IPSL Climate Modelling Centre

Modélisation du climat et projections du climat futur

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Outlook

I. Short history of climate science and climate modeling

II. Climate and climate change simulations

III. Climate change and climate variaility

IV. Conclusions

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]

Emergence of the physics of climate

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Joseph Fourrier

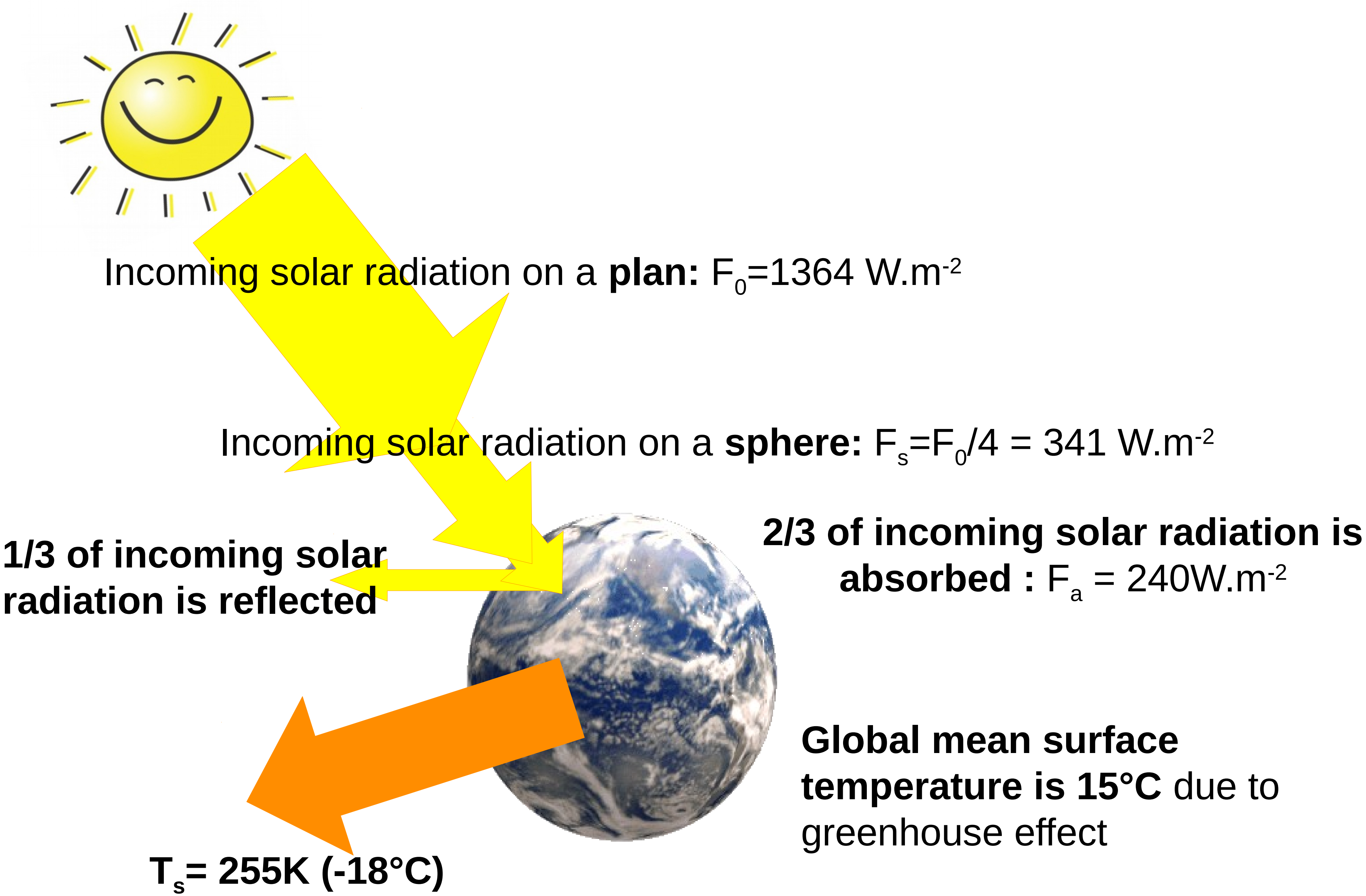
(1768-1830)

➢ 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.* »

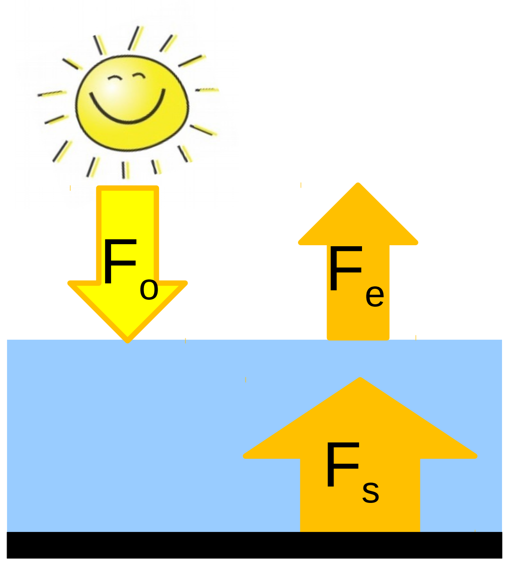
➢ He ***envisages that climate may change***: « *The establishment and progress of human society, and the action of natural powers, may, in extensive regions, produce remarkable changes in the state of the surface, the distribution of waters, and the great movements of the air. Such effects, in the course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

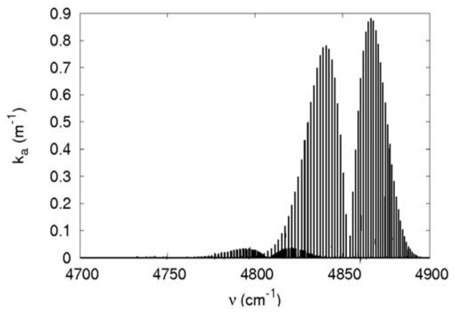
[Dufresne, 2006]

Equilibrium temperature of a planet



What radiation heat transfer theory tell us





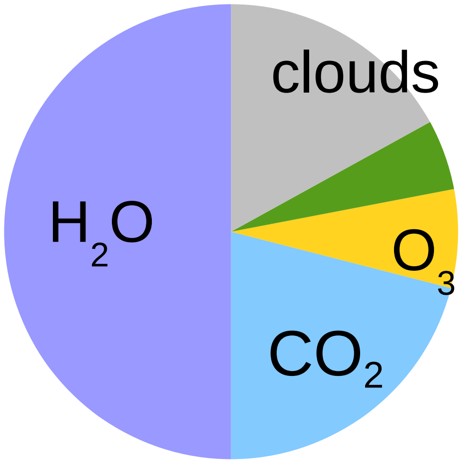
Gas radiative properties

Atmospheric characteristics

→ Computation of the radiative fluxes and the greenhouse effect

Current greenhouse effect:

	(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



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

From radiative transfer computation to climate modelling

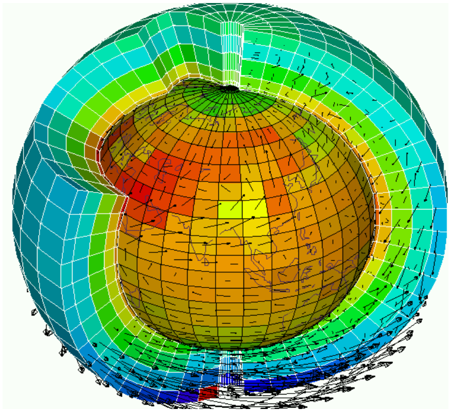
For a doubling of the CO_2 concentration:

- 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:

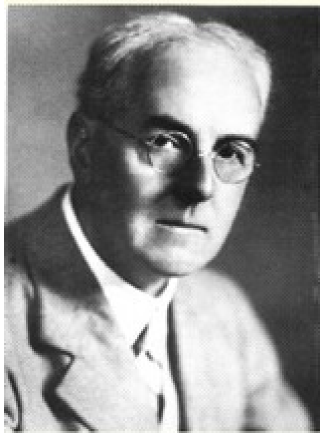
- Snow and sea ice reflect solar radiation; if they decrease, more solar energy will be absorbed ⇒ positive feedback
- Water vapour is the main greenhouse gas; if it increases, the greenhouse effect will be enhanced ⇒ positive feedback
- Clouds reflect solar radiation and contribute to the greenhouse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

Need of 3D numerical climate models



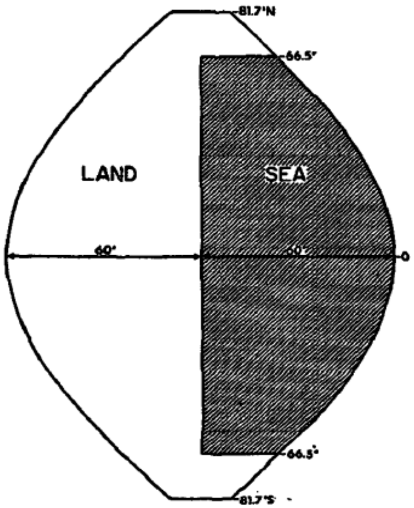
Numerical climate models
(numerical weather simulators)

Wilhelm Bjerknes
(1862–1951)

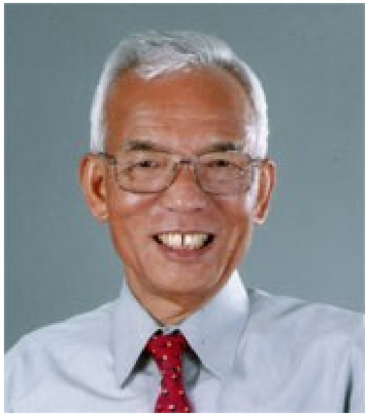


L. F. Richardson
(1881–1953)

J. von Neumann
(1903–1957)

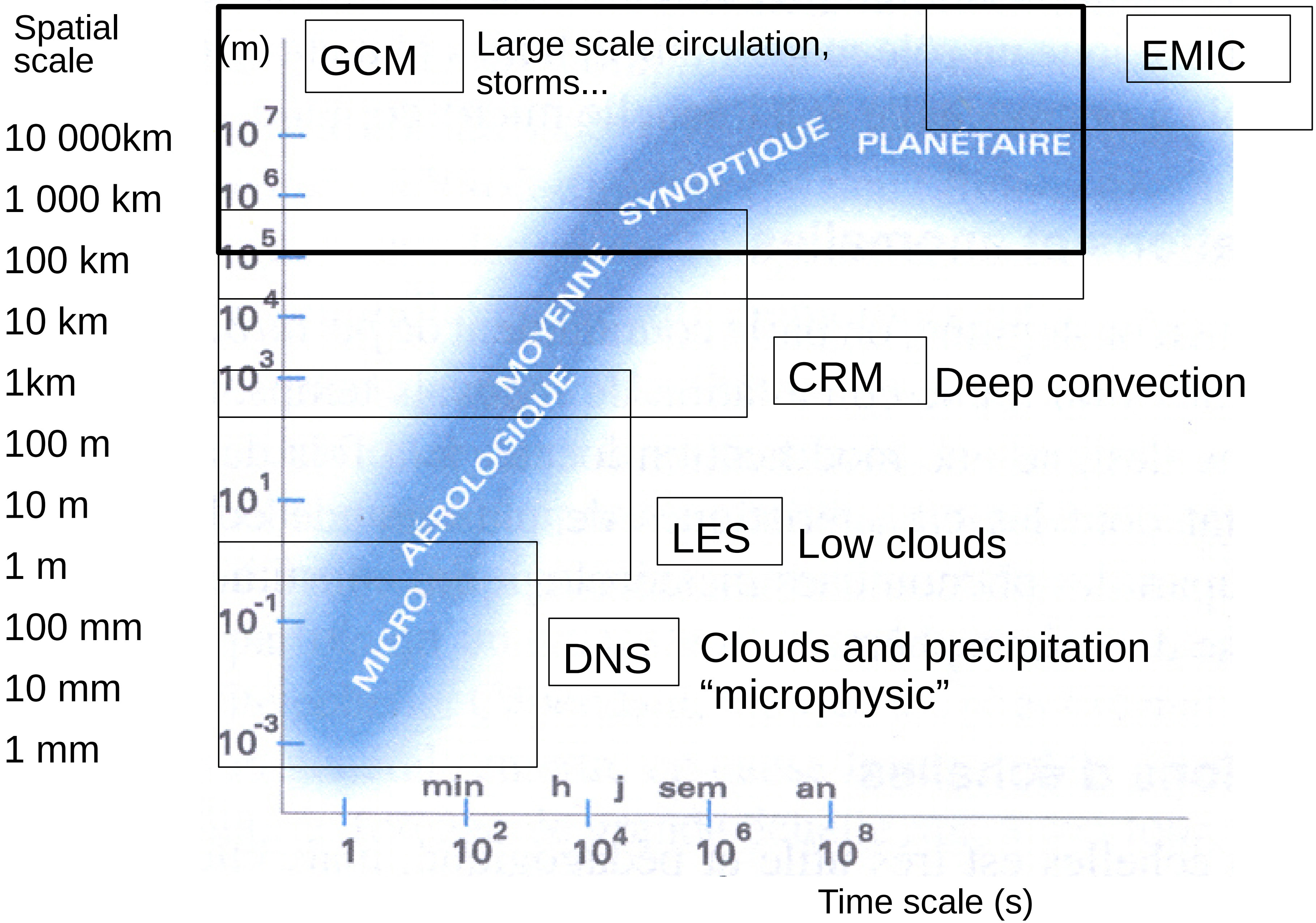


Jule Charney
(1917-1981)

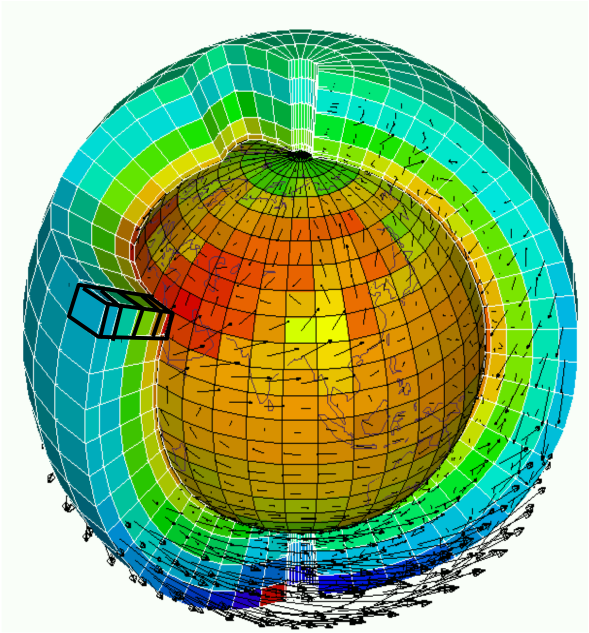


Syukuro Manabe
(1931-)

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)

  $Dq/Dt = S_q$

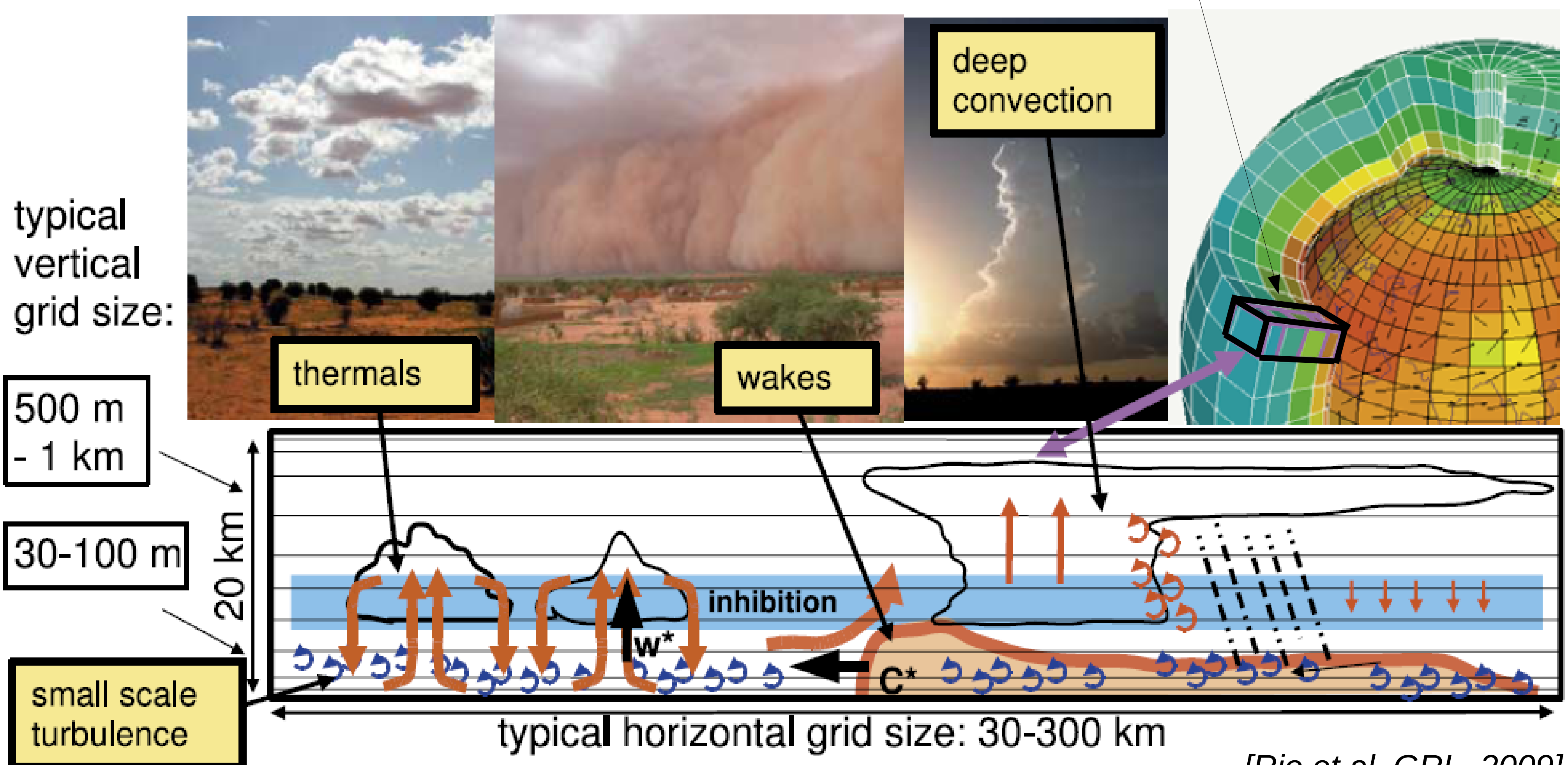
In red, source terms : other than fluid mechanics and unresolved scales

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

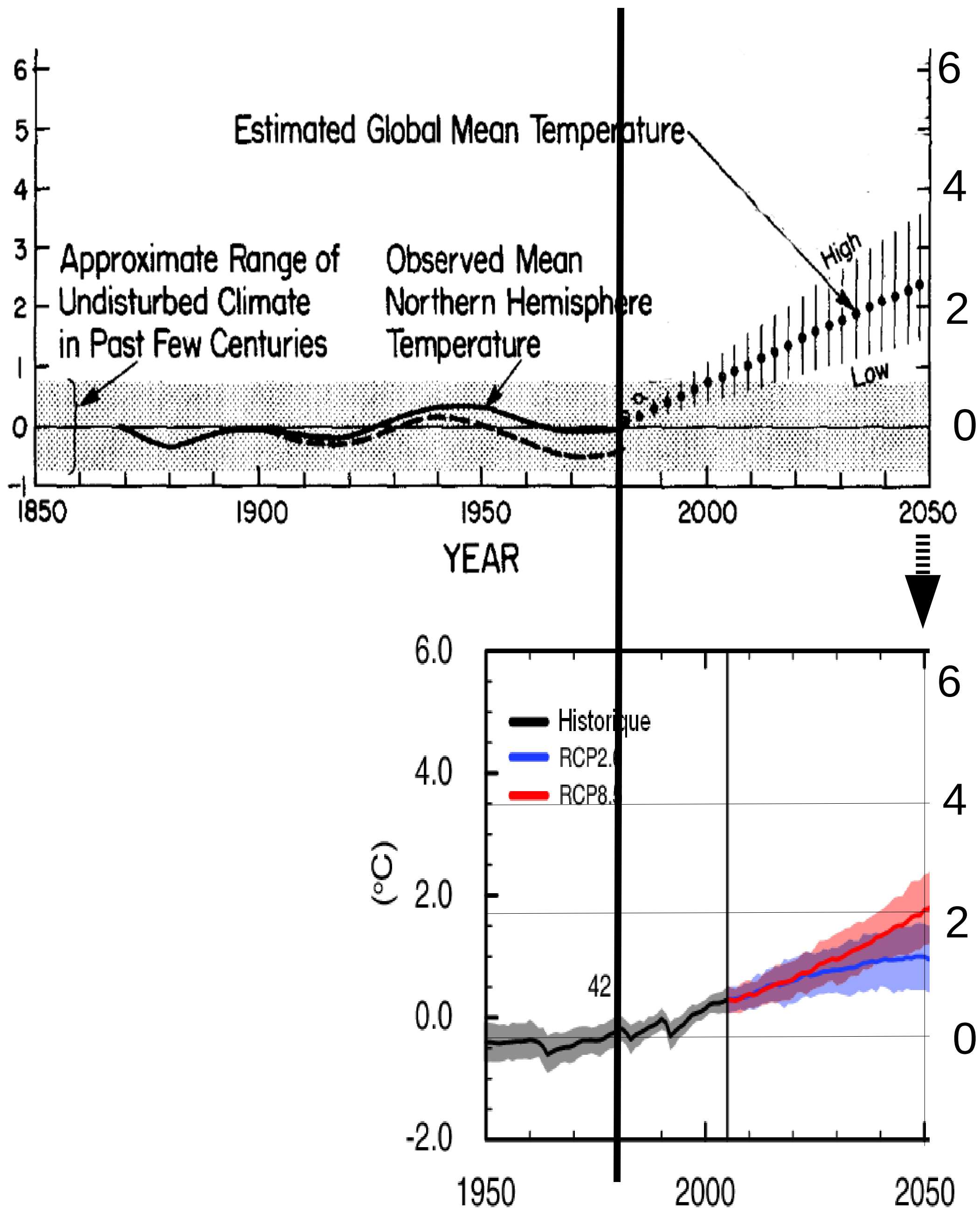
A typical vertical atmospheric column



[Rio et al, GRL, 2009]

