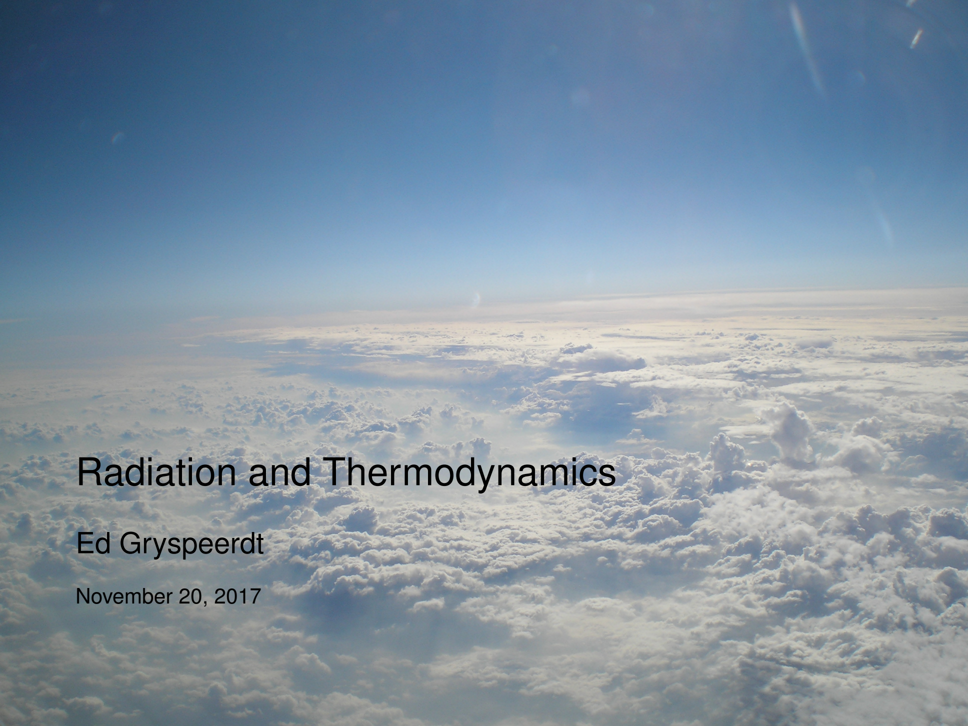


Radiation and Thermodynamics

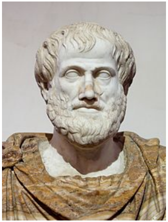
Ed Gryspeerdt

November 20, 2017

Learning outcomes

- Be able to calculate an approximate atmospheric temperature structure
- Be able to identify the important and uncertain components of the Earth's energy budget
- Understand the role of clouds in modifying radiation

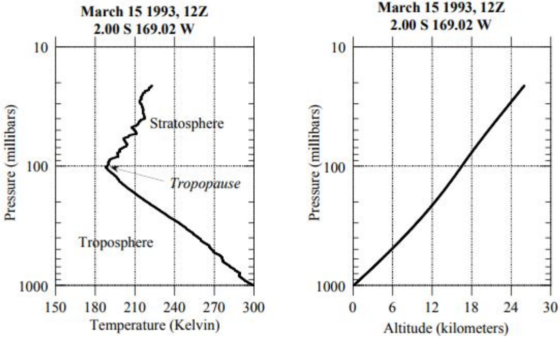
Ancient knowledge



"Why are clouds not formed in the upper air? They ought to form there the more, the further from the earth and the colder that region is."
"So we must take the reason why clouds are not formed in the upper region to be this: that it is filled not with mere air but rather with a sort of fire."

— Aristotle - Meteorologica ($\sim$350 BC)

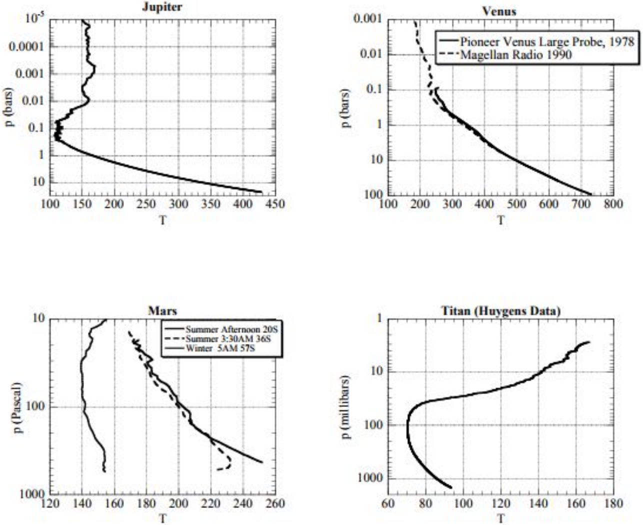
The atmospheric temperature structure



Key points:

- Warmer at the surface
- Coldest at tropopause (≈190K)
- Warms in stratosphere
- Pressure decreases with altitude (logarithmic)
- Troposphere cools nearly linearly with altitude

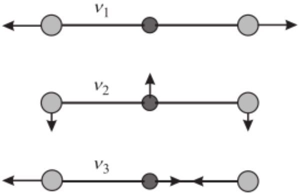
Other planets



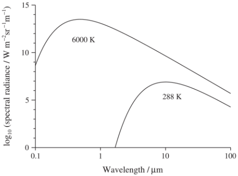
This pattern is remarkably similar on other planets - similar physics is involved!

