Climate

Today's agenda

The role of the natural atmosphere in the climate system

Human impact on the atmosphere and the climate

- Radiation balance (of the Earth)
- The greenhouse effect
- Radiative forcing
- Climate change

Literature connected with today's lecture:

Jacob chapter 7, and IPCC SPM (on webpage)

Exercises: 7:1 – 7:6

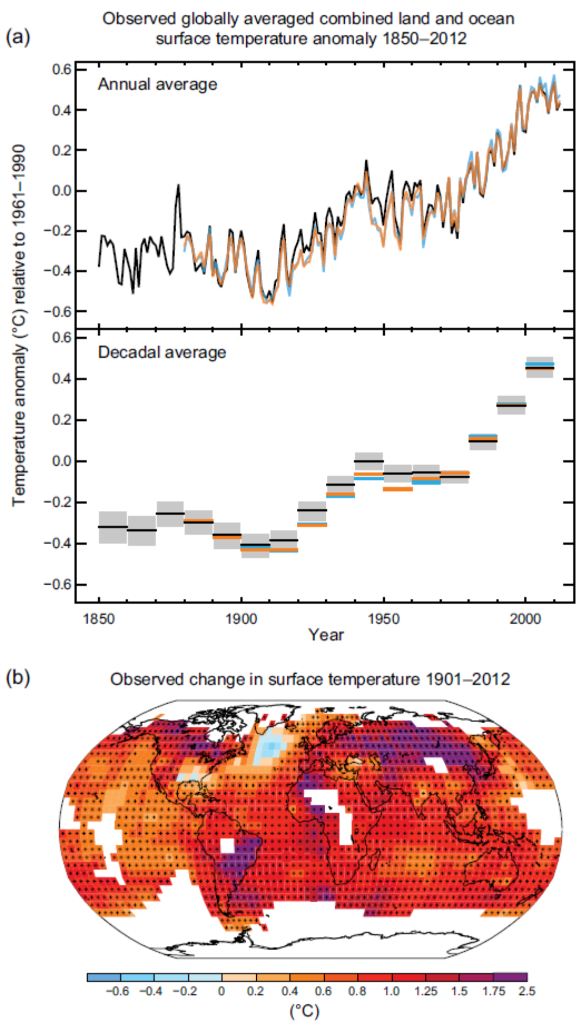
Climate – what's climate?

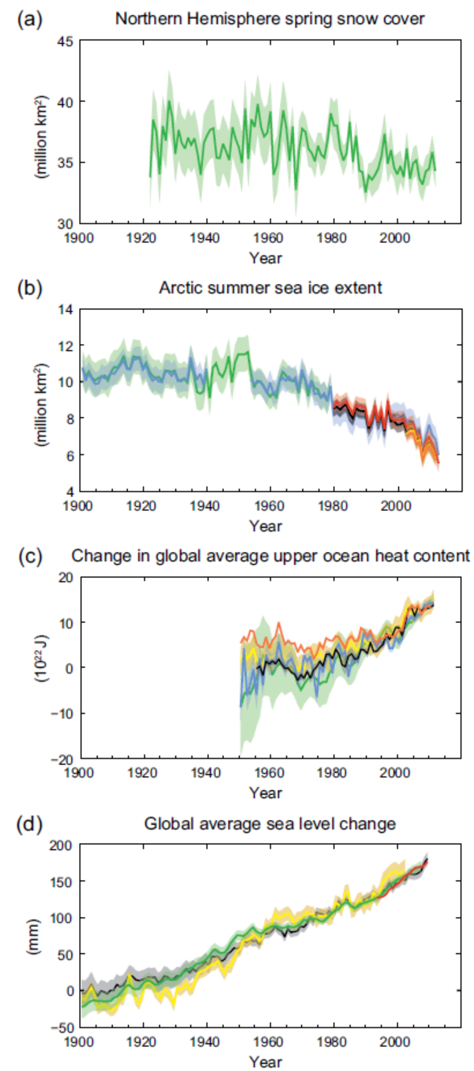
…climate is the statistics of weather conditions in an area over a long period of time…

(WMO)

- Temperature
- Humidity
- Atmospheric pressure
- Wind
- Atmospheric particle count
- Other meteorological variables

Why are we interested in climate?





