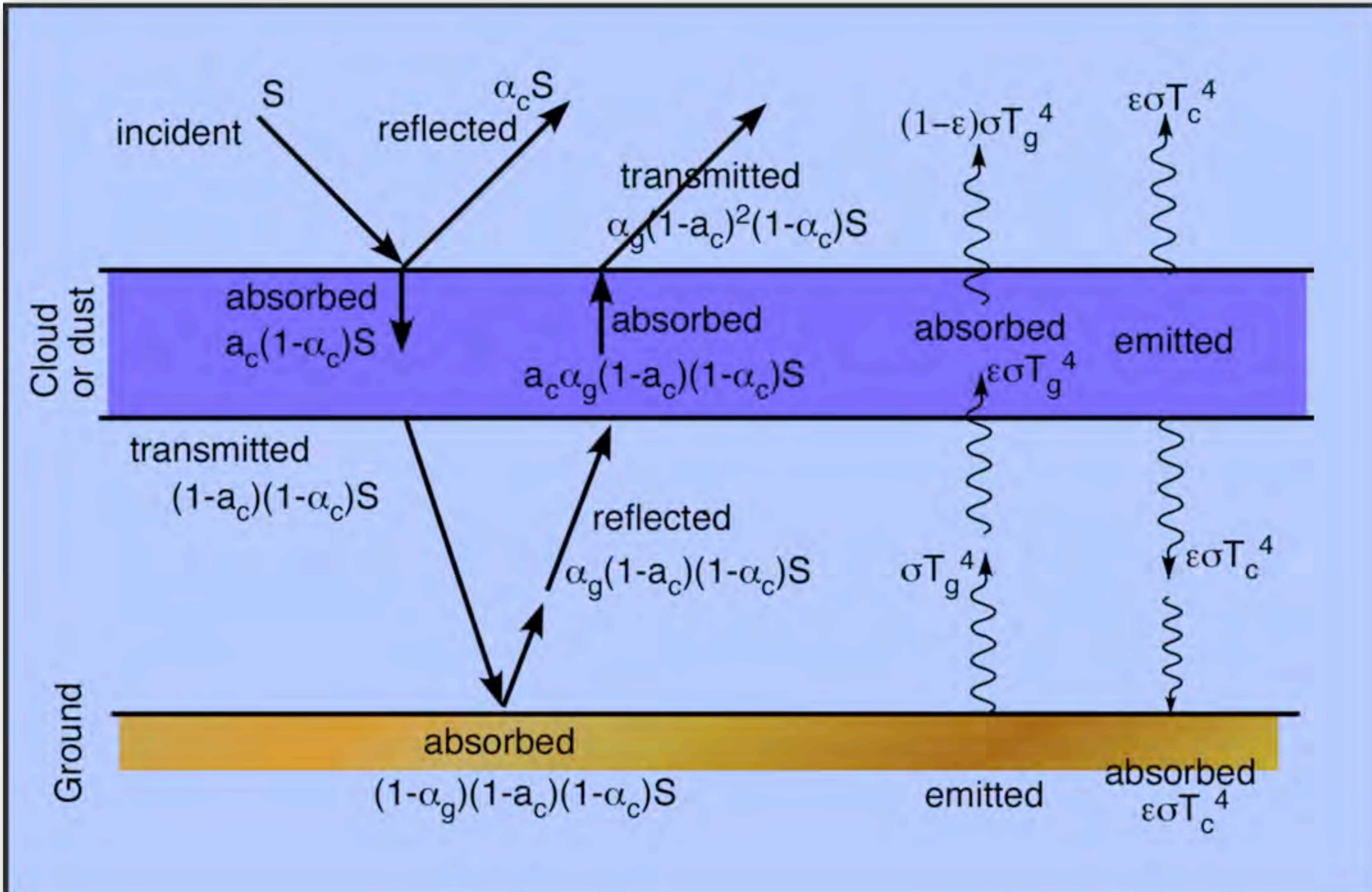
GCM Mode	# grid points	grid size	time step
T21	64 x 32	~5.6°	40min
T42	128 x 64	~2.8°	24min
T106	320 x 160	~1.1°	12min

Parameterizing sub-scale processes



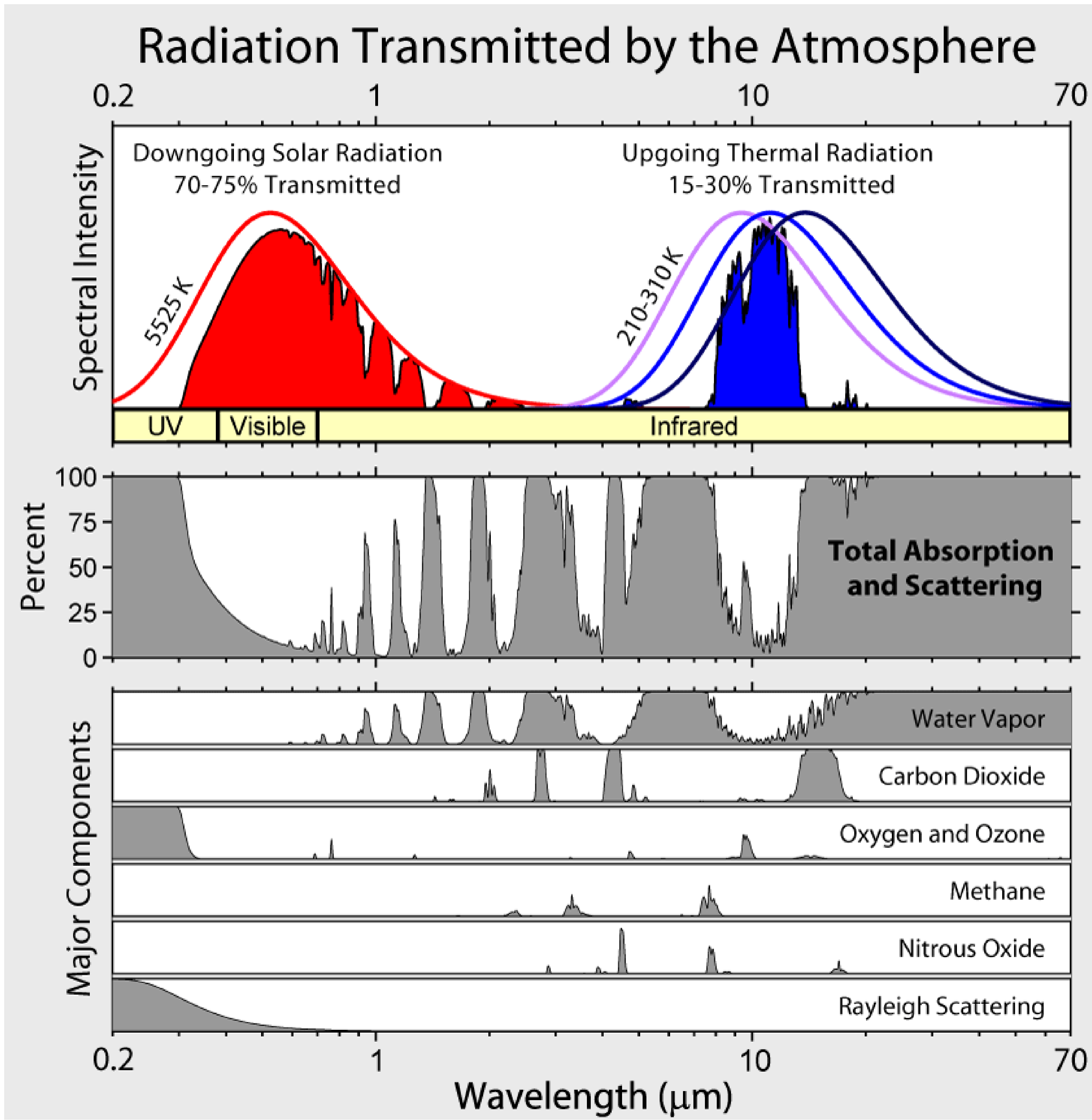
[http://www.chanthaburi.buu.ac.th/~wirote/met/tropical/textbook_2nd_edition/navmenu.php_tab_2_page_8.1.0.htm]

Sub-scale processes: Radiation in the atmosphere



[McGuffie & Henderson-Sellers, A Climate Modelling Primer, 2005]

Sub-scale processes: Radiation in the atmosphere

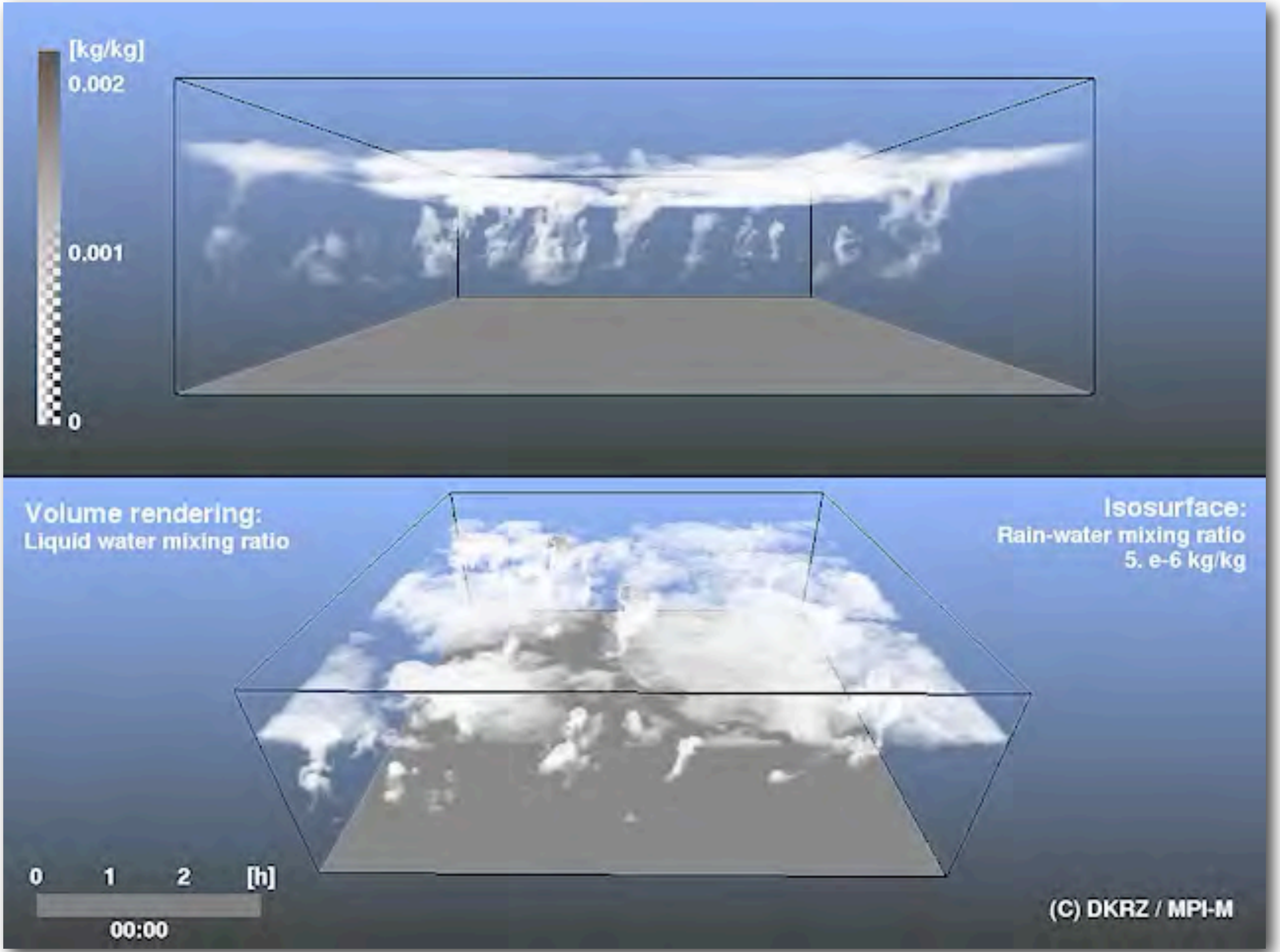


[plot adapted from: Peter Köhler, The Carbon Cycle, Lecture Notes, 2009]

Sub-scale processes: Clouds

[http://www.youtube.com/watch?v=CEe8vzJji3M]

Cloud System Resolving Models (CSRM)



[http://www.dkrz.de/dkrz/gallery/vis/atm_LES]

Ocean models

[http://www.youtube.com/watch?v=CEe8vzJji3M]

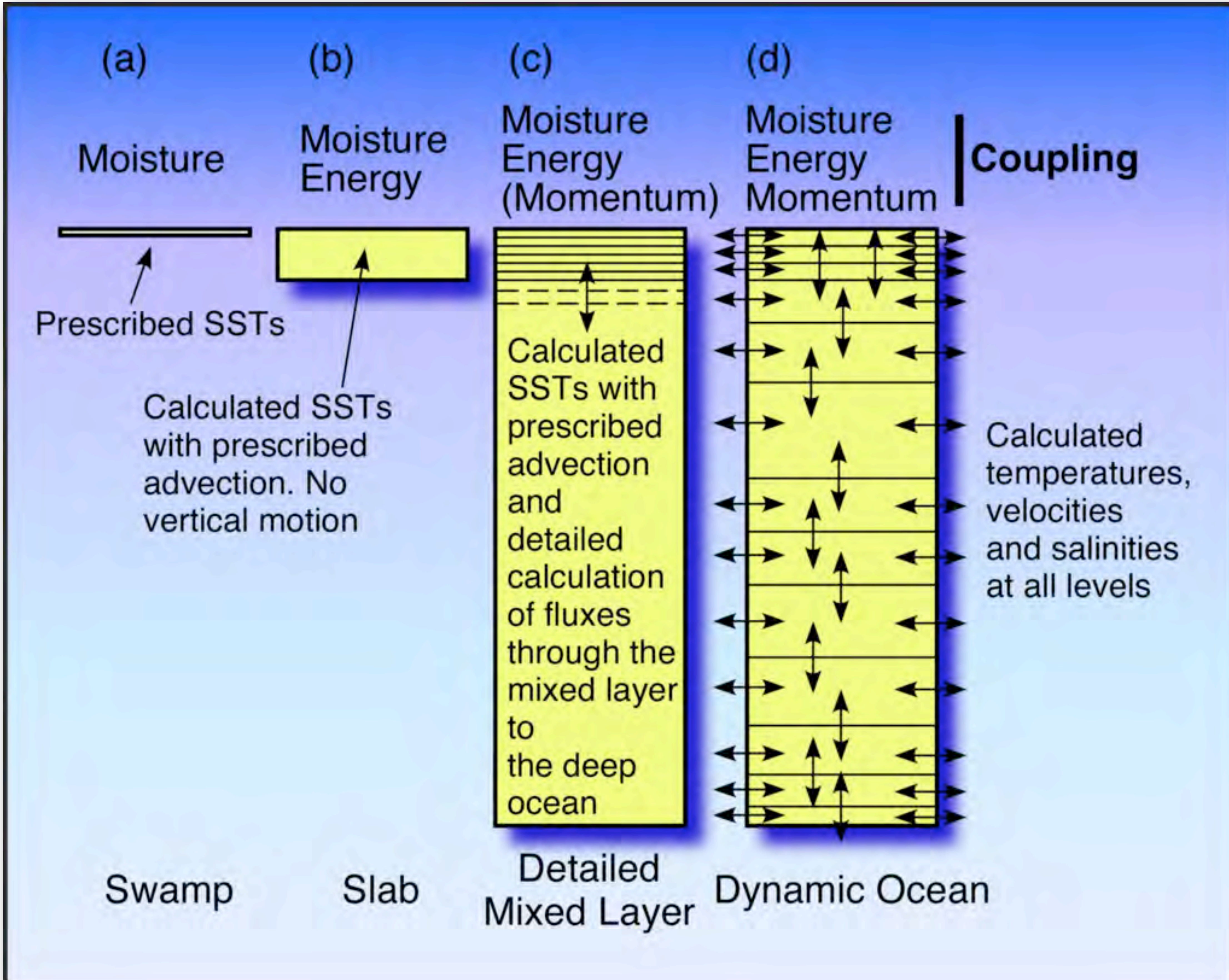
Fundamental equations of an ocean model

- 7 equations and 7 state variables
  3 velocity components {u,v,w}
  θ potential temperature
  S salinity
  ρ density
  p pressure