Matter and radiation

- A material absorbs photons of specific frequency



  - They must line up with an absorption line, corresponding to a difference between molecular energy levels
  - It is essentially transparent to other frequencies
- A material can scatter photons
  - For small particles, this is Rayleigh scattering
  - Scattering proportional to λ^{-4}
- A material can emit photons



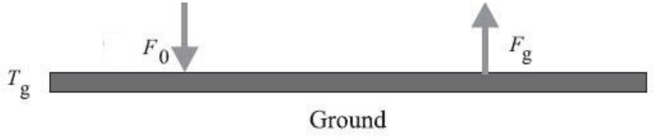
  - If it is a black body, it emits only as a function of it's temperature
  - The emissions spectrum is given by the Planck function (B(T))
  - Integrated over all wavelengths, it gives $F = \sigma T^4$

What temperature should a planet be?

Assuming:

- The temperature of the planet is constant (it is in equilibrium)
- The star/sun is the only source of energy (no internal heat source)
- The planet only loses energy by radiating to space

The incoming solar radiation must balance the rate of cooling to space.



Andrews, 2010

What temperature should a planet be?

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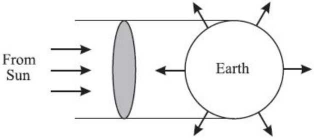
The incoming solar radiation must balance the rate of cooling to space.

How much energy does a planet receive per unit area?

- S_0 - The solar constant
- α - The bond albedo
- R_E - The radius of the planet/Earth



$$\frac{S_0 \pi R_E^2 (1-\alpha)}{4\pi R_E^2} = \frac{S_0(1-\alpha)}{4}$$

Andrews, 2010

What temperature should a planet be? (2)

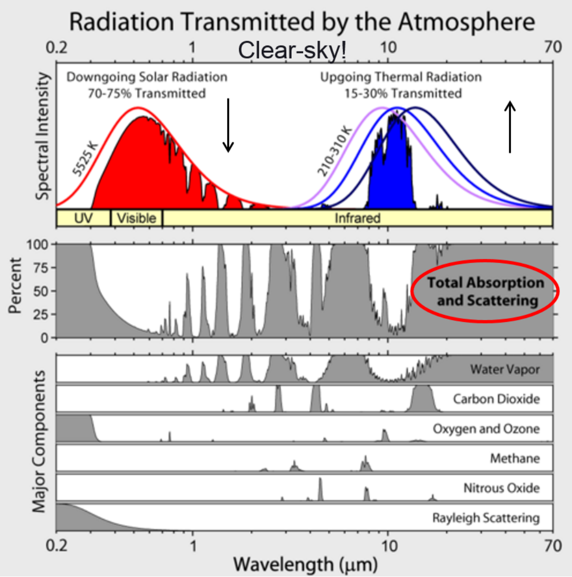
Assuming the planet is a black body, emission to space is σT_E^4
For Earth, this gives a T_E (“emitting temperature”) of

$$\frac{S_0(1-\alpha)}{4} = \sigma T_E^4$$
$$255K = T_E$$

Planet	$S_0(Wm^{-2})$	α	$T_E(K)$	$T_{surf}(K)$	$p_{surf}(atm)$
Earth	1368	0.3	255	288	1
Venus	2660	0.75	230	730	90
Mars	597	0.25	209	218	0.006
Mercury	8550	0.1	437	440	0

An atmosphere clearly plays a role

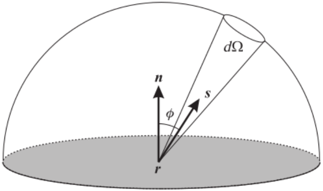
Atmospheric Composition



- Two main classes of photon in the atmosphere, visible and thermal
- Most visible photons are transmitted, most thermal ones are absorbed

Definitions

- Spectral radiance (L_ν) - the power per unit area, per unit solid angle, per unit frequency interval at **r** in direction **s**
- Radiance (L) - Spectral radiance integrated over frequency
- Irradiance (F) - Radiance integrated over all solid angles (flux per unit area)



For a plane surface emitting black body radiation ($L_\nu = B_\nu(T)$)

$$F(r,n) = \int_0^\infty \int_{2\pi} L_\nu n \cdot s d\Omega d\nu = \int_0^\infty \pi B_\nu(T) d\nu = \sigma T^4$$

Radiation and the atmosphere

There are three components to the radiance in the atmosphere

1) Direct beam:

Beer-Lambert for radiation passing through a medium:

$$dL_\nu = -L_\nu \sec\Theta dz \rho k_\nu^e$$

k_ν^e is the mass extinction coefficient - the sum of absorption and scattering by the medium

$$k_\nu^e = k_\nu^a + k_\nu^s$$

The ratio $k_\nu^s / k_\nu^e = \omega_\nu$ is the single scattering albedo

Integrating Beer-Lambert to depth D

$$L_\nu^D = L_\nu^{TOA} exp(-\int_{TOA}^{D} \rho \sec\Theta k_\nu^e dz) = L_\nu^{TOA} exp(-\tau_\nu)$$

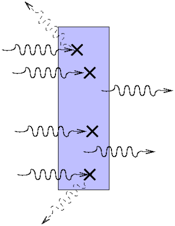
Where τ_ν is the “optical depth” $(= \int \sec\Theta \rho k_\nu^e dz = \frac{D}{\lambda_{mean}})$

Optical depth

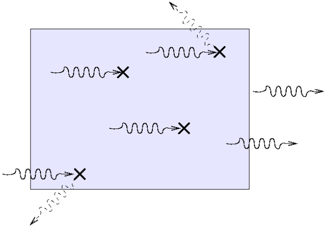
Optical depth combines information on:

- Layer size
- Density
- Opacity

It is the width of a material in units of “photon mean free paths”



Thin but dense material (τ)



Thick but tenuous (also τ)

Images from Michael Richmond

Atmospheric interactions (II)

2) Emitted energy

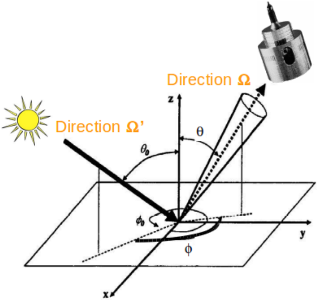
$$dL_\nu = J_\nu k_\nu^a \rho \sec\Theta dz$$
$$dL_\nu = B_\nu(T) k_\nu^a \rho \sec\Theta dz (\text{In LTE})$$

3) Radiation scattered into the incident direction
Need to know the "phase function" $P(\Omega, \Omega')$ - how light is scattered from angle Ω to Ω'. It is generally normalised such that

$$\frac{1}{4\pi}\int_{4\pi} P(\Omega, \Omega') d\Omega' = 1$$

Such that the scattering source term is

$$J_{s\nu} = \frac{\omega_\nu}{4\pi}\int_{4\pi} L_\nu(\Omega') P(\Omega, \Omega') d\Omega'$$



Atmospheric interactions (II)

The direct, emitted and scattered components together lead to the “radiative transfer equation”

$$\frac{dL_\nu}{d\tau_\nu} = -L_\nu + (1-\omega_\nu)B_\nu(T) + \frac{\omega_\nu}{4\pi}\int_{4\pi} L_\nu(\Omega')P(\Omega,\Omega')d\Omega'$$

To first order

- Solar - thermal emission is small
- Thermal radiation - scattering is small ($\omega_\nu = 0$)

For the thermal radiation case:

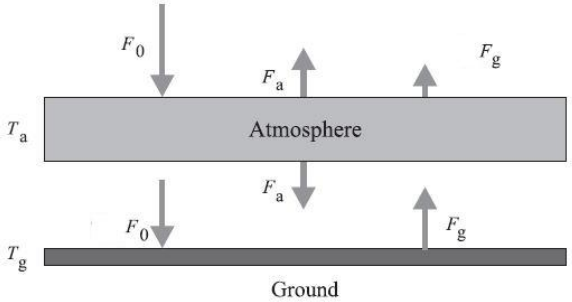
$$dL_\nu = -[L_\nu - B_\nu(T)]d\tau_\nu \text{(Schwarzschild's equation)}$$

$$\frac{d(e^{\tau_\nu}L_\nu)}{d\tau_\nu} = e^{\tau_\nu}B_\nu(T)$$

$$L_\nu(s) = L_\nu(0)e^{-\tau_\nu(s)} + \int_0^{\tau_\nu(s)} B_\nu[T(\tau'_\nu)]e^{-(\tau_\nu(s)-\tau'_\nu)}d\tau'_\nu$$

Energy balance with an atmosphere

Let's add an atmosphere that is transparent to visible light but absorbs thermal radiation.



$$F_0 = F_a = \sigma T_a^4$$
$$F_0 + F_a = F_g$$
$$2F_a = F_g$$

Using values appropriate for Earth, this gives $T_g \approx 300K$

(It is coincidental that the result is so close for Earth - try it for Venus!)

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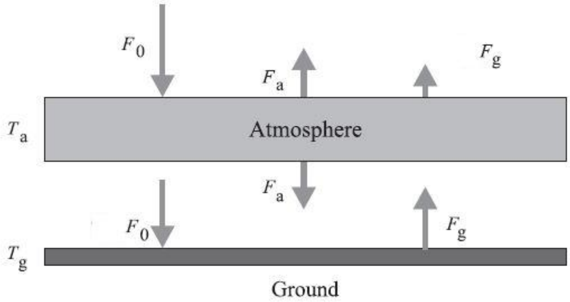

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Using values appropriate for Earth, this gives $T_g \approx 300K$

Is a single temperature for the atmosphere plausible?

