Physical basis of climate and climate change modelling

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Outlook

I. Emergence of climate and climate change science

II. Climate modeling

III. Climate and climate change simulations

IV. Understanding some climate phenomena

V. Climate changes and climate variability

VI. Conclusions

Emergence of the physics of climate

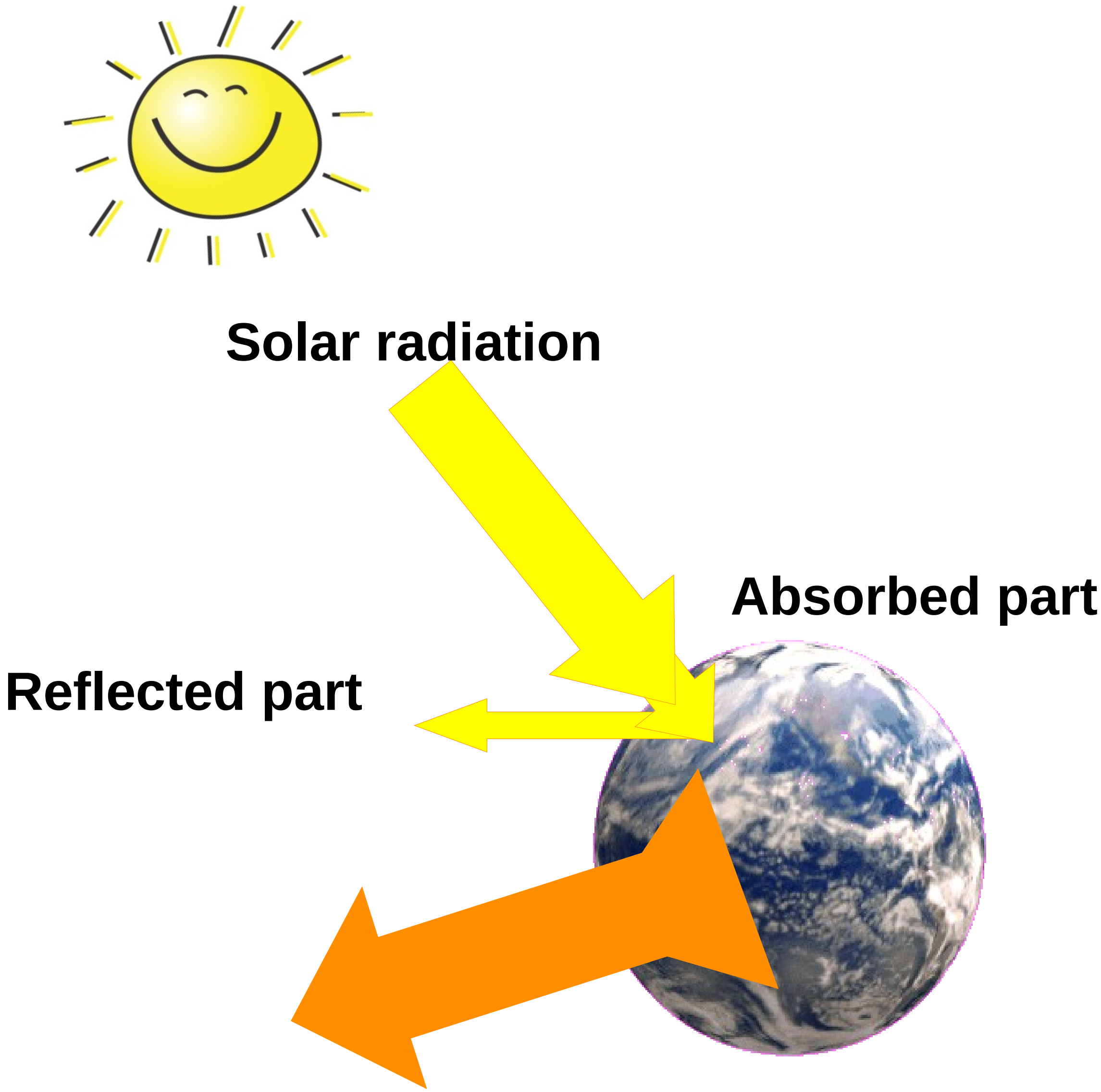
J. Fourrier:
• *Mémoire sur les températures du globe terrestre et des espaces planétaires,* Mémoires de l'Académie des Sciences de l'Institut de France,1824
• *General remarks on the Temperature of the Terrestrial Globe and the Planetary Spaces;* American Journal of Science, Vol. 32, N°1, 1837.

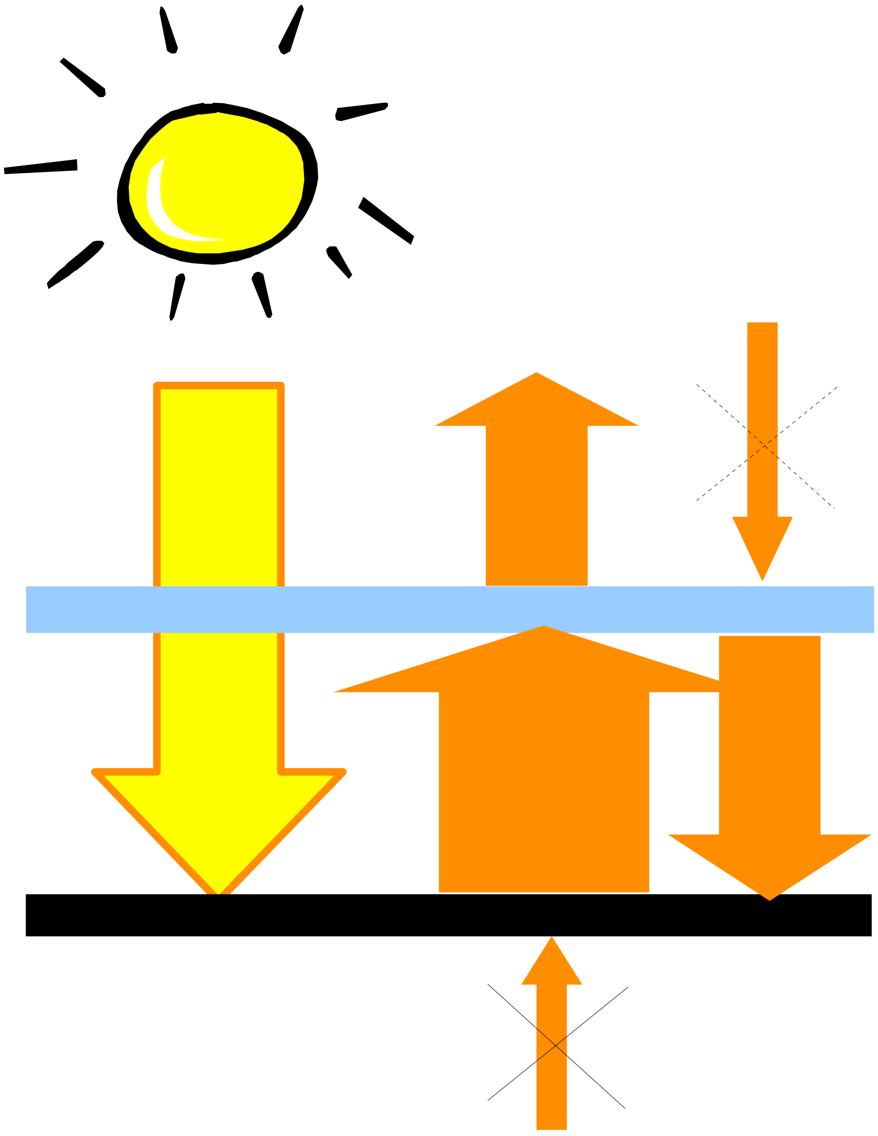
Joseph Fourrier
(1768-1830)

- 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]

Equilibrium temperature of a planet

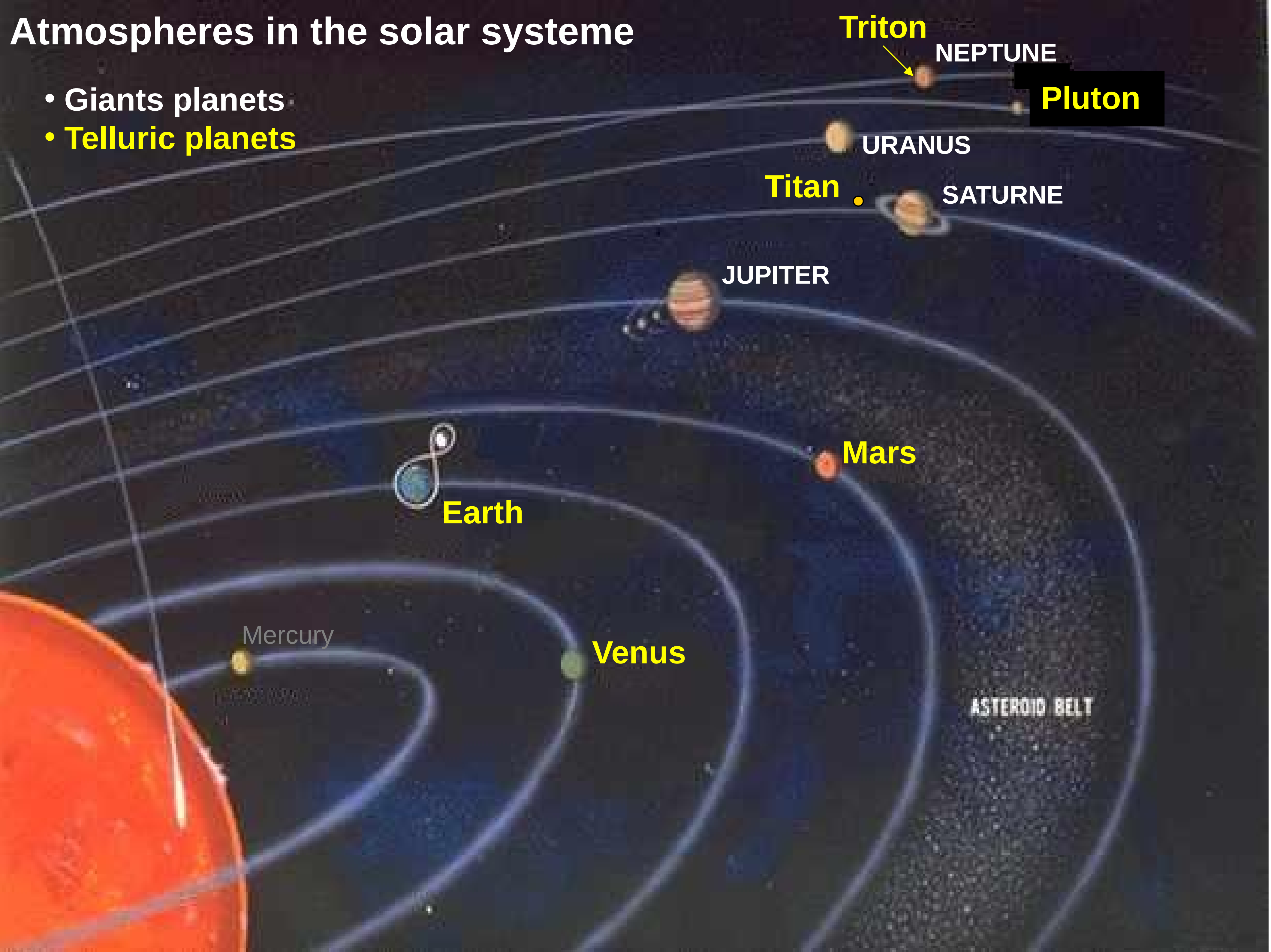




Global mean surface temperature is the result of the global energy budget

Atmospheres in the solar systeme

- Giants planets
- Telluric planets



Emergence of the physics of climate

J. Fourrier:
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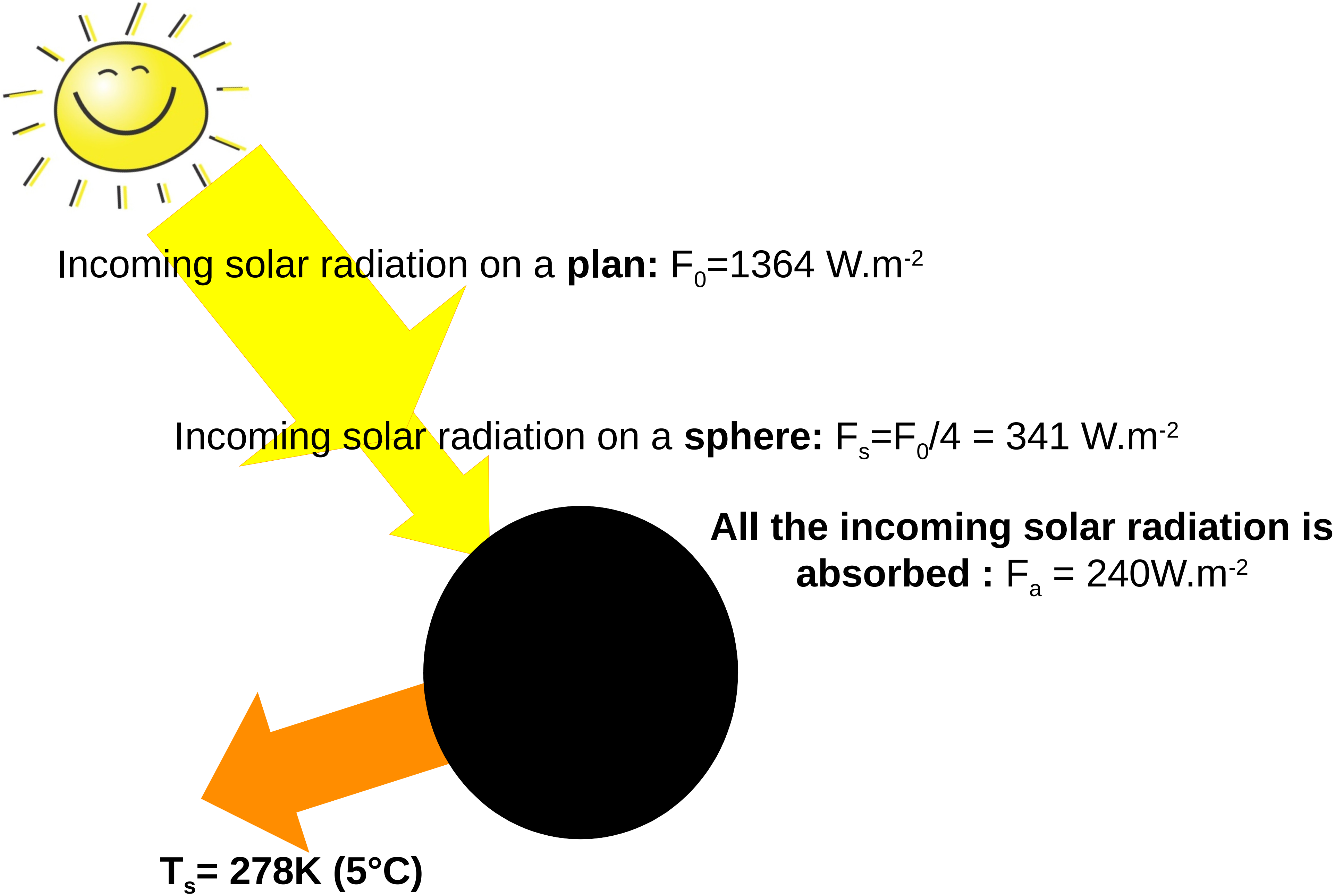
Joseph Fourrier
(1768-1830)

➢ 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.* »

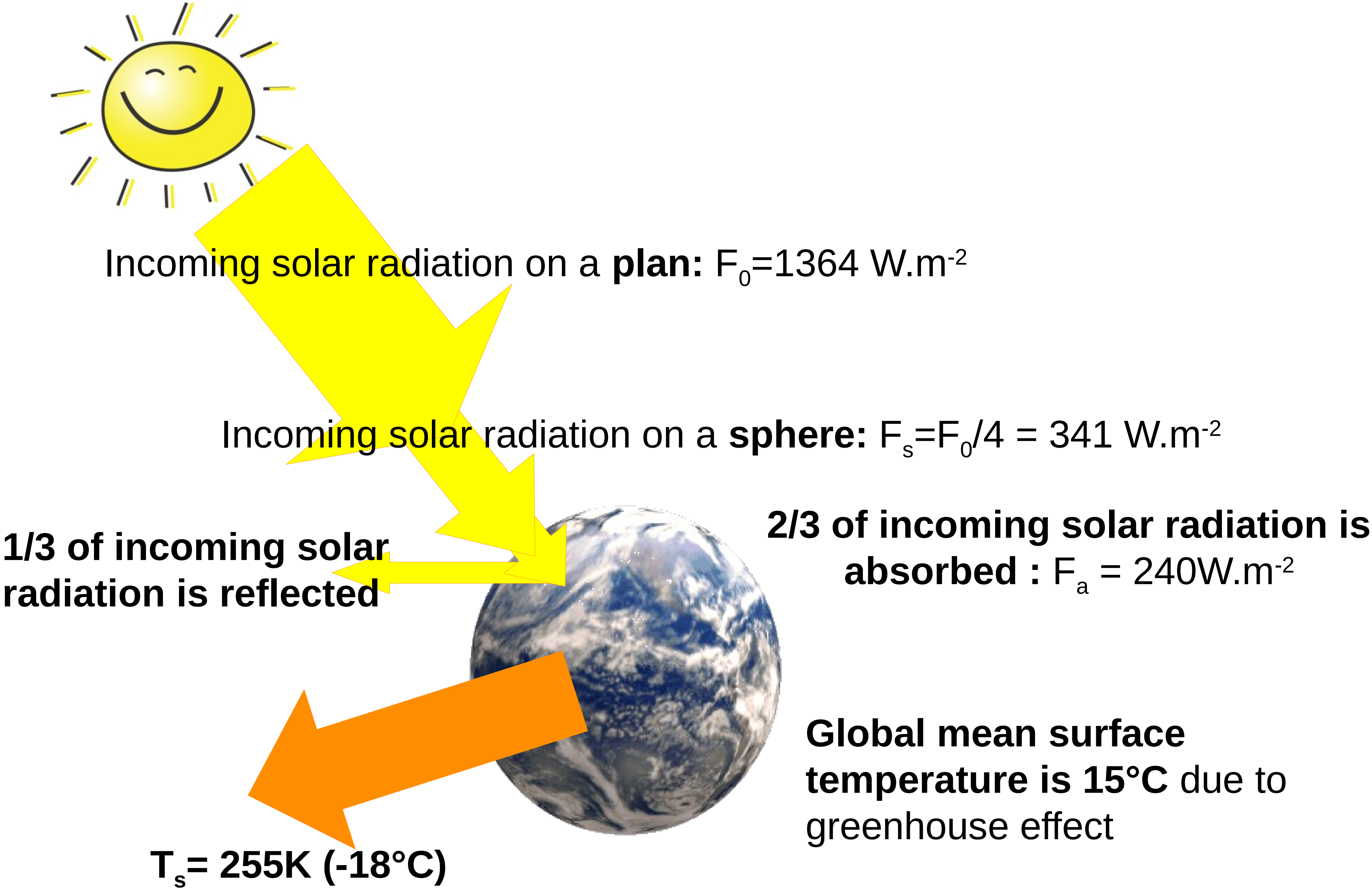
➢ He ***envisages that climate may change***: « *The establishment and progress of human society, and the action of natural powers, may, in extensive regions, produce remarkable changes in the state of the surface, the distribution of waters, and the great movements of the air. Such effects, in the course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

[Dufresne, 2006]

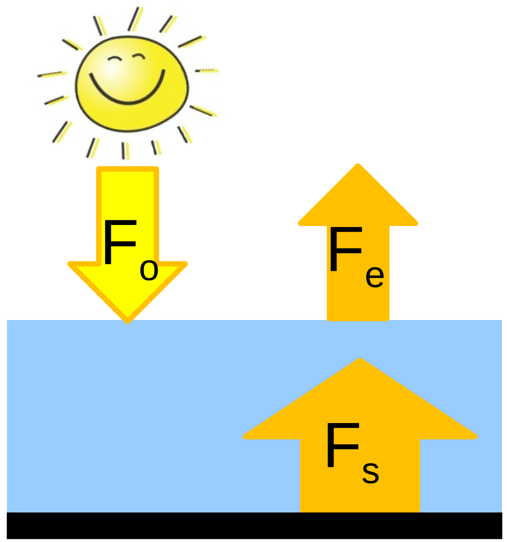
Equilibrium temperature of a planet



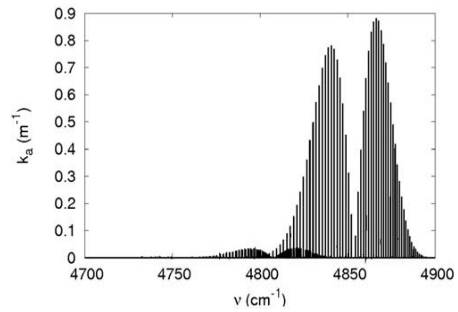
Equilibrium temperature of a planet



What radiation heat transfer theory tell us



Greenhouse effect: $G=F_s-F_e$



Gas radiative properties

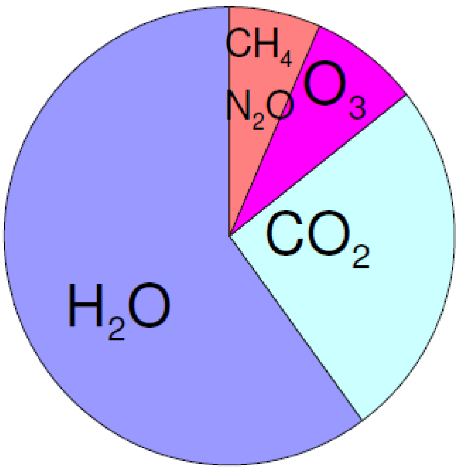
Atmospheric characteristics

Computation of the radiative fluxes 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

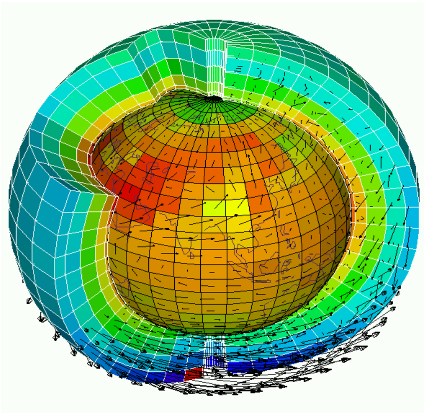
For a doubling of the CO_2 concentration:

- 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



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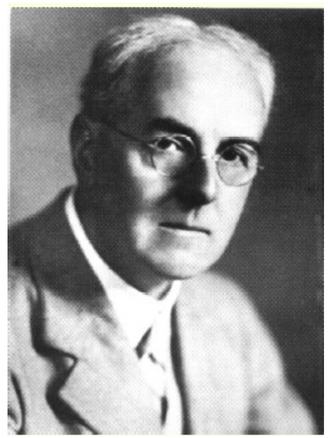
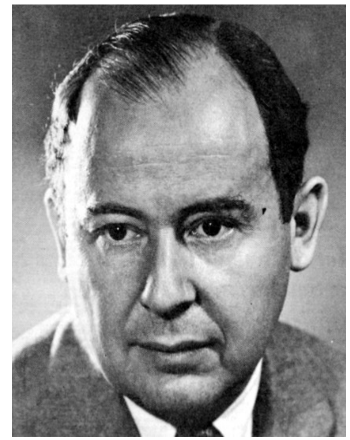
Numerical climate models
(numerical weather simulators)

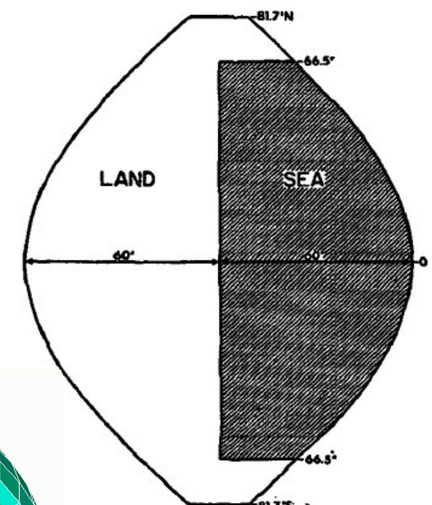
Wilhelm Bjerknes
(1862–1951)



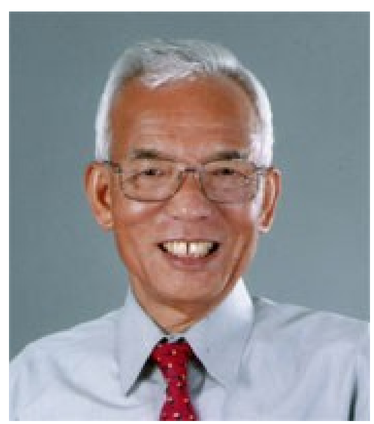
L. F. Richardson
(1881–1953)



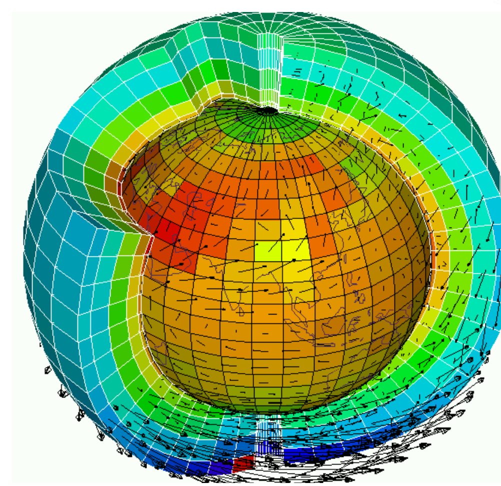
J. von Neumann
(1903–1957)

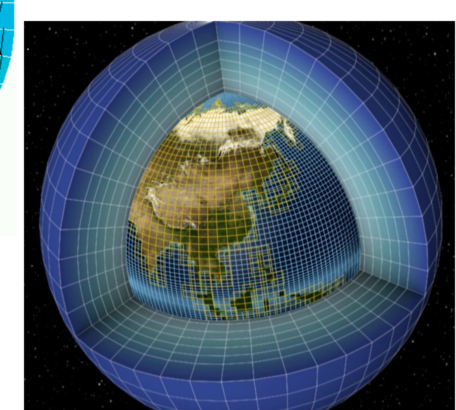


Jule Charney
(1917-1981)