- *fundamental equations (Navier-Stokes equations) similar to the ones for the atmosphere*

- key difference:
  air is a compressible gas,
  sea water is an incompressible liquid

Ocean models of different complexity

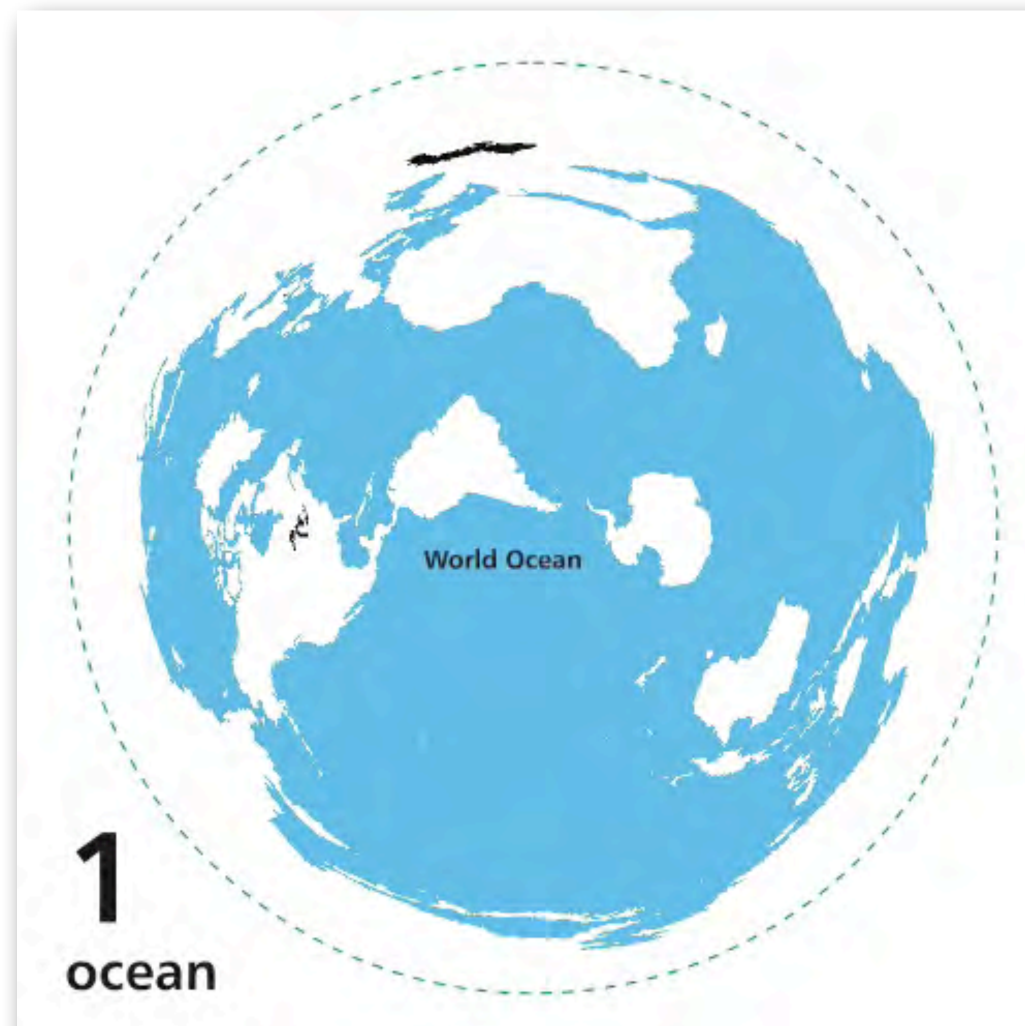


[McGuffie & Henderson-Sellers, A Climate Modelling Primer, 2005]

Ocean grids

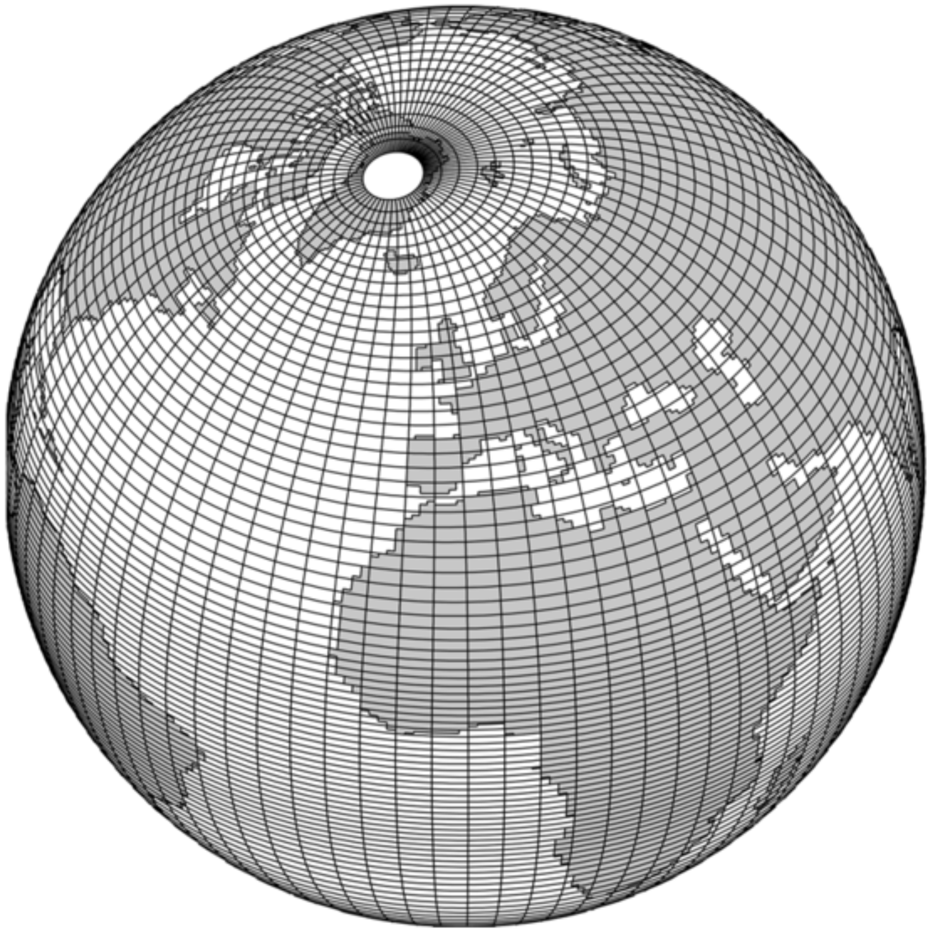
- Challenge: irregular domain
  - *complex coastlines*
  - *3 basins, multiple connected*
  - *narrow straits and passages*
  - *top, bottom and side boundary layers*

[http://www.meted.ucar.edu/oceans/ocean_models/]

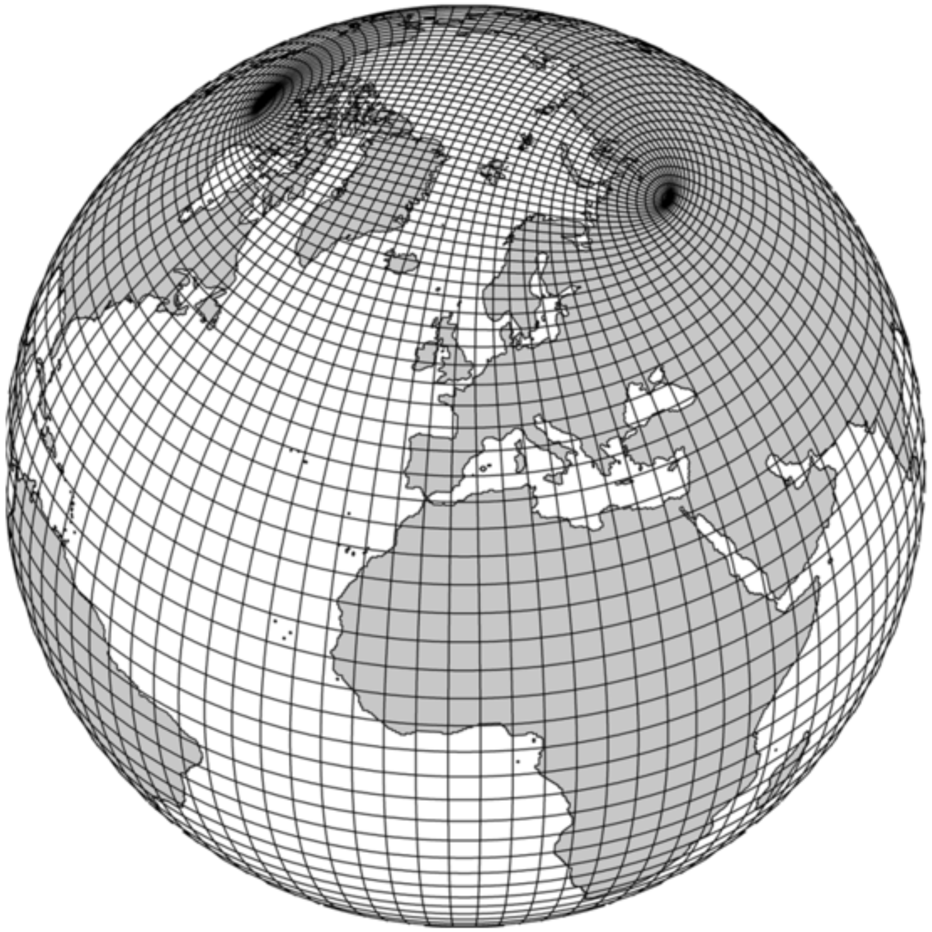


http://en.wikipedia.org/wiki/File:World_ocean_map.gif

Horizontal ocean modelling: Bipolar and tripolar grids



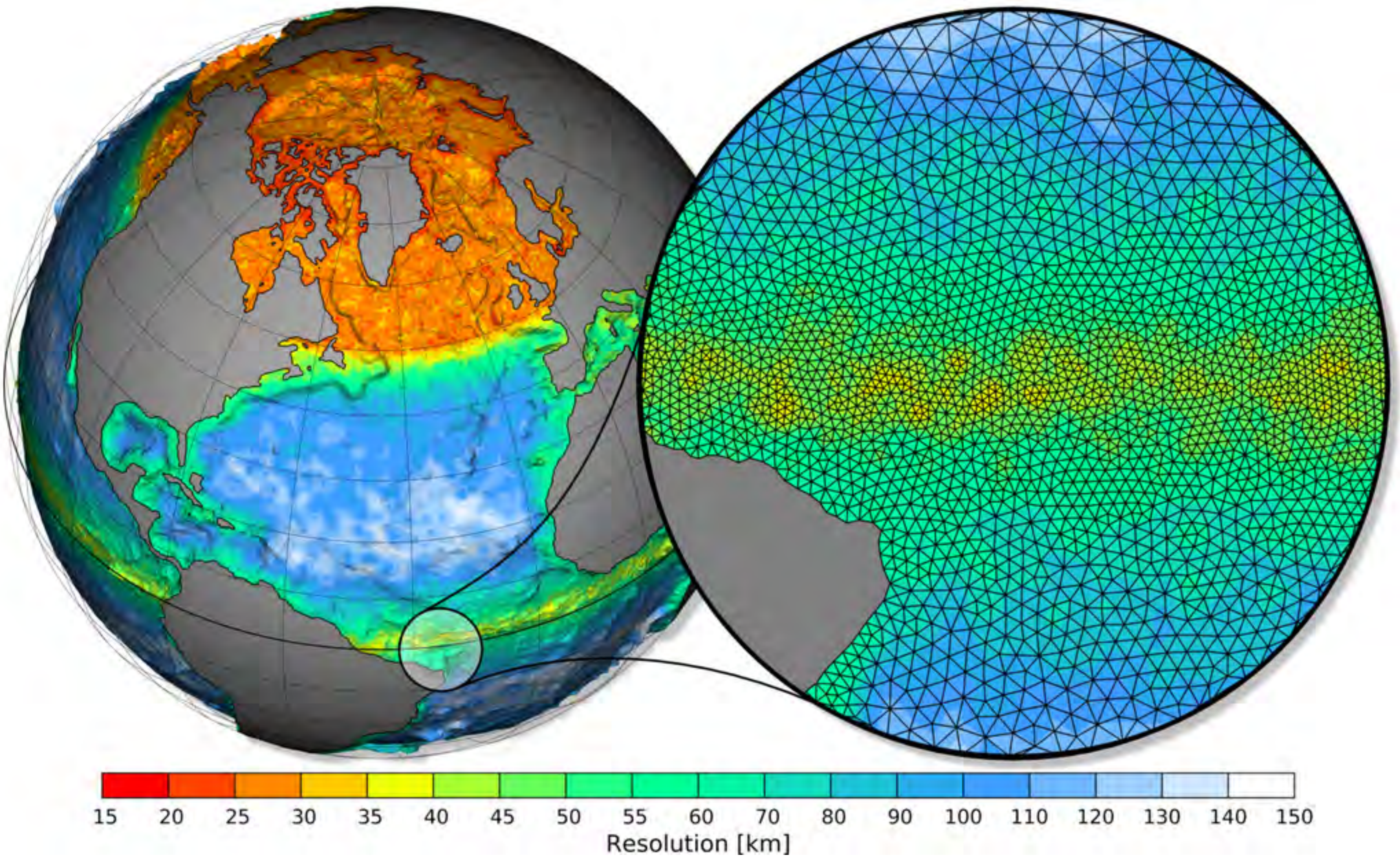
A. 1.125° bipolar grid (every 4th grid line shown)
- 320 x 384 grid cells
- enhanced meridional (N-S) resolution near equator



