Physique et modélisation du climat et de ses variations

Jean-Louis Dufresne
jean-louis.dufresne@lmd.ipsl.fr

Laboratoire de Météorologie Dynamique et Institut Pierre-Simon Laplace

Climatiques, CIRM, Marseille, 13-17 janvier 2025

Outlook

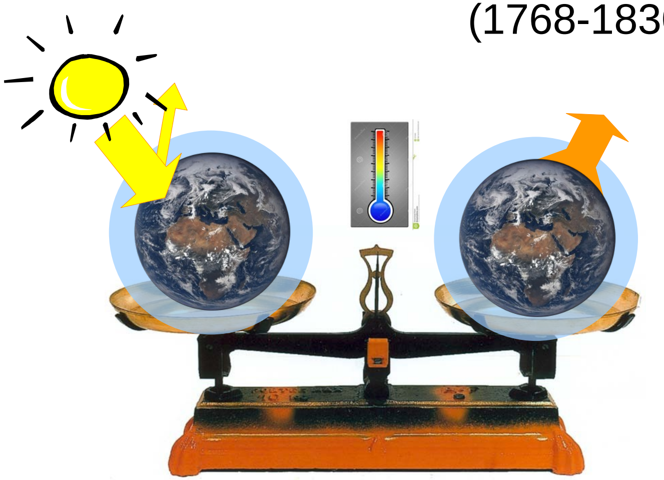
I. Earth radiative budget and the greenhouse effect
II. Numerical climate models
III. Simulating and attributing recent climate changes
IV. Scenarios and future climate changes
V. Climate sensitivity and climate feedbacks
VI. Climate variability and past climate changes

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)

- 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



- The **heat diffusion** with the interior of Earth has a **negligible impact** on the surface temperature
- Contradicts the thermal death of Earth

[Dufresne, 2006]

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)

- He ***envisages the importance of any change of the sun***
«The least variation in the distance of that body[the sun] from the earth would occasion very considerable changes of temperature. »

He refuted this possibility, which led him to assume the existence of a "temperature of space", which he took to be equal to that of the poles in winter.

- He ***envisages that climate may change***: « *The establishment and progress of human society, and the action of natural powers, may, in extensive regions, produce remarkable changes in the state of the surface, the distribution of waters, and the great movements of the air. Such effects, in the course of some centuries, must produce variations in the mean temperature for such places* ».

[Dufresne, 2006]

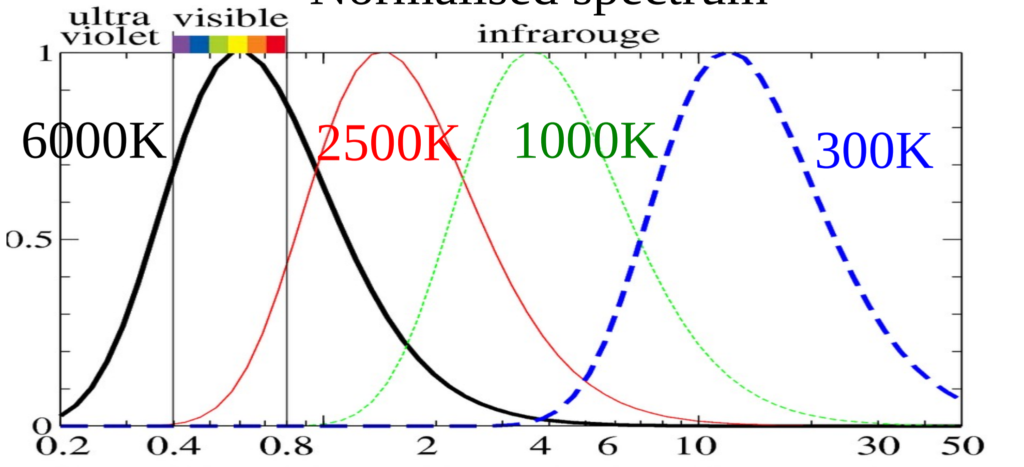
Spontaneous emission of radiation

Planck law ("Black body" emission)

$$B_\lambda(T) = \frac{C_1\,\lambda^{-5}}{\pi\,\left(e^{C_2/\lambda T} - 1\right)}$$

B_λ in W.m^{-2}.µm^{-1}.sr^{-1}

T in K, C_1 et C_2 are constants



Semi-transparent media:

$L_\lambda(T) = \varepsilon_\lambda\, B_\lambda(T)$ with ε_λ spectral emissivity

($0 \le \varepsilon_\lambda \le 1$; black body: $\varepsilon_\lambda = 1$)

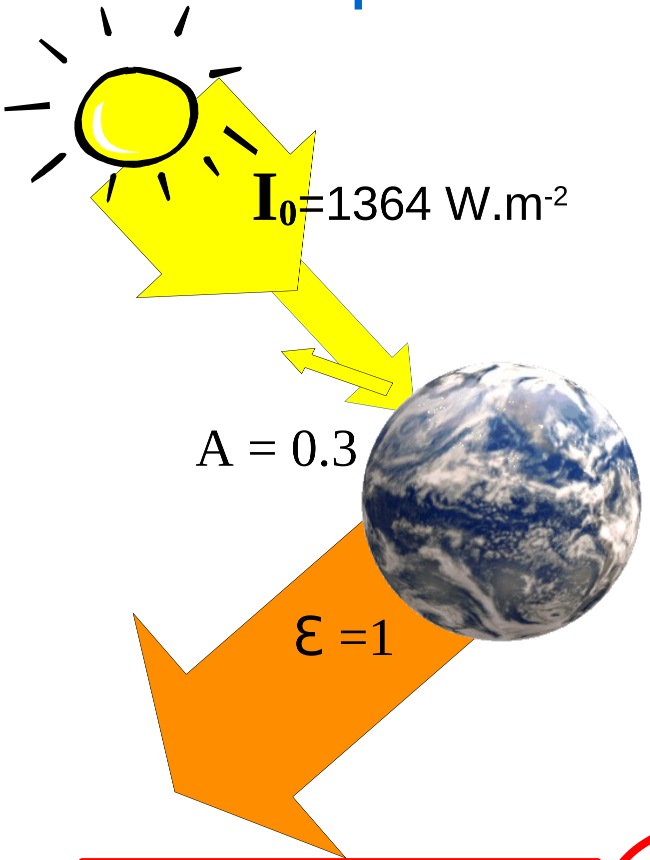
Kirchhoff law: emissivity ε_λ = absorptivity α_λ at the spectral level

Stefan-Boltzmann law (integral of the Planck law over the whole spectrum and over one hemisphere).

Power F lost by emission of radiation by a body of temperature T : $\boxed{F = \sigma T^4}$

With σ = 5,67 10^{-8} : Stefan-Boltzmann constant, F in W.m^{-2}, T in K

Equilibrium temperature of planet Earth



Average incoming solar radiation on a **sphere:** $I_s = I_0/4$

We assume the surface temperature is uniform

absorbed solar (shortwave) radiation**:**
$F_a = (1\text{-}A)\ I_0/4 = 240 \text{W.m}^{-2}$

emitted terrestrial (longwave) radiation**:**
$F_e = \varepsilon\ \sigma\ T_e^4$

Steady state: the heat power gained by absorption is equal to that lost by emission: $\mathbf{F_a = F_e}$

$$\sigma \epsilon T_e^4 = (1 - A) I_0 / 4$$

T_e: Emission temperature

T_e= 255K (-18°C)

longwave radiation **emitted by the Earth** toward space:
F_e **= 240** W.m^{-2}

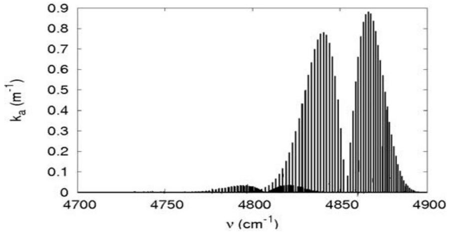
Greenhouse effect
$G=F_s-F_e$

longwave radiation **emitted by surface:**
F_s = 390 W.m^{-2}

Global mean surface temperature $T_s \approx$ 15°C

Radiative calculations are now accurate

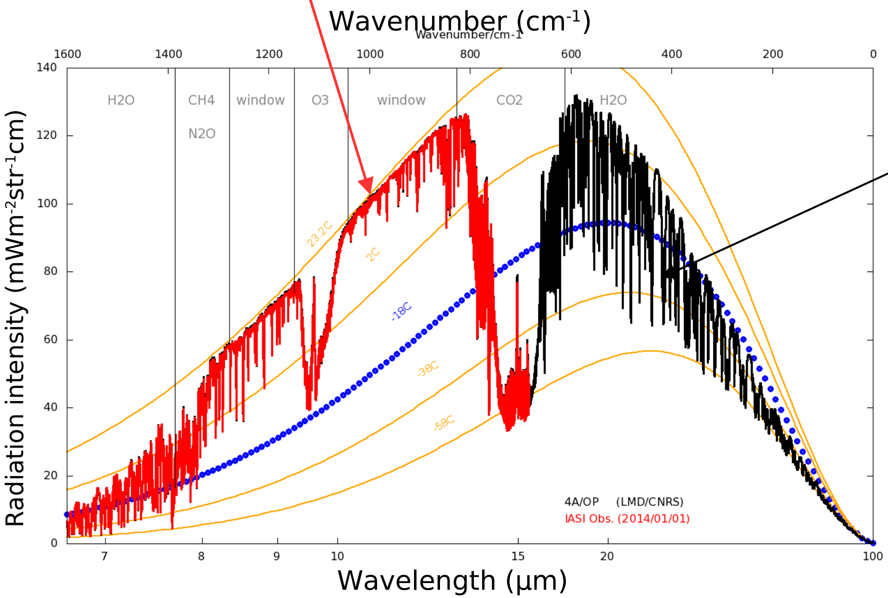
IASI instrument



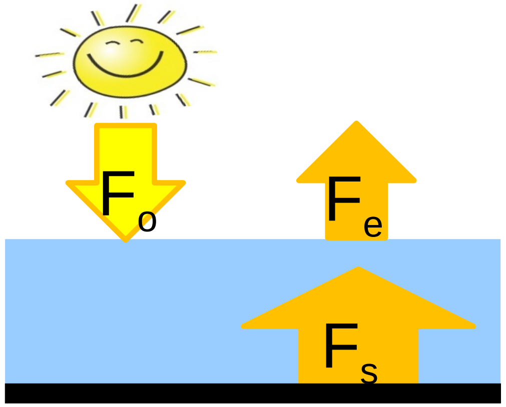
Gas radiative properties

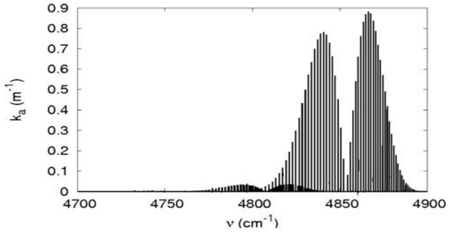
Atmospheric characteristics

4A line-by-line model



Greenhouse effect is computed and observed





Gas radiative properties

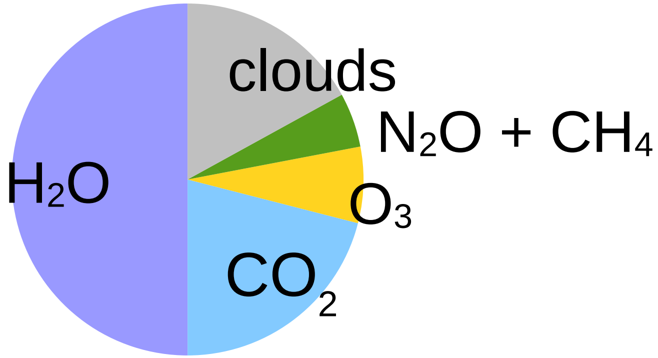
Atmospheric characteristics

Greenhouse effect: $G=F_s-F_e$

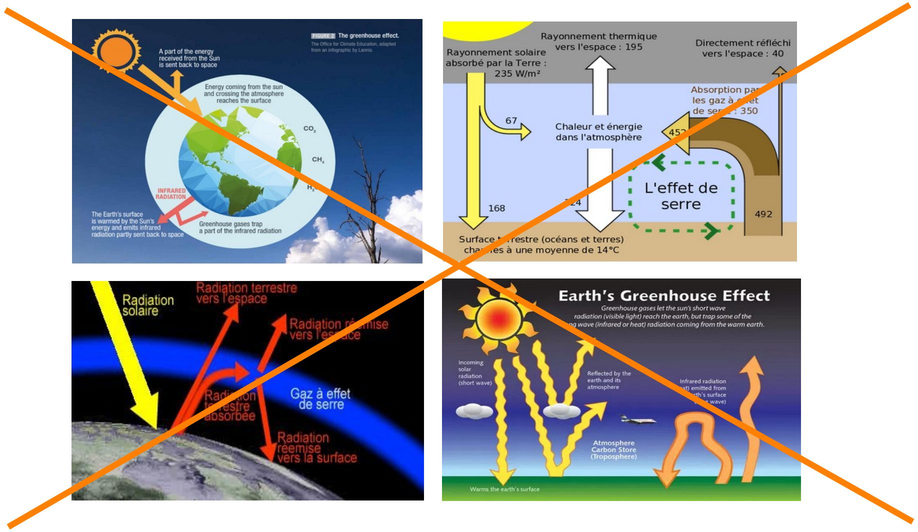
Computation of the radiative fluxes F_s and F_e and the greenhouse effect G

