

## Cooling - radiative transfer

Allison pointed out that most of the time most of the atmosphere is clear because condensation introduces strong heating that has to be balanced by large areas of clear-sky cooling. Why does the clear sky cool?

Use solutions to Schartzchild's equation, applied to flux, remembering that  $F^{\text{net}} = F^- - F^+$  and that each solution contains a boundary term and attenuated source terms. Re-group to express as exchanges: heating by surface emission; cooling to space; exchanges with layers below you ( $\tau' > \tau$ ), and exchanges with layers above. Terms from warmer locations tend to warm.

$$\begin{aligned} \frac{dF^{\text{net}}}{d\tau} &= [B_s - B(\tau)]e^{-(\tau_s - \tau)} - \\ &\quad B(\tau)e^{-\tau} + \\ &\quad \int_{\tau}^{\tau^*} [B(\tau') - B(\tau)]e^{-(\tau' - \tau)} d\tau' + \\ &\quad \int_0^{\tau} [B(\tau) - B(\tau')]e^{-(\tau - \tau')} d\tau' \end{aligned}$$

The first term is the exchange with the surface; the second cooling to space; the last two are exchanges with the rest of the atmosphere. We'll call the sum of the last two terms  $EX$ .

First, simply the terms by writing the in terms of the optical distance between two locations, i.e.

$$\int_{\tau}^{\tau^*} [B(\tau') - B(\tau)]e^{-(\tau' - \tau)} d\tau' = \int_0^{\tau^* - \tau} [B(\tau + x) - B(\tau)]e^{-x} dx$$

where  $x = \tau - \tau'$ , and  $\int_0^{\tau} [B(\tau) - B(\tau - x)]e^{-x} dx =$

- $\int_0^{\tau} [B(\tau) - B(\tau - x)]e^{-x} dx$  where  $x = \tau' - \tau$  and the minus sign comes from switching the order of the  $B$  terms

In general the limits of the two integrals don't overlap... but parts of them do. Consider a level  $\tau < 1/2\tau^*$ . (Draw a picture.)

Write the integral as a symmetric part and an antisymmetric part:

$$\begin{aligned}
 EX = & \int_0^{\tau^*-\tau} [B(\tau+x) - B(\tau)]e^{-x} dx - \int_0^{\tau} [B(\tau) - B(\tau-x)]e^{-x} dx = \\
 & \int_0^{\tau} [B(\tau+x) - 2B(\tau) - B(\tau-x)]e^{-x} dx + \\
 & \int_{\tau}^{\tau_s-\tau} [B(\tau+x) - B(\tau)]e^{-x} dx
 \end{aligned}$$

In the anti-symmetric or uncompensated portion of the atmosphere there's pure warming (or cooling) - but attenuated by a substantial portion of the atmosphere. Exchange with the surface works the same. The integrand is a finite difference in  $B(\tau)$ .

In the symmetric portion of the atmosphere heating from warmer layers is partially offset by cooling to colder layers at the same optical distance. The form is a second-order finite difference - if  $\frac{d^2 B}{d\tau^2}$  is constant there's perfect cancellation.

But space has "no" emission - nothing to exchange with. So total cooling is dominated by cooling to space... especially when the first and second derivatives of temperature w.r.t optical depth are small

**So atmospheric cooling is dominated by cooling-to-space**

## Cooling maximizes at $\tau = 1$

Assert that cooling to space implies maximum cooling at  $\tau = 1$ . This isn't obvious in optical depth coordinates, rather it occurs for in coordinate systems in which  $d\tau/d\xi \propto \xi$ . (Height and pressure such coordinates e.g. yesterday's example  $\tau = \tau_0 e^{-z/H}$ )

"the  $\tau = 1$  law holds for such coordinates because  $\tau \approx 1$  is a "sweet spot" in between  $\tau \ll 1$  (where the optical depth gradient  $d\tau/d\xi$  goes to 0) and  $\tau \gg 1$  (where the transmissivity  $e^{-\tau}$  goes to 0)." (Jeevanjee and Fueglistaler 2020 <https://doi.org/10.1175/JAS-D-18-0352.1>)

## Let's get real

So what's doing all this absorption?

To understand links between radiation, clouds, and circulation we need to think about water - water vapor and clouds.

Clouds are the most opaque material in the atmosphere at almost all wavenumbers. They are the most visible objects; they also control the IR (e.g. warmer nights when cloudy). We'll come back to them.

Water vapor is the most important greenhouse gas i.e. it affects the TOA energy budget most, so also the cooling.

CO<sub>2</sub> is the biggest cause of climate change but that's 'cause we change its concentration directly; water just follows temperature.

## Water vapor absorption spectrum

Gases interact with radiation at *absorption lines*: discrete wavenumbers corresponding to a particular quantum mechanical transition, ordered as electronic (nah), vibrational, rotational, or combinations of vibration and rotation.

- frequency is set by the properties the molecule (atomic mass, bond strength, moment of inertia)
- "strength" includes molecular cross-section and the likelihood of molecules being in the initial state
- lines are broadened by pressure/finite lifetime and temperature/doppler

Mass absorption coefficient varies by orders of magnitude within fractions of a wavenumber

[Switch to a slide of water vapor absorption coefficient?]