Typical time step : a few minutes to half an hour

Premières projections climatiques
alors que la température a peu augmenté



[Kellogg 1977]

[GIEC 2013]

Premières projections climatiques
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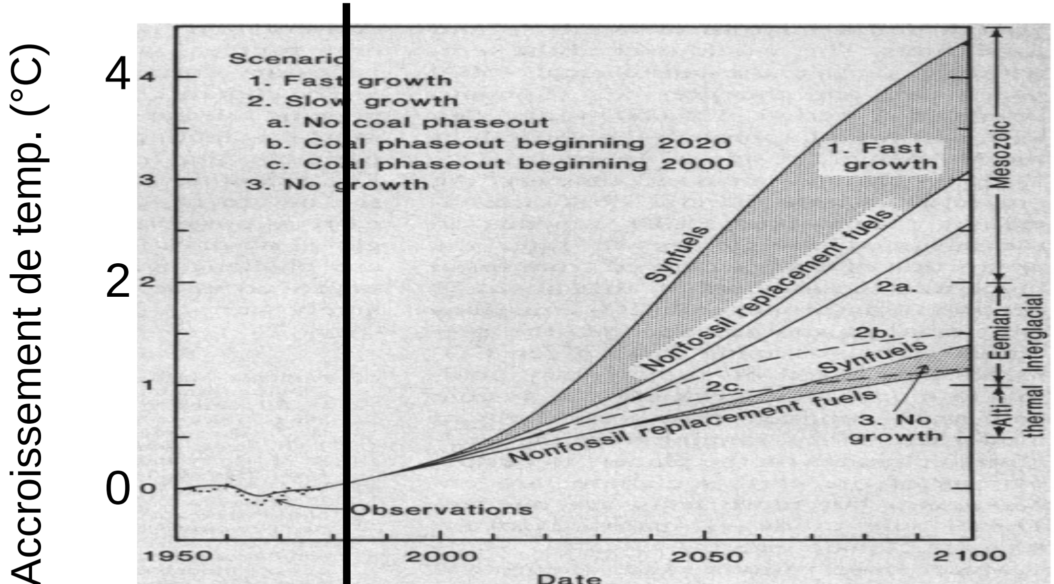
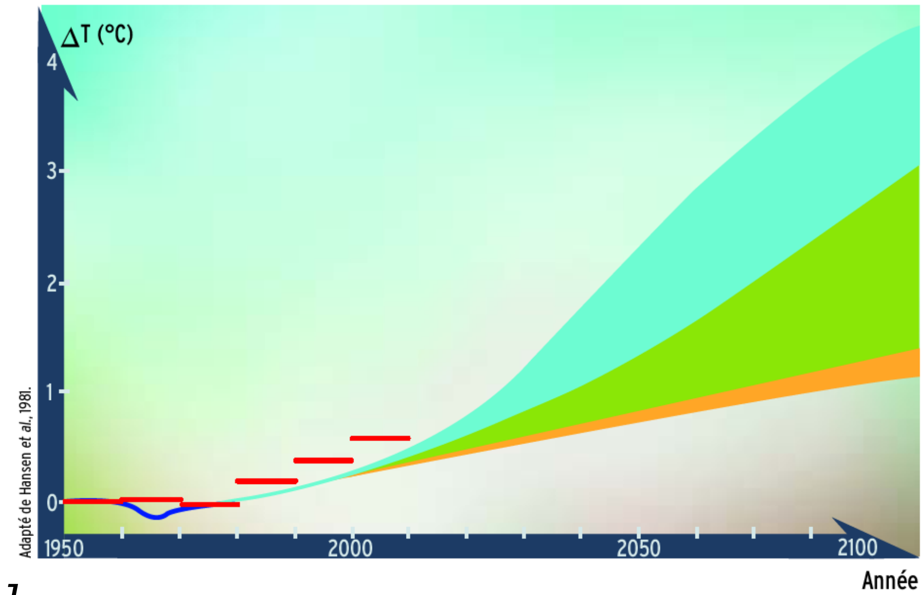
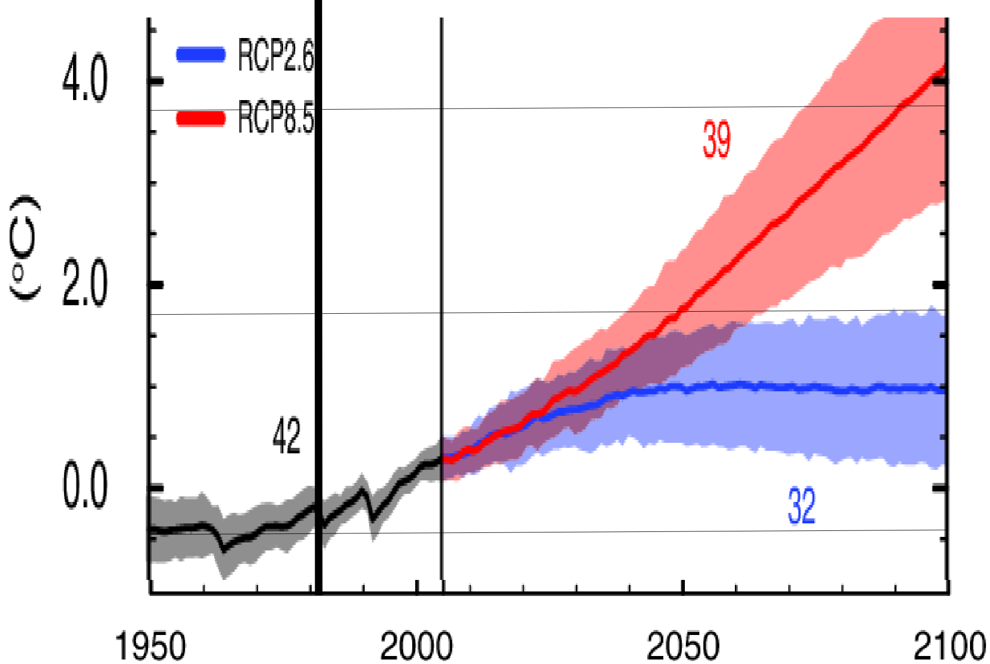




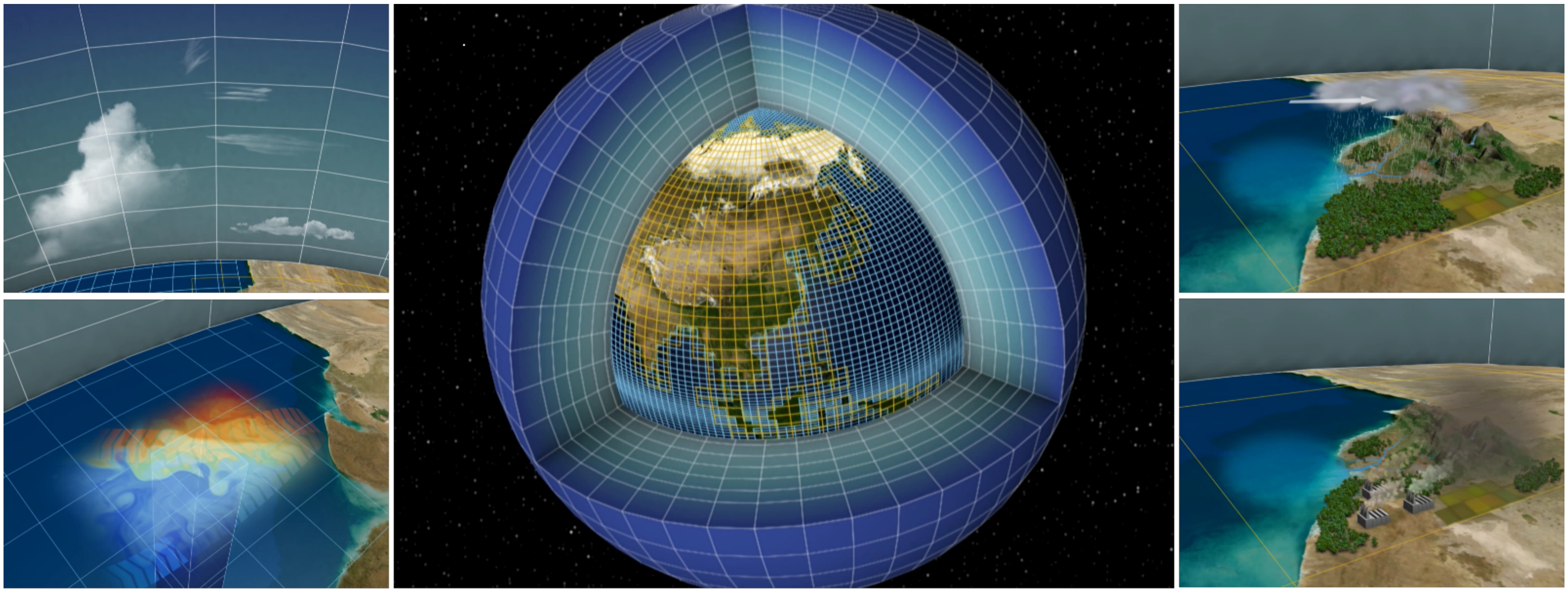
[Hansen et al. 1981]

Observations (postérieures)
Moyennes sur 10 ans



[GIEC 2013]

Modèle de climat
(Modèle de circulation générale)



Images issues d'un film présentant la modélisation du climat. Copyright CEA

- Une représentation 3D de l'atmosphère l'océan glaces de mer et surfaces continentales (couplages de différents modèles)
- Une représentation du couplage avec les cycles biogéochimiques dans l'atmosphère l'océan et le continent

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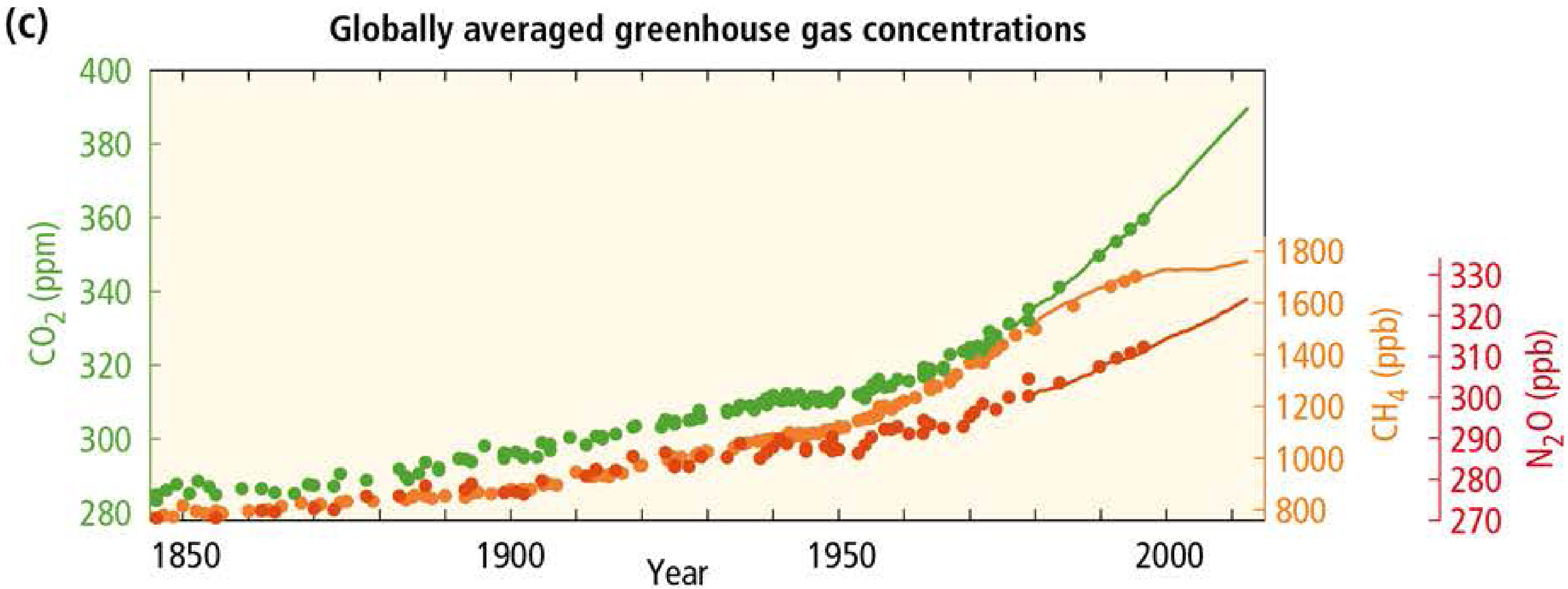
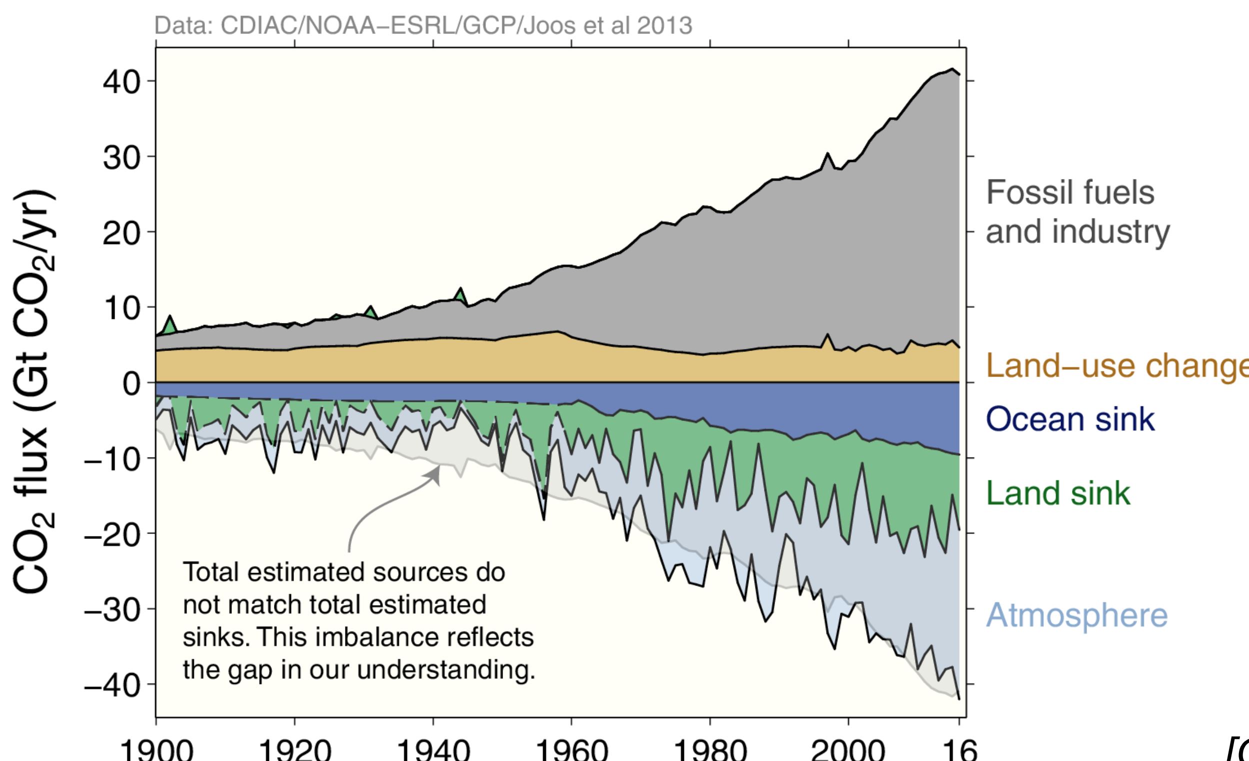
Rôle des activités humaines



[GIEC 2014]



[Global Carbon Project]

Emissions moyennes de CO_2 pour 2003-2012

1 GtC = 3.67 $GtCO_2$

8,6 ± 0,4 GtC y^{-1}

+

0,8 ± 0,5 GtC y^{-1}

4,3 ± 0,1 GtC y^{-1}
45%

2,6 ± 0,5 GtC y^{-1}
27%

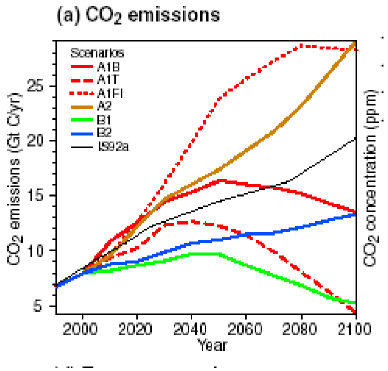
27%
2,6 ± 0,8 PgC y^{-1}

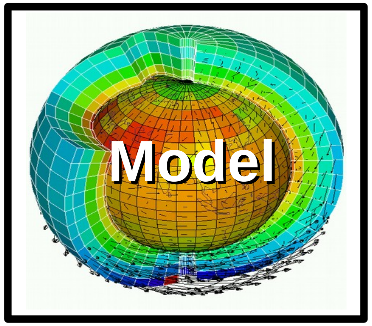
http://www.globalcarbonproject.org/ (Global Carbon Project, 2011)

