Éléments sur la physique du climat et des changements climatiques

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"Thermique atmosphérique et adaptation au changement climatique"

Outlook

I. Basics of climate physics

II. The greenhouse effect

III. Climate modelling

IV. Future climate changes

Emergence of the physics of climate

J. Fourrier:

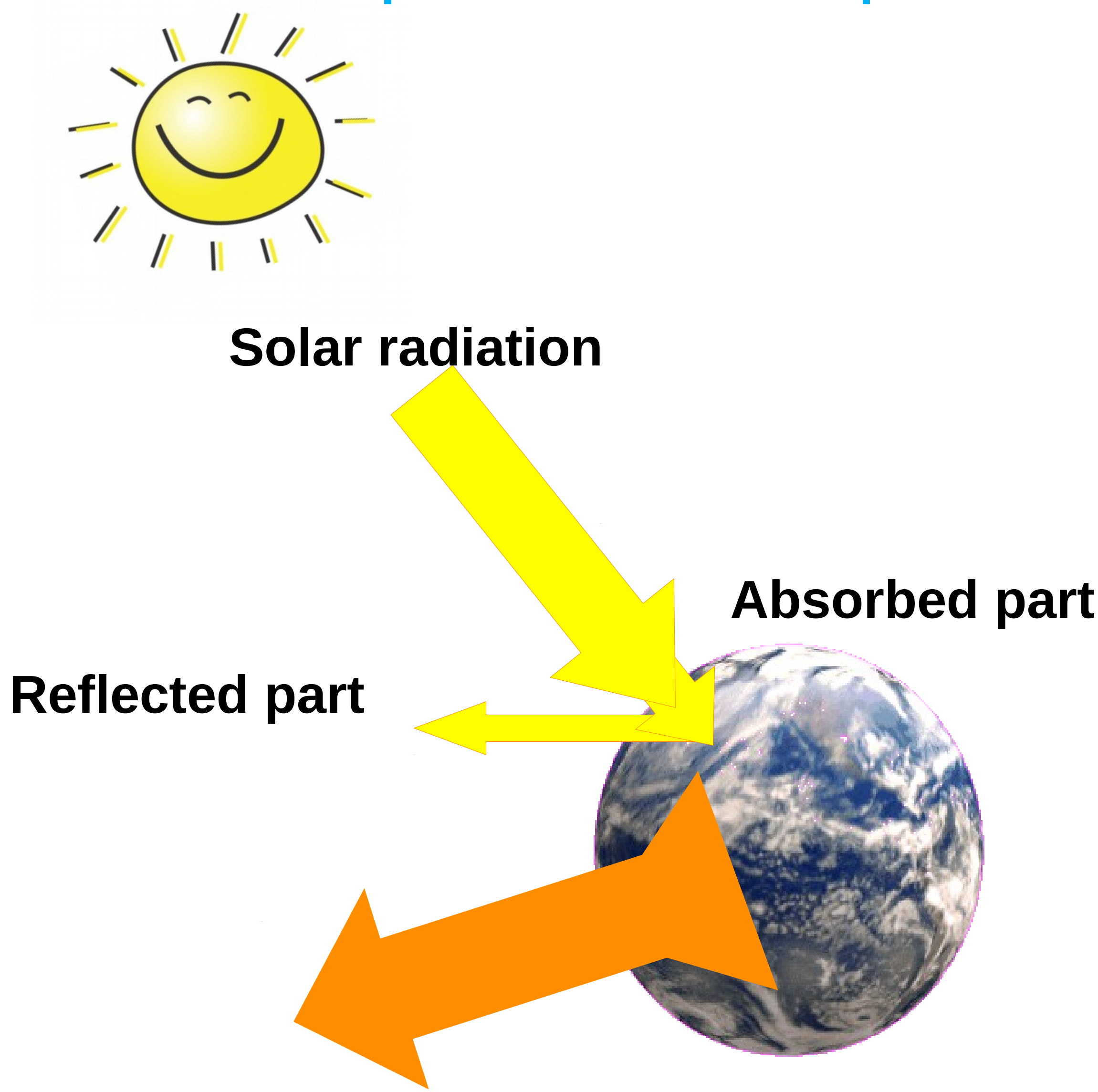
• *Mémoire sur les températures du globe terrestre et des espaces planétaires*, Mémoires de l'Académie des Sciences de l'Institut de France,1824
• *General remarks on the Temperature of the Terrestrial Globe and the Planetary Spaces;* American Journal of Science, Vol. 32, N°1, 1837.

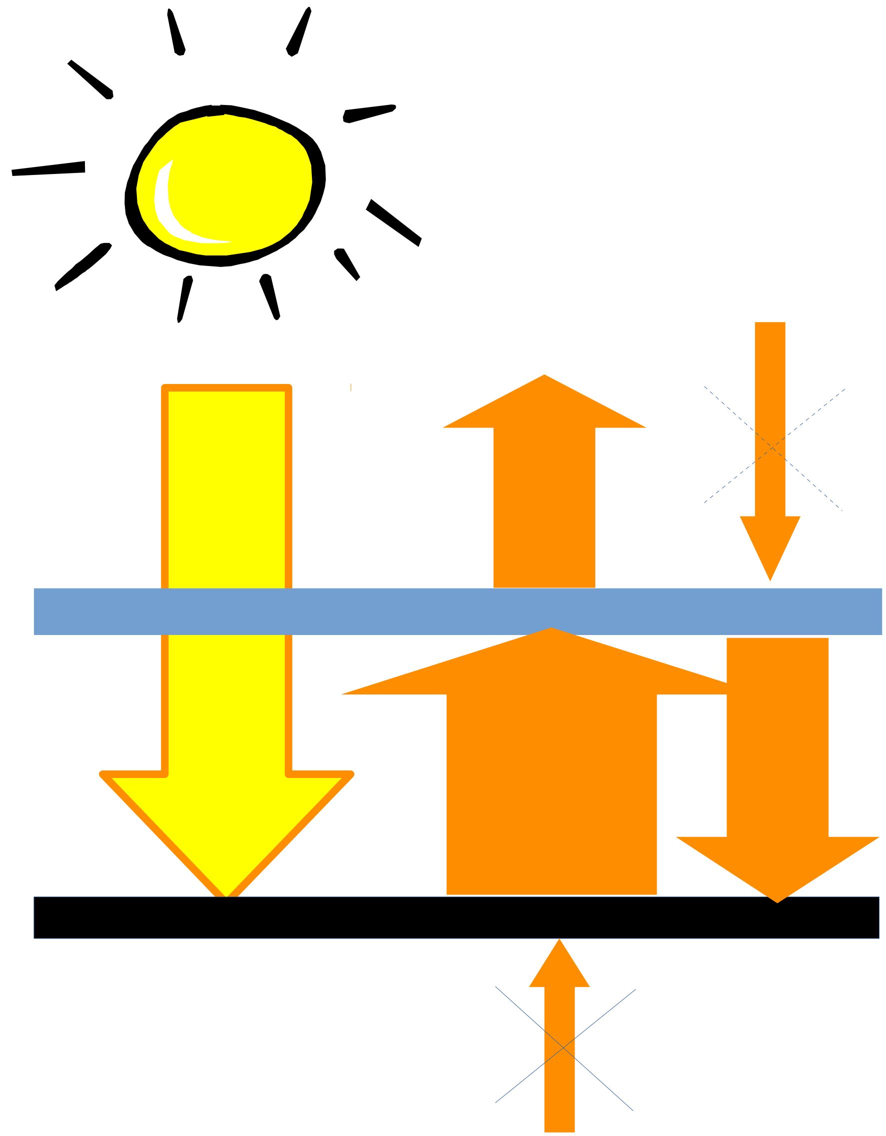
Joseph Fourrier
(1768-1830)

- He consider the Earth like any other planet
- 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
- He formulates the principle of the **greenhouse effect**
- He envisages the importance of any ***change of the sun***
- He envisages that ***climate may change***

[Dufresne, 2006]

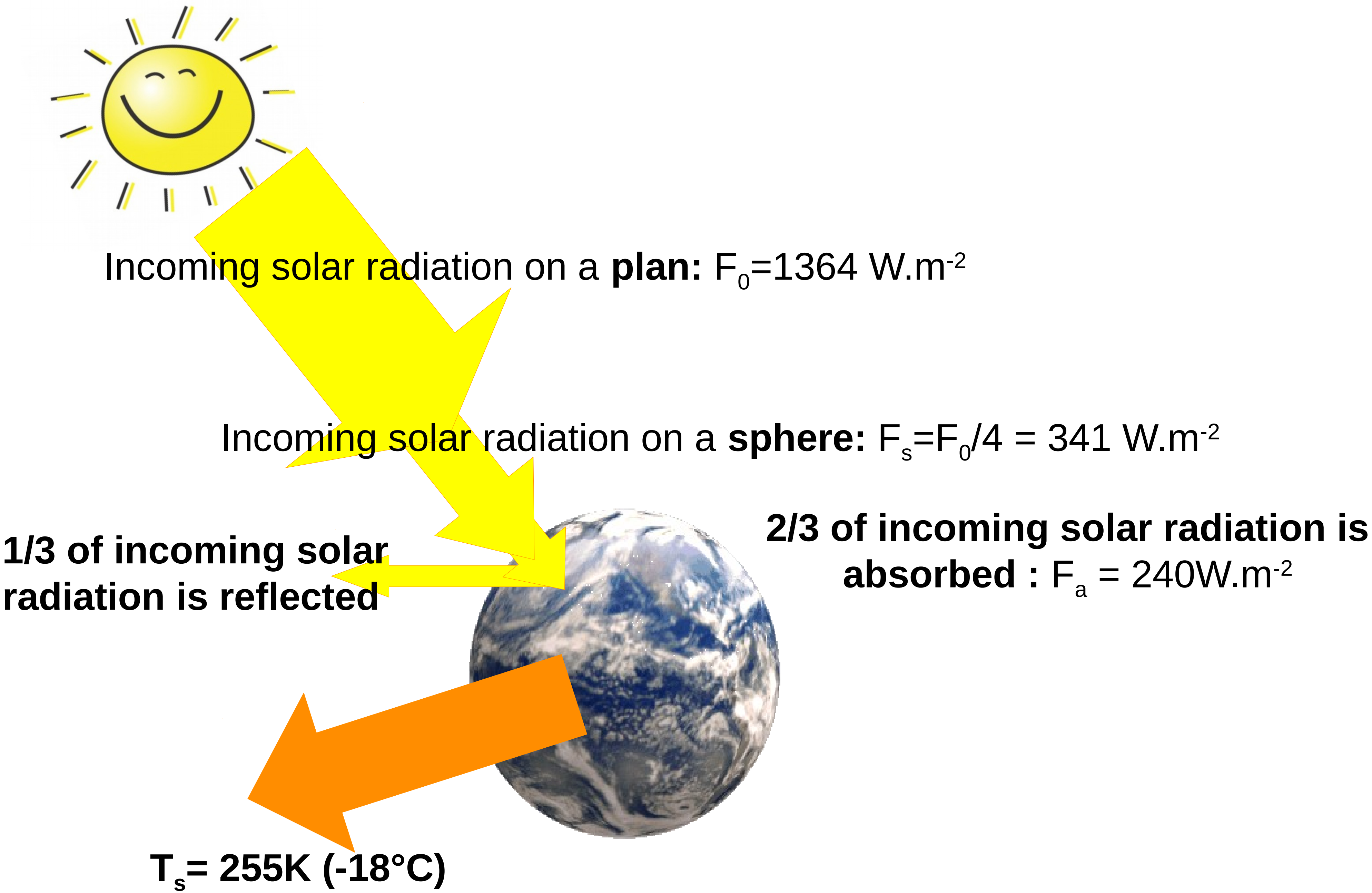
Equilibrium temperature of a planet



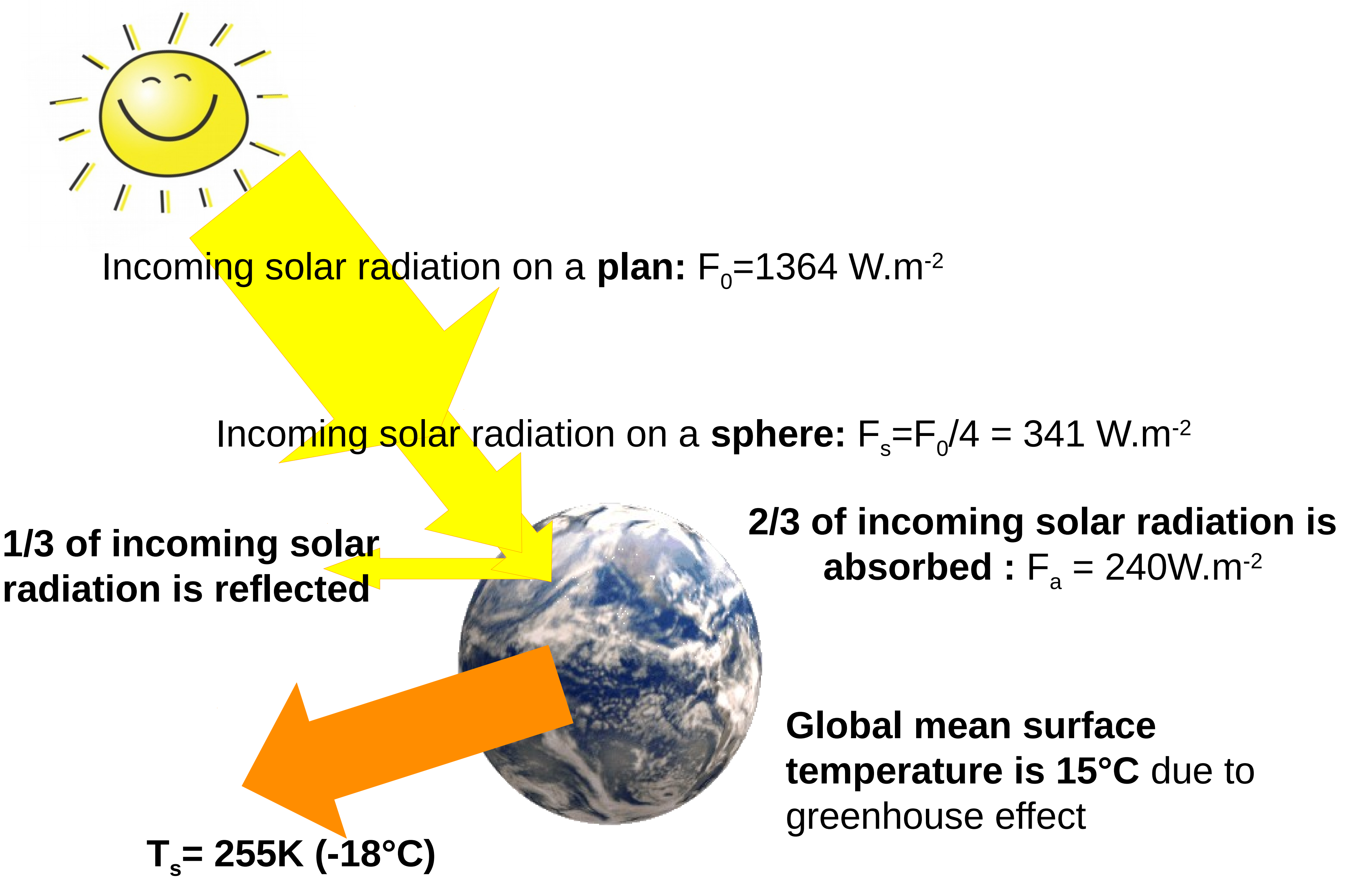


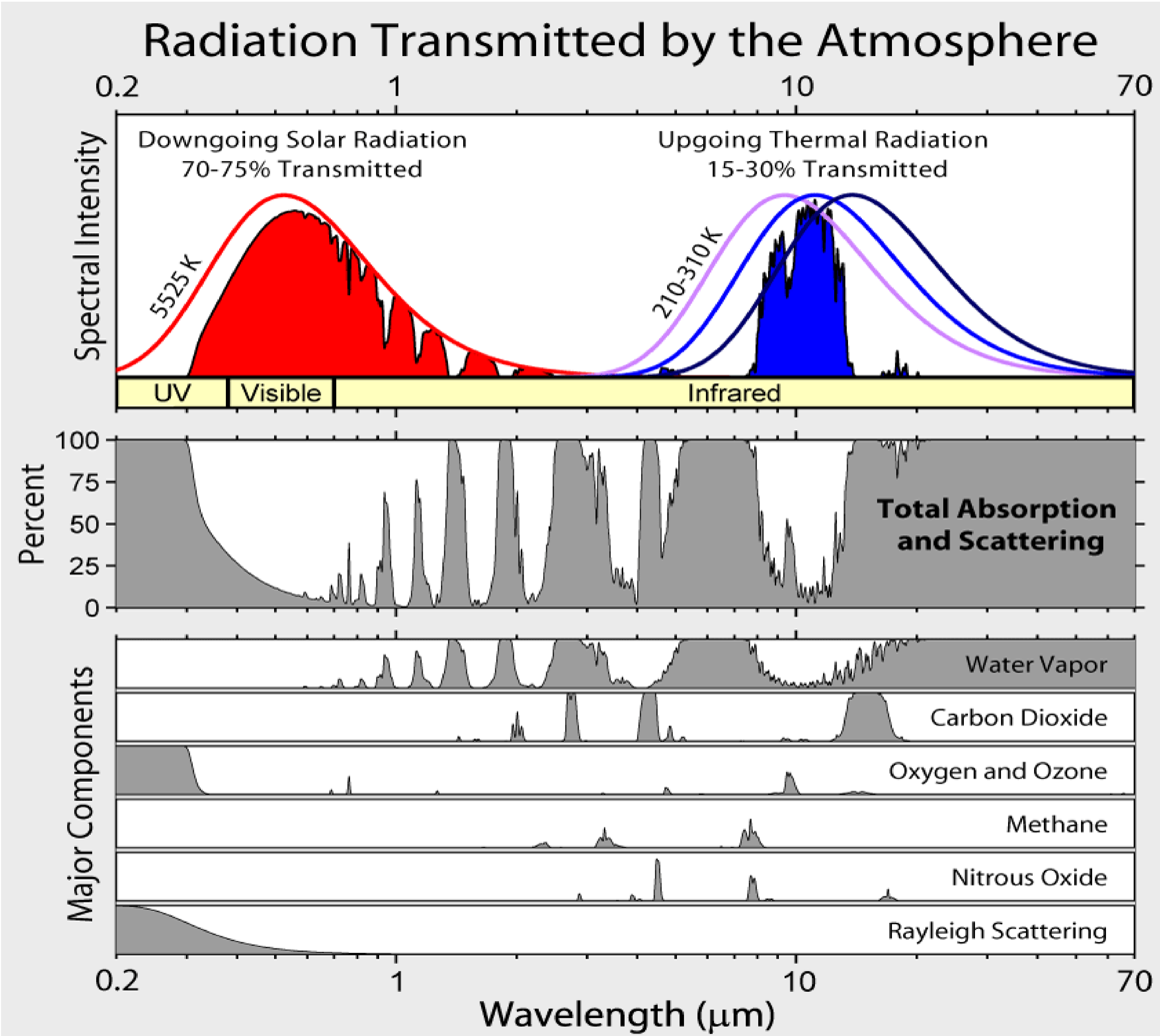
Global mean surface temperature is the result of the global energy budget

Equilibrium temperature of a planet



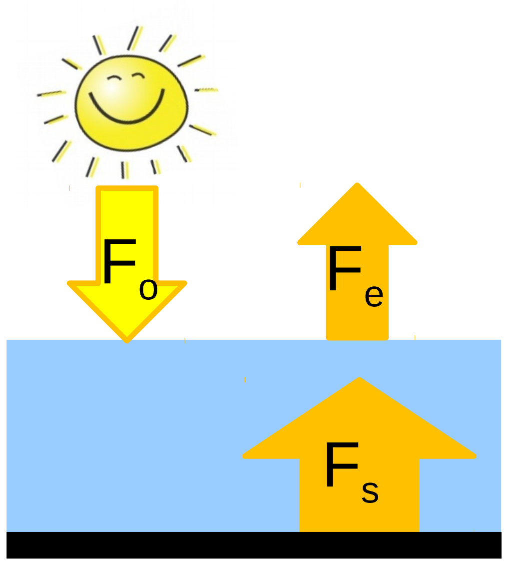
Equilibrium temperature of a planet



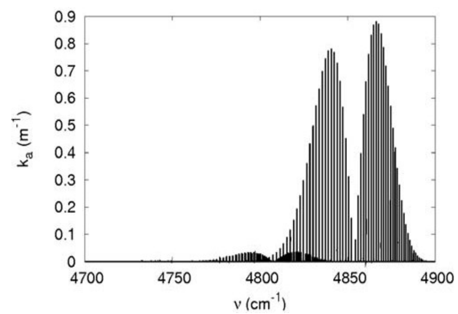


Radiation Transmitted by the Atmosphere
0.2
1
10
70
Spectral Intensity
Downgoing Solar Radiation
70-75% Transmitted
Upgoing Thermal Radiation
15-30% Transmitted
5525 K
210-310 K
UV
Visible
Infrared
Percent
100
75
50
25
0
Total Absorption
and Scattering
Major Components
Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering
0.2
1
10
70
Wavelength (μm)

What radiation heat transfer theory tell us



Greenhouse effect: $\boldsymbol{G=F_s-F_e}$



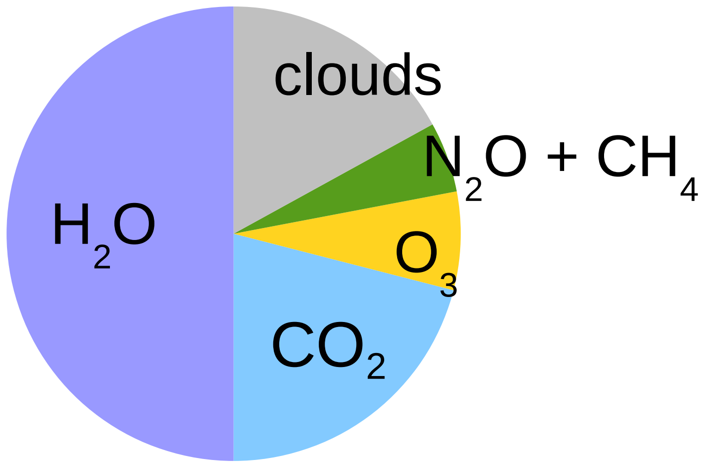
Gas radiative properties

Atmospheric characteristics

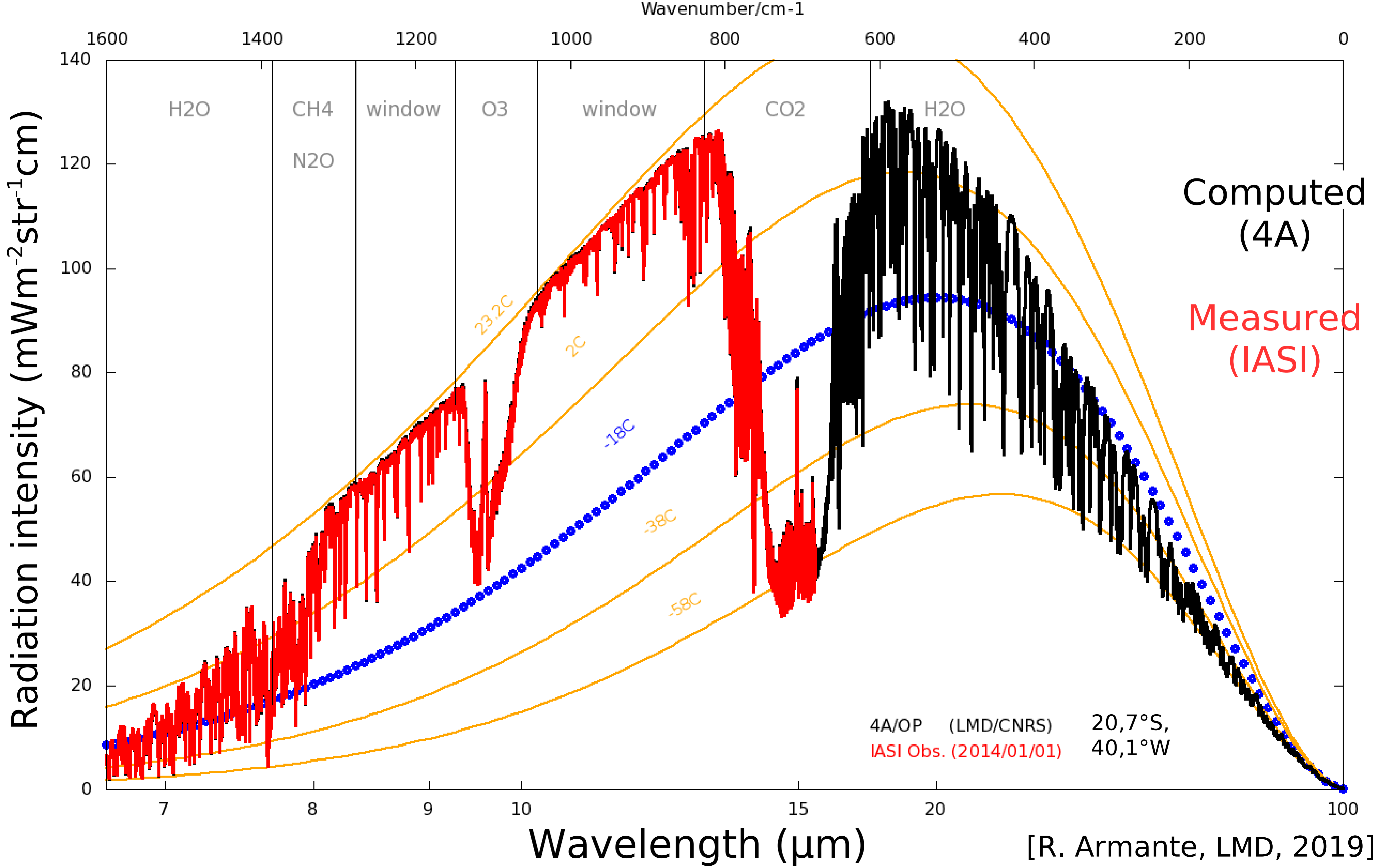
→ Computation of the radiative fluxes $\boldsymbol{F_s}$ and $\boldsymbol{F_e}$ and the greenhouse effect $\boldsymbol{G}$