(It is coincidental that the result is so close for Earth - try it for Venus!)

Radiative equilibrium

How about a continuous atmosphere in radiative equilibrium (no heating)?

- Multiple layers, thickness dτ

$$dL_\nu = -[L_\nu - B_\nu(T)]d\tau_v$$

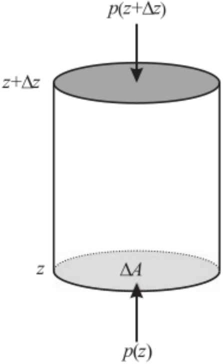
$$\begin{aligned} -\frac{dF^\uparrow}{d\tau^*} &= -F^\uparrow + \pi B(T) \\ \frac{dF^\downarrow}{d\tau^*} &= -F^\downarrow + \pi B(T) \\ F_z &= F^\uparrow - F^\downarrow = \mathrm{const.} = F_0 \end{aligned}$$

τ^* is the scaled optical depth (takes into account non-vertical path length)

$$d\tau = k\rho sec\theta dz$$

How are gases distributed?

If the atmosphere is at rest, the forces must balance (known as hydrostatic equilibrium)



$$g\rho\Delta A\Delta z = p(z)\Delta A - p(z+\Delta z)\Delta A$$

$$p(z+\Delta z) \approx p(z) + \frac{dp}{dz}\Delta z$$

$$g\rho = -\frac{dp}{dz}$$

Pressure scale height

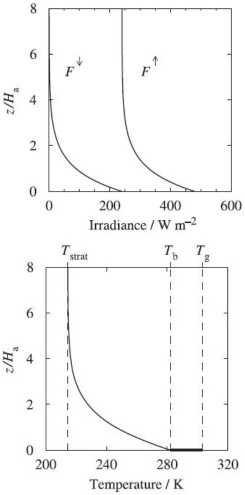
If the atmosphere is an ideal gas $p = \rho RT$

$$\frac{dp}{dz} = -g\rho$$
$$\frac{dp}{dz} = -\frac{gp}{RT}$$

For a constant temperature:

$$\int_{p_0}^{p} \frac{dp'}{p'} = -\int_{0}^{z} \frac{g}{RT} dz'$$
$$p = p_0 e^{-gz/RT}$$
$$p = p_0 e^{-z/H}$$
$$\rho = \rho_0 e^{-z/H}$$
$$H = R_a T/g \approx 8km$$

Radiative equilibrium



After a bit of maths, we get (assuming an absorber scale height of H_a)

$$T(z) = \left[\frac{F_0}{2\sigma}\left(1 + \tau_g^* e^{-z/H_a}\right)\right]^1 /4$$

$$T(\text{bottom of atm}) = T_E \left(\frac{1 + \tau_g^*}{2}\right)^{1/4}$$

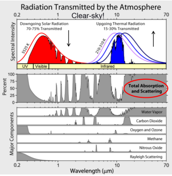
$$T(\text{ground}) = T_E \left(\frac{2 + \tau_g^*}{2}\right)^{1/4}$$

What happens when you have a temperature discontinuity in the atmosphere?
Is warm air at the bottom stable?

(see Andrews, Intro to Atmospheric Physics, p83)

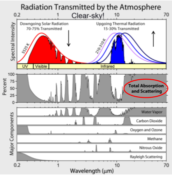
Summary

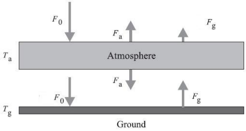
- The atmosphere is mostly transparent to visible light and absorbs thermal IR



Summary

- The atmosphere is mostly transparent to visible light and absorbs thermal IR
- The emitting temperature of a planet is usually colder than the surface temperature
    - An atmosphere is required (except for Mercury...)
    - The temperature structure of the troposphere is not determined by radiative balance





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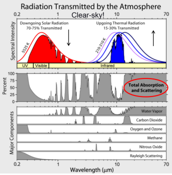
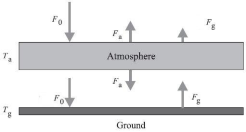
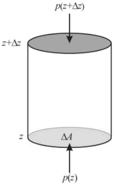
- The atmosphere is mostly transparent to visible light and absorbs thermal IR
- The emitting temperature of a planet is usually colder than the surface temperature
    - An atmosphere is required (except for Mercury...)
    - The temperature structure of the troposphere is not determined by radiative balance
- The pressure in the atmosphere decreases exponentially







Potential temperature

What happens when you move air vertically?

- As the pressure goes down, an air parcel expands and cools.
- We want a "temperature" that is independent of this

From the first law of thermodynamics

$$dU = dQ - dW \rightarrow dQ = dU + pdV$$
$$dQ = c_p dT - Vdp$$

If adiabatic (dQ = 0) and an ideal gas (p=ρRT)

$$c_p dT - Vdp = 0 \rightarrow \frac{c_p}{R_a} \int_{\Theta}^{T} \frac{dT}{T} = \int_{p_s}^{p} \frac{dp}{p}$$
$$\Theta = T(\frac{p_0}{p})^{\kappa}, \kappa = \frac{R_a}{c_p}$$

Θ is the potential temperature.