B. 0.25° tripolar grid (every 16th grid line shown)
- 1440 x 1152 grid cells
- isotropic (equal) grid near equator
- target resolution for NorESM

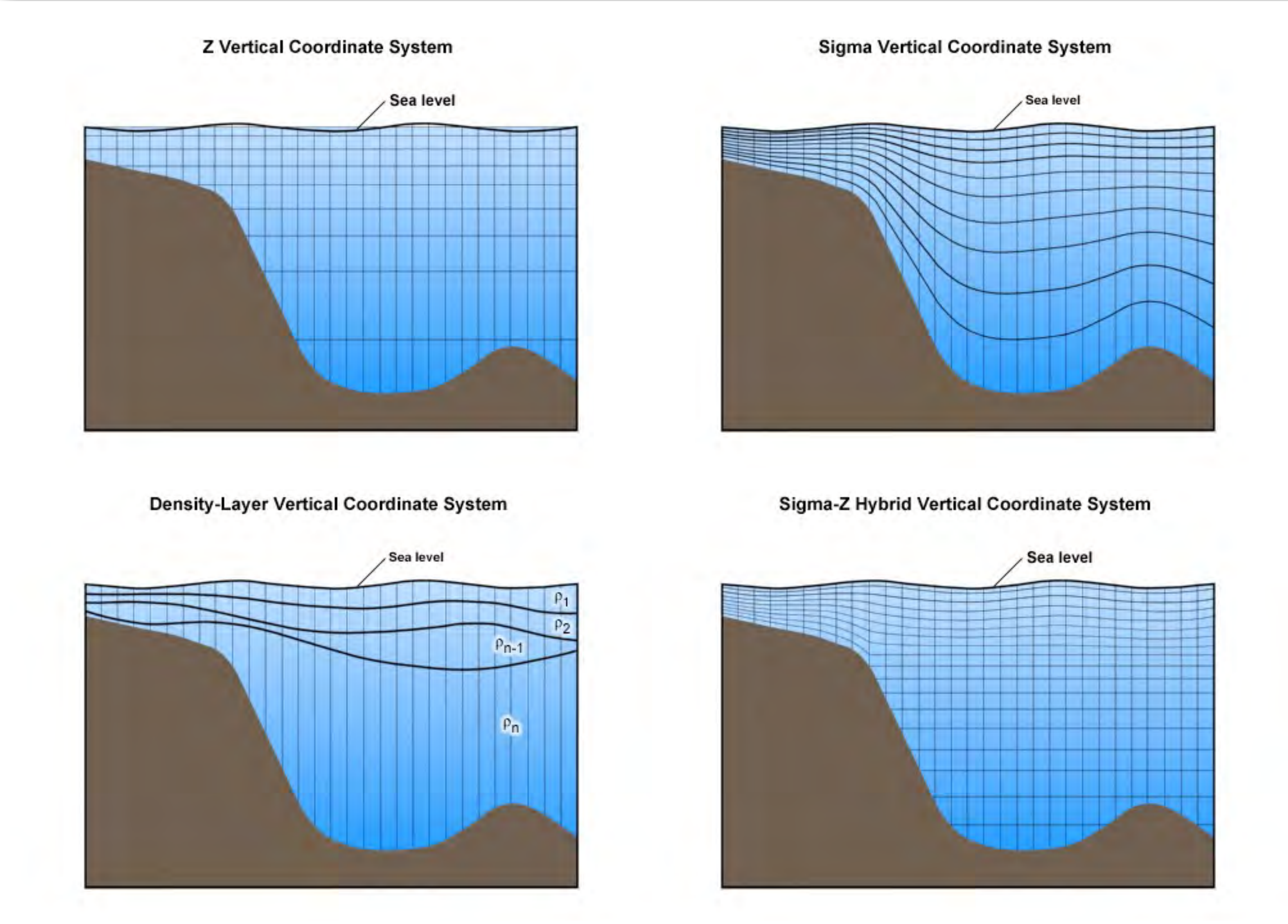
[https://expearth.uib.no/?page_id=28#Model

Horizontal ocean modelling: Finite Elements



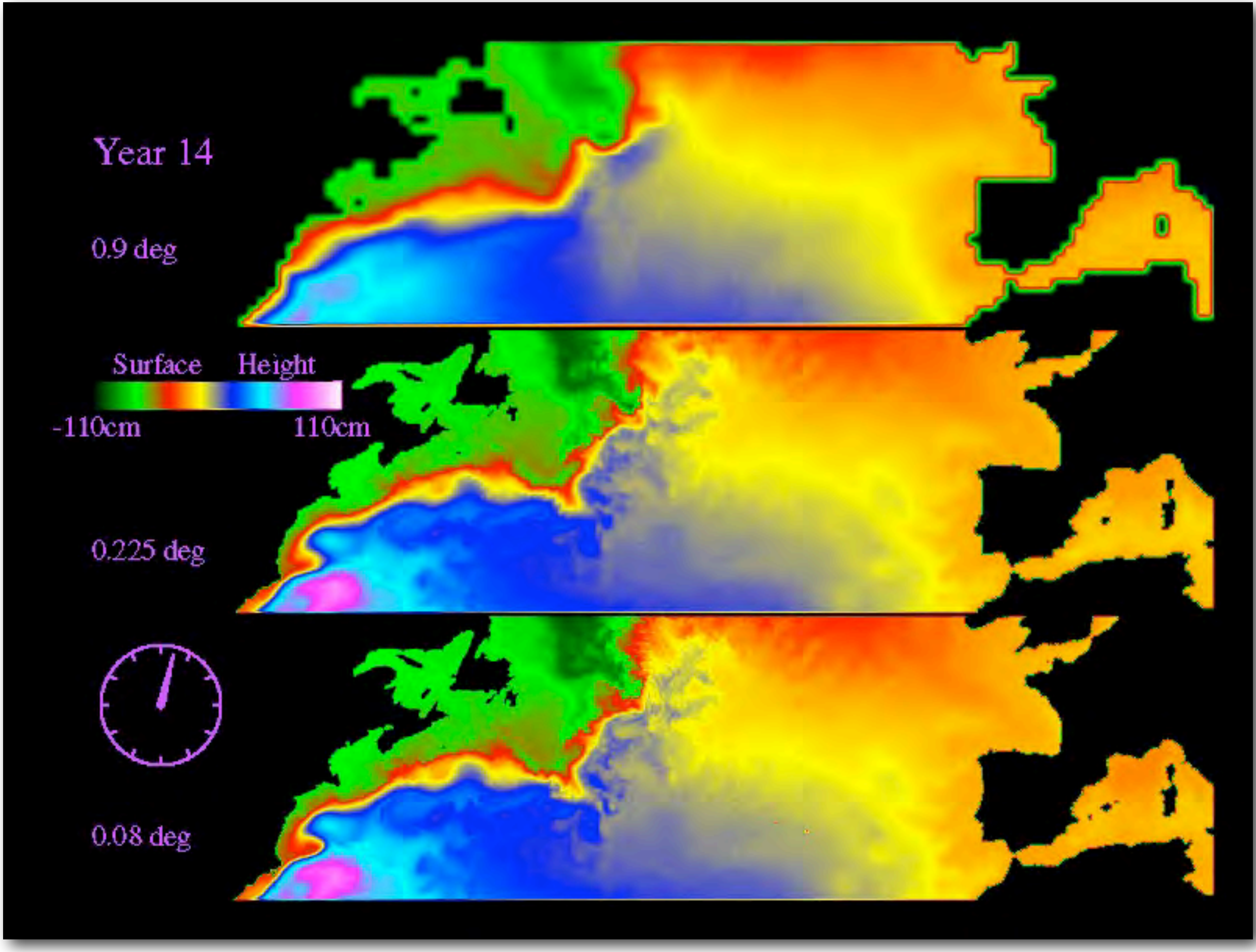
[https://fesom.de/models/awi-esm/]

Vertical ocean model grids



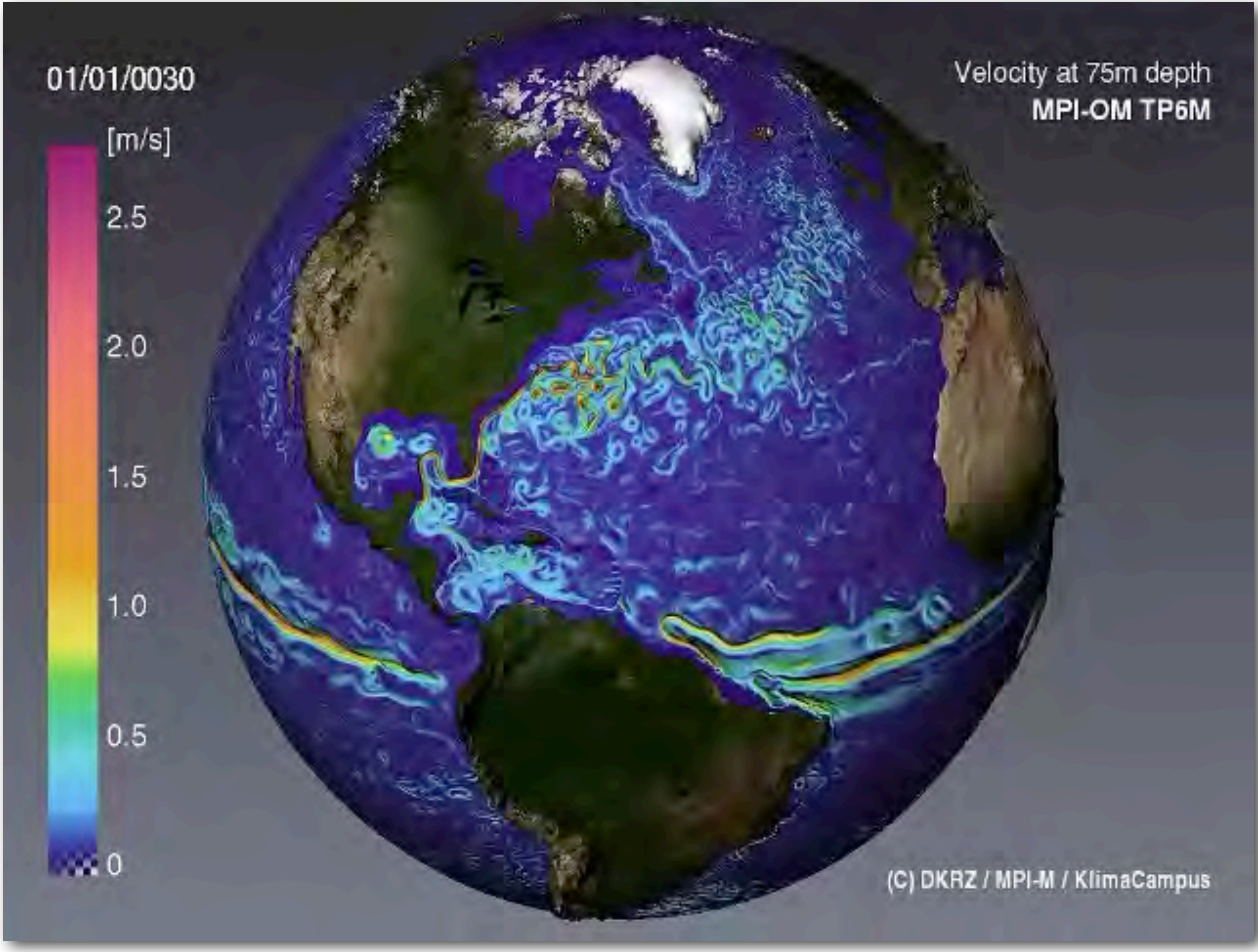
[http://www.meted.ucar.edu/oceans/ocean_models/]

Model resolution: Surface height in the North Atlantic



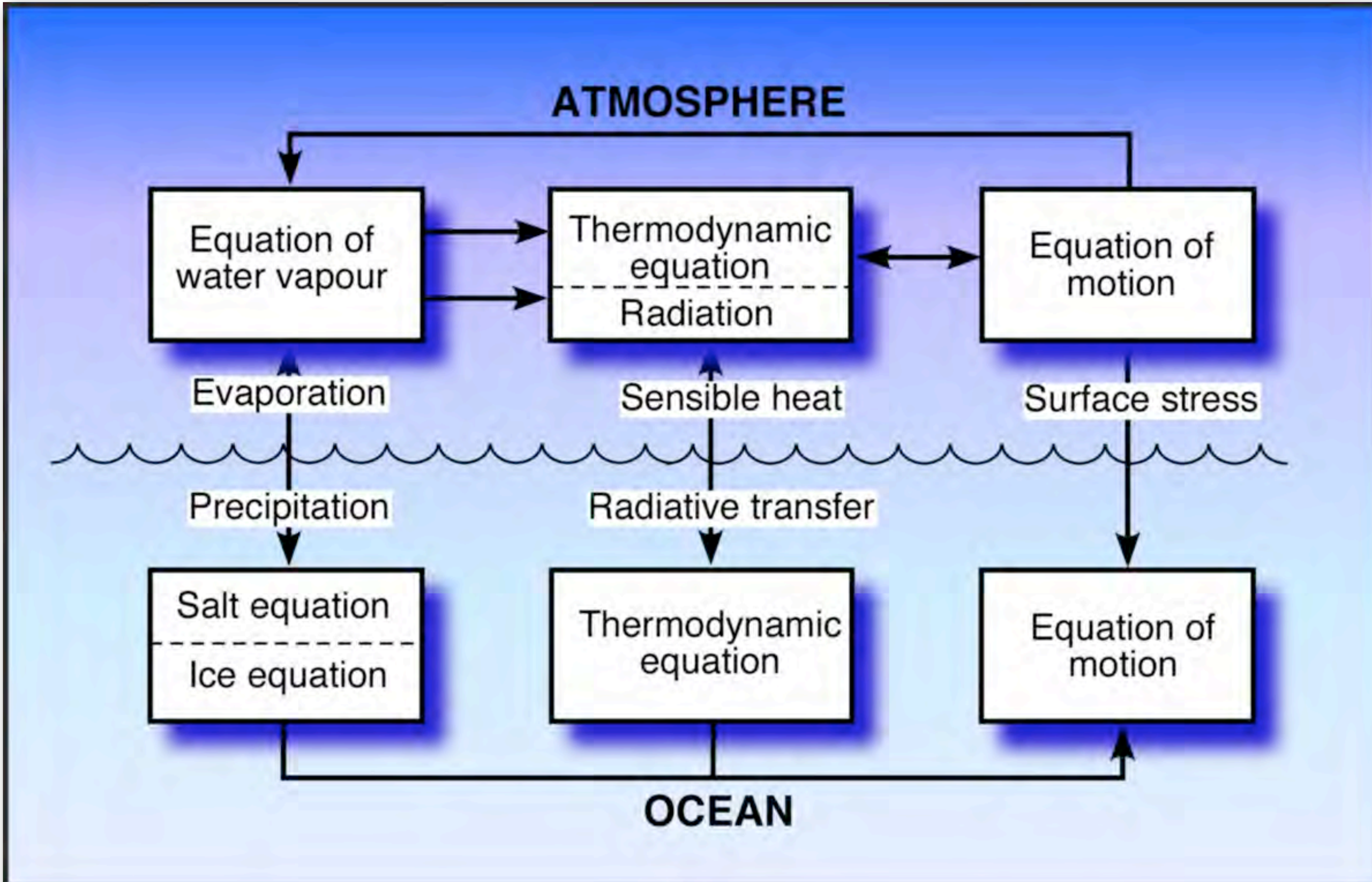
[McGuffie & Henderson-Sellers, A Climate Modelling Primer, 2005]

