

Climate Dynamics 2012

Lectures given by:

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Assistants:

Wim Ridderinkhof (w.ridderinkhof@uu.nl)



Monday 1100-1245, MIN 205

Wednesday 900-1045, BBL-CLZ 116

Next Wednesday is an oral lecture

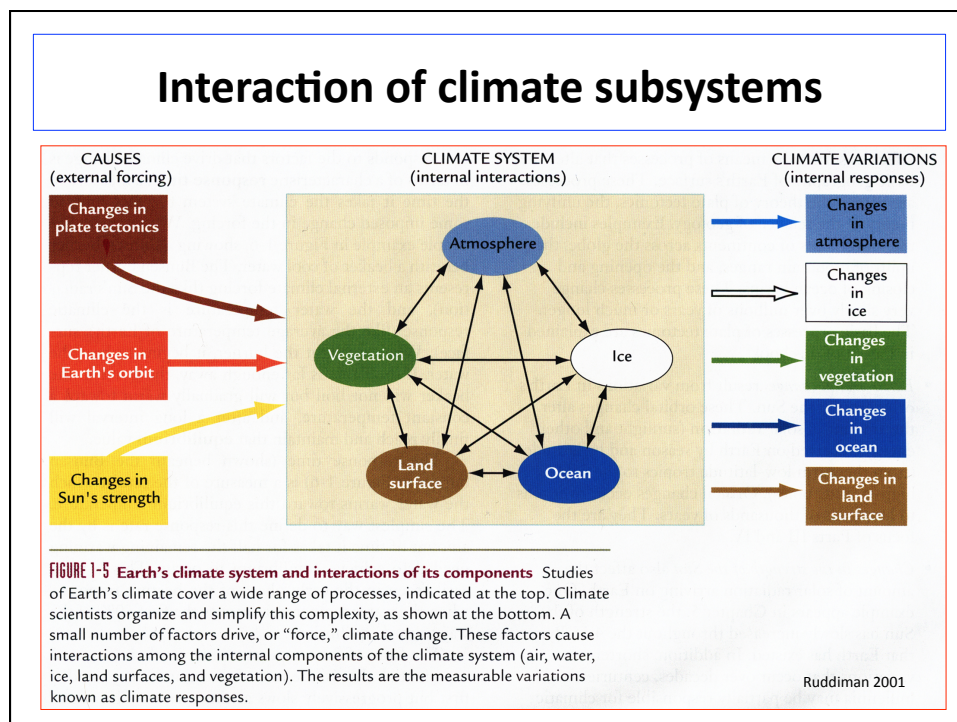
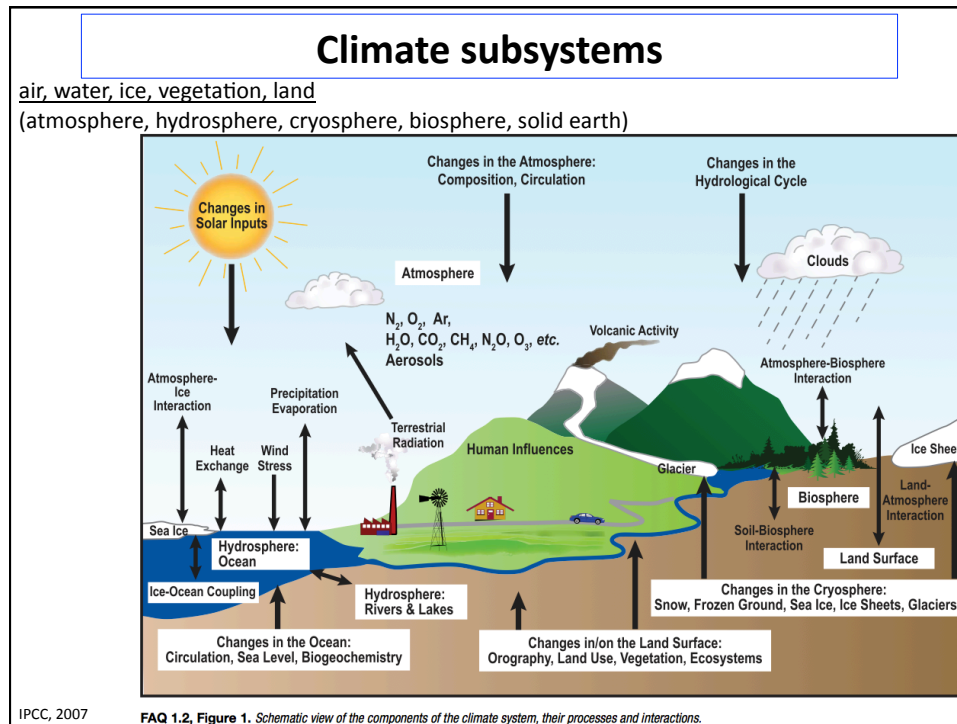
Also next week on both Monday and Wednesday oral lectures!!

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

Climate Dynamics 2012

What do you expect to learn from this course?

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



Climate Dynamics: a broad subject

Based on: meteorology, oceanography, chemistry, astronomy, glaciology, geology, physical geography, biology, biochemistry, hydrology, ... and of course mathematics

Emphasis here is on relatively idealized mathematical (quantitative) **non-linear models** describing interactions of different parts of the climate system, that can be used to address **big questions** of climate science

What determines the temperature distribution in the atmosphere?

What is the role of (1) Solar radiation, (2) ozone, (3) "greenhouse gases", (4) water cycle (clouds) and (4) atmospheric and ocean circulation?

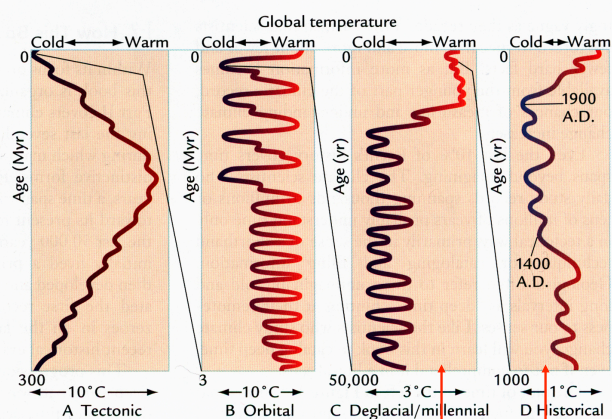
What is the cause of glacial cycles; is the cause "internal" or "external"?

The climate is variable, like the weather

Timescales

Many timescales: tectonic, orbital, deglacial, millennial, historical

FIGURE 1-3 Time scales of climate change Changes in Earth's climate span several time scales, arrayed from longer to shorter: (A) the last 300 million years, (B) the last 3 million years, (C) the last 50,000 years, and (D) the last 1000 years. Here progressively smaller changes in climate at successively shorter time scales are magnified out from the larger changes at longer time scales.



Temperature at Earth's surface

role of oceans?????

