

Climate Dynamics (lecture 5)

Water cycle and energy balance

Energy fluxes

Water vapour and radiation

Cloud cover

Clouds and radiation

Radiative convective model with water cycle

Effect of water cycle on radiative convective equilibrium

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

Energy fluxes (2000-2004) and water cycle

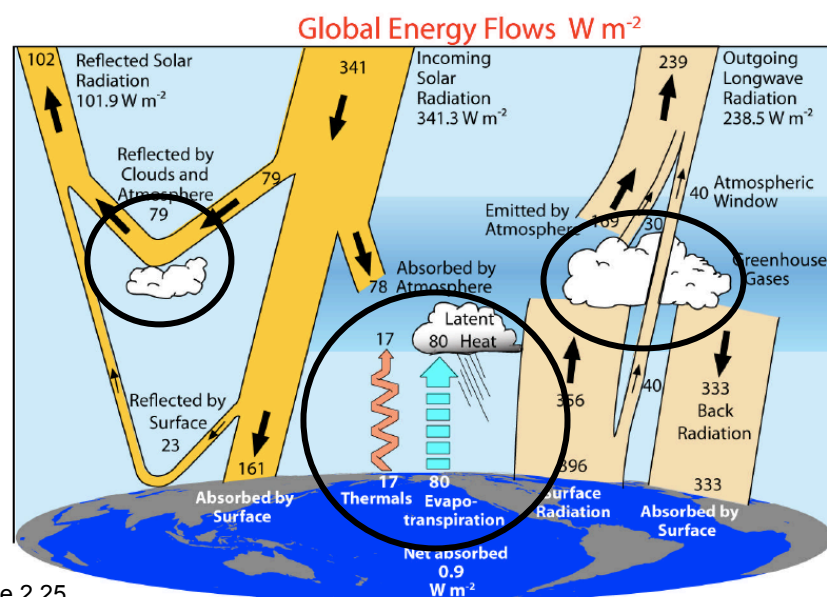
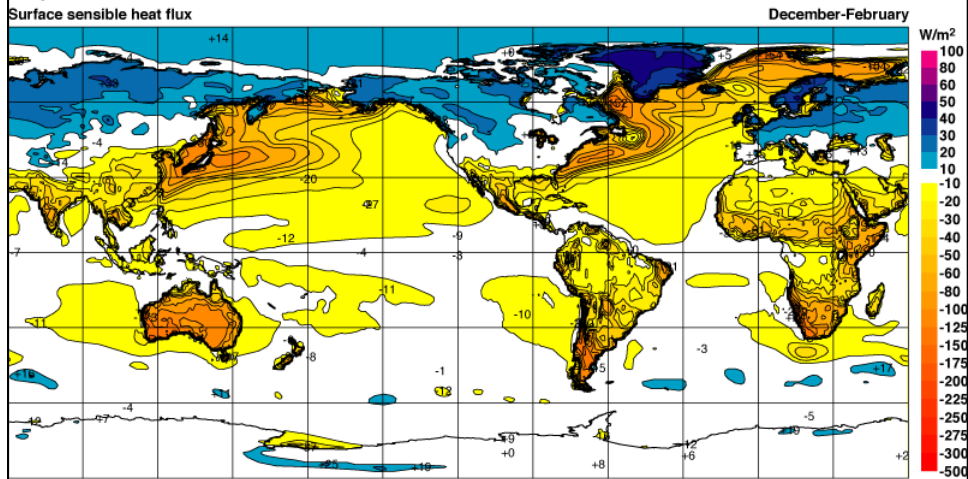


