Climate Dynamics (lecture 6)

Section 2.16-2.19

Spectral dependence of absorption of radiation, feedbacks and *climate sensitivity*

Spectral dependence of absorption of Solar radiation

Absorption of Solar radiation by ozone

Atmospheric infrared window and climate sensitivity

(grey/non-grey atmosphere)

Cloud-feedbacks

Water vapour feedback

What next?

http://www.staff.science.uu.nl/~delde102/climatedynamics.htm

Energy fluxes (2000-2004)

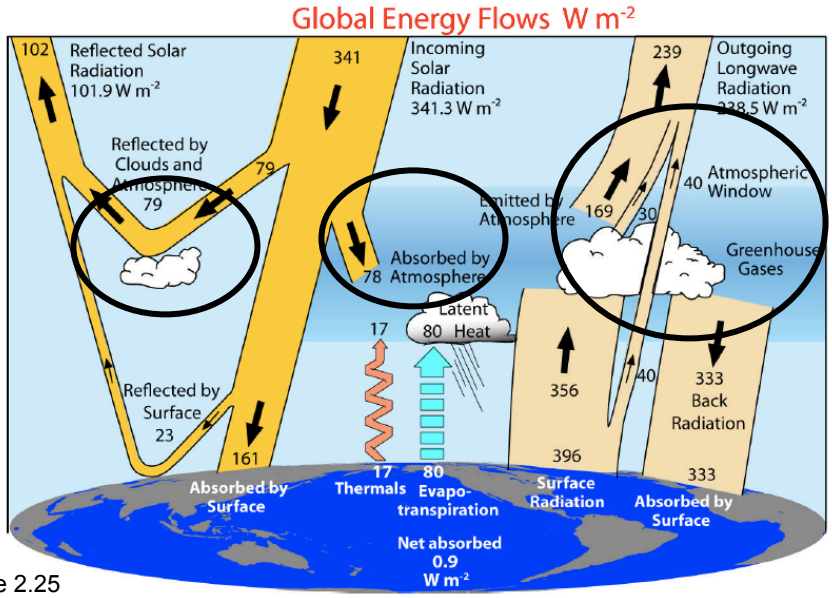
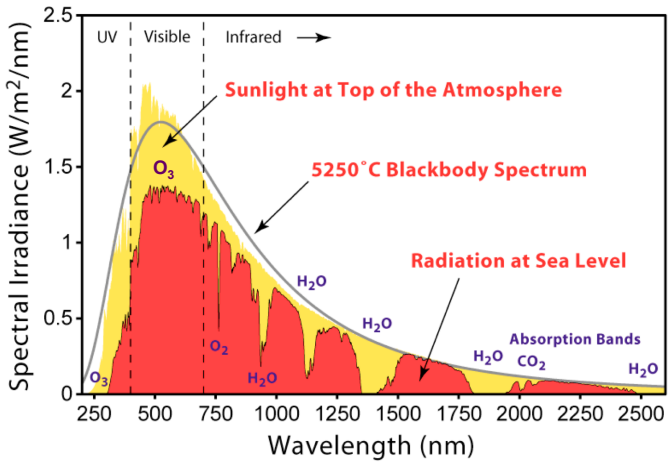


Figure 2.25

Spectral distribution of Solar radiation

Figure 1.20



Spectral distribution of Solar radiation **reaching the top of the top of the atmosphere (yellow) and reaching sea level (red)** (1 nm=10^{-9}m). Also shown is the spectrum of a black body with a temperature of 5250°C, which is approximately the Sun's surface temperature. Ozone and water vapour are the principal constituents that absorb Solar radiation. Adapted from the following source: http://www.globalwarmingart.com/.

Apply Bougeur-Lambert-Beer law to downward propagation of Solar radiation

$$I_{n+1} = I_n \exp\left(-\frac{\kappa_a \Delta p}{\rho g \cos\theta}\right)$$

Irradiance at level n+1

zenith angle (fig. 2.41)