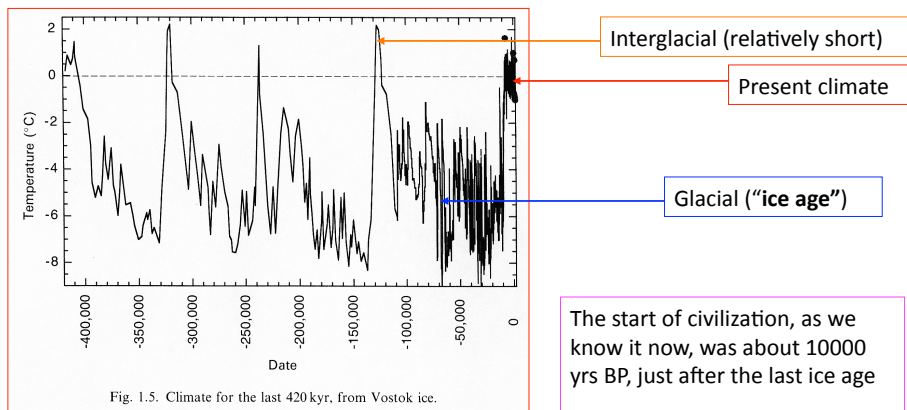
Ruddiman 2001

Themes

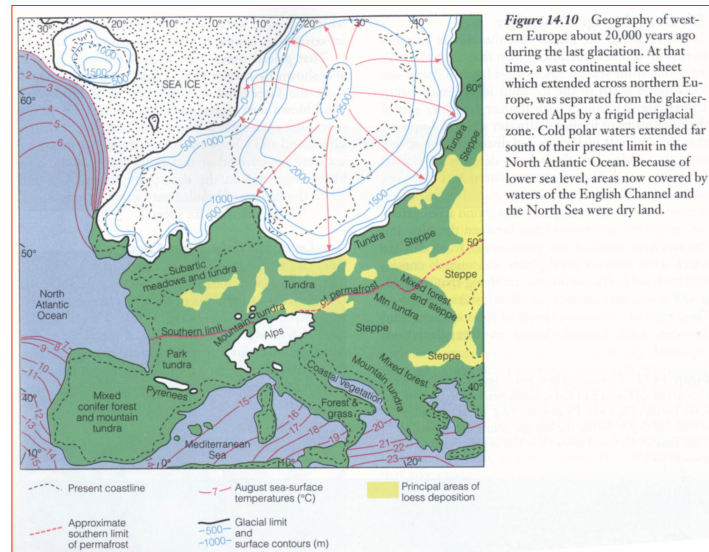
Important themes according to Ruddiman

(W.F. Ruddiman, 2001: Earth's Climate, Past and Future. Freeman and Company, 465 pp.)

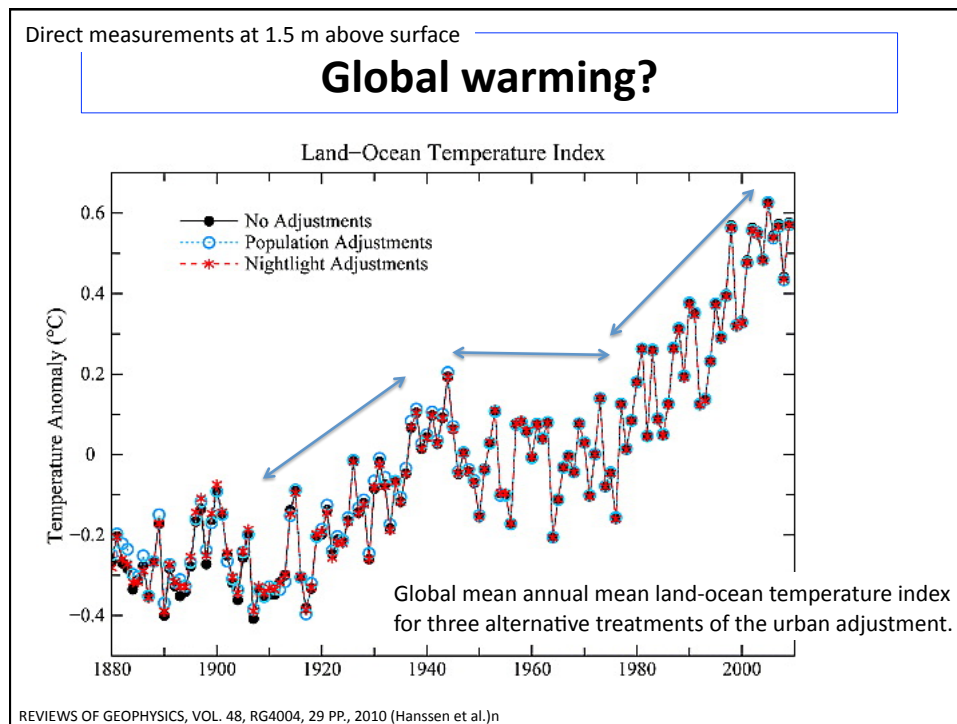
1. Interactions and feedbacks among the many subsystems of earth's climate system
2. The natural response times of these numerous subsystems



Glaciation over Europe 20000 years ago



SPB, 1999



Contents and time table Climate Dynamics

Climate Dynamics (NS-363B) Time Table 2013

Monday: 11:00-12:45, MIN205
Wednesday: 9:00-10:45, BBL CLZ 103/106

Week	Day	Date	Type*	Topic, sections or problems
6	Mon	04/2	HC	<i>Introduction/ Atmospheric Composition</i> , parts of sec. 1.8-1.12 (Aarnout)
6	Wed	06/2	HC	<i>Greenhouse Effect/ Radiation Balance</i> , sections 2.1-2.5 (Aarnout)
7	Mon	11/2	HC	<i>Radiative-Convective Model</i> , sections 2.7-2.9 (Aarnout)
7	Wed	13/2	HC	<i>Energy fluxes associated with the water cycle</i> , sec. 2.10-2.15 (Aarnout)
8	Mon	18/2	WC	problems 2.2, 2.4, 2.6 (Wim)
8	Wed	20/2	WC	Excel problem (computers required) (hand in answers: 27/2) (Wim) ⁺
9	Mon	25/2	HC	<i>Climate sensitivity & radiative forcing</i> , sec. 2.16-2.20 (Aarnout)
9	Wed	27/2	WC	problems 2.9, 2.11 , (Wim) deadline Excel problem (5%)
10	Mon	04/3	HC	<i>Ice-albedo feedback</i> , sec. 2.20-2.22 (Aarnout)
10	Wed	06/3	HC	<i>Energy- and CO₂-budget of Oceans</i> (Aarnout)
				Choose Theme for essay
11	Mon	11/3		no classes
11	Wed	13/3		no classes
12	Mon	18/3	WC	problem 2.15 (computers required) (hand in answers: 27/3) (Niels) ⁺
12	Wed	20/3	HC	<i>History of Earth's climate</i> (Roderik)
13	Mon	25/3	WC	problems 2.16, 2.17 (Wim)
13	Wed	27/3	WC	deadline problem 2.15 (5%)
				Choose theme for presentations
14	Mon	01/4	Easter	
14	Wed	03/4	HC	<i>Paleoclimatological observations 1</i> (Roderik)
15	Mon	08/4	WC	<i>Paleo1</i> (Wim) deadline essay (15%; obligatory) .
15	Wed	10/4		no classes
16	Mon	15/4		Test 1 (09:00-12:00) (25%; minimum grade: 5) (Wim)
16	Wed	17/4		no classes

download from: <http://www.staff.science.uu.nl/~delde102/ScheduleClimateDynamics.pdf>

