Climate

The role of the natural atmosphere in the climate system

Human impact on the atmosphere and the climate

- Radiation balance
- The greenhouse effect
- Radiative forcing
- Climate change

Literature connected with today's lecture:
Jacob, chapter 7
Exercises:
7:1 – 7:6

Radiation

- Total radiation from a black body:

  F = σT^4; σ = Stefan-Boltzmann constant

Unit of F: [W m^{-2}]

- Planck's law (black body):

$$\frac{dF}{d\lambda} = \frac{2\pi hc^2}{\lambda^5(\exp(\frac{hc}{kT\lambda})-1)}$$

- Kirchhoff's law:

An object (e.g. the atmosphere) absorbs fraction ε [0 - 1] at wavelength $\lambda \Rightarrow$ emission of the same fraction of the black body radiation for the temperature of the body and at that wavelength

Exercise 7:1

7:1) The sun with radius $r = 6.96 \cdot 10^8$ m emits radiation like a black body of T = 5780 K.
Calculate the total power [*effekt*] emitted by the sun!

Radiation intensity from a blackbody :

$F = \sigma T^4 = 5.67 \cdot 10^{-8} \cdot 5780^4 \, W/m^2 = 6.33 \cdot 10^7 \, W/m^2$

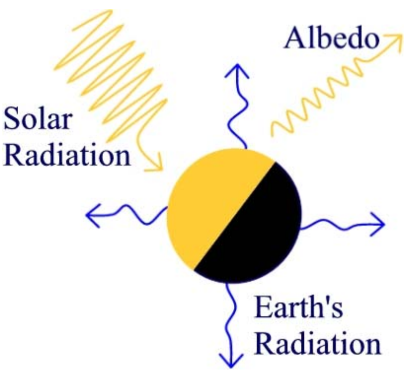
The power irradiated from the sun:

$P = F \cdot A = F \cdot 4\pi r^2 = 4\pi \cdot (6.96 \cdot 10^8)^2 \cdot 6.33 \cdot 10^7 \, W = 3.85 \cdot 10^{26} \, W$

Radiation Balance of the Earth

- Solar radiation
  - Approximately black body at 5800 K
- ⇒ Radiation to the Earth (solar constant):

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



- Satellites show that the earth reflects 28% of the solar radiation (albedo; A = 0.28)
  - Reflected: $\Phi = F_S A$
  - Absorbed by the earth: $\Phi = (1 - A) F_S$
- Absorption by the earth (average per area)

$\Phi = F_S(1\text{-}A)\pi R_E^2 / 4 \pi R_E^2 = F_S(1\text{-}A)/4$

- Radiation balance
  - The earth emits the same amount
  - Consider the earth as a black body:

$\sigma T_E^4 = F_S(1\text{-}A)/4; \quad T_E = 257$ K

- The earth viewed from space
  - effective temperature -16°C
- Climate – Temperature at the surface

Exercise 7:2

b: Planet H is at distance $d_H = 8 \cdot 10^7$ km from sun with the albedo $A_H = 0.85$. The solar constant at the earth $F_{SE} = 1370$ W/m^2 with $d_E = 1.5 \cdot 10^8$ km and $A_E = 0.28$. Calculate the effective temperature of the two planets!

Effective temperature:

Radiation balance => $(1-A)F_S/4 = \sigma T^4$ =>

$T = [(1-A) F_S/4\sigma]^{0.25}$

Earth:

$T_E = [(1-A_E)F_{SE}/4\sigma]^{0.25} = 257$ K

Planet H:

We need the solar constant: $F_S \sim 1/d^2$ =>

$F_{SH}/F_{SE} = d_E^2/d_H^2$ =>

$F_{SH} = F_{SE} \cdot d_E^2/d_H^2 = 4820$ W/m^2 =>

$T_H = [(1-A_H)F_{SH}/4\sigma]^{0.25} = 238$ K

c: Based on the properties of the two planets: Can we say anything about the climate on the surface of the two planets?

The effective temperature tells us how much a planet radiates to space

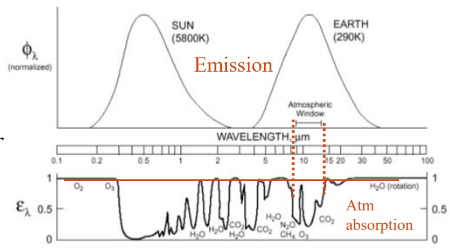
Part of that radiation from the atmosphere

The atmosphere also affects the radiation at the surface and hence the climate

ANSWER: NO

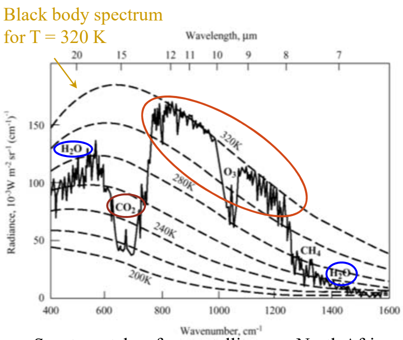
Atmospheric Absorption of Radiation

- 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

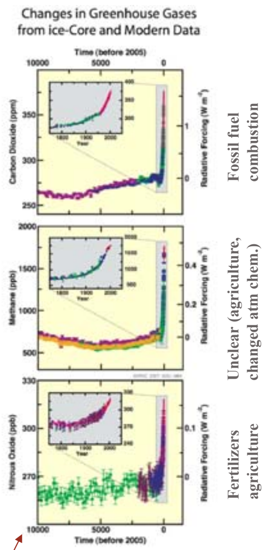
- The earth radiation spectrum differs from black body radiation
  - Absorption and re-emission in the atmosphere
  - The atm temp decreases with altitude
  - Temp determines radiation (σT^4) – Less radiation from a cold body
- Combination of black bodies of different temperatures



Spectrum taken from satellite over North Africa

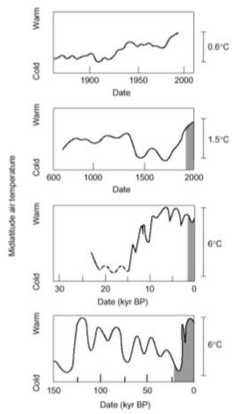
- Atmospheric "window" (8-13μm):
  - Weak absorption in the atm ⇒
  - Radiation from surface T≈320K (North Africa!)
- CO_2 at 15 μm:
  - T≈215K
  - effective emission altitude ~ 10 km
- H_2O (7 & 20 μm):
  - T≈260K
  - effective emission altitude ~ 5 km (precipitation keeps H_2O at low altitudes)
- The 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**

Climate Change Caused by Man?



Last ice age, 11 500 y ago

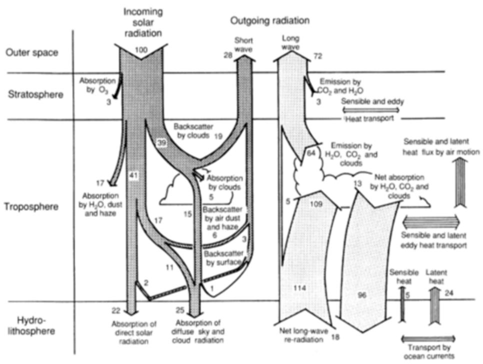
- Natural GH effect (CO_2, H_2O) increases surface temp by 33° C
- Ongoing climate change:
  - Increasing air and ocean temp
  - Reduced snow cover
  - Rising sea level
- Increased GHG concentration has increased the GH effect
- GHG emissions explain climate change?
  - Historical temp variations larger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



- Natural variations explain the increased temperature?
  - Contradicted by climate models, which 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."

Radiation Balance

Global energy balance (annual mean)



Short wave radiation (in):
- 28% reflected (19% clouds)
- 72% absorbed (47% surface)

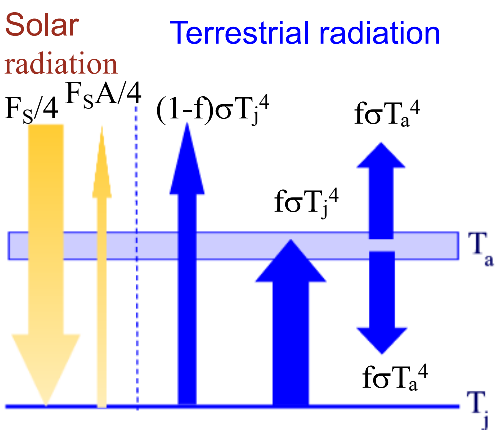
Long wave radiation:
- 96% atmosphere → surface

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% stronger than the total radiation from the sun

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

$$\Rightarrow$$

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

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

Exercise 7:3c

c: Planet H at $8 \cdot 10^7$ km from sun with albedo 0.85 has an atmosphere that absorbs 40% of the longwave radiation. How much does its atmospheric greenhouse effect change the temperature at the surface of planet H?

Without atmosphere:

The average surface temperature equals the effective temperature

$T_{surface1} = T_{eff} = [(1-A_H)F_{SH}/4\sigma]^{0.25} = 237.6\ K$

With an atmosphere (according to the model):

$T_{surface2} = [(1-A_H)F_{SH}/(4\sigma(1-f_H/2))]^{0.25}$

From previous exercise we know $F_{SH} = 4820\ W/m^2$

Enter numbers $T_{surface2} = 251.2\ K$

$\Delta T = T_{surface2} - T_{surface1} = 13.6\ K$

Climate Change

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

H_2O feedbacks

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

Climate Change

- Feedbacks due to change
  - complicated
  - large quantitative uncertainties

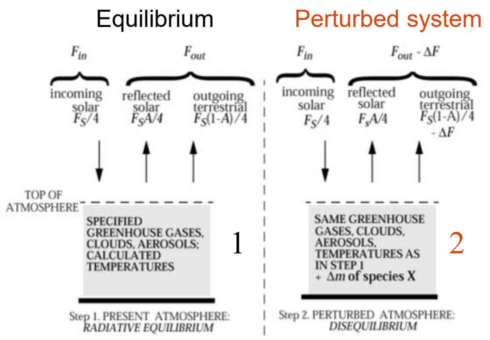
- The initial phase is directly connected with the radiative properties
  - better understood quantitatively
- The potential of climate change of e.g. greenhouse gases known with high accuracy
- **Radiative Forcing** (“*strålningsdrivning*”)

Radiative Forcing

- Which is the initial change caused by a change in radiative properties?
- Starting conditions (Equilibrium)
  - Radiation model
  - Specify system components
  - Compute temperatures

- Perturb the system
  - Specify new components
  - Temperatures are kept unchanged
  - Causes difference between incoming and outgoing radiation
  - **Radiative Forcing** ΔF [W/m^2]

- ΔF a ”theoretical” product (nature does not ”freeze” the starting temperatures)
- ΔF frequently used to describe the potential of climate perturbations



$\Delta F_1 = 0;$ $\Delta F_2 = F_{in,2} - F_{ut,2}$

Exercise 7:3d

The earth's atmospheric concentration of greenhouse gases increase the atmospheric absorbed fraction f of longwave radiation from 0.77 to f' = 0.78. Calculate the radiative forcing induced by increased greenhouse gases!

Step 1: Calculate temperature in the unperturbed system:

$F_S/4 = F_S A/4 + (1\text{-}f)\sigma T_E^4 + f\sigma T_a^4 = [2f\sigma T_a^4 = f\sigma T_E^4] = F_S A/4 + (1\text{-}f/2)\sigma T_E^4$

$T_E = [(1\text{-}A)F_S/(4\sigma(1\text{-}f/2))]^{0.25} = 290$ K

Step 2: Freeze the temperature and calculate the radiative forcing:

$\Delta F = F_{in} - F_{out} = F_S/4 - F_S A/4 - (1\text{-}f'/2)\sigma T_E^4$

Equilibrium in the unperturbed system => $F_S/4 = F_S A/4 + (1\text{-}f/2)\sigma T_E^4$ =>

$\Delta F = F_S A/4 + (1\text{-}f/2)\sigma T_E^4 - F_S A/4 - (1\text{-}f'/2)\sigma T_E^4 =$

$= \frac{1}{2}(f' - f)\sigma T_E^4 = \frac{1}{2}\Delta f\sigma T_E^4 = 2.0\ \mathrm{W/m^2}$

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:

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

Combine (2) and (3) and neglect second order terms:

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

from (1) and (4):

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

where:

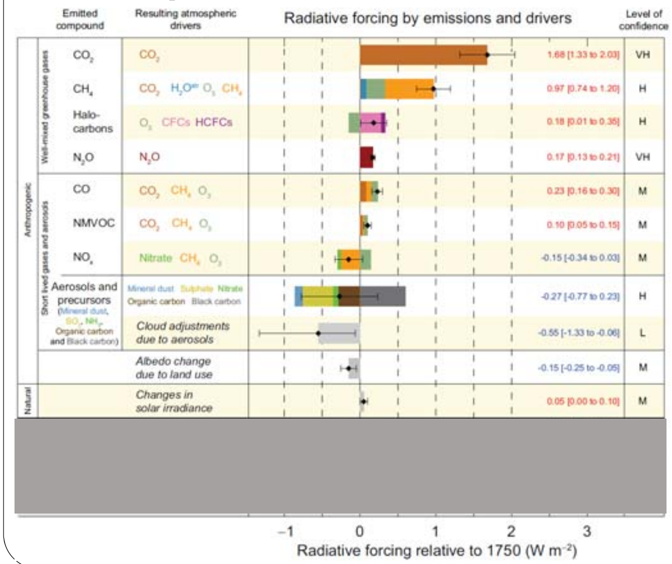
$$\lambda = \frac{1}{4(1-\frac{f}{2})\sigma T_0^3} = 0.3\ \mathrm{K/(W/m^2)}$$

($T_0 = 288$ K; $f = 0.77$)

λ = climate sensitivity parameter

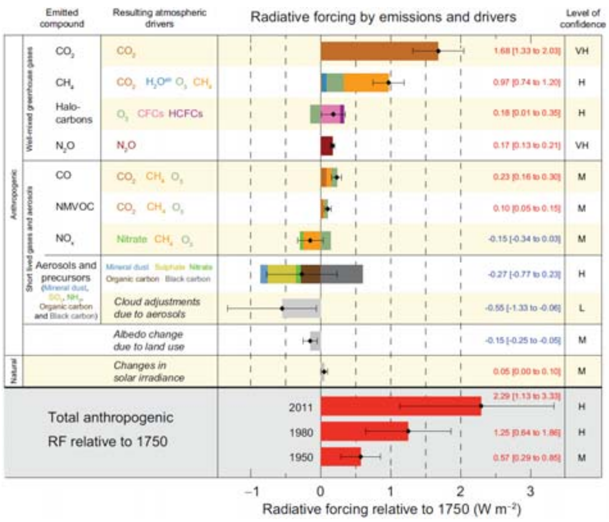
Radiative Forcings of Pollutants

UN climate panel (IPCC):



- 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:
  - ΔT = λΔF = 0.3x2.3 = 0.7 K
  - ΔT observed last 100 y: 0.8 K
- 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