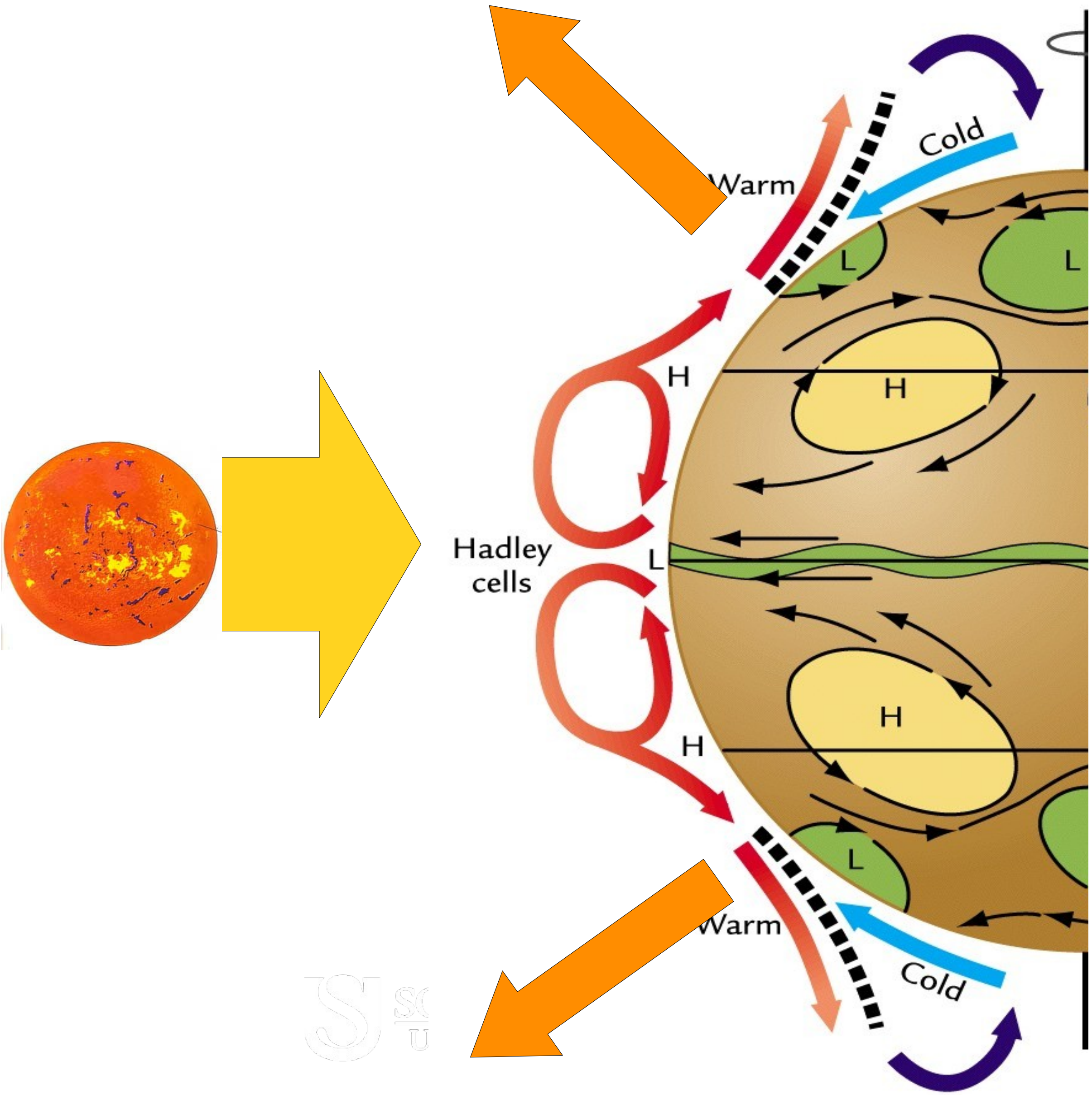


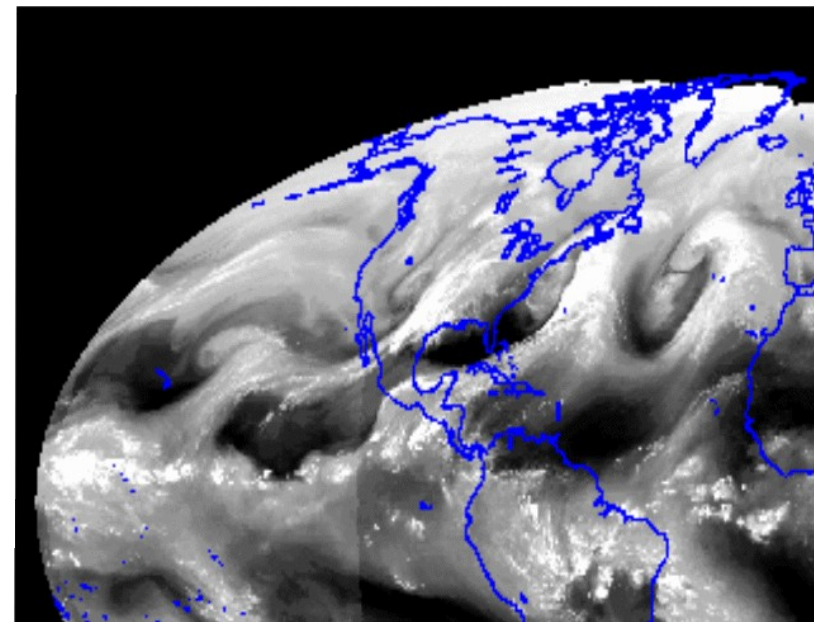
Syukuro Manabe
(1931-)

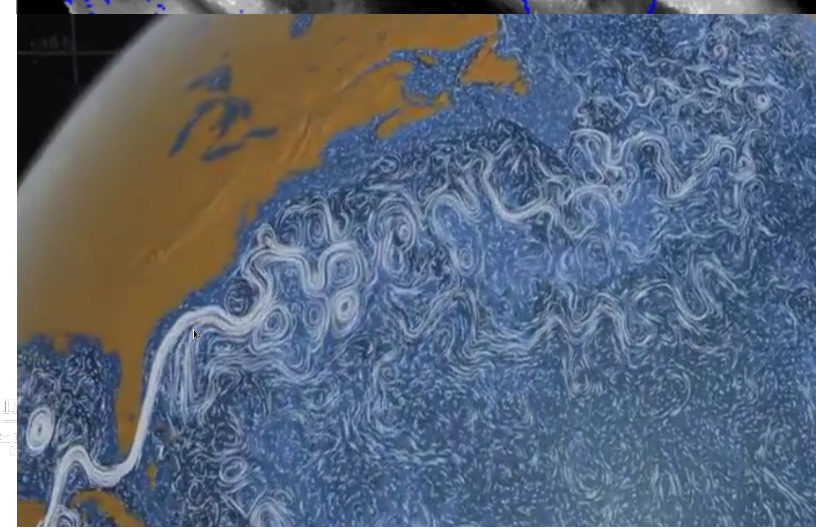




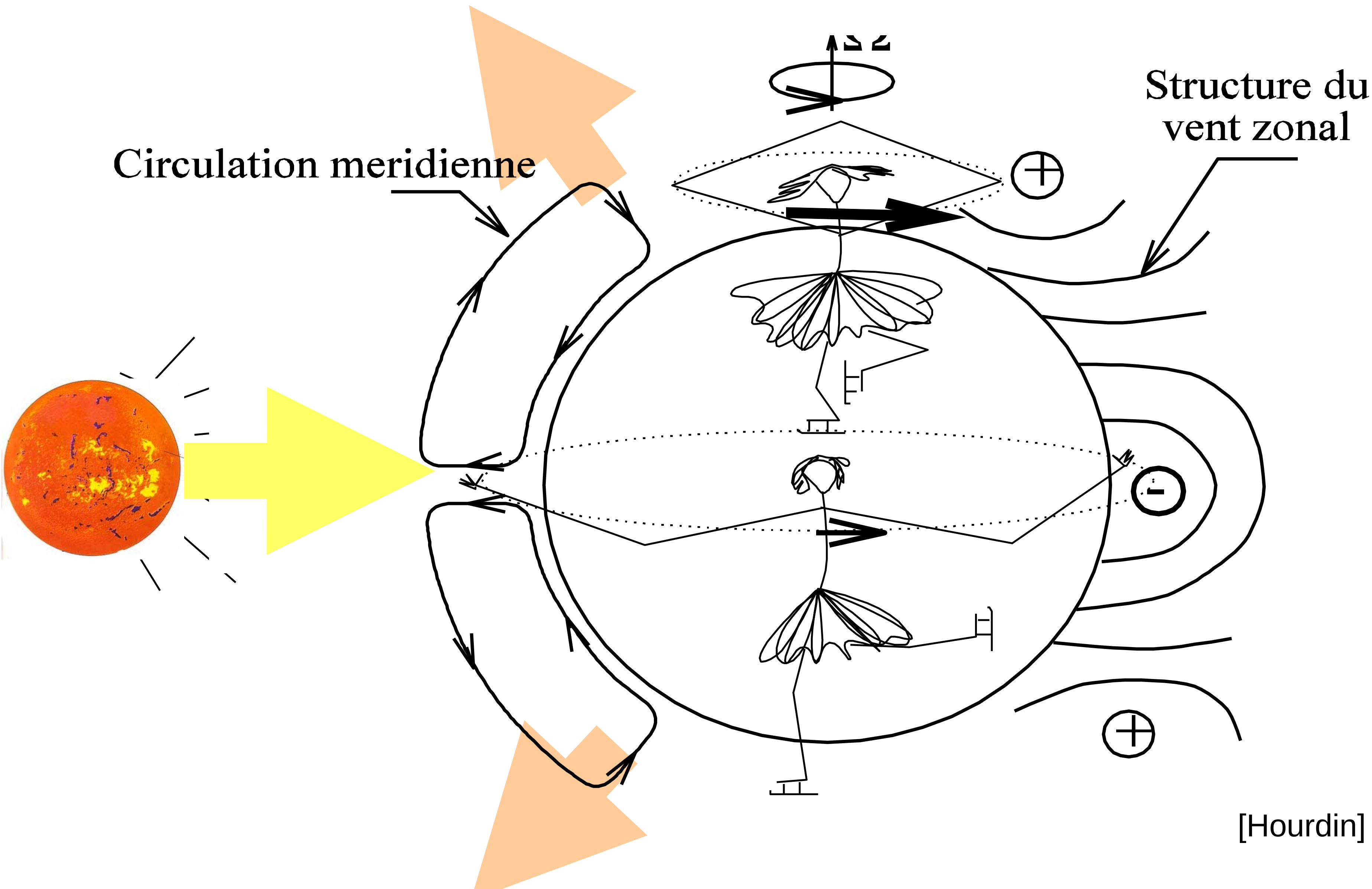
Large scale circulation: Meridional heat transport and the effects of Earth rotation



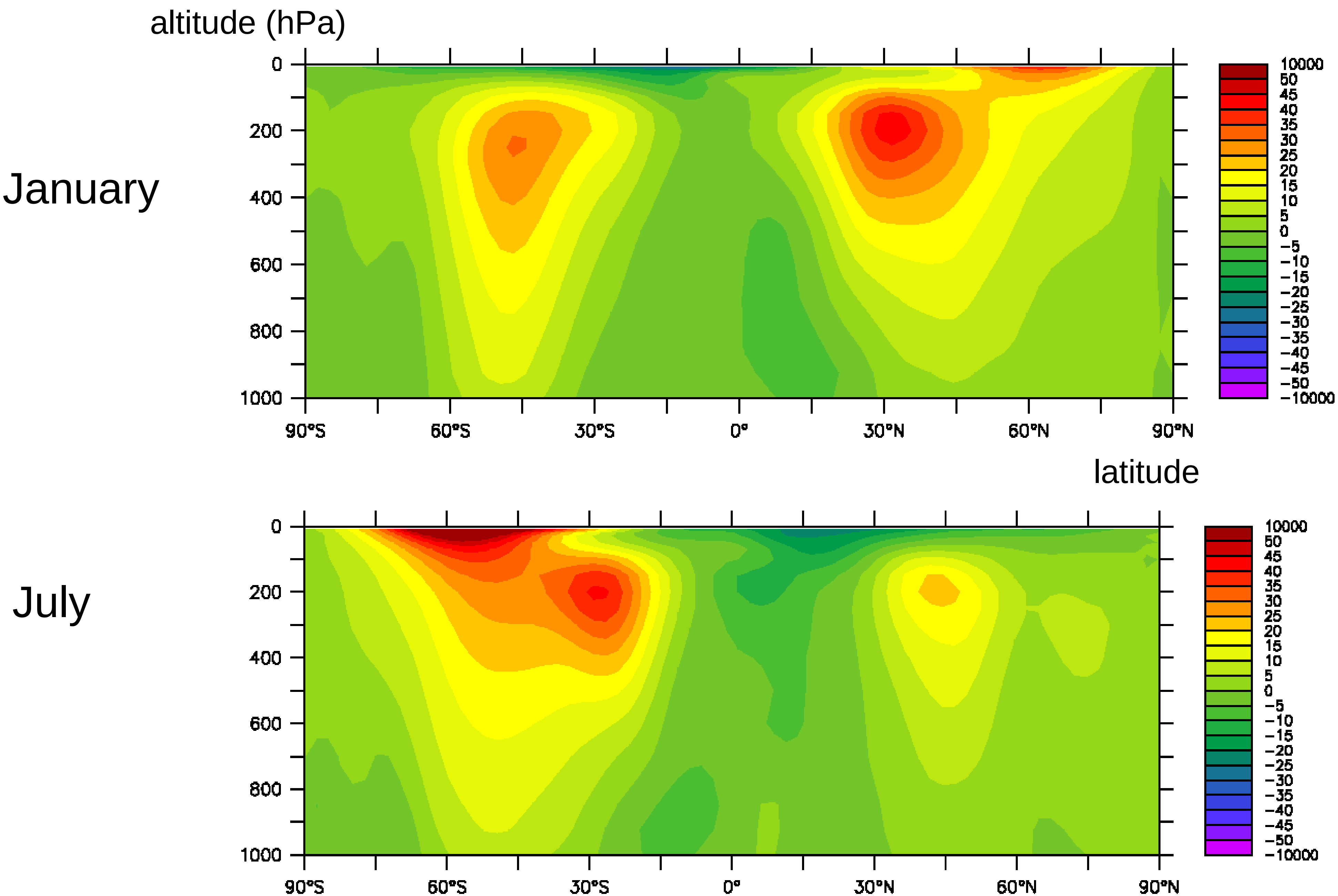




Hadley cell and its extension polarword

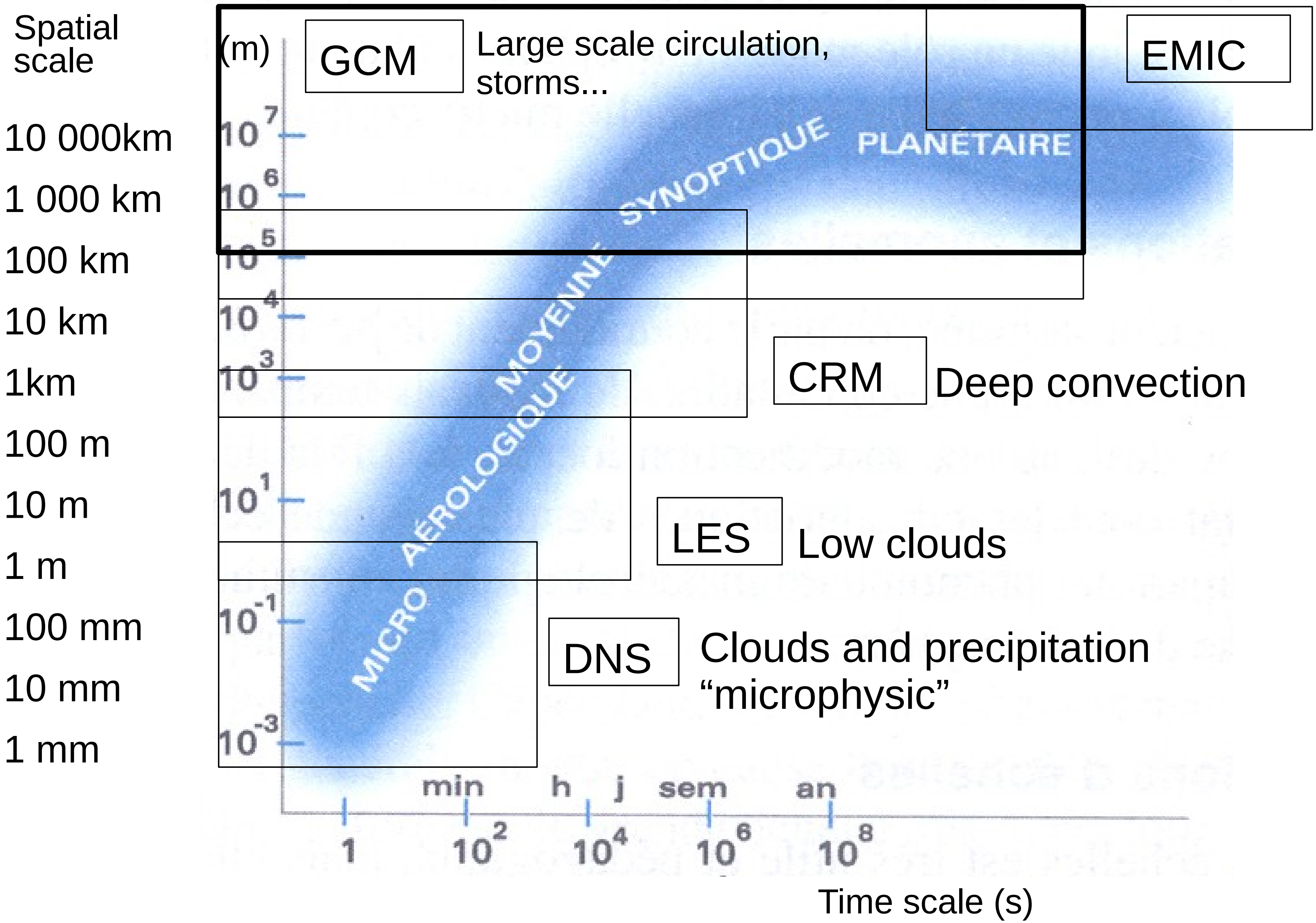


Zonal wind

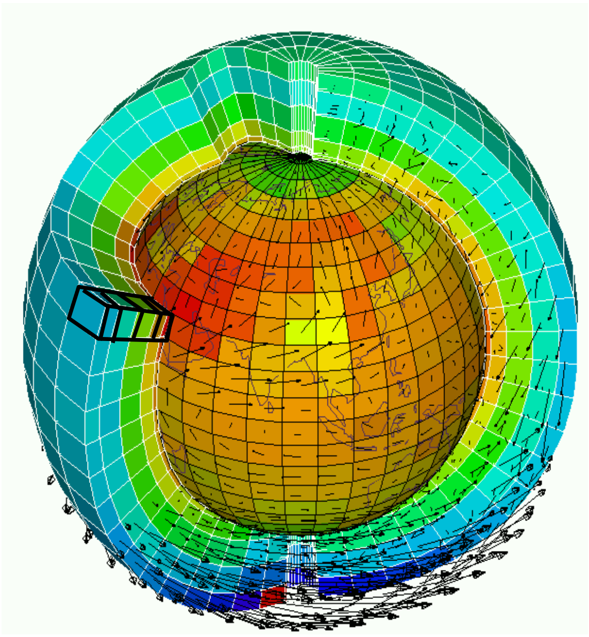


altitude (hPa)
January
July
latitude
0
200
400
600
800
1000
90°S
60°S
30°S
0°
30°N
60°N
90°N
10000
50
45
40
35
30
25
20
15
10
5
0
−5
−10
−15
−20
−25
−30
−35
−40
−45
−50
−10000

Relevant spatial and time scales



General circulation models (GCMs)



Dynamical core : discretized version of the equations of fluid mechanics

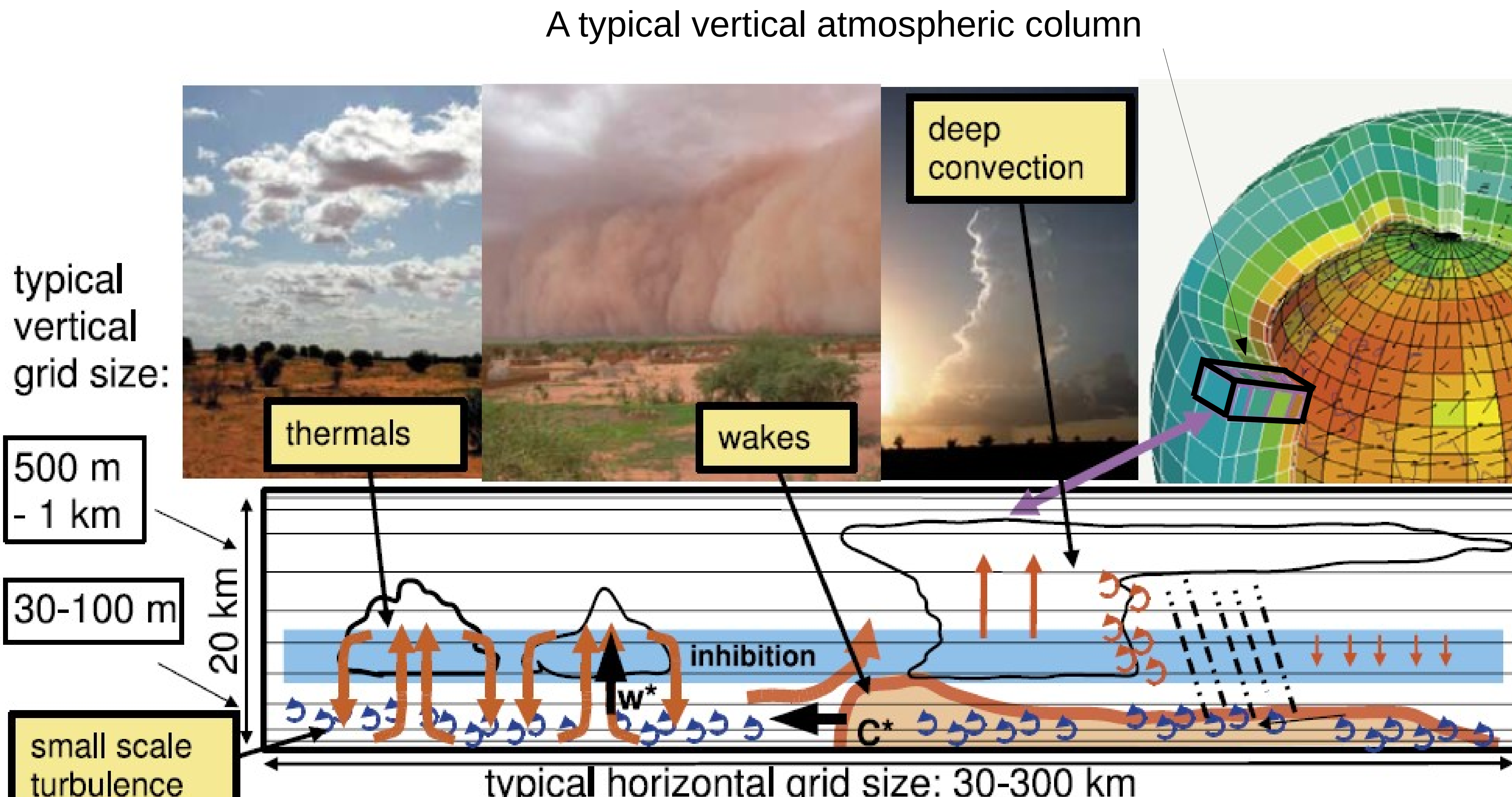
- Mass Conservation
  $D\rho/Dt + \rho \, \mathrm{div}\underline{U} = 0$
- Energy Conservation
  $D\theta / Dt = Q / Cp \; (p_0/p)^\kappa$
- Momentum Conservation
  $D\underline{U}/Dt + (1/\rho)\, \underline{\mathrm{grad}}p - \underline{g} + 2\, \underline{\Omega} \wedge \underline{U} = \underline{F}$
- 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

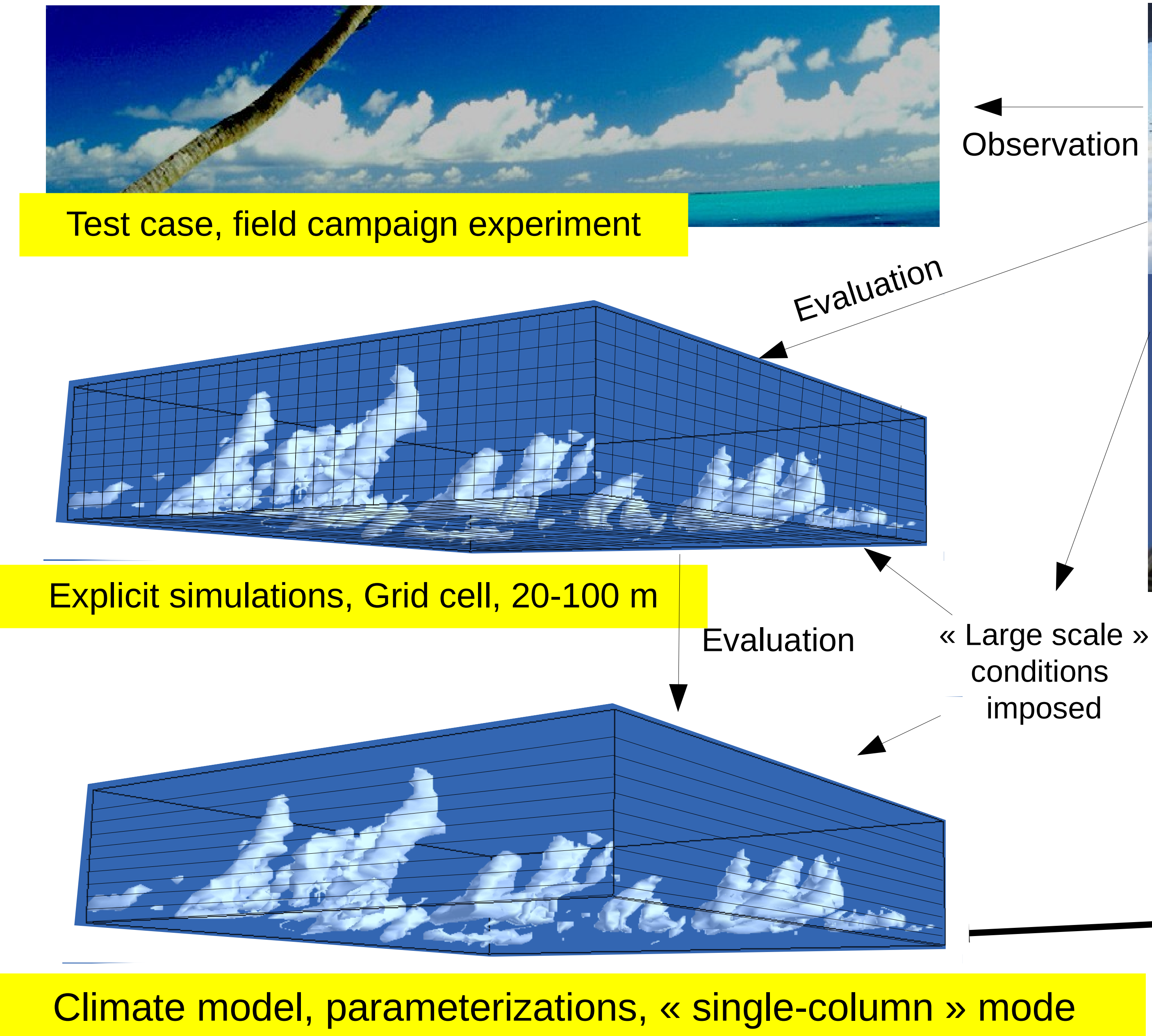
Modeling of unresolved scales
Development of parameterization

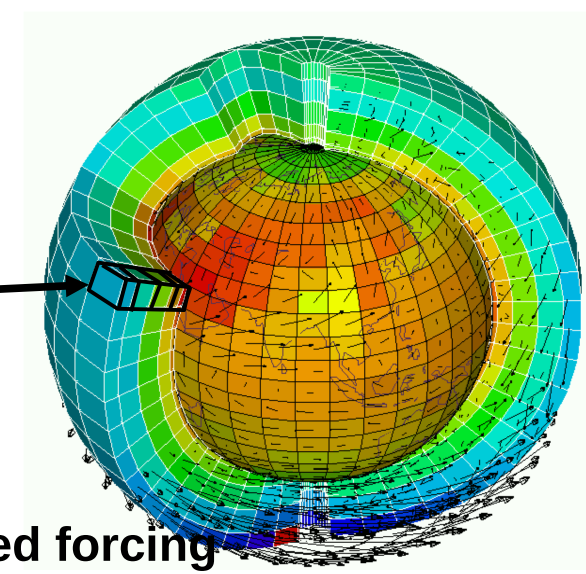


[Rio et al, GRL, 2009]