Current greenhouse effect and the various contributions

	($W.m^{-2}$)	(%)
Total	150	
Water vapour	75	50
CO_2	32	21
ozone	10	7
N_2O+CH_4	8	5
Clouds	25	17

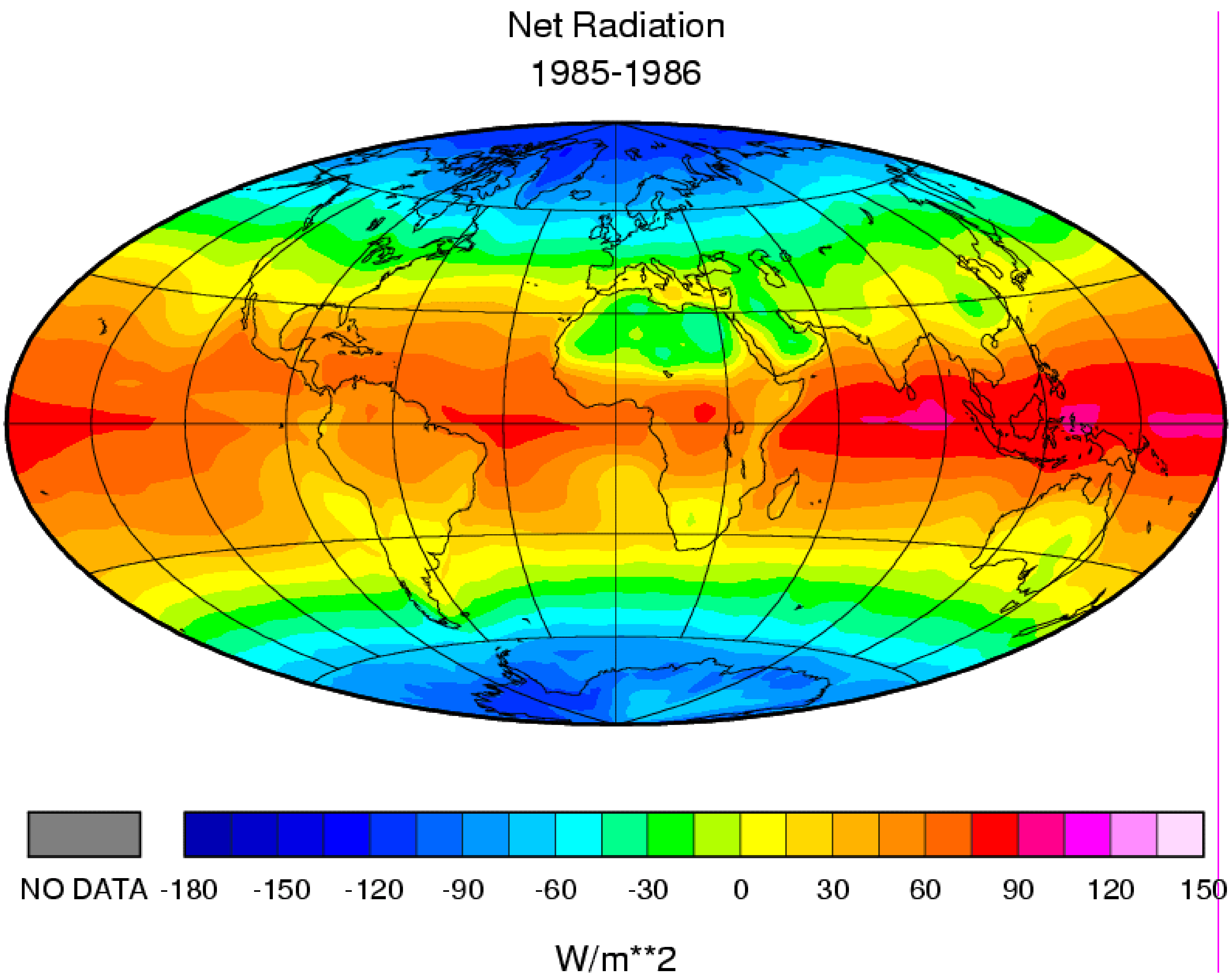


Spectrum of the radiation emitted by the Earth as measured by satellites



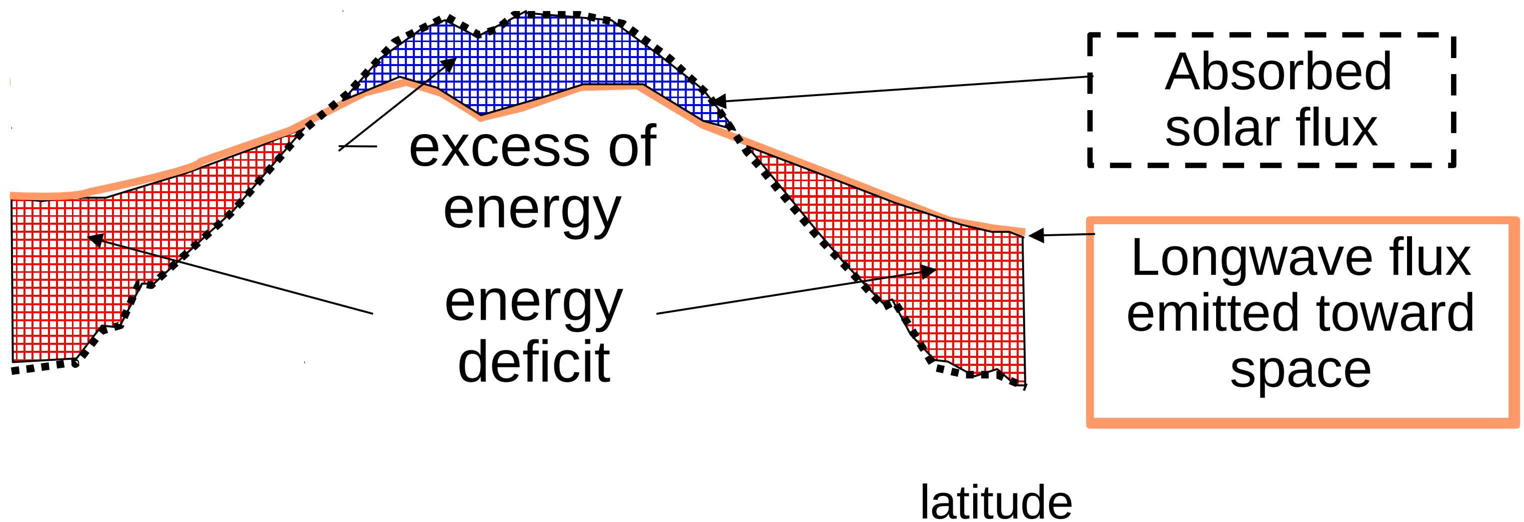
[R. Armante, LMD, 2019]

Energy balance at the top of the atmosphere

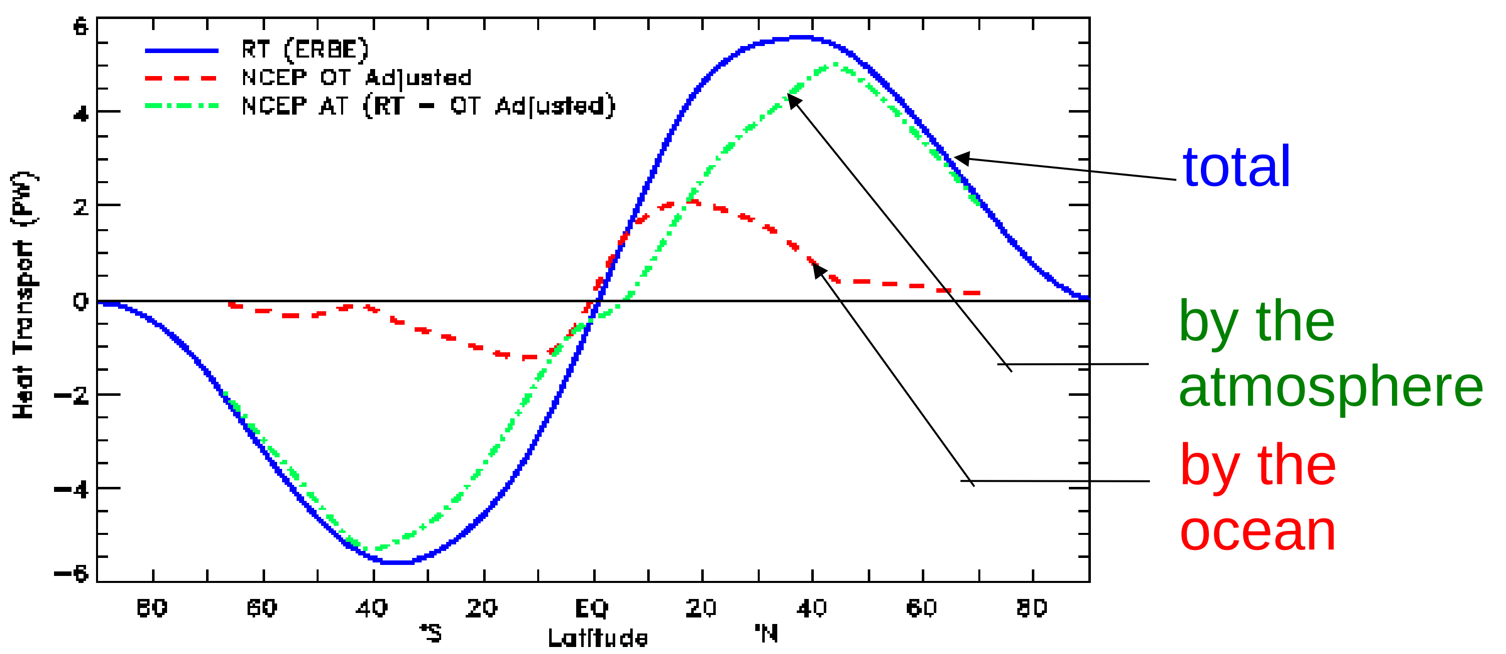


Energy redistribution in latitude

Energy balance at the top of the atmosphere (W/m2)



Meridional heat transport (PW, 10^{15}W)



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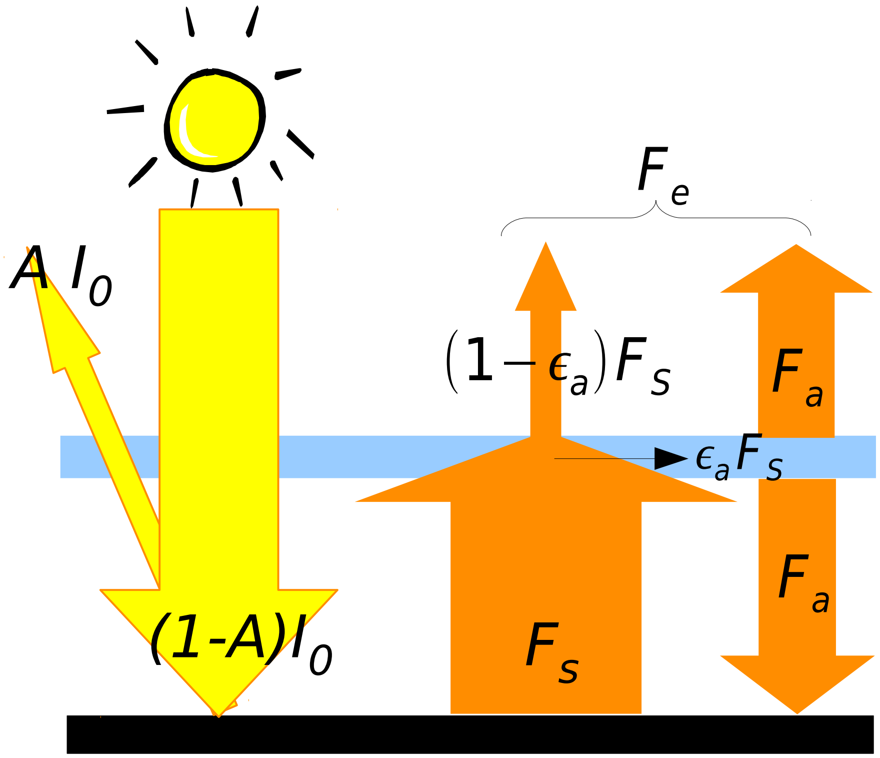
Single layer greenhouse model



Atmospheric layer:

- Isothermal
- Perfectly transparent to solar radiation
- Absorbs thermal infrared: emissivity=absorptivity=ε_a

Surface: albedo A, emissivity = 1

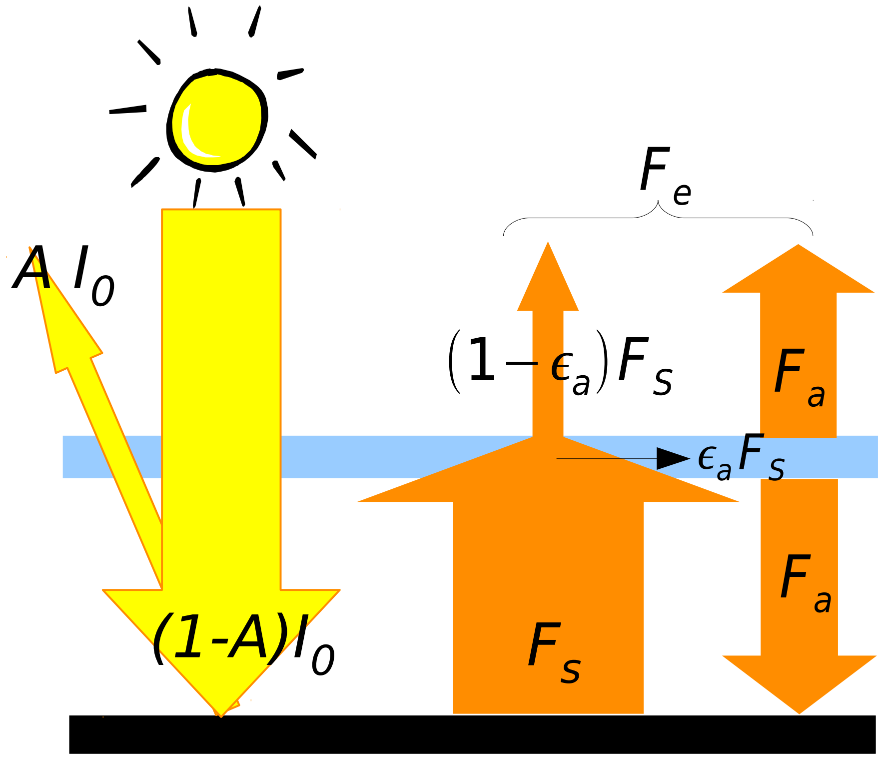
Equations:

$$\begin{cases} F_s = (1-A) I_0 + F_a \\ F_a = F_s \epsilon_a / 2 \\ F_s = \sigma T_s^4 \qquad \left(F_a = \epsilon_a \sigma T_a^4\right) \end{cases}$$

That gives:

$$\sigma T_s^4 = \frac{(1-A) I_0}{1-\epsilon_a/2}$$

Single layer greenhouse model



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That gives:

$$\sigma T_s^4 = \frac{(1-A)I_0}{1-\epsilon_a/2}$$

➢The surface temperature T_s depends on the **incoming solar flux I_s, albedo A** and atmospheric **absorptivity ε_a in the infrared**

➢**The greenhouse effect**

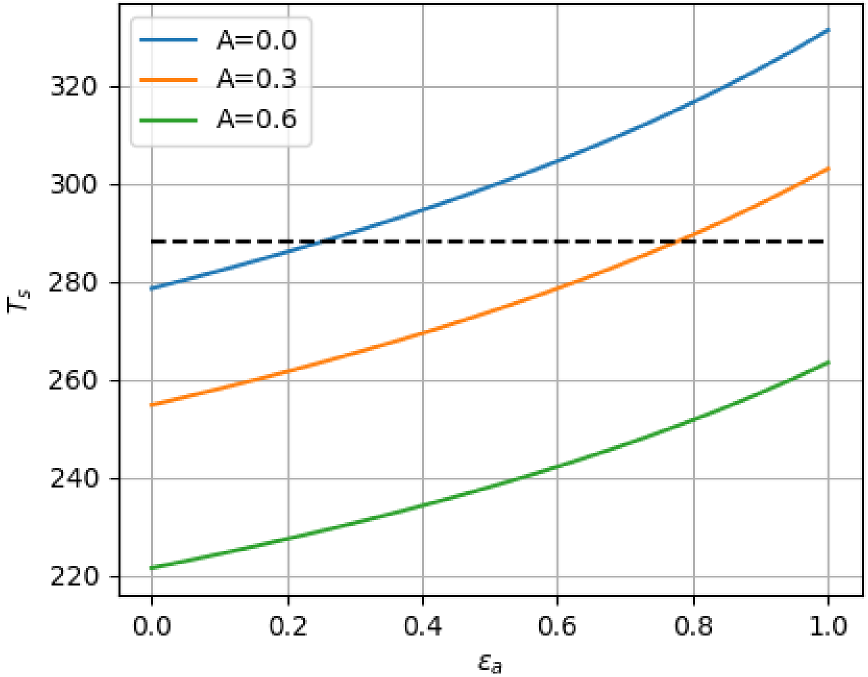
$$G = F_s - F_e = (1-A)I_0\left(\frac{1}{1-\epsilon_a/2} - 1\right)$$

varies between 0 when ε_a=0 and *(1-A)I₀* when ε_a=1. **It is maximum when ε_a=1**

Single layer greenhouse model

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

$$T_s = f(\epsilon_a)$$



The single-layer model gives the right orders of magnitude, but has some important limitations, especially for CO_2

Single layer greenhouse model

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

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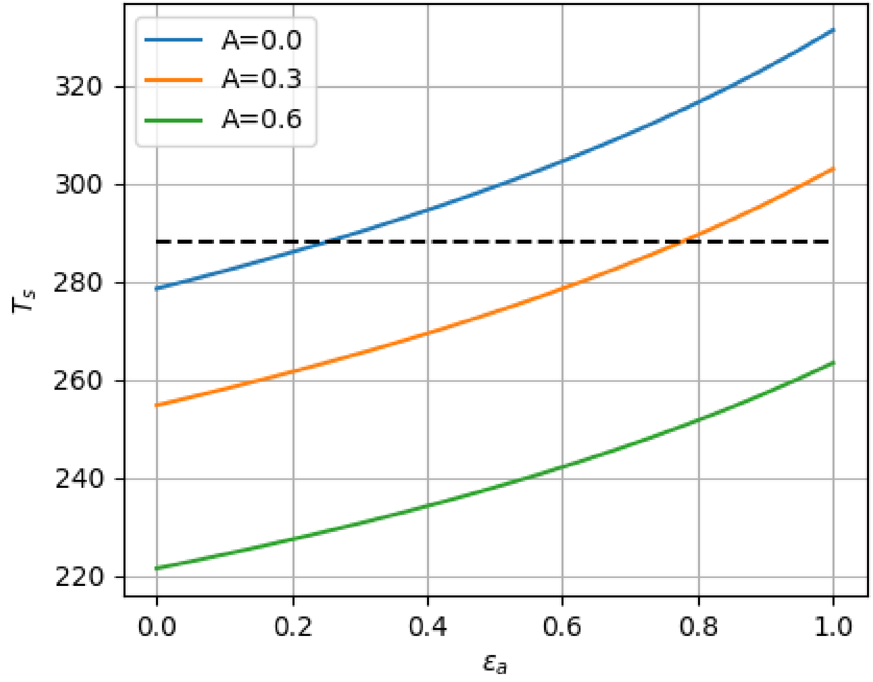

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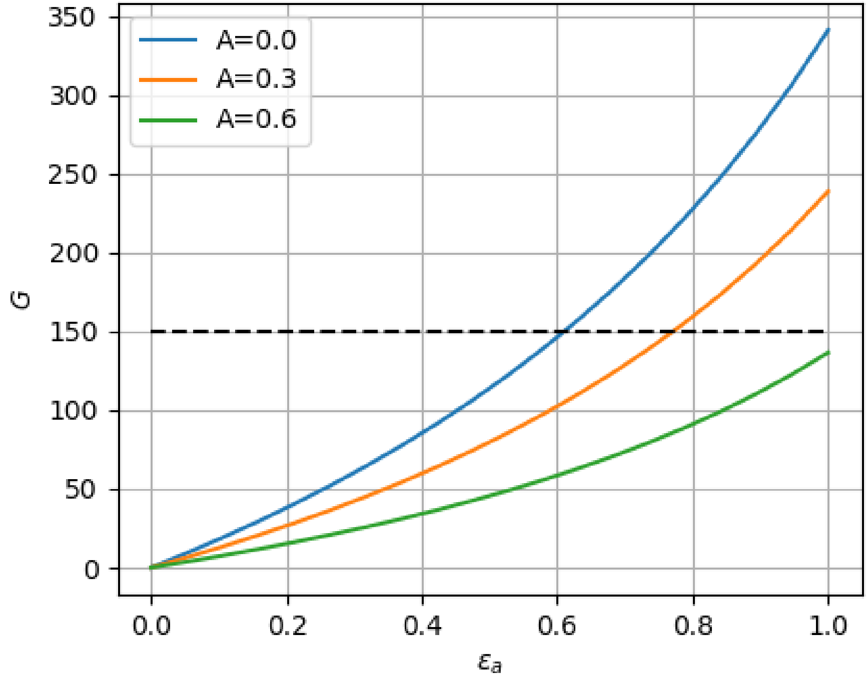

