IPSL Climate Modelling Centre

Physical basis of past, recent and future climate changes

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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 postulates global climate can be explained by physical laws
- 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

[Dufresne, 2006]

Emergence of the physics of climate

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Joseph Fourrier

(1768-1830)

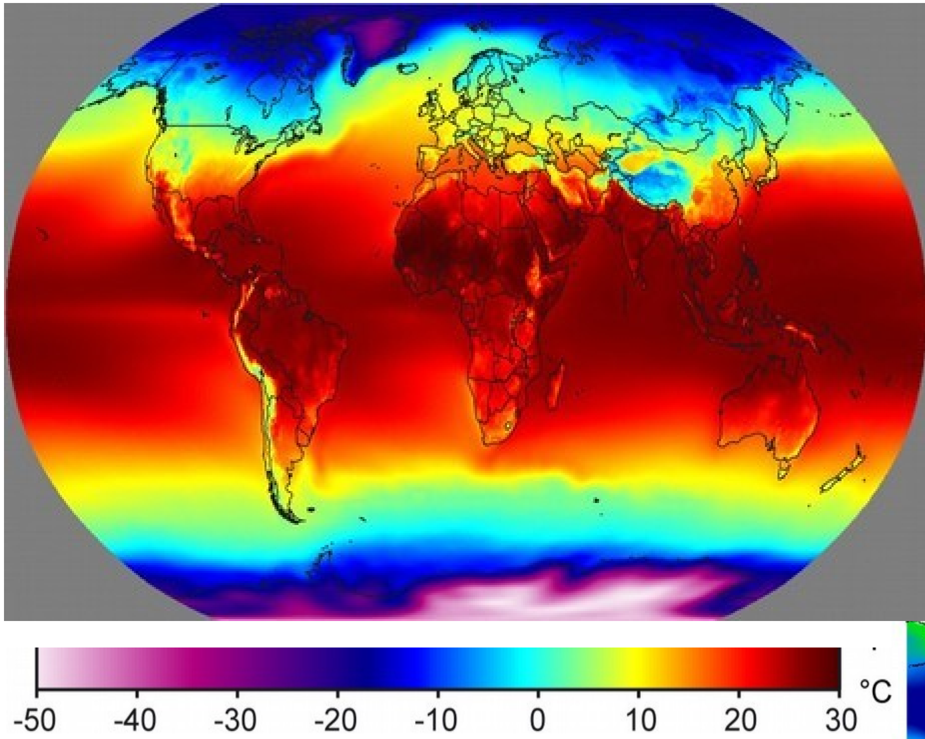
➢ He ***envisages the importance of any change of the sun*** « *The least variation in the distance of that body[the sun] from the earth would occasion very considerable changes of temperature.* »

➢ He ***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]

Does « global climate » make sens?

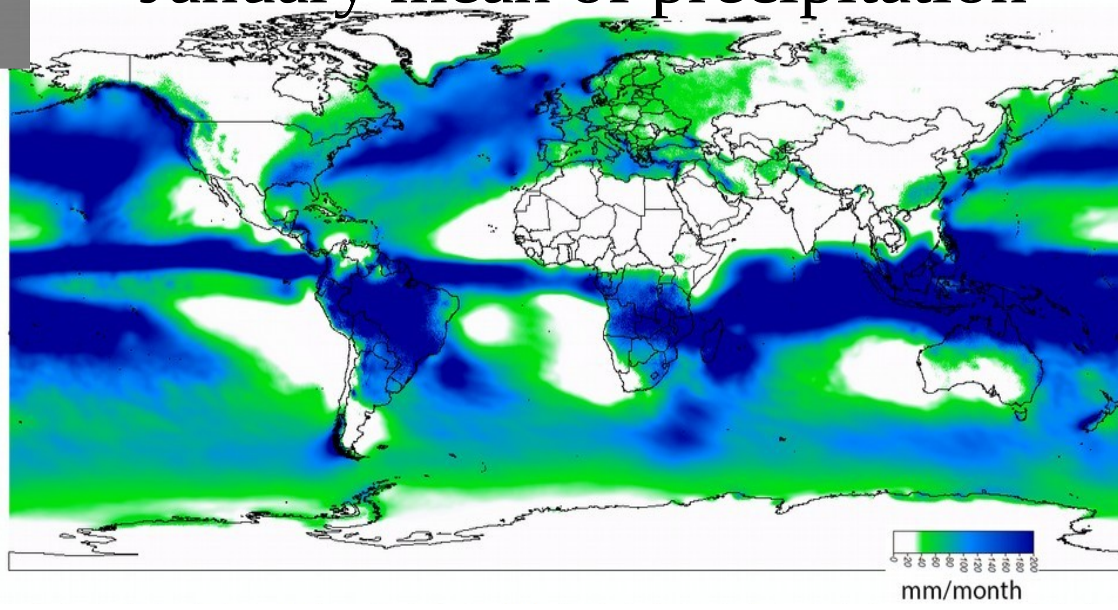
Annual mean of surface temperature



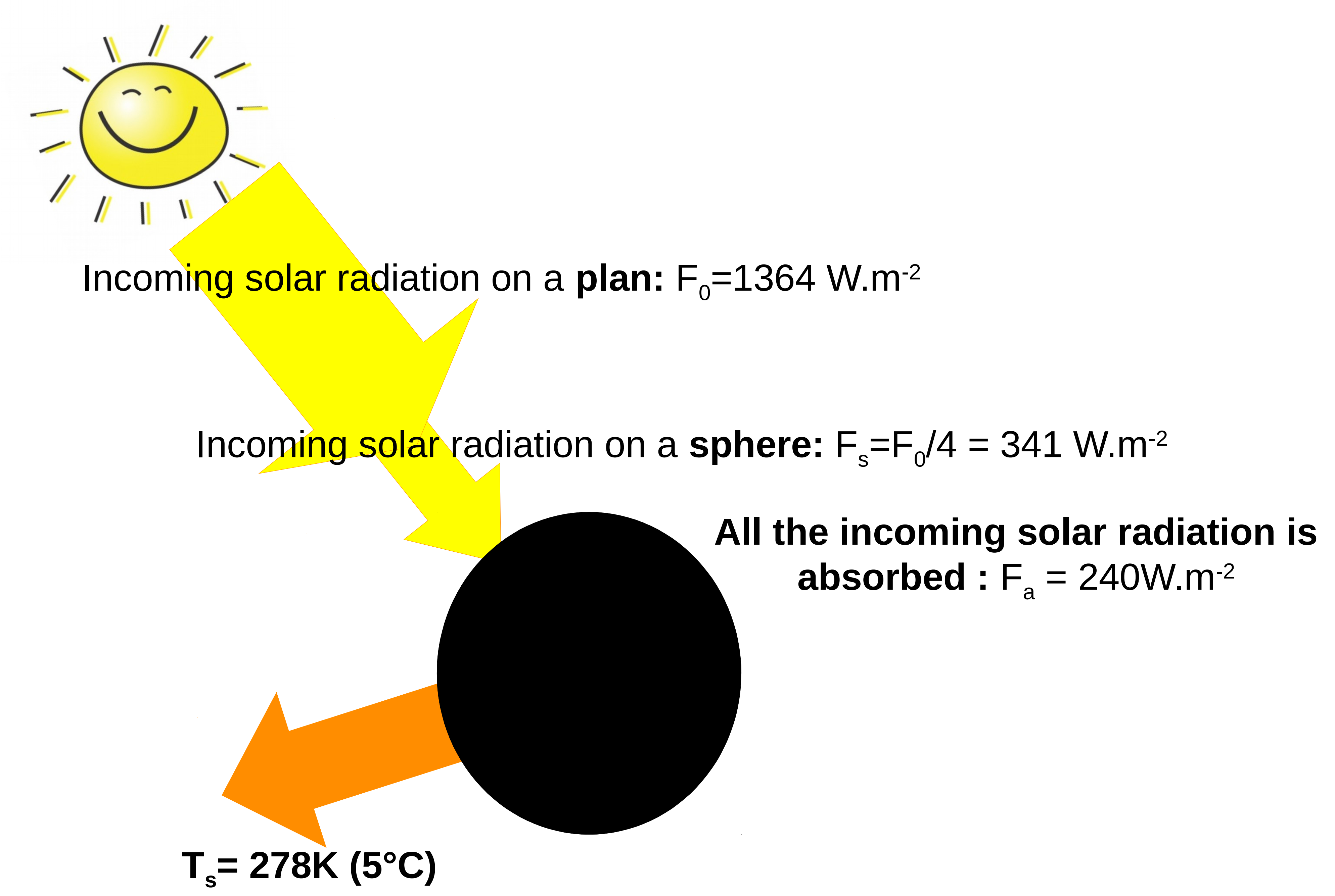
Climate : statistical properties of weather.

From Greek « klima », i.e. «sky tilt », title of surface relative to the sun

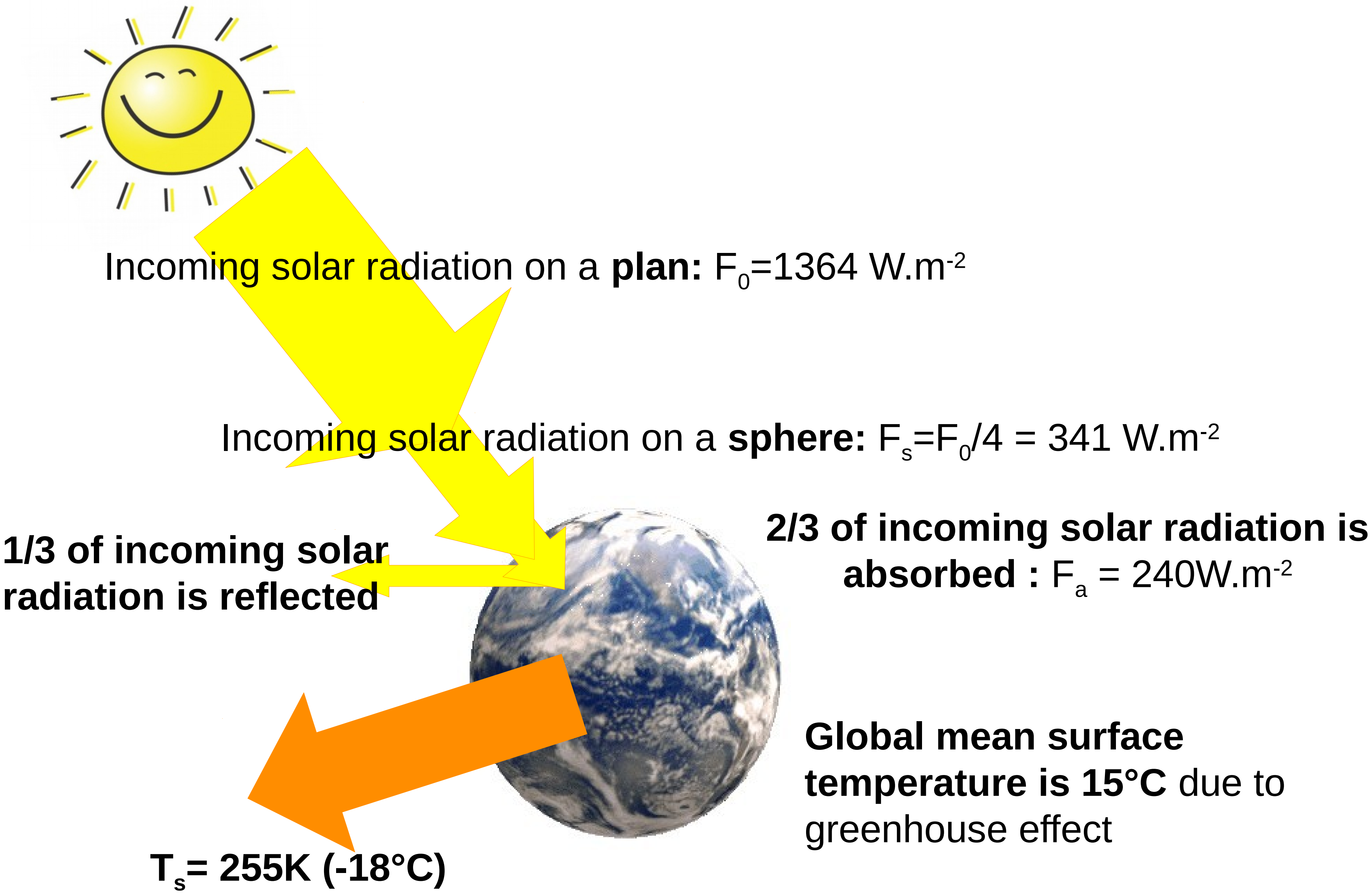
January mean of precipitation



Equilibrium temperature of a planet

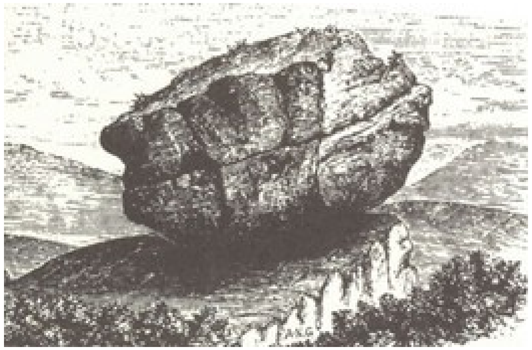


Equilibrium temperature of a planet



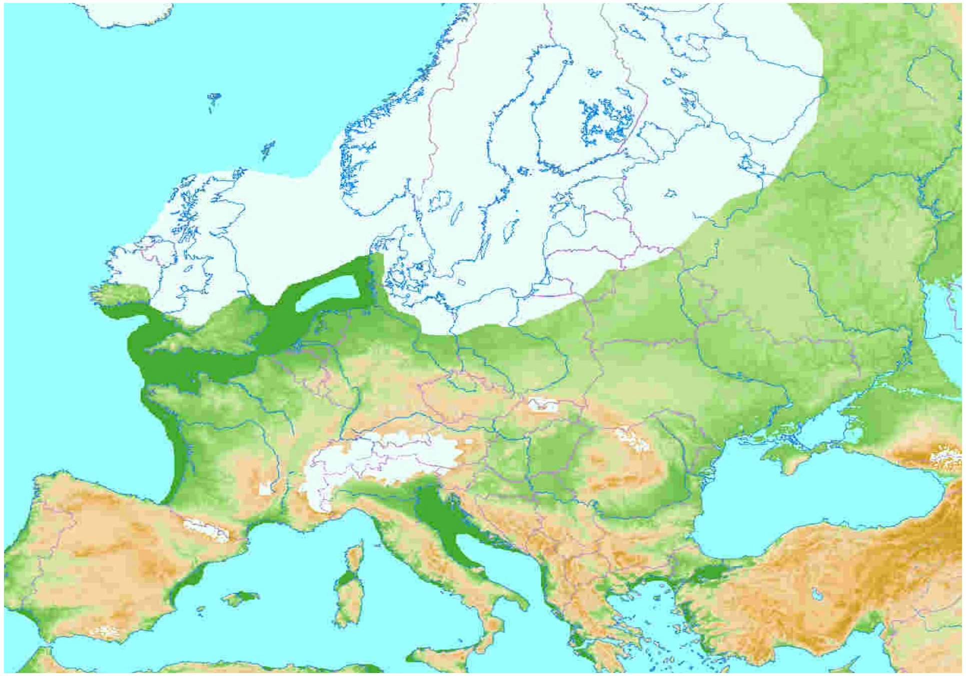
Discovery of past climate changes
The hypothesis of glacial periods (1840-1860)

Jean de Charpentier



Erratic blocks

Louis Agassiz



Discovery of past climate changes

A period described by cave paintings

Cosquer

Lascaux

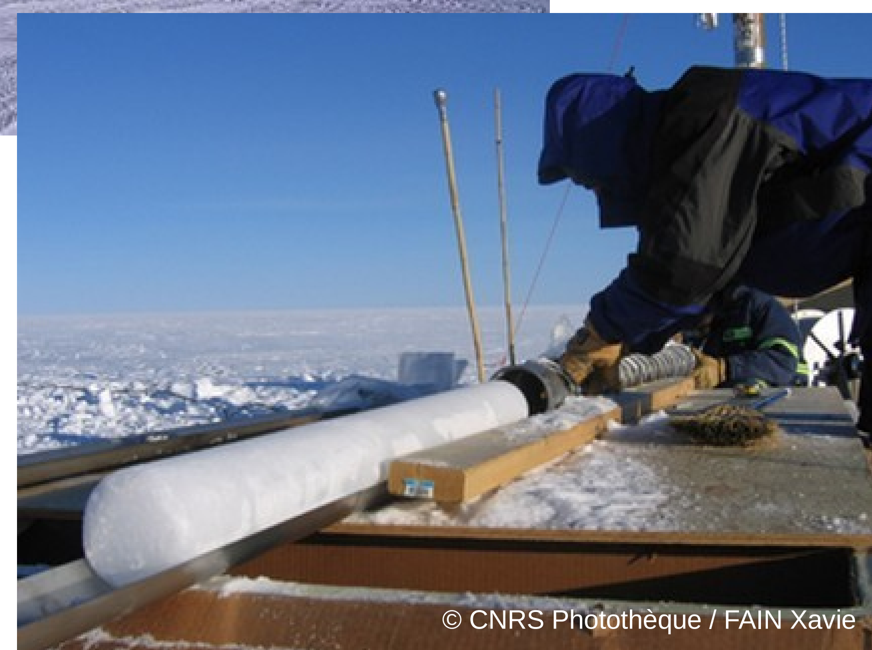
Chauvet

Origin of these variations : sun or CO_2 (1860-1900) ?

James Croll

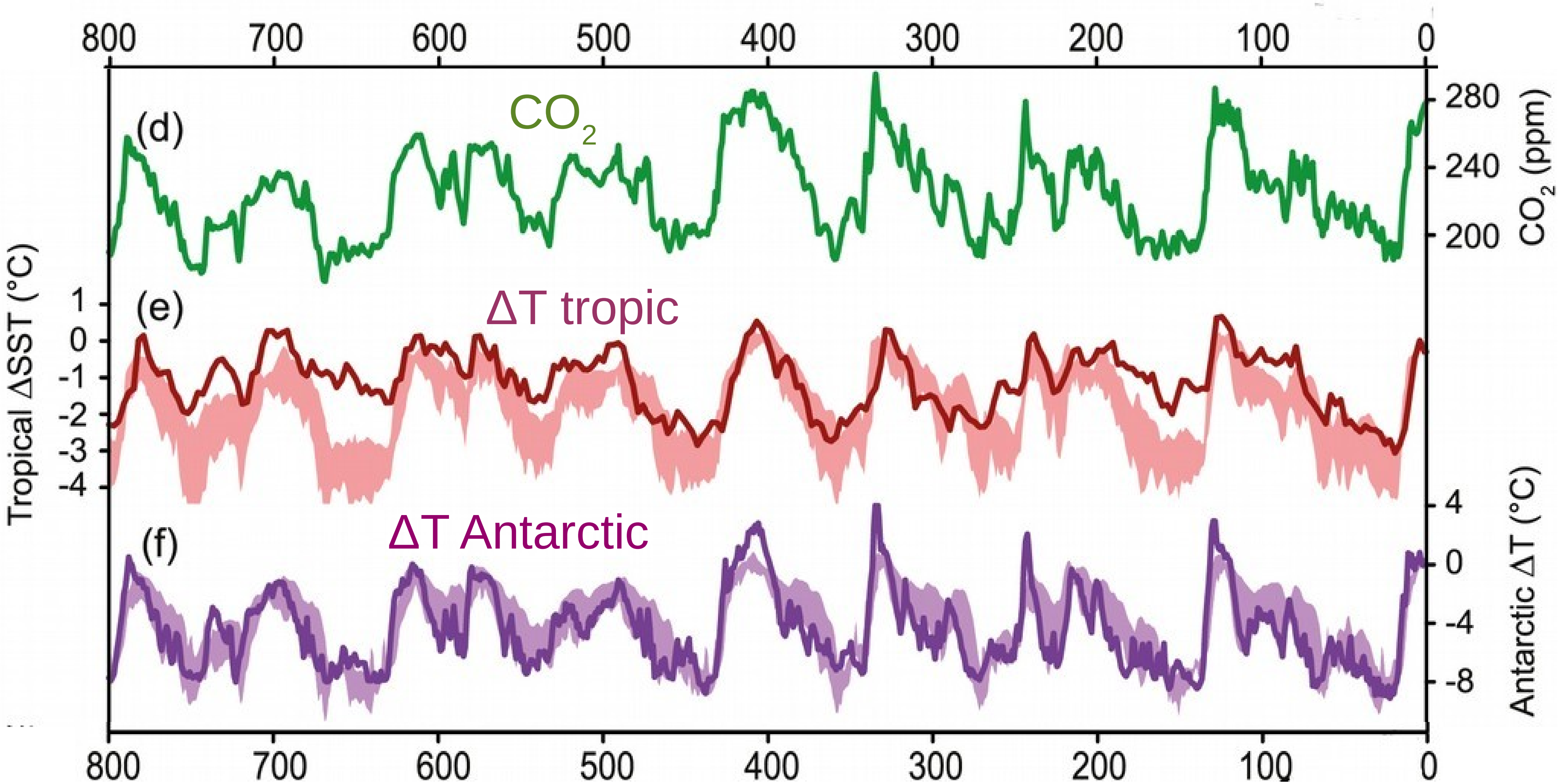
Svante Arrhenius

Discovery of past climate changes



Ice cores in Antarctica and Greenland

Discovery of past climate changes



in thousands of years since the present

after [IPCC, AR5, 2013]

Outlook

I. Emergence of climate and climate change science

II. Climate modeling

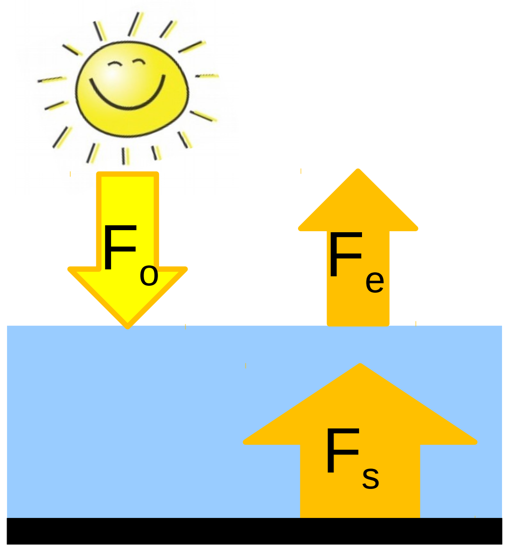
III. Climate and climate change simulations

IV. Focus on some climate phenomena

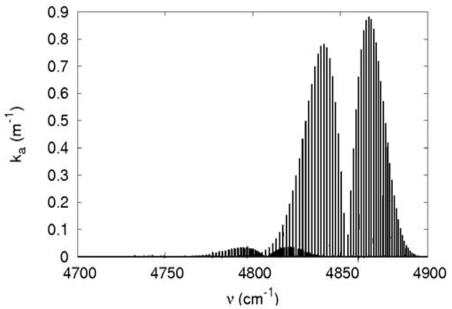
V. Climate changes and climate variability

VI. Conclusions

What radiation heat transfer theory tell us



Greenhouse effect: $G=F_s-F_e$



Gas radiative properties

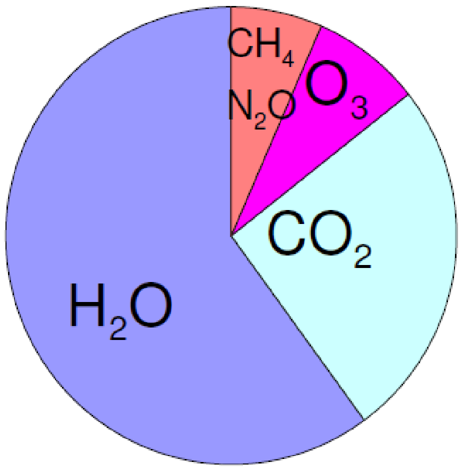
Atmospheric characteristics

Computation of the radiative fluxes and the greenhouse effect

Current greenhouse effect: G ≈ 150 $W.m^{-2}$

Contribution of atmospheric gases (clear sky)

Water vapour	60%
CO_2	26%
Ozone O_3	8%
$N_2O + CH_4$	6%



For a doubling of CO_2 concentration, green house effect increases by **≈ 3.7 $W.m^{-2}$**

From radiative transfer computation to climate modelling

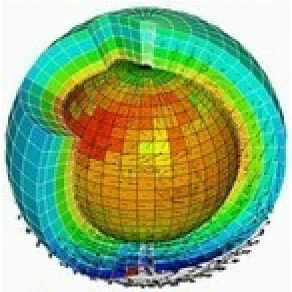
For a doubling of the CO_2 concentration:

- the green house effect increases by 3.7 $W.m^{-2}$
- the temperature increases by ≈ 1.2 K, if nothing change except an uniform increase of temperature that only impact radiation

But feedbacks exist:

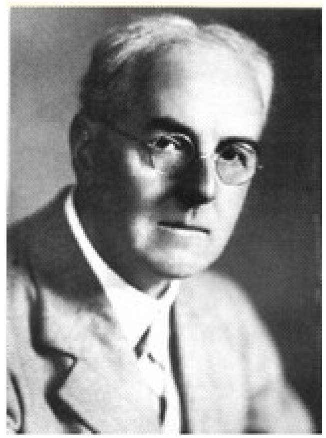
- Snow and sea ice reflect solar radiation; if they decrease, more solar energy will be absorbed ⇒ positive feedback
- Water vapour is the main greenhouse gas; if it increases, the greenhouse effect will be enhanced ⇒ positive feedback
- Clouds reflect solar radiation and contribute to the greenhouse effect; if they change, the energy budget will be modified ⇒ positive or negative feedback

Need of 3D numerical climate models



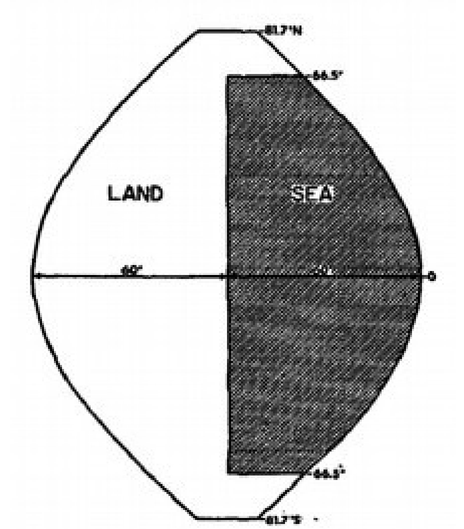
Numerical climate models
(numerical weather simulators)

Wilhelm Bjerknes
(1862–1951)

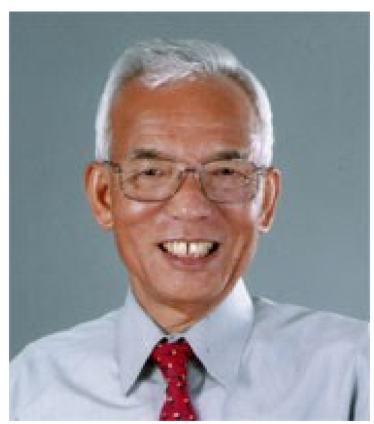


L. F. Richardson
(1881–1953)

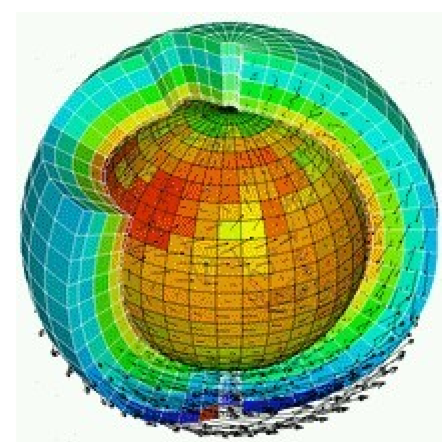
J. von Neumann
(1903–1957)



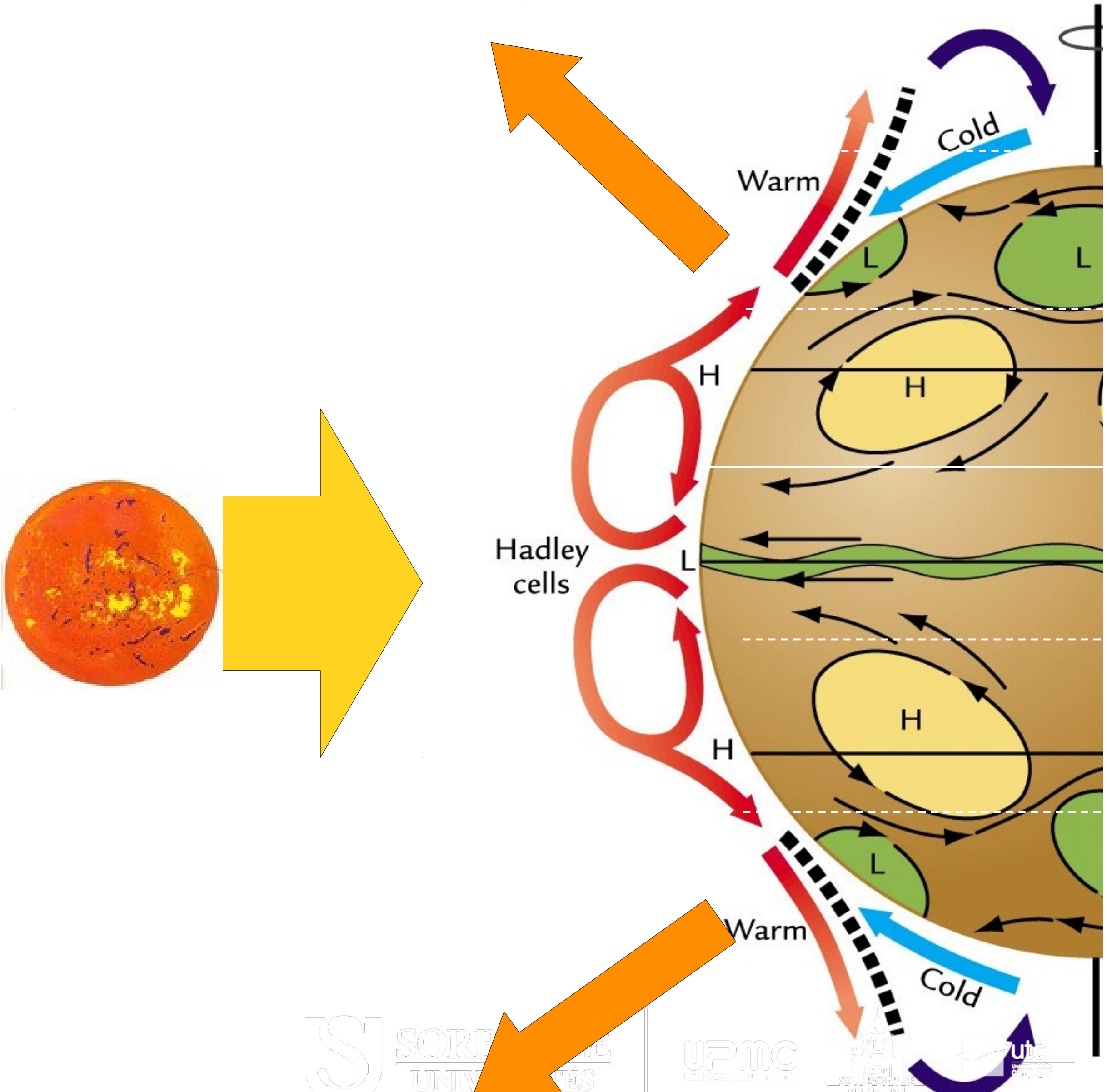
Jule Charney
(1917-1981)

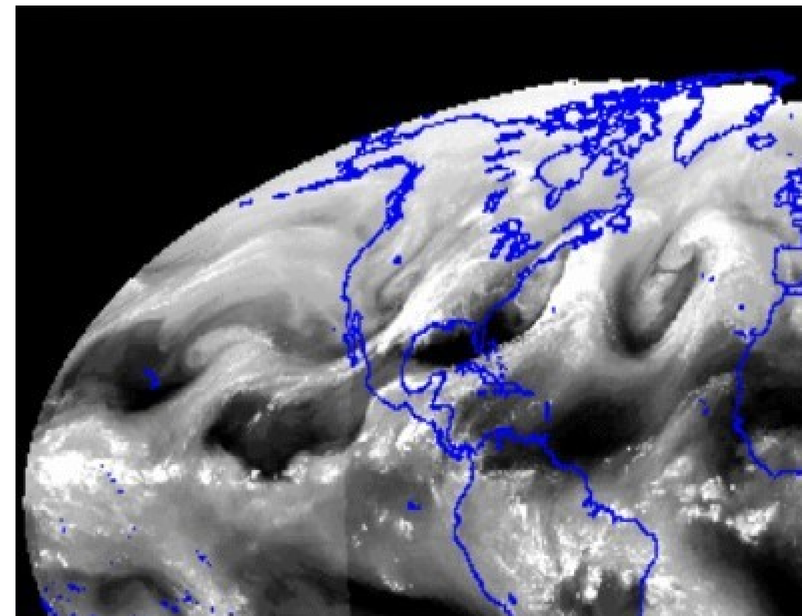


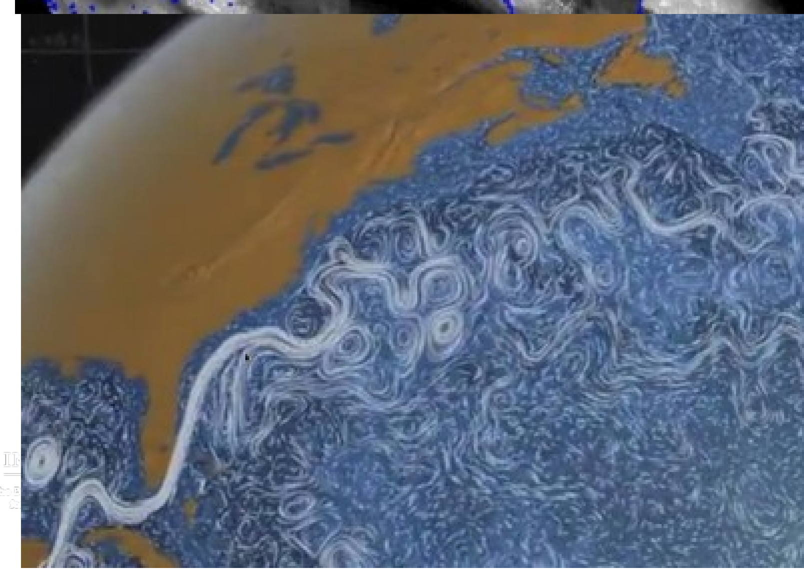
Syukuro Manabe
(1931-)



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

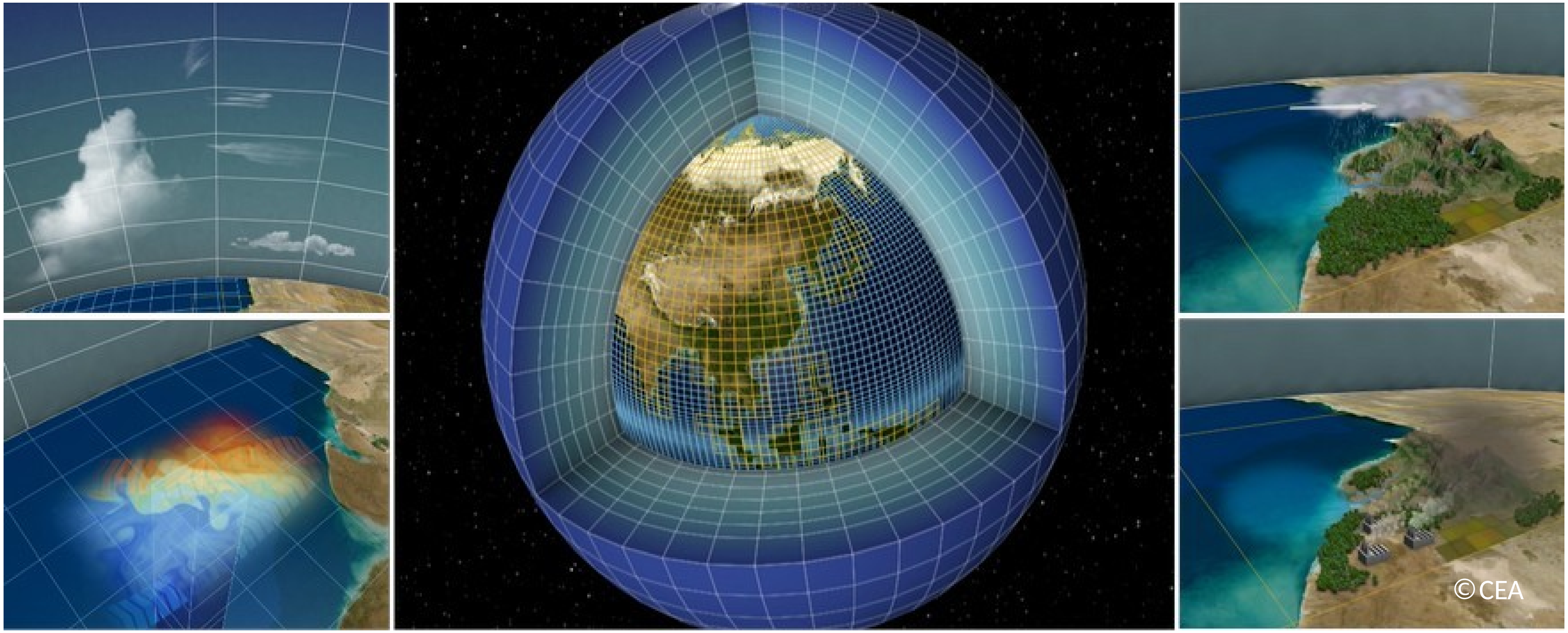






3D climate numerical models

- Physical laws (atmosphere, ocean, sea-ice....)
- Discretization (temporally and spatially)
- Modelling of the sub-grid phenomena, or parameterization



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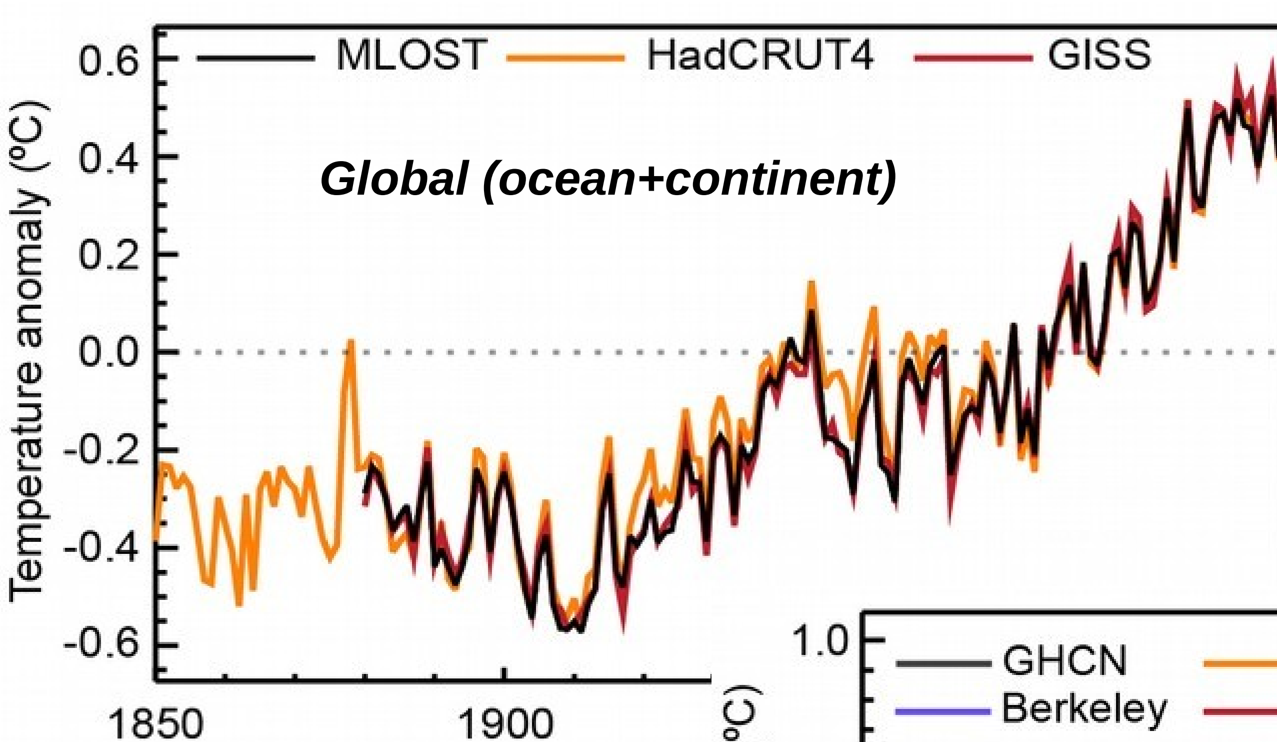
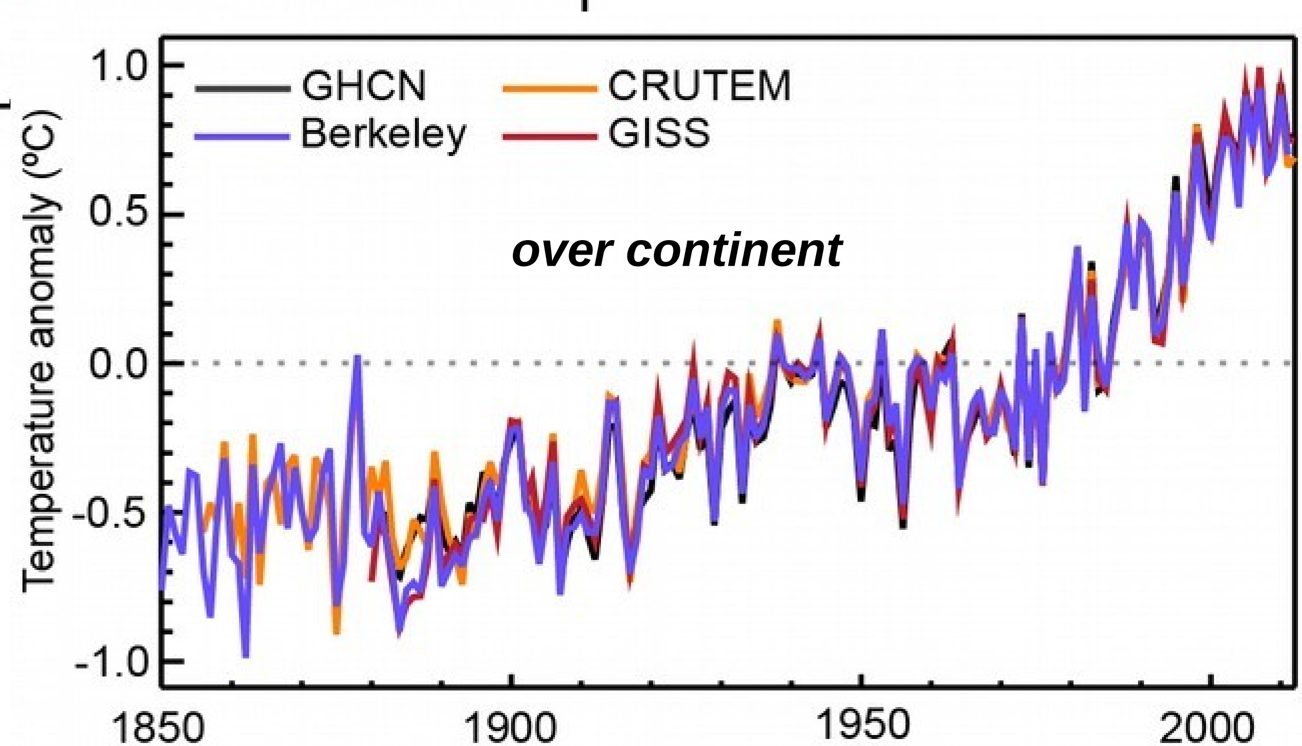
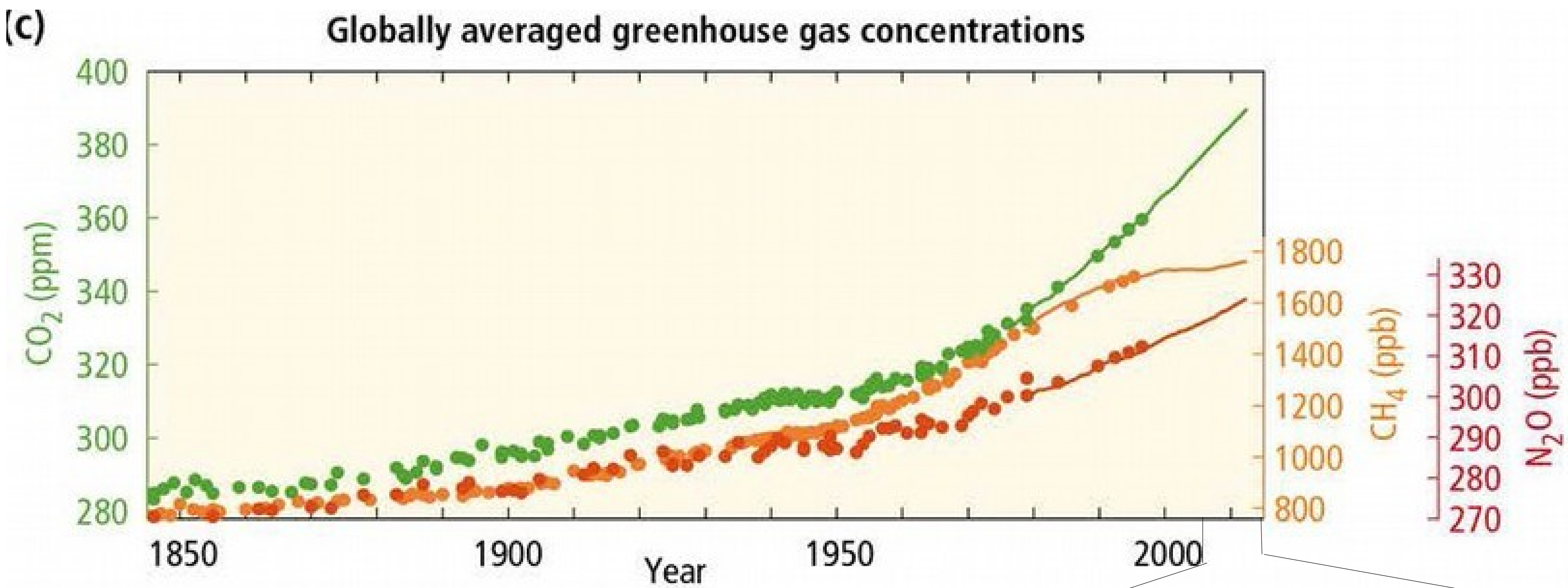
Recent changes in surface temperature



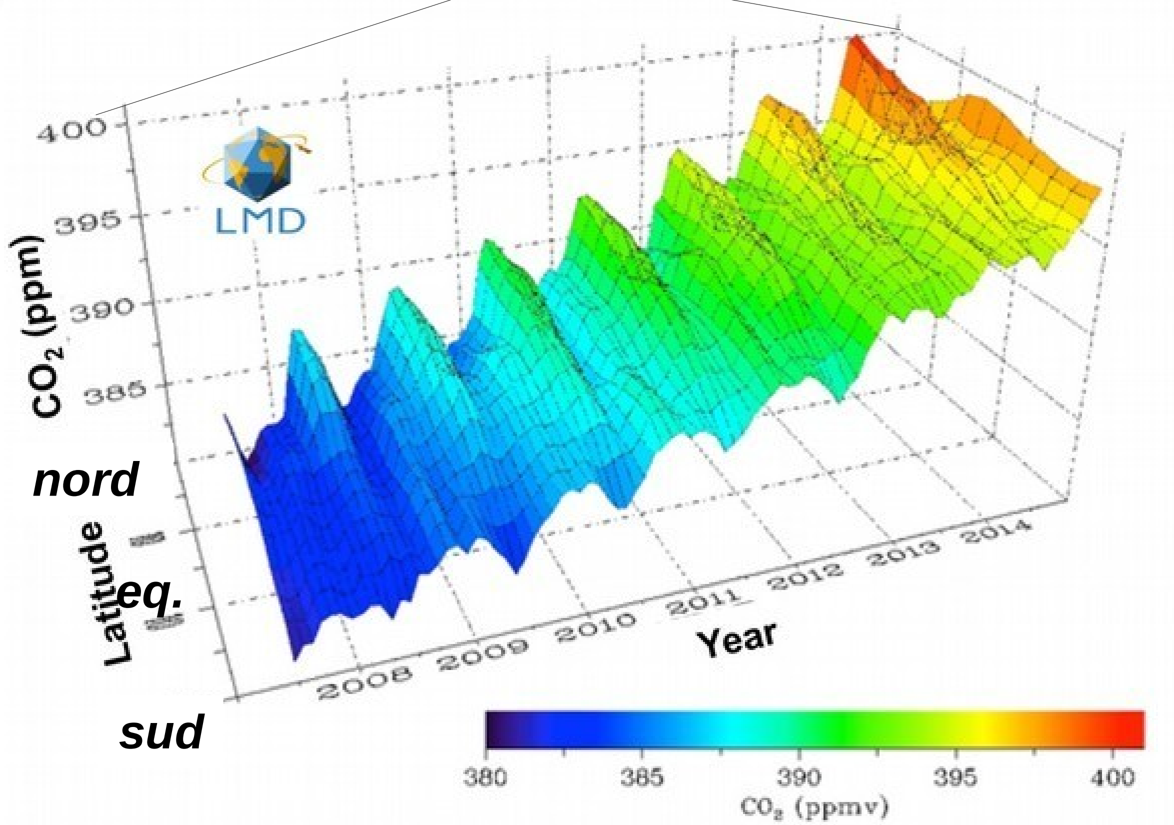


[IPCC AR5, 2013]

Role of human activities



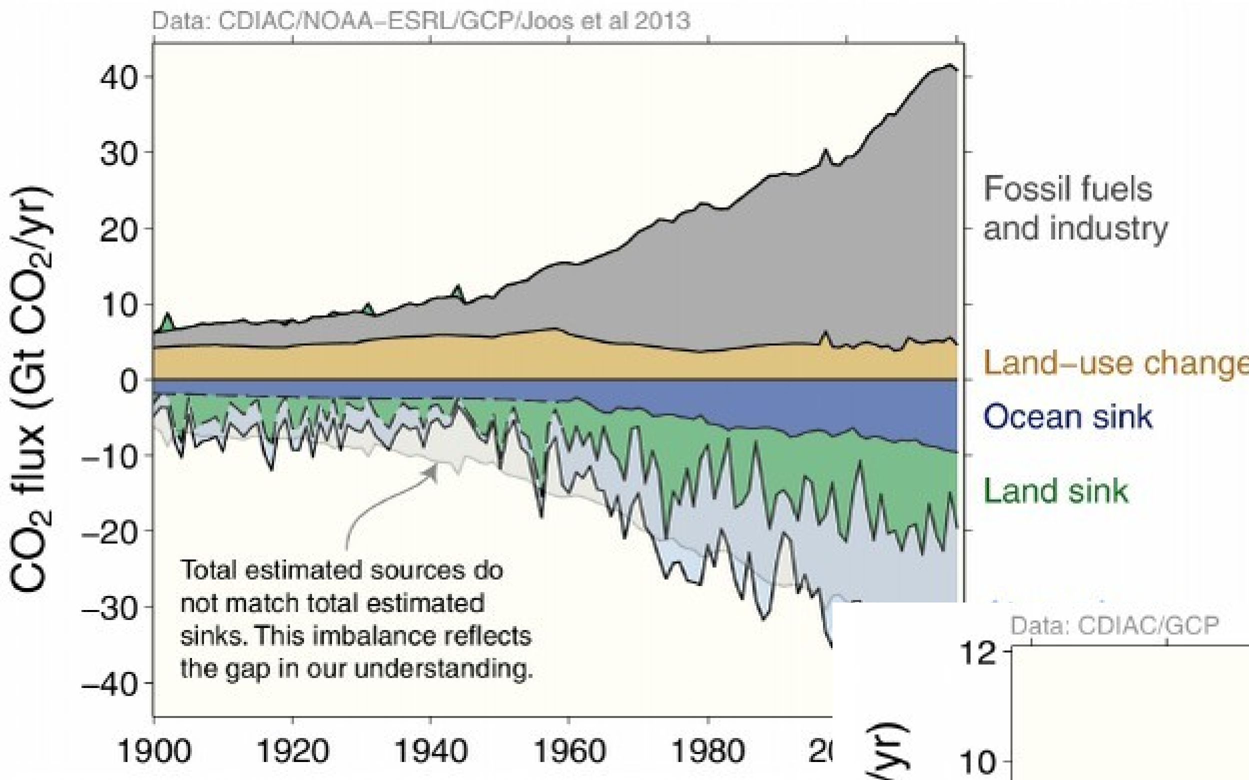
[IPCC 2014]

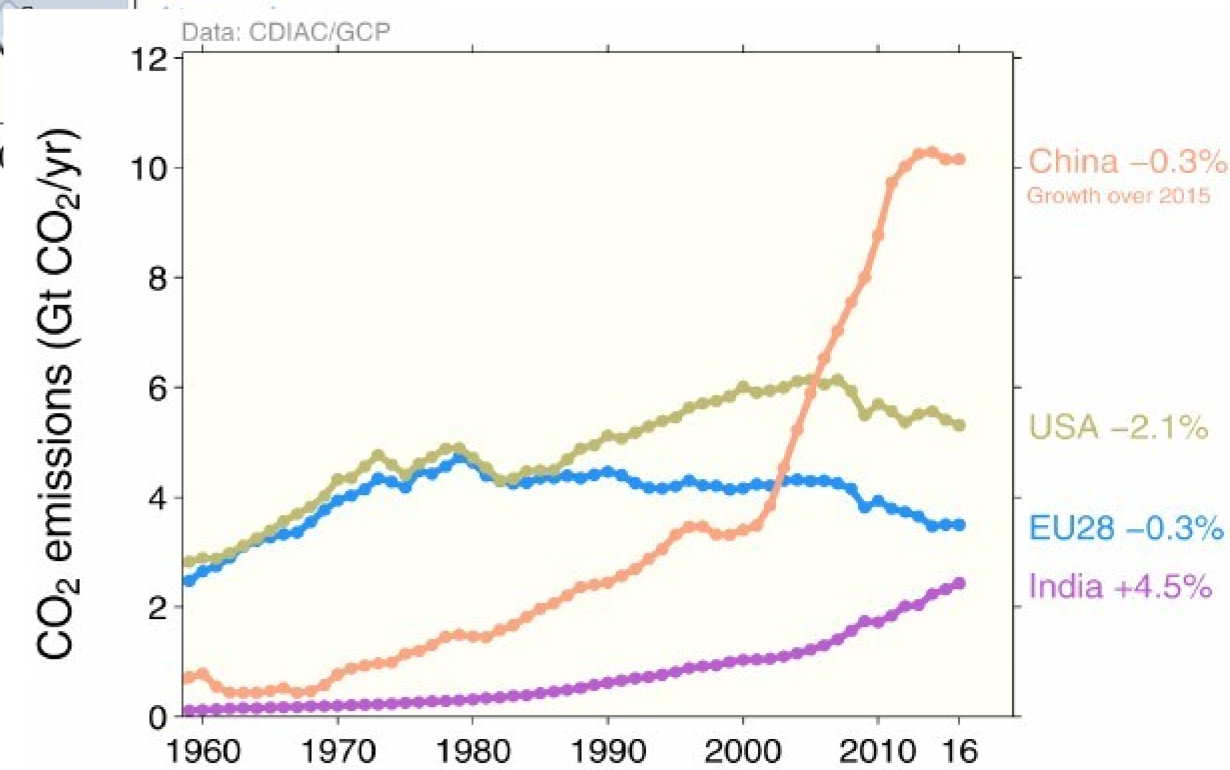


[Crevoisier et al.]

Role of human activities

[Global Carbon Project]





Mean CO_2 emissions for 2003-2012

1 GtC = 3.67 $GtCO_2$

$8,6 \pm 0,4$ GtC y^{-1}

+

$0,8 \pm 0,5$ GtC y^{-1}

$4,3 \pm 0,1$ GtC y^{-1}

45%

$2,6 \pm 0,5$ GtC y^{-1}

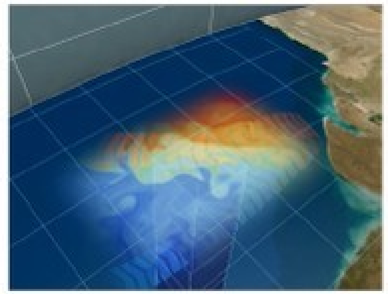
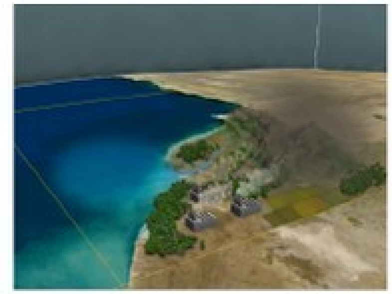
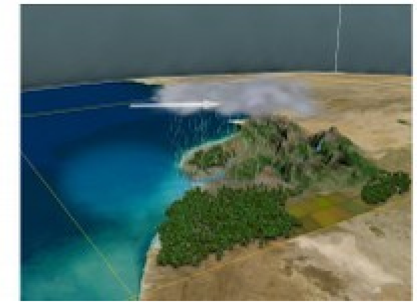
27%

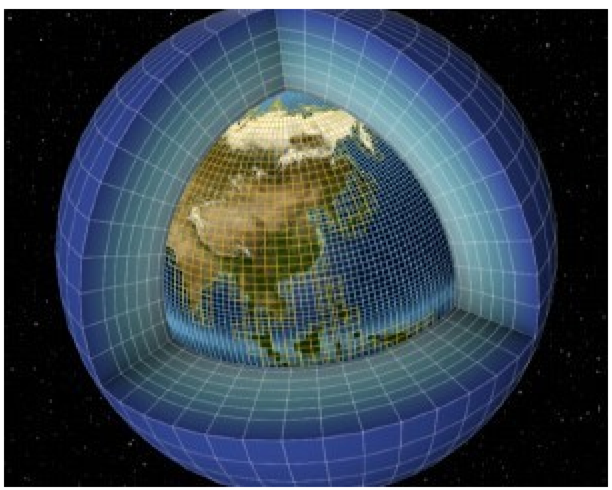
27%

$2,6 \pm 0,8$ PgC y^{-1}

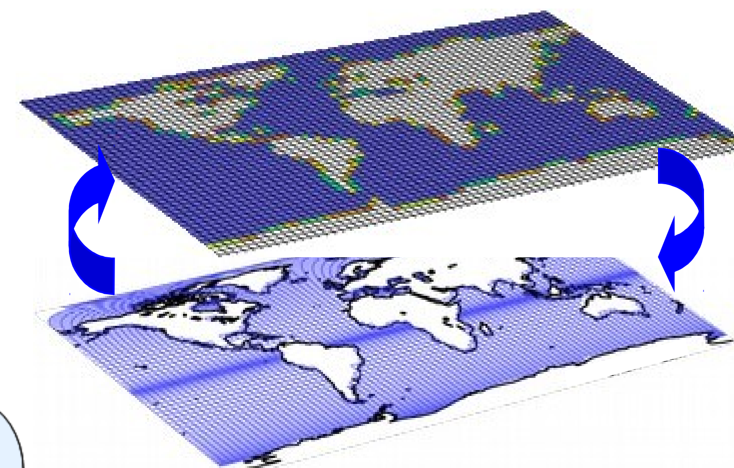
http://www.globalcarbonproject.org/ (Global Carbon Project, 2011)

The IPSL Earth System Model



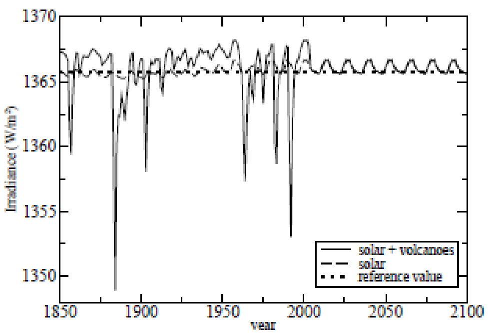
INCA / REPROBUS
(chimie atmosphérique)
(aérosol)
ORCHIDEE
(surfaces continentales)
(végétation)
LMDZ
(atmosphère)
OASIS
(coupleur)
OPA
(océan)
LIM
(glace de mer)
NEMO
PISCES
(biogéochimie marine)



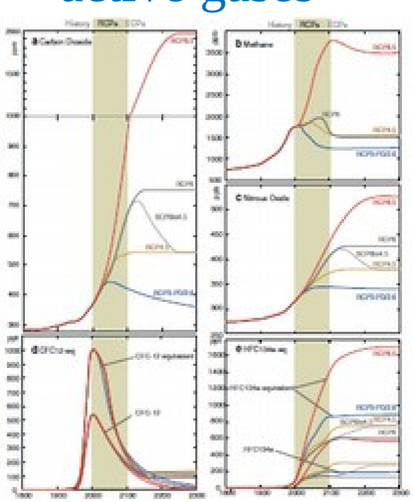
The IPSL Earth System Model

Natural and anthropogenic forcings

Solar and volcanoes



Green house gases and active gases



CO_2 concentration

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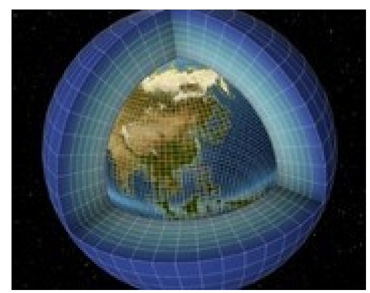
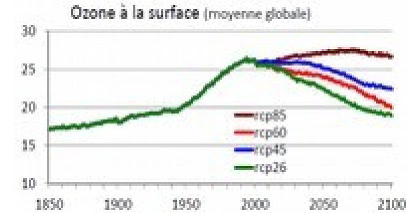
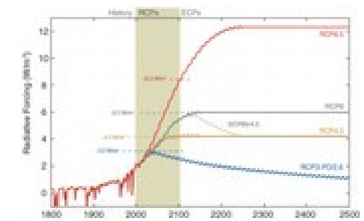


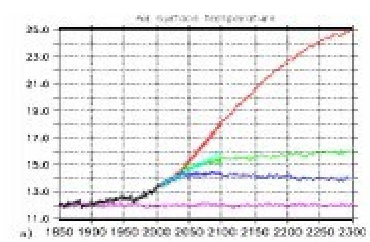
Atmospheric composition



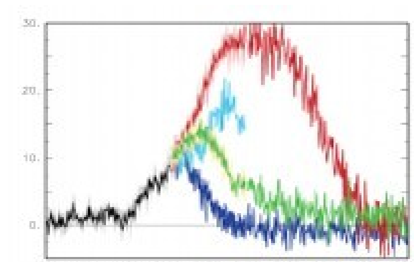
Radiative forcings



Climate changes

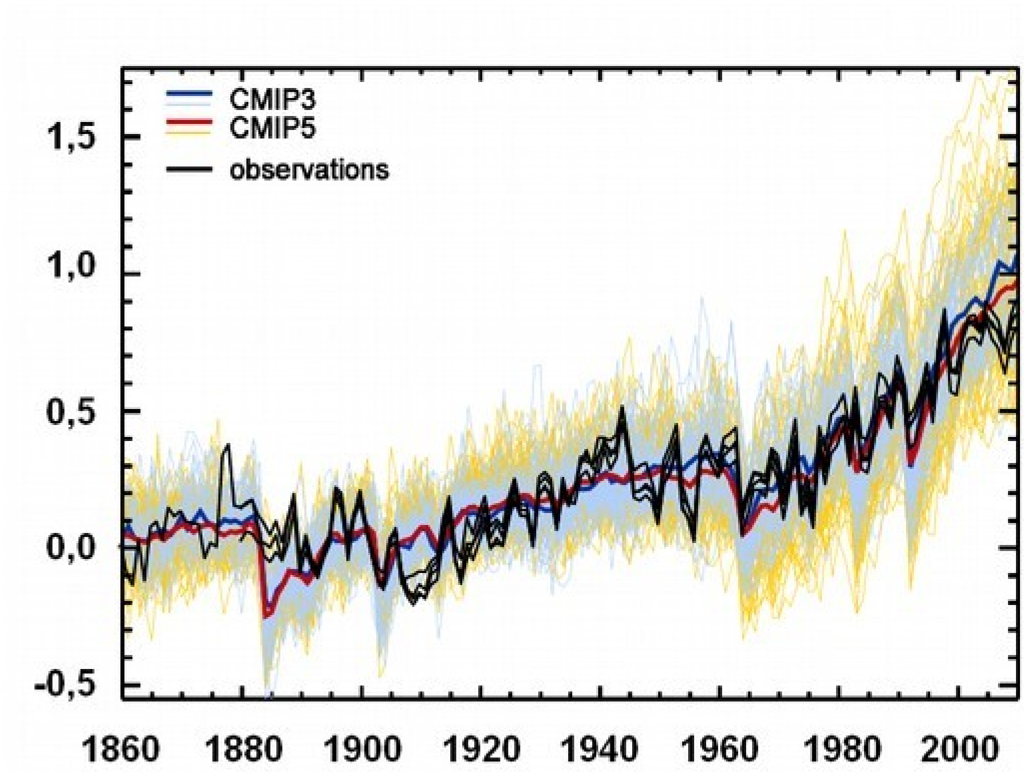


Authorized CO_2 emissions

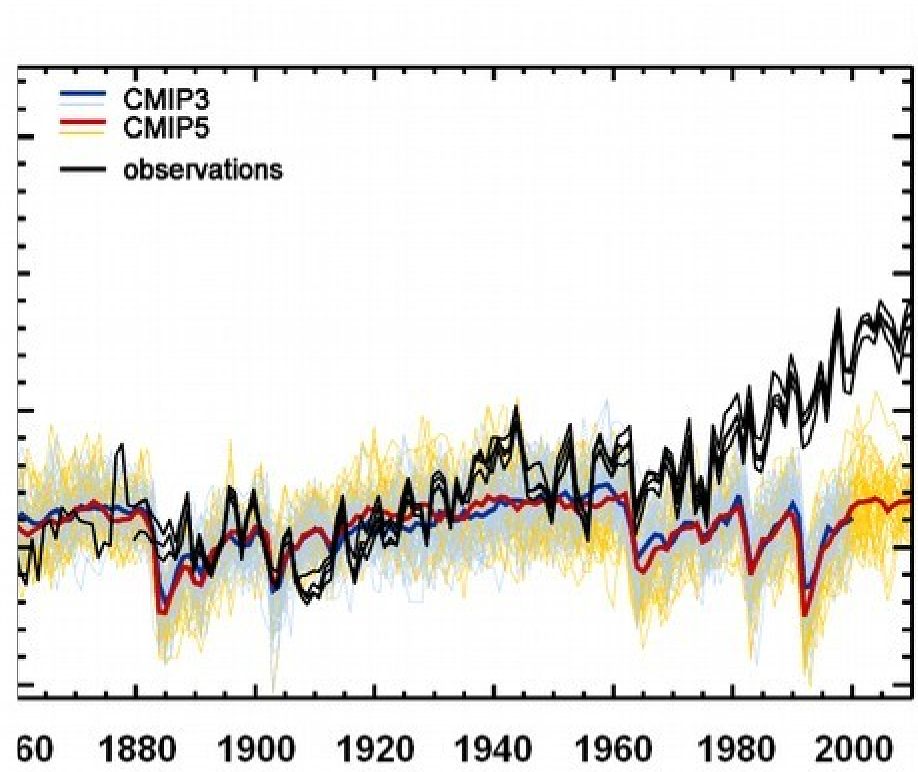


Recent Earth surface temperature trend

Simulations with natural and anthropological forcings



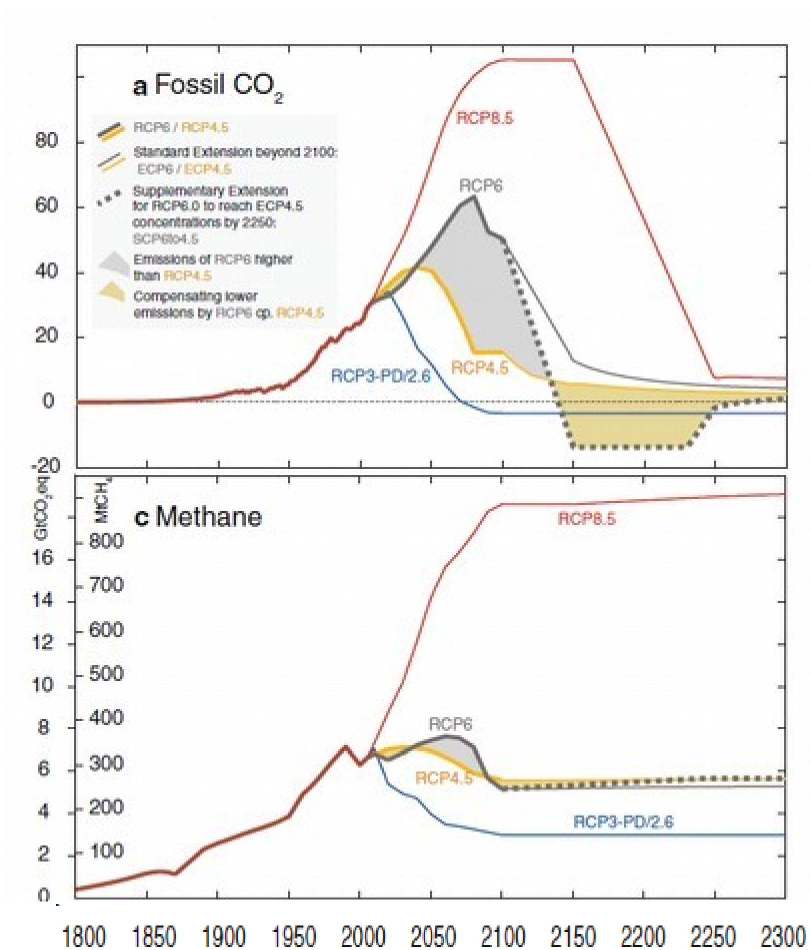
Simulations with natural forcings only



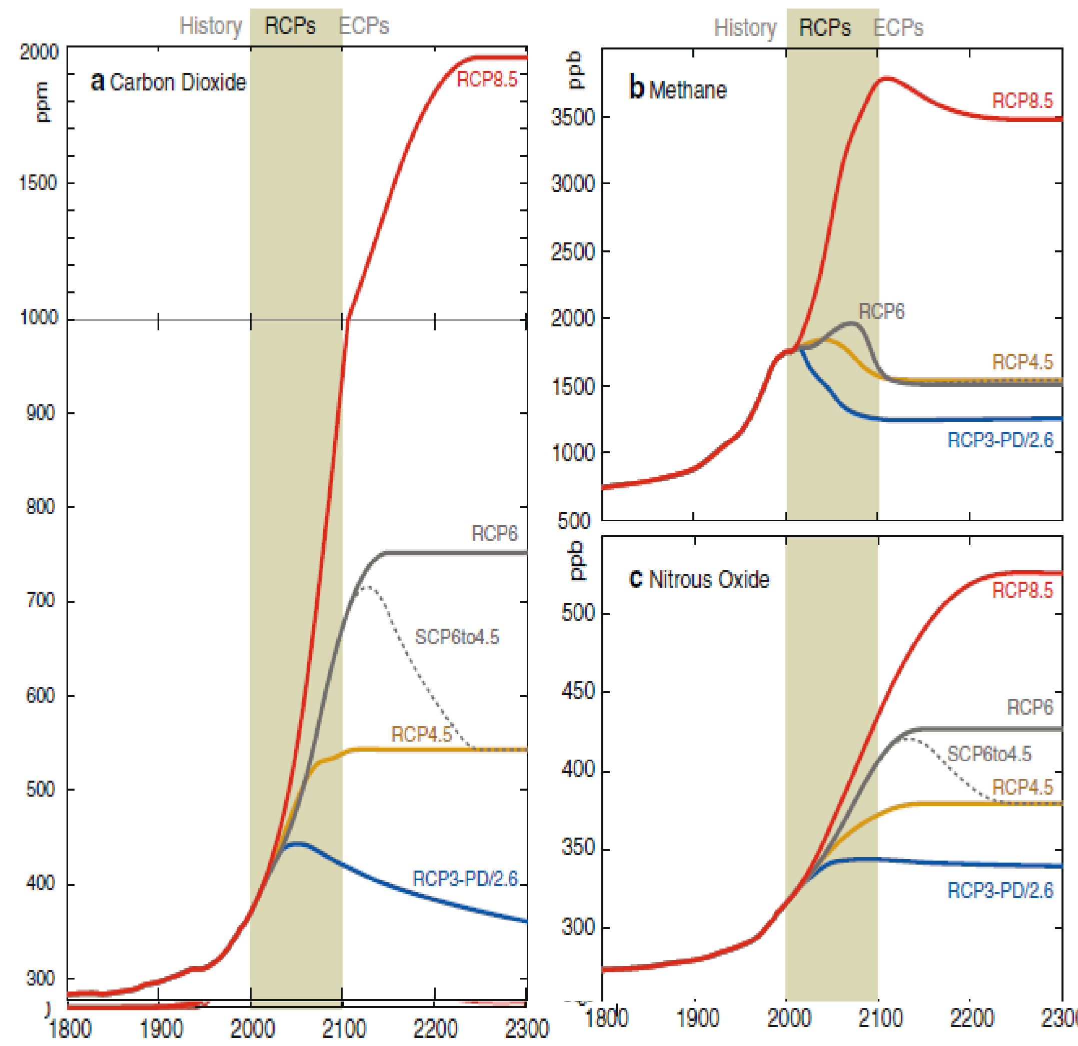
[IPCC, 2013]

Future scenarios:
gaz emission and concentration

emission

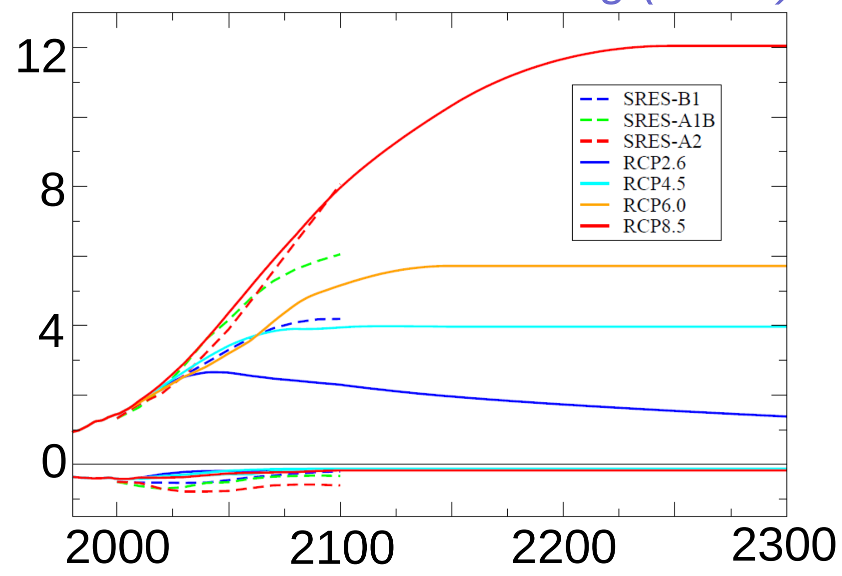


concentration



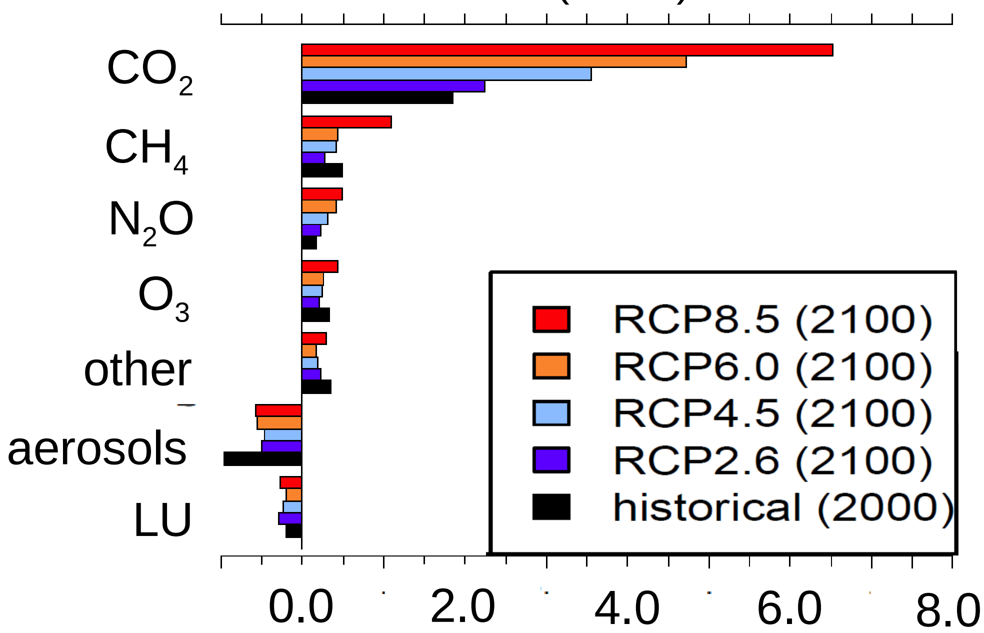
Radiative forcing of future scenarios

Total radiative forcing ($W.m^{-2}$)

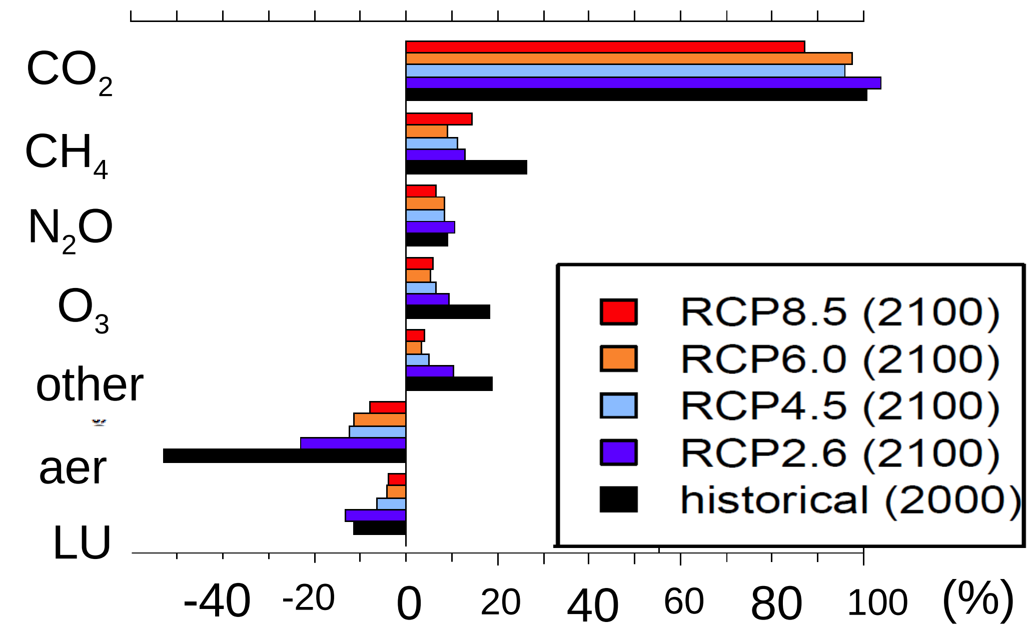


Contribution of individual forcings to total forcing relative to ***1850***

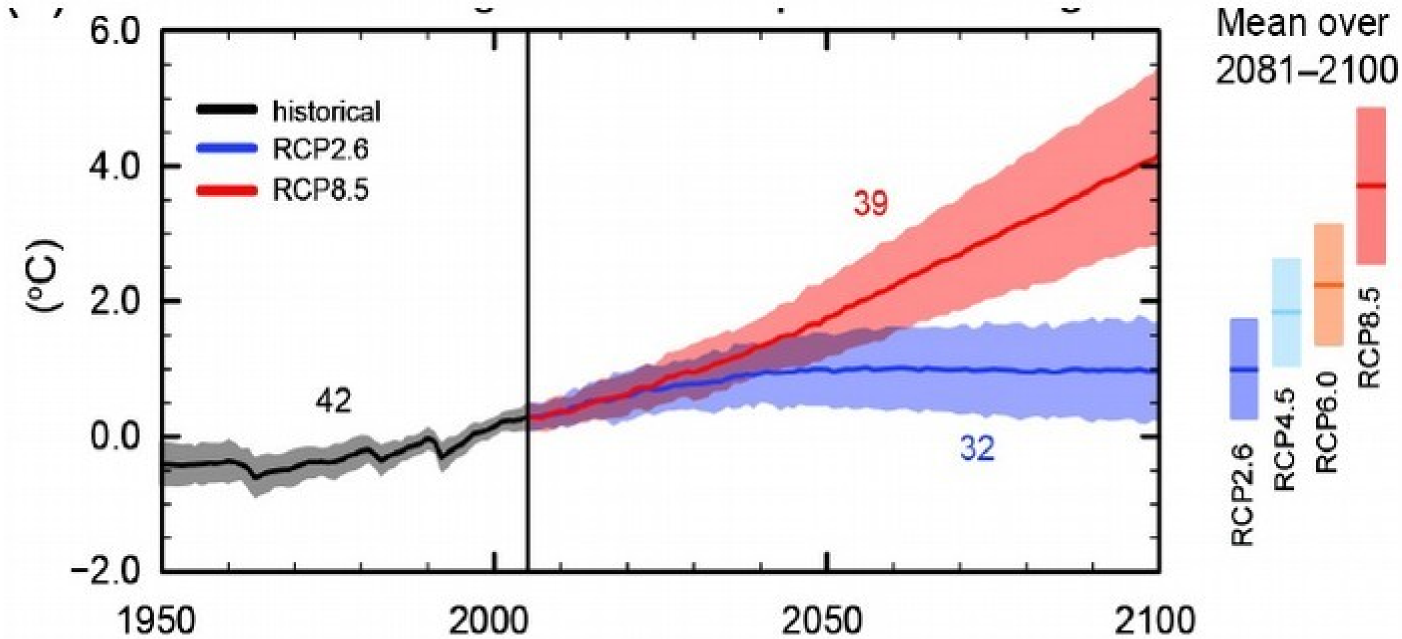
Values ($W.m^{-2}$)

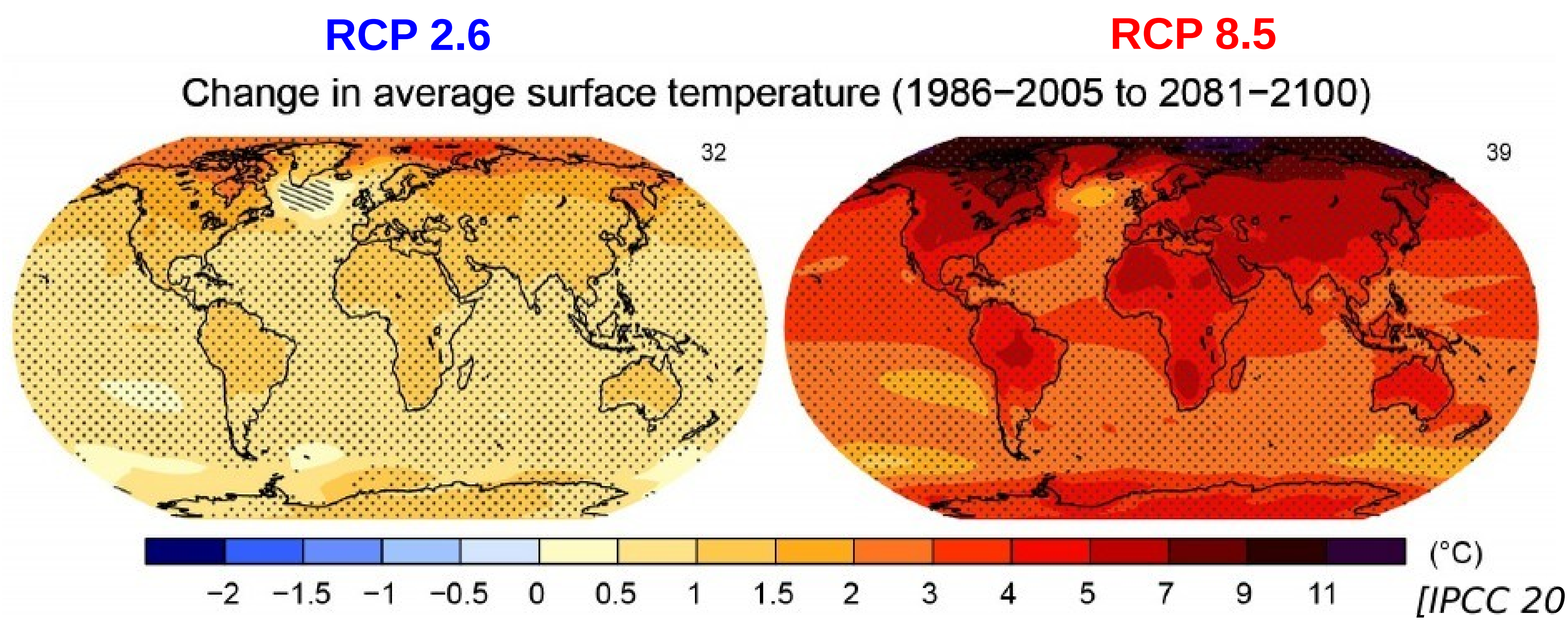


Relative values (%)



Global mean surface temperature change





[IPCC 2013]

Arctic sea-ice 1970-2100

September *(minimum extension)*

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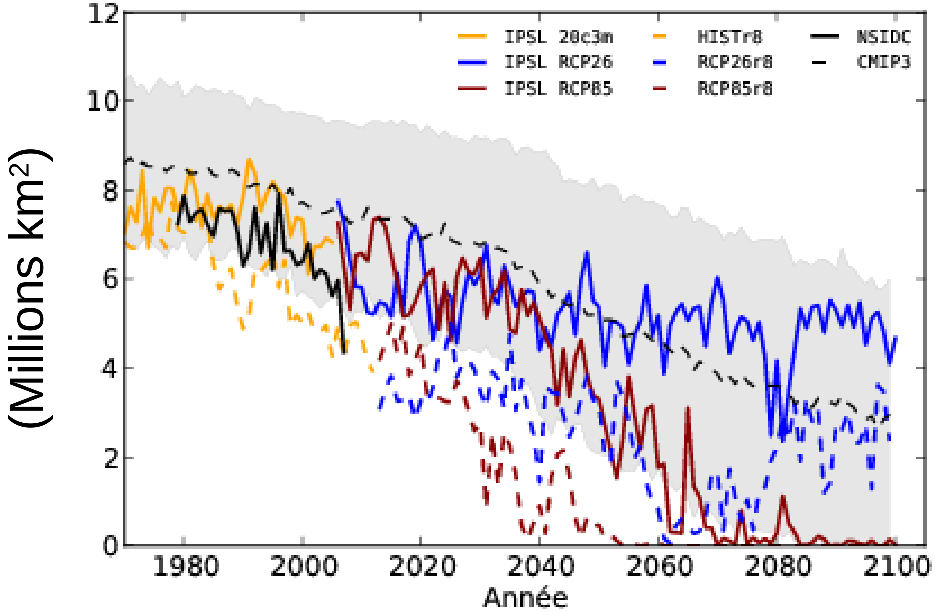
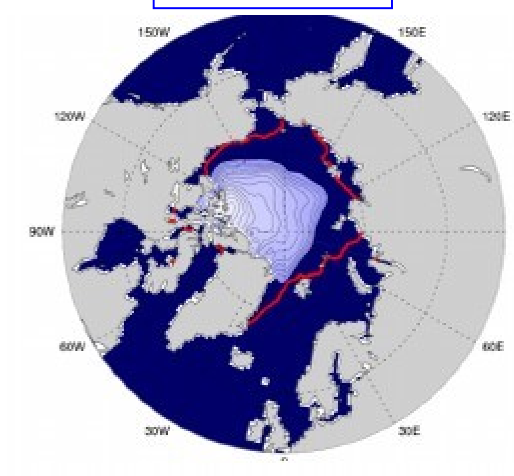
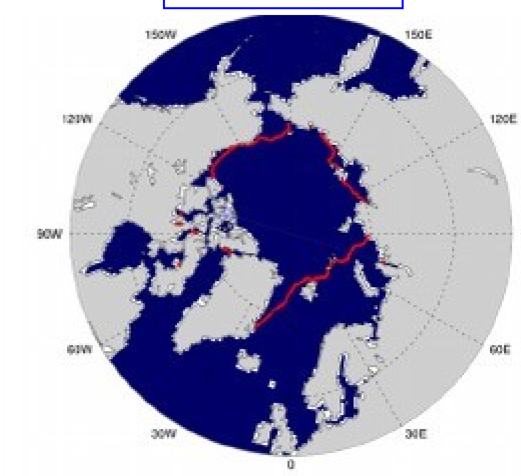


RCP 2.6

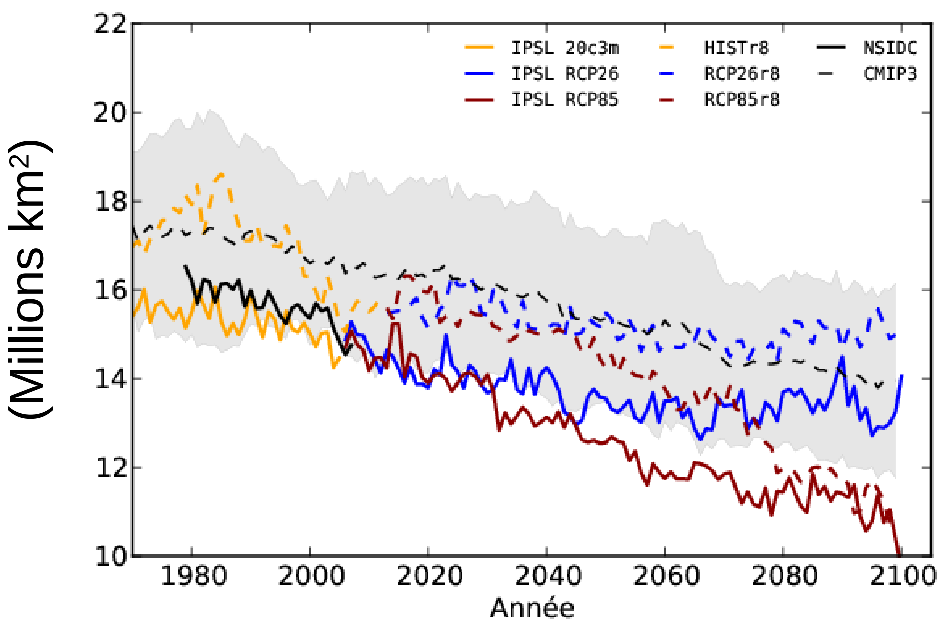


RCP 8.5



Mars *(maximum extension)*

IPSL-CM5A-LR



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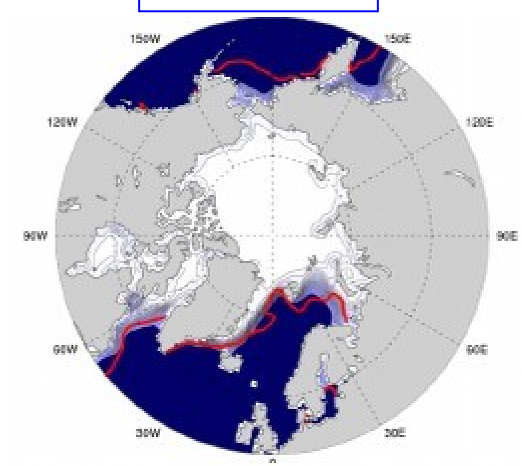

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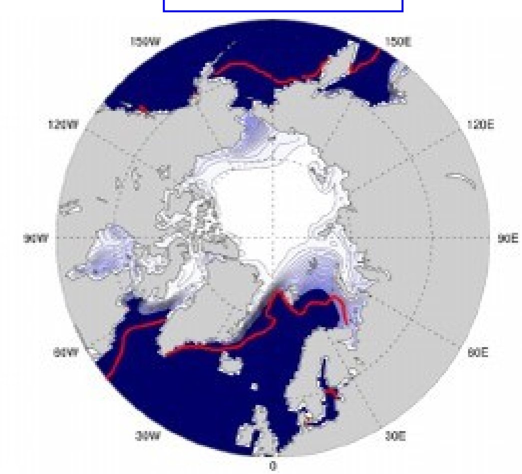
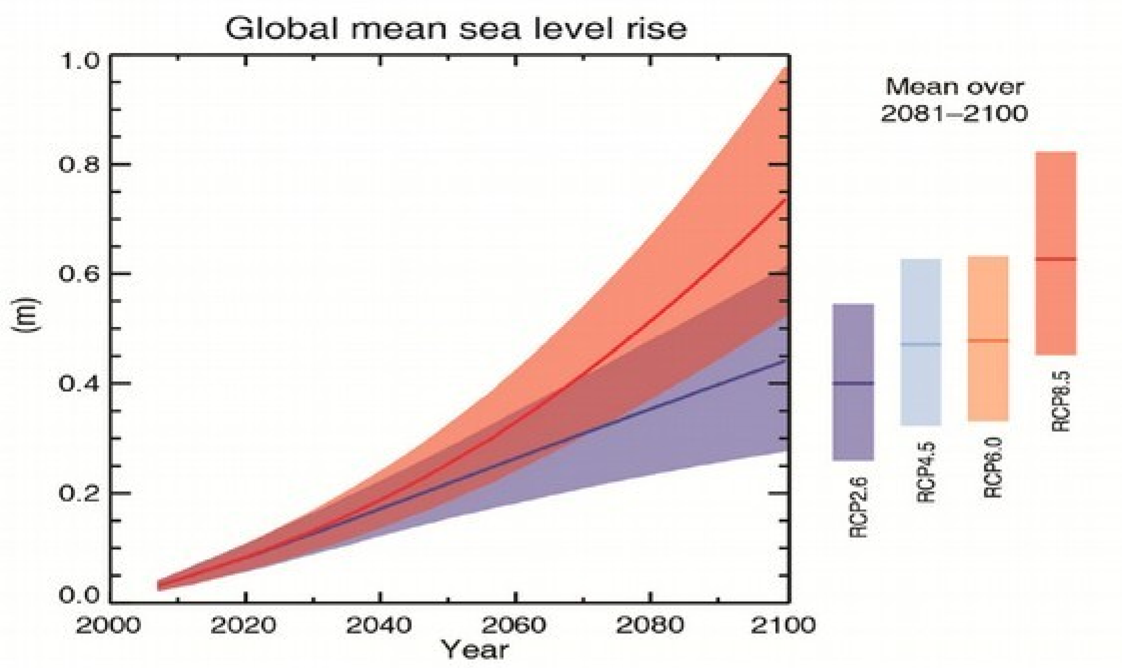
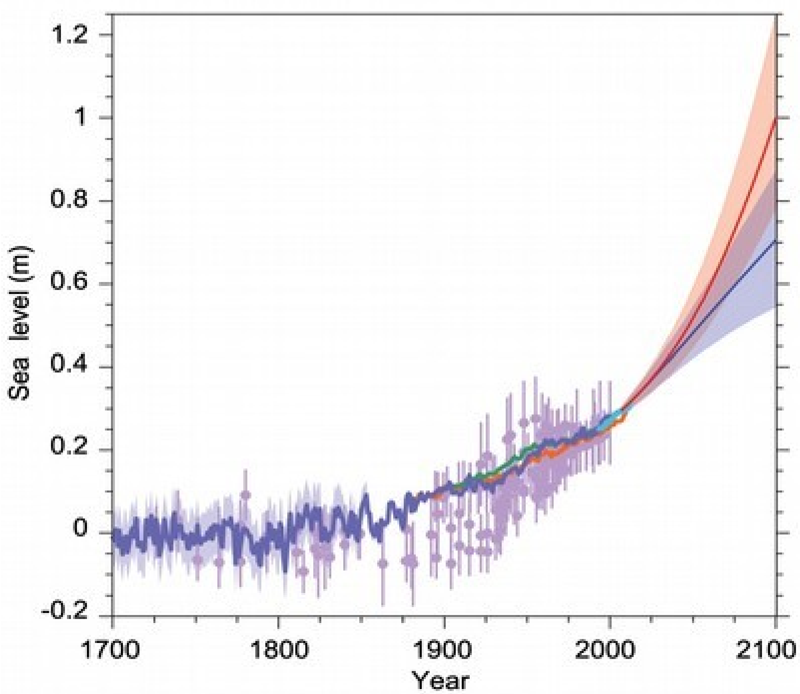
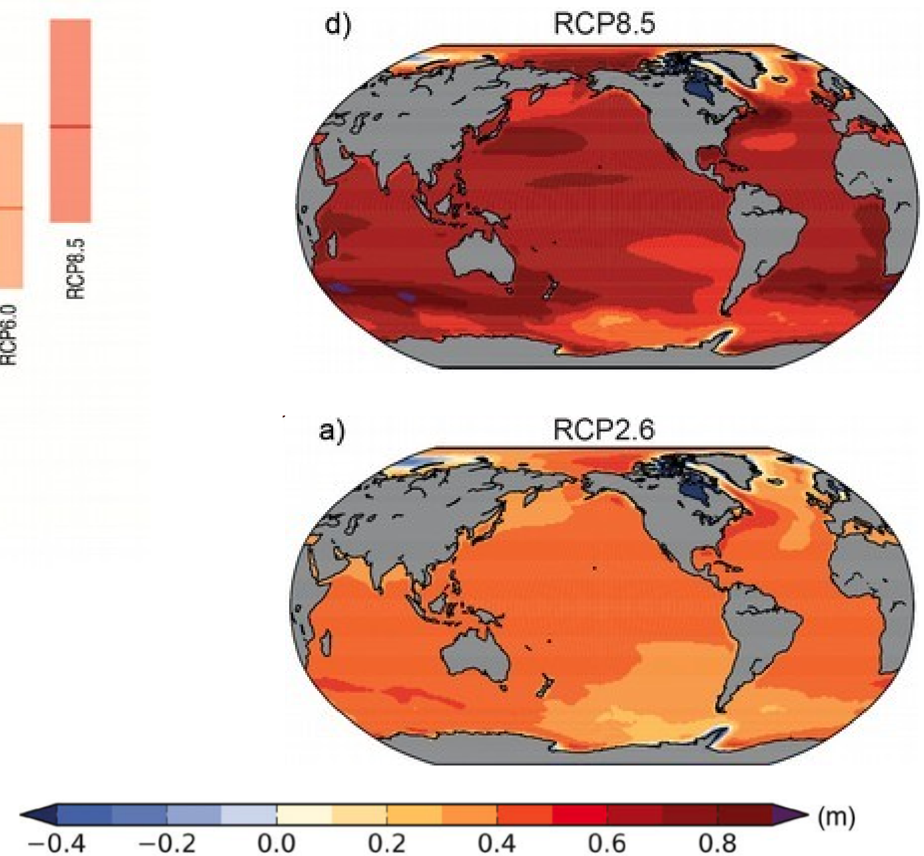


Sea level rise



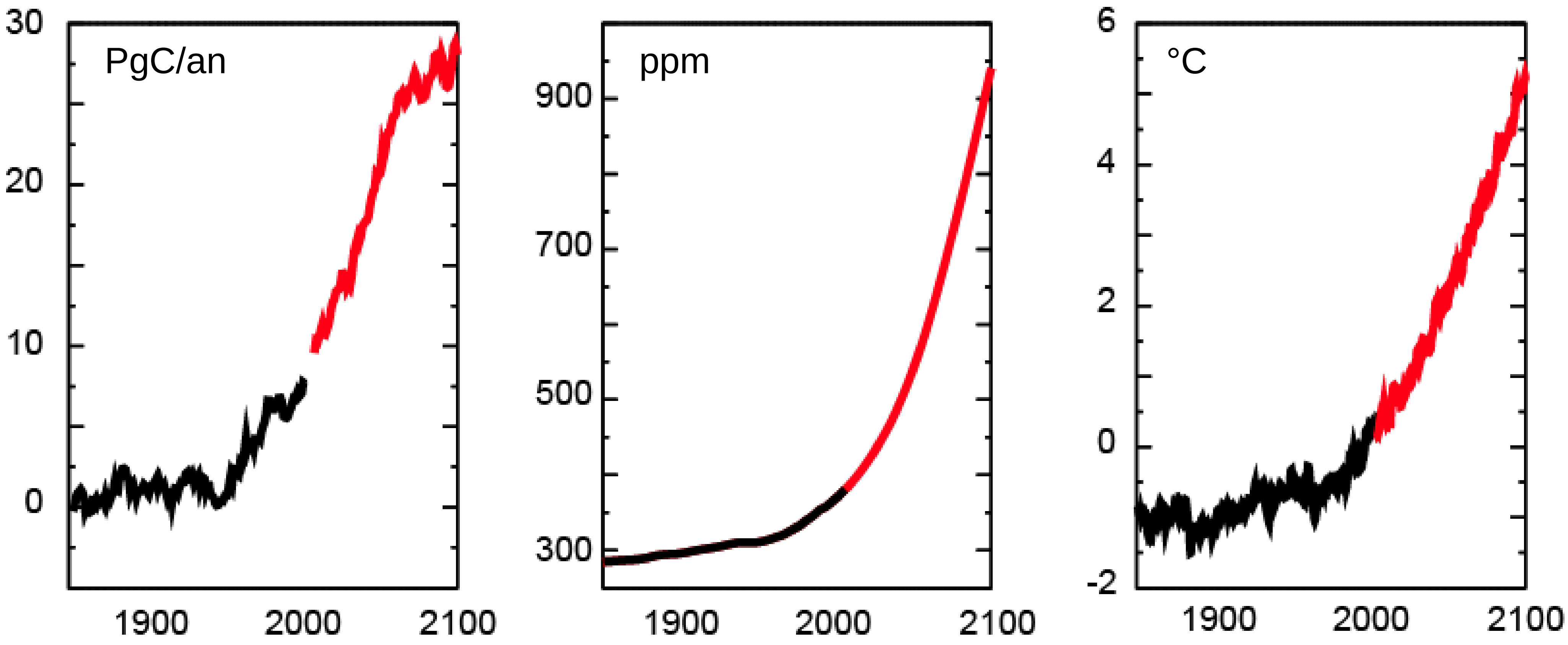




[IPCC, 2013]

Carbone emission, CO_2 concentrations and global temperature: time constants

Higher scenario : emissions, concentration and temperatures continue to grow

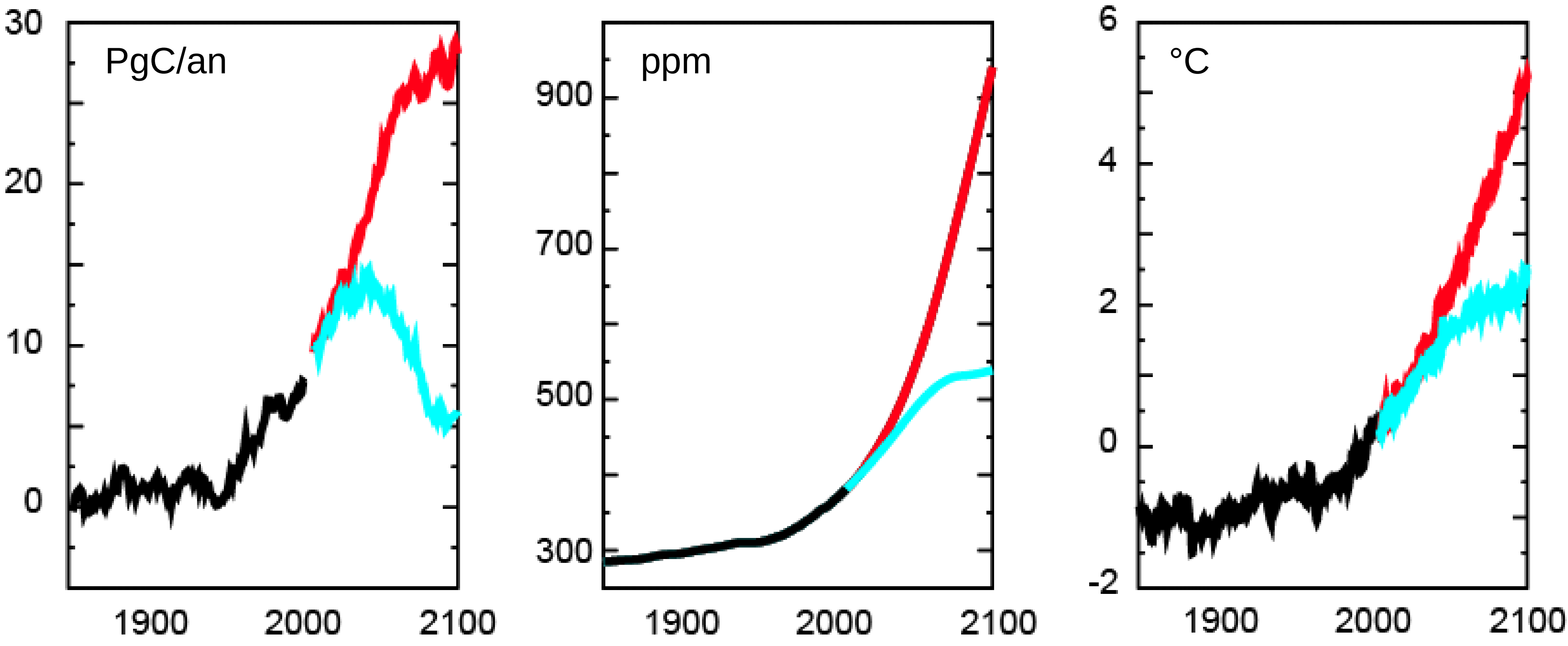


Courtesy L. Bopp

Carbone emission, CO_2 concentrations and global temperature: time constants

Higher scenario : emissions, concentration and temperatures continue to grow

Medium scenario : to stabilize CO_2 concentration 550 ppm, emissions need to be strongly reduced. However, temperature will continue to increase



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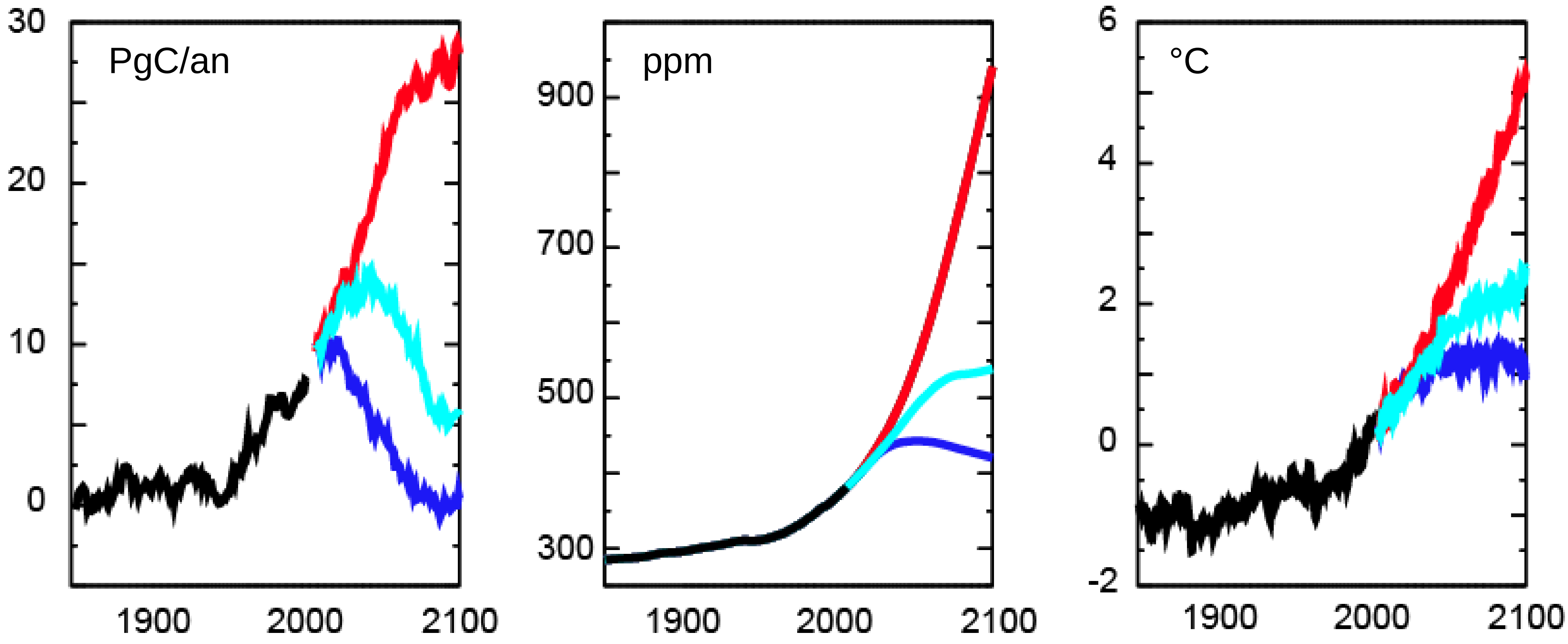
Higher scenario : emissions, concentration and temperatures continue to grow

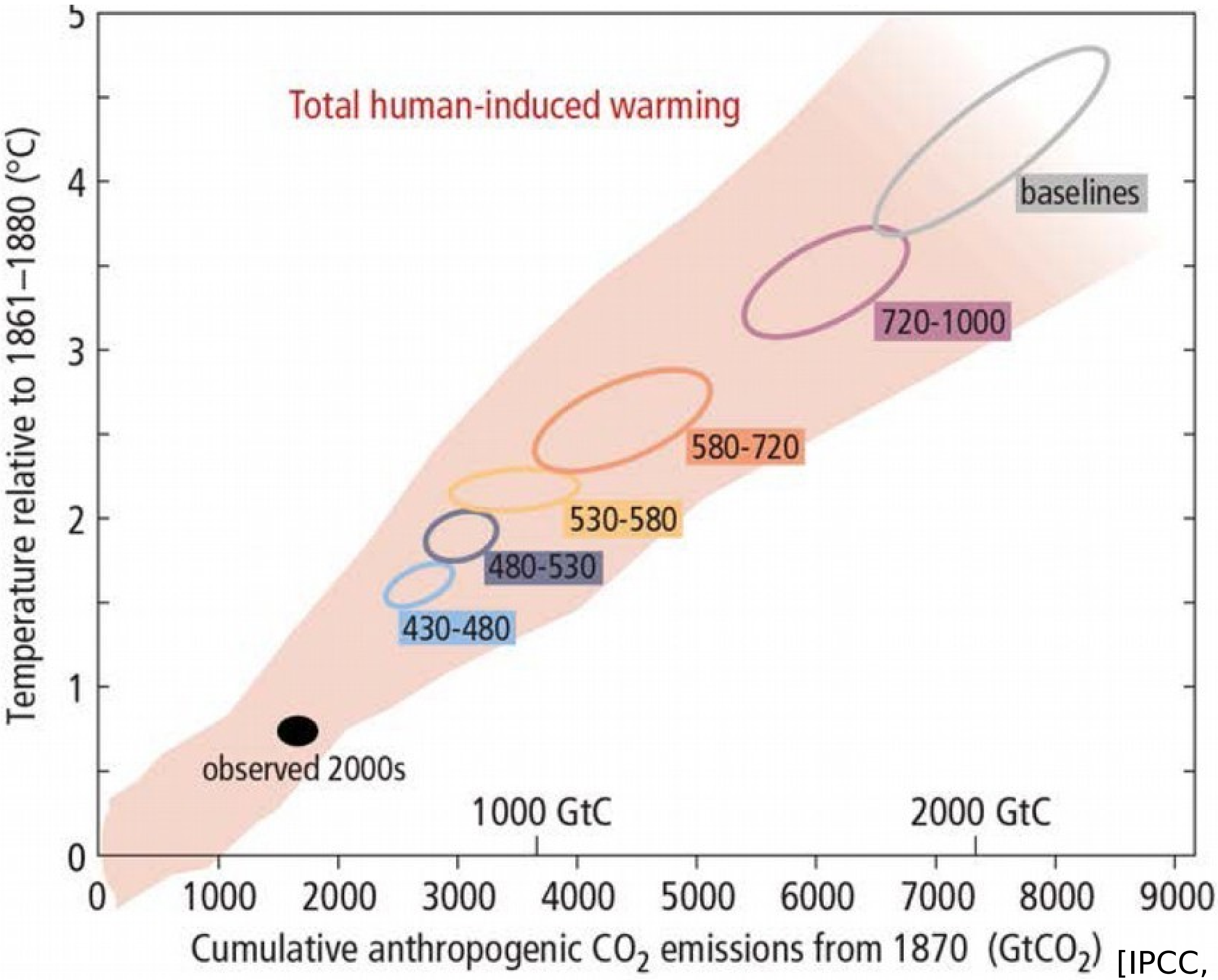
Medium scenario : to stabilize CO_2 concentration 550 ppm, emissions need to be strongly reduced. However, temperature will continue to increase

Lower Scenario : to limit a 2° global warming, CO_2 concentration has to be limited to less then 450 ppm, and emissions need be to be 0 before the end of the century



Courtesy L. Bopp

Temperature increase as a function of cumulative CO_2 emissions.



[IPCC, AR5]

Outlook

I. Emergence of climate and climate change science

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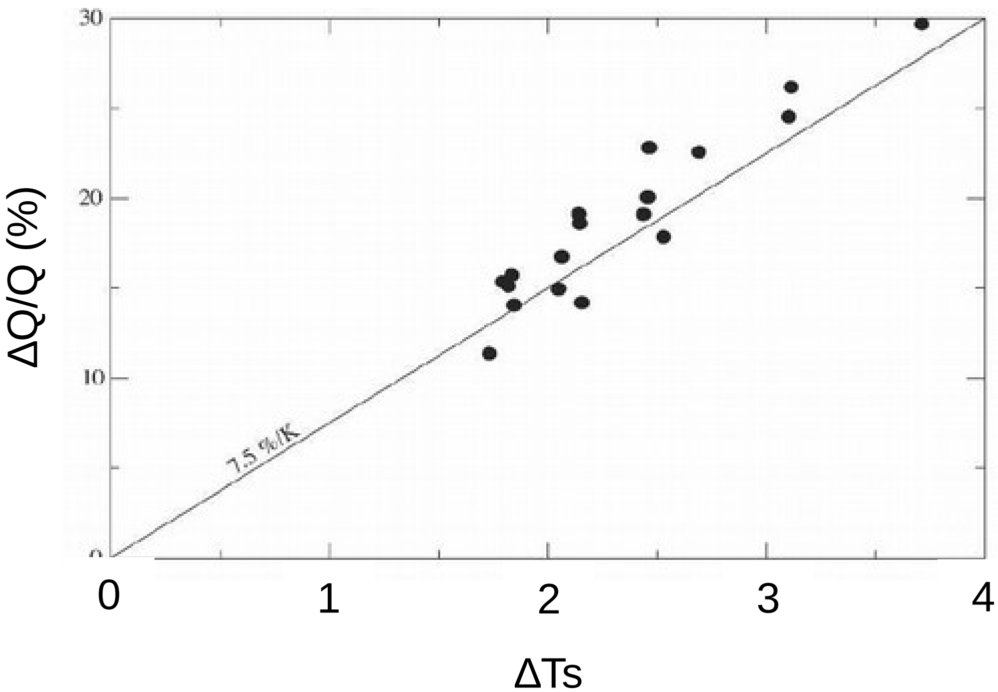
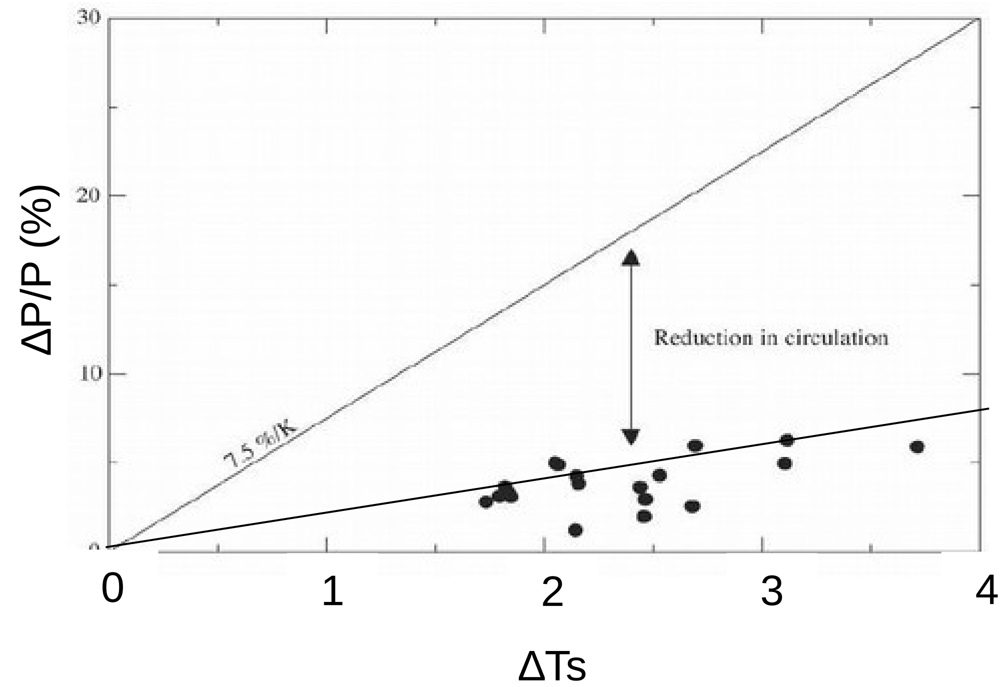
Precipitation changes

Change of the amount of **water vapor H_2O** vs change of the average surface **temperature**



$\Delta Q/Q\ (\%) \approx 7.5\ \Delta Ts$

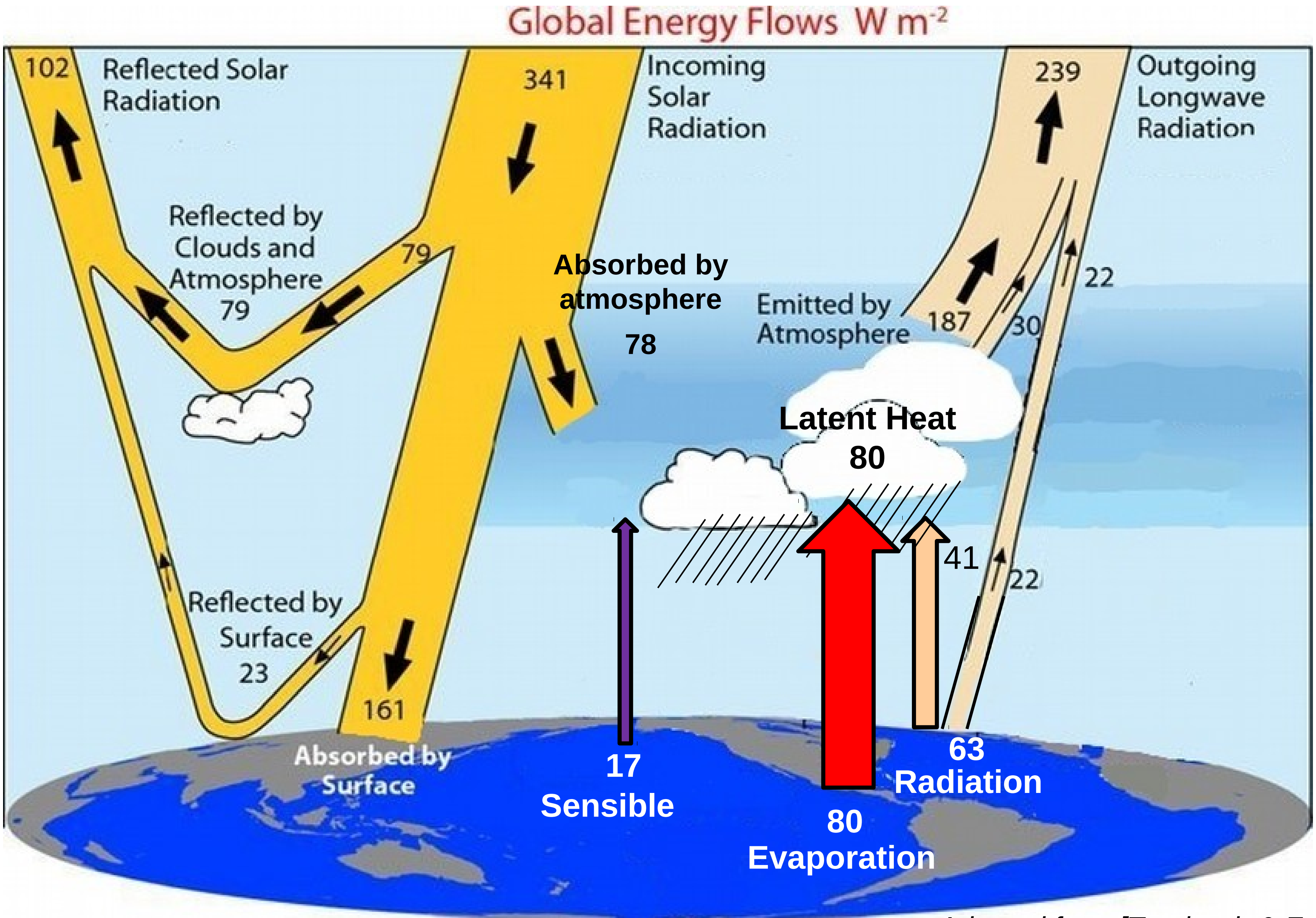
Change of **precipitation** vs change of the average surface **temperature**



$\Delta P/P\ (\%) \approx 1.5\ \Delta Ts$

The change of the global average precipitation does not depend directly from the change of global average water vapor

(Vecchi & Soden, 2007)

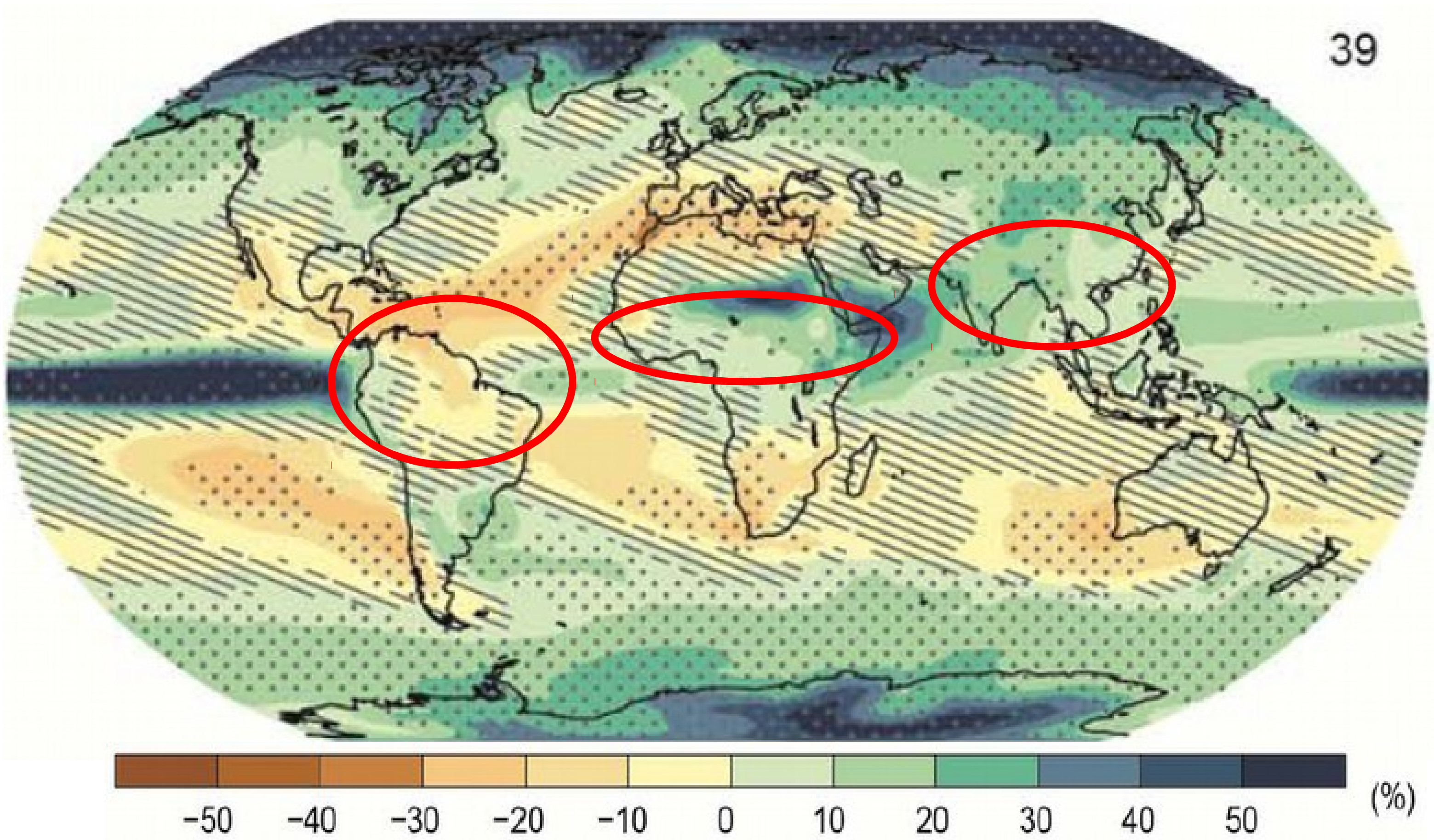


Adapted from [Trenberth & Fasullo, 2012]

*The **change of the global average precipitation** is constrained by the **radiative cooling** of the atmosphere*

Precipitation changes: Geographical distribution

Relative change in average precipitation, RCP8.5 scenario (2081-2100)



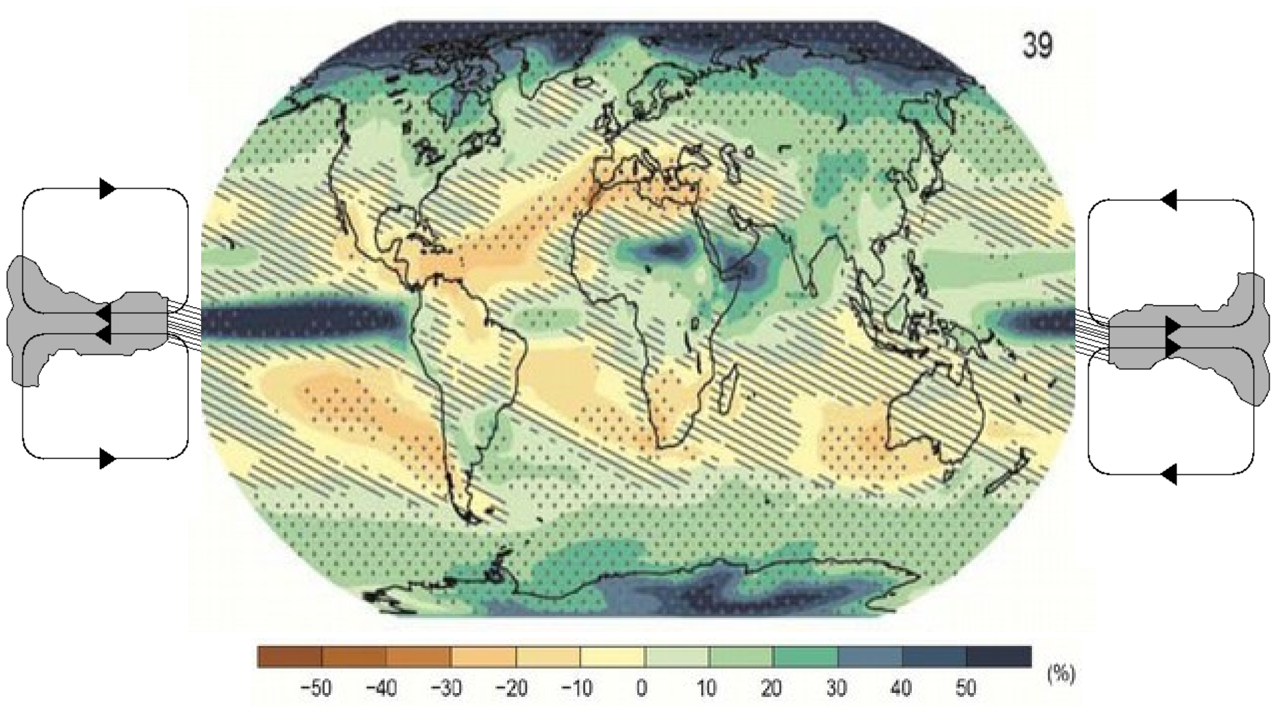
Low Signal/noise ratio

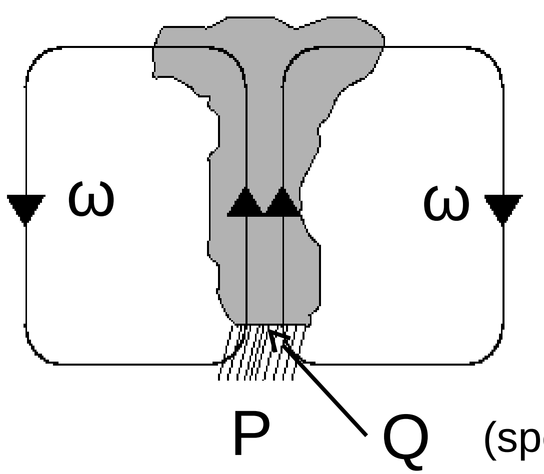
High signal/noise ratio and models agree

39 CMIP5 models

[IPCC, AR5]

Precipitation changes





(specific humidity)

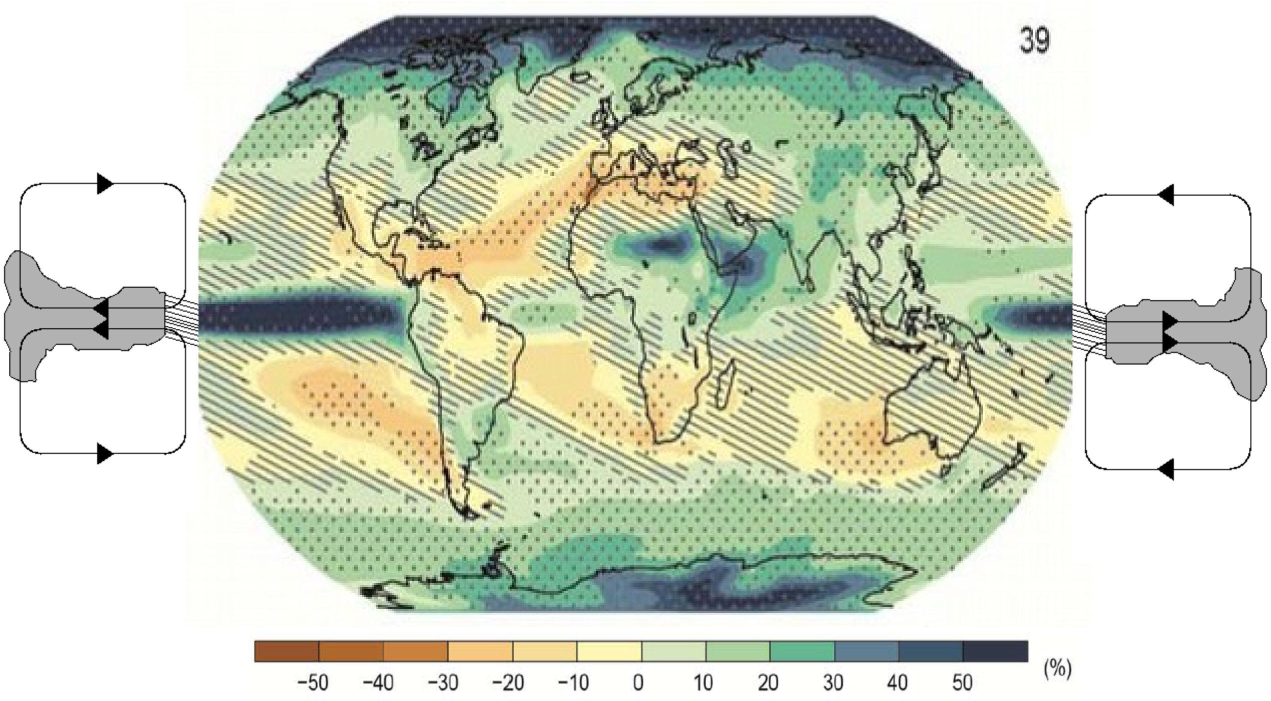
Precipitations changes

$$\Delta P \approx \omega \, \Delta Q + Q \, \Delta\omega$$

Thermodynamic response

Dynamic response

Precipitation changes



At the global scale:

- Precipitation increases in some regions while deceasing in others
- the contrast between wet and dry regions is expected to increase
- same with the contrast between wet and dry seasons

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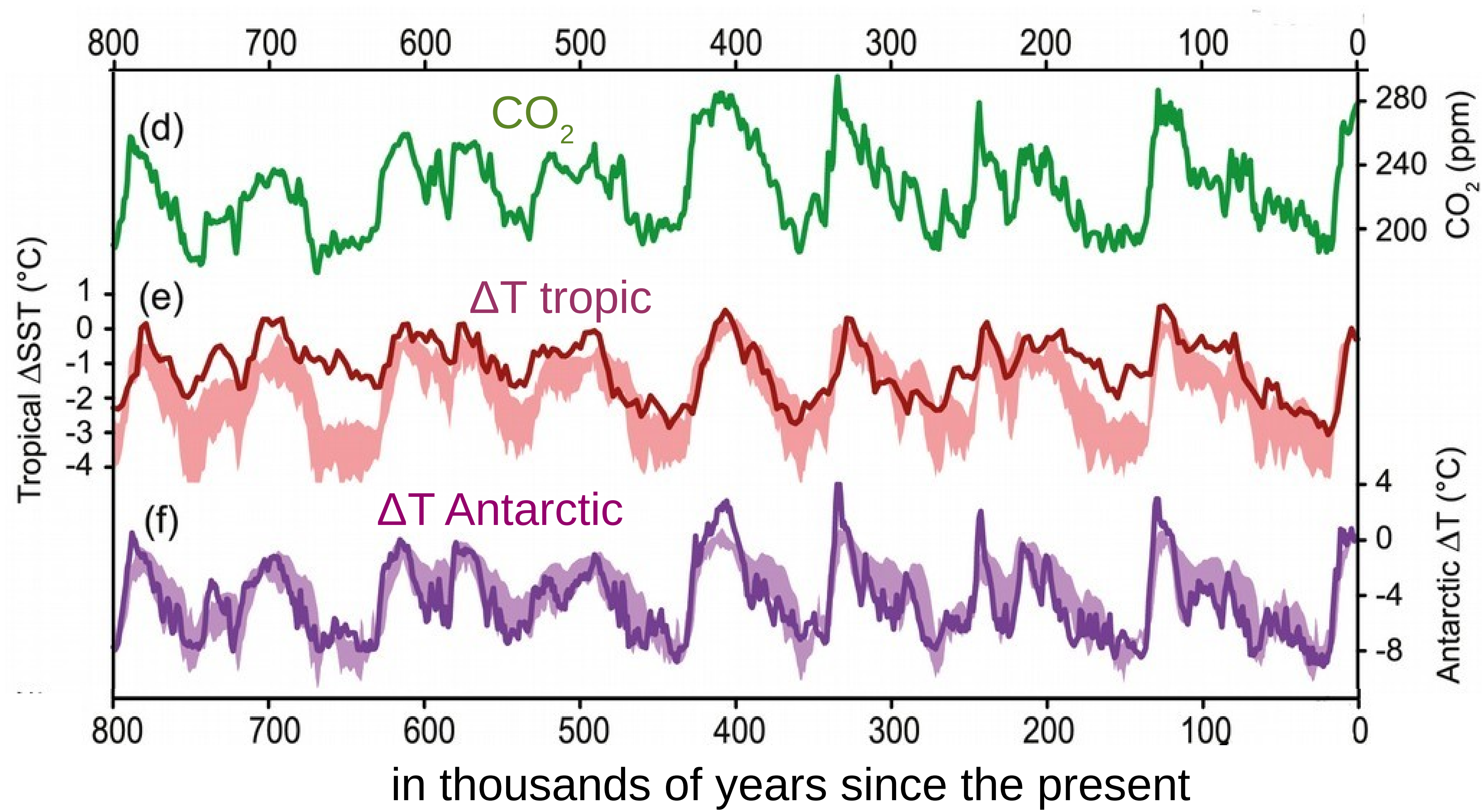
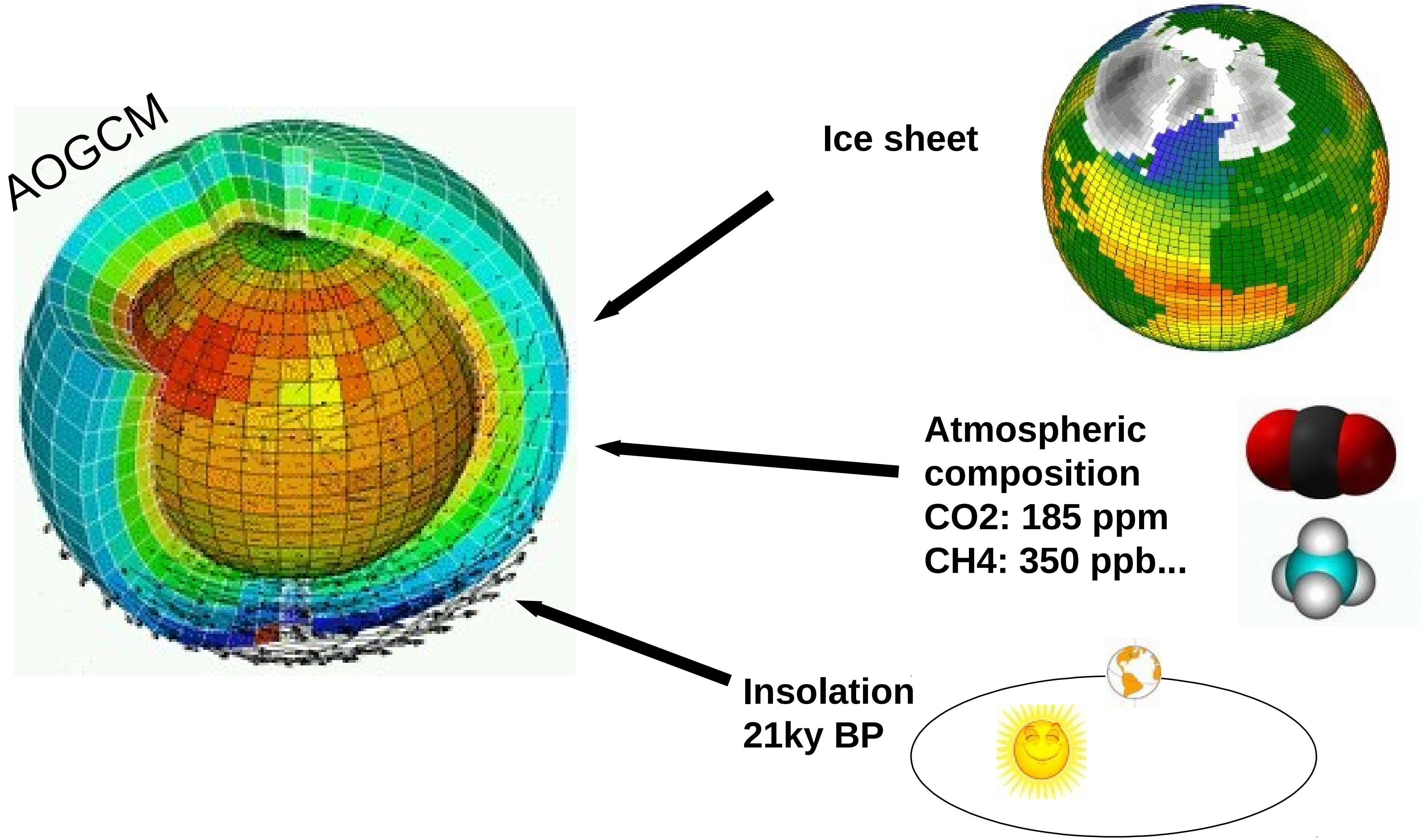
Paleoclimate changes



after [IPCC, AR5, 2013]

Simulation of Last Glacial Maximum (LGM)



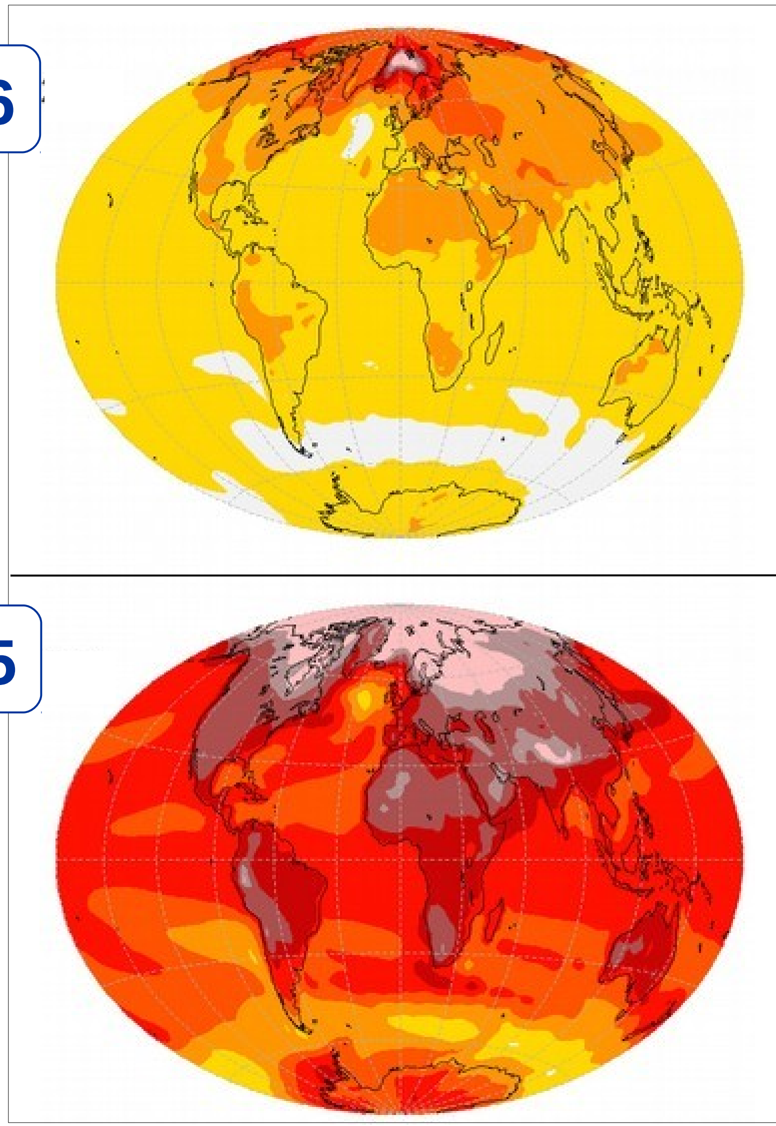
Greenhouse gas forcing ~ future climate
Other main forcings: ice sheet

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

Change in surface temperature

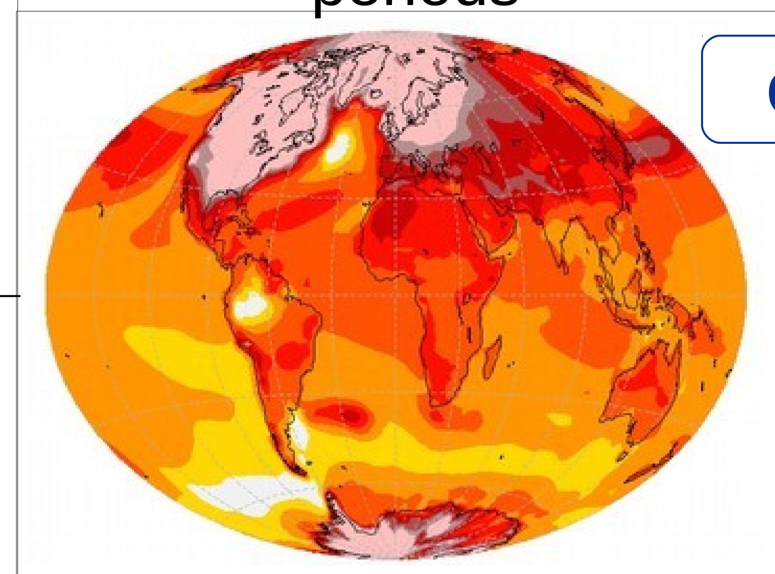
Difference between **2100** et **1990**

RCP2.6



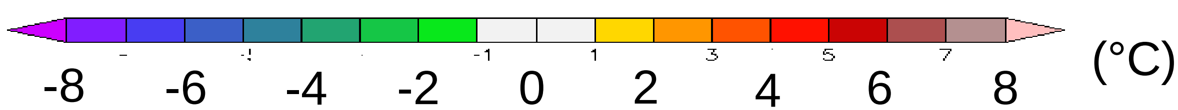
RCP8.5

Difference between **current** and **last glacial** maximum periods



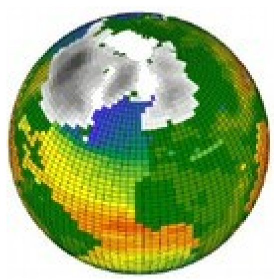
Glacial

Model : IPSL-CM5A-LR



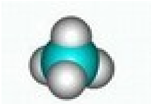
Land-sea contrasts and polar amplification in past and future climates

Last Glacial Maximum main forcings



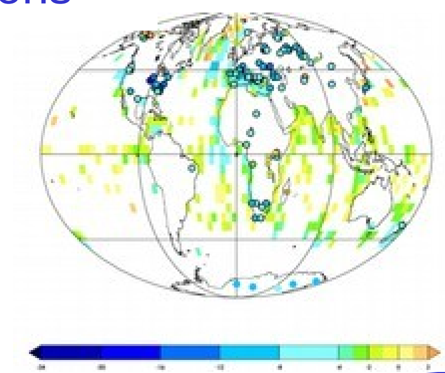
Ice-sheets

Greenhouse gases
CO_2: 185 ppm,
CH_4:350 ppb …



LGM climate reconstructions

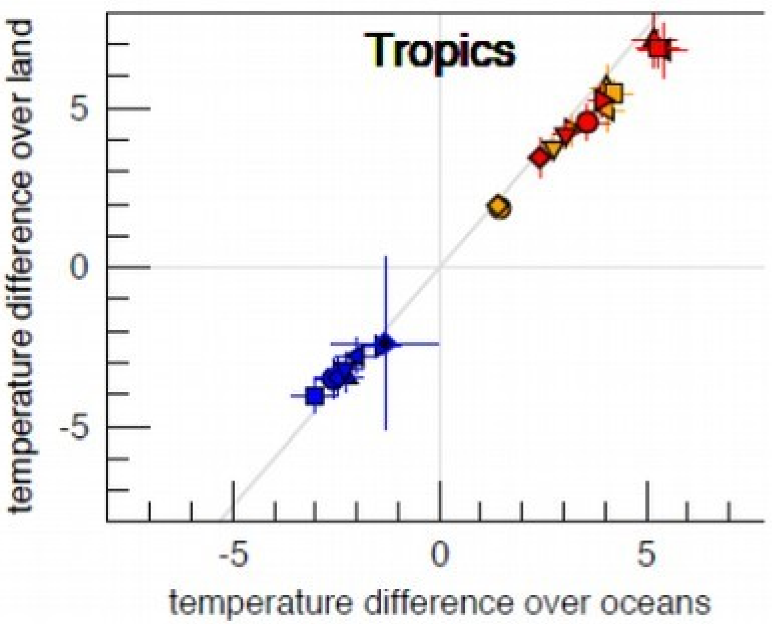
Land data
(pollen and plant macrofossils):
Bartlein et al, Clim Dynam 2011
Ocean data (multi proxy):
MARGO, NGS 2009
Ice-core data:
Masson-Delmotte et al pers. comm

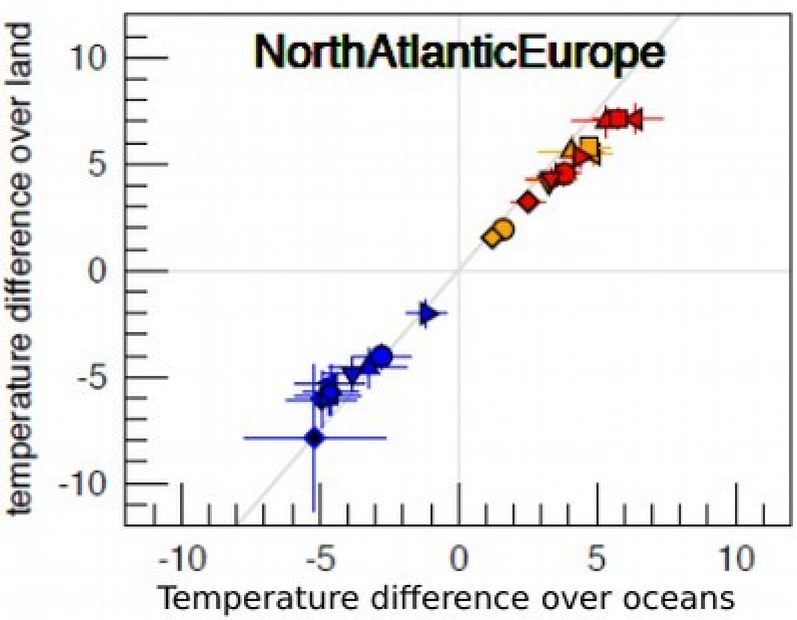


Relationships between LGM vs higher CO_2 climates?
Are the large scale relationships stable? Can we evaluate them from paleodata ?

Example:
Land sea contrasts

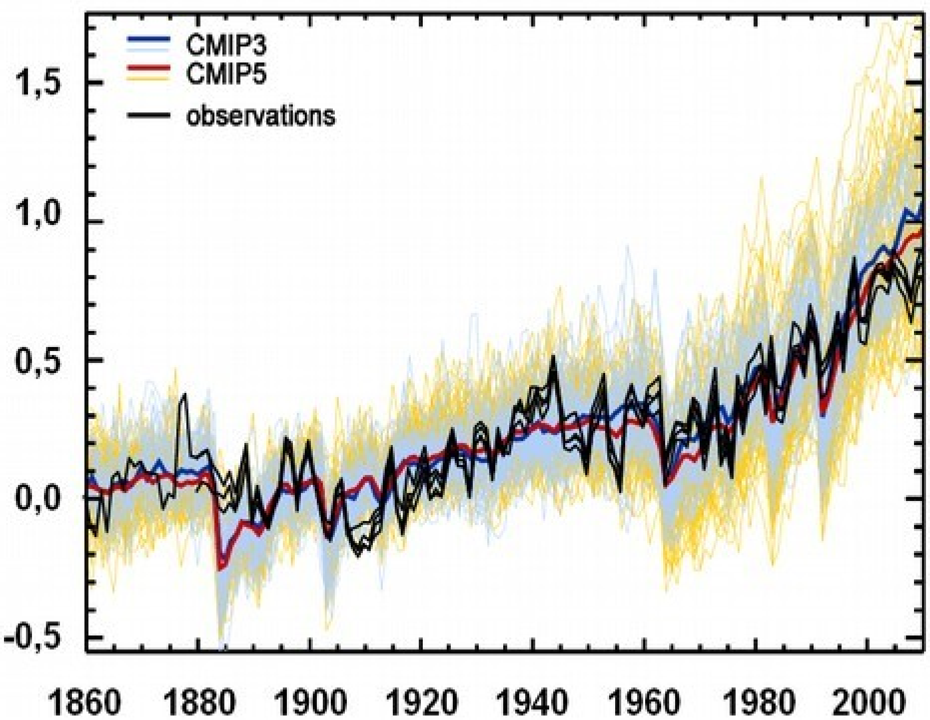
Note: all model averages calculated from grid points where LGM data is available





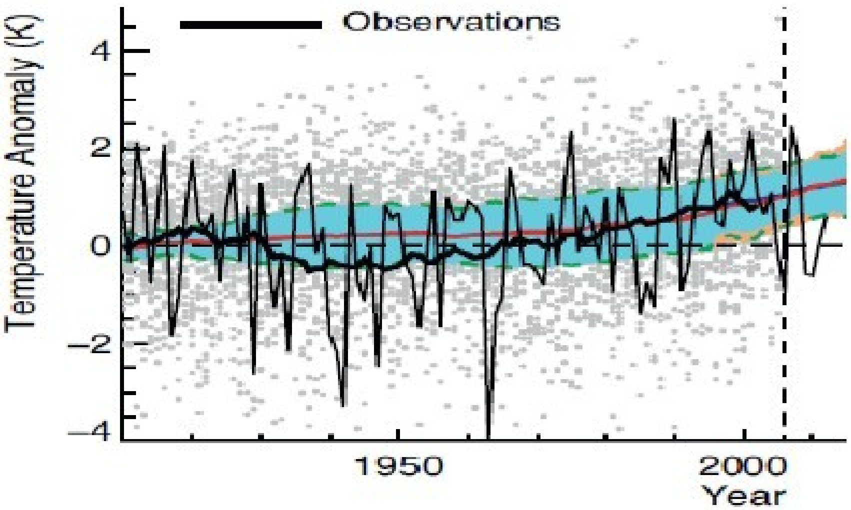
Surface temperature evolution: observation and models

Annual global mean

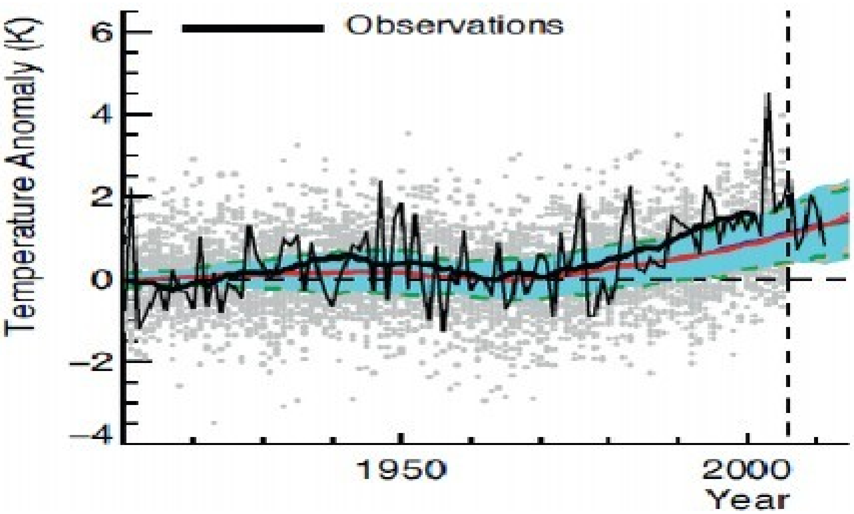


[IPCC, 2013]

Winter mean over France



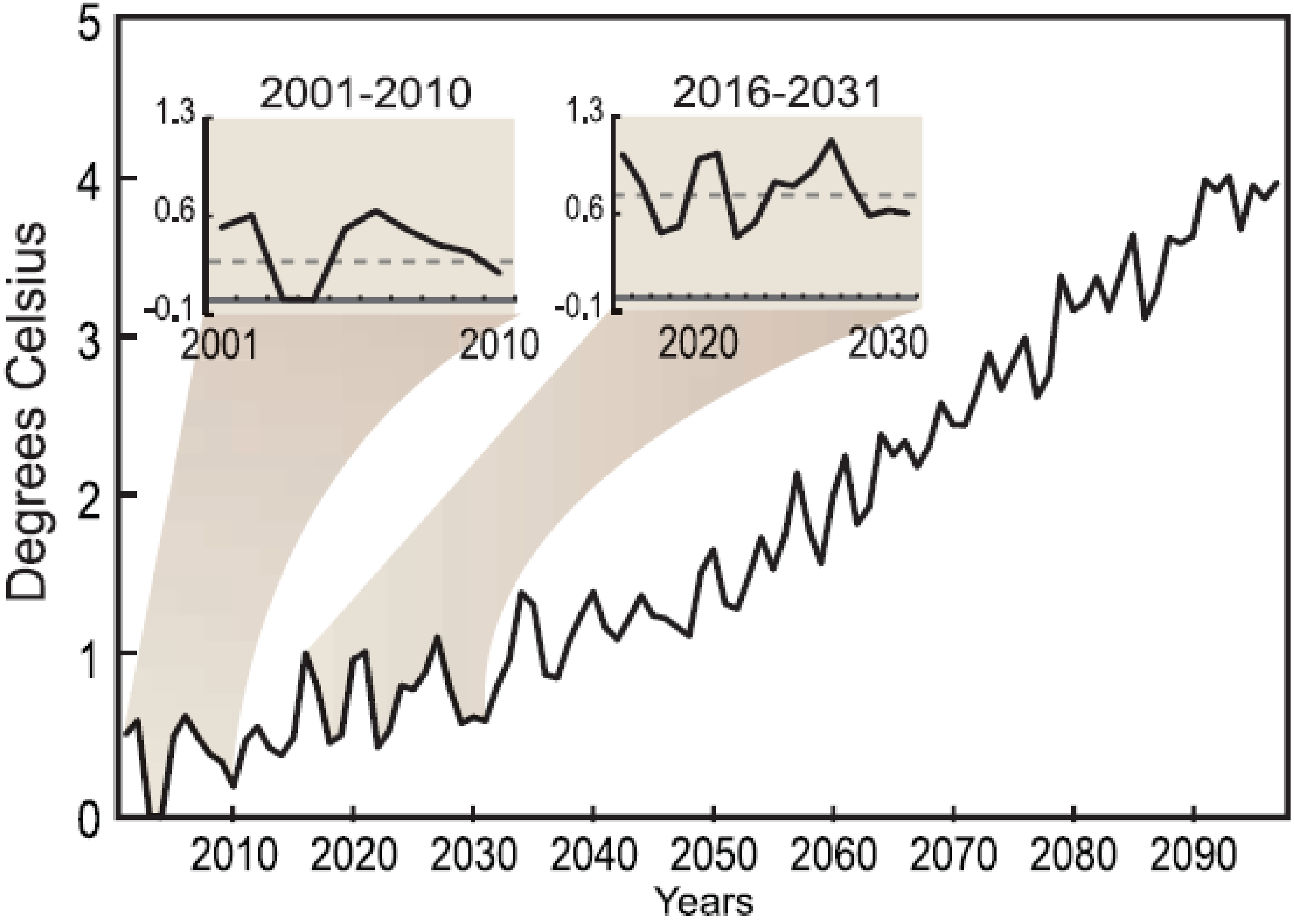
Summer mean over France



[Terray et Boé, 2013]

Climate changes and climate variability

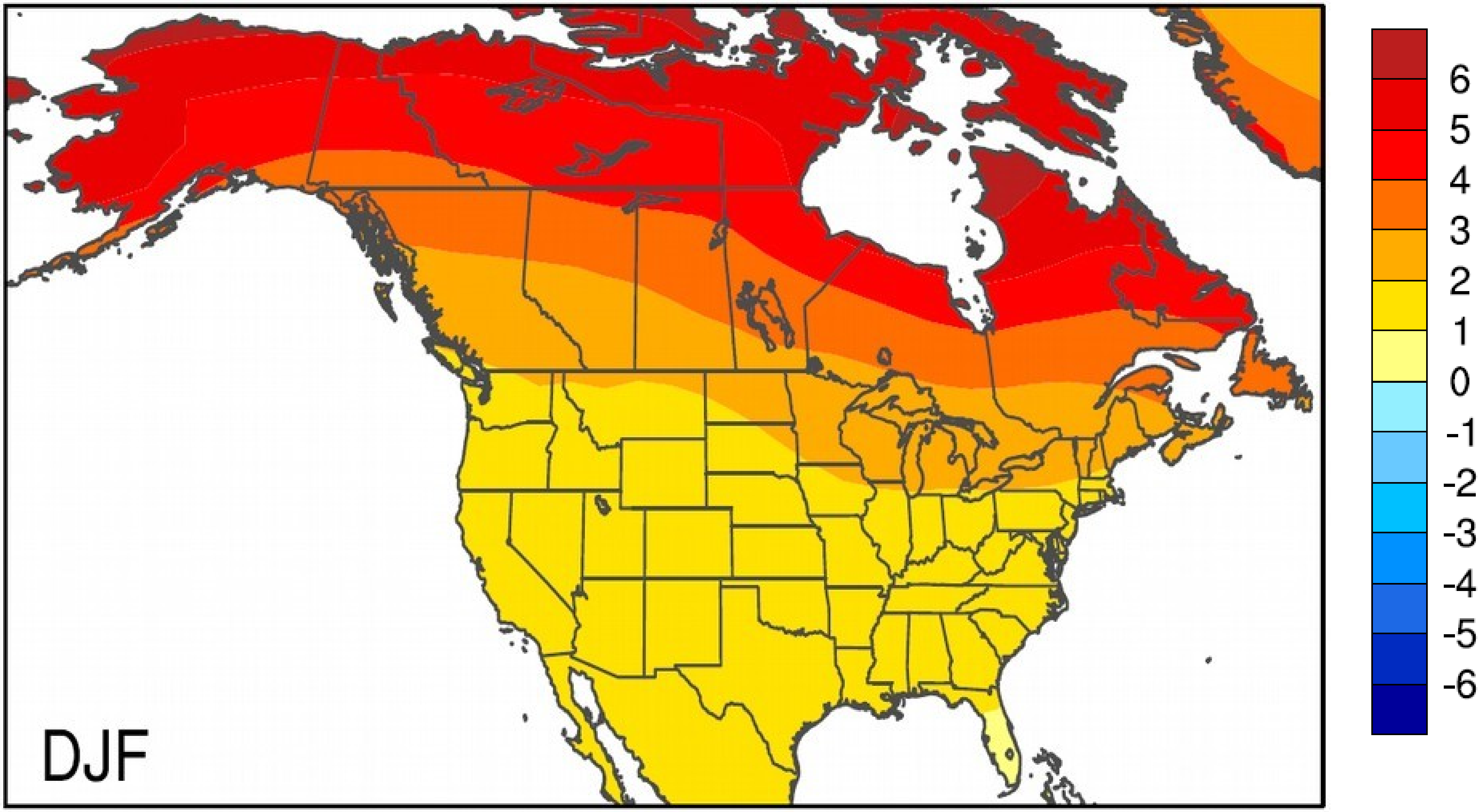
Simulations



Easterling and Wehner, 2009

Climate changes and climate variability

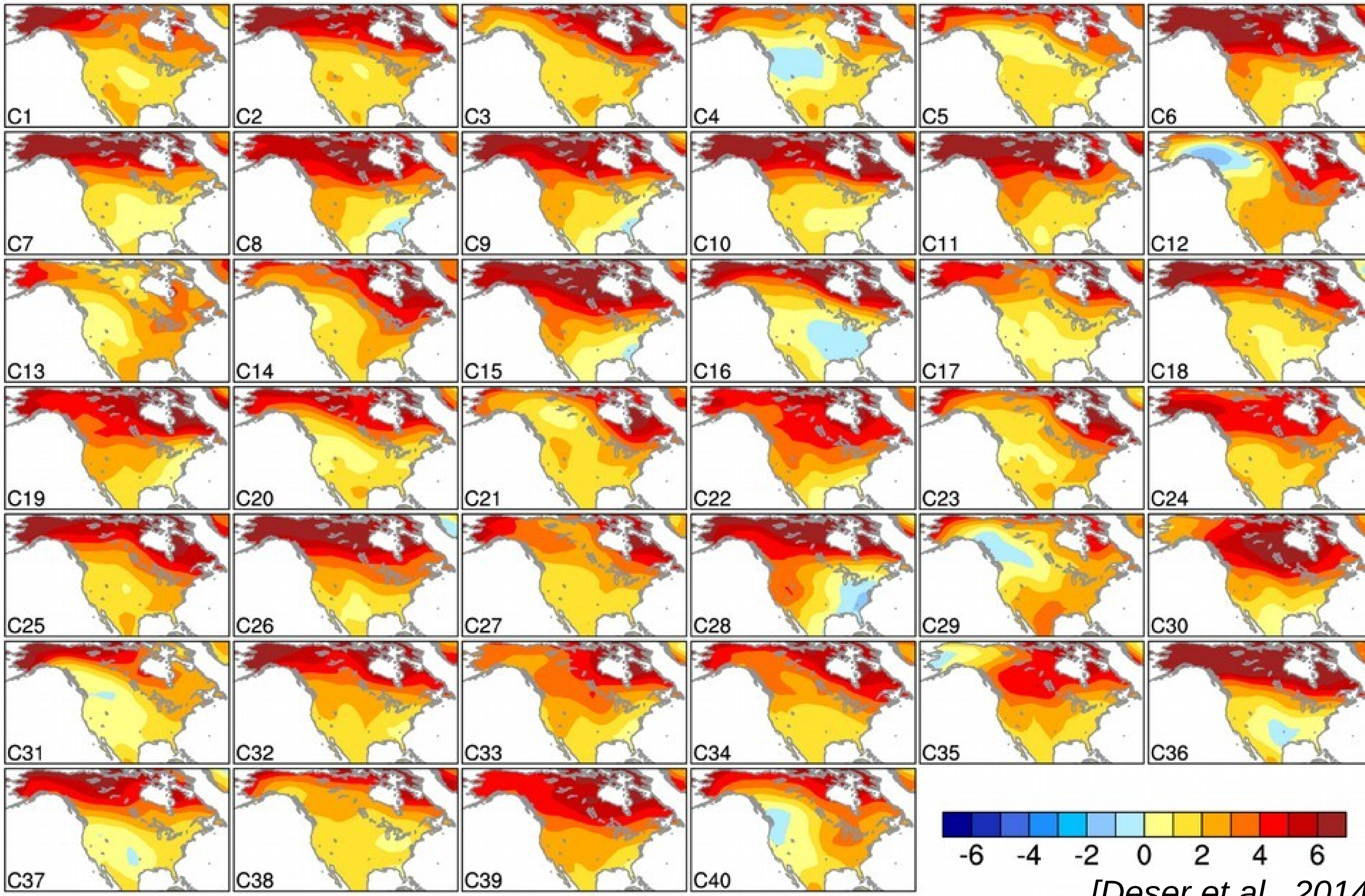
50-year trend in winter temperature (°C/50 yrs)
For an « intermediate high » scenario



[Deser et al., 2014]

Climate changes and climate variability

50-year trend in winter temperature (°C/50 yrs)



[Deser et al., 2014]

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

Outlook

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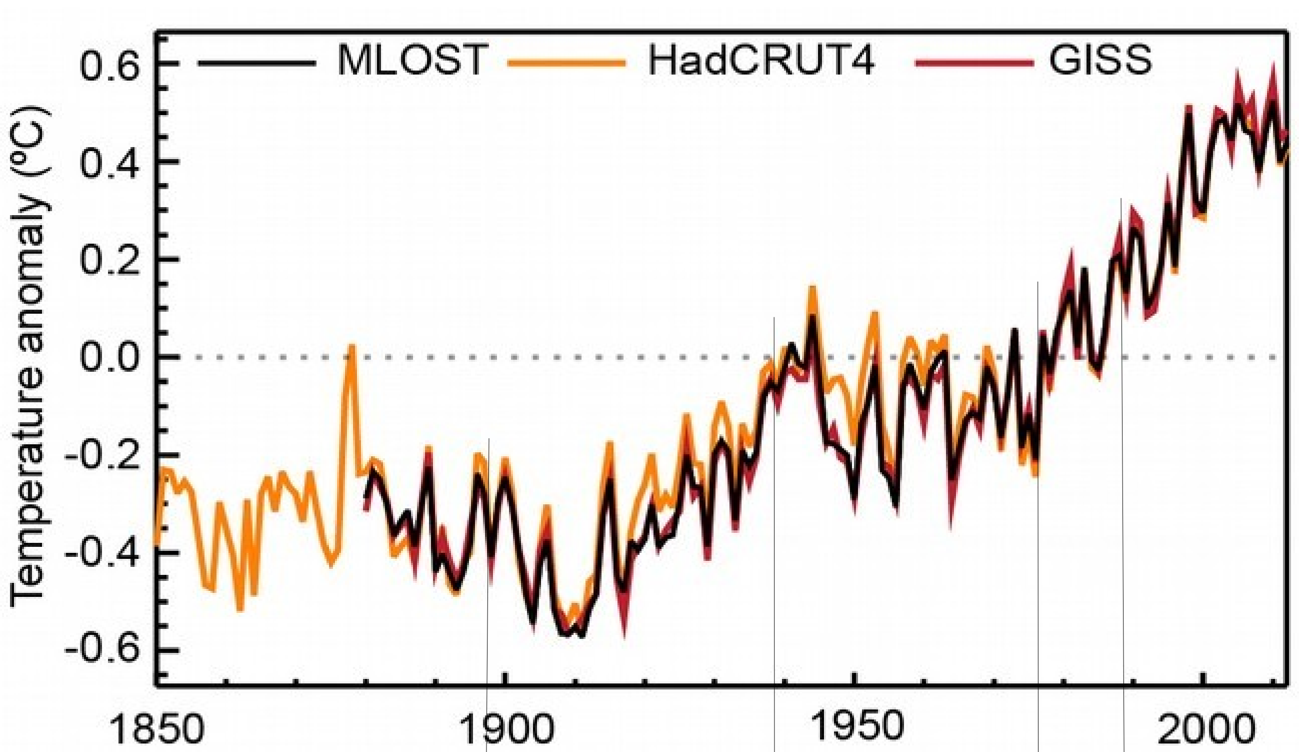
Climate change was predicted before being observed



[IPCC 2013]

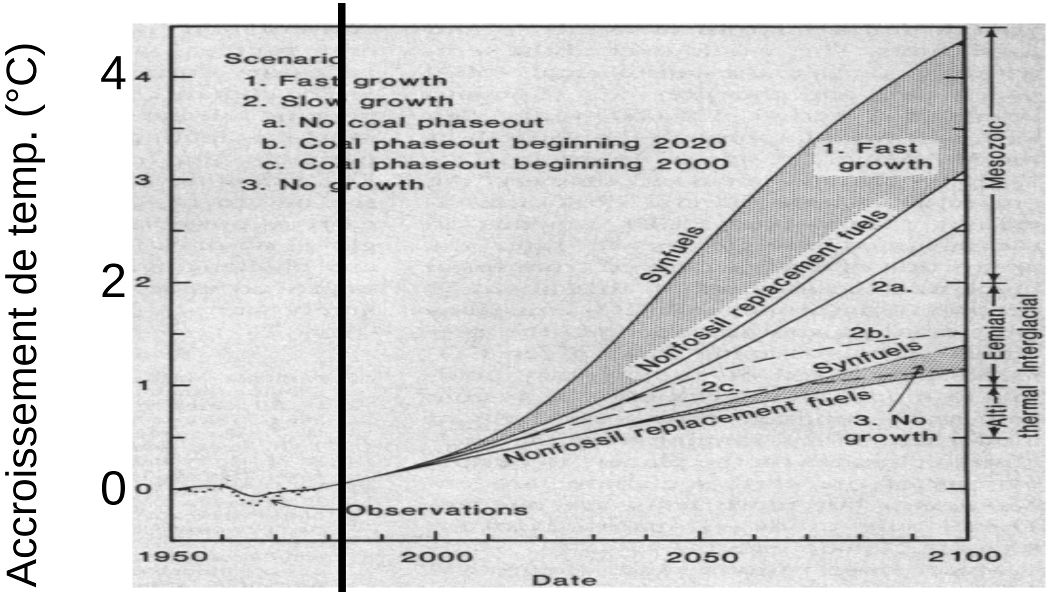
1897: S. Arrhenius: first estimate of CO2 role

1937: G. Callendar: new estimate of CO2 role

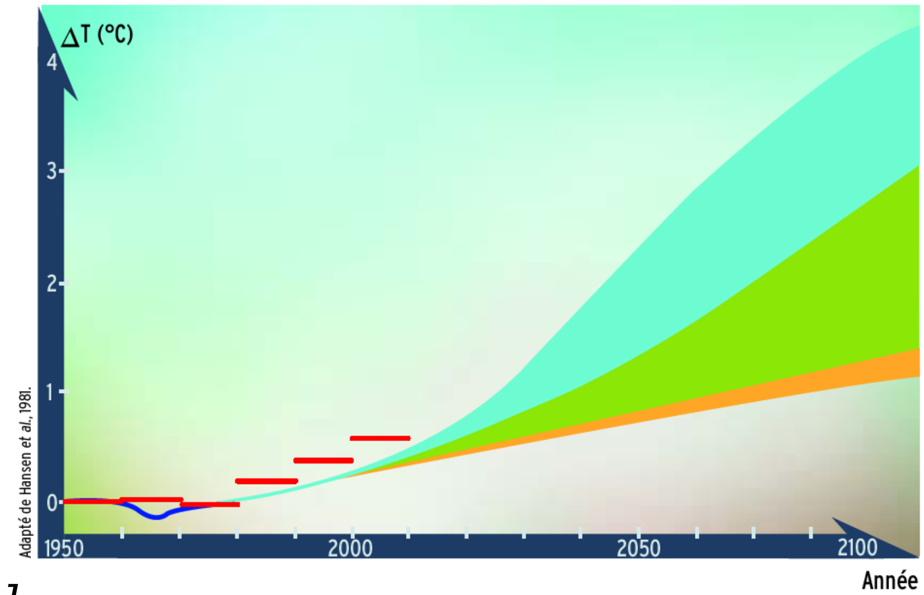
1970-1980: First climate change projections with numerical climate models

1988: Establishment of the IPCC

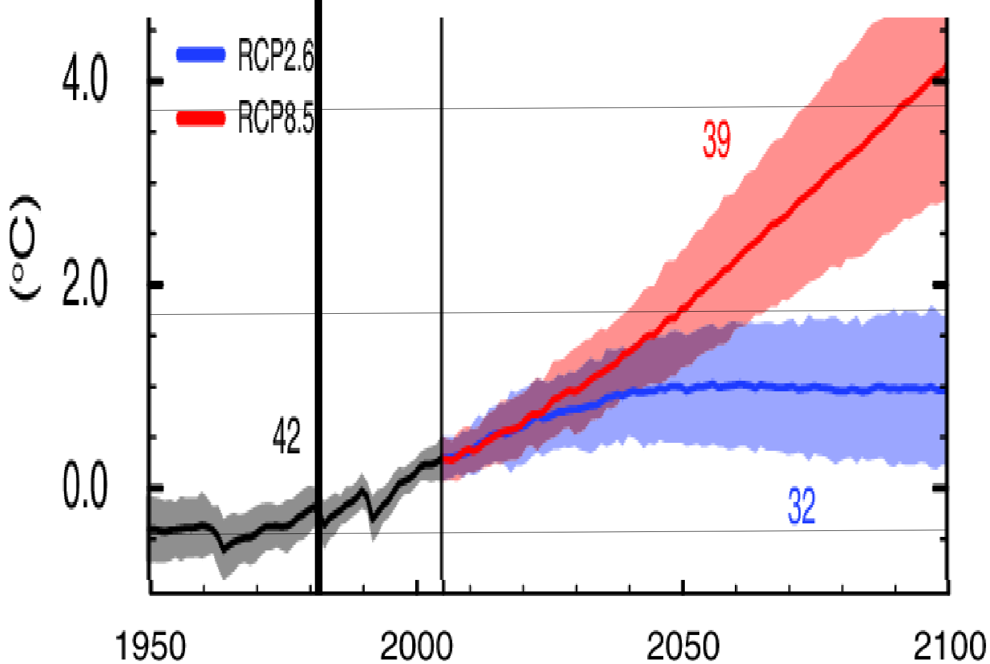
First climate change projections have been confirmed by observations and are still relevant



[Hansen et al. 1981]



Observations (posteriro)
Mean over 10 years



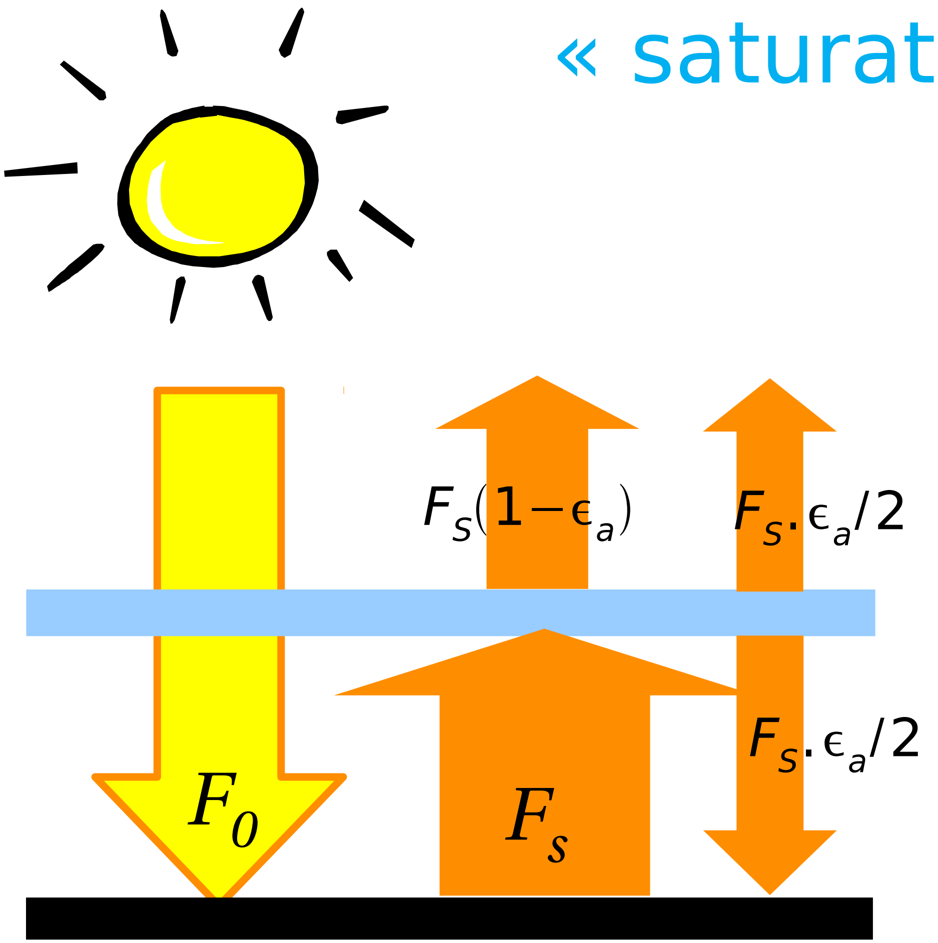
[IPCC 2013]

Conclusions

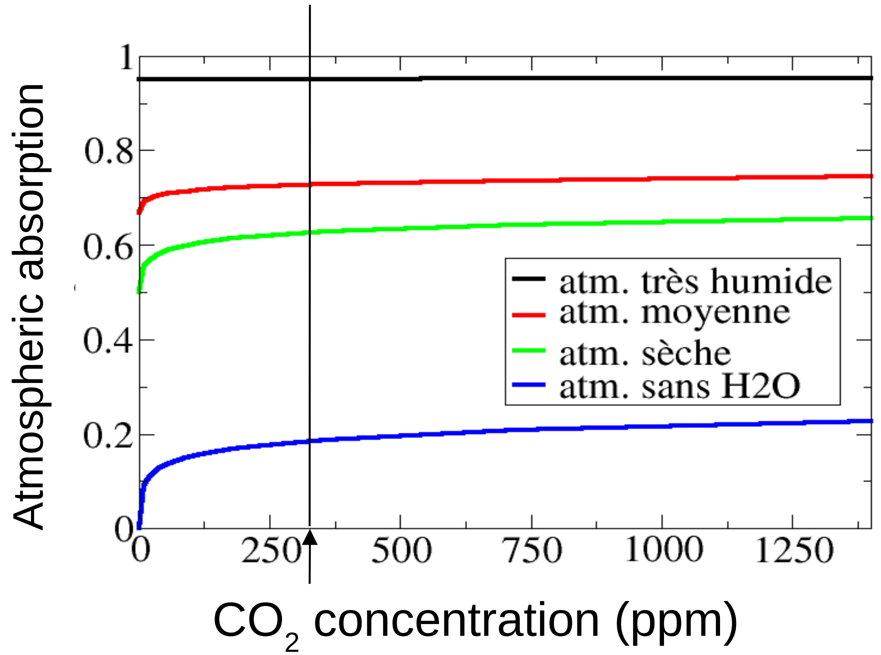
- Global warming and **the dominant role of human activities** is now well understood and well established
- Numerical climate modelling is based on **phenomenological equations** (physical, chemical…)
- If emission of greenhouse gases continue to increase, **future climate changes will be dramatic** compared to those that have existed for 15,000 years
- Climate change questions are evolving: moving from **alerting** to quantifying, describing and **anticipating associated risks**
- There is a **major qualitative shift** in the requirements regarding climate models. Importance of representing processes and understanding climate phenomena
- The more we look at regional phenomena, short time scales (decades) or extreme phenomena, the more uncertainties and natural variability become important.

Thank you for your attention

The CO2 greenhouse effect and the « saturation » paradox



Mean atmospheric absorption in the infrared



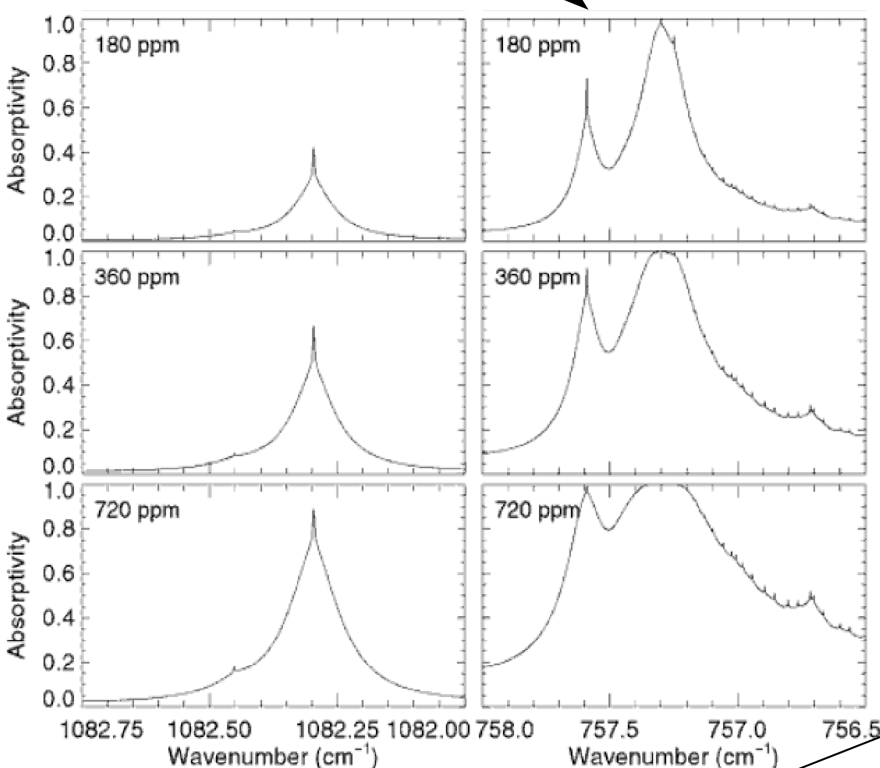
$$\sigma T_s^4 = \frac{F_0}{1-\epsilon_a/2}$$

How can the greenhouse effect increase if the atmospheric absorption don't?

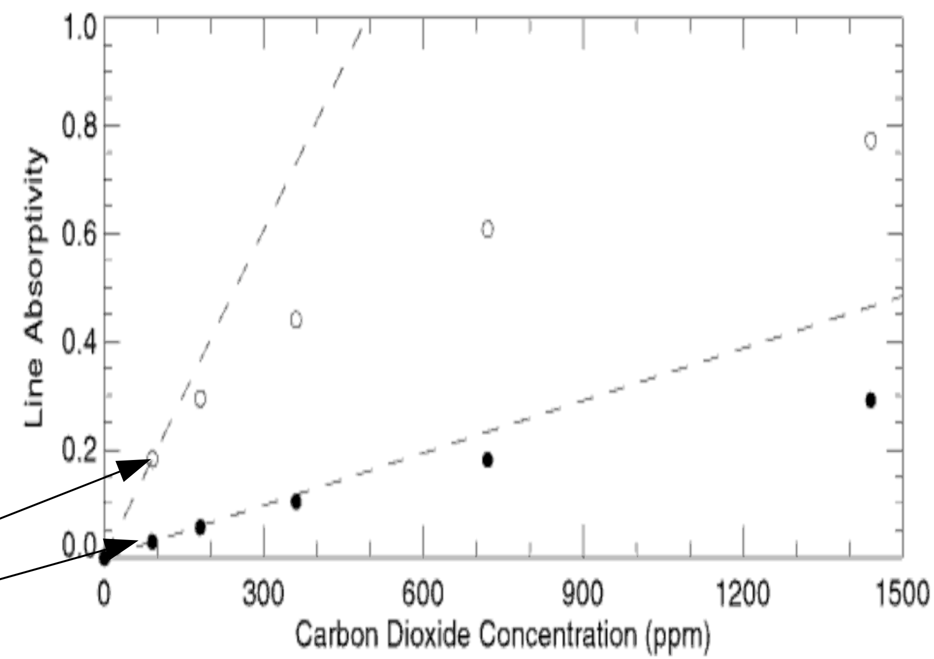
Saturation of absorption bands

Absorption by CO_2, for a vertical column of atmosphere

Absorption spectra,
for 3 CO2 concentrations and two narrow bands



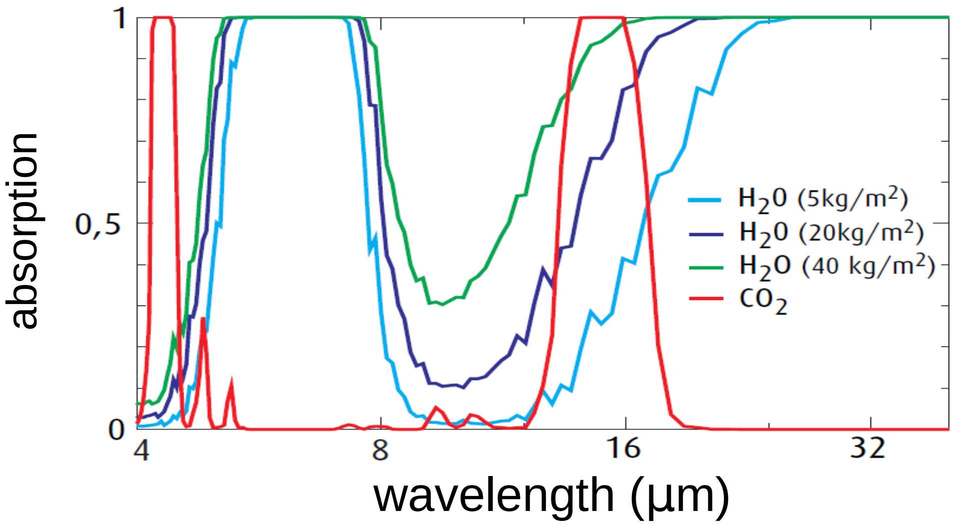
Total absorption of the two narrow bands



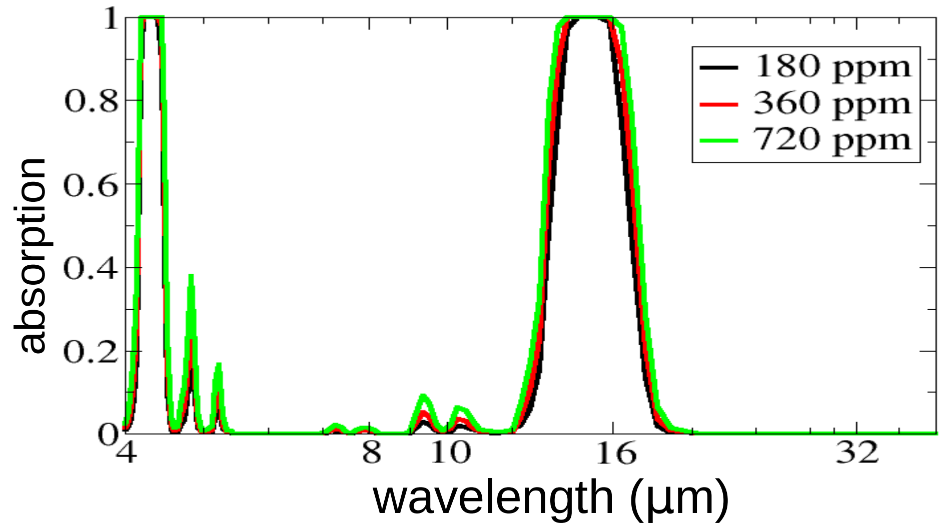
[Bohren and Clothiaux 2006]

Infrared absorption of the atmosphere

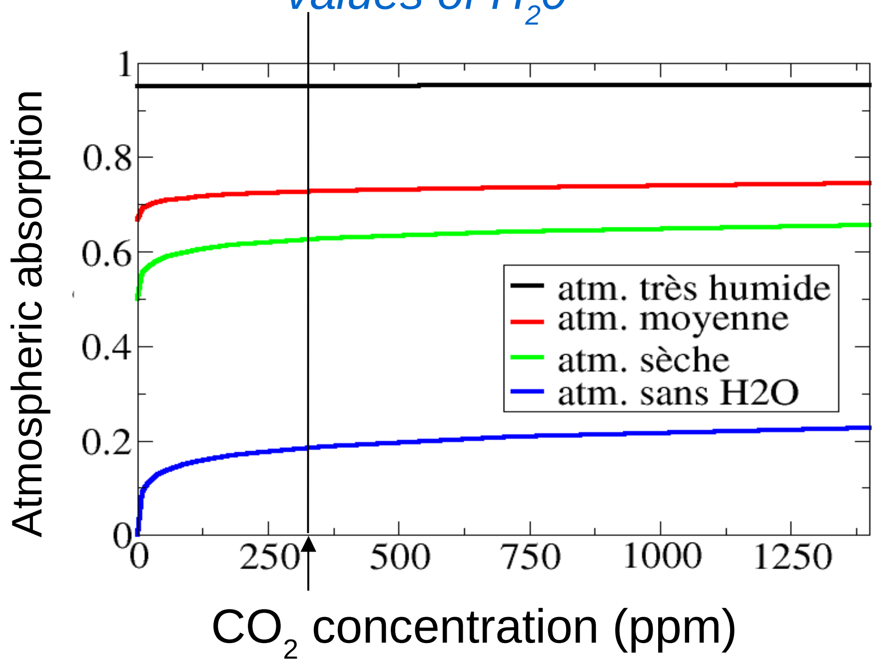
Different H_2O concentration



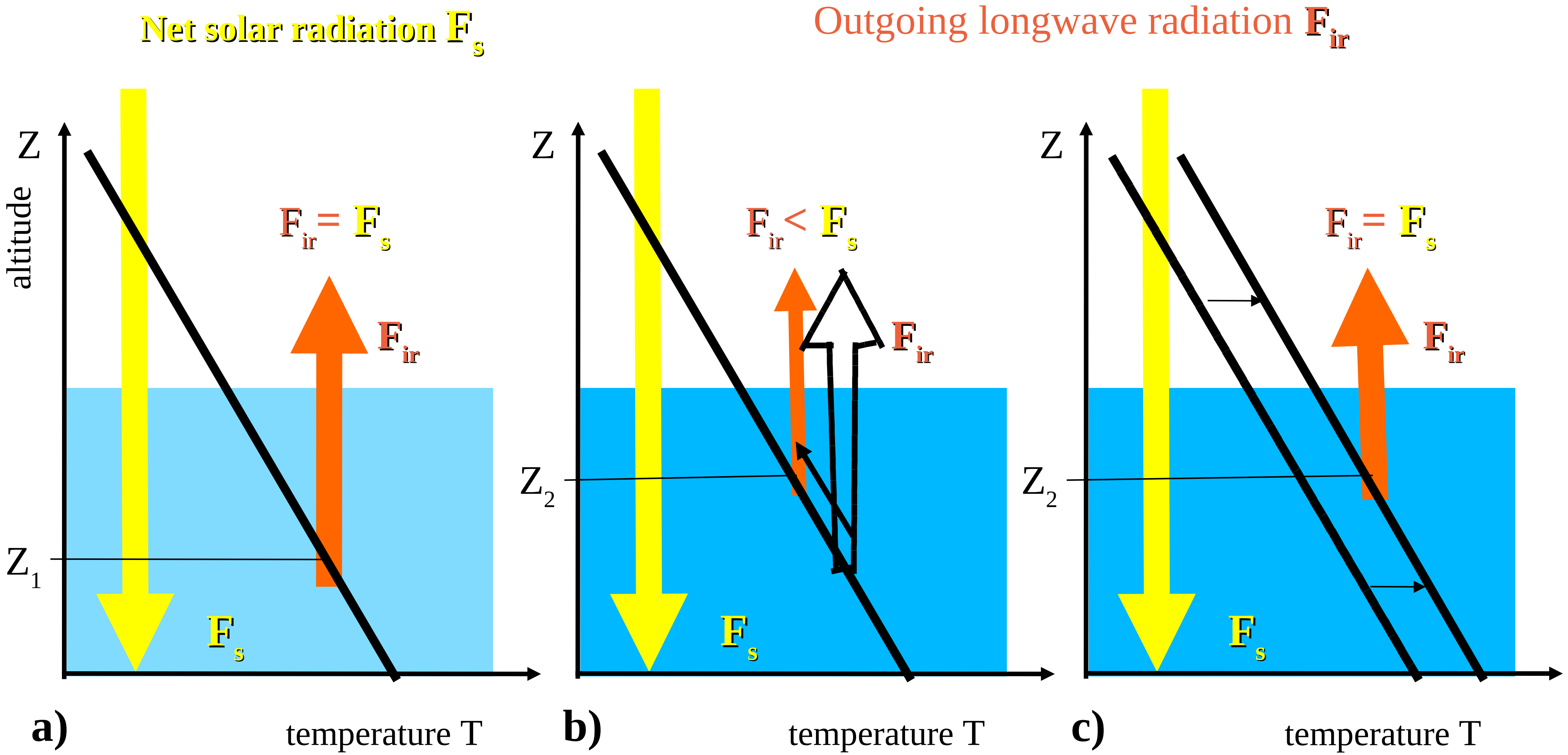
Different CO_2 concentration



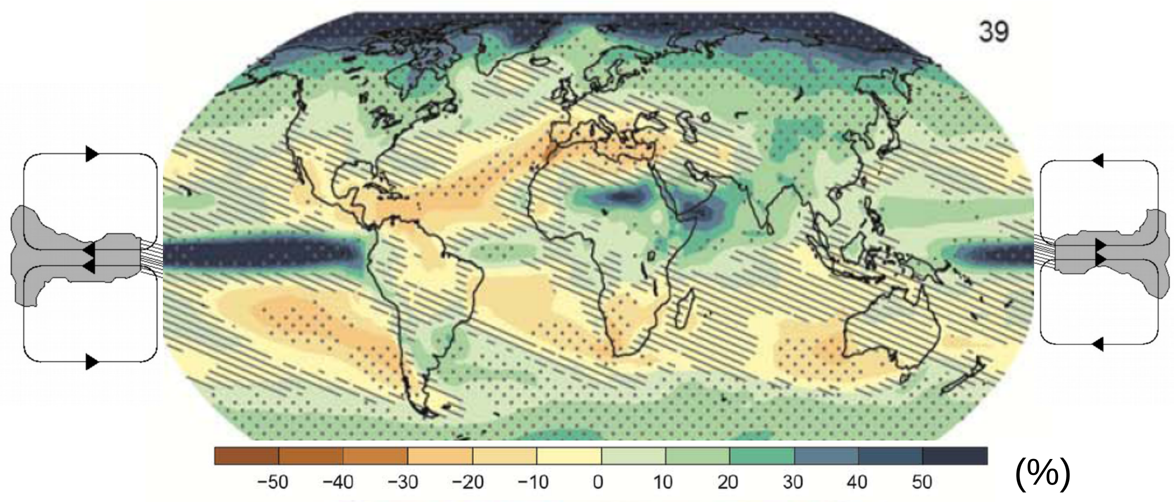
Infrared absorption of the atmosphere as a function *of CO_2*, for different *values of H_20*



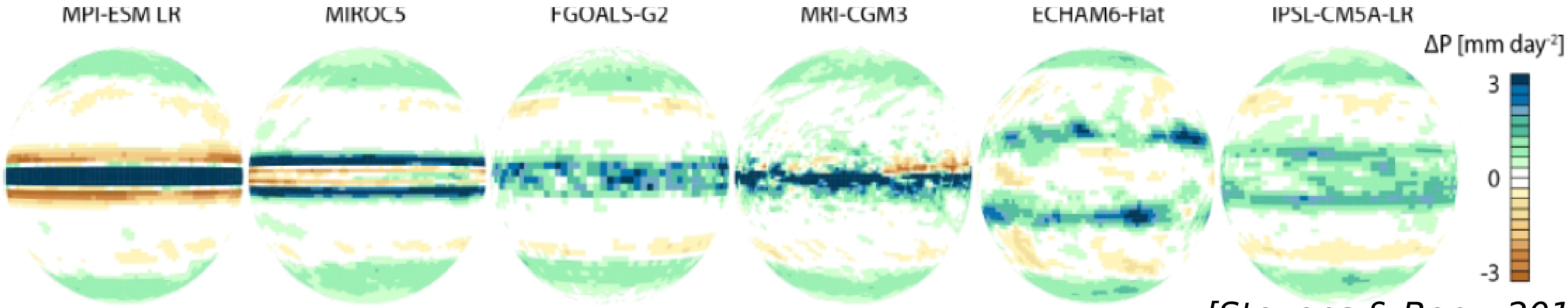
CO_2 increase and greenhouse effect



Precipitation changes



And in a simpler world? Precipitation changes in response **to a uniform increase of temperature** of 4K for **aqua-planets**



[Stevens & Bony, 2013]

A large fraction of the spread in precipitation changes originates from fundamental problems in water-vapor-temperature-circulation interactions