Typical time step : a few minutes to half an hour

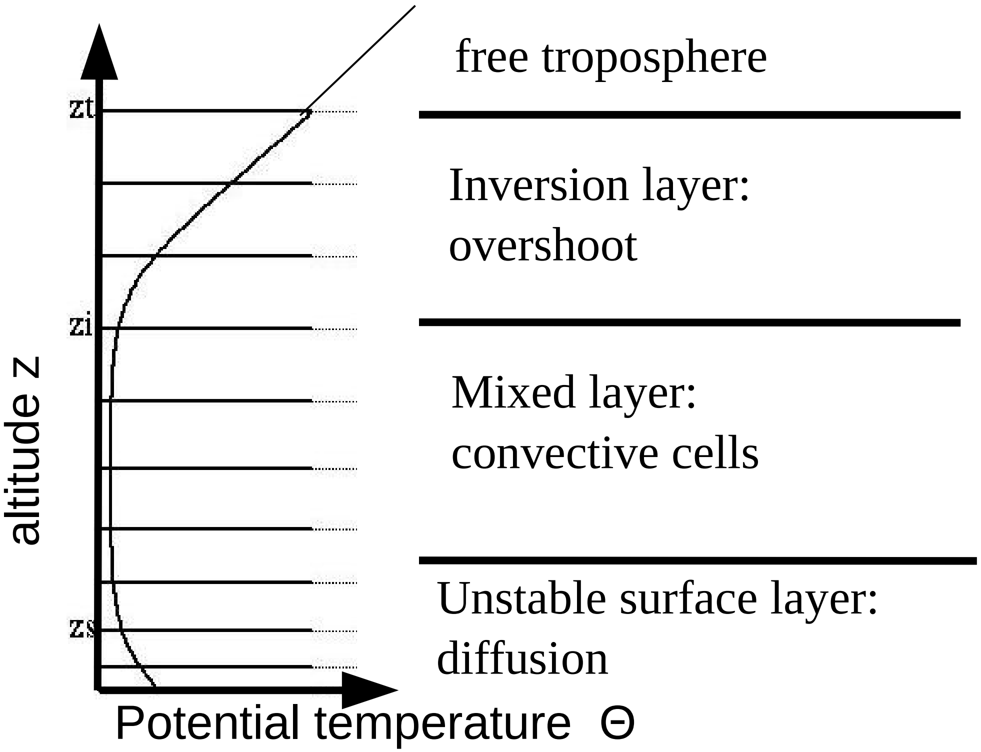
Parameterization development and the use of high resolution explicit models

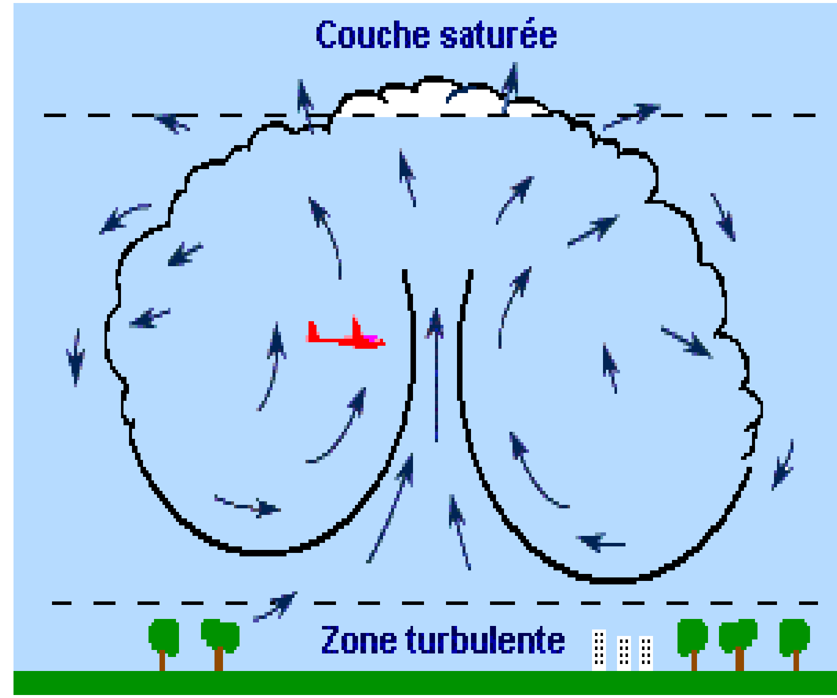




→ **Parameterizations are evaluated against other models**
→ **Can be done for realistic test cases but also with more idealized forcing (check the response of the parameterization to perturbations)**

Convective boundary layer clouds

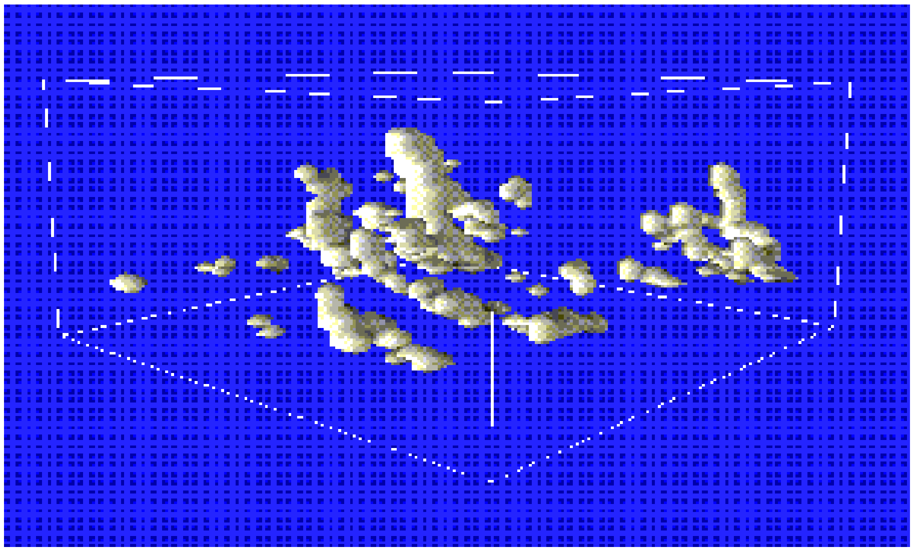




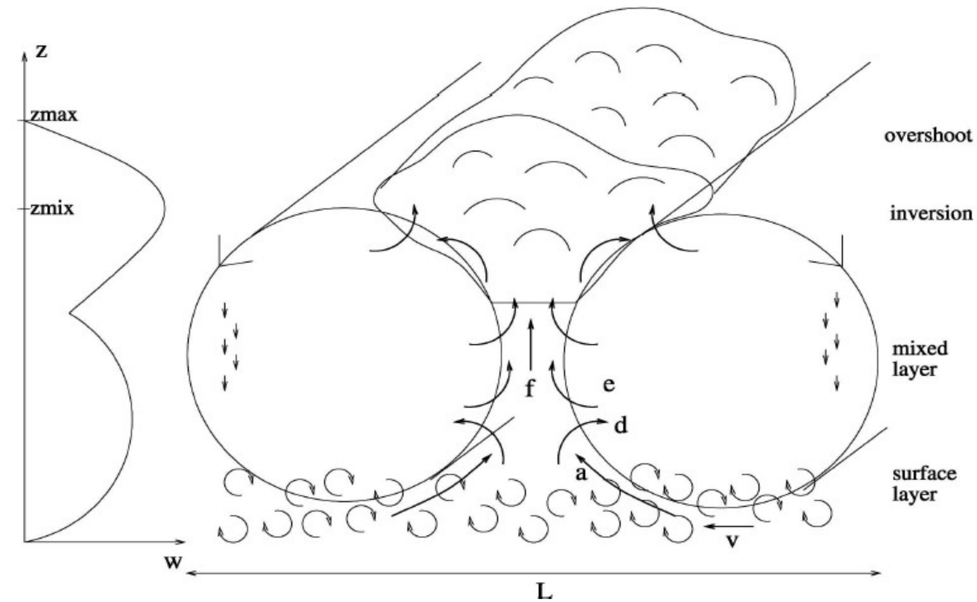
http://www.astrosurf.org/lombry/meteo-vol-a-voile.htm

Convective boundary layer clouds

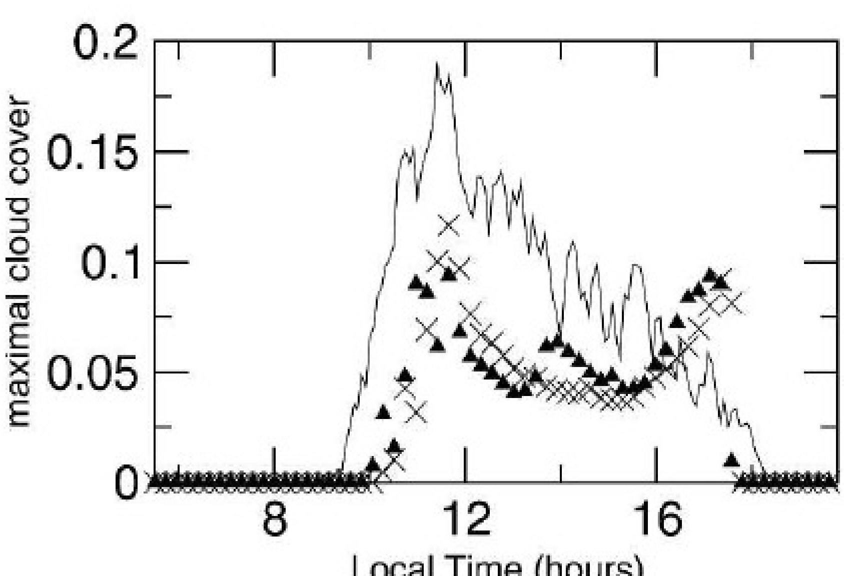
Reference simulation (LES model)

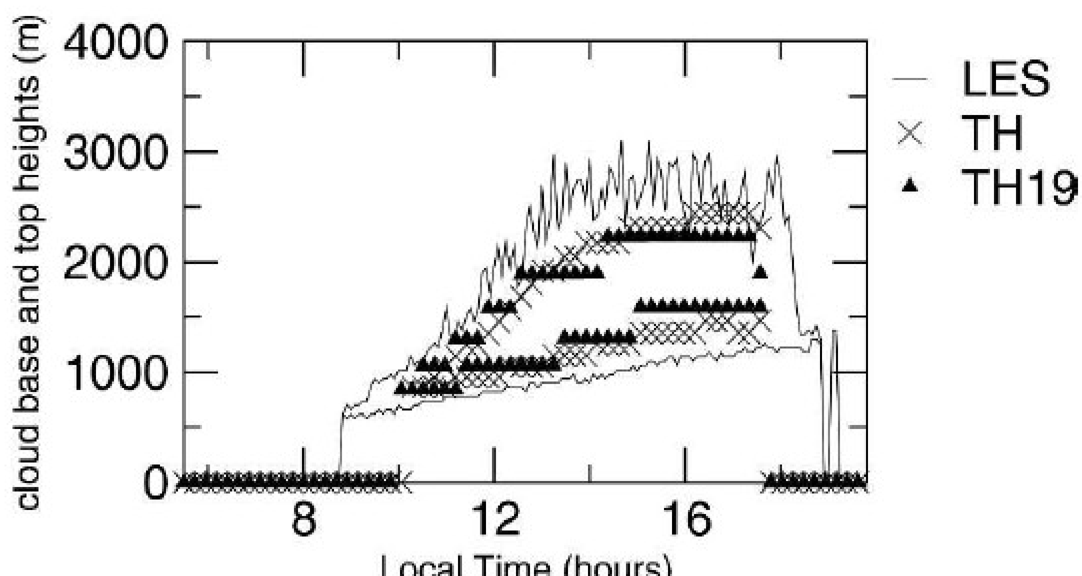


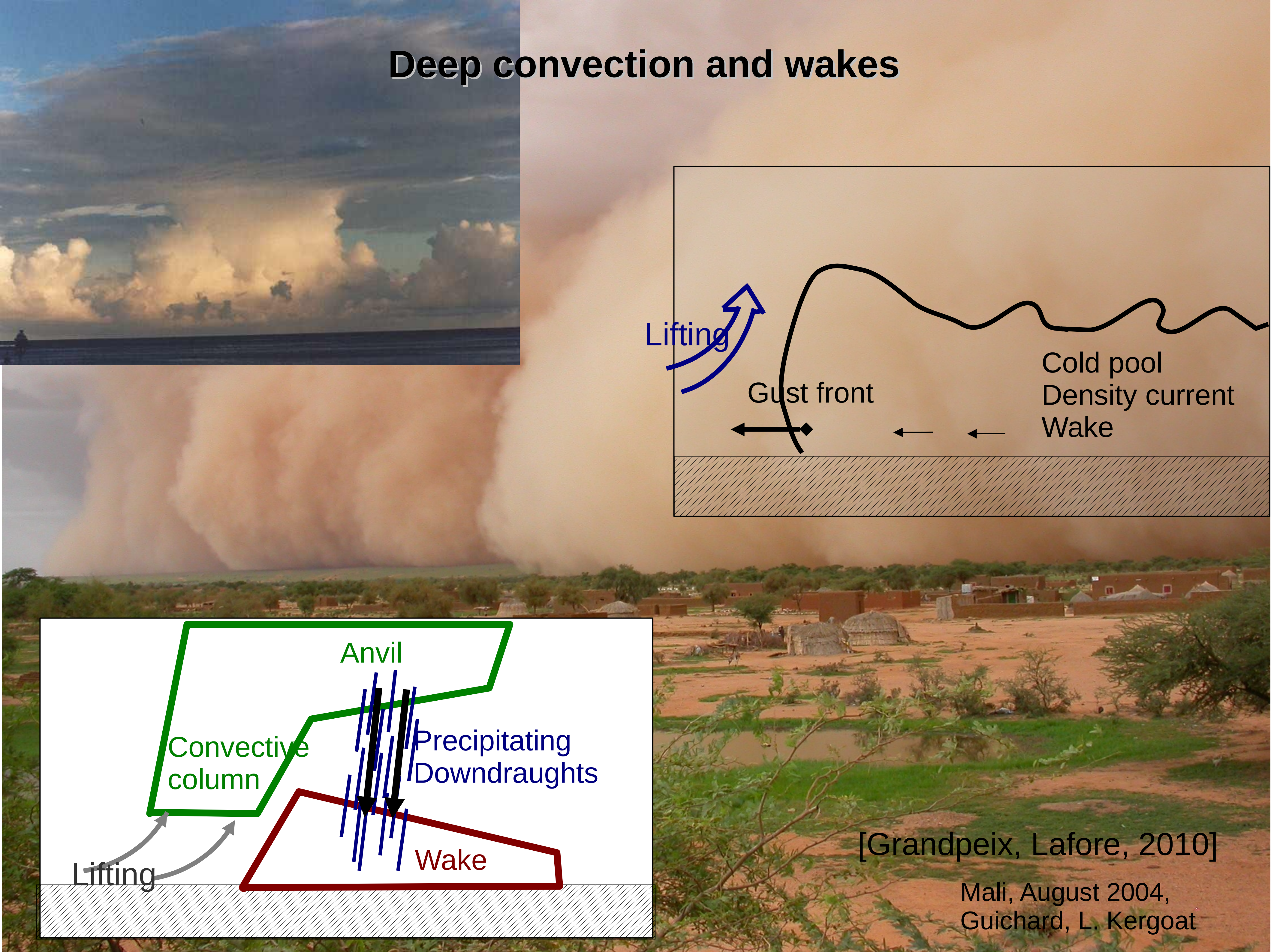
Heuristic model for the parameterization



Comparison between reference model and single column model fir case studies

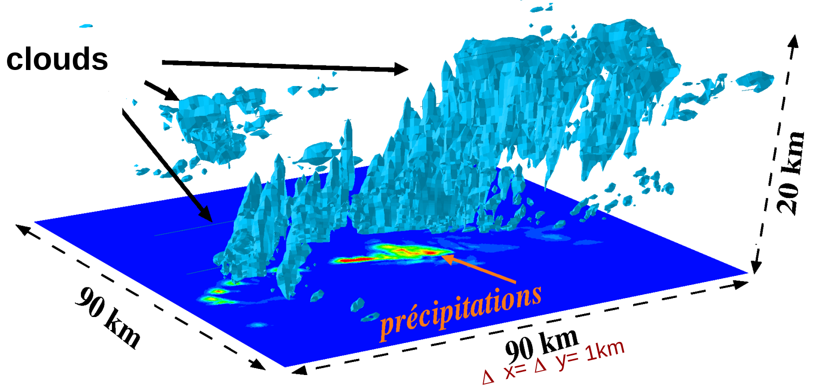




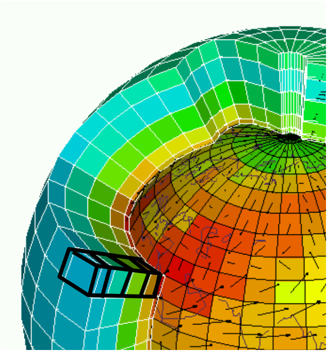

Deep convection and wakes
Lifting
Gust front
Cold pool
Density current
Wake
Anvil
Convective column
Precipitating Downdraughts
Lifting
Wake
[Grandpeix, Lafore, 2010]
Mali, August 2004,
Guichard, L. Kergoat

A multi-step evaluation, from 1D to 3D, with a progressive relaxation of constrains

LES or CRM models

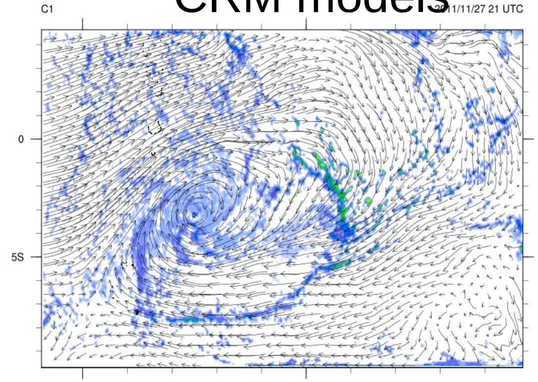


Single column model

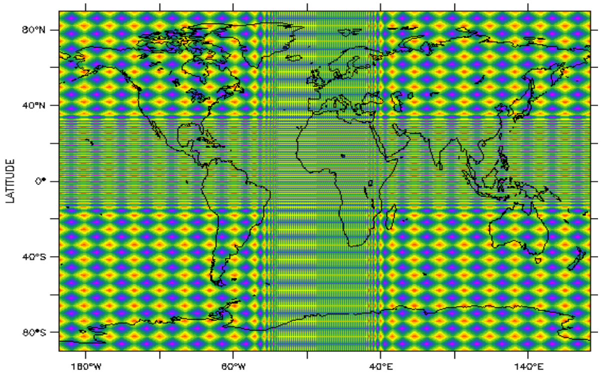


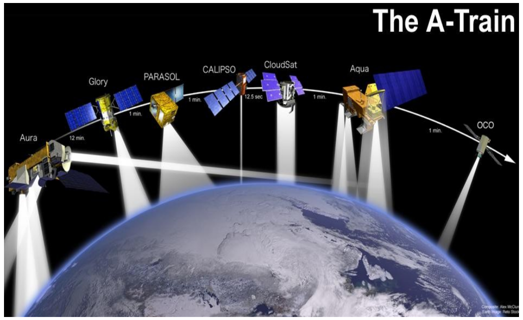
Same large scale atmospheric profile

Large domain CRM models

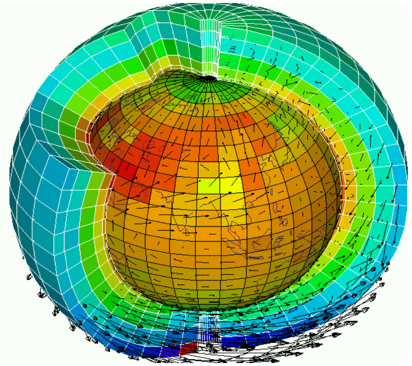


Same large scale circulation





Free or prescribed circulation



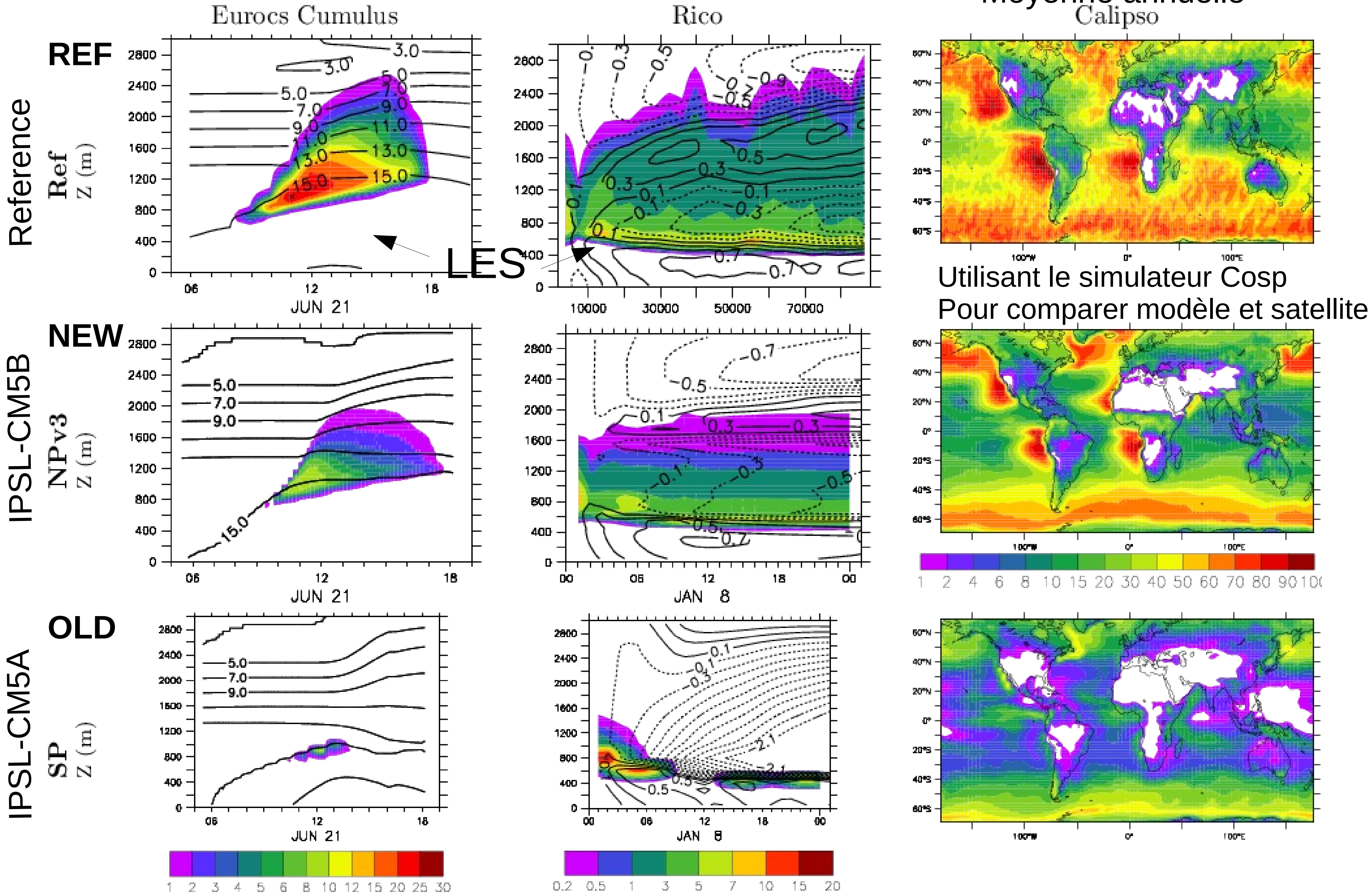
Le modèle du thermique et l'amélioration (robuste 1D&3D) des nuages bas

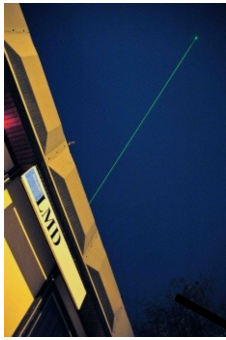
Cas test 1D

nébulosité (%) et vapeur d'eau (g/kg)

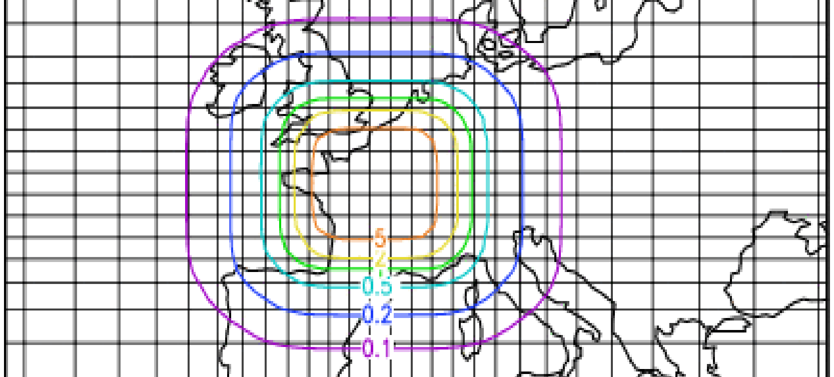
Simulations 3D

Couverture nuages bas (%)
Moyenne annuelle

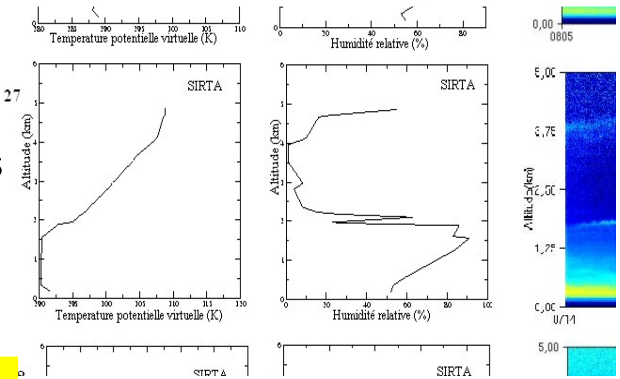




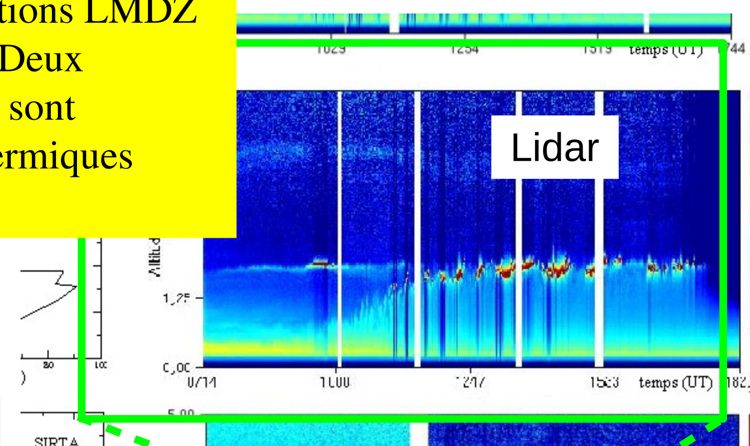
SIRTA observatory
a node for national and internationa networks