Contents and time table Climate Dynamics

17	Mon	22/4	HC	<i>Paleoclimatological observations 2</i> (Roderik)
17	Wed	24/4	WC	<i>Paleo2</i> (Wim)
18	Mon	29/4	HC	<i>Ice ages</i> (Roderik)
18	Wed	01/5	WC	<i>Ice ages</i> (Wim)
				deadline problem ice dating (10%)
19	Mon	06/5	HC	<i>Paleoclimate sensitivity</i> (Roderik)
19	Wed	08/5	WC	<i>Paleoclimate sensitivity</i> (Wim)
20	Mon	13/5	HC	<i>Ice in the climate system</i> (Roderik)
20	Wed	15/5	WC	<i>Ice in the climate system</i> (Wim)
21	Mon	20/5	Pentecost	
21	Wed	22/5	HC	<i>Climate Change</i> (Roderik)
22	Mon	27/5	WC	<i>Climate Change</i> (Wim)
22	Wed	29/5	HC	<i>Climate Modelling: from simple to complex GCM's</i> (Aarnout)
23	Mon	03/6	HC	<i>Sea level</i> (Roderik)
23	Wed	05/6	WC	<i>Sea level</i> (Wim)
24	Mon	10/6		Student presentations (15%; obligatory)
24	Wed	12/6		Student presentations
25	Mon	17/6		Student presentations
25	Wed	19/6		Evaluation/Questions
26	Mon	24/6		Test 2 (09:00-12:00) (25%; minimum grade: 5)
26	Wed	26/6		no classes

*HC=lecture; WC= practical
+ computer required; available in both BBL CLZ 103/106 and MIN205

download from: <http://www.staff.science.uu.nl/~delde102/ScheduleClimateDynamics.pdf>

Books used and Internet site

We will follow the following lecture notes*

[AtmosphericDynamics2013ACh1.pdf](#) (Aarnout van Delden) ← Lecture 1

[AtmosphericDynamics2013ACh2.pdf](#) (Aarnout van Delden) ← Lectures 2 to 7

History of climate and ice ages (Roderik van de Wal)

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

Other books

Archer, D., 2007: **Global warming: understanding the forecast**. Blackwell Publishing Ltd., 194 pp.

Hartmann, D.L., 1994: **Global Physical Climatology**. Academic Press, 408 pp.

Ruddiman, W., 2001, 2007: **Earth's climate: past and future**. W.H. Freeman and company. 465 pp.

Taylor, F.W., 2010: **Planetary Atmospheres**. Oxford University Press, 261 pp.

and many more... see lecture notes

Internet site

<http://forecast.uchicago.edu/lectures.html> (David Archers lecture series on Climate are warmly recommended)

Information from internet sites

<http://forecast.uchicago.edu/lectures.html> (David Archers lecture series on Climate are warmly recommended)
<http://www.aip.org/history/climate/> (a very good account of the history of the discovery of the greenhouse effect)
<http://www.cpc.ncep.noaa.gov/> (climate information from the American National Weather Service)
<http://www.realclimate.org/> (discussions on issues related to climate research)
<http://www.staff.science.uu.nl/~delde102/climatedynamics.htm> (information about the course on Climate Dynamics at Utrecht University, NS363B)
<http://www.staff.science.uu.nl/~delde102/AtmosphericDynamics.htm> (information about the lecture notes)
<http://www.ipcc.ch> (IPCC report on Climate Change (2007))
http://www.ecmwf.int/research/era/ERA-40_Atlas/index.html (climate atlas)
<http://ds.data.jma.go.jp/gmd/jra/atlas/eng/atlas-tope.htm> (climate atlas)
http://oceanworld.tamu.edu/resources/ocng_textbook/PDF_files/book_pdf_files.html
<http://www.realclimate.org/>
<http://www.faqs.org/faqs/sci/climate-change/basics/>
<http://nsidc.org/cryosphere/index.html>
<http://earthobservatory.nasa.gov/>
<http://www.windows.ucar.edu/tour/link=/earth/climate/climate.html&edu=high>
<http://www.cpc.ncep.noaa.gov/>

Information from internet sites

http://en.wikipedia.org/wiki/Main_Page
<http://en.wikipedia.org/wiki/Climate>
http://en.wikipedia.org/wiki/Category:Atmospheric_radiation
http://en.wikipedia.org/wiki/Category:Climate_change_feedbacks_and_causes
http://en.wikipedia.org/wiki/Category:History_of_climate
<http://en.wikipedia.org/wiki/Paleoclimatology>
http://en.wikipedia.org/wiki/Atmospheric_circulation

http://oceanworld.tamu.edu/resources/ocng_textbook/PDF_files/book_pdf_files.html
<http://www.realclimate.org/>
<http://www.faqs.org/faqs/sci/climate-change/basics/>
<http://nsidc.org/cryosphere/index.html>
<http://earthobservatory.nasa.gov/>
<http://www.windows.ucar.edu/tour/link=/earth/climate/climate.html&edu=high>
<http://www.cpc.ncep.noaa.gov/>

And many more!

Grade

3 exercises (*energy balance, radiation model and ice dating*) **(20%)**

Presentation on a “hot topic” in climate research **(15%)** (*in couples*)

Write a short (1000 words) **essay** based on a recently published research paper **(15%)**

2 exams (50%) (*grade should be 5/10 or more for both exams!!*)

What do you know about climate?

Background (physics, earth sciences, mathematics?)

Knowledge of the atmosphere and the oceans?
(have you done first and second year courses?)

