Schedule

1. **What are models?**
   Exercise: Python Skills

2. **Energy budget of the Earth**
   Exercise: Simple Energy Balance Model

3. **Nonlinearity, Feedback, and Predictability**
   Exercise: Nonlinearity and Feedbacks
   Exercise: Revised Energy Balance Model

4. **Parametrization and Sensitivity**

5. **Radiative budget**
   Exercise: 1-layer greenhouse model
   Exercise: 2-layer greenhouse model

6. **Introduction to fluid dynamics**
   Exercise: Analytical katabatic flow model

7. **Finite difference method**
   Exercise: Advection-Diffusion Equation
   Exercise: Boundary layer Evolution
   Exercise: Numerical katabatic flow model
   Exercise: Heat Equation

8. **Implicit finite difference methods**
   Exercise: Boundary layer evolution

9. **Optimization problem**
   Exercise: Surface energy balance
   Exercise: Sublimation

10. **COSIPY snow model**
    Exercise: Simulations with COSIPY

11. **Introduction to PALM**
    Exercise: Simulations with PALM

12. **How to write an article**

Greenhouse model

Learning objectives

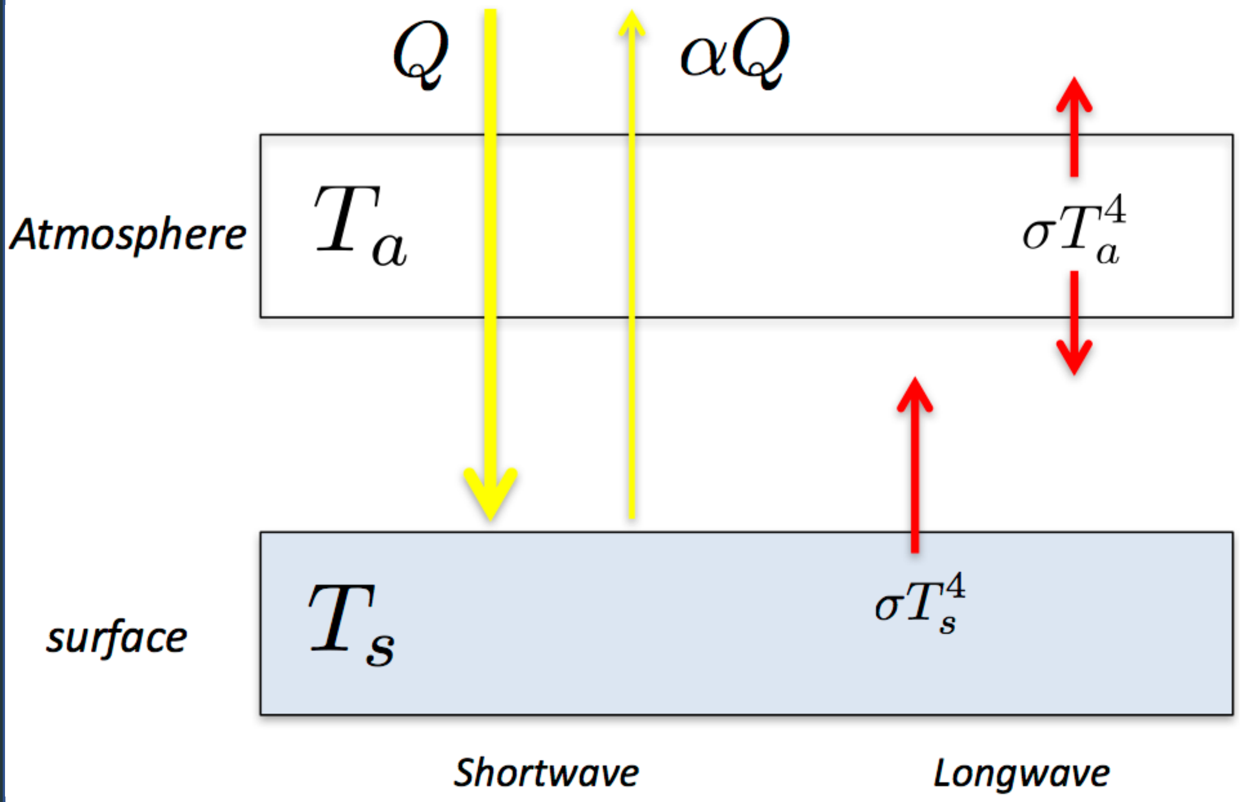
- Understanding how the greenhouse effect works