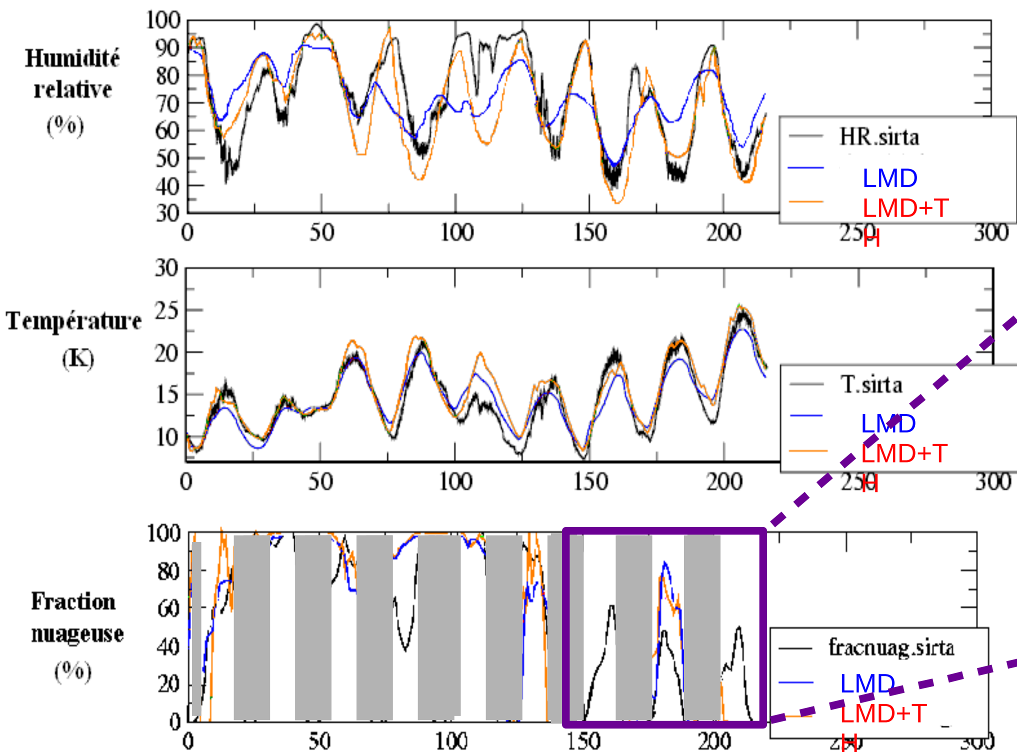


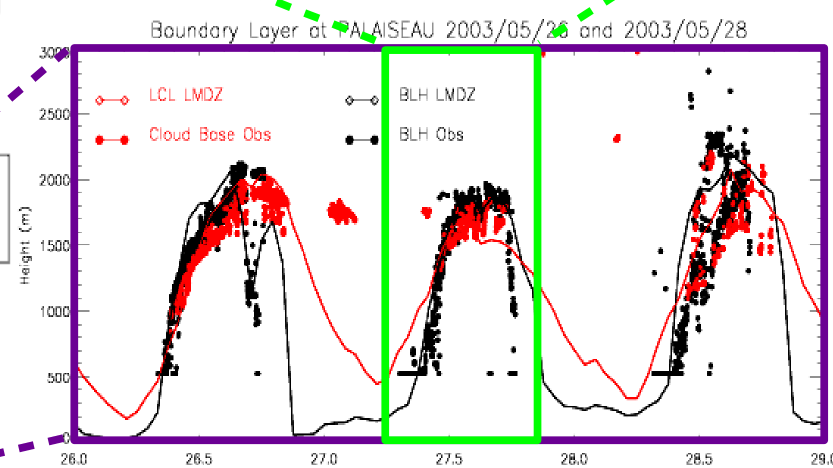
Sondages de Trappes



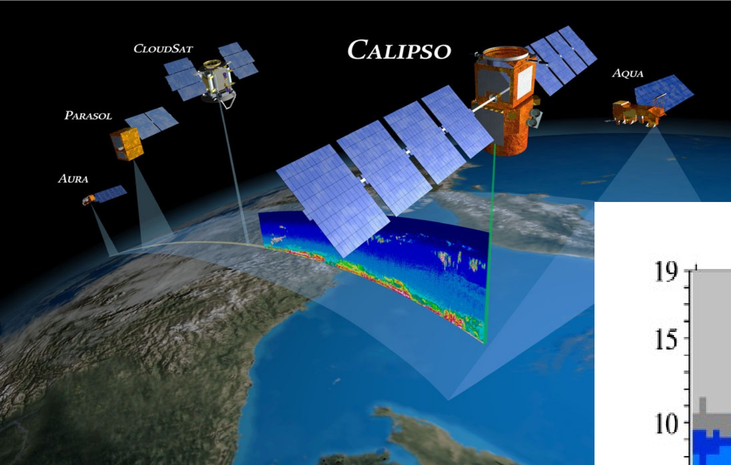
Comparaison de mesures SIRTA avec des simulations LMDZ guidées par des analyses et zoomé sur le SIRTA. Deux versions de la paramétrisation de la couche limite sont utilisées : couche limite du LMD avec ou sans thermiques (TH).



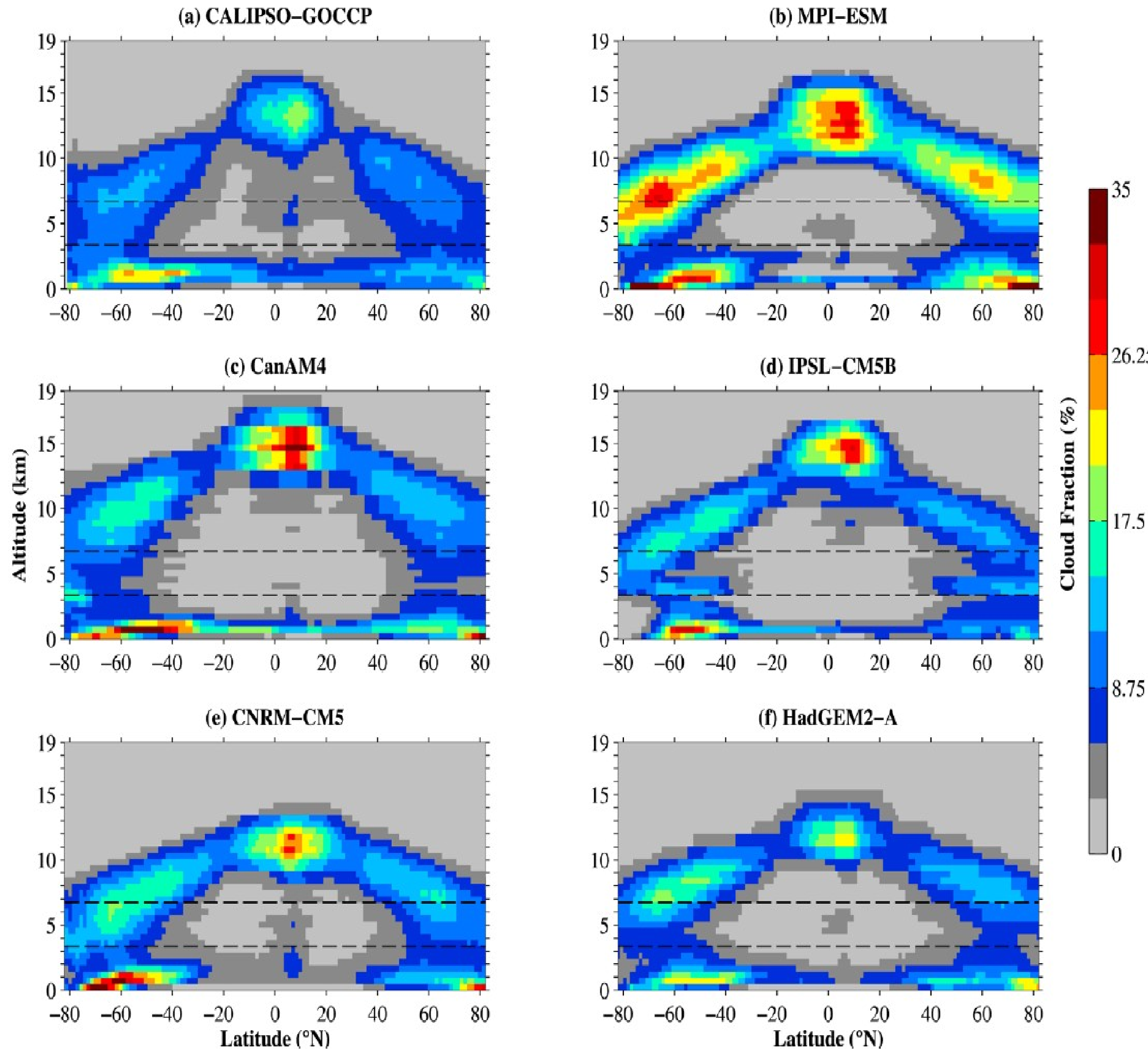




Hauteurs de couche limite et niveau de condensation
Diagnostics effectués par Anne Mathieu



Global scale, satellite observation

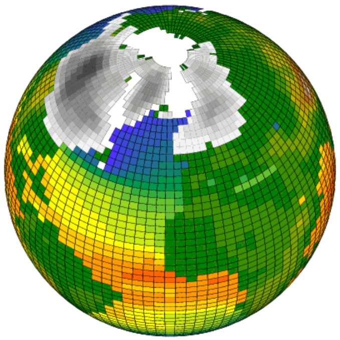


Zonal mean of the cloud vertical fraction observed by Calipso et simulated by models + obs. Simulator COSP

[Cesana & Chepfer, 2012]

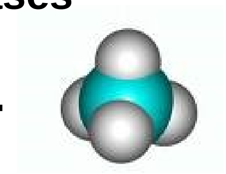
Land-sea contrasts and polar amplification in past and future climates

Last Glacial Maximum main forcings



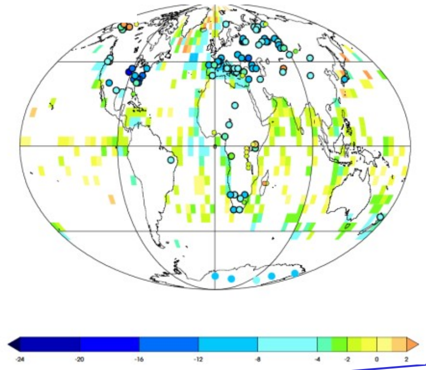
e-sheets

Greenhouse gases
CO2: 185 ppm,
CH4:350 ppb …



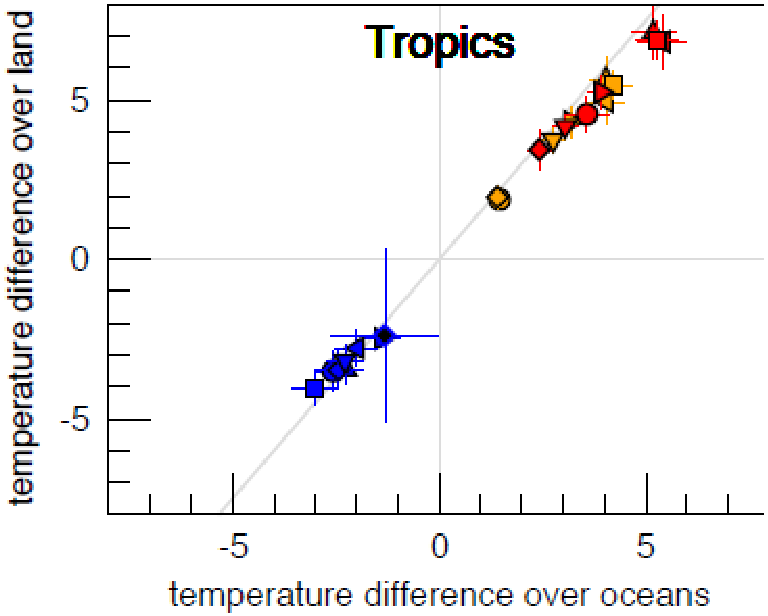
LGM climate reconstructions

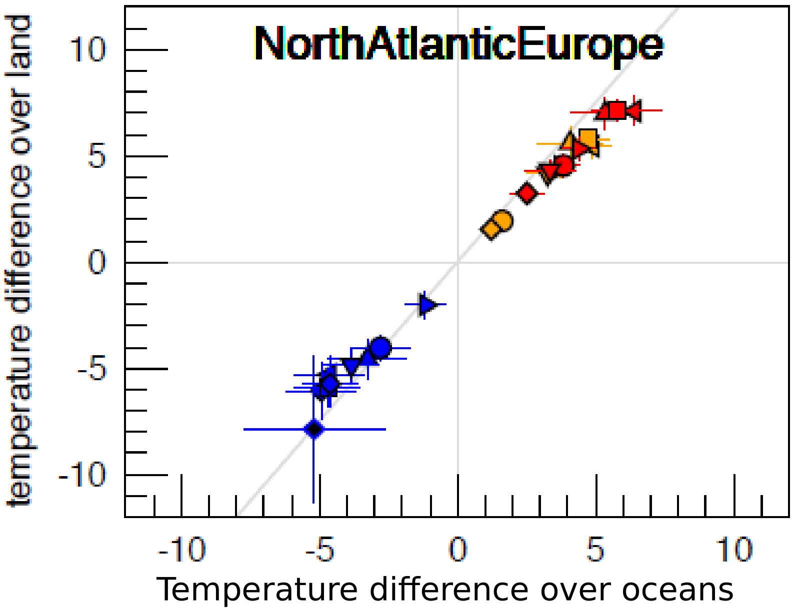
Land data
(pollen and plant macrofossils):
Bartlein et al, Clim Dynam 2011
Ocean data (multi proxy):
MARGO, NGS 2009
Ice-core data:
Masson-Delmotte et al pers. comm



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

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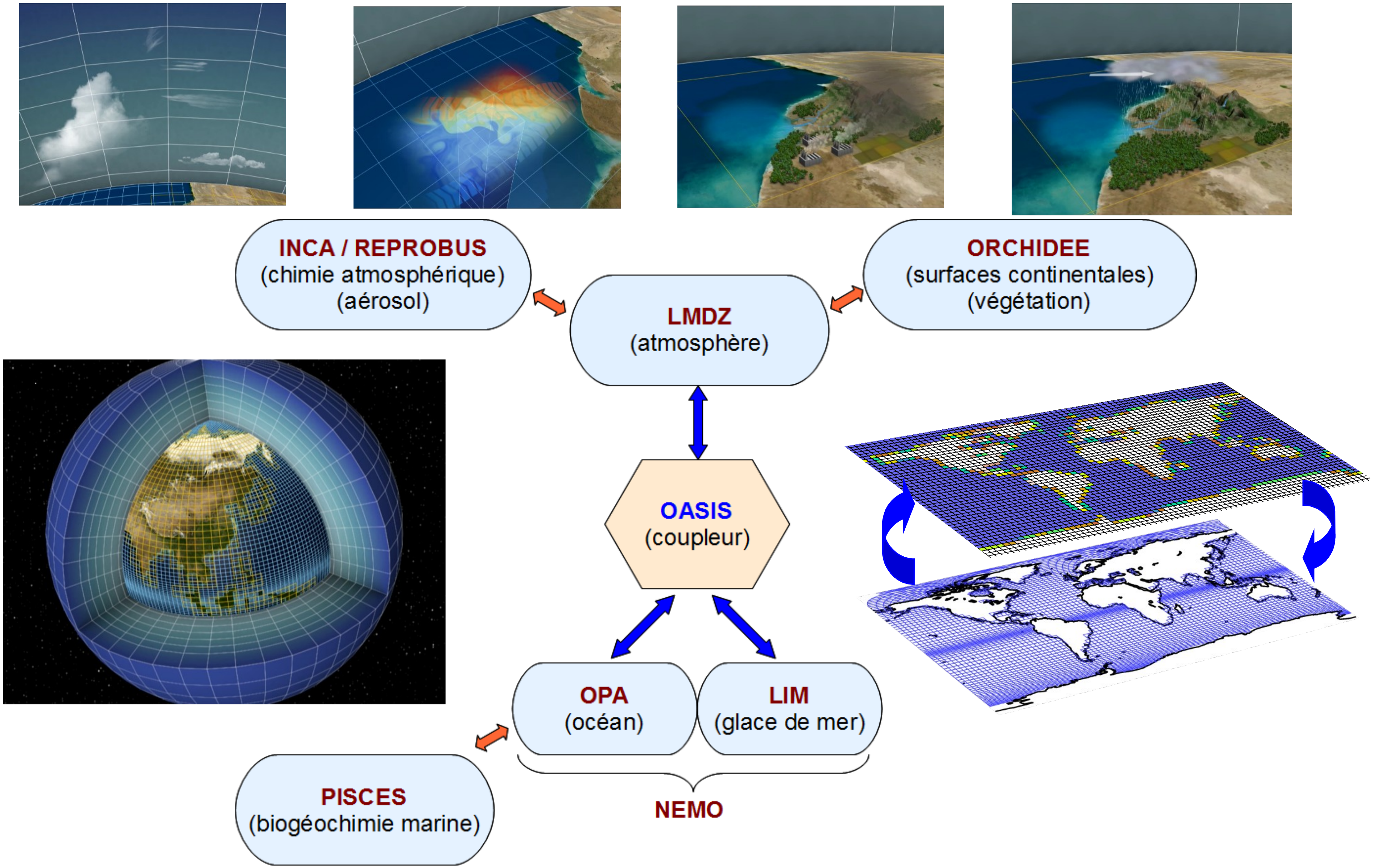
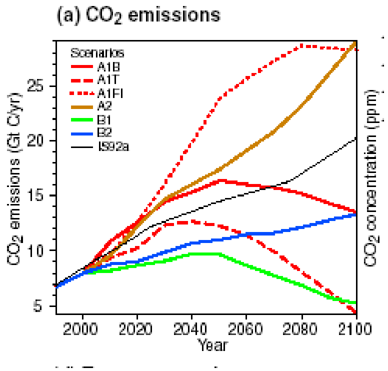
The IPSL Earth System Model

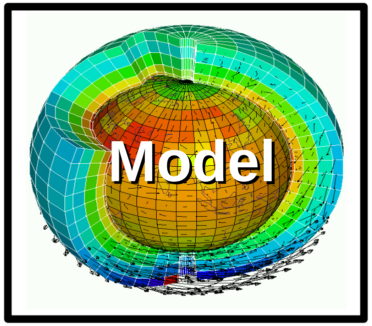


Climate simulations

Initial conditions
Temperature
water vapour
salinity
all over the globe

Boundary conditions (forcings)
Ex: insolation
Greenhouse gases





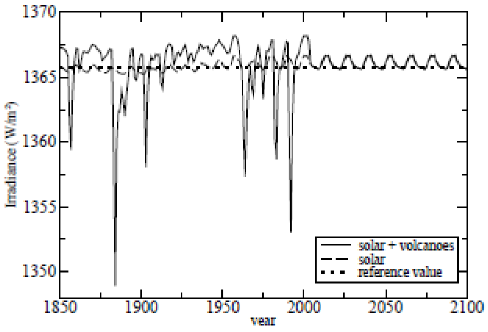
Results
Temperature
water vapour
salinity

