Introducing the Greenhouse Effect

EES 2110

Introduction to Climate Change

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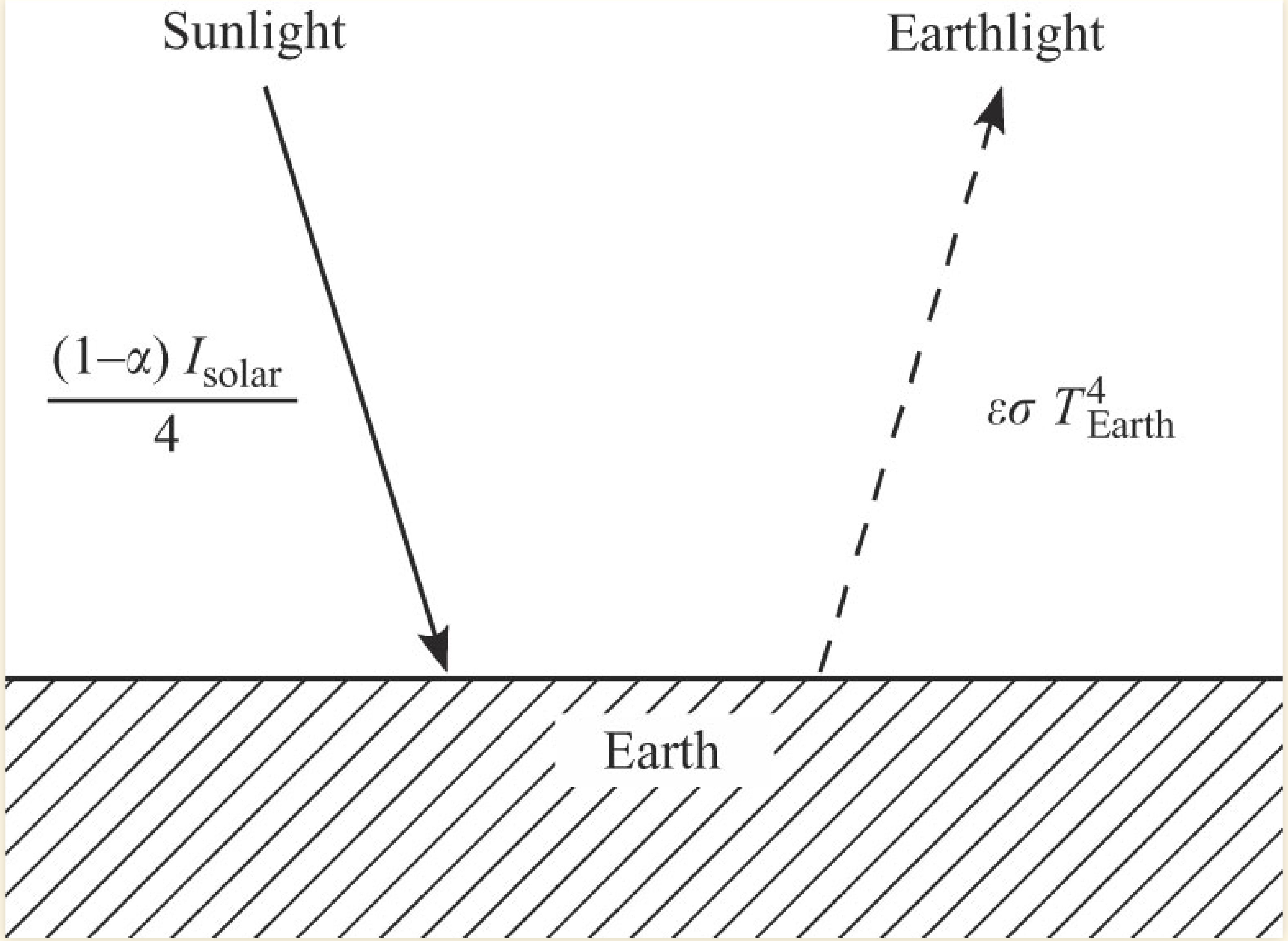
Class #4: Wednesday, January 18 2023

Basic Principles from Friday

- **Steady temperature means:**
  - $\text{Heat}_{\text{out}} = \text{Heat}_{\text{in}}$
- **Heat in:**
  - Sunlight (**shortwave**)
  - Does not depend on temperature
- **Heat out:**
  - Emitted radiation (**longwave**)
  - Depends on temperature
- If $\text{Heat}_{\text{out}} \neq \text{Heat}_{\text{in}}$,
  - Temperature rises or falls until $$\text{Heat}_{\text{out}} = \text{Heat}_{\text{in}}$$

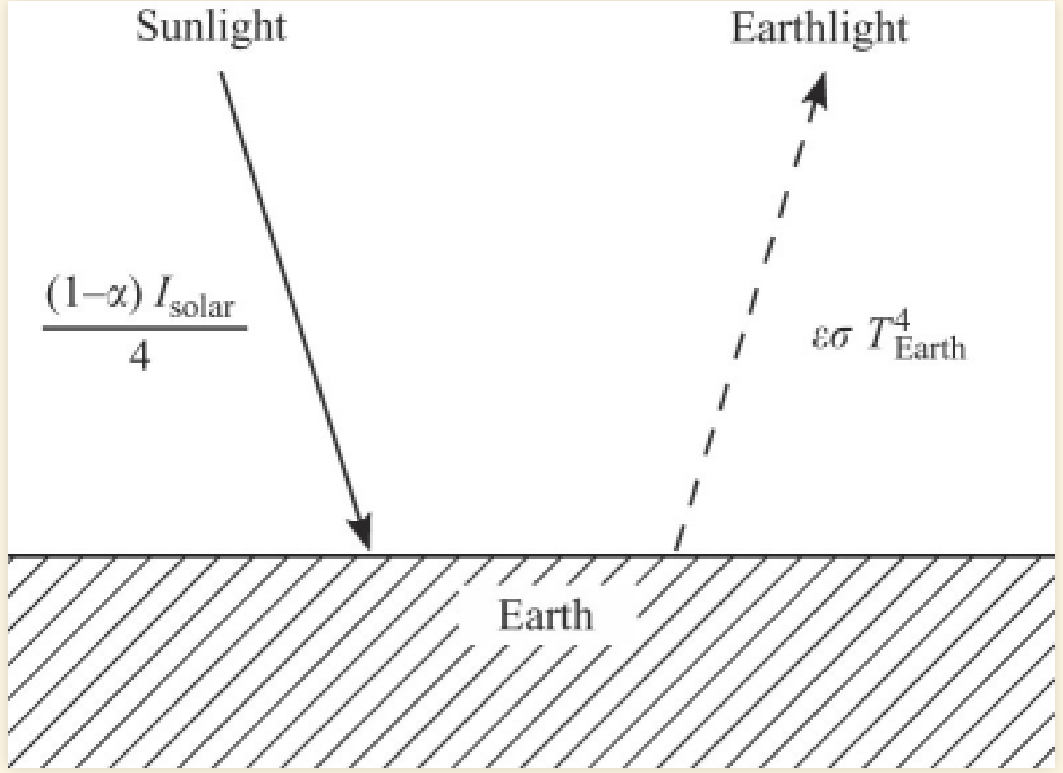
Temperature of the Earth

Bare-Rock Model: No Atmosphere



A subtle point...