Single layer greenhouse model

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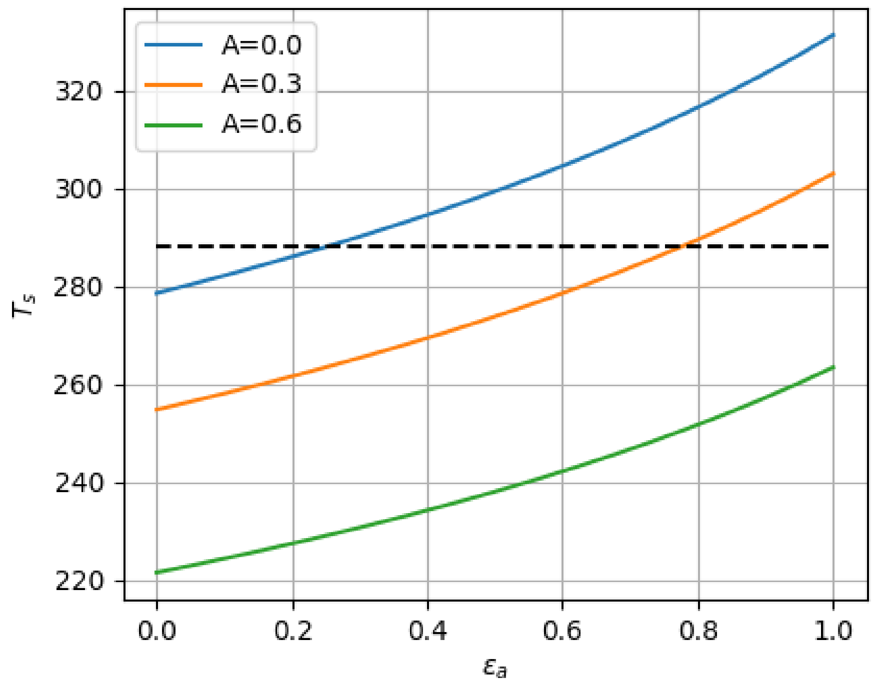

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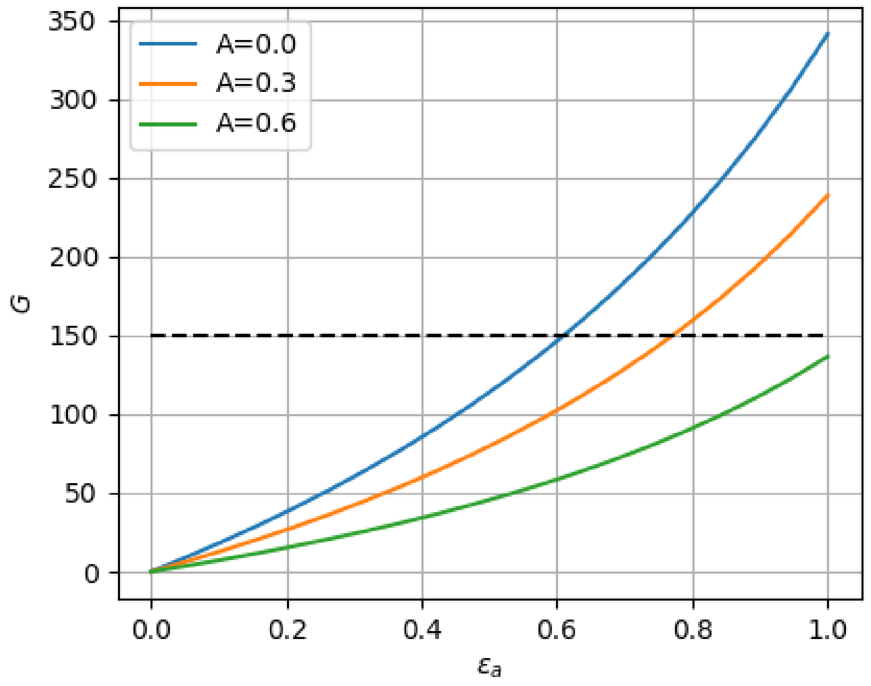
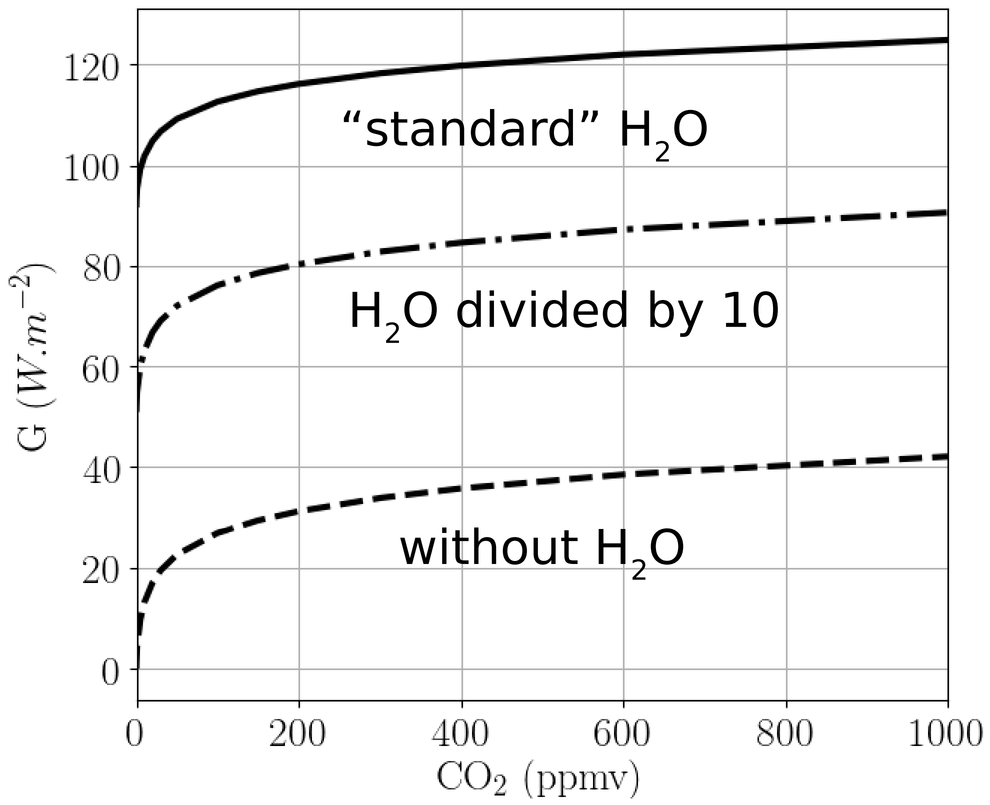


The single-layer model gives the right orders of magnitude, but has some important limitations, especially for CO_2

The CO_2 saturation paradox

Greenhouse effect as a function of
CO_2 concentration
for different H_2O concentrations



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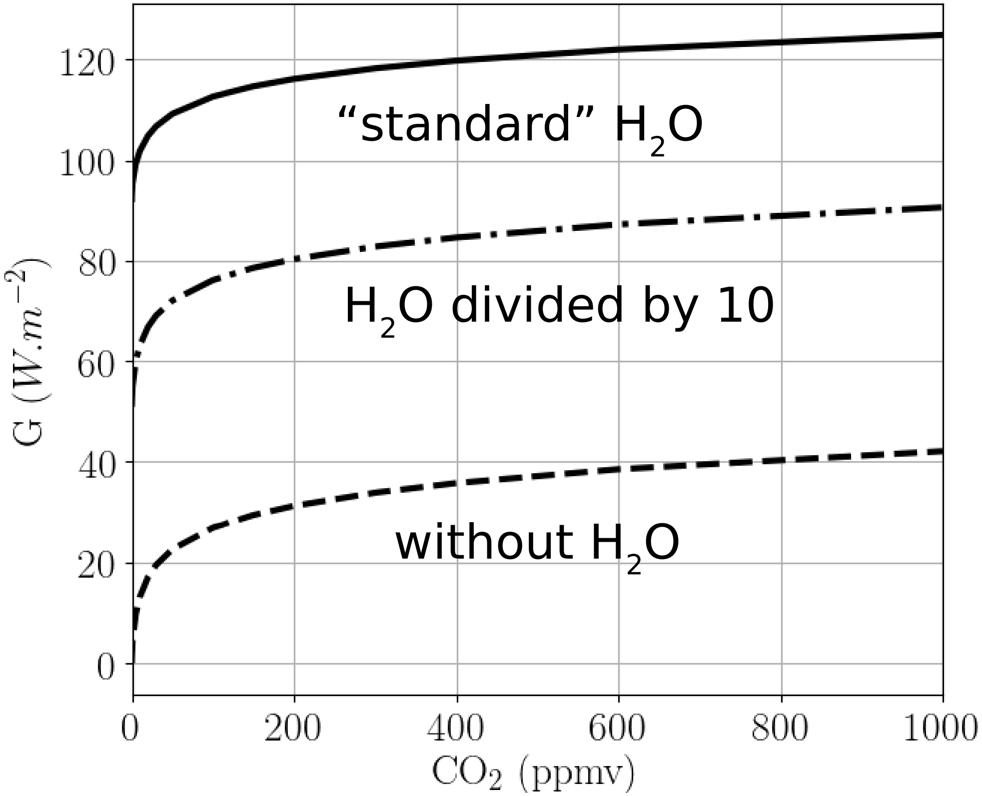
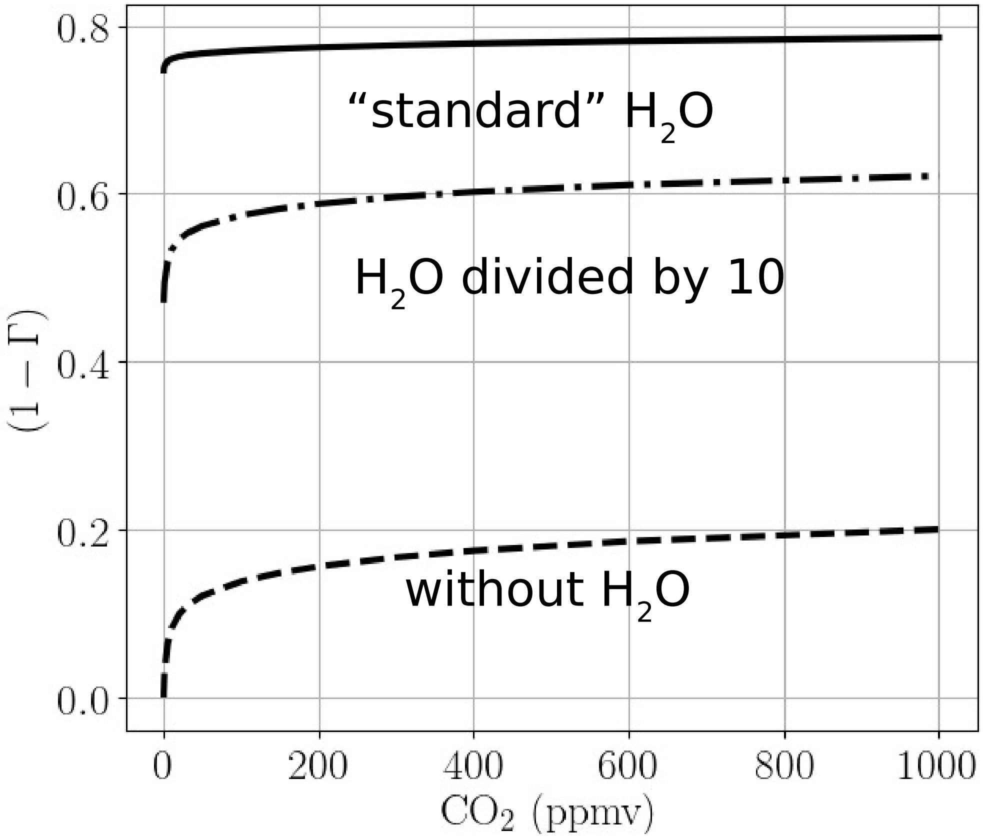


Total absorptivity ε_a of the atmosphere as a function of **CO_2 concentration** for different H_2O concentrations



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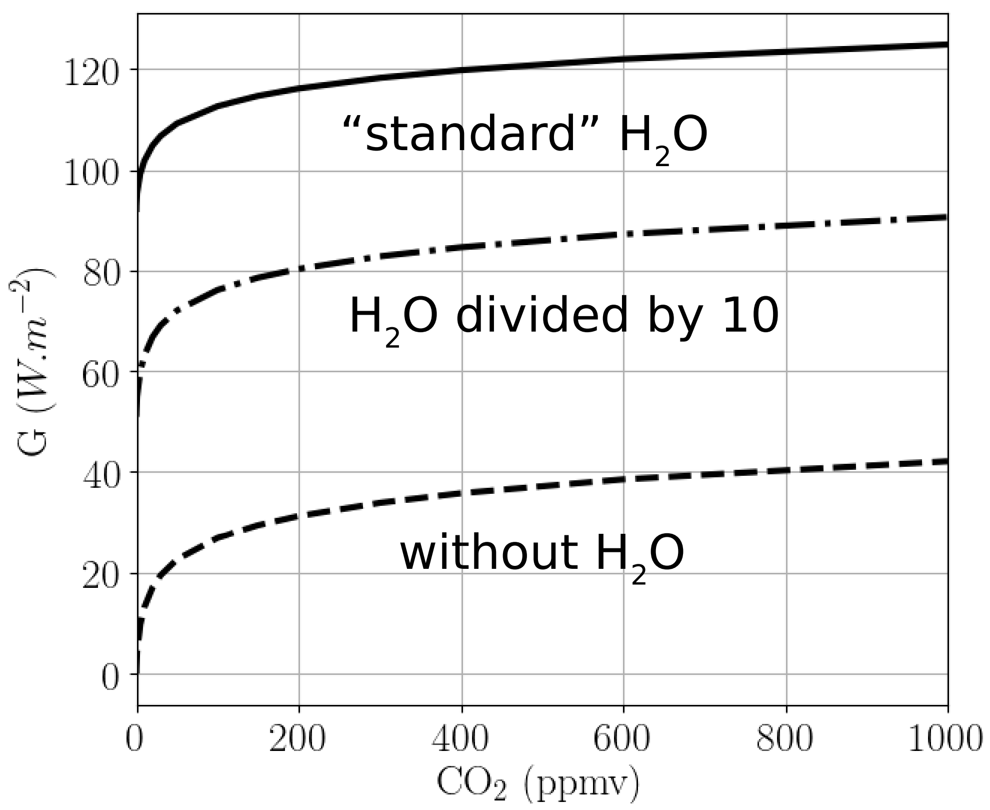

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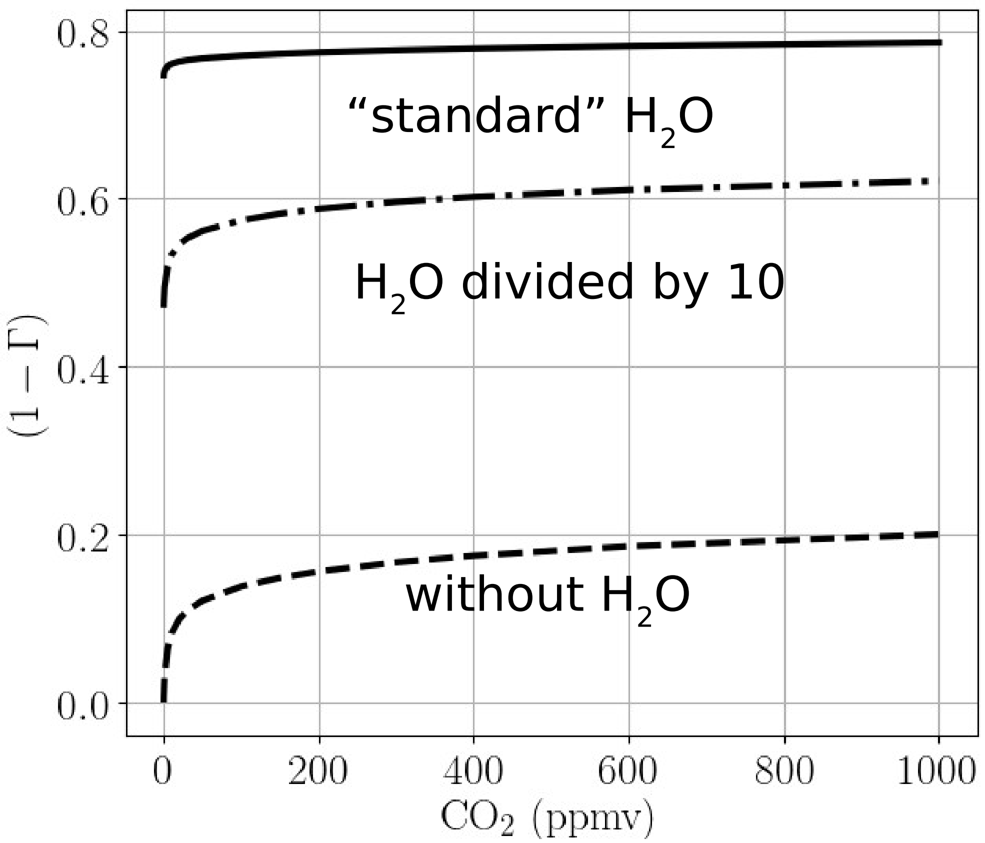
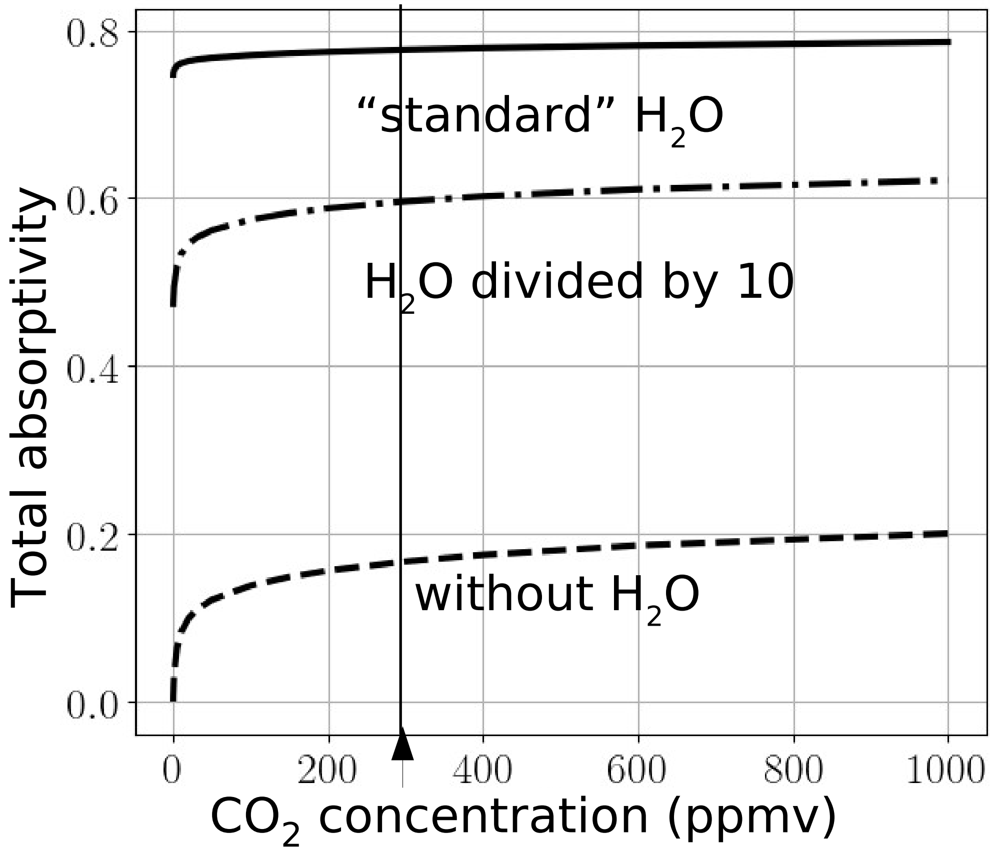


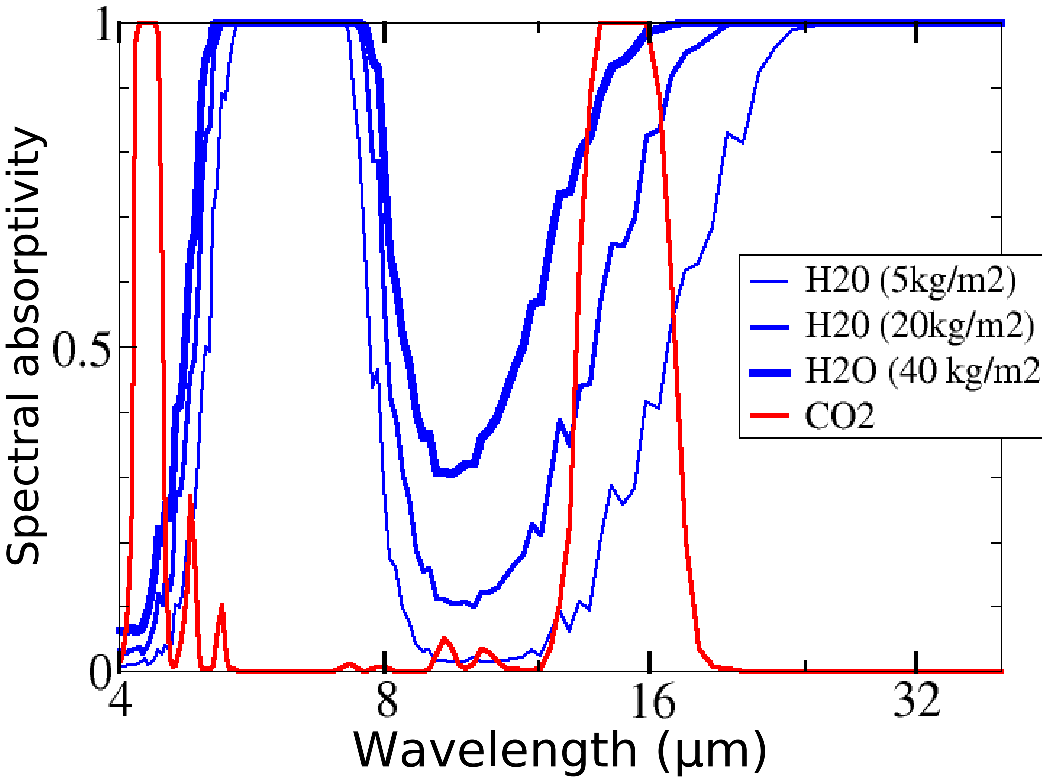
Why does the greenhouse effect increase with CO_2 while absorptivity does not?

1) Why does the absorptivity of CO_2 saturate while that of H_2O does not?

Total absorptivity ε_a of the atmosphere as a function of **CO_2 concentration** for different H_2O concentrations

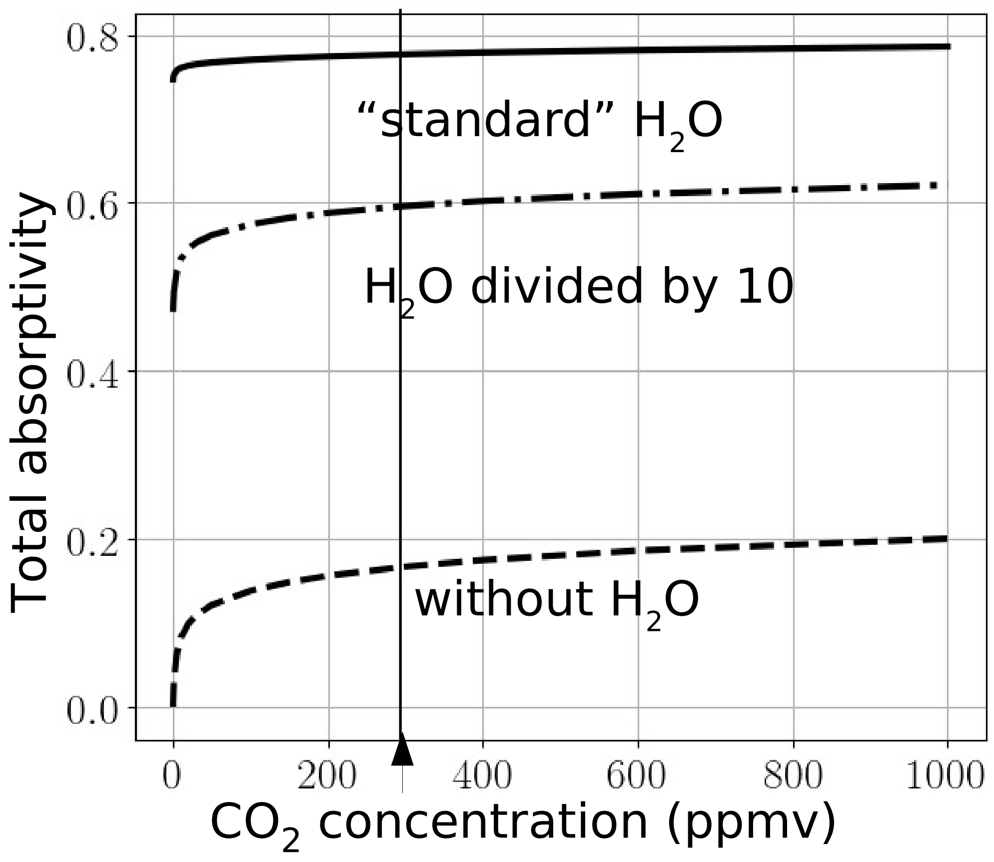


Spectral absorptivity ε_a of the atmosphere due to **CO_2** and **H_2O** for different H_2O concentrations

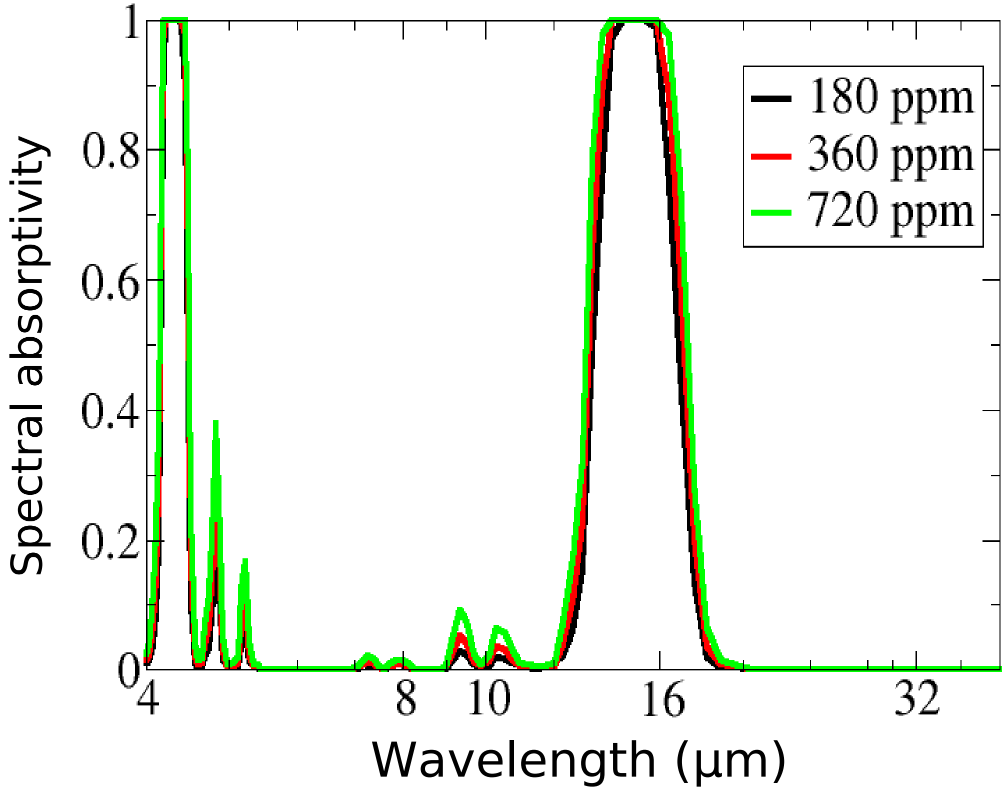


1) Why does the absorptivity of CO_2 saturate while that of H_2O does not?

Total absorptivity ε_a of the atmosphere as a function of **CO_2 concentration** for different H_2O concentrations

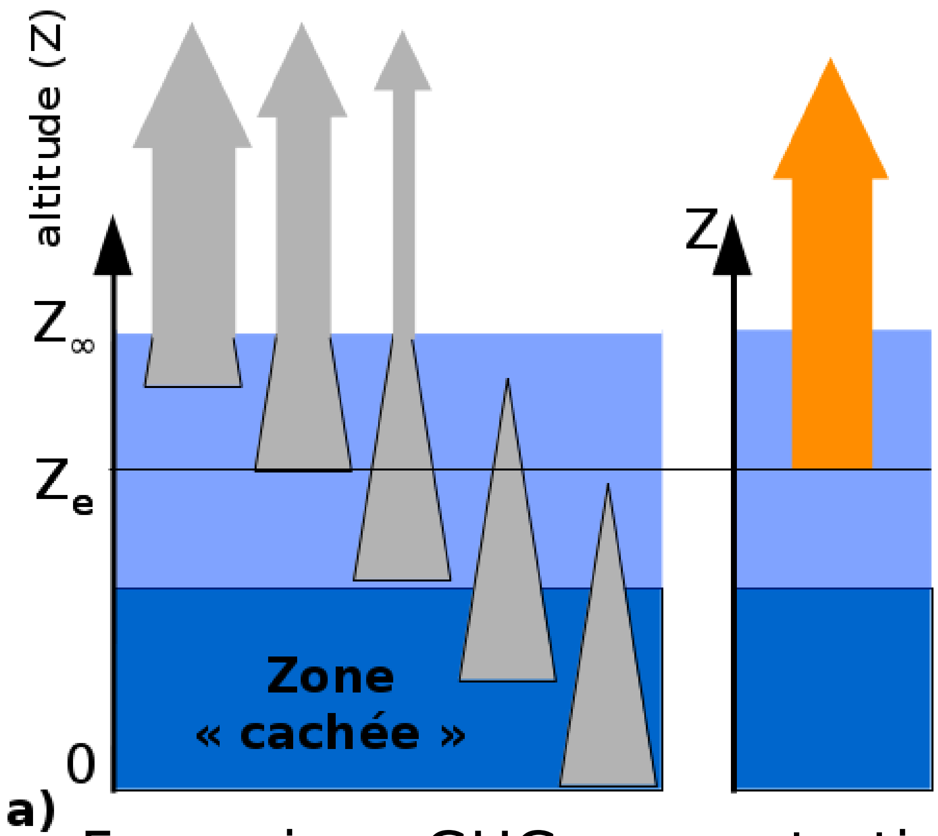


Spectral absorptivity ε_a of the atmosphere due to **CO_2** only for different CO_2 concentrations



2) Why is the greenhouse effect increasing even if the absorptivity is not increasing?

The concept of emission height



For a given GHG concentration

[Dufresne et Treiner, 2011]

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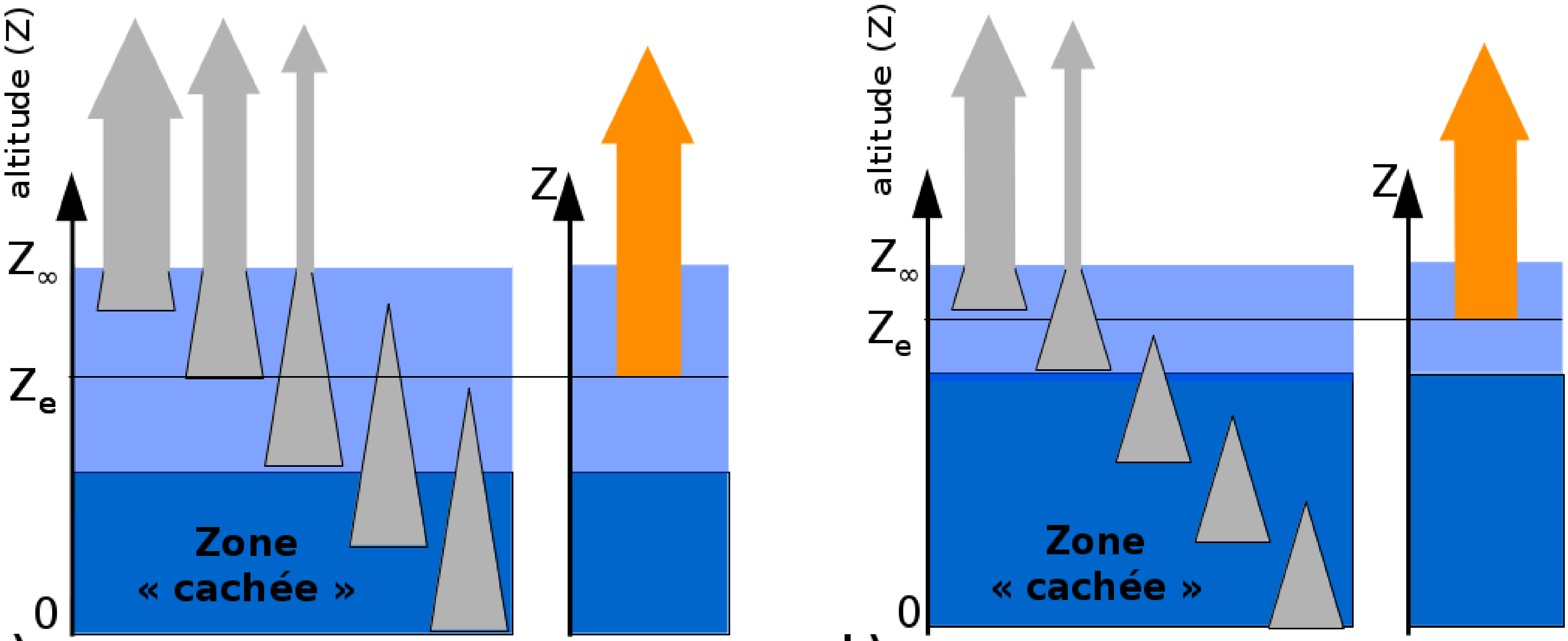
The concept of emission height

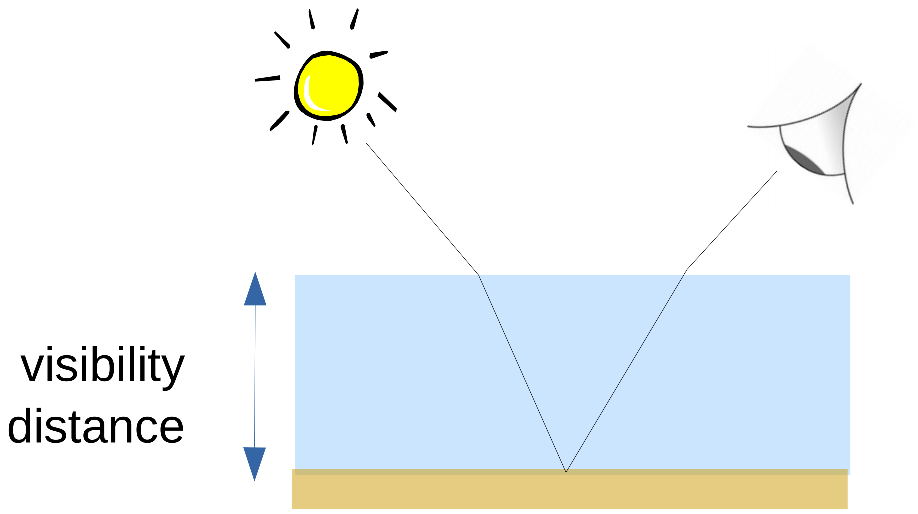


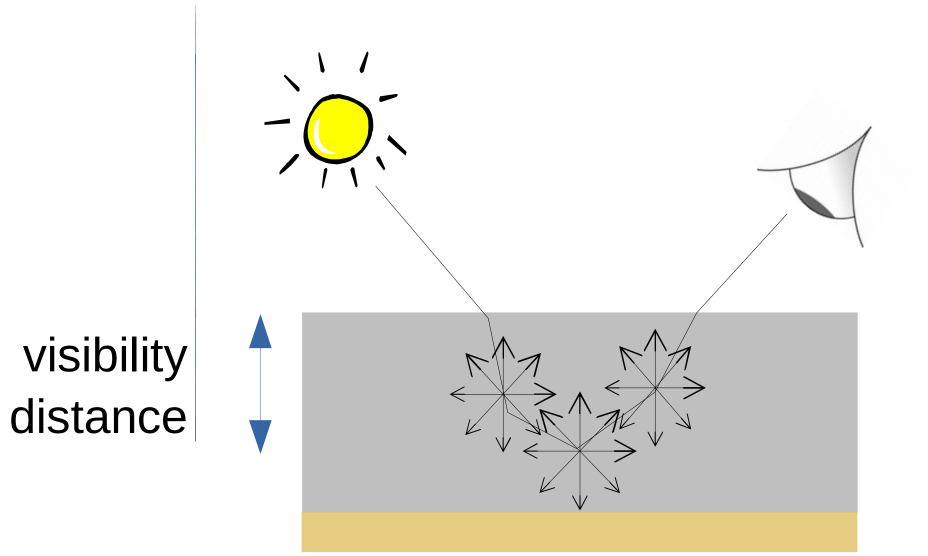
a) For a given GHG concentration

b) After an increase of the GHG concentration

[Dufresne et Treiner, 2011]

Analogy between emission height and visibility distance



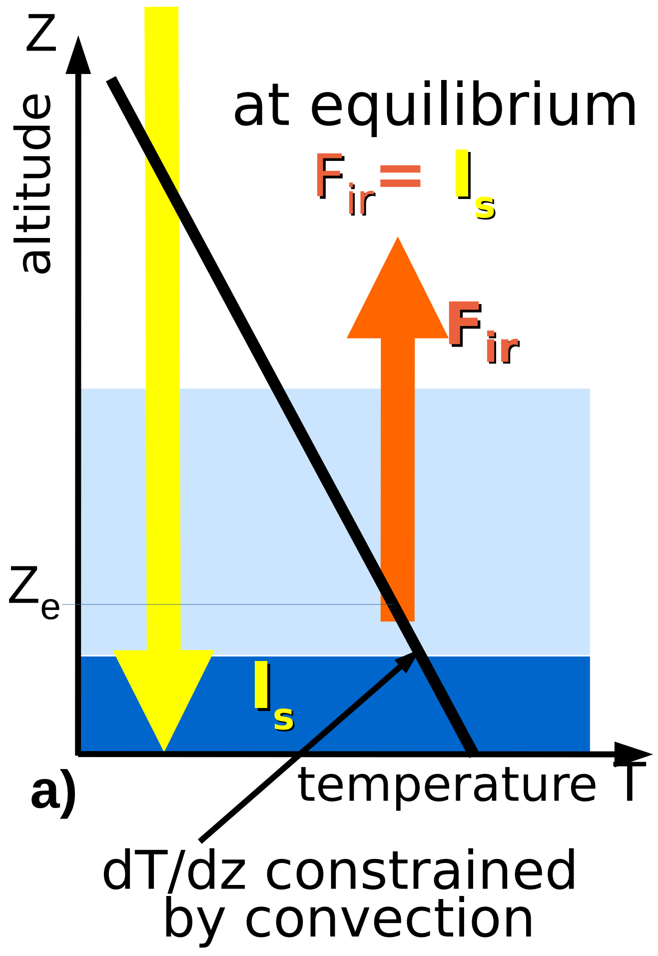


Greenhouse effect in a ***stratified*** atmosphere

I_s: solar radiation (SW)

F_{ir}: outgoing infrared (LW) radiation

Ze: emission height



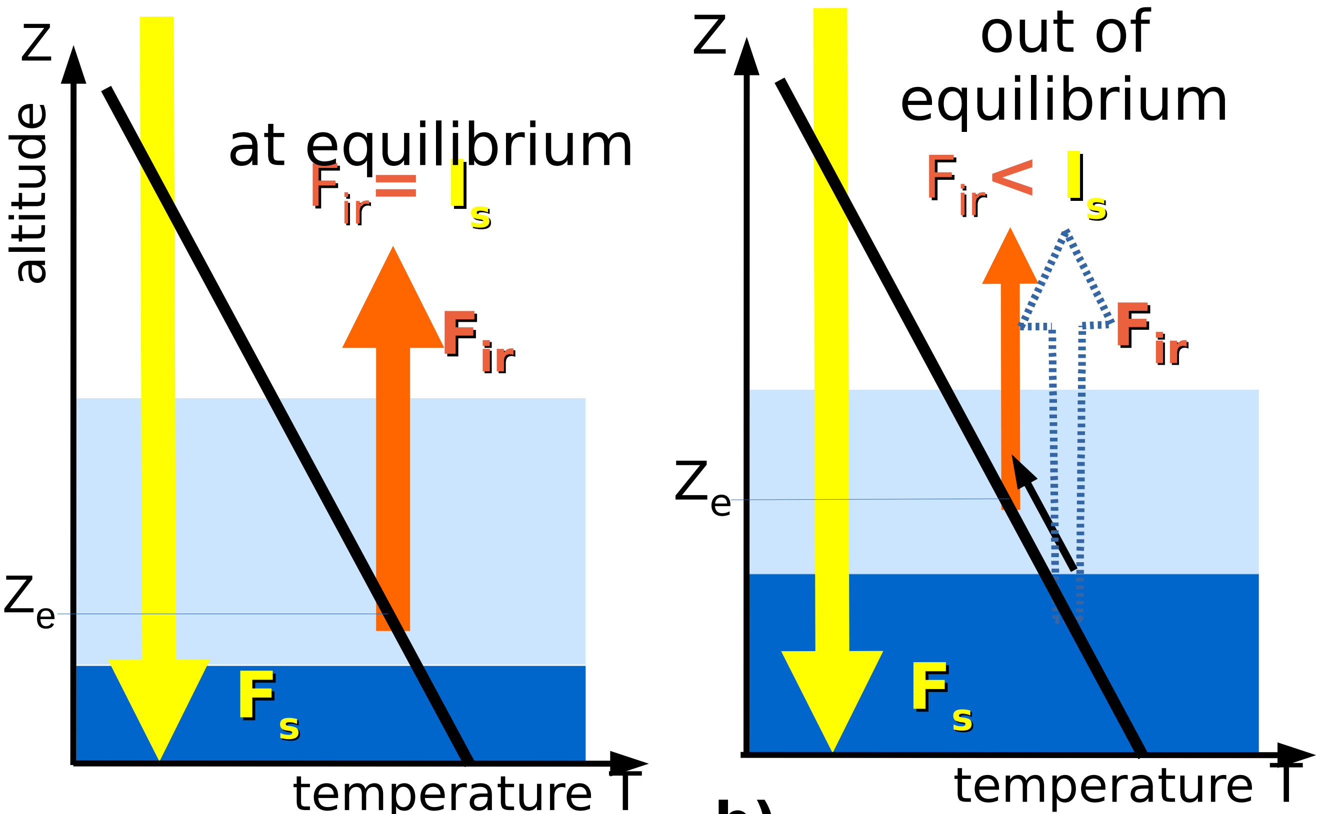
The concentration of greenhouse gases is vertically uniform.

Visible zone (photons emitted upwards reach the space)

Hidden zone (photons emitted upwards are absorbed and do not reach the space)

Greenhouse effect in a ***stratified*** atmosphere

Vertically uniform increase of the GHG concentration

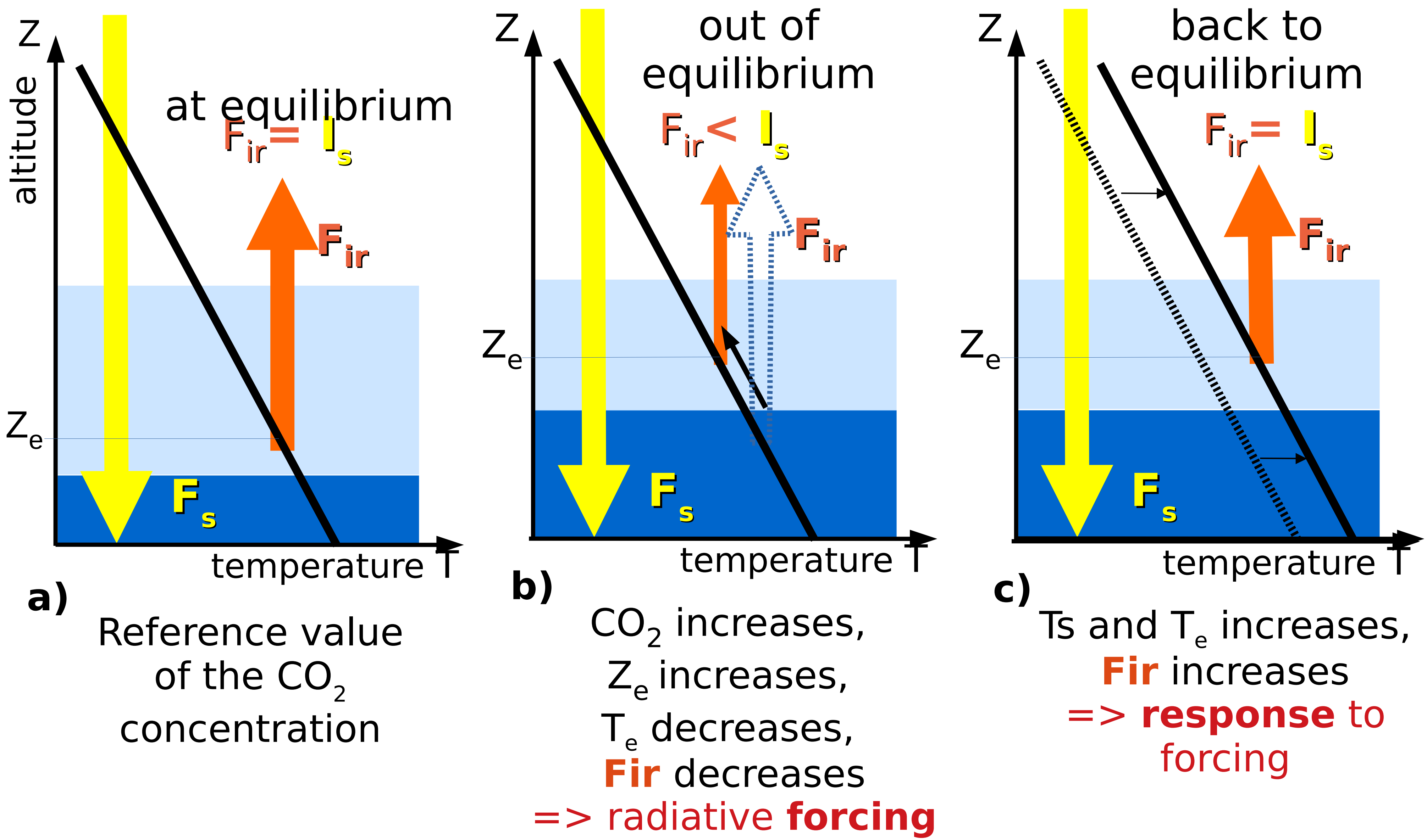


a) Reference value of the CO_2 concentration

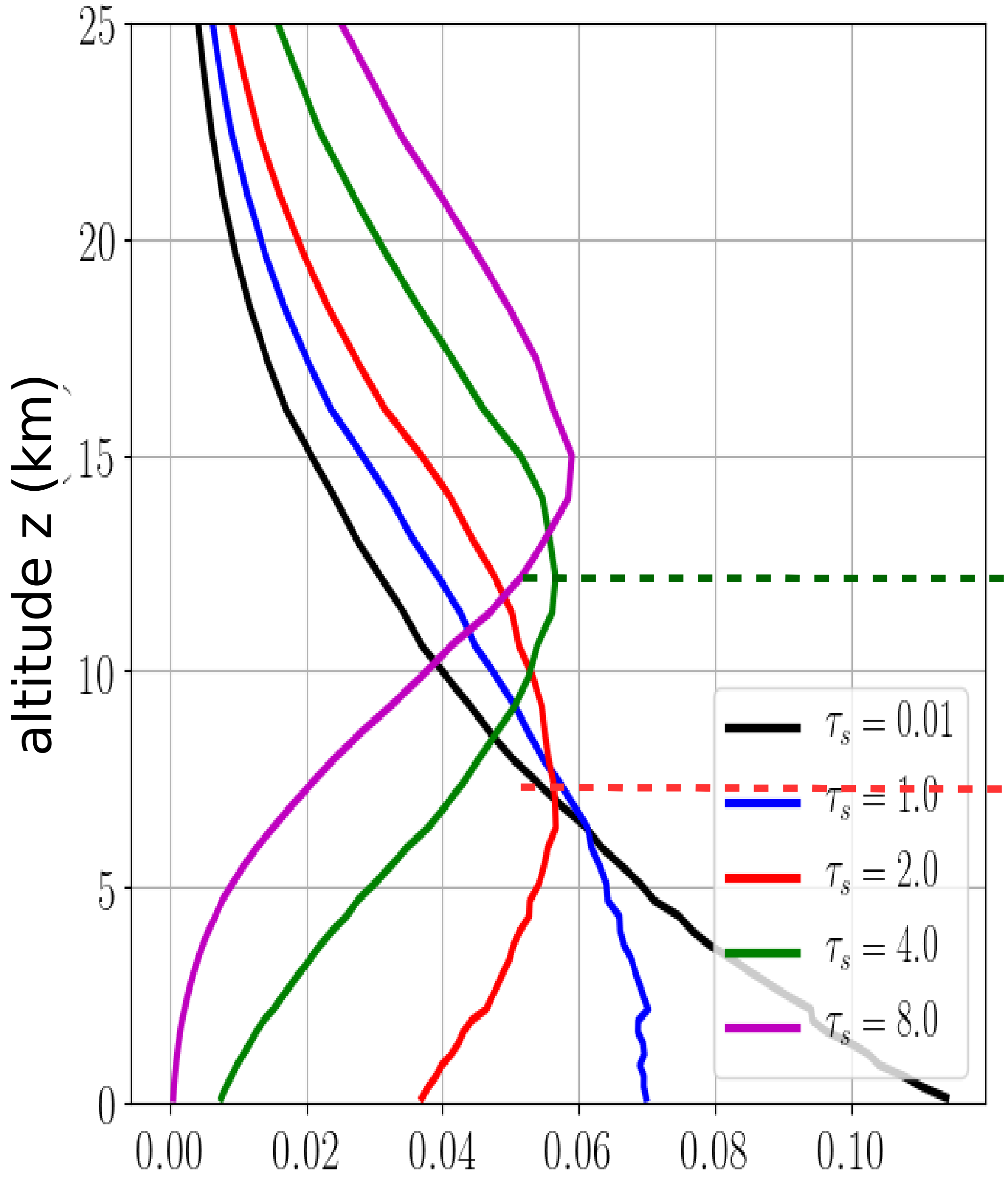
b) CO_2 increases,
Z_e increases,
T_e decreases,
Fir decreases
=> radiative **forcing**