Climate simulations

Initial conditions
Temperature
water vapour
salinity
all over the globe

Boundary conditions (forcings)
Ex: insolation
Greenhouse gases



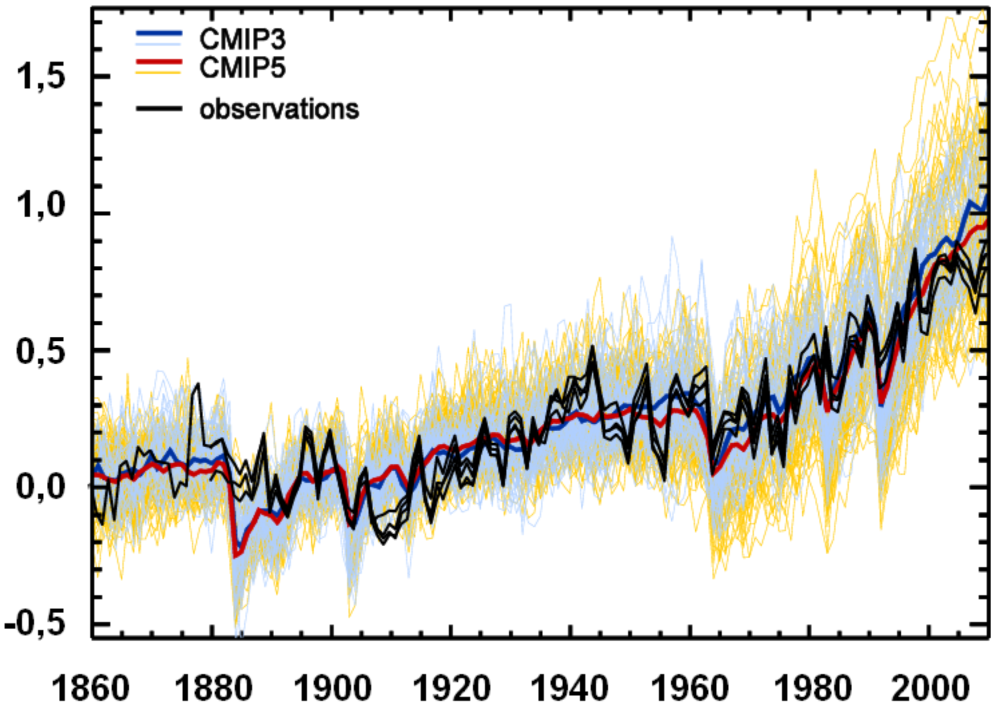


Results
Temperature
water vapour
salinity

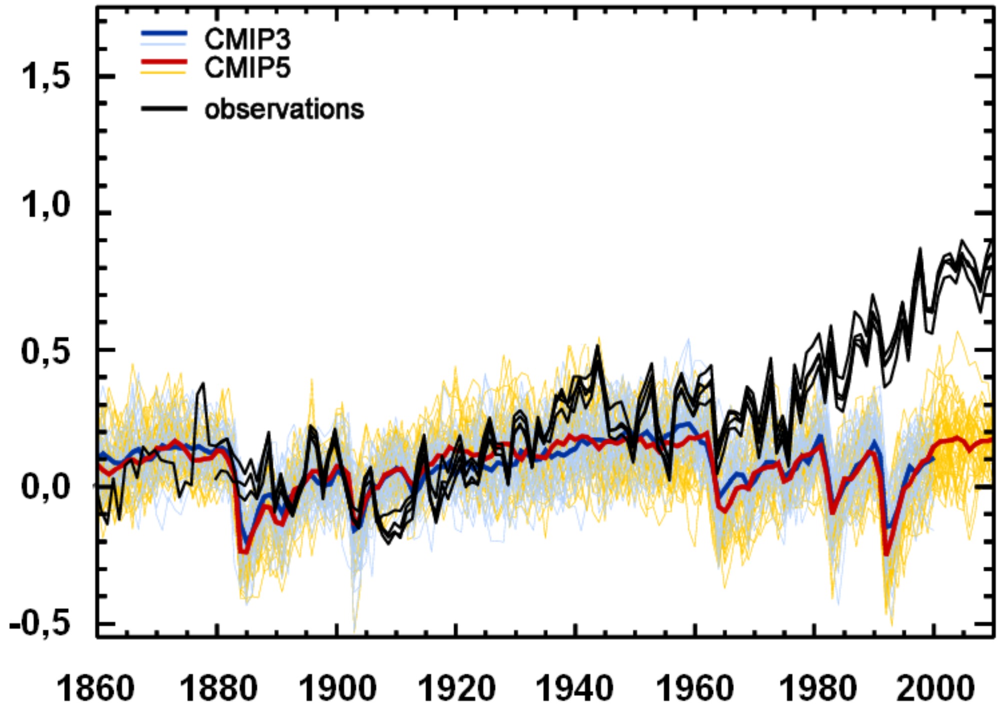
Statistical analysis

Recent Earth surface temperature trend

Simulations with natural and anthropological forcings



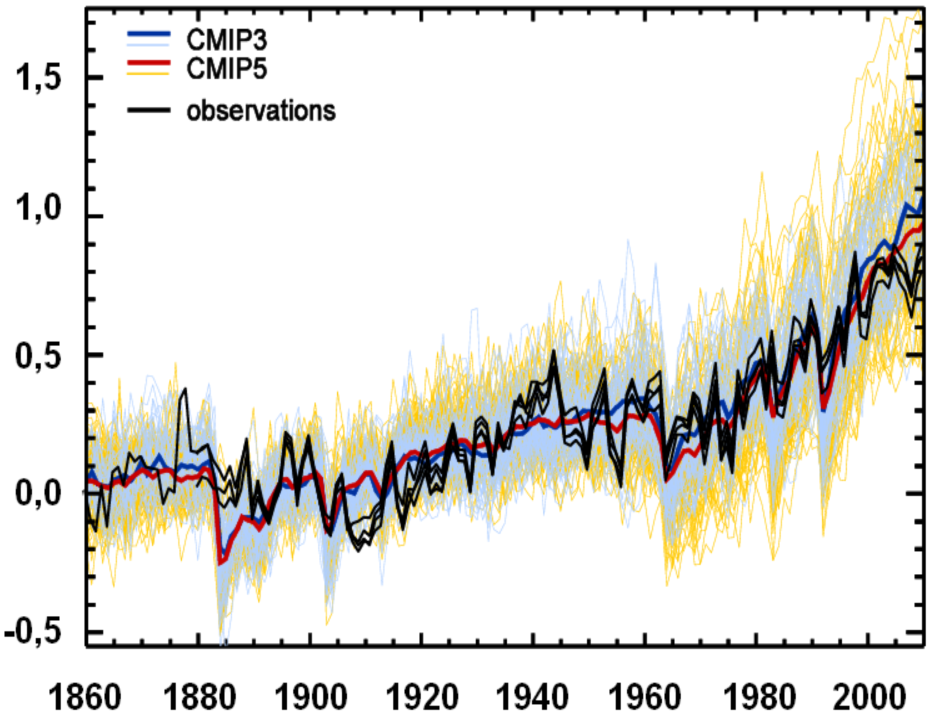
Simulations with natural forcings only



[IPCC, 2013]

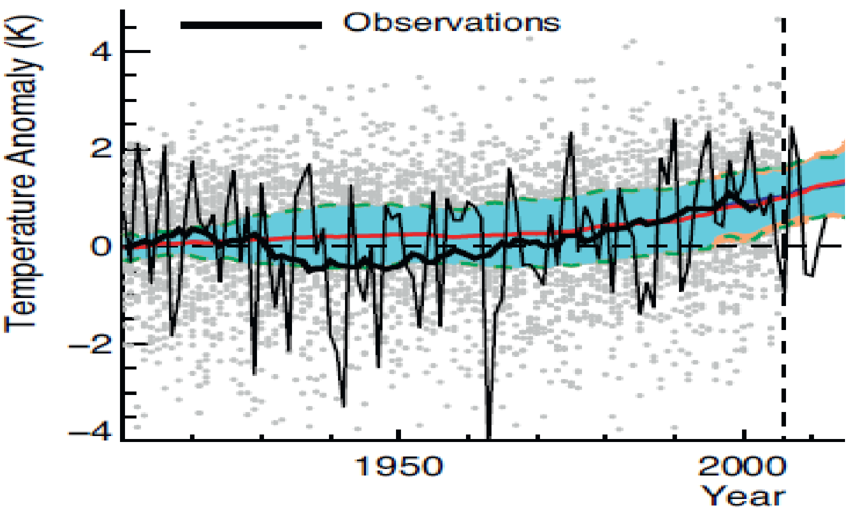
Surface temperature evolution: observation and models

Annual global mean

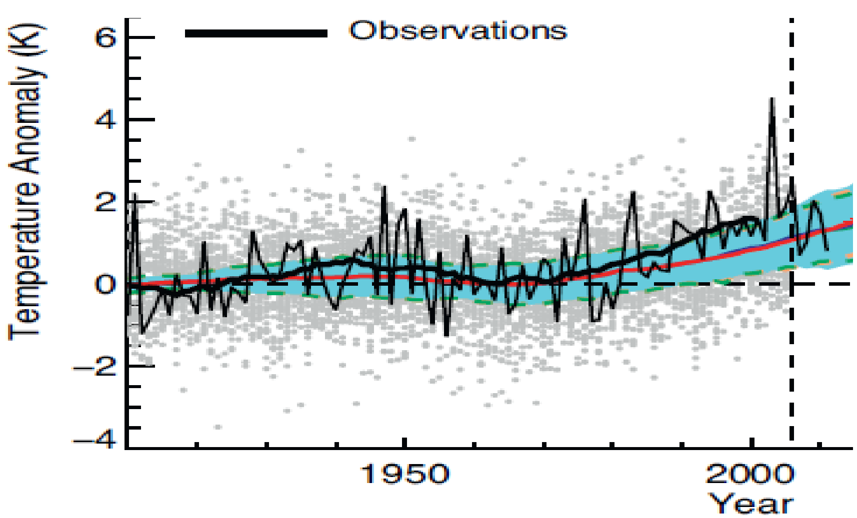


[IPCC, 2013]

Winter mean over France

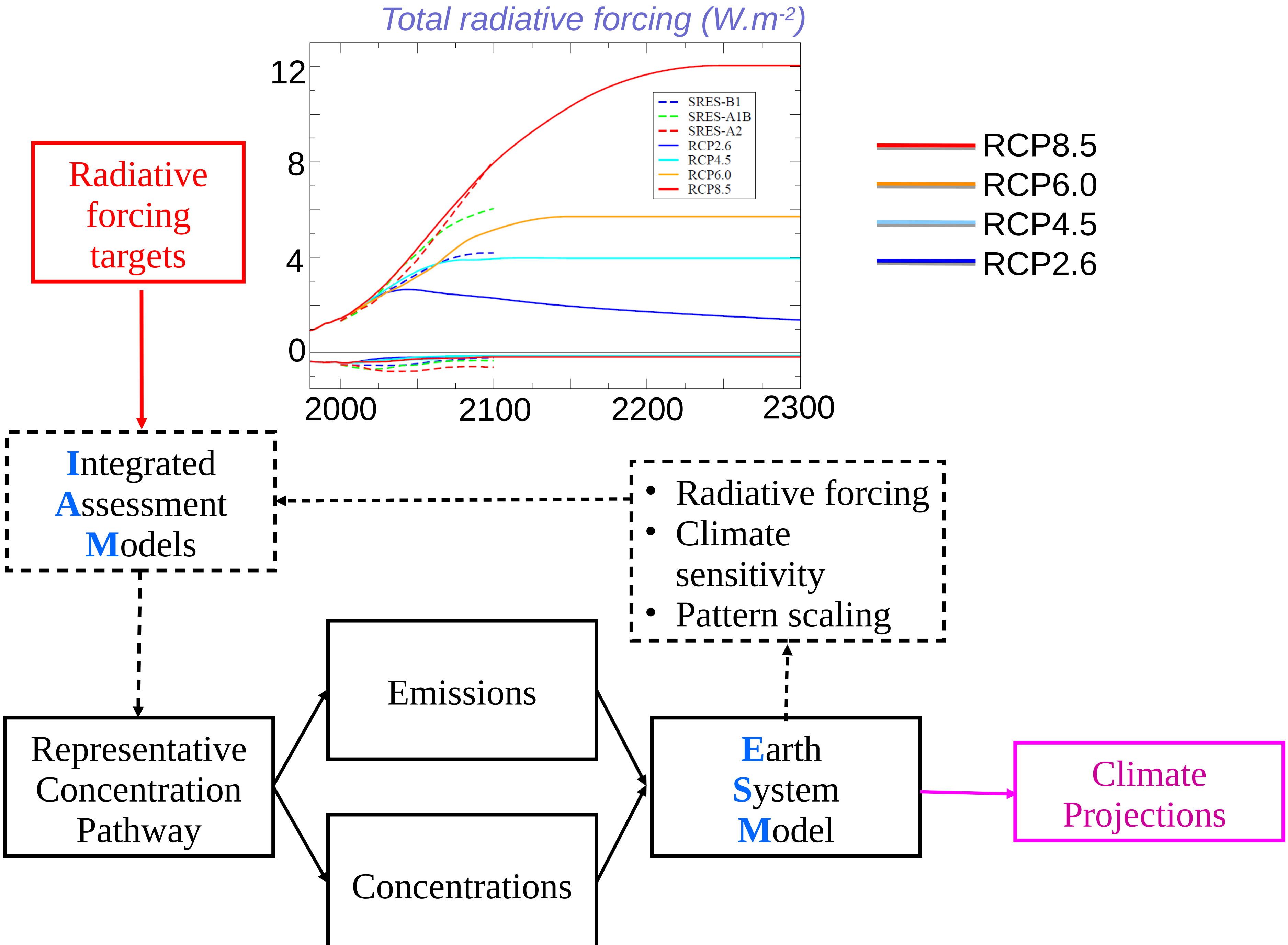


Summer mean over France



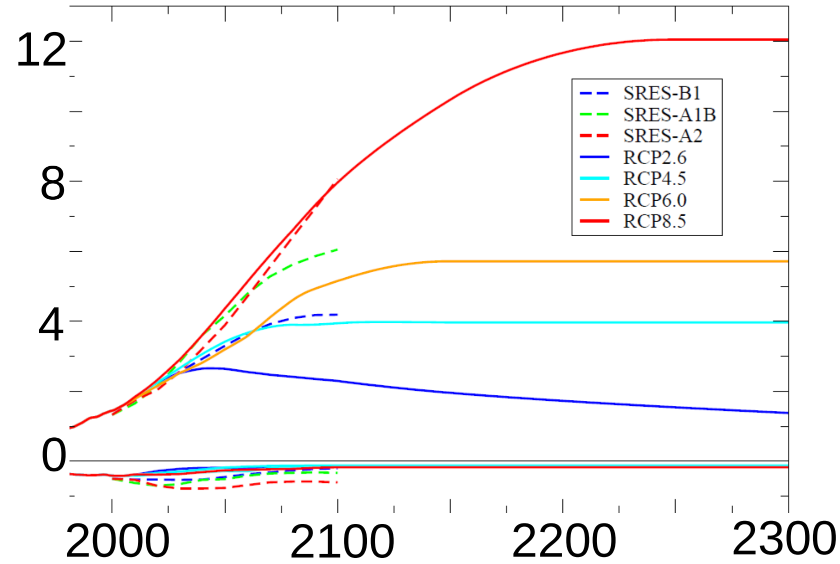
[Terray et Boé, 2013]

Scenario for future climate change projections

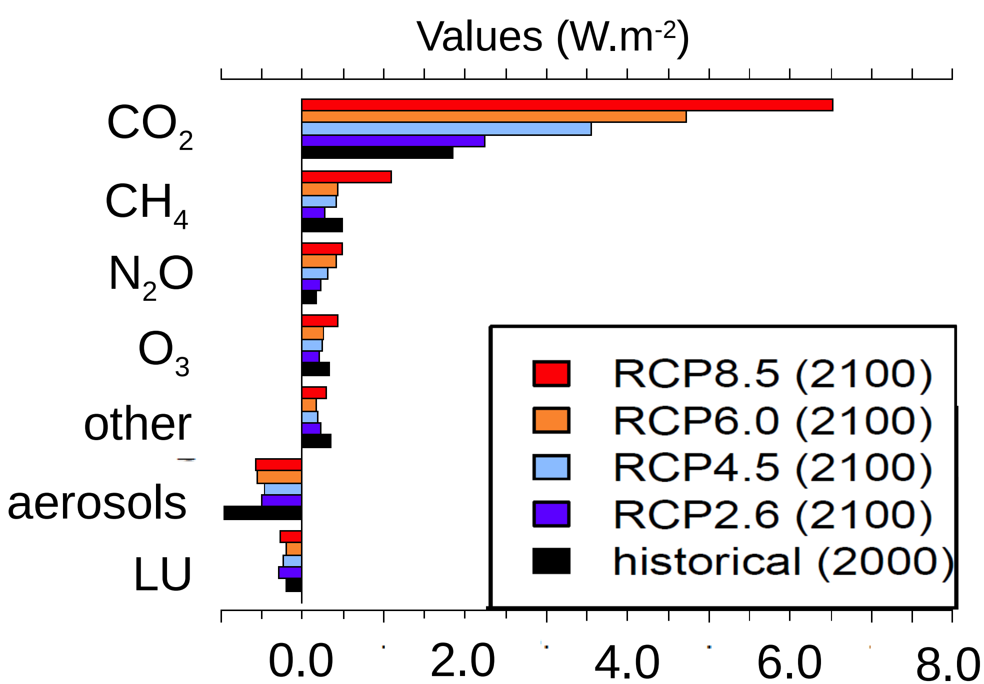


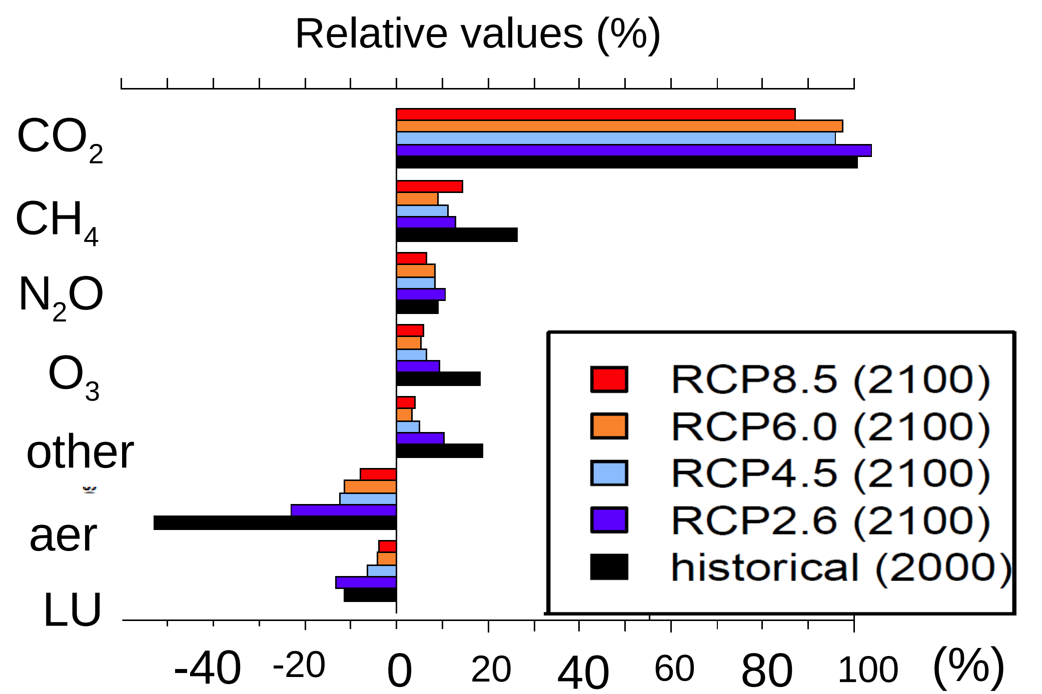
Radiative forcing of future scenarios

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



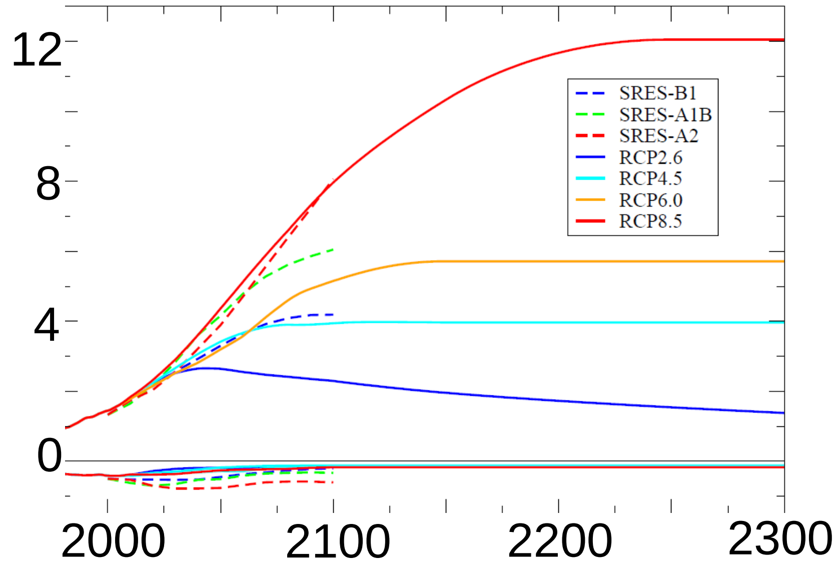
*Contribution of individual forcings to total forcing relative to **1850***



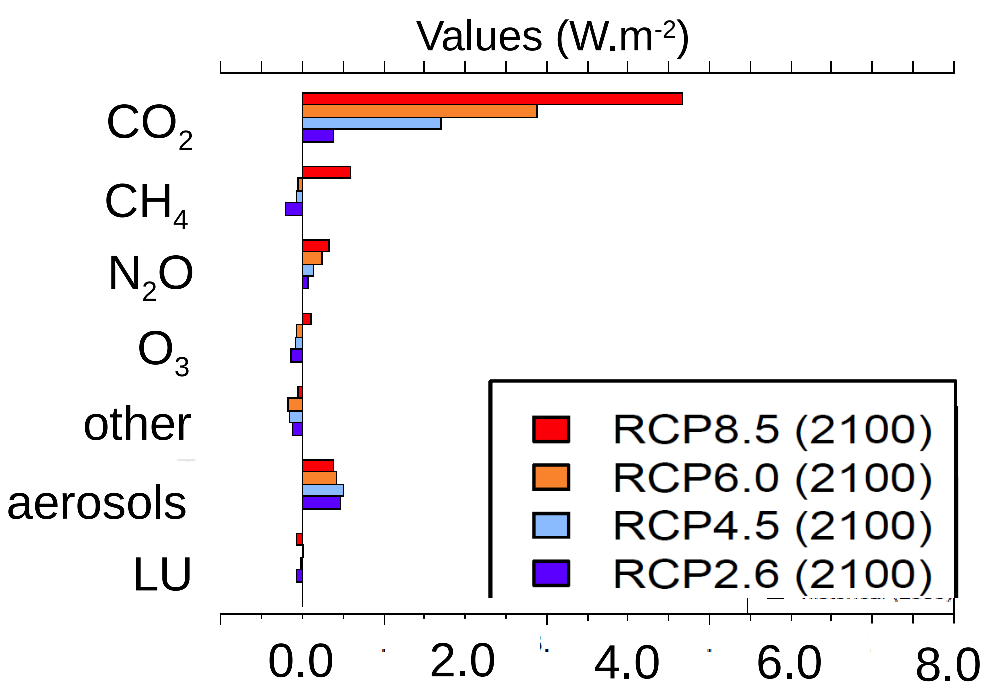


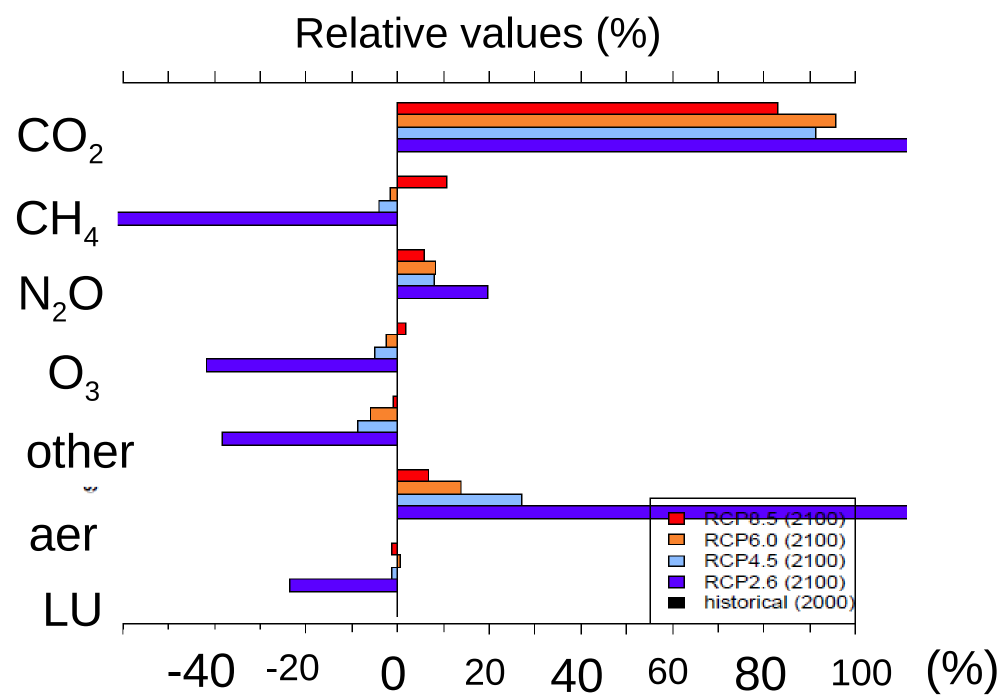
Radiative forcing of future scenarios

Total radiative forcing (W.m-2)