Figure 2.25

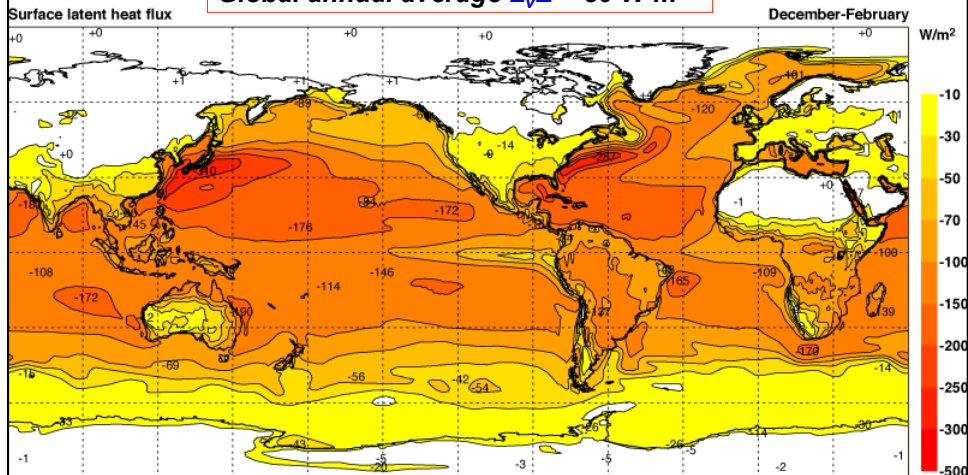
Surface sensible heat flux, H_s

Figure 2.26 **Estimate of global annual average $H_s = -8$ to -24 W m^{-2}**



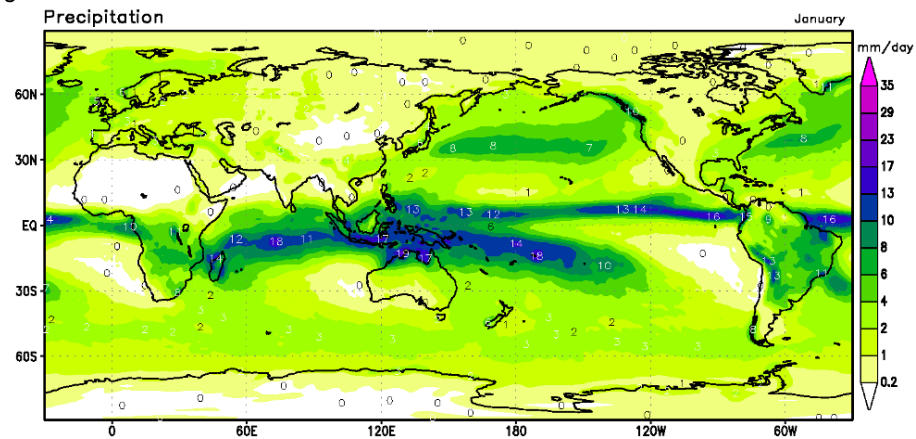
Latent heat flux due to evaporation, $L_v E$

Figure 2.26 **Global annual average $L_v E = 80 \text{ W m}^{-2}$**



Precipitation

Figure 1.17

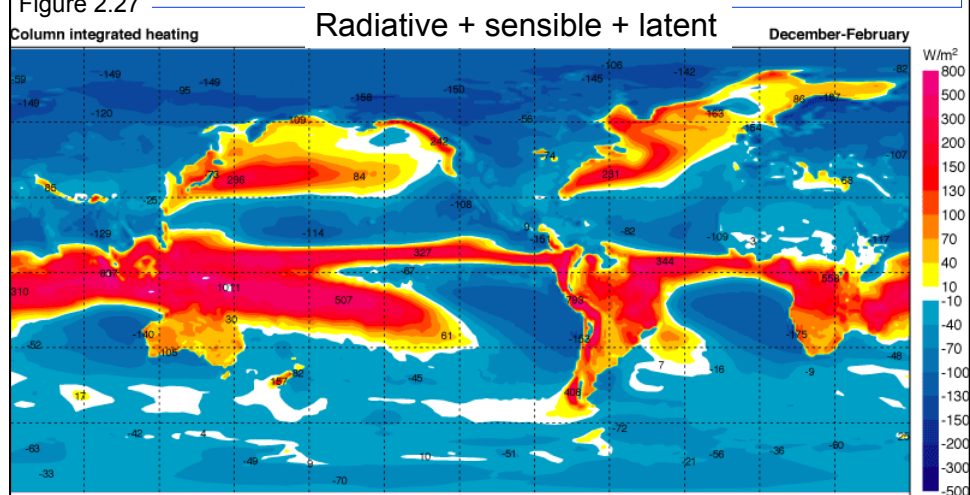


Global annual average precipitation = $2.8 \text{ kg m}^{-2} \text{ day}^{-1}$

Japanese reanalysis (1979-2004)

Integrated column heating

Figure 2.27



Global distribution of the average column integrated heating of the atmosphere in W m^{-2} in December January and February (DJF) The average is for the period 1979-2001. Source: http://www.ecmwf.int/research/era/ERA-40_Atlas.

This lecture:

How do we incorporate effects of water in the radiative convective model?

