# Diabatic-Dynamical Interaction in the General Circulation (lecture 1)

In the coming period we are going to study the **interaction between dynamics and diabatic processes**.

**Diabatic processes**:
*Absorption and emission of radiation*
*Energy transformations associated with the water cycle*

**Dynamics**:
*Atmospheric circulation*

http://www.staff.science.uu.nl/~delde102/C&HC.htm

# The General Circulation

## Zonal mean zonal wind, pressure and potential vorticity

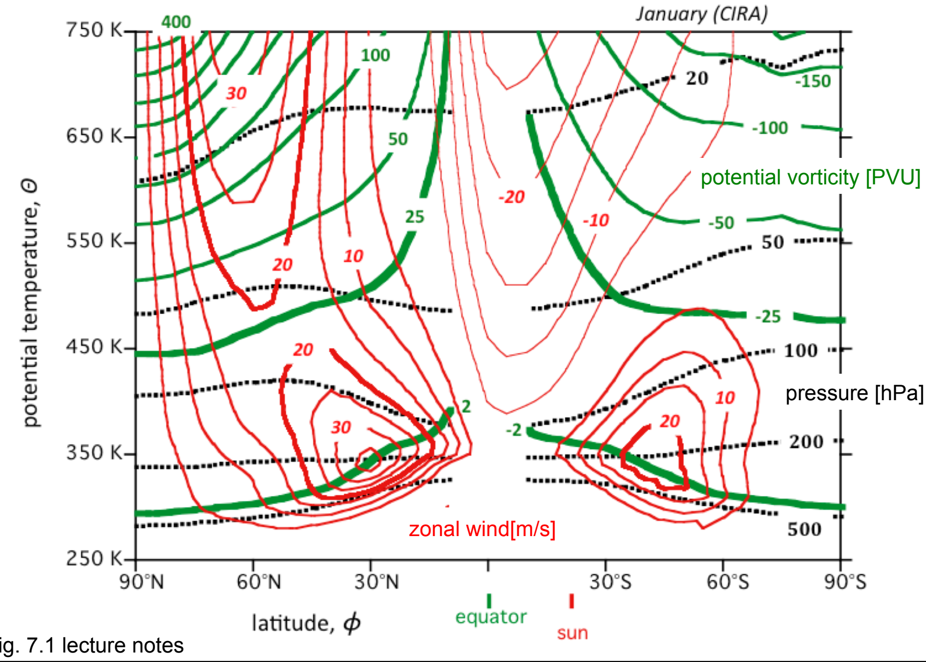



Fig. 7.1 lecture notes

## Zonal mean zonal wind, pressure and potential vorticity

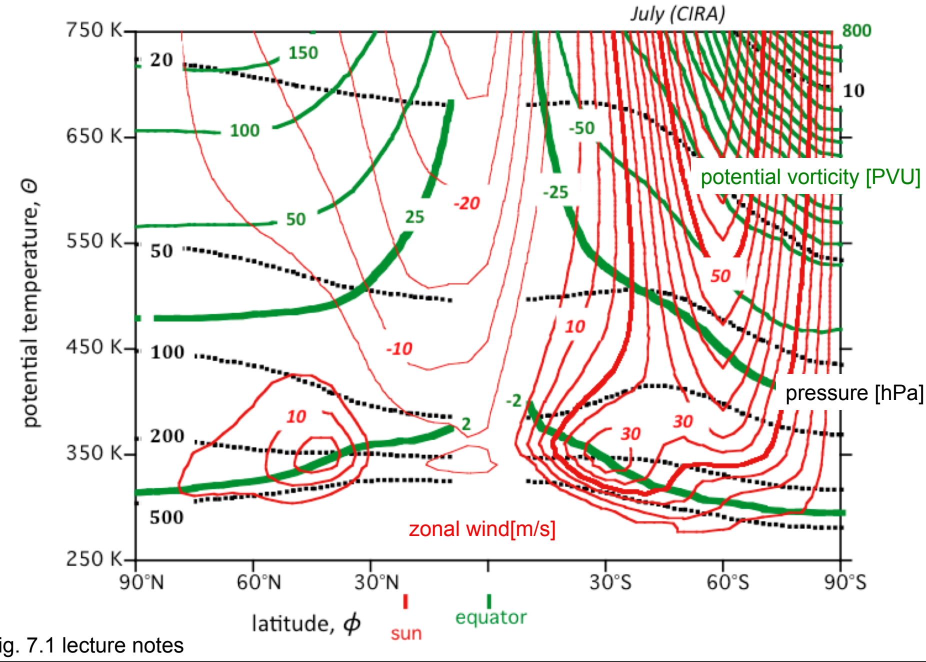
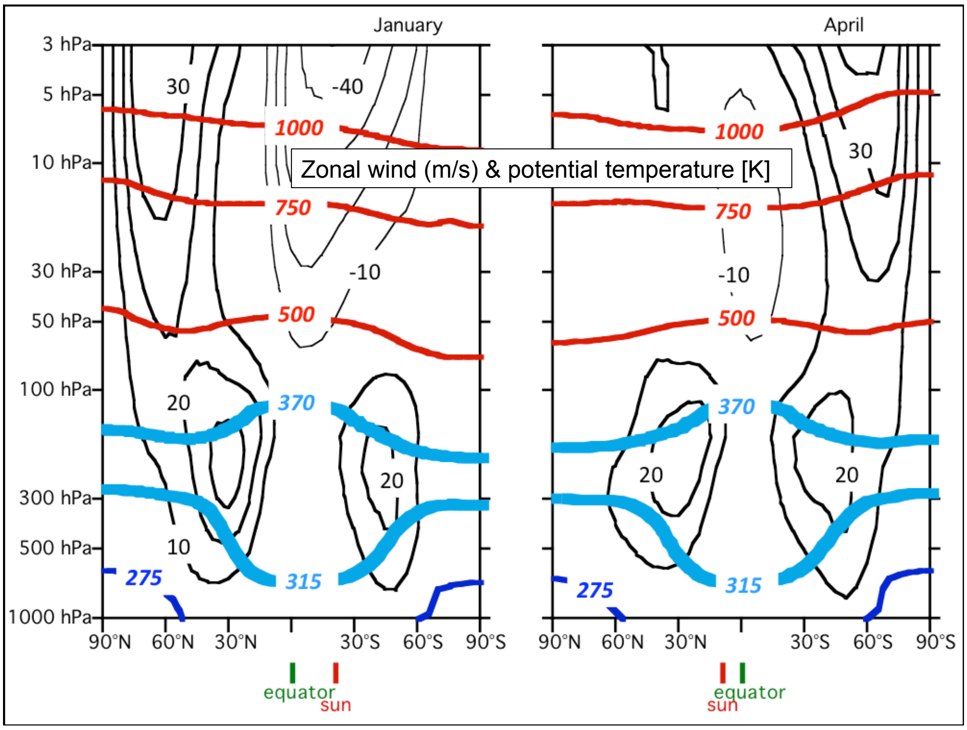
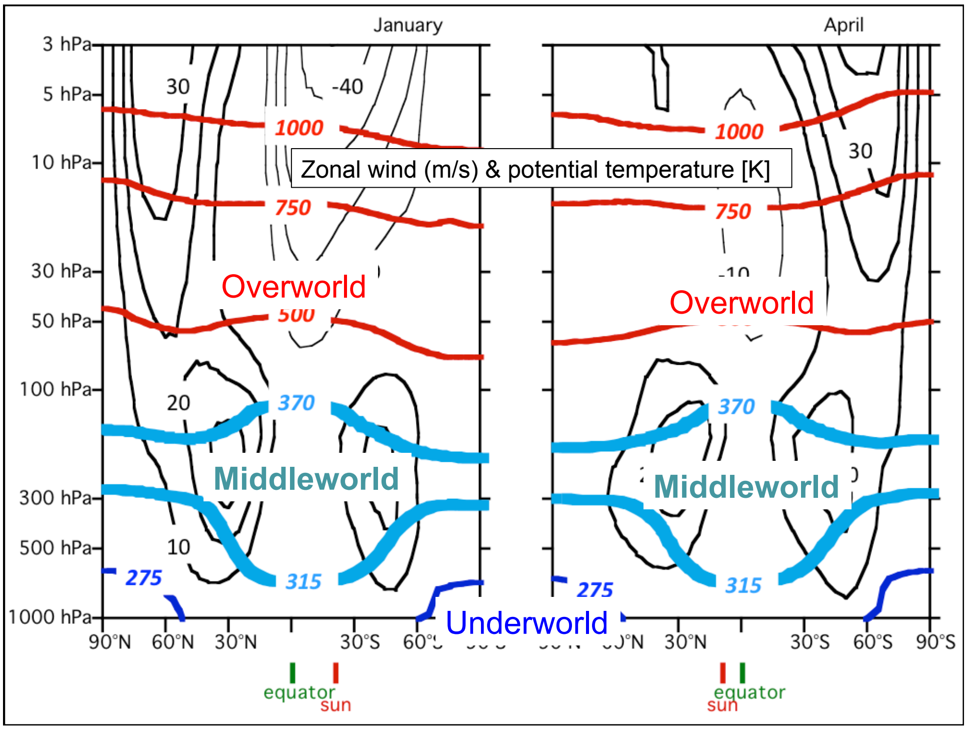