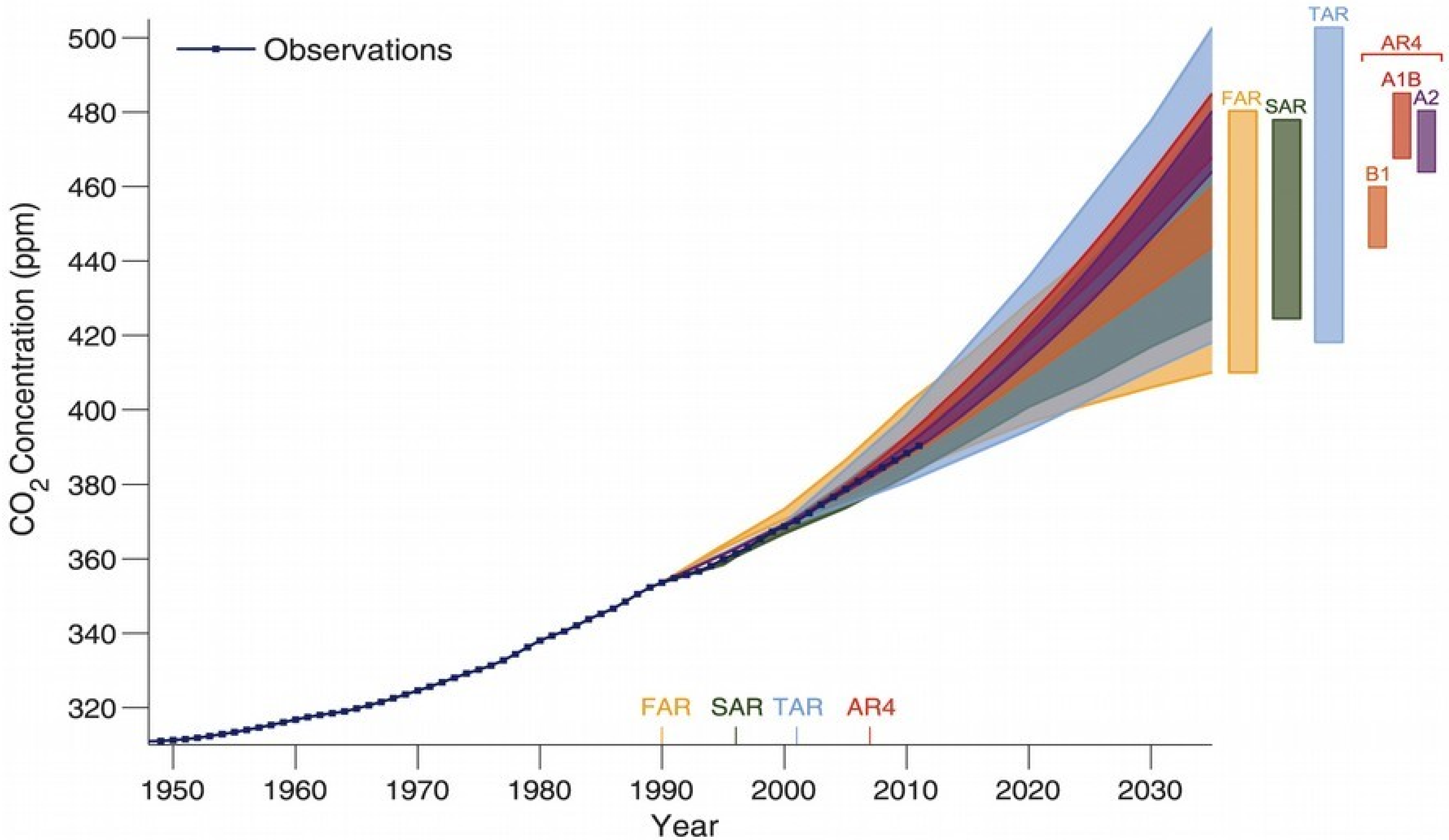


*Contribution of individual forcings to total forcing relative to **2000***





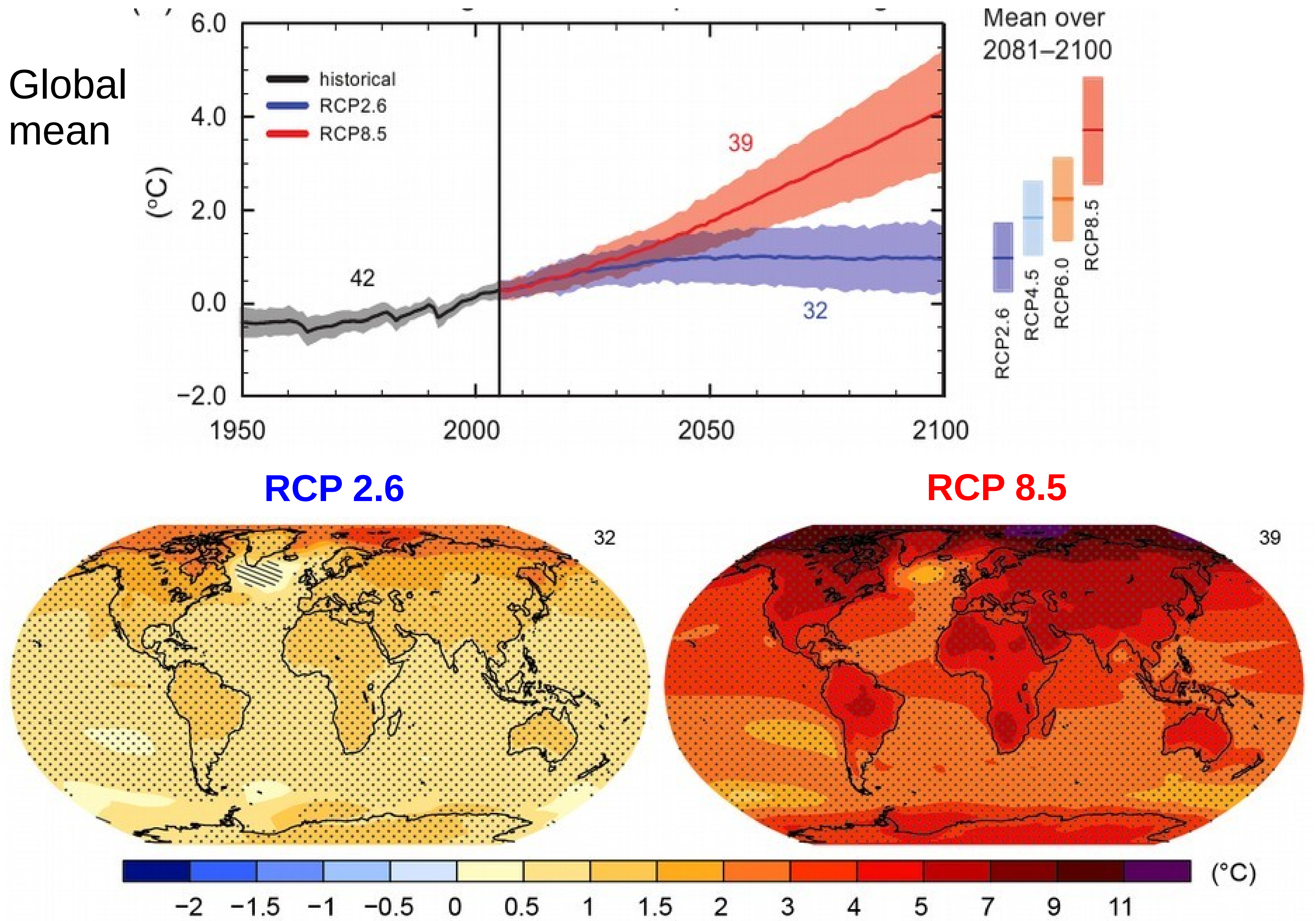
Radiative forcing of future scenarios



[IPCC, 2013]

Surface temperature change

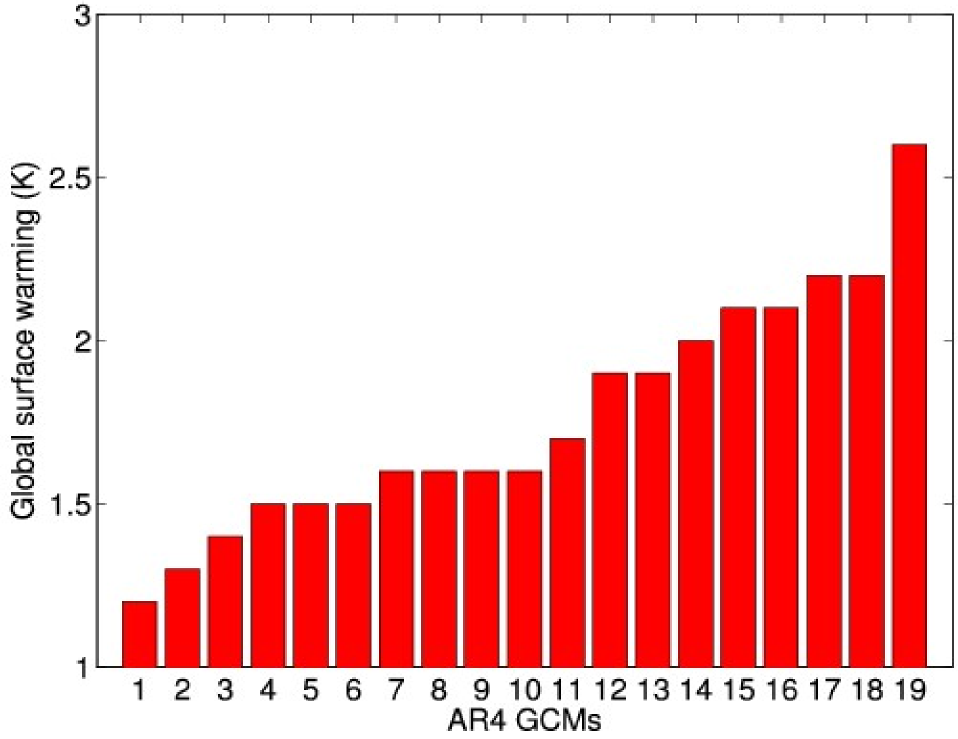
Global mean



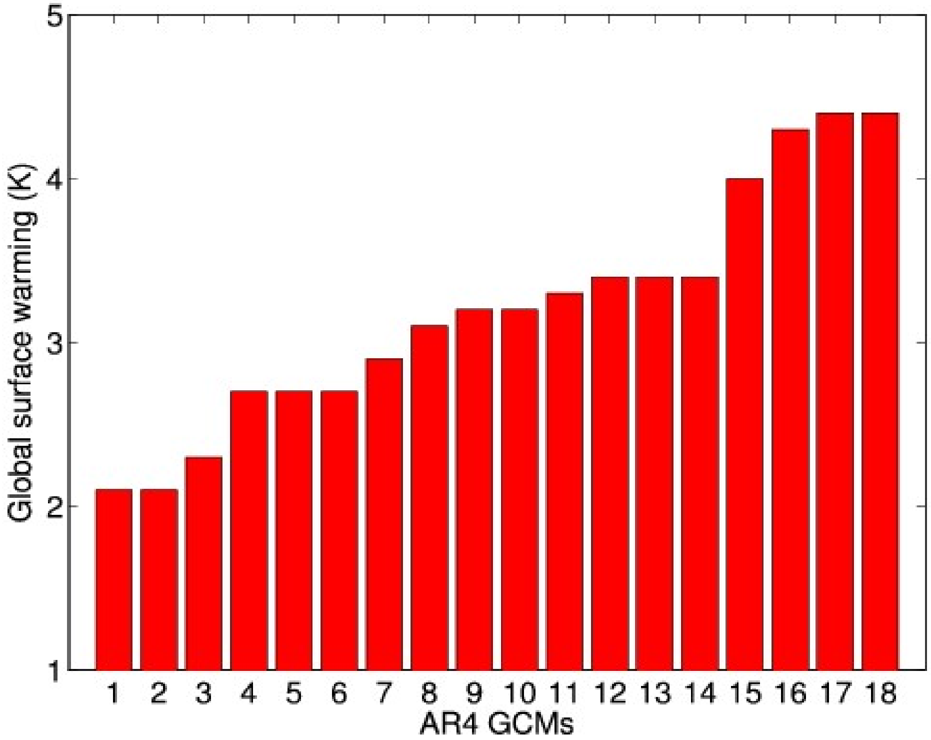
[IPCC 2013]

Why climate sensitivity estimate differs among models?

Transient Climate Response :
(1% CO2/yr, transient warming at 2xCO2)



Equilibrium Climate Sensitivity :
(warming for sustained 2xCO2)



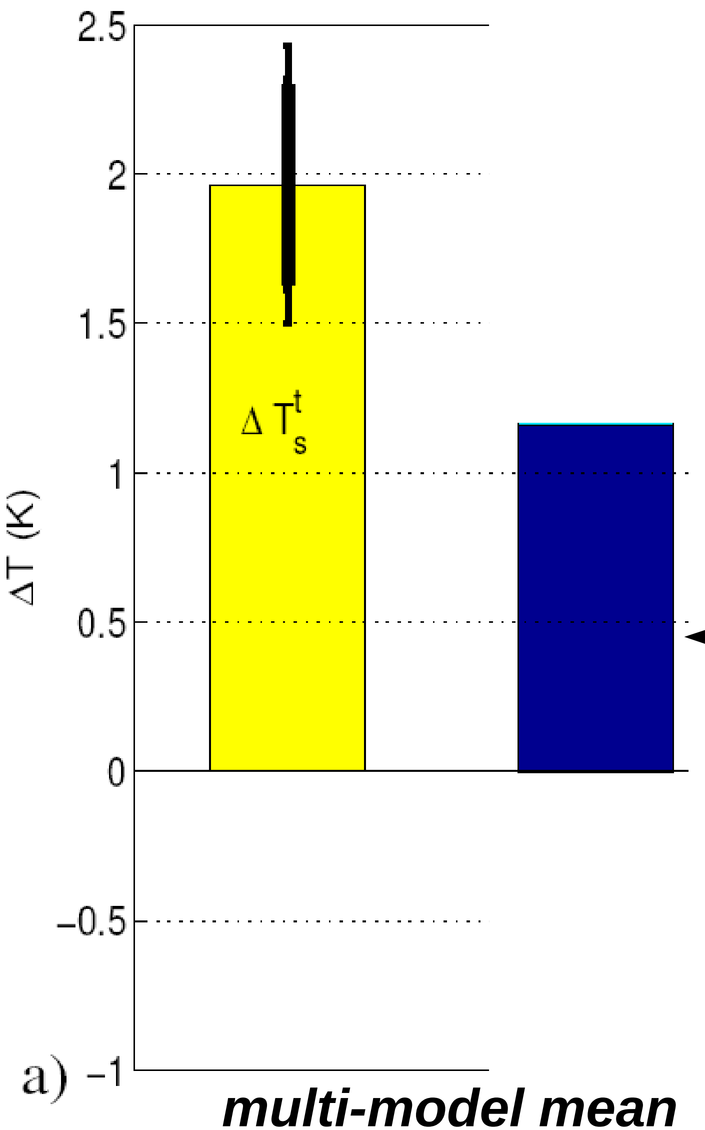
Climate sensitivity and TCR estimates depend on :

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

[IPCC, 2007]

Transient temperature response to a CO_2 doubling

(CO_2 increase 1%/year, 70 years)

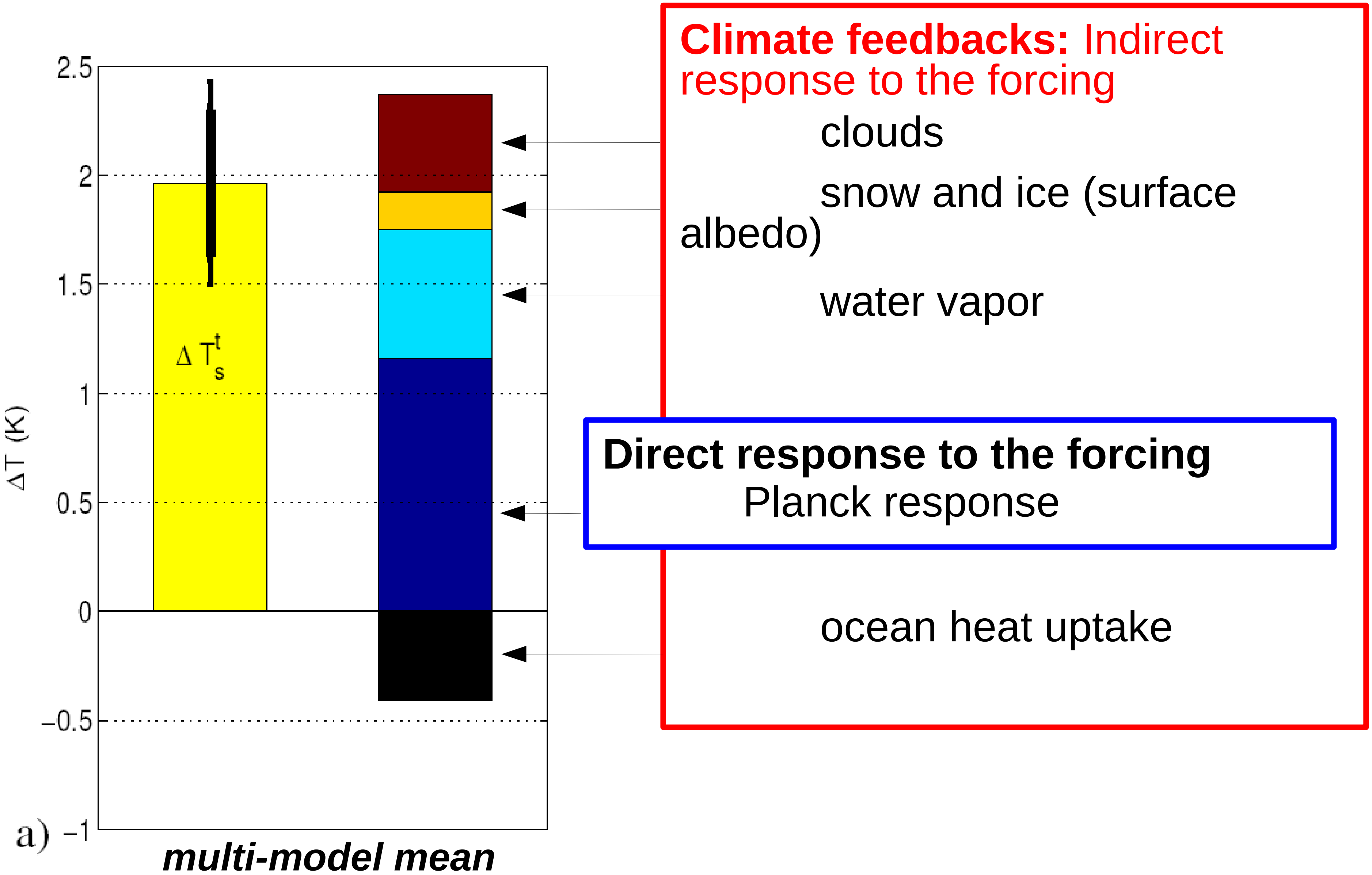


Direct response to the forcing
Planck response

(Dufresne & Bony, 2008)

Transient temperature response to a CO_2 doubling

(CO_2 increase 1%/year, 70 years)



(Dufresne & Bony, 2008)

