LMD

Environmental Sciences
Institut Pierre Simon Laplace
ICMC – IPSL Climate Modelling Centre
ICMC – IPSL Centre de Modélisation du Climat

Projection of future climate change at the global scale

Jean-Louis Dufresne

Paris, 26 février 2013

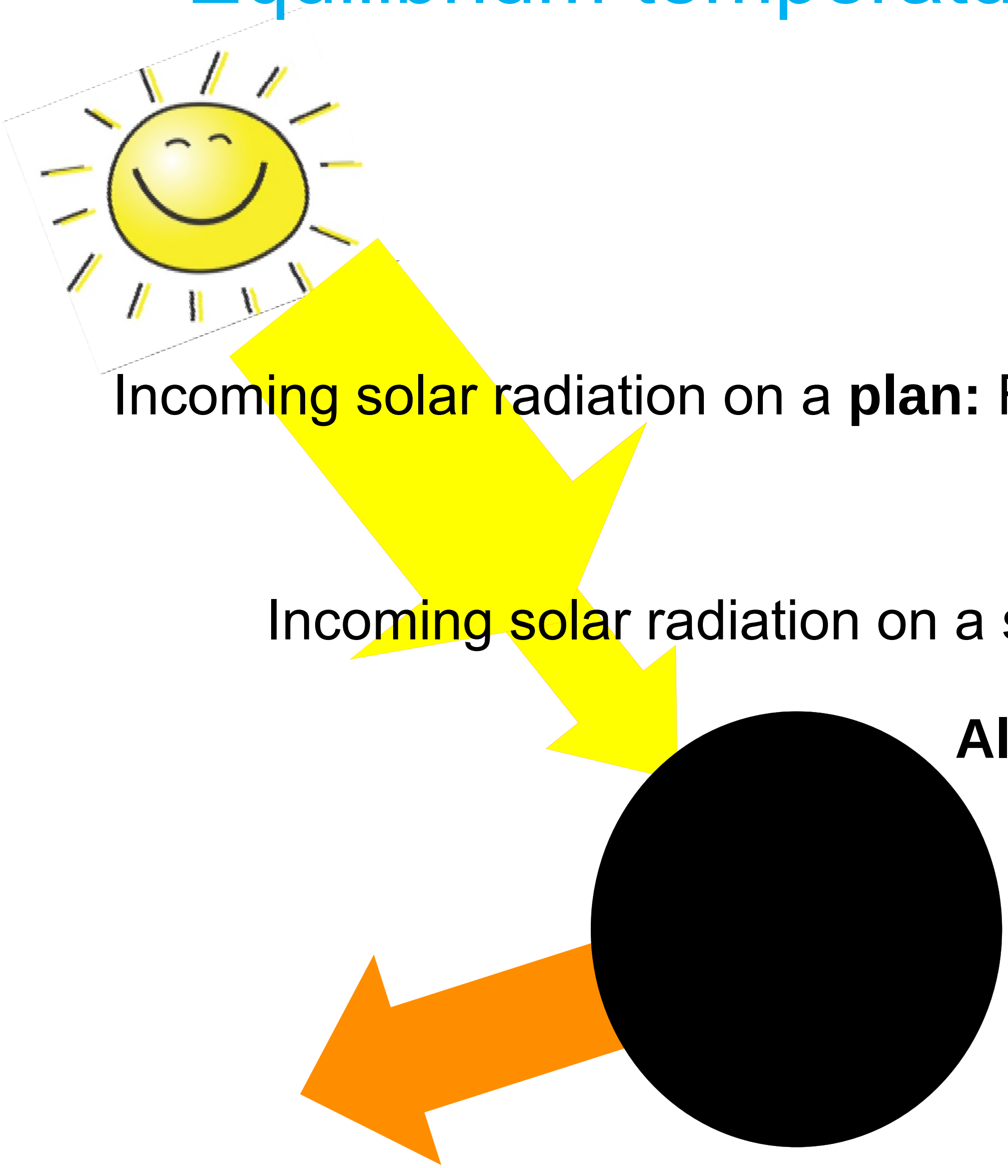
Outlook

I. Basic of climate change: greenhouse effect, forcing and feedbacks

II. Scenarios and forcings for climate change projections

III. Climate change projections at global scales

Equilibrium temperature of a planet



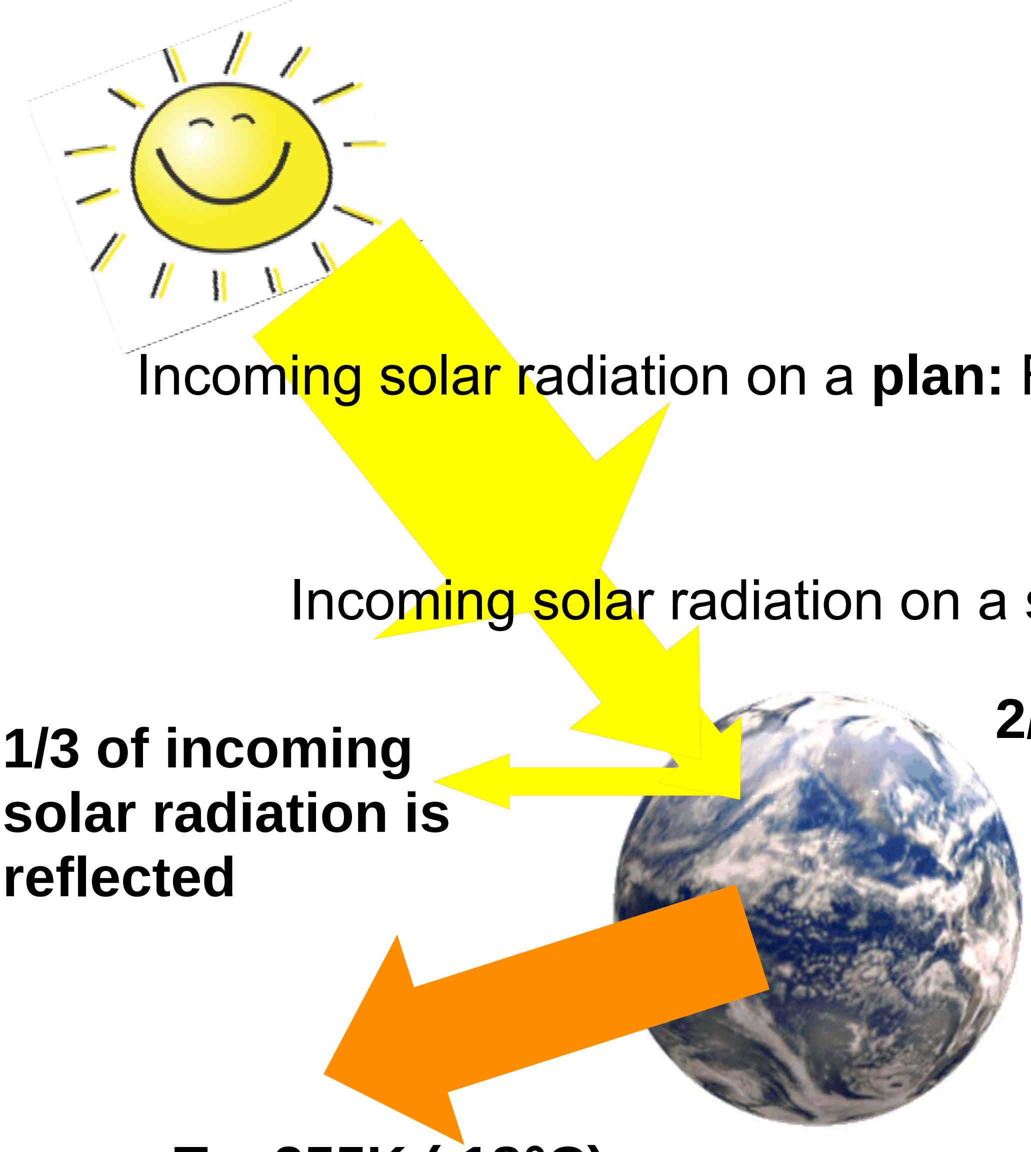
Incoming solar radiation on a **plan:** F_0=1364 W.m^{-2}

Incoming solar radiation on a **sphere:** F_s=F_0/4 = 341 W.m^{-2}

All the incoming solar radiation is absorbed : F_a = 240W.m^{-2}

T_s= 278K (5°C)

Equilibrium temperature of a planet



Incoming solar radiation on a **plan:** F_0=1364 W.m^{-2}

Incoming solar radiation on a **sphere:** F_s=F_0/4 = 341 W.m^{-2}

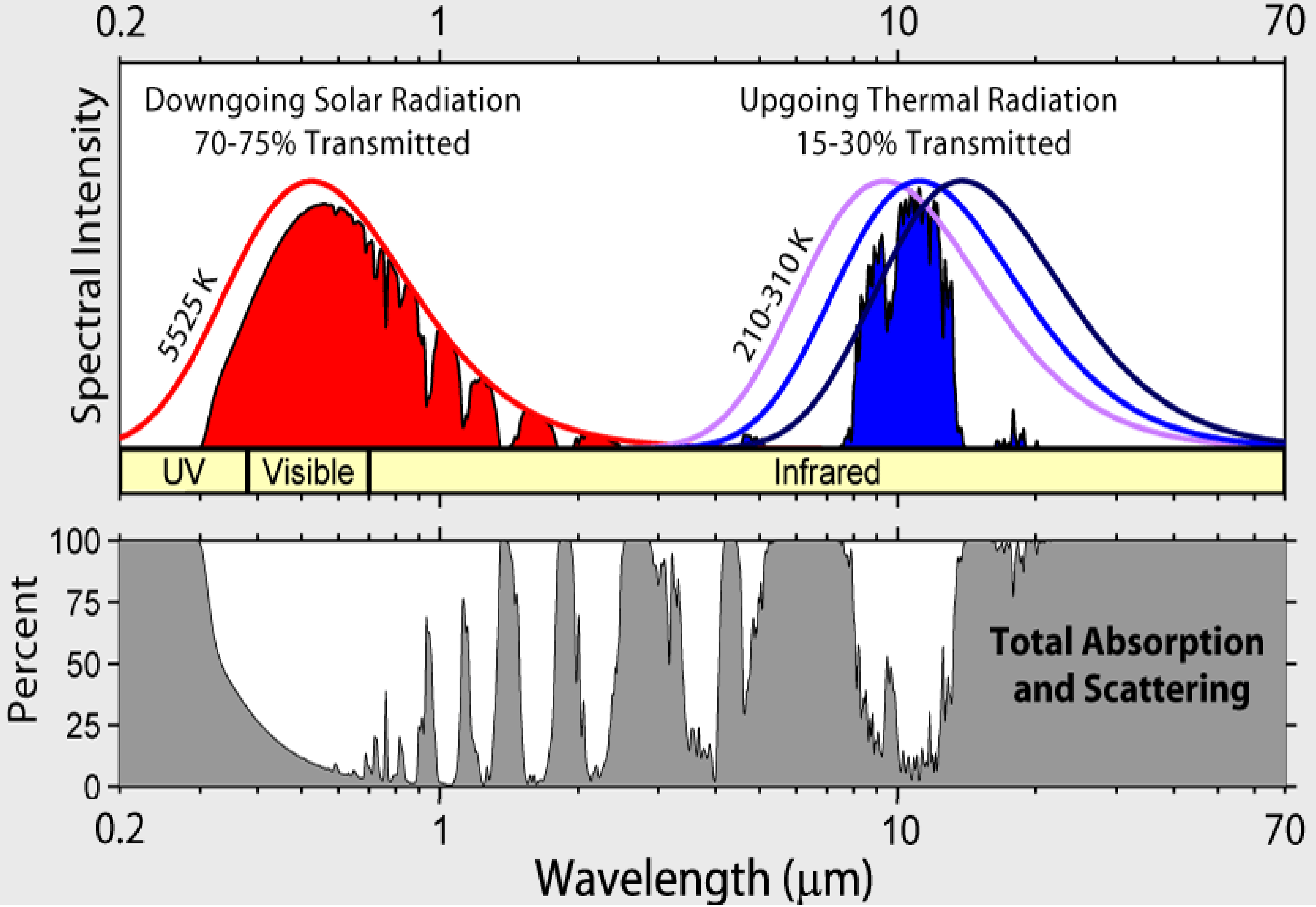
1/3 of incoming solar radiation is reflected

2/3 of incoming solar radiation is absorbed : F_a = 240W.m^{-2}

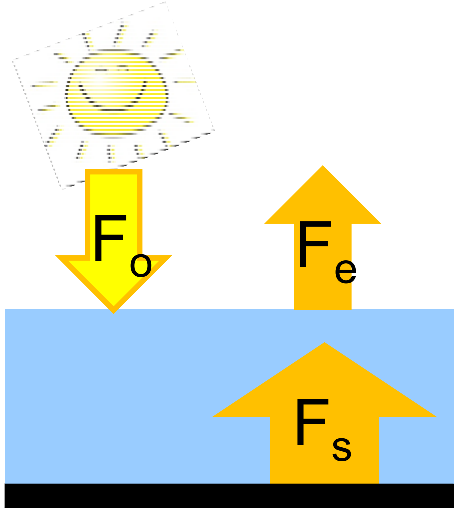
Global mean surface temperature is 15°C due to greenhouse effect

T_s= 255K (-18°C)

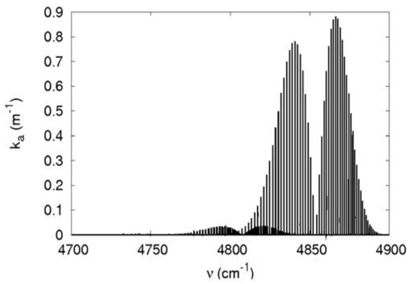
Radiation Transmitted by the Atmosphere



Green house effect



Greenhouse effect: $G=F_s-F_e$



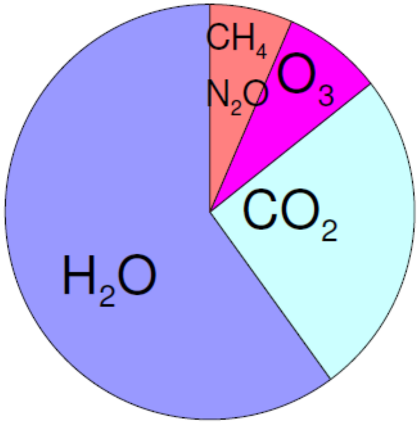
Gas radiative properties

Atmospheric characteristics

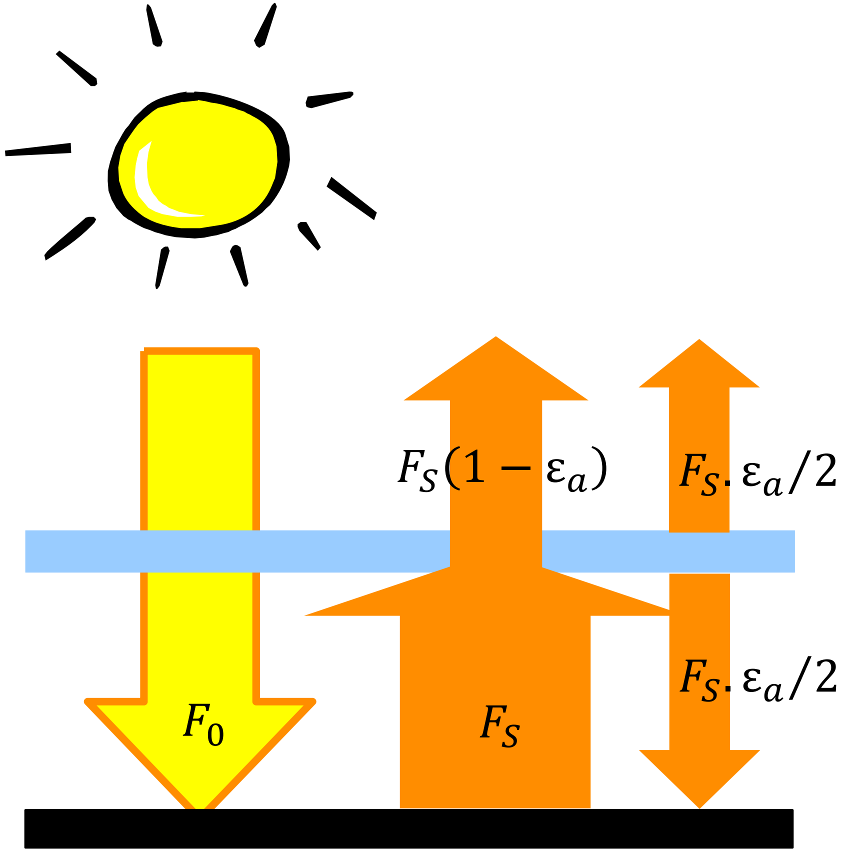
Computation of the radiative fluxes and the greenhouse effect

Contribution of atmospheric gases to **the natural greenhouse effect** on Earth

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



Single layer green house model



Atmosphere, glass (isotherm) :

- Solar (shortwave, SW) : transparent
- Infrared (longwave, LW) :
  - emissivity=absorptivity=ε_a
  - reflectivity=0

Surface: perfectly black in both shortwave and longwave

Heat budget at the surface:

$$\sigma T_S^4 = F_S$$

$$F_S = F_0 + F_S.\varepsilon_a/2$$

Therefore:

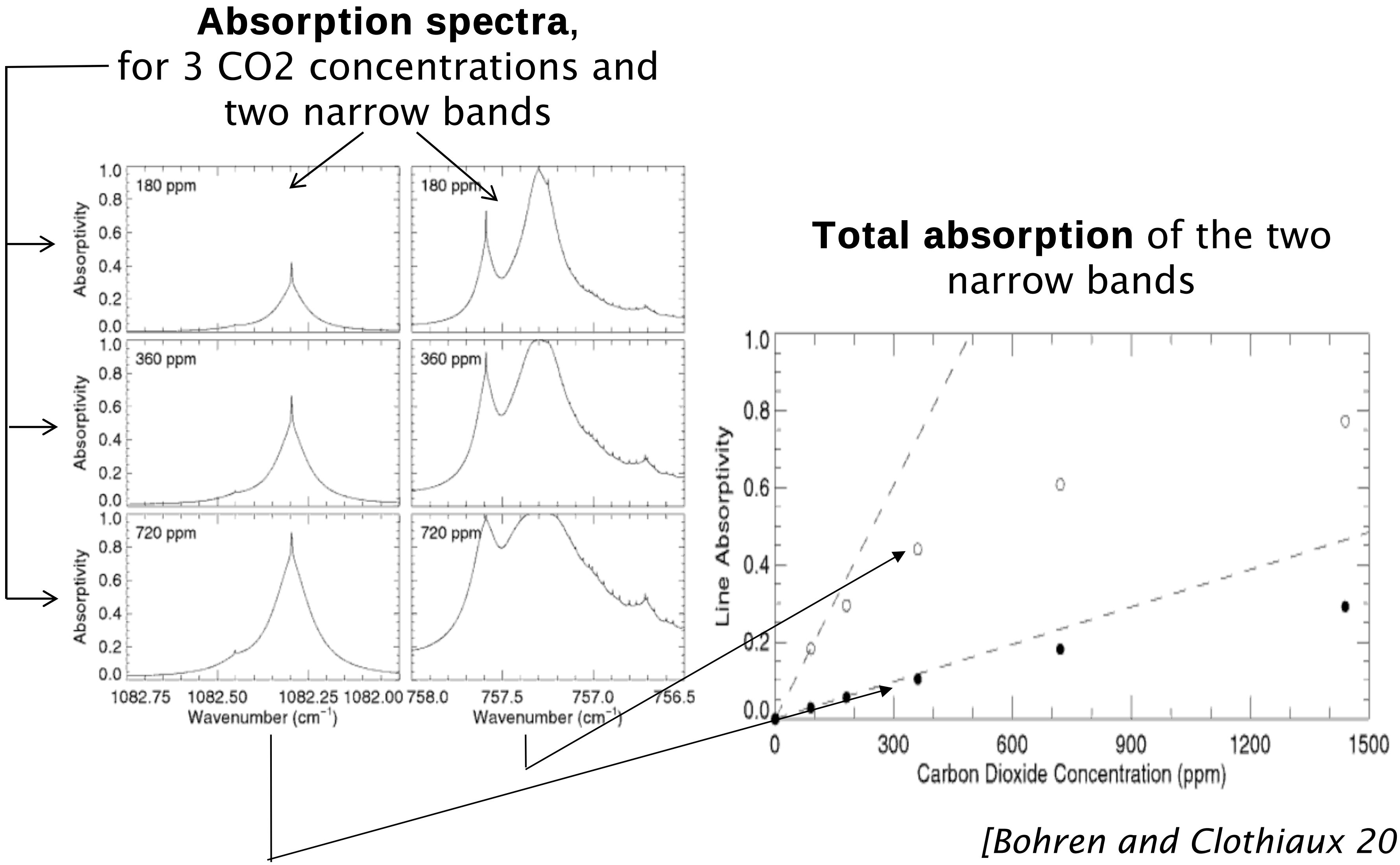
$$\sigma T_S^4 = \frac{F_0}{1-\varepsilon_a/2}$$

$$T_a^4 = T_S^4/2$$

- ➢Single layer green house model : surface temperature T_S depends on F_o and ε_a, and is maximum when ε_a=1
- ➢This simple model is not relevant for CO_2