One-layer model

Assumption

- Atmosphere is a single layer of air at temperature T_a
- Atmosphere is completely transparent to shortwave solar radiation.
- The surface absorbs shortwave radiation (1−α)Q
- Atmosphere is completely opaque to infrared radiation
- Both surface and atmosphere emit radiation as blackbodies ($\sigma T_s^4, \sigma T_a^4$)
- Atmosphere radiates equally up and down (σT_a^4)
- There are no other heat transfer mechanisms

One-layer model



$$\sigma T_s^4 = 2\sigma T_a^4$$

$$(1-\alpha)Q + \sigma T_a^4 = \sigma T_s^4$$

One-layer model

Task 1: Plug Eq. (7) into Eq. (6) and solve for the radiative equilibrium suface temperature T_e. Since all the outgoing longwave radiation to outer space results from the atmosphere, the atmospheric temperture T_a is identical to the emission temperature T_e.

Task 2: Where in the atmosphere do we find the calculated T_e? (Live-coding, `Download netCDF-file`)

Task 3: What is the surface temperature with the single layer model? Why does the model overestimate the surface temperature?

netCDF-files

xarray.Dataset

▶ Dimensions: (**level**: 17, **lat**: 73, **lon**: 144, **time**: 12, nbnds: 2)

▼ Coordinates:

level	(level)	float32	1e+03 925.0 850.0 ... 20.0 10.0
lat	(lat)	float32	90.0 87.5 85.0 ... -87.5 -90.0
lon	(lon)	float32	0.0 2.5 5.0 ... 352.5 355.0 357.5
time	(time)	object	0001-01-01 00:00:00 ... 0001-12-...