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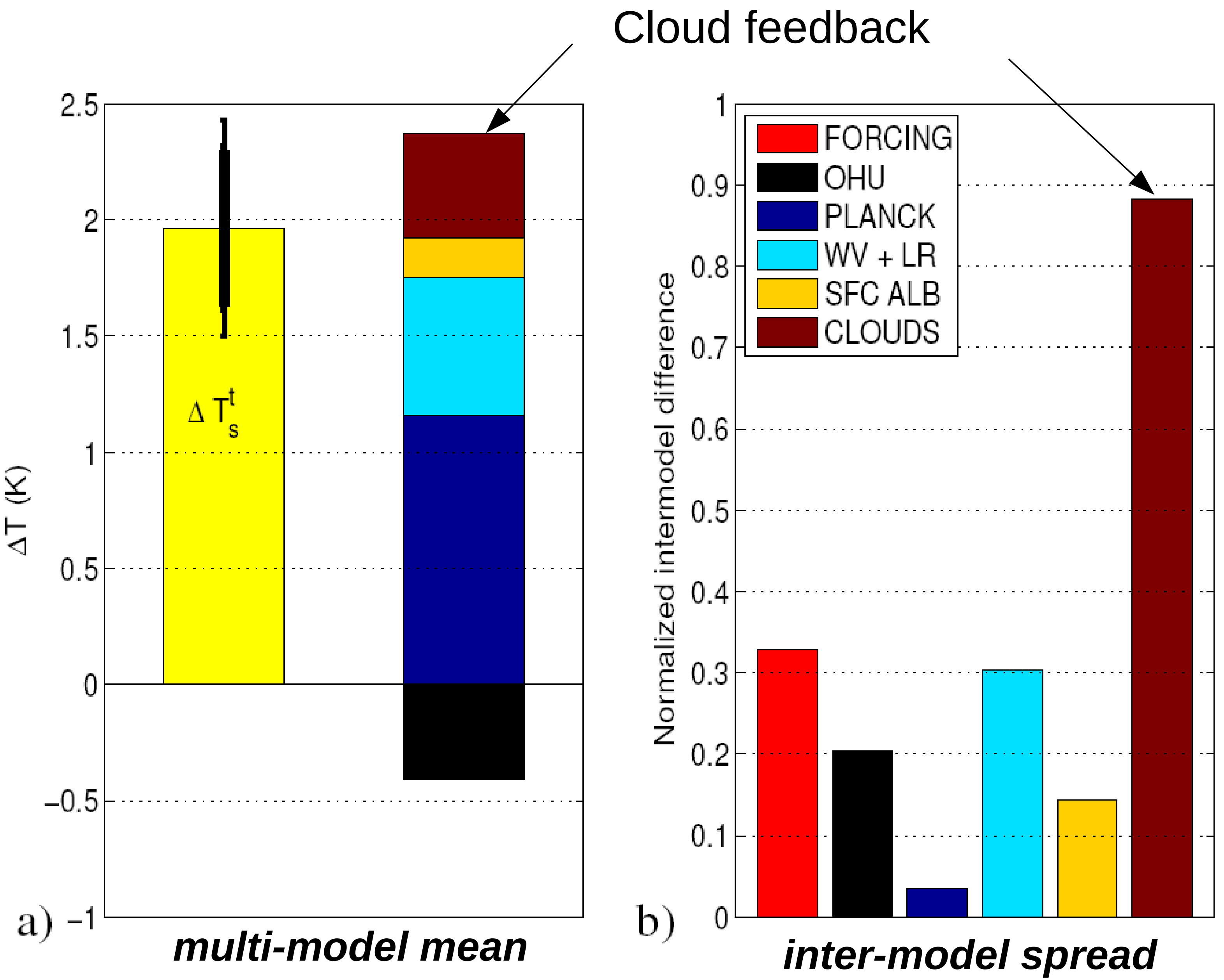
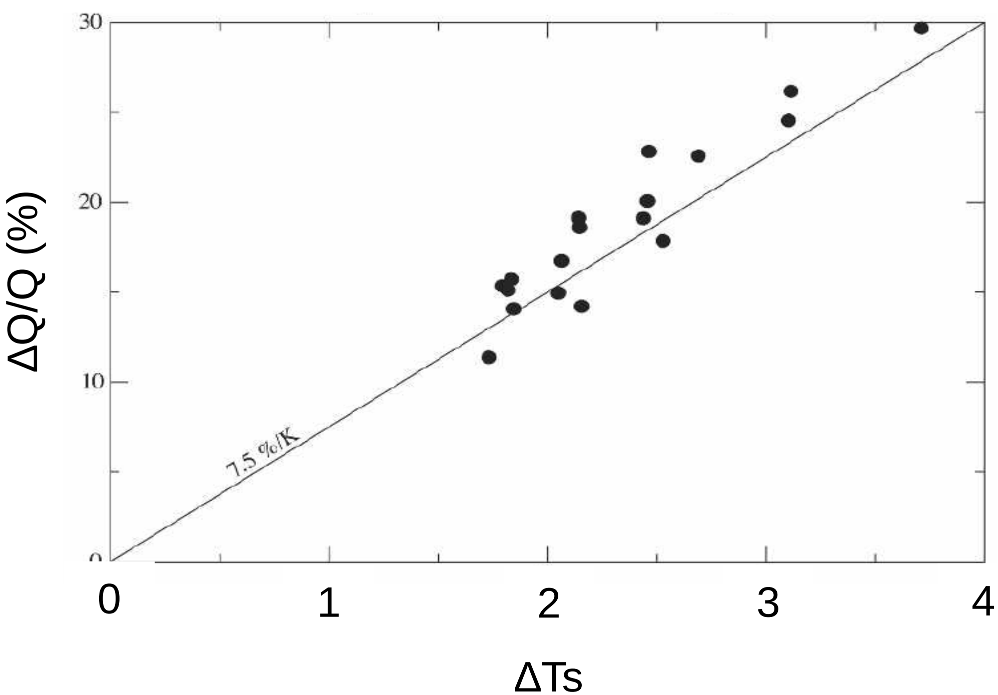


(Dufresne & Bony, 2008)

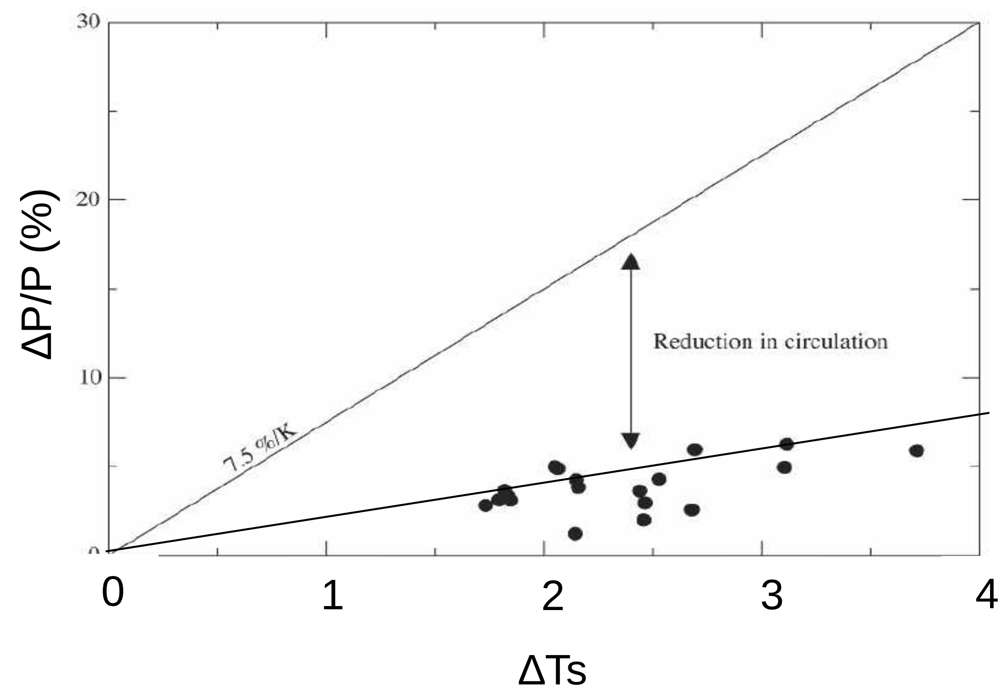
Precipitation changes

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



$\Delta Q/Q$ (%) ≈ 7.5 ΔTs

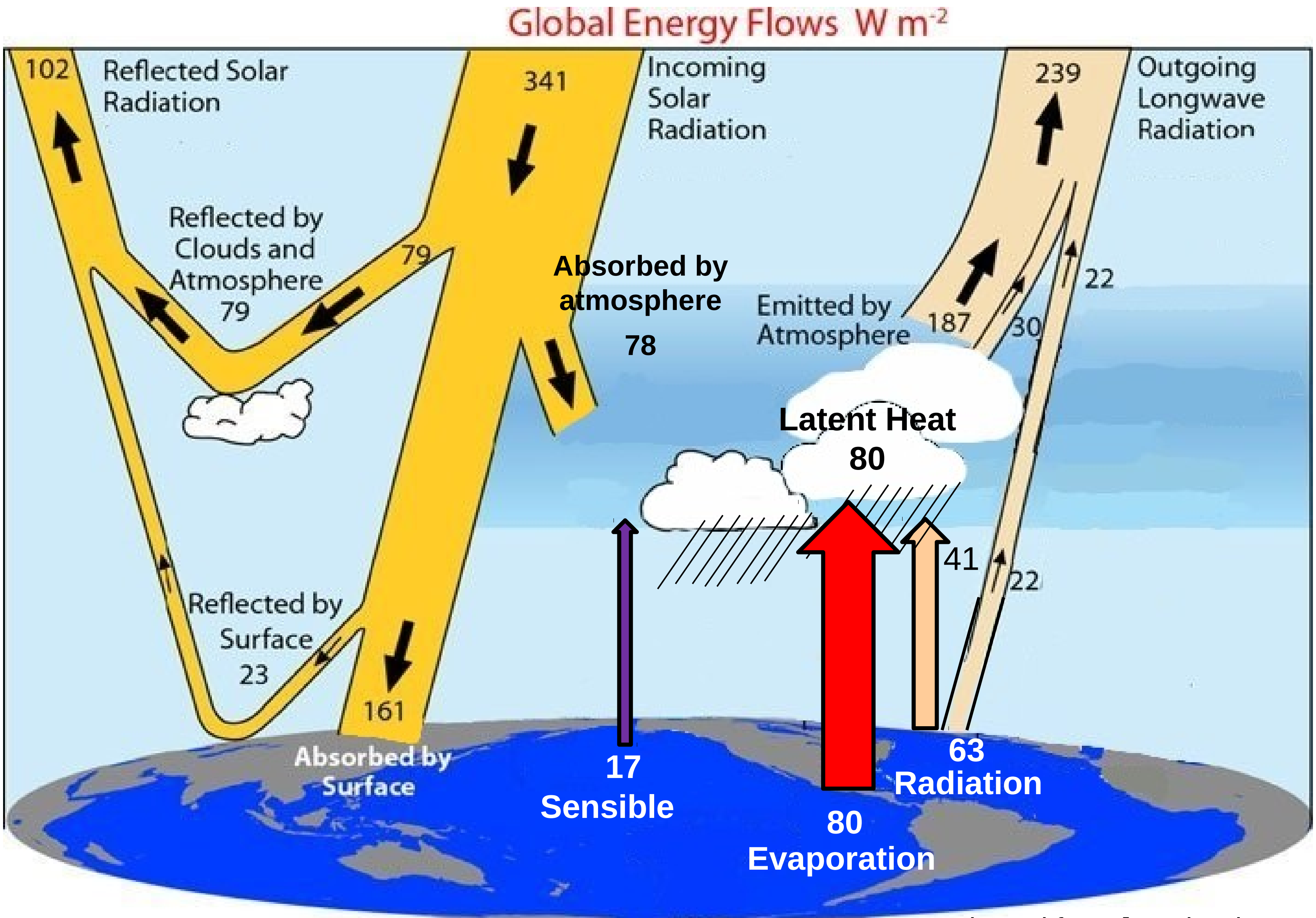
Change of **precipitation** vs change of the average surface **temperature**



$\Delta P/P$ (%) ≈ 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)

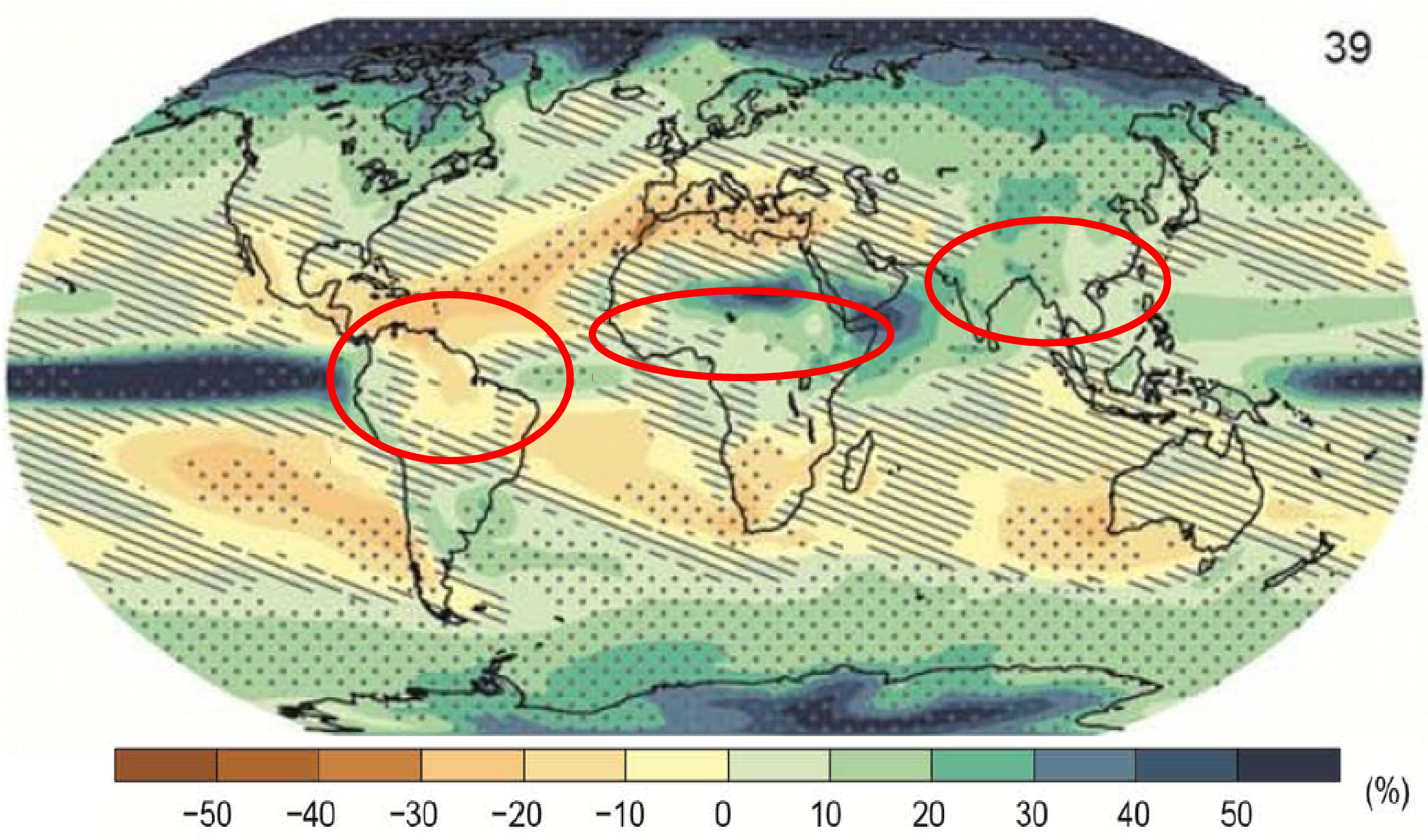


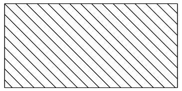
Adapted from [Trenberth & Fasullo, 2012]

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

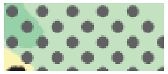
Precipitation changes: Geographical distribution

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





Low Signal/noise ratio

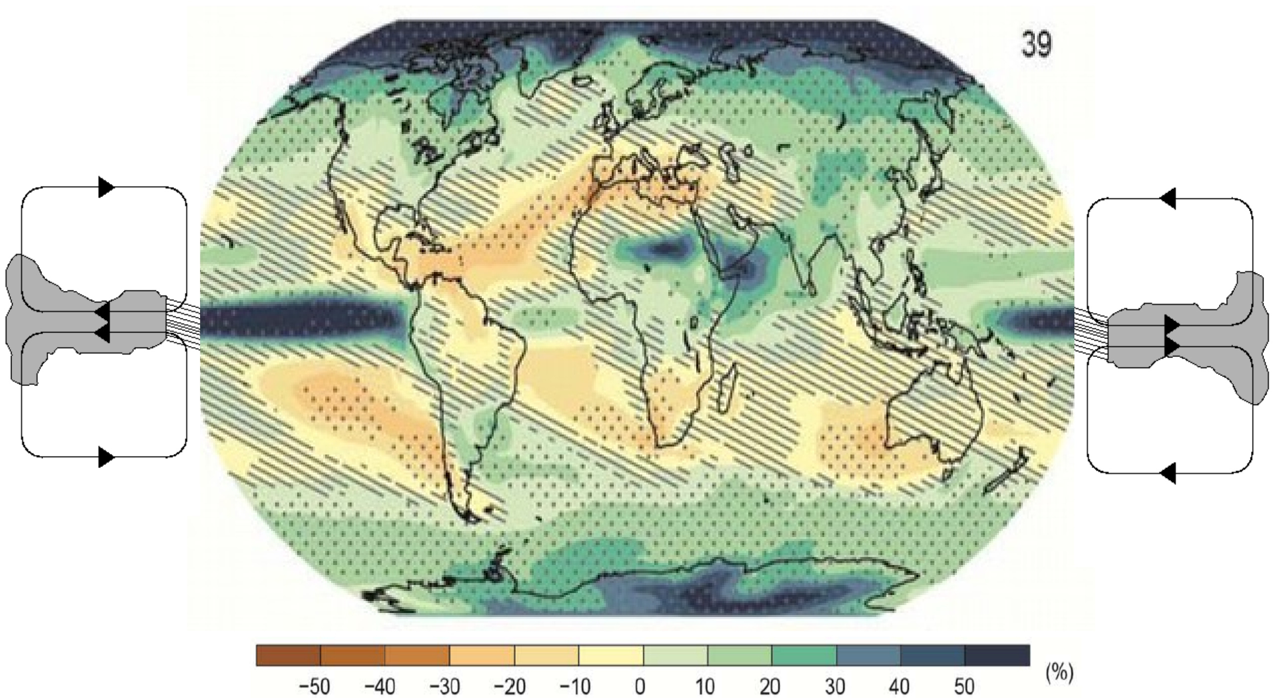


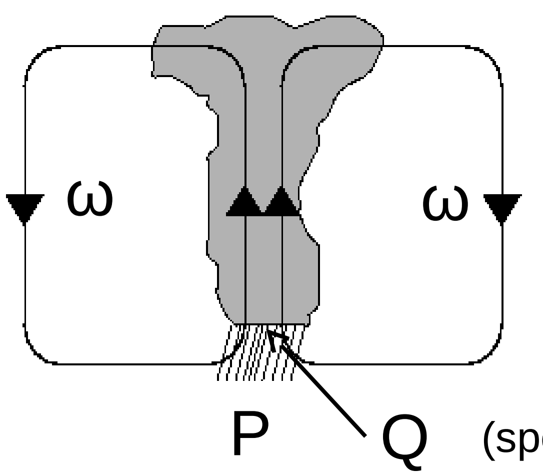
High signal/noise ratio and models agree

39 CMIP5 models

[IPCC, AR5]

Precipitation changes





(specific humidity)

