From atmospheric to Earth System Models :

a suite of numerical tools to understand, analyse and anticipate climate changes

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From atmospheric to Earth System Models :

a suite of numerical tools to understand, analyse and anticipate climate changes

a suite of physical and biogeochemical processes that need to be considered

Outlook

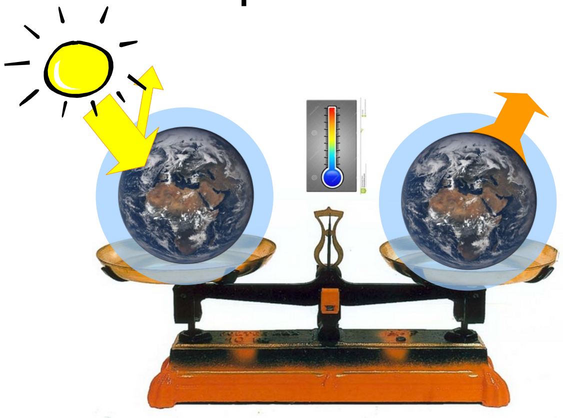
1) The energy balance models
2) Atmospheric single column models
3) Atmosphere-Ocean global circulation models
4) Earth system models
5) km scale models
6) Conclusion & Perspectives

Emergence of climate physics

J. Fourrier, 1824: *Mémoire sur les températures du globe terrestre et des espaces planétaires* (https://www.academie-sciences.fr/pdf/dossiers/Fourier/Fourier_pdf/Mem1827_p569_604.pdf)

Joseph Fourrier
(1768-1830)

- The **energy balance equation** drives the temperature of all the planets
- **The major heat transfers are**
  1. Solar radiation
  2. Infra-red radiation
  3. Diffusion with the interior of Earth



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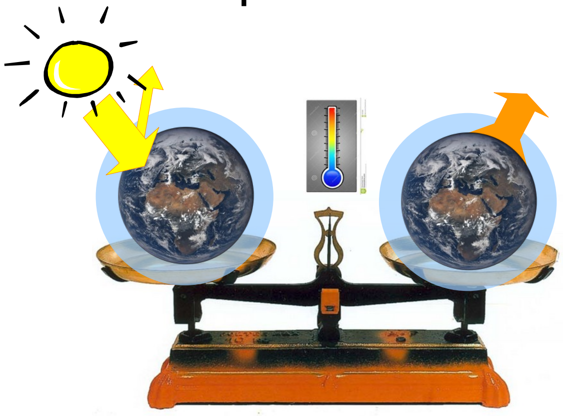

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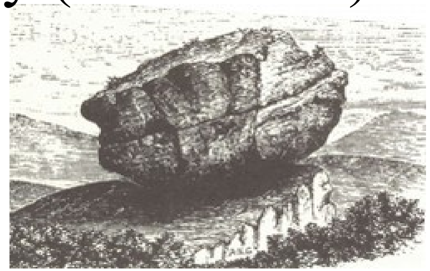
- The **heat diffusion** with the interior of Earth is **negligible,** that discards the thermal death of Earth predicted by Buffon

- Any change of Earth heat budget will leads to a temperature change

Paleo climate changes

The discovery (1840-1860)



J. de Charpentier

Erratic boulders

L. Agassiz

Cause of these global temperature variations: sun or CO_2 ?

(1860-1900)

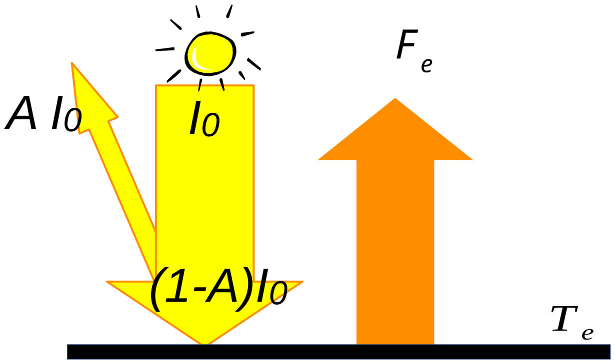
James Croll

Svante Arrhenius

Emission temperature

I_0: incoming solar radiation

A: planetary solar reflectivity (albedo)



Steady state: $(1-A)\ I_0 = F_e$

Stefan-Boltzmann: $F_e = \sigma T_e^4$

Emission temperature: $\boxed{\sigma T_e^4 = (1-A) I_0}$

On Earth : T_e= 255K (-18°C)

Emission temperature

I_0: incoming solar radiation

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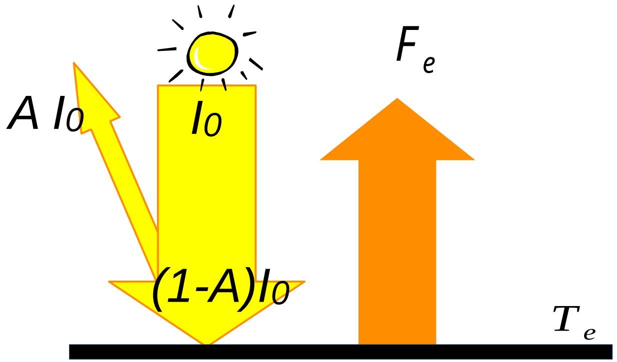

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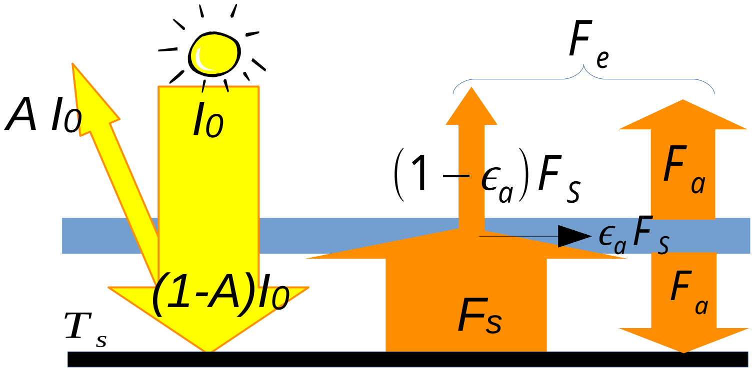
Single layer model

ε_a: planetary emissivity/absorptivity

Isothermal homogeneous atmosphere



Surface temperature: $\boxed{\sigma T_s^4 = \dfrac{(1-A) I_0}{1-\epsilon_a/2}}$

Earth observed surface temperature :

$T_s \approx$ 288K (15°C)

[Arrhenius 1896]

Single layer model

$\boldsymbol{\varepsilon_a}$: planetary emissivity/absorptivity

Isothermal homogeneous atmosphere

Arrhenius (1896):

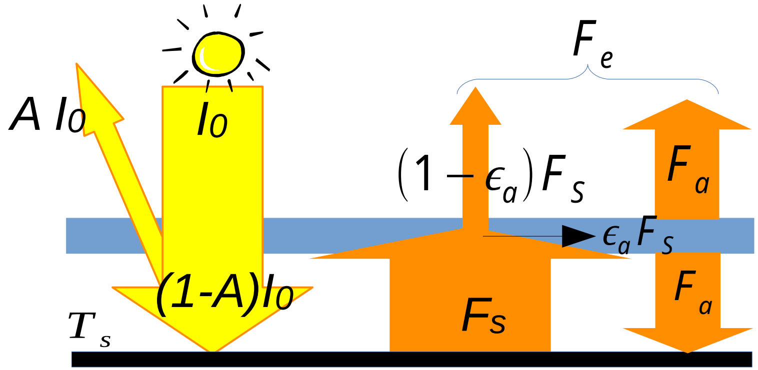
δCO_2 concentration

$$\boxed{\delta T_s = f(\delta I_0, \delta A, \delta \epsilon_a)}$$

A doubling of the CO_2 concentration

=> $\delta Ts \approx 4K$

Energy **B**alance **M**odels are still used, e.g. for climate sensitivity feedback analysis



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1) The energy balance models
2) **Atmospheric single column models**
3) Atmosphere-Ocean global circulation models
4) km scale models
5) Storm-resolving models
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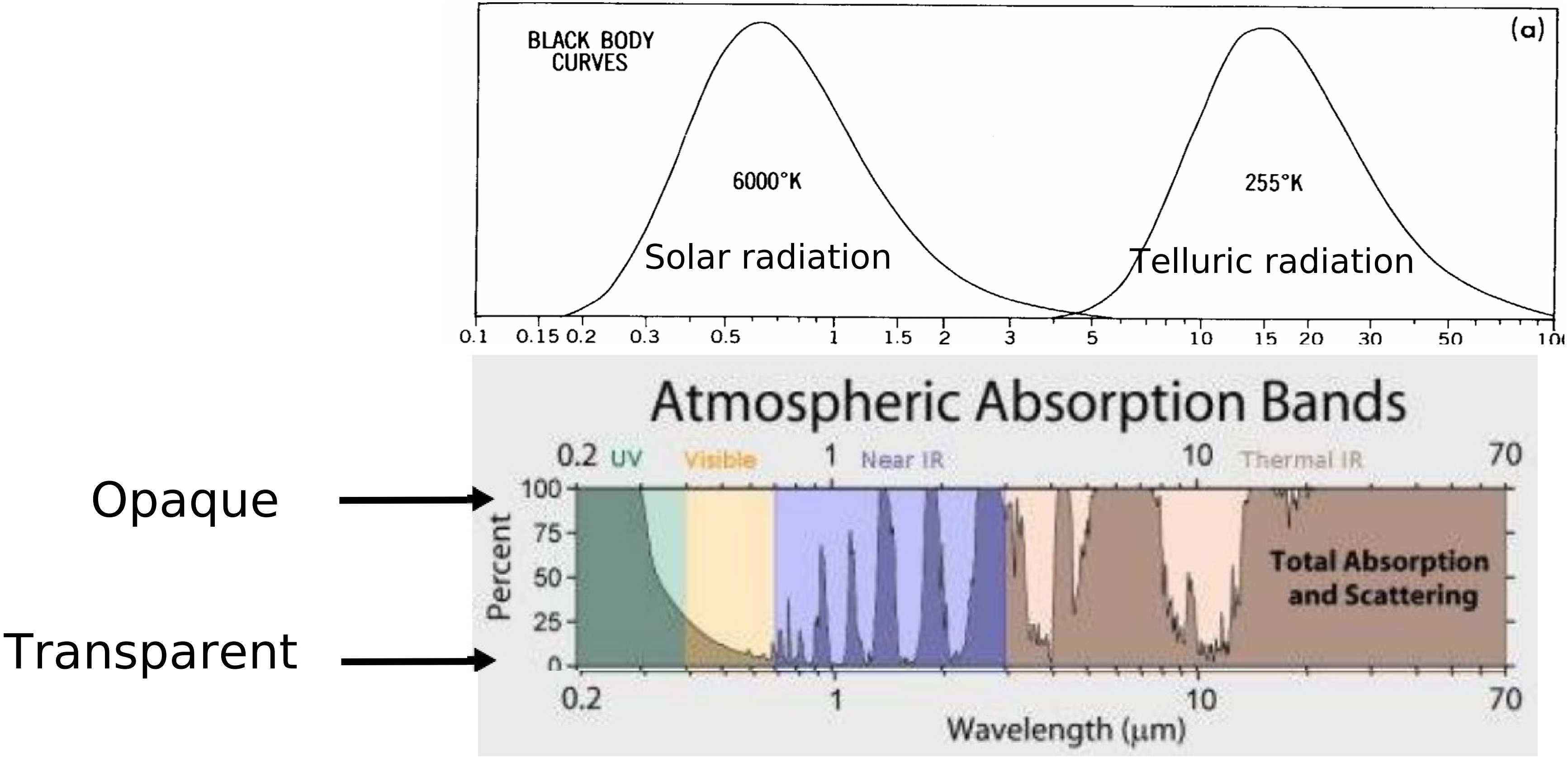
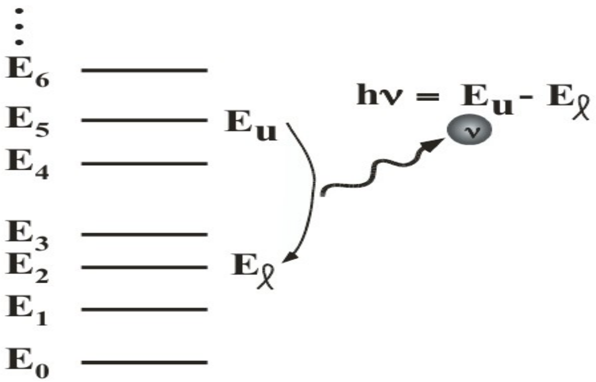
Absorption by the Earth atmosphere



Absorption by gases



- **Line emission and absorption** by transition between states of different energy
- In the infra-red: level of energy correspond to change in vibration and vibration-rotation of molecules
- Complex molecules are better absorbing

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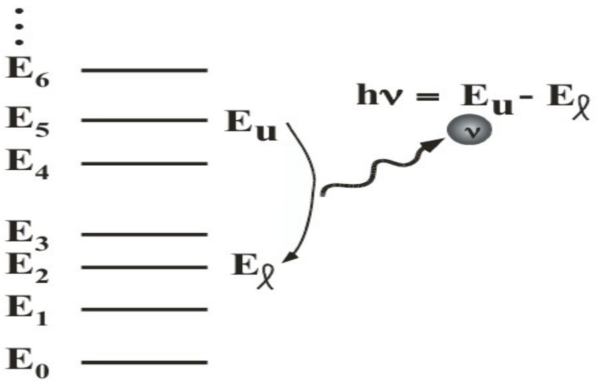

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Line profile:

- Spontaneous emission: negligible (long lifetime)
- Collision between molecules: most important. Lorentz profile
- Doppler effect: negligible except tant in the high atmosphere

The lines widen as the pressure increases. Lines are very thin in the stratosphere and above.