Dry adiabatic lapse rate

If air is moved adiabatically, dΘ = 0

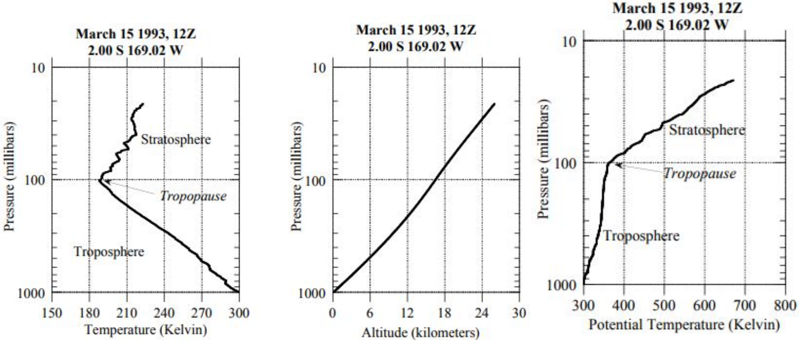
- What temperature profile would this produce?

Potential temperature is conserved

$$\begin{aligned} \frac{d\Theta}{dz} &= 0 \\ \rightarrow -\frac{dT}{dz} &= \frac{g}{c_p} = \Gamma_d = 9.8 Kkm^{-1} \end{aligned}$$

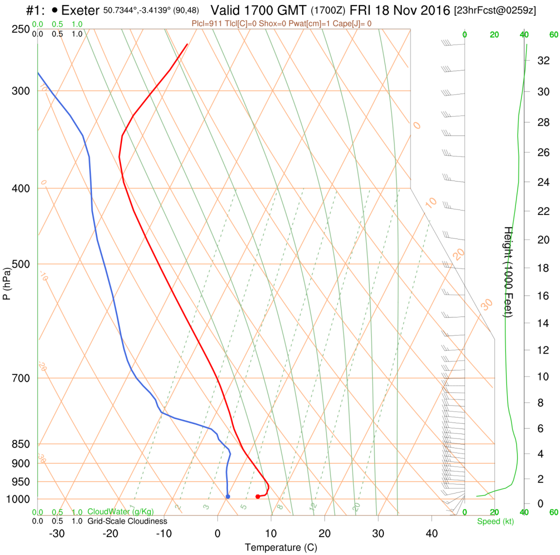
This is the “dry adiabatic lapse rate” - DALR

Potential temperature sounding



- Temperature decreases with altitude
- Potential temperature increases with altitude!
  - Hot air over cold air

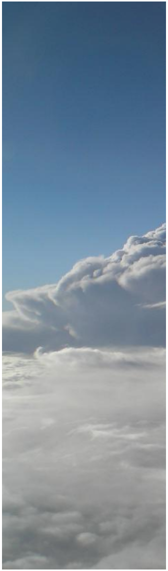
Does it ever occur?



- Model simulated sounding from Exeter
- Orange lines sloping up to the left are dry adiabats
- Red line is temperature profile

What about water?

- A parcel of air cools as it rises
  - This increases the relative humidity
- When the parcel reaches saturation, water condenses
  - This heats the parcel (reducing the lapse rate)
- The temperature drop with height is reduced
  - $\Gamma_s \approx 6\text{-}9\,\mathrm{K\,km^{-1}}$
- If the condensed water falls out (precipitation)
  - Water carries only a small amount of heat
  - This is near (or pseudo) adiabatic



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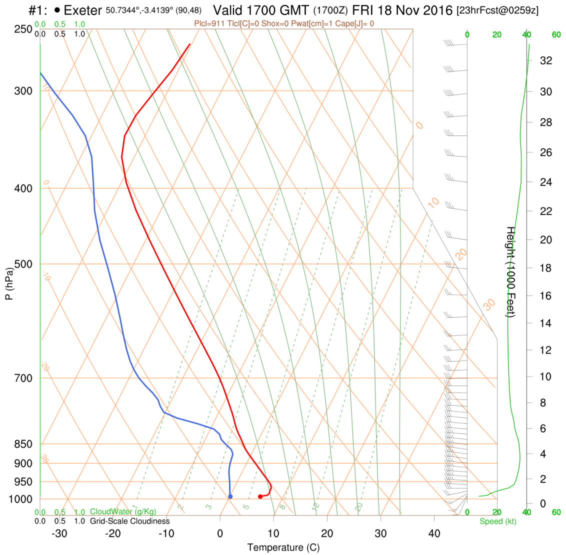
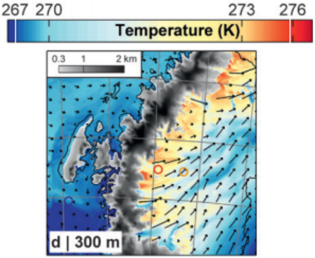


- Model simulated sounding from Exeter
- Green curvy lines are moist adiabats
- Blue line is the dew point temperature

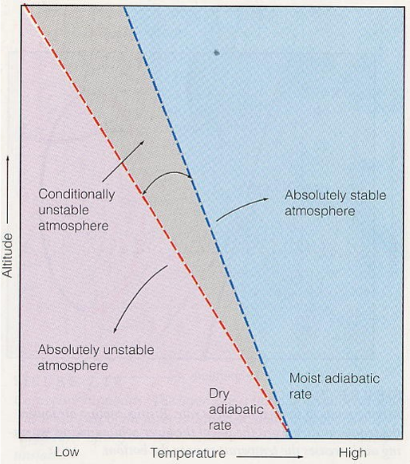
Föhn winds



As moist ascent is not reversible (cannot put the precipitation back!)