- Emissivity ε is fraction absorbed
- Albedo α is fraction reflected
- For an opaque surface, $\alpha + \varepsilon = 1$
- So how is $\alpha = 0.30$ and $\varepsilon = 1.00$?
- α & ε are different for shortwave & longwave.
  - Shortwave: $\alpha = 0.30$, $\varepsilon = 0.70$
  - Longwave: $\alpha = 0.00$, $\varepsilon = 1.00$



Temperature of Earth (Bare Rock Model)

1. $F_{\text{out}} = F_{\text{in}}$ (Heat flux balances)
2. On average,

   $$F_{\text{in}} = \frac{(1 - \alpha)}{4} I_{\text{solar}}$$

   - Why the factor of 4 in the denominator?
     - It's a geometric factor for the average intensity of sunlight.
3. $F_{\text{out}} = \varepsilon \sigma T^4$.
4. Solve for T:

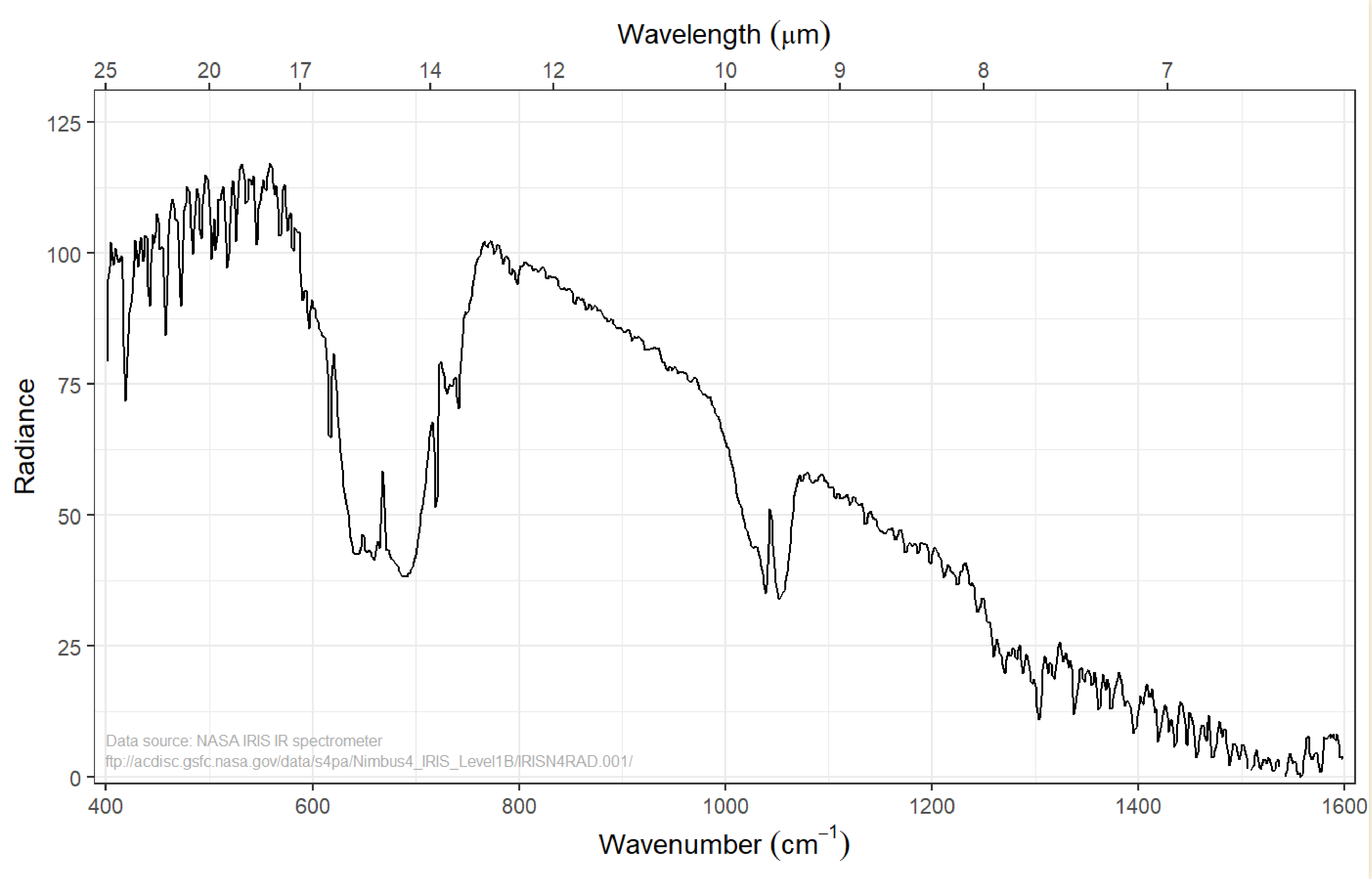
   $$\large T = \sqrt[4]{\frac{(1-\alpha) I_{\text{solar}}}{4 \varepsilon \sigma }}$$

   $$\begin{align*} I_{\text{solar}} &= 1350~\mathrm{W/m^2}\\ \alpha &= 0.30\\ \varepsilon &= 1\\ \sigma &= 5.67 \times 10^{-8}\, \mathrm{W\, m^{-2}\, K^{-4}}\\ T &= 254~\mathrm{K} = -19^\circ\mathrm{C} = -2^\circ\mathrm{F}\\ \text{Actual surface temperature} &= 288~\mathrm{K} = \hphantom{-} 15^\circ\mathrm{C} = 59^\circ\mathrm{F} \end{align*}$$