Fig. 7.1 lecture notes


January
April
Zonal wind (m/s) & potential temperature [K]
3 hPa
5 hPa
10 hPa
30 hPa
50 hPa
100 hPa
300 hPa
500 hPa
1000 hPa
90°N 60°N 30°N 30°S 60°S 90°S
90°N 60°N 30°N 30°S 60°S 90°S
1000
750
500
370
315
275
30
-40
-10
20
10
equator
sun


January
April
Zonal wind (m/s) & potential temperature [K]
3 hPa
5 hPa
10 hPa
30 hPa
50 hPa
100 hPa
300 hPa
500 hPa
1000 hPa
Overworld
Overworld
Middleworld
Middleworld
Underworld
1000
750
370
315
275
30
-40
20
10
equator
sun

# What do we want to understand?

Position and intensity of subtropical jet

Cold tropical tropopause

Position of extratropical tropopause

Separation between subtropical jet and stratospheric jet

Zonal mean zonal stratospheric wind reversal

Seasonal cycle of the Hadley circulation

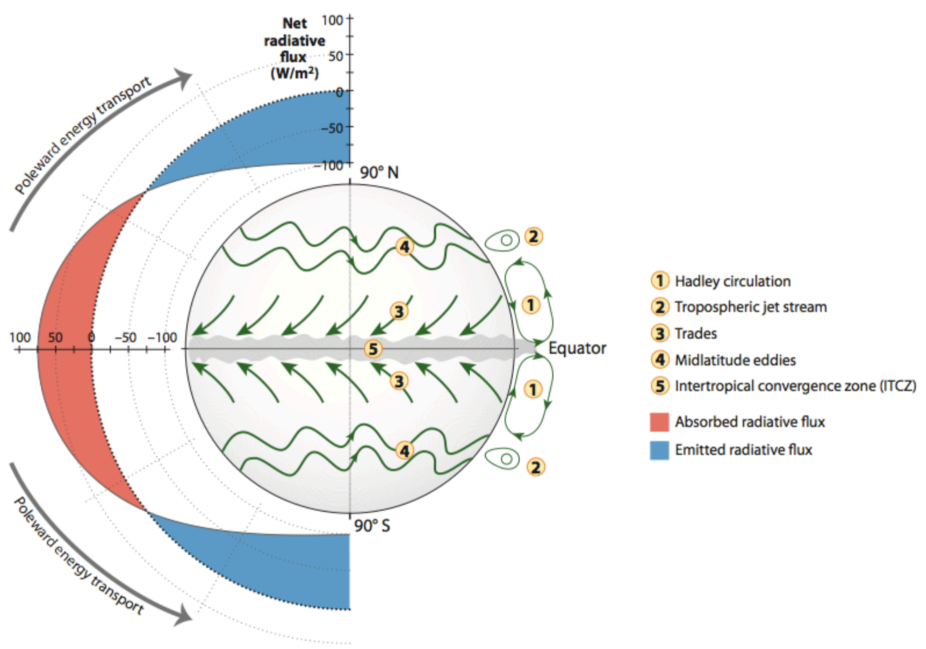
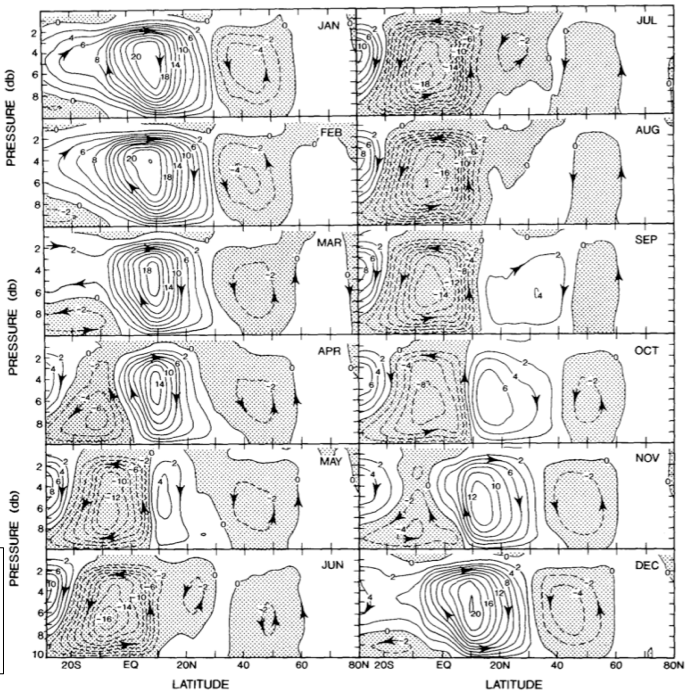