Evaporation at the Earth's surface
Vertical distribution of water vapour
Latent heat release due to condensation
Clouds

BOX 2.3: Atmosphere with one well-mixed greenhouse gas

Radiative equilibrium

Atmospheric temperature:

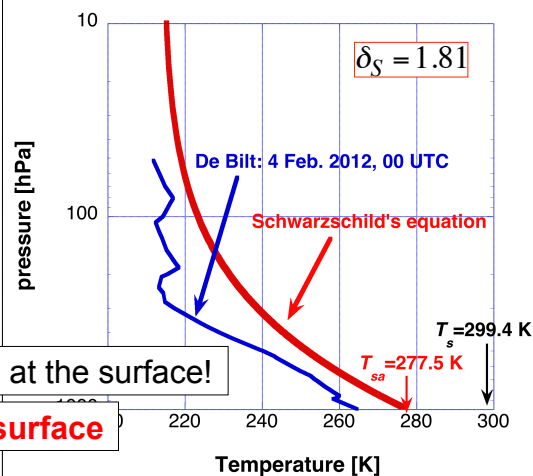
$$T = T_{skin}(\delta + 1)^{1/4}$$

Surface temperature:

$$T_S = T_{skin}(\delta_S + 2)^{1/4}$$

logarithmic scale →

$\sigma_a = 0.3 \text{ m}^2 \text{ kg}^{-1}$; $r_a = 390 \text{ ppm}$
 $\alpha_p = 0.3$; $S_0 = 1366 \text{ W m}^{-2}$; $p_s = 1000 \text{ hPa}$



Discontinuity in temperature at the surface!

>> **Static instability at the surface**

Water vapour in the radiative convective model

Arrhenius (1896) and many others¹:

prescribe relative humidity, RH

Global annual average *RH* is about 75-80 %

¹ see e.g. Manabe and Wetherald, 1967: <http://journals.ametsoc.org/toc/atasc/24/3>

Water vapour in the radiative convective model

Instead:

Prescribe density profile of water vapour :

$$\rho_v = \rho_{v,g} \exp\left\{-\frac{z}{H_v}\right\} \quad (\text{see lecture 1})$$

$$PW = \rho_{v,g} H_v$$

PW = Precipitable water

Scale height, H_v , is prescribed (2 km)

Time-evolution *PW* is governed by following equation

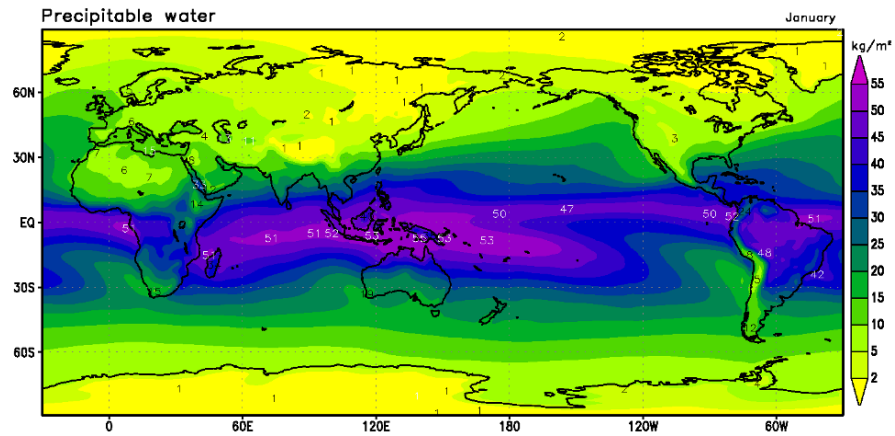
$$\frac{dPW}{dt} = E - P$$

E = evaporation at Earth's surface

P = precipitation

Precipitable water (PW)

Figure 1.16



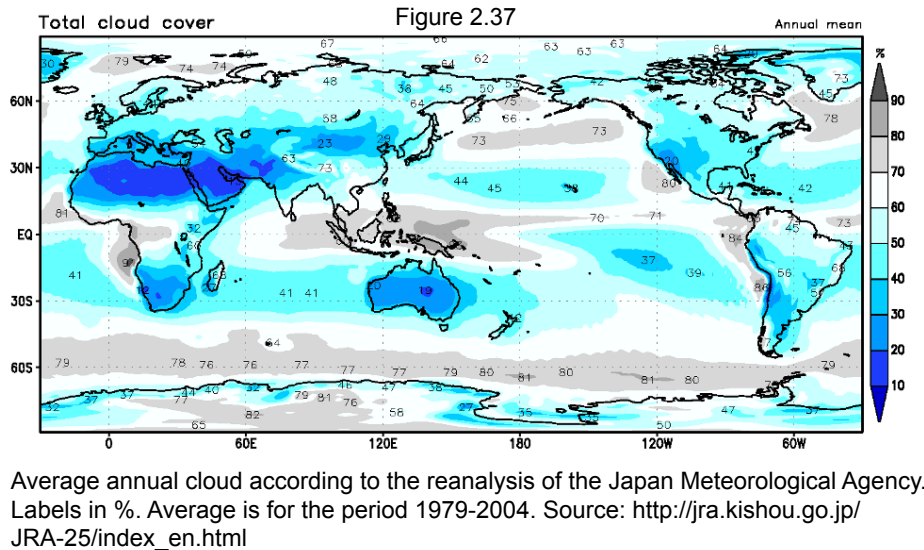
Global annual average $PW=25 \text{ kg m}^{-2}$