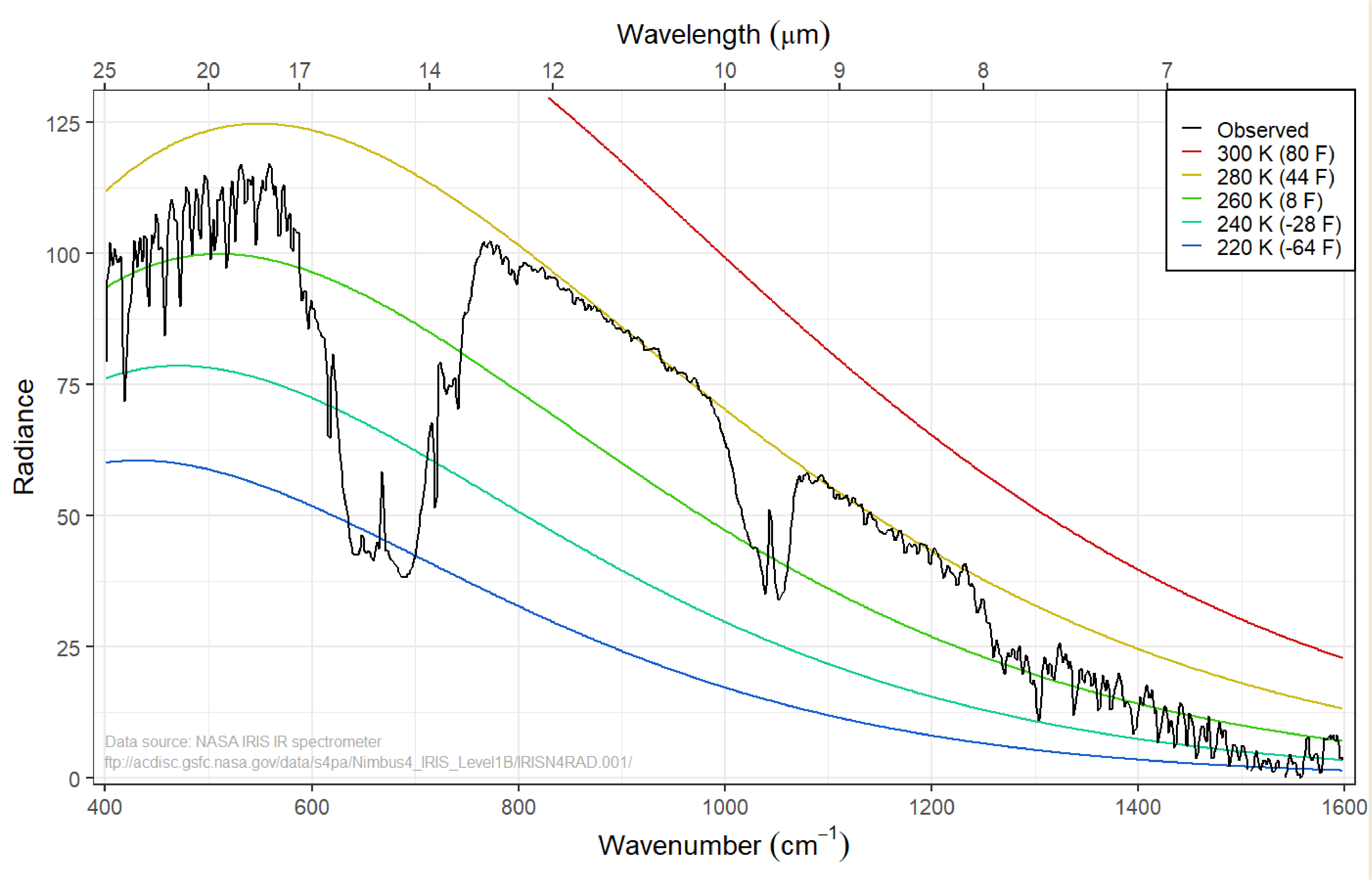
Terrestrial Planets

	Earth	Mars	V
Distance from sun	1 AU	1.5 AU	0.
\(1 / \text{Distance}^2\)	1.00	0.44	
Solar constant	\(1350~\mathrm{W}/\mathrm{m}^2\)	\(600~\mathrm{W}/\mathrm{m}^2\)	\(2604~\mathrm{
Albedo	0.30	0.17	
\(T_{\text{bare rock}}\)	\(254~\mathrm{K}~(-2^\circ\mathrm{F})\)	\(216~\mathrm{K}~(-70^\circ\mathrm{F})\)	\(240~\m -27^\circ\
\(T_{\text{surface}}\)	\(288~\mathrm{K}~(59^\circ\mathrm{F})\)	\(240~\mathrm{K}~(-28^\circ\mathrm{F})\)	\(700~\m 800^\circ\
\(\Delta_T\)	\(34~\mathrm{K}~(61^\circ\mathrm{F})\)	\(24~\mathrm{K}~(42^\circ\mathrm{F})\)	\(460~\m 828^\circ\

Oops! We forgot the atmosphere!