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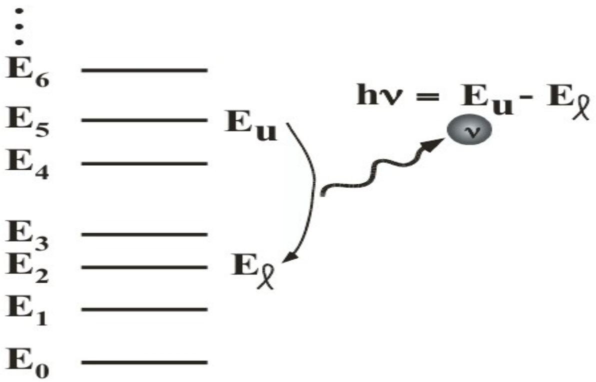

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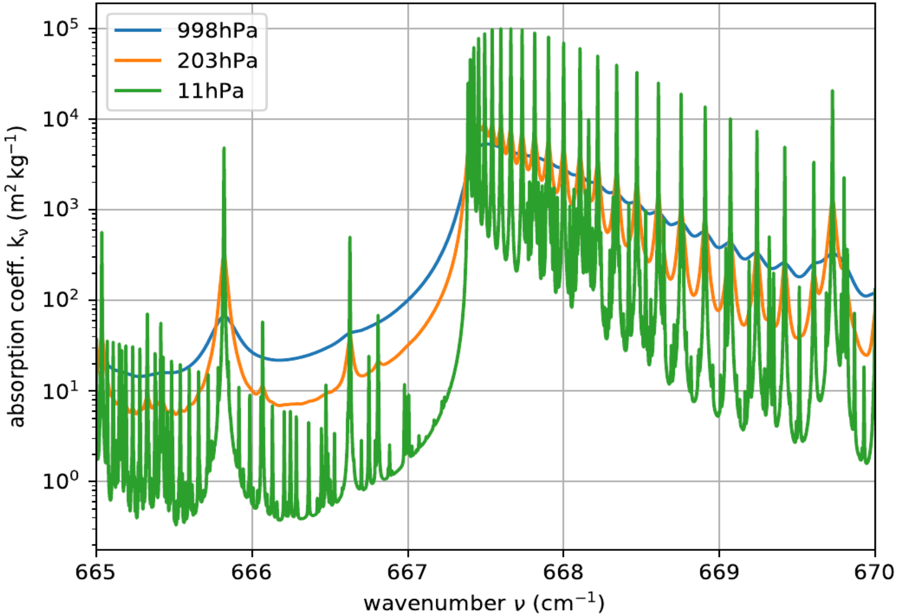
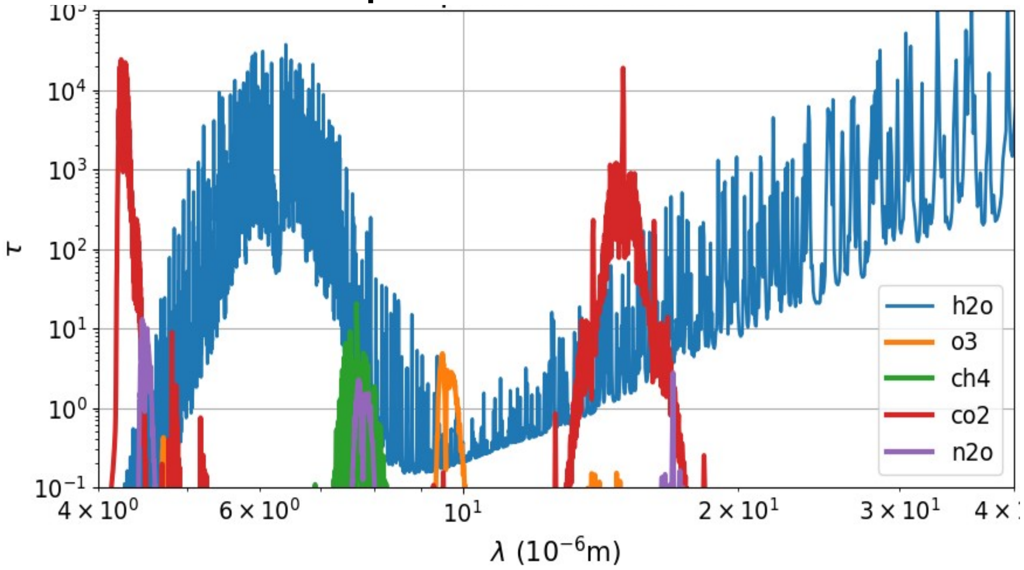
Absorption by CO_2 near 667cm^{-1}

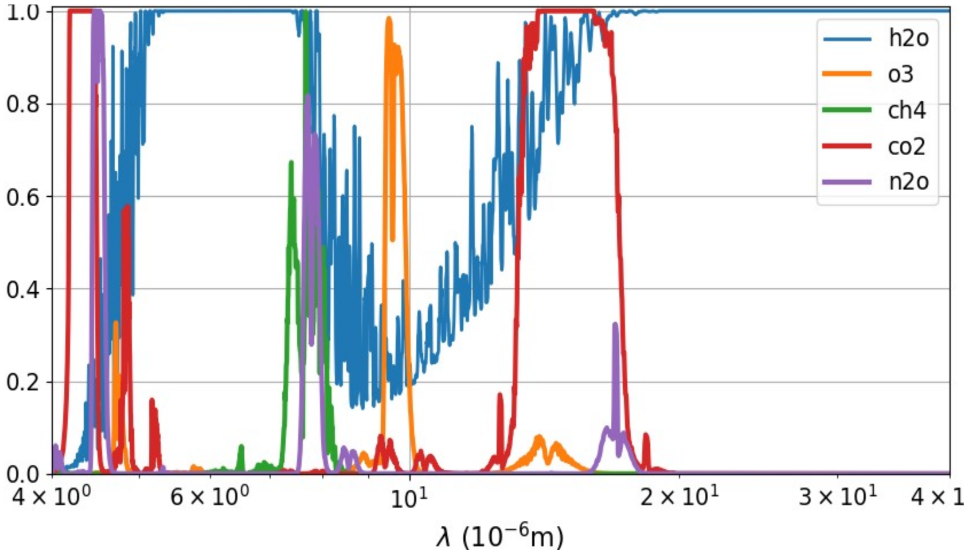


Atmospheric absorption in the infrared

Optical thickness



Absorptivity



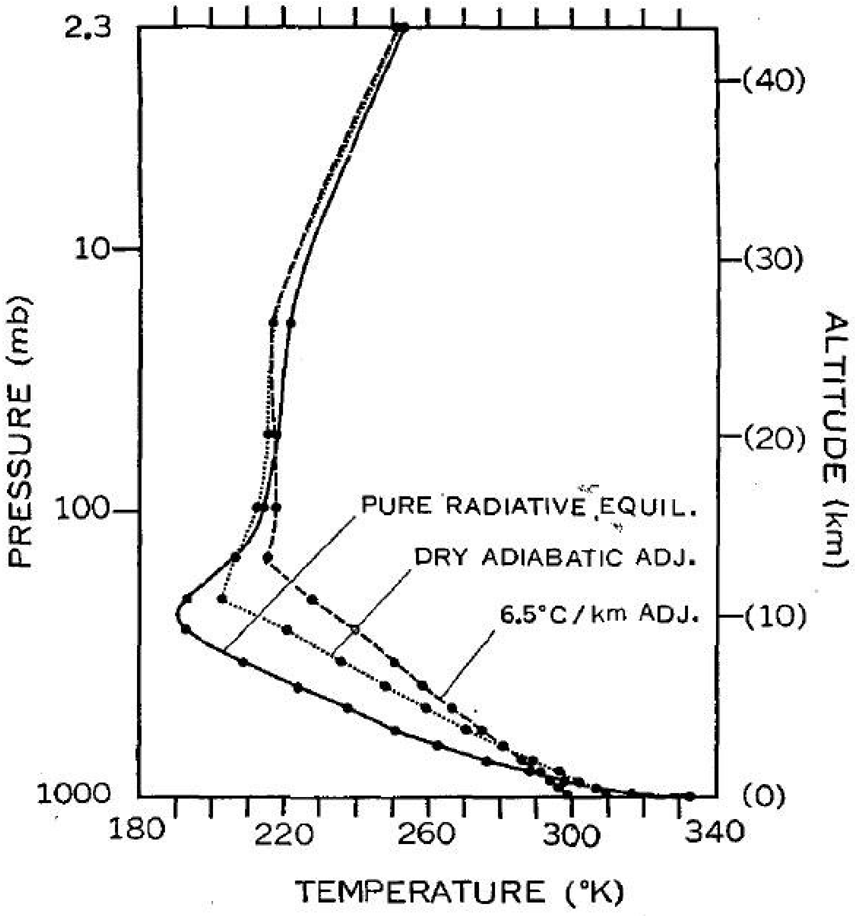
In the 50-60s:

- experimental and theoretical progress in gaz spectroscopy
- direct numerical integration over frequencies are very expensive because of absorption lines (“line by line” models used as reference)
- statistical modelling of absorption lines makes radiative transfer calculations in the atmosphere possible (wide or narrow band statistical models)

Single column model (from the 60's)

Manabe and Strickler, 1964: *Thermal Equilibrium of the Atmosphere with a convective adjustment*

- The atmosphere is cooled by the emission of infrared radiation into space
- This cooling destabilizes the atmosphere and creates convection
- ***Convection*** tends to bring the vertical temperature profile towards the ***critical profile*** (convective adjustment)



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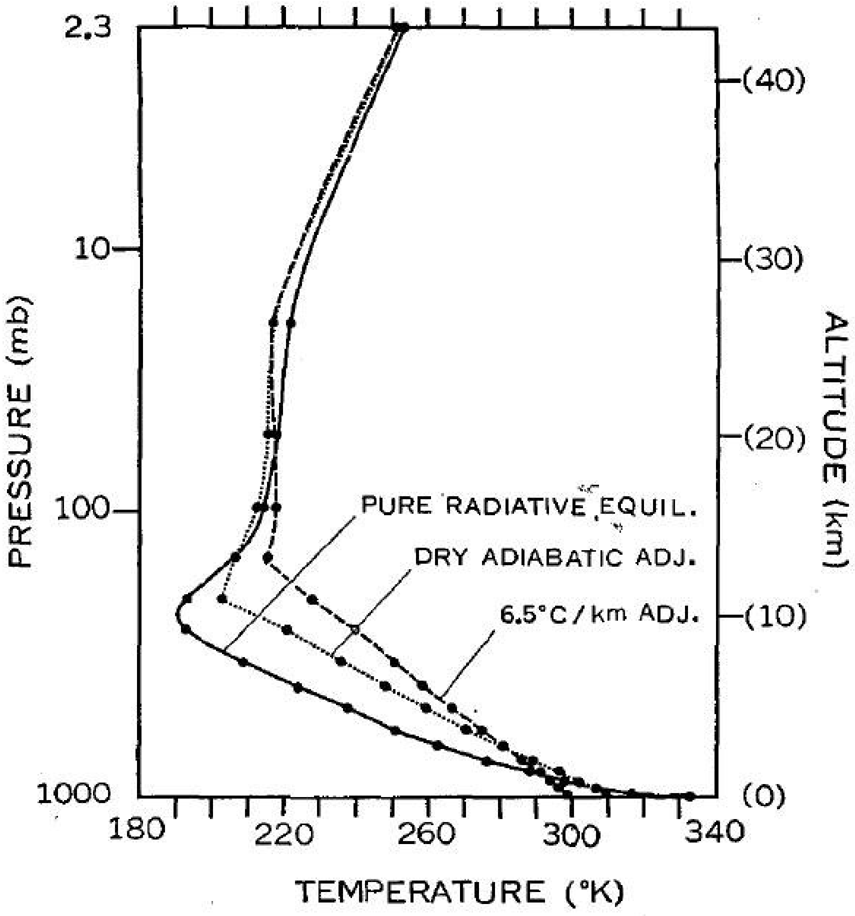
Critical profile: **dry air** parcel moving up or down:

- Energy conservation, Perfect gaz, Hydrostatic equilibrium, No heat exchanges (adiabatic)

$$\Rightarrow \boxed{\frac{dT}{dz} = -\frac{g}{C_p} = \Gamma_a \approx -10\,K/km}$$



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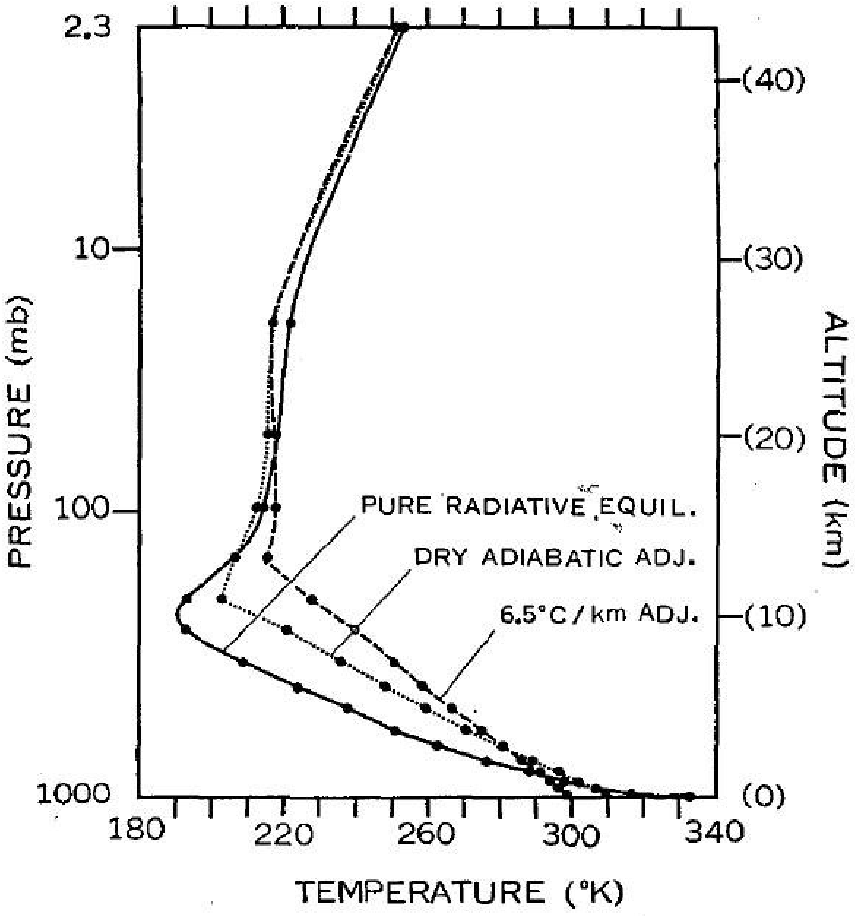
Humid air: including latent heat: $\boxed{\Gamma \approx -7\,K/km}$