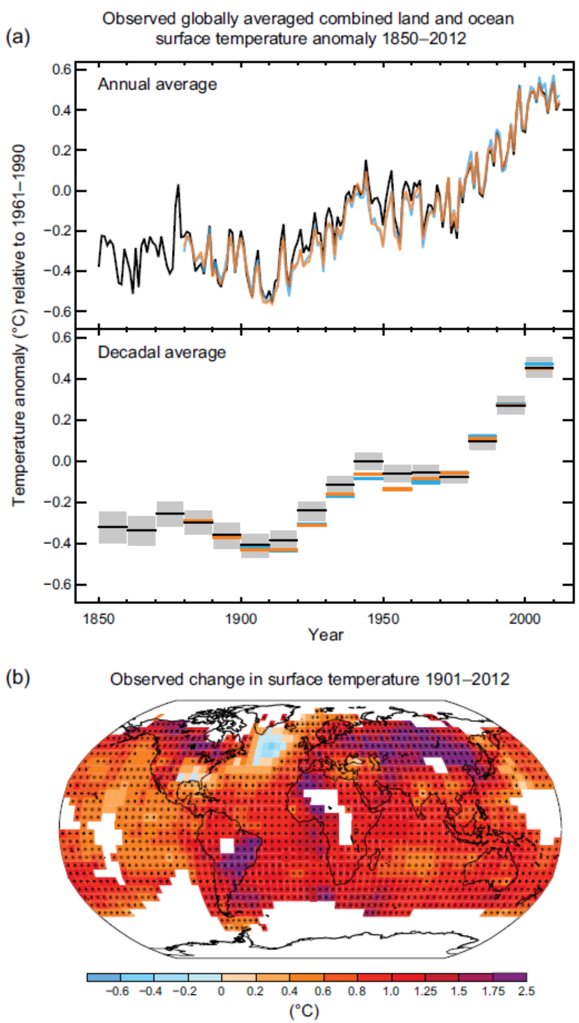
Snow cover decreases

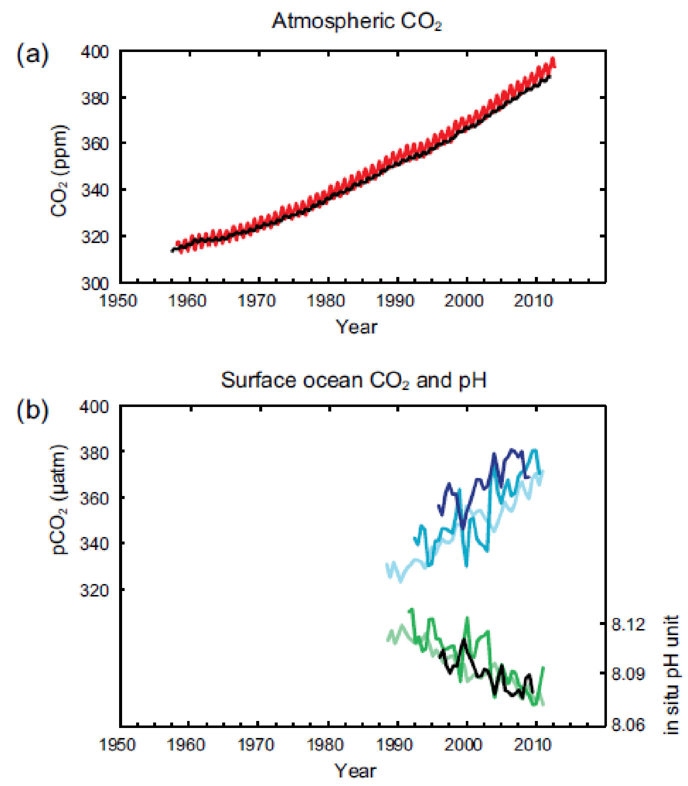
Arctic sea ice decreases

Oceans are warming

Sea level rises

CO_2 – temperature – ocean acidity





Atmos CO_2 increases

Atmos CO_2 increases

Incr acidity (decr pH)

The Sun warms the Earth

- Black body radiation – Emitted intensity, I, [W/m^2]

  $I = \sigma T^4$

  (σ = Stefan-Boltzmann's constant [$\sigma = 5.67\ 10^{-8}$ W/(m^{2}K^4)])

- The sun is approximately a black body at 5800 K

- Radiation to the Earth - Solar constant:

  (distributed over Earth's shadow area, the area of a circle)

$$F_S = \frac{P}{4\pi d^2} = \frac{4\pi R_S^2 \sigma T_S^4}{4\pi d^2} = 1370\, W/m^2$$

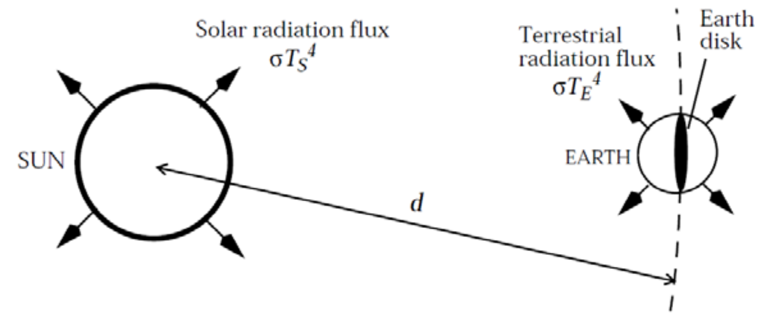


Figure 7-9 Radiative balance for the Earth

d= Earth's distance from sun
R_S=Radius of the sun
T_s = 5800 K
P: Power of the Sun

- The flux distributed over the entire surface of the Earth (the area of a sphere)

- The radiation flux per area at the Earth's surface becomes:

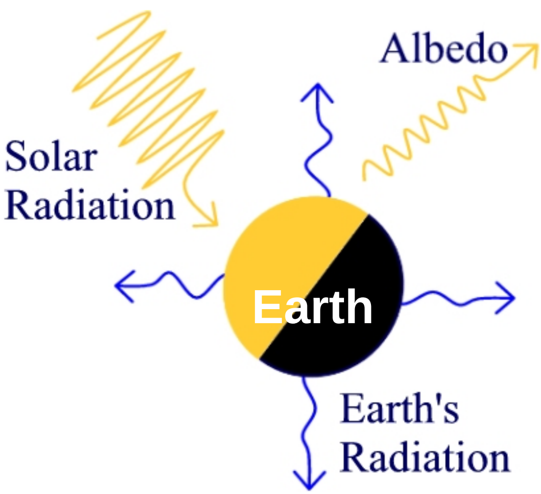
$$\Phi = \frac{\pi r^2}{4\pi r^2} \cdot F_S = \frac{F_S}{4} \approx \mathbf{340\ W/m^2}$$

Radiation Balance of the Earth

- Radiation flux at the Earth's surface

$$\Phi = \frac{\pi r^2}{4\pi r^2} \cdot F_s = \frac{F_s}{4} \approx \mathbf{340\ W/m^2}$$

- Satellites show that the Earth's Albedo is 28% (A=0.28)



- Reflection by the Earth (average per area)

  $\Phi = F_S A/4$

- Absorption by the Earth (average per area)

  $\Phi = F_S(1\text{-}A)/4$

- Radiation balance
  - The Earth emits the same amount as is absorbed
  - Consider the Earth as a black body:

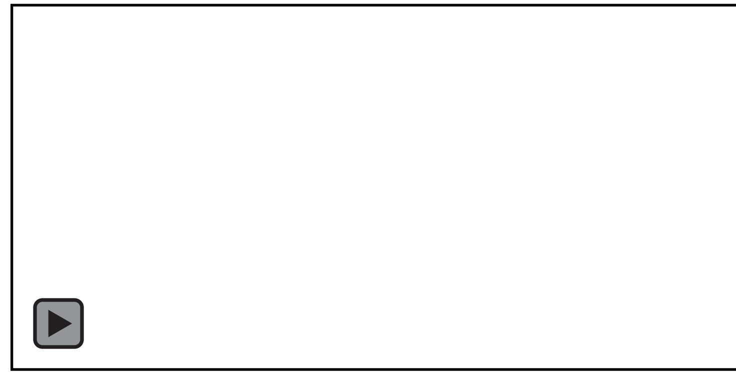
  $\sigma T_E^4 = F_S(1\text{-}A)/4$

  ⇒ $T_E = 257\ K$

- The earth viewed from space
  - Effective temperature -16°C
  - The temperature that the Earth would have had if it did not have an atmosphere (GHGs)