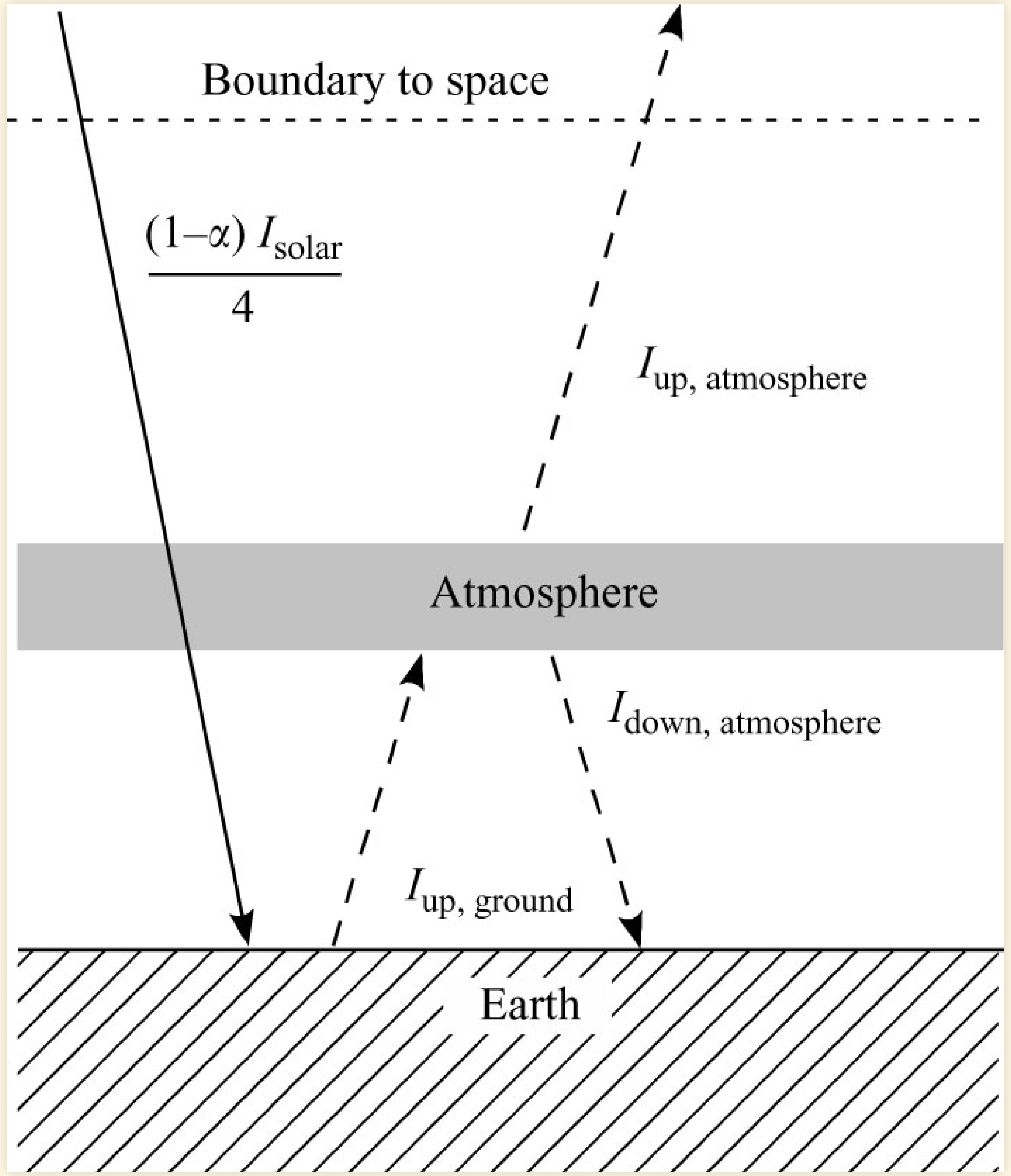


Does Earth look like a blackbody?



One-Layer Model of the Greenhouse Effect

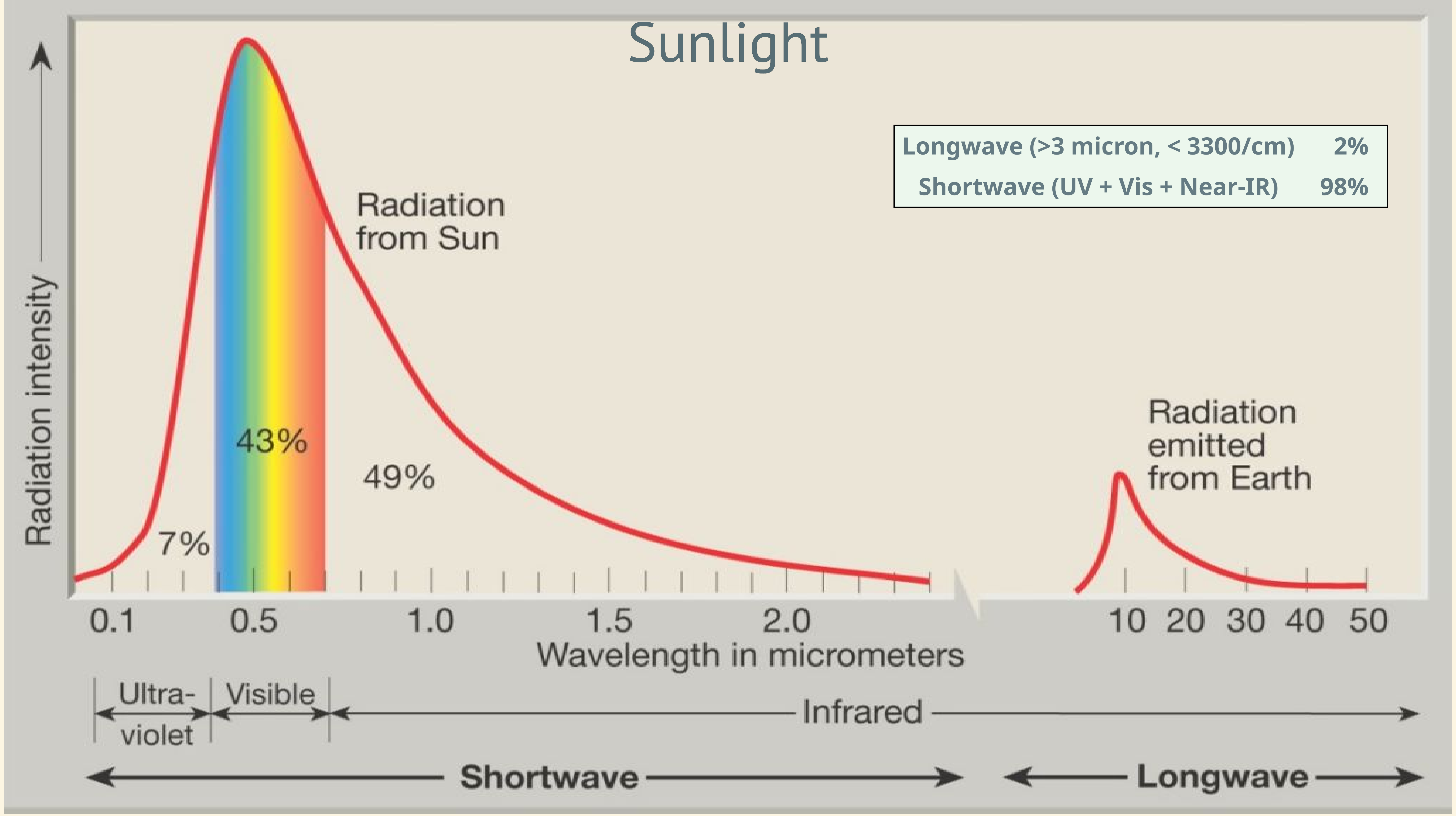
Layer Model



Boundary to space
$\frac{(1-\alpha)\, I_{solar}}{4}$
$I_{up,\ atmosphere}$
Atmosphere
$I_{down,\ atmosphere}$
$I_{up,\ ground}$
Earth