Saturation of absorption bands

Absorption by CO_2, for a vertical column of atmosphere



Absorption spectra, for 3 CO2 concentrations and two narrow bands

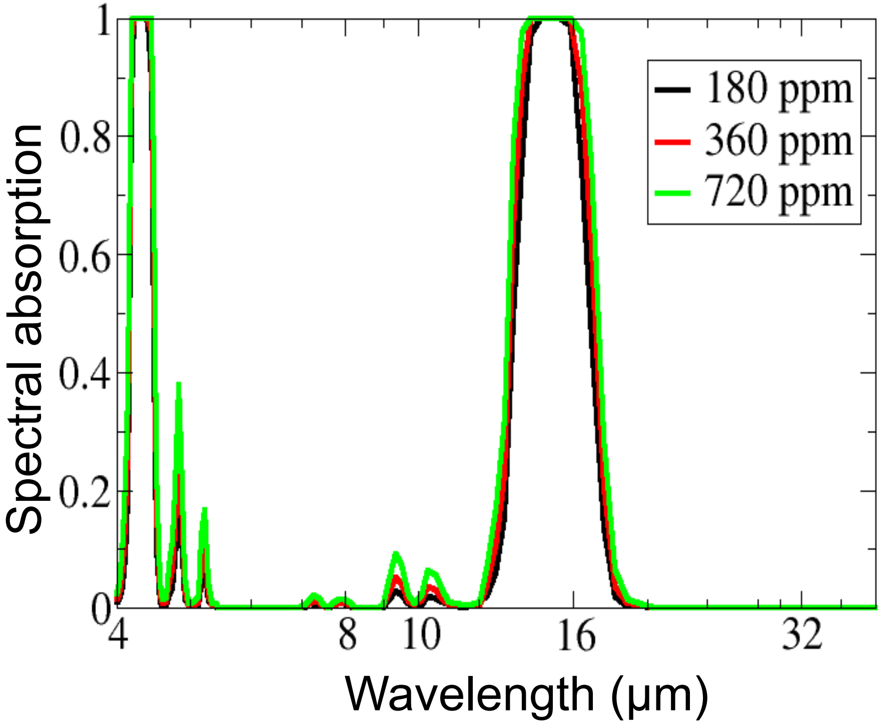
Total absorption of the two narrow bands

[Bohren and Clothiaux 2006]

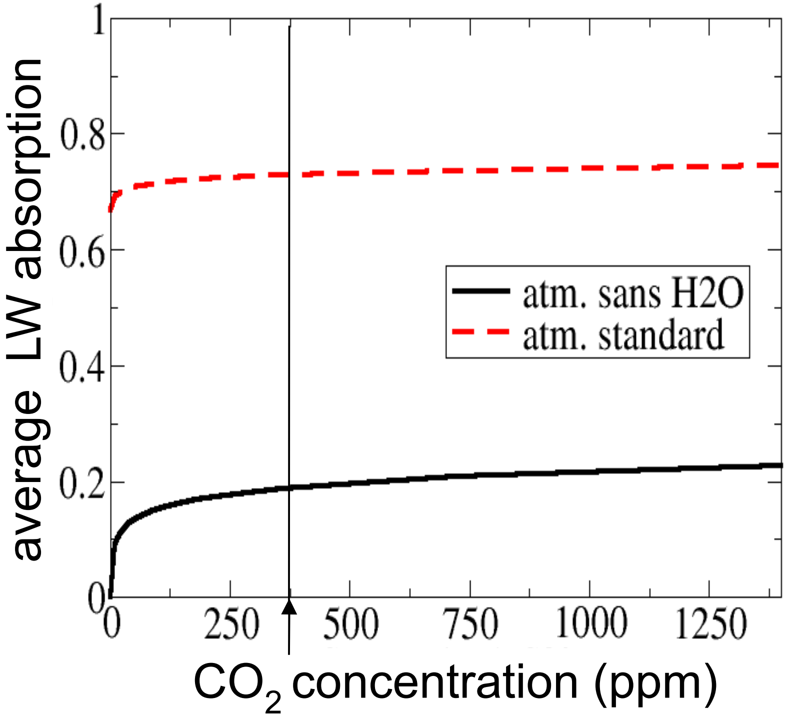
Saturation of absorption bands

Absorption by CO_2, for a vertical column of atmosphere

Spectral absorption, of the atmosphere with only CO_2, for 3 values of CO_2 concentration

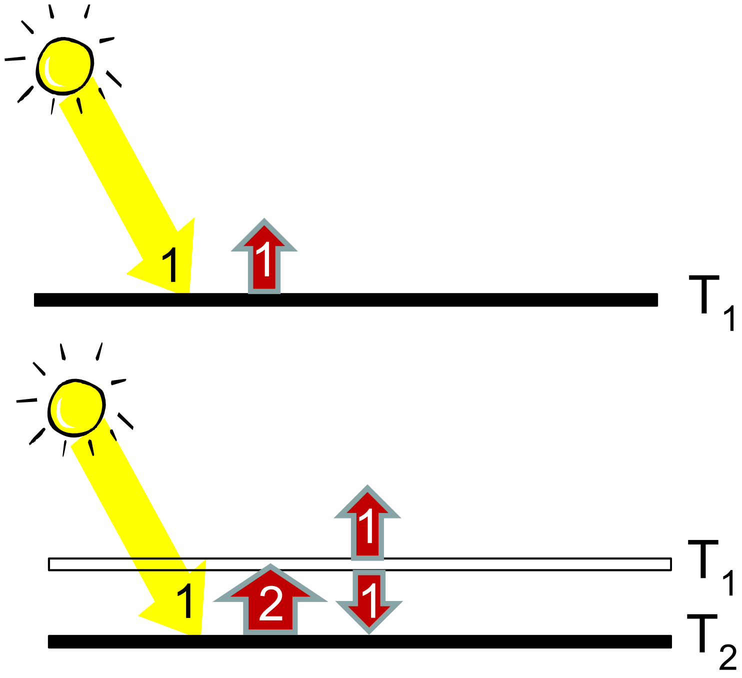


Average infrared absorption, as a function CO_2 concentration, for two H_20 values.

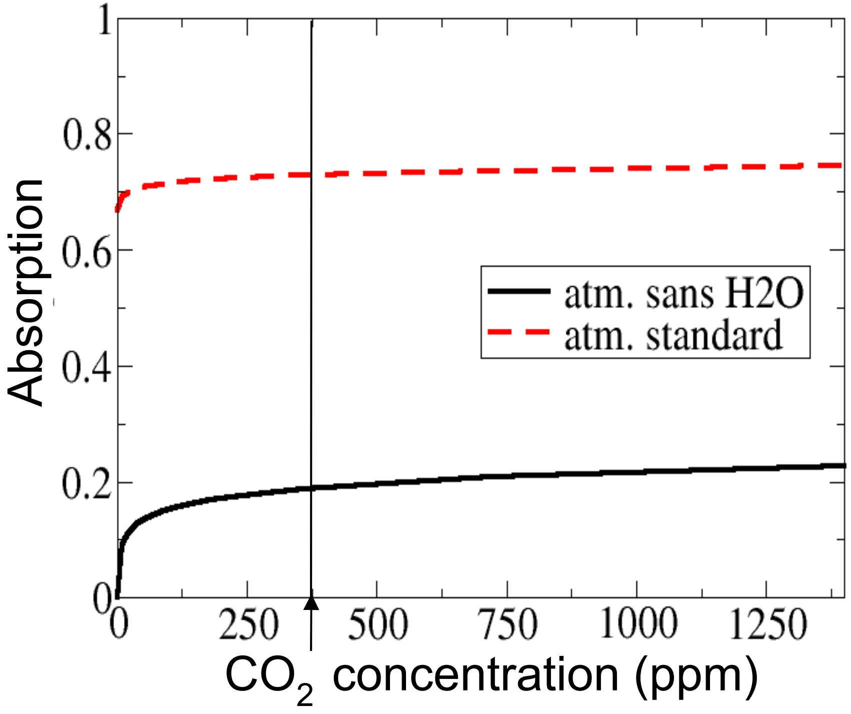


CO_2 increase and greenhouse effect

Single layer greenhouse model



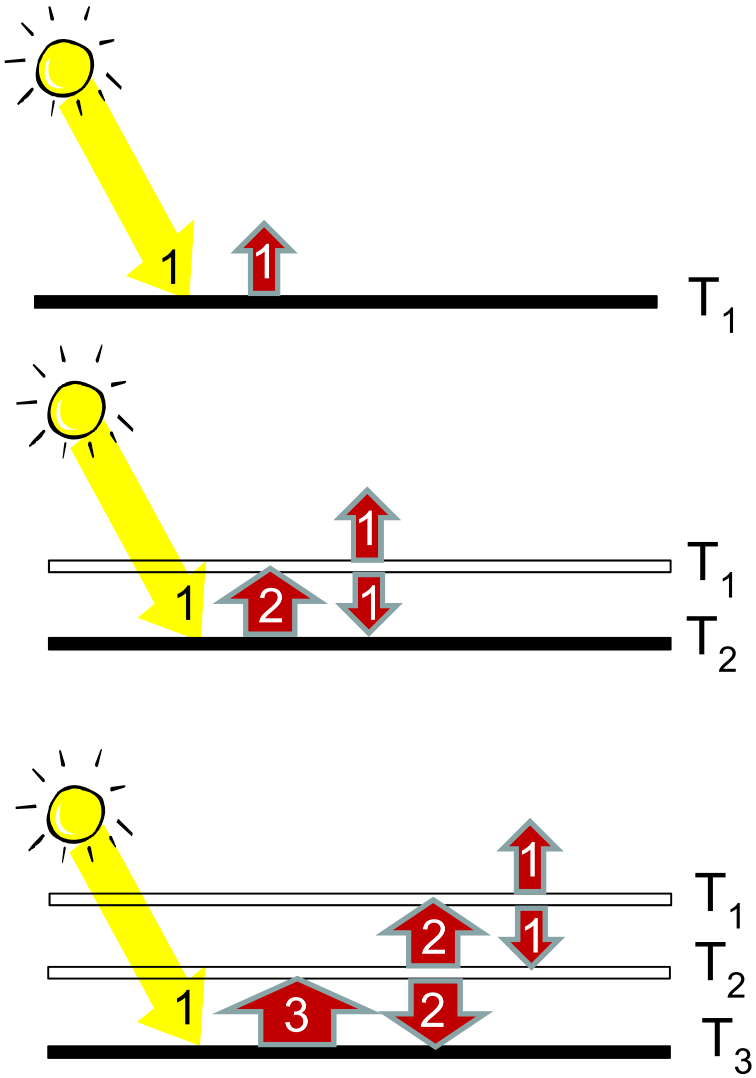
Atmospheric absorption as a function of CO_2,concentration, for two H_20 values



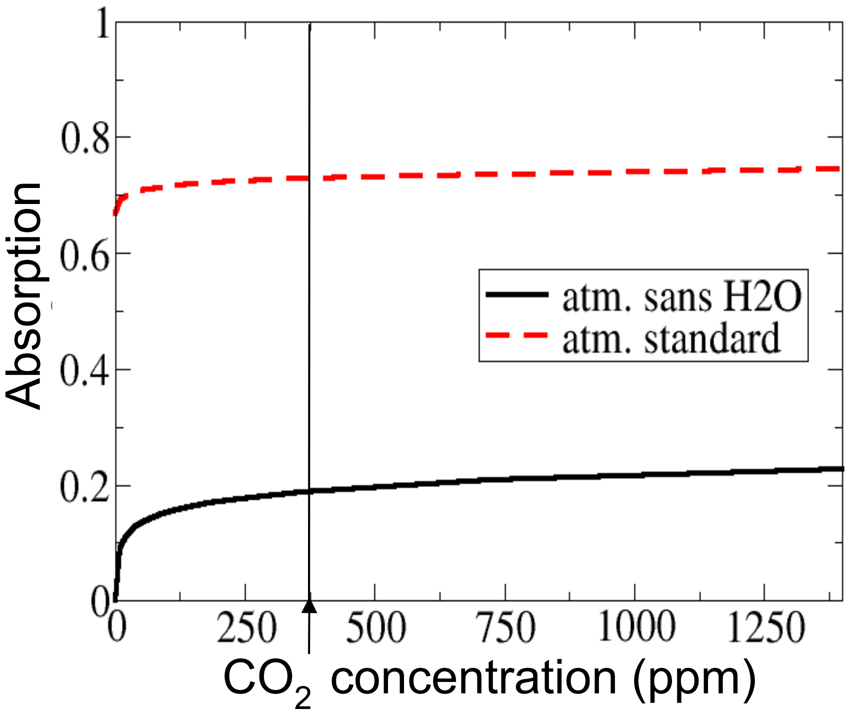
Have we reach a maximum greenhouse effect for CO_2?

CO_2 increase and greenhouse effect

Single layer greenhouse model

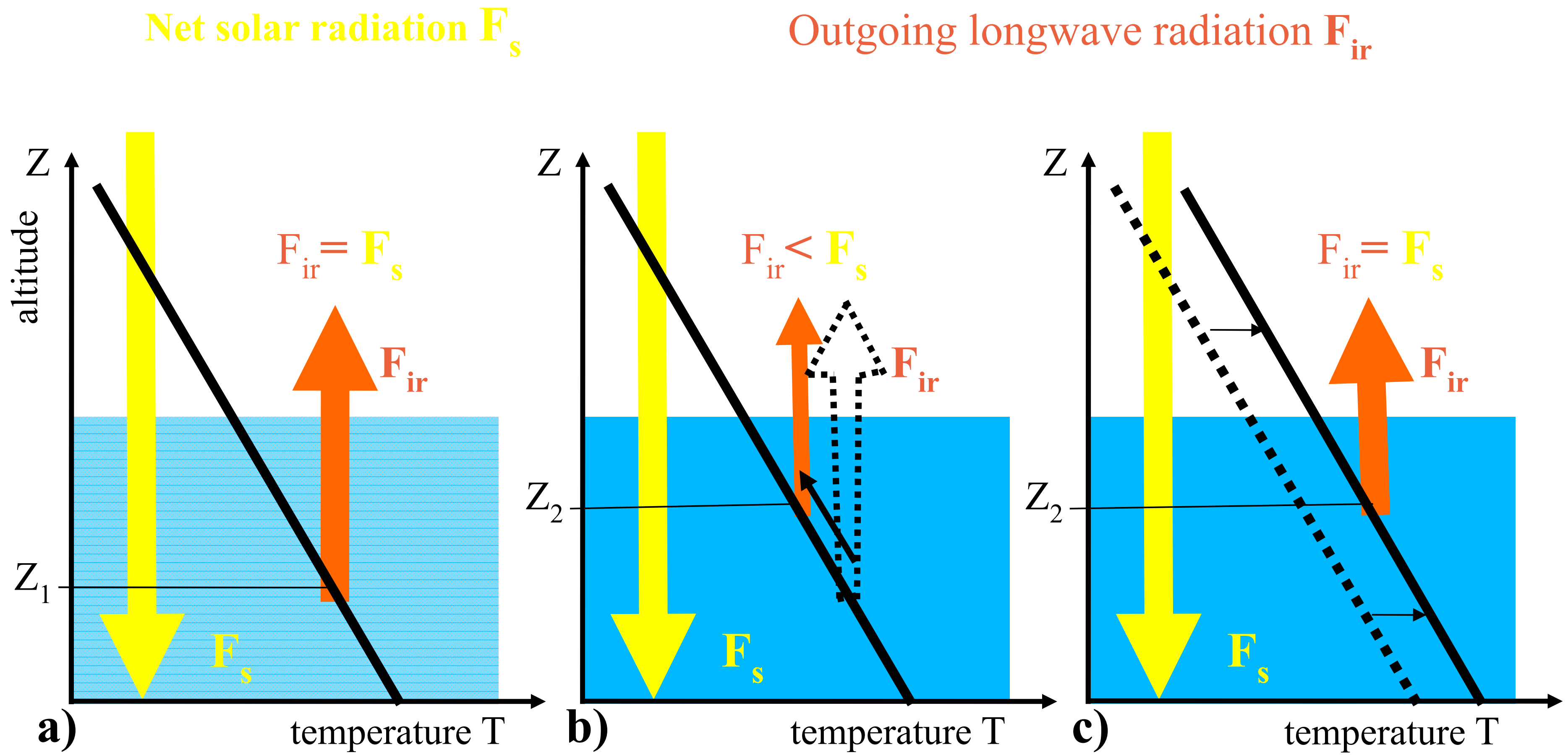


Atmospheric absorption as a function of CO_2,concentration, for two H_20 values

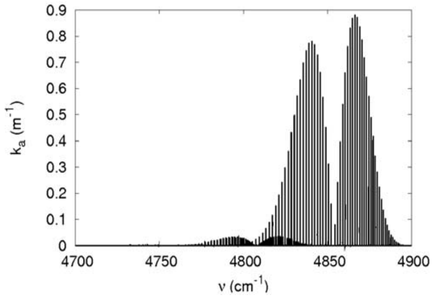


Have we reach a maximum greenhouse effect for CO_2?
NO!

CO_2 increase and greenhouse effect



In summary, 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 change except the temperature

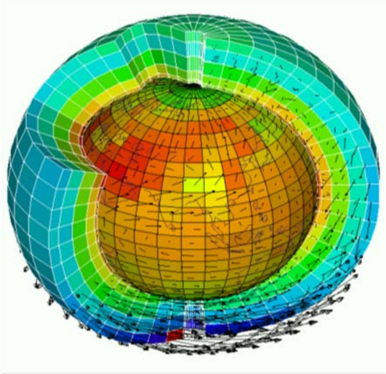
From radiative transfer computation to climate modelling

For a doubling of the CO_2 concentration, 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



Climate feedback

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

Global average surface temperature change

flux at TOA change

radiative forcing

“feedback parameter”