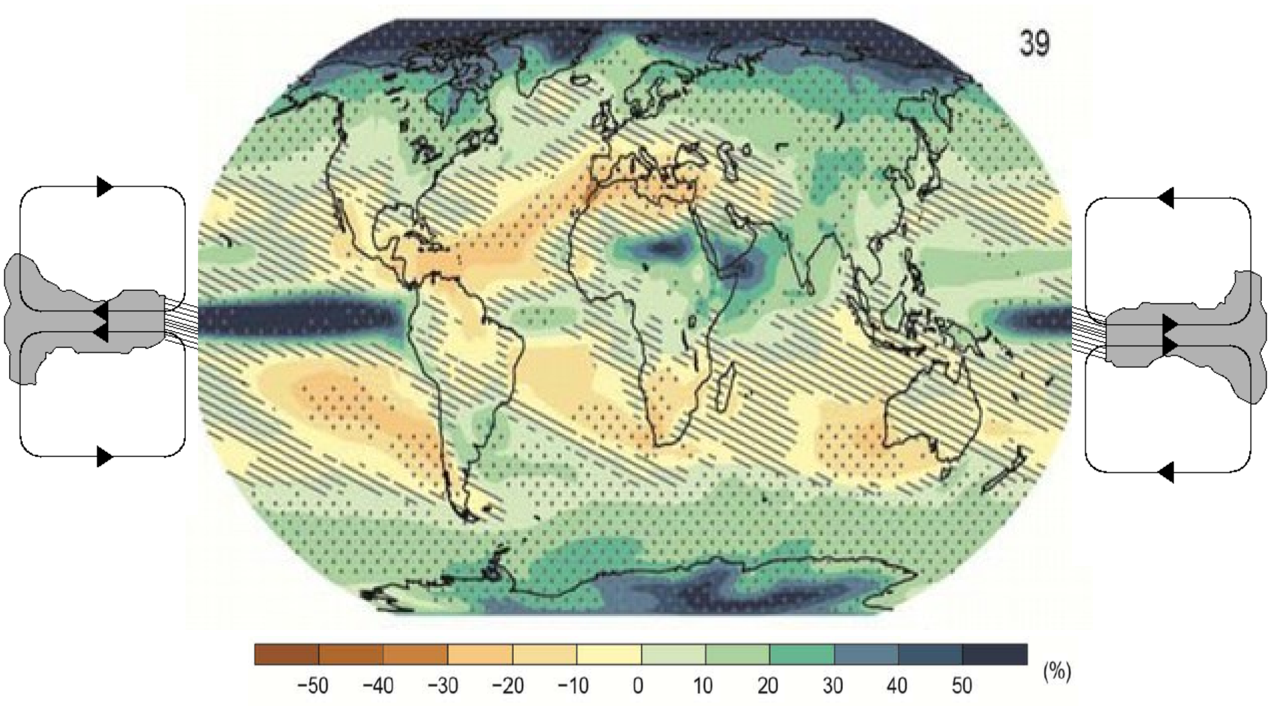
Precipitations changes

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

Thermodynamic response

Dynamic response

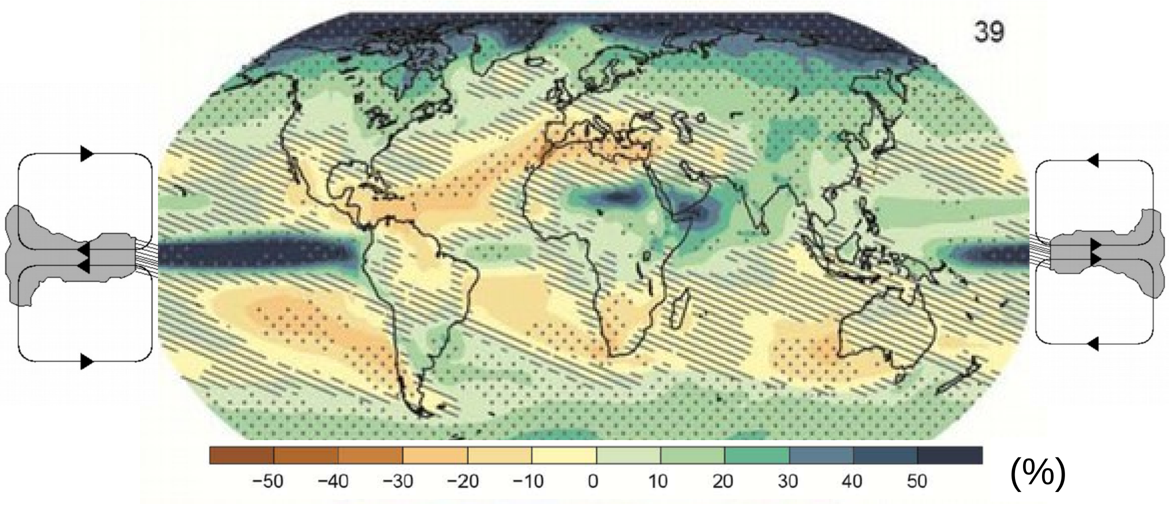
Precipitation changes



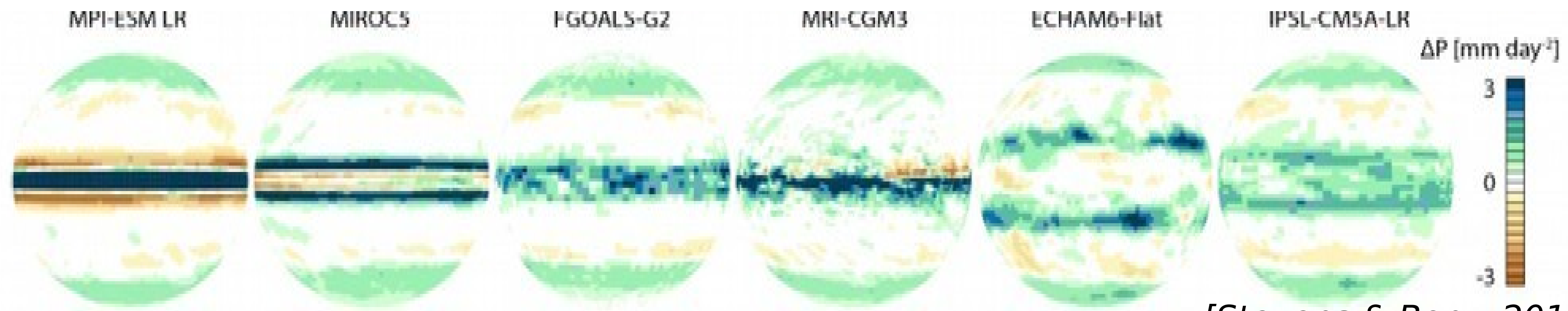
At the global scale:

- 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

Precipitation changes



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



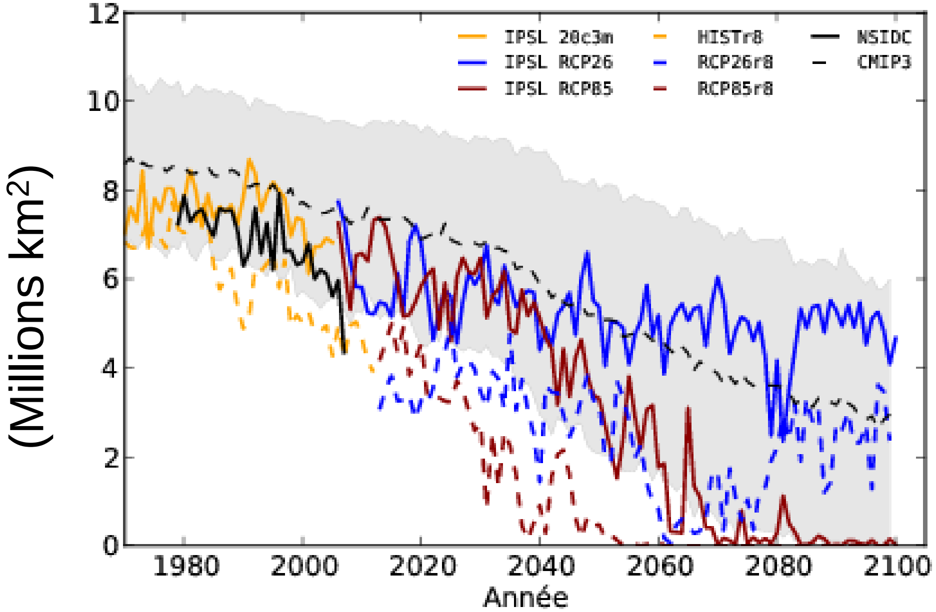
[Stevens & Bony, 2013]