Japanese reanalysis (1979-2004)

Clouds



Cloud cover fraction

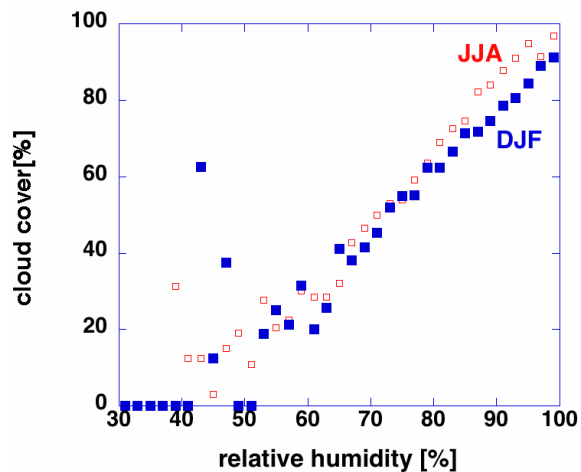


Cloud cover, A_c , related to relative humidity

$$PW = \rho_{v,g} H_v$$

$$\rightarrow A_c \propto RH_g ?$$

Weighted daily average cloud cover (in %) plotted against daily average **relative humidity at 1.5 m above the ground in De Bilt (1951-2008)**. For each bin of 2% in relative humidity the sum of all values of cloud cover is computed and this number is divided by the total number of events in the particular bin.



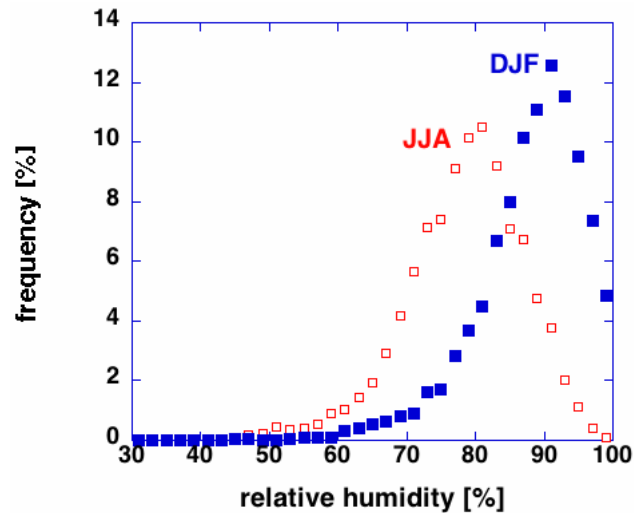
$$A_c = C(RH_g - RH_0) \text{ for } RH_g > RH_0$$

$$C = 1.5; RH_0 = 38\%$$

See figure 2.39

Probability density function RH_g

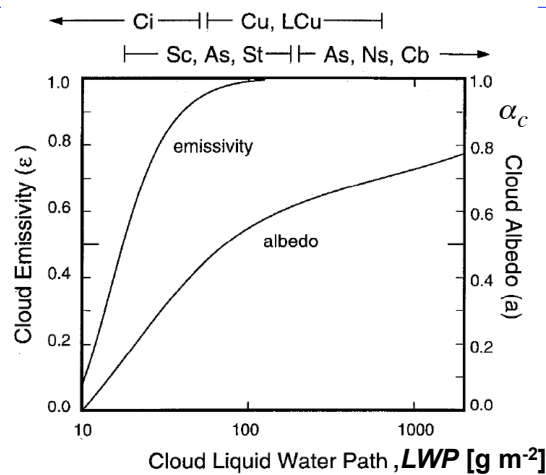
Frequency distributions of relative humidity at 1.5 m above the ground (divided into bins of 2%) in **De Bilt** (1951-2008) in the **summer season** in (JJA: June, July and August; red open squares) and for the **winter season** (DJF: December, January and February; blue solid squares).



