Energy Environment: Science Technology and Management (STEEM)
Greenhouse gases: Challenges and observations

Numerical modelling of recent and futur climate changes

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

LMD Climate Modelling and Climate Change Team
IPSL Climate Modelling Center

Outlook

I. Numerical climate models
II. Simulating and attributing recent climate changes
III. Scenarios and future climate changes
IV. Climate sensitivity and climate feedbacks
V. Climate variability and past climate changes

Emergence of the physics of climate

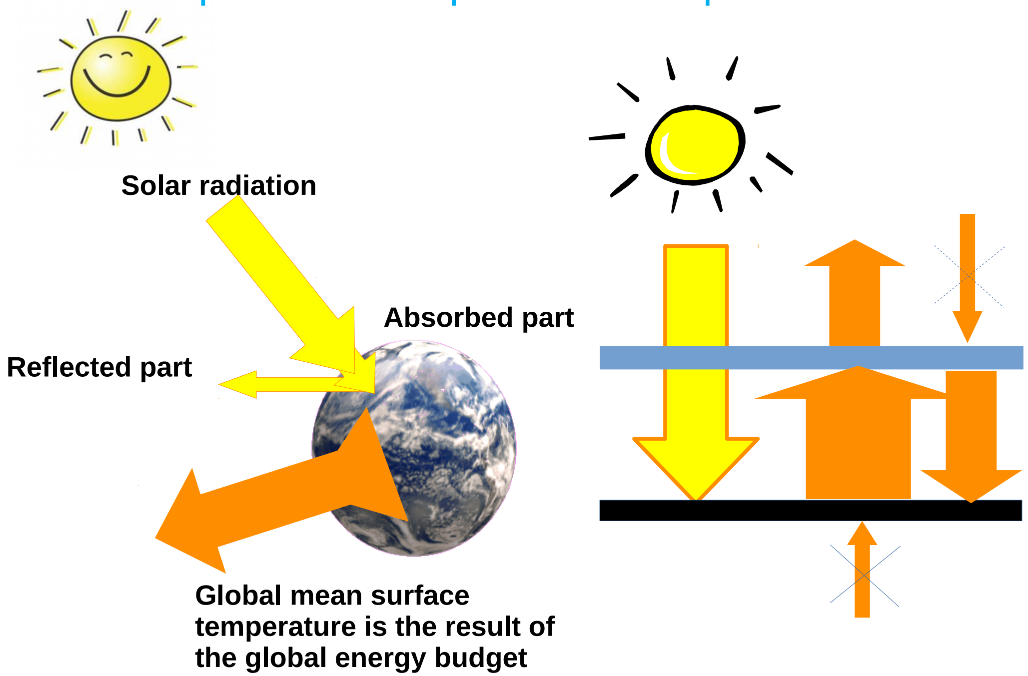
J. Fourrier:
- *Mémoire sur les températures du globe terrestre et des espaces planétaires,* Mémoires de l'Académie des Sciences de l'Institut de France,1824
- *General remarks on the Temperature of the Terrestrial Globe and the Planetary Spaces;* American Journal of Science, Vol. 32, N°1, 1837.

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

[Dufresne, 2006]

Equilibrium temperature of a planet



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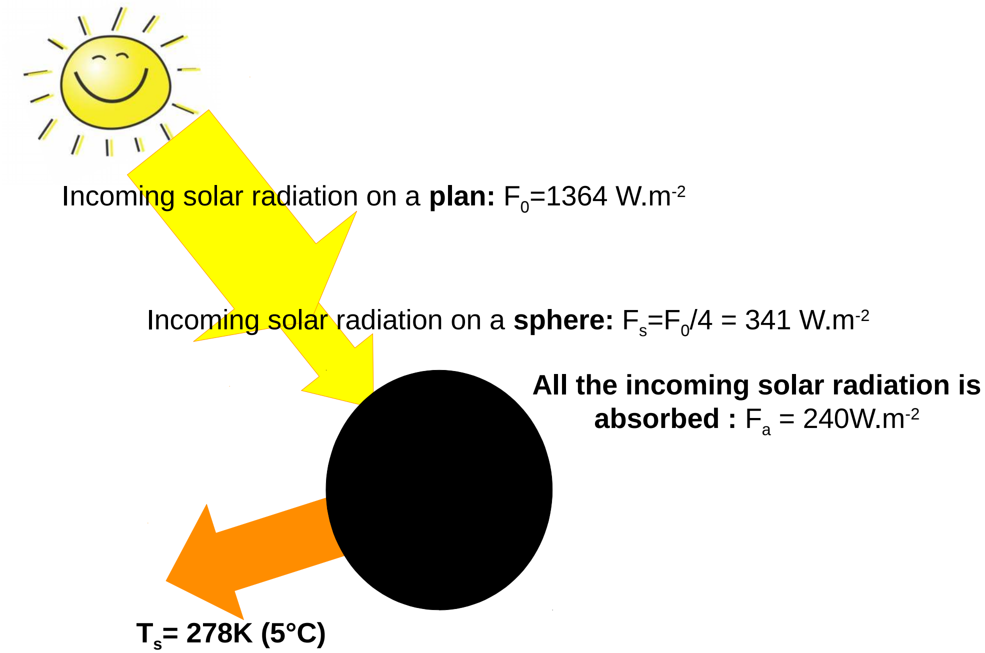
➤ He ***envisages the importance of any change of the sun*** « *The least variation in the distance of that body[the sun] from the earth would occasion very considerable changes of temperature.* »

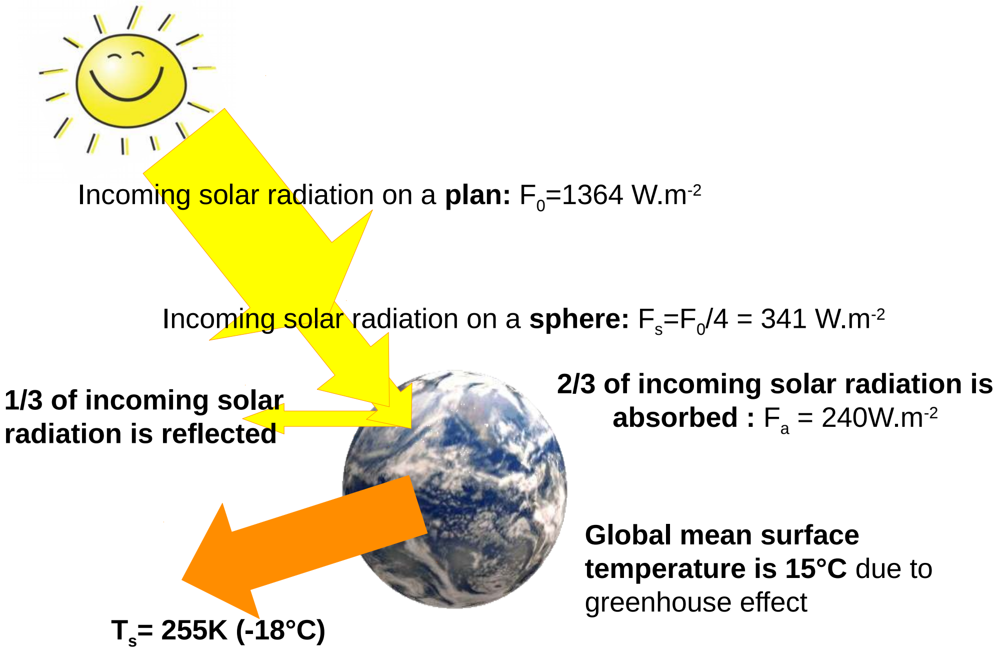
➤ He ***envisages that climate may change***: « *The establishment and progress of human society, and the action of natural powers, may, in extensive regions, produce remarkable changes in the state of the surface, the distribution of waters, and the great movements of the air. Such effects, in the course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

[Dufresne, 2006]

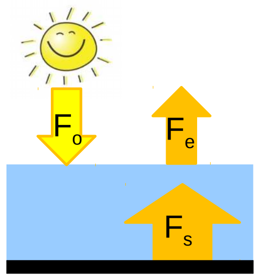
Equilibrium temperature of a planet



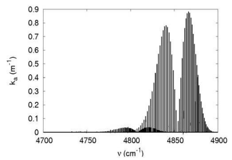
Equilibrium temperature of a planet



What radiation heat transfer theory tell us



Greenhouse effect: $G=F_s-F_e$



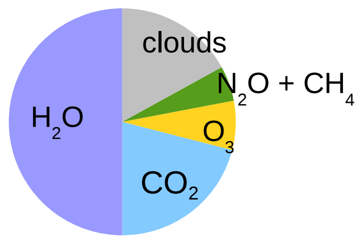
Gas radiative properties

Atmospheric characteristics

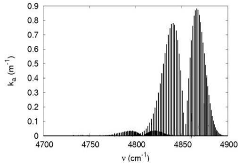
Computation of the radiative fluxes F_s and F_e and the greenhouse effect G

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



What radiation heat transfer theory tell us



Gas radiative properties

Atmospheric characteristics

Computation of the radiative fluxes and the greenhouse effect

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 changes except the temperature*

From radiative transfer computation to climate modelling

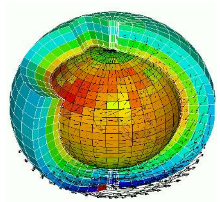
For a doubling of the CO_2 concentration:

- the green house effect increases by 3.7 W.m^{-2}
- the temperature increases by ≈ 1.2 K, if nothing change except the temperature

But feedbacks exist:

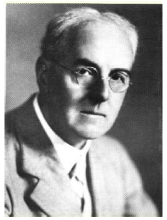
- Snow and sea ice reflect solar radiation; if they decrease, more solar energy will be absorbed ⇒ positive feedback
- Water vapour is the main greenhouse gas; if it increases, the greenhouse effect will be enhanced ⇒ positive feedback
- Clouds reflect solar radiation and contribute to the greenhouse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

Need of 3D numerical climate models



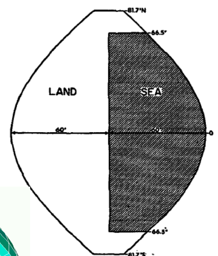
Numerical climate models (numerical weather simulators)

Wilhelm Bjerknes
(1862–1951)



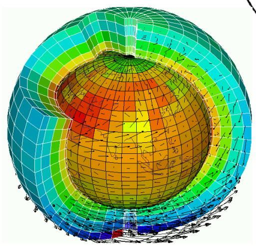
L. F. Richardson
(1881–1953)

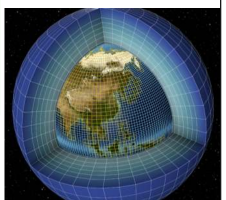
J. von Neumann
(1903–1957)



Jule Charney
(1917-1981)

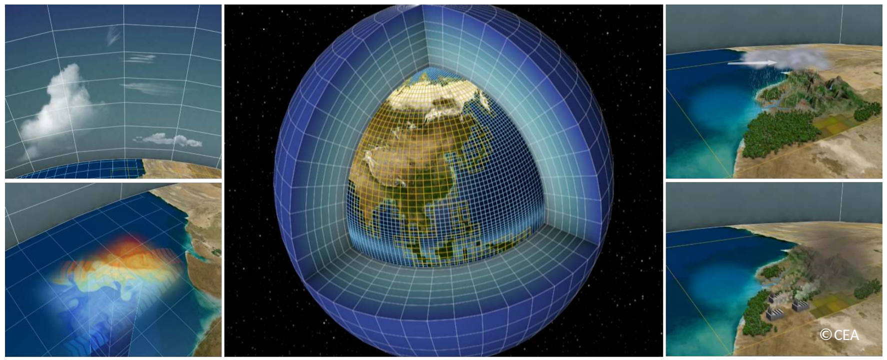
Syukuro Manabe
(1931-)