Greenhouse effect in a ***stratified*** atmosphere

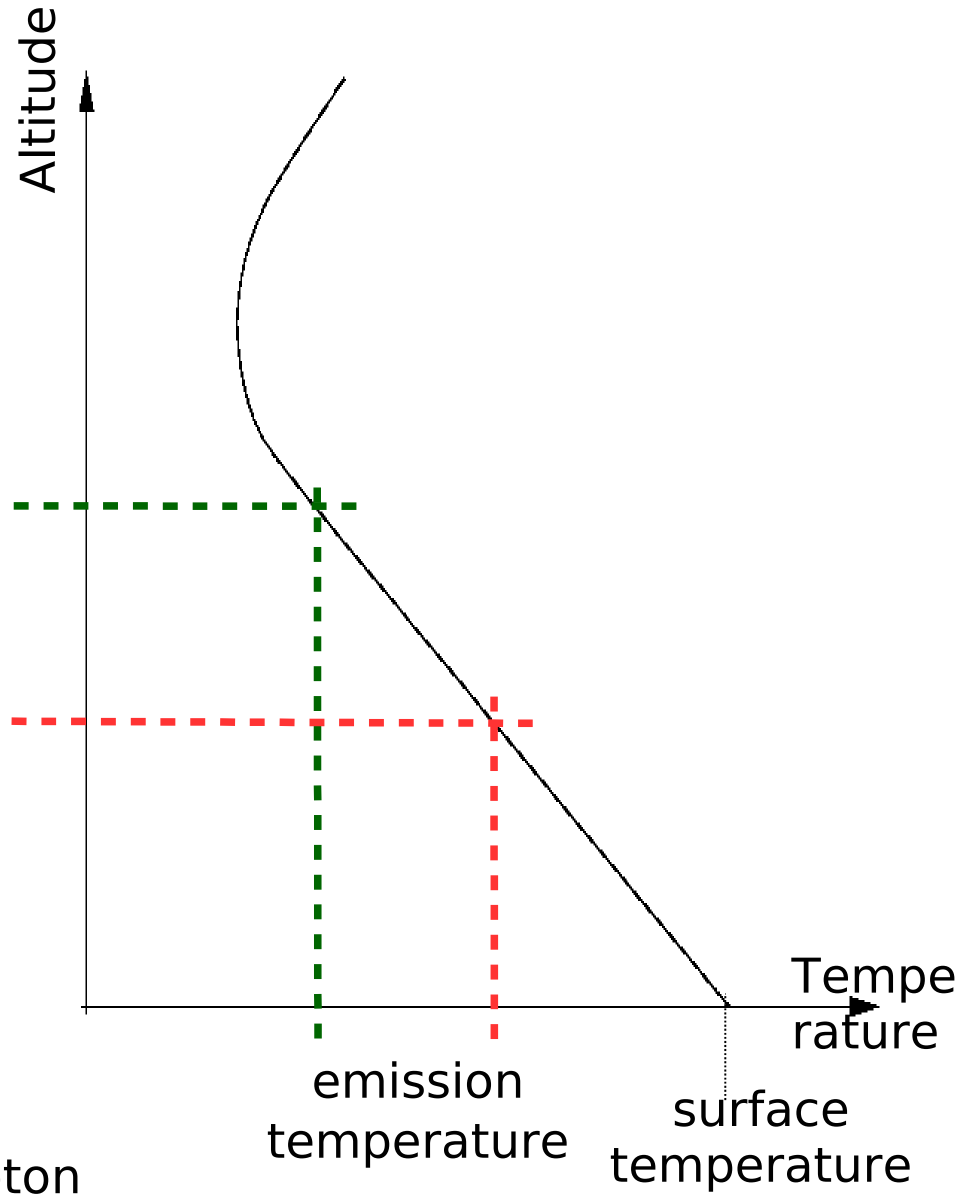
Vertically uniform increase of the GHG concentration



The concept of emission height

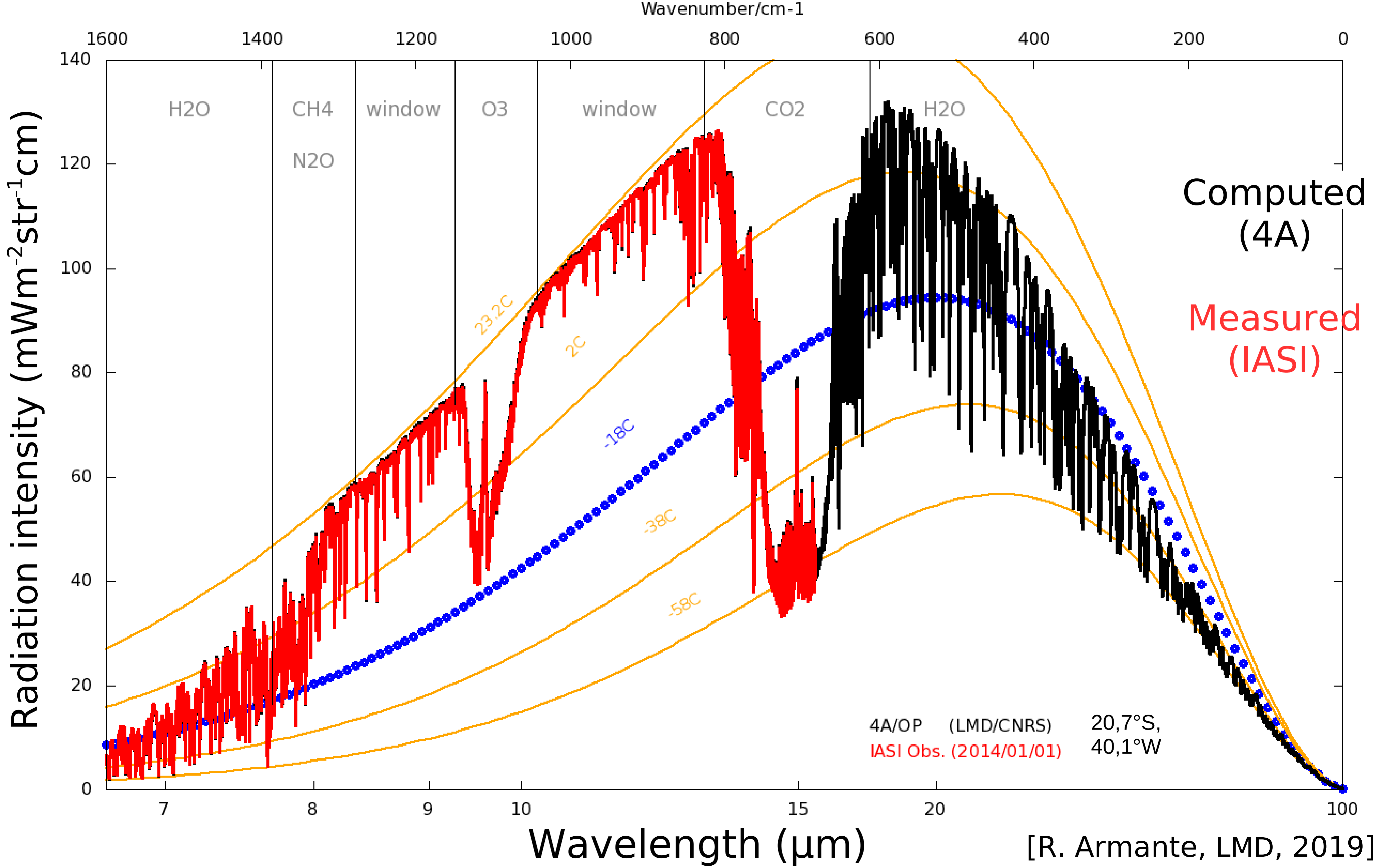


Probability density function (km^{-1}) that a photon reaching space has been emitted at altitude z for different optical thicknesses of the atmosphere



[Dufresne et al., 2020]

Spectrum of the radiation emitted by the Earth as measured by satellites



[R. Armante, LMD, 2019]

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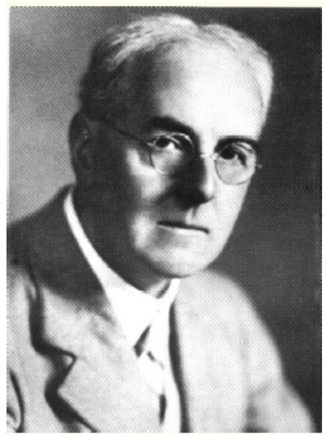
Numerical climate models
(numerical weather simulators)

Wilhelm Bjerknes

(1862–1951)

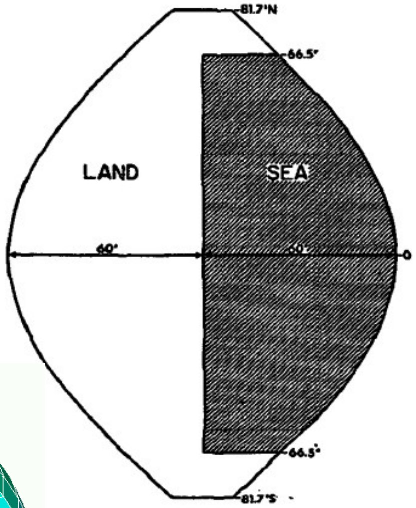


L. F. Richardson

(1881–1953)

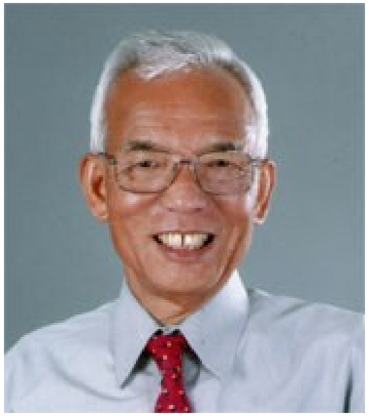
J. von Neumann

(1903–1957)



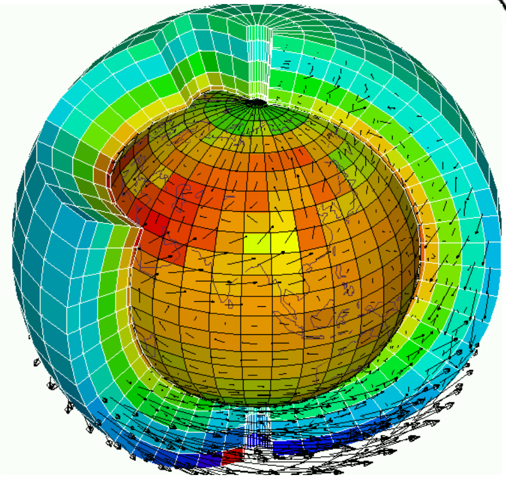
Jule Charney

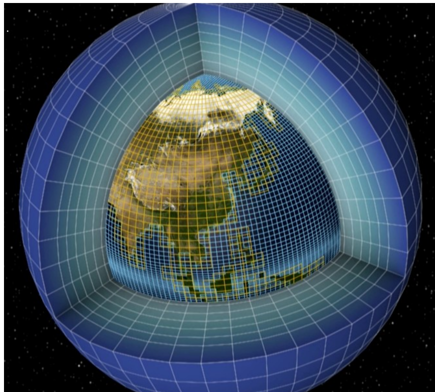
(1917-1981)



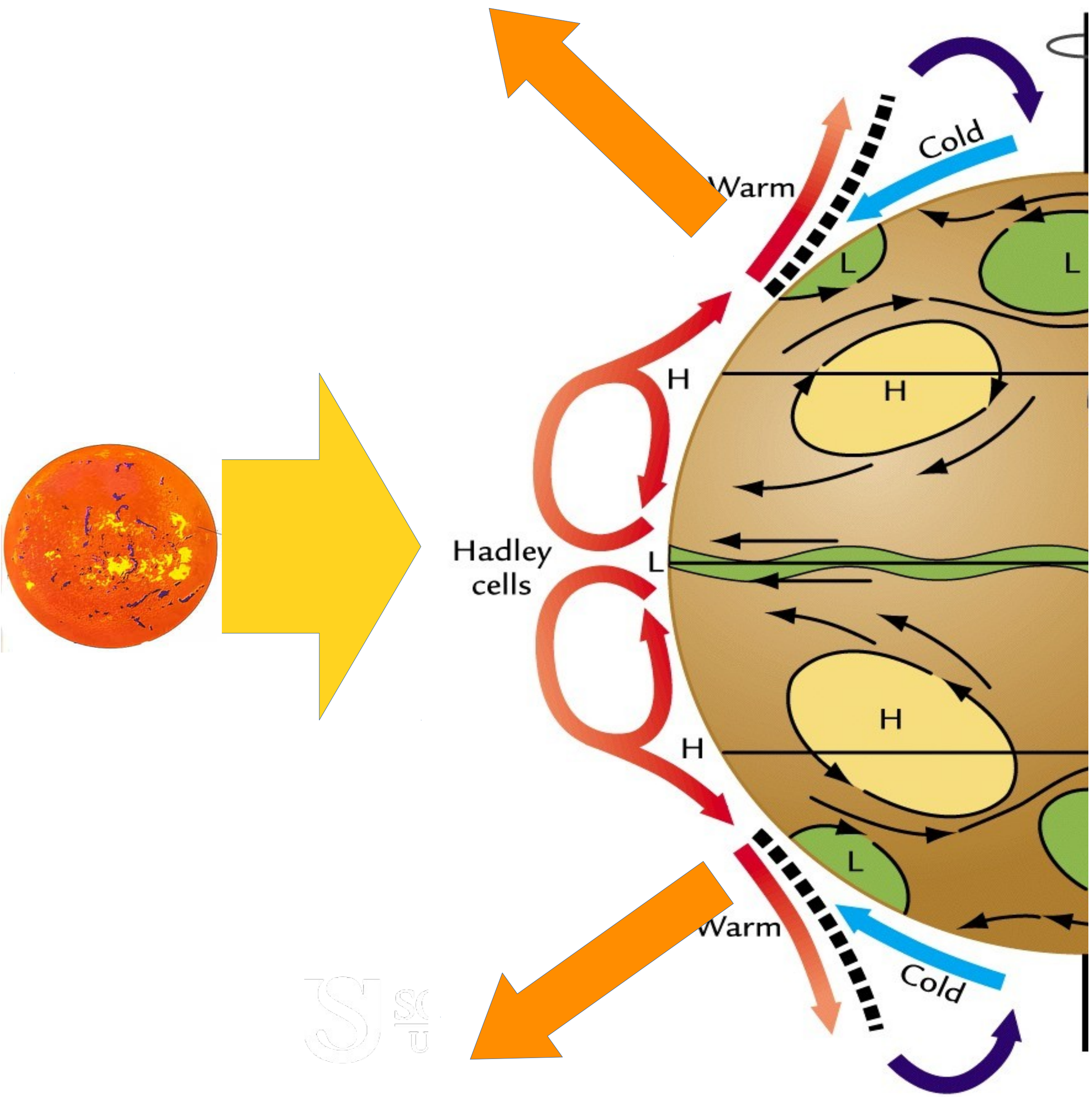
Syukuro Manabe

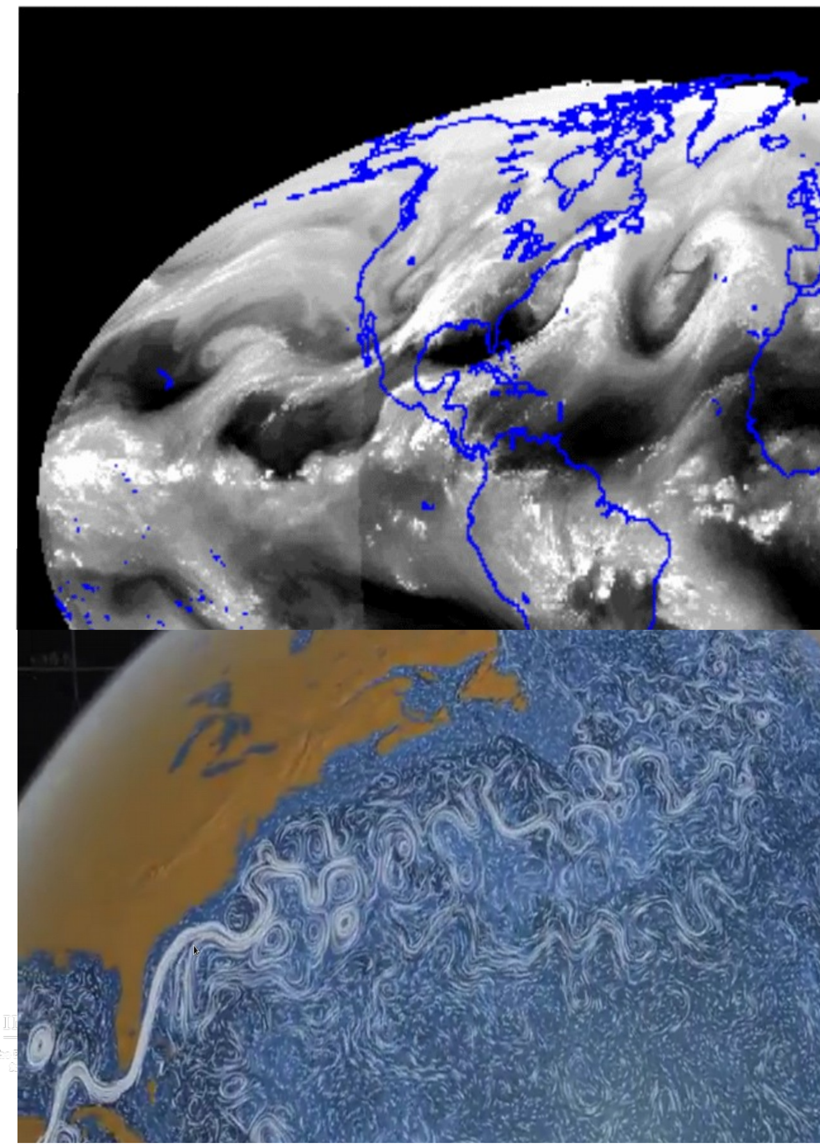
(1931-)



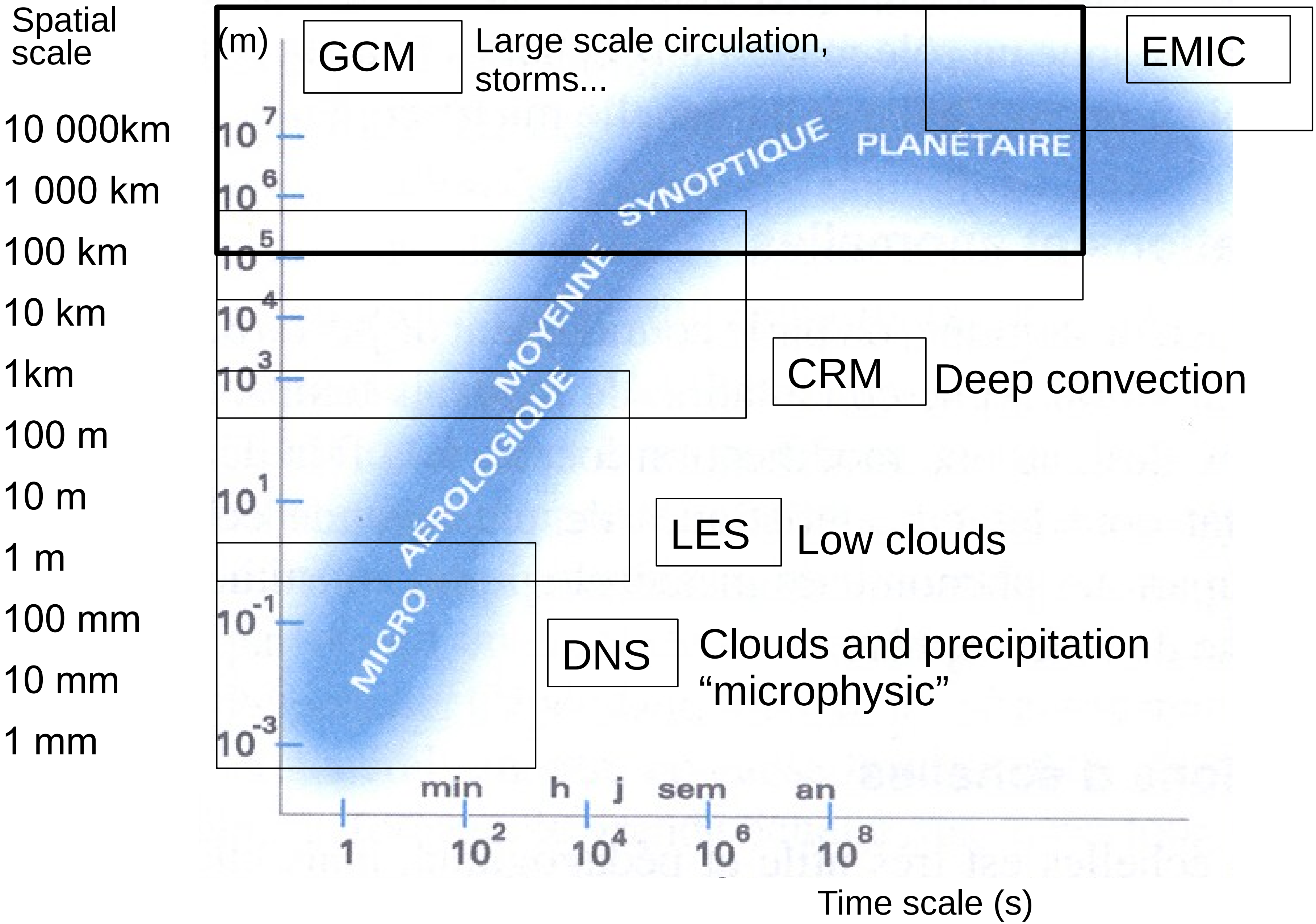


Large scale circulation: Meridional heat transport and the effects of Earth rotation