The greenhouse effect warms…

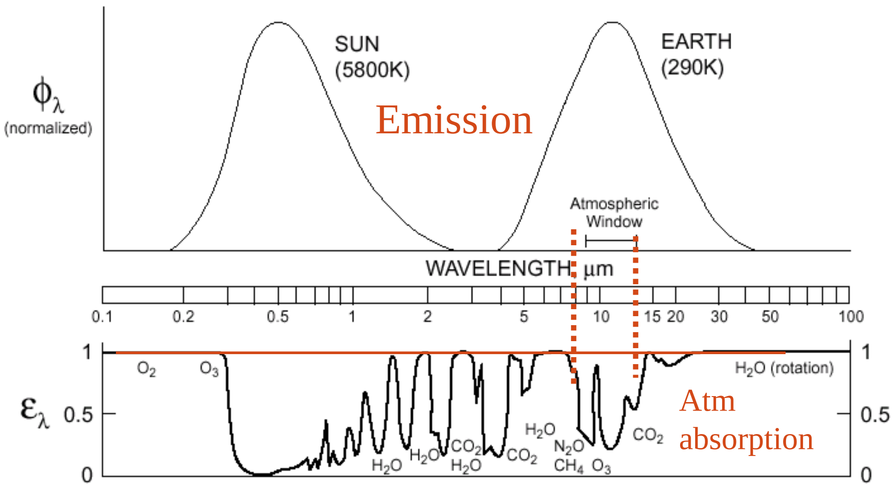
- An ”insulating” layer of GHGs
- Prevents radiation from penetrating through the atmosphere
- Keeps the energy in the Earth-atmosphere-system



- The Earth’s *surface* are heated by the Sun
- The Earth then emits radiation that get trapped by GHGs

Atmospheric Absorption of Radiation

- The sun – solar radiation
  - High temperature – short wavelength
- The earth – terrestrial radiation
  - Lower temp. – longer wavelength

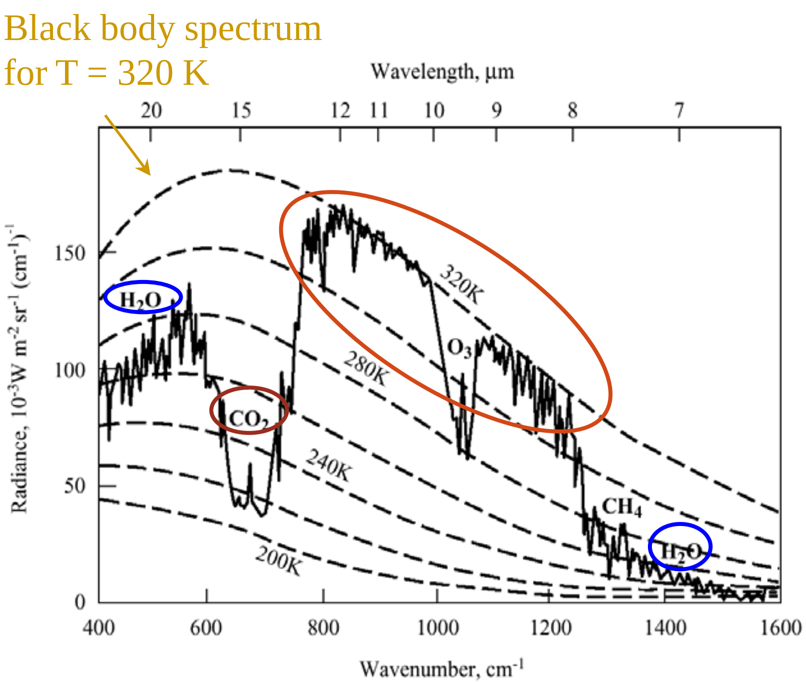


- UV absorbed by O_2 and O_3
- The atmosphere fairly transparent for solar radiation (H_2O)

- H_2O, CO_2, CH_4, N_2O, O_3 and CFC absorbs large fraction of the terrestrial radiation
- Atmospheric window ($\lambda = 8 - 13$ µm): Radiation direct from the surface to space

Radiation Spectrum of the Earth

- The Earth radiation spectrum differs from black body radiation
  - Absorption and re-emission in the atmosphere
  - The atm temp decreases with altitude
  - Temp determines radiation (σT^4) – Less radiation from a cold body
- Combination of black bodies of different temperatures

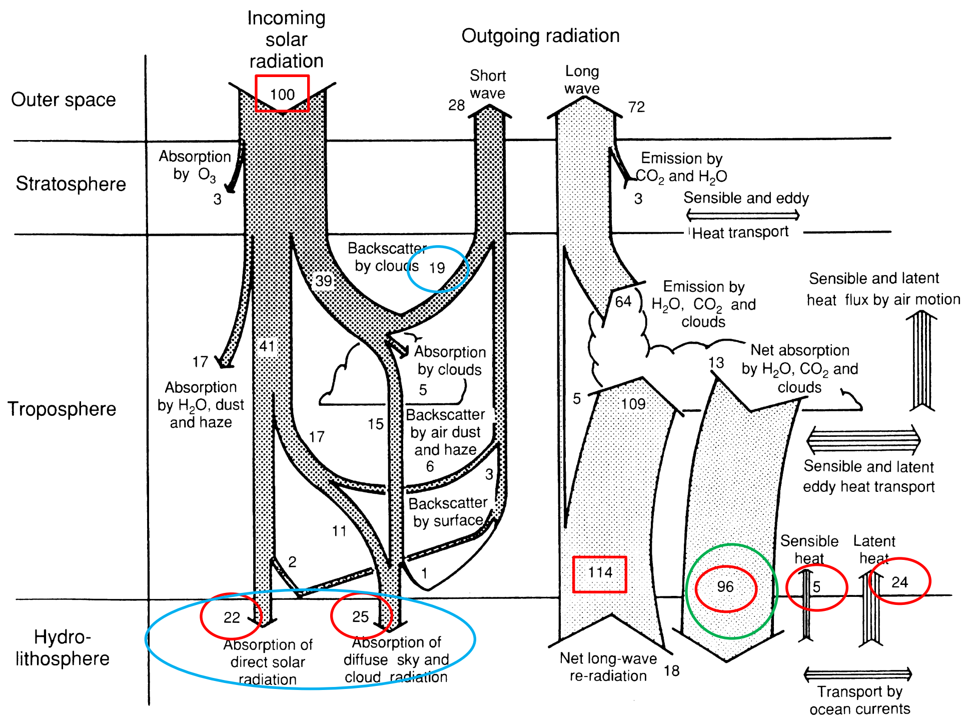


Spectrum taken from satellite over North Africa

- Atmospheric "window" (8-13µm):
  - Weak absorption in the atm ⇒
  - Radiation from surface T≈320K (North Africa!)
- CO_2 at 15 µm:
  - T≈215K
  - effective emission altitude ~ 10 km
- H_2O (7 & 20 µm):
  - T≈260K
  - effective emission altitude ~ 5 km (precipitation keeps H_2O at low altitudes)
- The greenhouse effect:
  - Atm absorption + atm temp decrease with altitude ⇒
  - Part of the terrestrial emission from lower temp ("deep valleys" in the spectrum) ⇒
  - **Radiation balance**
    - Total emission corresponding to 257 K (T_E) needed
    - => increased overall temperature to compensate for the dips in the spectrum
  - => Increased **surface temperature**

Radiation Balance

Global energy balance (annual mean)



Short wave radiation (in):

- 28% reflected (19% clouds)
- 72% absorbed (47% surface)

Long wave radiation:

- 96% atmosphere → surface

Non-radiative components:

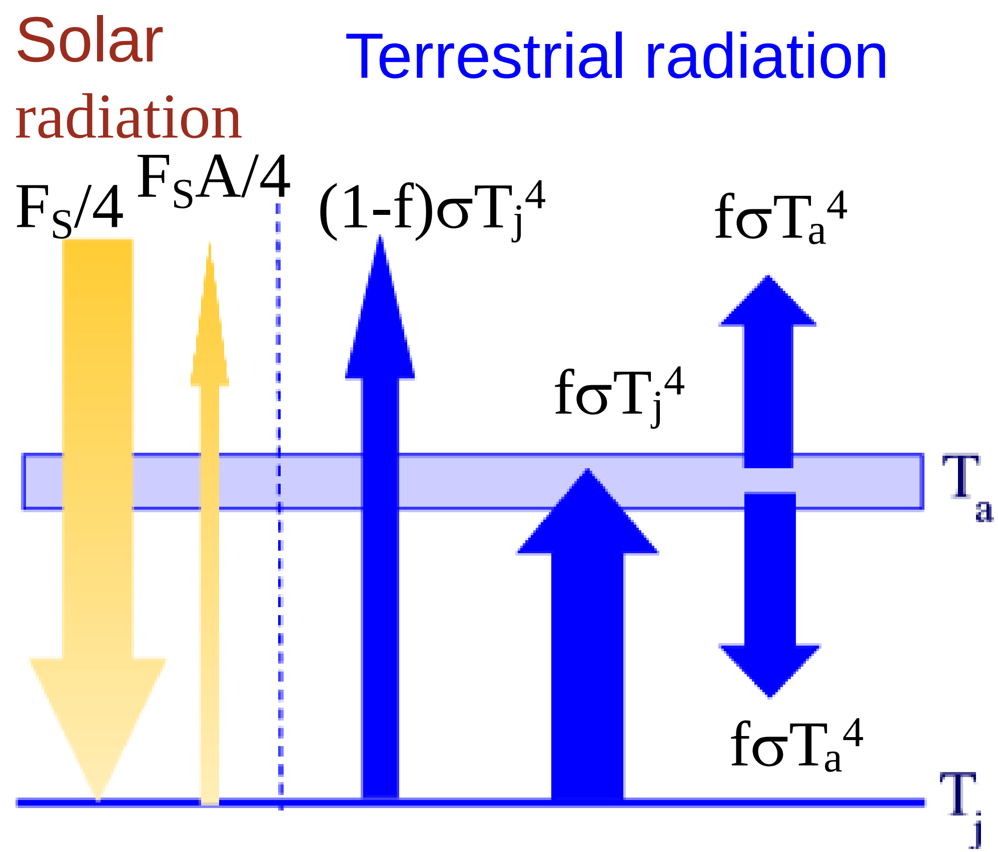
- 24 + 5% heat transport from surface to atmosphere (vapour formation, convection)

The greenhouse effect:

- The balance of the surface
  - Φ_{rel} = 22+25+96-24-5 = 114%
- The greenhouse effect increases the radiation to the surface
  - 14% higher than without an atmosphere

A Simple Climate Model

- **Assumptions on the atmosphere:**
  - Thin, isothermal layer
  - Absorbs fraction **f** of the terrestrial radiation
  - Transparent to solar radiation



Radiation balance:

Earth + atmosphere:

$$\frac{F_S(1-A)}{4} = (1-f)\sigma T_j^4 + f\sigma T_a^4$$

The Atmosphere: $f\sigma T_j^4 = 2f\sigma T_a^4$

$$\Rightarrow$$

$$T_j = \left(\frac{F_s(1-A)}{4\sigma(1-f/2)}\right)^{1/4}$$

Average surface temperature of the Earth: 288 K
- Obtained with *f = 0.77*

Now we have a simple climate model for understanding the atmosphere…

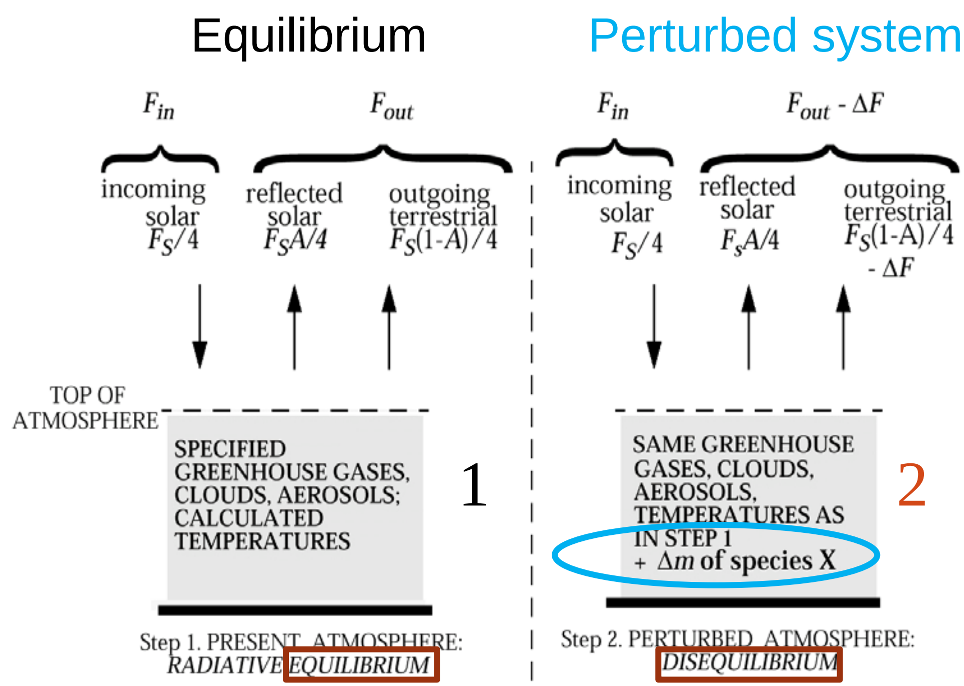
Radiative Forcing

The initial change caused by a change in radiative properties(!)
(excluding climate feed-backs)

1. Starting conditions (Equilibrium)
   - Radiation model
   - Specify system components
   - Compute temperature

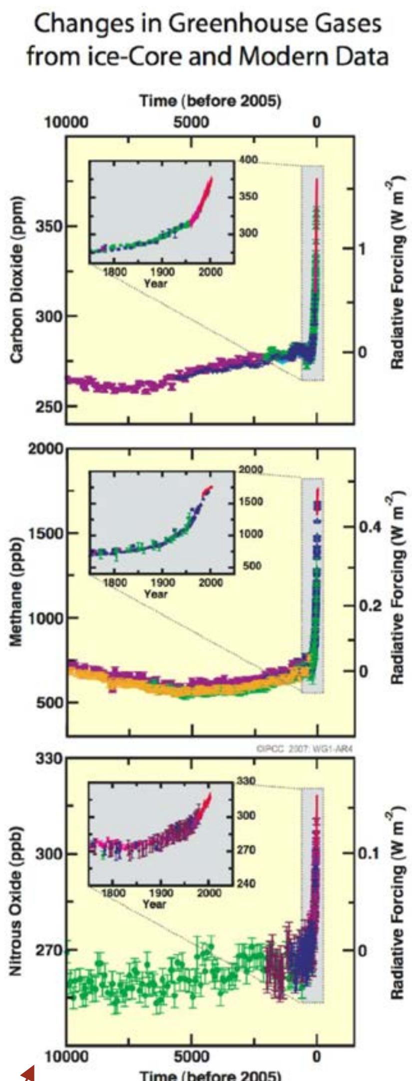
2. Perturb the system
   - Specify new components
   - Temperatures are kept unchanged
   - Causes difference between incoming and outgoing radiation

- **Radiative Forcing** ΔF [W/m^2]
  - Positive → Warming
  - Negative → Cooling
  - "Theoretical" product (nature does not "freeze" starting temp)
  - Frequently used to describe the potential of climate perturbations



$$\Delta F = F_{in,2} - F_{out,2}$$

Climate Change Caused by Man



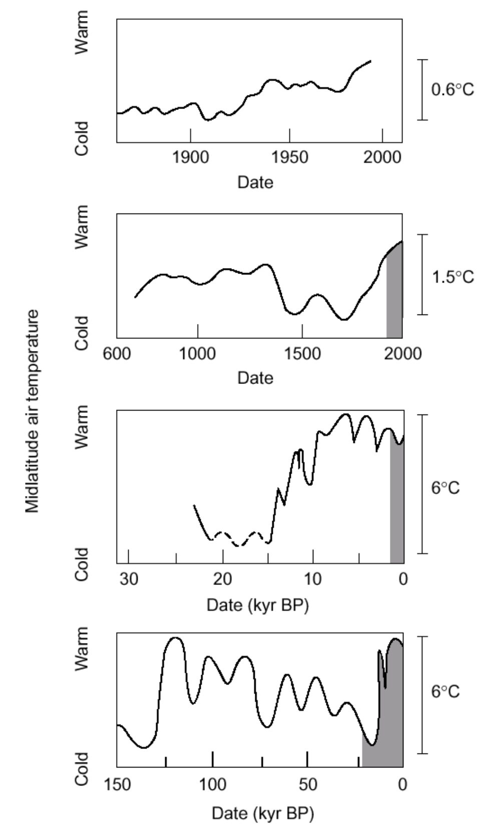
Fossil fuel combustion

Unclear (agriculture, changed atm chem.)

Fertilizers agriculture

Last ice age, 11 500 y ago

- Natural GH effect (CO_2, H_2O) increases surface temp by 33° C
- Ongoing climate change:
  - Increasing air and ocean temp
  - Reduced snow cover
  - Rising sea level
- Increased GHG concentration has increased the GH effect
- GHG emissions explain climate change?
  - Historical temp variations larger – Due to variation in solar activity



- Natural variations do not explain the increased temperature in the last 200 years
  - Climate models predict further warming – IPCC (UN climate panel):
    - “ It is extremely likely that human influence has been the dominant cause of observed warming since the mid 20th century.”

Climate Change

- Change of the radiation properties causes:
  - Initial temperature change
  - Feedbacks due to change
- Combines to a climate change

More on clouds next lecture

H_2O feedbacks

- H_2O the most important GHG
  - Human's emissions small compared with the natural sources
- Increase of another GHGs $\Rightarrow$ increased temp $\Rightarrow$ evaporation of H_2O $\Rightarrow$ further increased temp $\Rightarrow$ more evaporation…
- Counteraction
  - cloud formation and precipitation
  - Prevents H_2O from reaching high (cold) altitudes
- The role of clouds in a temperature change is unclear:
  - more H_2O $\Rightarrow$ increased cloudiness $\Rightarrow$ increased albedo
  - more H_2O $\Rightarrow$ larger cloud drops $\Rightarrow$ faster formation of precipitation $\Rightarrow$ reduced cloudiness $\Rightarrow$ reduced albedo
- Large quantitative uncertainties concerning clouds in the climate system

Climate Change

- Feedbacks due to change
  - complicated
  - large quantitative uncertainties
- The initial phase is directly connected with the radiative properties
  - better understood quantitatively
- The potential of climate change of greenhouse gases (radiative forcing) is known with high accuracy

Climate Sensitivity

- How does ΔF relate to a temperature change when feedbacks are neglected?

Radiative Forcing (greenhouse gases):

$$\Delta F = F_S(1-A)/4 - (1-\frac{f+\Delta f}{2})\sigma T_0^4 =$$
$$= (1-\frac{f}{2})\sigma T_0^4 - (1-\frac{f+\Delta f}{2})\sigma T_0^4 = \frac{\Delta f}{2}\sigma T_0^4 \qquad (1)$$

Assume a new temperature equilibrium:

$$\frac{F_S(1-A)}{4} = (1-\frac{f}{2})\sigma T_0^4 = (1-\frac{f+\Delta f}{2})\sigma (T_0 + \Delta T_0)^4 \qquad (2)$$

Small perturbations: (neglect second order terms…)

$$(T_0 + \Delta T_0)^4 \approx T_0^4 + 4T_0^3 \Delta T_0 \qquad (3)$$

Combine (2) and (3)

$$\Delta T_0 = \frac{T_0 \Delta f}{8(1-\frac{f}{2})} \qquad (4)$$

from (1) and (4):

$$\Delta T_0 = \lambda \Delta F;$$

where:

$$\lambda = \frac{1}{4(1-\frac{f}{2})\sigma T_0^3} = 0.3\ \mathrm{K/(W/m^2)}$$

$(T_0 = 288\ \mathrm{K};\ \ f = 0.77)$

λ = climate sensitivity parameter

Problem

IPCC estimate that a doubling of the CO_2 concentration causes a radiative forcing (ΔF) of 4.4 W/m^2. Assuming no feedbacks on temperature change, how much will the average temperature change on earth?

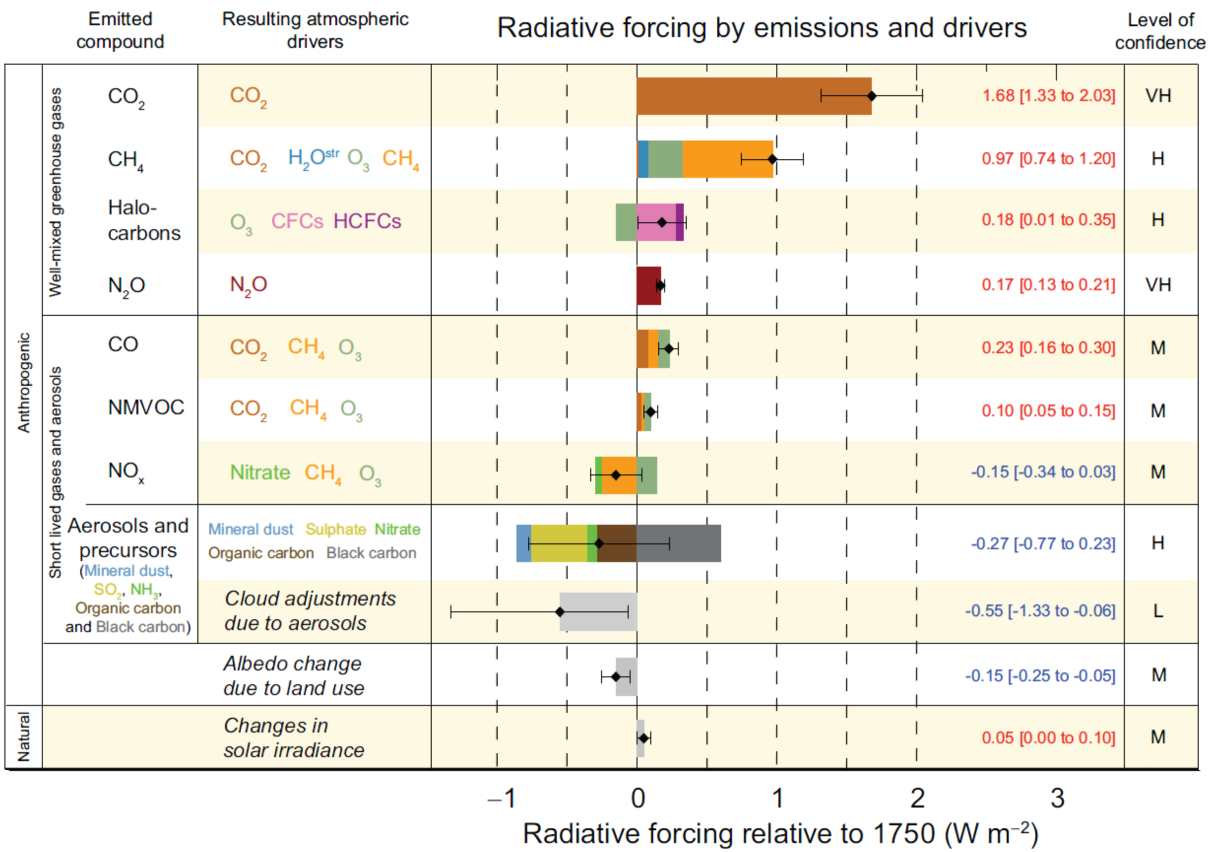
Hint: The climate sensitivity parameter λ

Solution: $\Delta T = \lambda \cdot \Delta F = 0.3 \cdot 4.4 =$ **1.3 K**

…of rapid warming

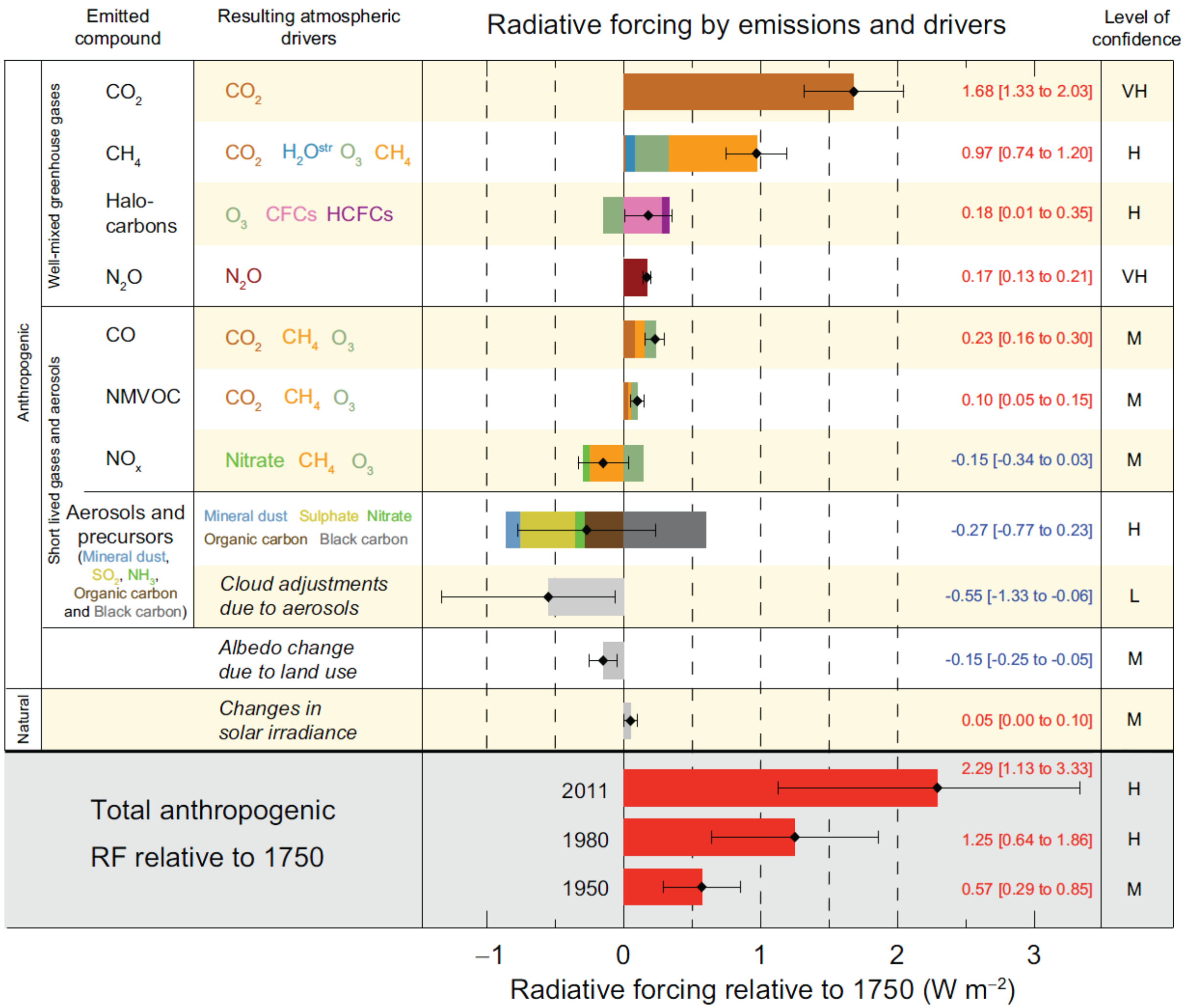
Feed-back in the climate system gives further warming

Radiative Forcings of Pollutants



- Radiative forcing
  - Expresses change in radiative properties or potential climate change
  - Difficult to translate to temperature change due to feedbacks
- The radiative forcing by greenhouse gases (GHG) quantitatively known
- Larger uncertainties in the direct aerosol effect
- The indirect aerosol effect poorly known quantitatively

Radiative Forcings of Pollutants

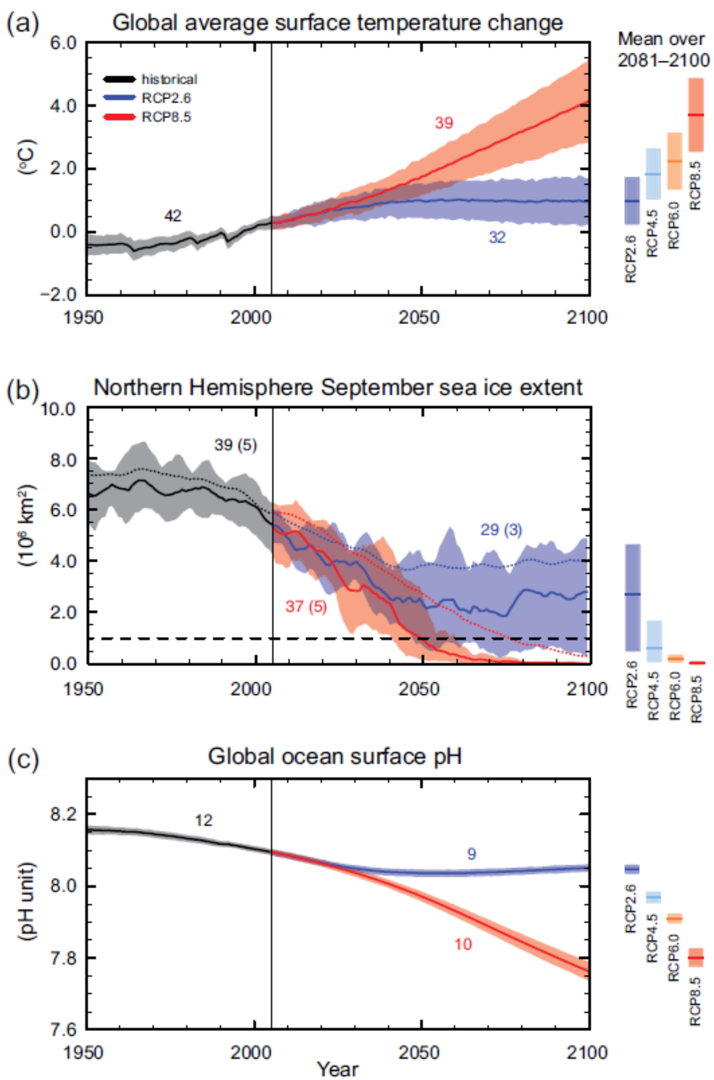


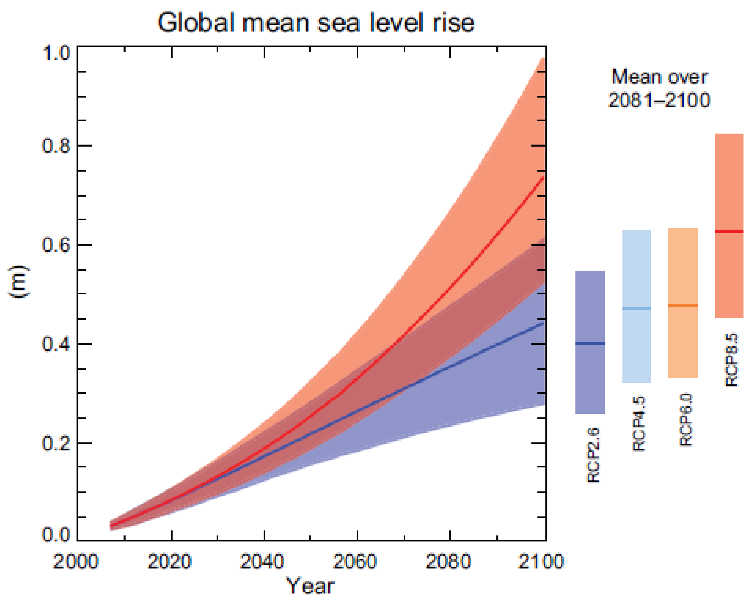
- Anthropogenic ΔF: $+2.3\ W/m^2$
- Climate sensitivity factor (λ) – neglecting feedbacks:
  - $\Delta T = \lambda \Delta F = 0.3x2.3 = 0.7\ K$
  - ΔT observed last 100 y: 0.8 K
  - Slow feed-backs will result in future warming
- Large uncertainty 1.1 – 3.3 W/m^2
  - Mainly from aerosols
- => Large uncertainties in the climate sensitivity
- => Aerosol forcings have the potential to mask the warming from greenhouse gases
- Might delay detection of dangerous climate change