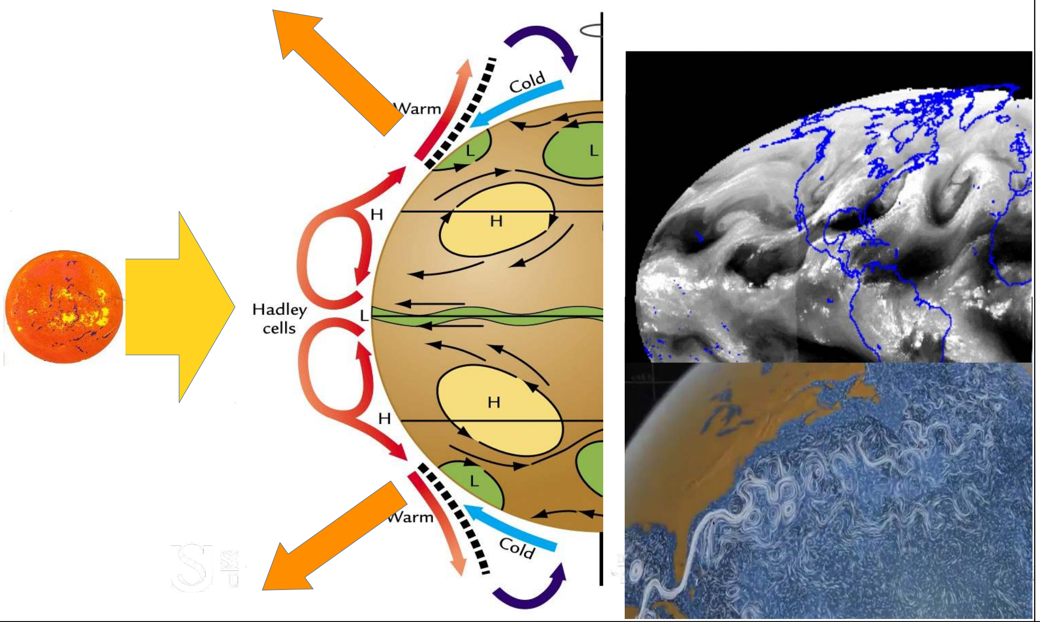


3D climate numerical models

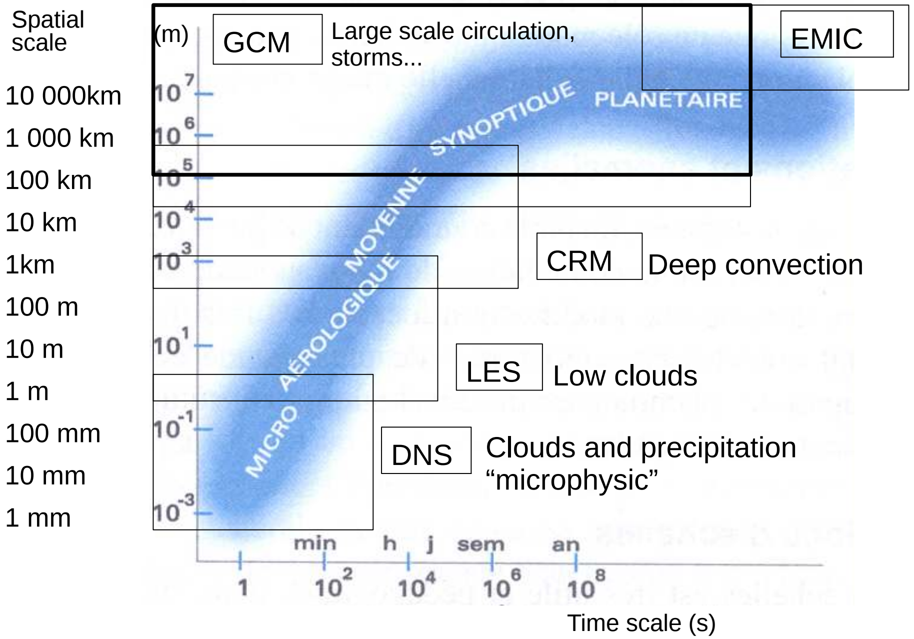
- Physical laws (atmosphere, ocean, sea-ice....)
- Discretization (temporally and spatially)
- Modelling of the sub-grid phenomena, or parameterization



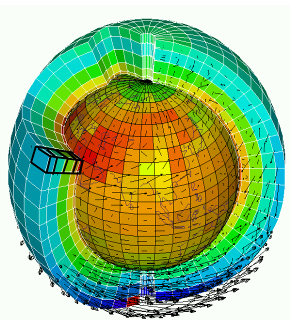
Large scale circulation: Meridional heat transport and the effects of Earth rotation



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)

  $Dq/Dt = S_q$

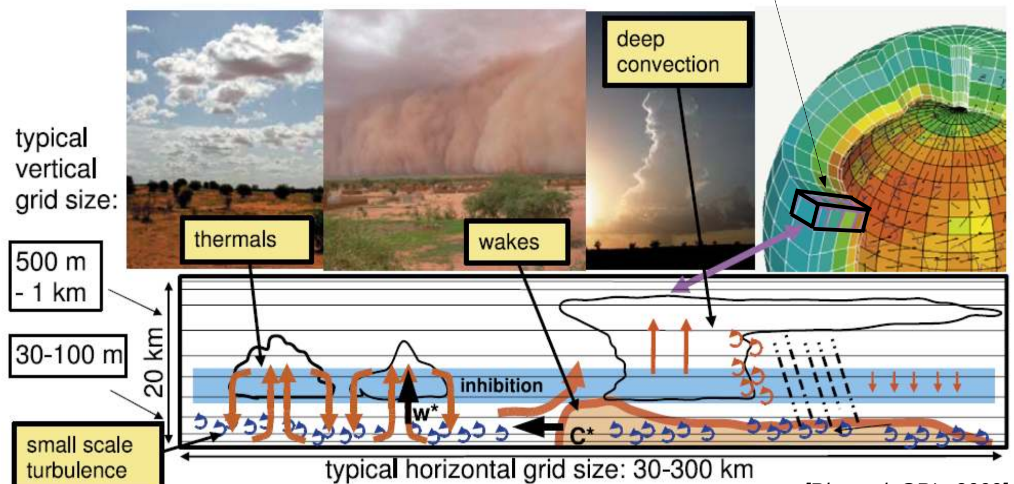
In red, source terms : other than fluid mechanics and unresolved scales

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

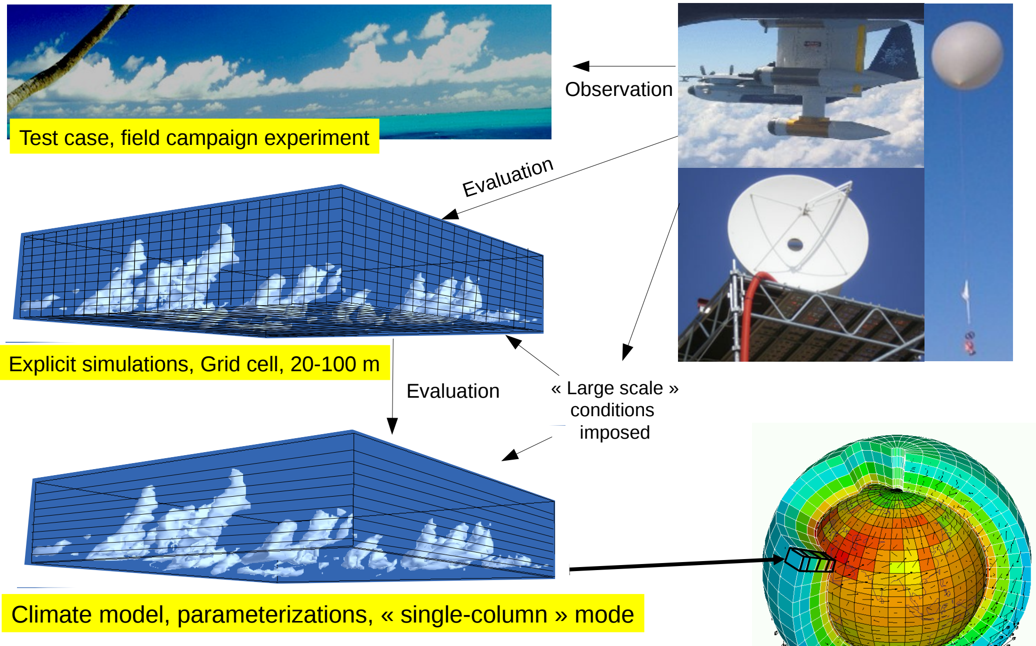
A typical vertical atmospheric column



[Rio et al, GRL, 2009]

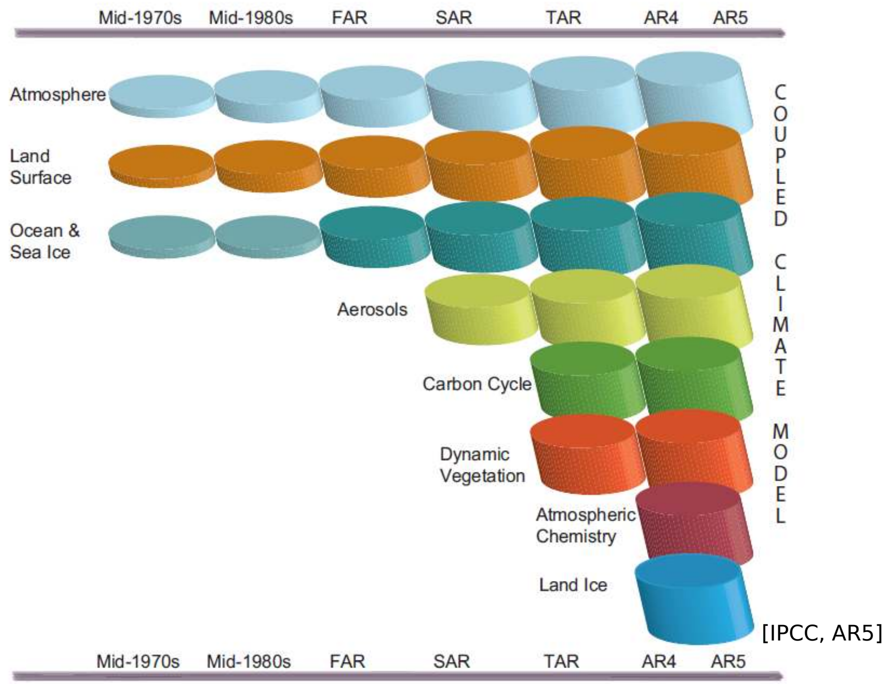
Typical time step : a few minutes to half an hour

Parameterization development and the use of high resolution explicit models



→ **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



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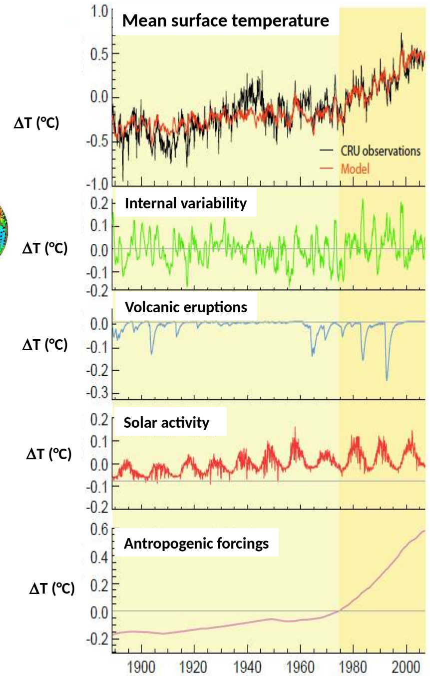
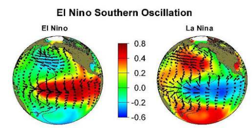
What drives climate variations and changes ?