Statistical analysis

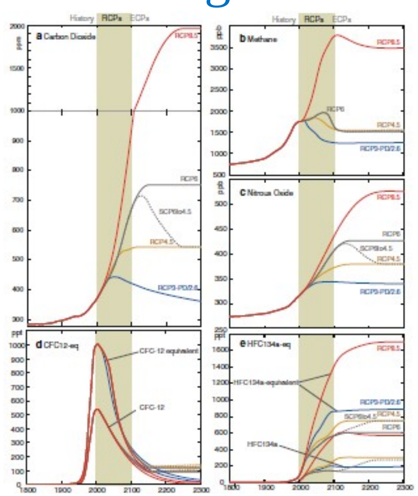
The IPSL Earth System Model

Natural and anthropogenic forcings

Solar and volcanoes

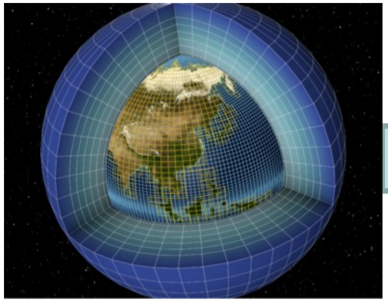


Green house gases and active gases

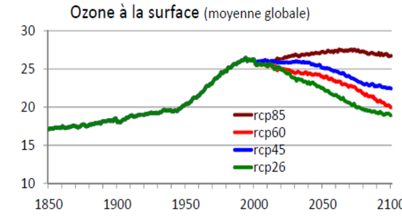


CO_2 concentration

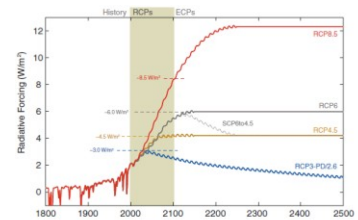
IPSL-CM5A-LR



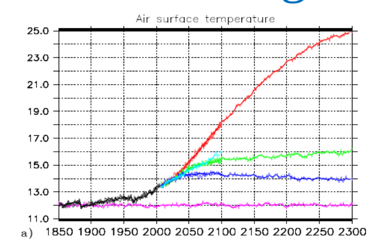
Atmospheric composition



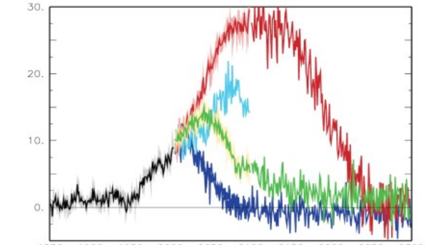
Radiative forcings



Climate changes

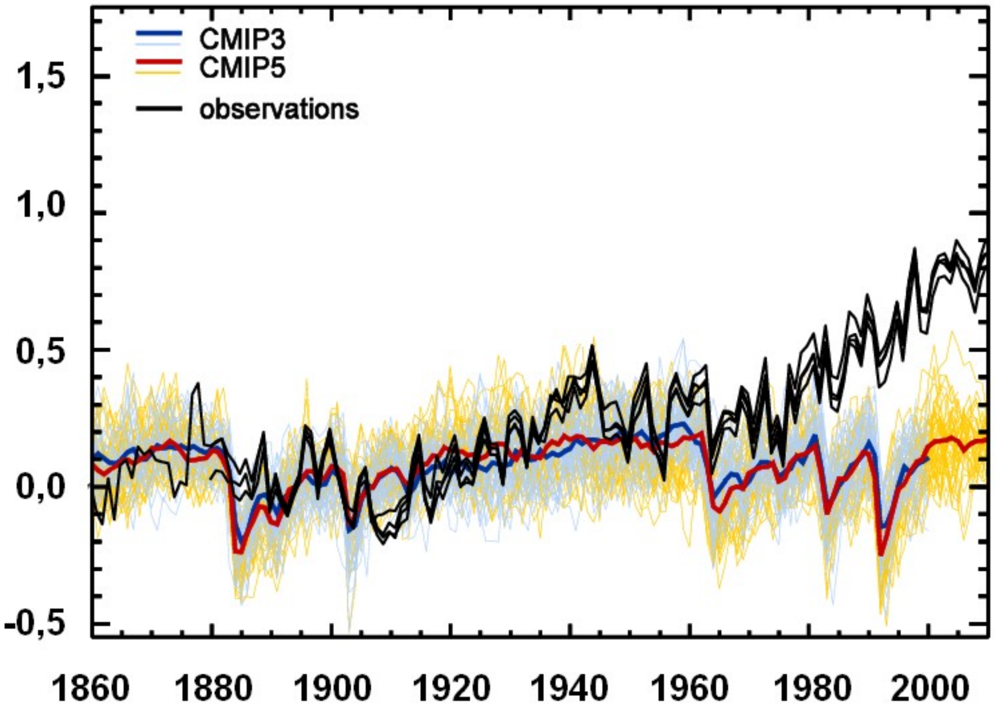


Authorized CO_2 emissions

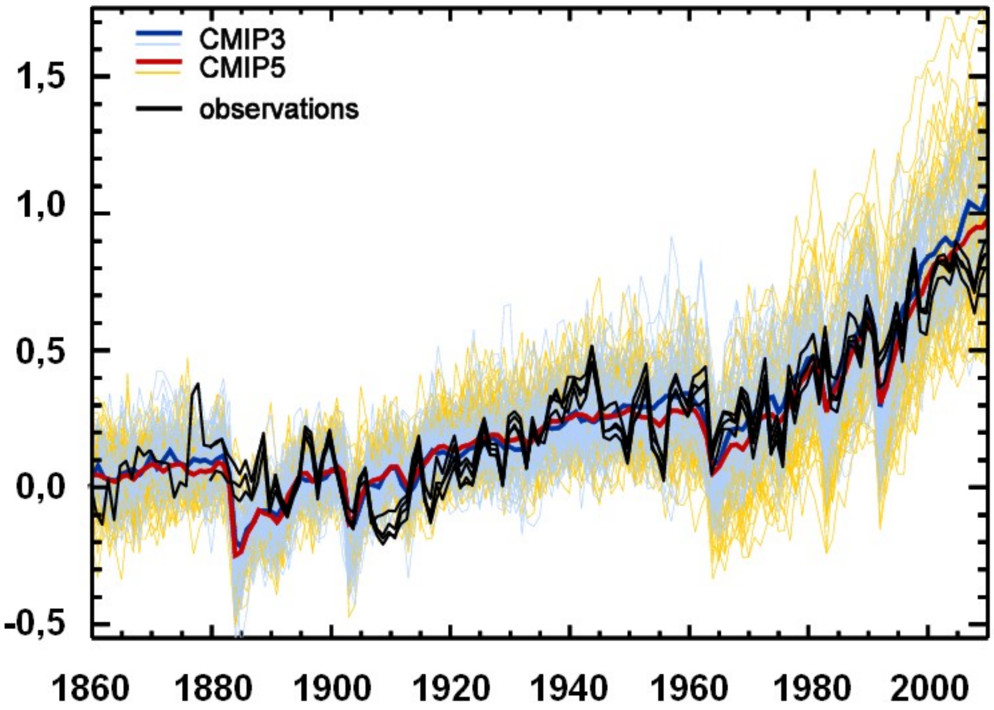


Recent Earth surface temperature trend

Simulations with natural forcings only

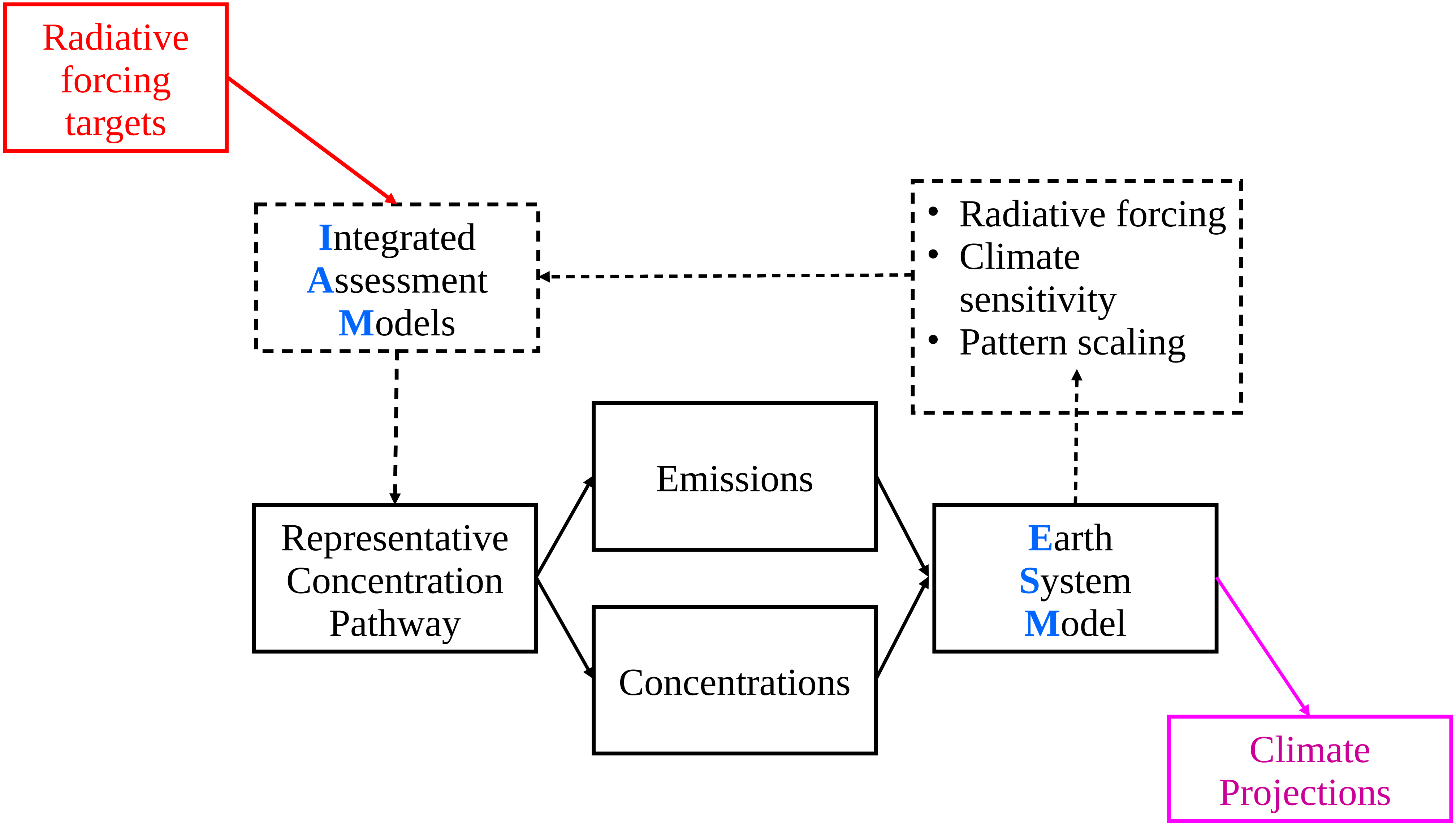


Simulations with natural and anthropological forcings



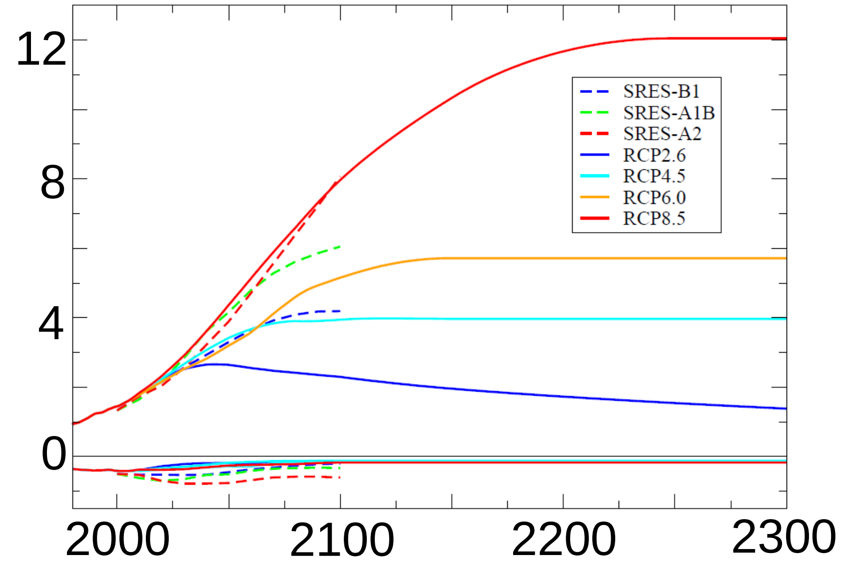
[IPCC, 2013]

Scenario for future climate change projections



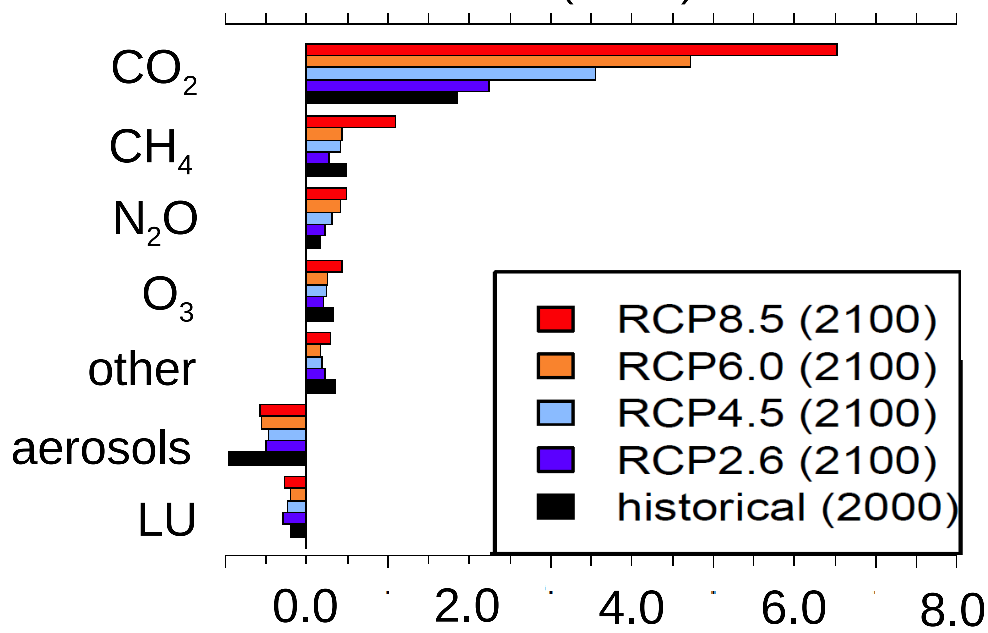
Radiative forcing of future scenarios

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

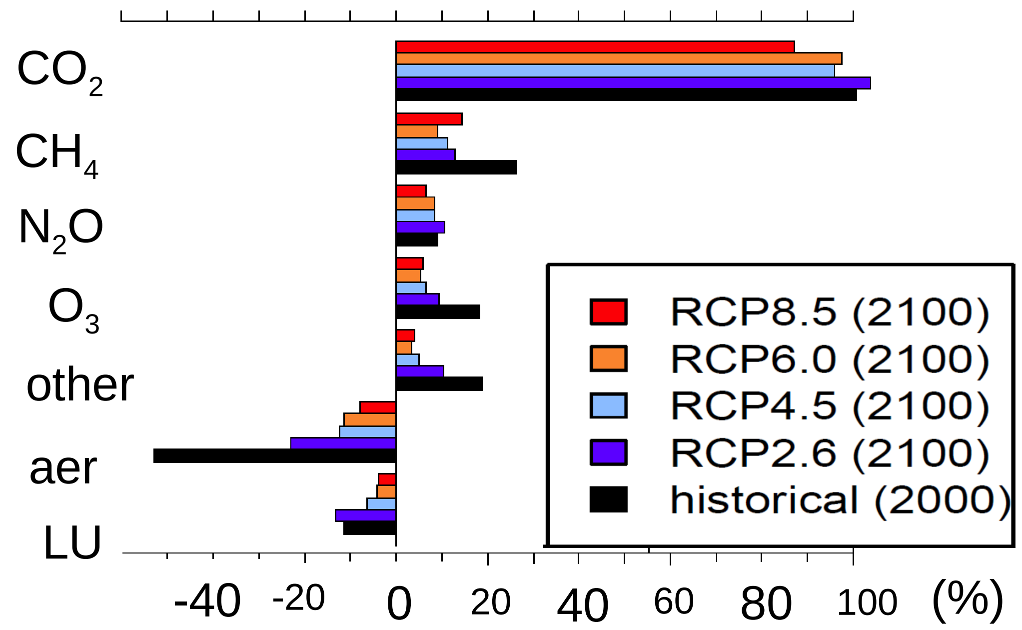


Contribution of individual forcings to total forcing relative to ***1850***

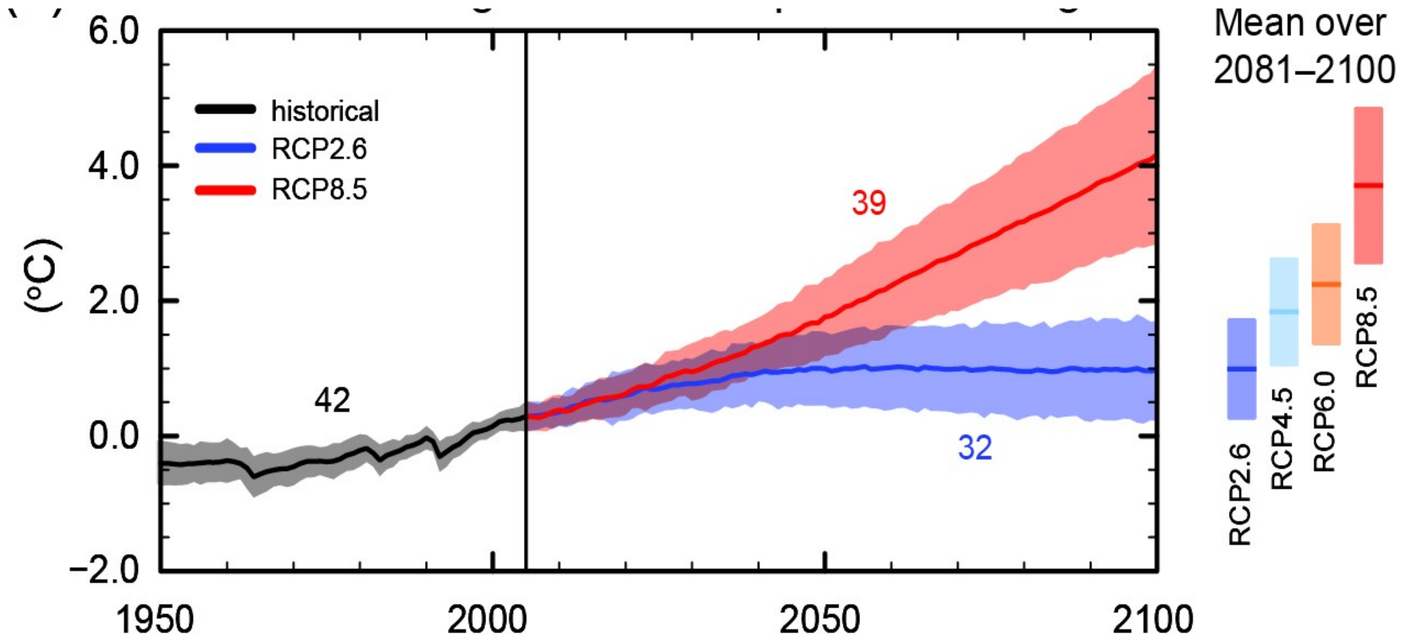
Values ($W.m^{-2}$)

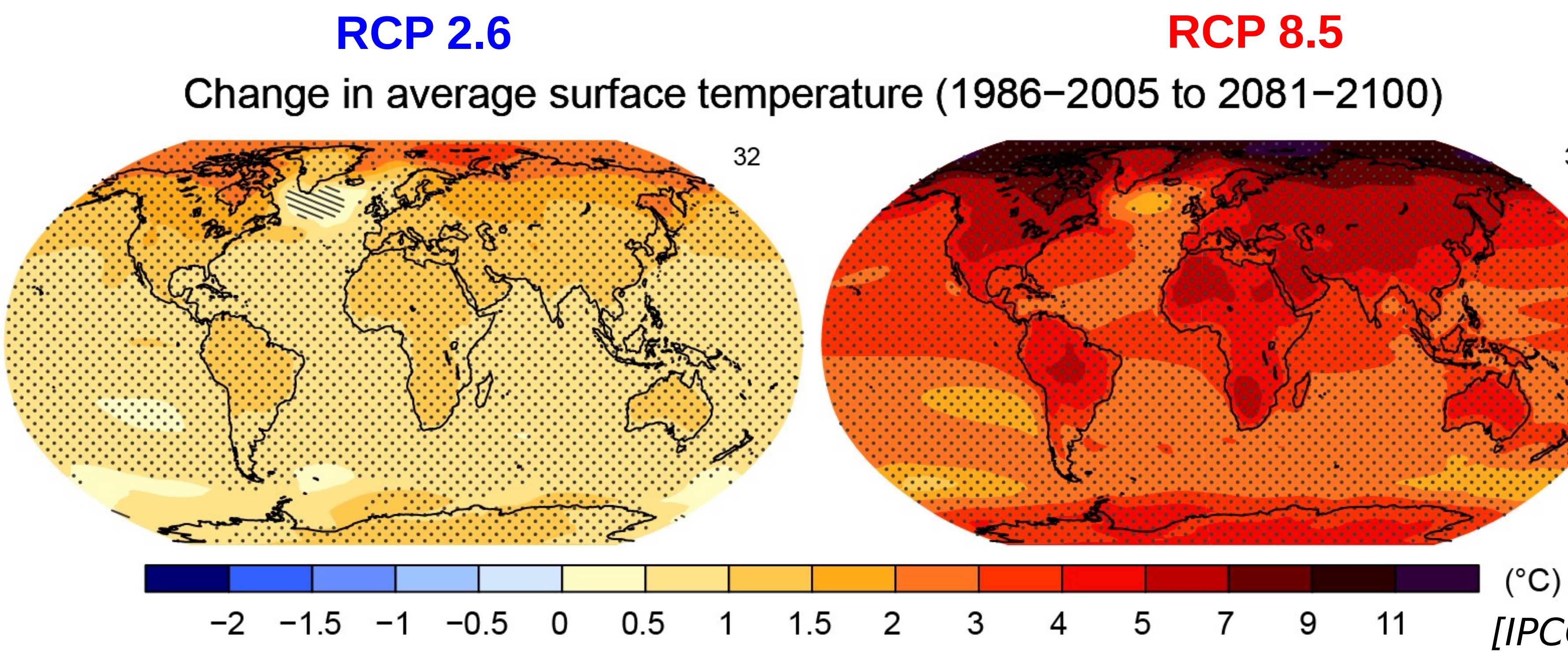


Relative values (%)



Global mean surface temperature change





[IPCC 2013]

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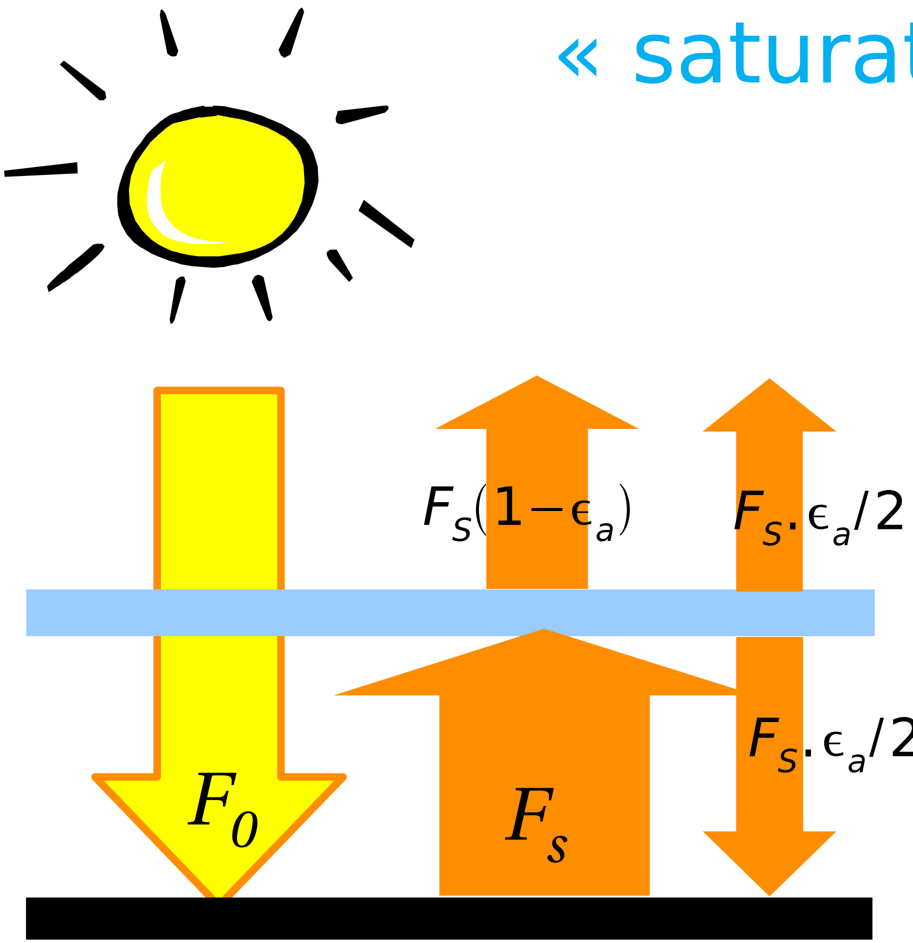
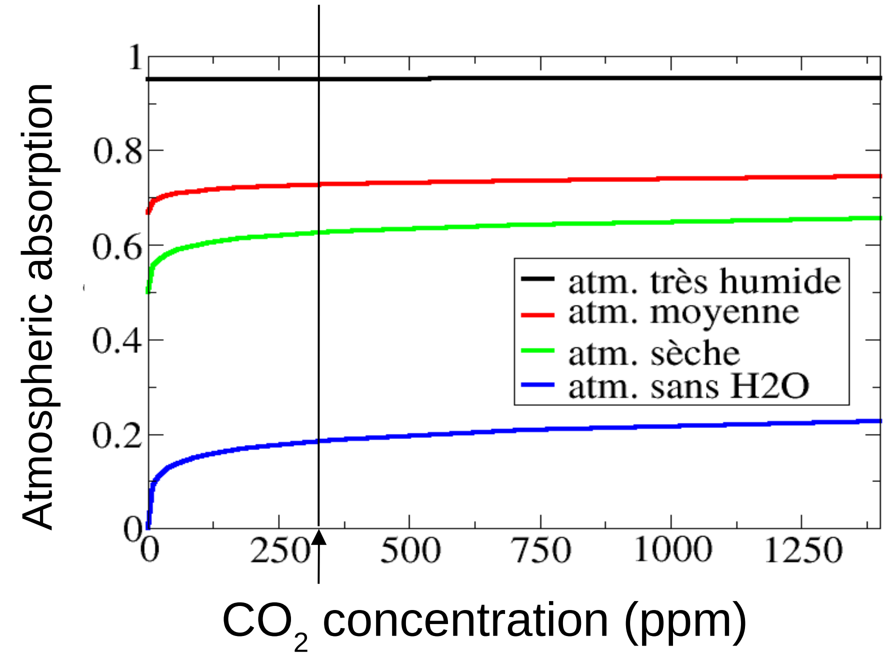
The CO2 greenhouse effect and the « saturation » paradox



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

Mean atmospheric absorption in the infrared

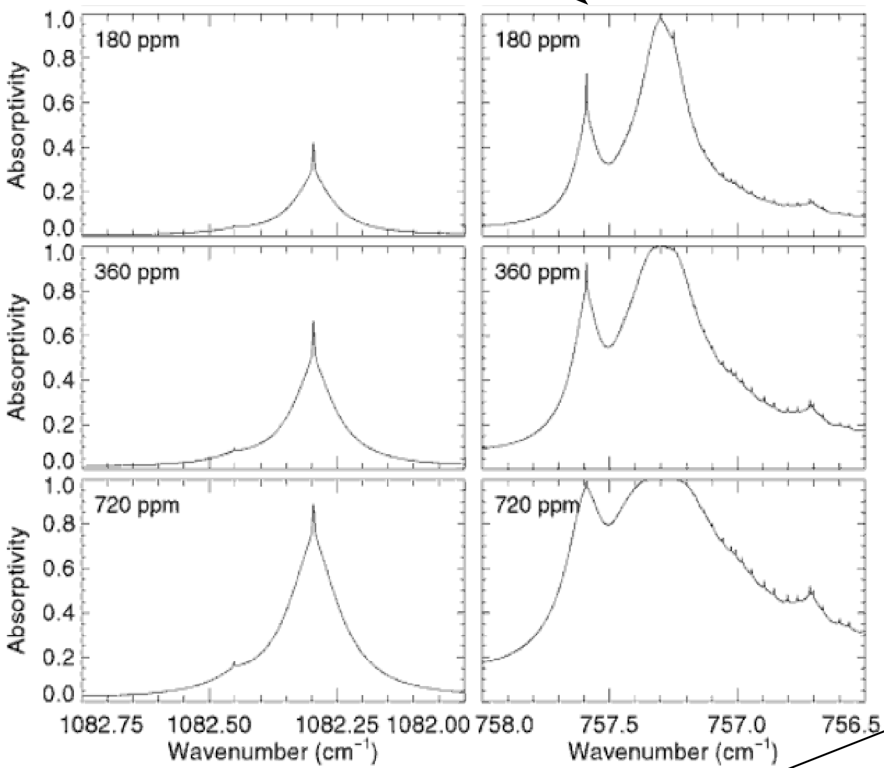


How can the greenhouse effect increase if the atmospheric absorption don't?

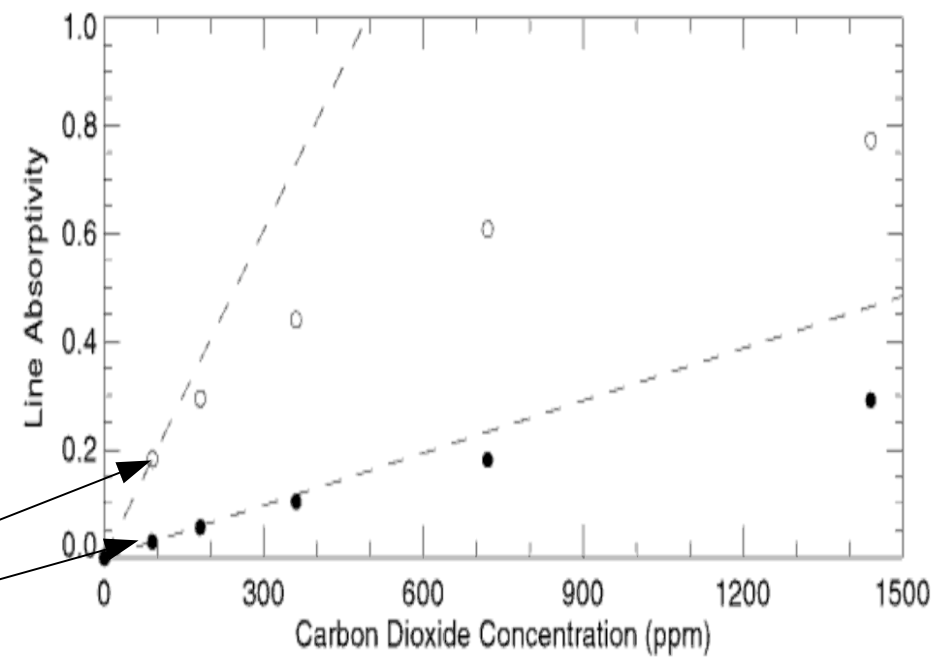
Saturation of absorption bands

Absorption by CO_2, for a vertical column of atmosphere

Absorption spectra, for 3 CO2 concentrations and two narrow bands



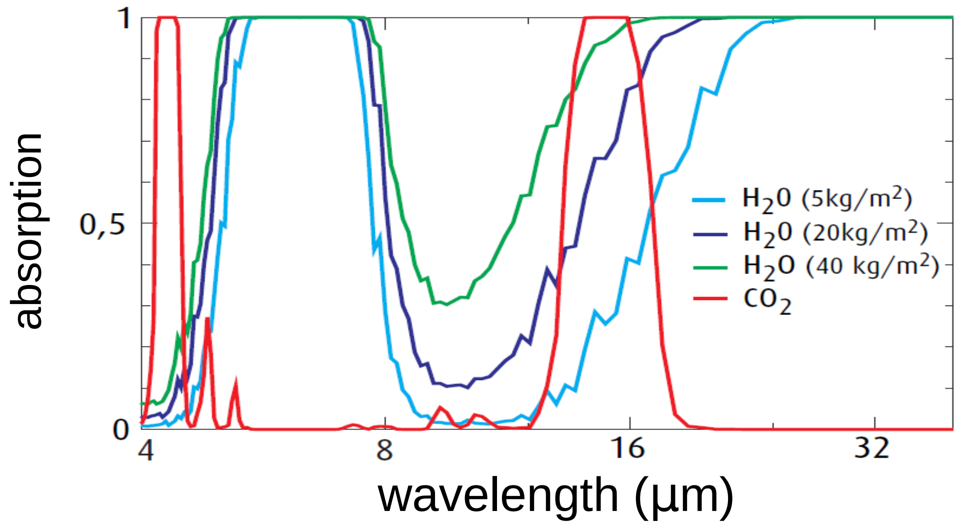
Total absorption of the two narrow bands



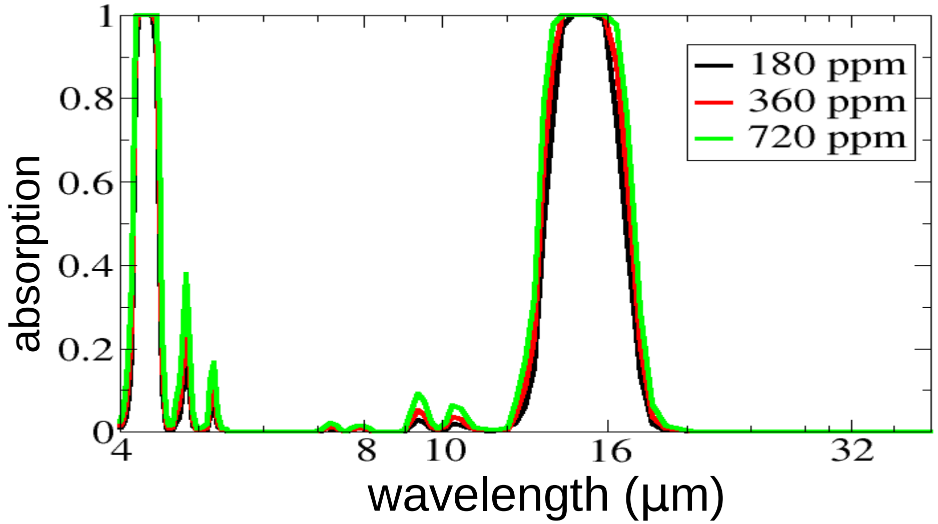
[Bohren and Clothiaux 2006]