Figure: J,C.H. Chiang (2009). **Ann.Rev.Earth Plan.Sci., 37**, 263.

## Hadley Cells

Annual cycle of the zonal-mean *streamfunction*, $\Psi_m$ in units of $10^{10}$ kg $s^{-1}$. averaged over the period 1964-1989, derived from radiosonde measurements.

(from Oort, A.H., and J.J. Yienger, 1996: Observed interannual variability in the Hadley circulation and its connection to ENSO. **J.Climate, 9**, 2751-2767).




# Important processes

**Radiation**

**Circulation**

**Energy sources/sinks associated with phase changes of water**

**"Wave drag"**

# Lecture notes

**Chapter 12 of lecture notes on Atmospheric Dynamics**

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

Potential vorticity

Wave drag

Chapters 2 , 7, 8 , 10 and 11 are also of interest

Radiative transfer

Primitive equation model

Hadley circulation

# Program of the C&HC-2

23 April: Introduction to radiative transfer; "grey gas"; radiative equilibrium

*study sections 2.1-2.4 & boxes 2.1-2.4;*

***(1)** problem 12.1 (response time)* ***(0.5)***

30 April: Radiatively determined state; Reanalyses

***(2)** problem 12.2 (radiation at TOA; ERA-Interim)* ***(2.0)***

7 May: Radiative-dynamical interaction in a dry atmosphere; GCM's

***(3)** article for review (**yes/no**); Topic of presentation (GCM)*

14 May: Role of water cycle in the general circulation (the ITCZ)

***(4)** problem 12.3 (check of model assumptions)* ***(2.5)***

21 May: Role of wave drag in the general circulation (the surf zone)

***(5)** problem 12.5-12.9 (what-if? thought experiments)* ***(1)***

4 June: The Hadley-circulation

***(6)** problem 12.12 (Hadley-circulation theory)* ***(1)***

11 June: Isentropic coordinates and potential vorticity (inversion)

***(7)** problem 12.10 (isentropic density profile)* ***(1)***

18 June: Zonal mean mass- and potential vorticity budget

25 June: ***(8)** presentations on GCM's (**2.0**)*

No exam

# Content of first lecture

**Introduction to radiative transfer**

**Absorption of radiation**: Bougeur-Lambert-Beer Law.

**Radiative energy budget equation**: Schwarzschild's equation.

**Radiative equilibrium**: solution of Schwarzschild's equation.

>>Radiatively determined temperature as a function height

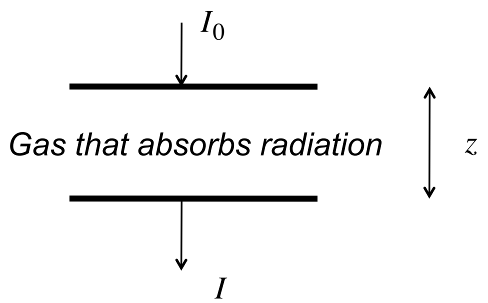
Division of the atmosphere in **troposphere and stratosphere.**