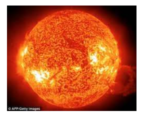


Internal variability



Volcanic activity

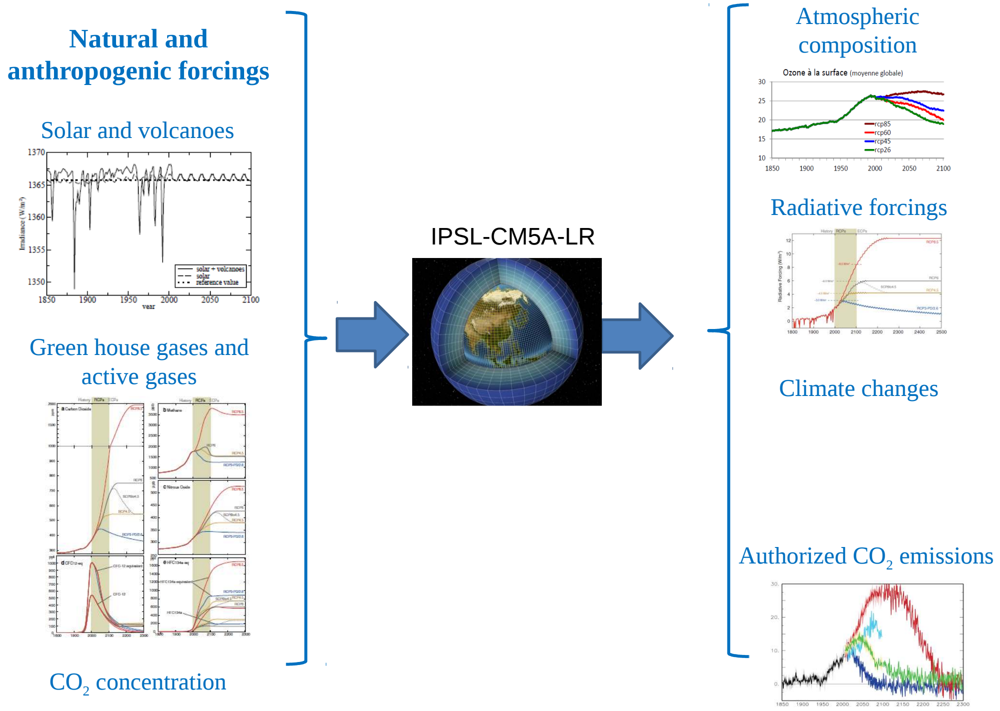
Solar activity



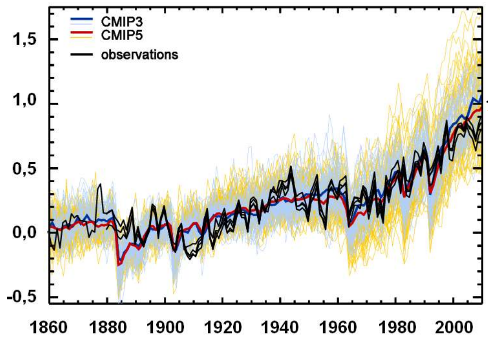
Anthropogenic factors

Adapted from Lean 2010

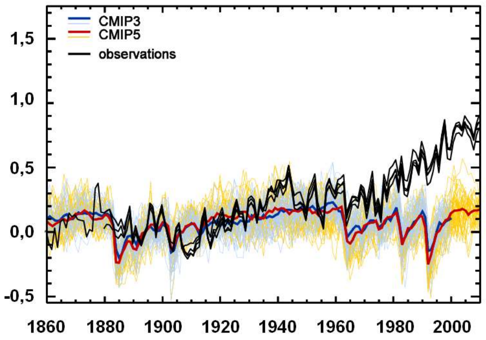
The IPSL Earth System Model



Human activities and recent climate change



Mean surface temperature anomalies **observed** and **computed** considering *both the natural and anthropogenic perturbations* (observed volcanic eruptions and changes of the solar activity, the green house gases, the aerosols...)

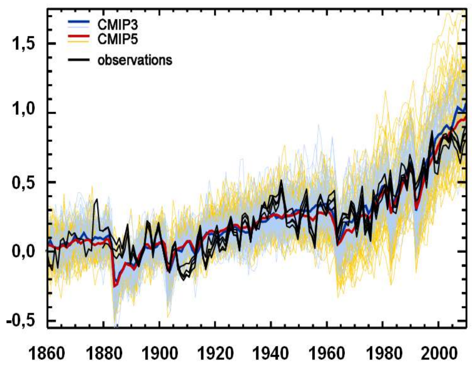


Mean surface temperature anomalies **observed** and **computed** considering *only the natural perturbations* (observed volcanic eruptions and changes of the solar activity...)

(IPCC, 2013)

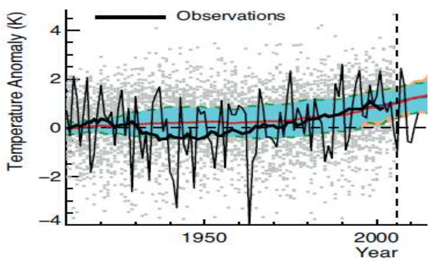
Surface temperature evolution: observation and models

Annual global mean

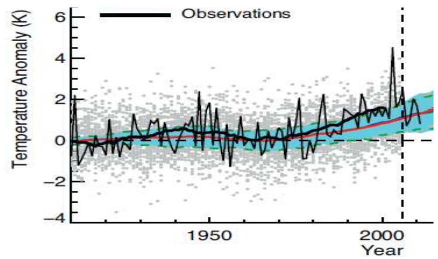


[IPCC, 2013]

Winter mean over France

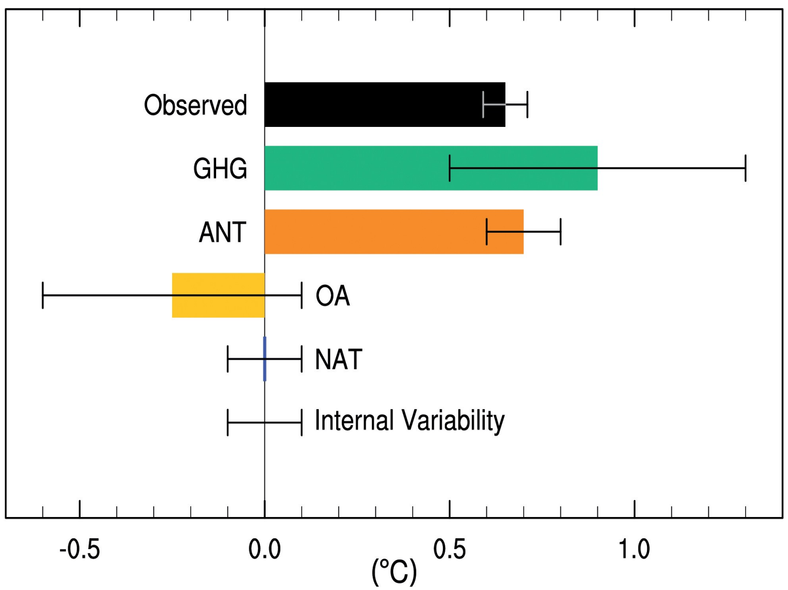


Summer mean over France



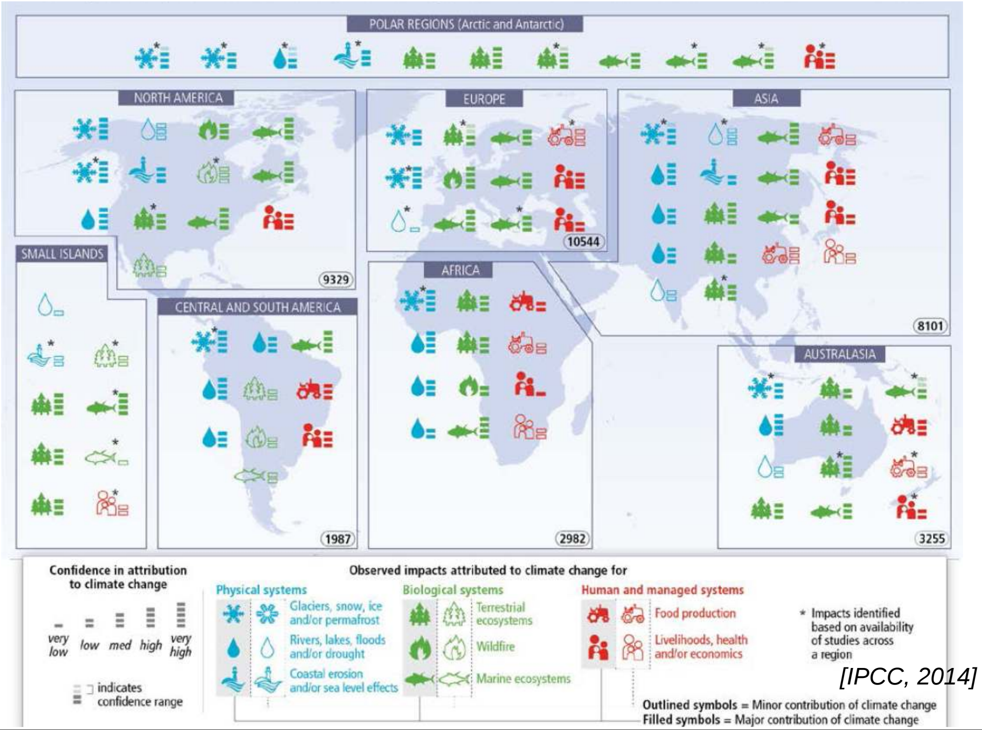
[Terray et Boé, 2013]

Origin of the global warming trends over the 1951-2010 period



[IPCC, 2013]

Observed impact attribute to climate change



[IPCC, 2014]

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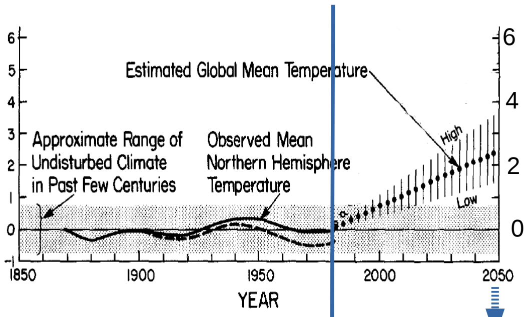
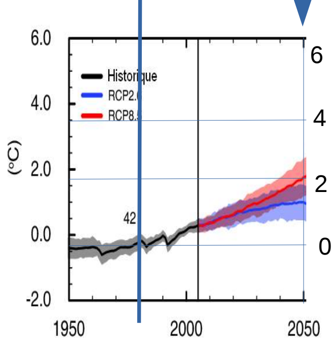
First climate projections before global warming has been observed

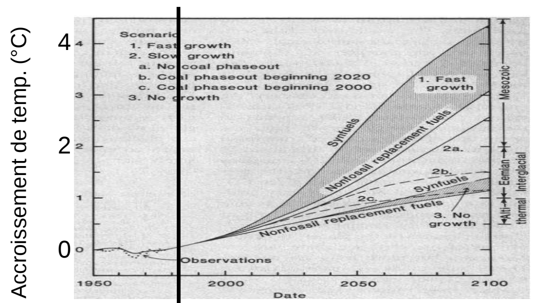


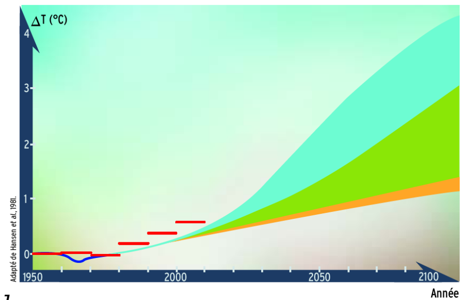
[Kellogg 1977]



[GIEC 2013]

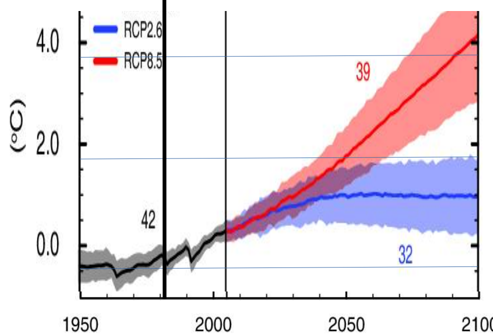
First climate projections before global warming has been observed





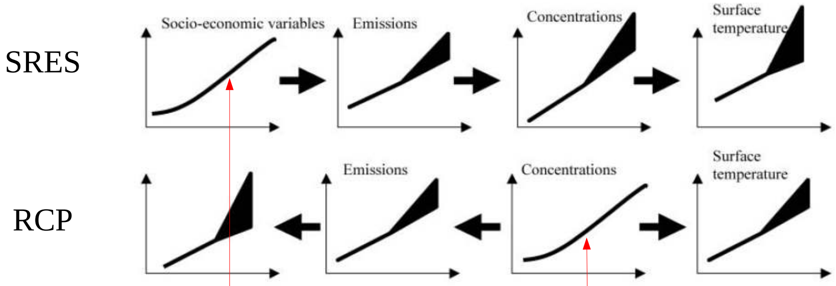
[Hansen et al. 1981]

Observations, average over 10 years, posterior to publication



[IPCC AR5, 2013]

Scenarios for future climate change projections



[Hibbard et al., EOS, 2007]