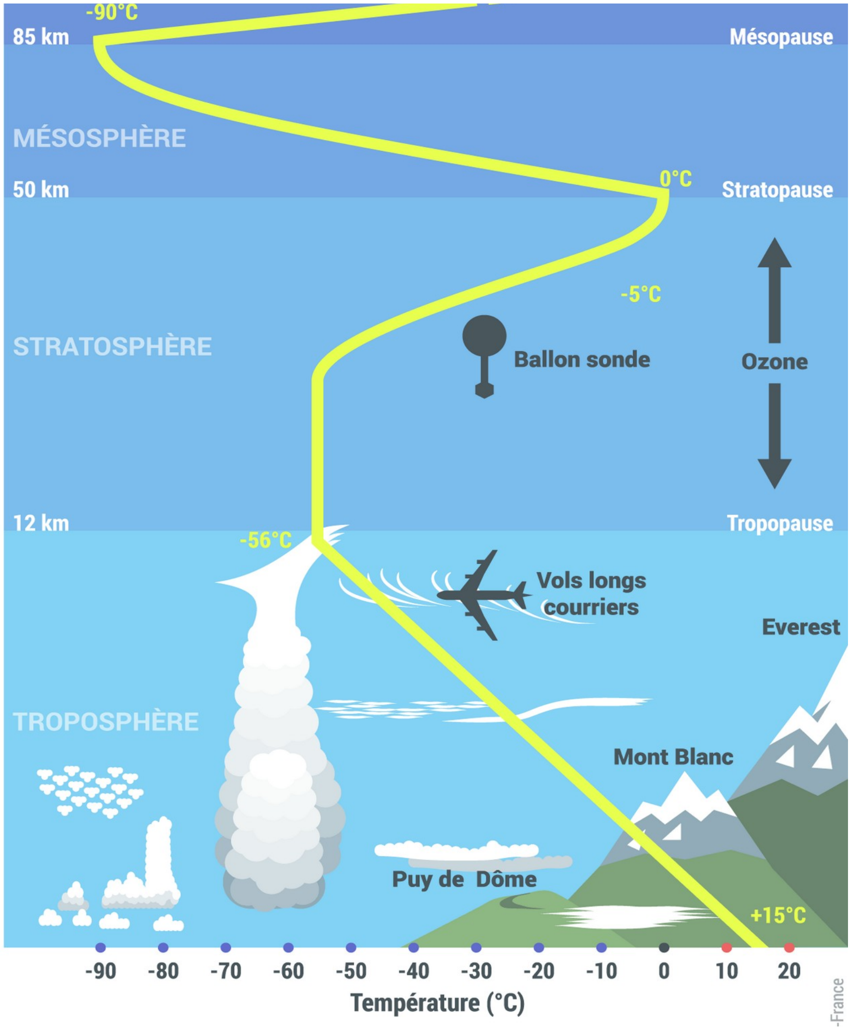


[Manabe and Strickler, 1964]

Vertical profile of the atmosphere

Stratosphere:
- *Radiative equilibrium*
- Temperature driven by radiation

Troposphere:
- *Radiative-convective equilibrium*
- ***Temperature profile driven by the thermodynamic***



Fraction of the total mass of air below this altitude

99.9%

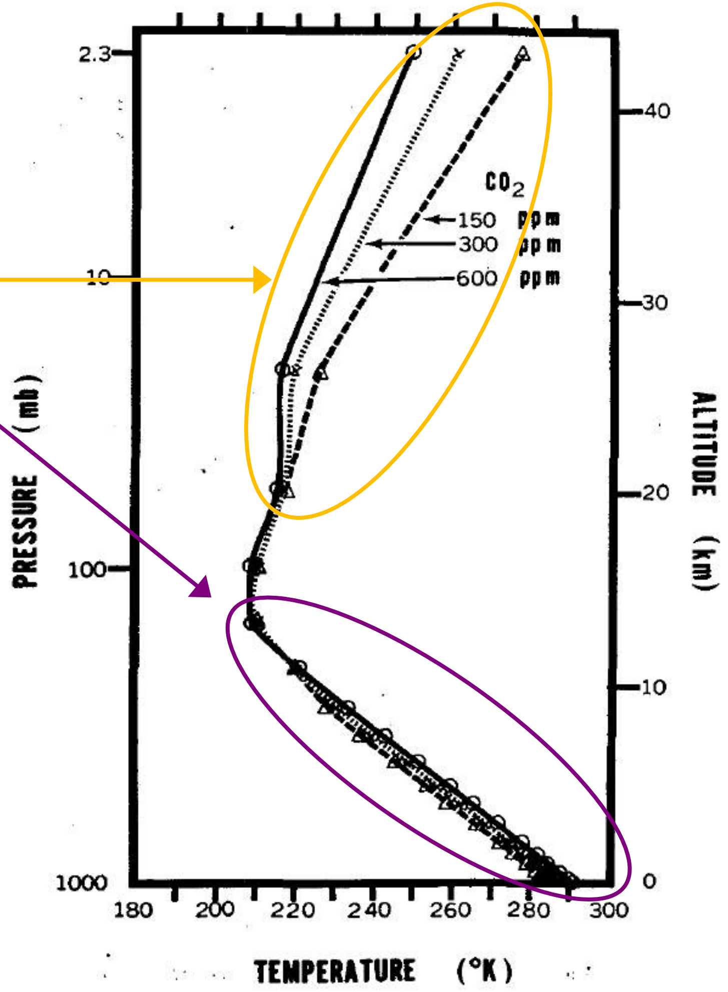
80-90%

Single column model (from the 60's)

Manabe and Wetherald, 1967: *Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity*

Sensitivity experiment: **doubling of CO_2 concentration:**

- Decrease of the stratospheric temperature
- Increase of the surface and tropospheric temperature



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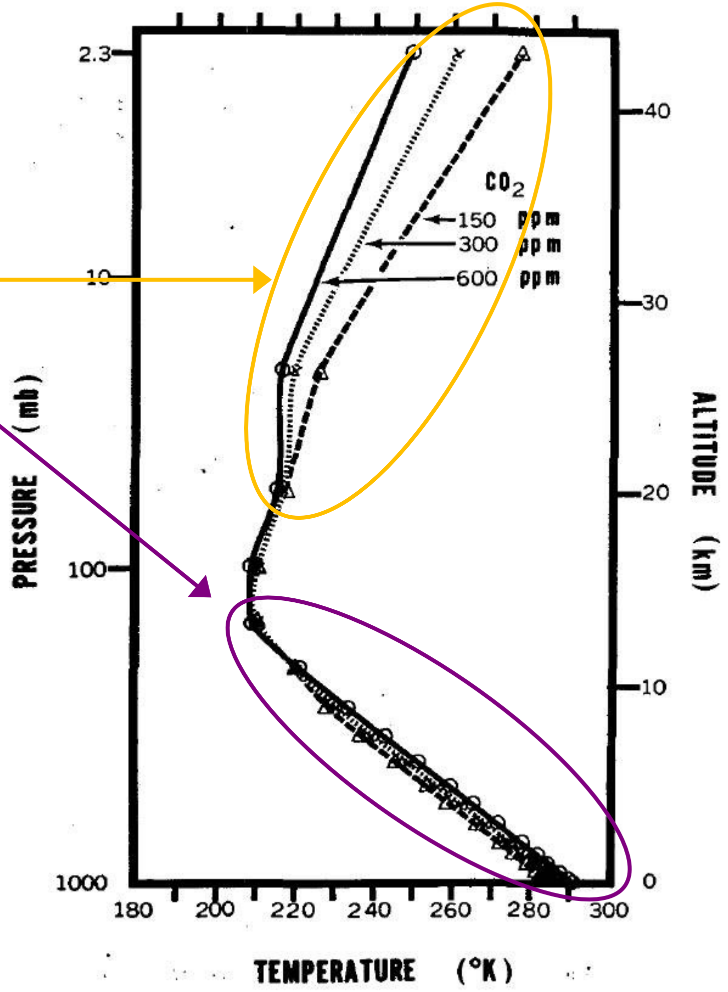
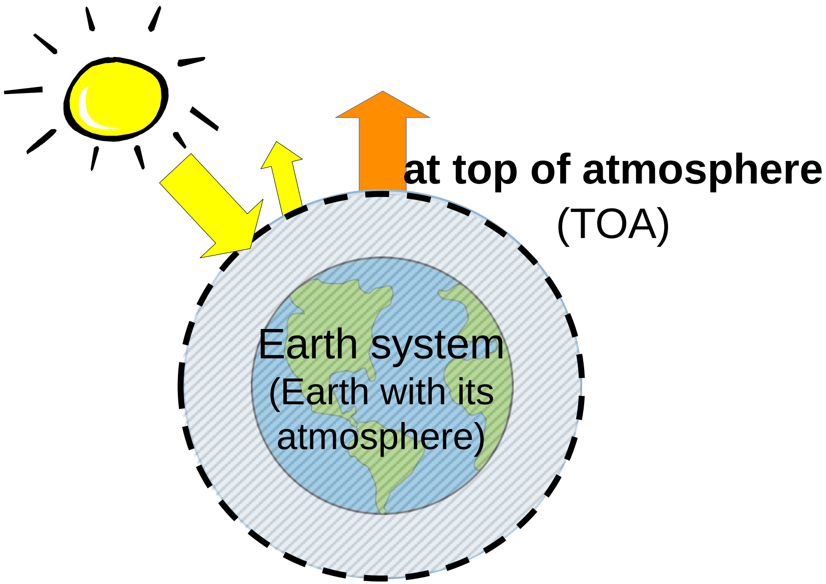
The temperature increase highly depends on water vapour evolution. At the surface:

- with **fixed absolute humidity** **$\Delta Ts = 1.4K$**
- with **fixed relative humidity** **$\Delta Ts = 2.9K$**



Energy budget at the surface or at the top of atmosphere?

Steady state (energy equilibrium): the energy balance is zero at both interfaces.



• The Earth (and other planets) is an open system with the rest of the universe
• Radiation is the only process of energy transfer
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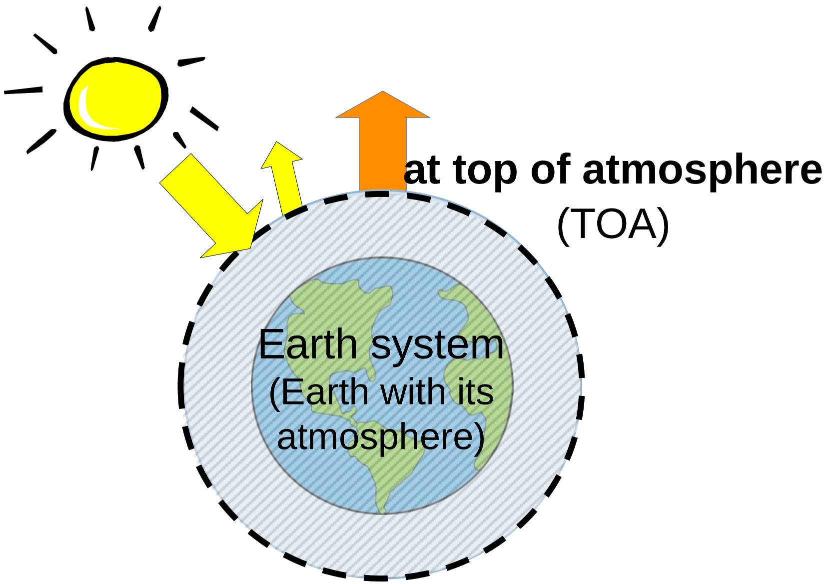

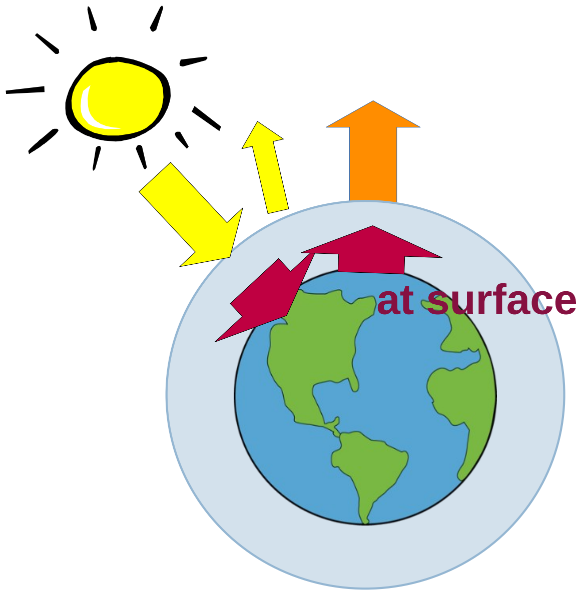

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- Radiation is the only process of energy transfer
- Incoming solar radiation is independent of the radiation emitted by the Earth

- Atmosphere and surface are two open systems
- Strong energy coupling between surface and atmosphere
- Many energy exchange processes