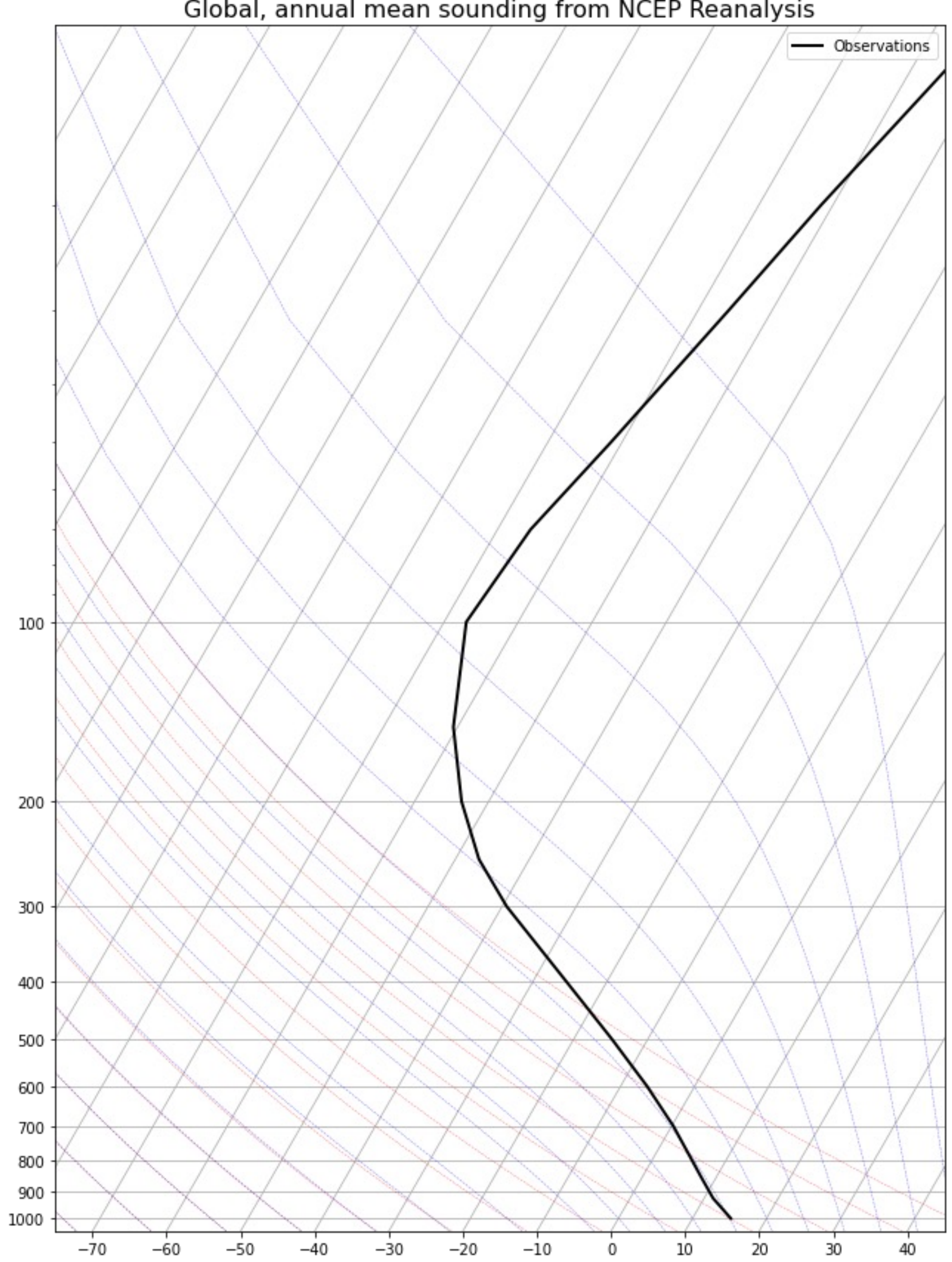
▼ Data variables:

climatology_bo...	(time, nbnds)	object	...
air	(time, level, lat, lon)	float32	...
valid_yr_count	(time, level, lat, lon)	float32	...

▼ Attributes:

description :	Data from NCEP initialized reanalysis (4x/day). These are interpolated to pressure sur faces from model (sigma) surfaces.
platform :	Model
Conventions :	COARDS
not_missing_thr...	minimum 3% values input to have non-missing output value
history :	Created 2011/07/12 by doMonthLTM Converted to chunked, deflated non-packed NetCDF4 2014/09
title :	monthly ltm air from the NCEP Reanalysis
dataset_title :	NCEP-NCAR Reanalysis 1
References :	http://www.psl.noaa.gov/data/gridded/data.ncep.reanalysis.derived.html

Radiosounding



One-layer model

Why does the one-layer model overestimate the surface temperature

- Atmosphere absorbs some solar radiation.
- Atmosphere is NOT a perfect absorber of longwave radiation
- Absorption and emission varies strongly with wavelength (atmosphere does not behave like a blackbody).
- Emissions are not determined by a single temperature but by the detailed vertical profile of air temperature.
- Energy is redistributed in the vertical by a variety of dynamical transport mechanisms (e.g. convection and boundary layer turbulence).
- weather for more than a couple of days

Two-layer model

Generalized and a slightly more realistic model of longwave radiative transfer

We will address two shortcomings of our single-layer model:

- No vertical structure
- 100 % longwave opacity

Relaxing these two assumptions gives us what turns out to be a very useful prototype model for **understanding how the greenhouse effect works**.