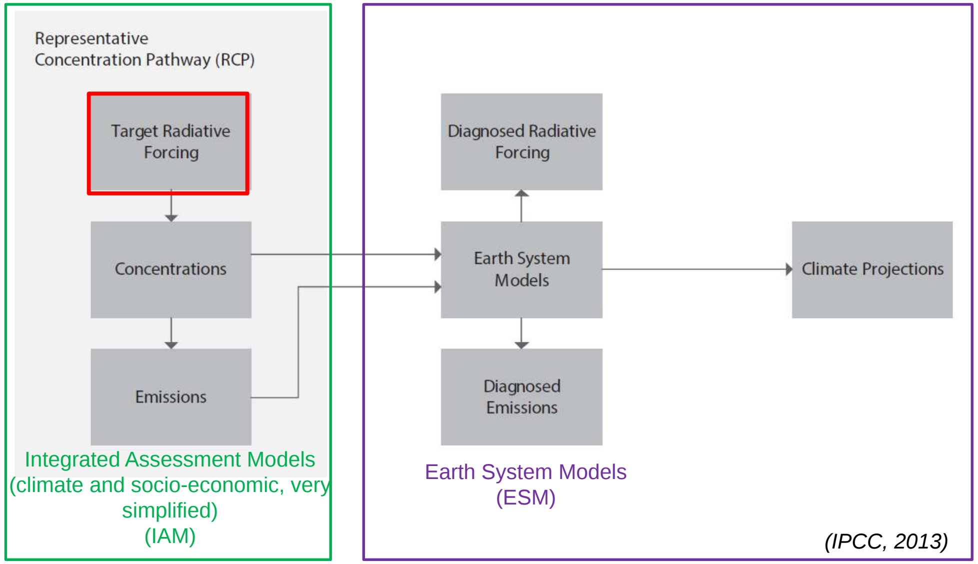
Scenario as the starting point of the full chain

Scenario as the gathering place between socio-economic and climate sciences

Scenarios for future climate change projections

Scenarios are defined with a target value of the ***radiative forcing (W.m^-2^)***

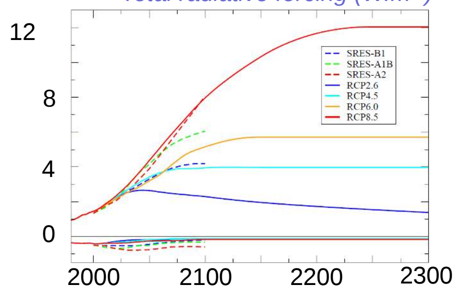
RCP : « Representative concentration pathways »



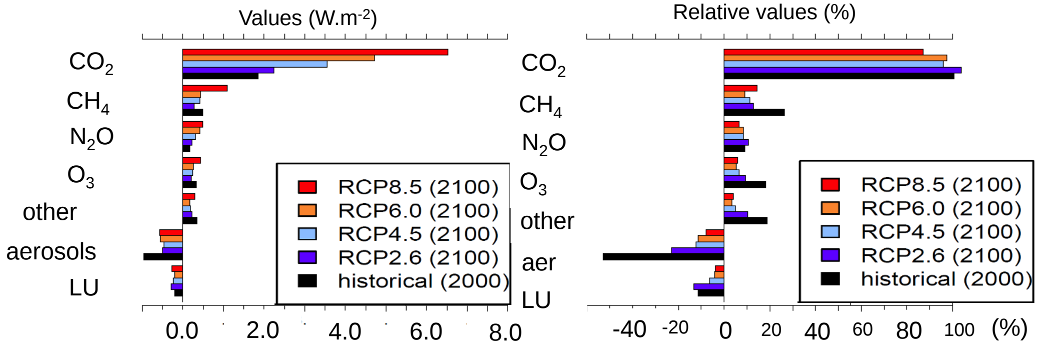
(IPCC, 2013)

Radiative forcing of future scenarios

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



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



Radiative forcing of future scenarios

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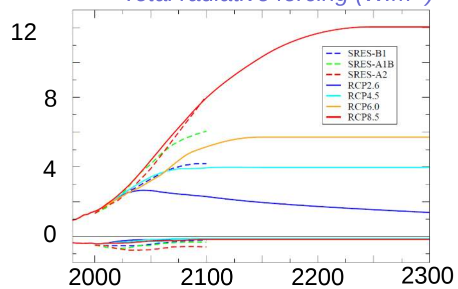
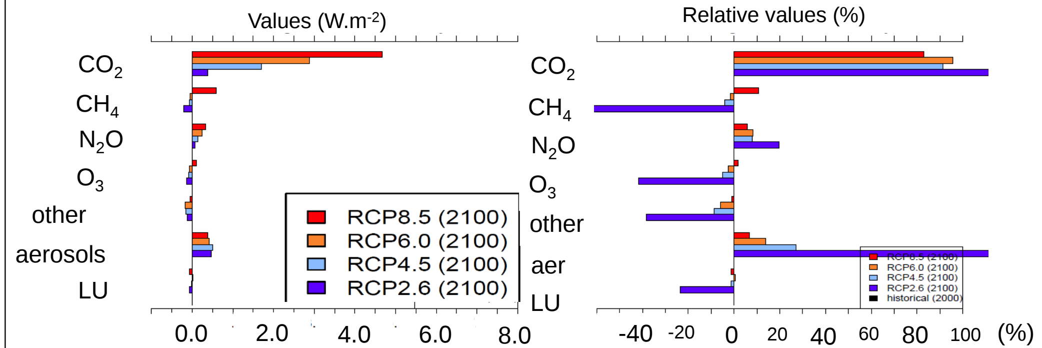


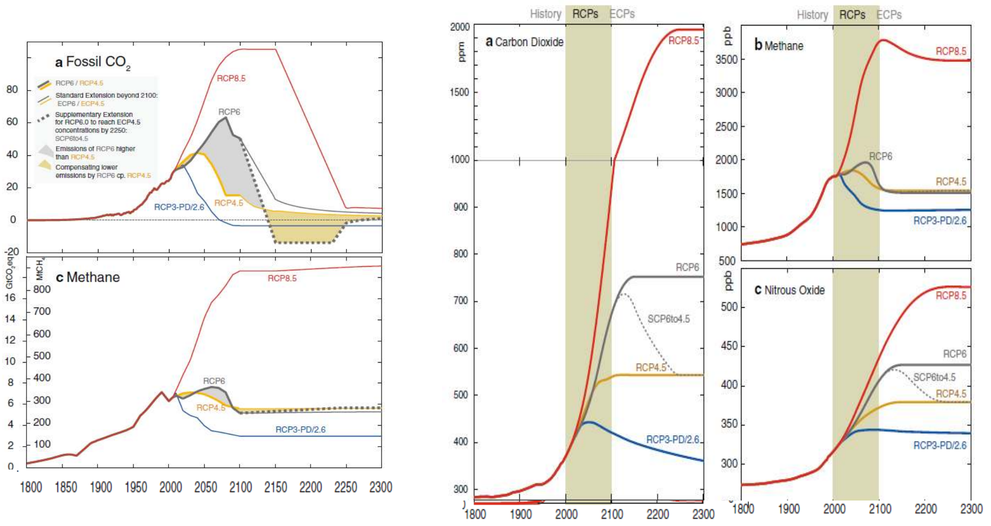
*Contribution of individual forcings to total forcing relative to **2000***



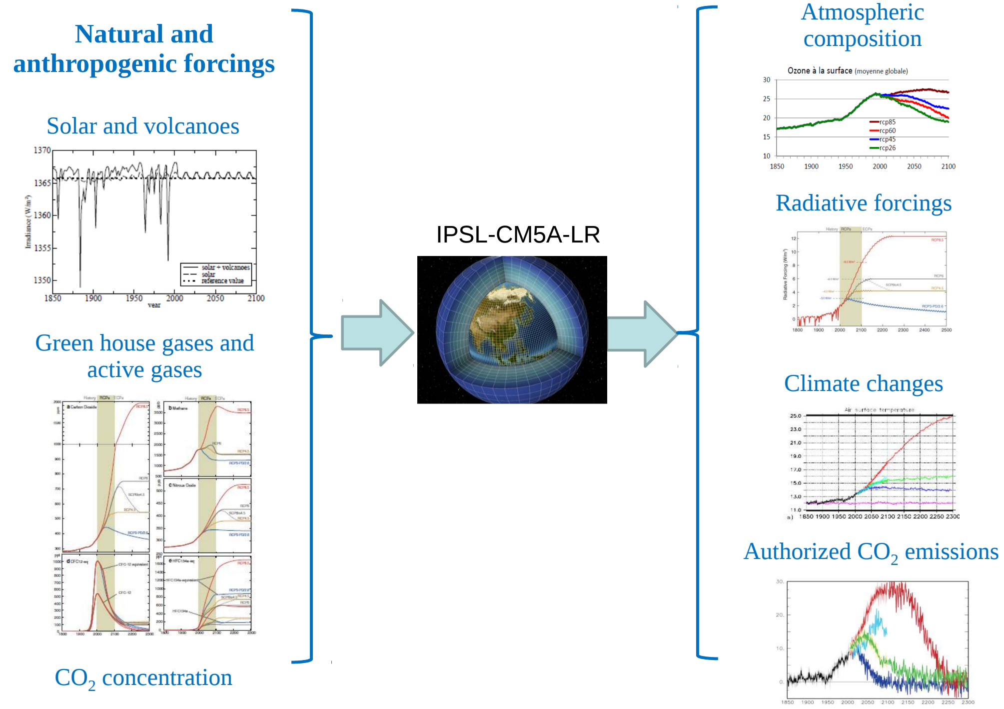
Future scenarios: gaz emission and concentration

emission

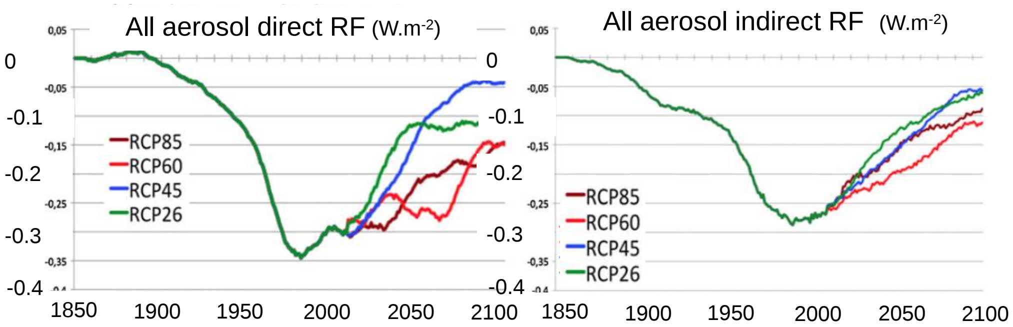
concentration

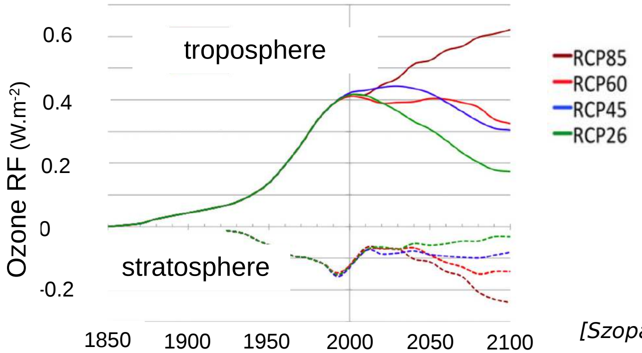


The IPSL Earth system model



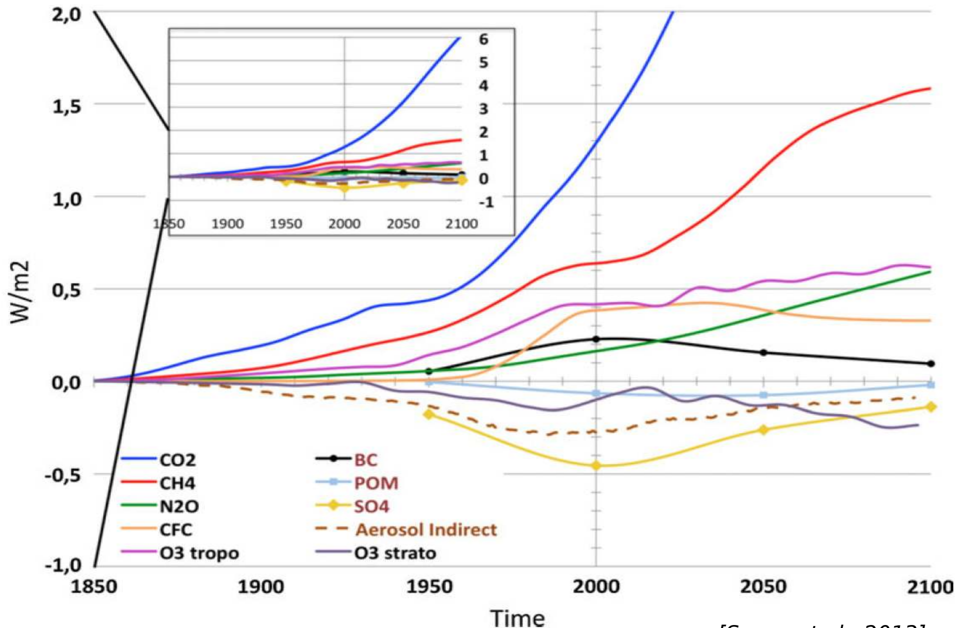
Ozone and aerosols computations (IPSL-CM5A-LR model)