When a new equilibrium is reached, ΔR=0

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

$$\lambda = \lambda_P + \lambda_w + \lambda_L + \lambda_c + \lambda_\alpha$$

Planck

water vapor

lapse rate

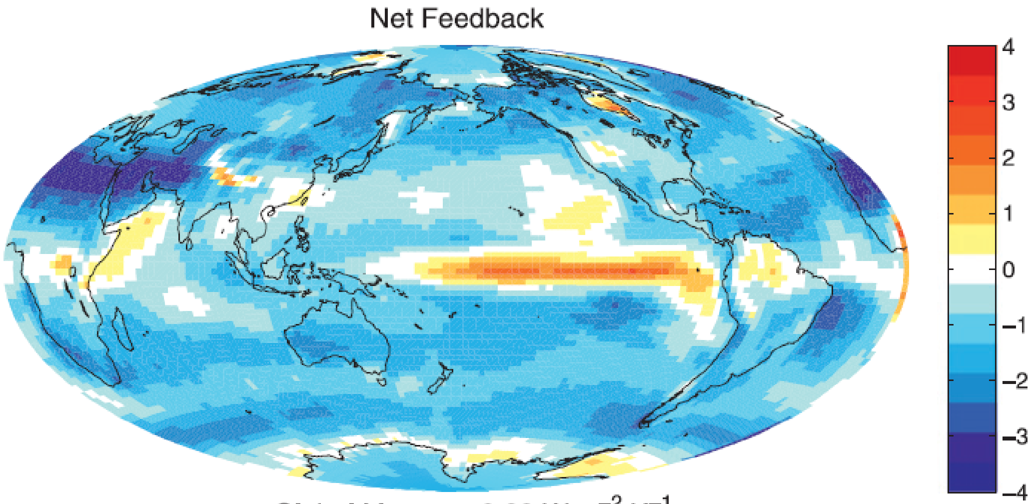
clouds

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

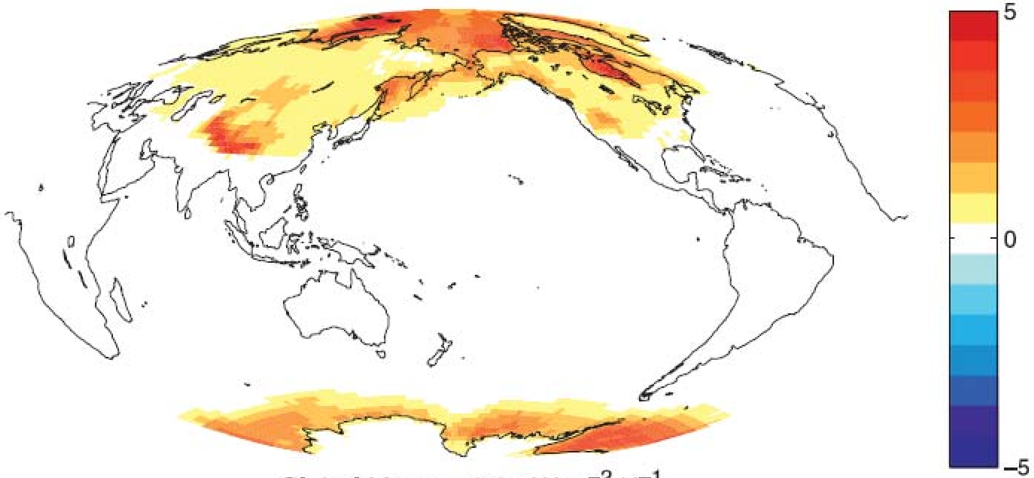
Climate feedback



Net Feedback

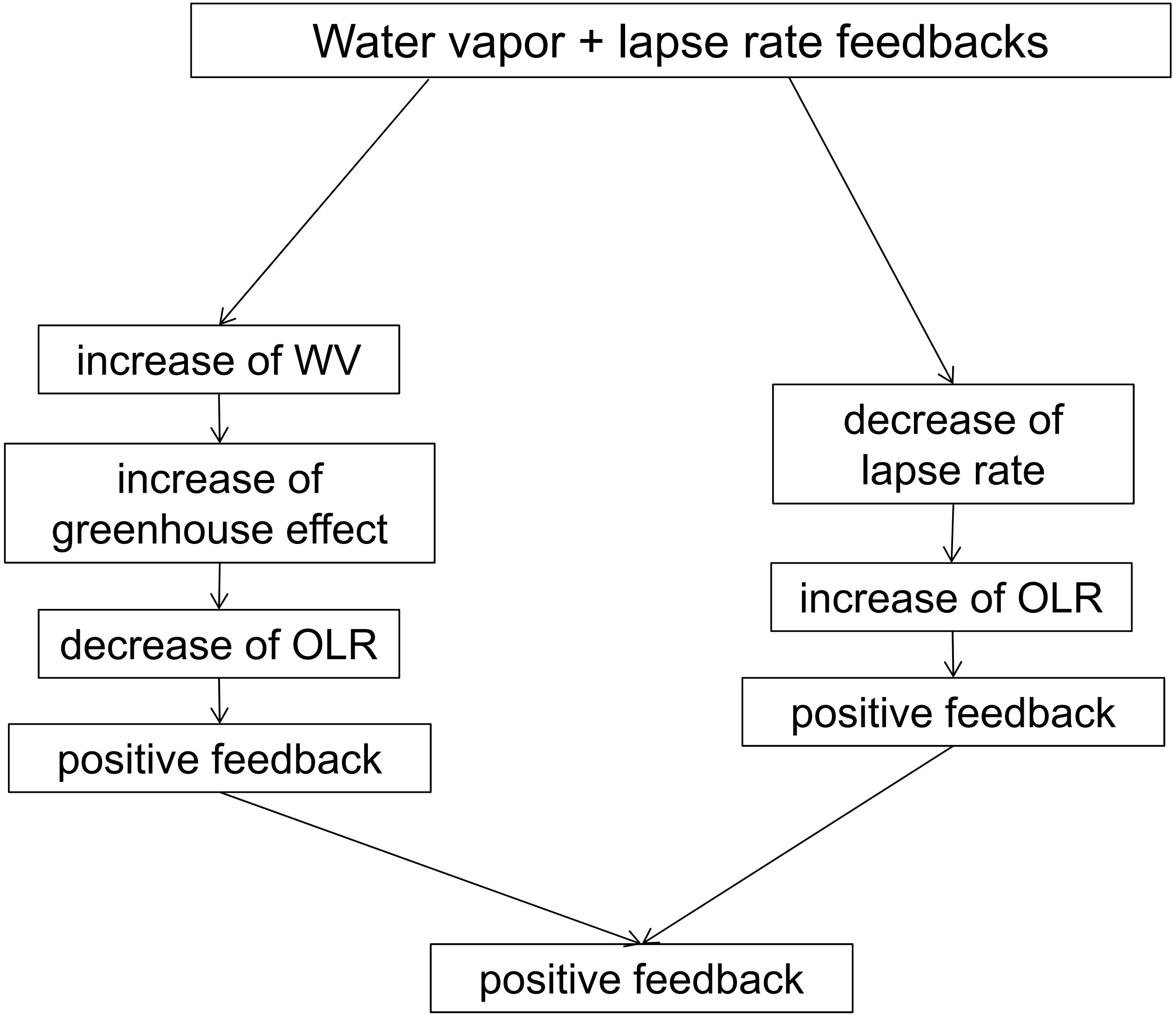
Global Mean = −0.98 W m^{-2} K^{-1}

Surface albedo feedback



Global Mean = 0.27 W m^{-2} K^{-1}

Water vapor feedback



Water vapor + lapse rate feedbacks

increase of WV

increase of greenhouse effect

decrease of OLR

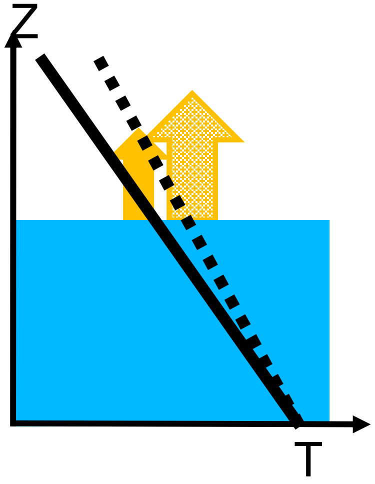
positive feedback

decrease of lapse rate

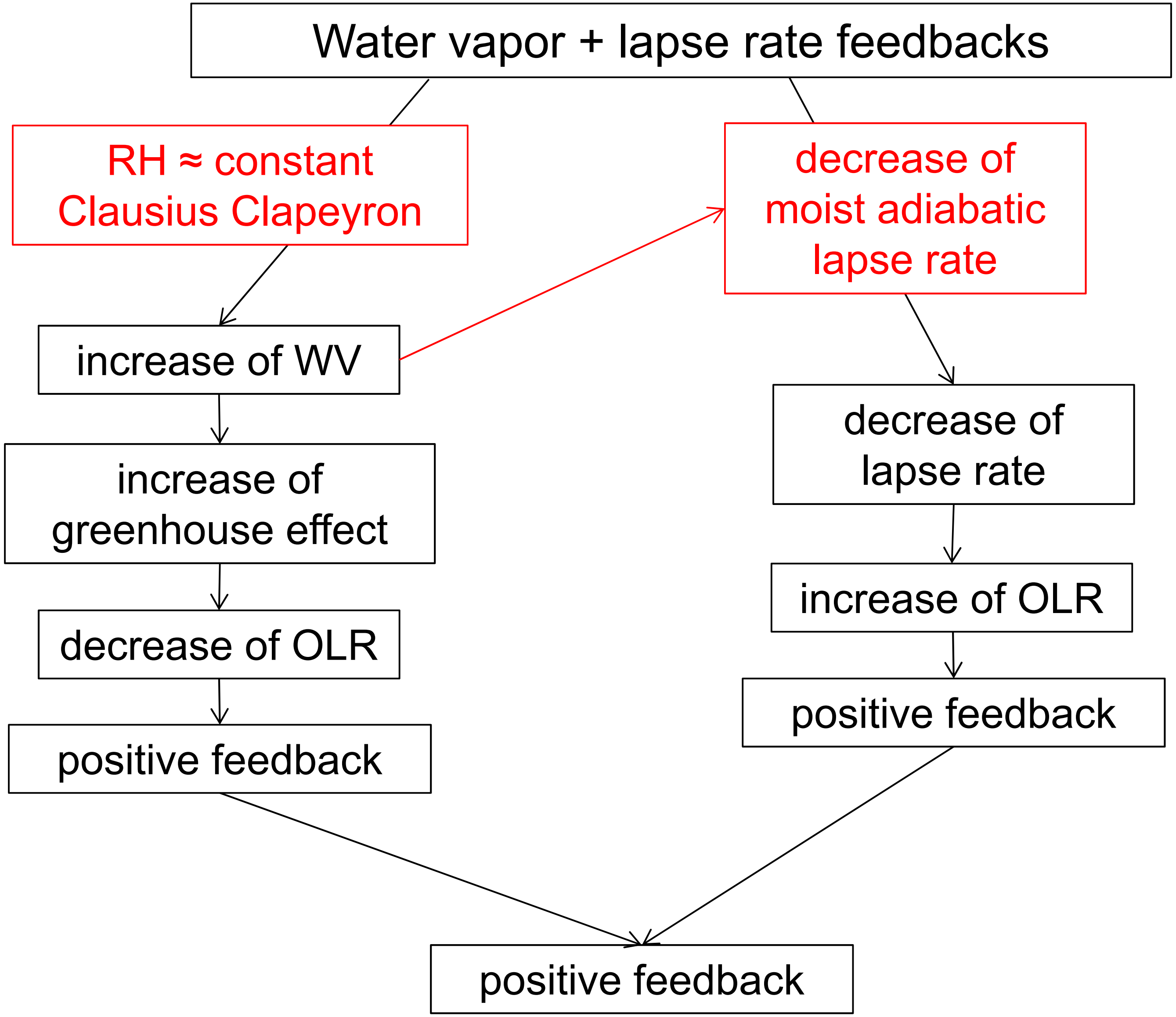
increase of OLR

positive feedback

positive feedback



Water vapor feedback



Water vapor + lapse rate feedbacks

RH ≈ constant
Clausius Clapeyron

increase of WV

increase of greenhouse effect

decrease of OLR

positive feedback

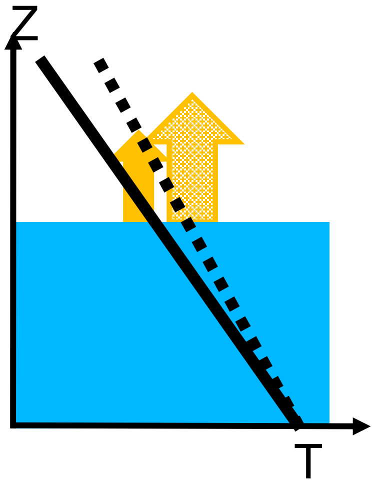
decrease of moist adiabatic lapse rate

decrease of lapse rate

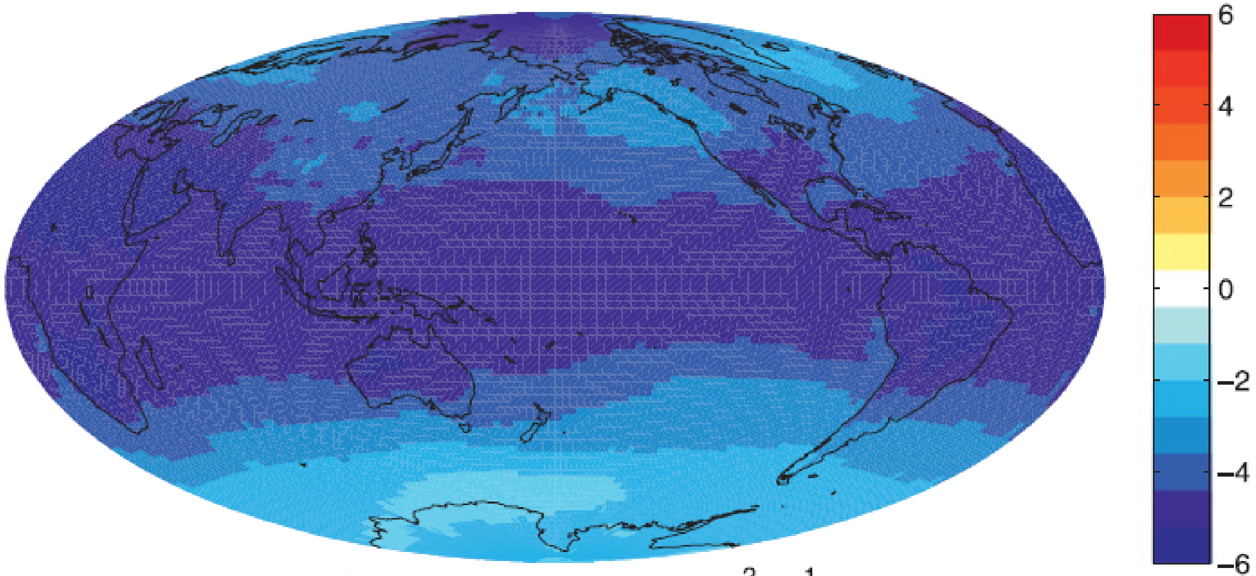
increase of OLR

positive feedback

positive feedback

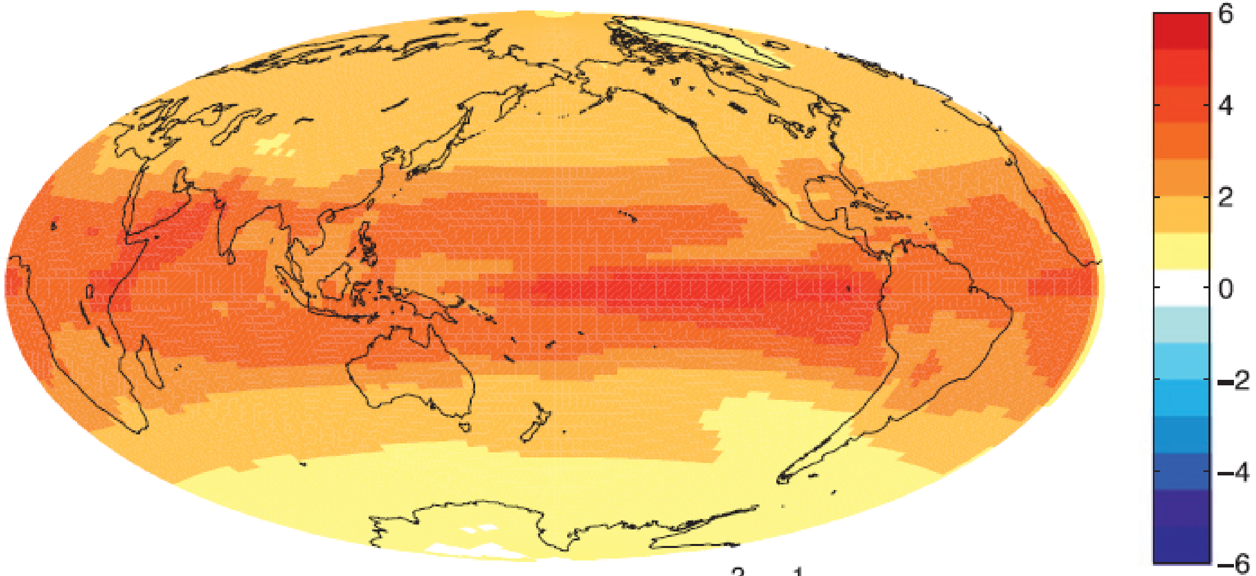


Temperature Feedback



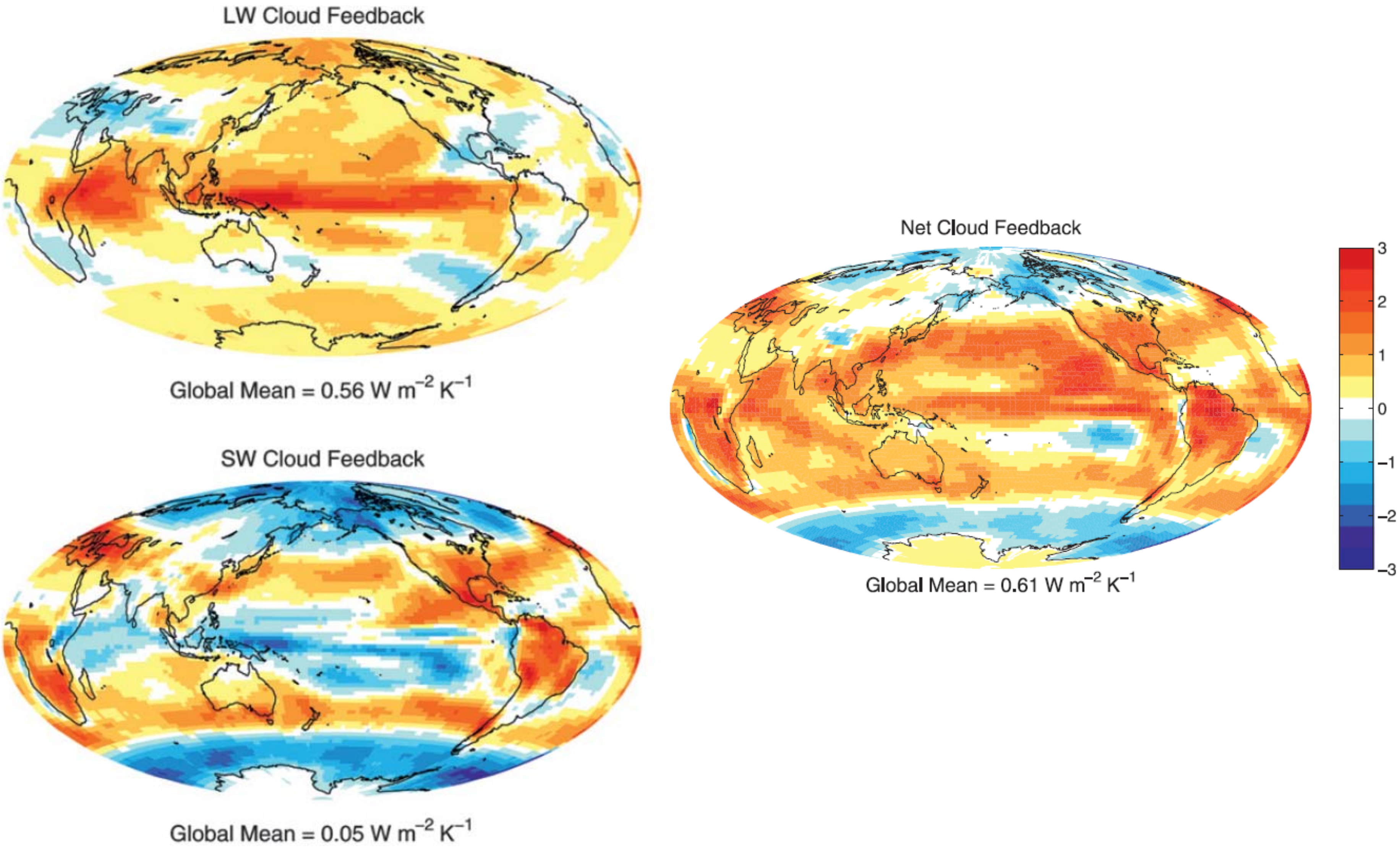
Global Mean = $-4.02\ \mathrm{W\ m^{-2}\ K^{-1}}$

Water Vapor Feedback



Global Mean = $2.16\ \mathrm{W\ m^{-2}\ K^{-1}}$

Cloud feedback


LW Cloud Feedback

Global Mean = 0.56 W m^{-2} K^{-1}

SW Cloud Feedback

Global Mean = 0.05 W m^{-2} K^{-1}

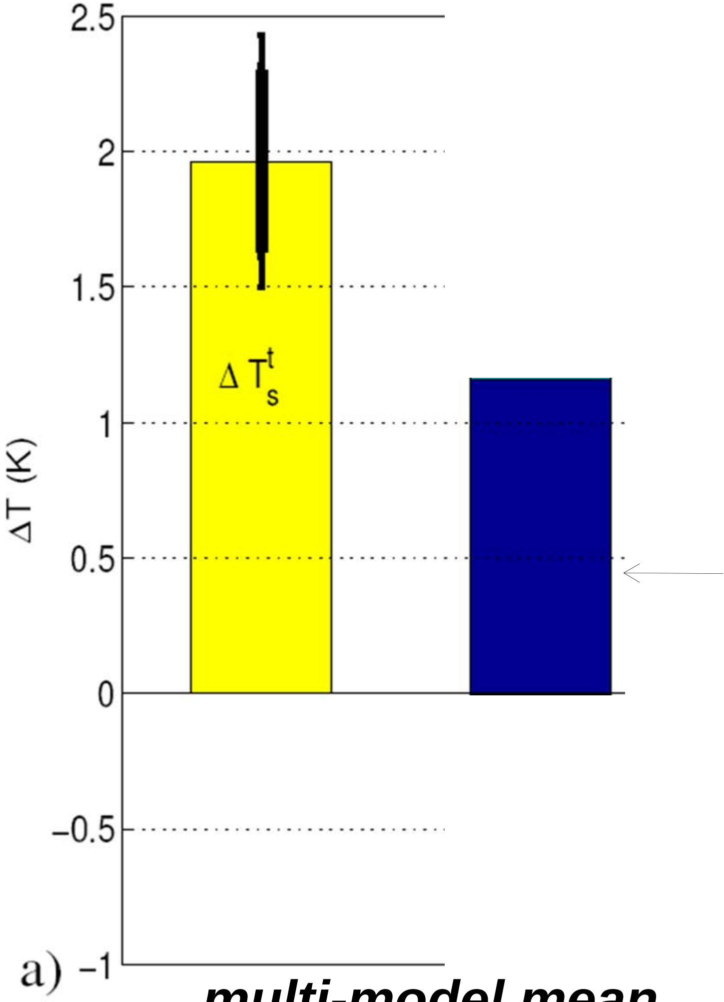
Net Cloud Feedback

Global Mean = 0.61 W m^{-2} K^{-1}

[Zelinka et al., 2012]

Transient temperature response to a CO_2 doubling

(CO_2 increase 1%/year, 70 years)