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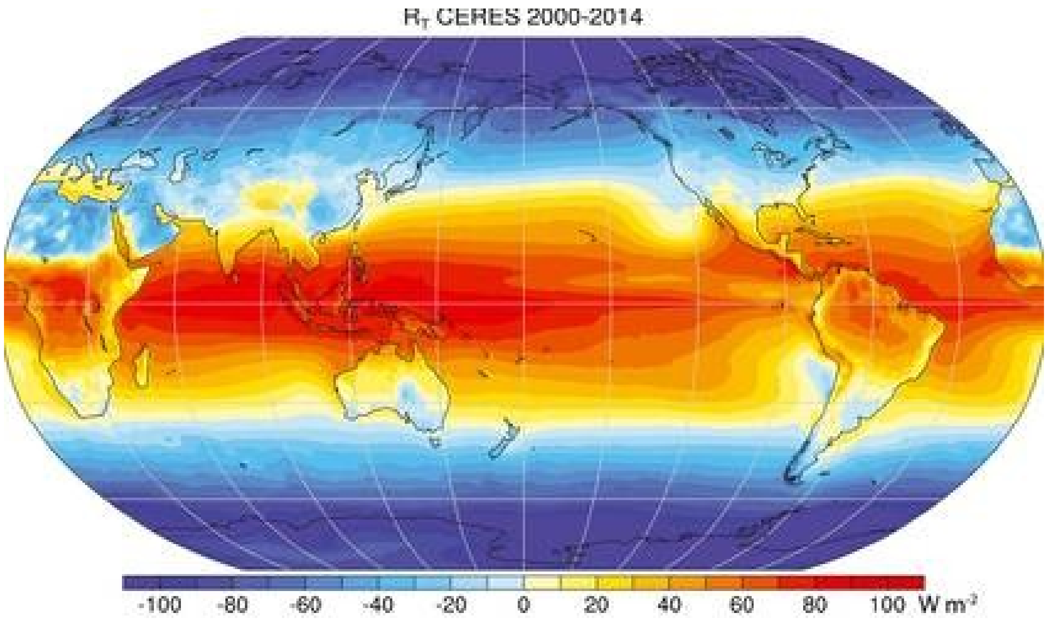
Average annual mean TOA net radiation



[from CERES mission, NASA]

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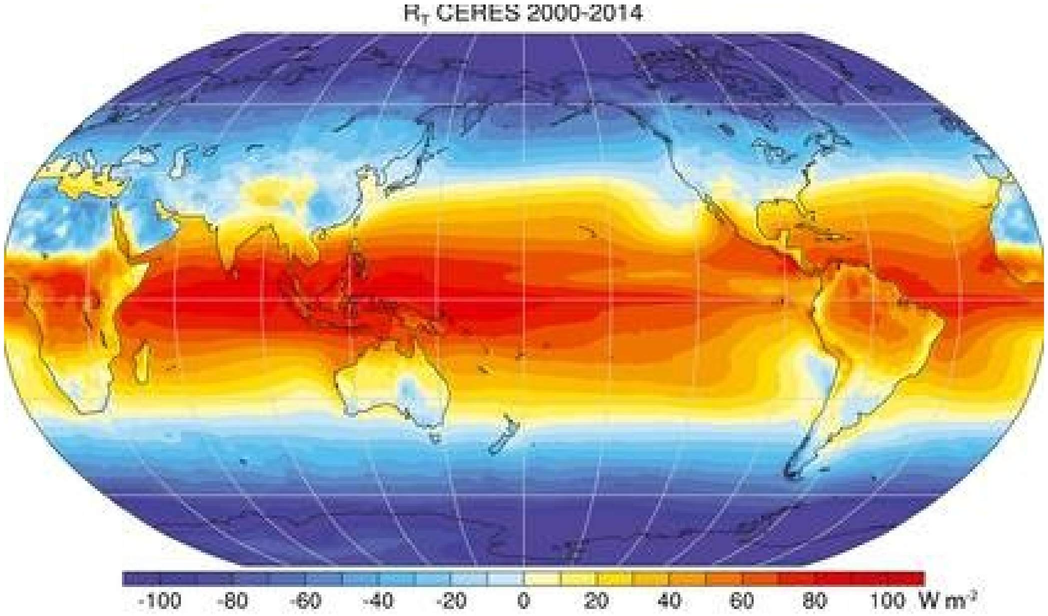
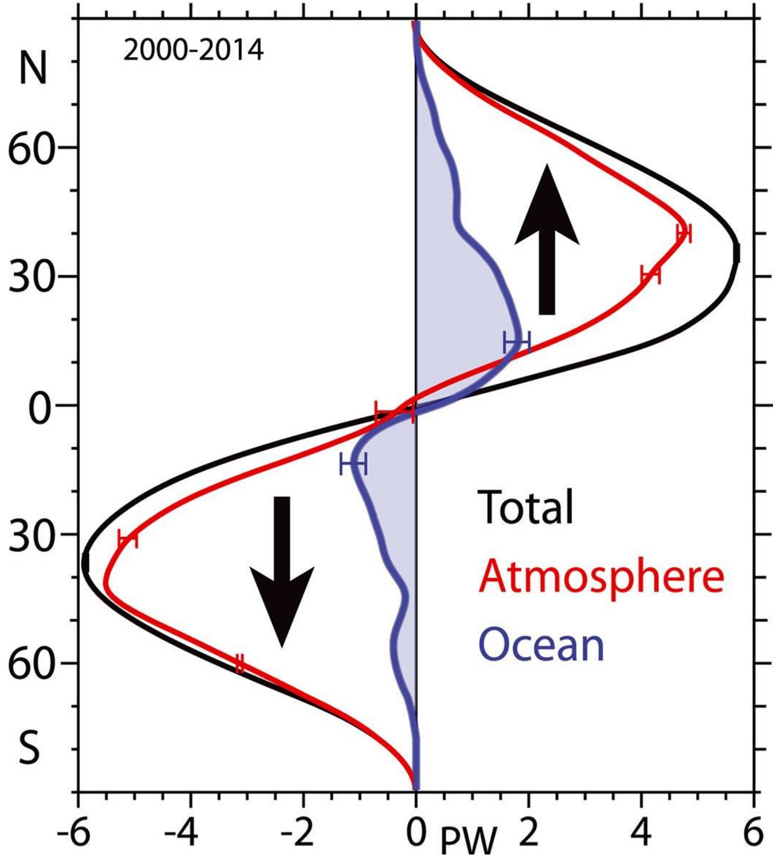


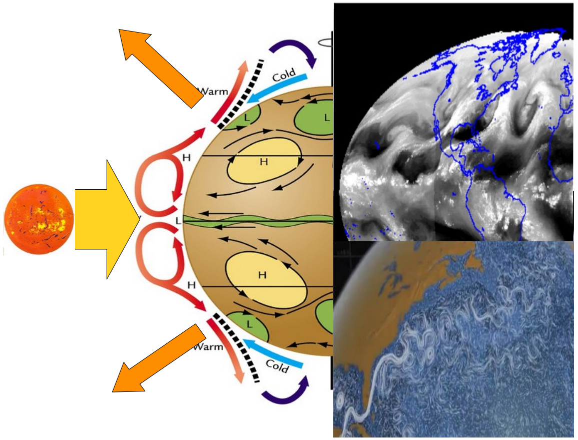
[from CERES mission, NASA]

Annual and zonal means northward energy transports

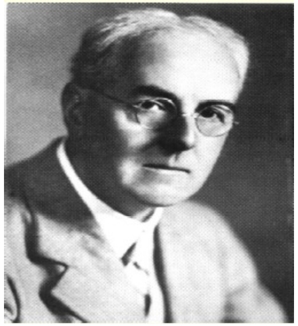


[Trenbert & Fatsulo, 2017]

Numerical climate models (from the 60's)
(numerical weather simulators)

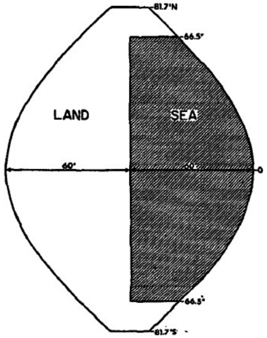


W. Bjerknes
(1862–1951)



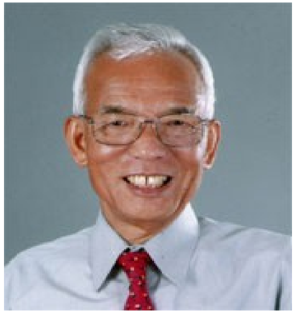
L. F. Richardson
(1881–1953)

J. von Neumann
(1903–1957)

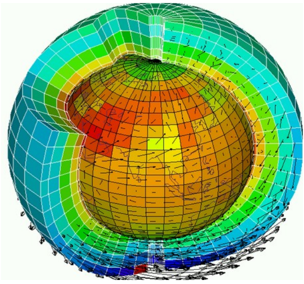


J. Charney
(1917-1981)

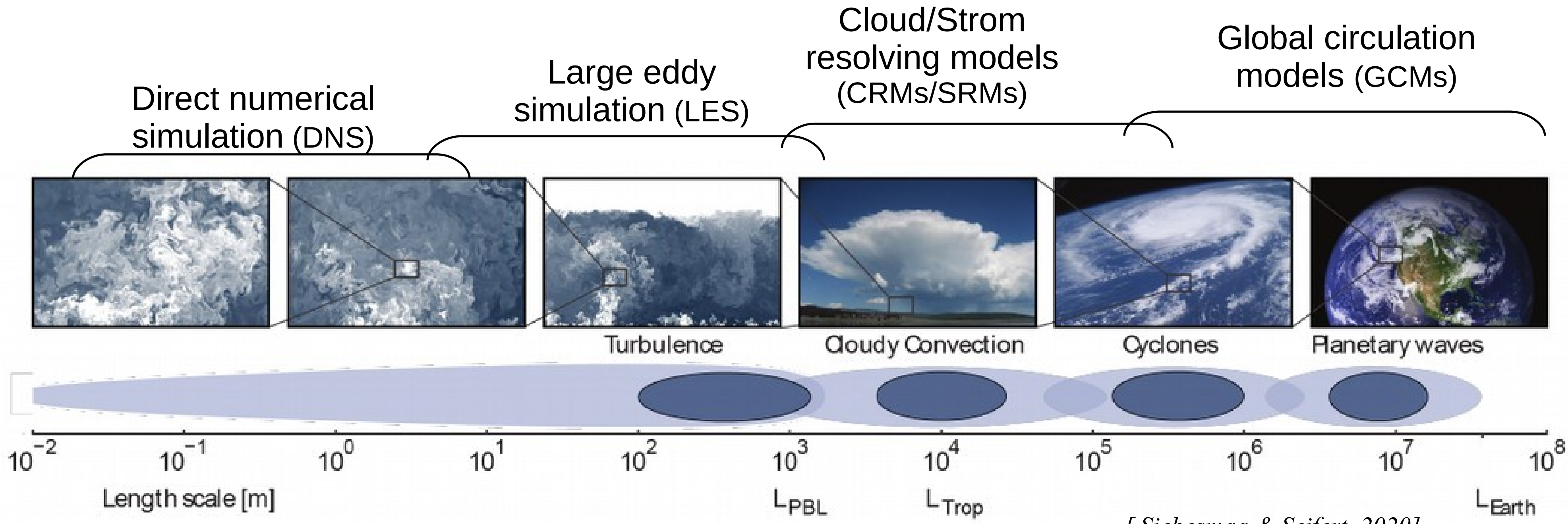
J. Smagorinsky
(1924-2005)



S. Manabe
(1931-)

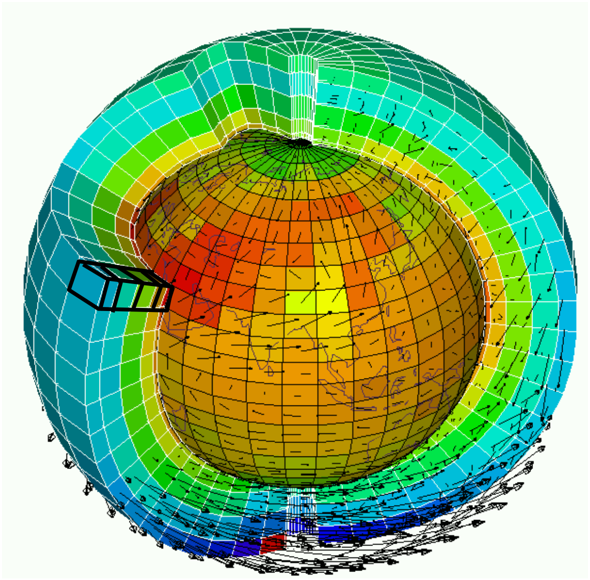


A variety of numerical models to handle the wide range of time and space scales involved



[Siebesmaa & Seifert, 2020]

General circulation models (GCMs)



Dynamical core : discretized version of the equations of fluid mechanics

- Mass Conservation

  $D\rho/Dt + \rho\,\mathrm{div}\underline{U} = 0$
- Energy Conservation

  $D\theta / Dt = Q / Cp\ (p0/p)^{\kappa}$
- Momentum Conservation

  $D\underline{U}/Dt + (1/\rho)\,\underline{\mathrm{grad}}p - \underline{g} + 2\,\underline{\Omega}\ {}^{\wedge}\underline{U} = \underline{F}$
- Conservation of Water (and other species)

  $Dq/Dt = Sq$

In red, source terms : other than fluid mechanics and unresolved scales

General Circulation Models

→ Developed in the 60s for the purpose of weather forecast

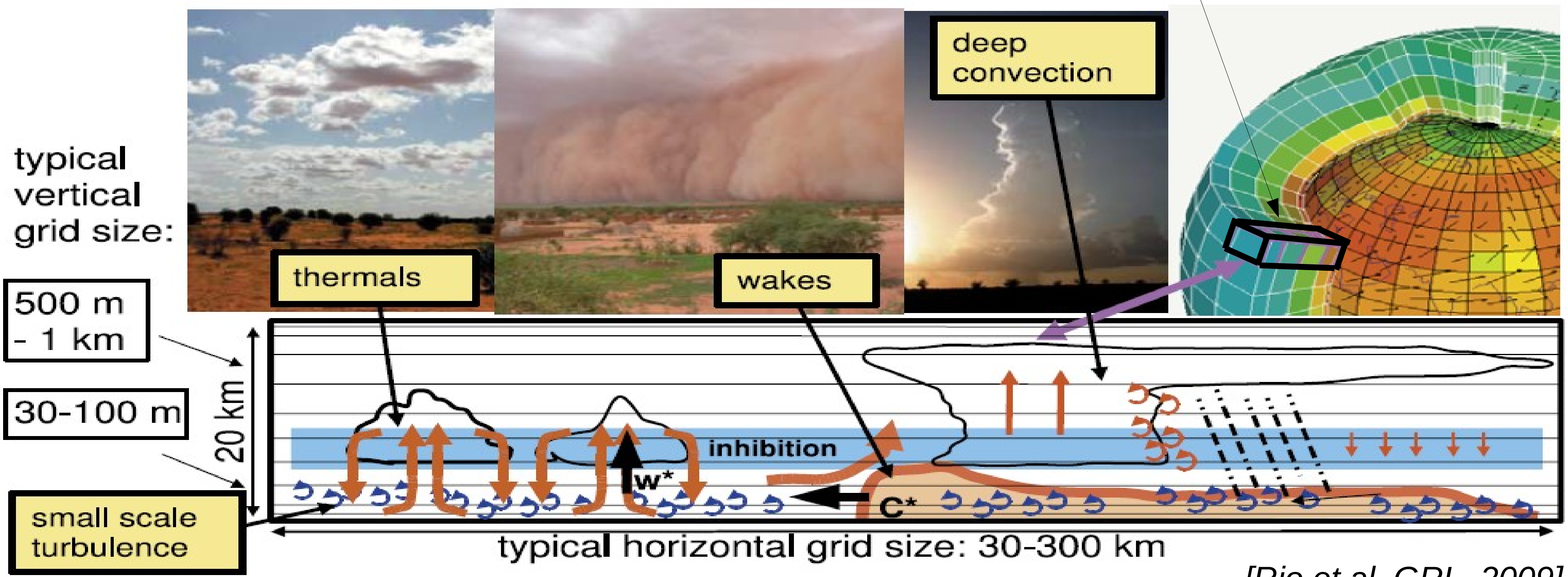
→ Based on a discretized version of the « primitive equations of meteorology »