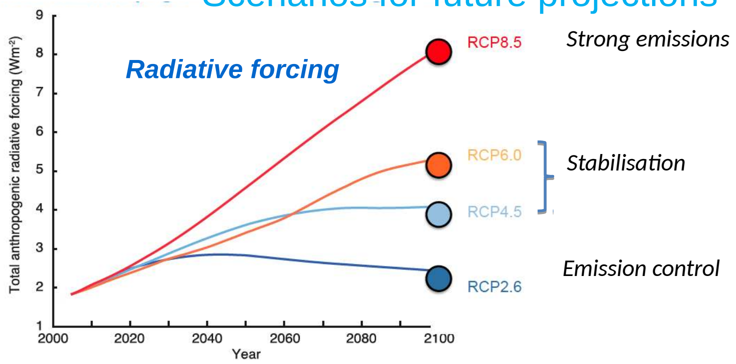
[Szopa et al., 2013]

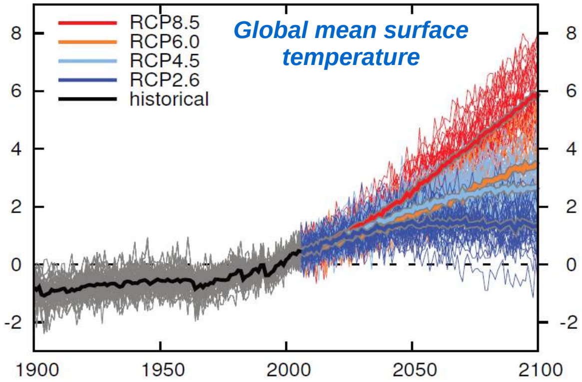
Radiative forcings for the historical period and the future RCP8.5 scenario (IPSL-CM5A-LR model)



[Szopa et al., 2013]

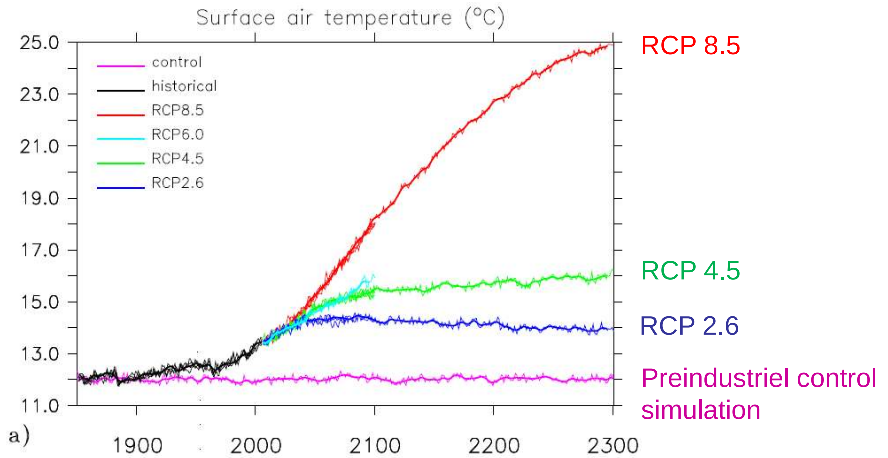
Scenarios for future projections





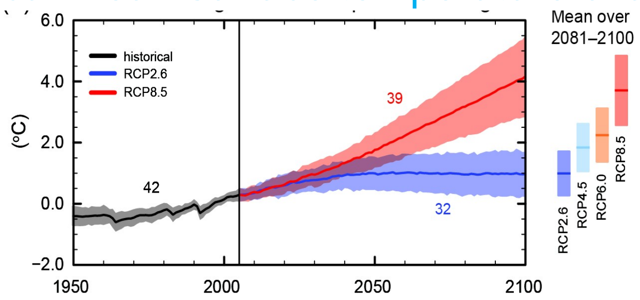
Global mean surface temperature

1850 to 2300
IPSL-CM5A-LR model



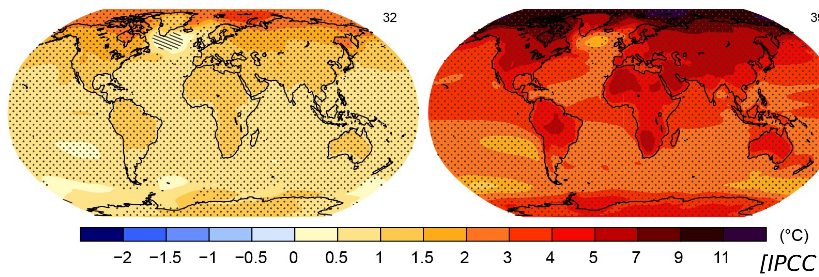
[Dufresne et al., 2013]

Global mean surface temperature change



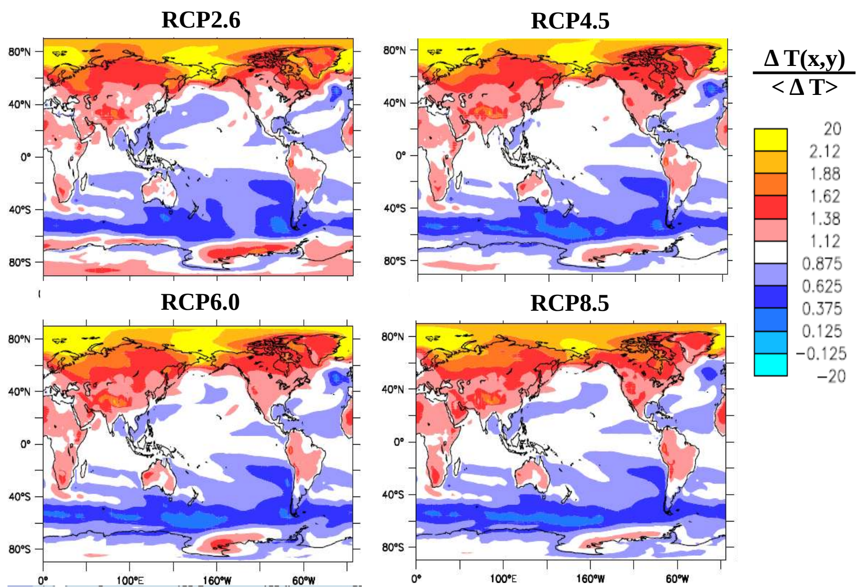
RCP 2.6 **RCP 8.5**

Change in average surface temperature (1986−2005 to 2081−2100)



[IPCC 2013]

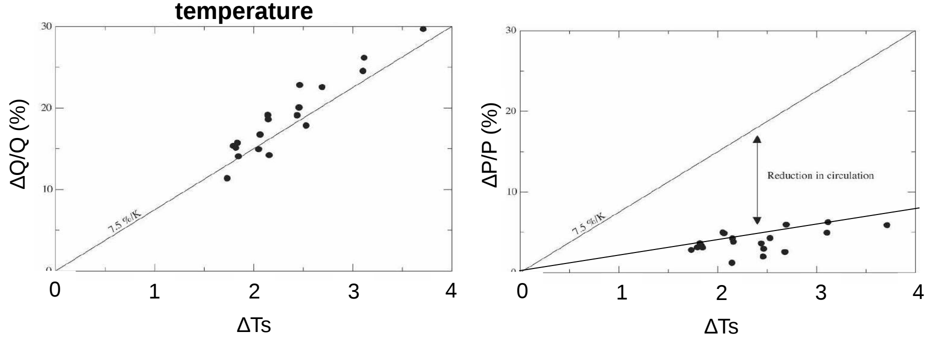
Spatial distribution of the normalized air surface temperature change $\Delta T(x,y)/\langle \Delta T \rangle$ in 2100



Precipitation changes

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

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

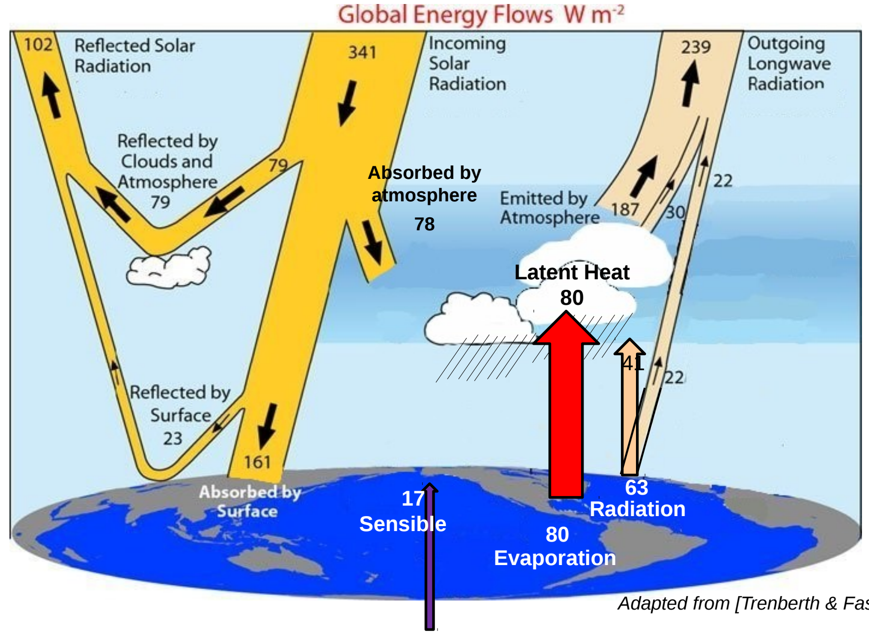


$\Delta Q/Q$ (%) ≈ 7.5 ΔTs

$\Delta P/P$ (%) ≈ 1.5 ΔTs

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

(Vecchi & Soden, 2007)

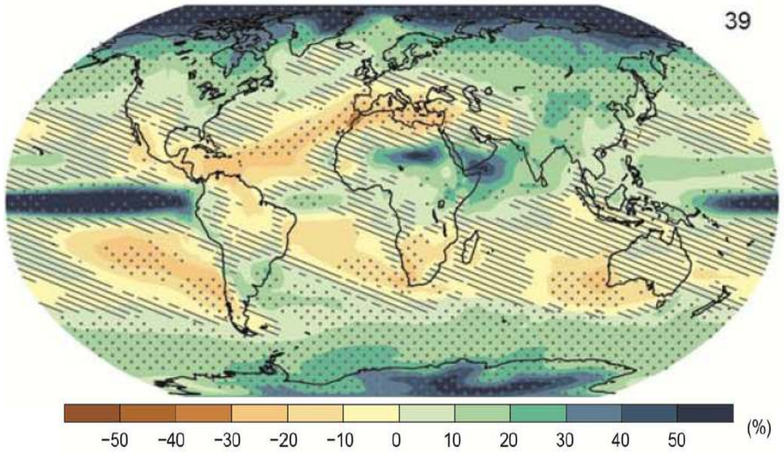


Adapted from [Trenberth & Fasullo, 2012]

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

Precipitation changes: Geographical distribution

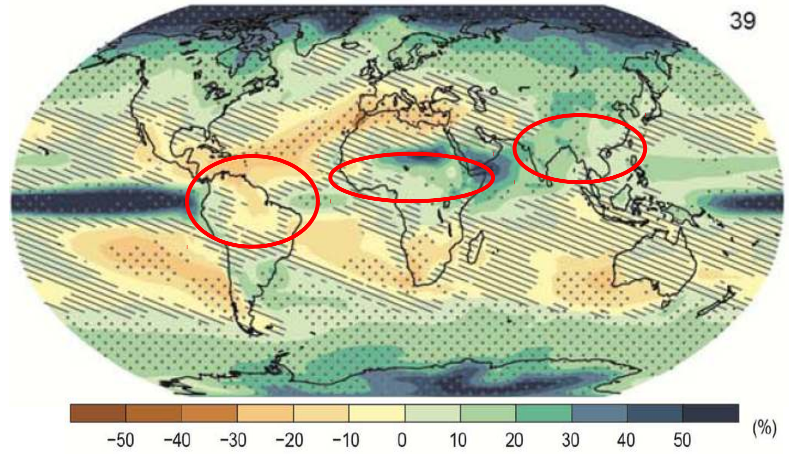
Relative change in average precipitation, RCP8.5 scenario (2081-2100)



[IPCC 2013]