Eddy-resolving ocean modelling



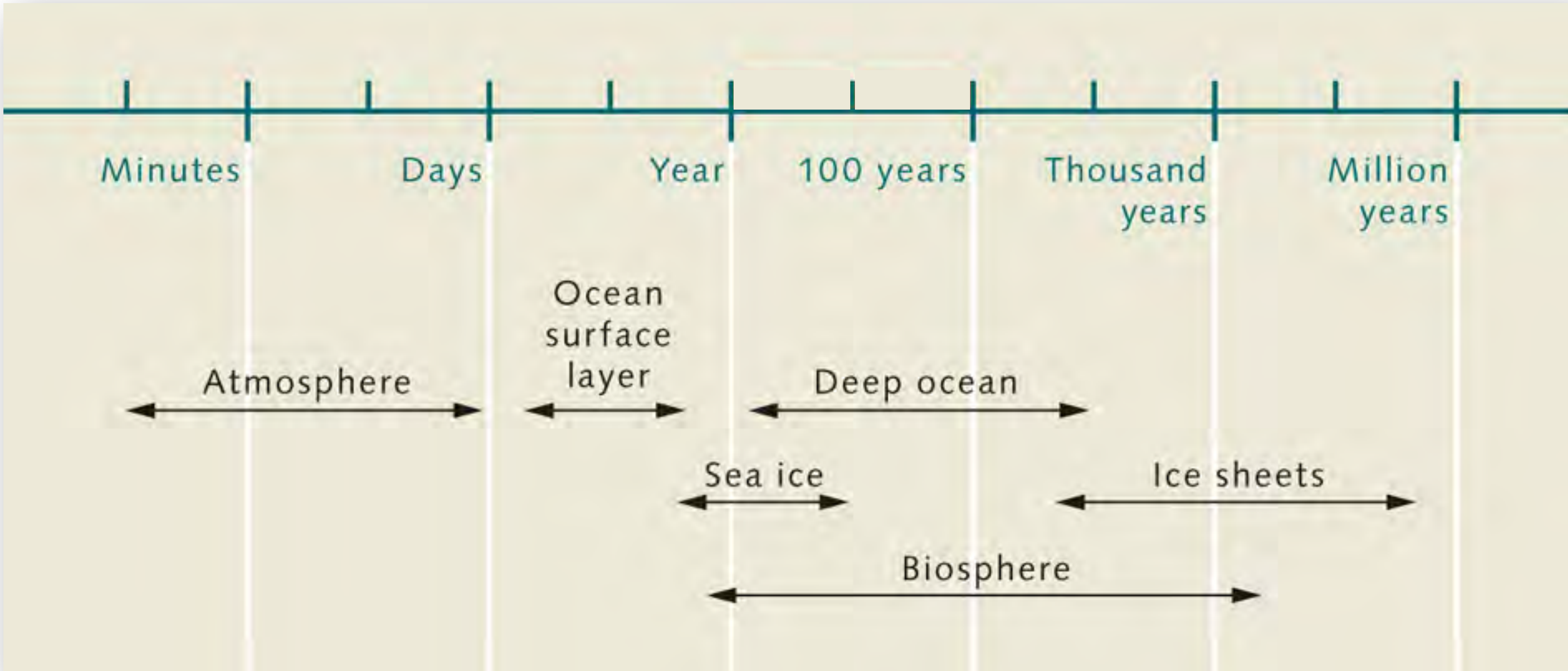
[www.dkrz.de]

Coupling of atmosphere and ocean GCM



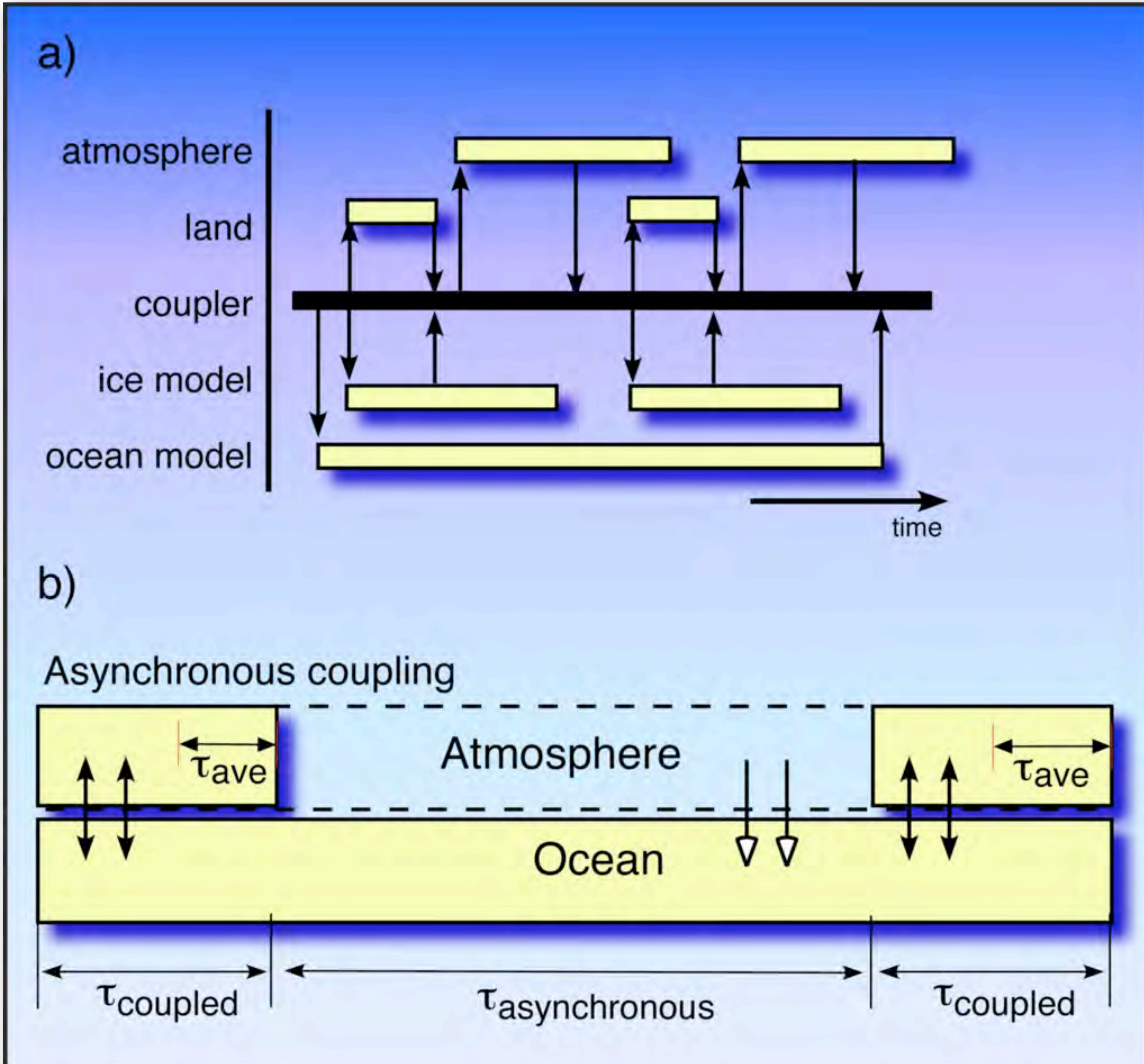
[McGuffie & Henderson-Sellers, A Climate Modelling Primer, 2005]

Time scales of climate model components



[http://worldoceanreview.com/en/files/2010/10/k1_d_zeitskala-klimasystem_e_en.jpg

Synchronous or asynchronous coupling



[McGuffie & Henderson-Sellers, A Climate Modelling Primer, 2005]

Model challenges: Complexity of interaction between different physical processes...

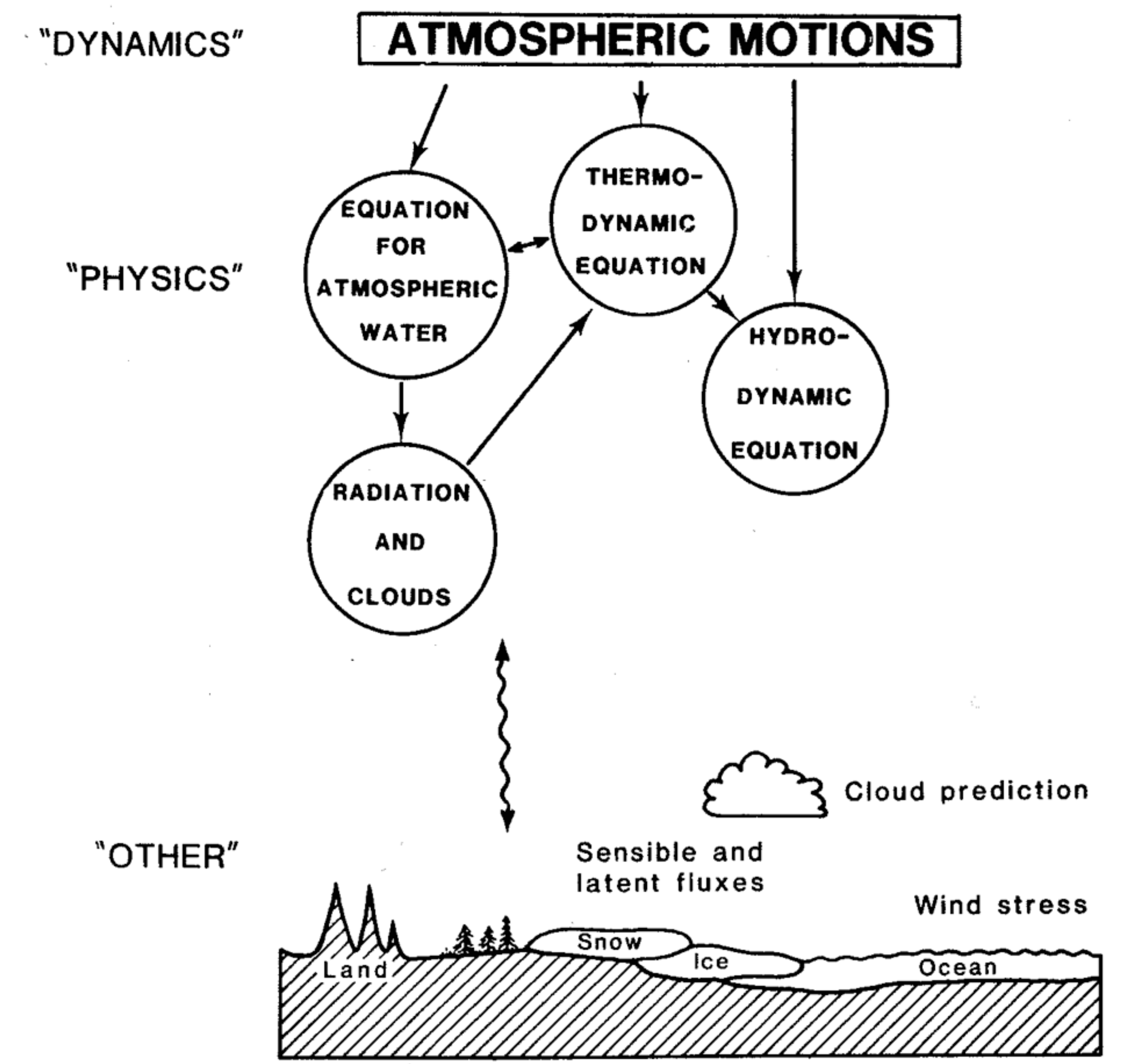
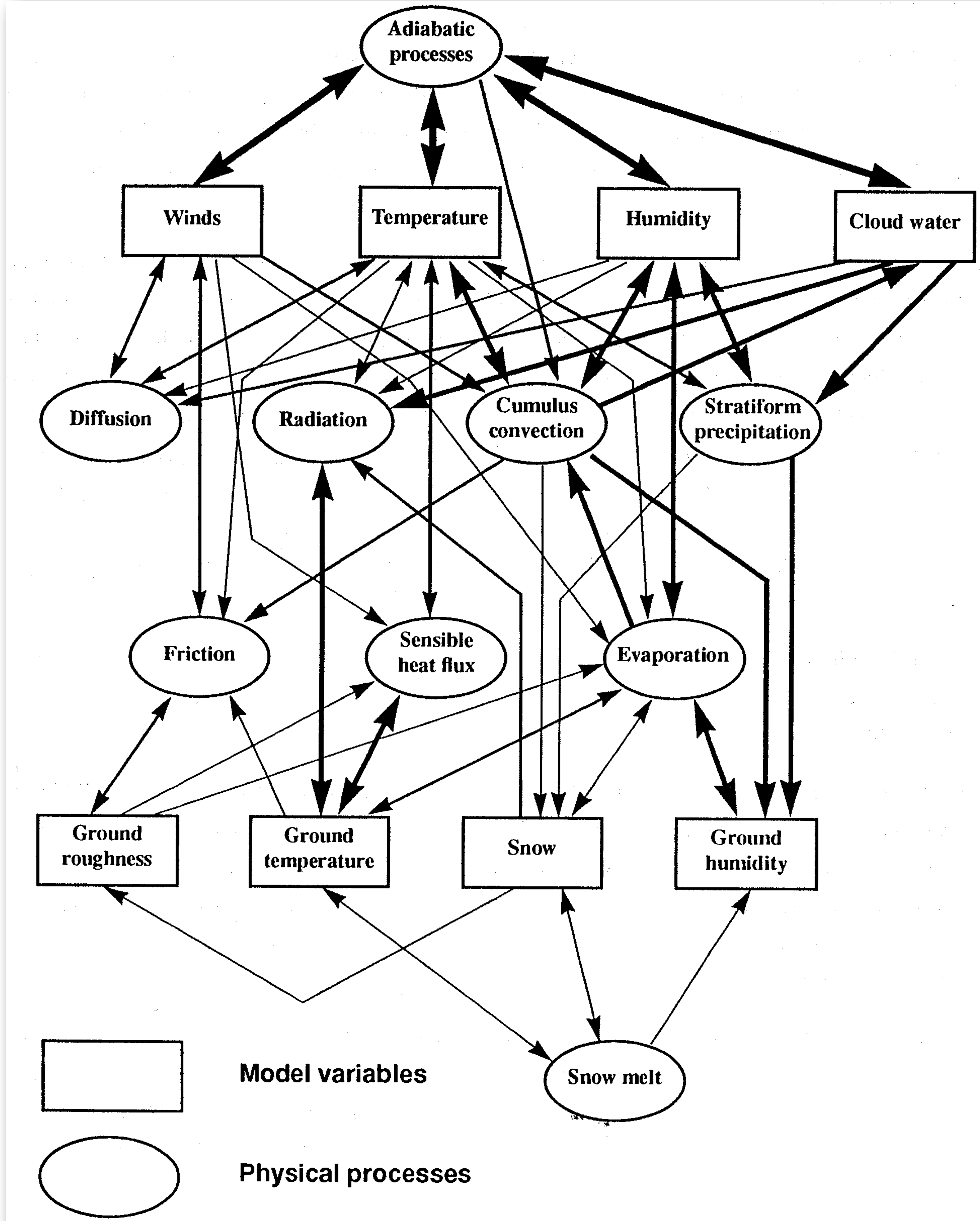