Infrared absorption of the atmosphere

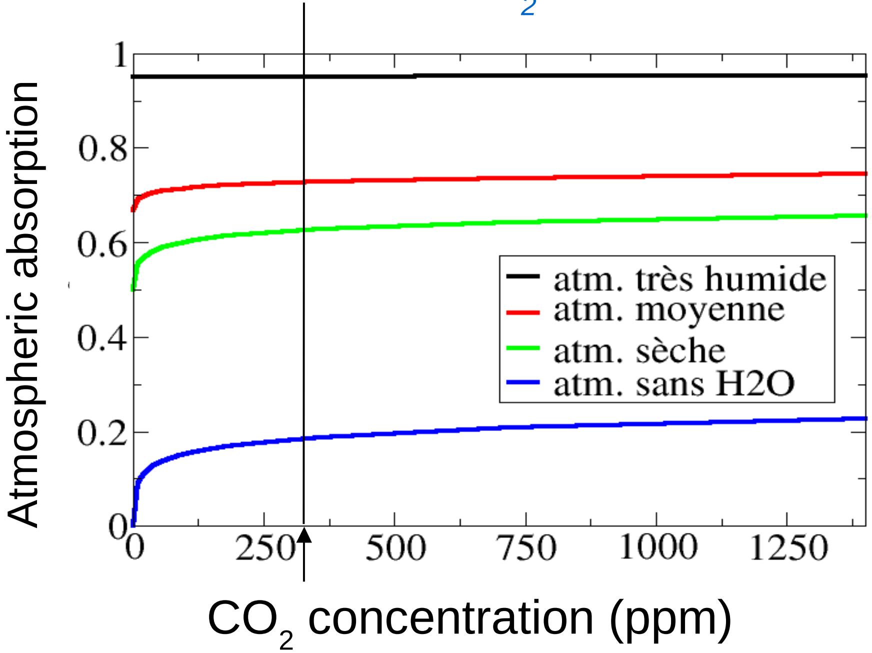
Different H_2O concentration



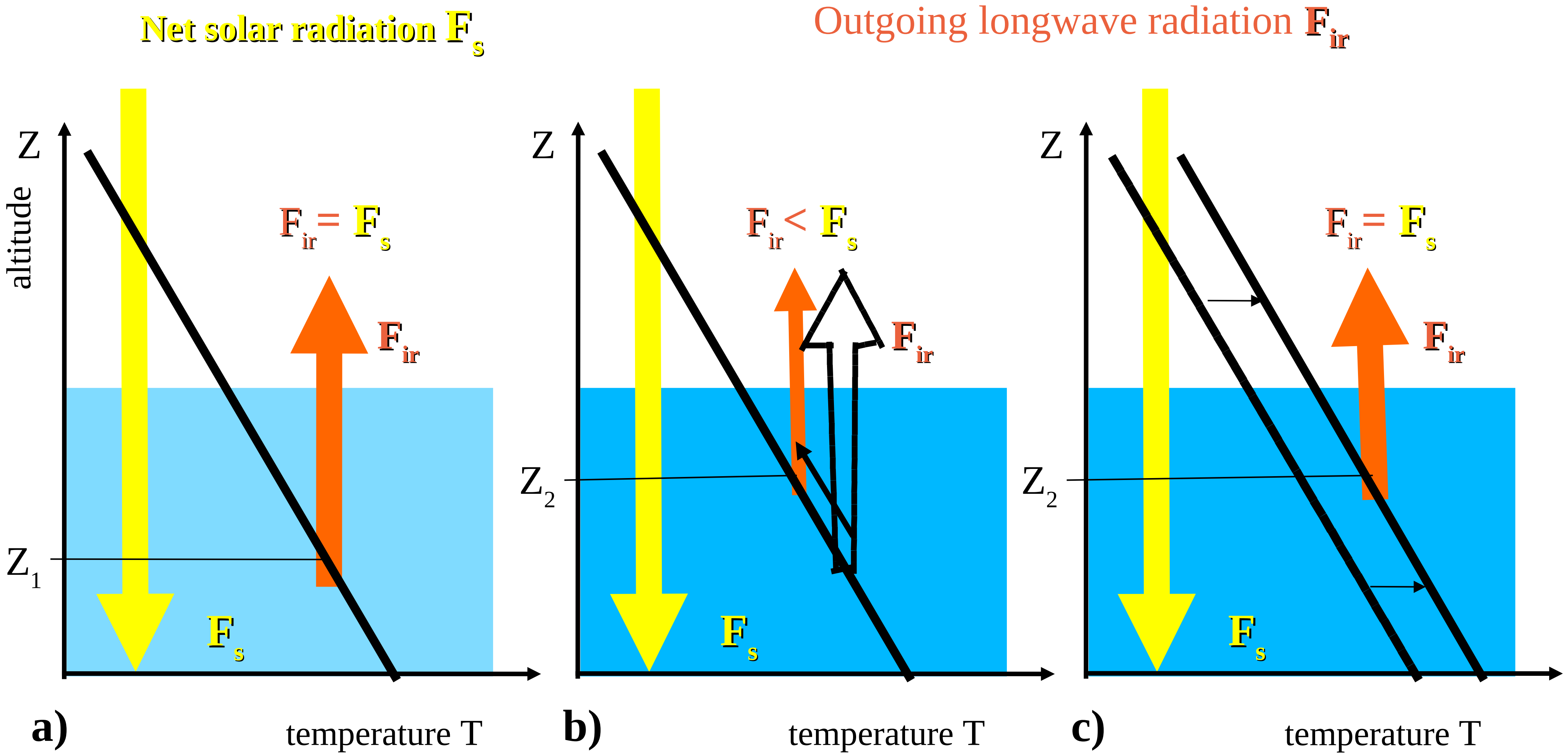
Different CO_2 concentration



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

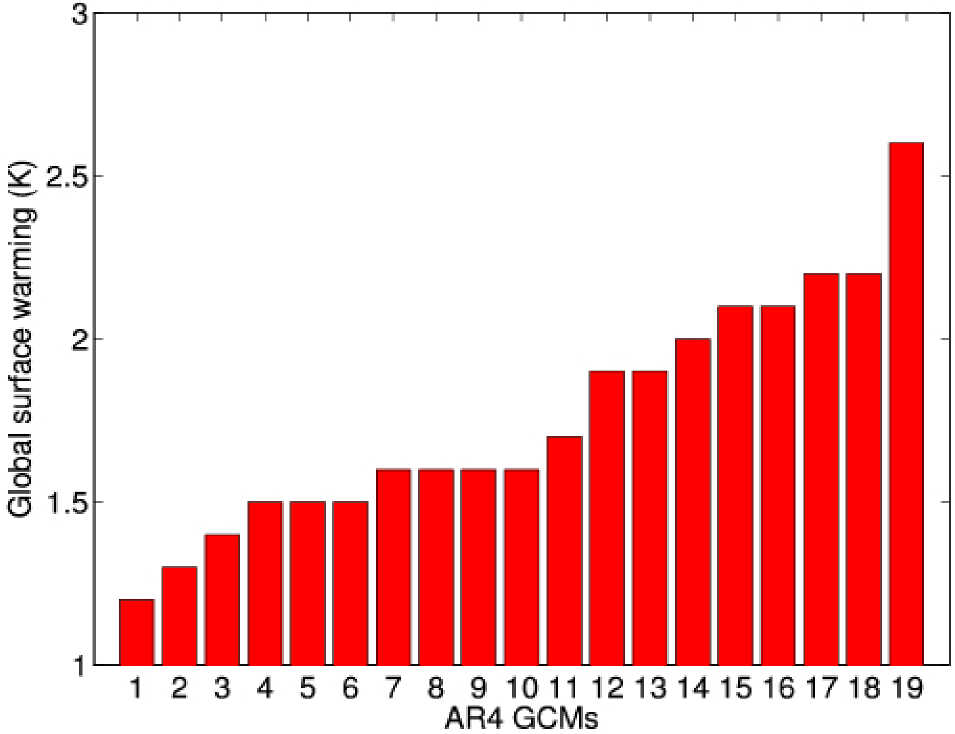


CO_2 increase and greenhouse effect

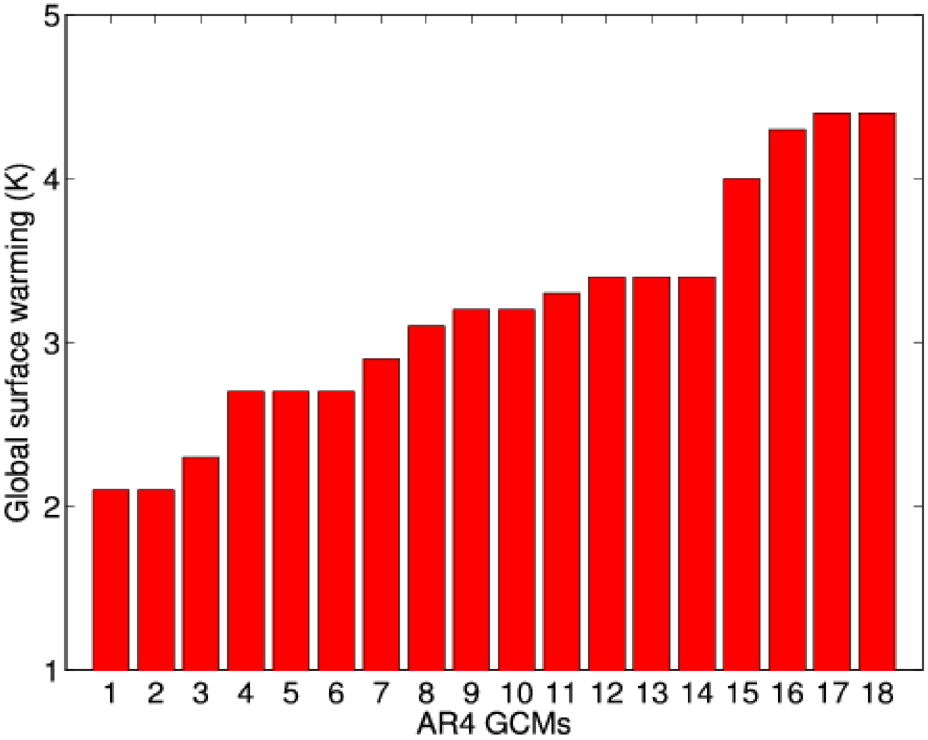


Why climate sensitivity estimate differs among models?

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



Equilibrium Climate Sensitivity :
(warming for sustained 2xCO2)



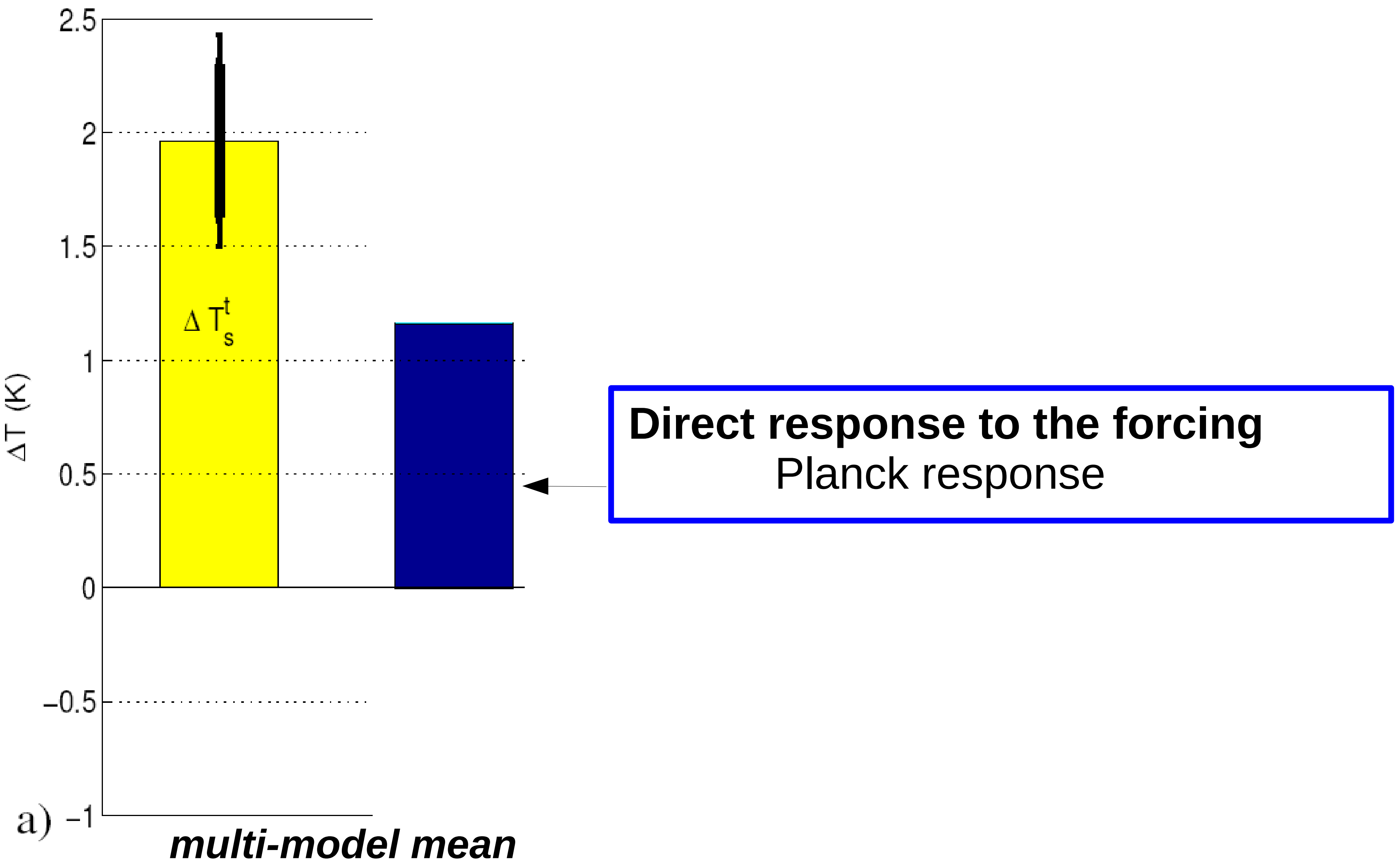
Climate sensitivity and TCR estimates depend on :

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

[IPCC, 2007]

Transient temperature response to a CO_2 doubling

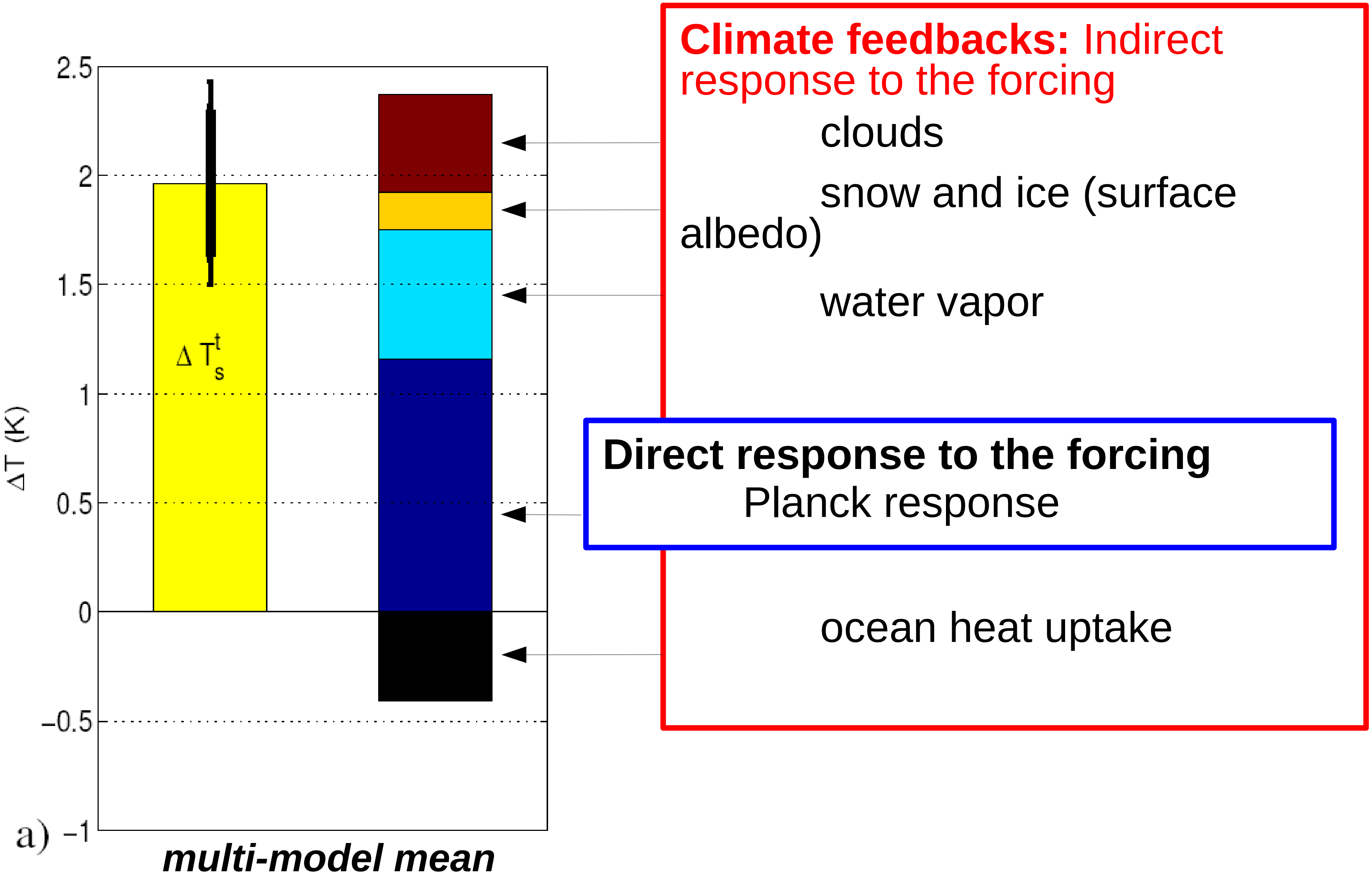
(CO_2 increase 1%/year, 70 years)



(Dufresne & Bony, 2008)

Transient temperature response to a CO_2 doubling

(CO_2 increase 1%/year, 70 years)



(Dufresne & Bony, 2008)

Transient temperature response to a CO_2 doubling

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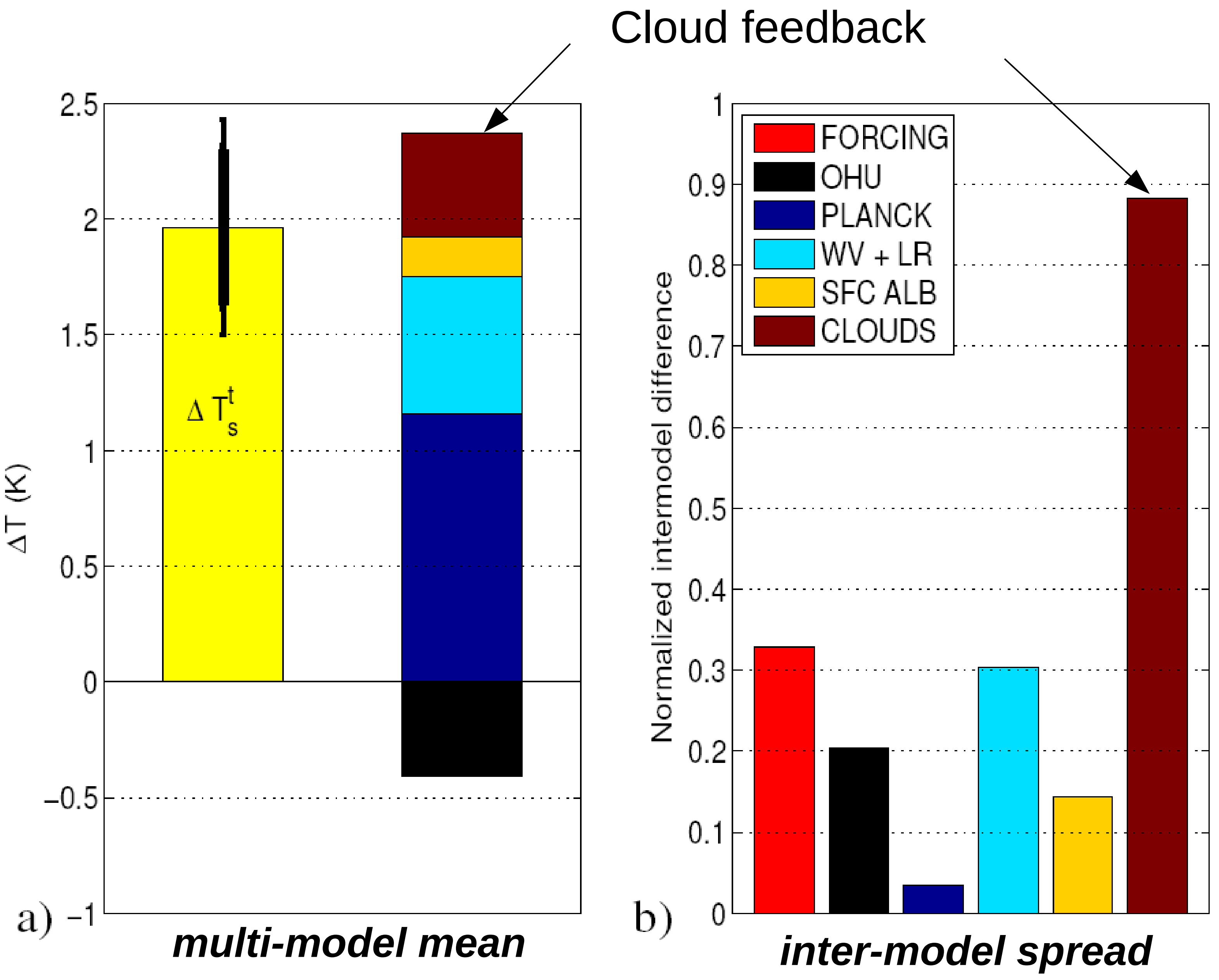
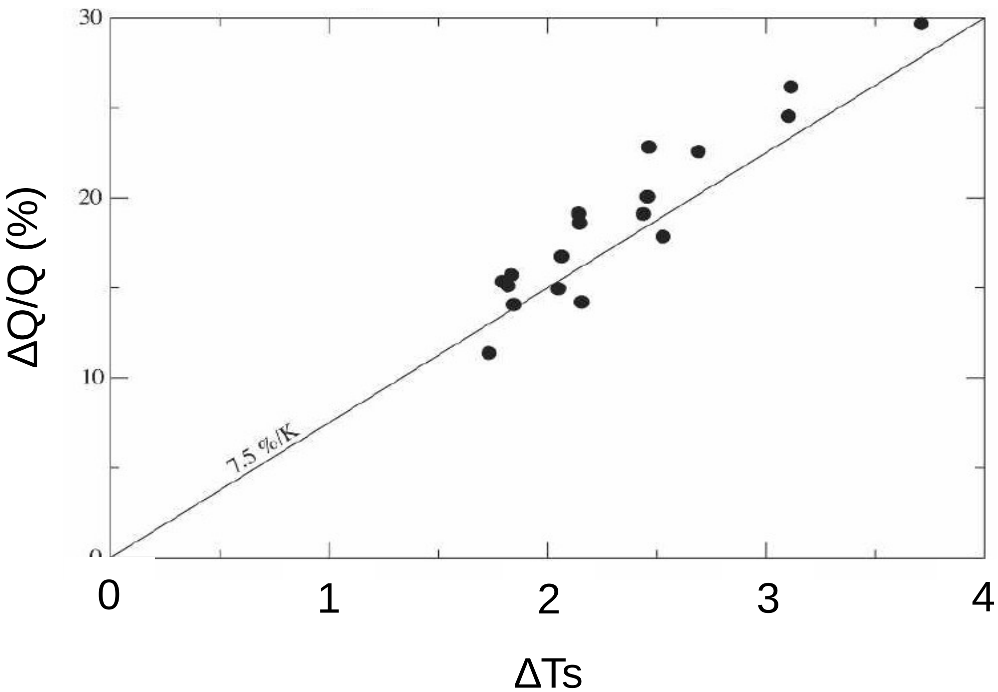


(Dufresne & Bony, 2008)

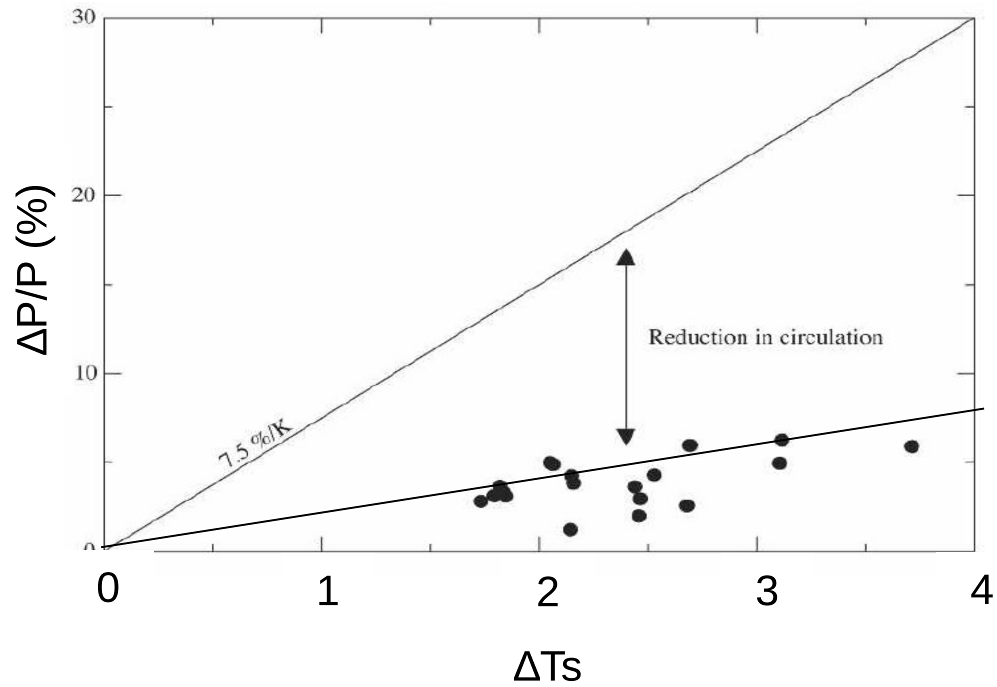
Precipitation changes

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



$\Delta Q/Q$ (%) ≈ 7.5 ΔTs

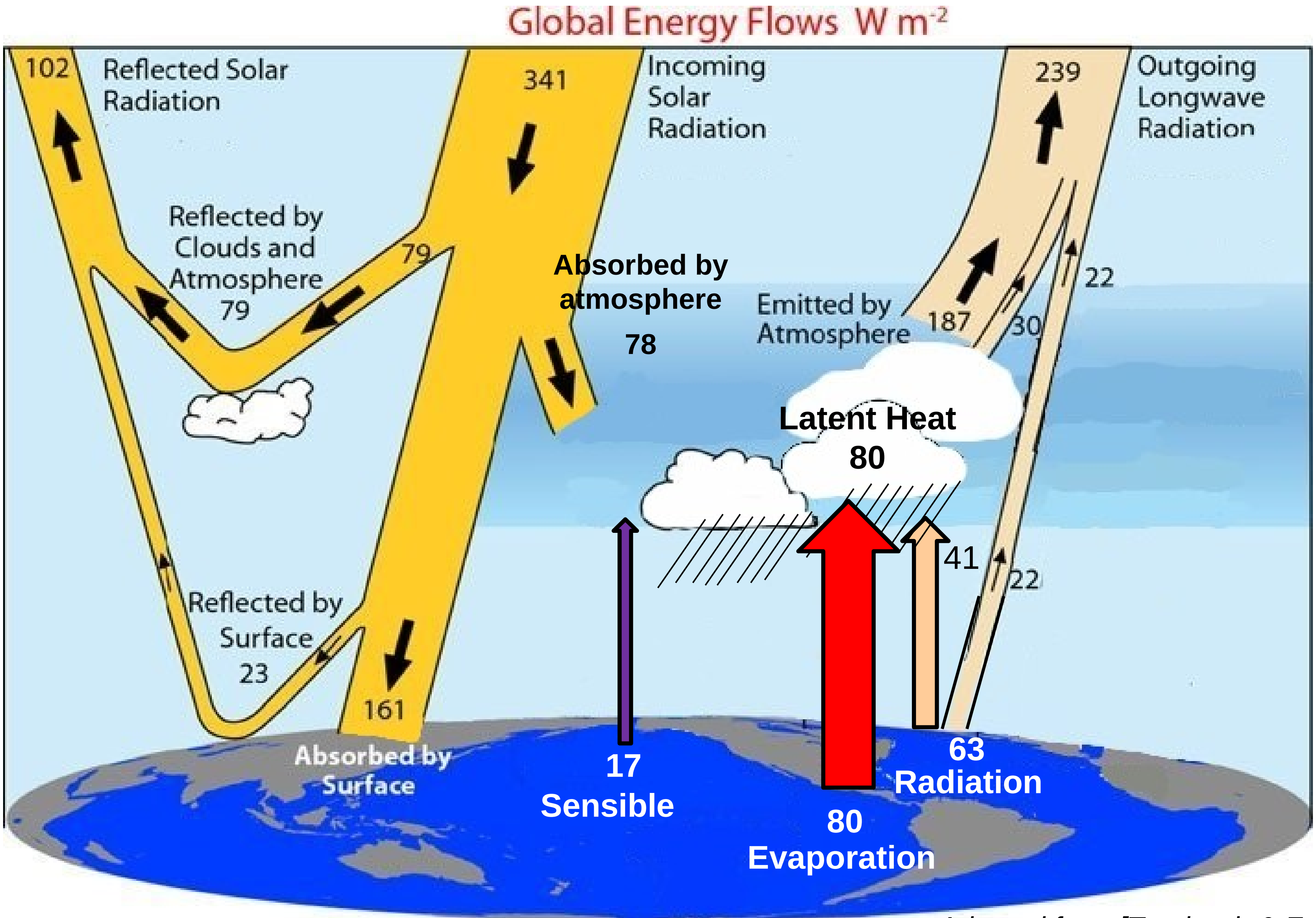
Change of **precipitation** vs change of the average surface **temperature**