Sunlight

Longwave (>3 micron, < 3300/cm)	2%
Shortwave (UV + Vis + Near-IR)	98%



Atmosphere

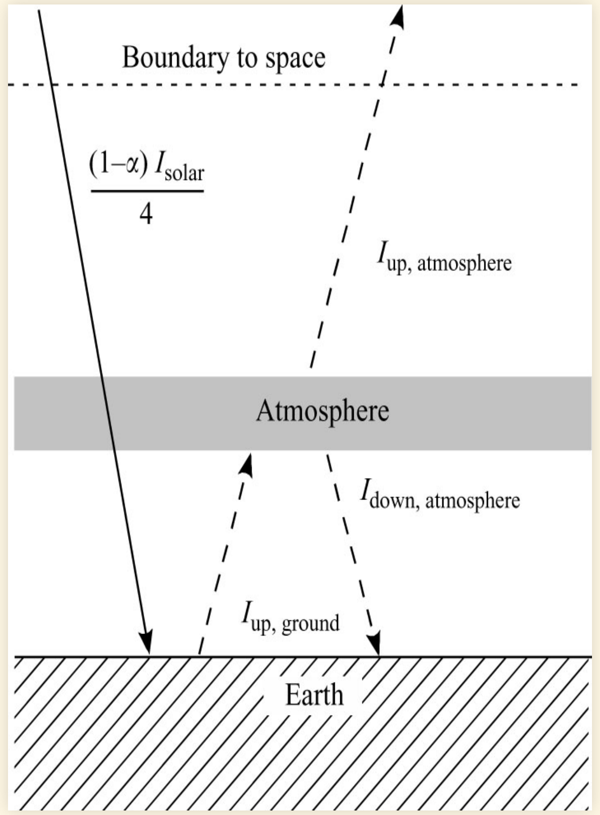
Make **simplifying assumptions**:

- Perfectly **transparent** to **shortwave** light
  - Like a pane of glass: \(\varepsilon = 0\)
- Perfectly **opaque** to **longwave** light
  - Like a blackbody: \(\varepsilon = 1\)

Anything that
transmits most shortwave
and
absorbs most longwave
is a greenhouse gas

Balance of energy for earth system

- Always start analyzing from the top down
  - Look at energy balance at the boundary to space, above the top of the atmosphere.



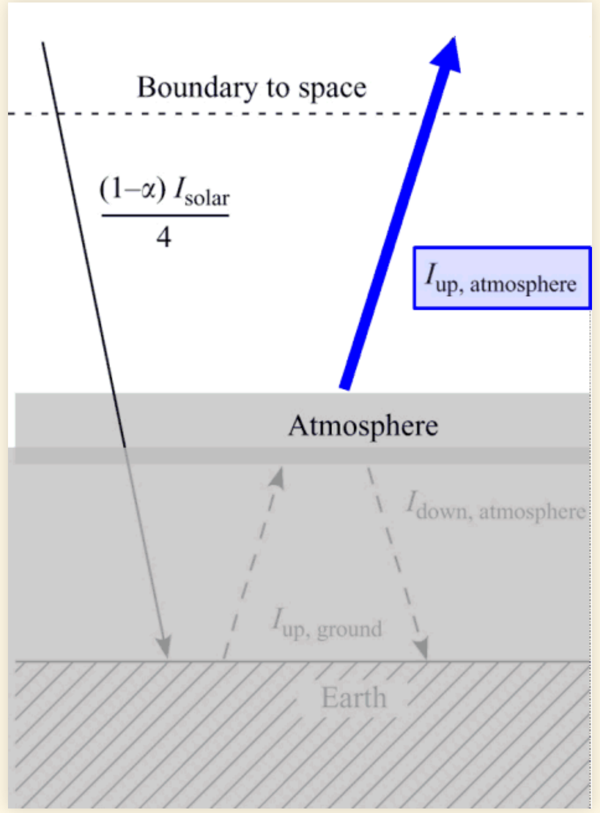
Balance of energy for earth system

- At top of atmosphere: $F_{\text{out}} = F_{\text{in}}$

  $$ \begin{align*} I_{\text{up, atmos}} &= I_{\text{in}}\quad \small{\text{(intensity of absorbed sunlight)}}\\ \varepsilon \sigma T_{\text{atmos}}^4 &= \frac{(1 - \alpha) I_{\text{solar}}}{4} \end{align*} $$

- Aha! We can find T_{atmos}!

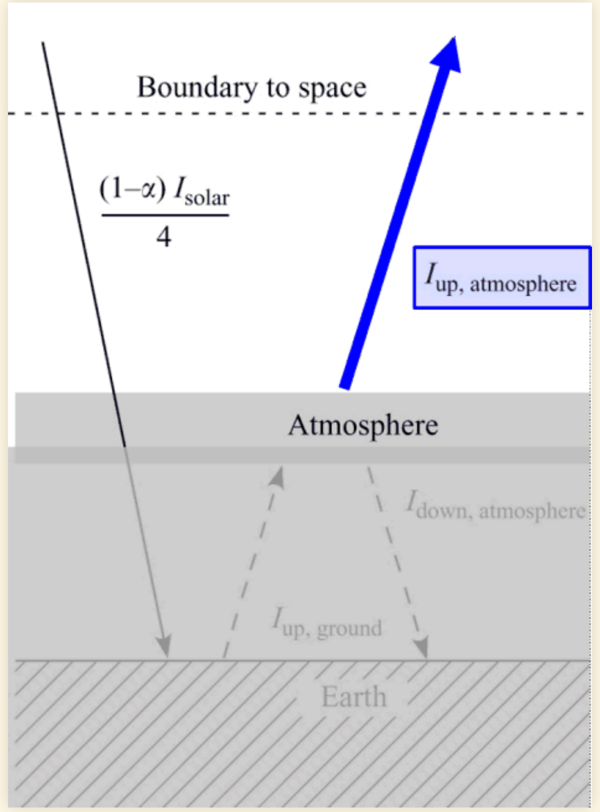
  $$ T_{\text{atmos}} = \sqrt[4]{\frac{(1-\alpha)\,I_{\text{solar}}}{4\varepsilon\sigma}} $$