See figure 2.38

Clouds and radiation

Figure 2.40



Model:

$$\alpha_c = 0.45$$

$$\alpha_g = 0.1$$

Cloud albedo and cloud emissivity as a function of liquid water path (in units of g m^{-2}) of a cloud. Cloud types associated with the values of liquid water path are displayed on the upper abscissa. Ci: cirrus, Cu: cumulus, Sc: stratocumulus, St: stratus, As: altostratus, Ns: nimbostratus, Cb: cumulonimbus. **A cloud appears to be optically black even for relatively thin clouds.**
Source: Webster (1994).

The water cycle in the radiative convective model

Clouds (liquid water),
water vapour,
evaporation at the earth's surface,
condensation in the atmosphere,
latent heat.

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There are two types of greenhouse gases: the **well mixed type** (*carbon dioxide*) and the **inhomogeneously distributed type** (*water vapour*). Next to this we assume the presence of *clouds* if the relative humidity exceeds a predefined critical value.

Clouds in the radiative convective model

The long wave radiation intensity is split into **2 beams**: a beam that goes through *the clear sky* (subscript 1) and a beam that goes through the *cloudy part of the sky* (subscript 2):

Intensity of radiation:

$$\begin{array}{ccc} \text{clear} & & \text{cloudy} \\ \downarrow & & \downarrow \\ I_1 = (1 - CC)I & \text{and} & I_2 = CCI \quad (I = I_1 + I_2) \end{array}$$

Clouds in the radiative convective model

Intensity of radiation:

$$\begin{array}{ccc} \text{clear} & & \text{cloudy} \\ \downarrow & & \downarrow \\ I_1 = (1 - CC)I & \text{and} & I_2 = CCI \quad (I = I_1 + I_2) \end{array}$$

Apply **Bouguer-Lambert-Beer Law** to the two beams separately:

$$\frac{dI_1}{I_1} = -\frac{1}{g}(q_m\sigma_m + q_v\sigma_v)dp$$

q = specific concentration

$$\frac{dI_2}{I_2} = -\frac{1}{g}\left(q_m\sigma_m + RH_c q_s\sigma_v + \left(\frac{q_L}{CC}\right)\sigma_L\right)dp$$

Absorption cross-sections are independent of wavelength!
("grey" radiative transfer)

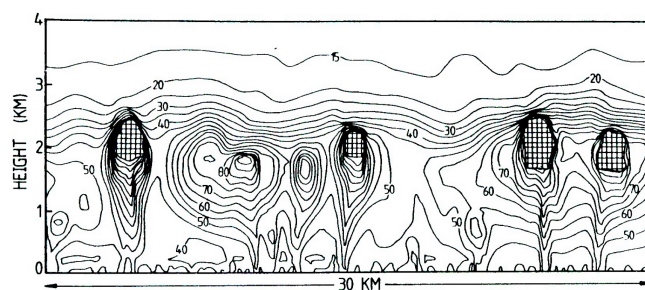
Parametrization of

Clouds & cloud cover in the radiative convective model

Cloud: Liquid water is present at a particular level if

$$RH > RH_c = RH_{c,0} + \Delta RH_c \left\{ \left(\frac{p}{p_g} \right)^2 - 1 \right\}$$

$$RH_{c,0} = 98\%; \Delta RH_c = 10\%$$



Model simulation of the relative humidity in the atmospheric boundary layer at midday in June in the Netherlands. The hatched regions correspond to clouds ($RH > 100\%$)

Parametrization of

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Cloud cover:

1. Prescribed: e.g. $CC=0.6$, or
2. The empirical relation is used

$$CC = C(RH_g - RH_0) \text{ for } RH_g > RH_0$$

Parametrization of**Precipitation and latent heat release in the radiative convective model**

Precipitation as a relaxation of the total specific water concentration towards a reference value of the relative humidity:

$$\frac{\partial q_w}{\partial t} = \frac{q_w - RH_c q_s}{\tau_c} \text{ if } q_w > RH_c q_s; \quad \frac{\partial q_w}{\partial t} = 0 \text{ if } q_w \leq RH_c q_s$$

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Liquid water content:

$$q_L = (q_v - RH_c q_s) \text{ if } \frac{\partial q_v}{\partial t} > 0; \quad q_L = 0 \text{ if } \frac{\partial q_v}{\partial t} = 0$$

Parametrization of**Precipitation and latent heat release in the radiative convective model**

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Latent heat release:

$$J = L_c \frac{\partial q_v}{\partial t} \frac{dp}{g} \left[\text{J s}^{-1} \text{m}^{-2} \right]$$

Evaporation in the radiative convective model

$$\frac{dPW}{dt} = E - P$$

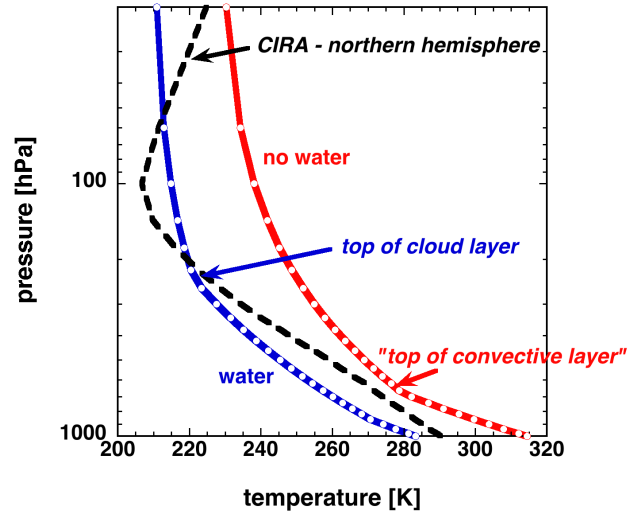
1. Evaporation energy-flux is prescribed, e.g. $L_v E = 80 \text{ W m}^{-2}$.
2. Bowen ratio, B , is prescribed and evaporation is computed from sensible heat flux

$$E = \frac{H_s}{BL_v} \left[\text{kg m}^{-2} \text{s}^{-1} \right]$$

Equilibrium solution of RCM with water cycle

Radiative-convective equilibrium temperature as a function of pressure according to the "**grey**" moist radiative convective model for two cases, compared to the "observed" COSPAR international reference atmosphere (CIRA) annual average temperature of the northern hemisphere (black dashed curve). The curve labeled "**no water**" (solid red curve) is for the case with no water vapour or clouds in the atmosphere. In the second case (blue solid curve labeled "**water**"), surface evaporation is 80 W m^{-2} , cloud fraction is 0.6 and $H_v=2000 \text{ m}$. In both cases the concentration of the well-mixed greenhouse gas is 400 ppmv..

Figure 2.43



Equilibrium solution of RCM with water cycle

Liquid water content as a function of pressure, according to the equilibrium solution of the moist radiative convective model assuming grey long wave radiative transfer. The total latent heat released is 80 W m^{-2} .

The total liquid water path of real clouds lies somewhere between 10 and 1000 g m^{-2} .

The equilibrium liquid water path of the simulated clouds is in the order of 173 g m^{-2} .

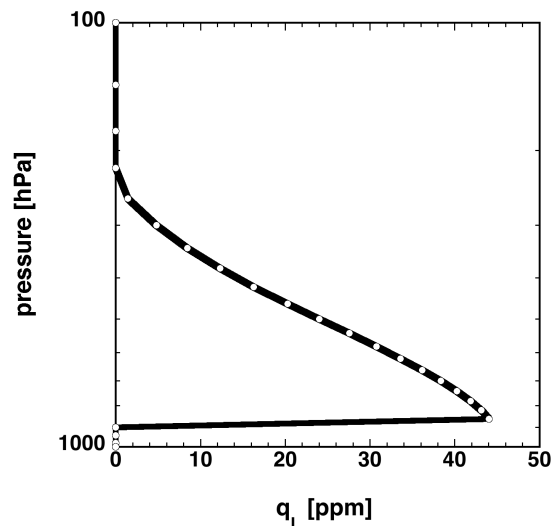


Figure 2.44

Conclusions

1. The presence of **water cools the climate**, due to higher planetary albedo (cloud albedo higher than ground albedo), cooling of surface by evaporation, transport of latent heat to higher levels, where it is released upon condensation, after which this heat can escape to space by radiation relatively easily.
2. Height and existence tropopause determined by latent heat release and associated cloud top height (note: this is not the only reason for the existence of the tropopause!!)

Next step is to make the radiation scheme more realistic

Next lecture

Wed. 6 March 2012:

Climate Sensitivity and feedbacks

Spectral dependence of absorption of radiation

Broad band radiation model

Infrared window and climate stability

Cloud feedback

Water vapour feedback

Ice-albedo feedback...>problems 2.16 & 2.17

Choose theme for essay