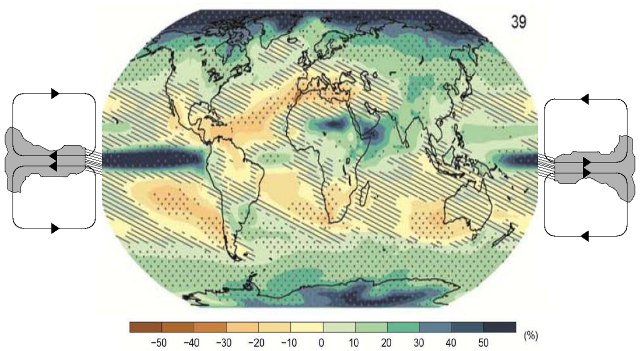
Precipitation changes: Geographical distribution

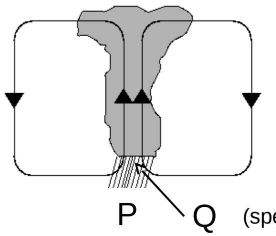
Relative change in average precipitation, RCP8.5 scenario (2081-2100)



[IPCC 2013]

Precipitation changes





(specific humidity)

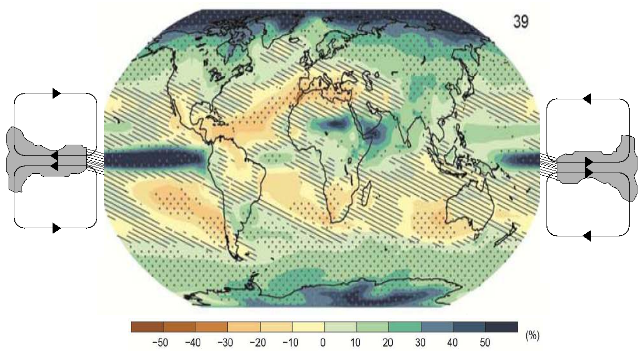
Precipitations changes

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

Thermodynamic response

Dynamic response

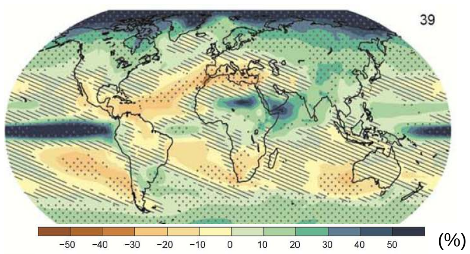
Precipitation changes



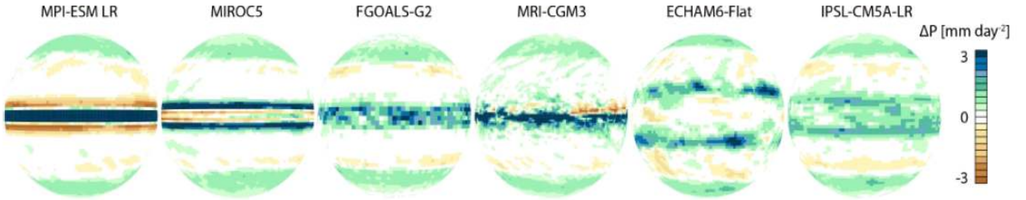
At the global scale:

- 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

Precipitation changes



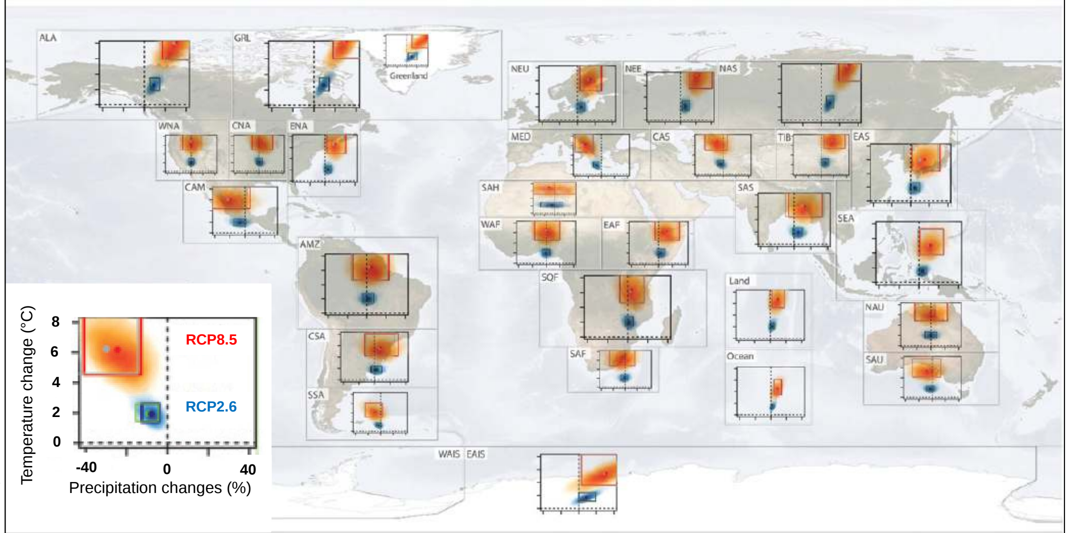
And in a simpler world? Precipitation changes in response **to a uniform increase of temperature** of 4K for **aqua-planets**



[Stevens & Bony, 2013]

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

Regional precipitation changes using a scaling approach

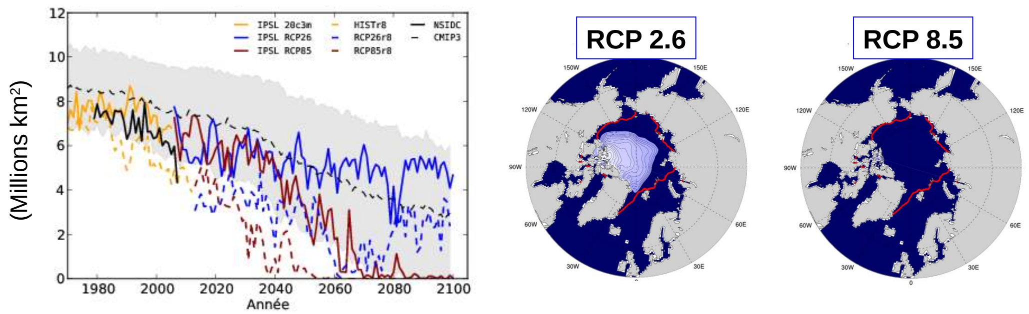


[Frieler et al., 2012]

Arctic sea-ice 1970-2100

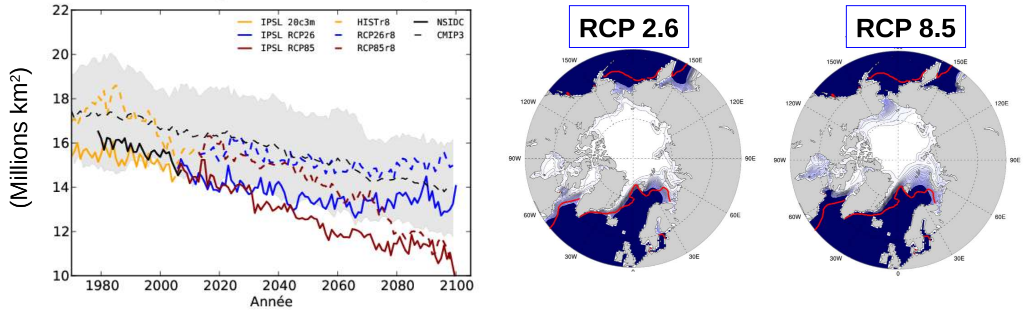
September *(minimum extension)*

IPSL-CM5A-LR

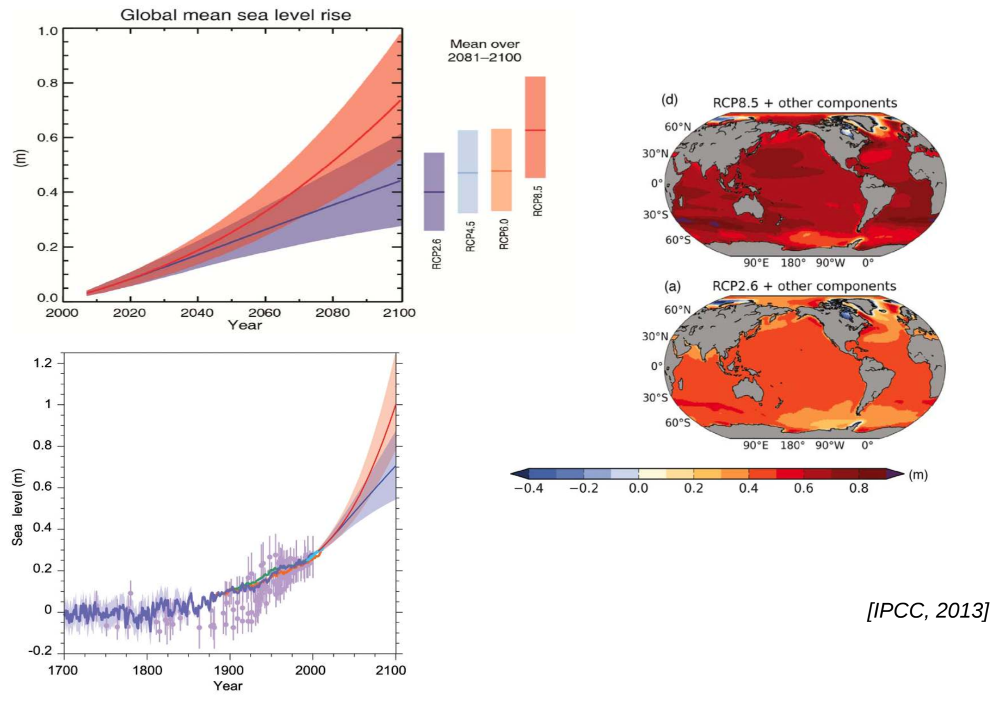


Mars *(maximum extension)*

IPSL-CM5A-LR



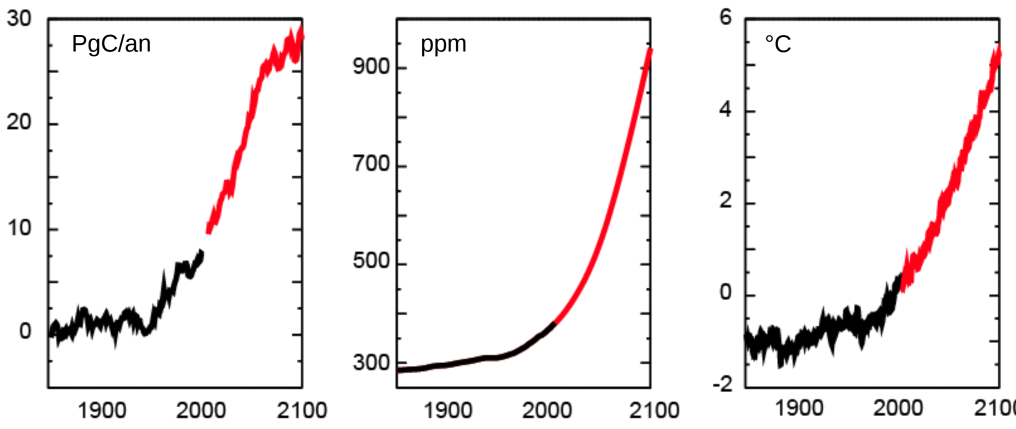
Sea level rise



[IPCC, 2013]