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



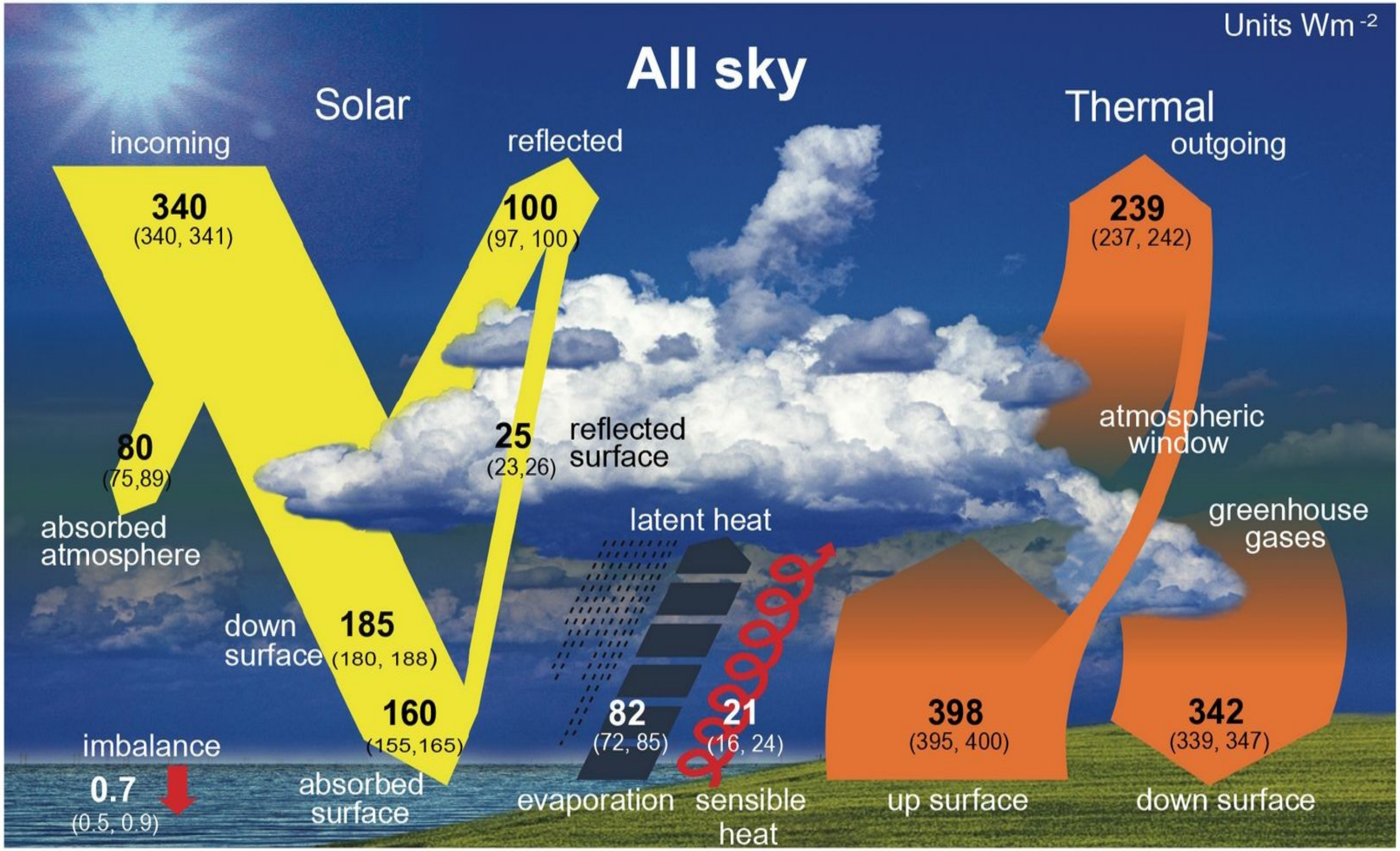
To understand the greenhouse effect, one must considered radiative fluxes at the top of atmosphere



Presentation of the greenhouse effect as an atmosphere heating the surface by emitting infrared radiation towards the surface:

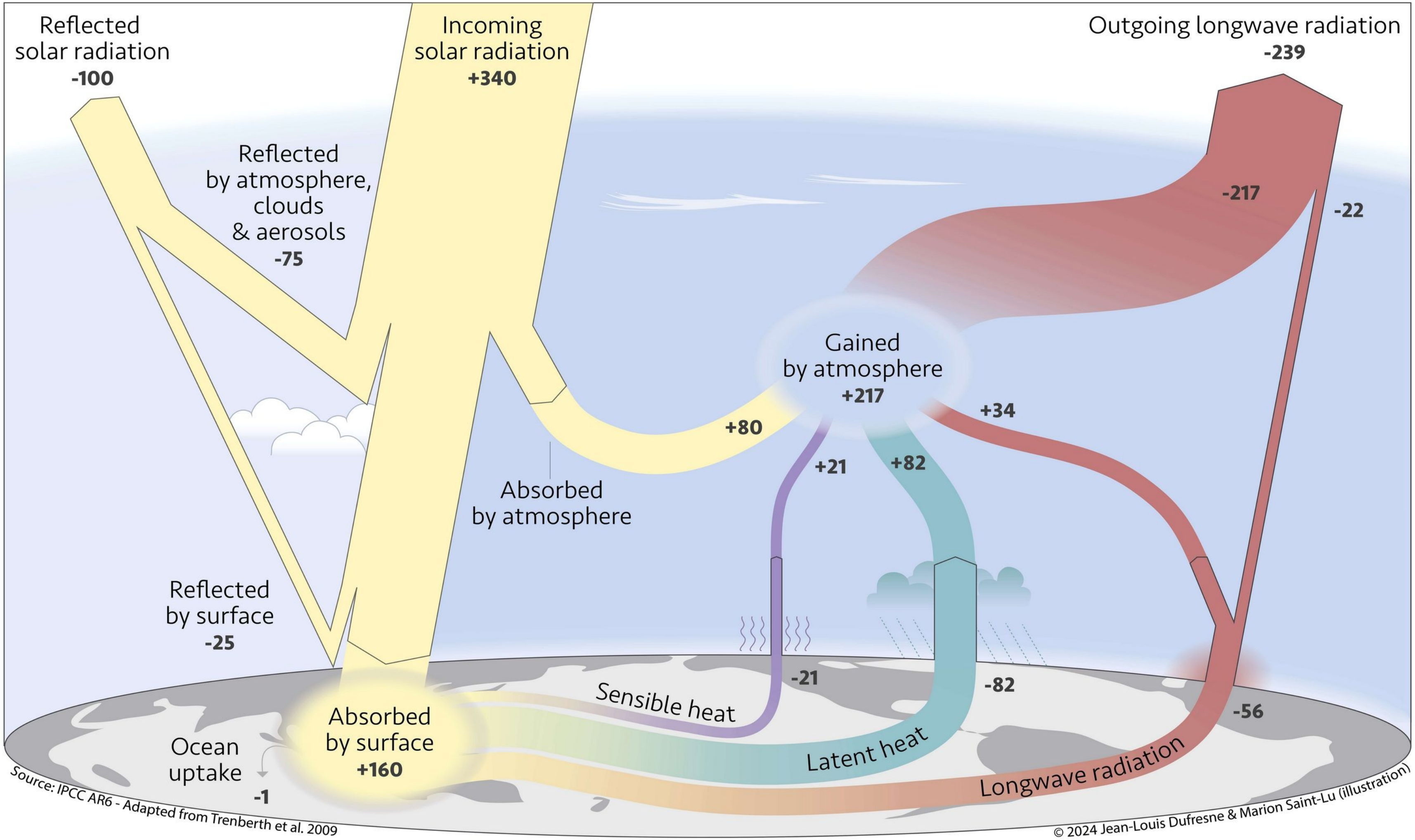
- Is inconsistent (false) with the definition of its measure: $G = F_s - F_e$
- Logically leads to erroneous coclusion, e.g. to question the role of CO_2 in the greenhouse effect (saturation effect, CO_2 masked by H_2O, etc.)
- Doesn't allow for an answer to these legitimate questions.

Energy flows in the Earth atmosphere



[IPCC AR6, ch7, 2021; Trenberth & Fasullo, 2012]

Energy flows in the Earth atmosphere



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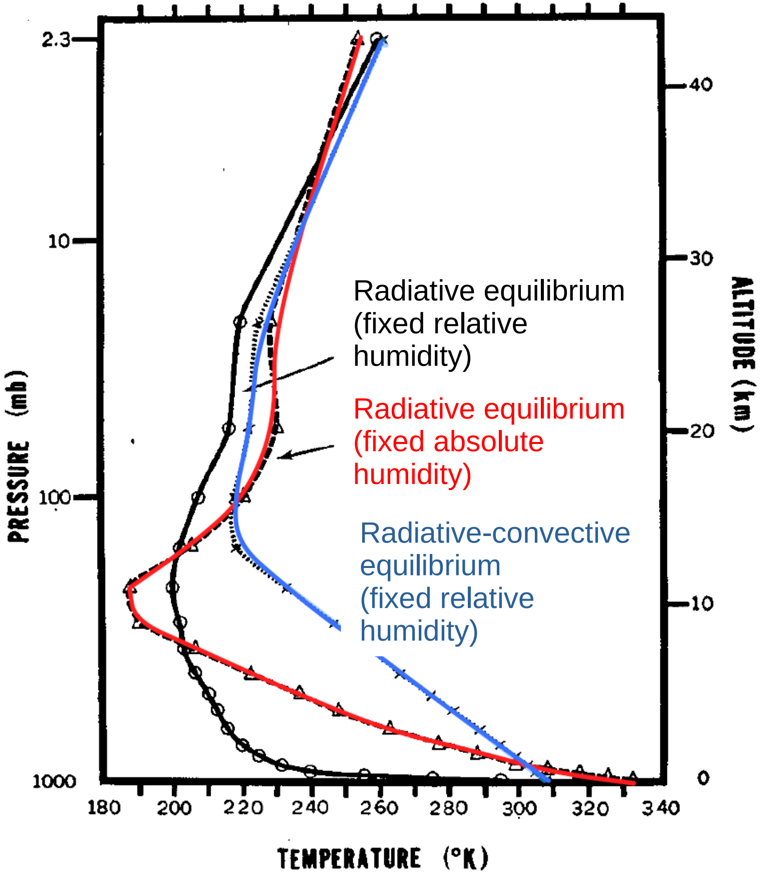
Single column model (from the 60's)

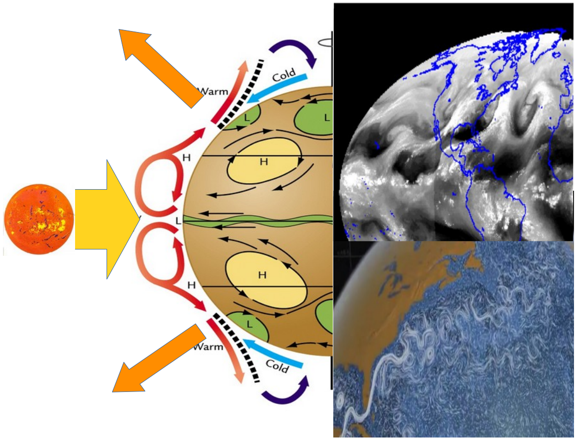
Vertical temperature profile at
- ***radiative*** equilibrium with **fixed relative humidity**
- ***radiative*** equilibrium with **fixed absolute humidity**
- ***radiative-convective*** equilibrium at ***fixed relative humidity***

This article was very influential as it showed:
- the fundamental role of convection
- the large difference whether absolute or relative humidity is kept constant
- that for a given CO_2 variation:
  - ***its effect on radiative fluxes had to be considered at the top of the atmosphere, not at the surface***
  - the variation in surface temperature was twice as high if relative humidity was kept constant and not absolute humidity
  - surface and tropospheric temperatures vary in the opposite direction to that of the stratosphere

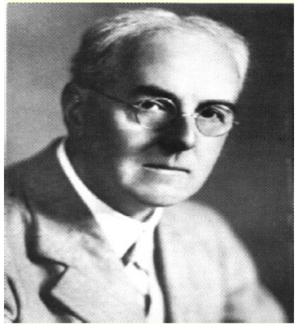


[Manabe and Wetherald, 1967]

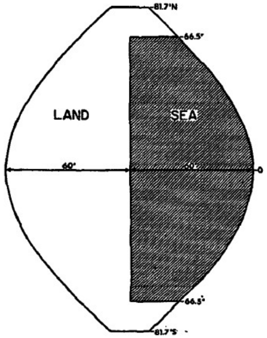
Numerical climate models (from the 60’s)
(numerical weather simulators)




W. Bjerknes
(1862–1951)

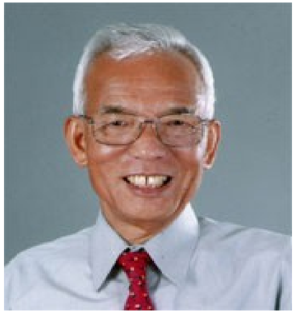

L. F. Richardson
(1881–1953)

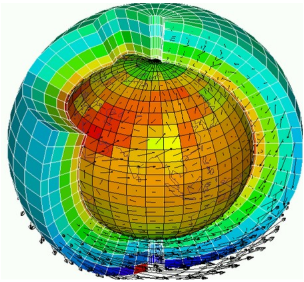

J. von Neumann
(1903–1957)



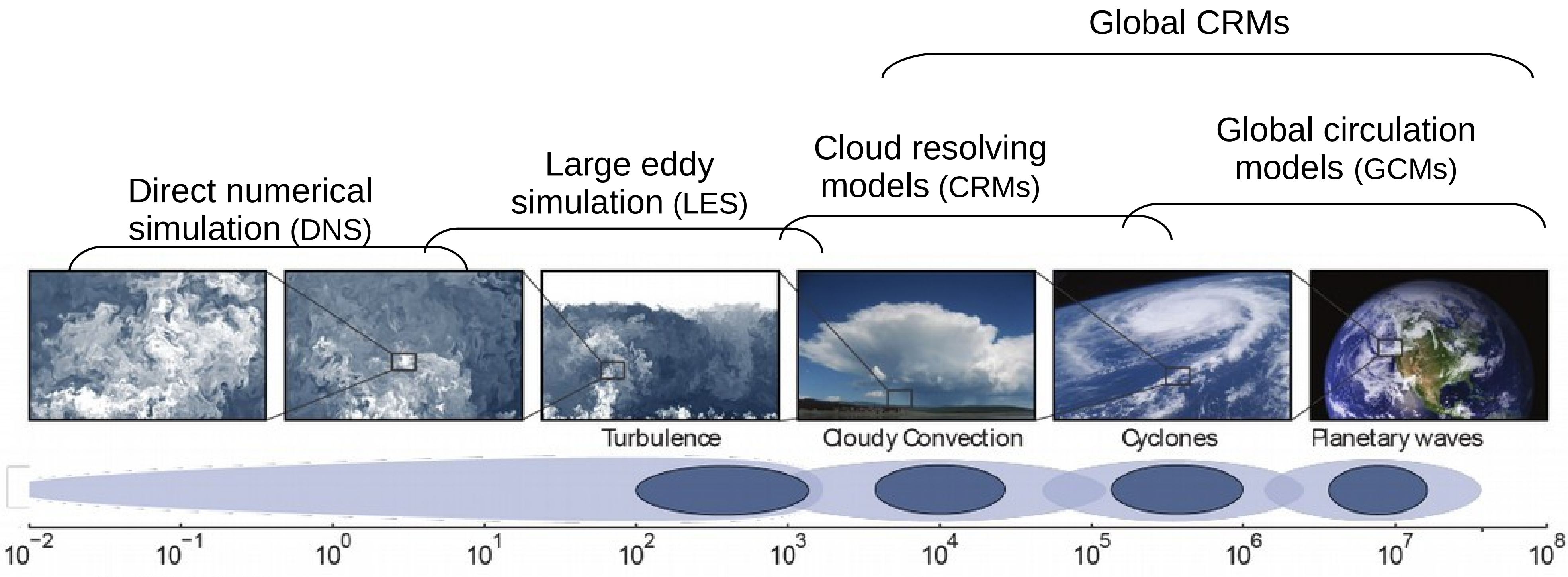

J. Charney
(1917-1981)


J. Smagorinsky
(1924-2005)


S. Manabe
(1931-)

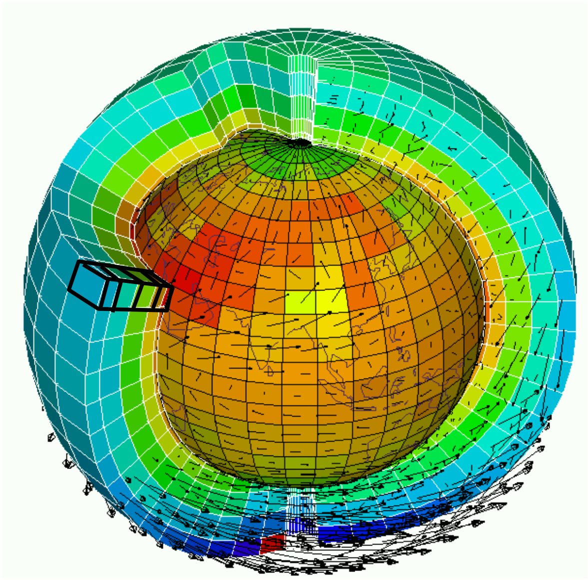


A variety of numerical models to handle the wide range of time and space scales involved