Balance of energy for earth system

$$\large T_{\text{atmos}} = \sqrt[4]{\frac{(1-\alpha)\,I_{\text{solar}}}{4\varepsilon\sigma}}$$

- Just like bare rock model!
- We call this the **skin temperature**



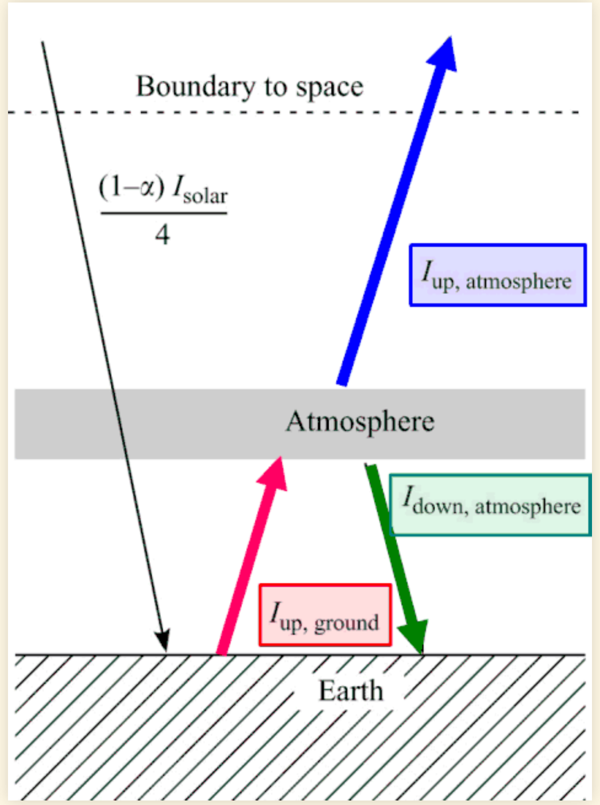
The Atmosphere as Earth's Skin

- The atmosphere is like a thin skin around the planet
  - Proportionally, it's like the skin on a peach
- The whole atmosphere emits longwave radiation, at every altitude
  - For simplicity, we sometimes pretend that all the radiation comes from a single thin layer, and call this the "skin".

Balance of energy for atmosphere

Atmosphere: $\text{Heat}_{\text{in}} = \text{Heat}_{\text{out}}$

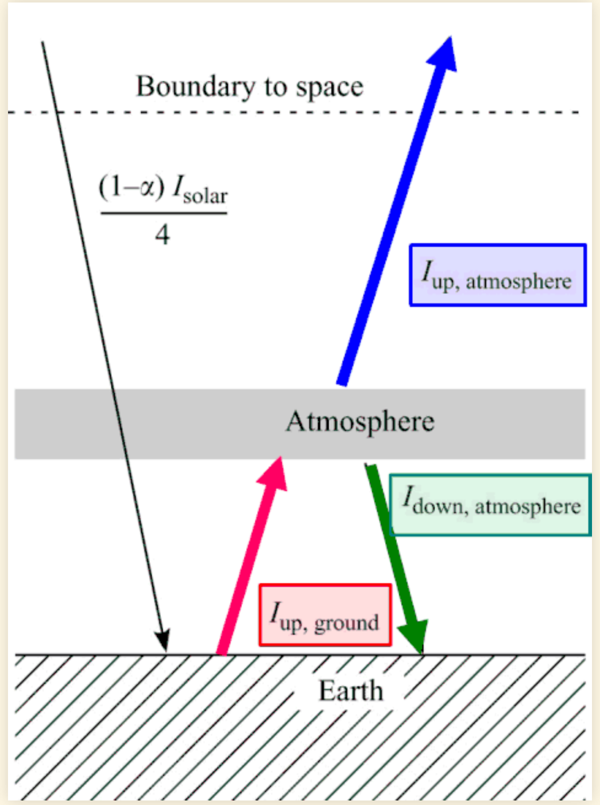
$$\begin{align*} \color{red}{I_{\text{up,ground}}} &= \color{blue}{I_{\text{up,atm}}} + \color{darkgreen}{I_{\text{down,atm}}}\\ \end{align*}$$



Balance of energy for atmosphere

Atmosphere: heat in = heat out.

\[\begin{align*} \color{red}{I_{\text{up,ground}}} &= \color{blue}{I_{\text{up,atm}}} + \color{darkgreen}{I_{\text{down,atm}}}\\ \color{blue}{I_{\text{up,atm}}} &= \color{darkgreen}{I_{\text{down,atm}}} = \varepsilon \sigma \color{darkcyan}{T^4_{\text{atm}}}\\ \end{align*} \]



Balance of energy for atmosphere

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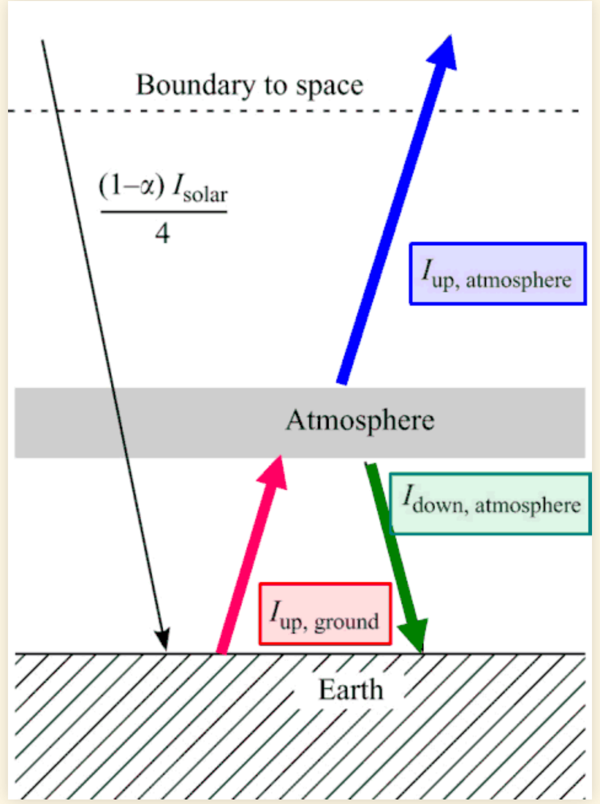

Balance of energy for atmosphere

Atmosphere: heat in = heat out.

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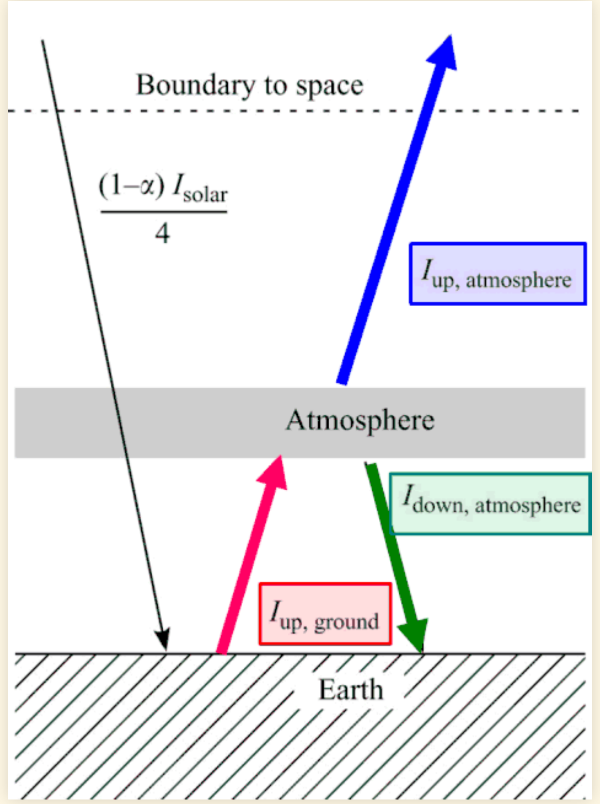


Principles:

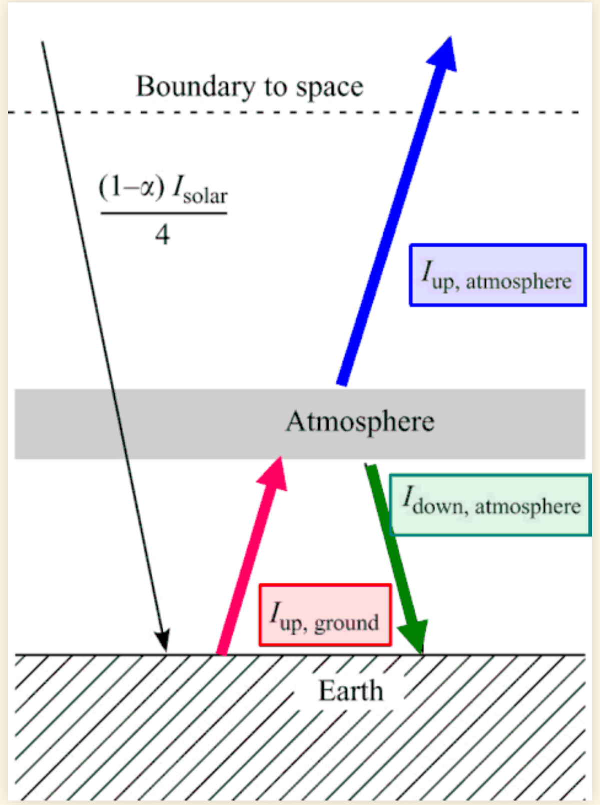
- Start at the top.
- For each layer, $\text{Heat}_{\text{out, up}} = \text{Heat}_{\text{out, down}}$
- Each layer balances $\text{Heat}_{\text{in, total}} = \text{Heat}_{\text{out, total}}$
  - Each layer has uniform temperature:
    - The top and bottom of the layer have the same temperature.
    - So the intensity emitted from the top and bottom is the same.
- The bottom layer of the atmosphere tells us $\text{Heat}_{\text{up, ground}}$
- Get ground temperature from $\text{Heat}_{\text{up, ground}}$

Finish the problem

$$\begin{align} \varepsilon \sigma \color{red}{T_{\text{ground}}^4} &= 2 \varepsilon \sigma \color{darkcyan}{T_{\text{atm}}^4}\\ \color{red}{T_{\text{ground}}^4} &= 2 \color{darkcyan}{T_{\text{atm}}^4}\\ \color{red}{T_{\text{ground}}} &= \sqrt[4]{2}\, \color{darkcyan}{T_{\text{atm}}}\\ &= 1.19 \color{darkcyan}{T_{\text{atm}}} \end{align}$$

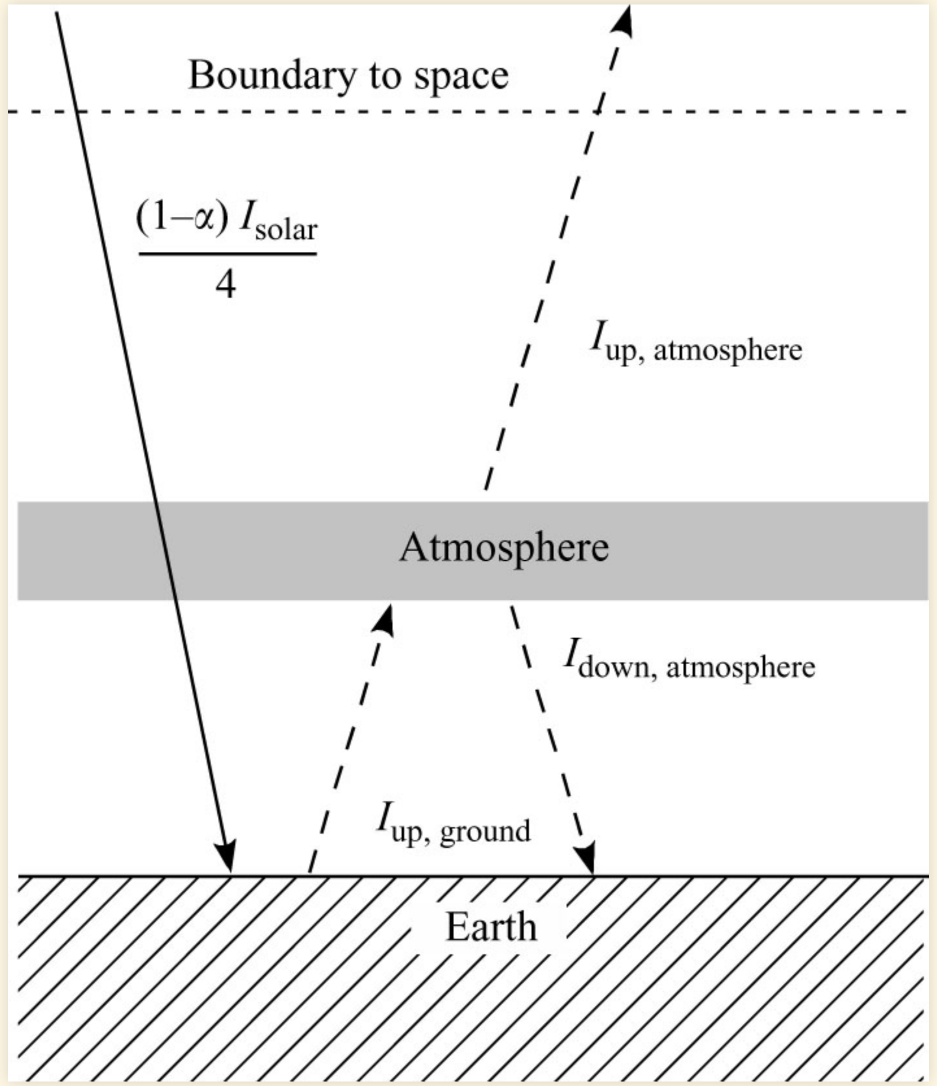
- Skin temp: ${\color{darkcyan}T_{\text{atm}}} = {\color{darkcyan}T_{\text{skin}}} = {\color{darkcyan}T_{\text{bare rock}}} = {\color{darkcyan}254~K}$
- Ground temp (1-layer): ${\color{red}T_{\text{ground}}} = \sqrt[4]{2} {\color{darkcyan}T_{\text{atm}}} = {\color{red}302~K}$
- Difference: $\text{Greenhouse effect} = 48~K$

Note: These numbers are slightly different from what's in the book. Don't worry about that.



1-Layer Model Summary

- When **shortwave radiation** hits surface:
  - Fraction α is *reflected*.
  - Fraction $1 - \alpha$ is *absorbed*.
- When **longwave radiation** hits surface or layer of atmosphere:
  - 100% is *absorbed*.
- When radiation is absorbed:
  - It transforms from **radiative energy** to **thermal energy**.
  - It stops behaving like *radiation*.
  - It becomes *vibrations of the molecules* in the dirt, water, or atmosphere.
- Separately from radiation being absorbed:
  - **Thermal radiation** is emitted from hot objects.
- Greenhouse effect *is not longwave radiation **reflecting** off atmosphere*
  - **Longwave radiation** is absorbed by atmosphere
  - **Radiation** changes into **thermal energy** in air molecules.
    - Air molecules get *hotter*.
  - Later, **air molecules** give off **thermal radiation**
    - This radiation is *different* to the radiation they absorbed.



Solving Layer Model Problems

General Principles:

Start at the top and work down:

1. Balance budget at boundary to space
   - Get “skin temperature” (top layer)
2. Balance budget at top layer of atmosphere
   - Get temp. of next layer down (2^{nd} from top)
3. Balance budget at next layer of atmosphere
   - Get temp. of next layer down (3^{rd} from top)
4. …
5. Balance budget at bottom layer of atmosphere
   - This gives surface (ground) temperature.

As long as the albedo and the solar constant don’t change, ***the skin temperature is always the same*** for all models: 254 K.

— *Understanding the Forecast*, p. 25.

“Balance the Budget”

$\text{Heat}_{\text{in}} = \text{Heat}_{\text{out}}$

- Nature balances the budget automatically.
- We use this fact to find the ground temperature.
- If you know that $\text{Heat}_{\text{in}} = \text{Heat}_{\text{out}}$, you can figure out the intensities you don’t know.
- If you know the intensity of heat going out of something, you know its temperature.

Terrestrial Planets

Earth, Mars, Venus

	Earth	Mars	
\(\text{Solar constant}\)	\ (1350~\mathrm{W}/\mathrm{m}^2\)	\ (600~\mathrm{W}/\mathrm{m}^2\)	(2604~\mathrr
\(\text{Albedo}\)	\(0.30\)	\(0.17\)	
\(T_{\text{radiative}}\)	\(254~\mathrm{K}\)	\(216~\mathrm{K}\)	\(240~
\ (\text{Actual}~T_{\text{surface}}\)	\(288~\mathrm{K}\)	\(240~\mathrm{K}\)	\(700~
One-Layer \(T_{\text{surface}}\)	\(302~\mathrm{K}\)	\(257~\mathrm{K}\)	\(286~

Vocabulary note:

- “radiative temperature”
- “skin temperature”
- “bare rock temperature”

all mean the same thing.

Earth, Mars, Venus

	Earth	Mars	
Solar constant	$1350~\mathrm{W}/\mathrm{m}^2$	$600~\mathrm{W}/\mathrm{m}^2$	(26
Albedo	0.30	0.17	
$T_{\text{radiative}}$	$254~\mathrm{K}$	$216~\mathrm{K}$	
$\text{Actual}~T_{\text{surface}}$	$288~\mathrm{K}$	$240~\mathrm{K}$	
One-Layer T_{surface}	$302~\mathrm{K}$	$257~\mathrm{K}$	
Difference	$14~\mathrm{K}$	$17~\mathrm{K}$	

One-layer model works pretty well for Earth.

Slightly worse for Mars

Terribly for Venus.

Earth, Mars, Venus

	Earth	Mars	
Solar constant	$1350~\mathrm{W}/\mathrm{m}^2$	$600~\mathrm{W}/\mathrm{m}^2$	(26
Albedo	0.30	0.17	
$T_{\text{radiative}}$	$254~\mathrm{K}$	$216~\mathrm{K}$	
$\text{Actual}~T_{\text{surface}}$	$288~\mathrm{K}$	$240~\mathrm{K}$	
One-Layer T_{surface}	$302~\mathrm{K}$	$257~\mathrm{K}$	
Difference	$14~\mathrm{K}$	$17~\mathrm{K}$	
Atmospheric pressure	$1013~\text{mb}$	$6~\text{mb}$	

1013 mb is Earth’s average air pressure at sea-level

- 1-layer model: The atmosphere is like a thin layer that absorbs 100% of longwave radiation.
- Not quite true for Earth. Some longwave radiation gets through to space.
- Mars’s atmosphere is so thin, it’s less opaque than Earth’s.
- Venus’s atmosphere is so thick, it’s like many layers.