Carbone emission, CO_2 concentrations and global temperature: time constants

Higher scenario : emissions, concentration and temperatures continue to grow

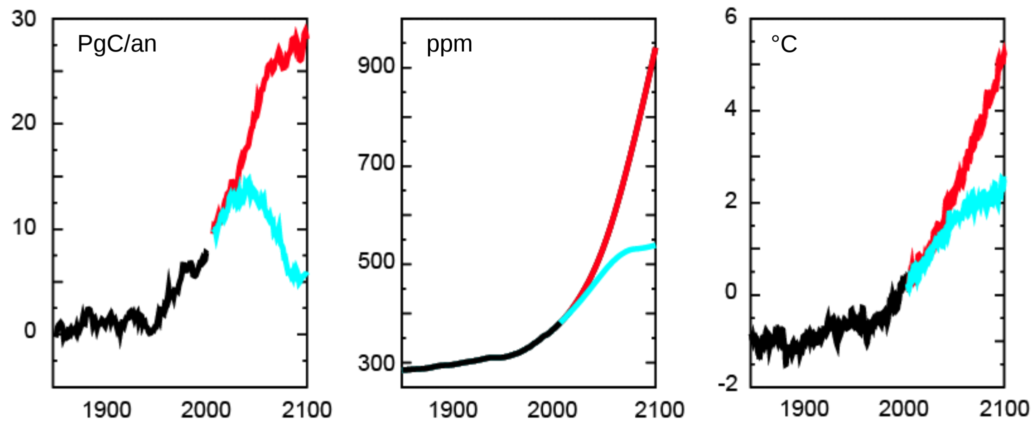


Courtesy L. Bopp

Carbone emission, CO_2 concentrations and global temperature: time constants

Higher scenario : emissions, concentration and temperatures continue to grow

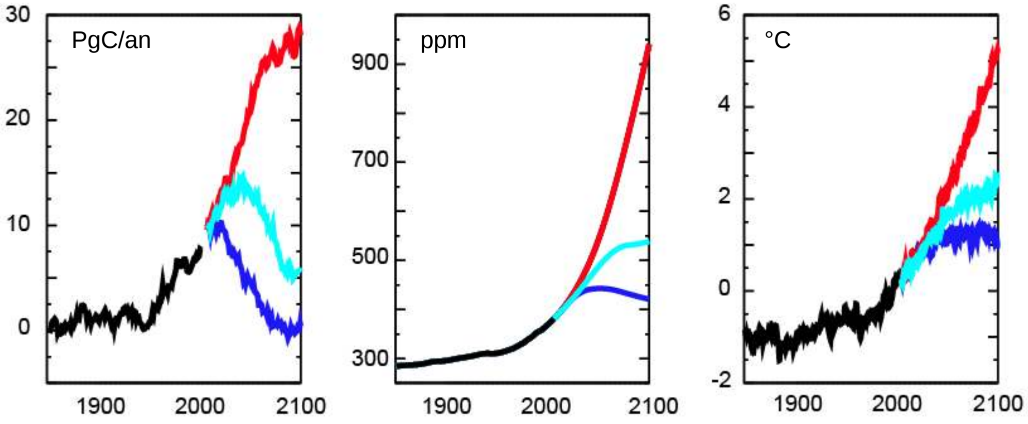
Medium scenario : to stabilize CO_2 concentration 550 ppm, emissions need to be strongly reduced. However, temperature will continue to increase



Courtesy L. Bopp

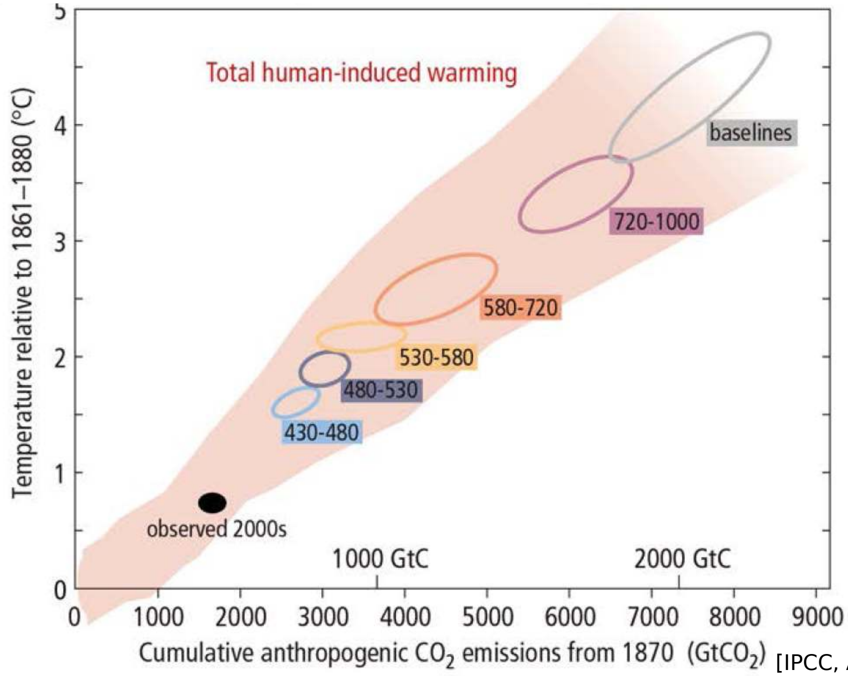
Carbone emission, CO_2 concentrations and global temperature: time constants

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
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.

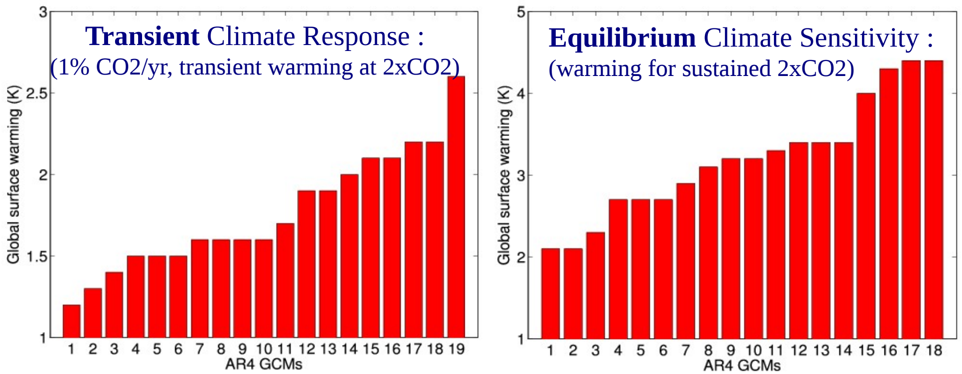


[IPCC, AR5]

Outlook

I. Numerical climate models
II. Simulating and attributing recent climate changes
III. Scenarios and future climate changes
IV. Climate sensitivity and climate feedbacks
V. Climate variability and past climate changes

Climate sensitivity estimates from CMIP3 GCMs (IPCC-AR4)



Climate sensitivity and TCR estimates depend on :

[IPCC, 2007]

- radiative forcing
- climate feedbacks
- ocean heat uptake (transient only)

How do these different components contribute to inter-model differences in climate sensitivity ?

Climate feedback

$$\boxed{\Delta R = \Delta Q + \lambda \Delta T_s}$$

flux at TOA change

radiative forcing

"feedback parameter"

Global average surface temperature change

When a new equilibrium is reached, ΔR=0

$$\Delta T_s^{\,e} = \frac{-\Delta Q_t}{\lambda}$$

$$\boxed{\lambda = \lambda_P + \lambda_w + \lambda_L + \lambda_c + \lambda_\alpha}$$

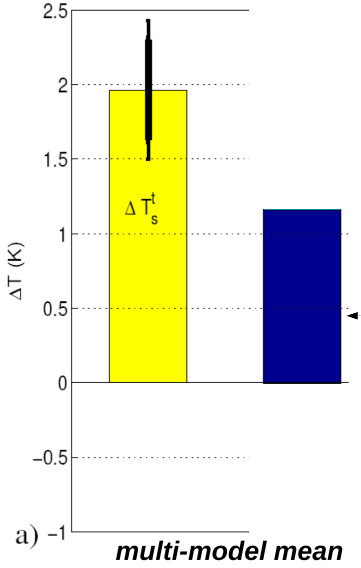
Planck, water vapor, lapse rate, clouds, surface albedo

$$\lambda = \frac{\partial R}{\partial T_s} = \sum_x \frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s}$$

λ can be diagnosed from model results with different technics

Transient temperature response to a CO_2 doubling

(CO_2 increase 1%/year, 70 years)

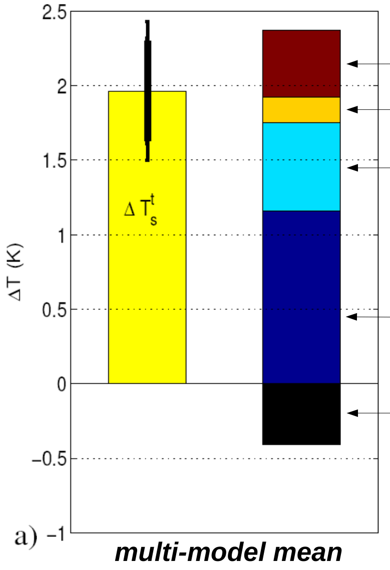


Direct response to the forcing
Planck response

(Dufresne & Bony, 2008)

Transient temperature response to a CO_2 doubling

(CO_2 increase 1%/year, 70 years)



Climate feedbacks: Indirect response to the forcing

clouds

snow and ice (surface albedo)

water vapor

Direct response to the forcing
Planck response

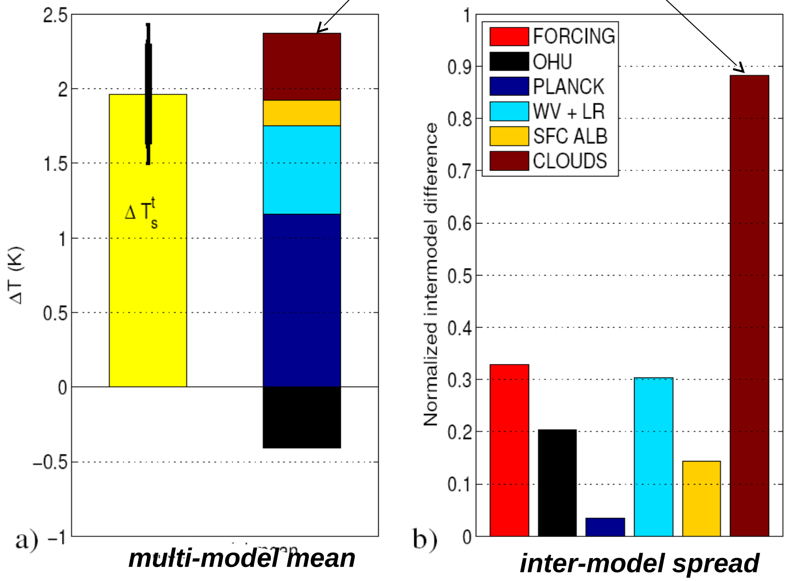
ocean heat uptake

(Dufresne & Bony, 2008)

Transient temperature response to a CO_2 doubling

(CO_2 increase 1%/year, 70 years)

Cloud feedback



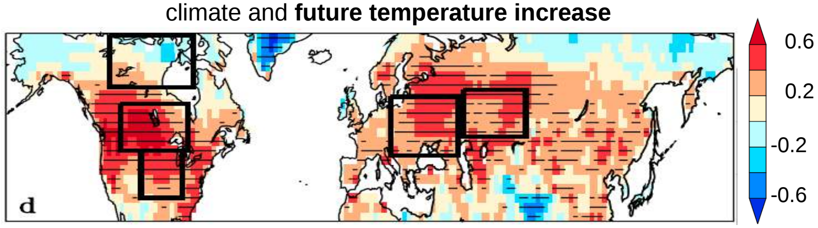
(Dufresne & Bony, 2008)

How model defaults influence model projections?

As a whole, there is **no simple relationship** between **model performances** with current conditions and **climate change projections simulated by models.**

However, some relation between model characterictics and simulated climate change under global warming exists for some variables/processes.

Correlation between **summer temperature bias** in current climate and **future temperature increase**



Warm bias is mainly due to a erroneous representation of evaporation and cloud cover over continents in models.