Box 2.2, 2.3 and 2.4 of the lecture notes

http://www.staff.science.uu.nl/~delde102/C&HC.htm

BOX 2.2

# Absorption of radiation




**Bouguer-Lambert-Beer Law:** $I = I_0 \exp(-\kappa z) \longrightarrow dI = -\kappa I dz$

$\kappa$ is the absorption coefficient

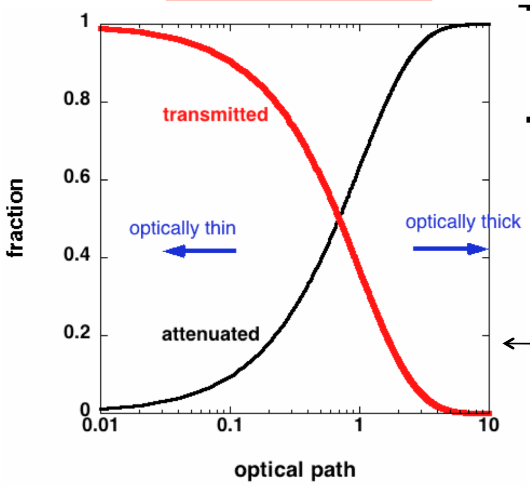
$\kappa z$ is the optical path

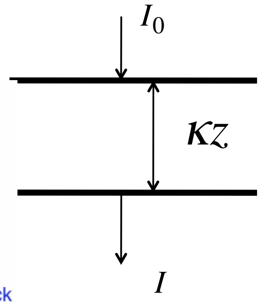
$\frac{1}{\kappa}$ is the absorption length (unit : m)

BOX 2.2

## Absorption of radiation

$\kappa z$ is the optical path




Fraction of the irradiance that is **transmitted (red)** or **absorbed (black)** as a function of optical path.

BOX 2.3

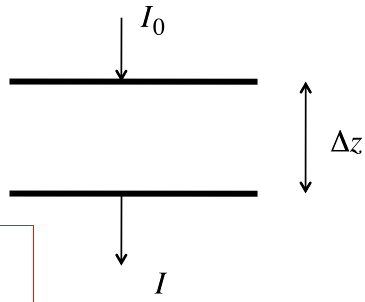
## Absorption cross section

$dI = -\kappa I dz$

$$\Delta I \equiv I_0 - I = \sigma_a n_a I_0 \Delta z$$

*absorption cross section in m² per molecule*

*molecule number density of aborbing gas*

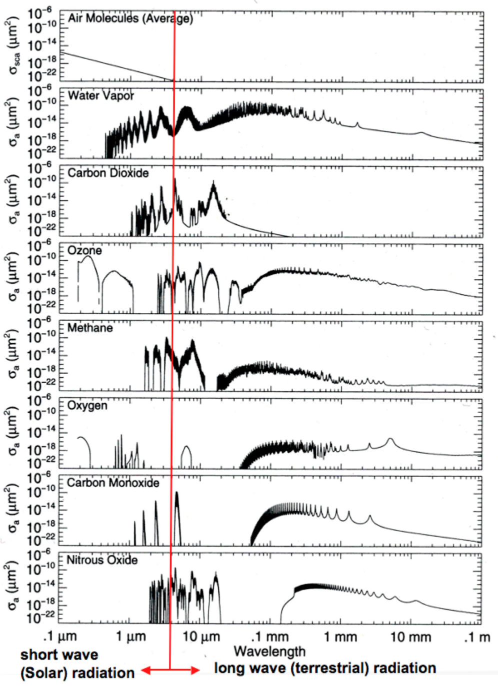


# Absorption cross section

FIGURE 2.48.

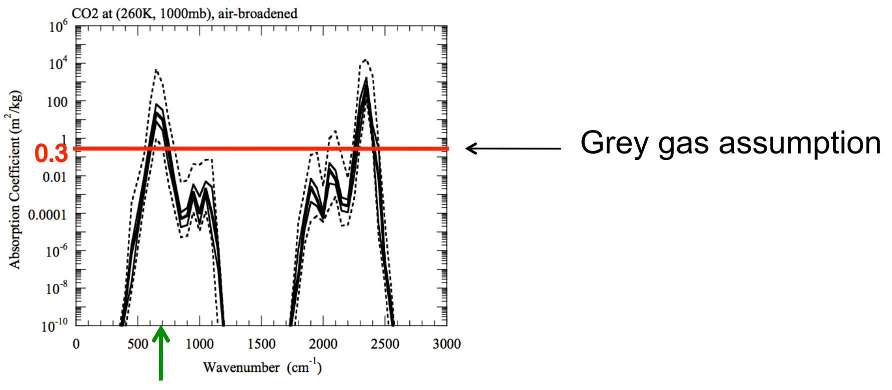
***Absorption cross sections*** *of the strongest absorbing atmospheric constituents*

**Grey gas**: absorption cross section is constant in long wave domain.




# Absorption cross section $CO_2$

Absorption cross section $CO_2$ depends on wavelength



# Kirchhoff's law

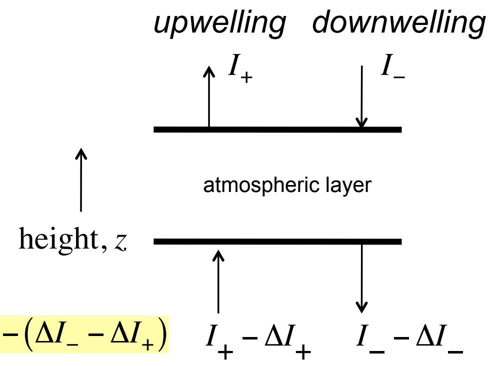
*absorption coefficient=emission coefficient*

Let us

**Investigate the temperature profile in an atmosphere which is transparent to Solar radiation**

# Upwelling and downwelling radiation

net in from the top $= I_- - I_+$



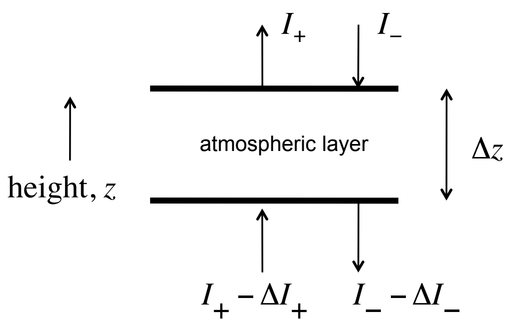

net out from the bottom $= (I_- - I_+) - (\Delta I_- - \Delta I_+)$

Net absorbed radiation is $(\Delta I_- - \Delta I_+)$

Radiation balance: $\Delta I_- = \Delta I_+$

BOX 2.4

# "Planck emission"




Previous slide: Radiation balance: $\Delta I_- = \Delta I_+$

***Fluxes include "Planck emission" of the atmospheric layer!!!***

Black body "Planck emission": $B \equiv \sigma T^4$

Atmospheric layer itself emits: $\kappa \Delta z B$

BOX 2.4

# Schwarzschild's equations

Energy budget:

upwelling radiation:

$$-\Delta I_+ = +\kappa \Delta z (I_+ - \Delta I_+) - \kappa B \Delta z$$

*absorbed* *emitted*

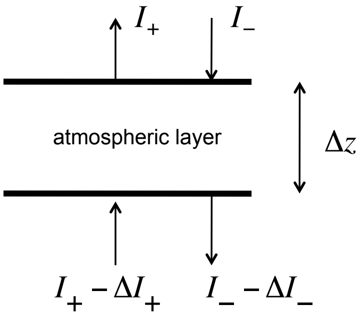
Optically thin layer:

$$-\Delta I_+ = +\kappa \Delta z I_+ - \kappa B \Delta z$$

Likewise:

downwelling radiation:

$$\Delta I_- = \kappa \Delta z I_- - \kappa B \Delta z$$




Previous slide: Radiation balance: $\Delta I_- = \Delta I_+$

BOX 2.4

# Schwarzschild's equations

**Energy budget:**

upwelling radiation:

$$-\Delta I_+ = +\kappa \Delta z I_+ - \kappa B \Delta z$$

downwelling radiation:

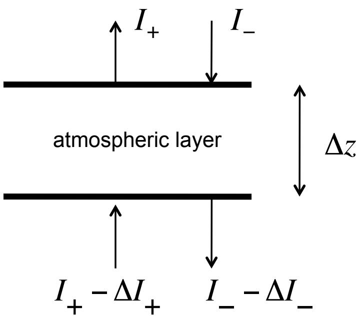
$$\Delta I_- = \kappa \Delta z I_- - \kappa B \Delta z$$