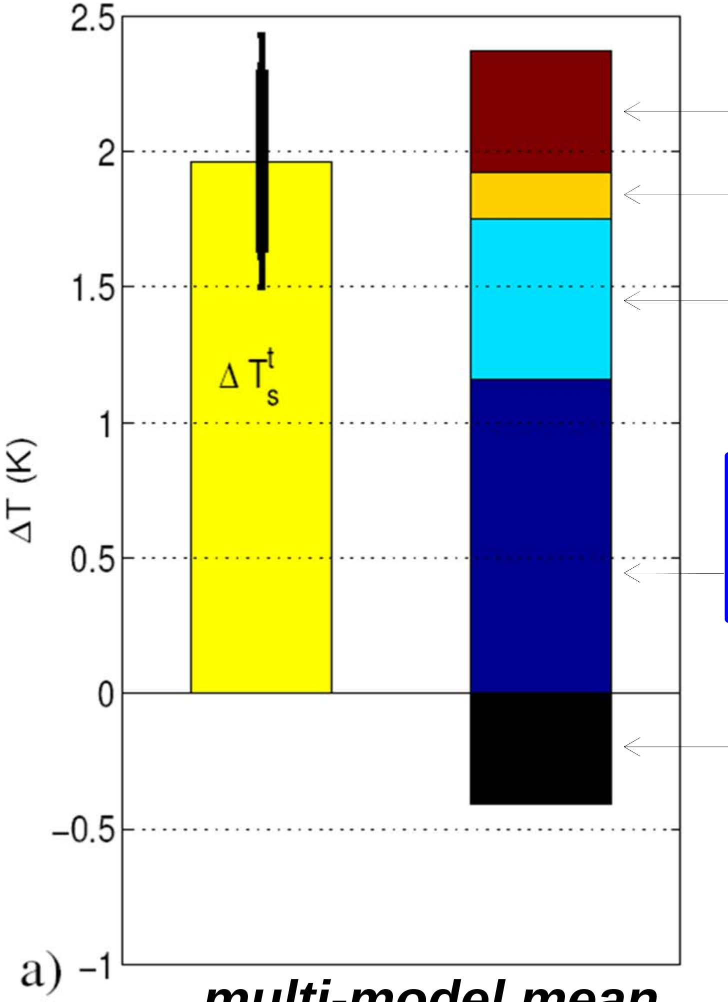
Direct response to the forcing
Planck response

multi-model mean

(Dufresne & Bony, 2008)

Transient temperature response to a CO_2 doubling

(CO_2 increase 1%/year, 70 years)



multi-model mean

Climate feedbacks: Indirect response to the forcing

clouds

snow and ice (surface albedo)

water vapor

Direct response to the forcing

Planck response

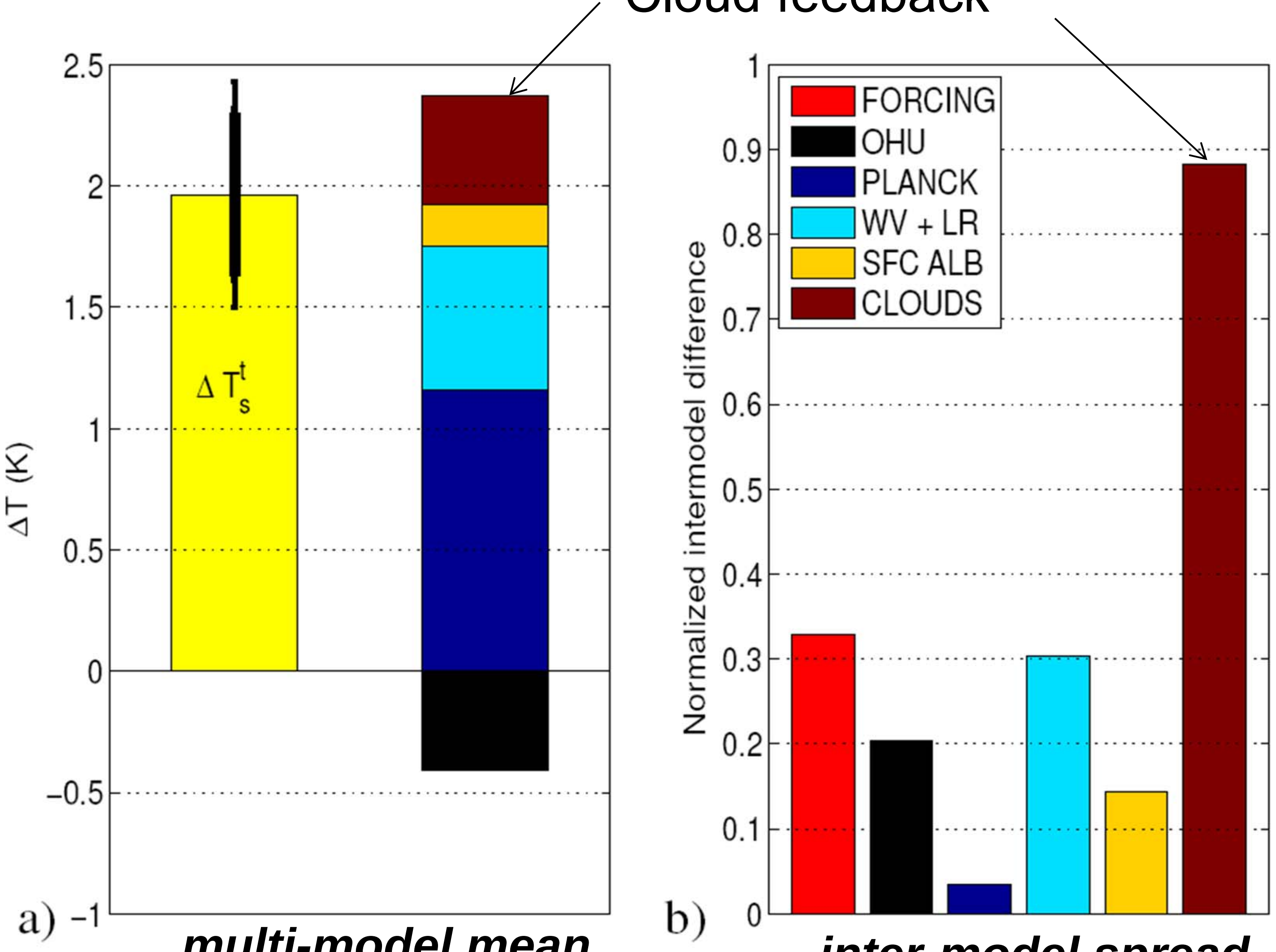
ocean heat uptake

(Dufresne & Bony, 2008)

Transient temperature response to a CO_2 doubling

(CO_2 increase 1%/year, 70 years)

Cloud feedback



multi-model mean

inter-model spread

(Dufresne & Bony, 2008)

Outlook

I. Basic of climate change: greenhouse effect, forcing and feedbacks

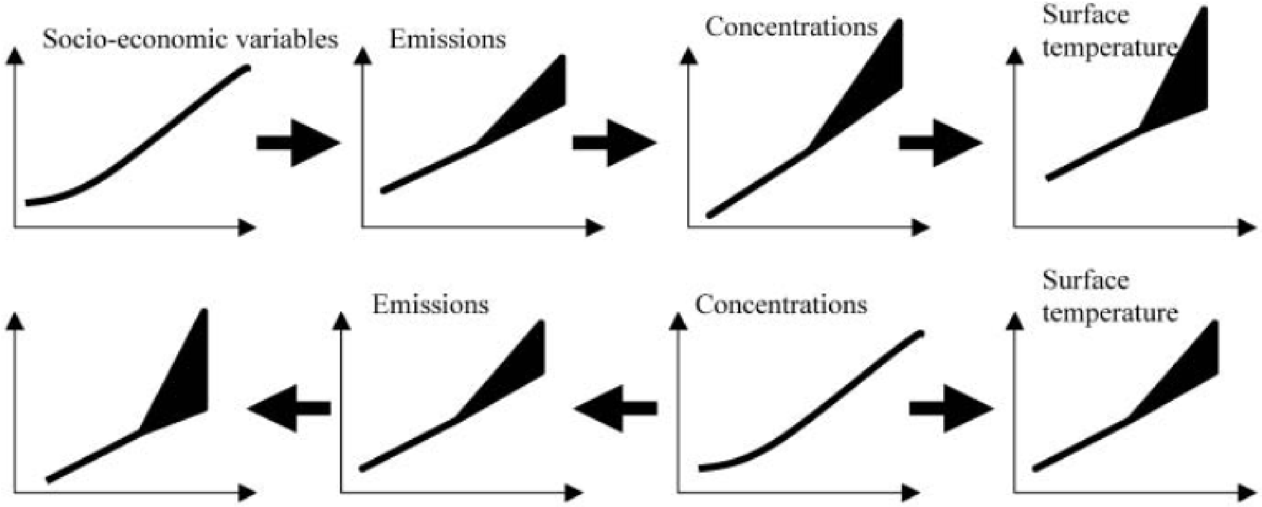
II. Scenarios and forcings for climate change projections

III. Climate change projections at global scales

Scenario for future climate change projections

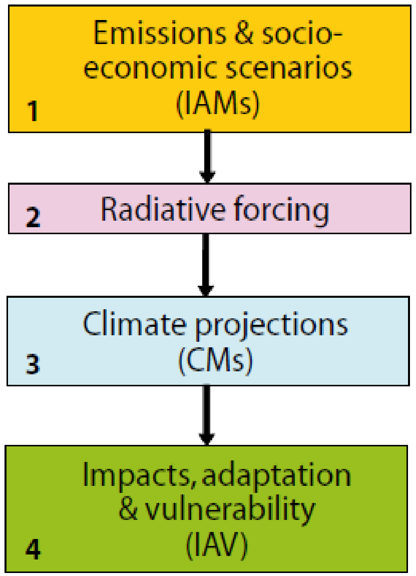
SRES

RCP



[Hibbard et al., EOS, 2007]

SRES **a) Sequential approach**

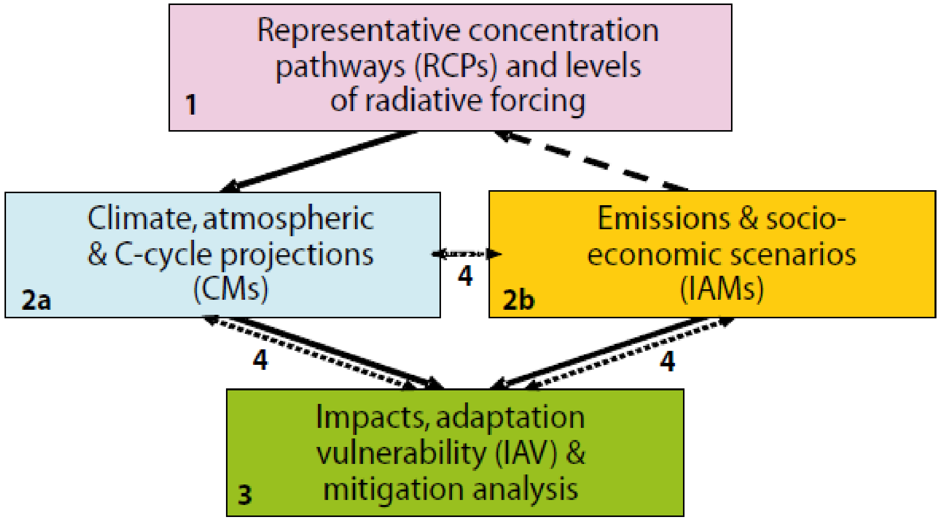

1 Emissions & socio-economic scenarios (IAMs)

2 Radiative forcing

3 Climate projections (CMs)

4 Impacts, adaptation & vulnerability (IAV)

RCP **b) Parallel approach**


1 Representative concentration pathways (RCPs) and levels of radiative forcing

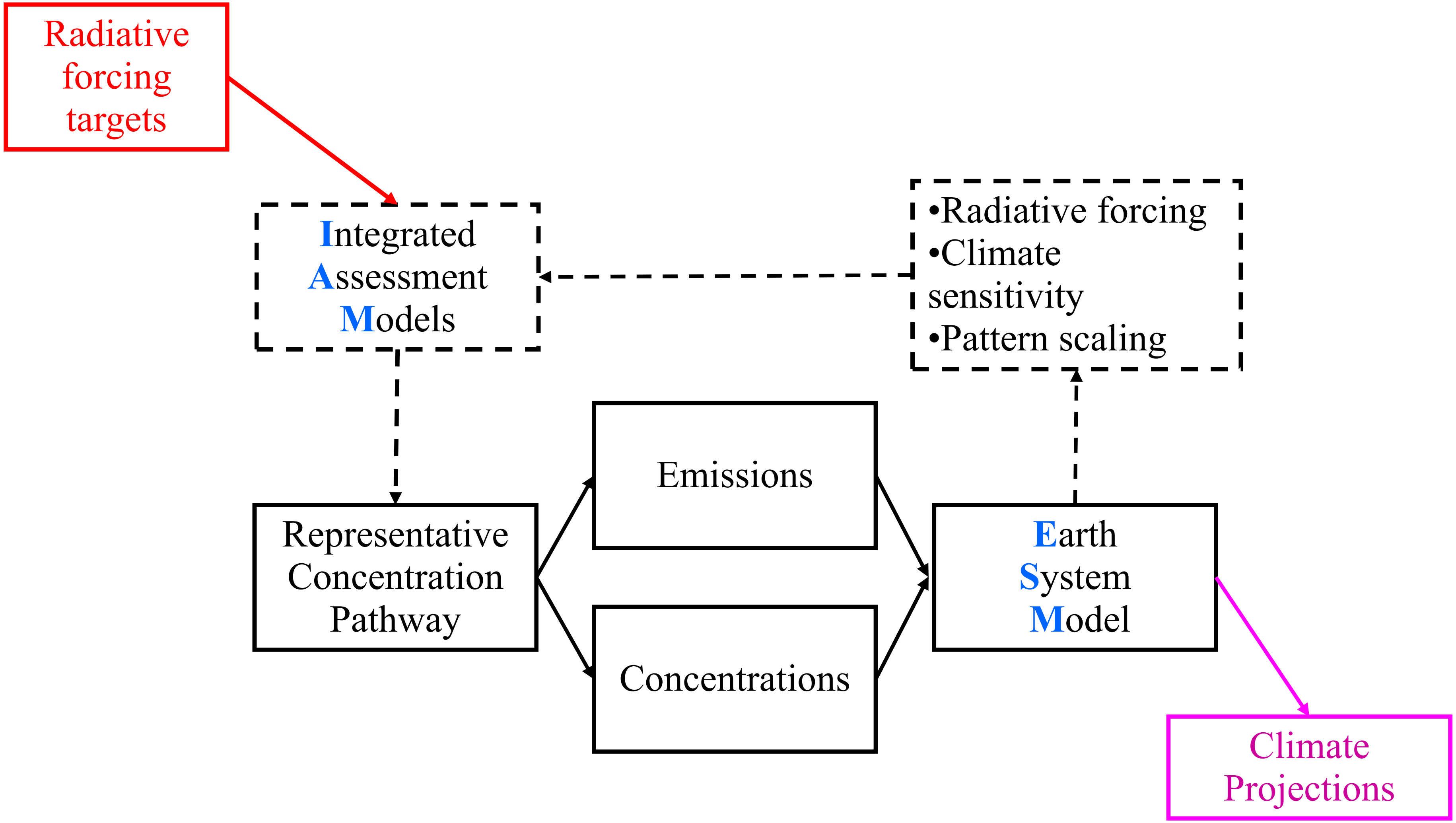
2a Climate, atmospheric & C-cycle projections (CMs)

2b Emissions & socio-economic scenarios (IAMs)

3 Impacts, adaptation vulnerability (IAV) & mitigation analysis

[Moss et al., IPCC, 2008]

Scenario for future climate change projections



Radiative forcing targets

Integrated **A**ssessment **M**odels

- Radiative forcing
- Climate sensitivity
- Pattern scaling

Emissions

Representative Concentration Pathway

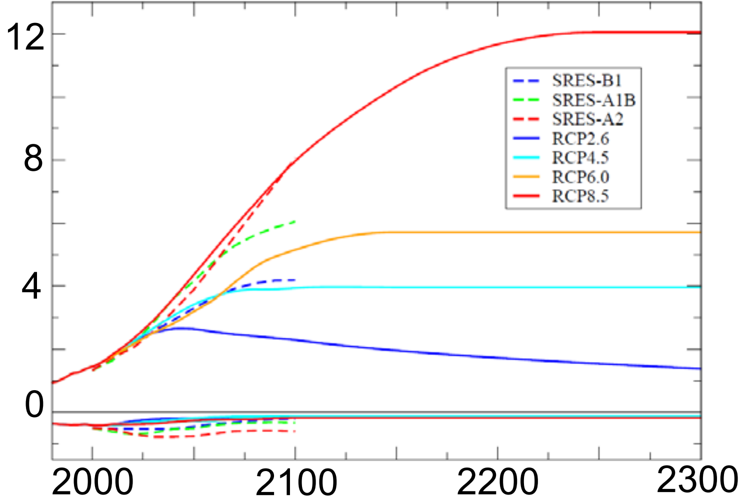
Earth **S**ystem **M**odel

Concentrations

Climate Projections

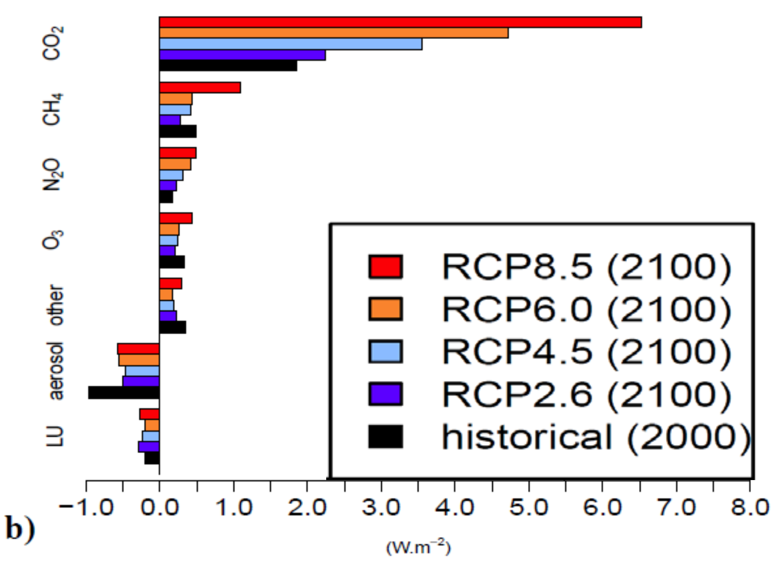
Radiative forcing of future scenarios

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

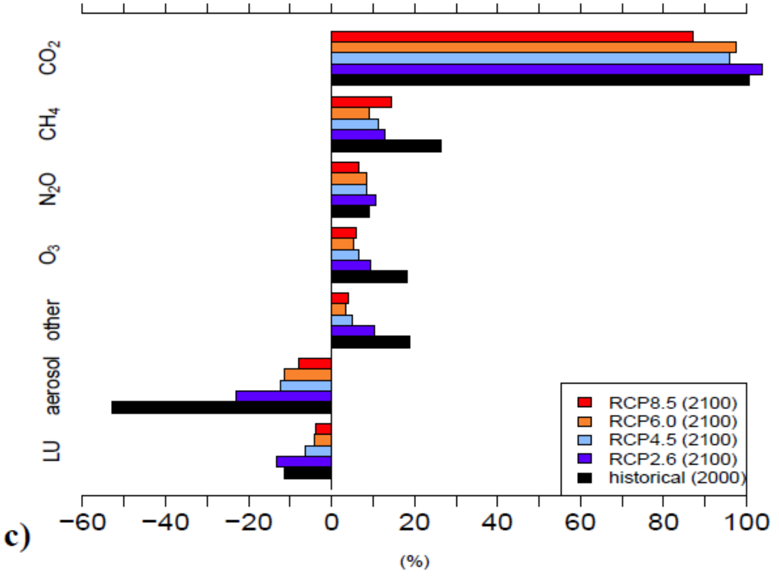


Contribution of individual forcings to total forcing relative to ***1850***

Values (W.m^{-2})

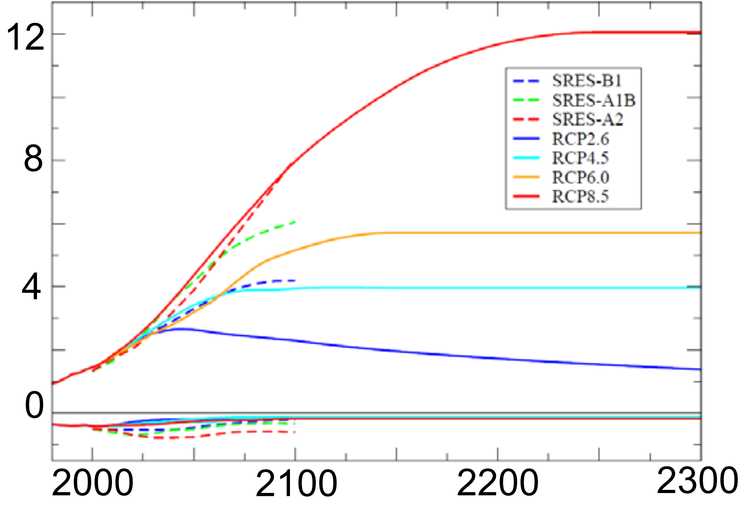


Relative values (%)

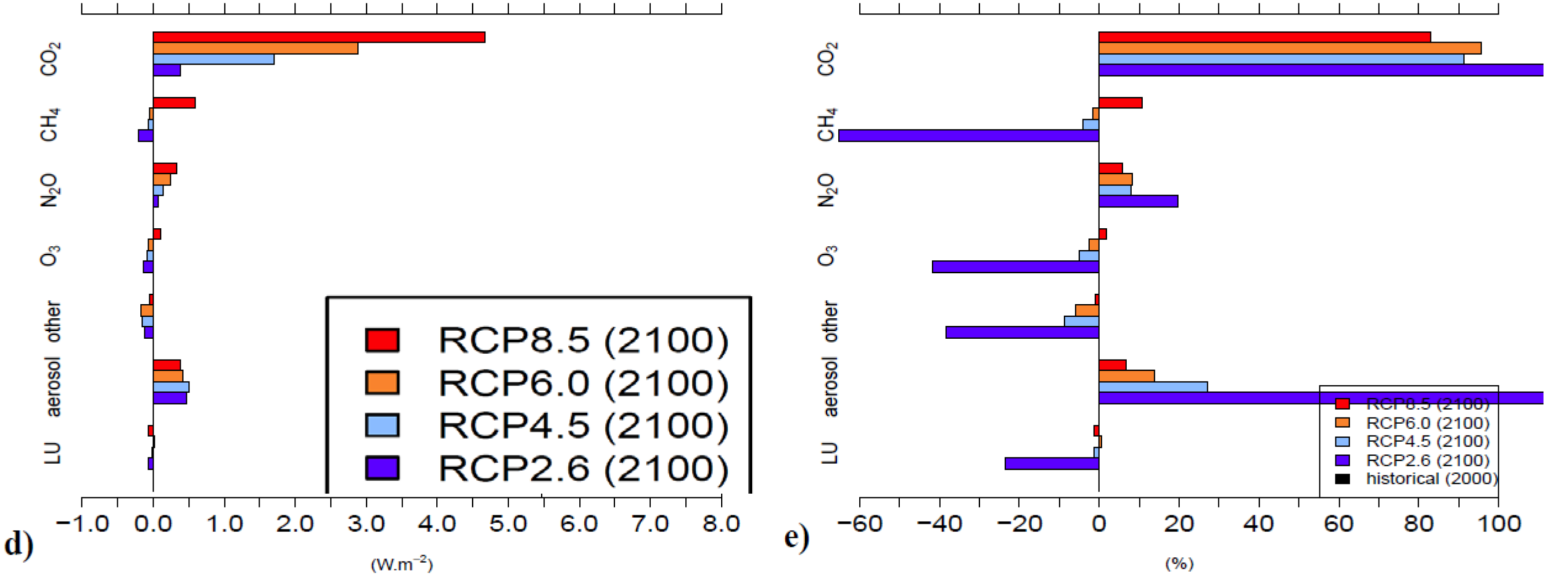


Radiative forcing of future scenarios

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

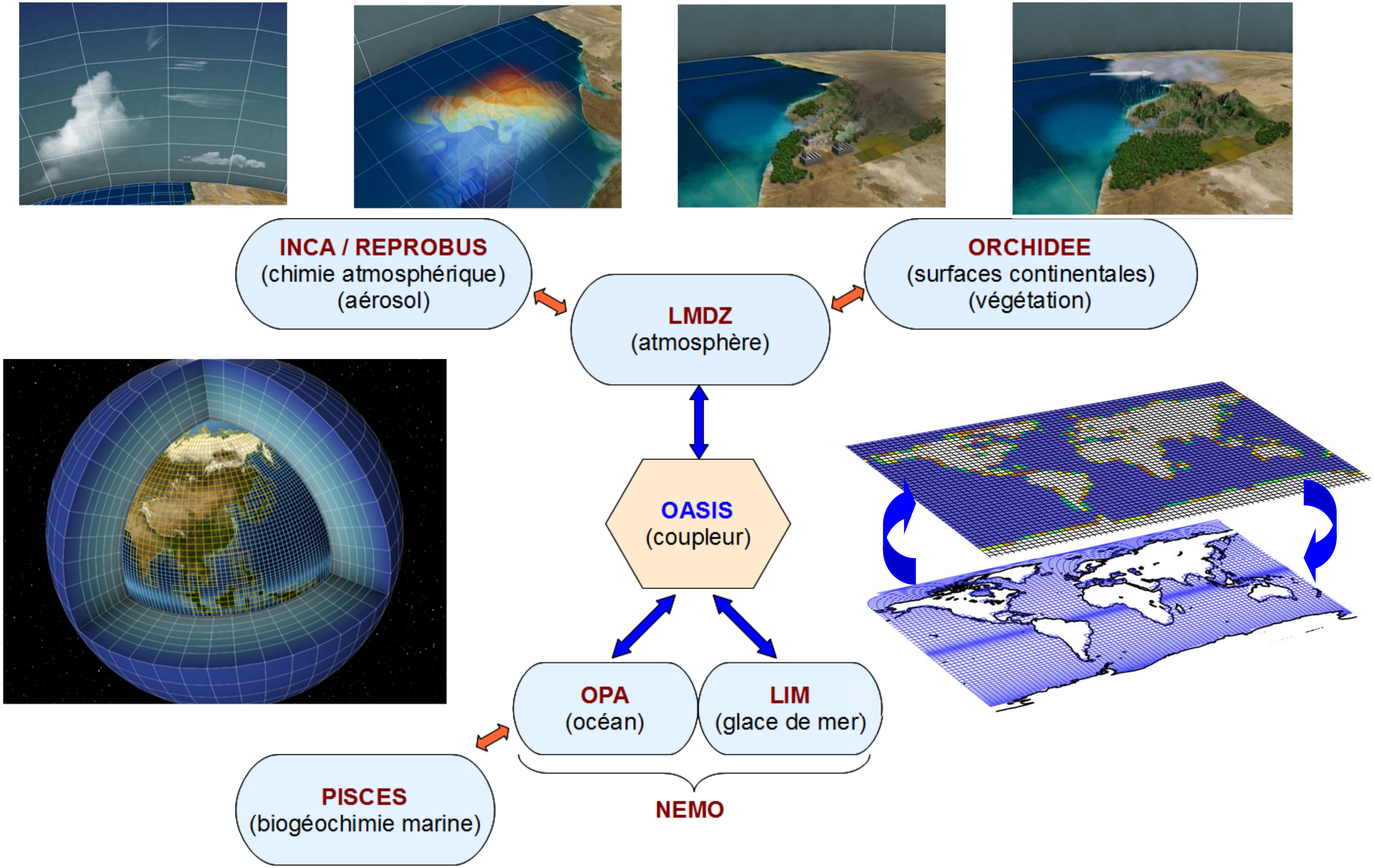


*Contribution of individual forcings to total forcing relative to **2000***


Values (W.m^{-2})

Relative values (%)

The IPSL Earth system model



INCA / REPROBUS
(chimie atmosphérique)
(aérosol)

ORCHIDEE
(surfaces continentales)
(végétation)

LMDZ
(atmosphère)

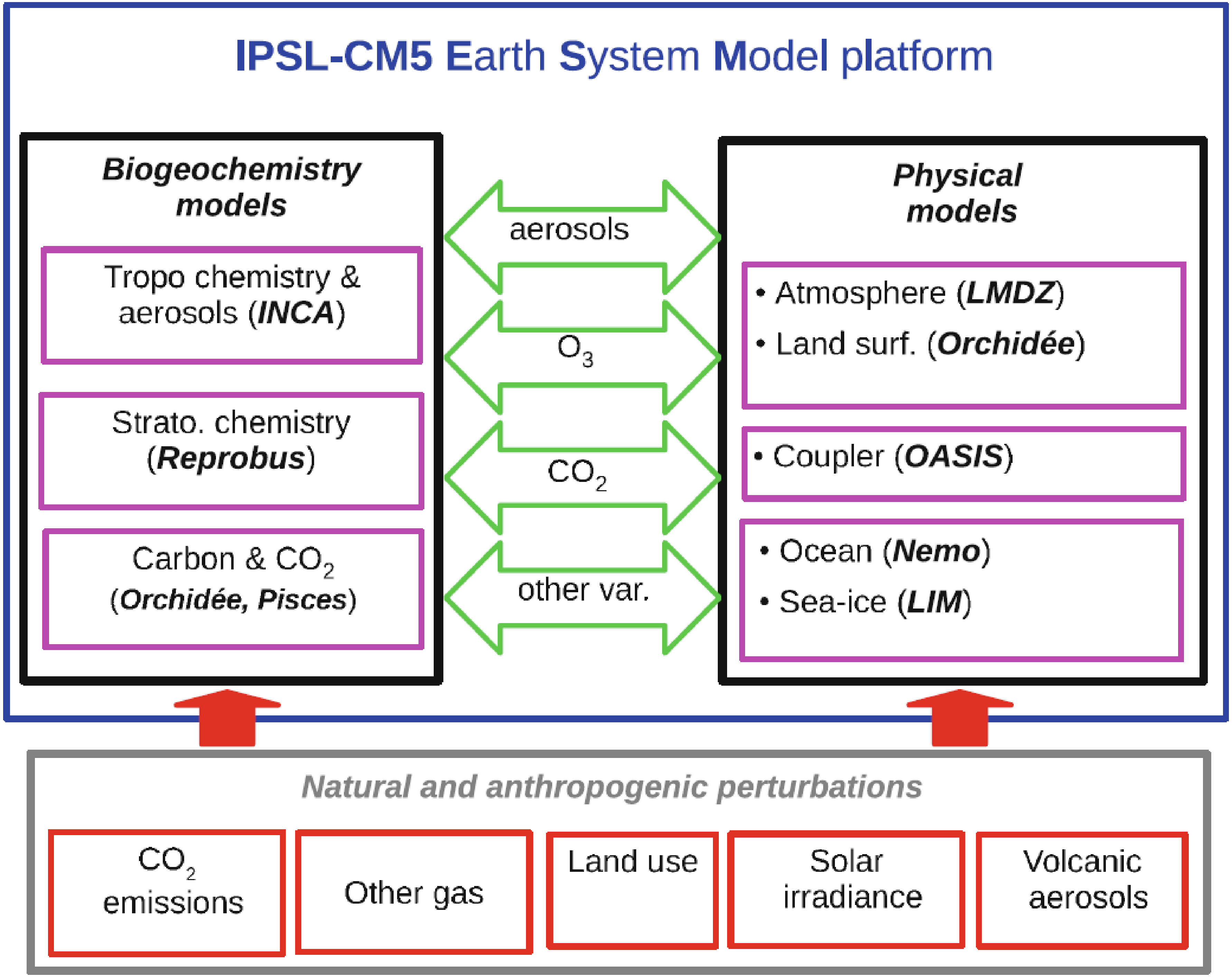
OASIS
(coupleur)

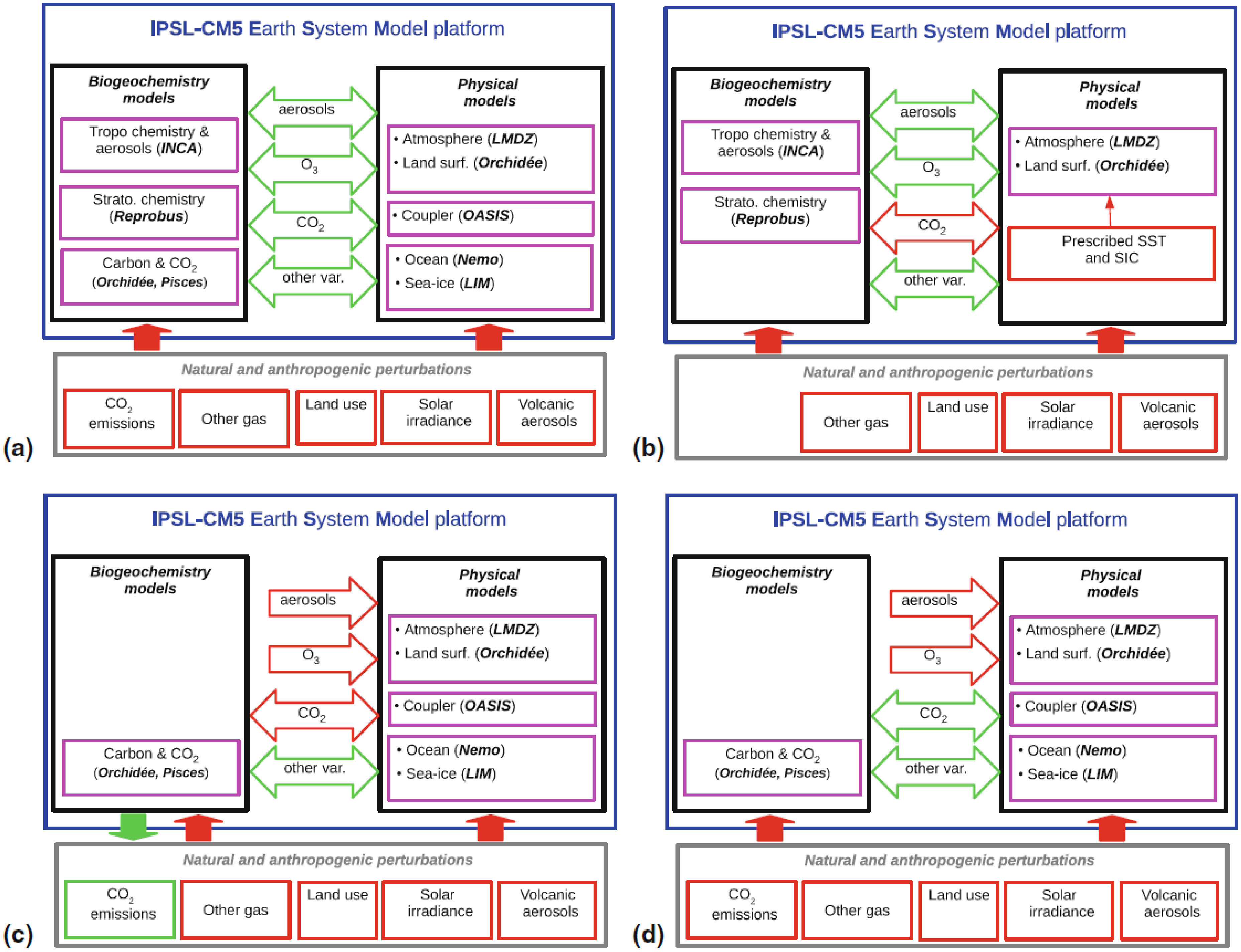
OPA
(océan)

LIM
(glace de mer)

PISCES
(biogéochimie marine)

NEMO


IPSL-CM5 Earth System Model platform
Biogeochemistry models
Tropo chemistry & aerosols (***INCA***)
Strato. chemistry (***Reprobus***)
Carbon & CO_2 (***Orchidée, Pisces***)
aerosols
O_3
CO_2
other var.
Physical models
• Atmosphere (***LMDZ***)
• Land surf. (***Orchidée***)
• Coupler (***OASIS***)
• Ocean (***Nemo***)
• Sea-ice (***LIM***)
Natural and anthropogenic perturbations
CO_2 emissions
Other gas
Land use
Solar irradiance
Volcanic aerosols



(a)
IPSL-CM5 Earth System Model platform
Biogeochemistry models
Tropo chemistry & aerosols (INCA)
Strato. chemistry (Reprobus)
Carbon & CO_2 (Orchidée, Pisces)
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• Land surf. (Orchidée)
Prescribed SST and SIC
Natural and anthropogenic perturbations
Other gas
Land use
Solar irradiance
Volcanic aerosols
(c)
IPSL-CM5 Earth System Model platform
Biogeochemistry models
Carbon & CO_2 (Orchidée, Pisces)
aerosols
O_3
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other var.
Physical models
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• Land surf. (Orchidée)
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Natural and anthropogenic perturbations
CO_2 emissions
Other gas
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(d)
IPSL-CM5 Earth System Model platform
Biogeochemistry models
Carbon & CO_2 (Orchidée, Pisces)
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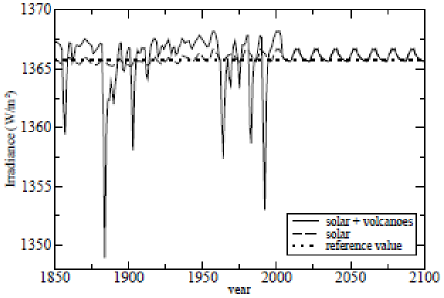
Natural and anthropogenic perturbations
CO_2 emissions
Other gas
Land use
Solar irradiance
Volcanic aerosols

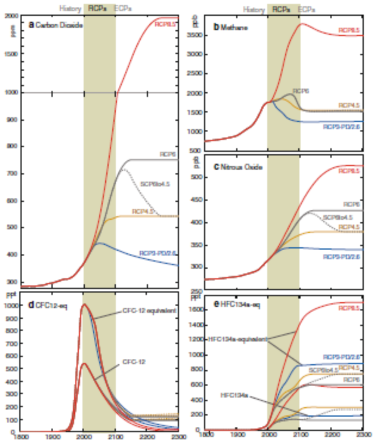
The IPSL Earth system model

Natural and anthropogenic forcings

Solar and volcanoes

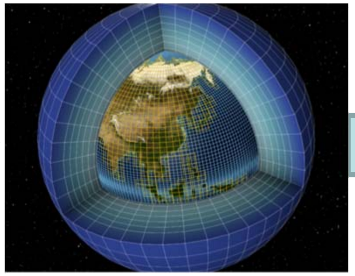


Green house gases and active gases

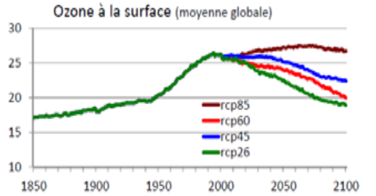


CO$_2$ concentration

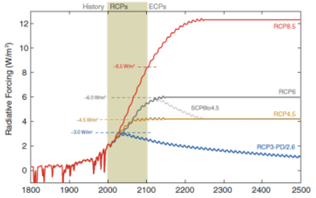
IPSL-CM5A-LR



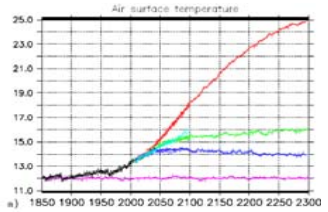
Atmospheric composition



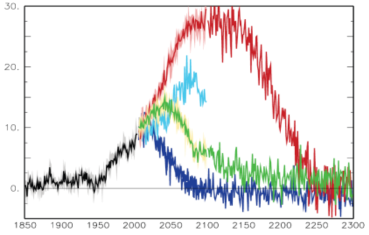
Radiative forcings



Climate changes



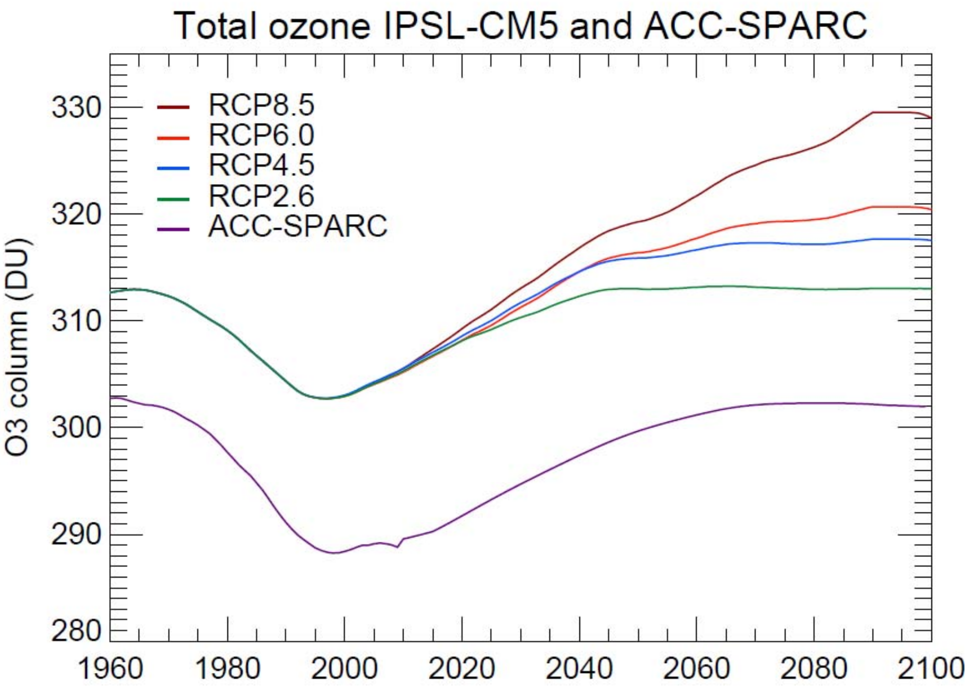
Authorized CO$_2$ emissions



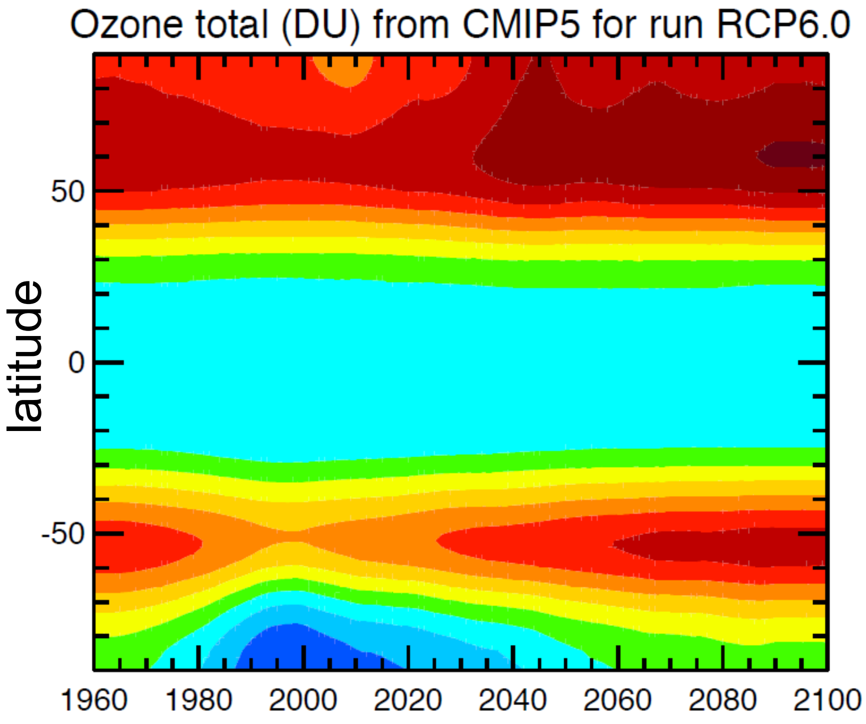
Ozone and aerosols computations

Compute ozone concentrations as a function of emissions and climate change

Global mean amount of ozone



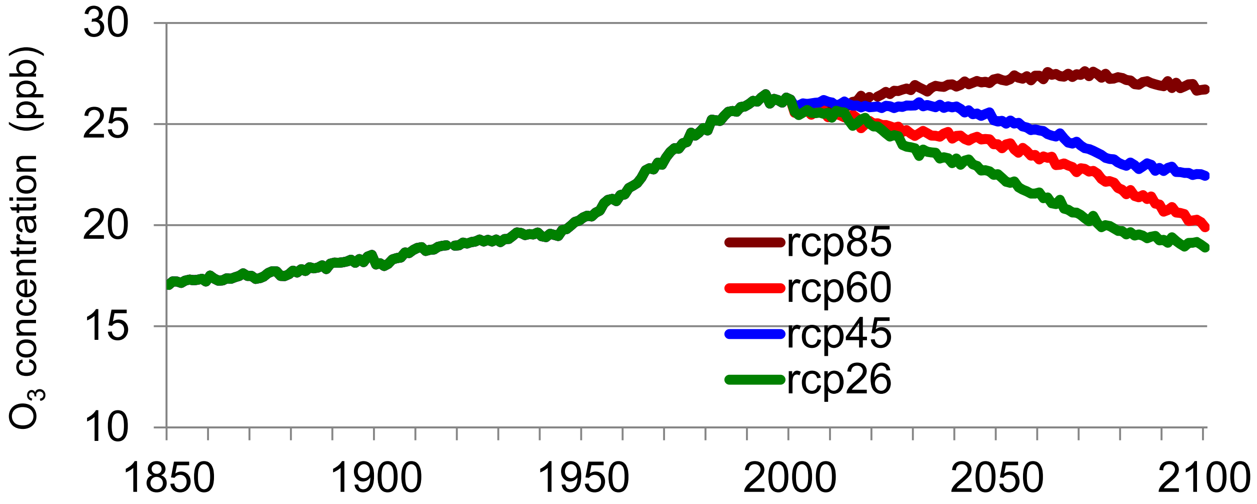
Zonal mean of ozone



[Bekki et al. 2013]

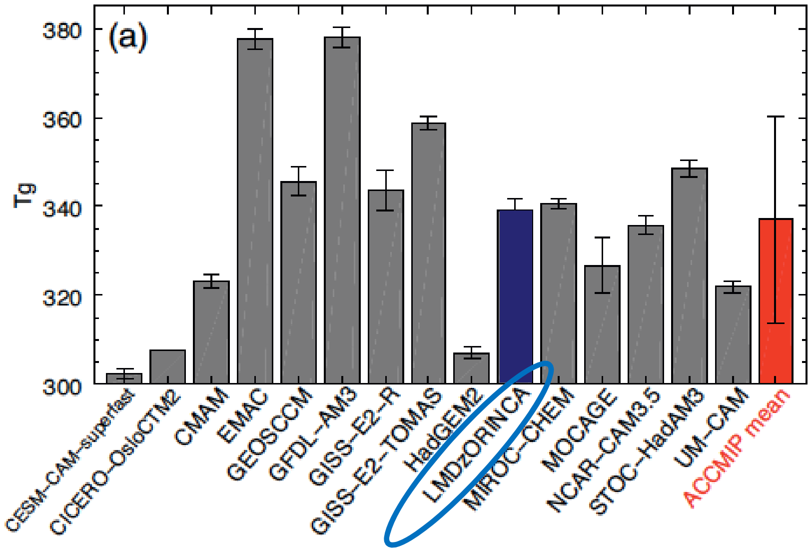
Tropospheric ozone

Ozone at surface (global mean)

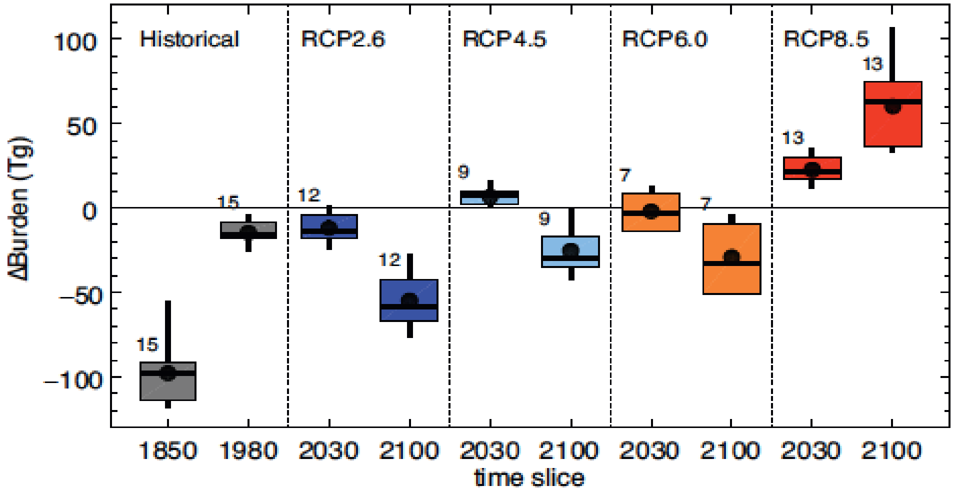


IPSL
LMDZ-INCA
[Szopa et al., 2013]

Amount of tropo ozone in 2000



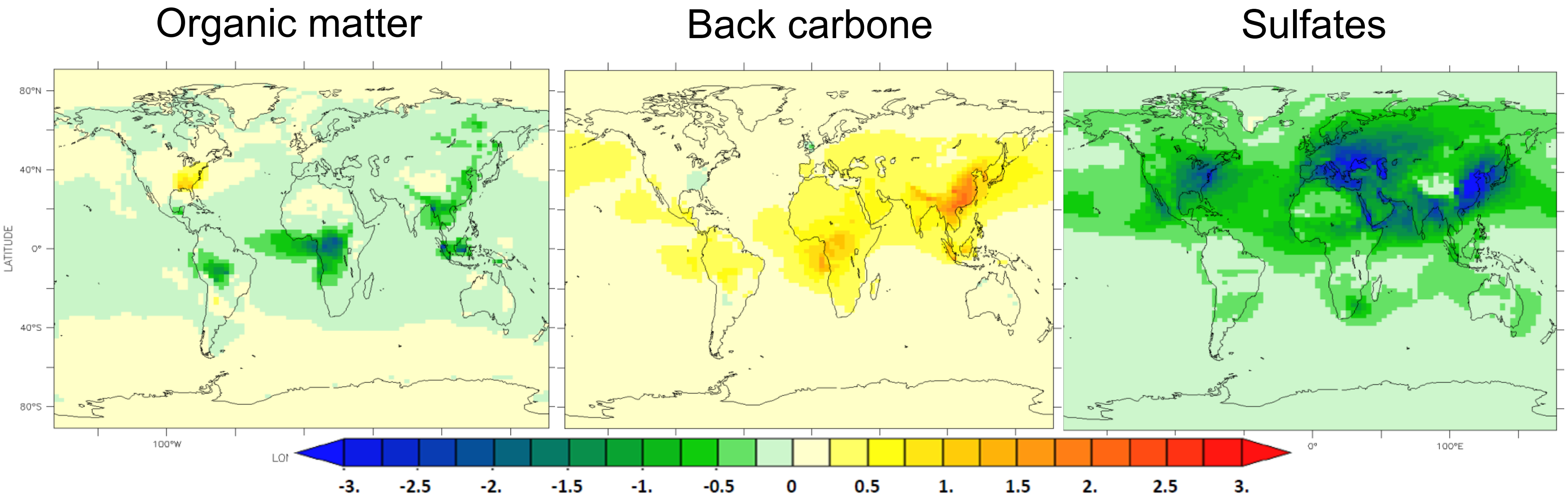
Ozone change relative to year 2000

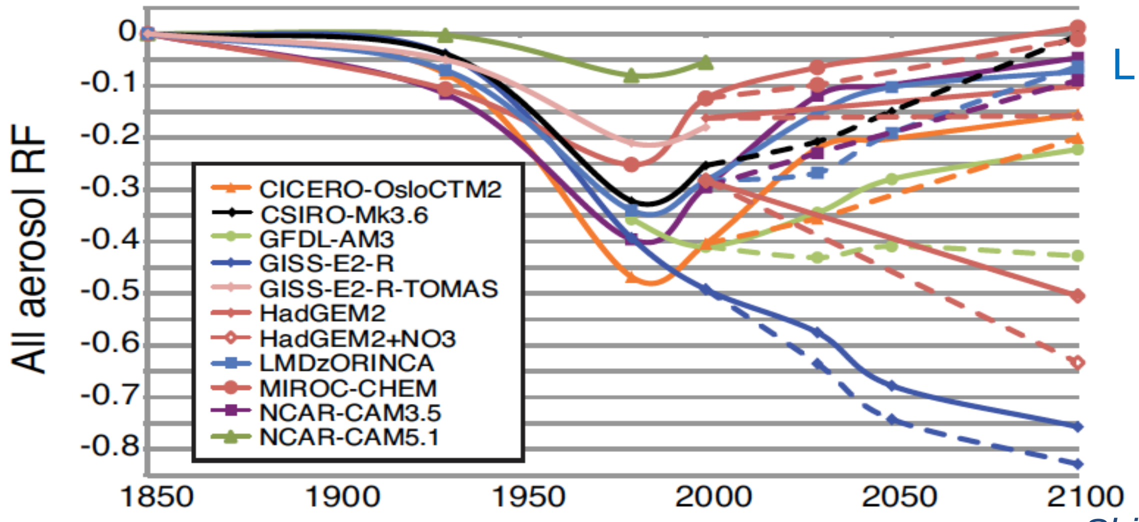


[Young et al. 2013]

Aerosols

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

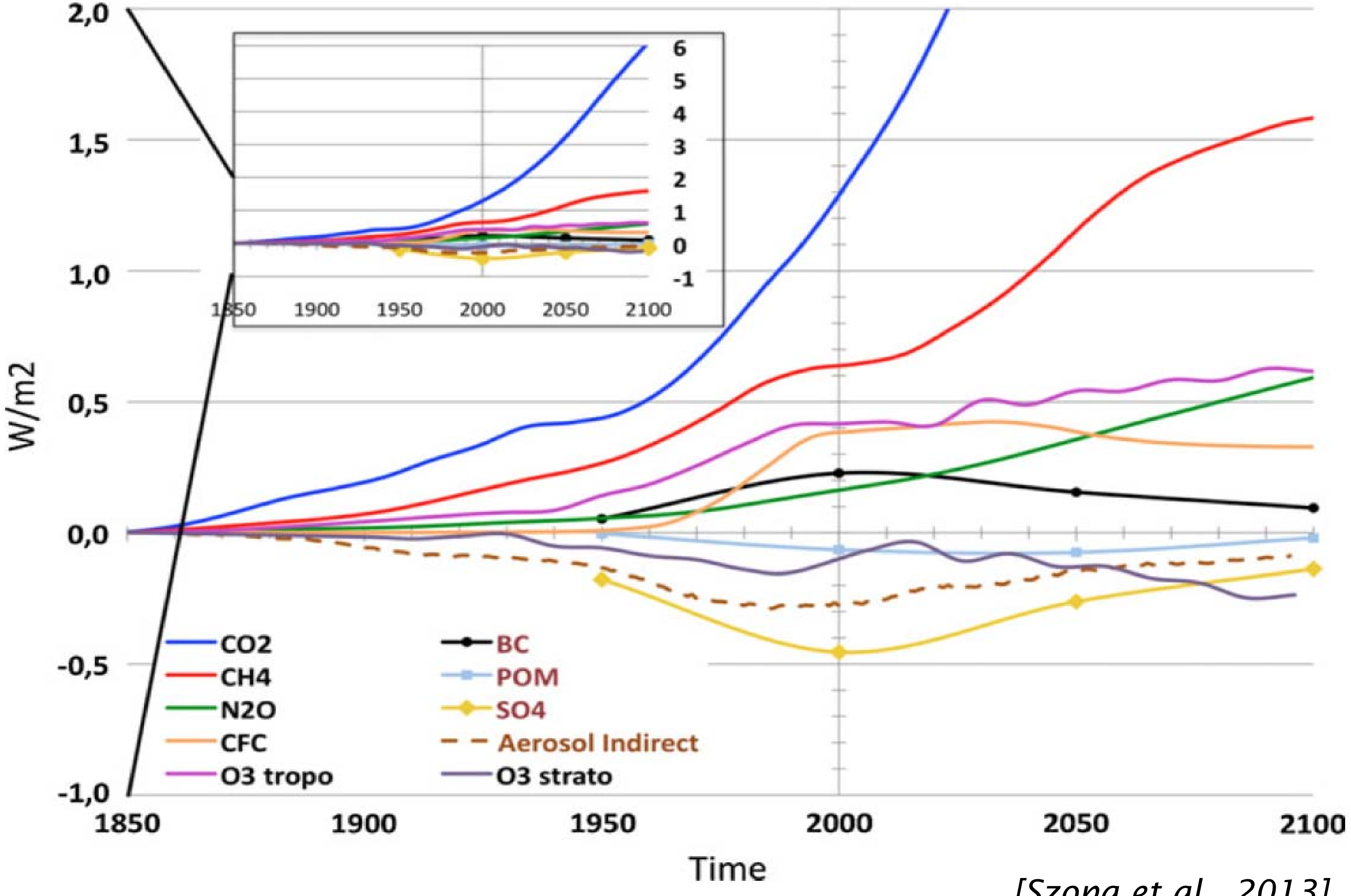




LMDz-INCA

Shindell et al., 2012

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



[Szopa et al., 2013]

Outlook

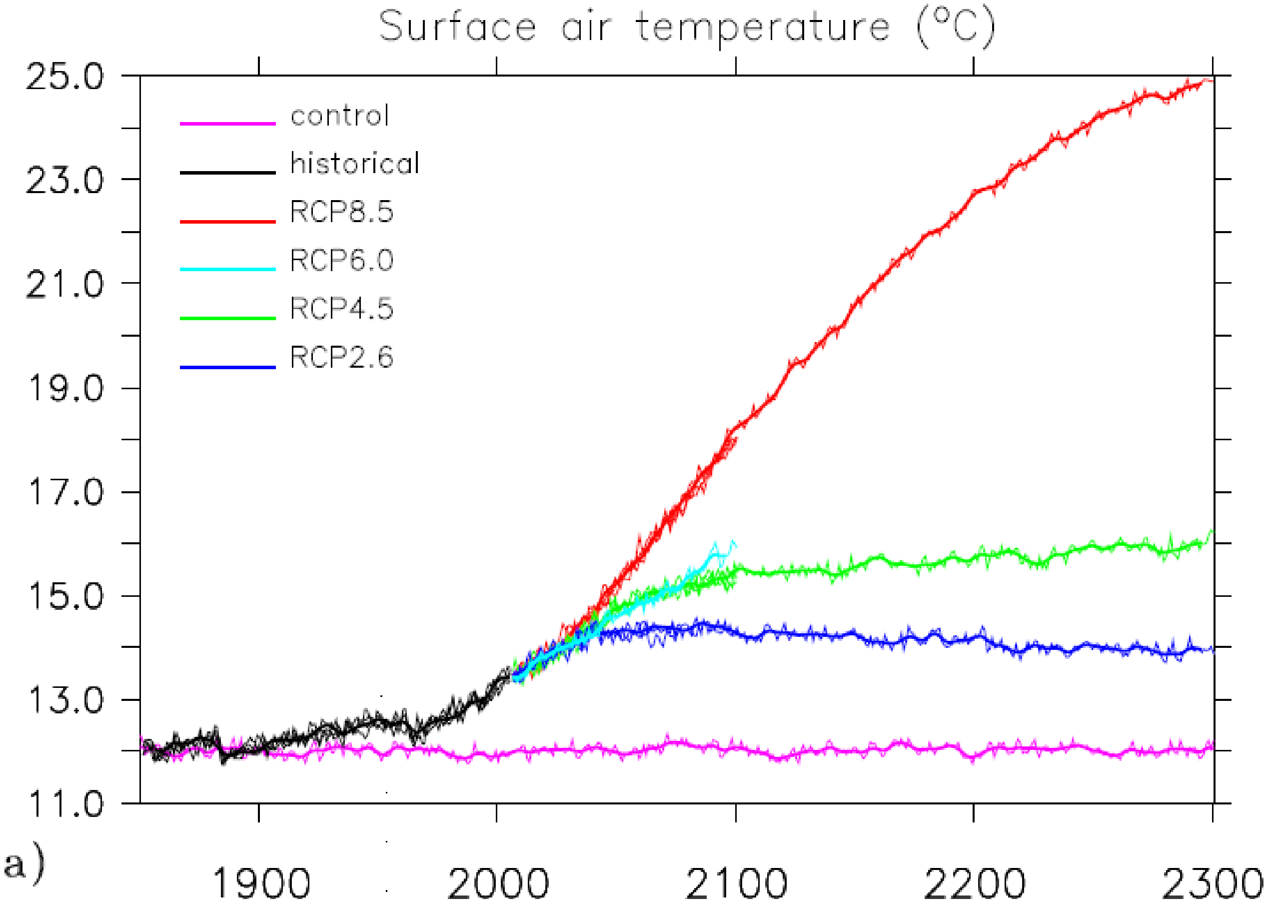
I. Basic of climate change: greenhouse effect, forcing and feedbacks

II. Scenarios and forcings for climate change projections

III. Climate change projections at global scales

Global mean surface temperature

1850 to 2300
IPSL-CM5A-LR model



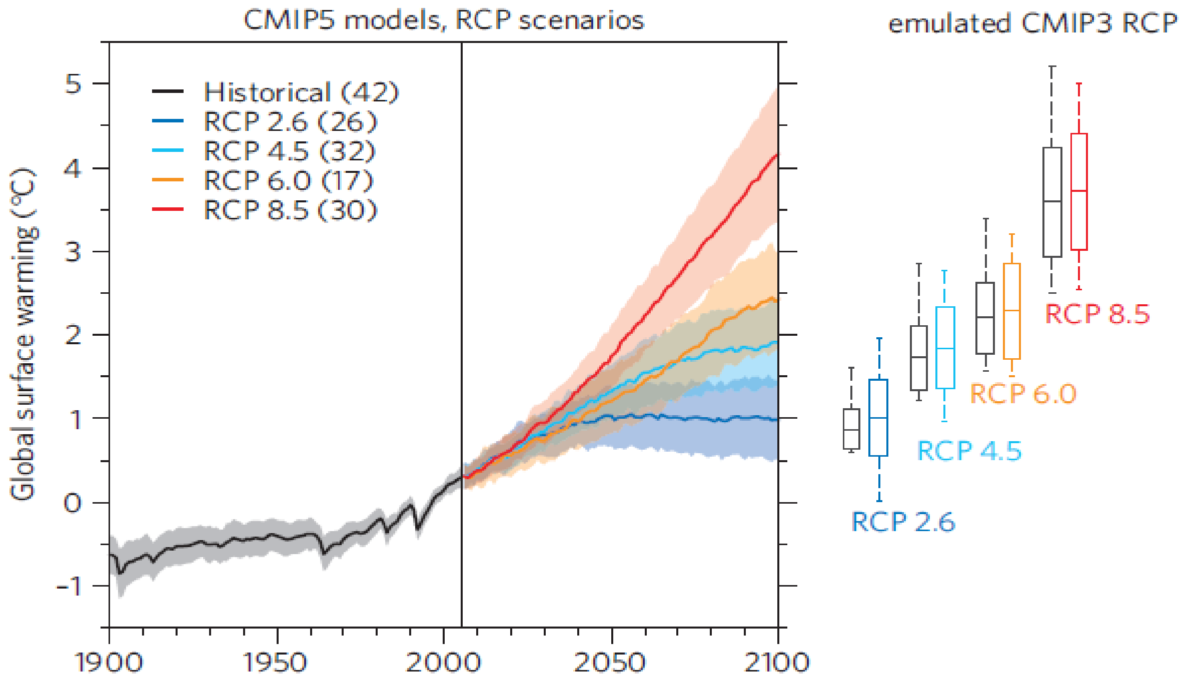
RCP 8.5

RCP 4.5

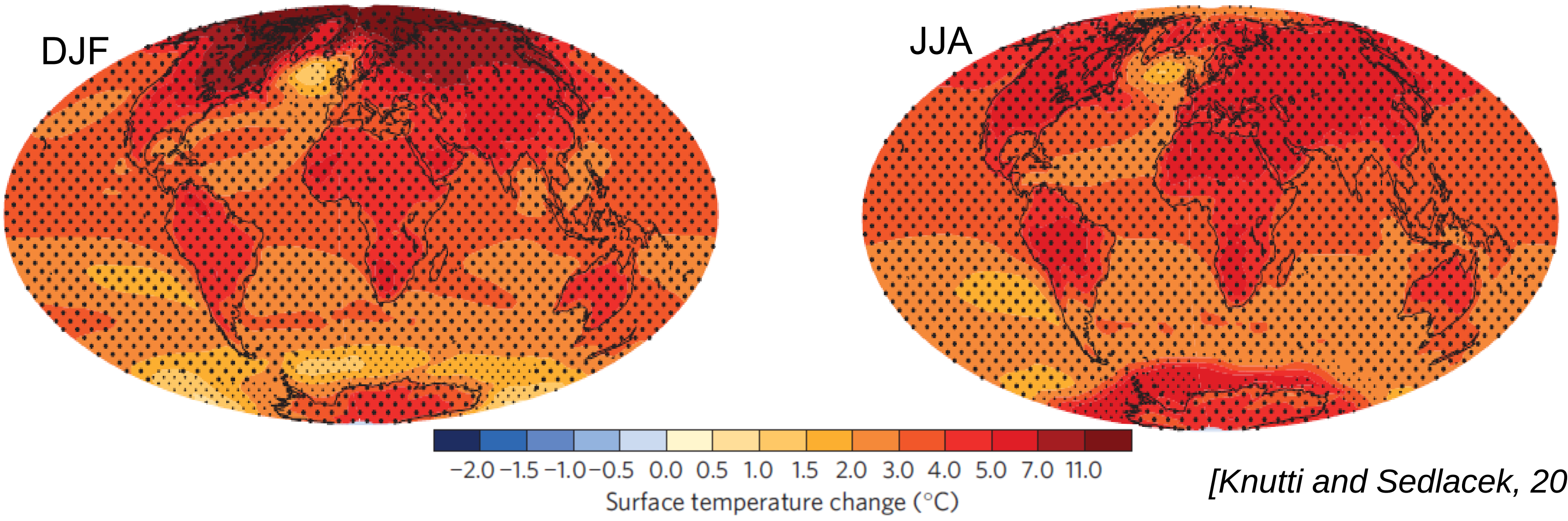
RCP 2.6

Preindustriel control simulation

Global mean surface temperarture change

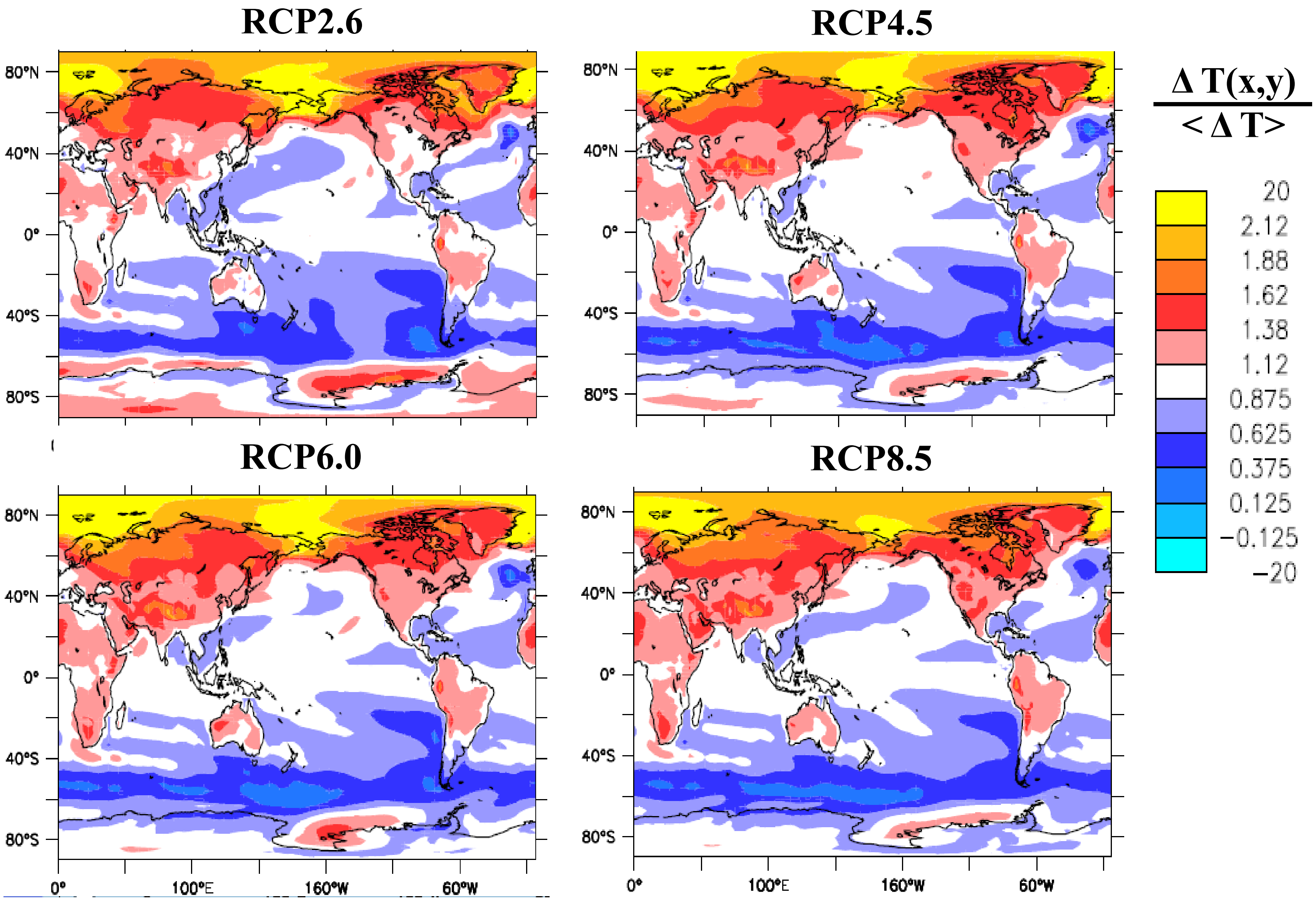


Mean surface warming around 2090 relative to 1990 for CMIP5 models



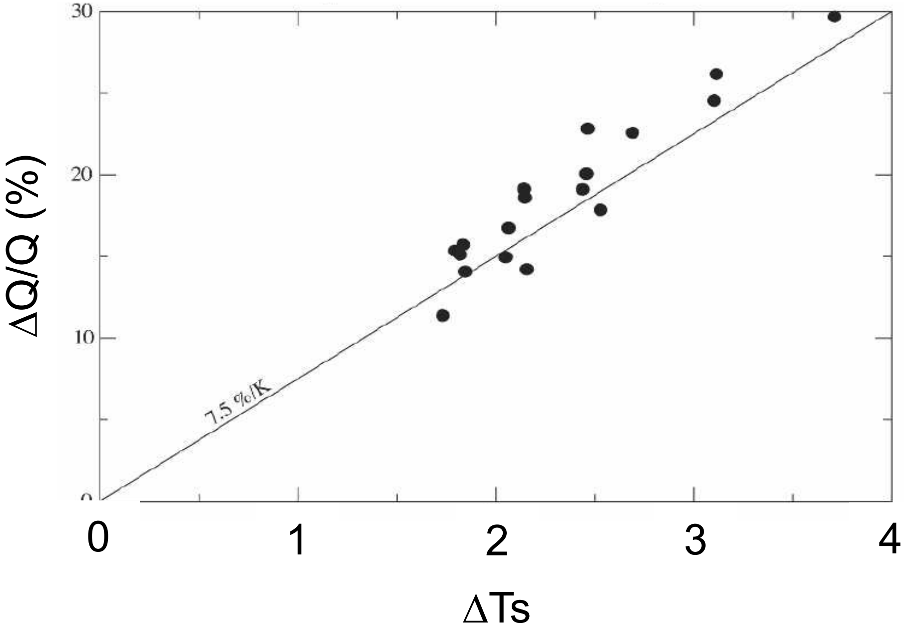
[Knutti and Sedlacek, 2012]

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



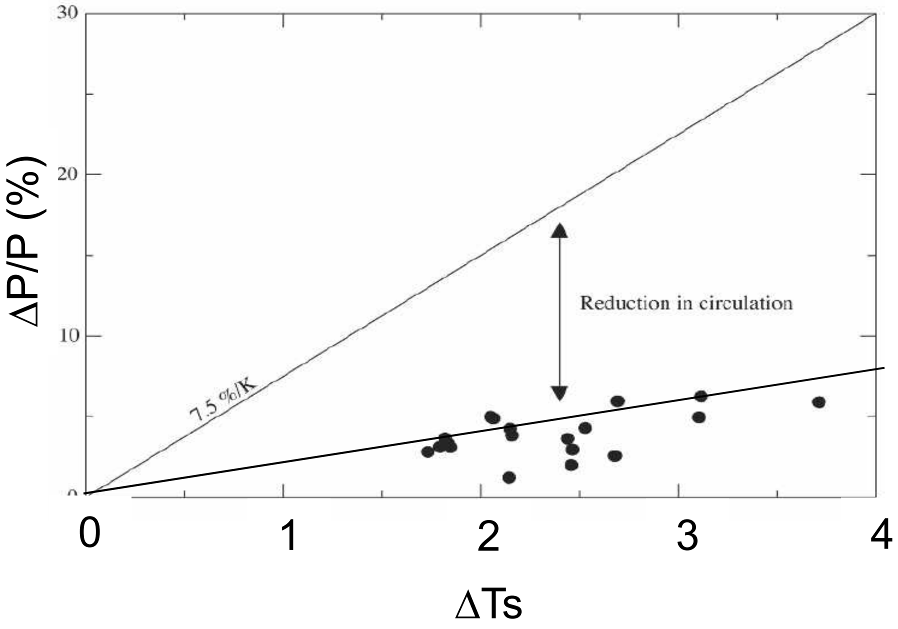
Precipitation changes

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



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

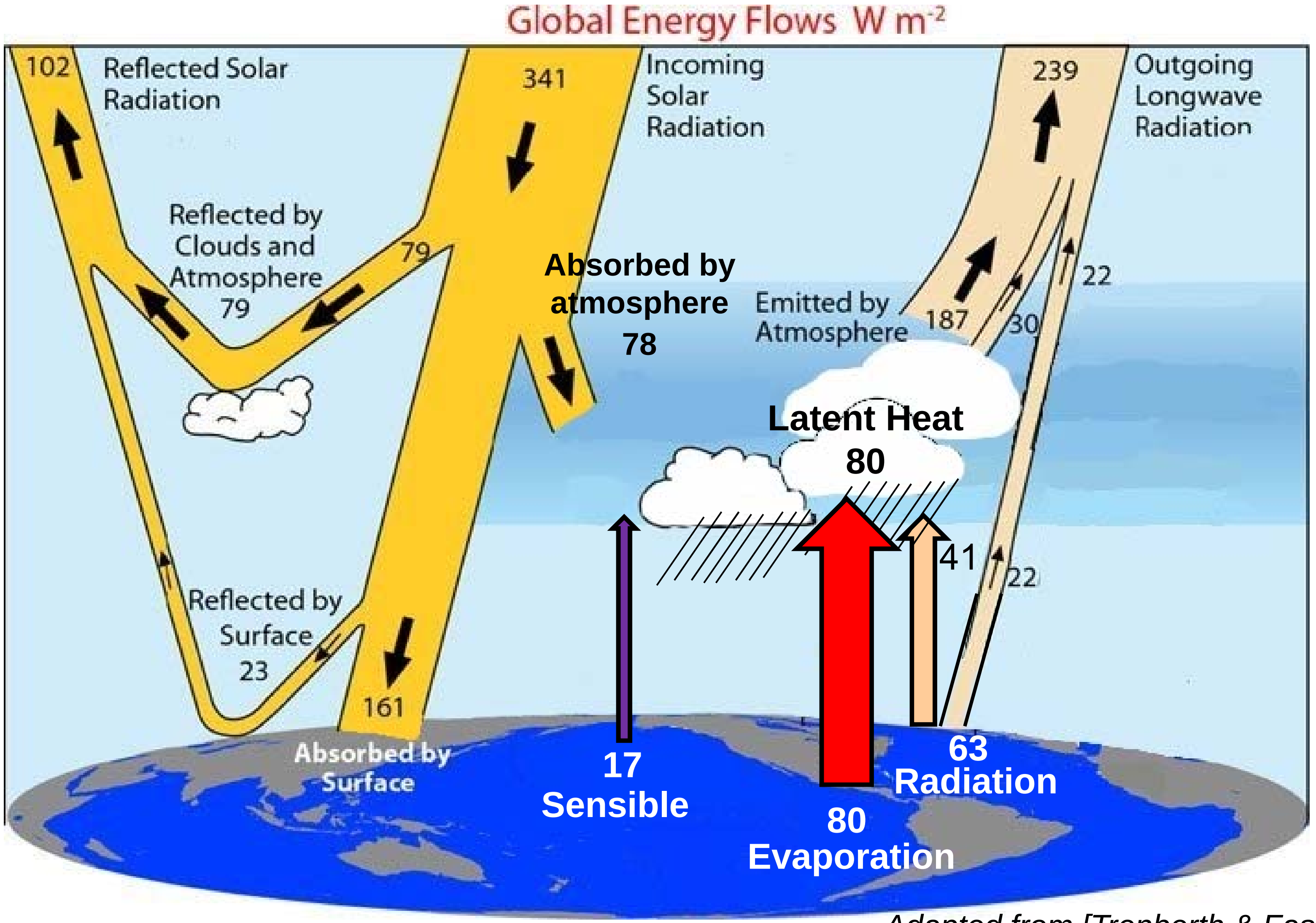
Change of **precipitation** vs change of the average surface **temperature**



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

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

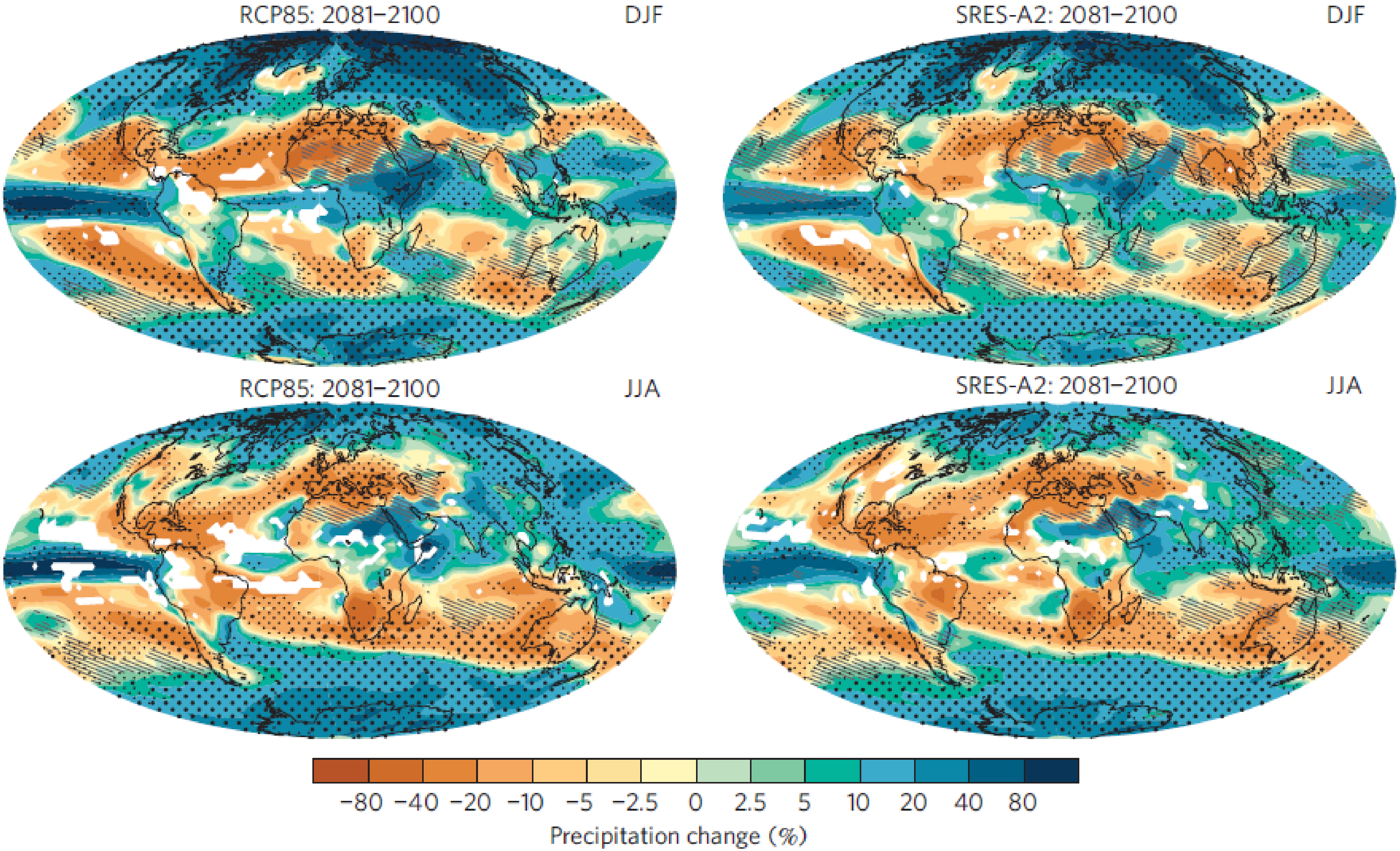
(Vecchi & Soden, 2007)



Adapted from [Trenberth & Fasullo, 2012]

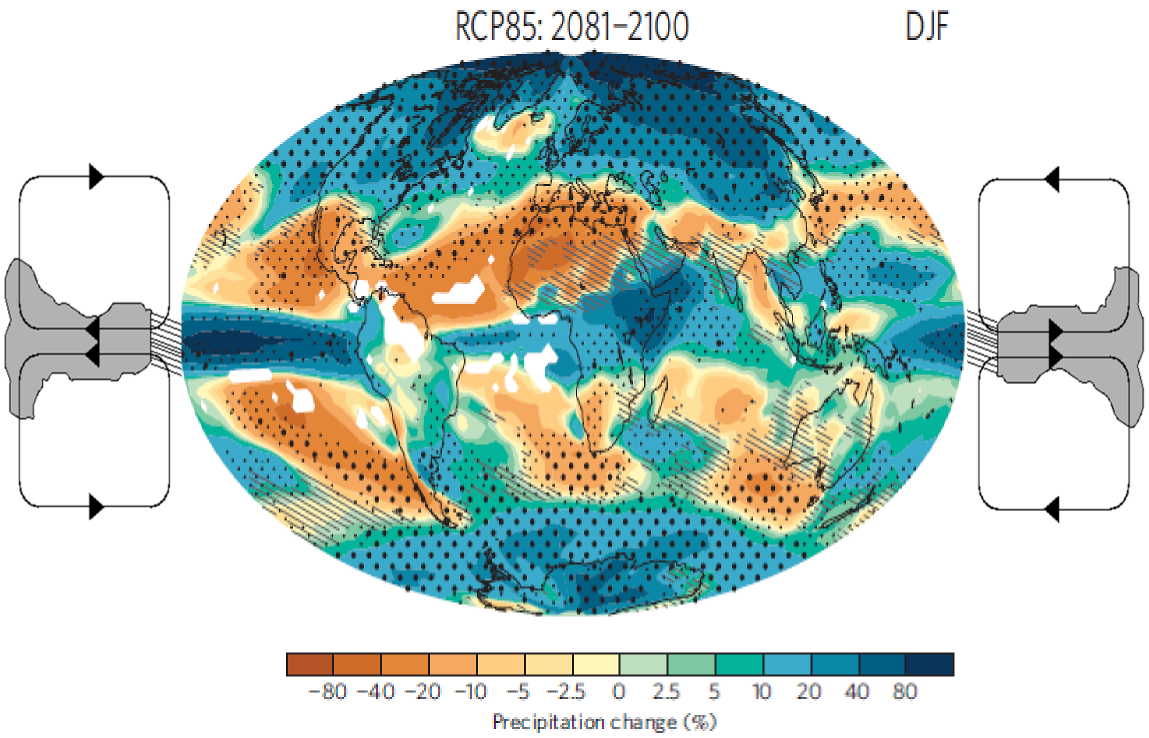
*The **change of the global average precipitation** is constrained by the **radiative cooling** of the atmosphere*

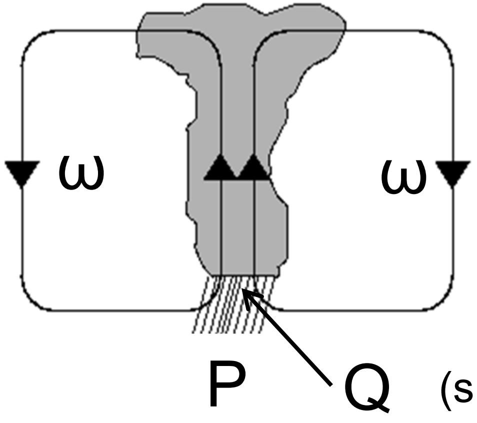
Precipitation changes



[Knutti and Sedlacek, 2012]

Precipitation changes





(specific humidity)

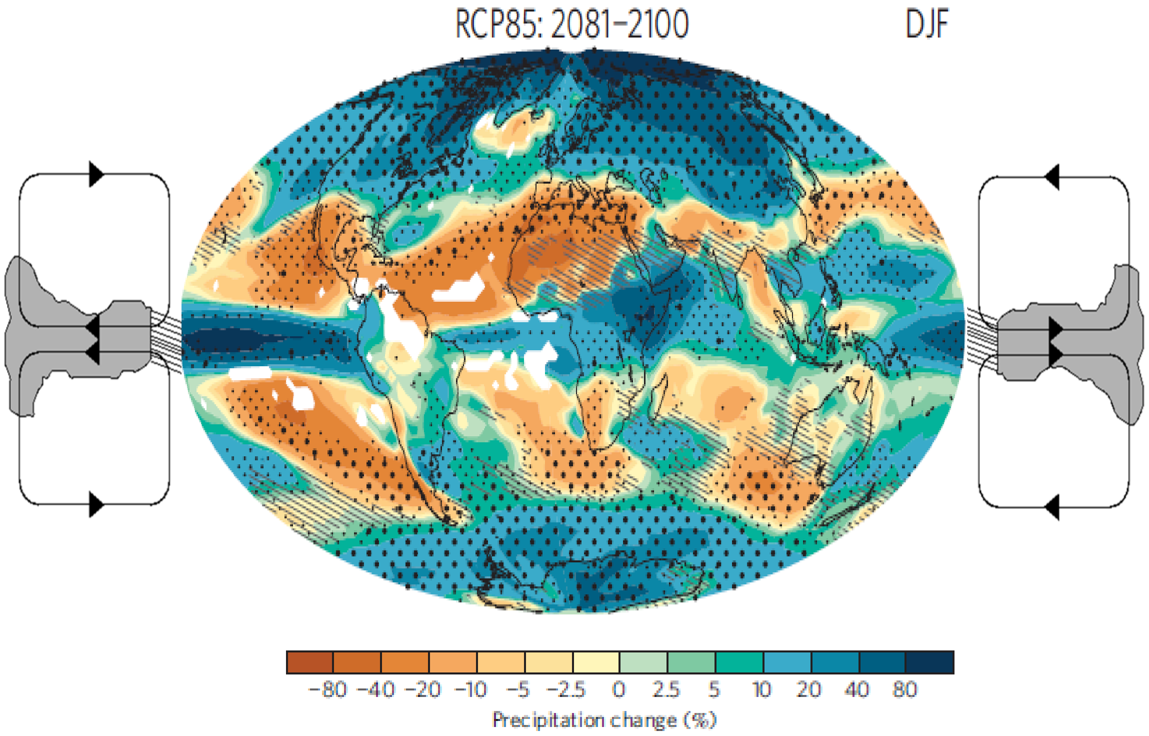
Precipitations changes

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

Thermodynamic response

Dynamic response

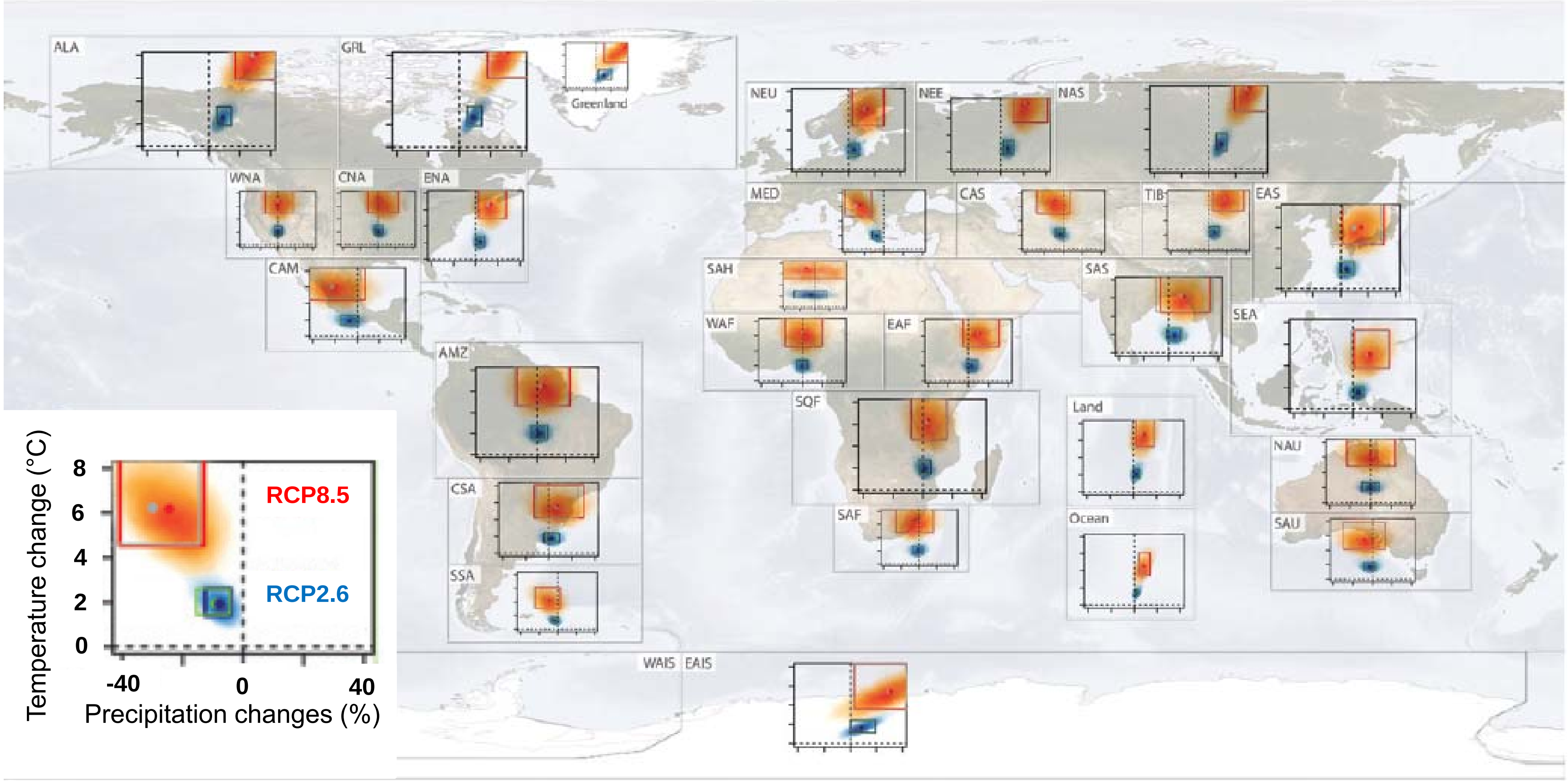
Precipitation changes



At the global scale:

- the contrast between wet and dry regions is expected to increase
- same with the contrast between wet and dry seasons

Regional precipitation changes using a scaling approach

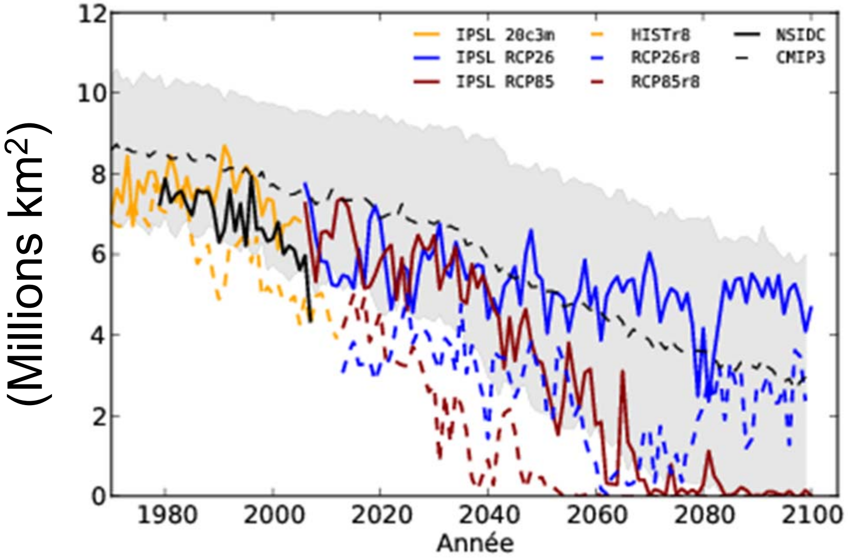


[Frieler et al., 2012]

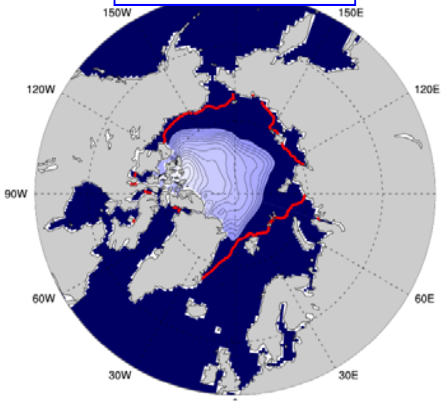
Arctic sea-ice 1970-2100

September *(minimum extension)*

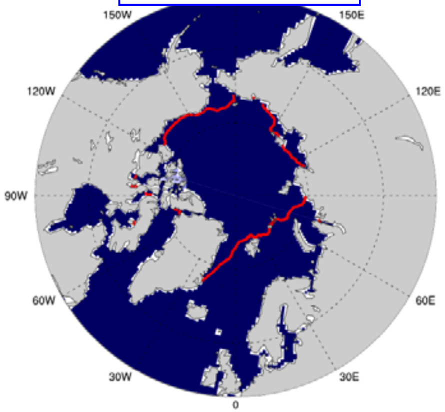
IPSL-CM5A-LR



RCP 2.6

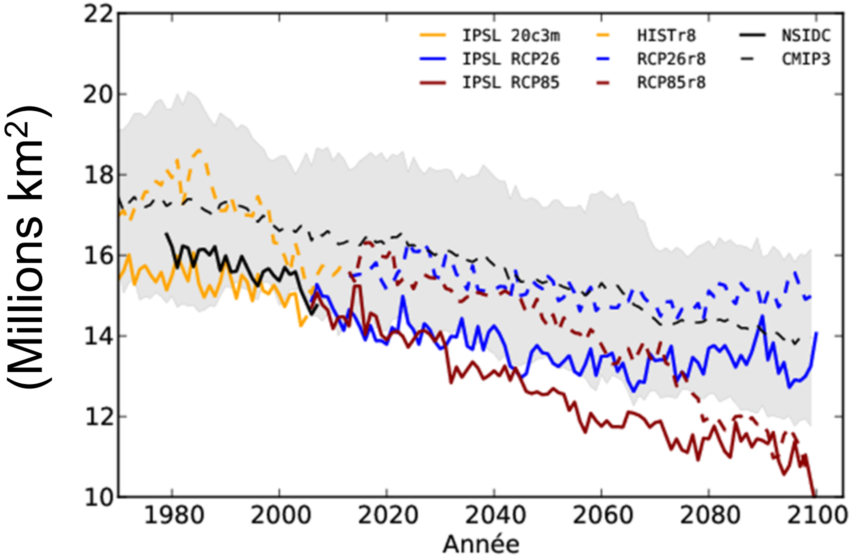


RCP 8.5

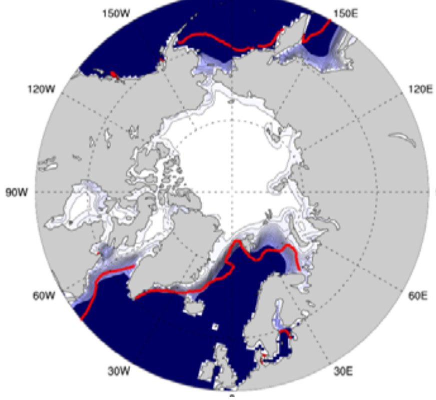


Mars *(maximum extension)*

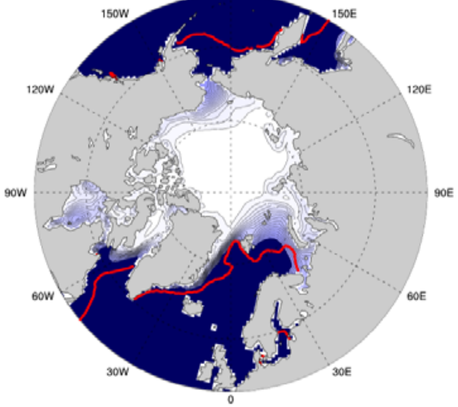
IPSL-CM5A-LR



RCP 2.6

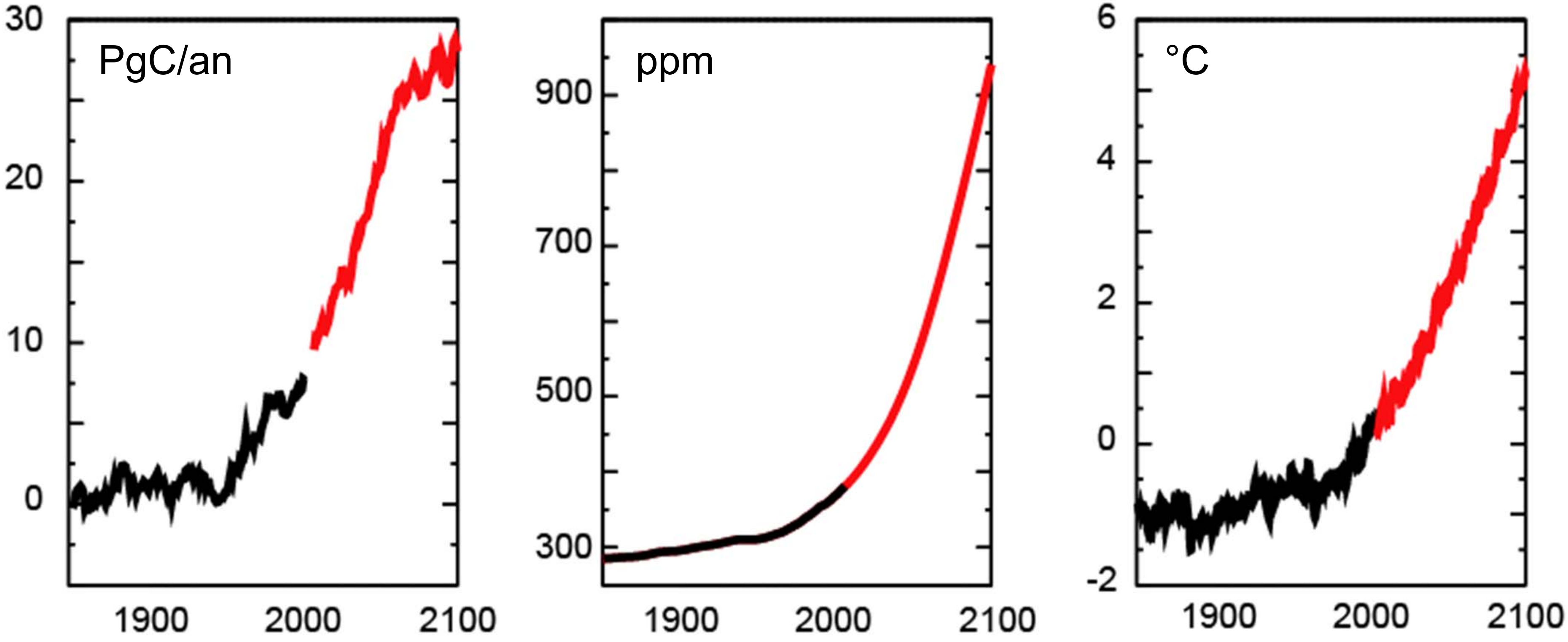


RCP 8.5



Carbone emission, CO_2 concentrations and global temperature: time constants

Higher scenario : emissions, concentration and temperatures continue to grow

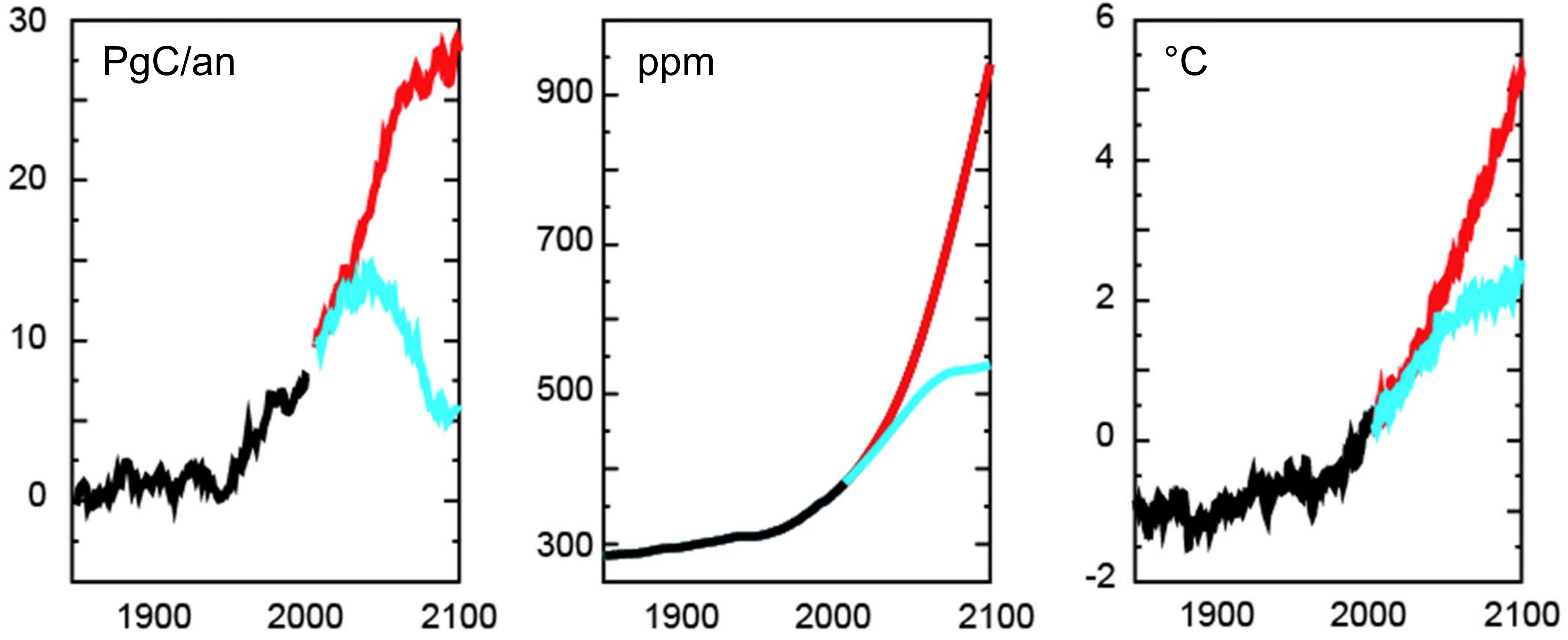


Courtesy L. Bopp

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



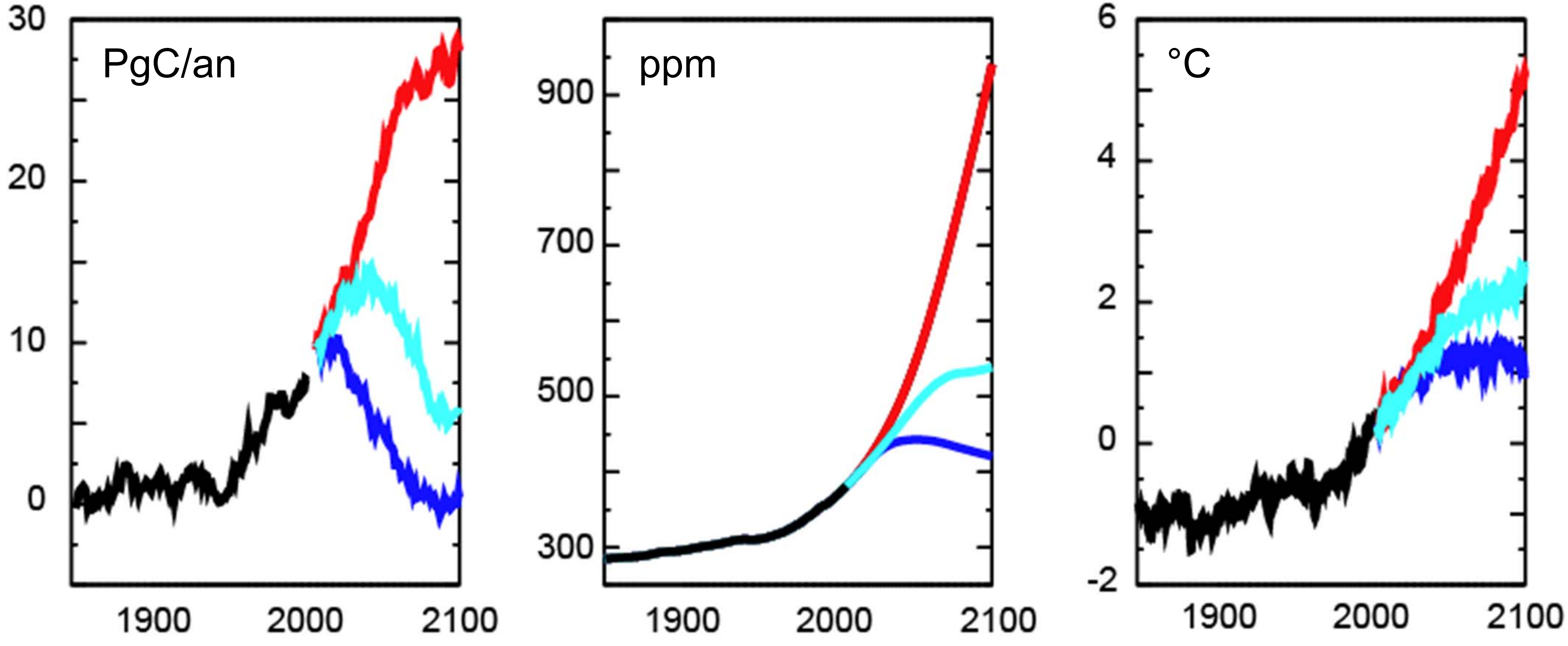
Courtesy L. Bopp

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

Thank you for your attention