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

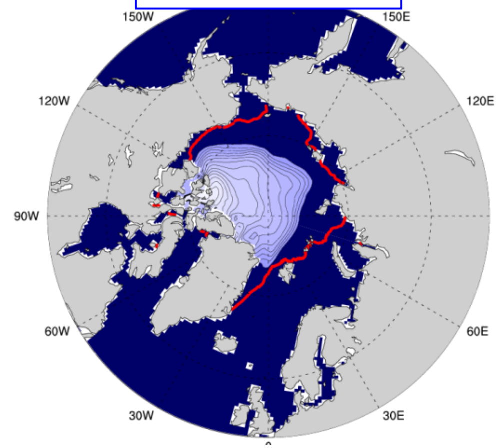
Arctic sea-ice 1970-2100

September *(minimum extension)*

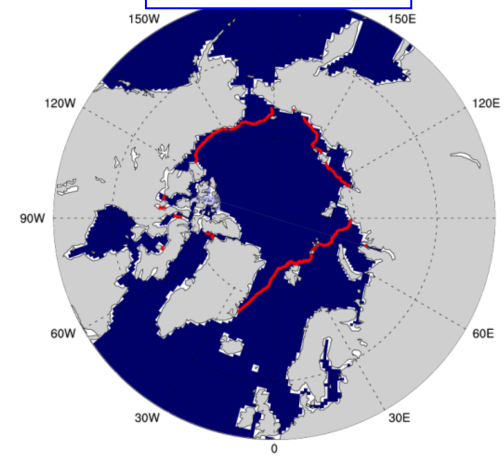
IPSL-CM5A-LR



RCP 2.6

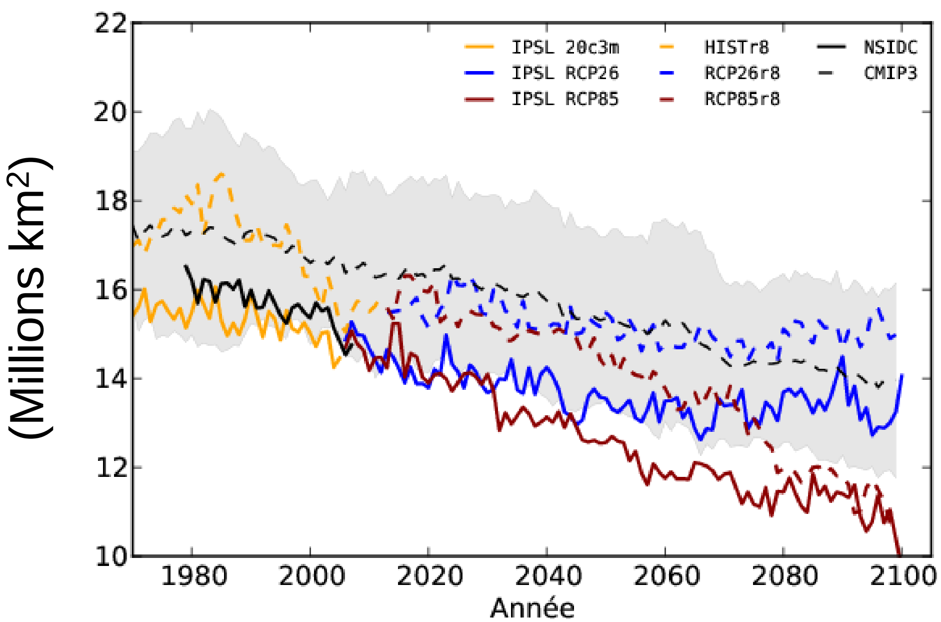


RCP 8.5

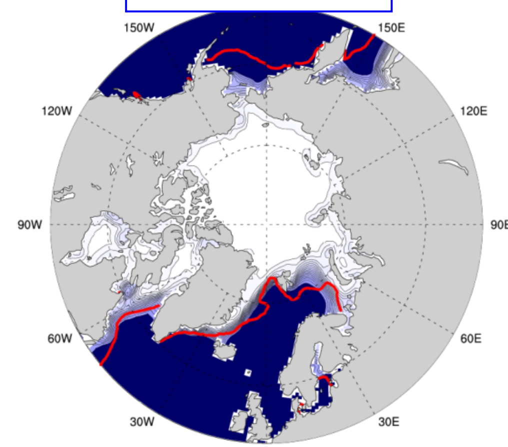


Mars *(maximum extension)*

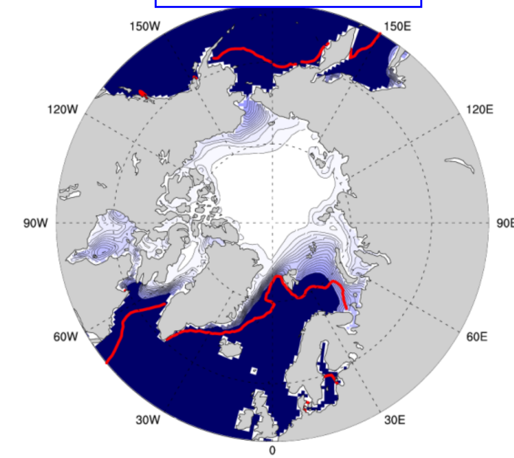
IPSL-CM5A-LR



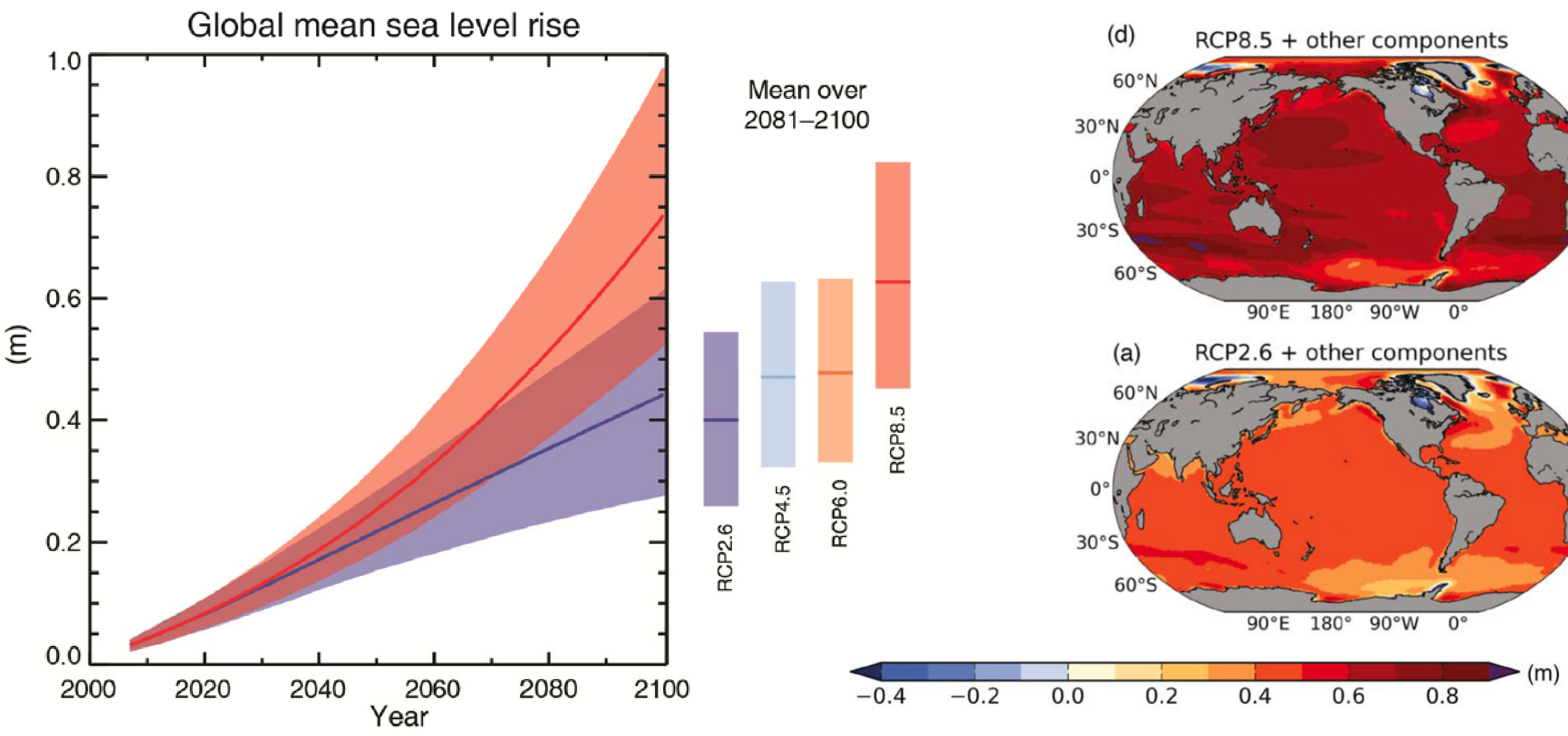
RCP 2.6



RCP 8.5

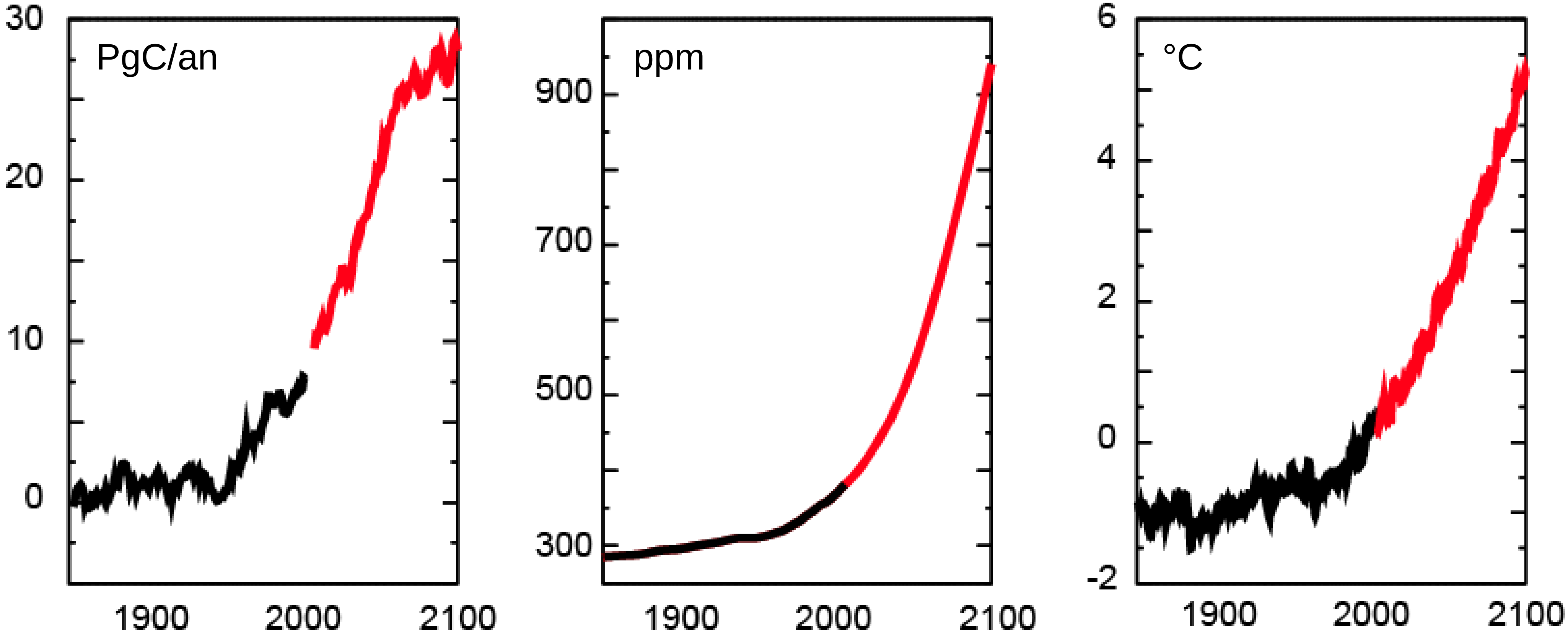


Sea level change



Carbone emission, CO_2 concentrations and global temperature: time constants

Higher scenario : emissions, concentration and temperatures continue to grow

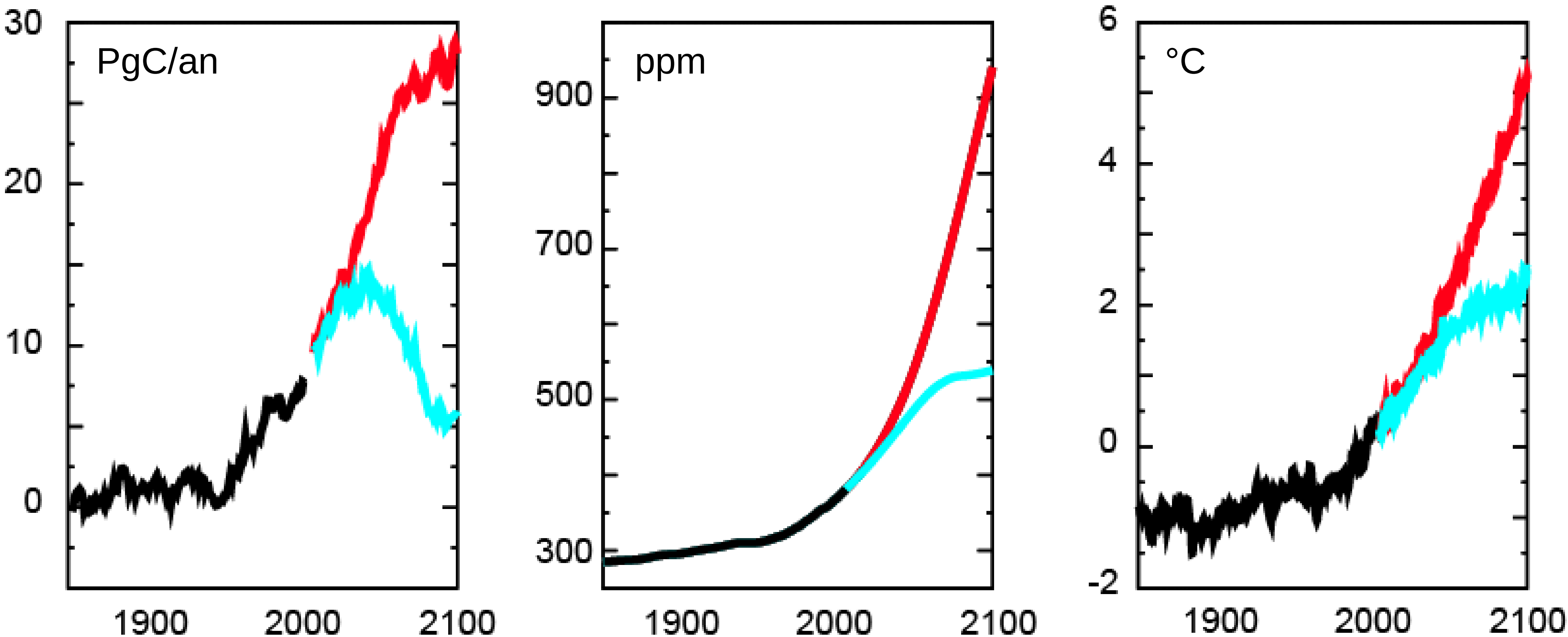


Courtesy L. Bopp

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



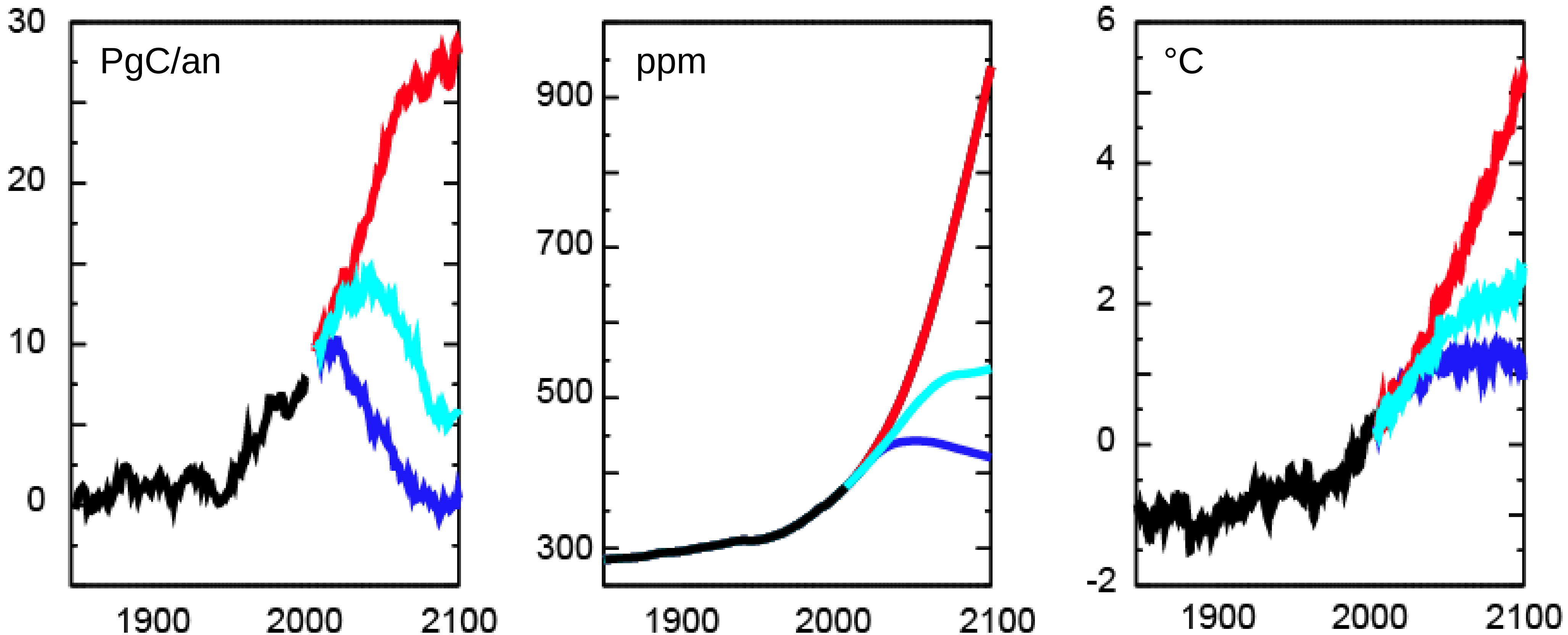
Courtesy L. Bopp

Carbone emission, CO_2 concentrations and global temperature: time constants

Higher scenario : emissions, concentration and temperatures continue to grow

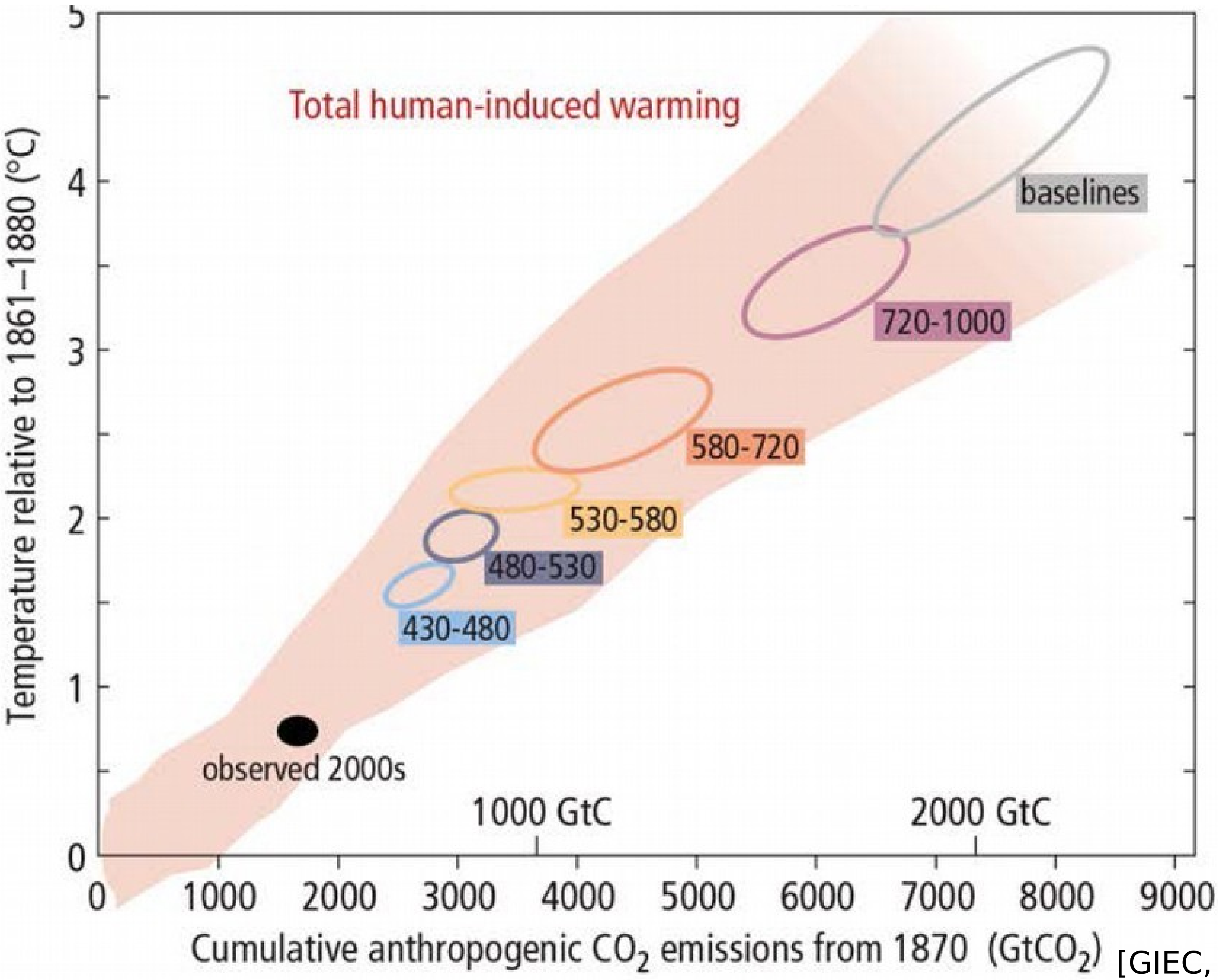
Medium scenario : to stabilize CO_2 concentration 550 ppm, emissions need to be strongly reduced. However, temperature will continue to increase

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

Accroissement de température versus les émissions cumulées de CO_2.



[GIEC, AR5]

Outlook

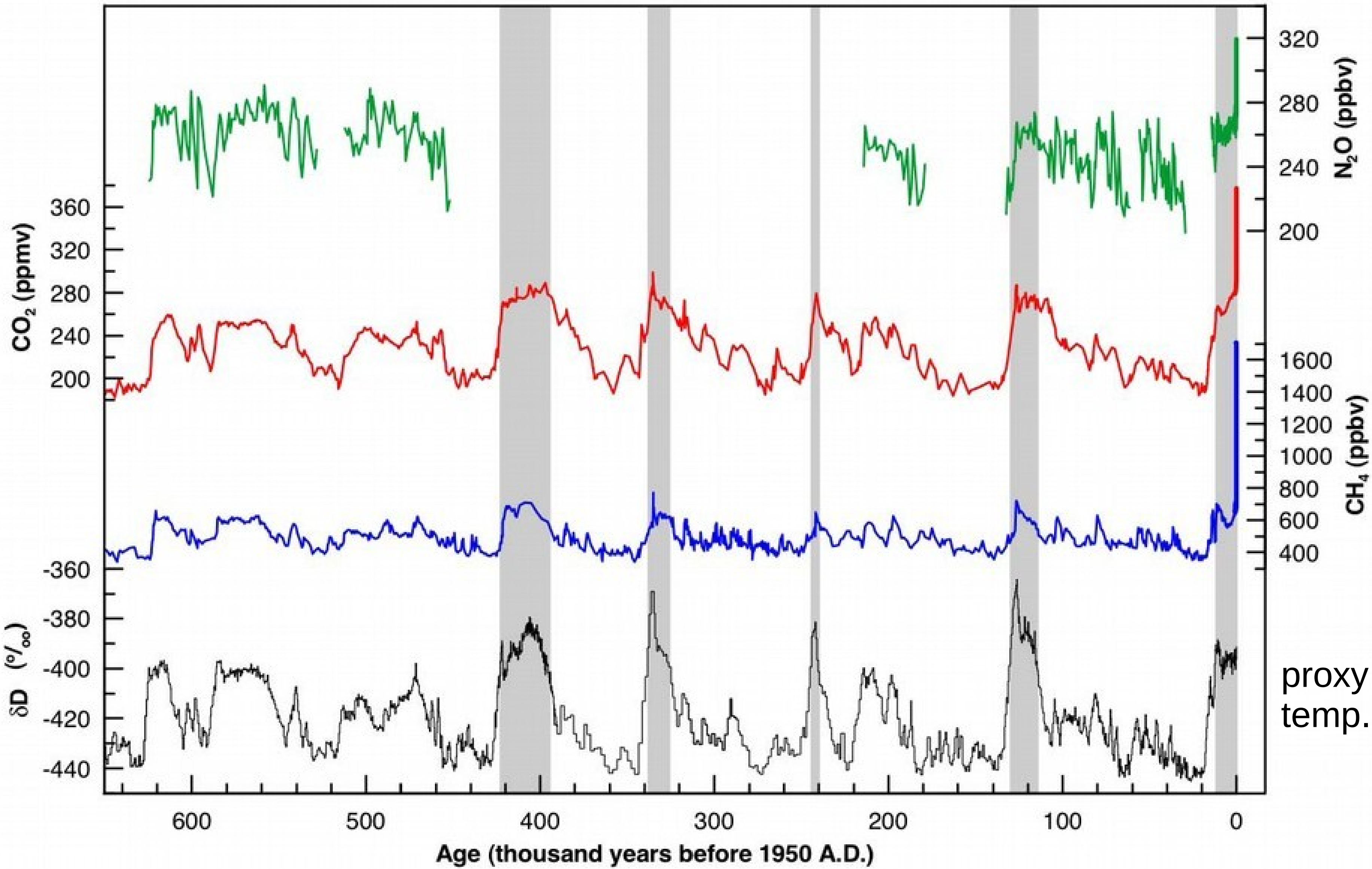
I. Short history of climate science and climate modeling

II. Climate and climate change simulations

III. Climate change and climate variaility

IV. Conclusions

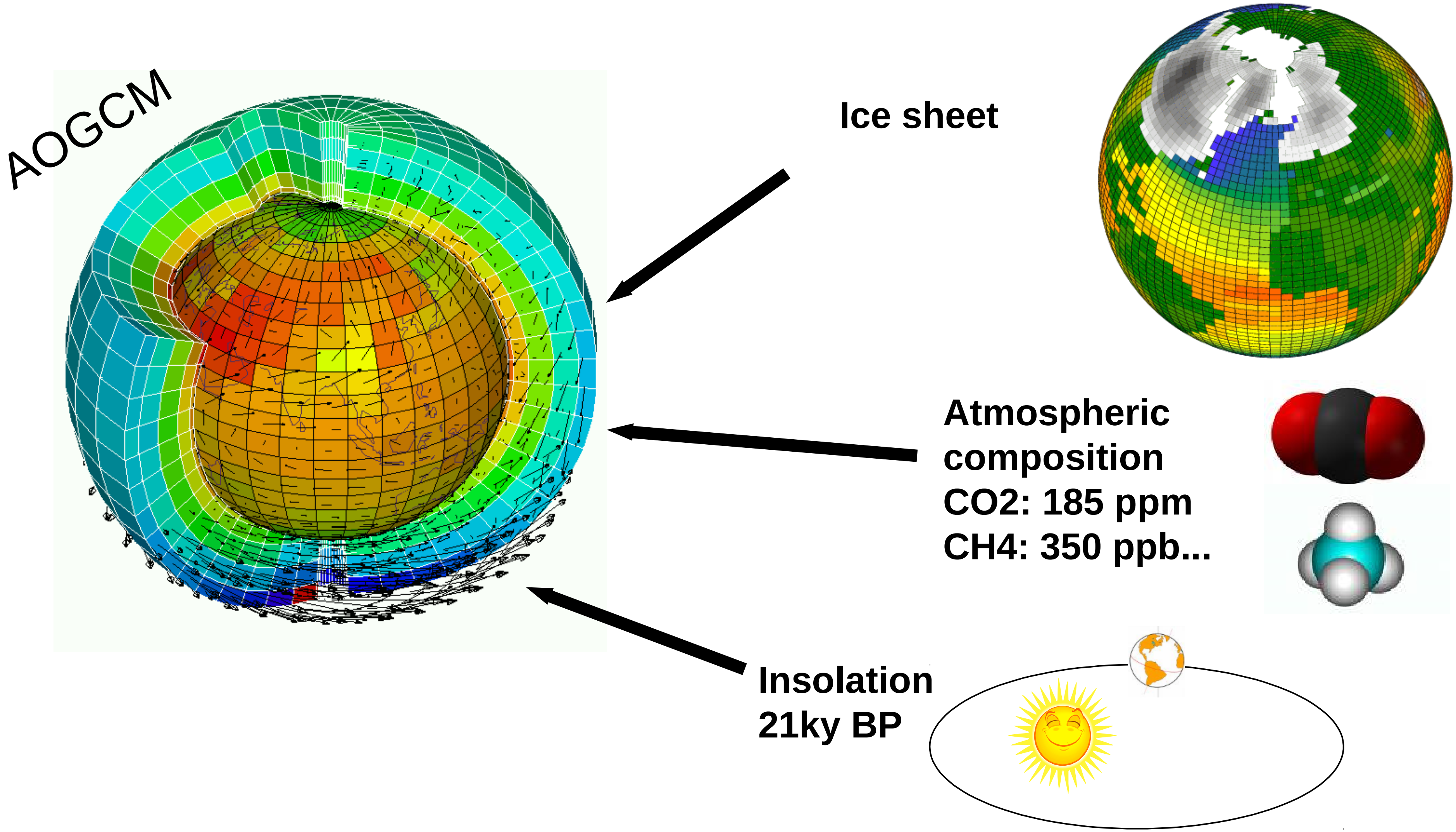
Paleoclimate changes



proxy temp.

[IPCC, 2013]

Simulation of Last Glacial Maximum (LGM)



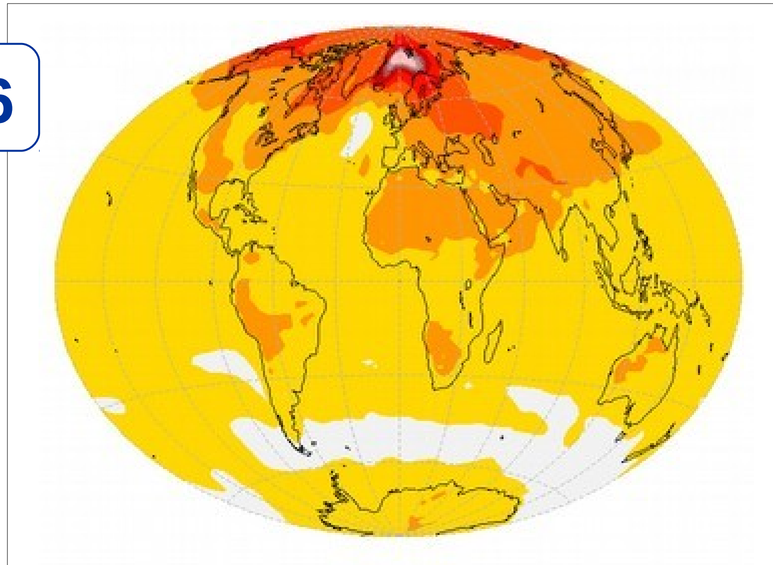
Greenhouse gas forcing ~ future climate
Other main forcings: ice sheet