- Rain falls on the windward side of mountains (MALR)
- Dry air descends on the lee side (DALR)
- This can generate warm winds on the lee side of mountains
- Common in Southern Germany during winter

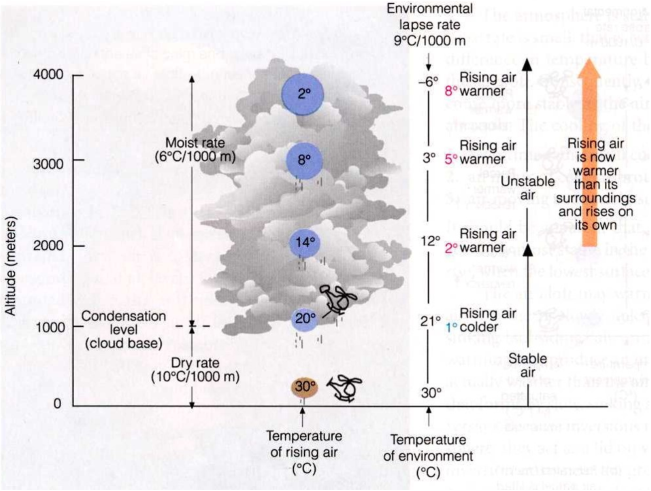
Atmospheric stability



Ahrens, 1996

- $>$DALR - Absolutely unstable
- $<$Moist lapse rate - Absolutely stable
- Otherwise, conditionally unstable...

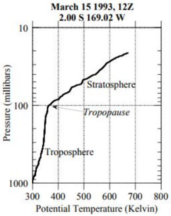
Conditional stability

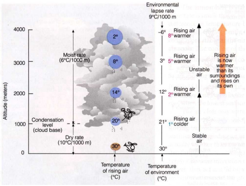


Ahrens, 1996

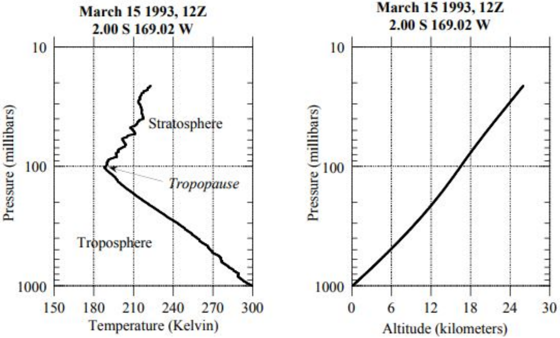
Thermodynamics summary

- Adiabatic movements of dry air lead to a temperature profile of $9.8\ \mathrm{K\,km^{-1}}$
- Moist air reduces the lapse rate (but isn't reversible)
- An unstable atmosphere will lead to convection
  - This sets a limit on how quickly temperature reduces with height
- The temperature of the lower atmosphere is controlled by these lapse rates
  - It is not in radiative equilibrium





The atmospheric temperature structure



Key points:

- Warmer at the surface (transparent to VIS, absorbs IR)
- Warms in stratosphere (Absorption by O_3)
- Cools nearly linearly with altitude ($dT/dz = -c_p/g$)
- Coldest at tropopause (convective vs. radiative equilibrium)
- Pressure decreases with altitude ($dp/dz = -\rho g$)

What other factors

What other factors might affect the temperature structure?

- Absorbers (e.g. dust)

What other factors

What other factors might affect the temperature structure?

- Absorbers (e.g. dust)
- Clouds

What other factors

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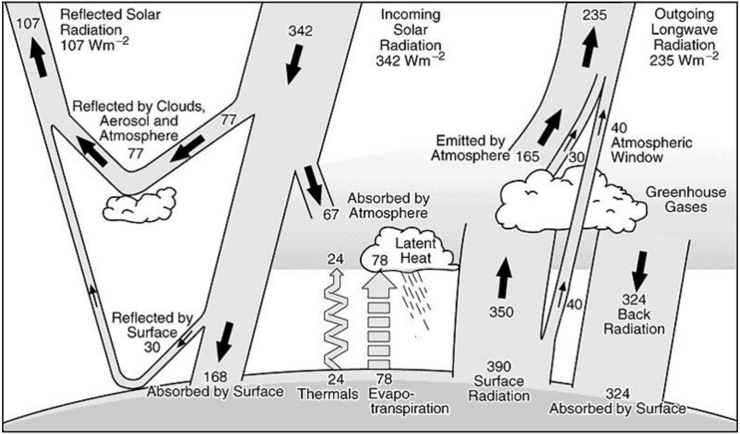
- Absorbers (e.g. dust)
- Clouds
- Composition changes (c_p)

What other factors

What other factors might affect the temperature structure?