[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
  $D\theta / Dt = Q / C_p \; (p_0/p)^{\kappa}$
- 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)
  $Dq/Dt = S_q$

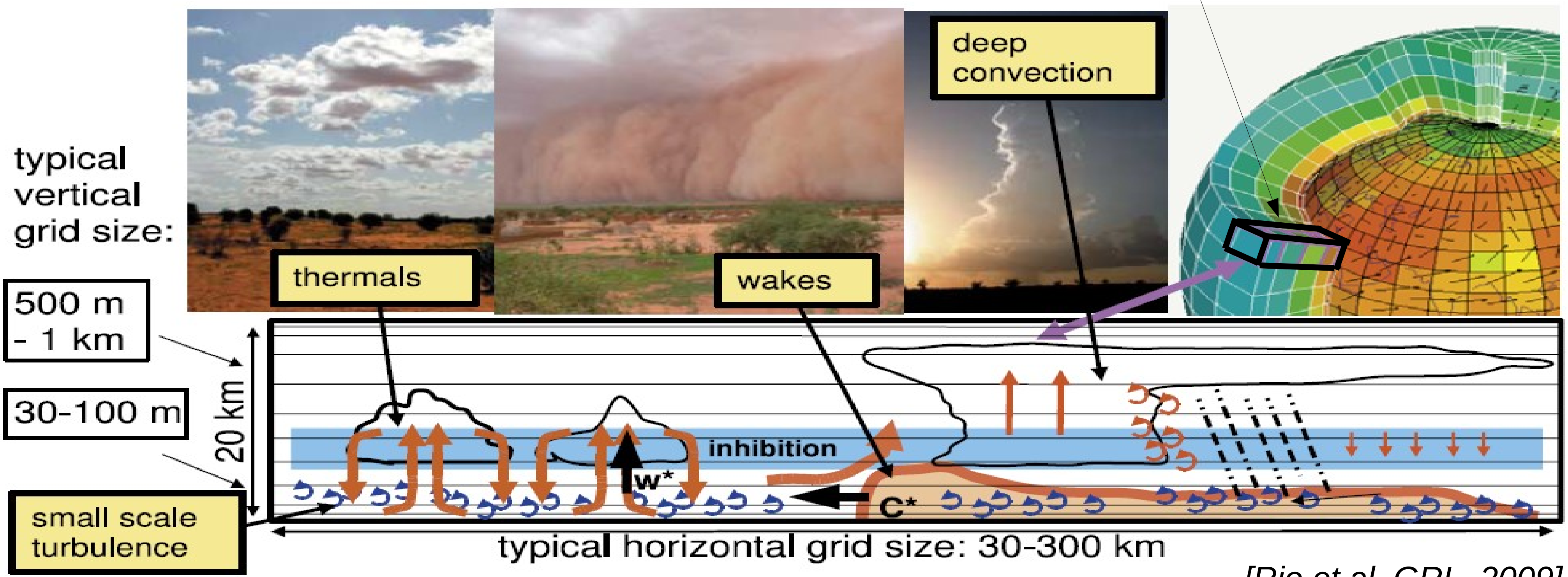
In red, source terms : other than fluid mechanics and unresolved scales

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 with sub-models (parameterization)

A typical vertical atmospheric column



[Rio et al, GRL, 2009]

Typical time step : a few minutes to half an hour

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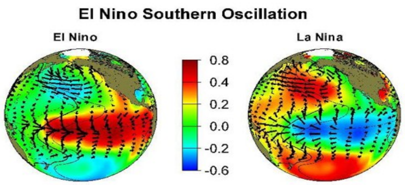
What drives climate variations and changes ?

Internal variability



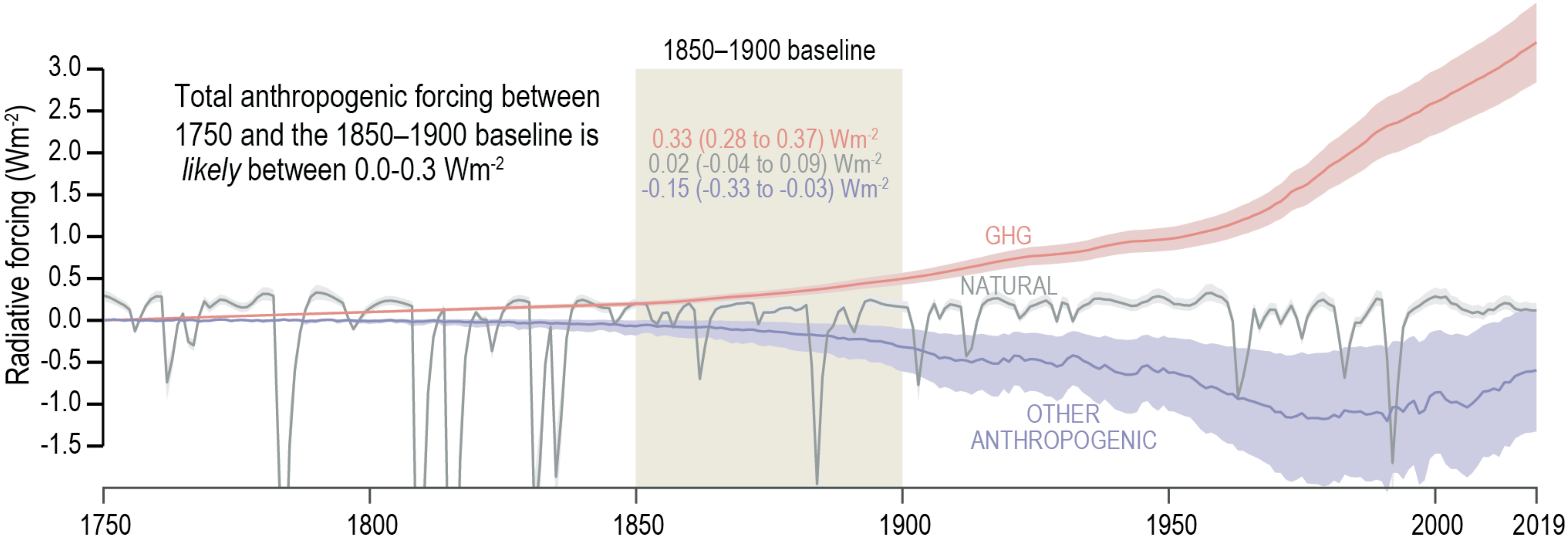
Natural forcings

volcanos

solar

Anthropogenic forcings

GHG(CO_2, $CH_{4,...}$), aerosols, etc.



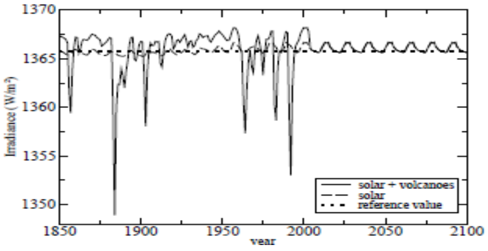
[IPCC, 2021]

Use of Earth System Models (ESMs)

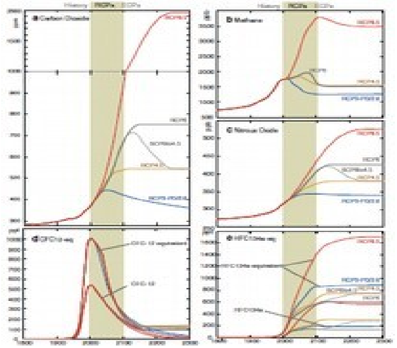
e.g. the IPSL « Earth System Model »

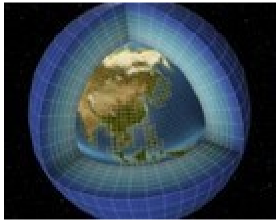
Natural and anthropogenic forcings

Sun and volcanos



Greenhouse or chemical reactive gases



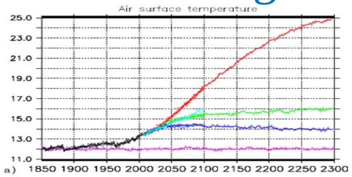


Climate model

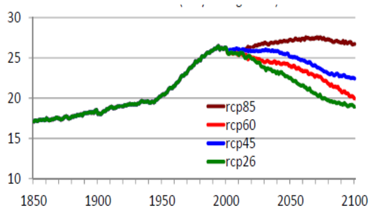
- 3D representation of the atmosphere, ocean, sea-ice, land-surface (coupling of different models)
- Representation and coupling with the biogeohemical cycles

Results

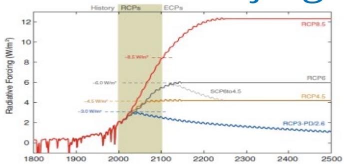
Climate changes



Atmosphere composition

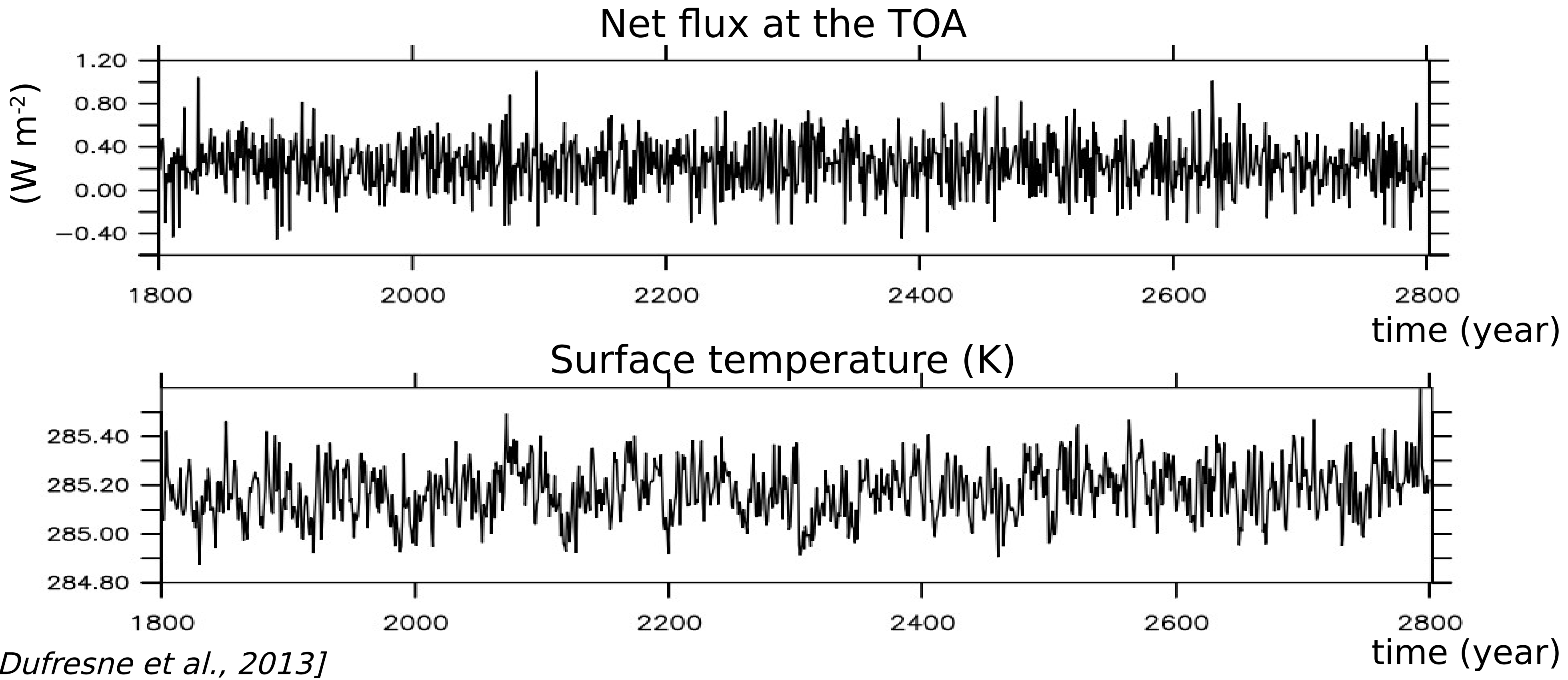


Radiative forçings



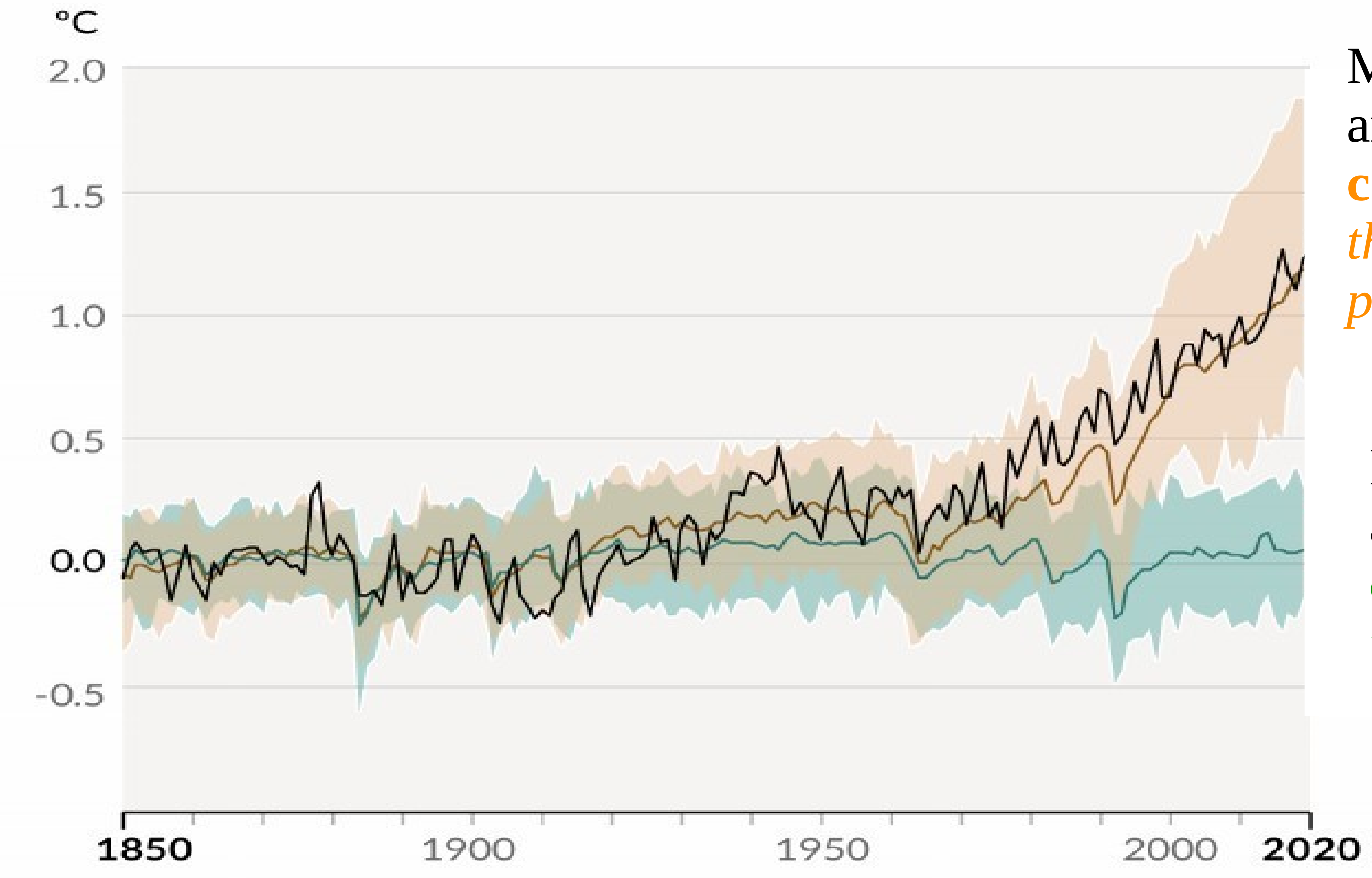
Performing a control run to obtain a stationary reference simulation

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]

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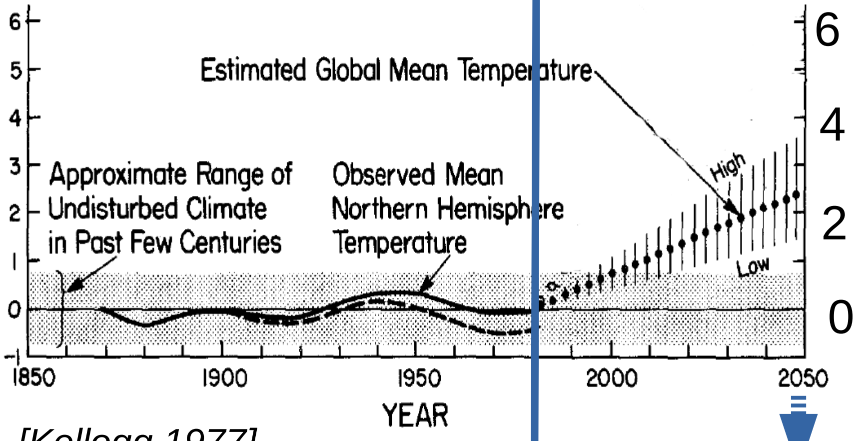
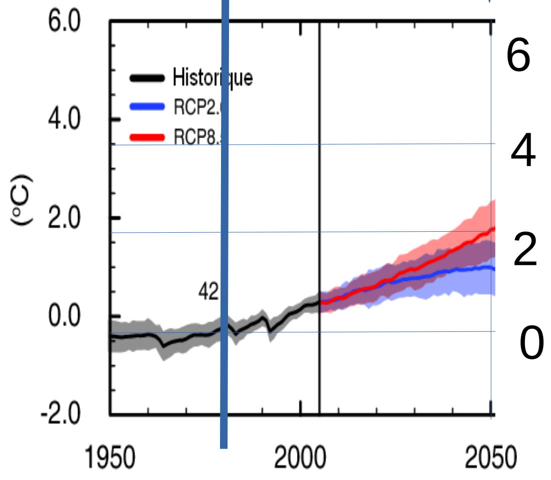
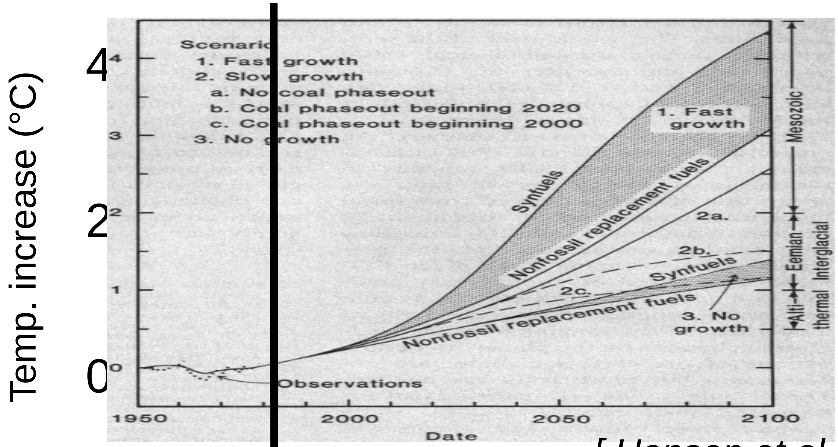
First climate projections before global warming has been observed



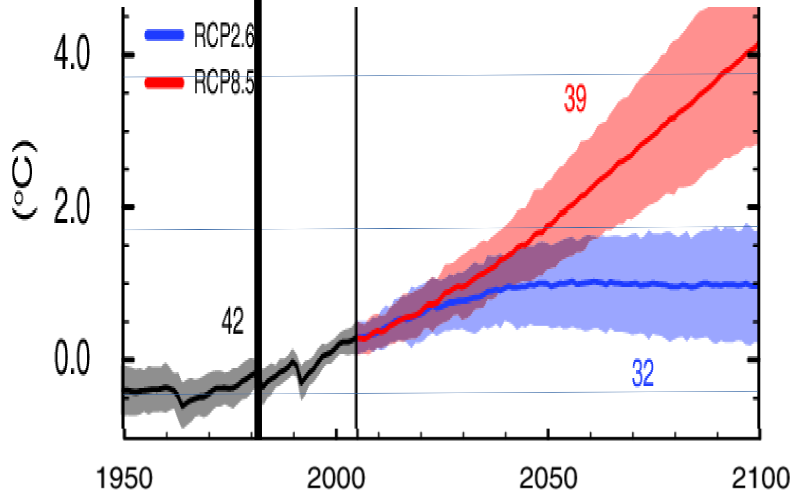
[Kellogg 1977]



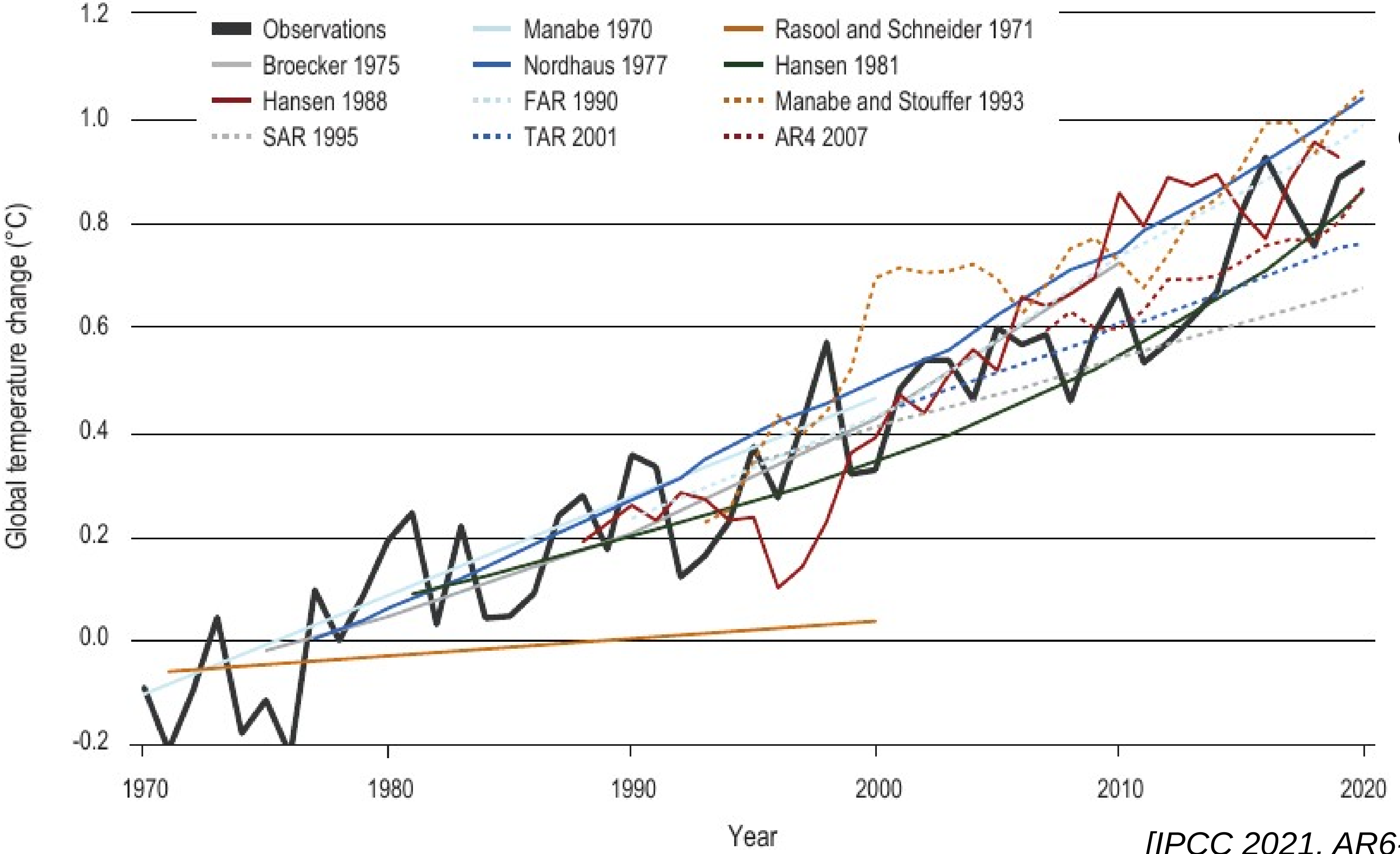
[IPCC 2021]



[Hansen et al. 1981]



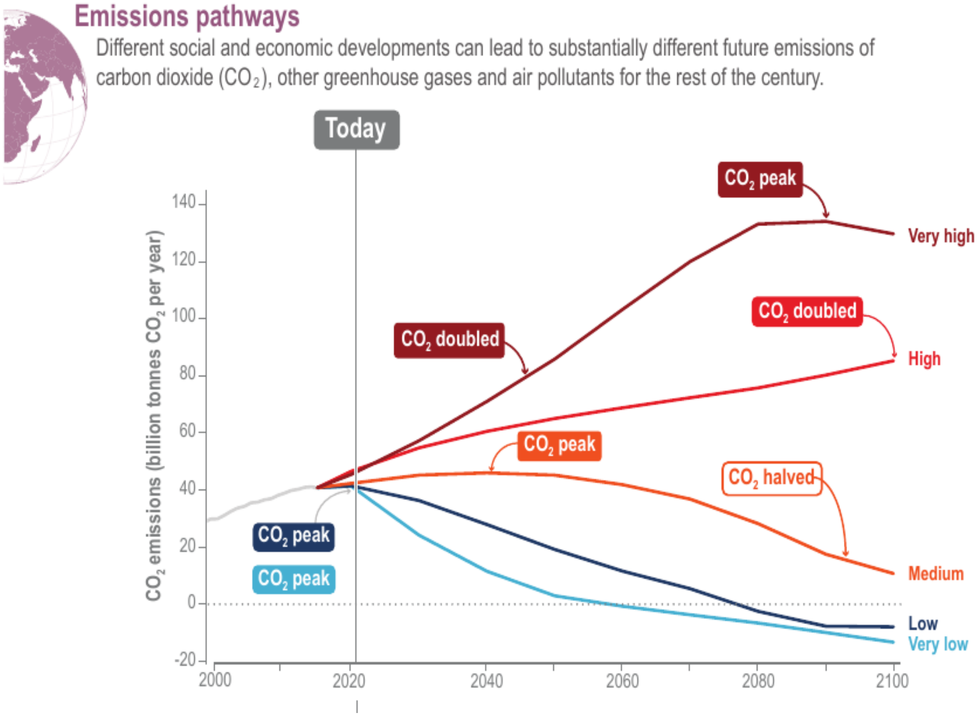
Recent warming was predicted by models simulations

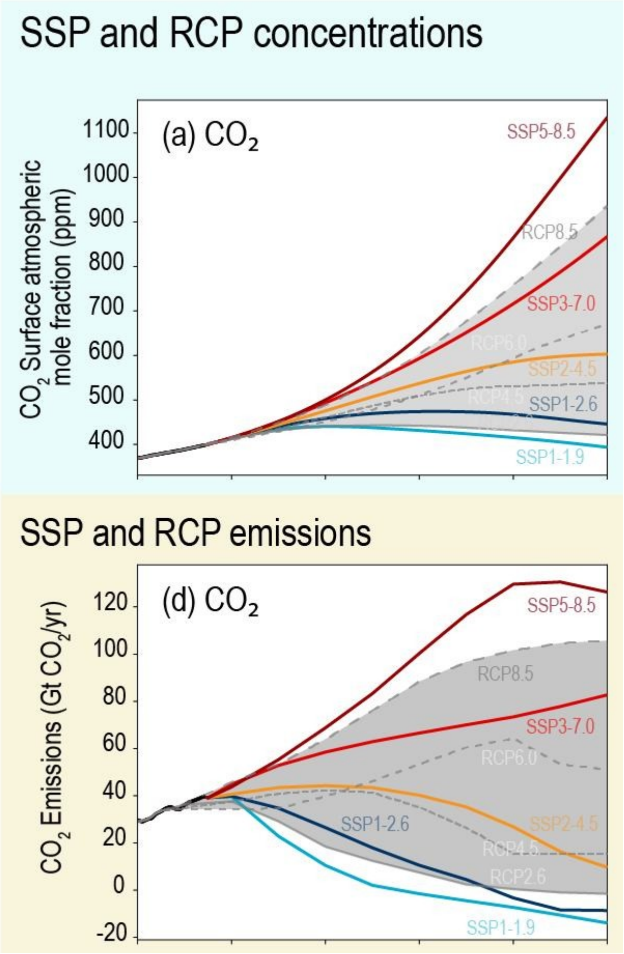


observations

[IPCC 2021, AR6-WG1, Ch1]

Future scenarios





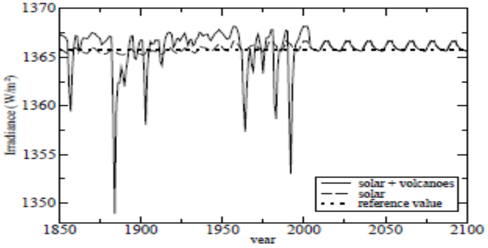
- + *CH_4, N_2O, etc.*
- + *aerosol precursors*
- + *land use*

[IPCC 2021, AR6]

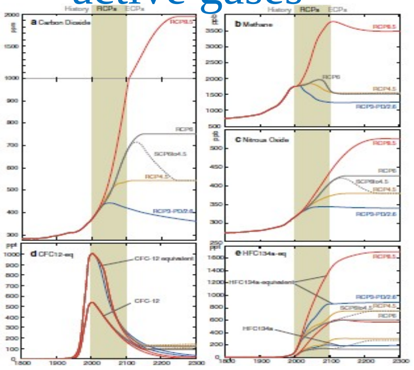
Use of Earth System Models (ESMs)

Natural and anthropogenic forcings

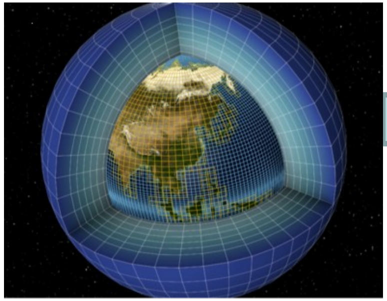
Solar and volcanoes



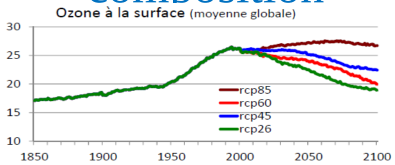
Green house gases and active gases



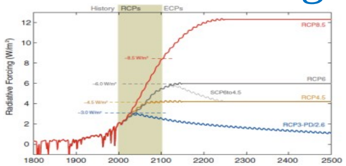
CO_2 concentration



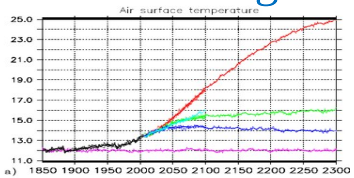
Atmospheric composition



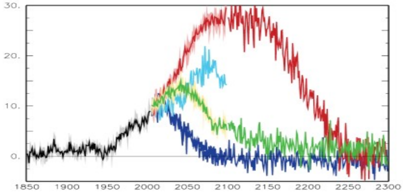
Radiative forcings



Climate changes

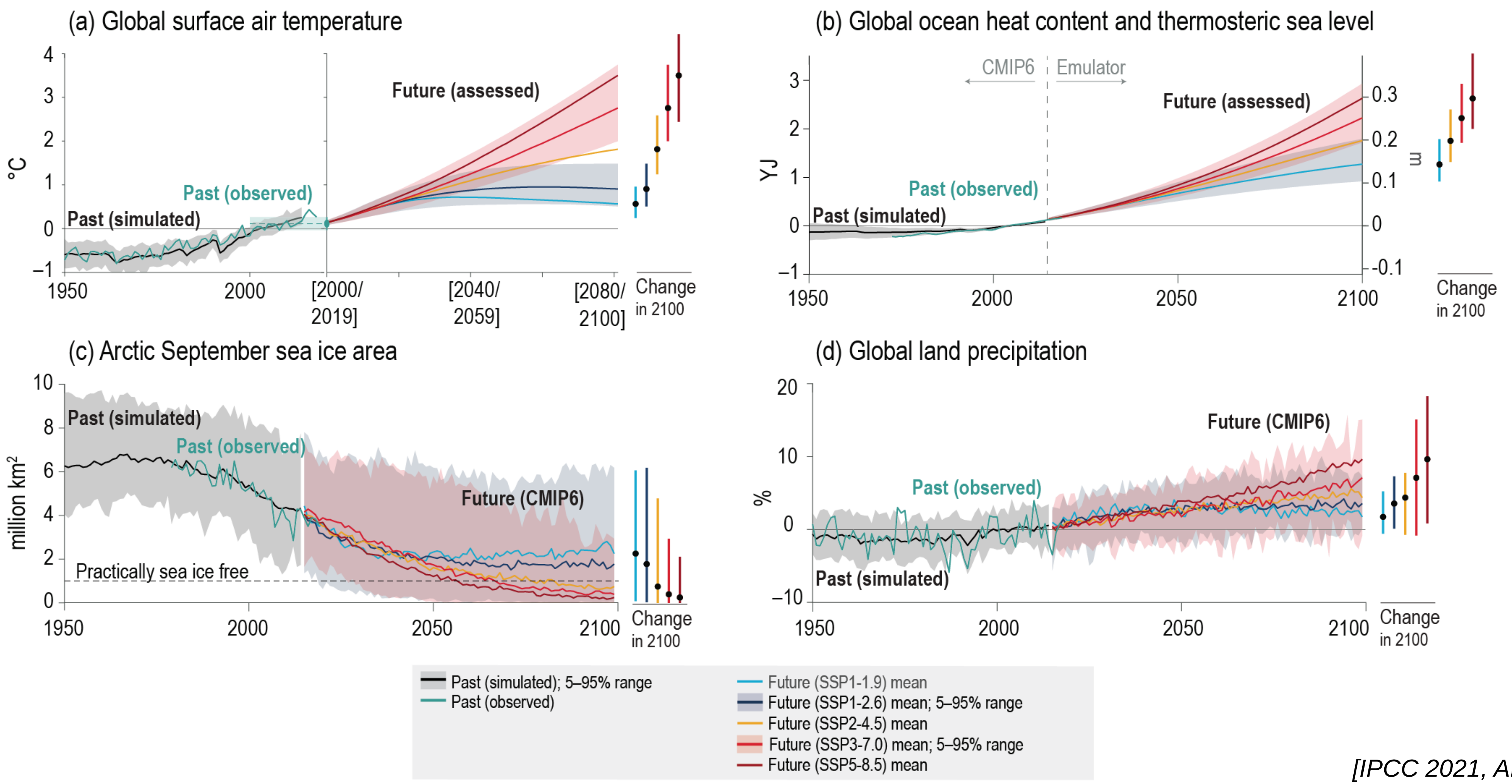


Authorized CO_2 emissions



Recent and future change of four key indicators of the climate system

Atmospheric temperature, ocean heat content, Arctic summer sea ice, and land precipitation



[IPCC 2021, AR6]

In the IPCC's AR6 report, changes by warming level are studied, not only as a function of year.

The amplitude of most changes of the climate system depend on the amplitude of global warming.

=> Questions (and answers) about future climate change can be more specific

=> We have moved from "what climate change will be in the year YYYY" to

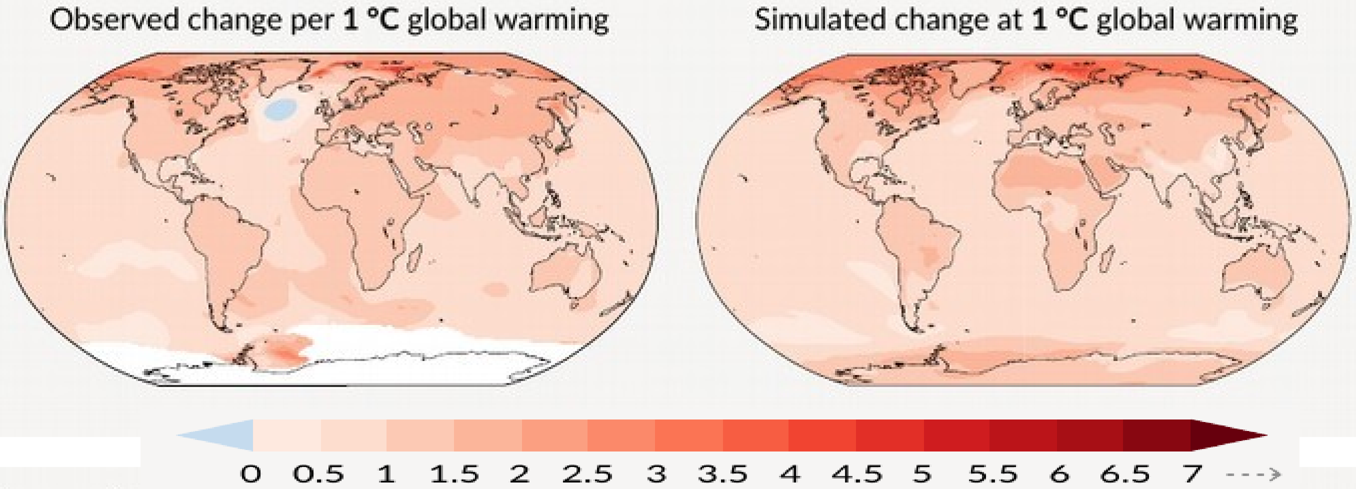
- what will be the climate changes for a global warming of X°C

- how much CO_2 can be emitted to reach (or not exceed) a warming of X°C?

- when will this happen?

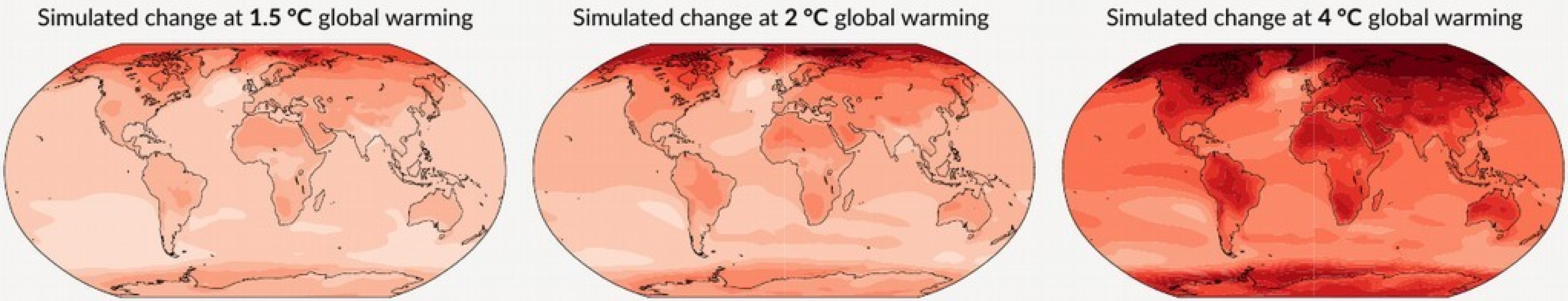
a) Annual mean temperature change (°C) at 1 °C global warming

Warming at 1 °C affects all continents and is generally larger over land than over the oceans in both observations and models. Across most regions, observed and simulated patterns are consistent.



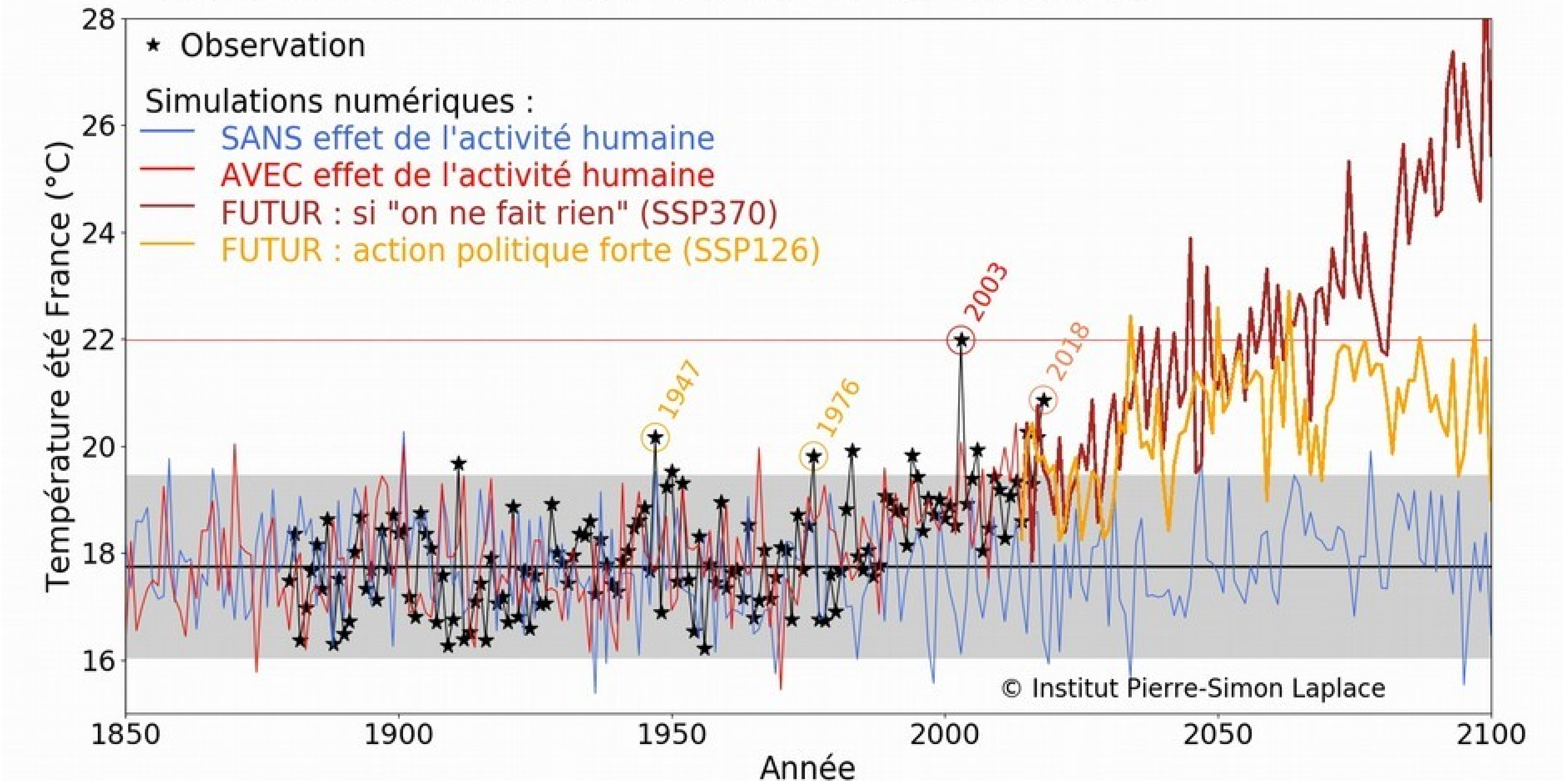
b) Annual mean temperature change (°C) relative to 1850-1900

Across warming levels, land areas warm more than oceans, and the Arctic and Antarctica warm more than the tropics.



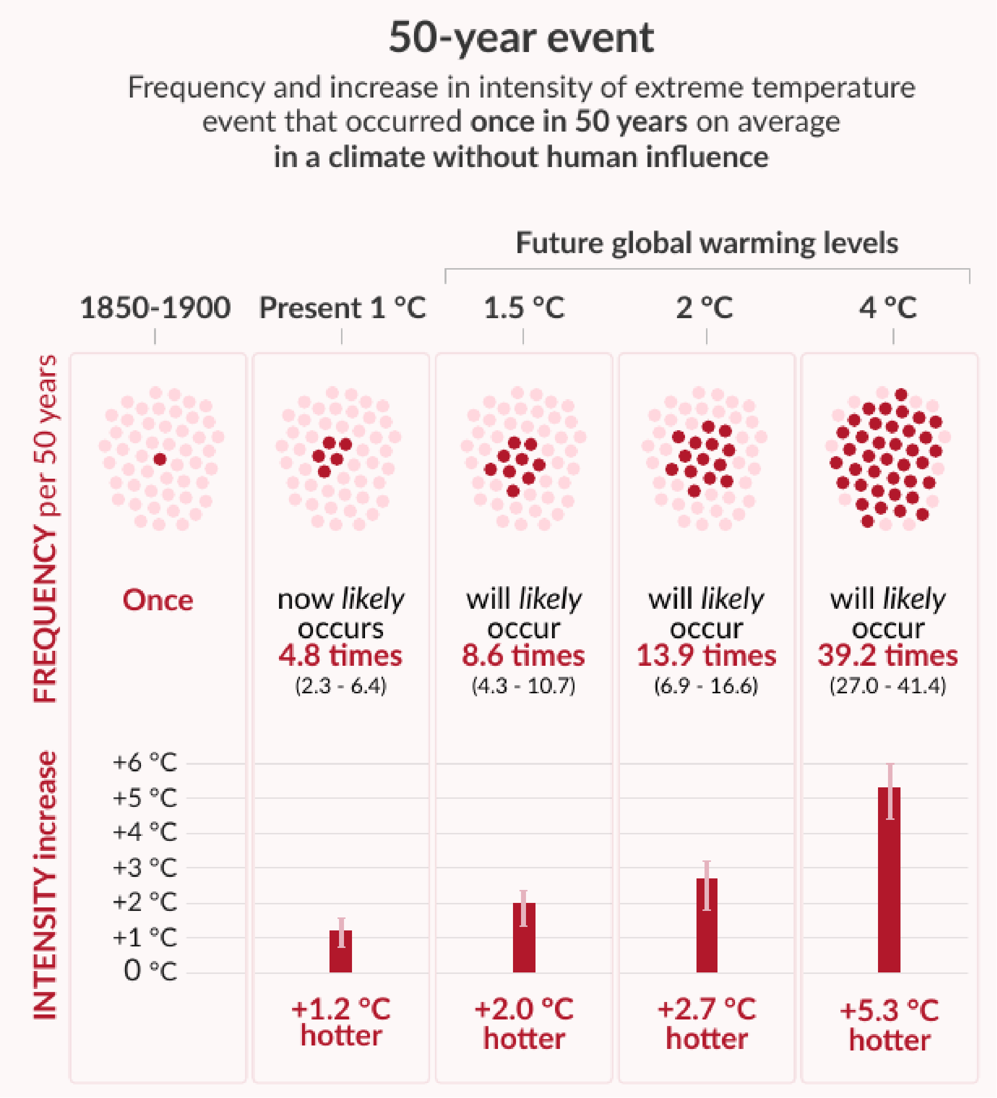
[IPCC 2021, AR6]

Mean summer temperature in France (Jun-August)



[Courtesy of F. Hourdin, LMD/IPSL]

Hot extremes over continents

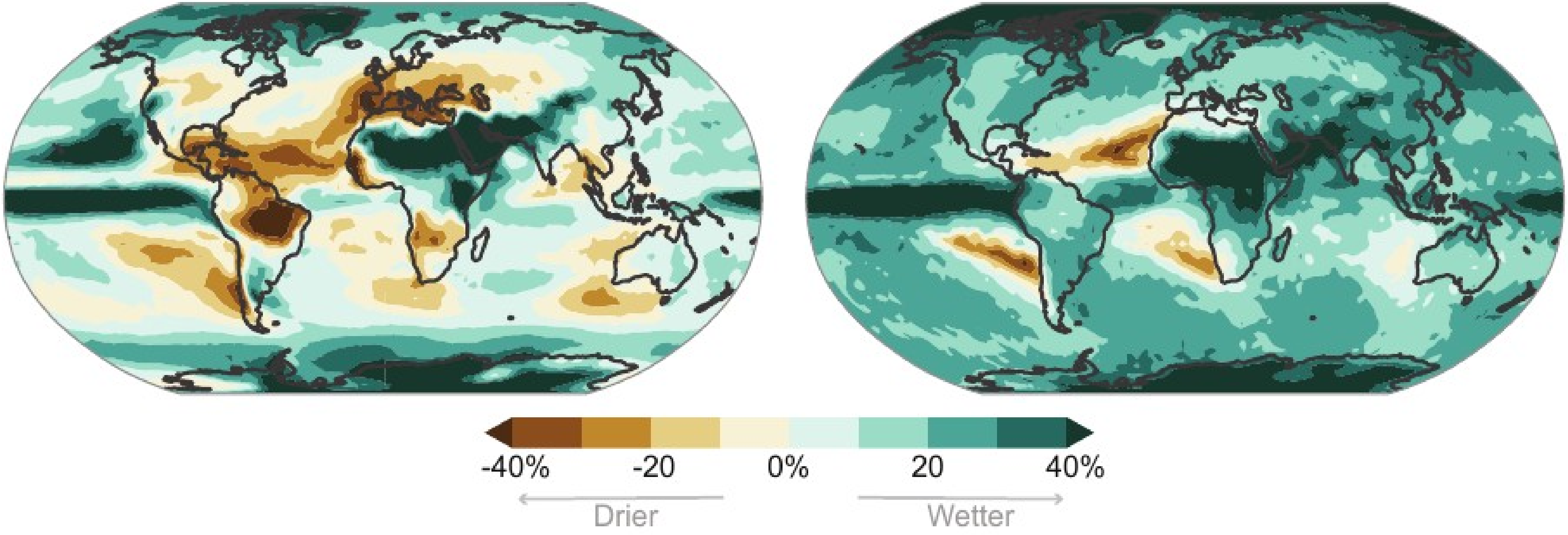


[IPCC 2021, AR6]

Change in precipitations amount

Relative change of the **mean**

Relative change of the **extrems**

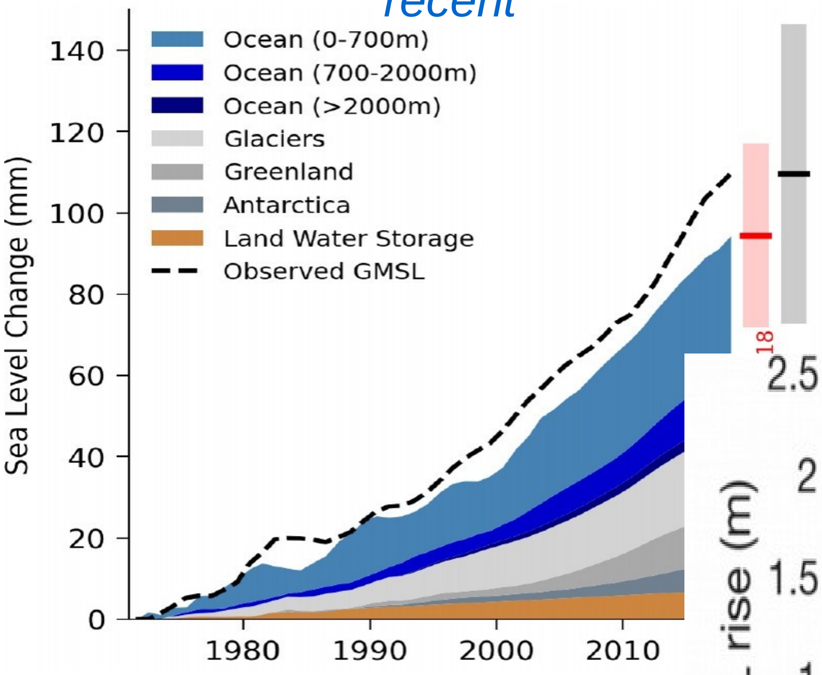


For a global mean surface temperature increase of 4°C

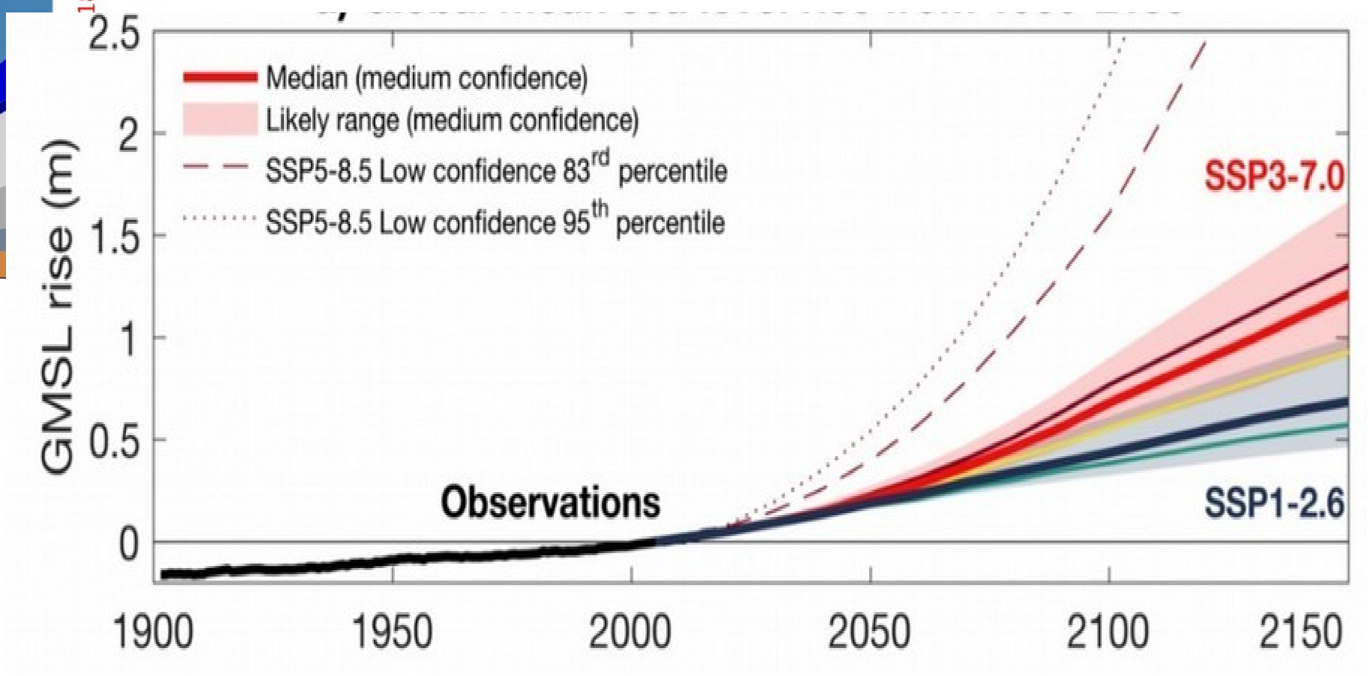
[IPCC AR6-WG1, ch. 11]

Sea level change

recent



future

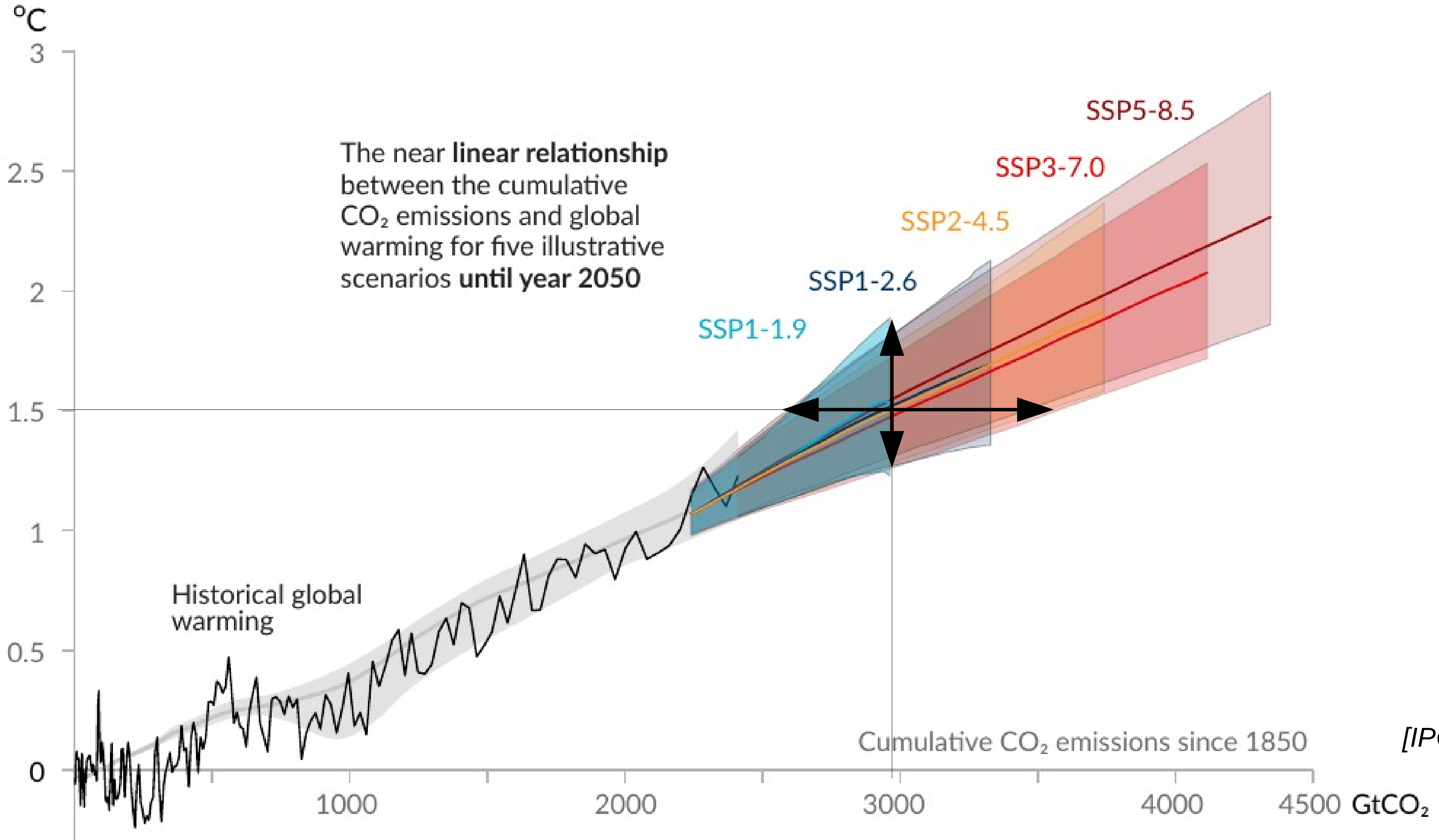


[IPCC 2021, AR6-WG1]