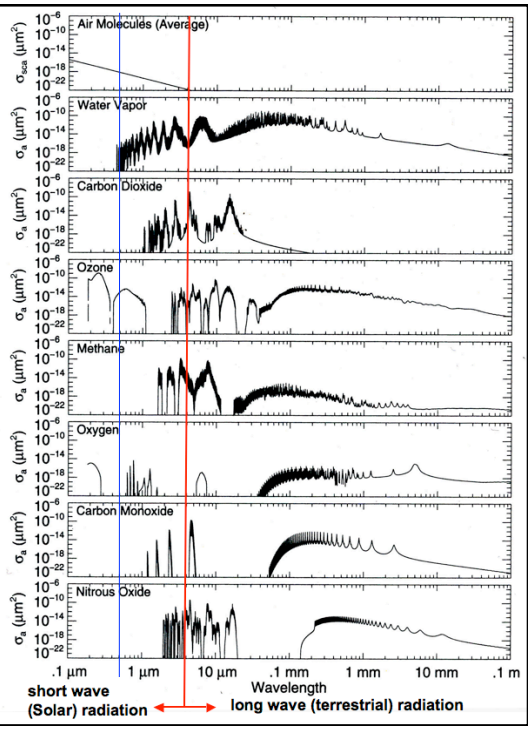
$$\kappa_a = n_a \sigma_a$$

Number of molecules per unit volume

Absorption cross section per molecule

Optical path: $\delta \equiv \left(\frac{n_a \sigma_a \Delta p}{\rho g \cos\theta}\right)$

Absorption cross sections

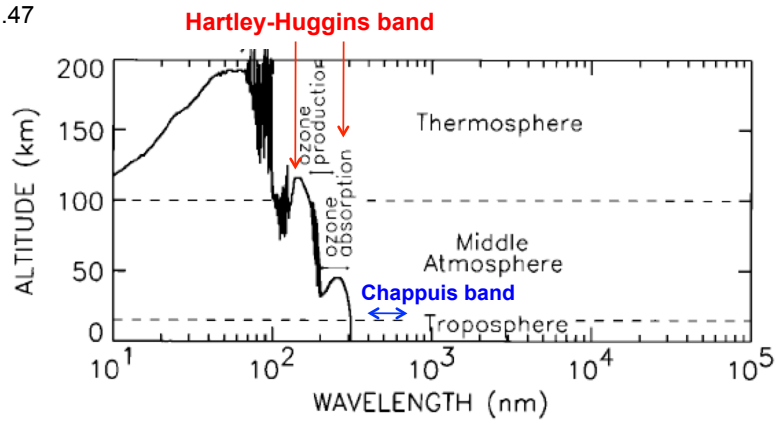


Blue line: peak short wave spectrum

Fig. 2.48

Absorption of Solar radiation

Figure 2.47



Altitude at which the incident energy from an overhead Sun is attenuated by a factor of 1/*e* (**unit optical path**) plotted as a function of wavelength of the incident radiation. Also indicated are the wavelength intervals that dominate ozone production and absorption (section 1.12).

Source: Lean, J. and D. Rind, 1998: Climate forcing by changing Solar radiation. **J. Climate, 11**, 3069-3094.

"Very broad band model" of Solar radiation

Split short wave spectrum into 4 bands or channels:
Channel 1: ***Hartley-Huggins* band** (**6%** of SW-radiation)
Channel 2: remaining radiation (14% of SW-radiation)
Channel 3: ***Chappuis* band** (**27%** of SW-radiation)
Channel 4: ***near infrared*** (53% of SW-radiation) (absorbed by water vapour and CO_2)

Assume that
Channel 1: is completely absorbed above 20 hPa*
Channel 2: no absorption
Channel 3: $\sigma_a[O_3]=0.285\times10^{-24}\ m^2=0.285\times10^{-12}\ \mu m^2$
Channel 4: $\sigma_a[H_2O]=\sigma_a[CO_2]=0$