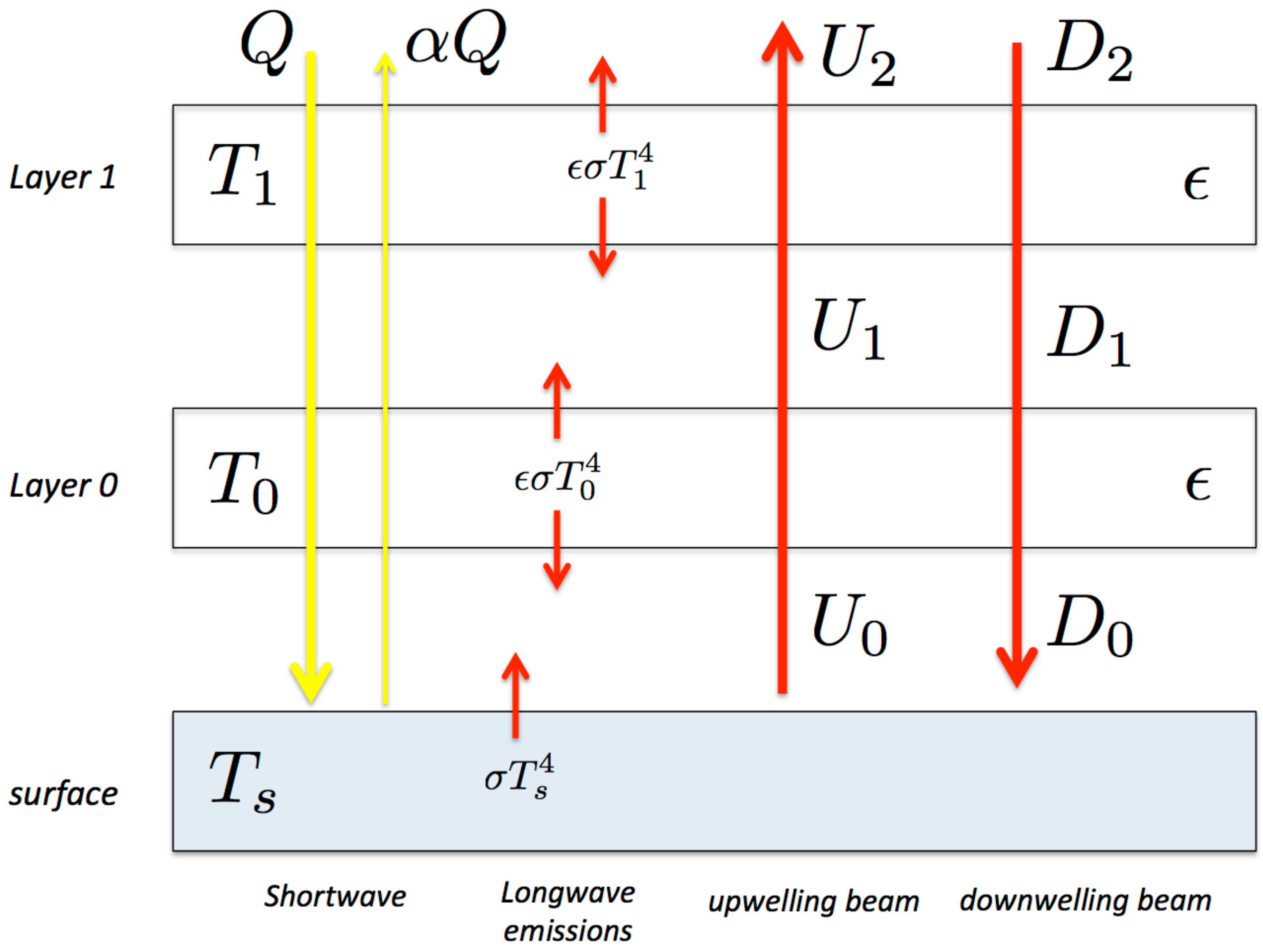
Two-layer model

Assumption

- The atmosphere **is transparent to shortwave radiation**
- Divide the atmosphere up into **two layers of equal mass** (the dividing line is thus at 500 hPa pressure level)
- Each layer **absorbs only a fraction ϵ** of whatever longwave radiation is incident upon it
- Assume **ϵ is the same in each layer**

This is called the **grey gas model**, where **grey** here means the emission and absorption have **no spectral dependence** (same at every wavelength).