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

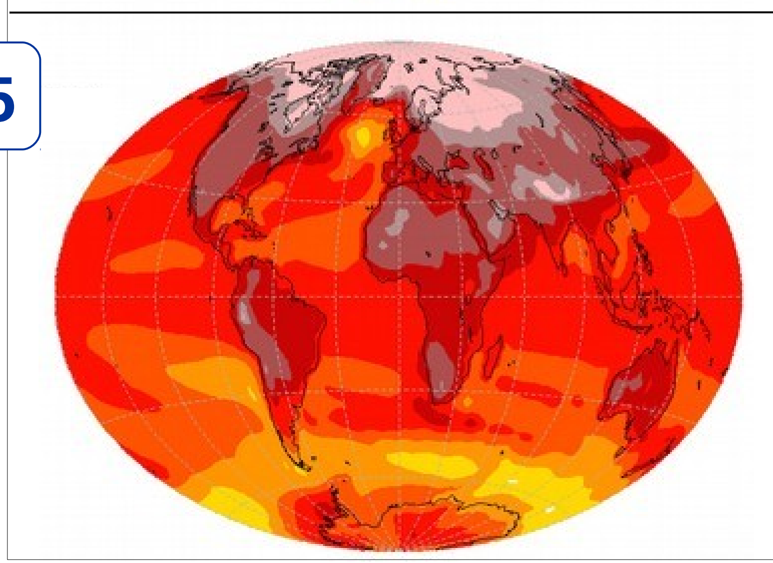
Change in surface temperature

Difference between **2100** and **1990**

RCP2.6

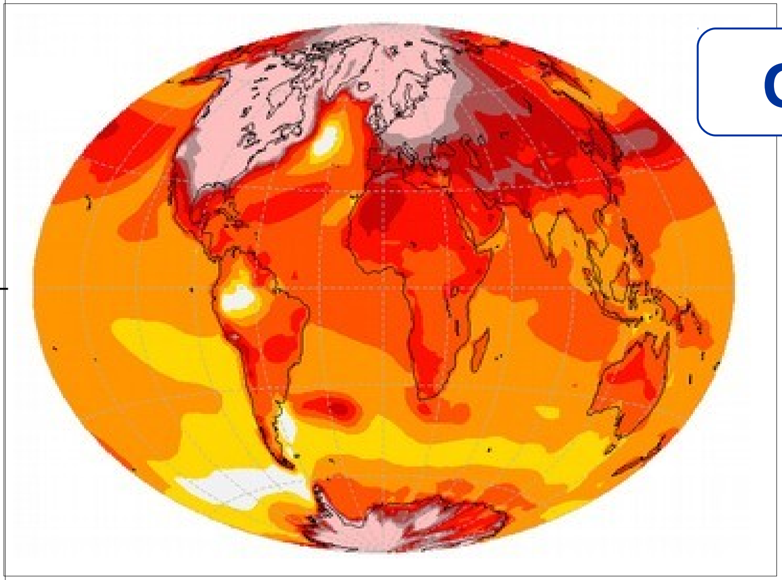


RCP8.5

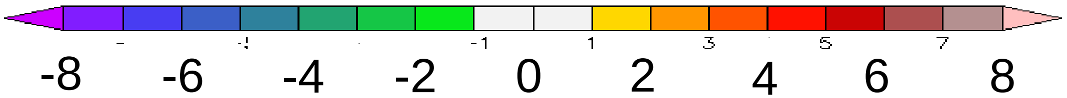


Difference between **current** and **last maximum periode**

Glacial

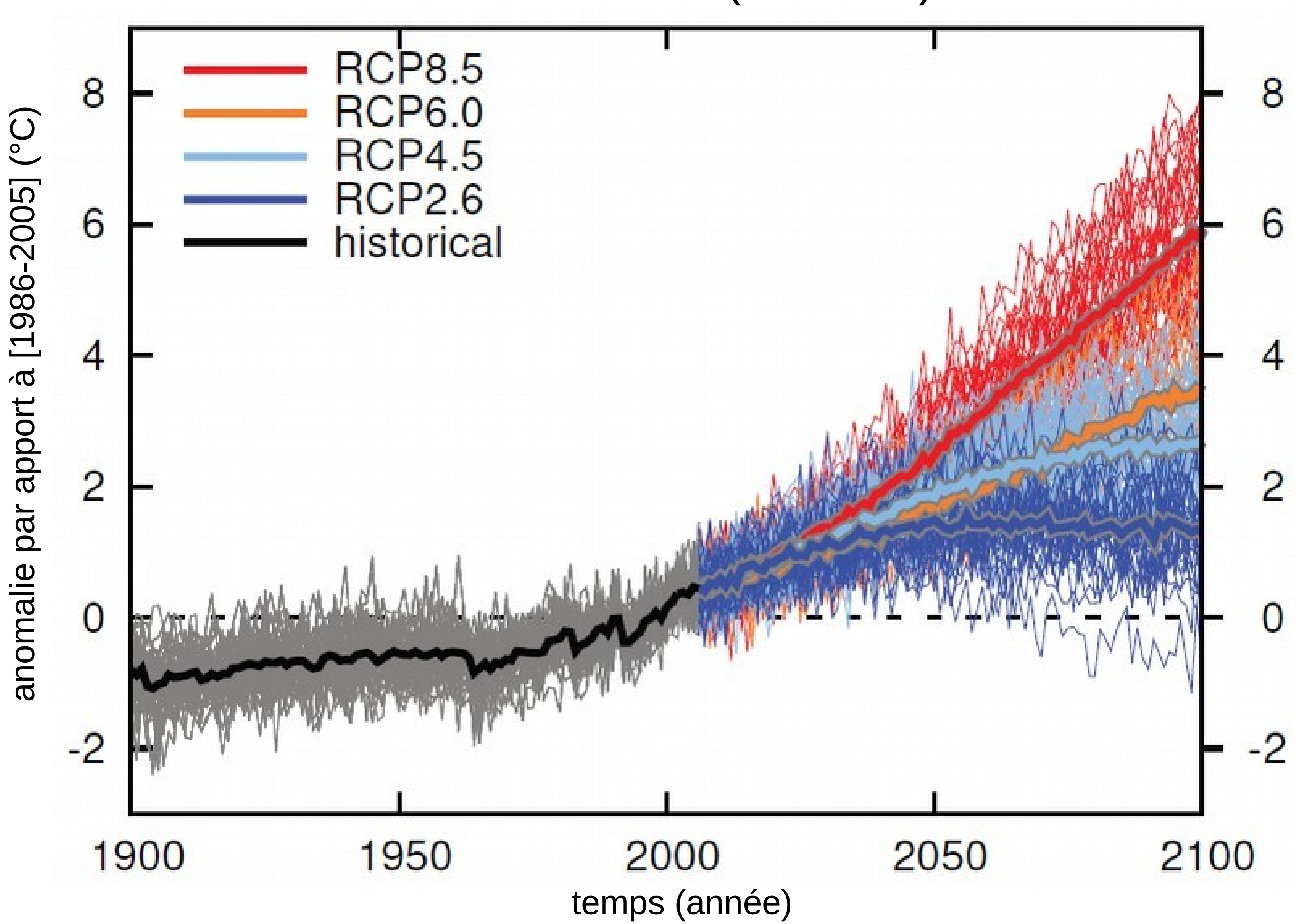


Model : IPSL-CM5A-LR



Changement climatique et variabilité interne

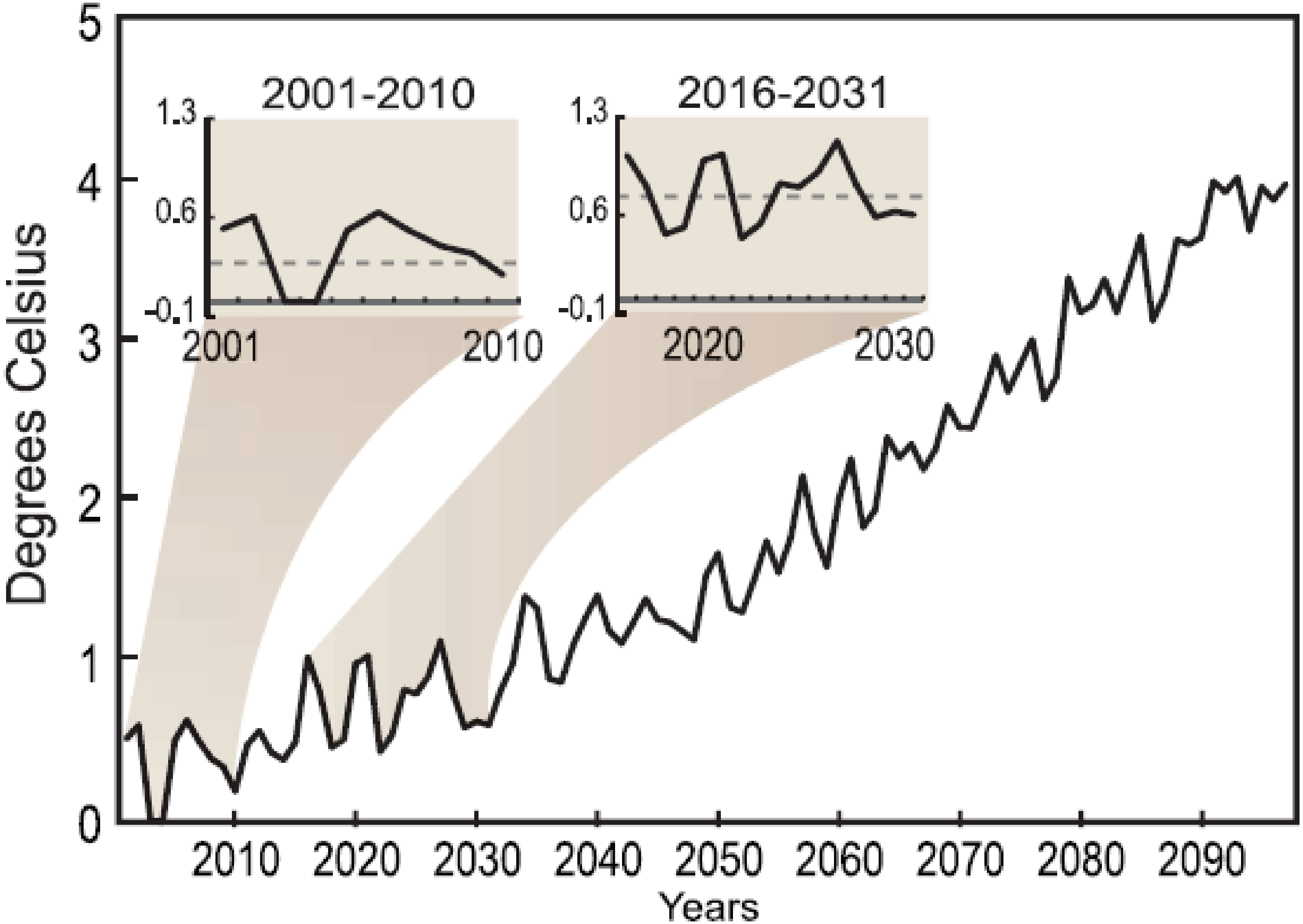
Température moyenne au dessus des continents,
en hiver boréal (dec.-fev.)



[GIEC 2013]

Climate change and climate variability

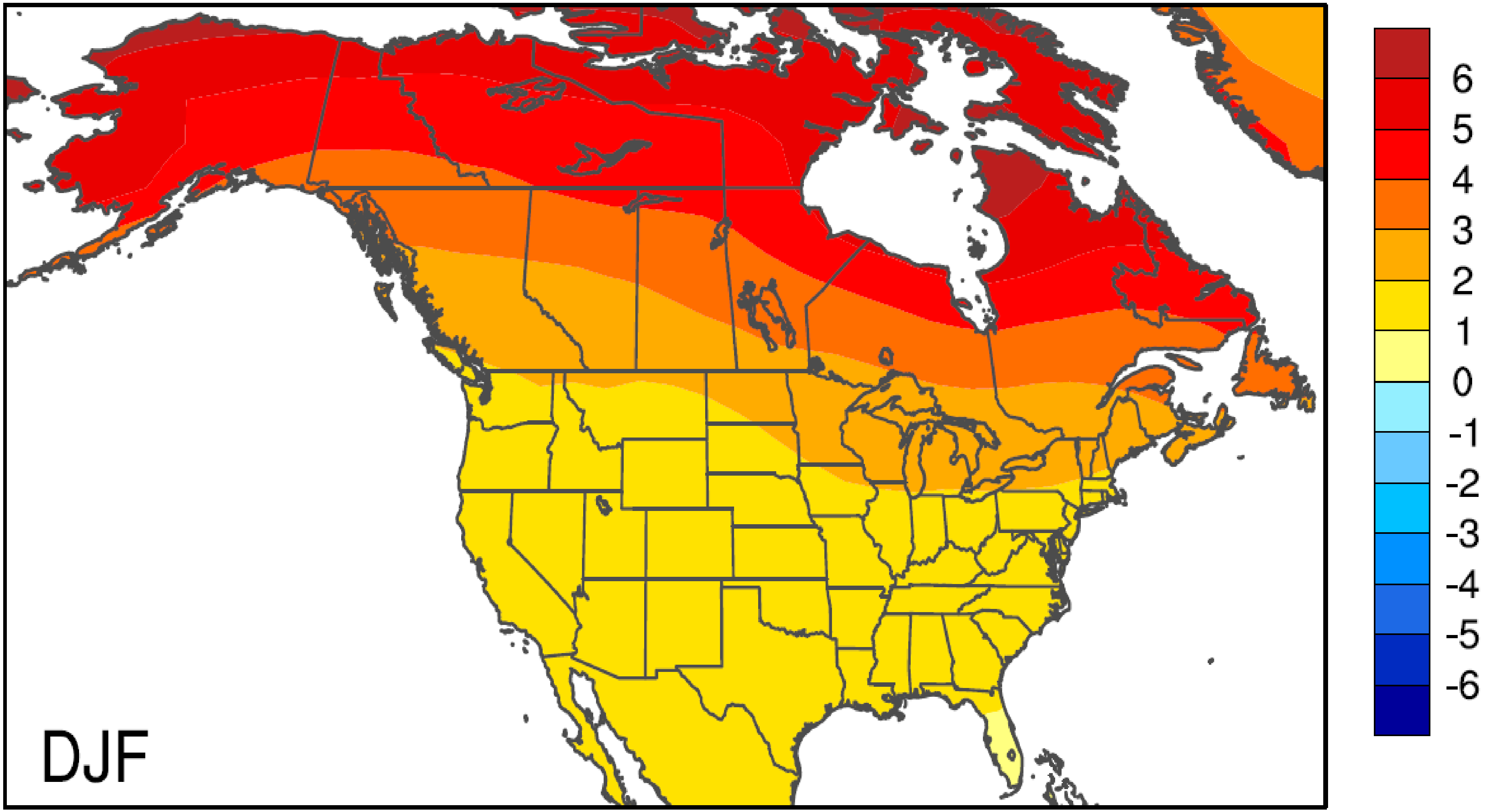
Simulations



Easterling and Wehner, 2009

Changement climatique et variabilité interne

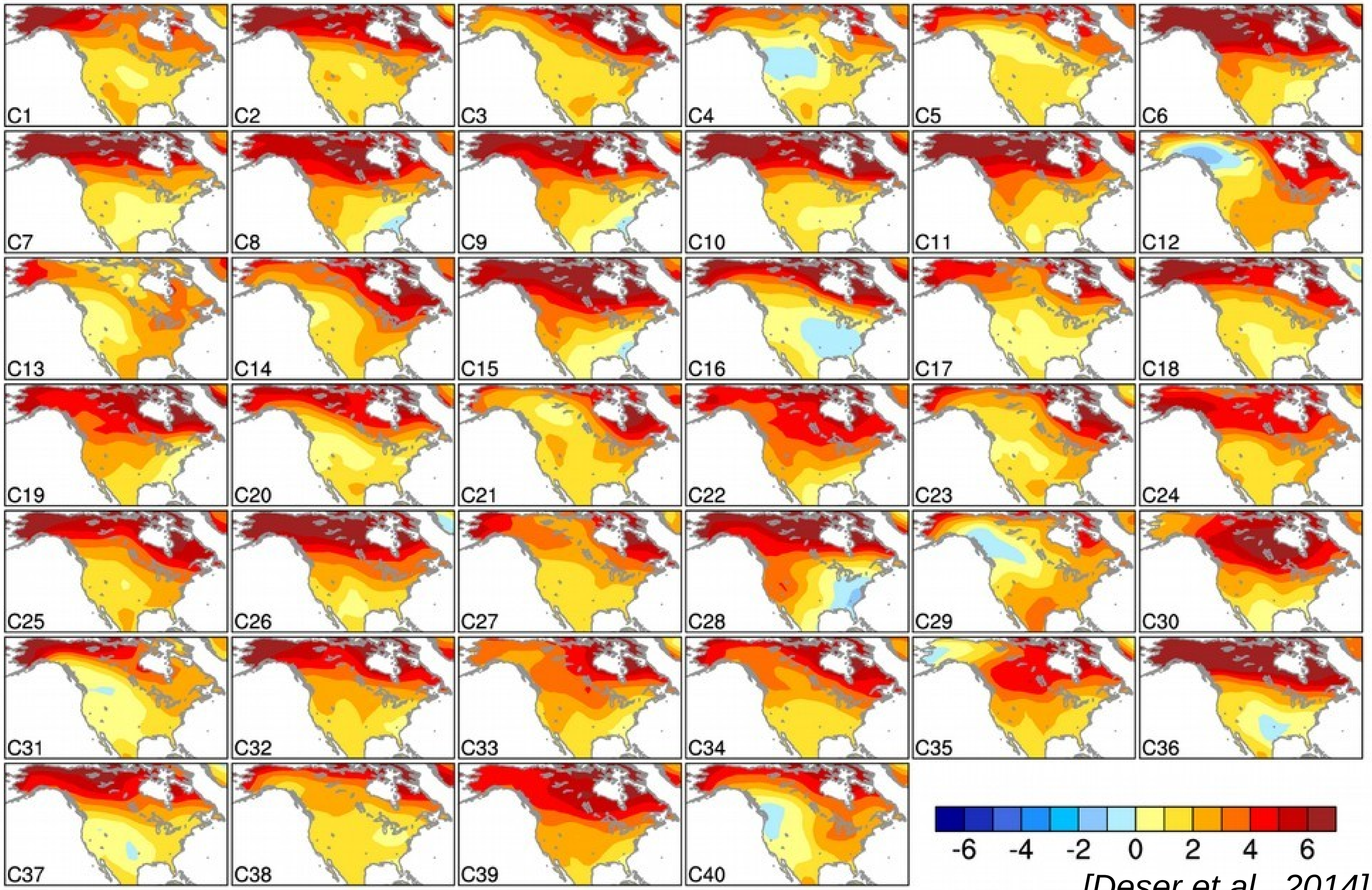
Tendance sur 50 ans de la température hivernale (°C/50 ans)
pour un scénario « intermédiaire - haut »



[Deser et al., 2014]

Changement climatique et variabilité naturelle

Tendance sur 50 ans de la température hivernale (°C/50 ans)



[Deser et al., 2014]

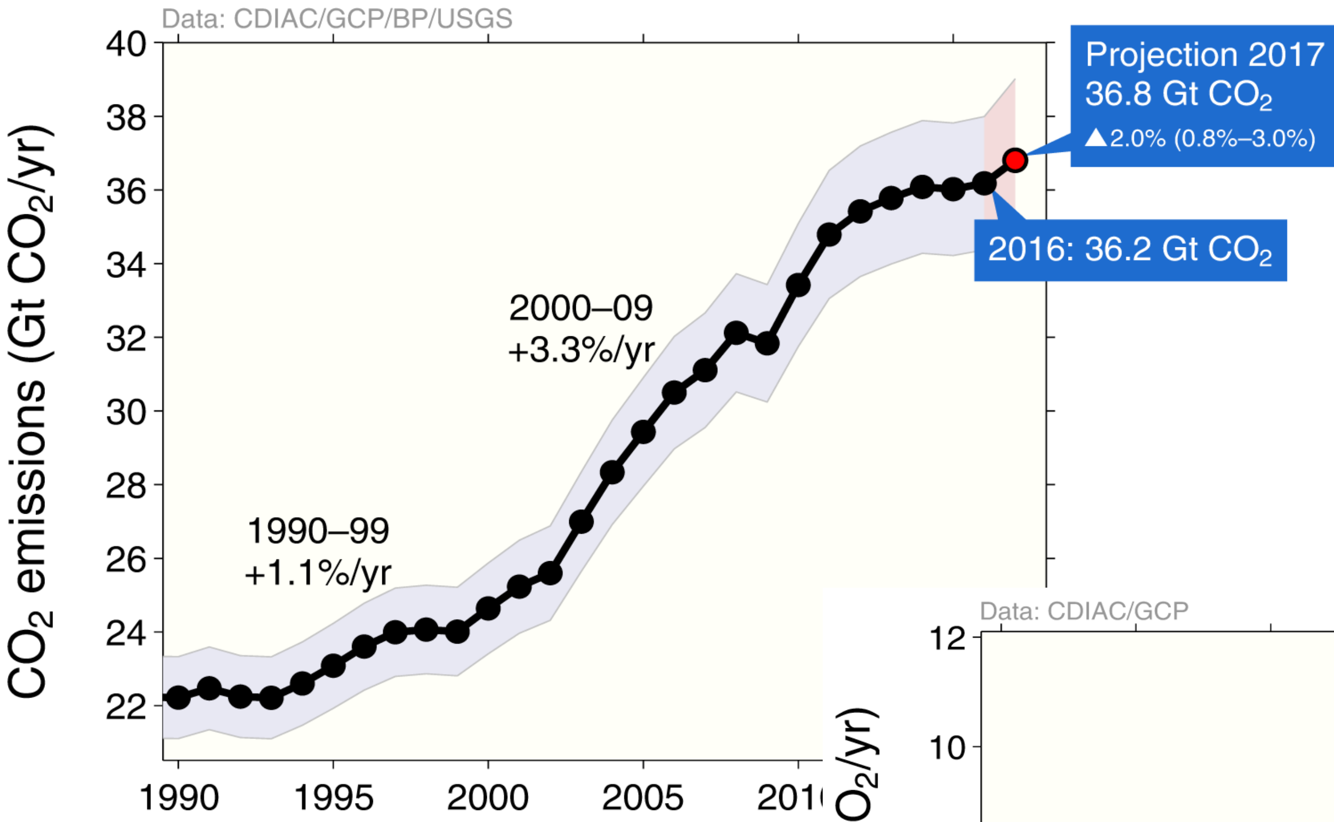
Variabilité interne et variations dues à des forçages

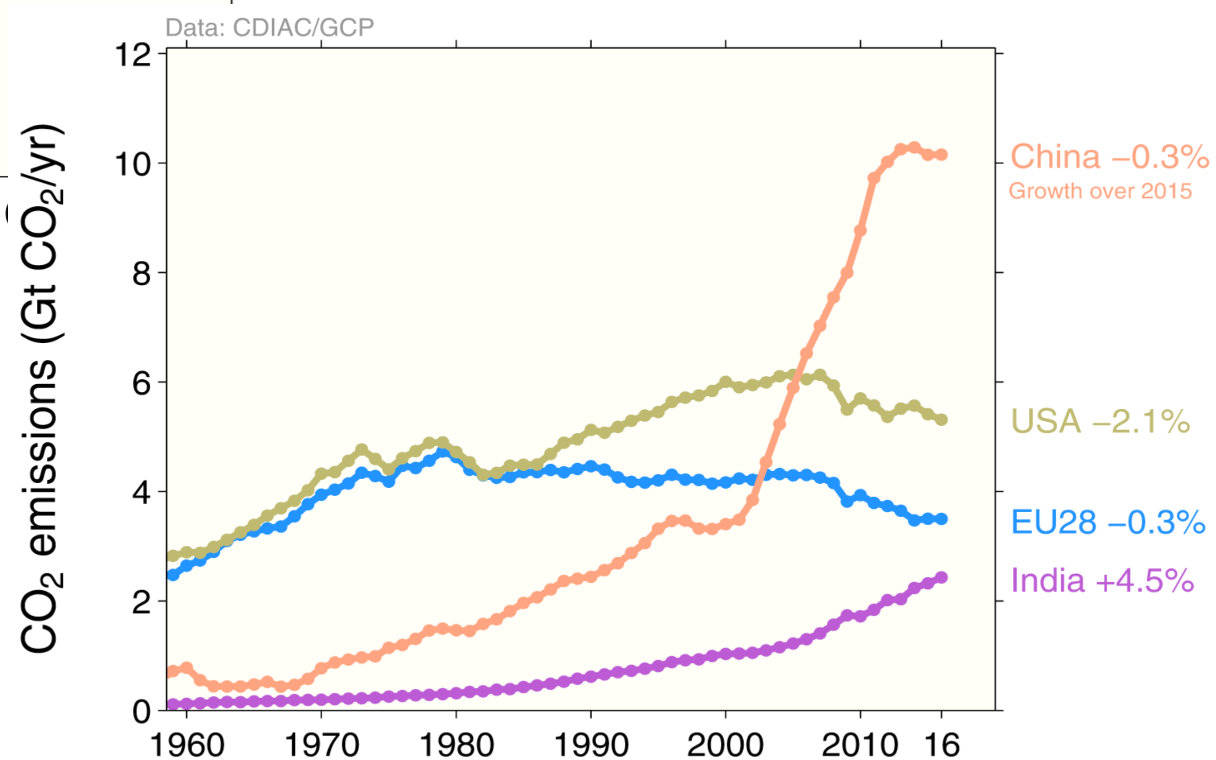
Les variations climatiques ont plusieurs origines:

$$\underbrace{\Delta T}_{\text{variation}} \approx \underbrace{\underbrace{\Delta T_{int}}_{\text{Variabilité interne}} + \underbrace{\frac{\partial T}{\partial Q}\Delta Q_{nat}}_{\text{Réponse aux forçages naturels}}}_{\text{Variabilité naturelle}} + \underbrace{\frac{\partial T}{\partial Q}\Delta Q_{ant}}_{\text{Réponse aux forçages anthropiques}}$$

- L'importance relative de ces termes dépend de la moyenne spatiale et temporelle considérée, et de l'amplitude des forçages
- Les différences entre observations et résultats de modèles, ou entre résultats de modèles, peuvent inclure tous ces termes

Évolution récente des émissions de CO_2





[Global Carbon Project]

Conclusions

- L'**accroissement de la température** globale et le rôle dominant des activités humaines sont maintenant **bien établis**, compris

- La **confiance des scientifiques du climat** sur le rôle des activités humaines s'est progressivement établie **dans les années 90**

- Les questions relatives aux changements climatiques évoluent: **passage de l’alerte à la quantification**, la description et l’anticipation des risques associés

- Il y a un **saut d’ordre de grandeurs sur les exigences** vis-à-vis des modèles climatiques. Importance de la représentation des processus et de la compréhension des phénomènes climatiques

- Plus on s’intéresse aux phénomènes **régionaux**, aux courtes échelles de temps (décennies) ou aux phénomènes extrêmes, **plus les incertitudes et la variabilité naturelle deviennent importants**

- Un des enjeux : éviter que les pays en développements ne passent pas par la case « pétrole et charbon » ?

Thank you for your attention