First half of the lecture series about:

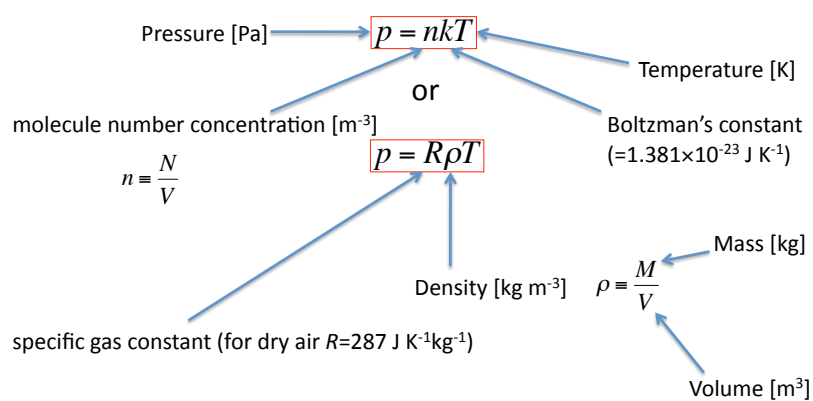
The atmosphere

Composition (greenhouse gases)
 greenhouse effect
 Radiative equilibrium
 Radiative-convective equilibrium
 Absorption & emission characteristics
 Climate sensitivity: role of
 infrared window, water vapour, clouds, ice/snow

The Ocean

Meridional overturning circulation
 CO₂-budget

Atmosphere of Earth as a mixture of gases that can be described by the *ideal gas law*



Concentration by volume

$$V = \frac{NkT}{p}$$

Volumes (V) occupied by different gases at the same temperature and pressure are proportional to the numbers of molecules of the gases (N)

molecule number concentration of carbon dioxide [m^{-3}]

number fraction: $\frac{n_{\text{CO}_2}}{n_a} = \frac{p_{\text{CO}_2}}{p_a}$

$p = nkT$ is also called concentration by volume

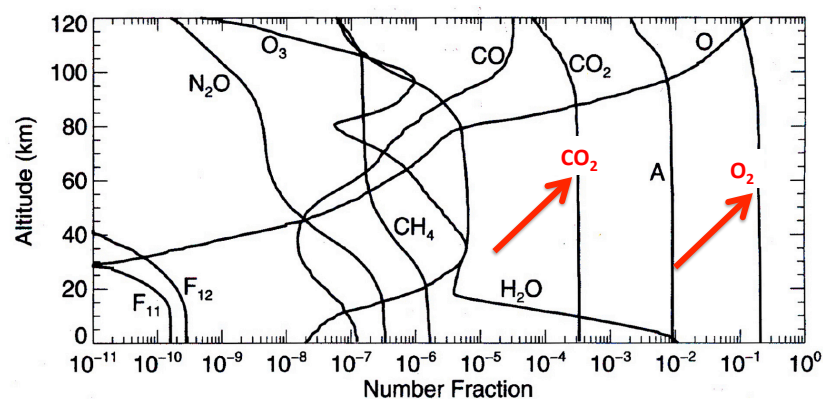
partial pressure exerted by CO_2

molecule number concentration of atmosphere [m^{-3}]

Present (december 2010) CO_2 -concentration is about 0.000390, or 390 ppmv (**parts per million by volume**)

Section 1.8

Present composition of the atmosphere



Oxygen, nitrogen and carbon dioxide are **well mixed** (concentration constant with height)

Carbon dioxide concentration through the ages

Warm Middle Cretaceous, 100 MA BP

3900 ppmv! →

Now: 390 ppmv

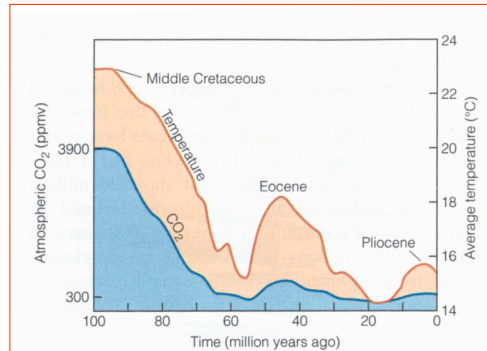
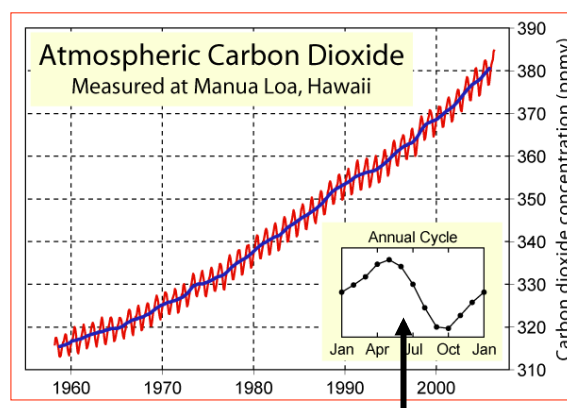


Figure 14.19 A geochemical reconstruction of changing atmospheric CO₂ concentration and average global temperature over the past 100 million years. High CO₂ values and high temperatures in the Middle Cretaceous contrast with much lower modern values. Other intervals of higher temperature and CO₂ occurred during the Eocene and the Middle Pliocene.

SPB, 1999

Past 60 years

Carbon dioxide in the atmosphere

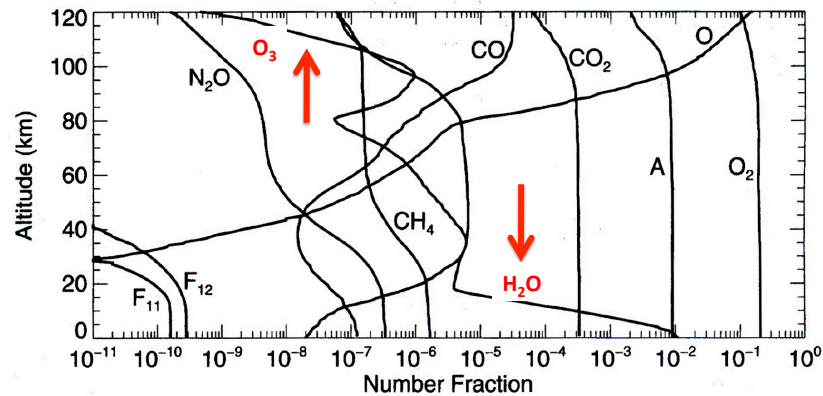


Seasonal cycle determined by biosphere!

http://en.wikipedia.org/wiki/Carbon_dioxide
<http://www.esrl.noaa.gov/gmd/>

Section 1.8

Present composition of the atmosphere



Ozone and water vapour are not well mixed
(concentration not constant with height)

Radiosonde observation network

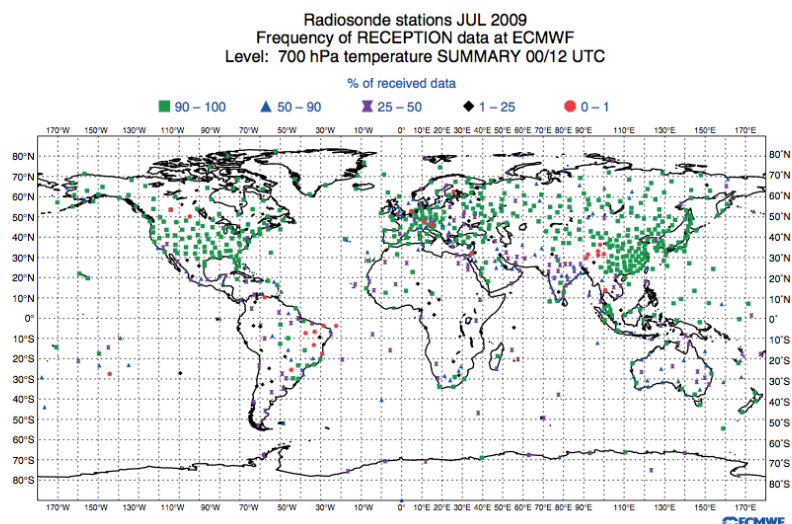


FIGURE 2 | Radiosonde station reporting performance, based on percentage of complete twice-daily coverage in July 2009 by the European Centre for Medium-Range Weather Forecasts. The poorer performance away from Northern Hemisphere mid-latitudes is typical of both contemporary and historical patterns. Figure courtesy of Antonio Garcia-Mendez and ©ECMWF.