*with 25 levels the highest model level is at 20 hPa

Radiative convective equilibrium

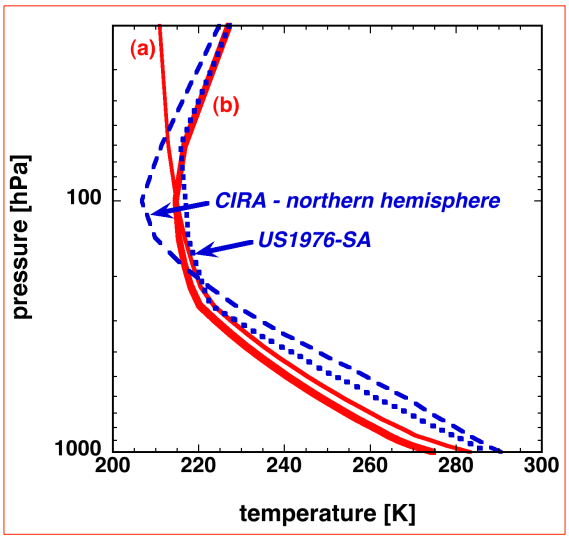
Fig. 2.50

(a) No absorption of *SR*
(b) Absorption of *SR* by O_3

***O_3* prescribed according to observations.**

Furthermore:
***CC*=0.6,**
***pCO_2*=400 ppmv,**
***E*=80 W m^{-2}**

SA=US1976 Standard Atm.
CIRA=COSPAR-International reference atmosphere

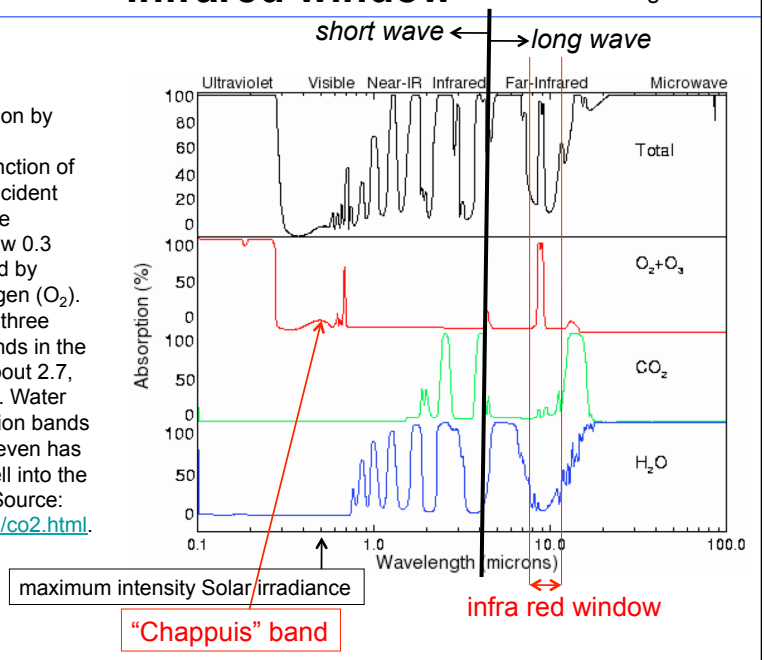


LW transmission=grey!

Infrared window

Fig. 2.29

Absorption of radiation by various gases in the atmosphere as a function of wavelength of the incident radiation. Most of the ultraviolet light (below 0.3 microns) is absorbed by ozone (O_3) and oxygen (O_2). Carbon dioxide has three large absorption bands in the infrared region at about 2.7, 4.3, and 15 microns. Water has several absorption bands in the infrared, and even has some absorption well into the microwave region. Source: http://brneurosci.org/co2.html.



"Very broad band model" of long wave radiation

Spectral irradiance as a function of wavelength for a **black body** with a temperature of, respectively, 288 K, 255 K and 210 K. The wavelength interval of, respectively, the infrared window and of the carbon dioxide absorption band indicated by straight vertical dashed lines. The percentages refer to the spectral irradiance within the specified interval as a fraction of the total spectral irradiance at the specified temperature. At lower temperatures relatively less and less energy is emitted in the "window"-interval because the curve shifts to higher wavelengths.