Two-layer model



$$U_2 = (1-\epsilon)U_1 + \epsilon\,\sigma\,T_1^4$$

$$U_1 = (1-\epsilon)\,\sigma\,T_s^4 + \epsilon\,\sigma\,T_0^4$$

$$U_0 = \sigma\,T_s^4$$

Two-layer model

> **Task 4**: Since there is no more atmosphere above layer 1, this upwelling beam is our OLR for this model. Plug U_1 into the equation of U_2 and solve the equation. What do the terms represent?

$$OLR = U_2 = (1-\epsilon)^2 \sigma T_s^4 + \epsilon(1-\epsilon)\sigma T_0^4 + \epsilon \sigma T_1^4$$

Here the three terms represent **contributions to the total OLR** that **originate from each of the three levels**

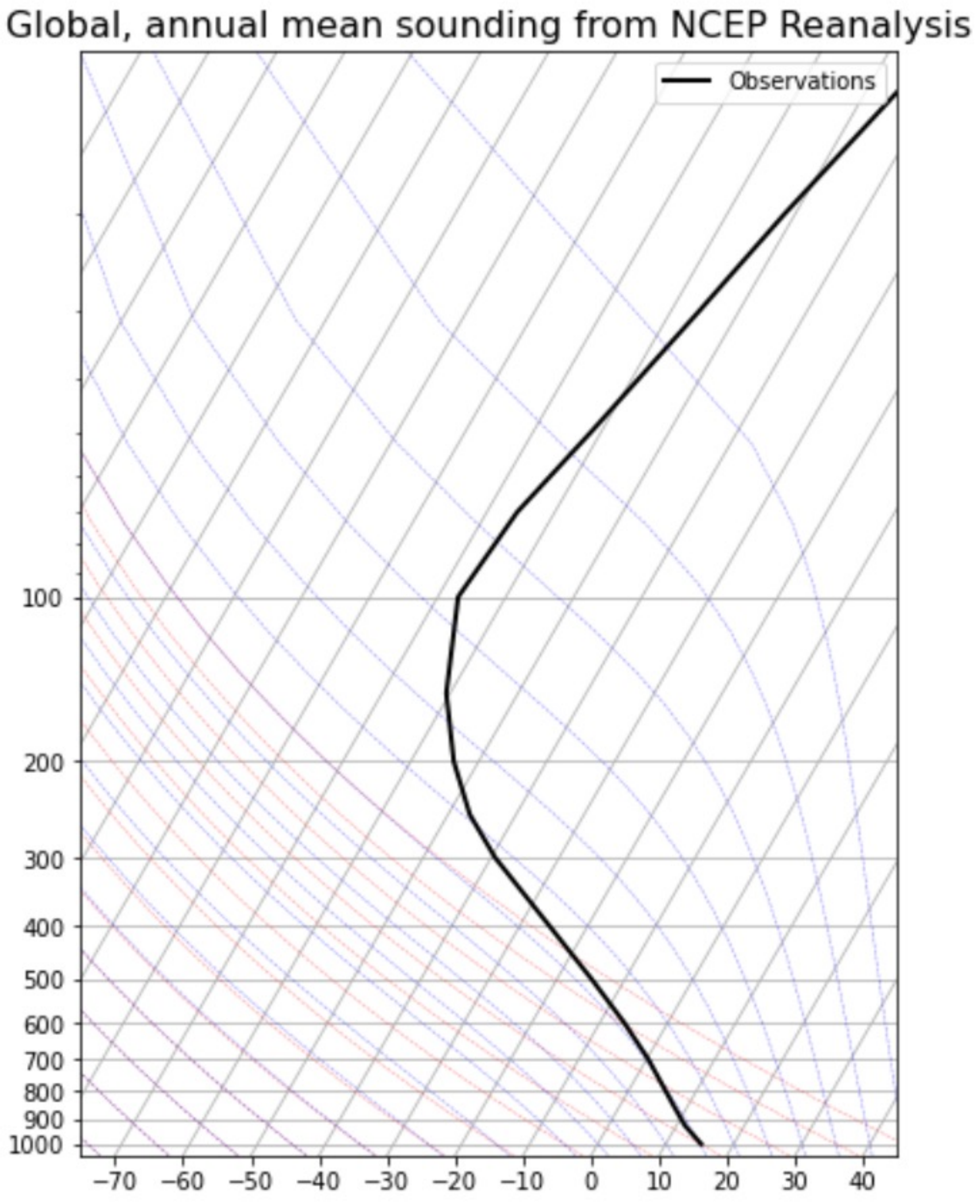
Two-layer model

> **Task 5**: Write a Python function for the `OLR` (Task 3).

> **Task 6**: What happens if ϵ is zero or one? What does this mean physically?

Two-layer model

Task 6: Determine the average temperatures (1000-500 hPa, 500 hPa to tropopause) for the two-layer model from the following sounding.



Two-layer model

> **Task 8**: Find graphically the best fit value of ϵ using the observed temperatures and OLR.

> **Task 9**: Write a Python function to calculate each term in the OLR. Plug-in the observed temperatures and the tuned value for epsilon and calculate the terms.

> **Task 10**: Changing the level of emission by adding absorbers $\epsilon = \epsilon + \Delta\epsilon$, e.g. by 10 %. Suppose further that this increase happens abruptly so that there is no time for the temperatures to respond to this change. We hold the temperatures fixed in the column and ask how the radiative fluxes change. Do you expect the OLR to increase or decrease? Which terms in the OLR go up and which go down?

Radiative Forcing

We now define a very important quantity:

"Radiative forcing" is the change in total radiative flux at the top of the atmosphere (TOA) after adding absorbers