→ On the Earth but also very rapidly on other planets

→ A number of important process are subgrid scale and must be parameterized

Modeling of unresolved scales with sub-models (parameterization)

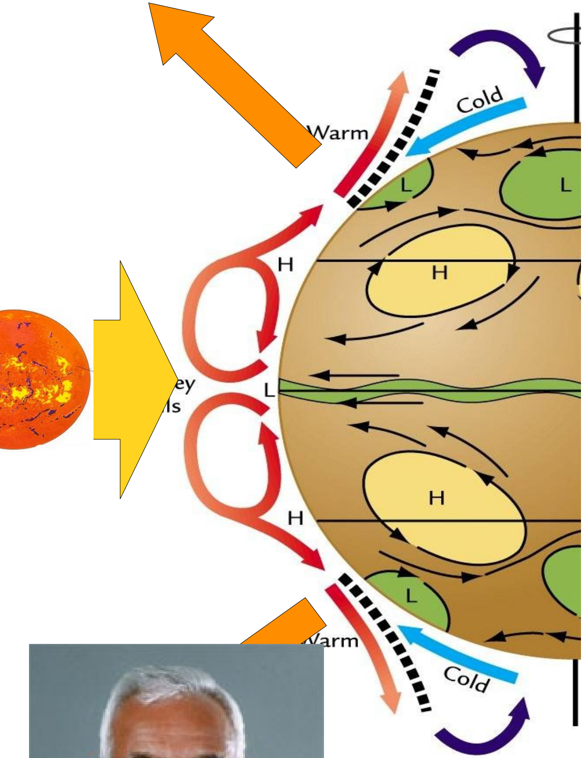
A typical vertical atmospheric column

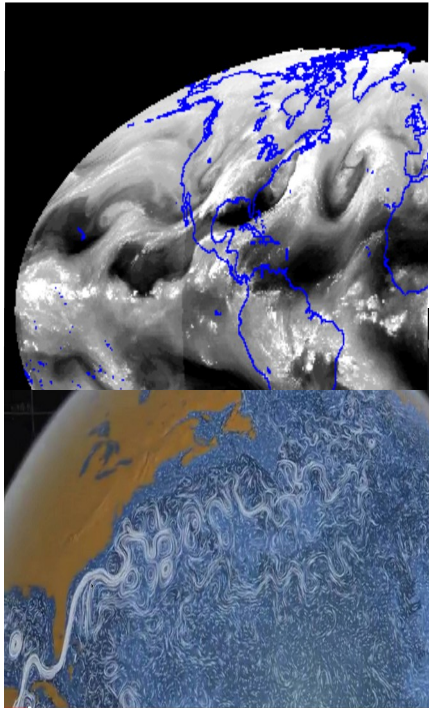


[Rio et al, GRL, 2009]

Typical time step : a few minutes to half an hour

Climate: from radiation, rotation, circulation

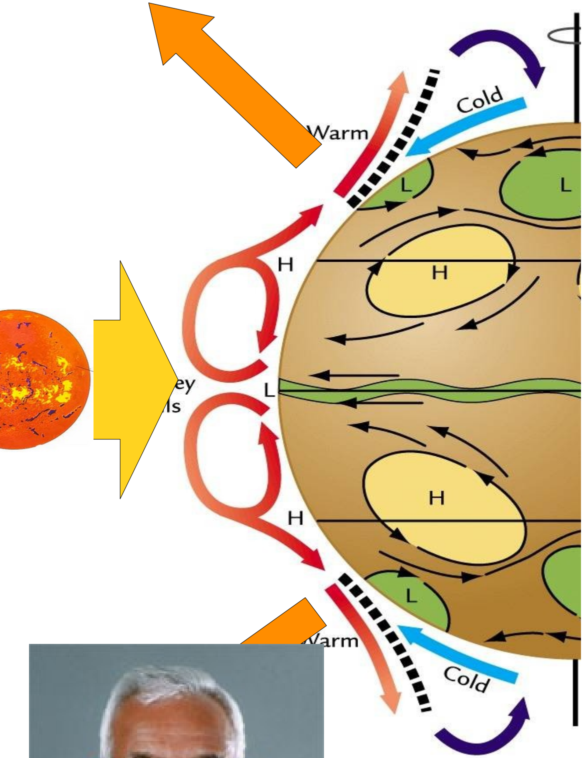


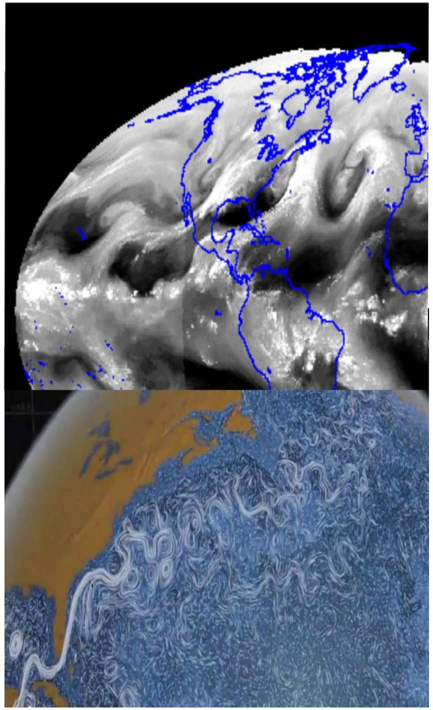


Syukuro Manabe (1931-)

Nobel prize in Physics 2021

Climate: from radiation, rotation, circulation to dynamical systems





- Atmospheric circulation, water vapor, clouds, snow, surface ocean, sea ice, etc.
- Same + ocean circulation, CO_2 continental biosphere, CH_4, etc.
- Ice sheets, continental CO_2
- Geological" CO_2 (continental erosion, volcanism)

Time constant (years)

10

100

1000

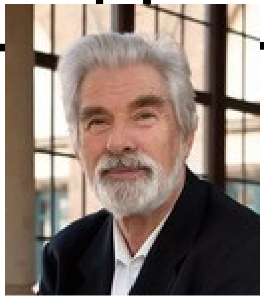
$>10^6$

Syukuro Manabe (1931-)

Nobel prize in Physics 2021

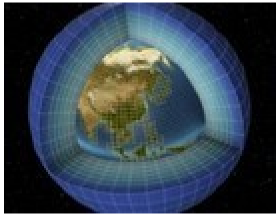
Klaus Hasselmann (1931-)

Nobel prize in Physics 2021



Use of Climate models

e.g. the IPSL



Climate model

3D representation of the atmosphere, ocean, sea-ice, land-surface (coupling of different models)

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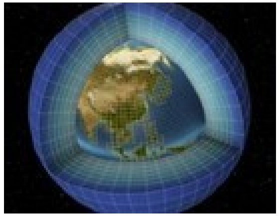
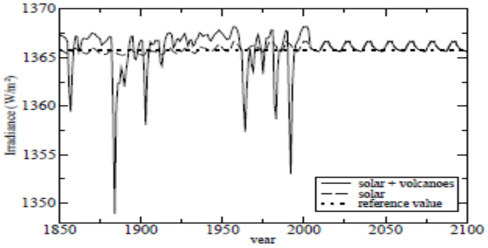
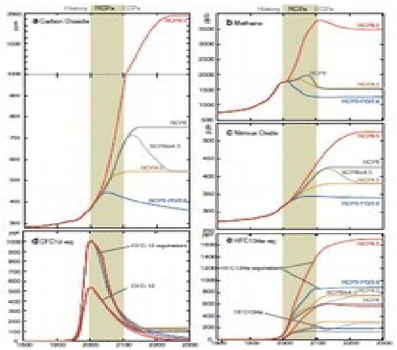


Natural and anthropogenic forcings

Sun and volcanos



Greenhouse gases



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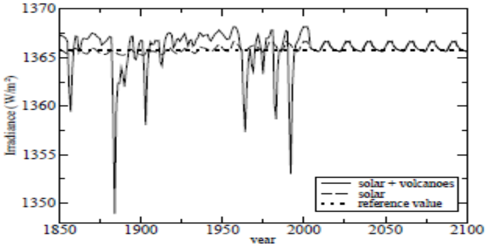

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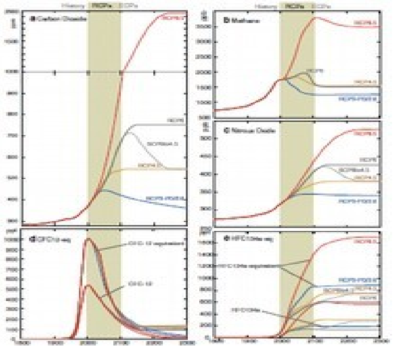
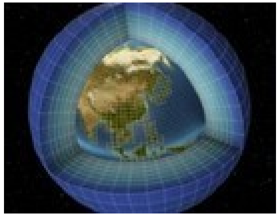
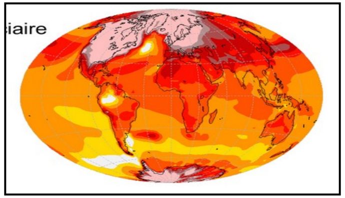


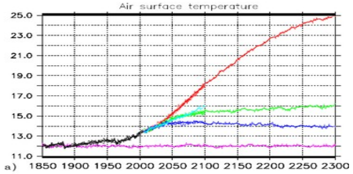
e.g. the IPSL



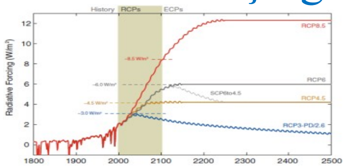
Climate model
3D representation of the atmosphere, ocean, sea-ice, land-surface (coupling of different models)