Figure 5.1 The processes incorporated in an AGCM. It is generally true that more computational effort is expended on the dynamics and the physics than on the other processes incorporated in AGCMs

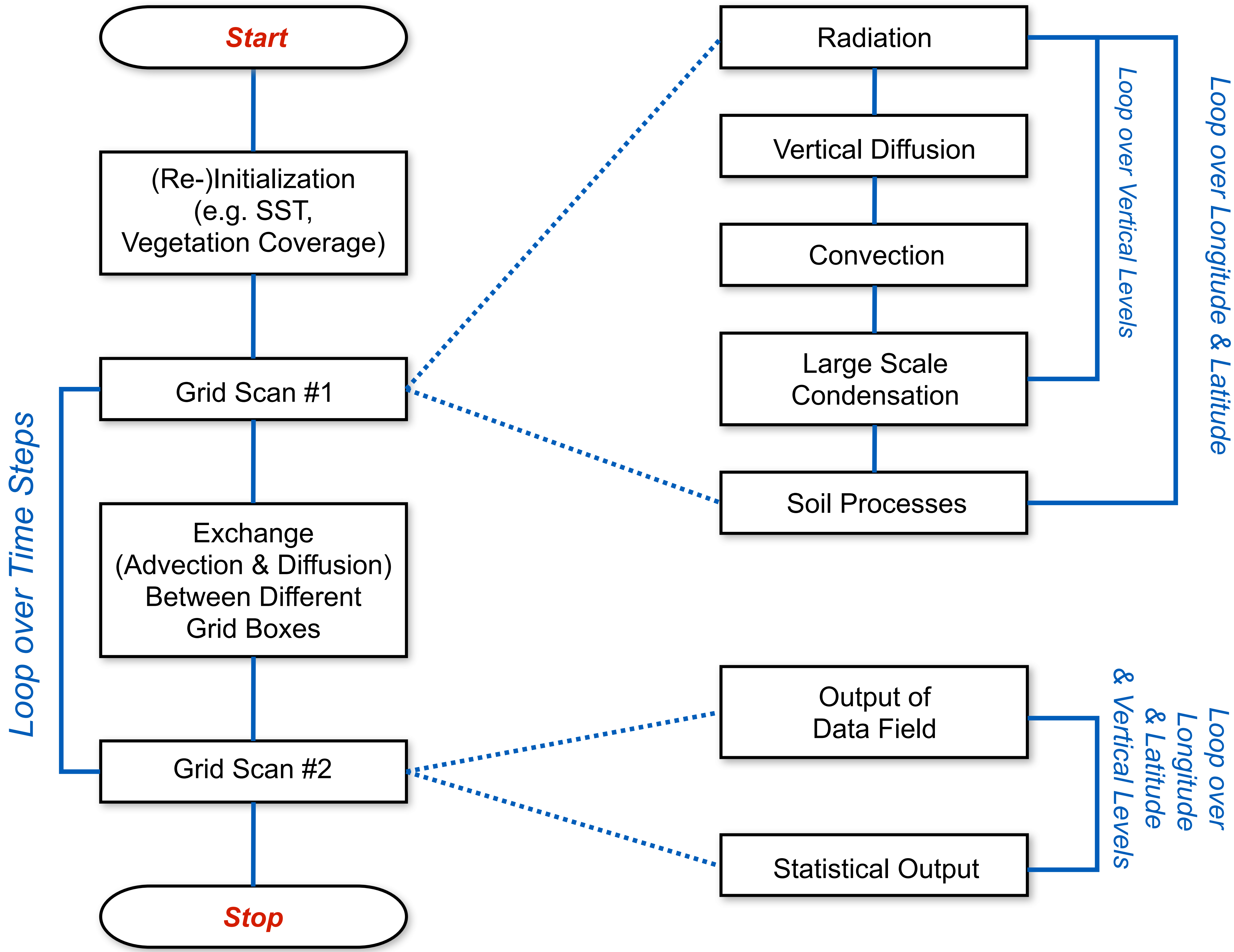
[McGuffie & Henderson-Sellers, A Climate Modelling Primer]

Model challenges: Complexity of interaction between different physical processes...

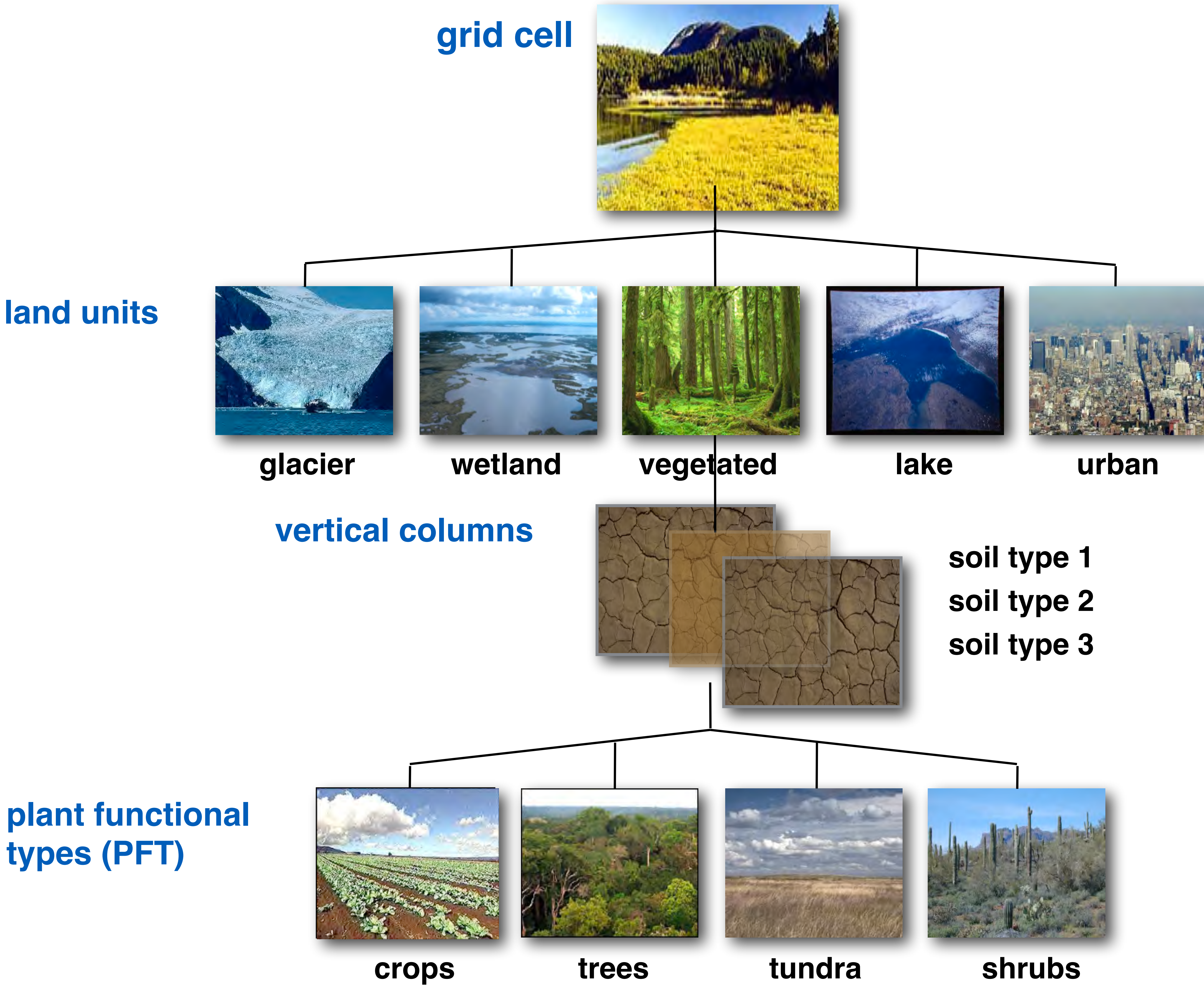


[MPI Meteorology Hamburg, The ECHAM3 AGCM, Tech. Report No. 6, 1993]

Example: An atmosphere GCM flow diagram



Land surface models



[adapted from: http://www.asp.ucar.edu/colloquium/2006/climate-model/]

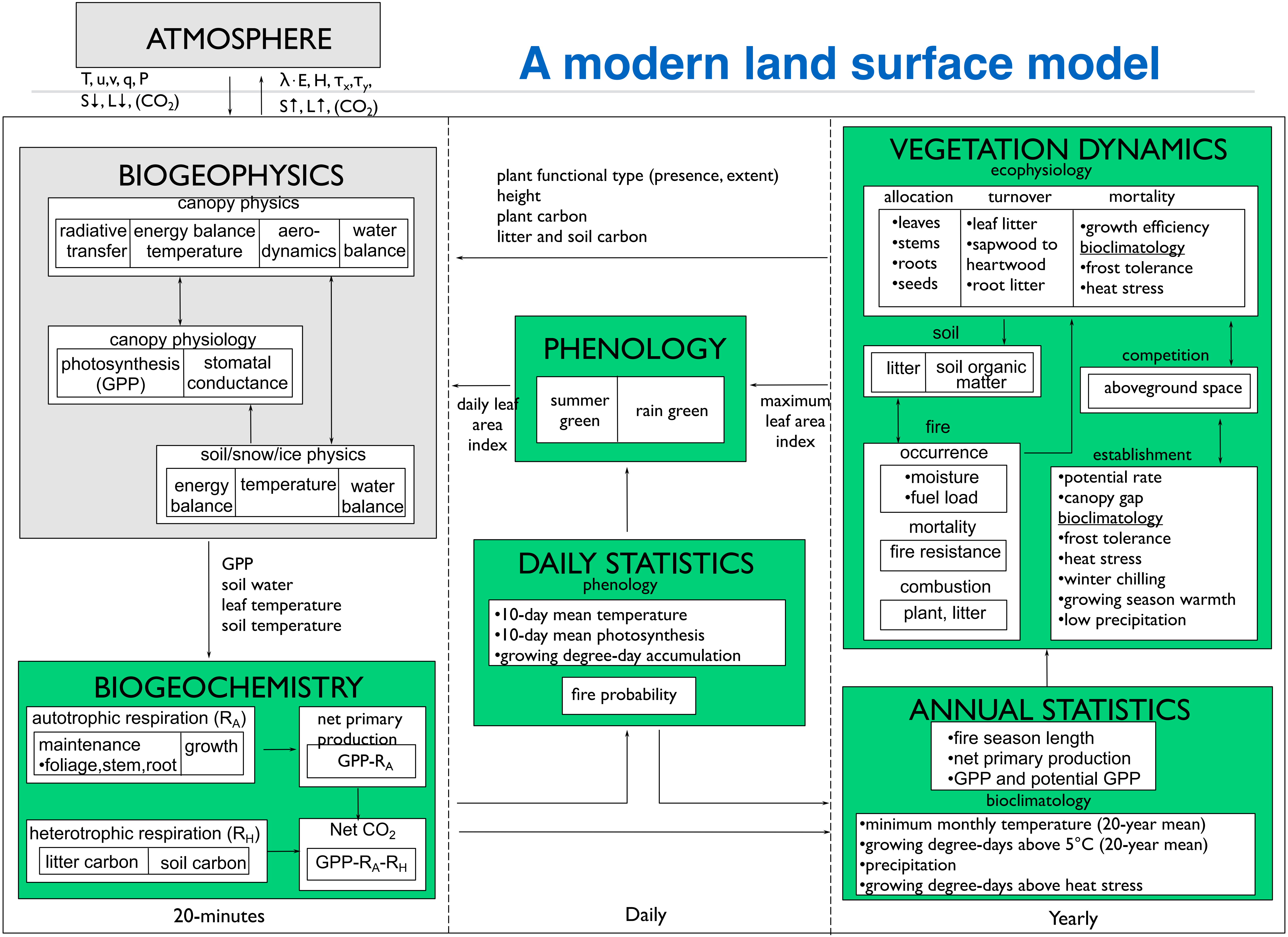
Key processes of land surface models (LSM)

The land-surface model solves (at each timestep)