In this model, **only the longwave flux can change**, so we calculate the radiative forcing as

$$R = -\Delta OLR$$

(with the minus sign so that R is **positive when the climate system is gaining extra energy**).

Two-layer model

Task 11: Calculate the radiative forcing for the previous simulation.

Task 12: What is the greenhouse effect for an isothermal atmosphere?

Task 13: For a more realistic example of radiative forcing due to an increase in greenhouse absorbers, we use our observed temperatures and the tuned value for epsilon. Assume an increase of epsilon by 2 %. What is the radiative forcing? What does this mean for the OLR?

Greenhouse model

Summary

- Putting a **layer of longwave absorbers** above the surface keeps the **surface substantially warmer**, because of the **back-radiation** from the atmosphere (greenhouse effect).

- The **grey gas** model assumes that each layer absorbs and emits a fraction ϵ of its blackbody value, independent of wavelength.

- With **incomplete absorption** ($\epsilon<1$), there are contributions to the OLR from every level and the surface (there is no single **level of emission**)

- Adding more absorbers means that **contributions to the OLR** from **upper levels** go **up**, while contributions from the surface go **down**.

Greenhouse model

Summary

- This upward shift in the weighting of different levels is what we mean when we say the **level of emission goes up**.
- The **radiative forcing** caused by an increase in absorbers **depends on the lapse rate**.
- For an **isothermal atmosphere** the radiative forcing is zero and there is **no greenhouse effect**
- The radiative forcing is positive for our atmosphere **because tropospheric temperatures tend to decrease with height**.