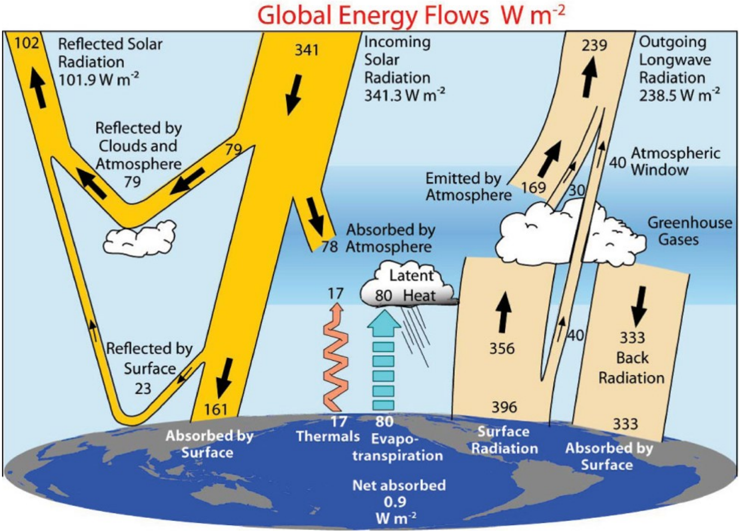
- Absorbers (e.g. dust)
- Clouds
- Composition changes (c_p)
- Atmospheric depth (g?)

The energy budget



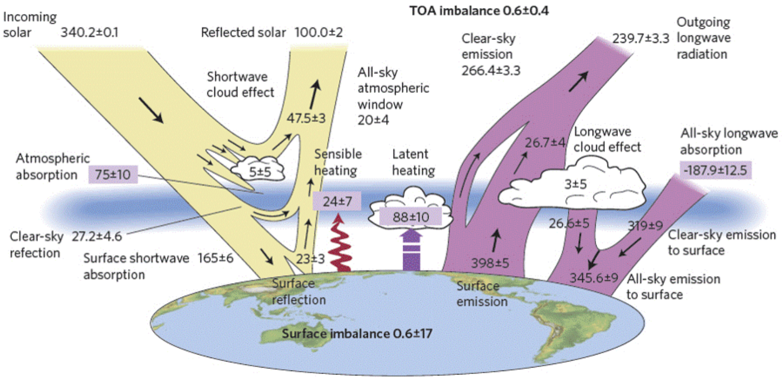
Kiehl et al, 1997

The energy budget



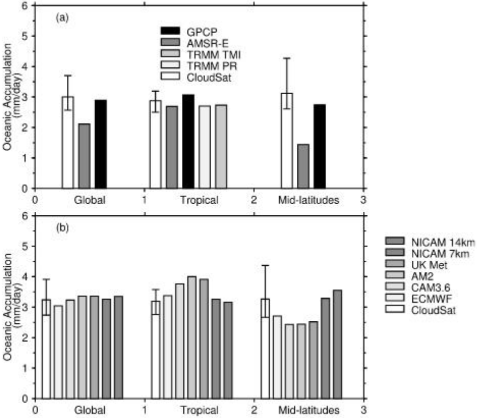
Trenberth et al, 2009

The energy budget



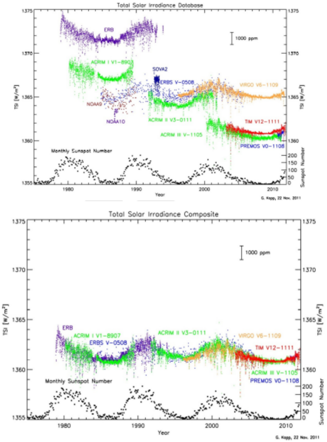
Stephens et al., 2012

Latent heat flux



- The latent heat flux is related to precipitation rate
- Area-averaged precipitation is very difficult to measure
- Significant disagreements between observations and models

Top of atmosphere fluxes

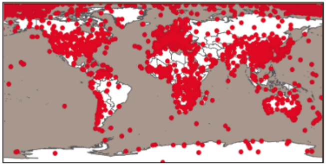


TSI from Kopp and Lean, 2011

- Achieving absolute calibration is difficult
- Need overlapping satellite instrument records
- Scattering in multiple directions (need model of surface)
- Best estimate comes from closing using the surface imbalance... (CERES EBAF)

Surface fluxes

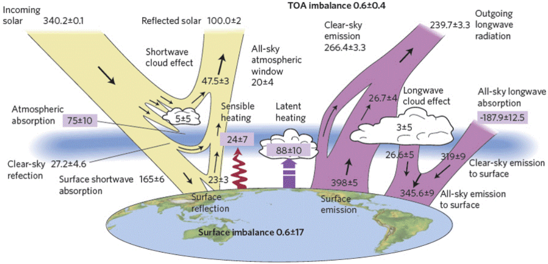
- Surface flux measurements are sparse (especially over the ocean)
  - Map shows locations in Global Energy Balance Archive (GEBA)
- Global estimate requires radiative transfer calculations
  - Convert top of atmosphere (TOA) measurements to surface ones
- Surface imbalance is 0.6 ± 17!