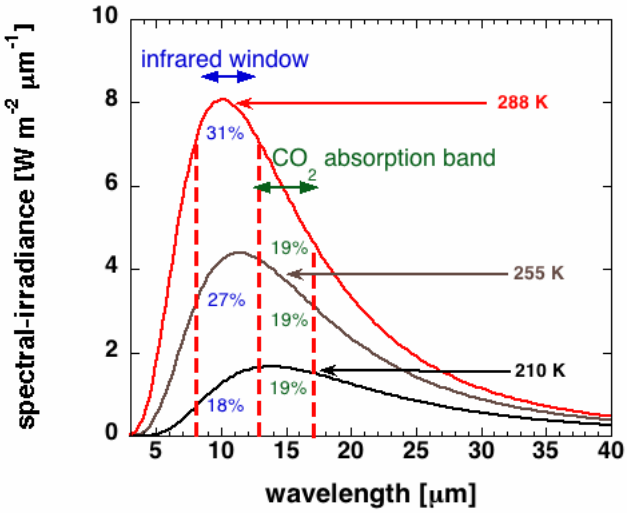
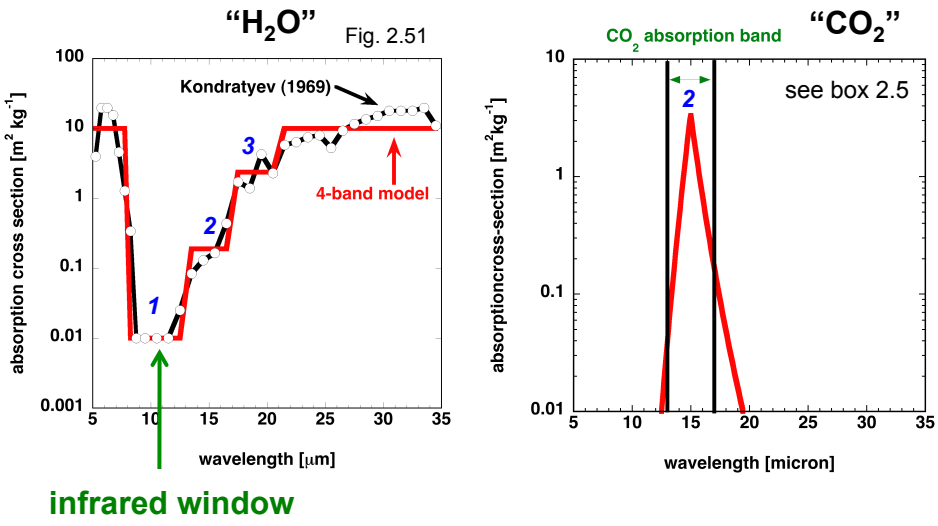


Fig. 2.30

"Very broad band model" of LW-radiation

Band 1: 8-13 μm; *Band 2*: 13-17 μm; *Band 3*: 17-21 μm; *Band 4*: aggregate of the rest



Radiative-convective model: assumptions

Atmosphere divided into 25 layers of equal mass

Radiation scheme: 4 SWR bands; 4 LWR bands

Ozone concentration prescribed

One well-mixed greenhouse gas (CO_2)

Water vapour density distribution prescribed

Cloud cover fraction related to relative humidity at the ground

Non-radiative fluxes at the surface parametrized

Precipitation parametrized as a relaxation process to prescribed relative humidity

Aerosols are neglected

Radiative convective model equilibrium

Radiative convective equilibrium in an atmosphere which is grey to long-wave radiation (grey curve), i.e. absorption coefficients are wavelength-independent, and in **in an atmosphere which where long wave absorption coefficients depend on wavelength (blue curves).**

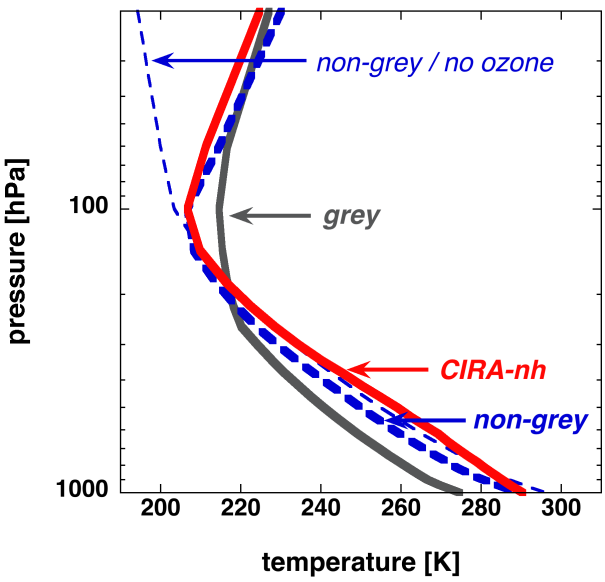


Figure 2.53

Influence of infra-red window on surface temperature and climate sensitivity

The **equilibrium temperature at the Earth's surface** and the **net atmospheric *long wave* transmission coefficient (τ)** as a function of concentration of the well-mixed greenhouse gas in a "grey" atmosphere (dashed curves) and in an atmosphere with an infrared window (**solid** curves).

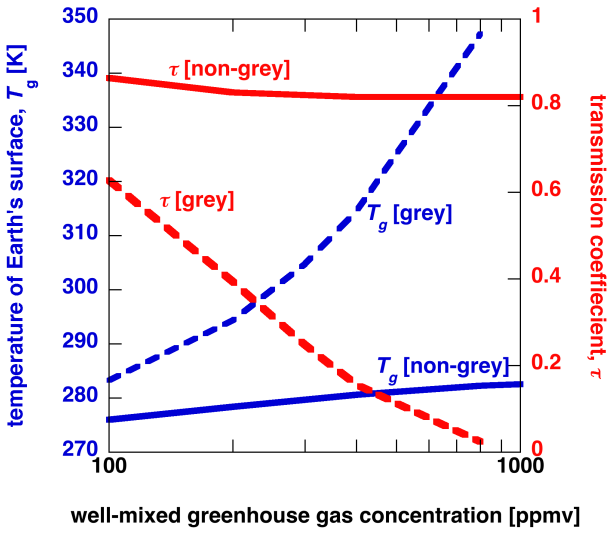
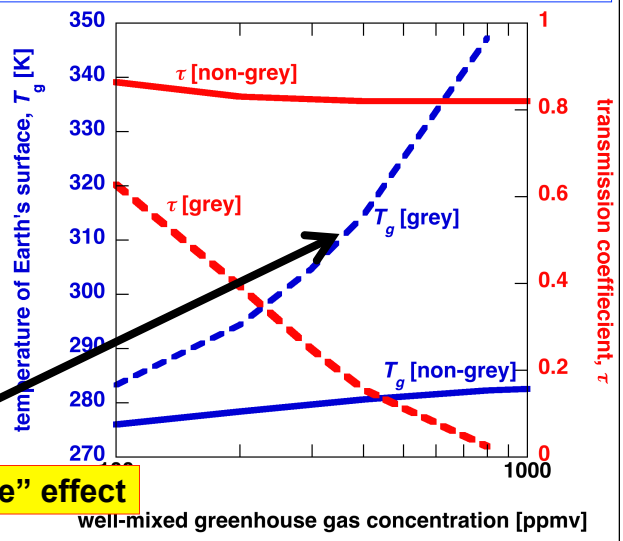


Figure 2.54

Influence of infra-red window on surface temperature and climate sensitivity

The **equilibrium temperature at the Earth's surface** and the **net atmospheric *long wave* transmission coefficient (τ)** as a function of concentration of the well-mixed greenhouse gas in a "grey" atmosphere (dashed curves) and in an atmosphere with an infrared window (**solid** curves).



"Runaway greenhouse" effect

Figure 2.54

Influence of cloud fraction on surface temperature

The influence of cloud cover on global average **surface equilibrium temperature**, according to the moist radiative convective model. Also shown are the **net atmospheric (planetary) long wave transmission coefficient** (τ_p) the **planetary albedo** (α_p).

For fixed CO_2-concentration!

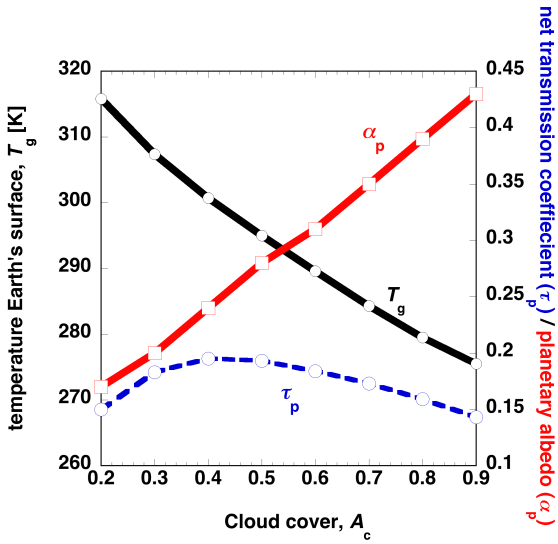


Figure 2.55

Water vapour feedback

Relative humidity approximately constant!

The water vapour feedback according to the moist radiative convective model. The equilibrium temperature at the Earth's surface is plotted as function of concentration of the well- mixed greenhouse gas.

The **blue line** is for an **atmosphere with water cycle**.

The **black line** is the temperature for an **atmosphere lacking water (no evaporation; no clouds)**.