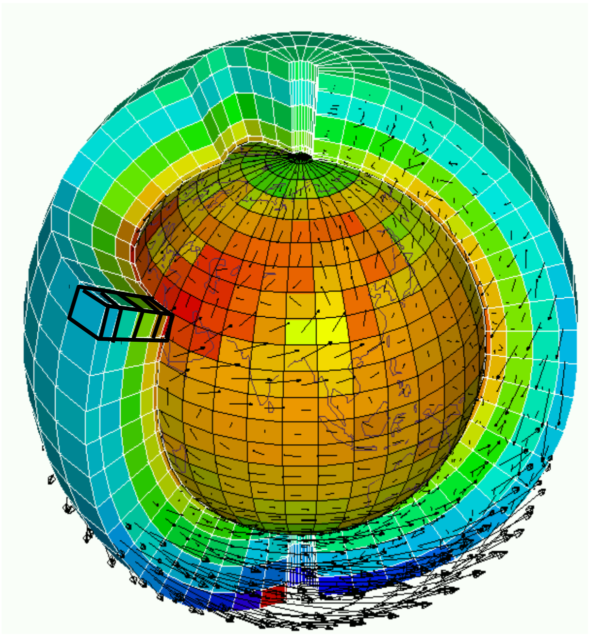




Relevant spatial and time scales



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

  $D\theta / Dt = Q / Cp\ (p_0/p)^{\kappa}$
- 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)

  $Dq/Dt = S_q$

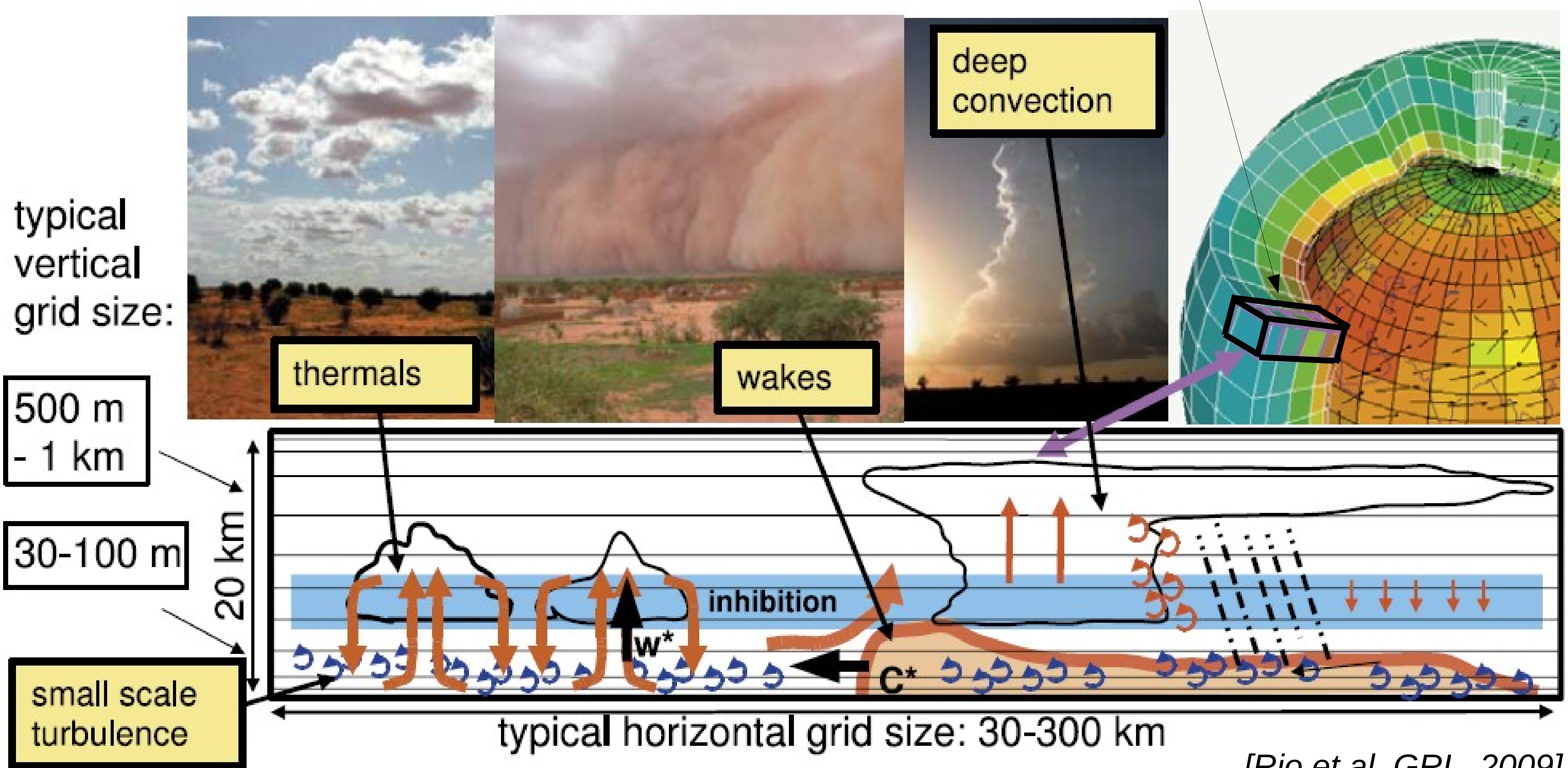
In red, source terms : other than fluid mechanics and unresolved scales

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
Development of parameterization

A typical vertical atmospheric column



[Rio et al, GRL, 2009]

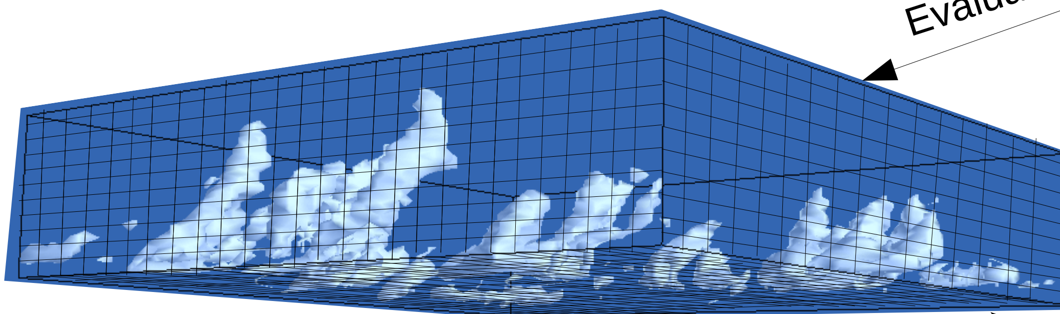
Typical time step : a few minutes to half an hour

Parameterization development and the use of high resolution explicit models

Test case, field campaign experiment

Observation

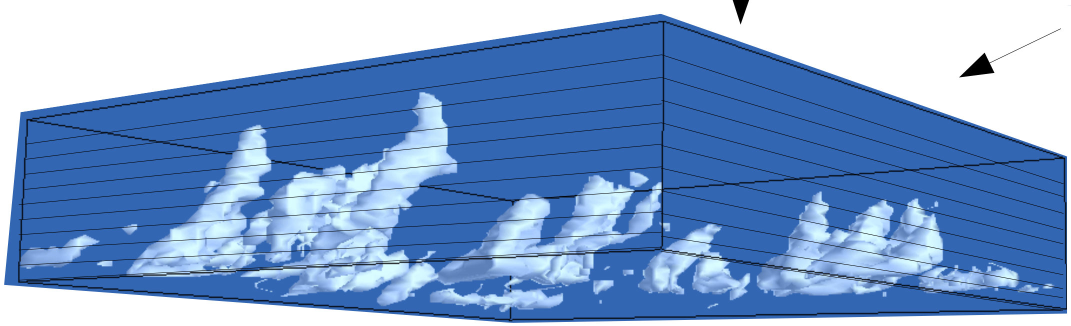
Evaluation

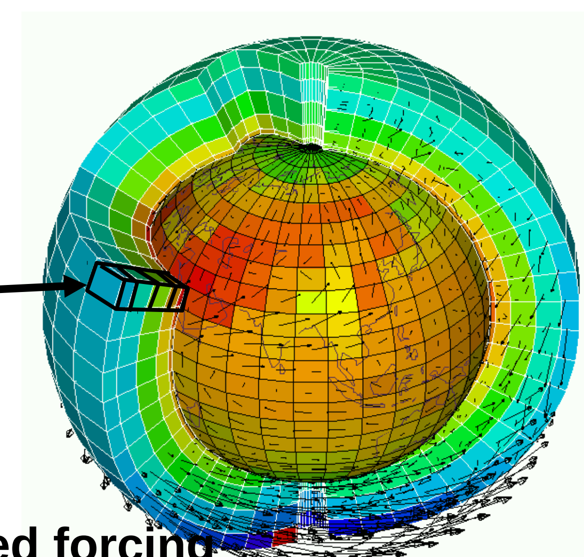


Explicit simulations, Grid cell, 20-100 m

Evaluation

« Large scale » conditions imposed



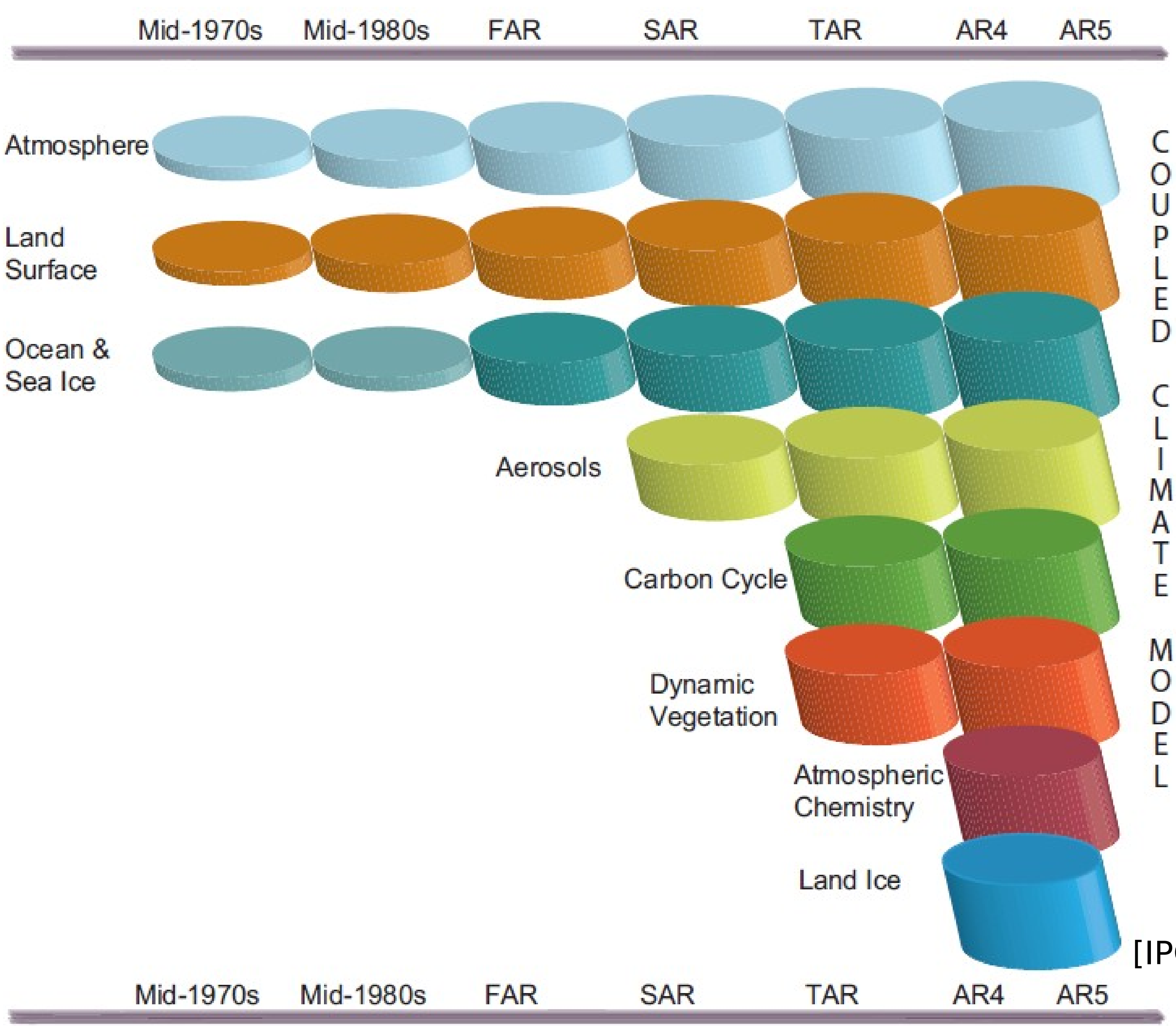


Climate model, parameterizations, « single-column » mode

→ **Parameterizations are evaluated against other models**

→ **Can be done for realistic test cases but also with more idealized forcing (check the response of the parameterization to perturbations)**

Evolution of climate models

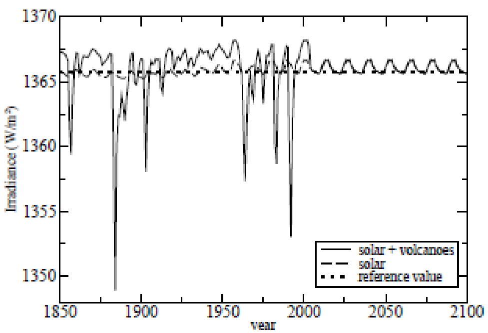


[IPCC, AR5]

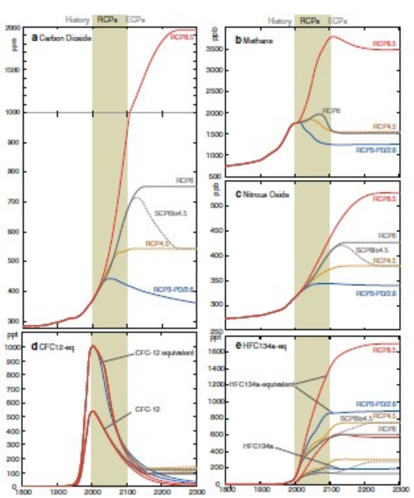
The IPSL Earth System Model

Natural and anthropogenic forcings

Solar and volcanoes

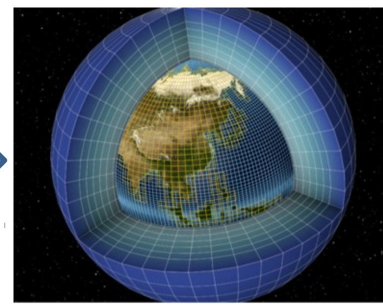


Green house gases and active gases

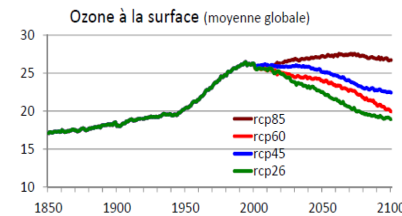


CO_2 concentration

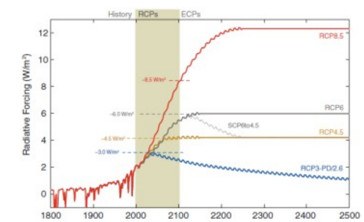
IPSL-CM5A-LR



Atmospheric composition

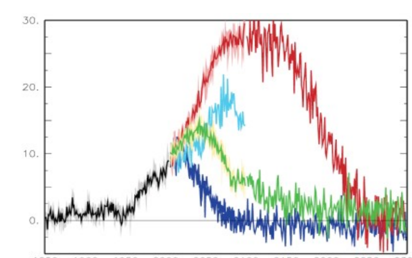


Radiative forcings

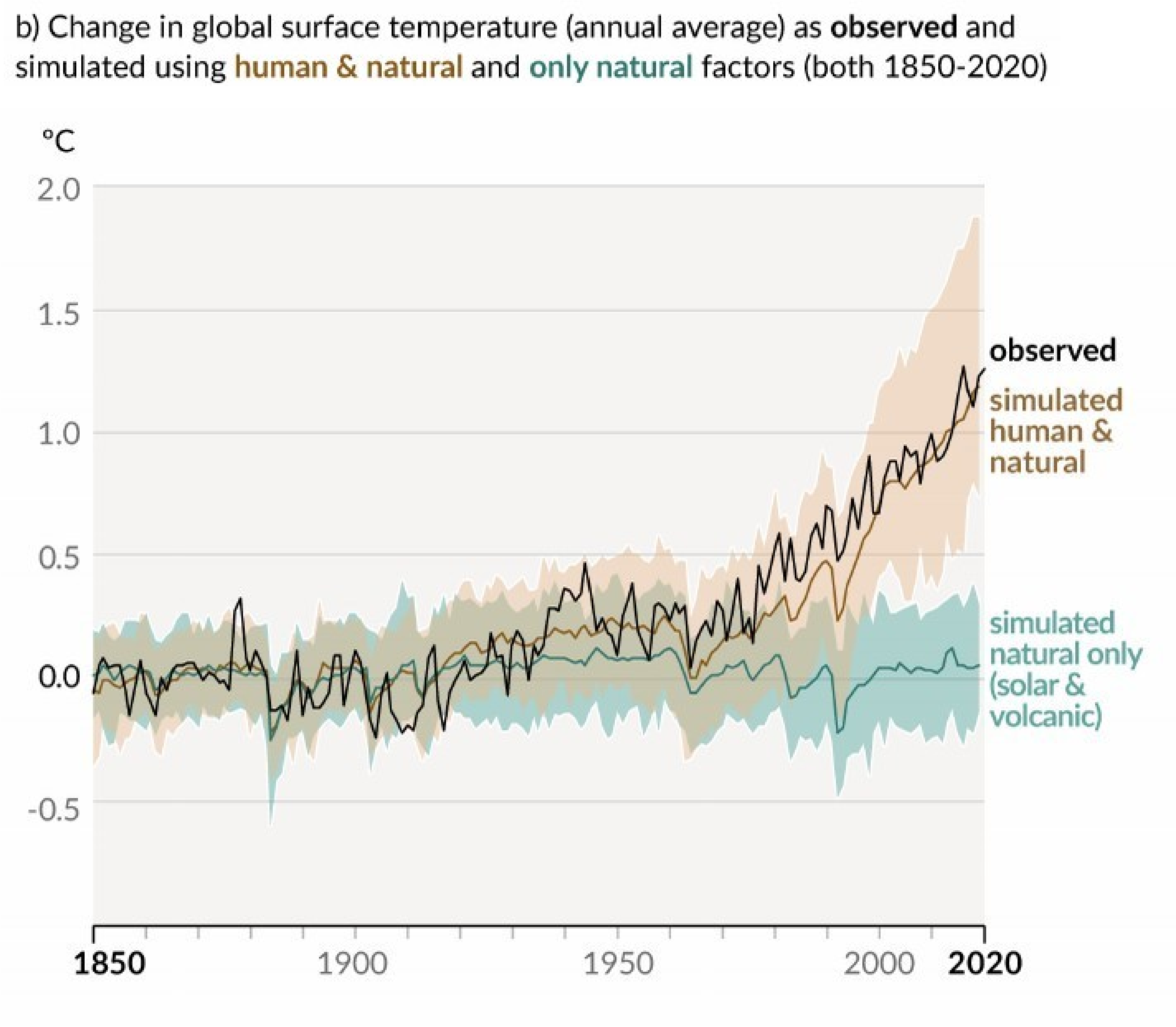


Climate changes

Authorized CO_2 emissions



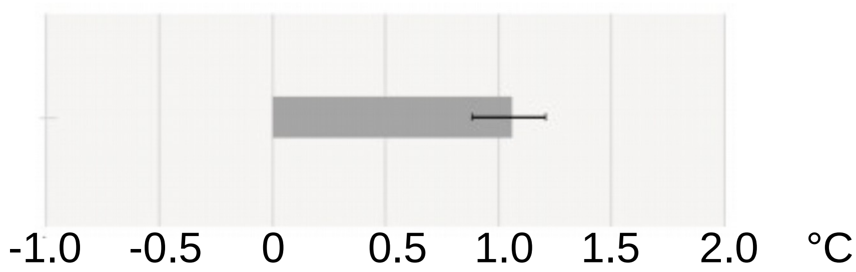
Human activities and recent climate change



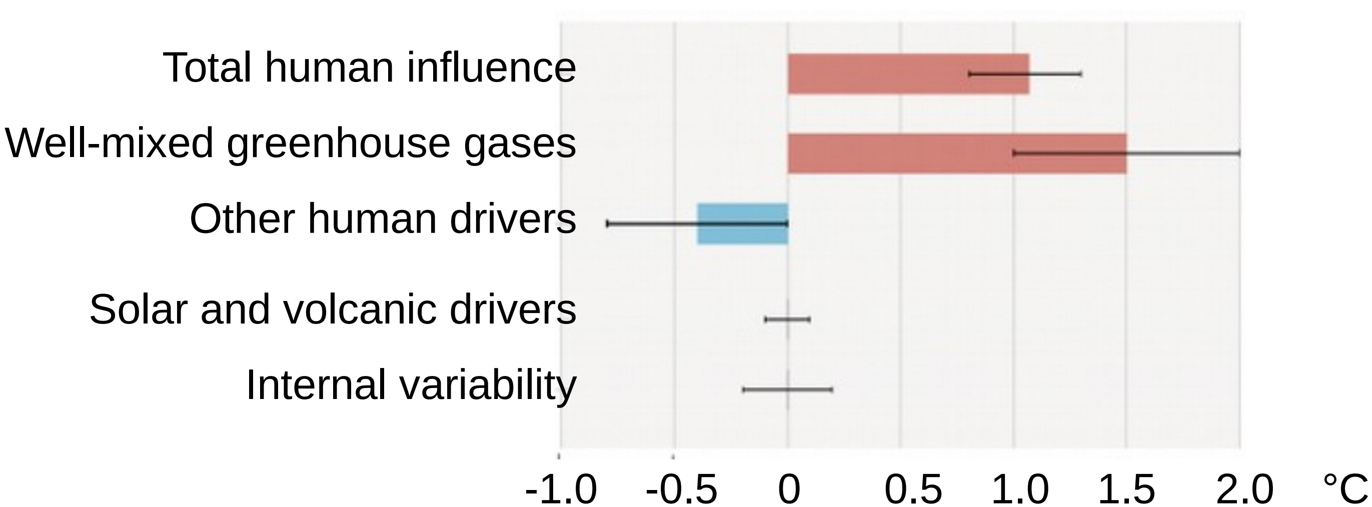
[IPCC, 2021]