Section 1.8

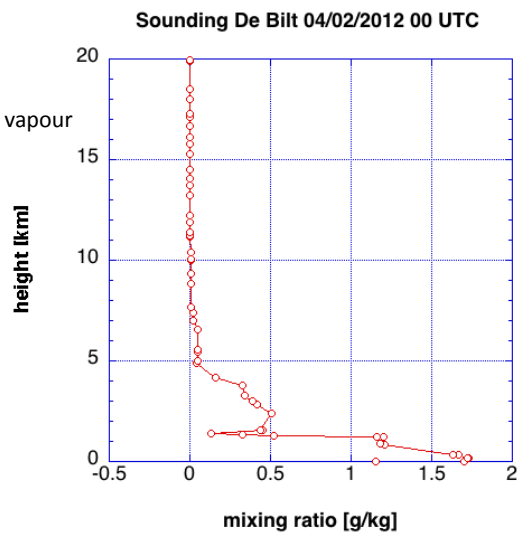
Mixing ratio=concentration by mass

water vapour:

$$r_v = \frac{\rho_v}{\rho_d}$$

density of water vapour

density of dry air

Section 1.8 *Mixing ratio depends on temperature through the Clausius-Clapeyron relation*

Temperature

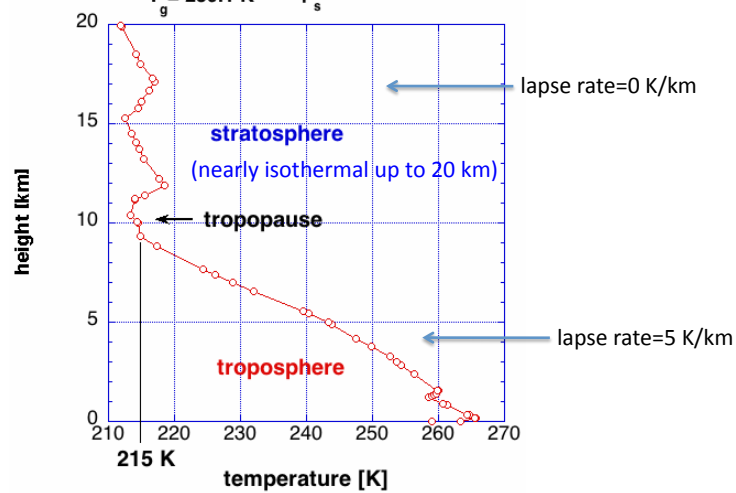
Sounding DeBilt 04/02/2012 00 UTC

$RH_g = 93\%$

$PW = 3.58 \text{ kg m}^{-2}$

$T_g = 259.1 \text{ K}$

$p_s = 1040 \text{ hPa}$



Section 1.9

Water vapour distribution: related to

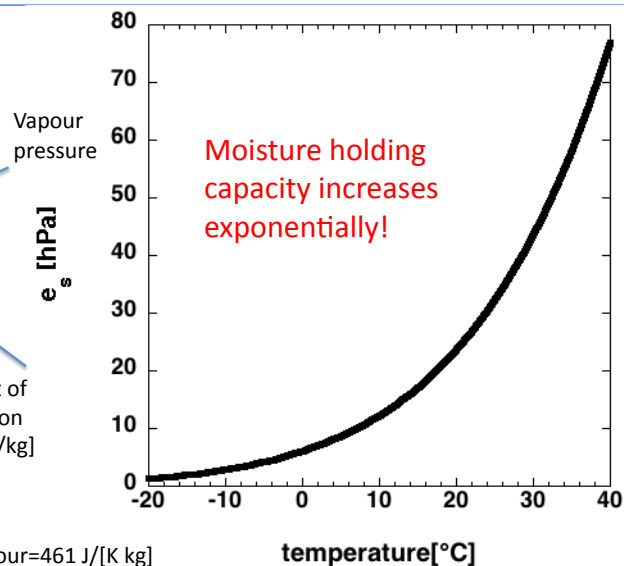
Clausius Clapeyron equation

Equation of state for water vapour for a system in equilibrium consisting of vapour and liquid:

$$\frac{\partial \ln e_s}{\partial T} = \frac{L_v}{R_v T^2}$$

Latent heat of condensation
[2500000 J/kg]

Specific gas constant water vapour=461 J/[K kg]



Section 1.10

Vertical distribution of humidity in the atmosphere

$$T(z) = T_g - \Gamma z$$

lapse rate

$$\rho_v \propto \exp\left(-\frac{L_v \Gamma}{R_v T_g^2} z\right)$$

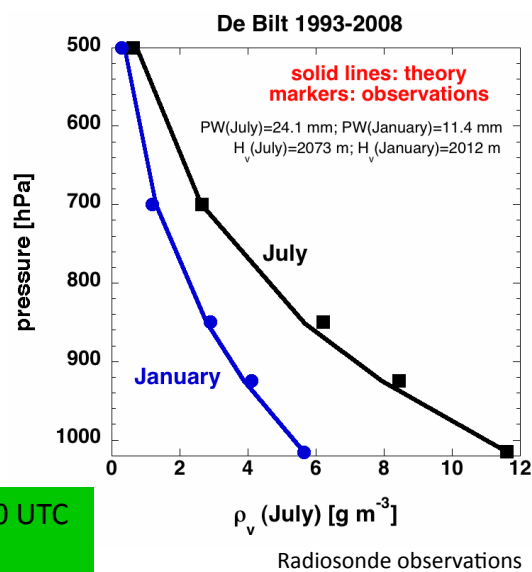
"Scale height" for water vapour:

$$H_v = \frac{R_v T_g^2}{L_v \Gamma}$$

In general:

$$\rho_v = \rho_{v,g} \exp\left(-\frac{z}{H_v}\right)$$

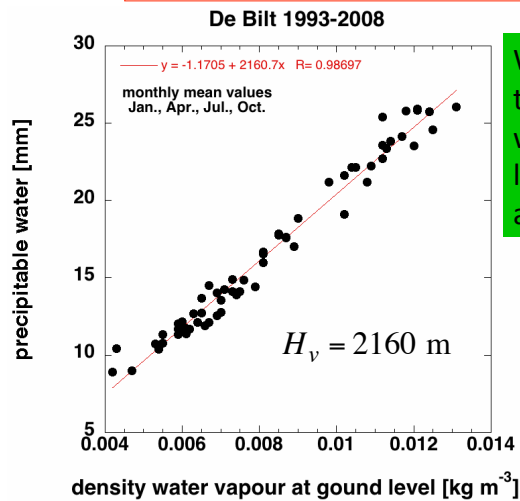
Compute H_v for 4 feb 2012 00 UTC over the De Bilt



Section 1.10

Precipitable water (PW) and surface humidity

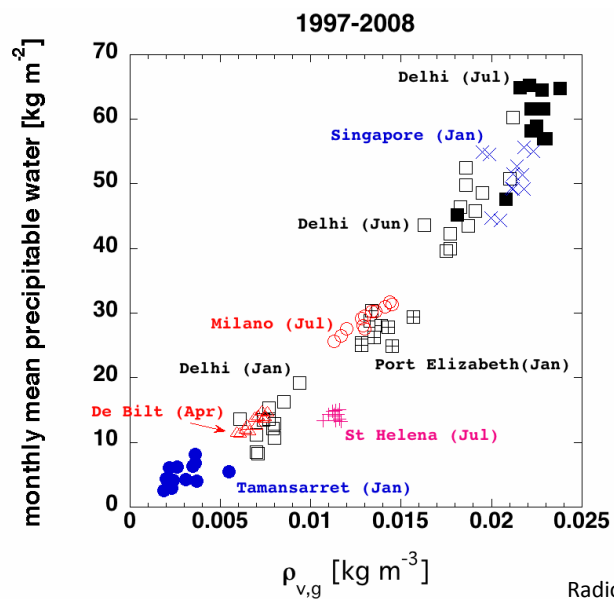
$$PW = \int \rho_v dz = \int \rho_{v,g} \exp\left(-\frac{z}{H_v}\right) dz = \rho_{v,g} H_v$$



What percentage of the total column precipitable water is contained in the layer between the ground and $z=H_v$?

Radiosonde observations

Section 1.10

Precipitable water (PW) and surface humidity

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

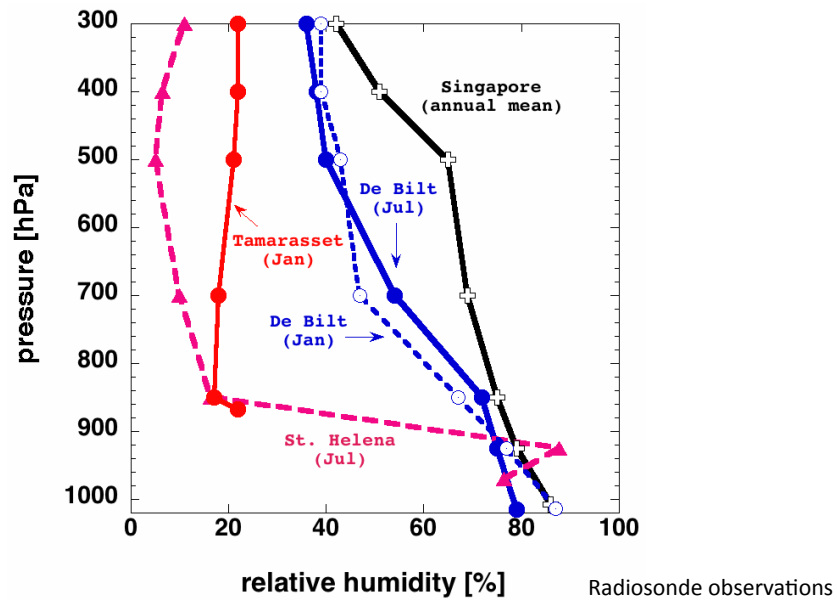
Is this equation applicable in the case of the sounding of 4 February 2012 in De Bilt (see previous slide)?

Radiosonde observations

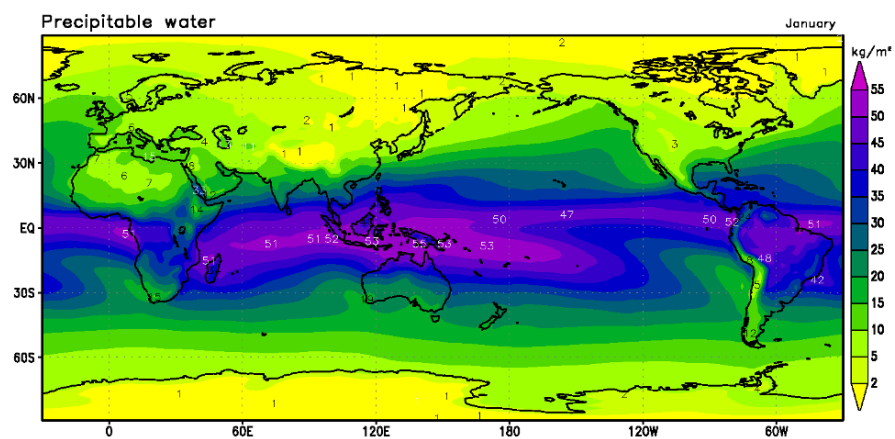
Section 1.10

Relative humidity

$$RH = \frac{e}{e_s}$$



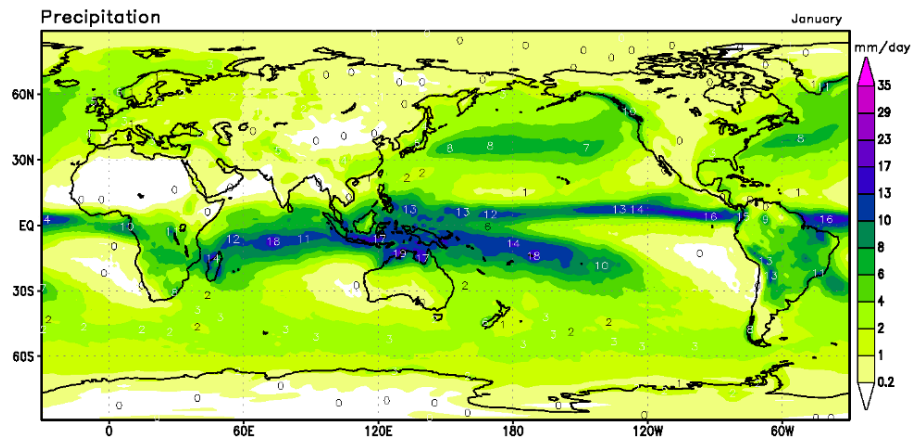
Section 1.11

Precipitable water (*PW*)

Japanese reanalysis (1979-2004)

Section 1.11

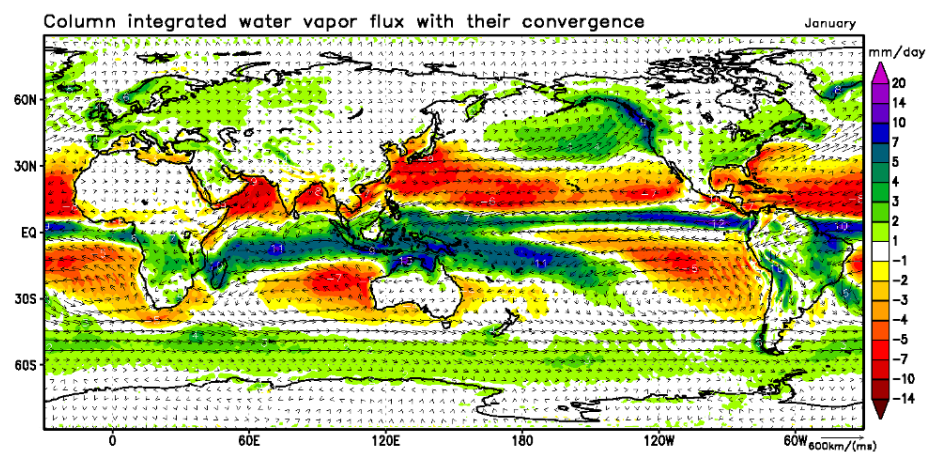
Precipitation



Japanese reanalysis (1979-2004)

Section 1.11

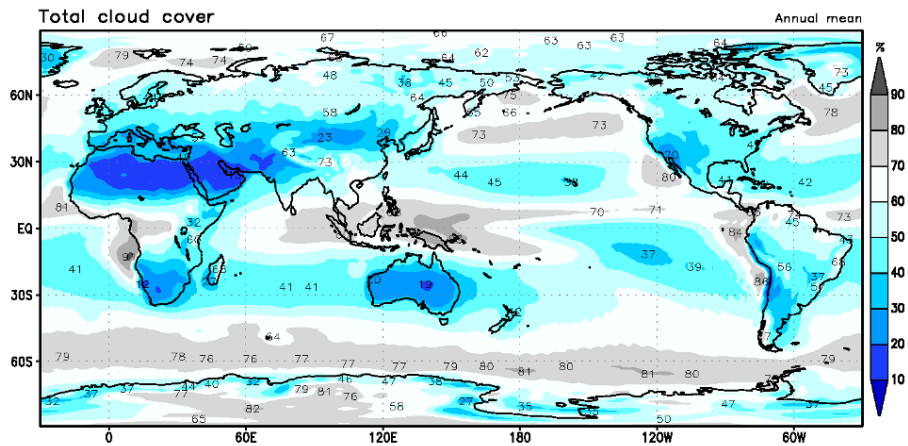
Water vapour flux



Japanese reanalysis (1979-2004)

Section 2.12

Cloud cover



Average annual cloud according to the reanalysis of the Japan Meteorological Agency. Labels in %. Average is for the period 1979-2004. Source: http://jra.kishou.go.jp/JRA-25/index_en.html

Figure 2.37

According to **Halley (1689)** and **Hadley (1735)**

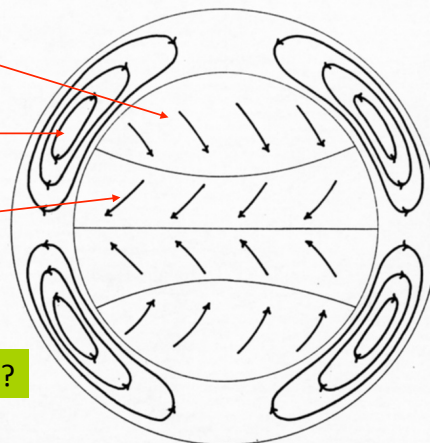
The zonal mean meridional atmospheric circulation

E.N. Lorenz (1967)

westerlies

"Hadley cell"

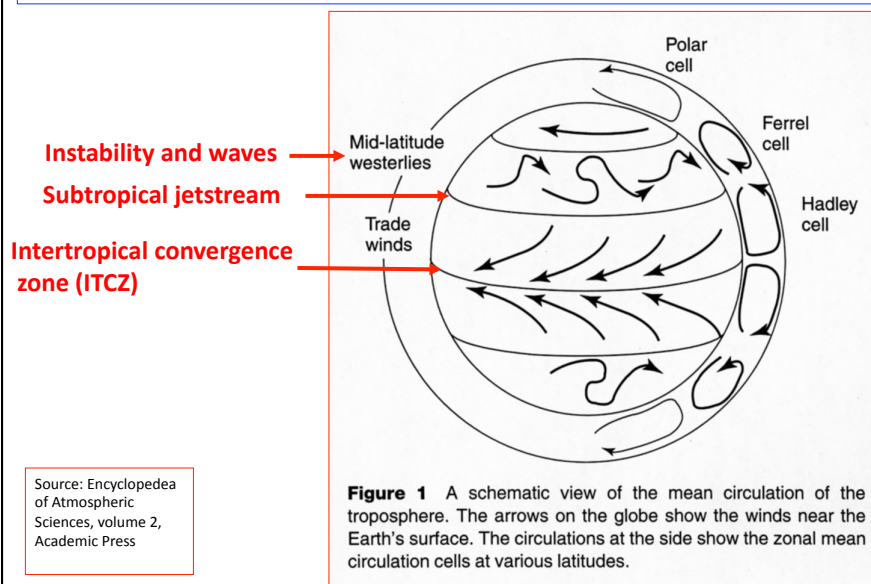
easterlies



What is wrong with this picture?

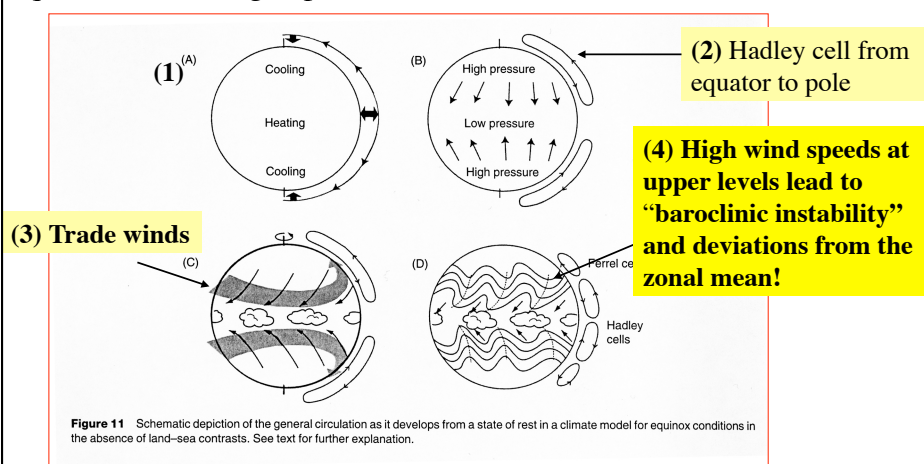
Figure 30. — A schematic representation of the general circulation of the atmosphere as envisioned by Hadley (1735)

Zonally symmetric circulations: present view



How is this situation established?