- **Surface energy balance** (and other energy balances, e.g. in canopy, snow, soil)
  - $S^{\downarrow} + L^{\downarrow} = S^{\uparrow} + L^{\uparrow} + \lambda E + H + G$
    - $S^{\downarrow}$, $S^{\uparrow}$ are down(up)welling solar radiation
    - $L^{\downarrow}$, $L^{\uparrow}$ are down(up)welling longwave radiation
    - λ is latent heat of vaporization, E is evaporation
    - H is sensible heat flux
    - G is ground heat flux
- **Surface water balance** (and other water balances such as snow and soil water)
  - $P = E_S + E_T + E_C + R_{Surf} + R_{Sub\text{-}Surf} + \Delta SM / \Delta t$
    - P is rainfall
    - E_S is soil evaporation, E_T is transpiration, E_C is canopy evaporation
    - R_{Surf} is surface runoff, $R_{Sub\text{-}Surf}$ is sub-surface runoff
    - $\Delta SM / \Delta t$ is the change in soil moisture over a timestep
- **Carbon balance** (and plant and soil carbon pools)
  - $NPP = GPP - Ra = (\Delta C_f + \Delta C_s + \Delta C_r) / \Delta t$
  - $NEP = NPP - Rh$
  - NBP = NEP - Combustion
    - NPP is net primary production, GPP is gross primary production
    - Ra is autotrophic (plant) respiration, Rh is heterotrophic (soil) respiration
    - ΔC_f, ΔC_s, ΔC_r are foliage, stem, and root carbon pools
    - NEP is net ecosystem production, NBP is net biome production
    - Combustion is carbon loss during fire

[adapted from: http://www.asp.ucar.edu/colloquium/2006/climate-model/]

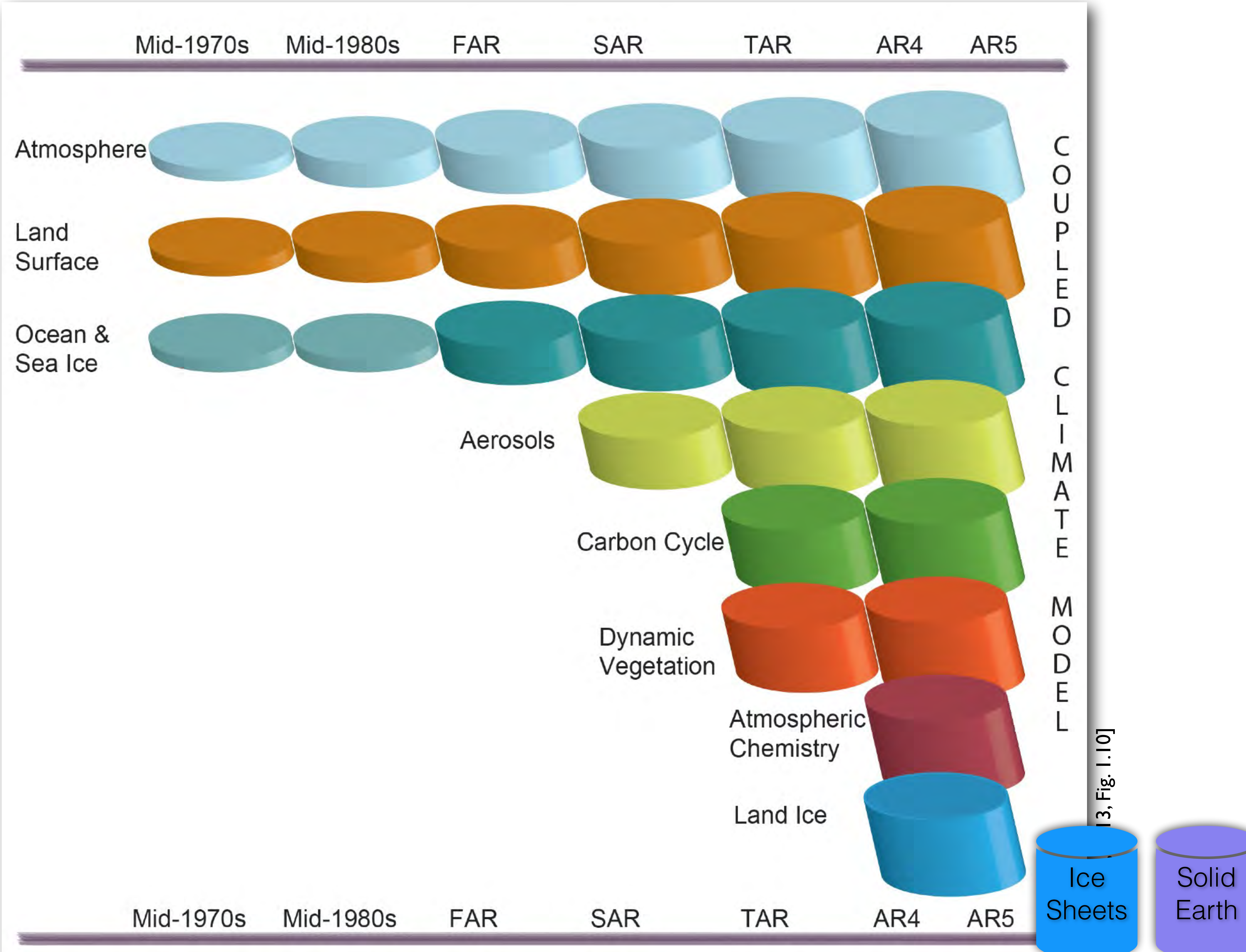
A modern land surface model



Bonan et al. (2003) Global Change Biology 9:1543-1566

[adapted from: http://www.asp.ucar.edu/colloquium/2006/climate-model/]

Historical development of climate models



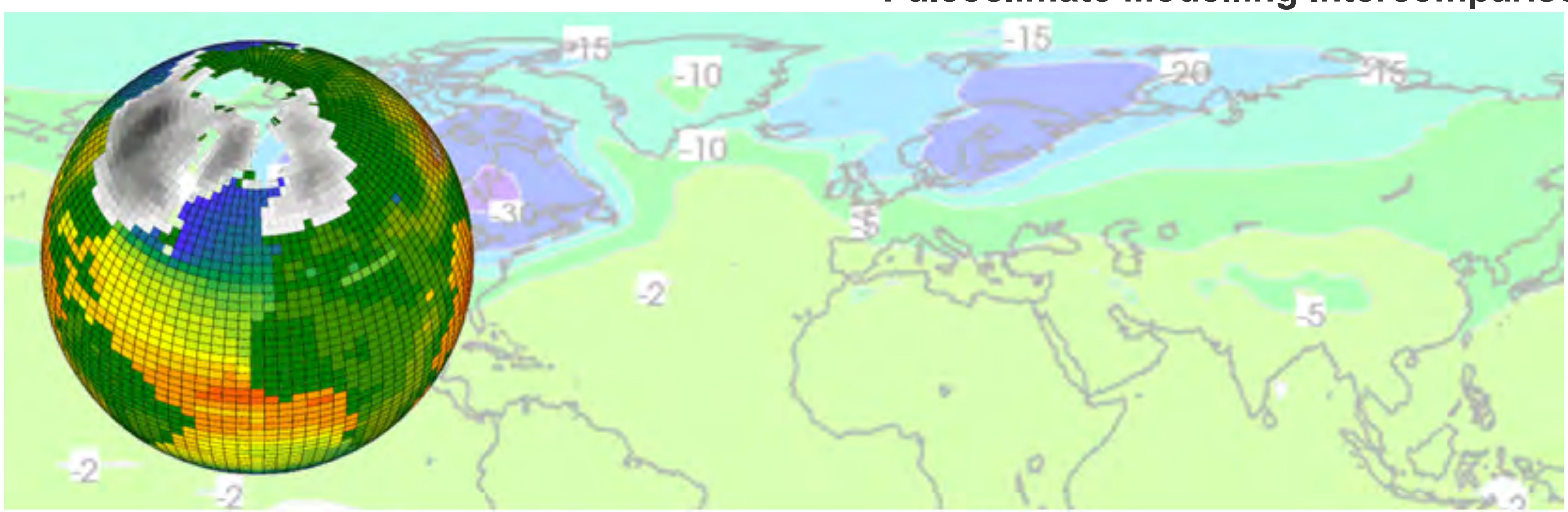
Climate models: Paleoclimate simulations

Idea: Run GCM under (very) different boundary conditions but with the same physical parameterizations to test their general validity and robustness

- Example: Climate of the Last Glacial Maximum (LGM)
  - *massive ice sheets over North America and Eurasia (T_{Surf} & albedo change)*
  - *sea level lowered by 108m (exposed continental shelf regions)*
  - *decreased atmospheric CO_2 level (LGM: 180 ppm, present: 360ppm)*
  - *comparable incoming solar radiation*

PMIP

Paleoclimate Modelling Intercomparison Project



[https://pmip.lsce.ipsl.fr]

PMIP4 results: Comparison of LGM simulations

The PMIP4-CMIP6
Last Glacial Maximum experiments:
preliminary results and comparison
with the PMIP3-CMIP5 simulations

M. Kageyama et al.,
Climate of the Past, 2020, in review

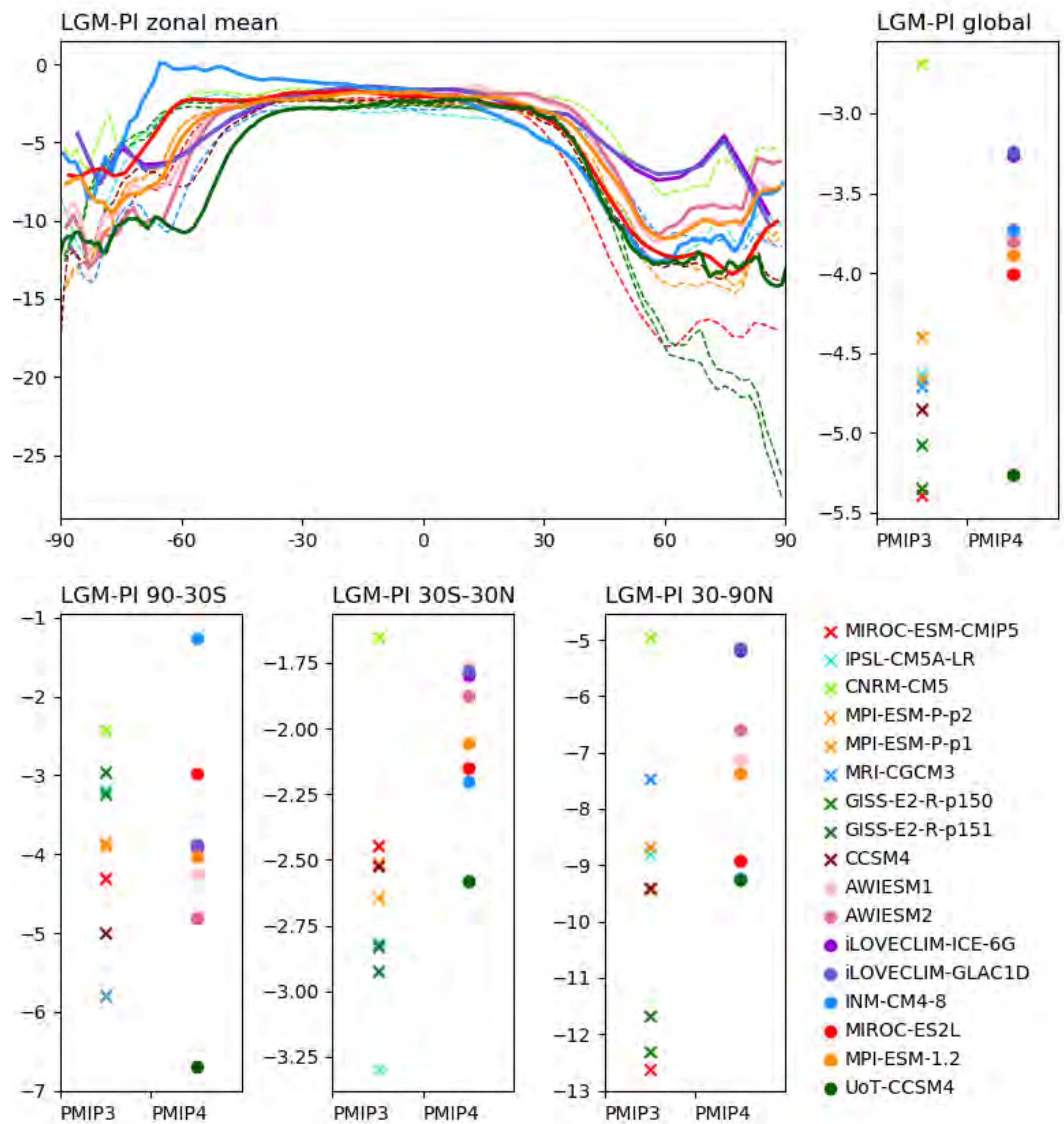


Figure 2: Mean annual temperatures LGM – PI anomalies in °C. Top left: zonal means, PMIP3 model results shown as dashed lines, PMIP4 model results shown as thick solid lines; top right: global means, PMIP3 model results shown by crosses, PMIP4 models shown by filled circles; the three bottom panels show, from left to right, the averages over the southern hemisphere extratropics (90°S to 30°S), the tropics (30°S to 30°N) and the northern extratropics (30°N to 90°N).