Origins of the global warming

Observed warming 2010-2019 relative to 1850-1900



Aggregated contributions to 2010-2019 warming relative to 1850-1900

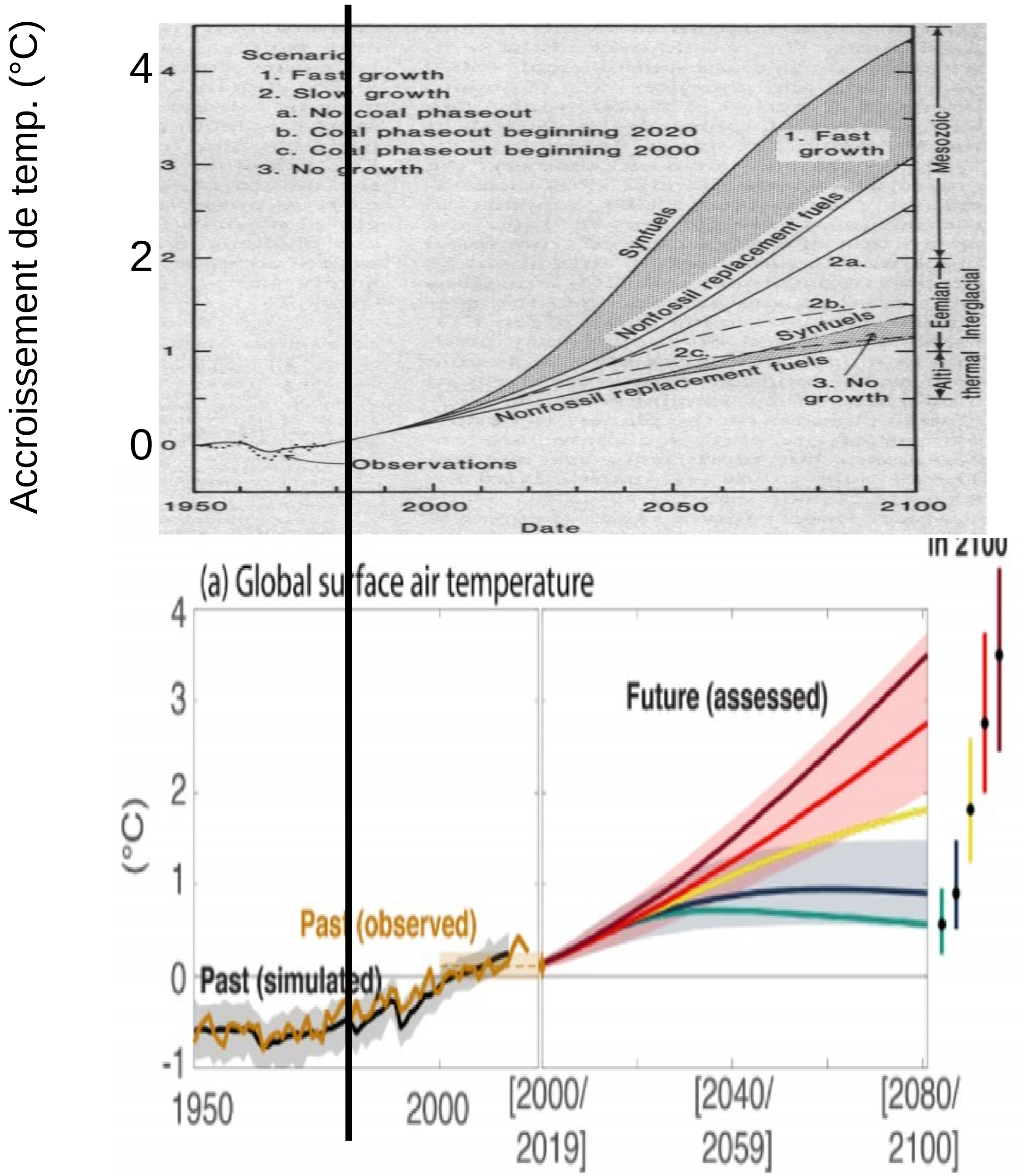


[IPCC, 2021]

Outlook

I. Basics of climate physics
II. The greenhouse effect
III. Climate modelling
IV. Future climate changes

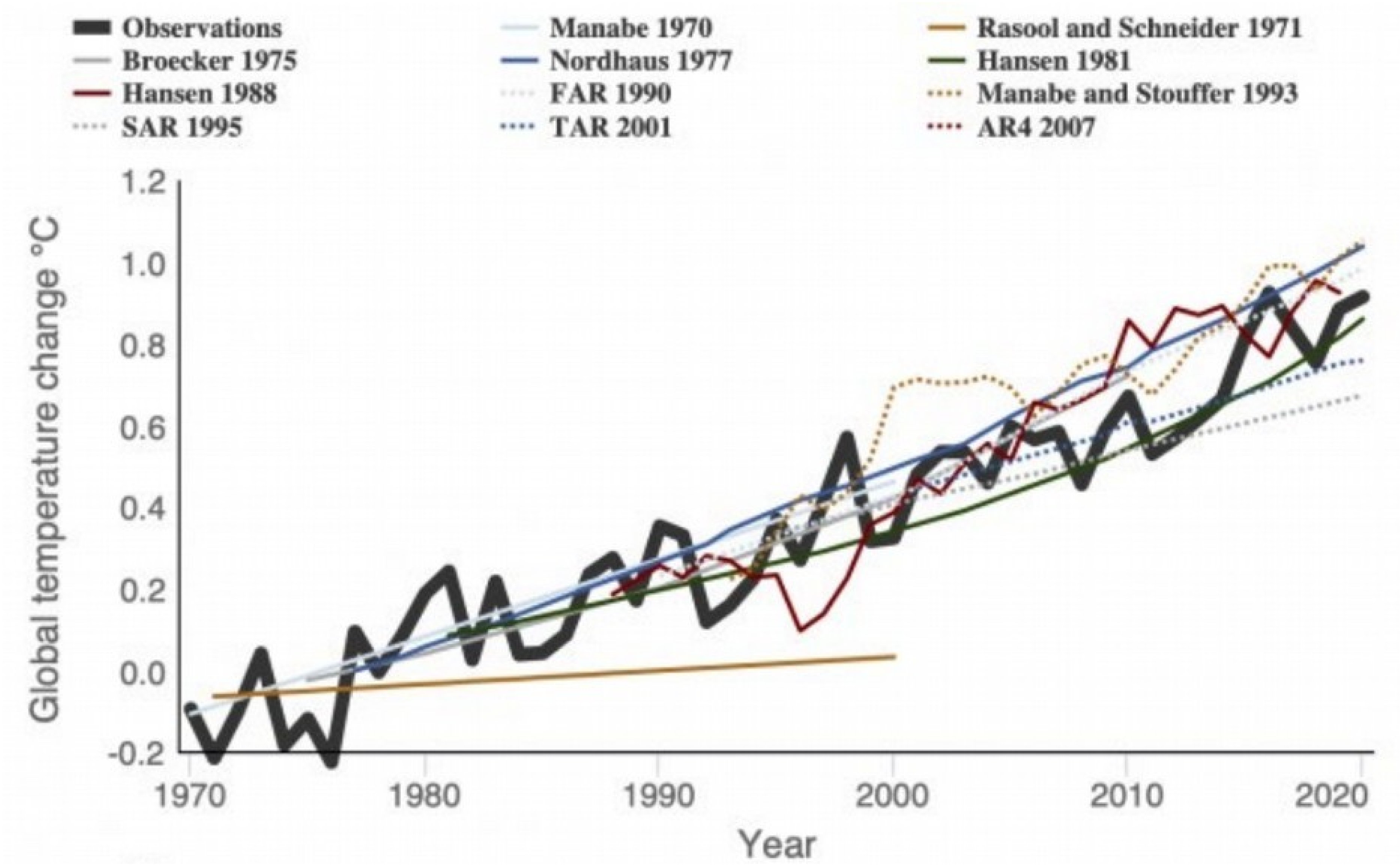
First climate projections before global warming has been observed



[Hansen et al. 1981]

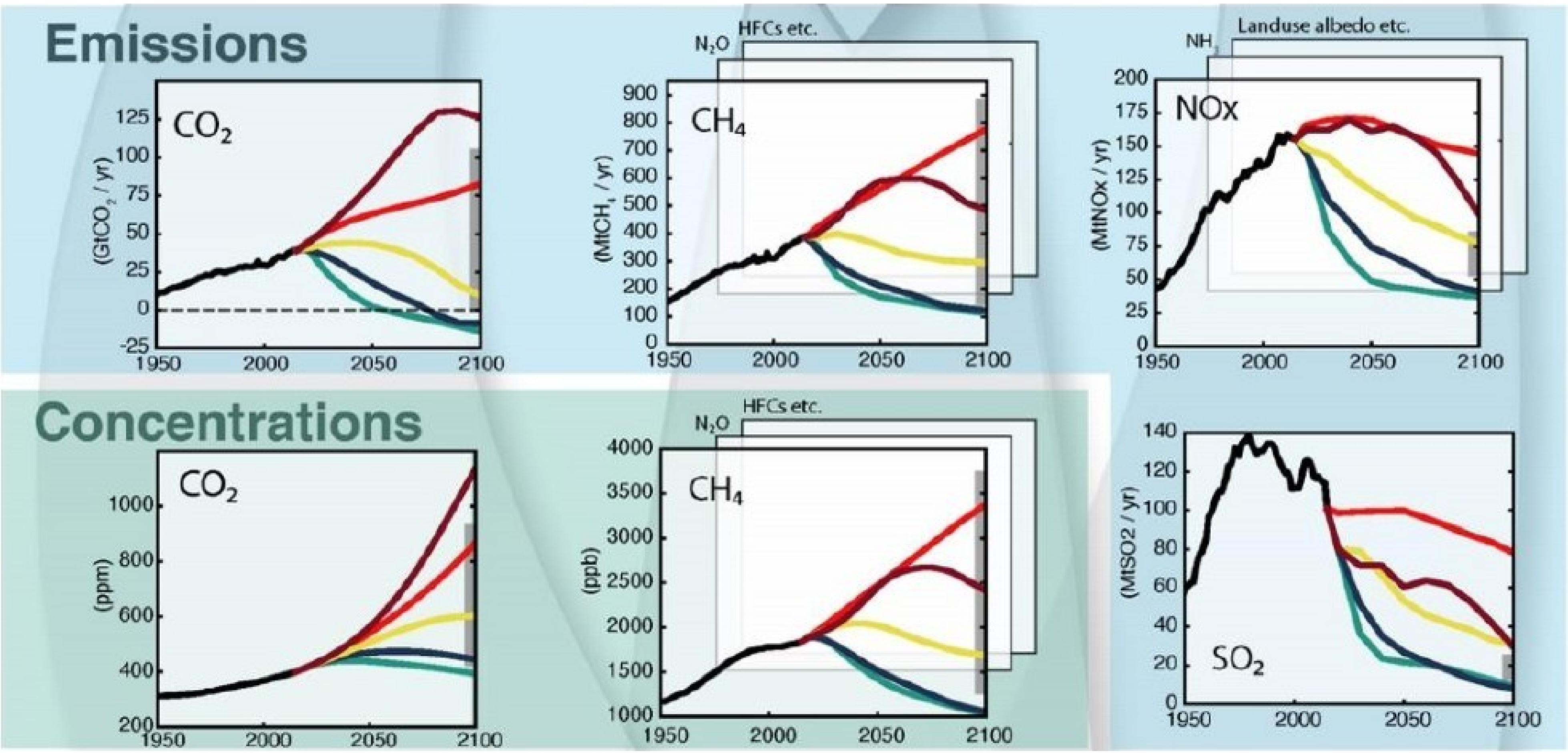
[IPCC 2021, TS]

Assessing past projections



[IPCC 2021, AR6-WG1, Ch1]

Future emission based on different socio-economic scenario

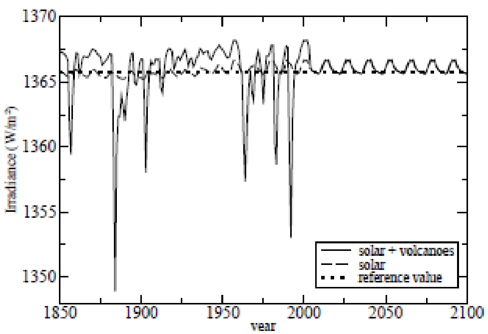


[IPCC AR6-WG1, TS]

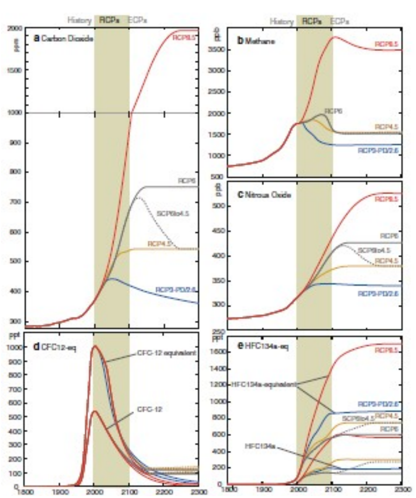
The IPSL Earth system model

Natural and anthropogenic forcings

Solar and volcanoes

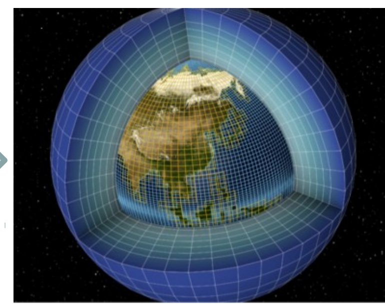


Green house gases and active gases

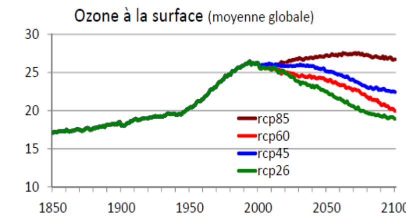


CO_2 concentration

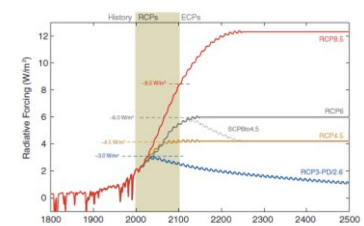
IPSL-CM5A-LR



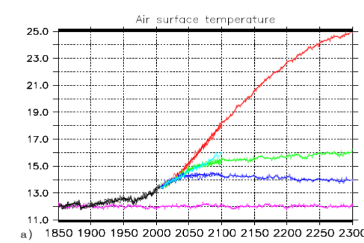
Atmospheric composition



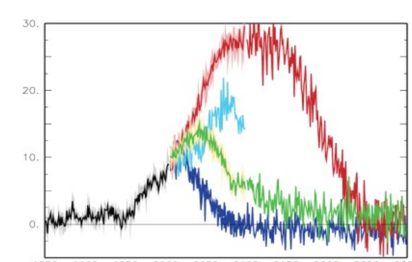
Radiative forcings



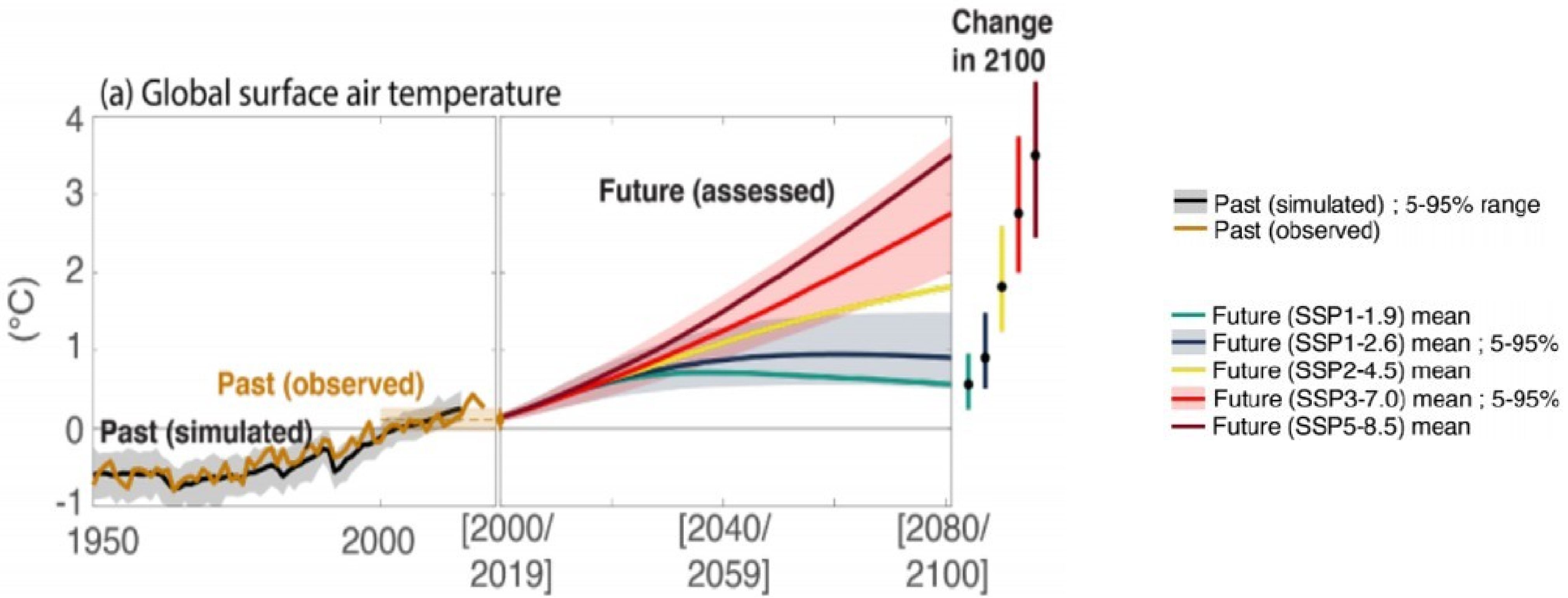
Climate changes

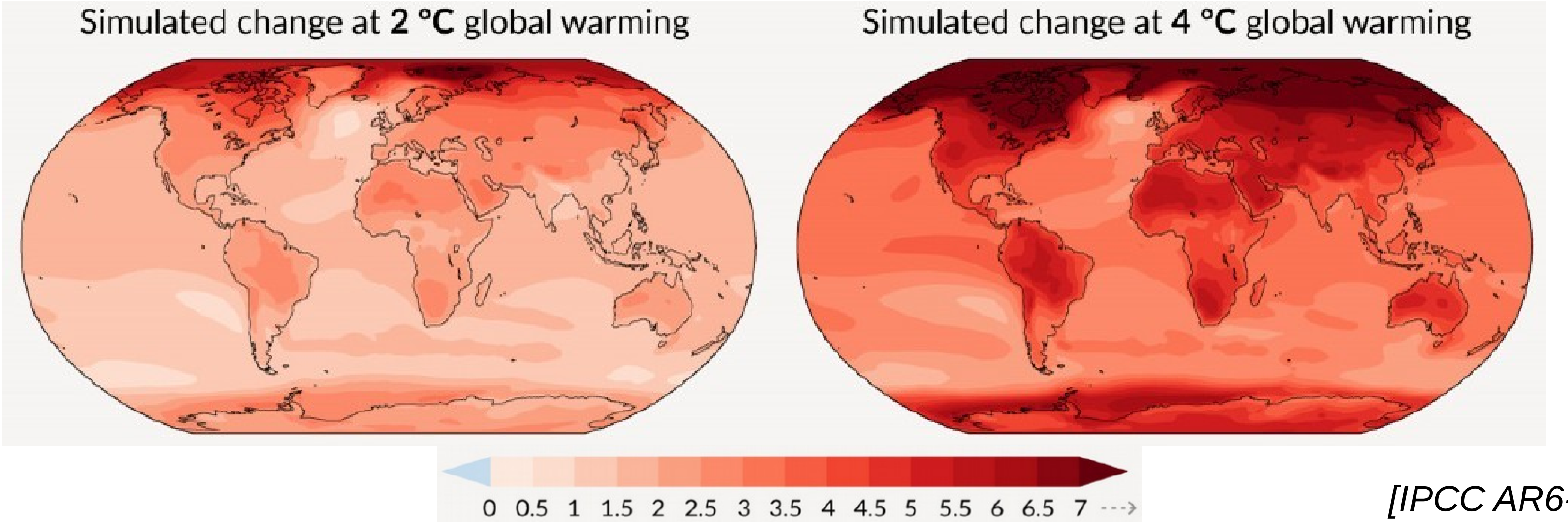


Authorized CO_2 emissions



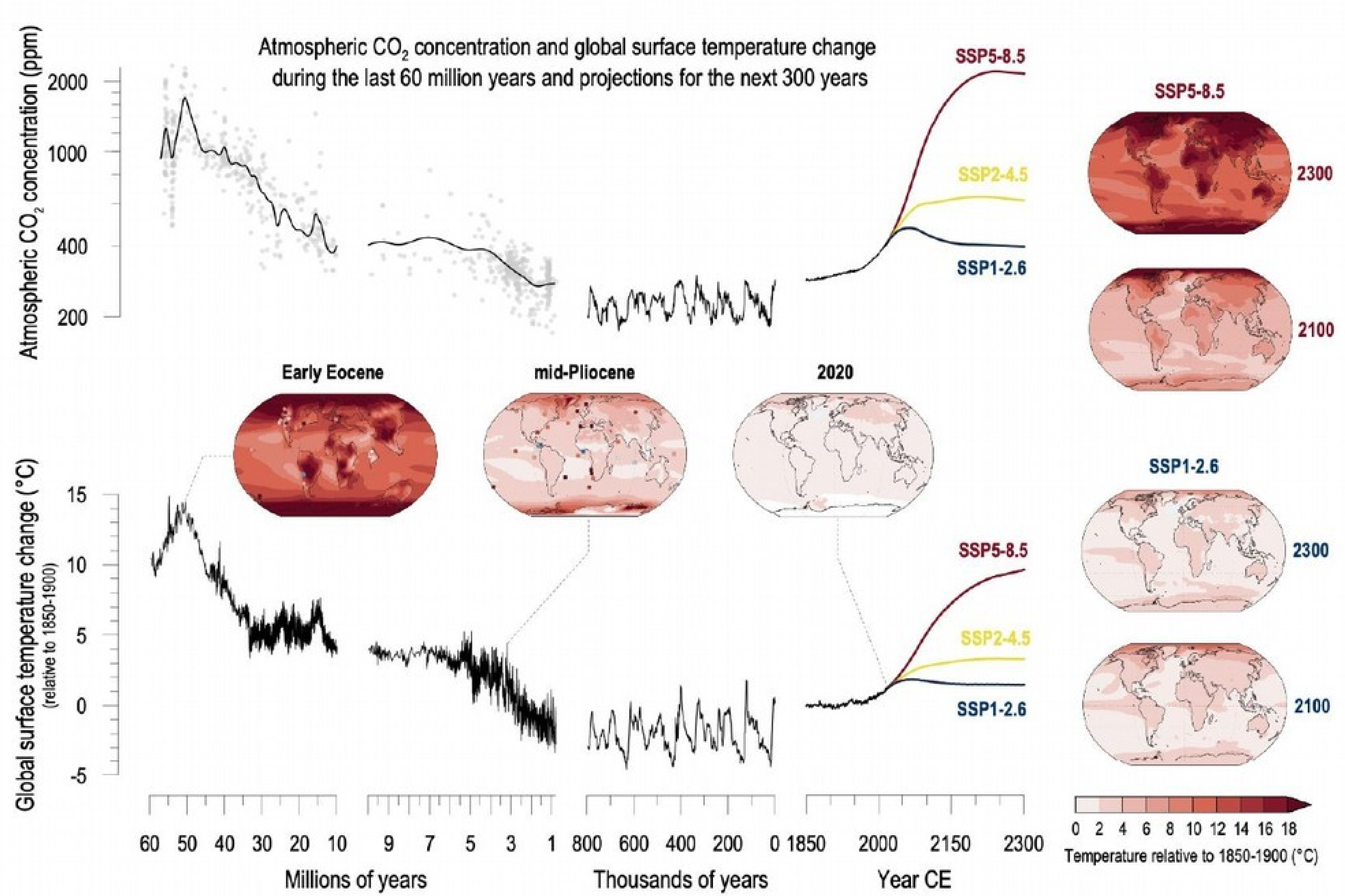
Global mean surface temperature change





[IPCC AR6-WG1, TS]

Past, recent and possible future changes

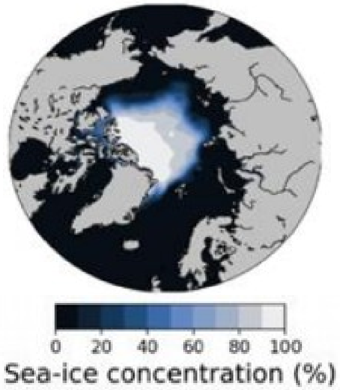


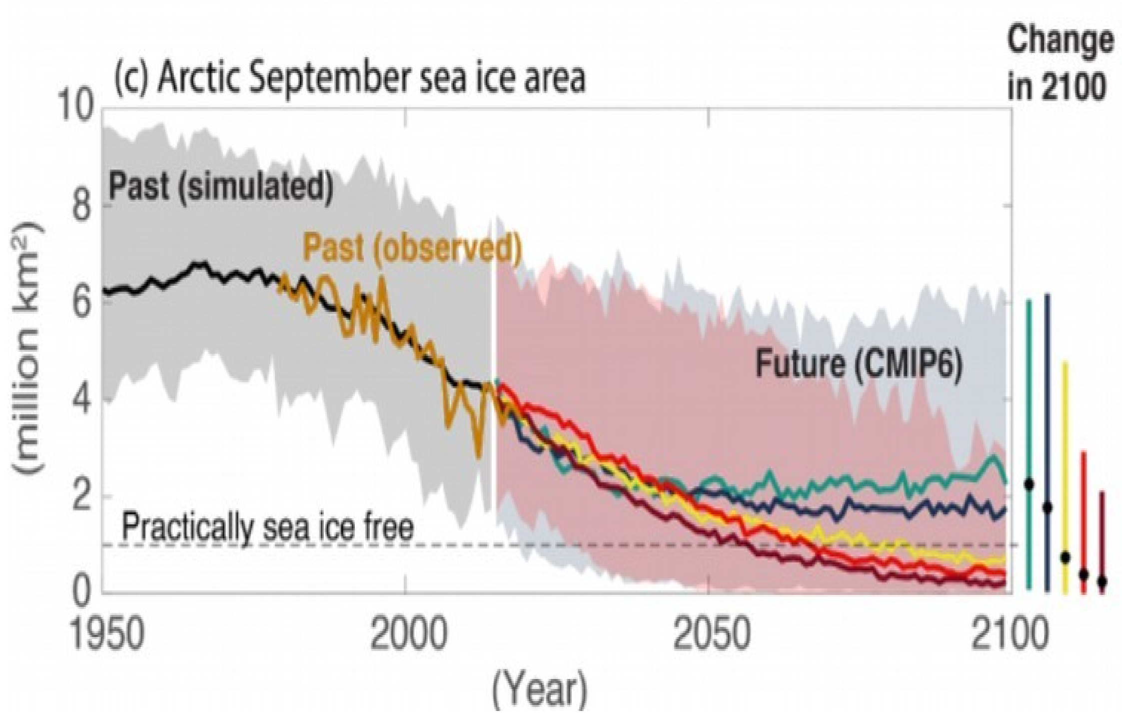
[IPCC AR6-WG1, TS]