$\Delta P/P$ (%) ≈ 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)

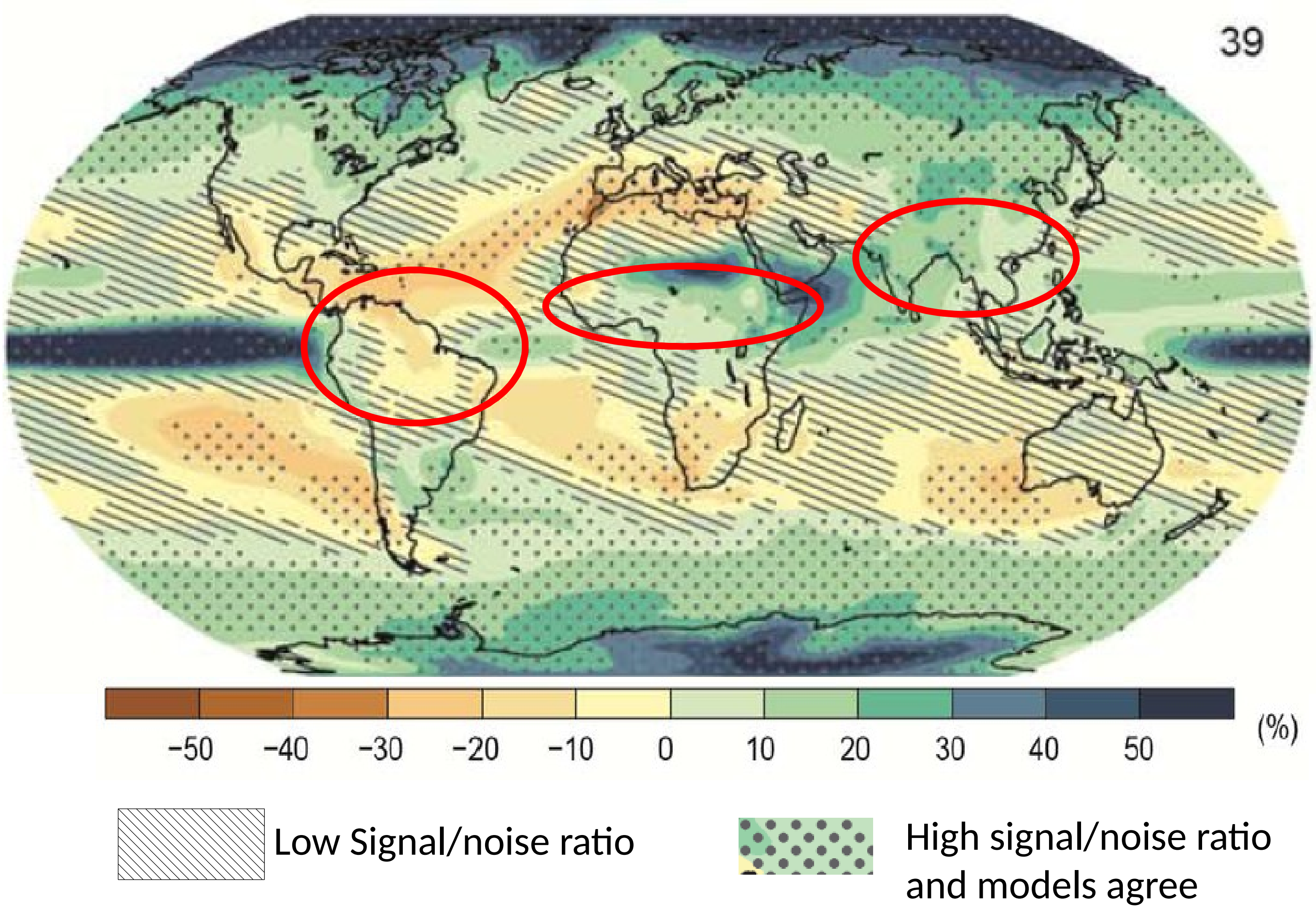


Adapted from [Trenberth & Fasullo, 2012]

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

Precipitation changes: Geographical distribution

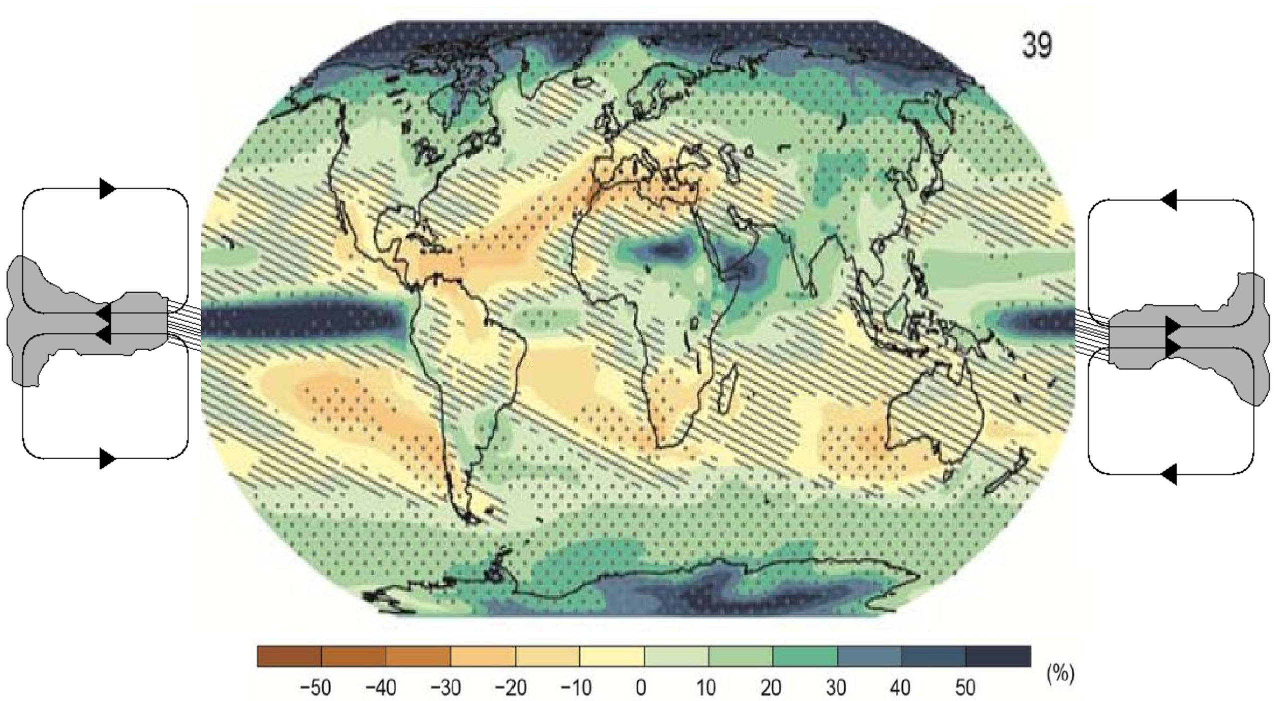
Relative change in average precipitation, RCP8.5 scenario (2081-2100)

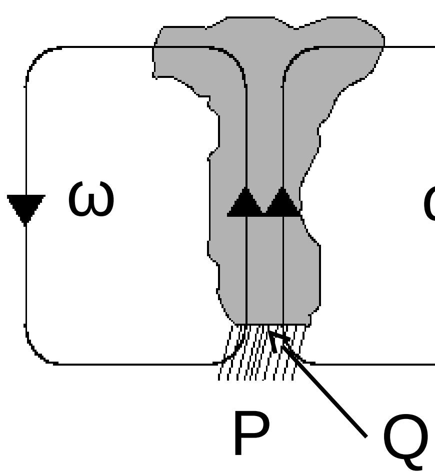


39 CMIP5 models

[IPCC, AR5]

Precipitation changes





(specific humidity)

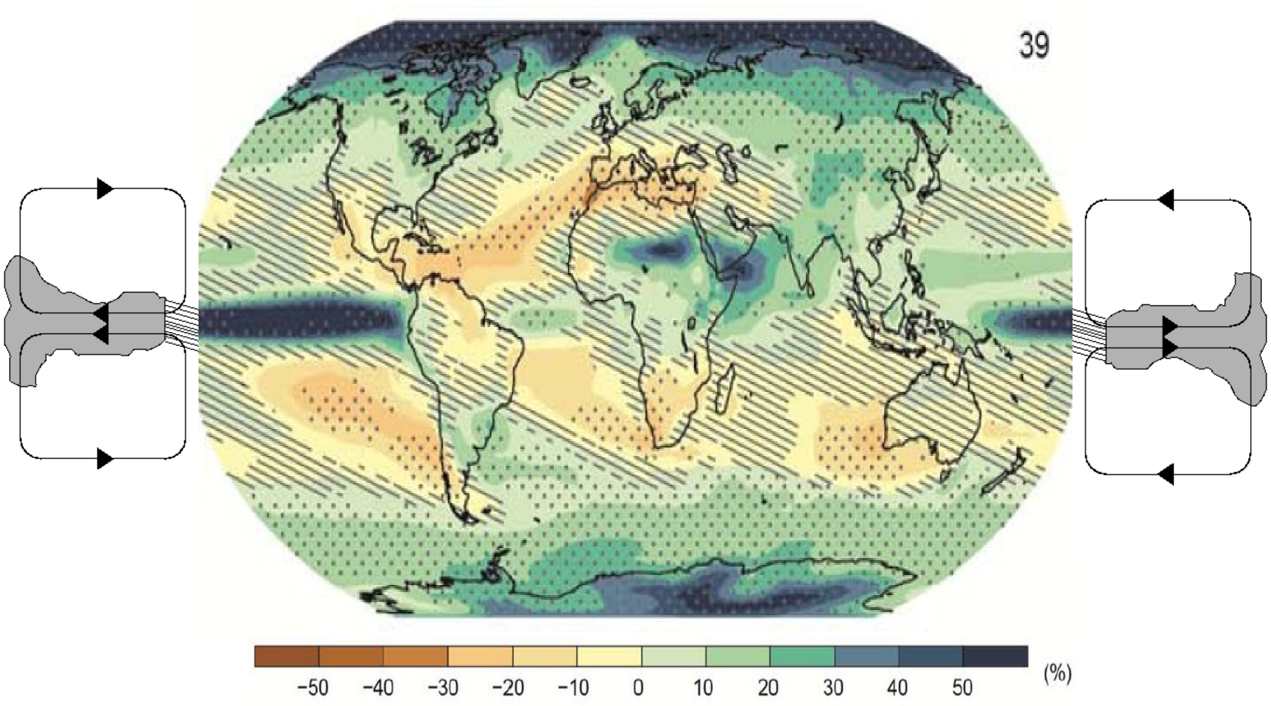
Precipitations changes

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

Thermodynamic response

Dynamic response

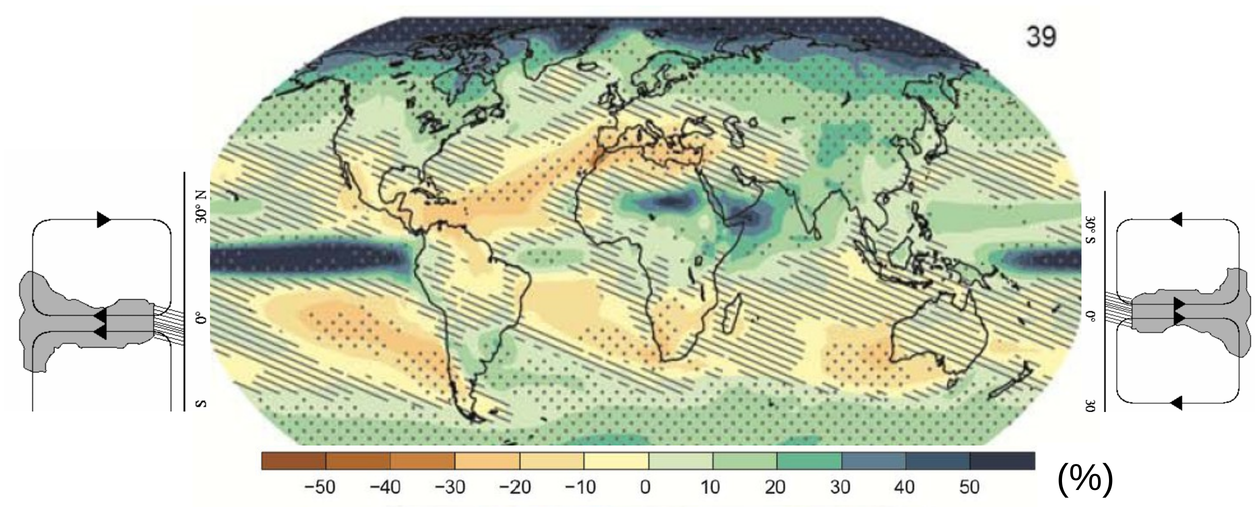
Precipitation changes



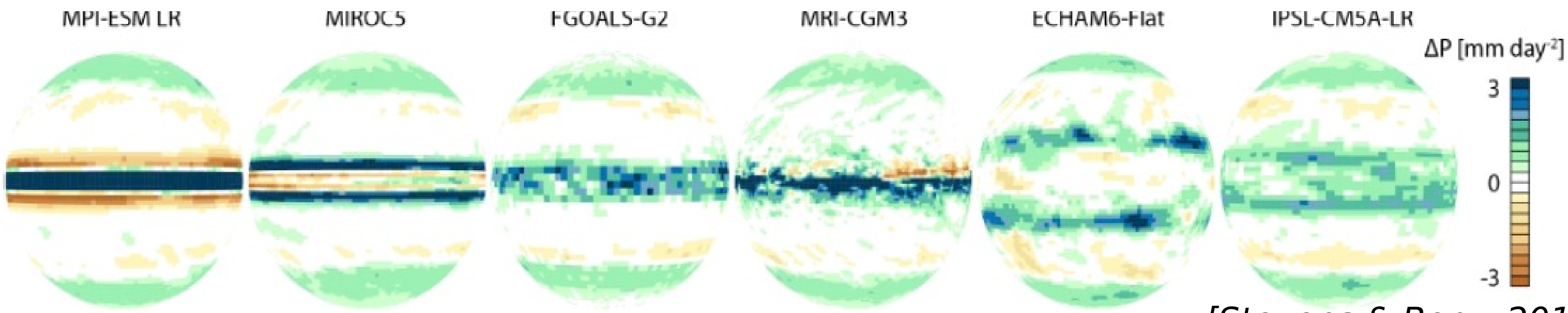
At the global scale:

- 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

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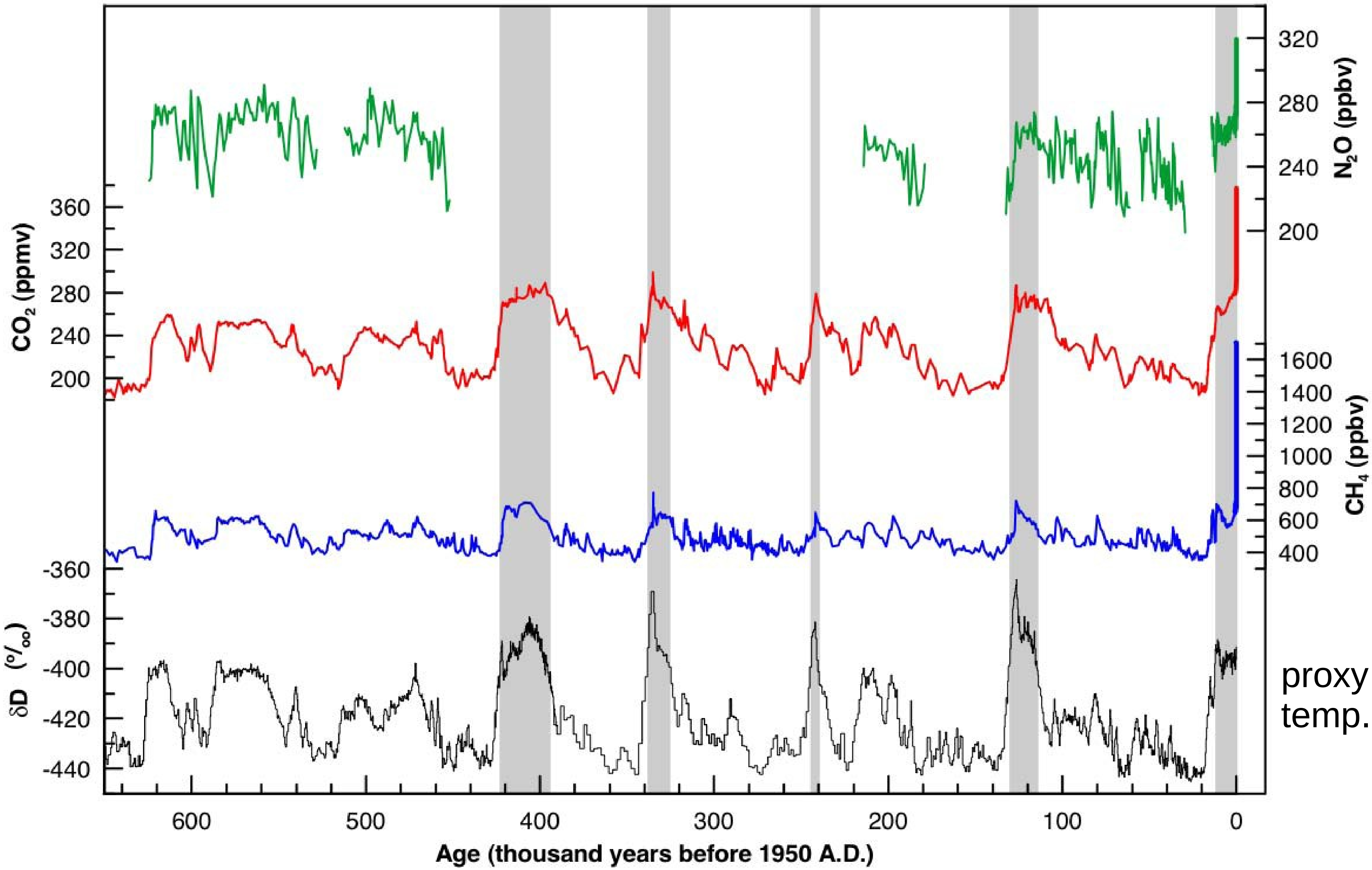
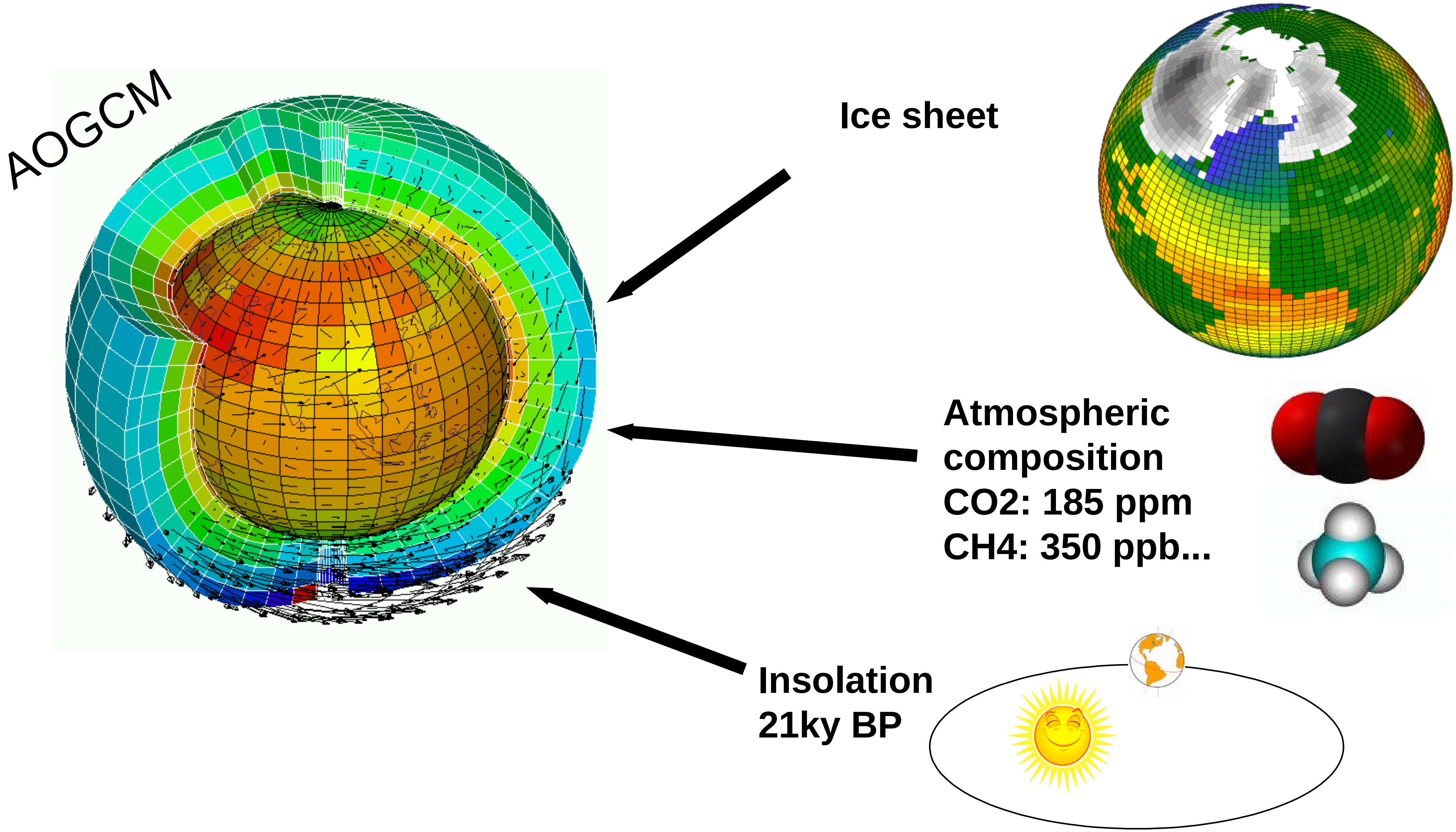
Paleoclimate changes



proxy
temp.

[IPCC, 2013]

Simulation of Last Glacial Maximum (LGM)

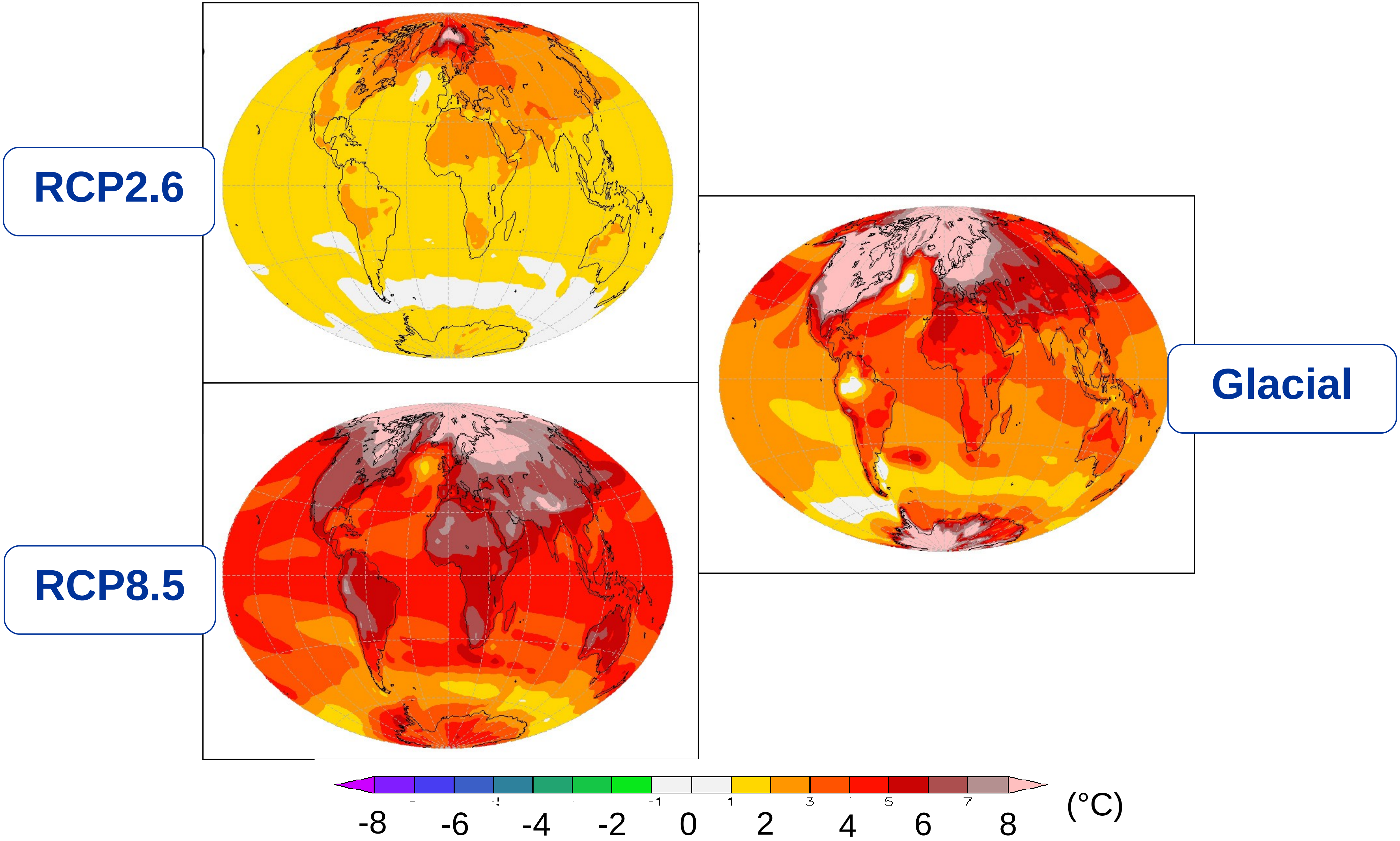


Greenhouse gas forcing ~ future climate
Other main forcings: ice sheet

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

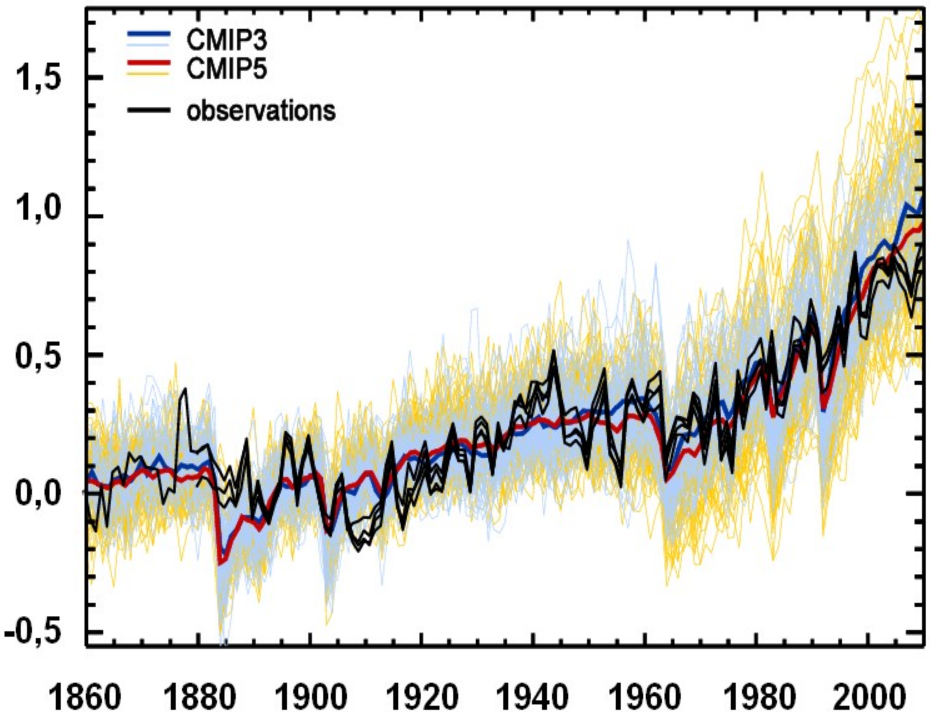
Change in surface temperature

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



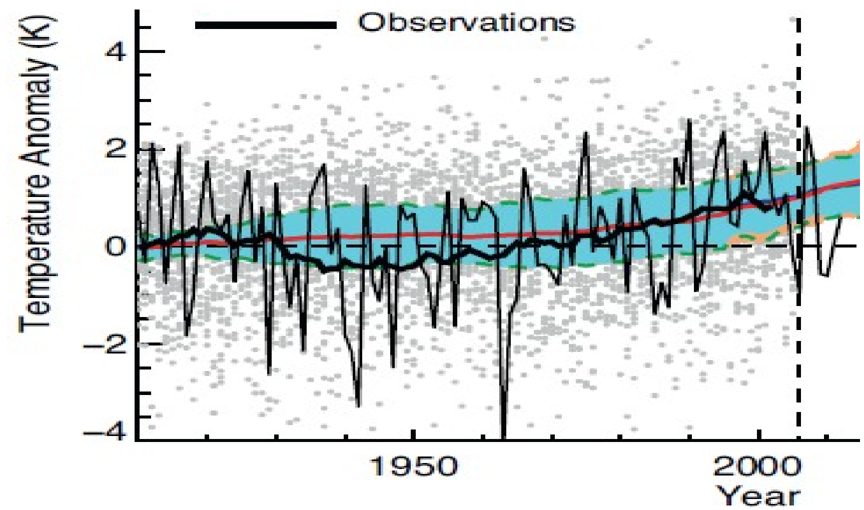
Surface temperature evolution: observation and models

Annual global mean

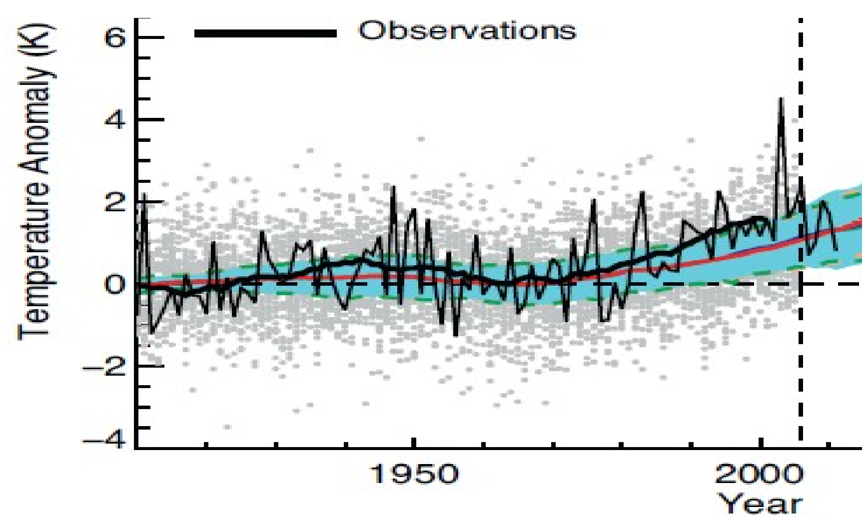


[IPCC, 2013]

Winter mean over France



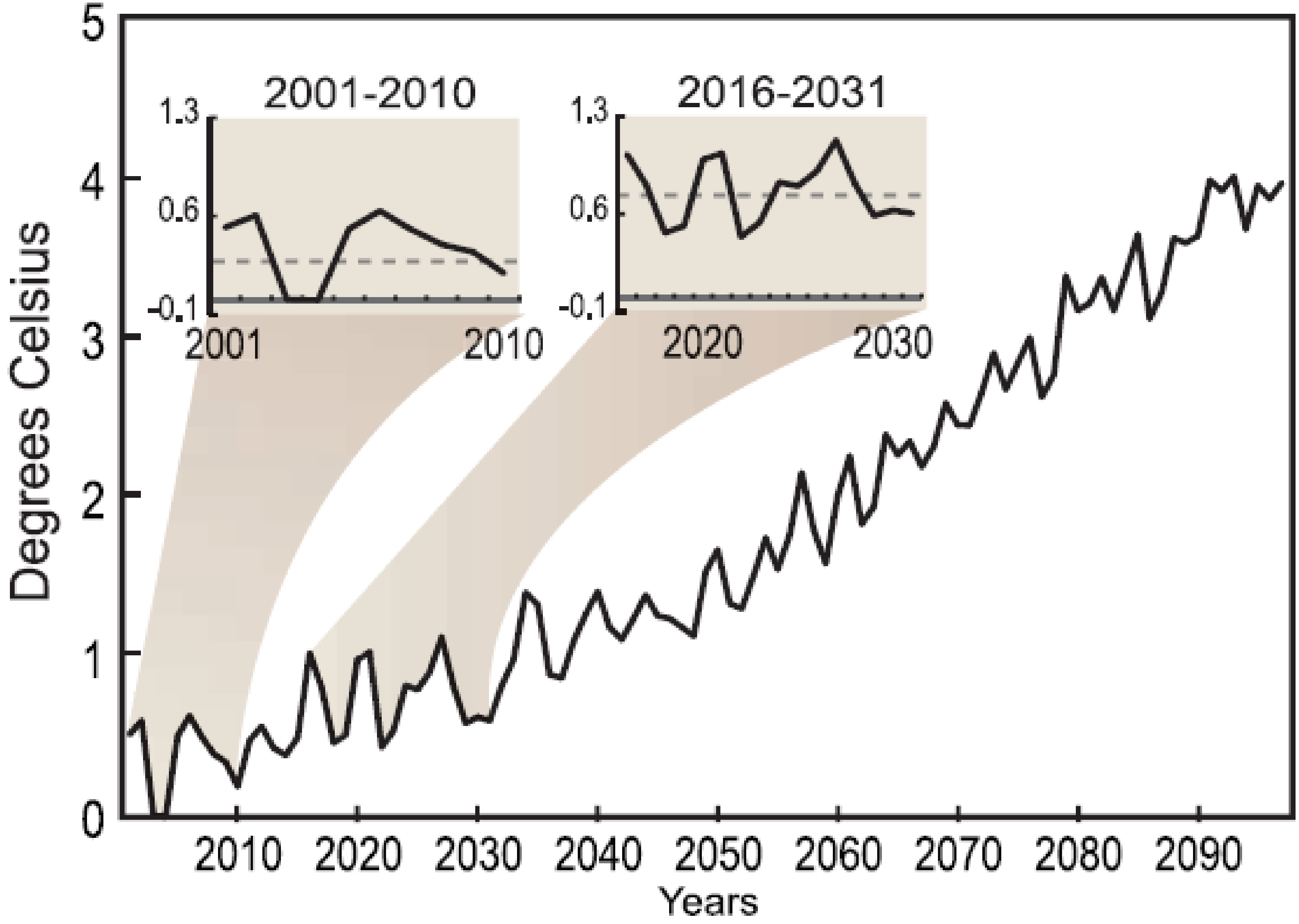
Summer mean over France



[Terray et Boé, 2013]

Les variations du climat sont elle régulières?
Variations et variabilité du climat

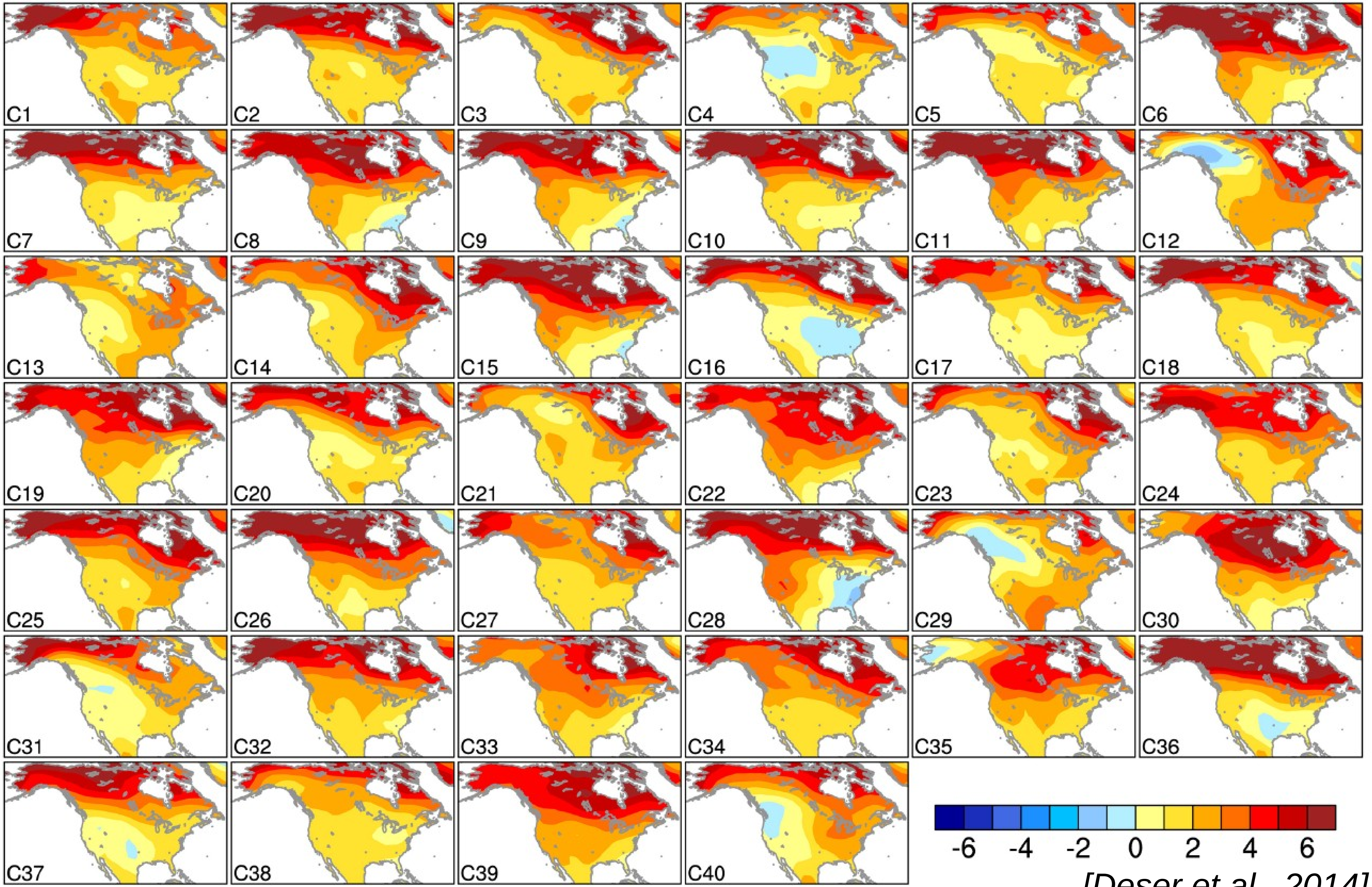
Simulations



Easterling and Wehner, 2009

Changement climatique et variabilité naturelle

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



[Deser et al., 2014]

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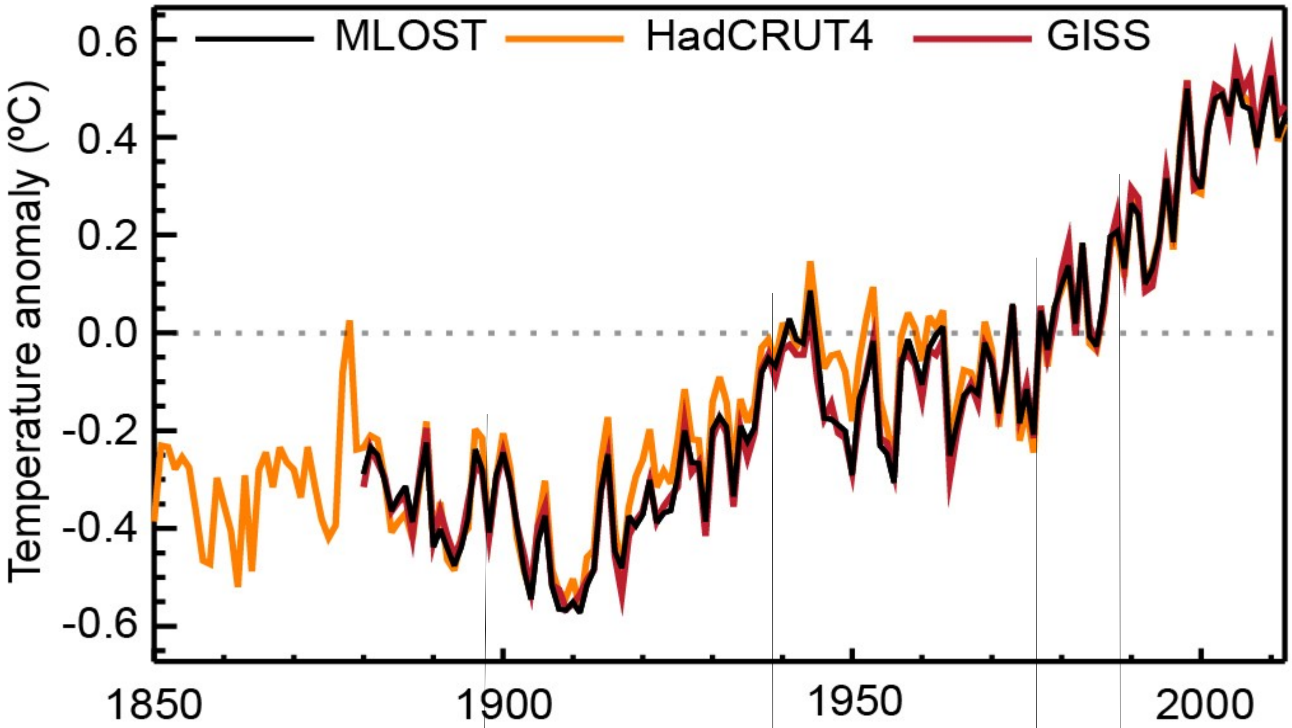
Premières projections climatiques alors que la température a peu augmenté



[GIEC 2013]

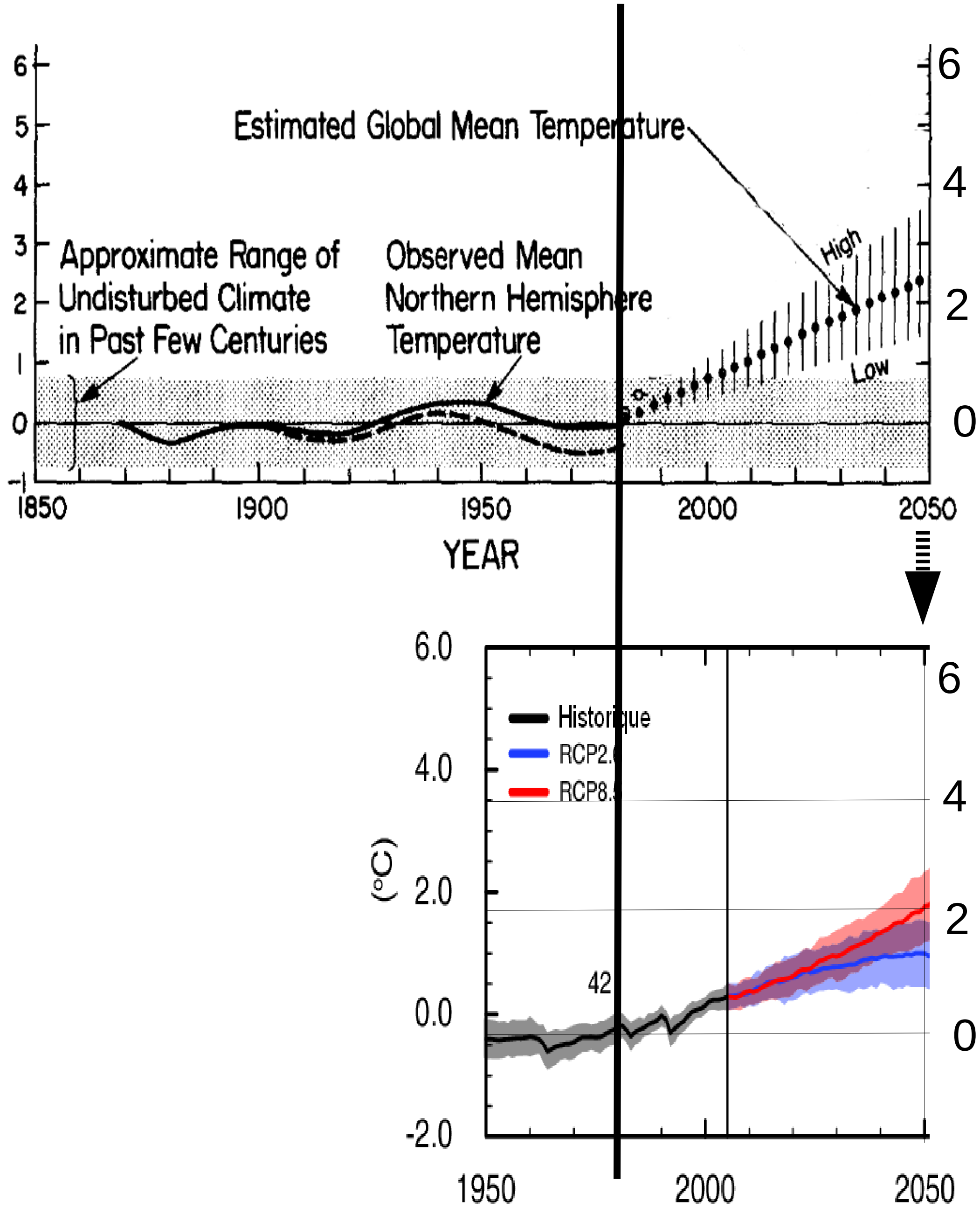
1897: S. Arrhenius: première estimation du rôle du CO2

1937: G. Callendar: nouvelle estimation du rôle du CO2

1970-1980: Premières projections climatiques avec des modèles numériques

1988: Création du GIEC

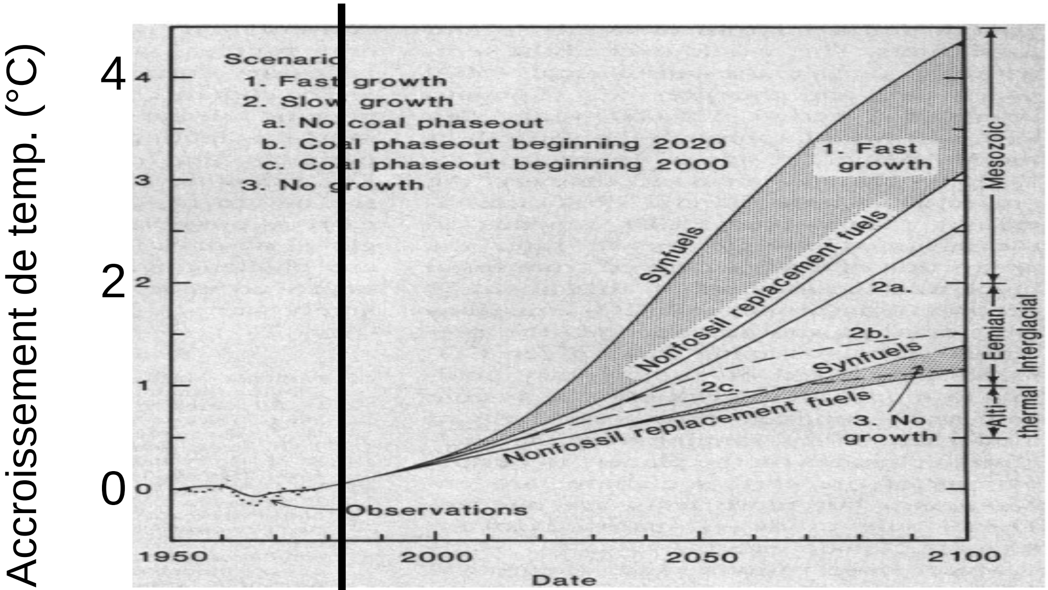
Premières projections climatiques
alors que la température a peu augmenté



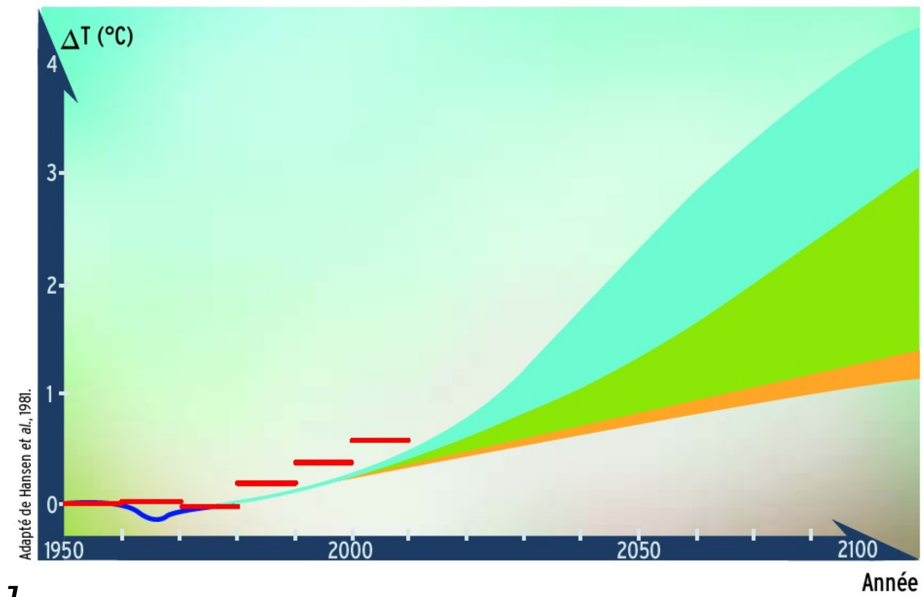
[Kellogg 1977]

[GIEC 2013]

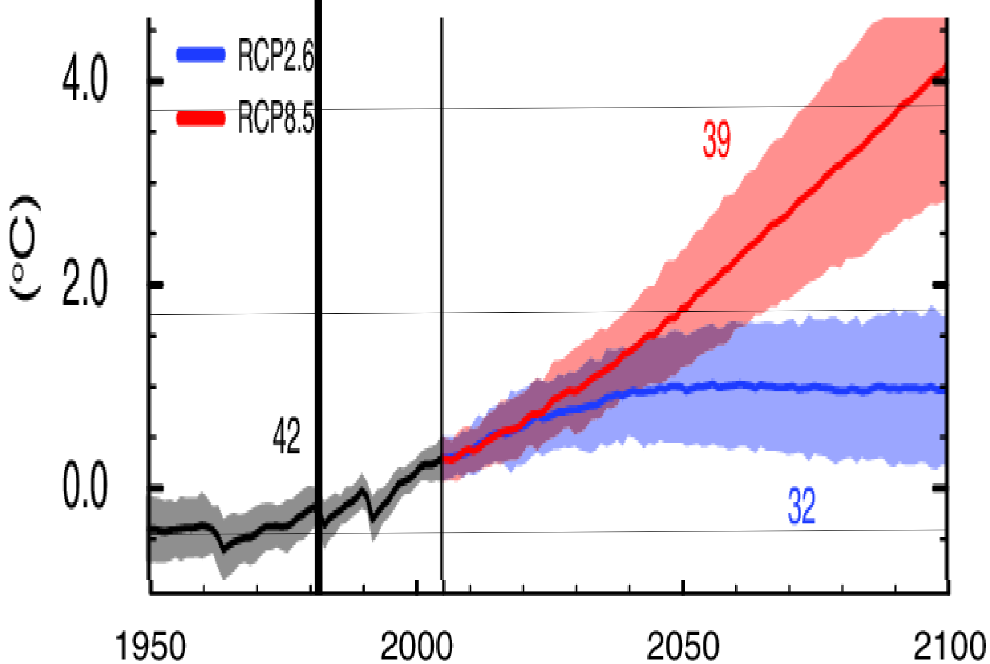
Premières projections climatiques alors que la température a peu augmenté



[Hansen et al. 1981]



Observations (postérieures)
Moyennes sur 10 ans



[GIEC 2013]

Conclusions

La construction et la confiance dans les modèles climatiques repose sur un ensemble méthodologique :

- Le rôle important jouée par **quelques lois physiques fondamentales**
- Les allers-retours permanents entre le **découpage** du système complet pour se focaliser sur une partie et l'**étude du système complet** (développement, évaluation, compréhension)
- L'analyse des résultats des modèles pour **comprendre** leurs fonctionnements : résultats **robustes versus dispersion**
- La comparaison aux changements observés

Changements climatiques futurs :

- Les questions évoluent et passent de l'**alerte** à la quantification et l'**anticipation des risques** associés
- Dans cette évolution, 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


Merci de votre attention