Outlook

I. Earth radiative budget and the greenhouse effect
II. Numerical climate models
III. Simulating and attributing recent climate changes
IV. Scenarios and future climate changes
V. Climate sensitivity and climate feedbacks
VI. Climate variability and past climate changes

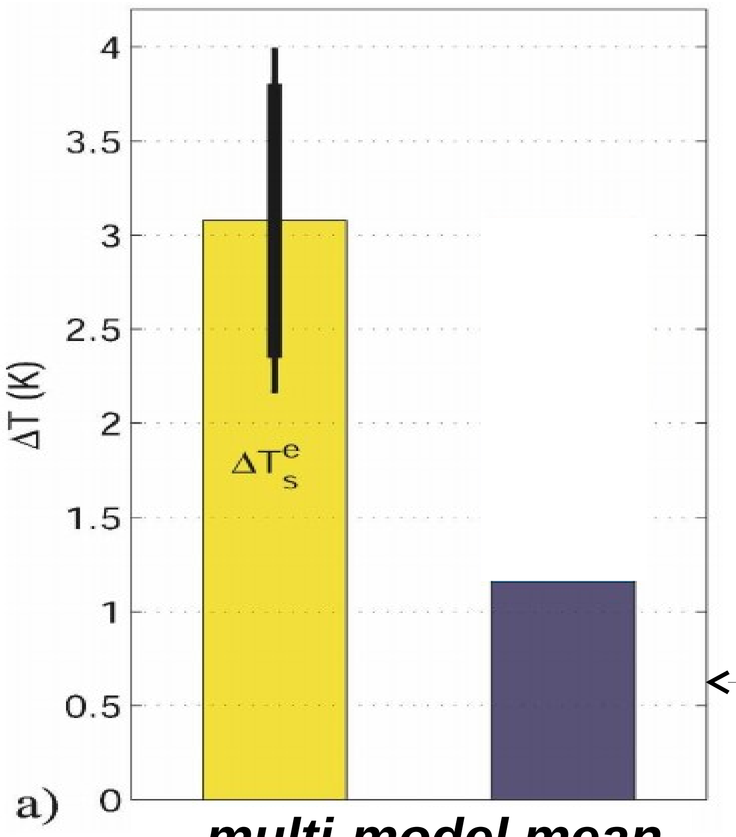
Global surface temperature increase since 1850-1900 (°C) as a function of cumulative CO_2 emissions.



[IPCC 2021, AR6]

How much individual feedbacks contribute to global warming

Equilibrium temperature response to a CO_2 doubling



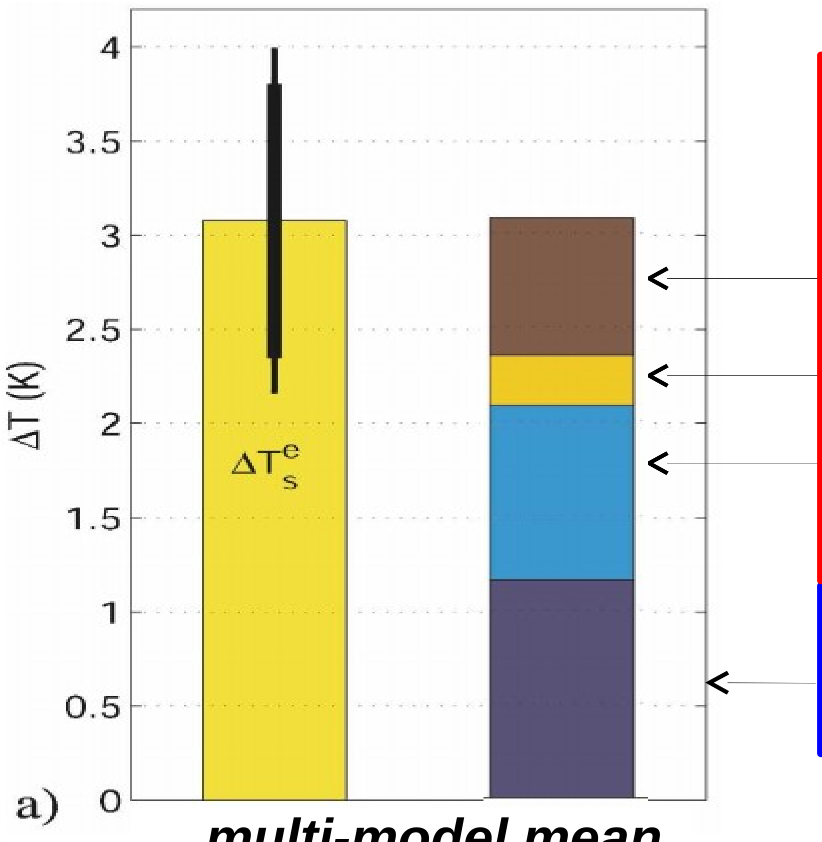
multi-model mean

Direct response to the forcing
Planck response

(Dufresne & Bony, 2008)

How much individual feedbacks contribute to global warming

Equilibrium temperature response to a CO_2 doubling



multi-model mean

Climate feedbacks: Indirect response to the forcing

- clouds
- snow and ice (surface albedo)
- water vapor

Direct response to the forcing

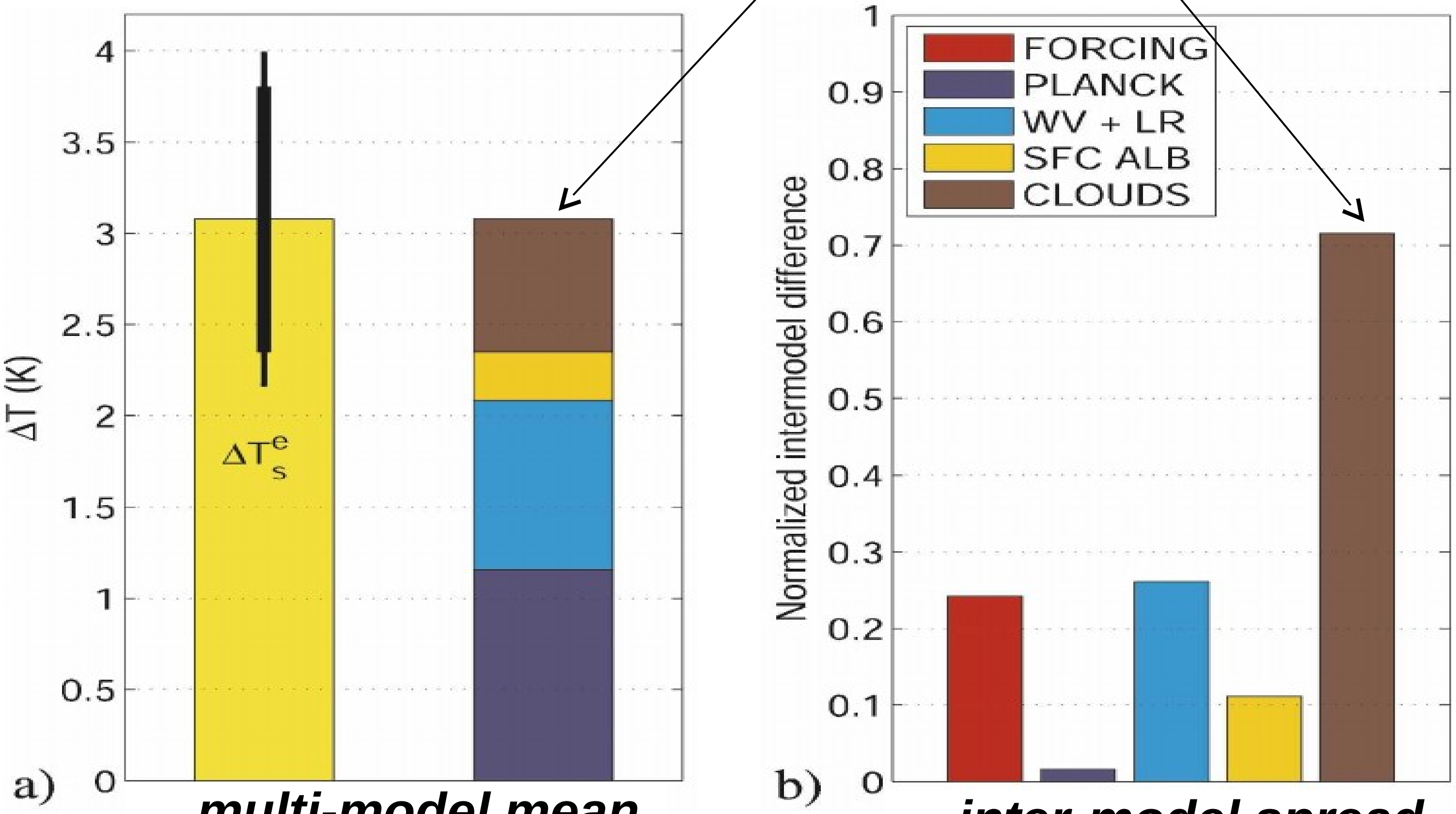
- Planck response

(Dufresne & Bony, 2008)

How much individual feedbacks contribute to global warming

Equilibrium temperature response to a CO_2 doubling

Cloud feedback



multi-model mean ***inter-model spread***

(Dufresne & Bony, 2008)

Outlook

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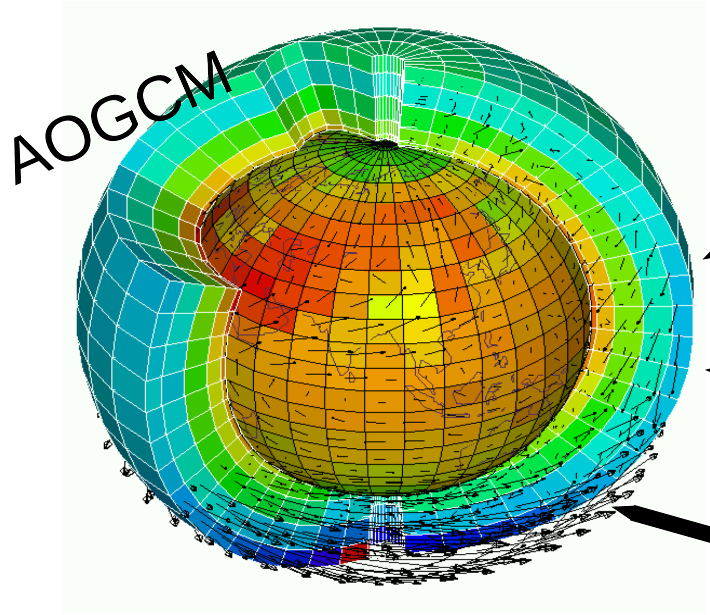
Internal variability and variations due to forcings

Climate variations have different origines:

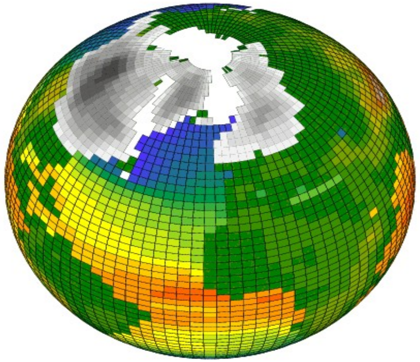
$$\underbrace{\Delta T}_{\text{variation}} \approx \underbrace{\underbrace{\Delta T_{int}}_{\text{Internal variability}} + \underbrace{\frac{\partial T}{\partial Q}\Delta Q_{nat}}_{\text{Response to natural forcings}}}_{\text{Natural variability}} + \underbrace{\frac{\partial T}{\partial Q}\Delta Q_{ant}}_{\text{Response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

- 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

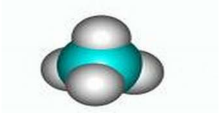
Simulation of Last Glacial Maximum (LGM)



Ice sheet



Atmospheric composition
CO_2: 185 ppm
CH_4: 350 ppb...