Speaking very broadly water vapor in the IR has absorption features in the far-IR due to rotation and in the mid-IR due to vibration+rotation. If you squinted hard you could decide these were exponential, or linear in the logarithm of the absorption coefficient

$$k_w(\nu) = k_w(\nu_0)e^{(\nu-\nu_0)/l}$$

We can pick different  $\nu_0, l$  for the vibrational-rotational and rotational bands (  $150\text{cm}^{-1}, 60\text{cm}^{-1}$  for rotation,  $1350\text{cm}^{-1}, 60\text{cm}^{-1}$  for vibration-rotation)

[Draw a picture of Planck function and absorption coefficient. Max B is maybe  $550\text{ cm}^{-1}$ , min

$k$  is  $\sim 900 \text{ cm}^{-1}$  in the center of the water vapor window ]

## Water vapor spectroscopy and tropospheric cooling

For this argument we will ignore pressure and temperature broadening so  $k_w(\nu)$  is constant. For simplicity we'll assume a troposphere with constant relative humidity and a dry stratosphere - probably with mixing ratio  $q$  equal to the value at the tropopause/temperature minimum.

Imagine starting at the top of the atmosphere. To cool very much we need

$\tau_{\nu_0} = k_w(\nu_0)WVP \approx 1$ . (with  $WVP = \int_0^p \rho_w dp$  being the amount of water mass -- water vapor path -- above pressure  $p$ ). This pressure is the tropopause, since cooling is after all what's responsible for convection and mixing.

As pressure and temperature increase along a moist adiabat, water vapor mixing ratio increases. The most absorbing part of the spectrum is now optically thick and no longer cools, but a new set of wavenumbers with lower  $k$  reaches the sweet spot  $\tau = 1$ .

- Cooling rate depends on the size of the wavenumber set nearing or just surpassing  $\tau = 1$  per unit pressure (ignoring small changes in  $B_\nu(T)$ )
- Exponential increase in  $P$  with  $T$  matches exponential falloff in  $k$  with  $\nu$  so  $\mathcal{H}_p$  is essentially constant - the whole atmosphere is unstable
- Relative humidity doesn't matter because Clausius–Clapeyron always dominates
- But gradients in RH introduce local heating/cooling maxima
- Cooling is dominated by rotation because that's where the Planck function is large

## What about clouds? (and longwave)

Clouds are different than gases because

- they're optically thick
- they white, or at least grey - spectrally uniform
- they scatter sunlight

As an afterthought - water vapor also absorbs solar radiation, mostly in the near-infrared. The spectroscopy isn't very different than in the IR though there are more bands... but

Main impact is absorption which scales like, but damps, cooling

Clouds in the *longwave*

- locally cool at cloud top - all wavenumbers that aren't optically thick from water vapor emit happily
- locally heat cloud base in spectral regions where  $\tau - \tau_s \ll 1$
- reduce outgoing longwave at the TOA (lower temperatures win over less transmissive atmosphere c.f. surface)

The impact of clouds on the radiation budget - the cloud radiative effect - is normally defined as

$$\text{CRE} = F_{\text{clr}}^{\text{net}} - F_{\text{all}}^{\text{net}}$$

Evaluated at TOA, positive values mean that clouds increase the energy absorbed by the earth and atmosphere ("warming")

When describing the response to warming

$$\frac{\Delta \text{CRE}}{\Delta T} \neq \lambda_{\text{cld}}$$

because the clear sky components can also change with warming

## A very brief excursion to the shortwave

In the shortwave the atmosphere absorbs (mostly gases) and scatters (mostly clouds). Absorption is relatively small.

I'm spending almost no time on the shortwave because a) SW heating by gases is small relative to LW cooling, and b) clouds scatter and so don't strongly affect local heating. Their main impact is to change boundary fluxes.

It's convenient to divide shortwave radiation into *direct* and *diffuse* components;

$$\mu \frac{d}{d\tau} I^{\text{dir}} = -I^{\text{dir}}$$

and

$$\begin{aligned} \mu \frac{d}{d\tau} I^{\text{dif}} = & -I^{\text{dif}} \\ & + \frac{\omega_0}{4\pi} P(\mu_0, \phi_0 \rightarrow \mu, \phi) I_0 e^{-\tau/\mu_0} \\ & + \frac{\omega_0}{4\pi} \int_0^{2\pi} \int_{-1}^1 P(\mu', \phi' \rightarrow \mu, \phi) I^{\text{dif}} d\mu' d\phi' \end{aligned}$$

The direct component obeys Beer-Lambert-Bouguer

The diffuse component introduces  $\omega_0$ , the single scattering albedo, and the scattering phase function  $P(\mu', \phi' \rightarrow \mu, \phi)$  which describes how the medium redirect light from the direct beam (2nd line) and diffuse field (3rd line) into the direction we're considering

## Two-stream insights

Methods to solve this equation exist; one can also compute fluxes using the *two-stream* approach

- azimuthally average the diffue RTE
- make assumptions about the form of  $P$  and  $I \times P$  to do integrals analytically ( $P \rightarrow g$ )
- solve resulting two coupled ODEs for flux up, down

What you learn:

- solutions depend on  $\Gamma\tau = 2\sqrt{1 - \omega_0 g}\sqrt{1 - \omega_0}\tau$
- solutions for  $I^+$  or  $R$  reach their asymptotic value more slowly then for LW because multiple scattering can "undo" itself even for isotropic scattering

[draw a picture]

- For clouds  $\tau_{\text{SW}} \approx 2\tau_{\text{LW}}$  because scattering is affected by diffraction
- clouds almost conservative ( $\omega_0 \approx 1$ ); diffraction make them strongly forward scattering ( $g \approx .85$ ) i.e. far from isotropic
- this means that  $\frac{dR}{d\tau} > 0$  over a much wider range of  $\tau$  in the SW than in the LW, so cloud feedbacks are non-zero over a much wider range

In [ ]: