Introducing the Greenhouse Effect

EES 3310/5310

Global Climate Change

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Class #4: Wed. Aug. 29 2018

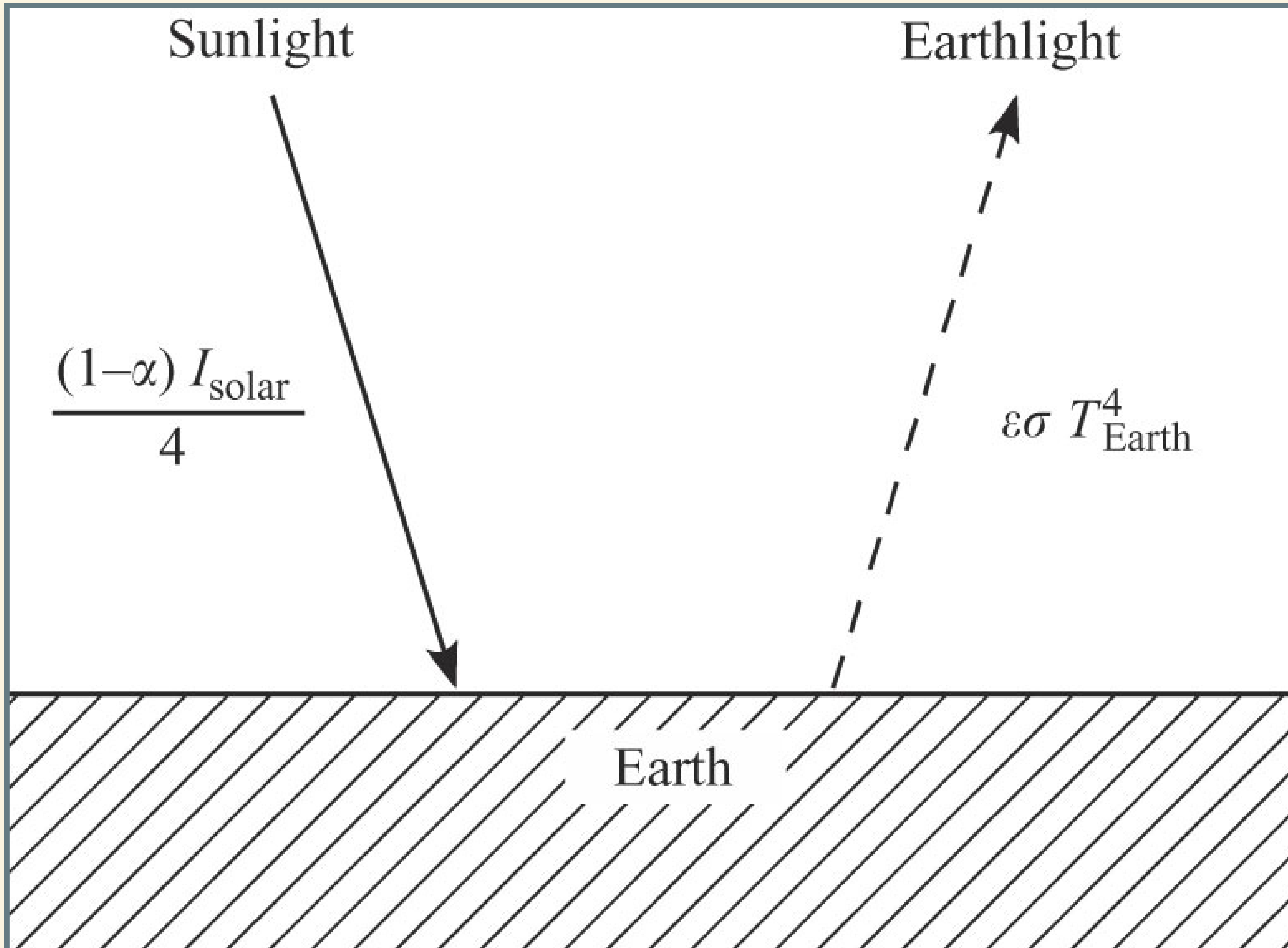
Basic Principles from Monday

- **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

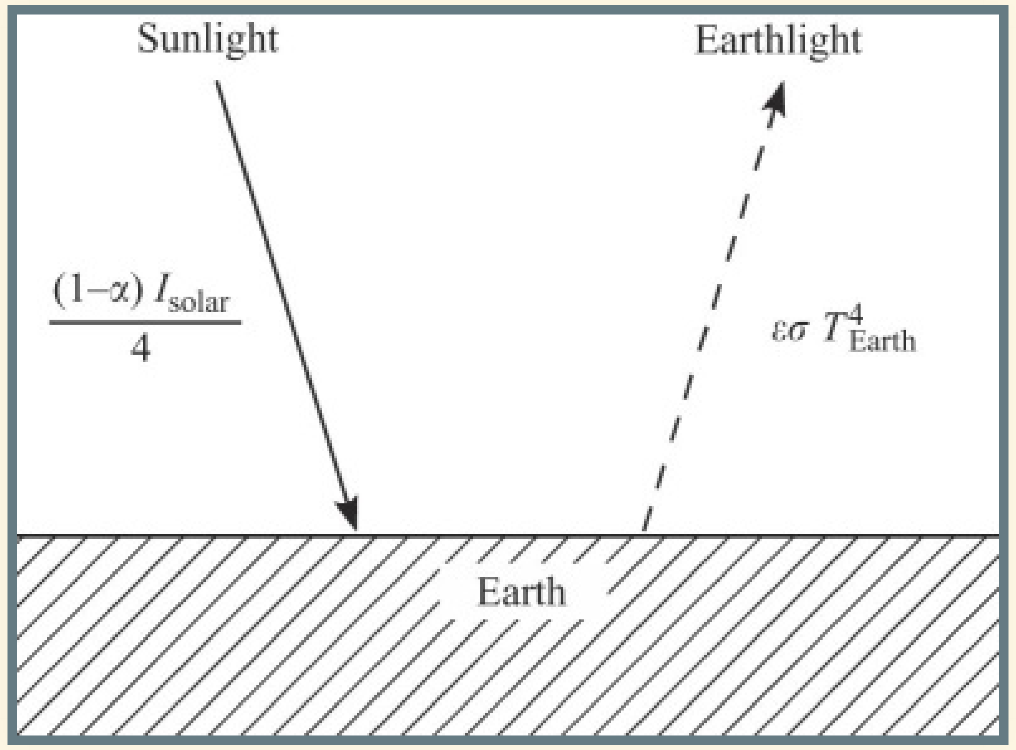
$$\text{Heat}_{\text{out}} = \text{Heat}_{\text{in}}$$

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,

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

3. $F_{\text{out}} = \varepsilon \sigma T^4$.
4. Solve for T:

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

$$\begin{aligned} I_{\text{solar}} &= 1350 \text{ W/m}^2 \\ \alpha &= 0.30 \\ \varepsilon &= 1 \\ \sigma &= 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \\ T &= 254 \text{ K} = -19^\circ\text{C} = -2^\circ\text{F} \end{aligned}$$

If the sun got 5% brighter, how much warmer would the earth become?

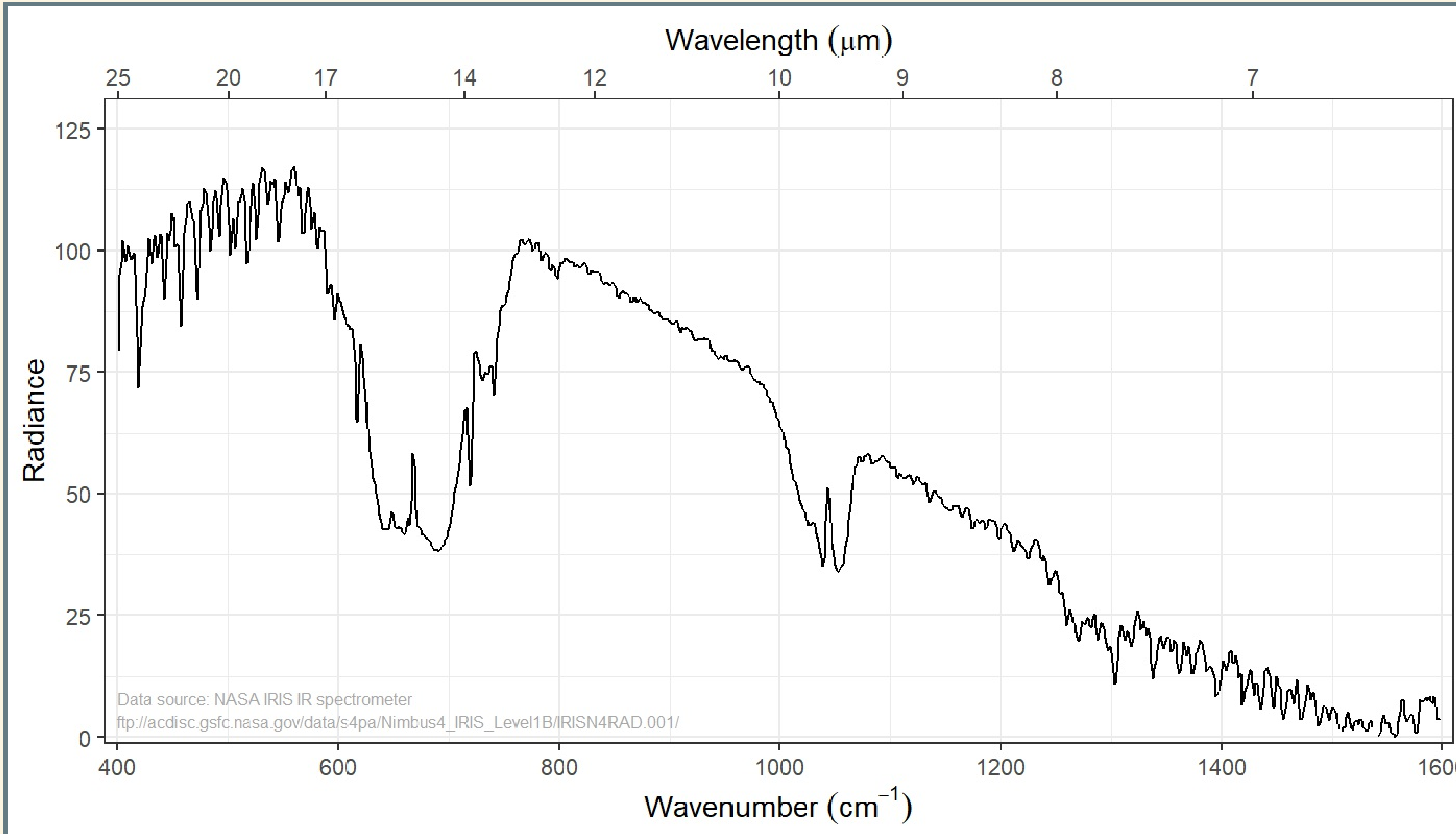
$$T = \sqrt[4]{\frac{(1-\alpha)I_{\text{in}}}{4\varepsilon\sigma}}$$

- **Normal:**
  - $I_{\text{in}} = 1350\ \text{W}/\text{m}^2$
  - $T = 254\ \text{K}$
- **5% Brighter:**
  - $I_{\text{in}} = 1.05 \times 1350\ \text{W}/\text{m}^2 = 1418\ \text{W}/\text{m}^2$
  - $T = 257\ \text{K}$
- $\Delta T = 3\ \text{K} = 6^\circ\text{F} = 1.2\%$ warmer

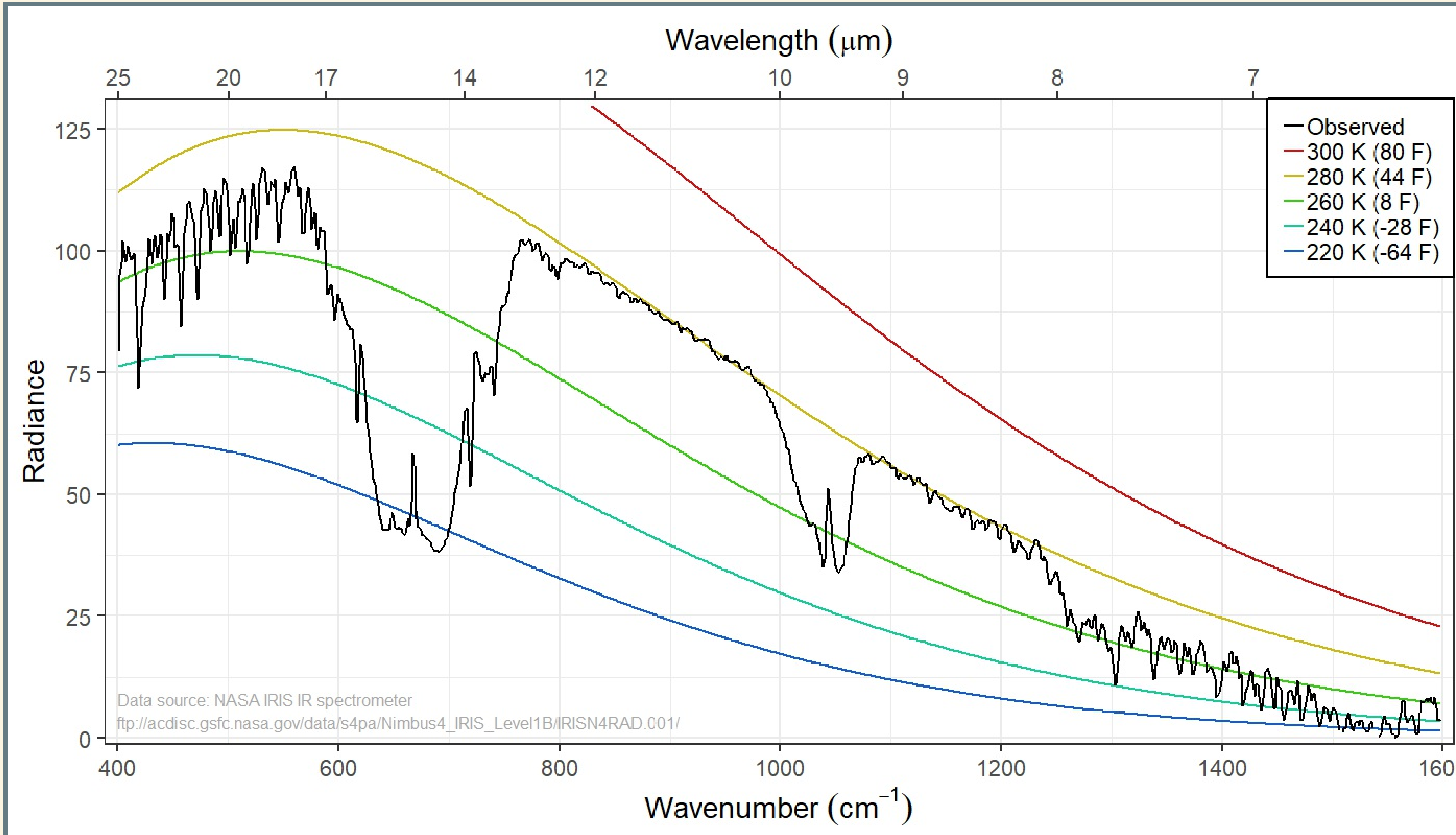
Terrestrial Planets

	Earth	Mars	Venus
Distance from sun	1 AU	1.5 AU	0.72 AU
$1/\text{Distance}^2$	1.00	0.44	1.9
Solar constant	$1350\ \text{W}/\text{m}^2$	$600\ \text{W}/\text{m}^2$	$2604\ \text{W}/\text{m}^2$
Albedo	0.30	0.17	0.71
$T_{\text{bare rock}}$	254 K (-2°F)	216 K (-70° F)	240 K (-27° F)
T_{surface}	295 K (71° F)	240 K (-28° F)	700 K (800° F)
Δ_T	41 K (74° F)	24 K (42° F)	460 K (828° F)

Oops! We forgot the atmosphere!

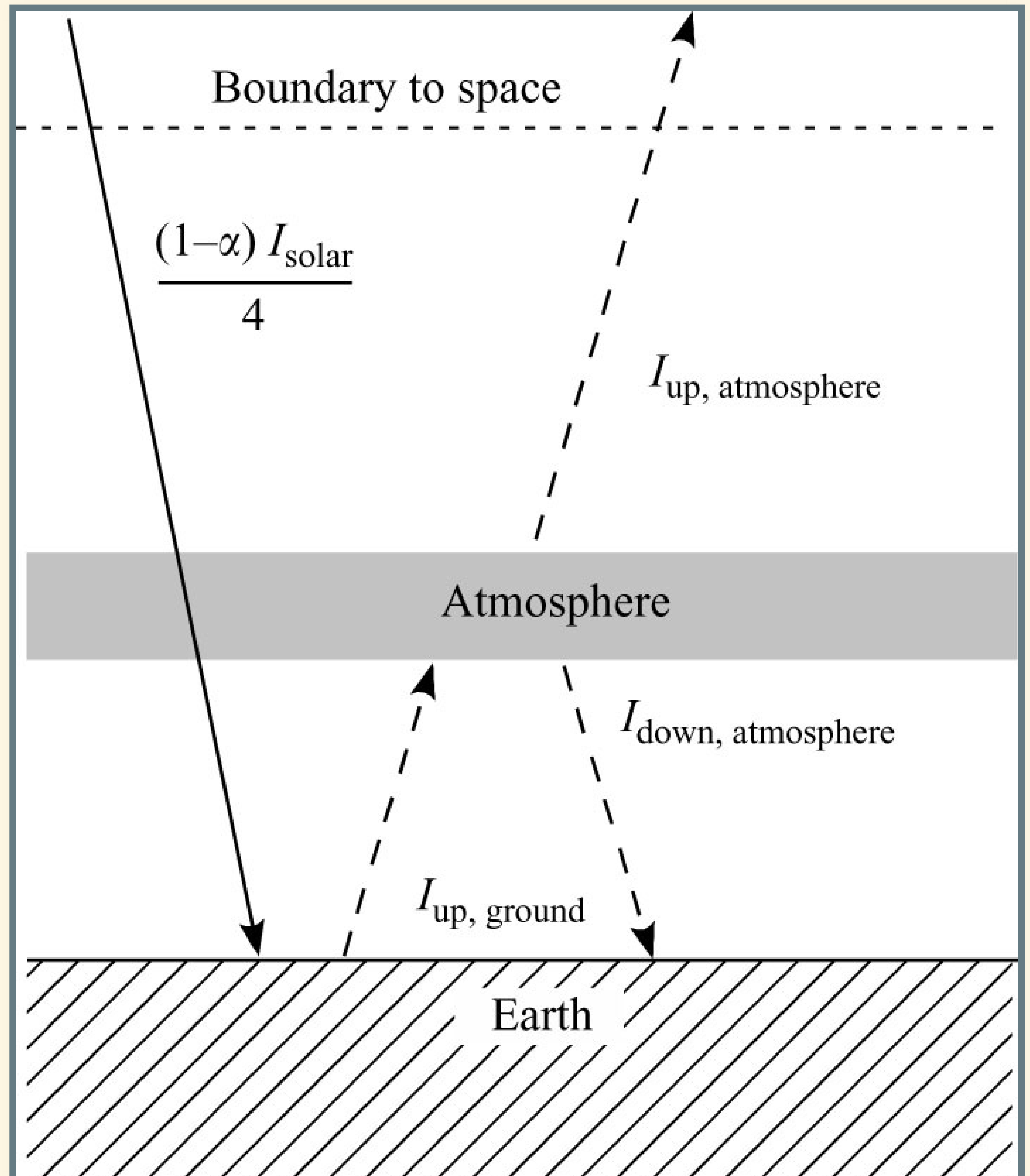


Does Earth look like a blackbody?



One-Layer Model of the Greenhouse Effect

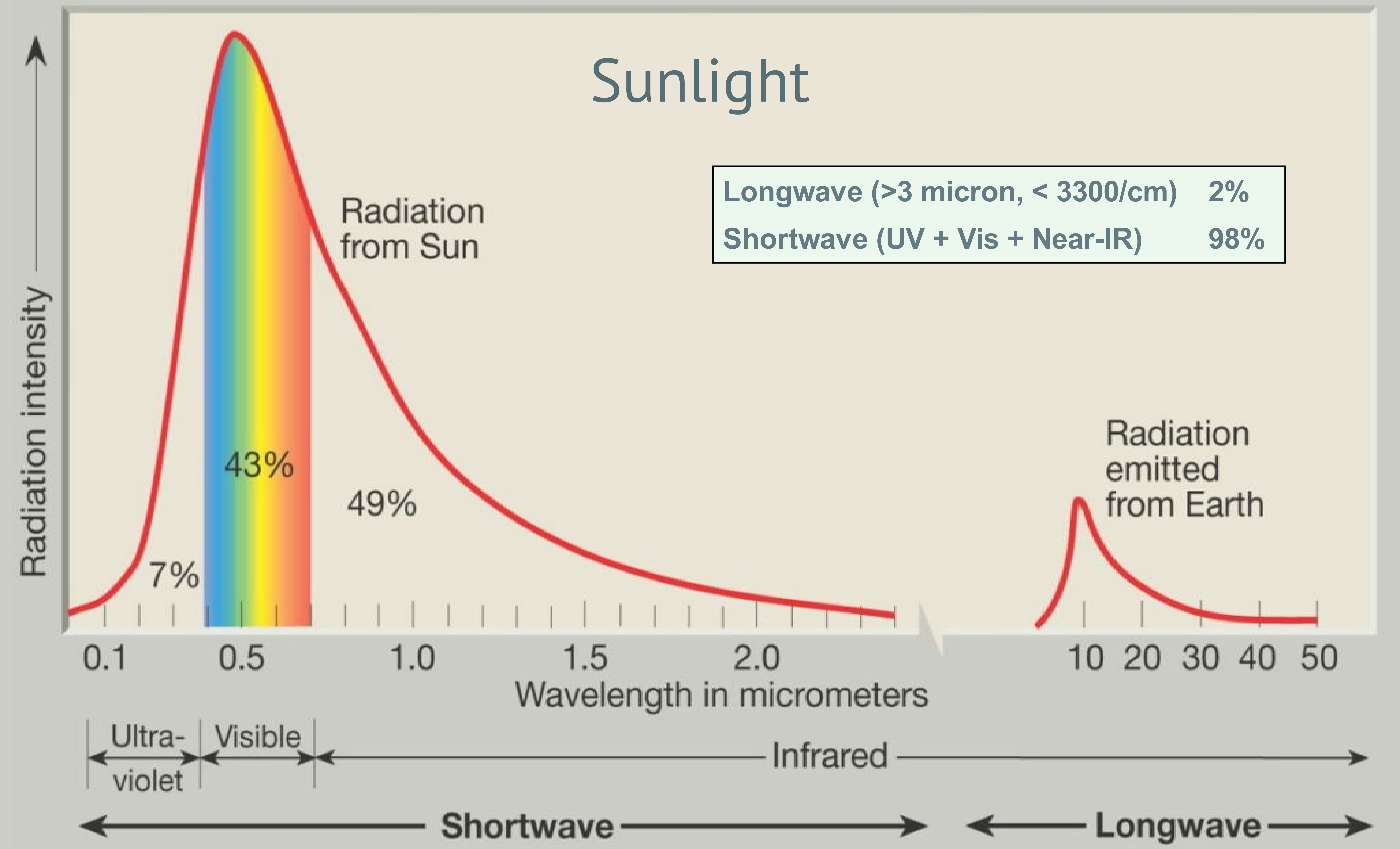
Layer Model



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

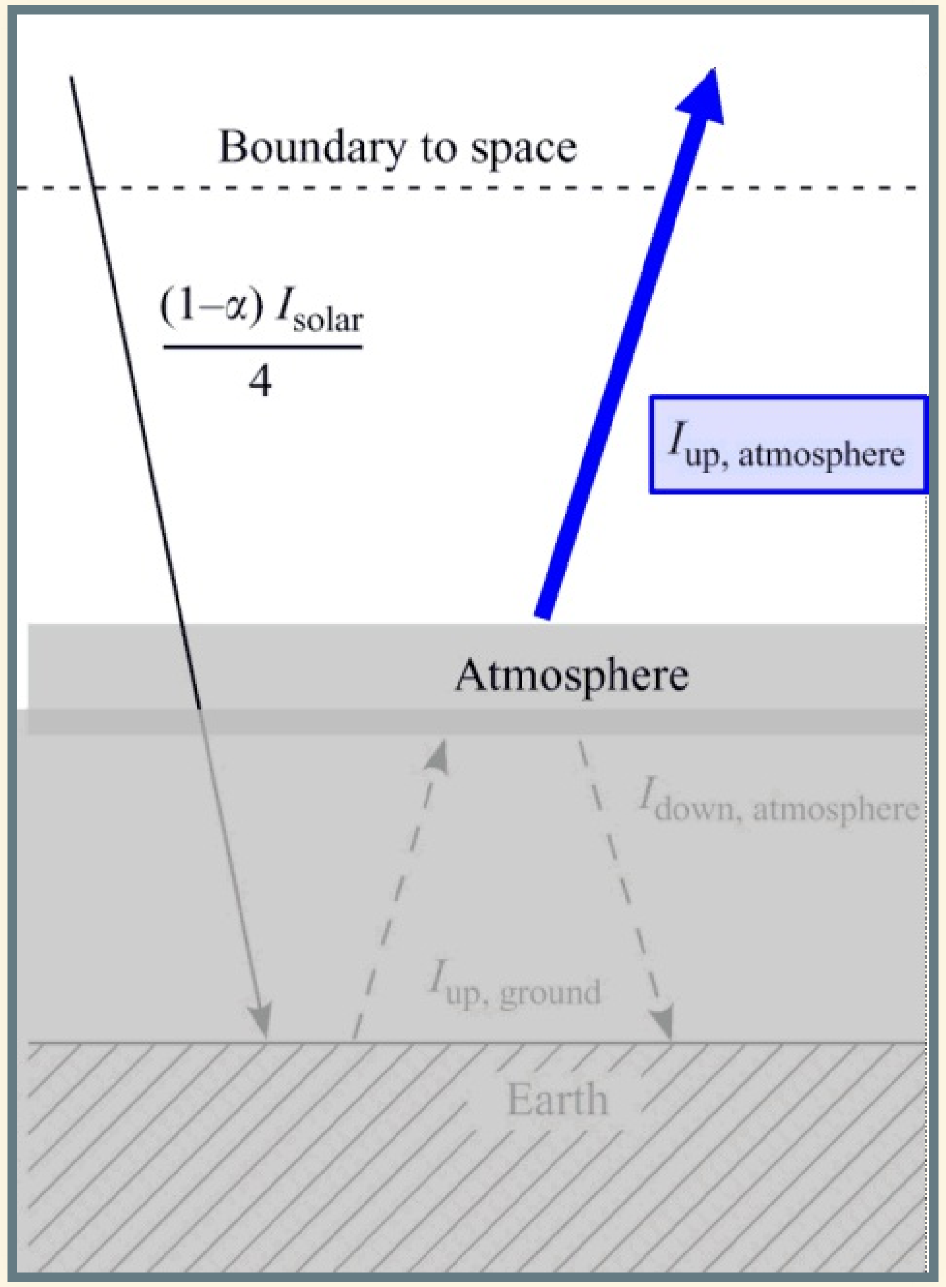
- At top of atmosphere: $F_{\text{out}} = F_{\text{in}}$

$$I_{\text{up, atmos}} = I_{\text{in}} \quad \text{(intensity of absorbed sunlight)}$$

$$\varepsilon\sigma T_{\text{atmos}}^4 = \frac{(1-\alpha) I_{\text{solar}}}{4}$$

- Aha! We can find T_{atmos}!

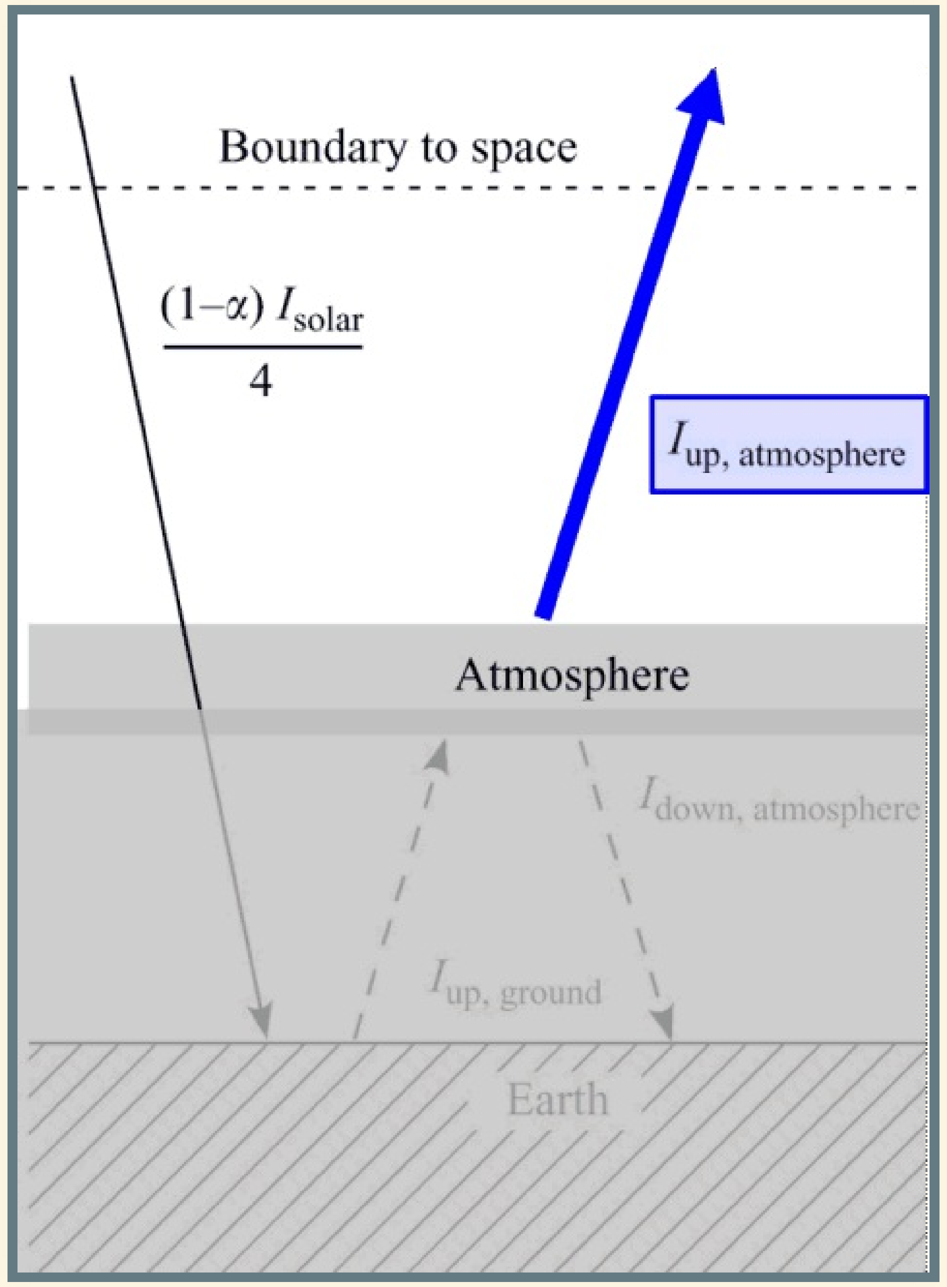
$$T_{\text{atmos}} = \sqrt[4]{\frac{(1-\alpha)\, I_{\text{solar}}}{4\varepsilon\sigma}}$$



Balance of energy for earth system

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

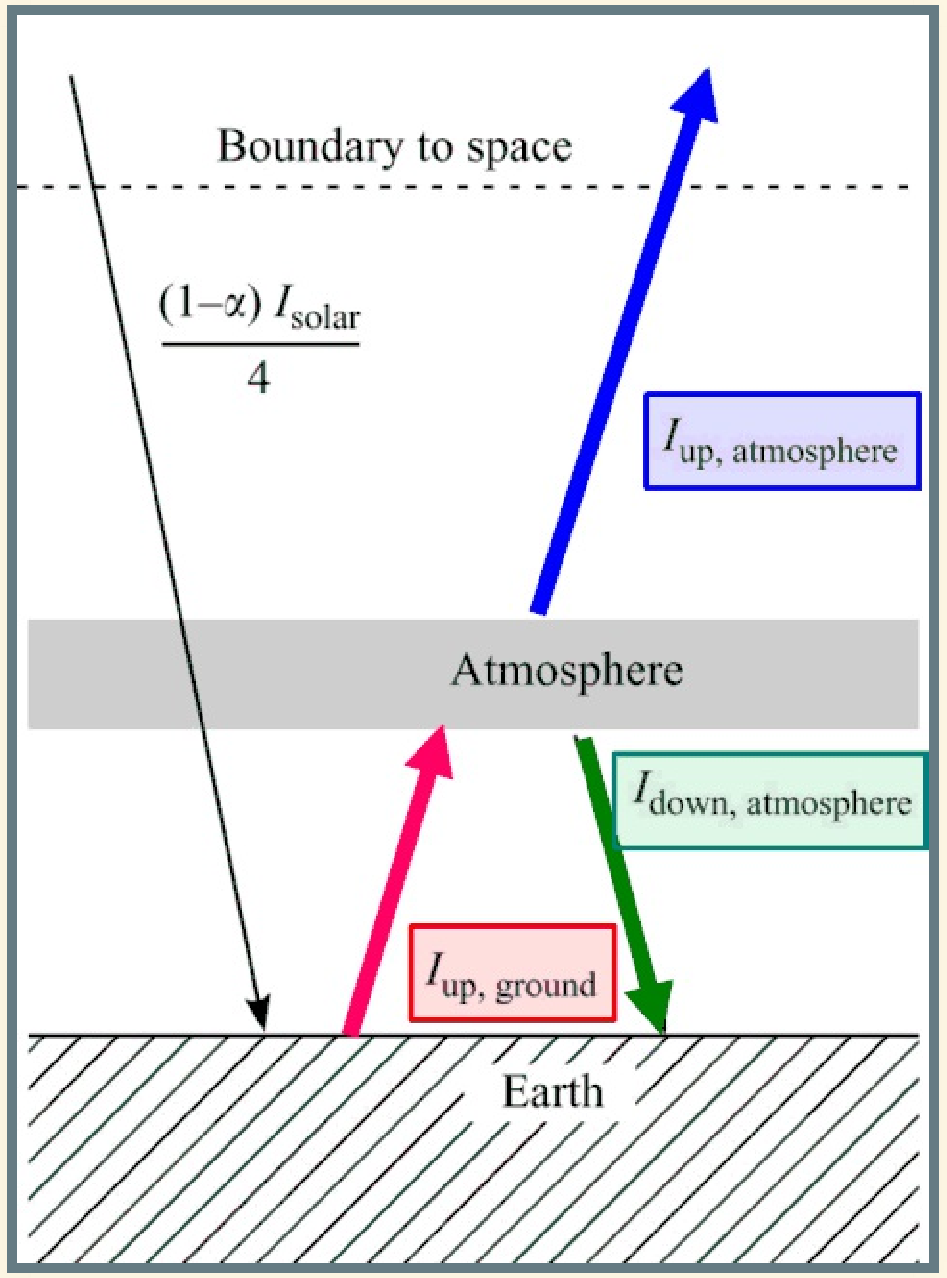
- Just like bare rock model!
- We call this the **skin temperature**



Balance of energy for atmosphere

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

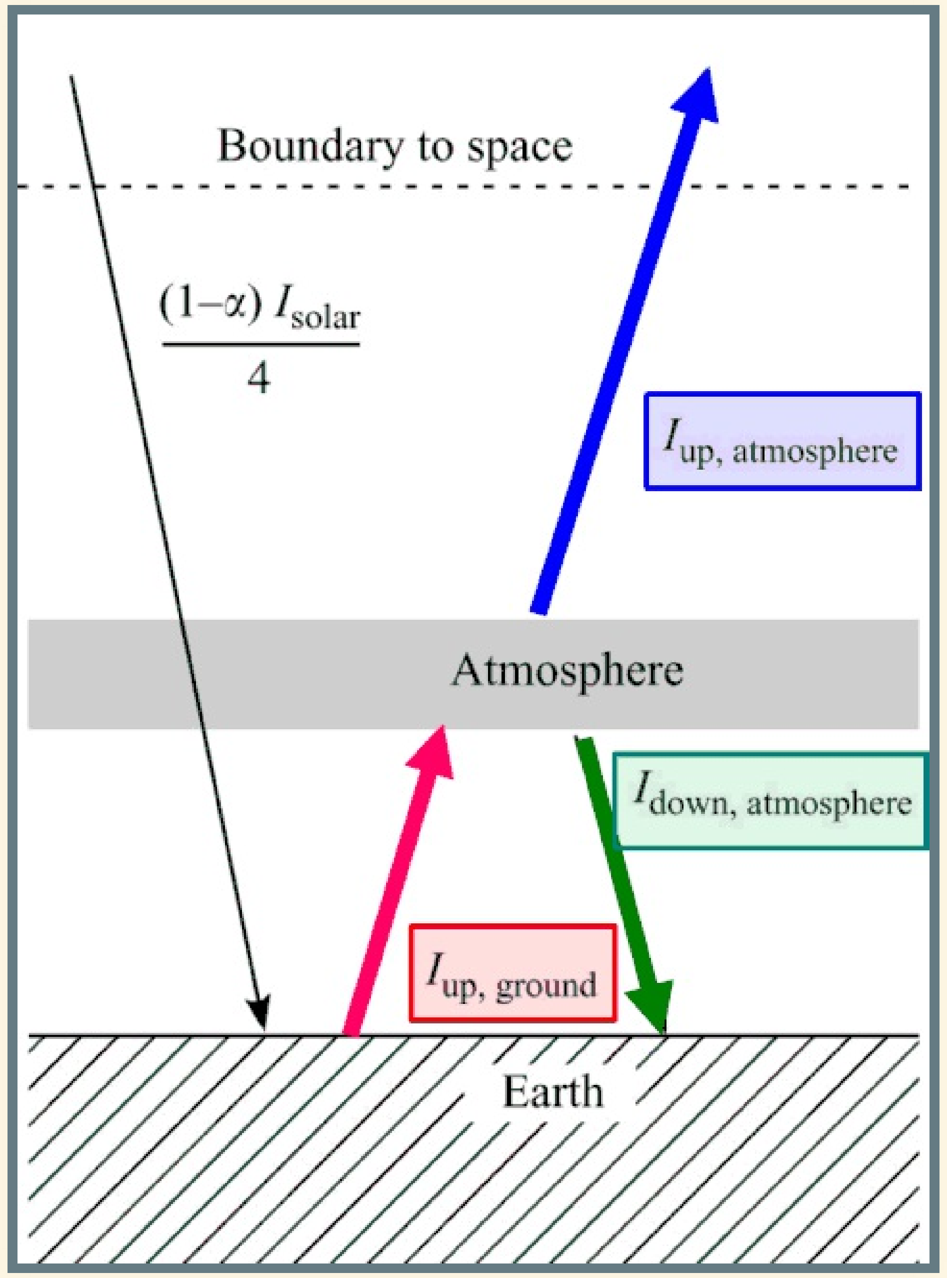
$$I_{\text{up,ground}} = I_{\text{up,atm}} + I_{\text{down,atm}}$$



Balance of energy for atmosphere

Atmosphere: heat in = heat out.

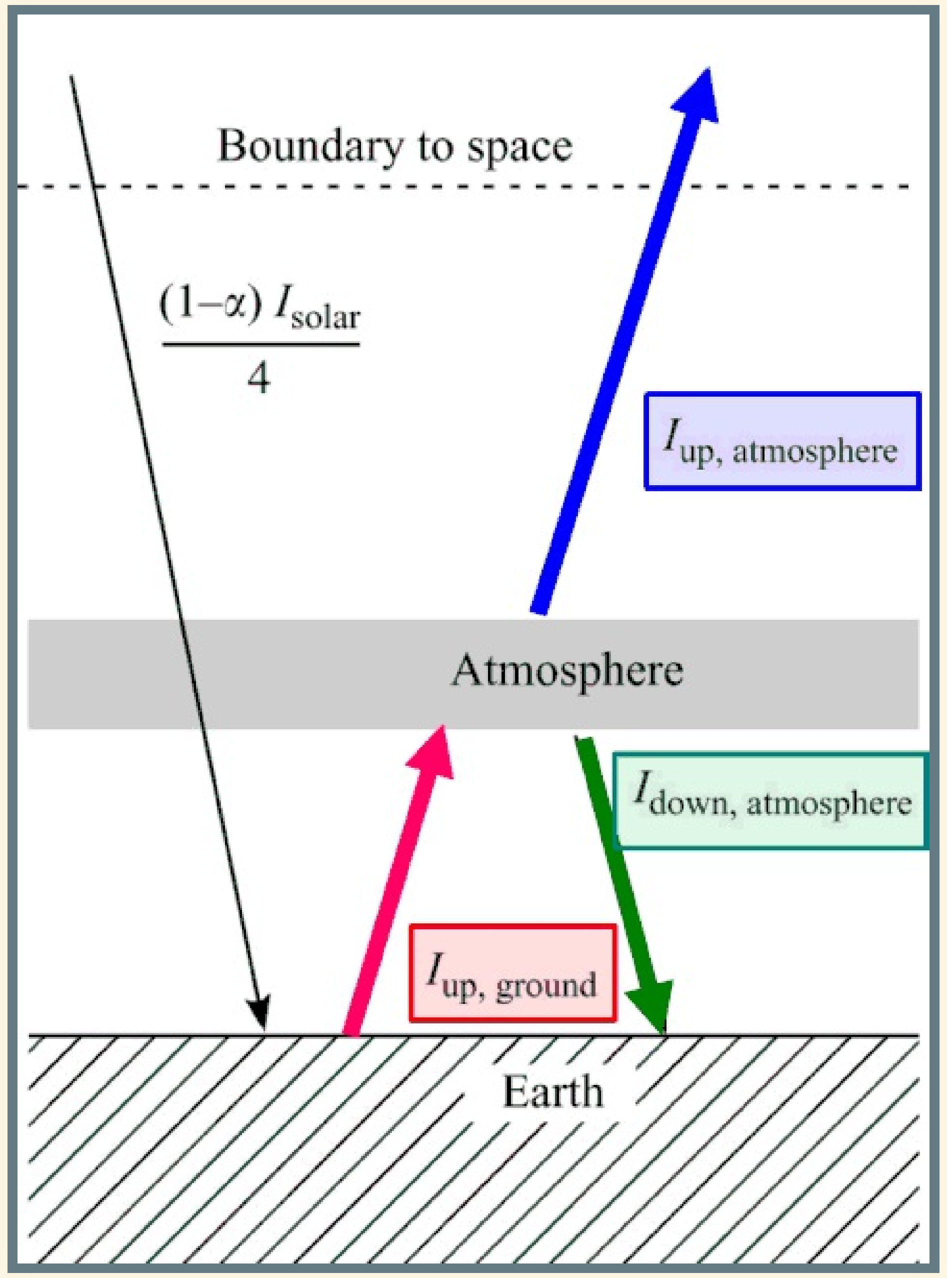
$$I_{\text{up,ground}} = I_{\text{up,atm}} + I_{\text{down,atm}}$$
$$I_{\text{up,atm}} = I_{\text{down,atm}} = \varepsilon\sigma T_{\text{atm}}^4$$



Balance of energy for atmosphere

Atmosphere: heat in = heat out.

$$I_{\text{up,ground}} = I_{\text{up,atm}} + I_{\text{down,atm}}$$
$$I_{\text{up,atm}} = I_{\text{down,atm}} = \varepsilon\sigma T_{\text{atm}}^4$$
$$I_{\text{up,ground}} = \varepsilon\sigma T_{\text{ground}}^4$$



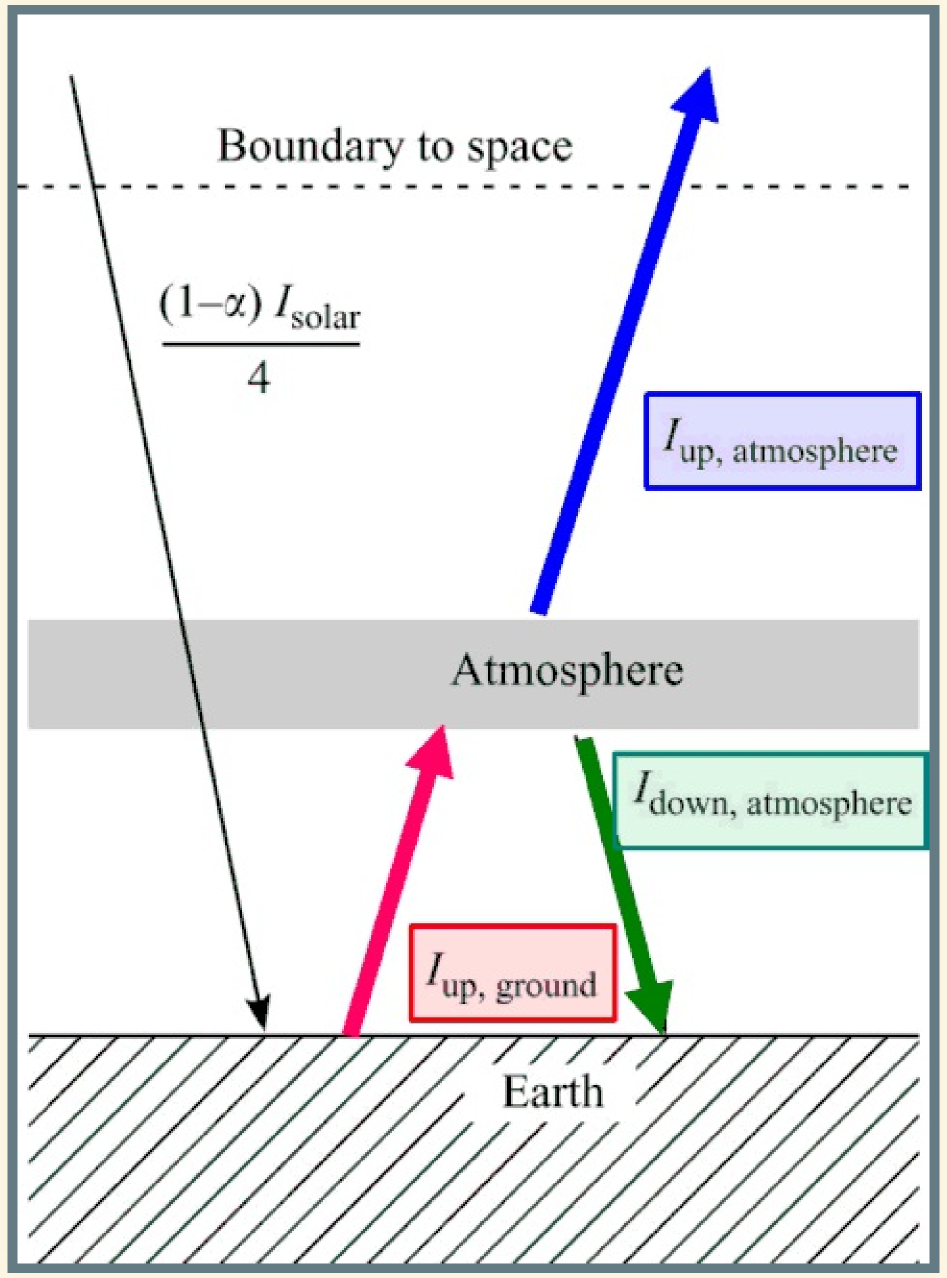
Balance of energy for atmosphere

Atmosphere: heat in = heat out.

$$
\begin{aligned}
I_{\text{up,ground}} &= I_{\text{up,atm}} + I_{\text{down,atm}} \\
I_{\text{up,atm}} &= I_{\text{down,atm}} = \varepsilon\sigma T_{\text{atm}}^4 \\
I_{\text{up,ground}} &= \varepsilon\sigma T_{\text{ground}}^4 \\
\varepsilon\sigma T_{\text{ground}}^4 &= 2\varepsilon\sigma T_{\text{atm}}^4
\end{aligned}
$$

Principles:

- Start at the top.
- For each layer, $\text{Heat}_{\text{out, up}} = \text{Heat}_{\text{out, down}}$
- Each layer balances $\text{Heat}_{\text{in, total}} = \text{Heat}_{\text{out, total}}$
- The bottom layer of the atmosphere tells us $\text{Heat}_{\text{up, ground}}$
- Get ground temperature from $\text{Heat}_{\text{up, ground}}$

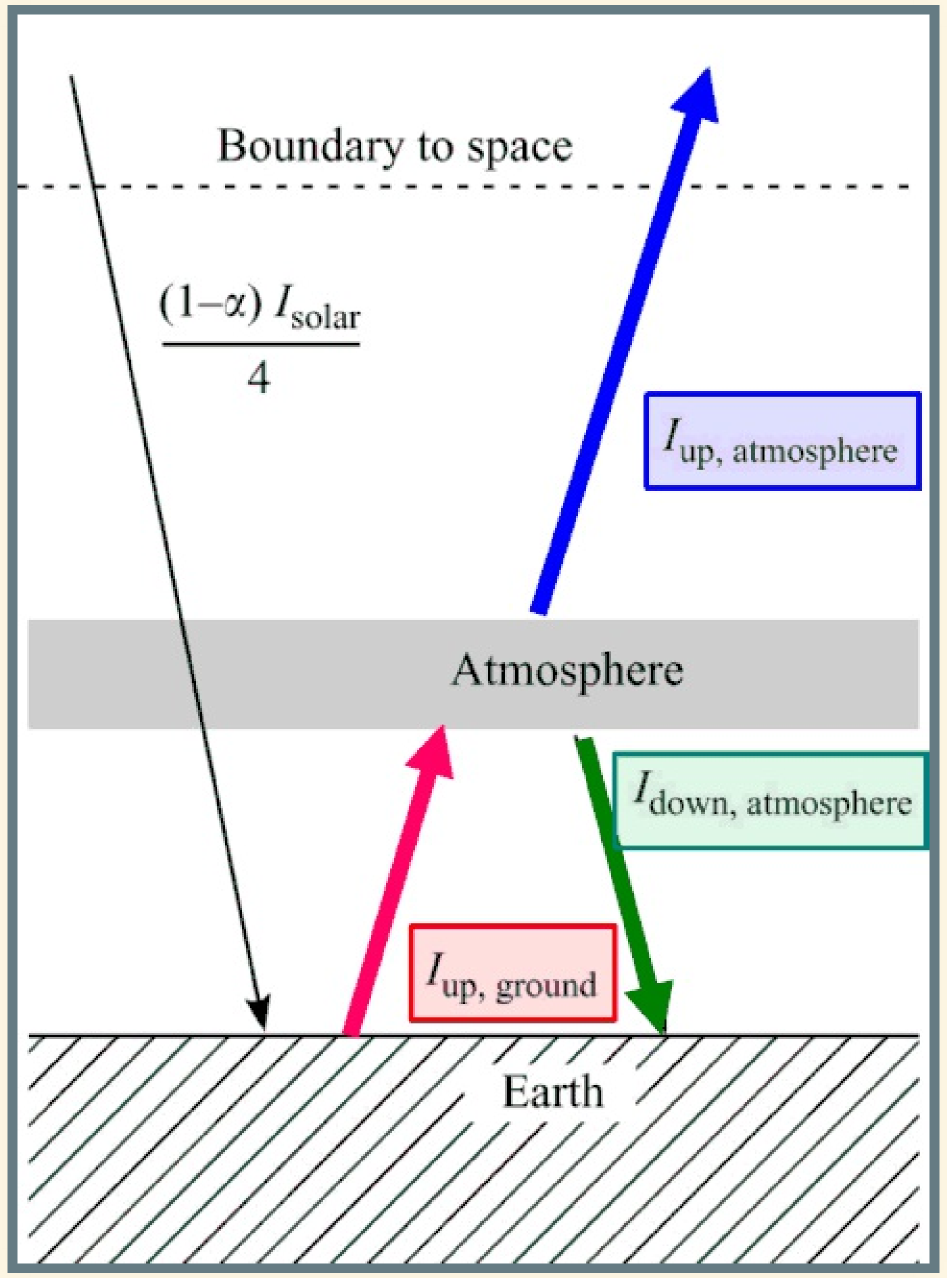


Finish the problem

$$\begin{aligned}
\varepsilon\sigma T_{\text{ground}}^4 &= 2\varepsilon\sigma T_{\text{atm}}^4 \\
T_{\text{ground}}^4 &= 2\,T_{\text{atm}}^4 \\
T_{\text{ground}} &= \sqrt[4]{2}\;T_{\text{atm}} \\
&= 1.19\,T_{\text{atm}}
\end{aligned}$$

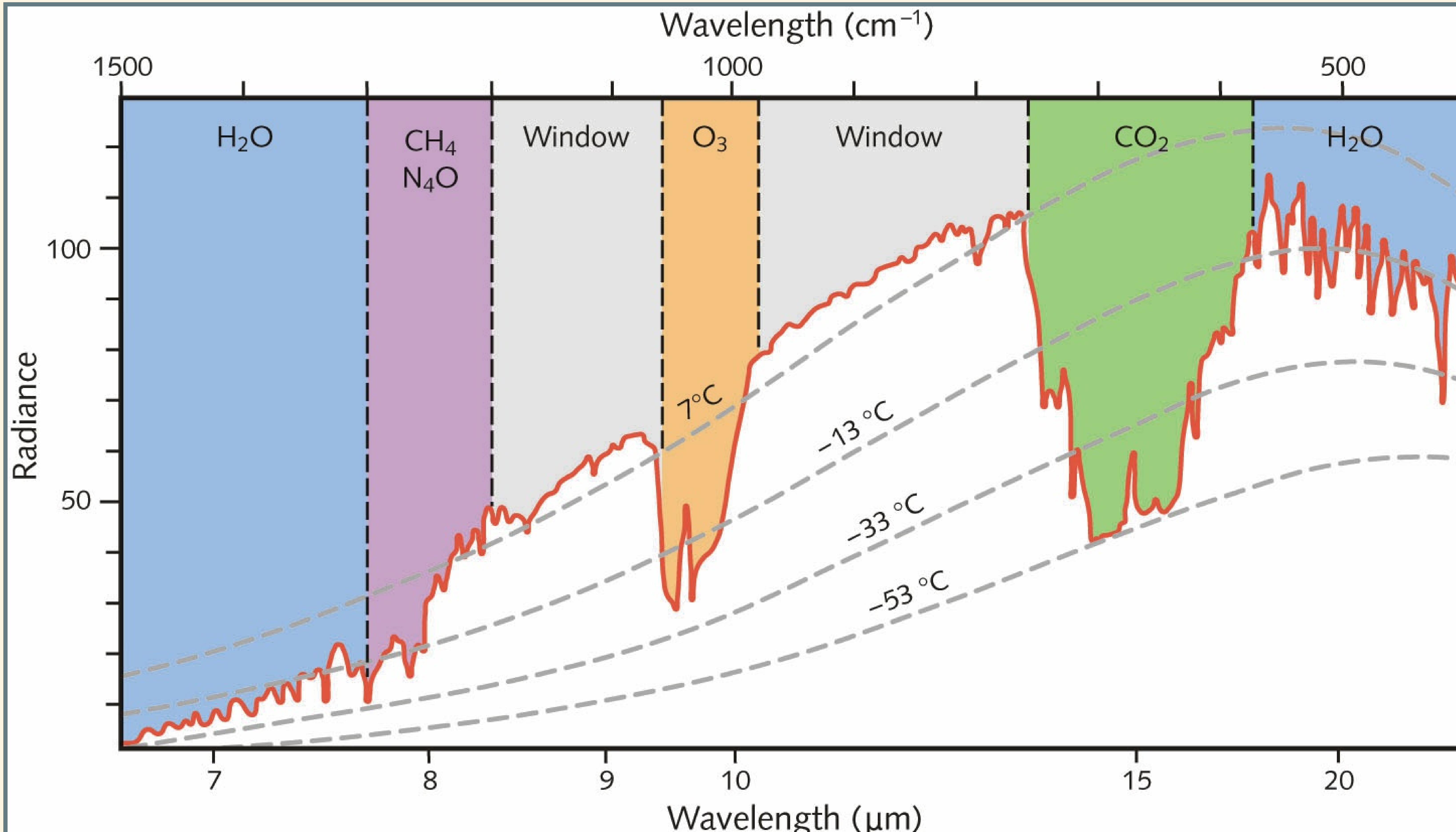
- Skin temp: $T_{\text{atm}} = T_{\text{skin}} = T_{\text{bare rock}} = 254\ K$
- Ground temp (1-layer): $T_{\text{ground}} = \sqrt[4]{2} T_{\text{atm}} = 302\ K$
- Difference: $\text{Greenhouse efffect} = 48\ K$

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

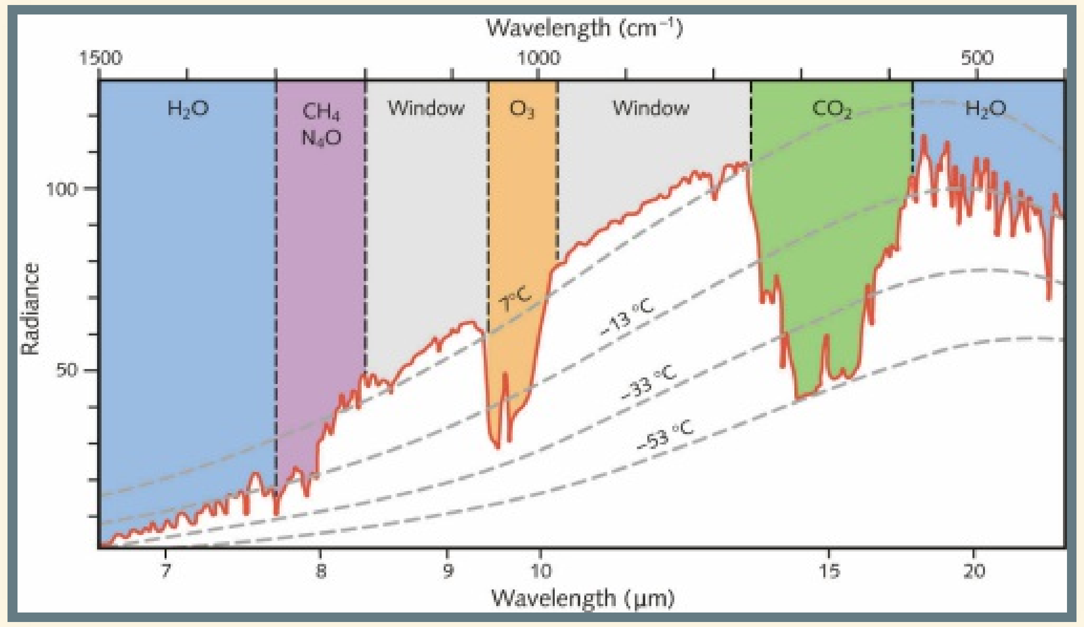


Greenhouse Gases

Greenhouse Gases



Greenhouse Gases

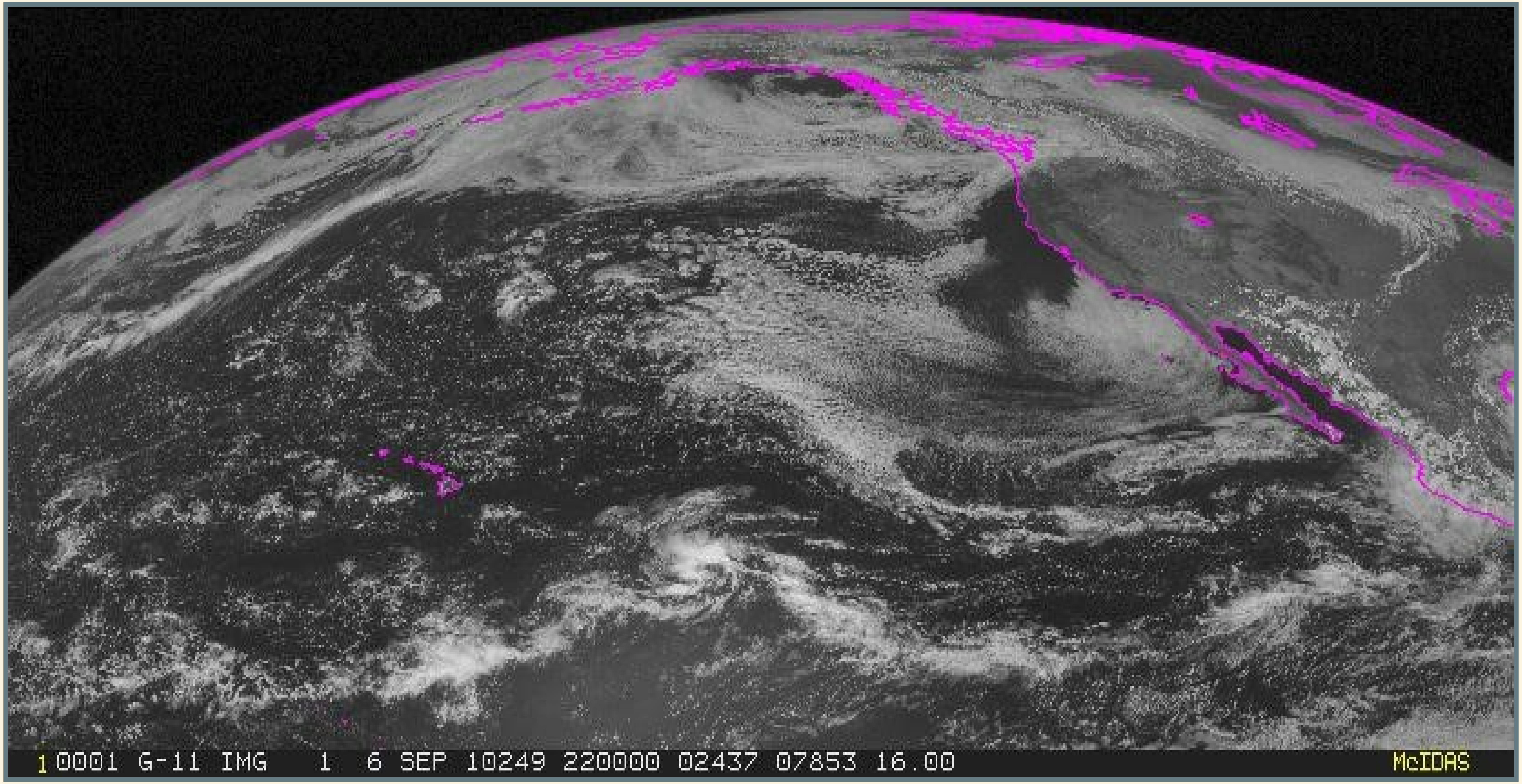


- Brightness: Stefan-Boltzmann law:
  - $I = \varepsilon \sigma T^4$
  - $\varepsilon = 1$

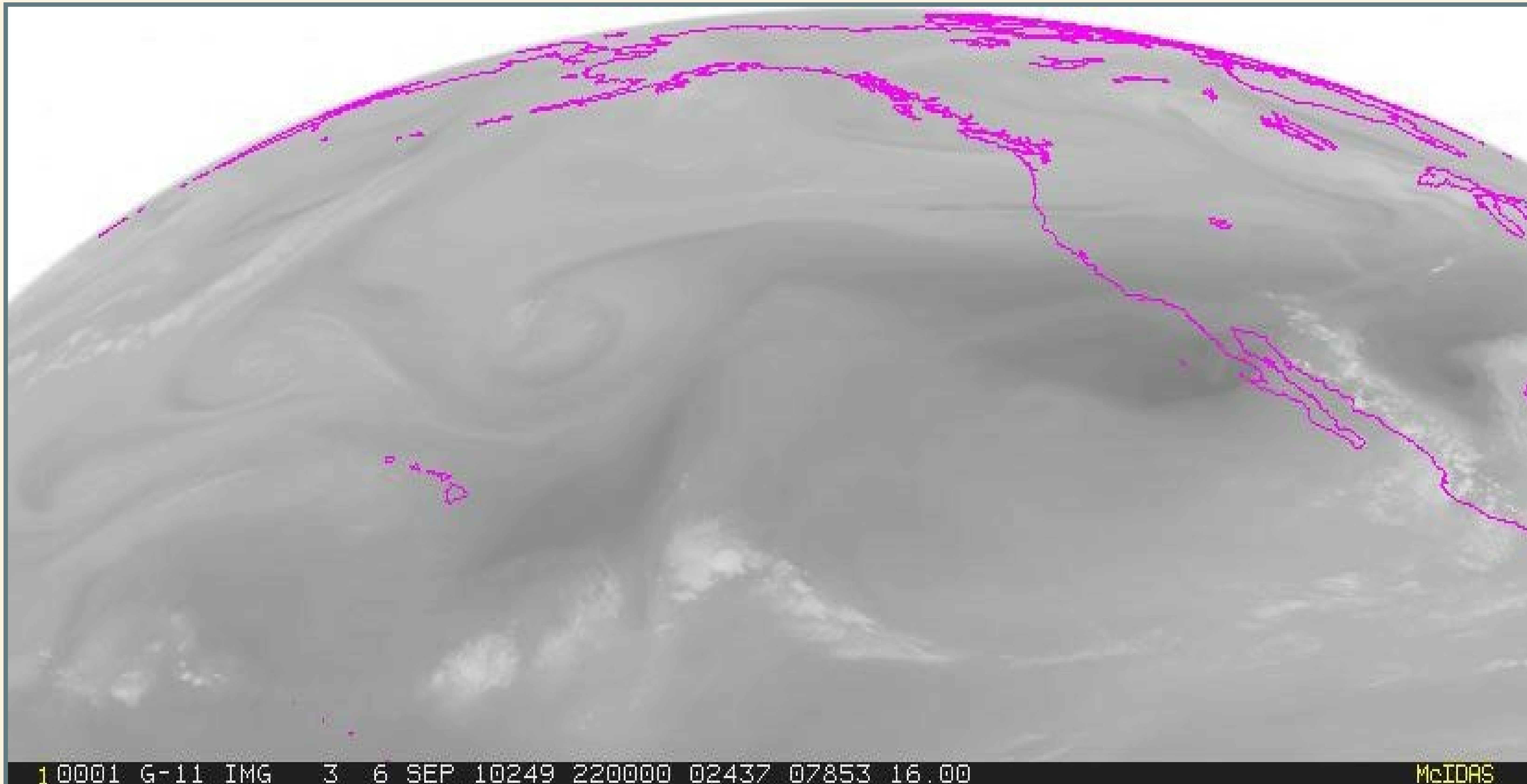
- Brighter = Hotter
- Hotter = closer to ground
  - Satellite can see through atmosphere to low altitude (hot, bright) in "window" region.
  - Satellite can see to middle-troposphere (cool) in "water vapor" region
  - Satellite can't see past top of troposphere (cold) in CO_2 region.