*Also indicated is the temperature increase for CO_2-doubling: which is the **"equilibrium climate sensitivity"***

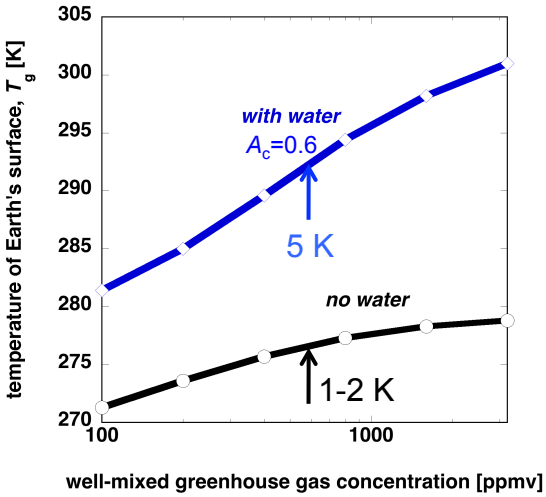
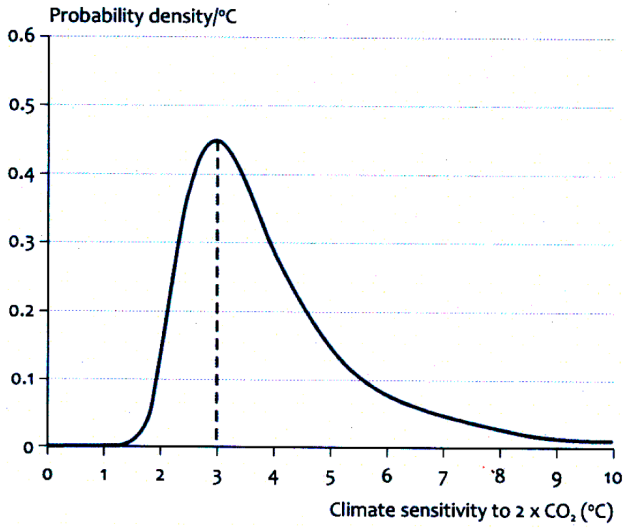


Figure 2.56

Climate sensitivity according to state of the art climate models

Probability distribution of climate sensitivity (smoothed curve).



Box 2.8

Section 2.20:

Radiative forcing

Instantaneous change in radiation balance at the top of the atmosphere as a response to change in concentration of a greenhouse gas or of cloud cover fraction.

Problem 2.15 (Monday *18 March)*

http://forecast.uchicago.edu/Projects/modtran.orig.html

What next?

Week 11: *no* classes (retake week)

Monday *18 March*: **Radiative forcing**: problem 2.15 (radiation model – internet: http://forecast.uchicago.edu/Projects/modtran.orig.html).
Niels Alebregse will be you assistant here.

Wednesday *20 March*: History of Earth's (Roderik van de Wal)

Monday *25 March*: Problems 2.16 and 2.17 (Ice-albedo feedback) ←

Wednesday *27 March*: Ice-albedo feedback continued

Monday *1 April*: Easter

Test 1: 15/4 or 17/4

Ice-albedo feedback

Energy balance model due to Budyko and Sellers (1969)

Section 2.21

Predicts **global average surface equilibrium temperature as a function of latitude** taking into account very crudely the meridional transport of energy from the equator to the poles.

Focus on the estimation of the effect on the surface temperature of **changes in the planetary albedo** (due to changes in snow/ice cover) as a function of latitude, ϕ.

Budyko-Sellers model is based on one simple equation…

For **mean annual conditions**, the equation for the **zonally averaged heat balance** of the earth-atmosphere system is:

$$Q(1-\alpha) = I + A$$

$\boldsymbol{Q(\phi)}$=Solar radiation at TOA (top of the atmosphere)
$\boldsymbol{\alpha(\phi,T)}$=albedo;
$\boldsymbol{I(\phi,T)}$=outgoing long-wave radiation at TOA
$\boldsymbol{A(\phi,T)}$=loss (if A>0) of energy from a particular latitude belt as a result of the atmosphere and hydrosphere circulation, including heat redistribution of phase water transformations.

For the Earth-atmosphere system as a whole we have, $\boldsymbol{A=0}$, giving the "**zero-dimensional EBM**".