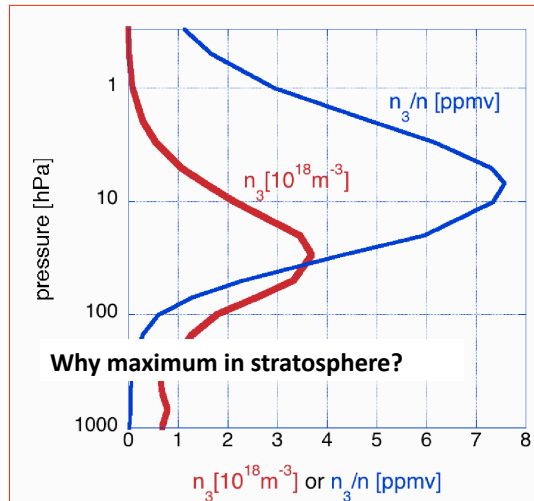
Thought experiment: initially atmosphere is at rest; then heating at the equator and cooling at poles (1)



Where is the ozone layer?

Globally averaged ozone distribution

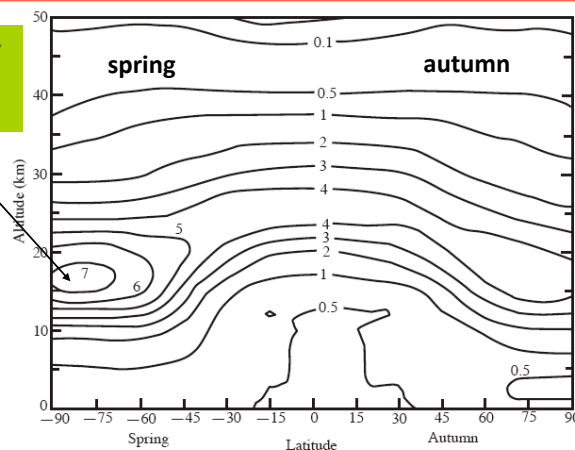
Time average (based on measurements made between 1980 and 1991), **global average ozone molecule number concentration** (n_3) and **ozone mixing ratio** (n_3/n) (n is the total molecule number concentration of air). Source: J.P.F Fortuin and H. Kelder, 1998: An ozone climatology based on ozonesonde and satellite measurements. *J. Geoph. Res.*, **103**, 31709-31734.



(fig. 2.34 lecture notes)

Why is there ozone in the stratosphere?

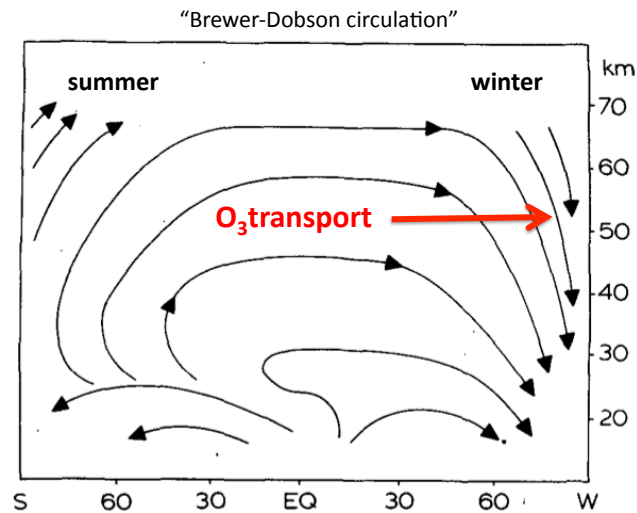
Most ozone over winter pole why (?)



Jacob, 1999 (p.170)

Figure 10-1 The natural ozone layer: vertical and latitudinal distribution of the ozone number density (10^{12} molecules cm^{-3}) at the equinox, based on measurements taken in the 1960s. From Wayne, R.P., *Chemistry of Atmospheres*, Oxford, 1991.

Mean circulation in the stratosphere and ozone transport to the pole



Dunkerton, 1978: *J.Atmos.Sci.*, 35, p.2330

What have we done today?

Monday February 4, 2013, 11:00-11:45

Introduction
 Equation of state
 Clausius-Clapeyron equation
 Composition of the atmosphere
 Water vapour- and cloud-distributions
 Ozone distribution
 General circulation

(sections 1.8-1.11 lecture notes)

In the coming weeks we will discuss each term in the diagram below in detail

Energy fluxes (2000-2004)

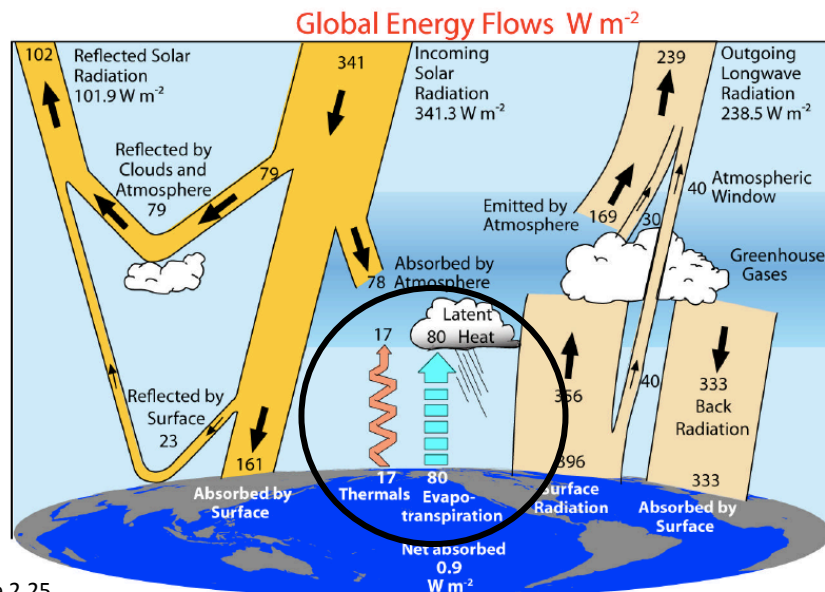


Figure 2.25

Next lecture

Wednesday February 6, 2013, 9:00-10:45, BBG, CLZ 103/106

Black body and Planck's law (*Box 1.3*)
Short- (Solar) and long-wave radiation
Bouguer-Lambert-Beer law
Absorption coefficient
Schwarzschild's equation
Radiation balance
Greenhouse effect
Introduction to radiative convective model

(sections 2.1-2.7; boxes 2.1-2.3)