[https://cp.copernicus.org/preprints/cp-2019-169/]

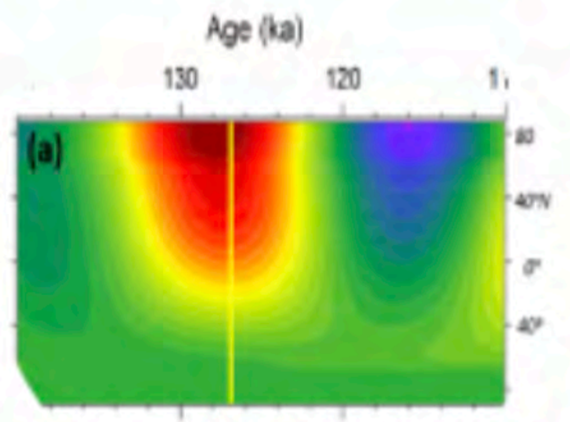
PMIP

Paleoclimate Modelling Intercomparison Project

Current PMIP working groups

Past2K

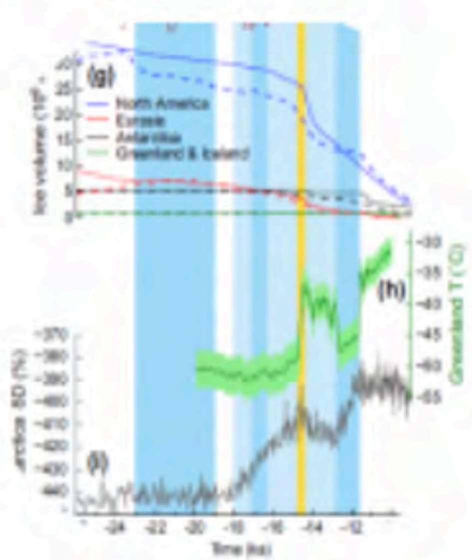
Quaternary Interglacials



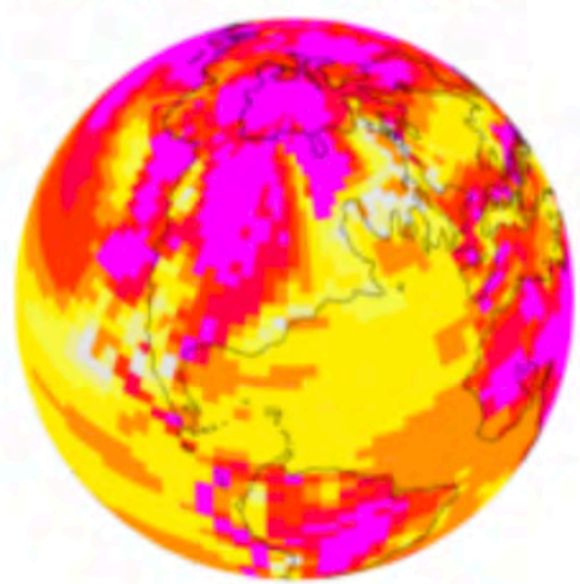
PlioMIP

PlioMIP 2

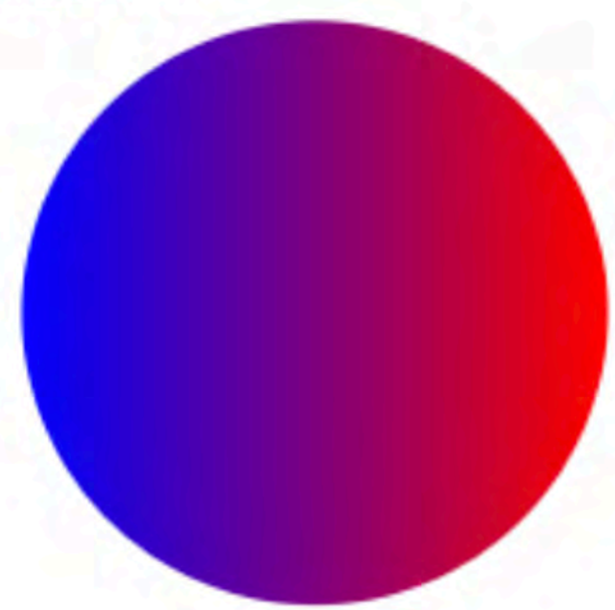
Last Deglaciation



Pre-Pliocene climates

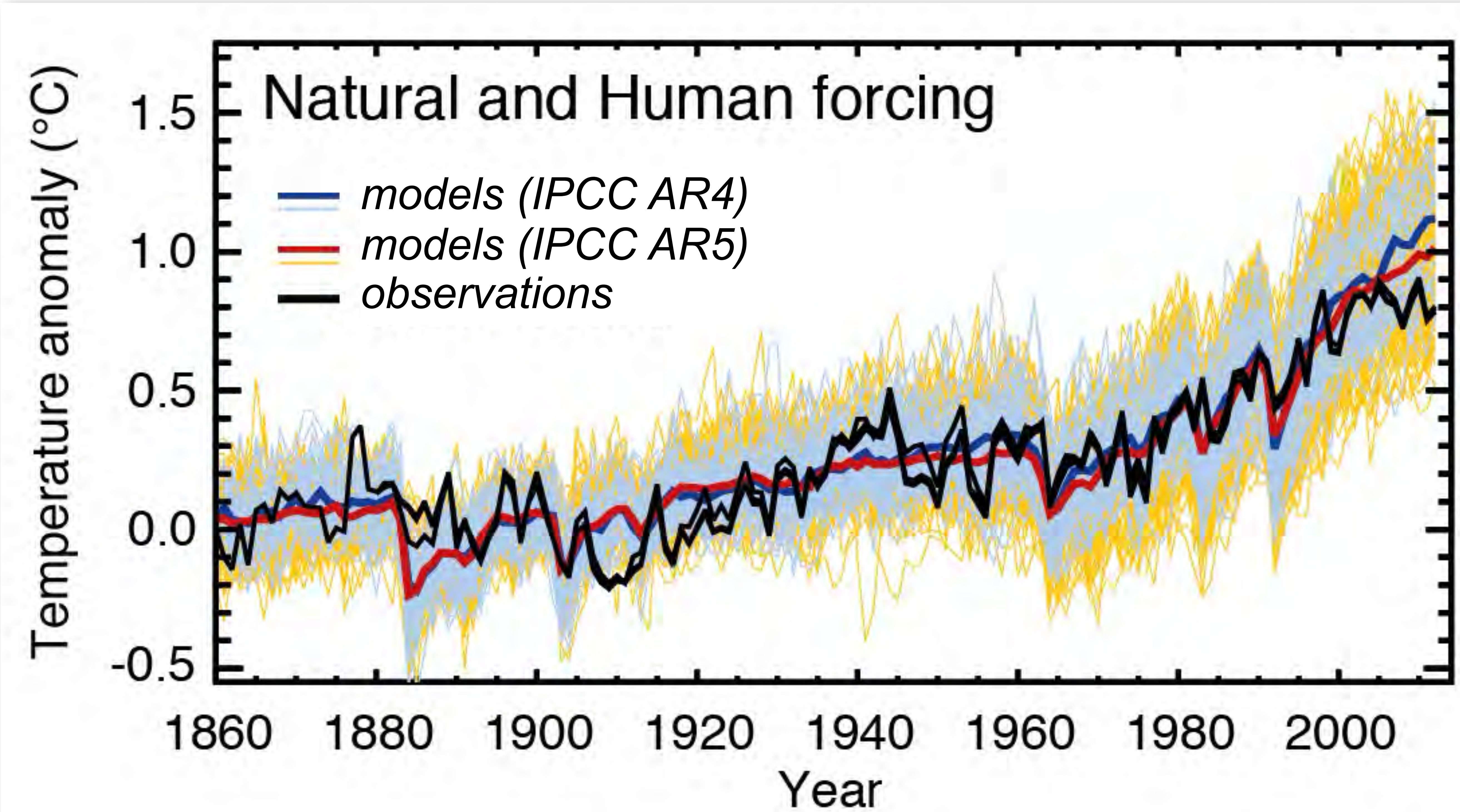


P2FVAR



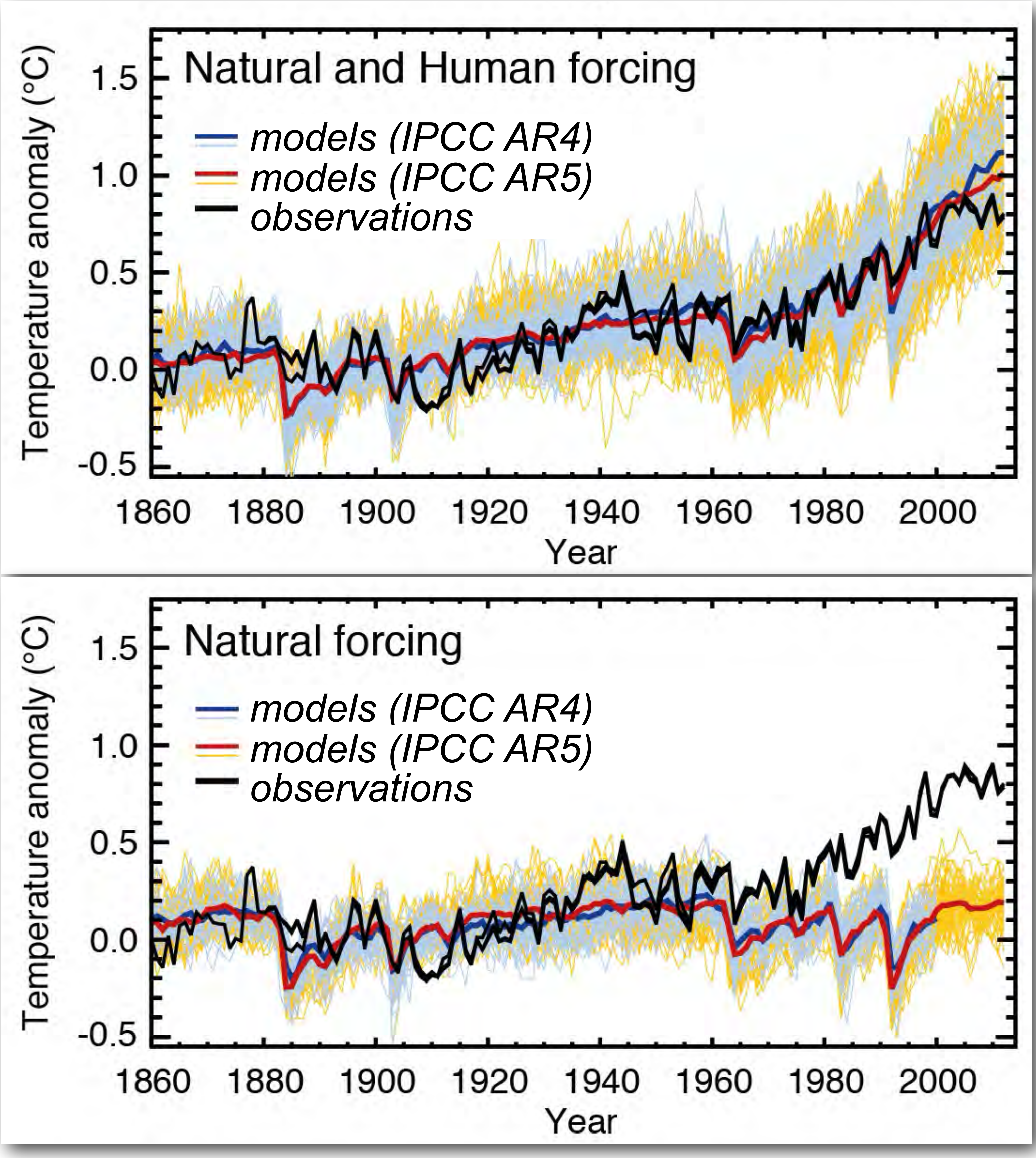
[https://pmip.lsce.ipsl.fr]

Climate models: The present climate

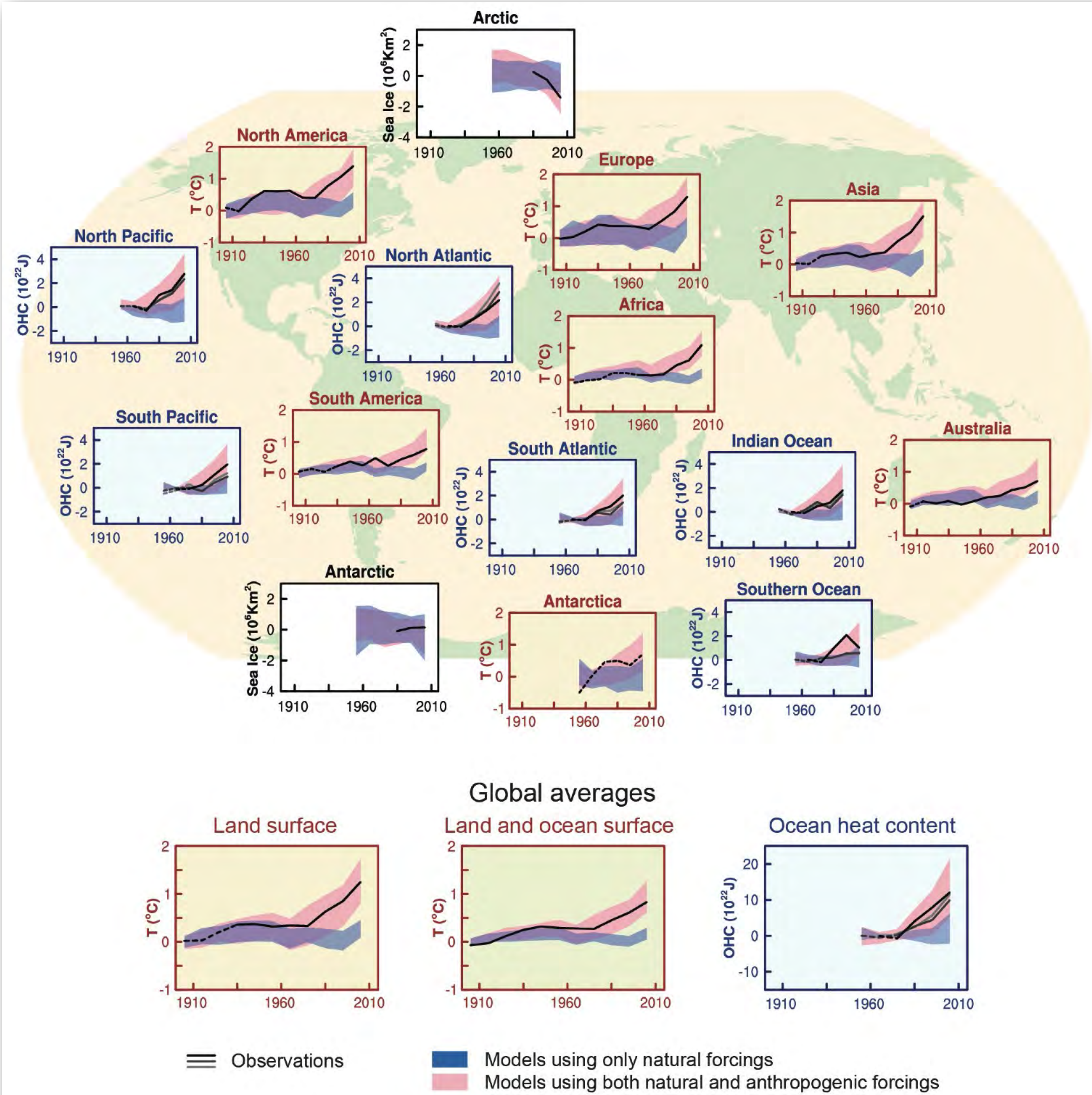


[IPCC, AR5, 2013, Fig. FAQ10.1-1]