$Q(1-\alpha) = I + A$

Energy imbalance at each latitude

Annual mean radiation

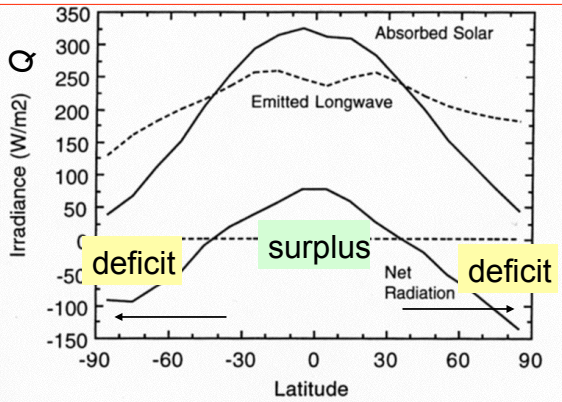


Fig. 2.12 Graphs of annual-mean absorbed solar radiation, OLR, and net radiation averaged around latitude circles.

Why is the emitted radiation less at poleward latitudes?

Hartmann, 1994, fig.2.12

Parametrization in Budyko-Sellers energy balance model

$$Q(1-\alpha) = I + A$$

$Q(\phi)$=Solar radiation at TOA (top of the atmosphere)
$\alpha(\phi,T)$=albedo;
$I(\phi,T)$=outgoing long-wave radiation at TOA
$A(\phi,T)$=loss (if A>0) of energy from a particular latitude belt as a result of the atmosphere and hydrosphere circulation, including heat redistribution of phase water transformations.

Can we express I, A and a in terms of T_g?

$$Q(1-\alpha) - I = A$$

Model with Budyko's parametrization

$$Q(1-\alpha) = I_0 + bT + \beta\left(T - T_p\right) = a^* + b^* T$$

with $a^* = I_0 - \beta T_p;\ b^* = b + \beta$

Introduce a **temperature dependent albedo**:

$$\alpha = \alpha_0 \text{ if } T \le T_0$$
$$\alpha = \alpha_0 + \frac{T - T_0}{T_1 - T_0}(\alpha_1 - \alpha_0) \text{ if } T_1 \ge T > T_0$$
$$\alpha = \alpha_1 \text{ if } T > T_1$$

For each latitude we have this equilibrium: $Q(1-\alpha) = a^* + b^* T$

The **absorbed solar radiation (ASR)** now depends on temperature as shown by the solid line in the figure (l.h.s. of eq. above).

The broken line in the figure represents the **energy loss** (r.h.s. of eq. above)

Equilibrium states are represented by the **intersections** of solid and broken lines

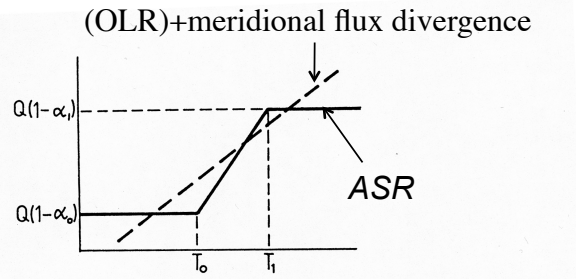


Figure 2.1. Absorbed solar radiation (solid line) and energy loss by outgoing terrestrial radiation and dynamical energy fluxes (broken line).

For each latitude we have this equilibrium: $Q(1-\alpha) = a^* + b^* T$

Slope of the solid line (ASR) between $T=T_0$ and $T=T_1$ is $\mu = \dfrac{Q(\alpha_0 - \alpha_1)}{T_1 - T_0}$

If $\mu < b^*$ there is **one equilibrium**

If $\mu > b^*$ there are possibly **three equilibria** depending on the value of a^*

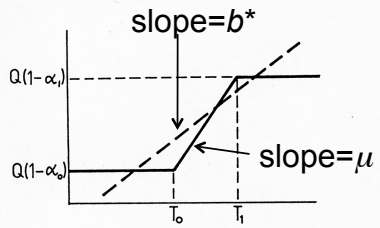


Figure 2.1. Absorbed solar radiation (solid line) and energy loss by outgoing terrestrial radiation and dynamical energy fluxes (broken line).

Budyko-Sellers model is a toy climate that illustrates…

the non-linear character of the climate system (more than one steady state for identical external conditions).

Problem 2.17 is concerned with analysing the steady states of this model (Monday 25/3)

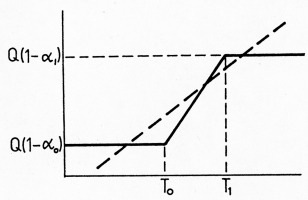


Figure 2.1. Absorbed solar radiation (solid line) and energy loss by outgoing terrestrial radiation and dynamical energy fluxes (broken line).

Theme for essay: send me your ideas by e-mail

See you on March 27