We have significantly changed the radiative properties

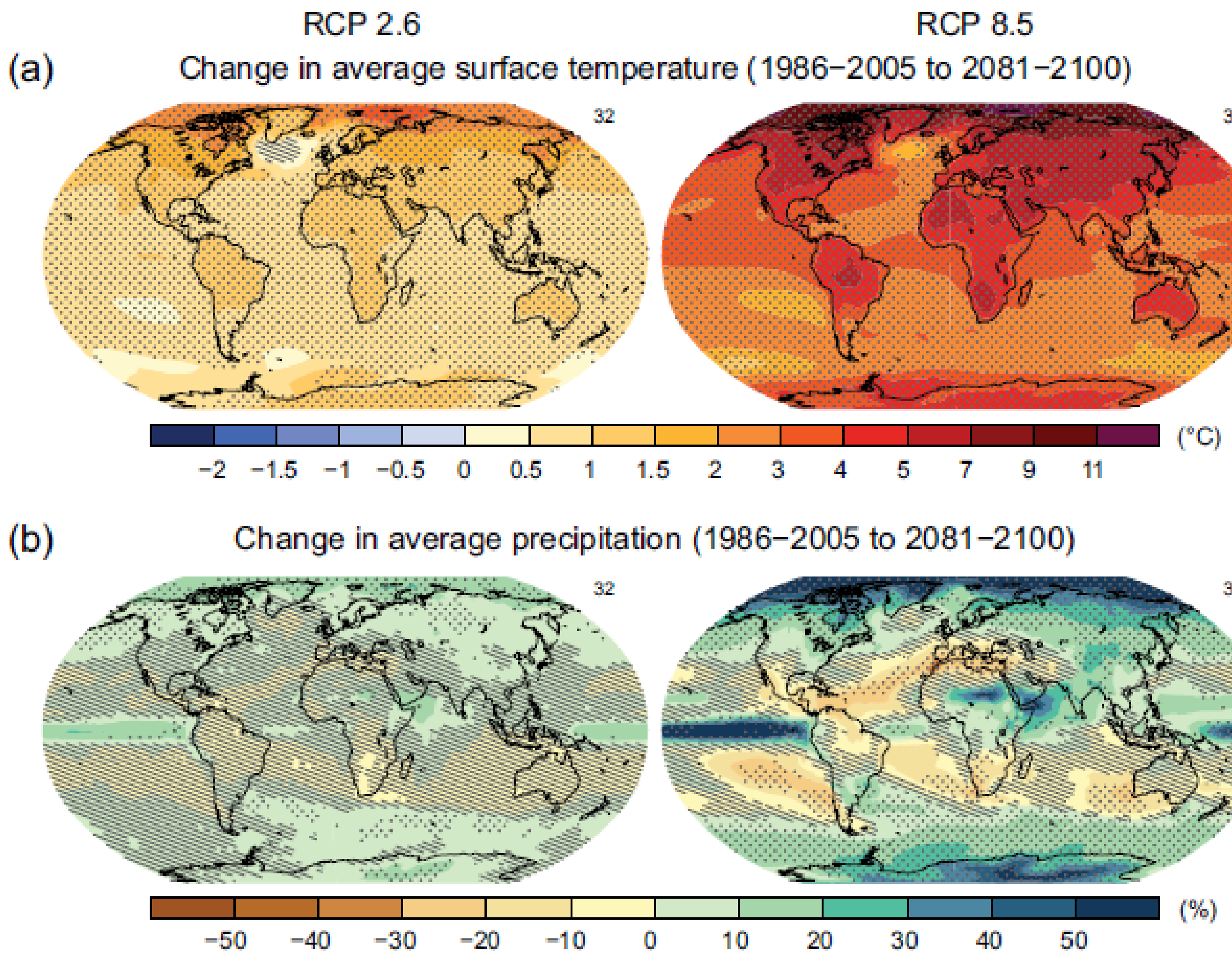
- Difficult to estimate temperature change due to feedbacks

Future scenarios

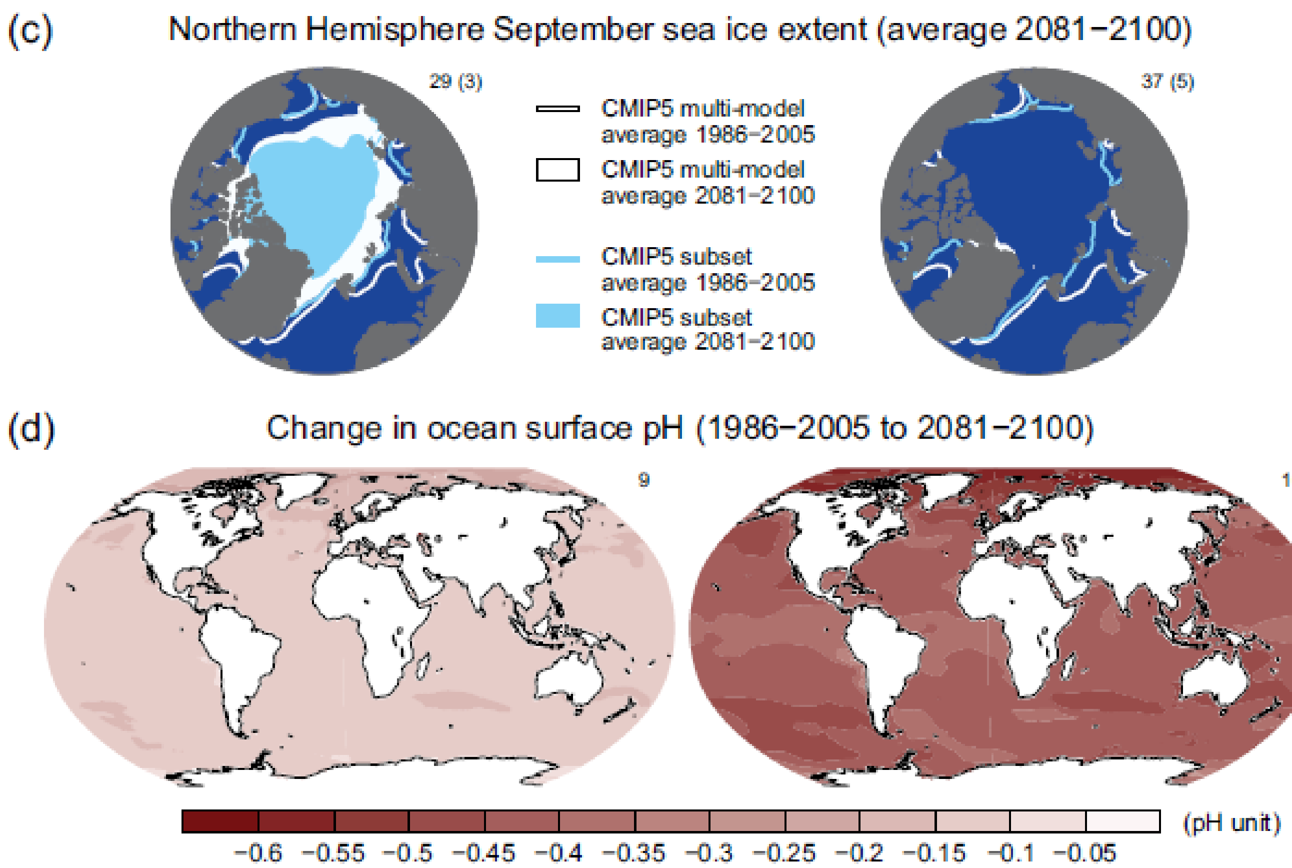




Future - Temperature and precepitation



Future – Ice extent and ocean acidity



What we talked about

The role of the natural atmosphere in the climate system

Human impact on the atmosphere and the climate

- Radiation balance (of the Earth)
- The greenhouse effect
- Radiative forcing
- Climate change (ongoing and future)

Literature connected with today's lecture:

Jacob chapter 7, and IPCC SPM (on webpage)

Exercises: 7:1 – 7:6

The end