[Cheruy et al., 2014]

Outlook

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Internal variability and variations due to forcings

Climate variations have different origines:

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

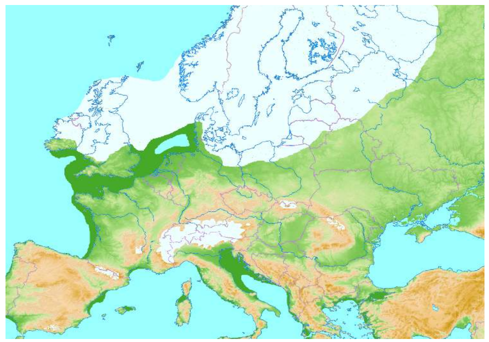
- The relative importance of these various termes depends on the spatial and time average considered, and on the amplitude of the forcings
- The differences between observations and models or between model results can include part or all of these terms, depending on the experimental setup

The discovery of past climate changes
Hypothesis of glacial periods (1840-1860)

Jean de Charpentier

Erratic rocks

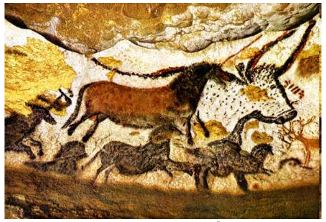
Louis Agassiz



The discovery of past climate changes

A period described by cave paintings

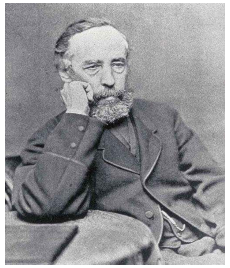
Cosquer



Lascaux

Chauvet

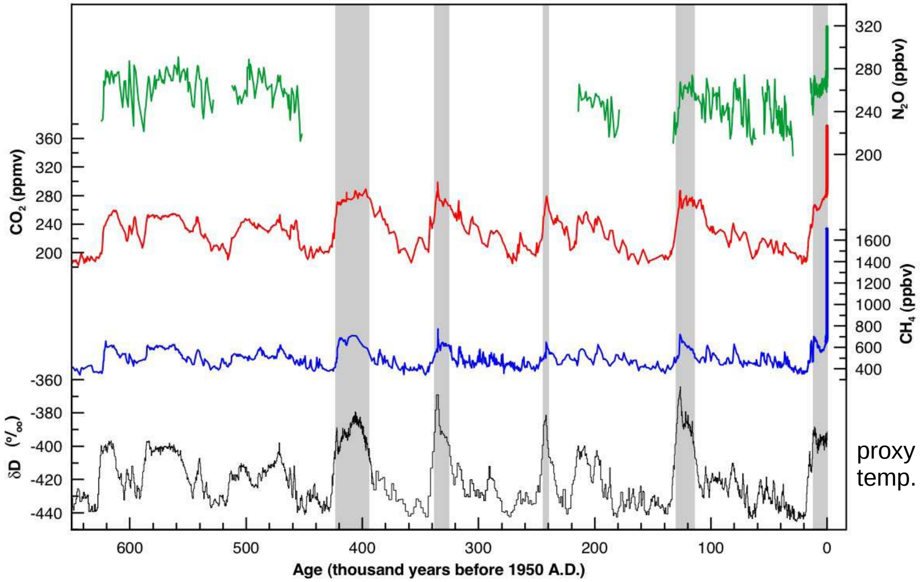
Origin of these variations : sun or CO_2 (1860-1900) ?



James Croll

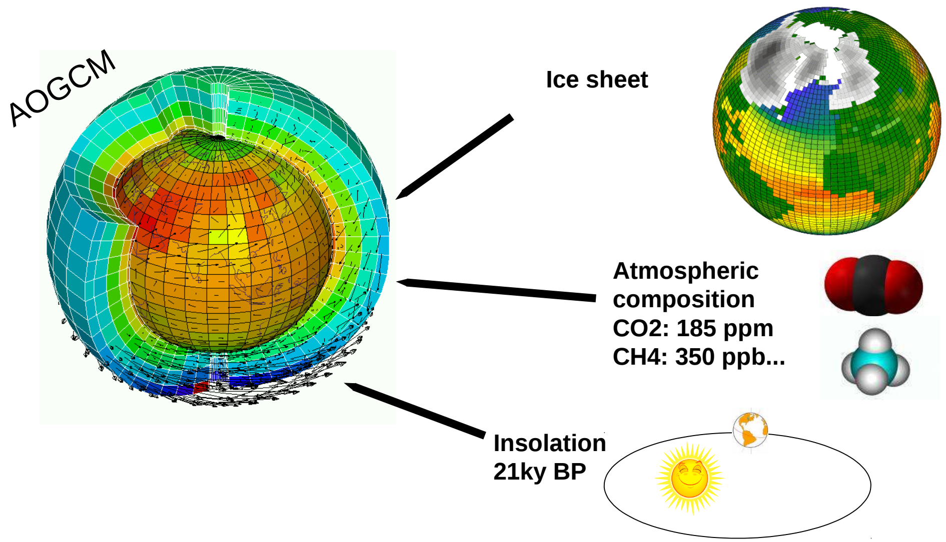
Svante Arrhenius

Paleoclimate changes



[IPCC, 2013]

Simulation of Last Glacial Maximum (LGM)

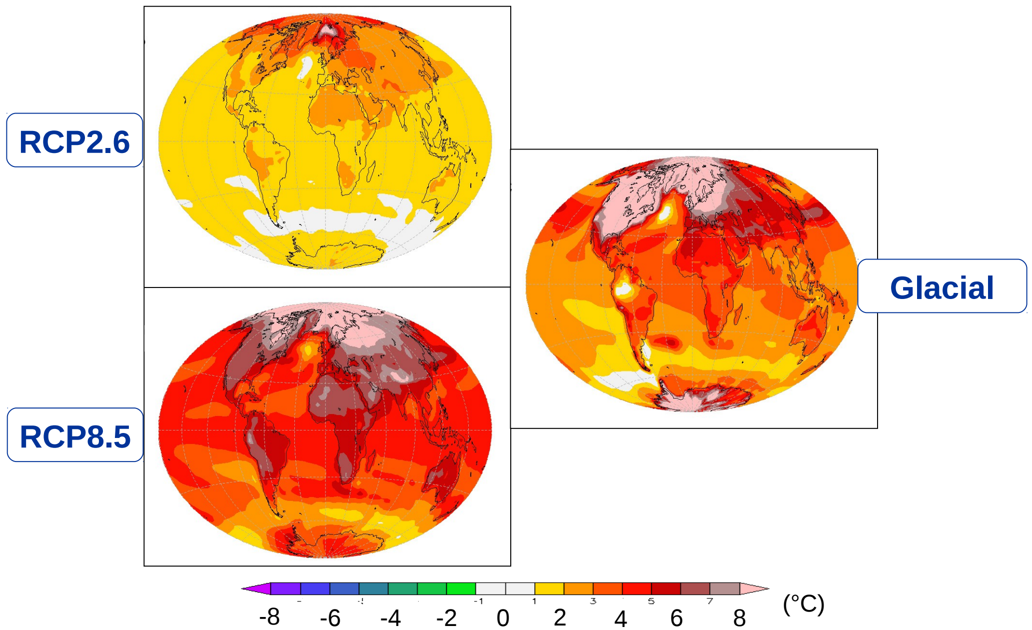


Greenhouse gas forcing ~ future climate
Other main forcings: ice sheet

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

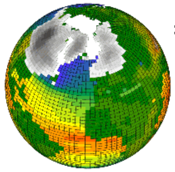
Change in surface temperature

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



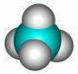
Land-sea contrasts and polar amplification in past and future climates

Last Glacial Maximum main forcings



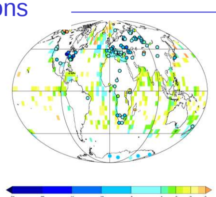
Ice-sheets

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



LGM climate reconstructions

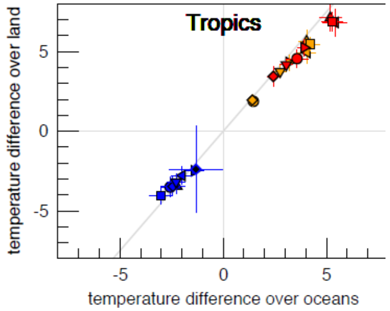
Land data
(pollen and plant macrofossils):
Bartlein et al, Clim Dynam 2011
Ocean data (multi proxy):
MARGO, NGS 2009
Ice-core data:
Masson-Delmotte et al pers. comm

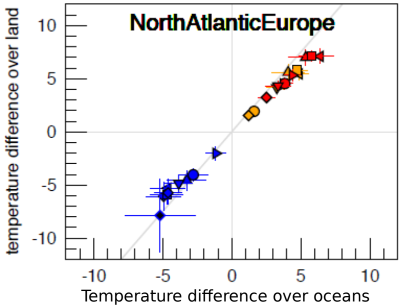


Relationships between LGM vs higher CO2 climates?
Are the large scale relationships stable? Can we evaluate them from paleodata ?

Example:
Land sea contrasts

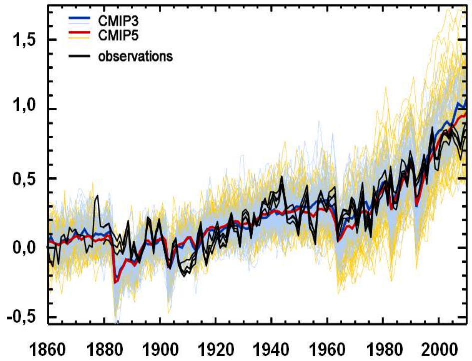
Note: all model averages calculated from grid points where LGM data is available





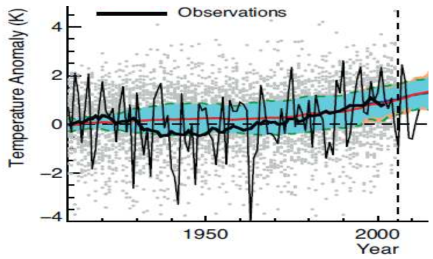
Surface temperature evolution: observation and models

Annual global mean

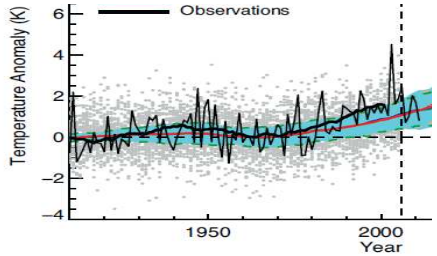


[IPCC, 2013]

Winter mean over France

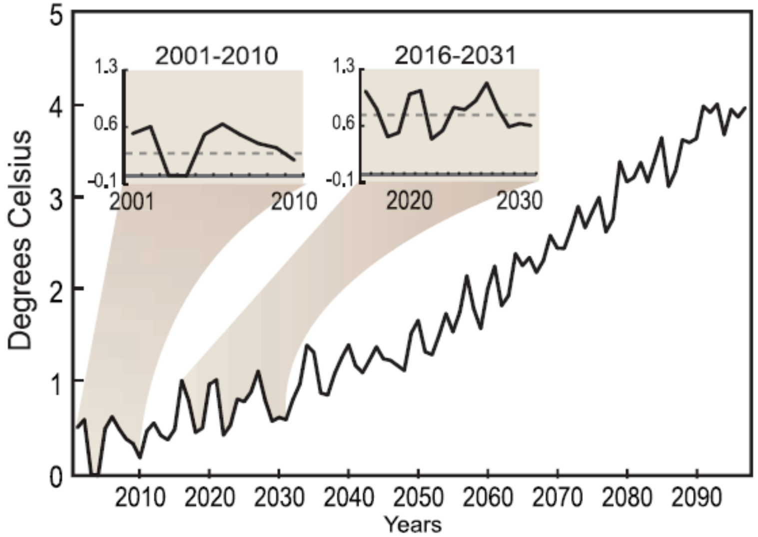


Summer mean over France



[Terray et Boé, 2013]

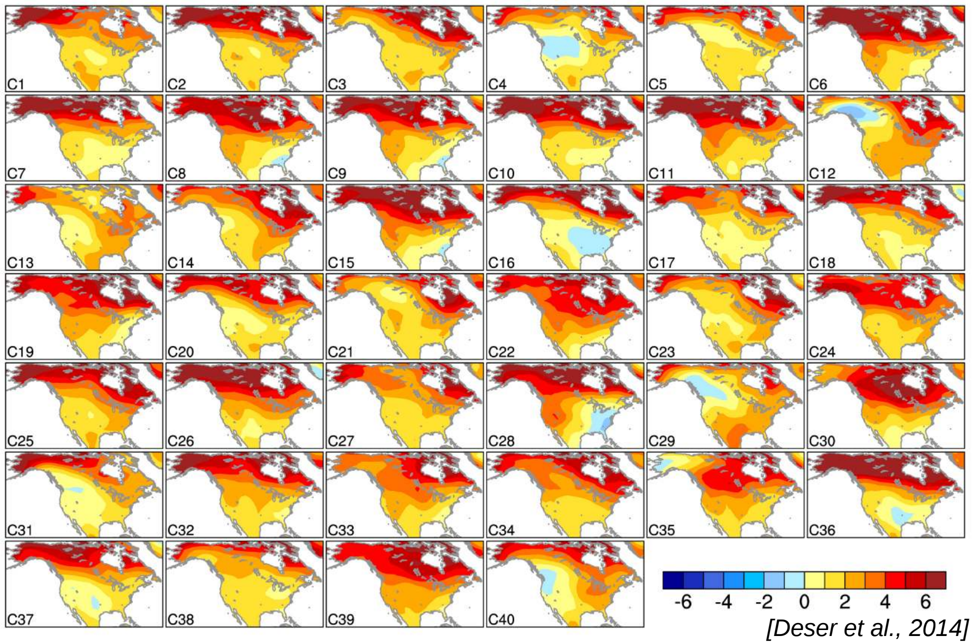
Climate change and climate variability



Easterling and Wehner, 2009

Climate change and climate variability

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



[Deser et al., 2014]