Climate models: The present climate

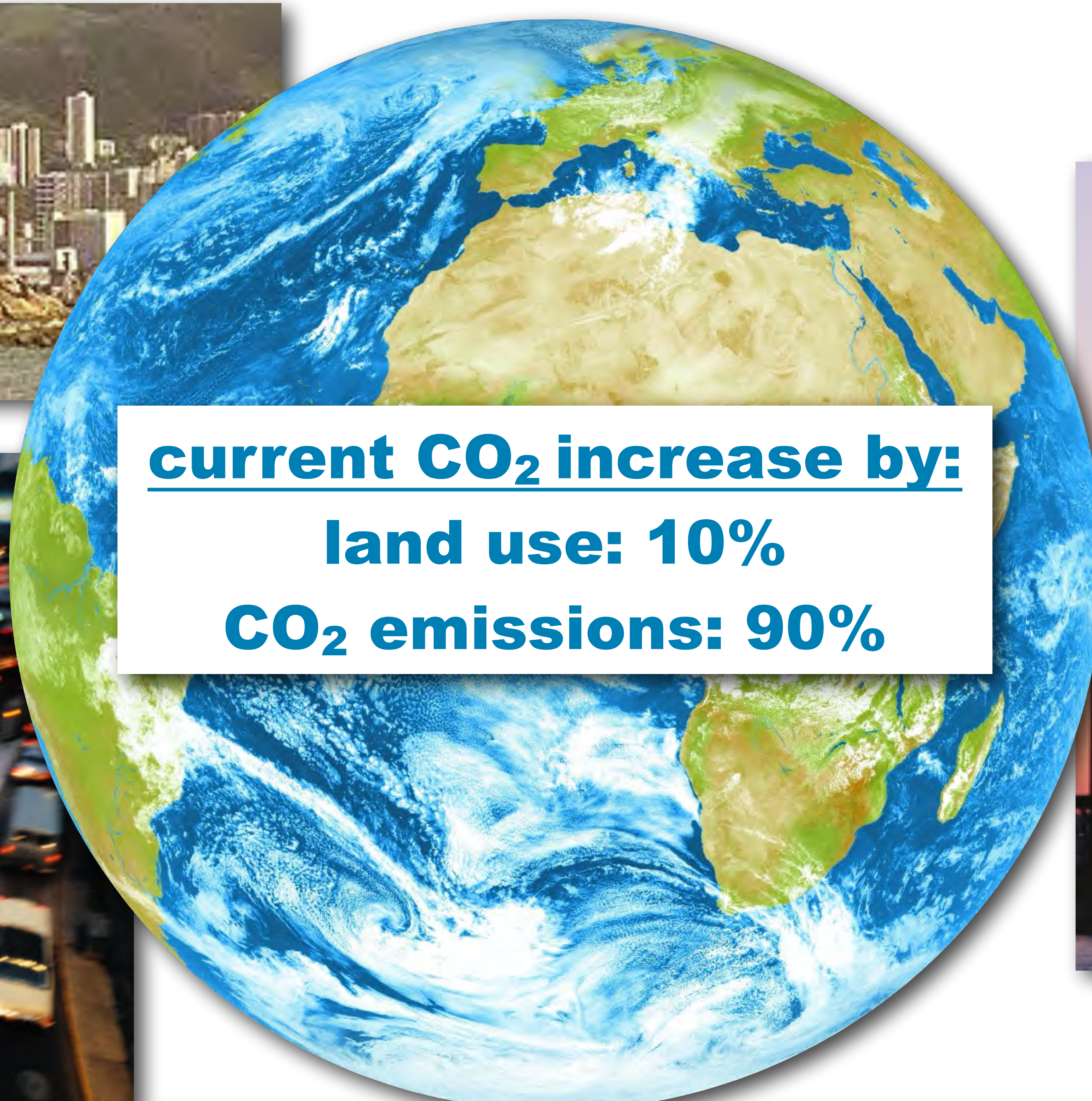


[IPCC, AR5, 2013, Fig. FAQ10.1-1]



[IPCC, AR5, 2013, Fig. SPM-06]

Climate models: Future scenarios



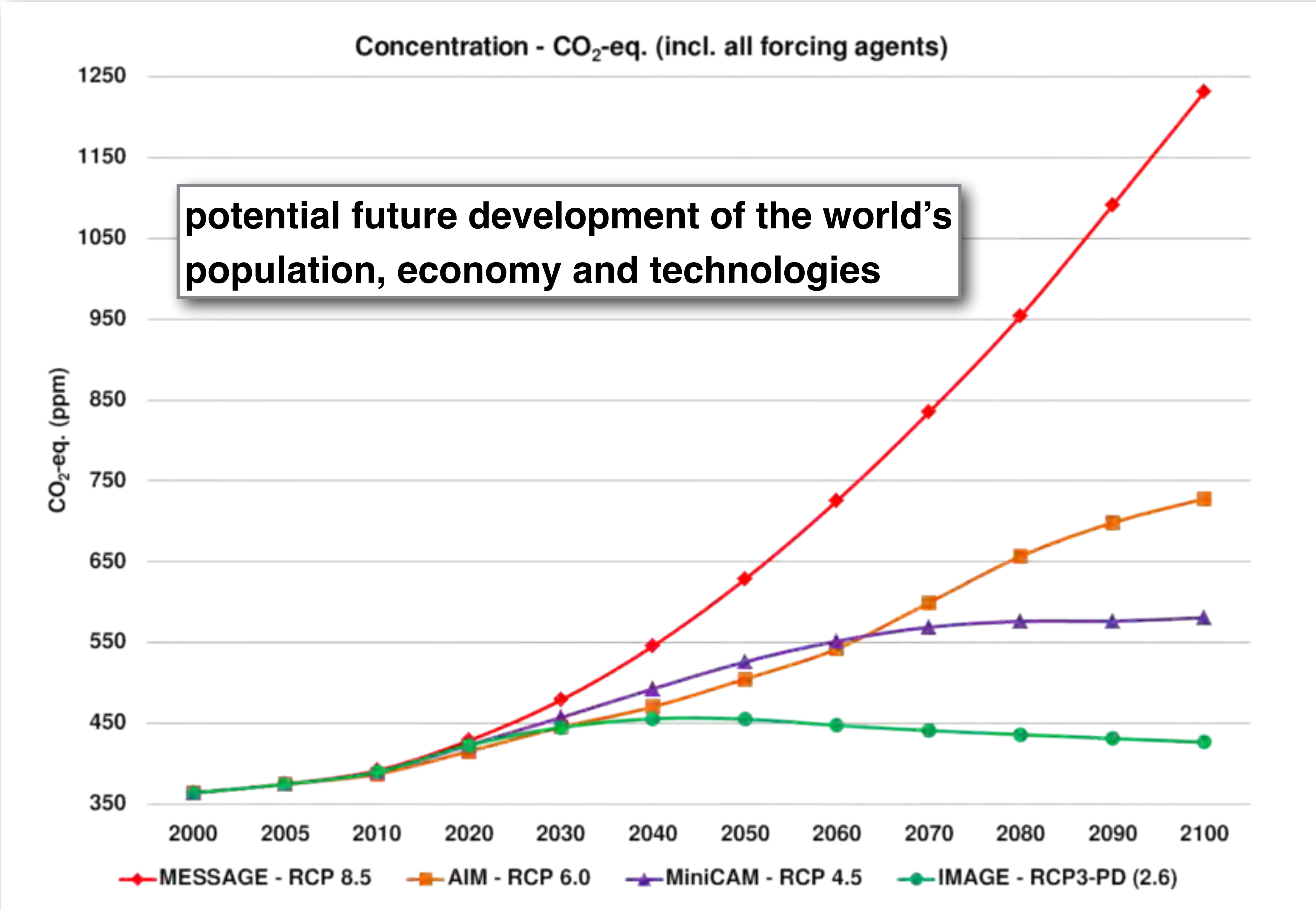
current CO_2 increase by:

land use: 10%

CO_2 emissions: 90%

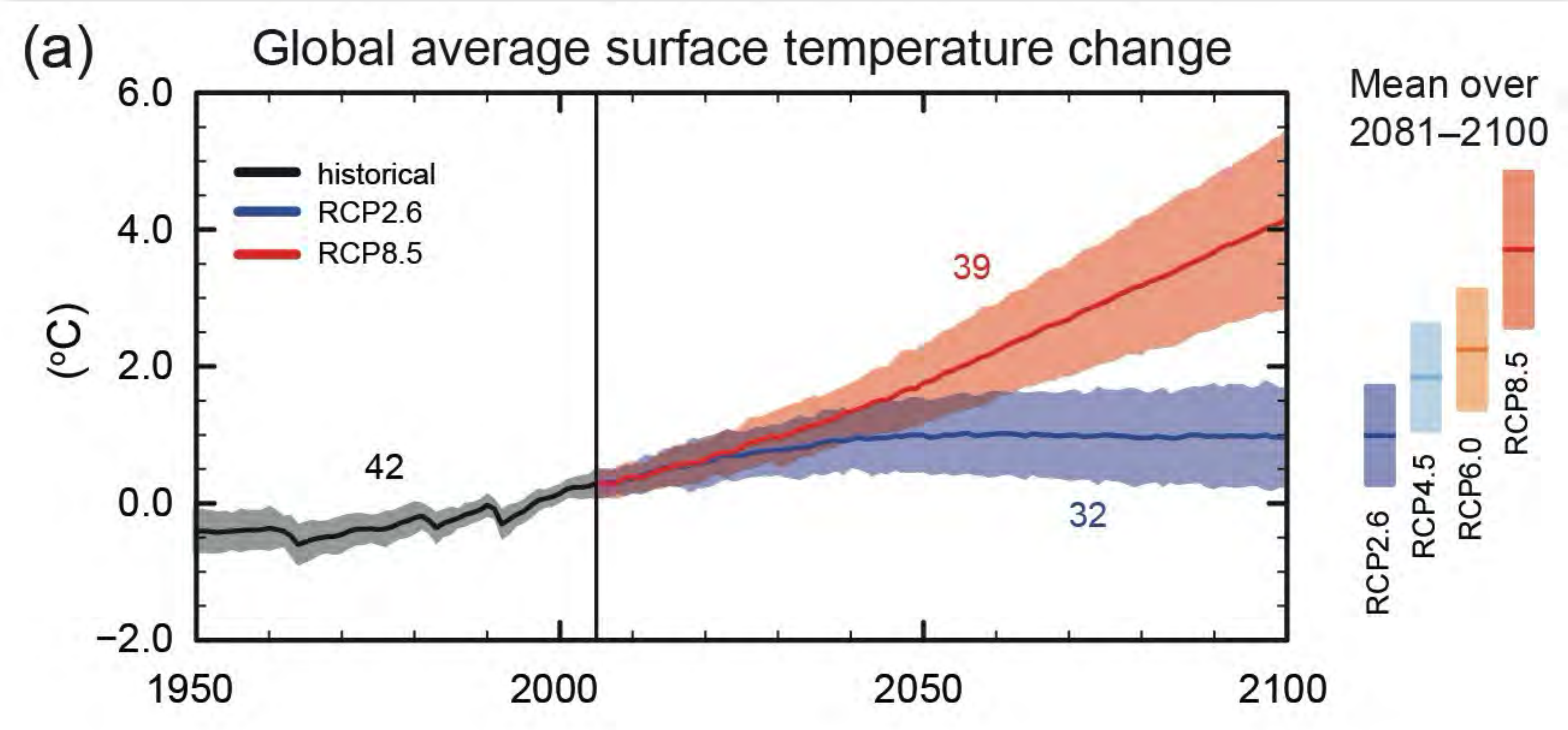
Future emissions of greenhouse gases

IPCC AR5: Representative Concentration Pathways (RCPs)



[http://en.wikipedia.org/wiki/Representative_Concentration_Pathways]

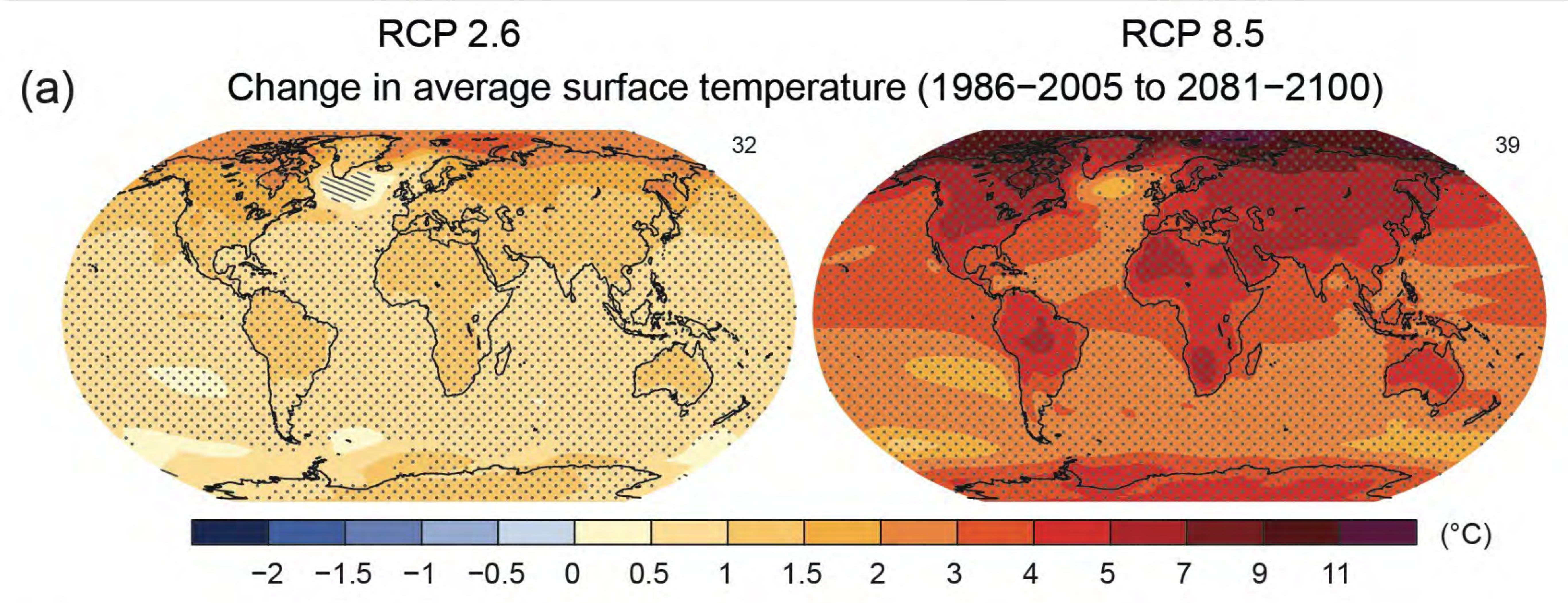
Climate models: Future global warming



[IPCC, AR5, 2013, Fig. SPM-07]

Climate models: Future global warming

Climate simulations reveal strongest warming in the polar regions (main reason: temperature - ice albedo feedback)



[IPCC, AR5, 2013, Fig. SPM-08]

Climate II
(Winter 2020/2021)

8th lecture:

Climate models

(Structure of climate models, components, climate scenarios: from past to the future)

End of lecture.

Slides available at:

https://paleodyn.uni-bremen.de/study/climate2020_21.html