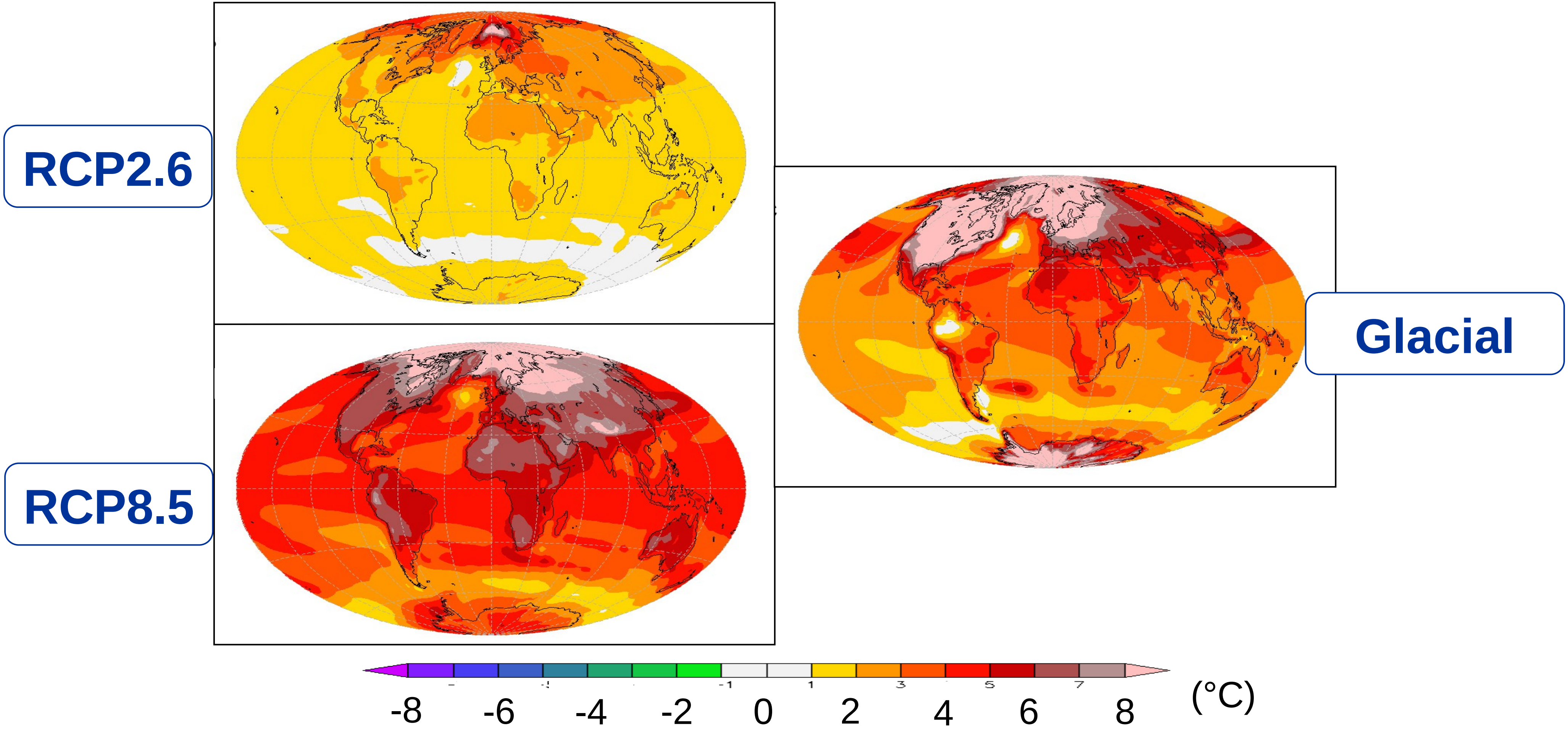
Insolation
21ky BP

Greenhouse gas forcing ~ future climate
Other main forcings: ice sheet

cf. http://pmip3.lsce.ipsl.fr

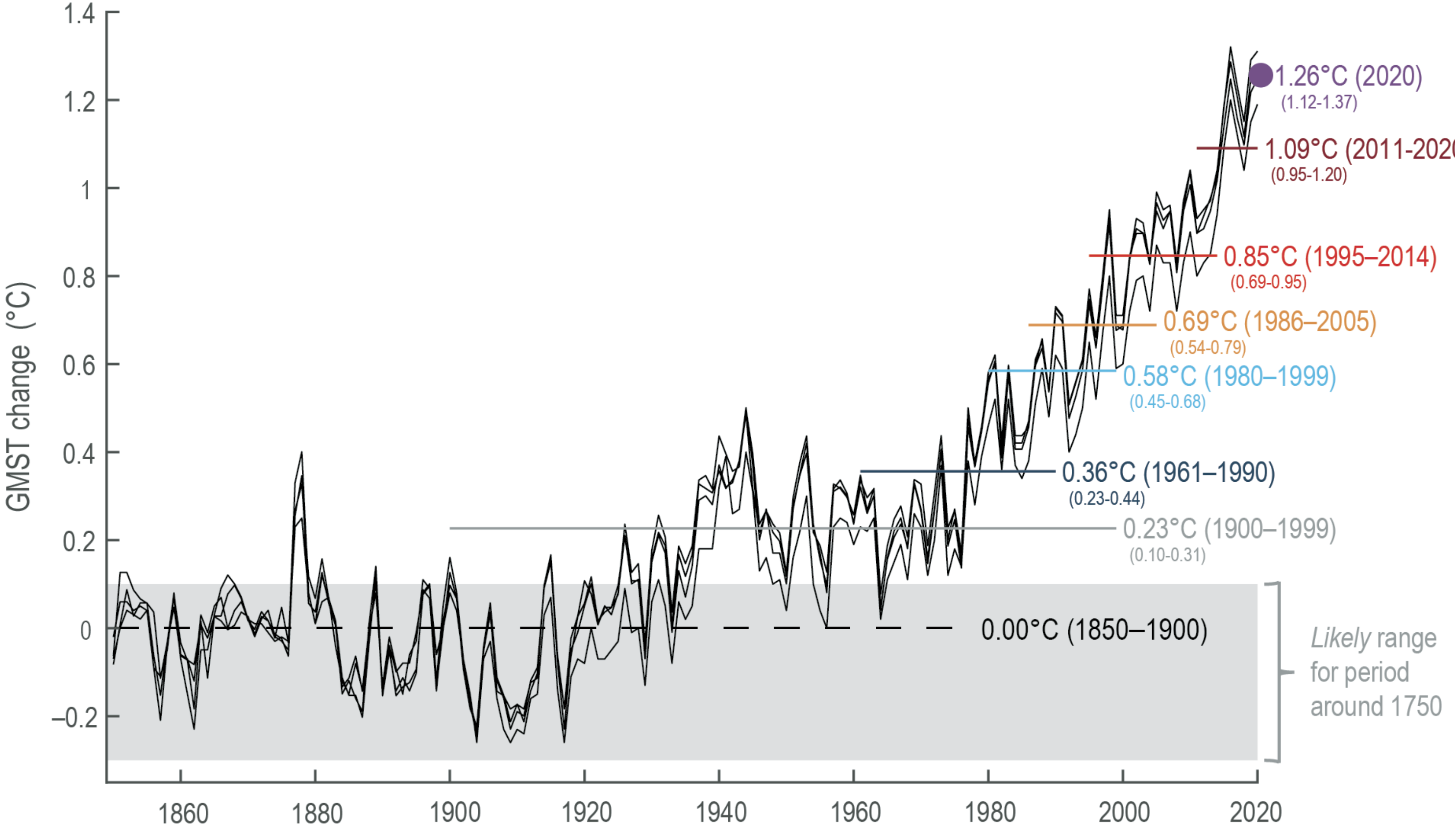
Change in surface temperature

Difference between **2100** and **1990** IPSL-CM5A-LR



Observed global mean surface temperature change

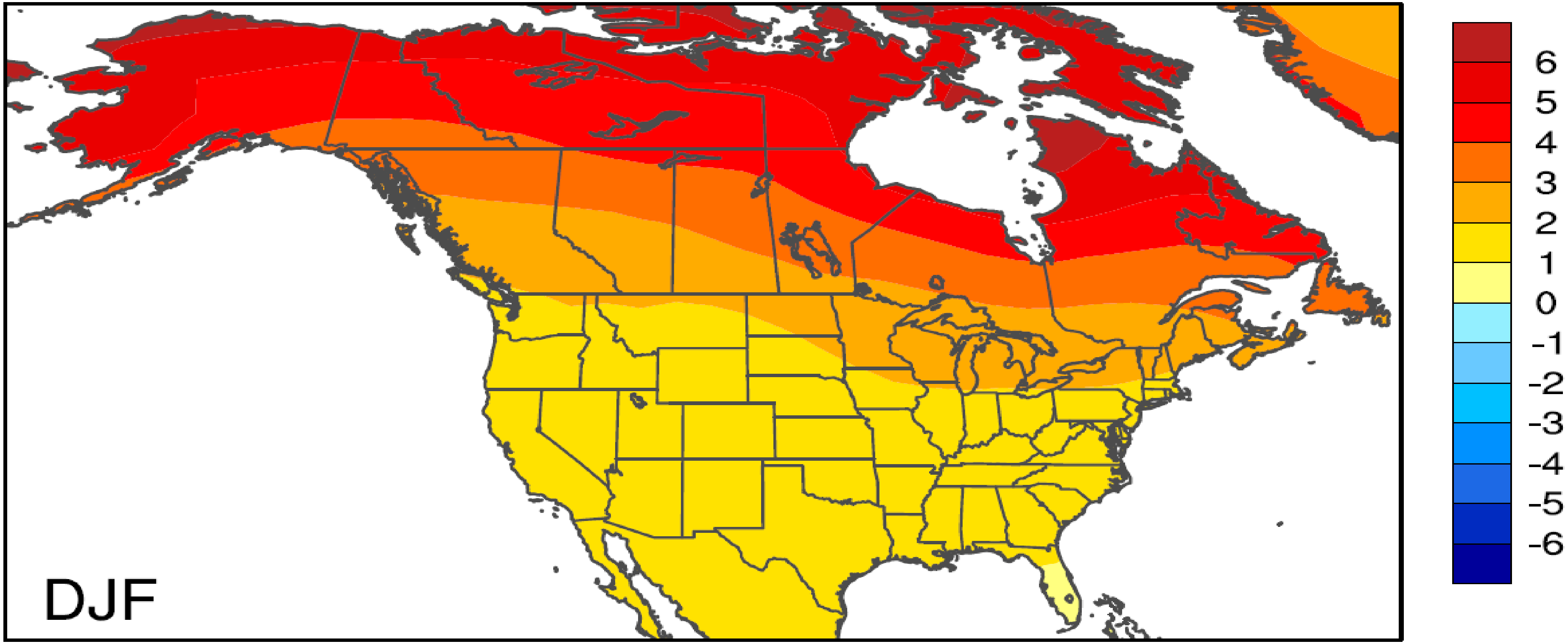
Relative to 1850–1900 using four datasets



[IPCC, 2021]

Climate change and climate variability

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

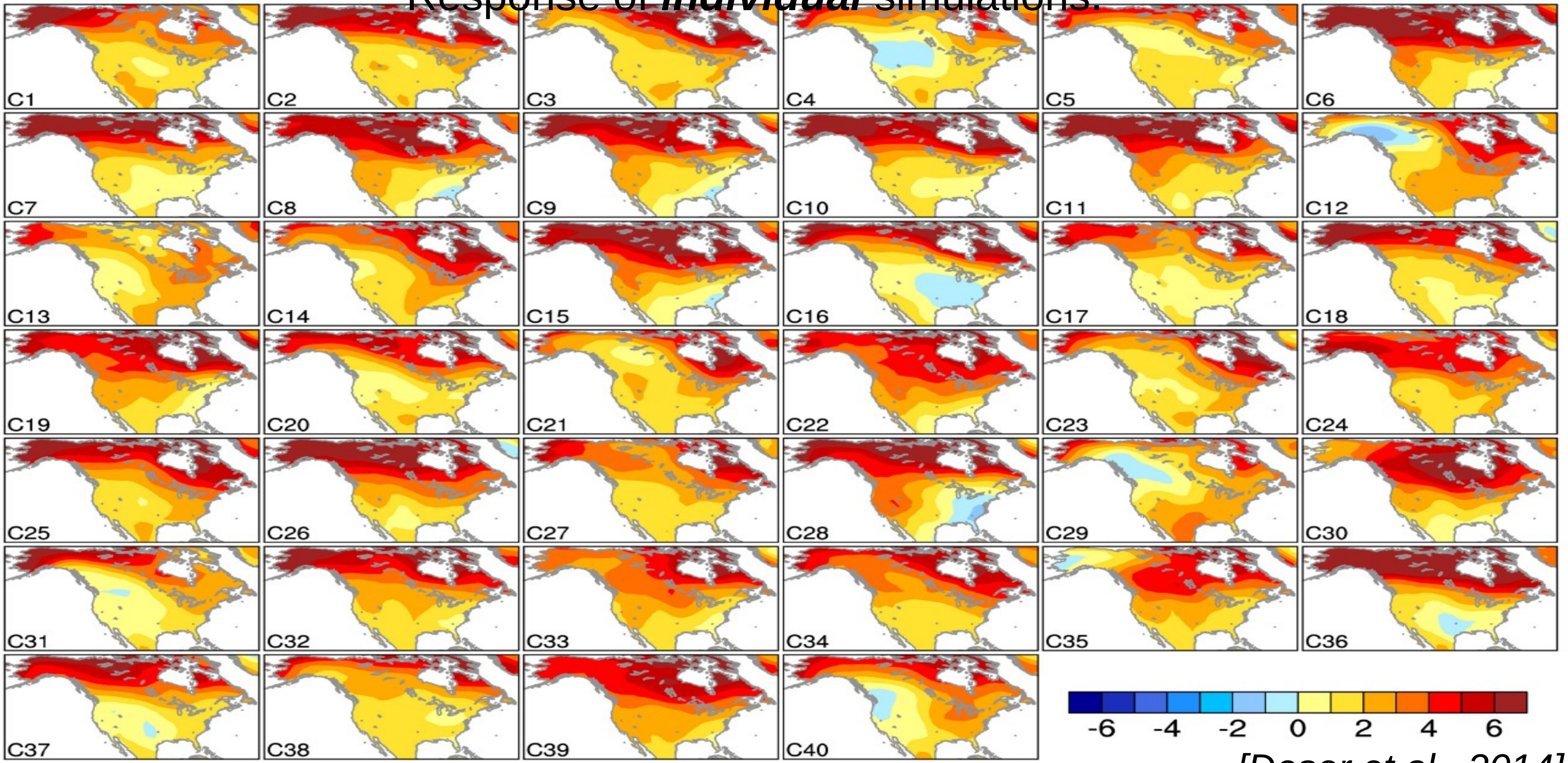


[Deser et al., 2014]

Climate change and climate variability

50 years trend of the winter surface temperature (°C/50 years).

Response of ***individual*** simulations.



[Deser et al., 2014]

Elements of perspective

From warning of the risks of major climate change to forecasting and managing the effects of these changes:

- Attributing the role of human activities on extreme climate events
- Adaptation to these changes on a local scale
- Links with related issues (biodiversity, etc.)

A few avenues for scientific development:

- Improving GCMs / ESMs
- Taking mesoscale phenomena into account
- Analysis of observations of the changing climate
- Analysis using a range of models and/or configurations with different level complexities (including theoretical models)

- and AI !!

www.ipcc.ch
Technical summary
Interactive atlas

Thank you for your attention