Arctic sea-ice

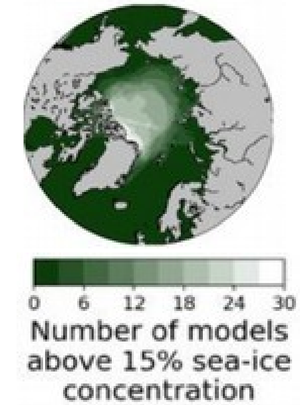
1979-1988

2010-2019



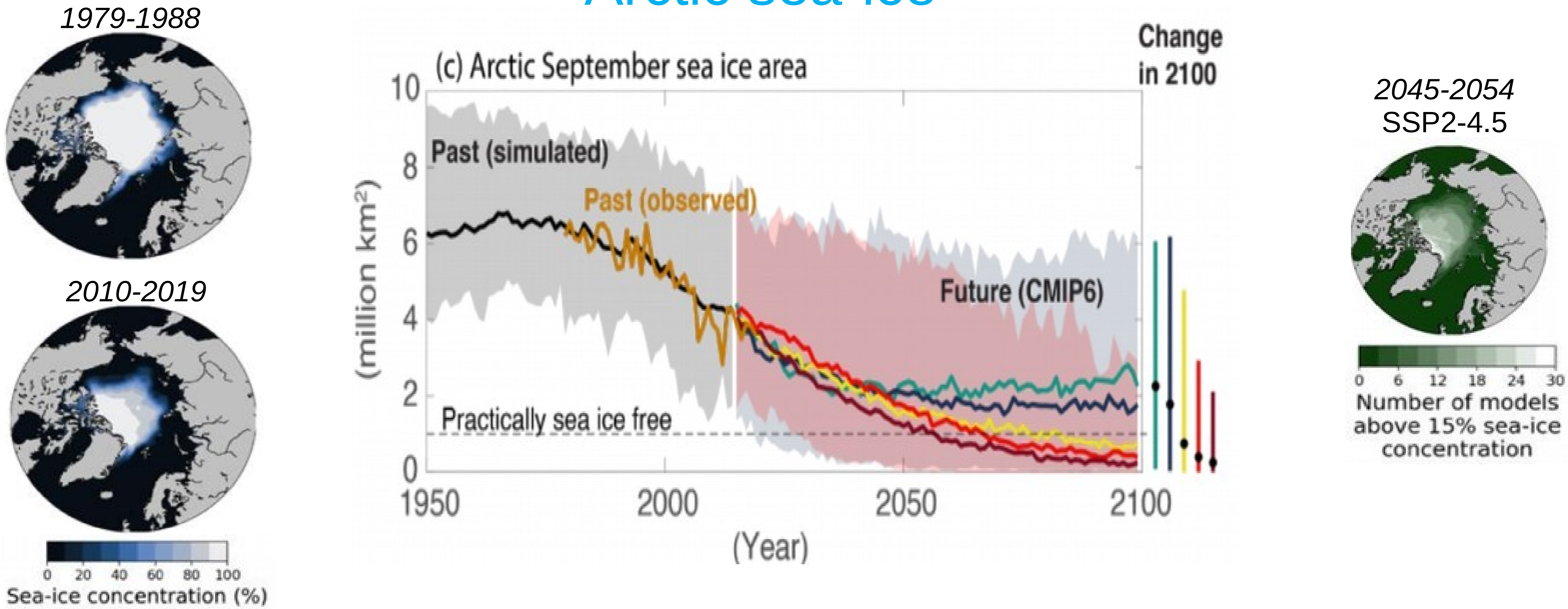


2045-2054
SSP2-4.5

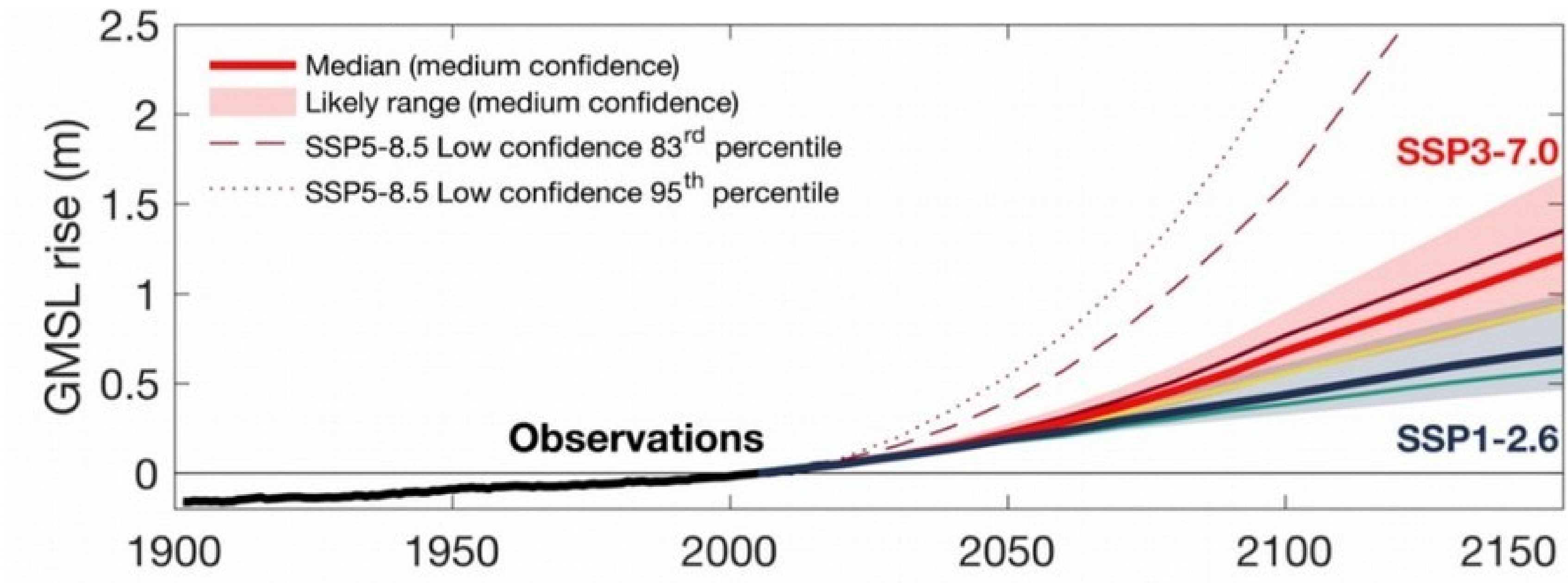


[IPCC AR6]

Arctic sea-ice

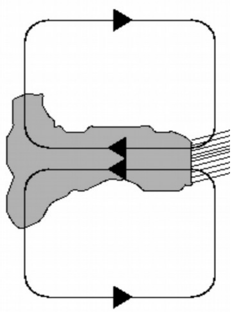


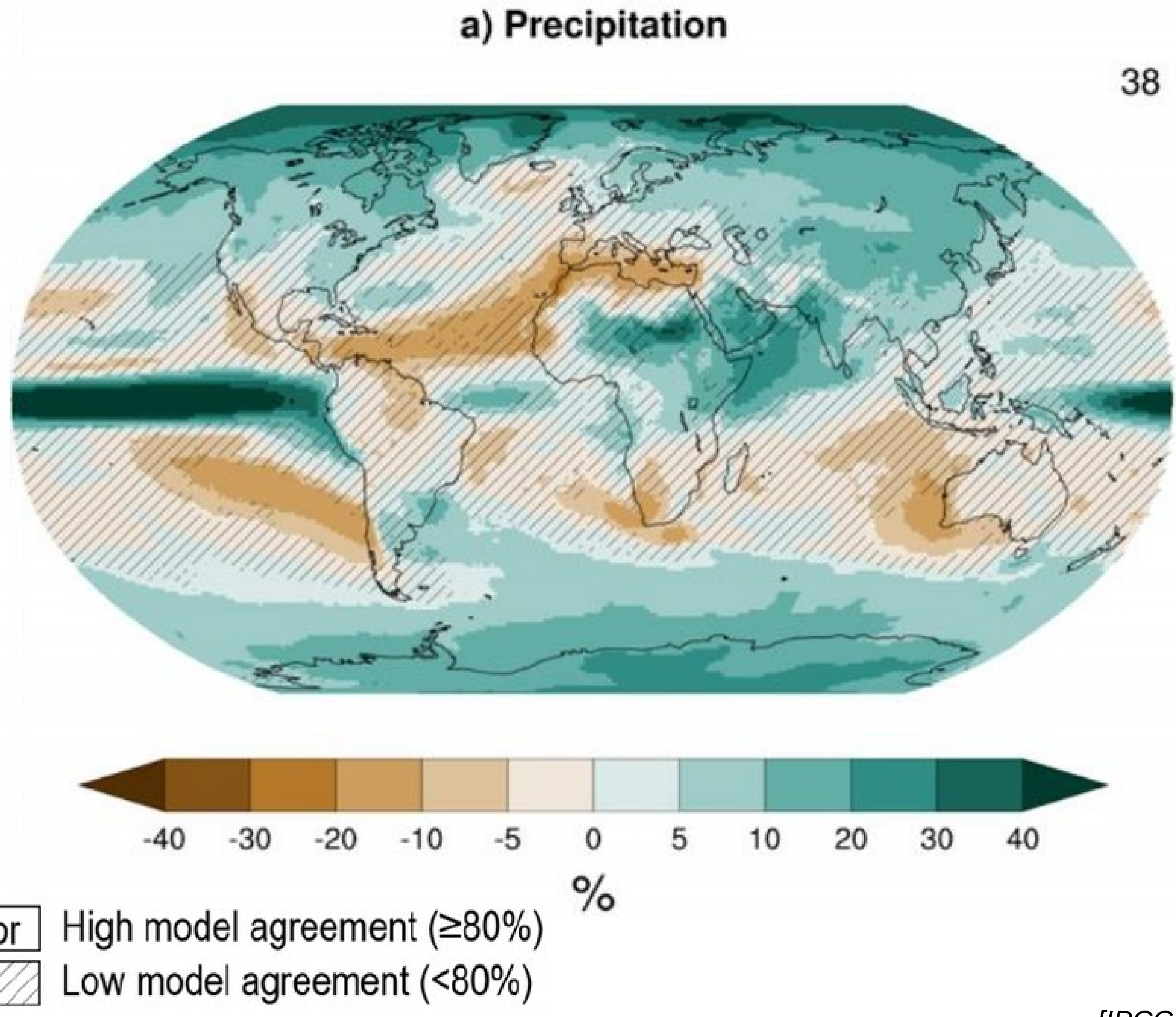
Global mean sea level



[IPCC AR6]

Precipitation changes for SSP2-4.5, ([2081-2100] vs [1995-2014])

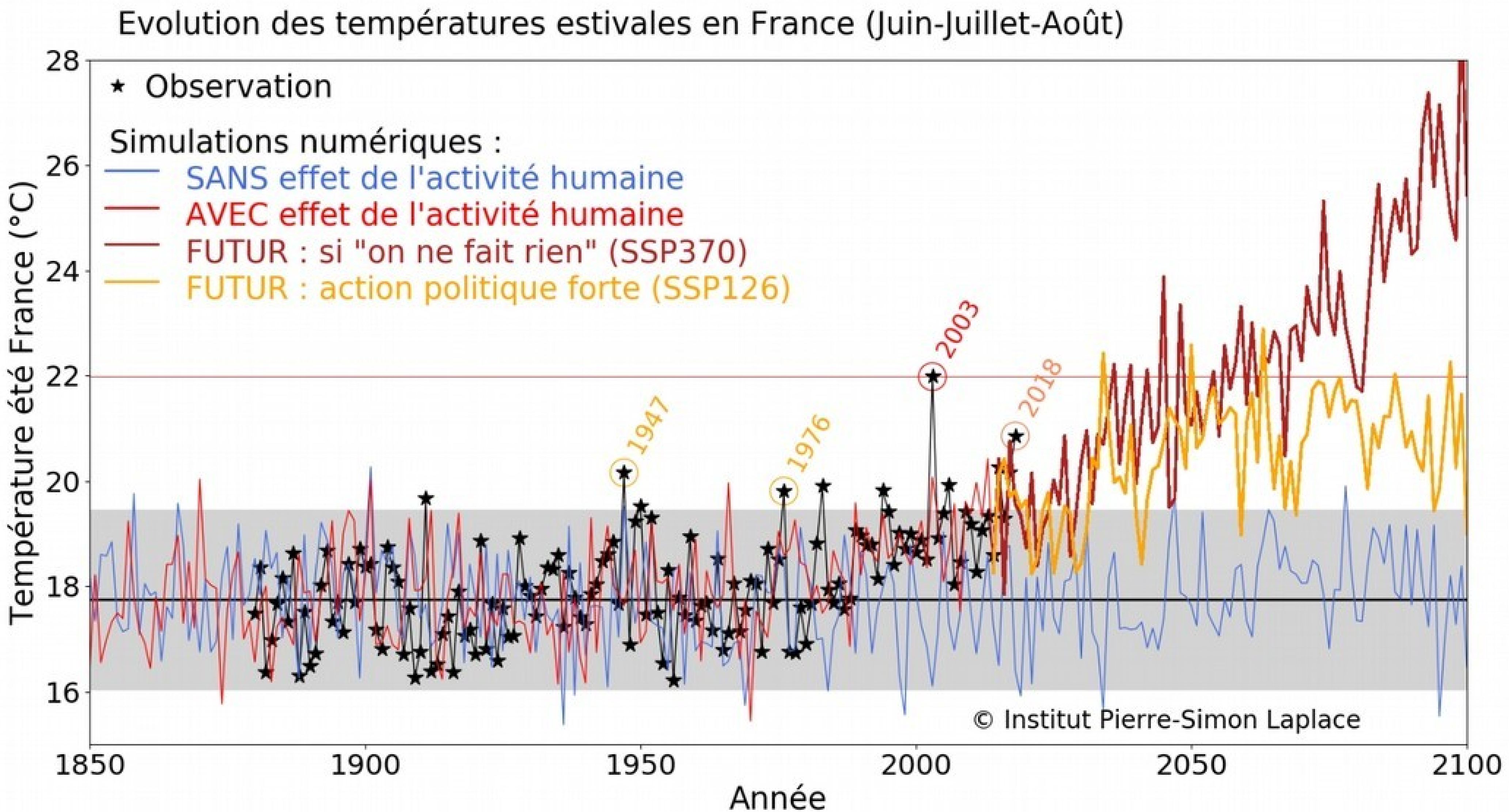




[IPCC AR6-WG1, TS]

Surface temperature evolution: observation and models

Summer mean temperature over France



Internal variability and variations due to forcings

Climate variations have different origines:

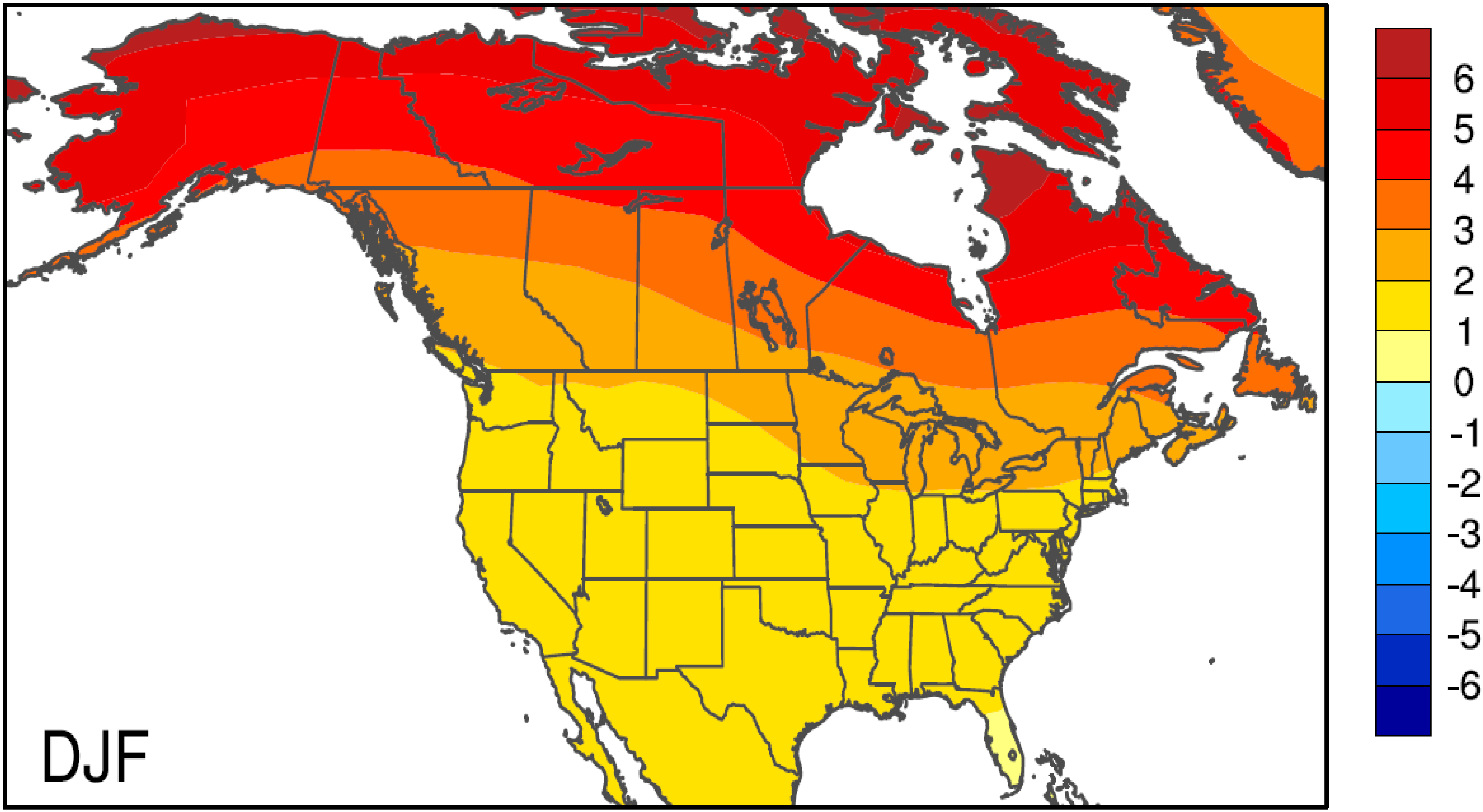
$$\underbrace{\Delta T}_{\text{variation}} \approx \underbrace{\underbrace{\Delta T_{int}}_{\text{Internal variability}} + \underbrace{\frac{\partial T}{\partial Q}\Delta Q_{nat}}_{\text{Response to natural forcings}}}_{\text{Natural variability}} + \underbrace{\frac{\partial T}{\partial Q}\Delta Q_{ant}}_{\text{Response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

- The relative importance of these various termes 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

Climate change and climate variability

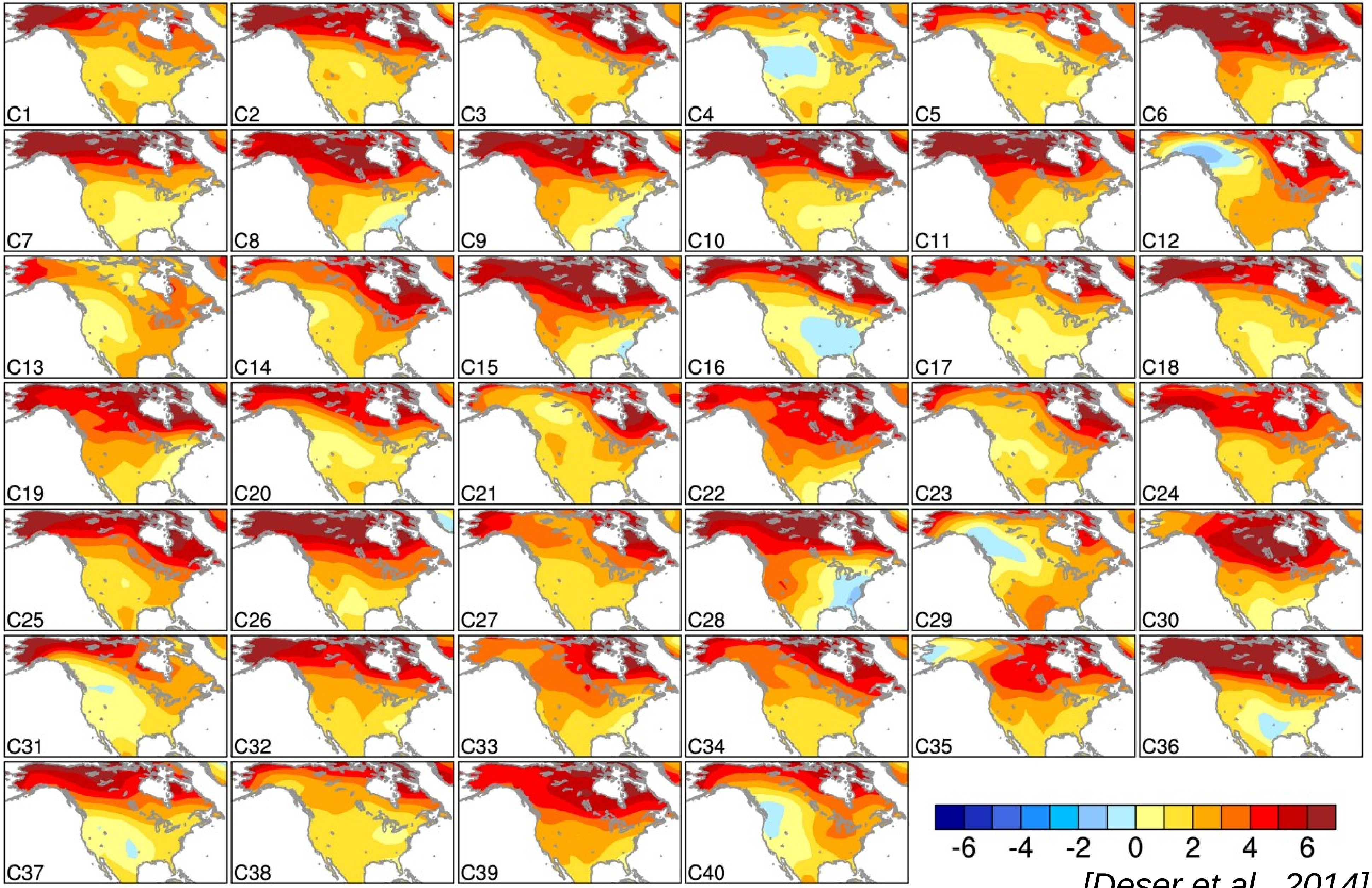
50 years trend of the winter surface temperature (°C/50 years)
for an "intermediate-high scenario". ***Average*** response.



[Deser et al., 2014]

Climate change and climate variability

50 years trend of the winter surface temperature (°C/50 years).
Response of ***individual*** simulations.



[Deser et al., 2014]


Merci de votre attention