Results
Climate changes



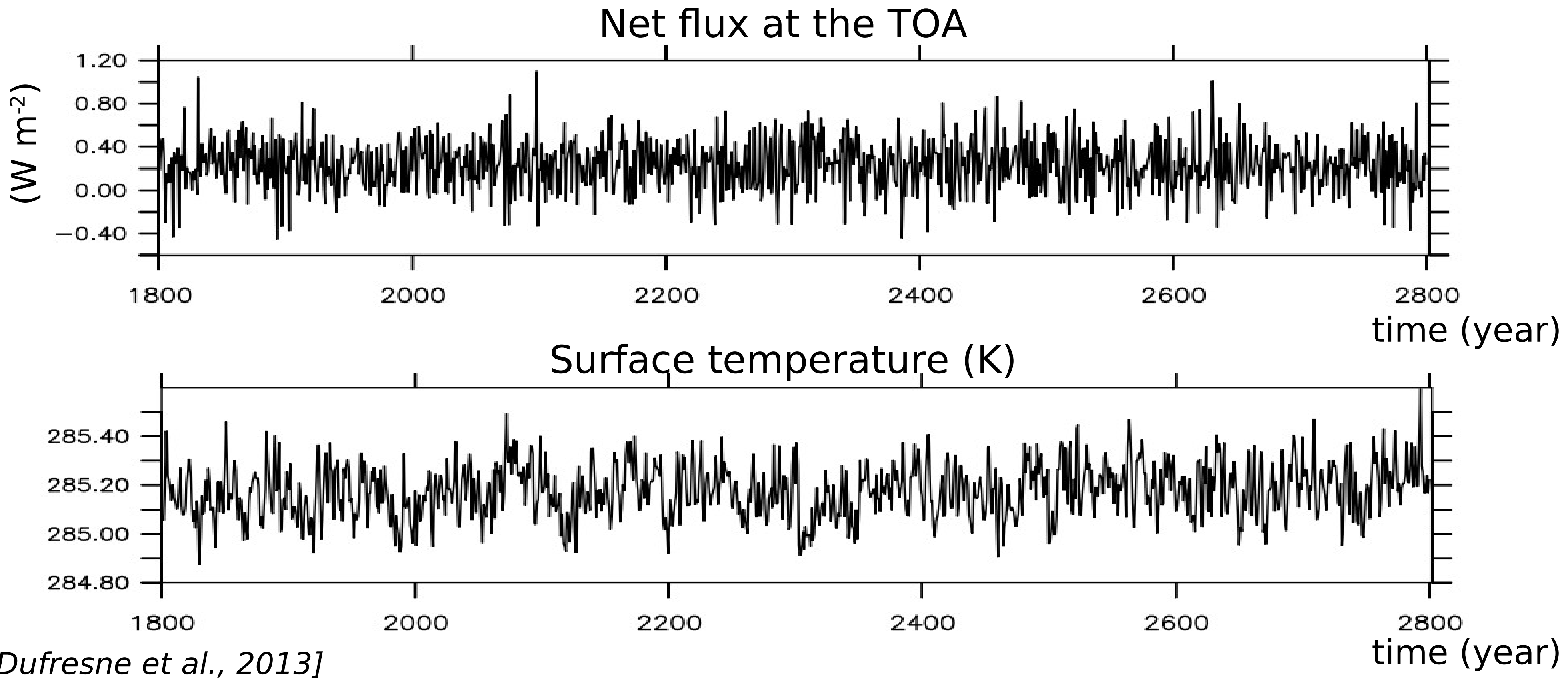


Radiative forçings



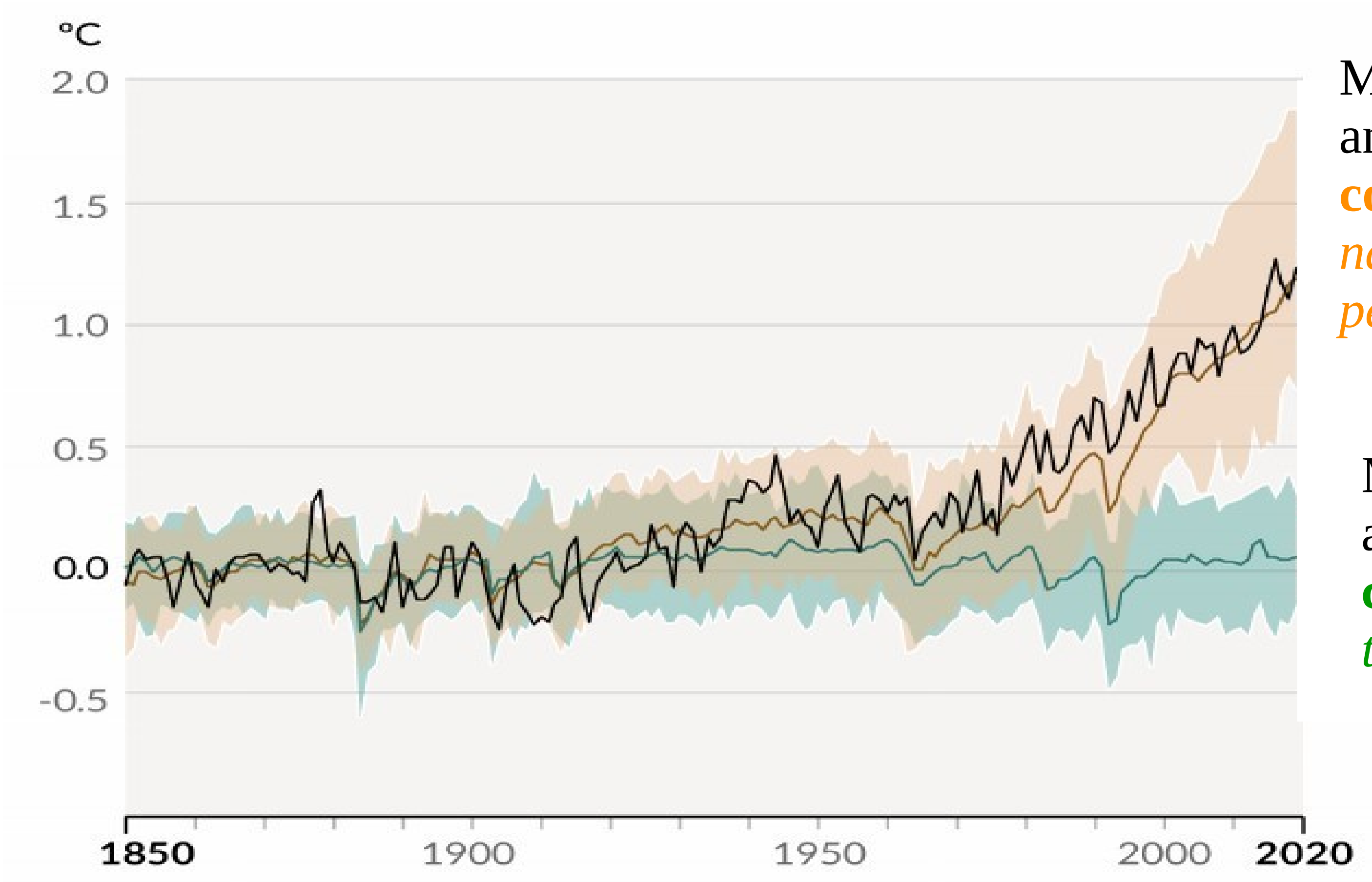
Performing a control run to obtain a stationary reference simulation

IPSL-CM5A-LR model, preindustrial control run



[Dufresne et al., 2013]

Human activities and recent global warming

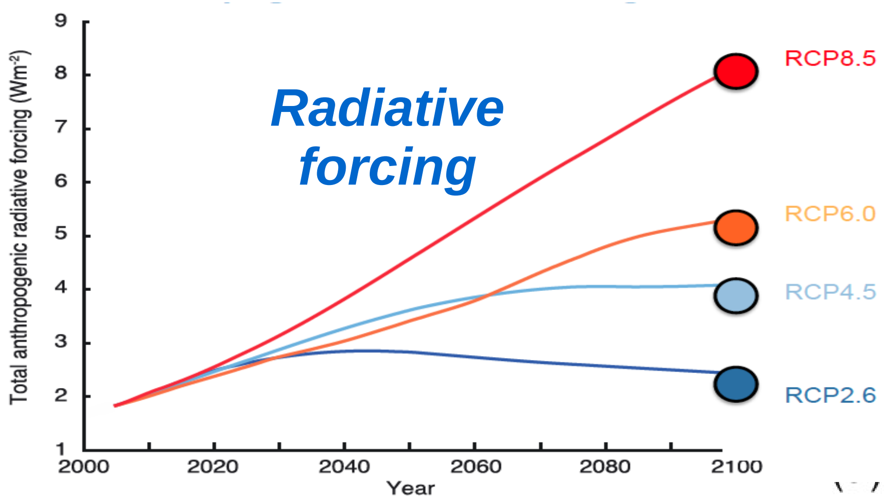


Mean surface temperature anomalies **observed** and **computed** considering *both the natural and anthropogenic perturbations*

Mean surface temperature anomalies **observed** and **computed** considering *only the natural perturbations*

[IPCC, 2021]

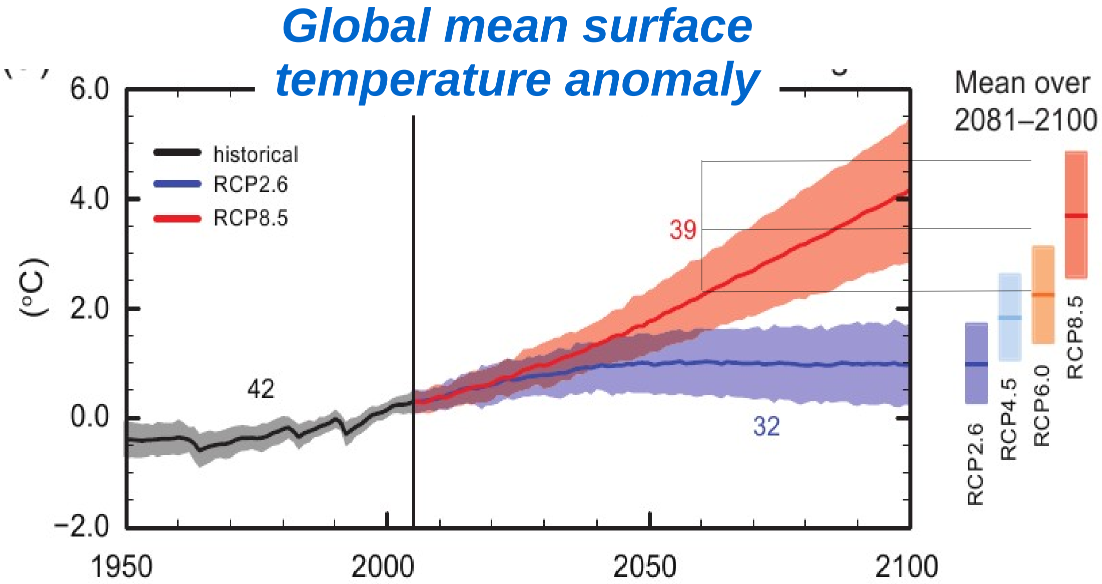
Scenario of futur evolutions



Strong emissions

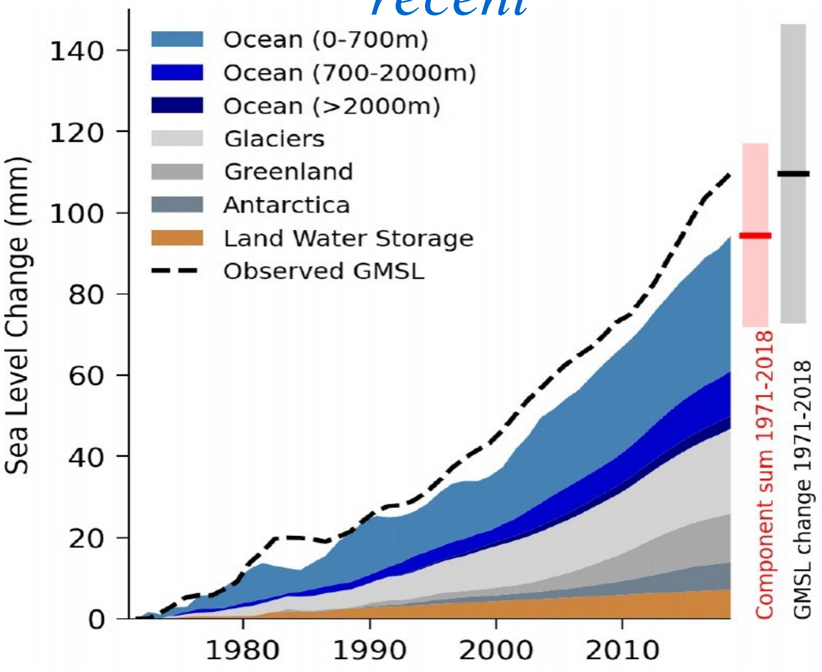
Stabilisation

Emission control



Sea level change

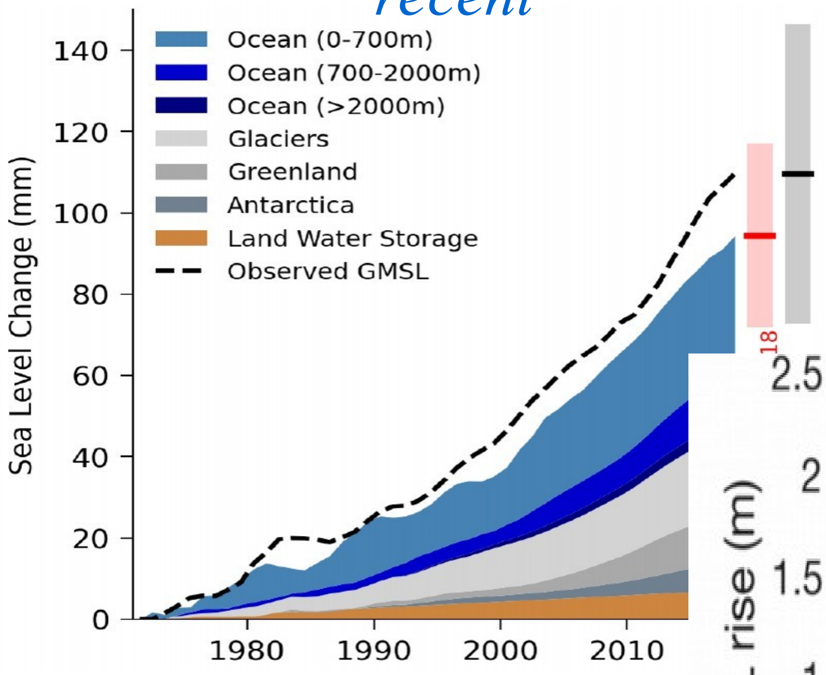
recent



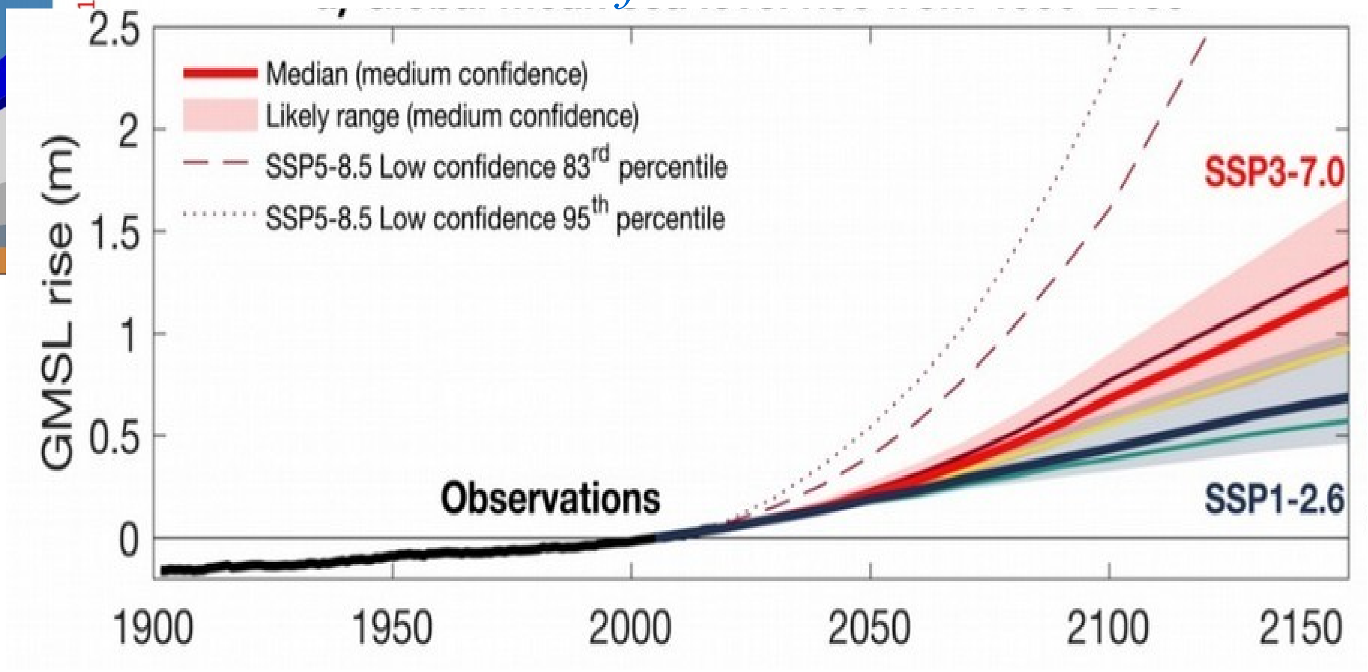
[IPCC 2021, AR6-WG1]