Surface flux measurement locations

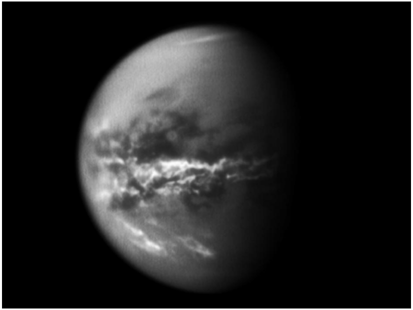
Energy budget summary

- The energy budget describes the flow of energy in the Earth system
- Measurements of many of the fluxes are tricky
- An full understanding requires very accurate calibration of satellite instruments



GERB radiative flux

Clouds and radiation



Clouds are a key control of the energy budget

- Small changes in clouds can have a large impact on the energy budget

Almost all planets in the solar system have clouds

- Except for Mercury (which has no atmosphere)
- Sometimes they are water, often they are other things (CH_4, NH_3)

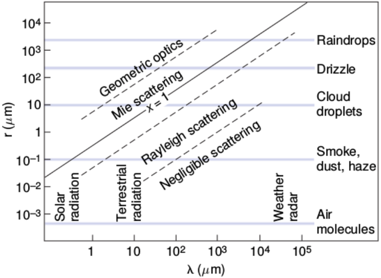
Clouds on Titan, NASA

Scatterers (Clouds and aerosol)

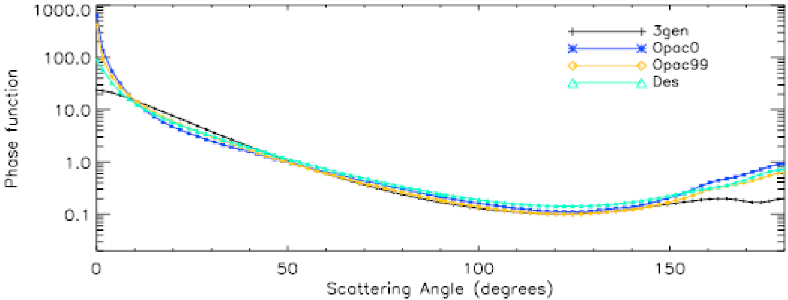
For spherical scatterers, the type of scattering is governed by the size parameter ($\chi = 2\pi r/\lambda$)

- $\chi << 1 \rightarrow$ (e.g. air molecules) - Rayleigh scattering ($\propto \lambda^{-4}$)
- Intermediate χ (e.g. cloud droplets) - Mie theory
- $\chi >> 1 \rightarrow$ (e.g. raindrops) - Geometric optics

Things become much more complicated with non-spherical scatterers (e.g. dust, soot, ice crystals)



Calculating cloud optical properties



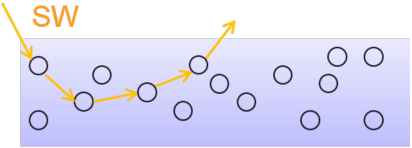
Photons can be scattered in any direction

- The probability of which direction is determined by the "phase function"

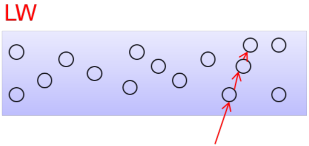
Most scattering is forward scattering

- So why are clouds reflective?

Multiple scattering



Redirection of beam via multiple collisions



50 % chance of abs at each collision:
~ black-body over cloud layer

Droplets are scattered multiple times in a cloud

- Even a small backscatter probability adds up over multiple collisions

Clouds are black for thermal radiation

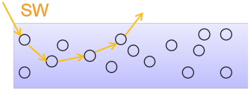
- Even a relatively thin cloud will absorb almost all the incident radiation (see problem sheet)

Optical depths and scattering

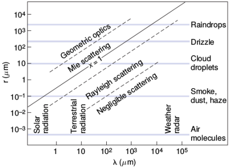
[Interactive demo]

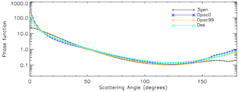
Clouds and radiation

- Clouds scatter visible light and absorb thermal/IR
- The scattering approximations used depend on particle size and wavelength
- The phase function determines scattering properties



Redirection of beam via multiple collisions





Summary

- Convection is important for energy transport in the lower atmosphere
  - Similar on many other planets (although the lapse rate is different)
  - The upper atmosphere is closer to radiative equilibrium
- The energy budget described the flow of energy in the Earth system
  - We will consider changes in in tomorrow (Climate change)
- Clouds play an important role in the atmosphere
  - The interact with water, and both visible and thermal/IR radiation