↓ $\Delta I_- = \Delta I_+$

+ $I_+ + I_- - 2B = 0$

and

- $\Delta I_+ + \Delta I_- = -\kappa (I_+ - I_-) \Delta z$



BOX 2.4

# Continuous homogeneous atmosphere

***Definition:*** $\bar{I} \equiv I_+ + I_-$ and $I \equiv I_+ - I_-$

*Previous slide:*

$$I_+ + I_- - 2B = 0 \longrightarrow \bar{I} = 2B$$

$$\Delta I_+ + \Delta I_- = -\kappa(I_+ - I_-)\Delta z \longrightarrow \Delta \bar{I} = -\kappa I \Delta z$$

$$\Delta I_- = \Delta I_+ \longrightarrow \Delta I = 0$$

*or in general:*

$$\bar{I} = 2B \qquad \frac{d\bar{I}}{d\delta} = I \qquad \frac{dI}{d\delta} = 0$$

$$B \equiv \frac{1}{2} I\delta + B_0$$

$B_0$ is an integration constant

Value of $B$ at $\delta$=0 (=TOA)

BOX 2.4

# Schwarzschild's equation: solution

$$\bar{I} \equiv 2B \qquad \frac{d\bar{I}}{d\delta} \equiv I \qquad \frac{dI}{d\delta} = 0$$

$$\longrightarrow B \equiv \frac{1}{2} I\delta + B_0$$

$B_0$ is an integration constant

Value of $B$ at $\delta$=0 (TOA)

At **TOA**:

$$I_+ = \frac{1}{4} S_0 (1 - \alpha_p) \equiv Q$$

and

$$I \equiv I_+ - I_- = I_+ = Q$$

$$\frac{dI}{d\delta} = 0 \text{ holds for all optical paths}$$

$$B \equiv \frac{1}{2}(Q\delta + 2B_0) \quad \text{for all } \delta$$

BOX 2.4

## Schwarzschild's equation: upper bc

$\bar{I} \equiv 2B$ → $\bar{I} = I + 2I_{-} \equiv 2B$

$\frac{d\bar{I}}{d\delta} \equiv I$

$\frac{dI}{d\delta} = 0$

at **TOA** this is: $I = 2B$ or $Q = 2B_0$

$B \equiv \sigma T^4 = \frac{1}{2} Q(\delta + 1)$

$B \equiv \frac{1}{2}(Q\delta + 2B_0)$ for all $\delta$

$I = Q$

BOX 2.4

## Skin temperature

**General solution:**

$B \equiv \sigma T^4 = \frac{1}{2} Q(\delta + 1)$ → $T = \sqrt[4]{\frac{Q(\delta+1)}{2\sigma}}$

If $\delta << 1$ then $T = \sqrt[4]{\frac{Q}{2\sigma}} \equiv T_{skin}$

**"skin temperature"**

$T_{skin}$ *is* temperature of the **optically thin stratosphere**

BOX 2.4

# Radiative equilibrium at surface

$$Q + I_- - I_+ = 0$$

upwelling radiation (emitted radiation): $I_+ = \sigma T_S^4$

downwelling radiation (back-radiation)

absorbed solar radiation
(atmosphere is transparent to Solar radiation)

Earth's surface is a black body

We had:

$\bar{I} \equiv 2B = I_+ + I_-$ or $I_- = 2B - I_+$

BOX 2.4

# Radiative equilibrium at surface

So we have:

$Q + I_- - I_+ = 0$

$I_+ = \sigma T_S^4$

$I_- = 2B - I_+$

$\rightarrow Q + 2B - 2\sigma T_S^4 = 0$

and

$$B \equiv \sigma T^4 = \frac{1}{2} Q(\delta + 1) = \frac{1}{2} Q(\delta_s + 1)$$

optical path at earth's surface

at earth's surface

Surface temperature:

$$T_S = \left( \frac{Q(\delta_S + 2)}{2\sigma} \right)^{1/4}$$

Atmospheric temperature, just above surface:

$$T_{Sa} = \left( \frac{Q(\delta_S + 1)}{2\sigma} \right)^{1/4}$$

BOX 2.4

## Radiative equilibrium: full solution

Atmospheric temperature:

$$T = \sqrt[4]{\frac{Q(\delta+1)}{2\sigma}} = T_{skin}(\delta+1)^{1/4}$$

Surface temperature:

$$T_S = \left(\frac{Q(\delta_S+2)}{2\sigma}\right)^{1/4} = T_{skin}(\delta_S+2)^{1/4}$$

Atmospheric temperature, just above surface:

$$T_{Sa} = \left(\frac{Q(\delta_S+1)}{2\sigma}\right)^{1/4} = T_{skin}(\delta_S+1)^{1/4}$$

$$T_S > T_{Sa}$$

*Surface temperature higher than atmospheric temperature near surface*

BOX 2.4

## Radiative equilibrium: full solution

Atmospheric temperature:

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

Surface temperature:

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

$\delta$ is related to height or pressure:

$$-\kappa dz = (\sigma_a q_a / g)dp = d(\sigma_a q_a p / g) \equiv d\delta$$

q is the specific concentration by mass of the absorber

$$\delta = \sigma_a q_a p / g \approx \sigma_a r_a p / g$$

$$\delta_s \approx \sigma_a r_a p_s / g$$

$r_a$ is the mixing ratio by mass of the absorber

BOX 2.4

## Radiative equilibrium: full solution

Atmospheric temperature:

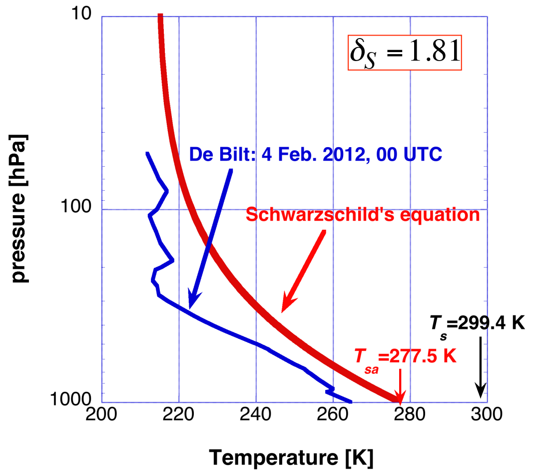
$$T = T_{skin}(\delta+1)^{1/4}$$

Surface temperature:

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

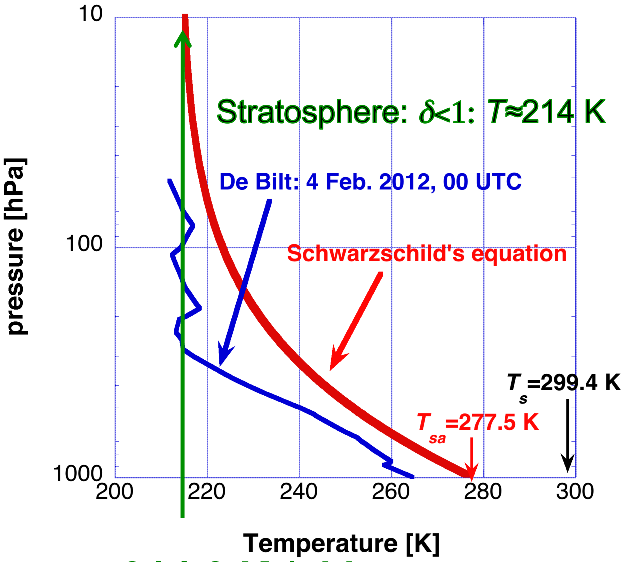
$\sigma_a = 0.3\ \mathrm{m^2 kg^{-1}}$; $r_a = 390$ ppmv

$\alpha_p = 0.3$; $S_0 = 1366\ \mathrm{W\ m^{-2}}$; $p_s = 1000$ hPa




BOX 2.4

## Radiative equilibrium: full solution




**214.2 K (skin temperature)**

**Stratosphere is the optically thin upper part of the atmosphere**

# Assignment 1

**Problem 12.1 HAND IN ANSWER on 30/4**

(study the theory of box 2.4 and chapter 2.4)

http://www.staff.science.uu.nl/~delde102/C&HC.htm

# Next lecture

Wednesday 30/4, 2014, 13:15

*Seasonal cycle of radiative equilibrium and radiatively determined state as a function of latitude, height and time*

*Radiation drives circulation, but circulations also determines radiation: Radiative-dynamical interaction*

http://www.staff.science.uu.nl/~delde102/C&HC.htm