Sea level change

recent



future



[IPCC 2021, AR6-WG1]

Internal variability and variations due to forcings

Climate variations have different origines:

$$\underbrace{\Delta T}_{\text{variation}} \approx \underbrace{\underbrace{\Delta T_{int}}_{\text{Internal variability}} + \underbrace{\frac{\partial T}{\partial Q}\Delta Q_{nat}}_{\text{Response to natural forcings}}}_{\text{Natural variability}} + \underbrace{\frac{\partial T}{\partial Q}\Delta Q_{ant}}_{\text{Response to anthropogenic forcings}}$$

- The relative importance of these various terms depends on the spatial and time average considered, and on the amplitude of the forcings
- The differences between observations and models or between model results can include part or all of these terms, depending on the experimental setup

From atmospheric to Earth System Models :

a suite of numerical tools to understand, analyse and anticipate climate changes

Outlook

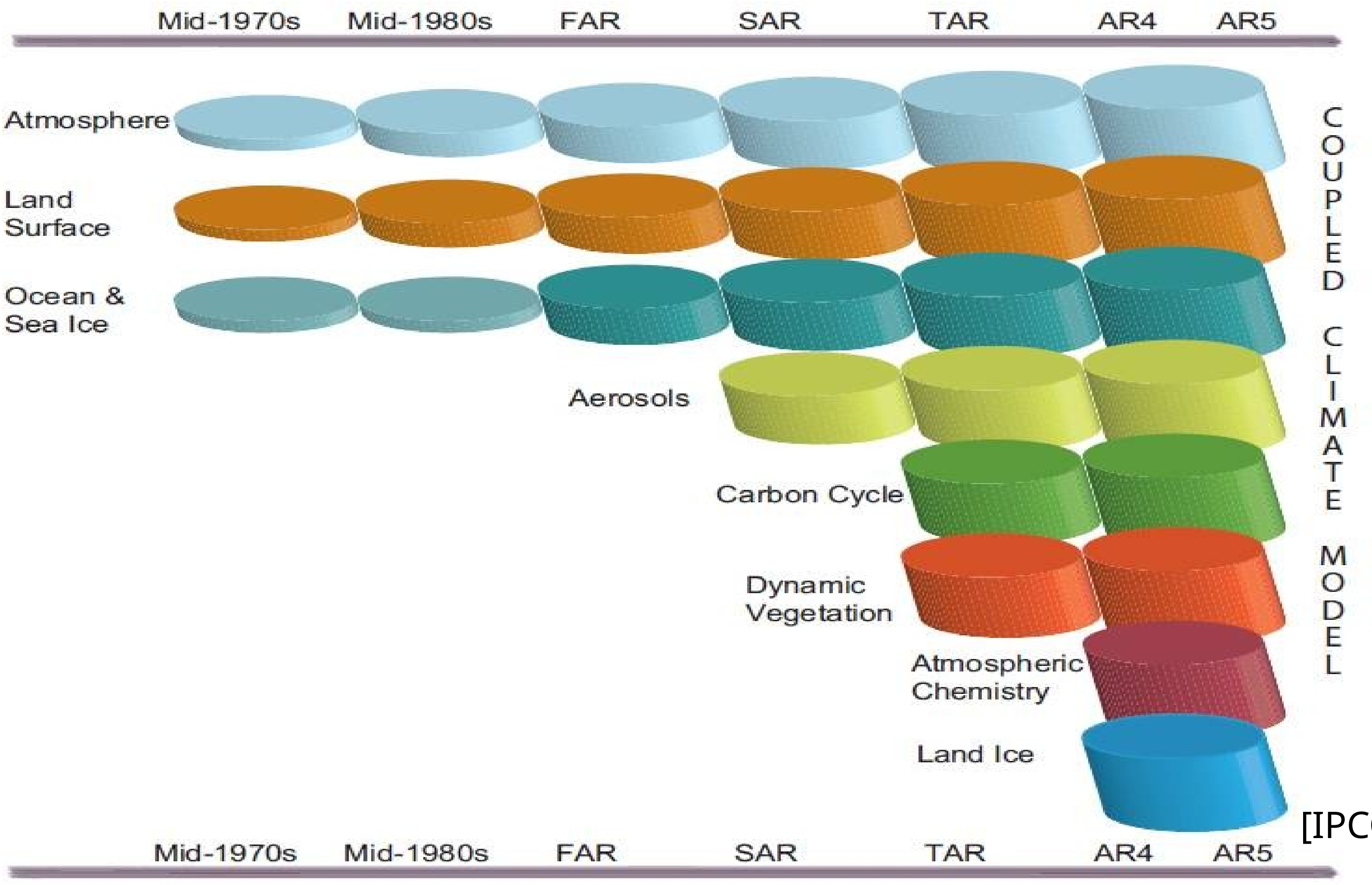
1) The energy balance models
2) Atmospheric single column models
3) Atmosphere-Ocean global circulation models
4) **Earth system models**
5) km scale models
6) Conclusion & Perspectives

From GCM to ESM

GCM (General Circulation Models):
externally prescribed variables (boundary conditions):
- topography, solar-activity, sun-Earth position, etc…
- atmospheric composition: Gaz and aerosols concentrations
- surface properties (albedo, roughness, etc.)

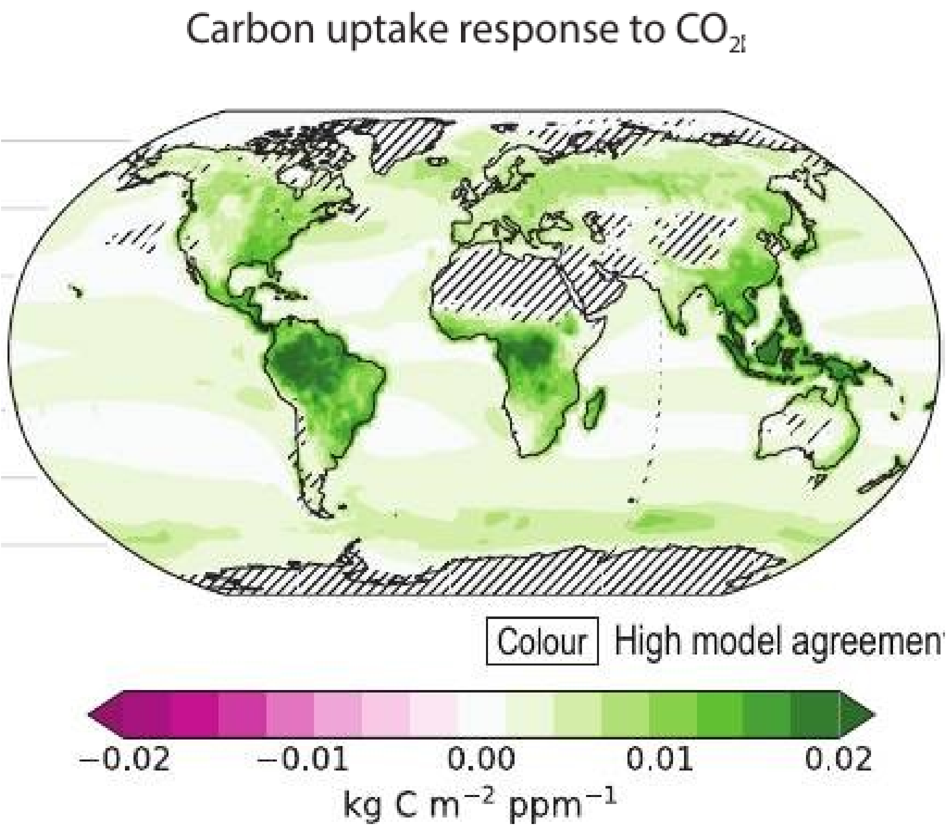
ESM: (Earth System Model):
- models to compute gaz and aerosols concentrations and surface properties are included (to some extend)
- boundary conditions may change, i.e. from gaz concentration to gaz emission

From GCM to ESM



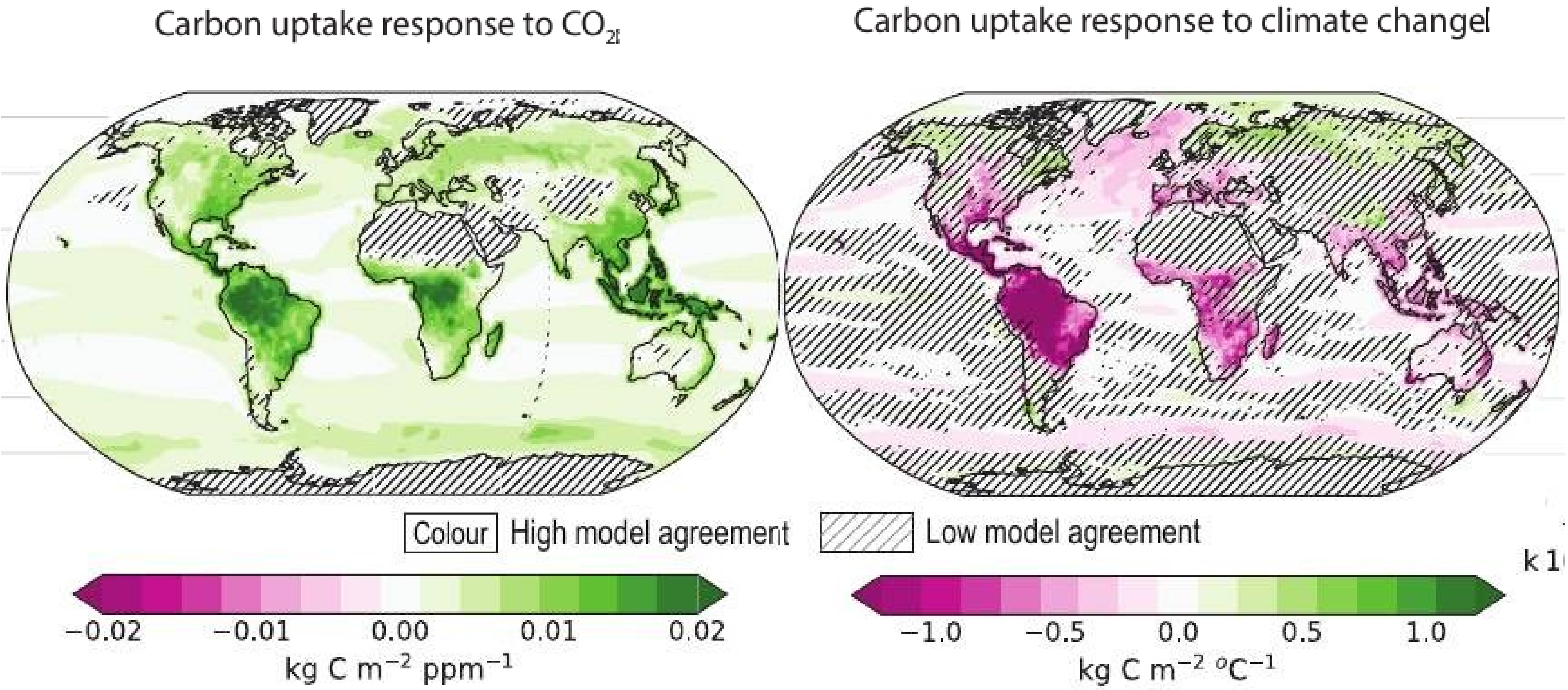
[IPCC, AR5]

Carbon cycle



[IPCC 2021, AR6]

Carbon cycle



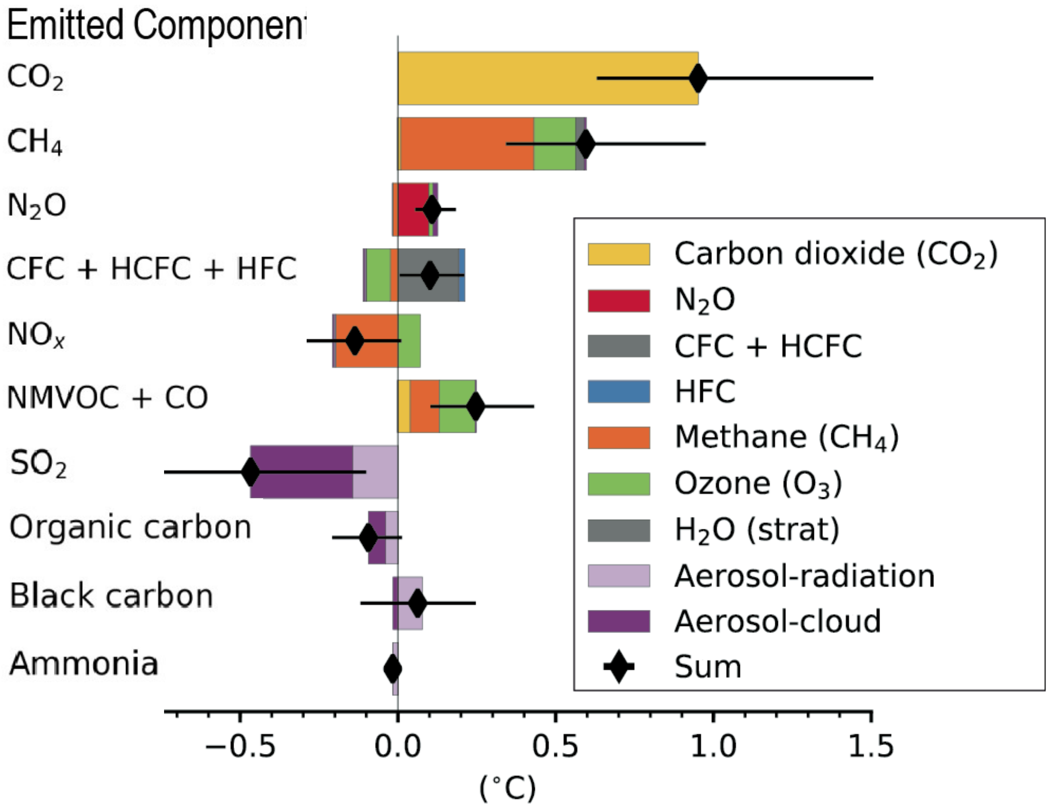
[IPCC 2021, AR6]

Total cumulative CO_2 emissions absorbed by land and oceans (colors) and remaining in the atmosphere (gray)

according to five scenarios (from 1850 to 2100)

[IPCC 2021, AR6]

Contribution from component emissions



[IPCC 2021, AR6, TS]

From atmospheric to Earth System Models :

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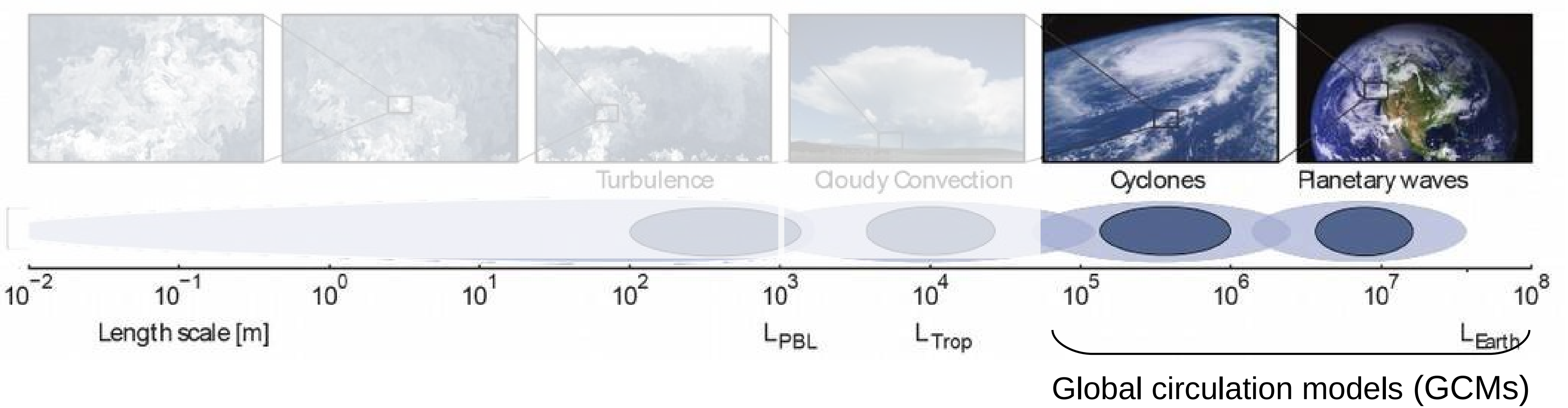
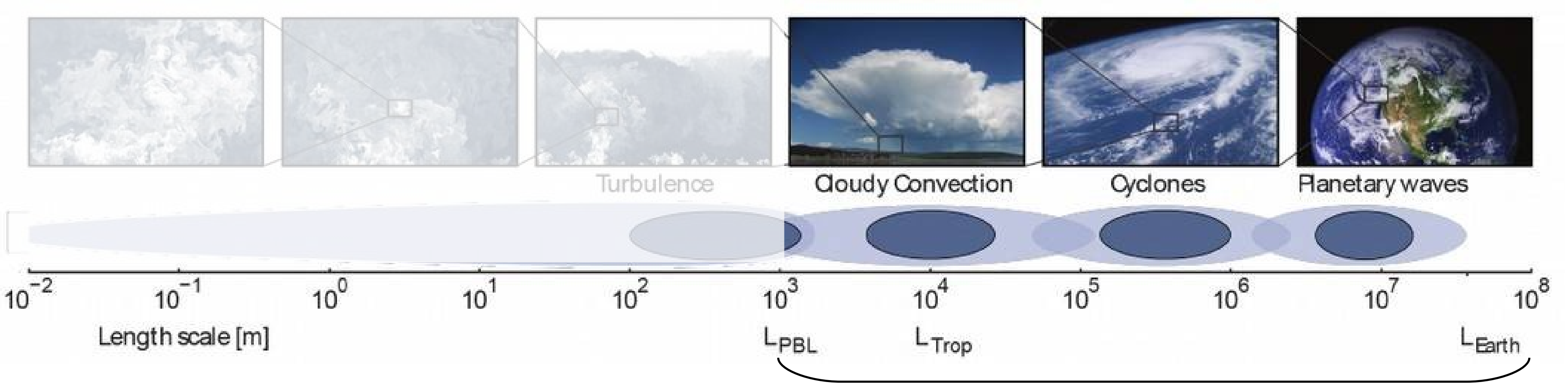
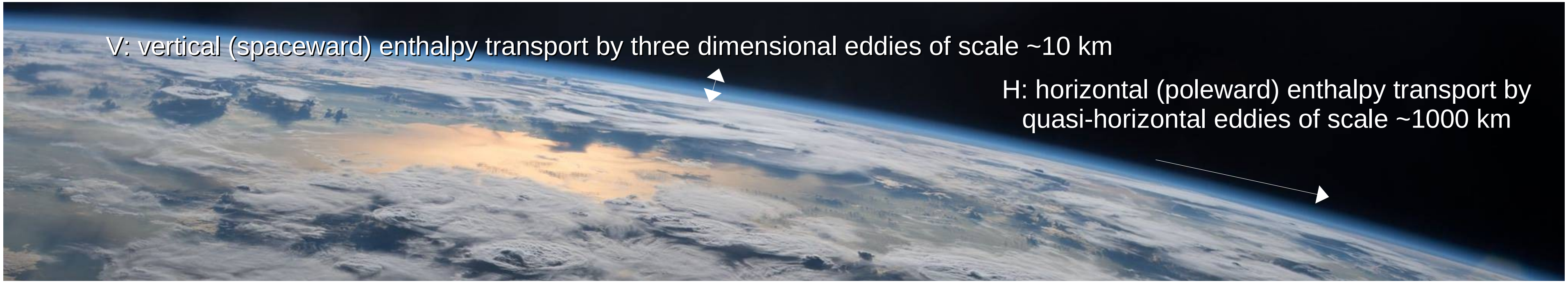
From GCM to km-scale models



From GCM to km-scale models



Global Cloud/Strom resolving models (CRMs/SRMs)



km-scale models

Among the advantages: explicit simulation of mesoscale phenomena, more direct comparison with current high resolution satellite observation, in situ observations, etc. Comparable to weather forecast models.

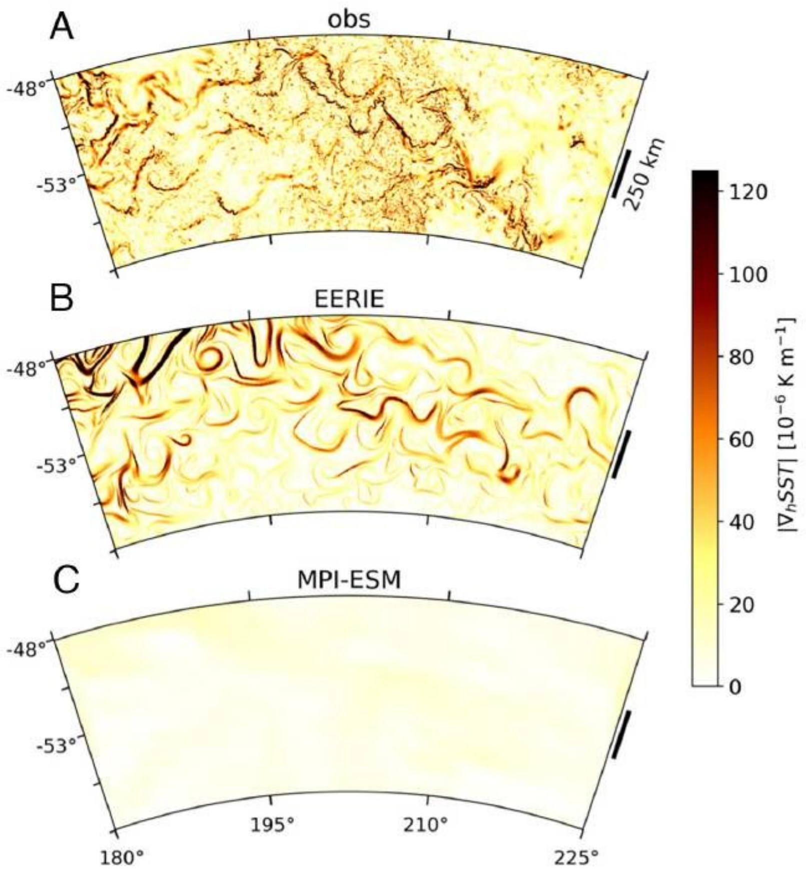
Among the disadvantages: refinement by a factor of 10 => computer cost x 10^4

km-scale coupled atmosphere-ocean models

- on March 21 of 2011 for observations
- on a random day in March for models

- grid spacing of 10 km in the atmosphere and 5 km in the ocean

Snapshots of SST gradient amplitude in the southern ocean



[Kang et al. 2026]

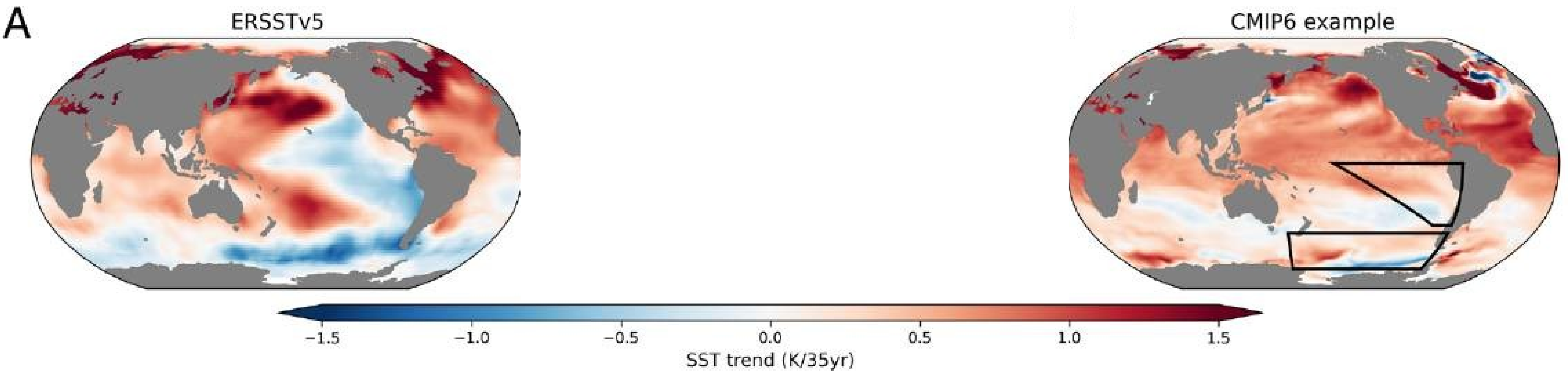
km-scale coupled atmosphere-ocean models

Does this matter for the global climate and climate change?

The pattern of surface warming impacts the magnitude of global warming (climate sensitivity).

A current open question: although climate is warming as predicted by GCM, East Pacific and Southern Ocean is cooling. Why? Natural variability? Response of some external forcings (ozone, aerosols)?

GSRM



[Kang et al. 2026]

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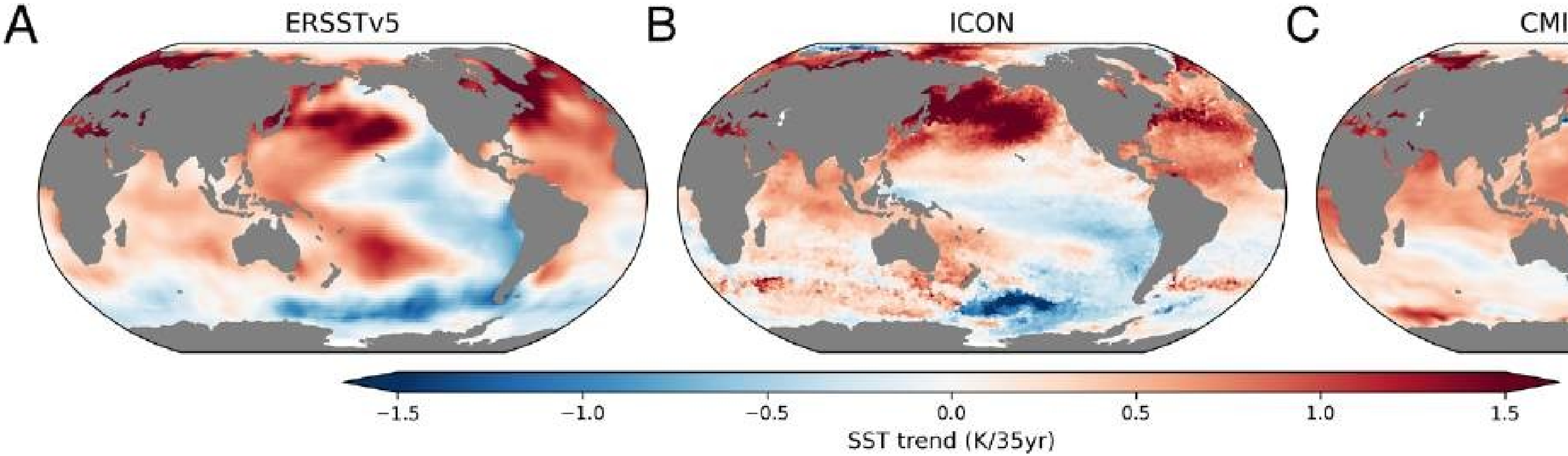

[Kang et al. 2026]

Conclusions and perspectives

- Atmosphere-ocean coupled climate models (80-90s) have evolved to ESM (2000-2010) are currently the most common tools
- A wide range of models are used to analyse and understand climate (geometry: 0D, 1D, 2D, 3D, resolution, complexity, etc.)
- Climate modelling has to face new challenges going from “global climate” to “local weather”, as needed for adaptation
- km scale climate models open new perspectives, but need very large computer resources
- The AI revolution will have an impact on climate modelling. Current research in many different directions, including:
  - Replacing some sub-scale models (parametrization)
  - Replacing/emulating all the model, e.g. to create ensembles of projections
  - …

Thank you for your attention

Questions ?

[J. Williams, ISS]