Earth Seen by Satellites

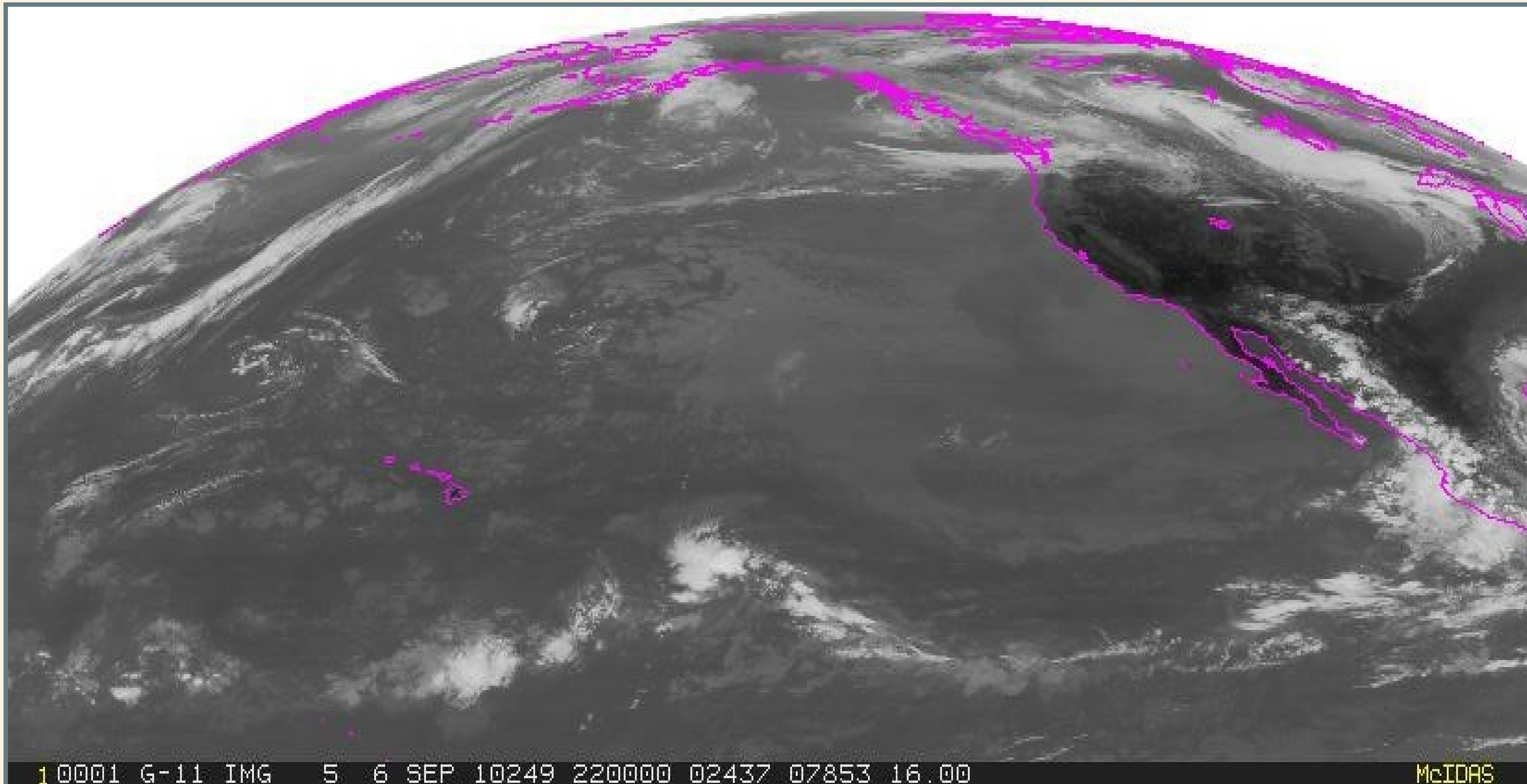
Visible



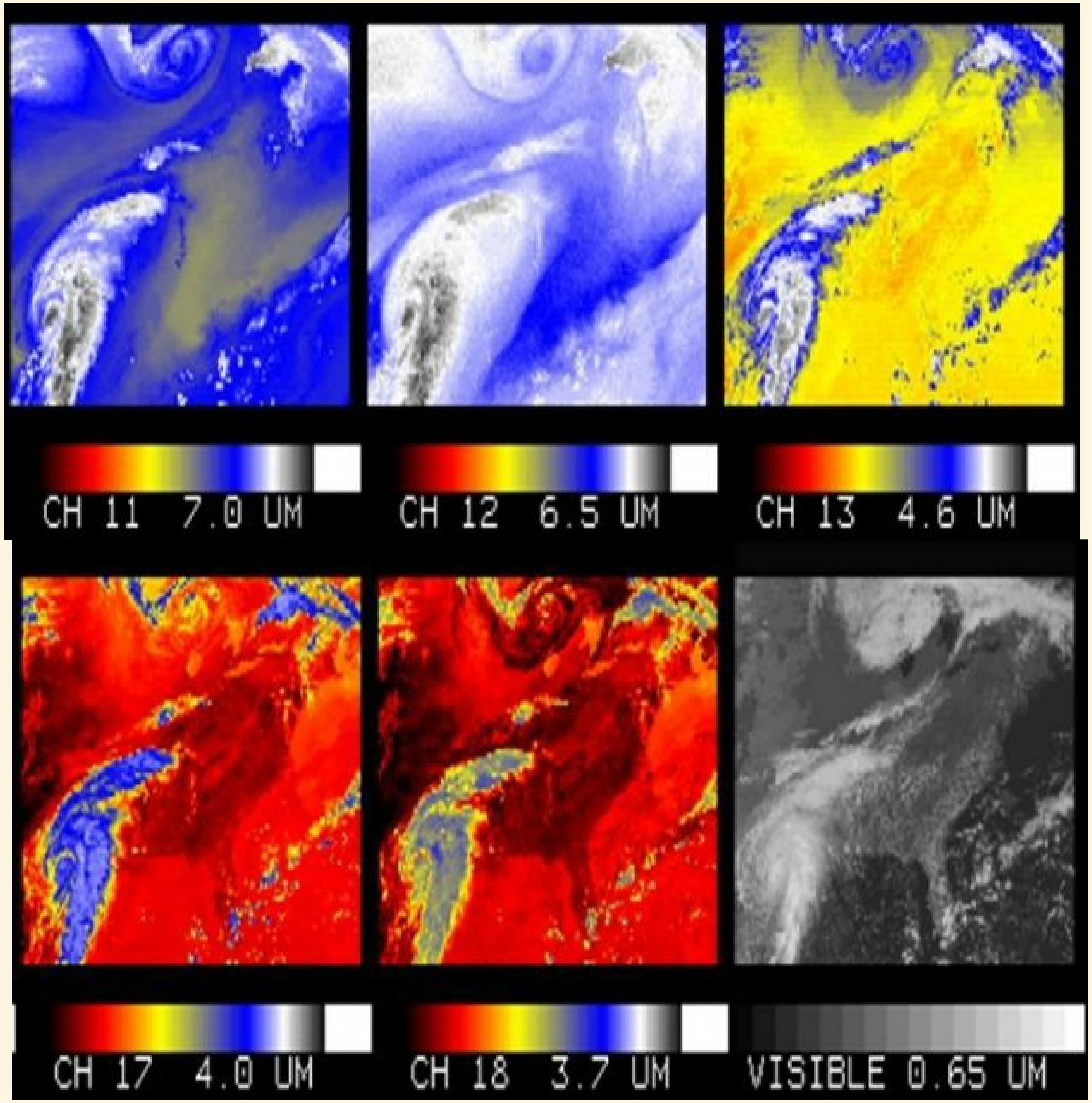
6.8 μm (Water Vapor)



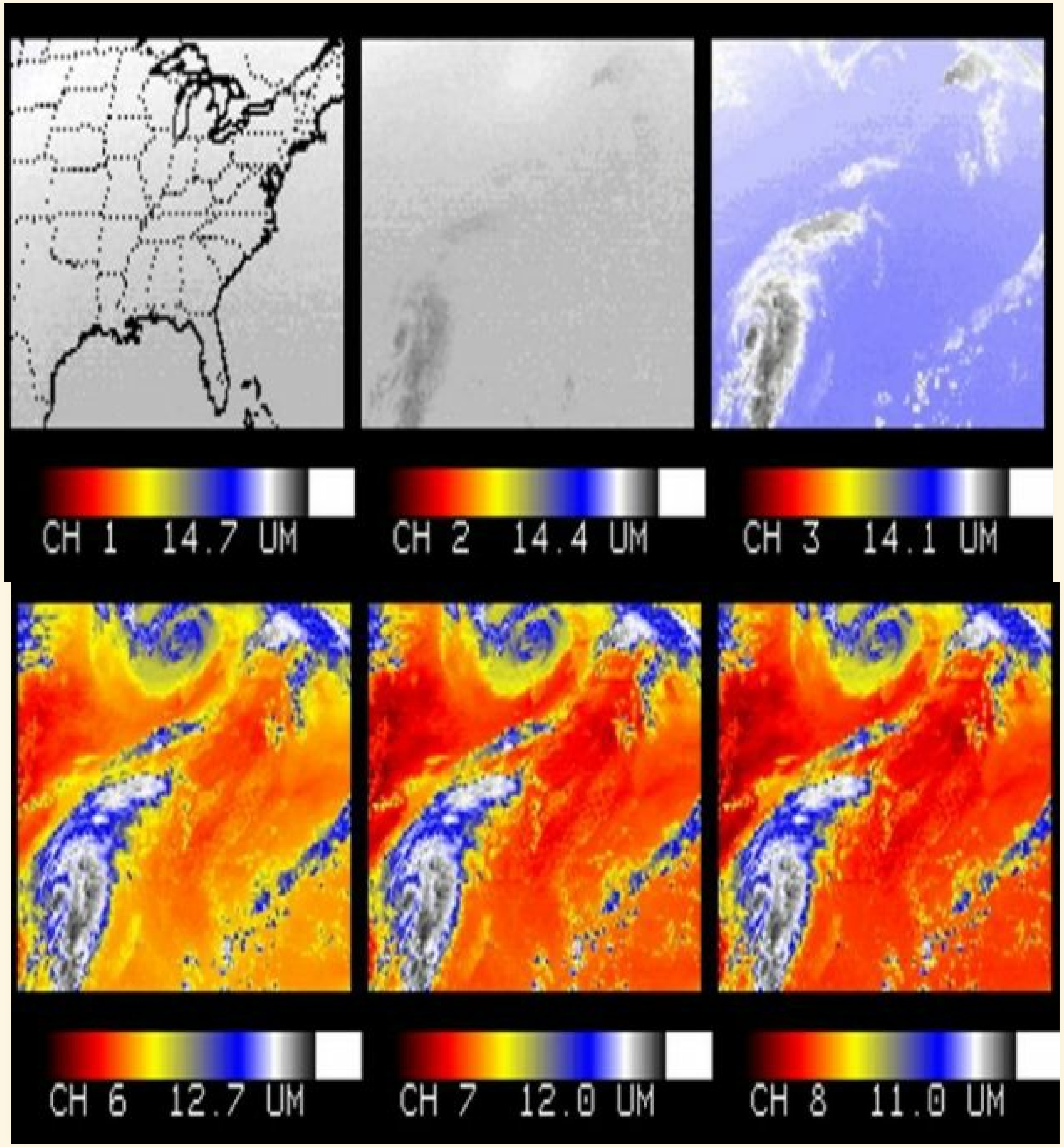
12.0 μm (Window)



Water, Window, Visible



CO_2 peak vs. Window



Terrestrial Planets

Earth, Mars, Venus

	Earth	Mars	Venus
Solar constant	1350 W/m^2	600 W/m^2	2604 W/m^2
Albedo	0.30	0.17	0.71
$T_{radiative}$	254 K	216 K	240 K
Actual $T_{surface}$	295 K	240 K	700 K
One-Layer $T_{surface}$	302 K	257 K	286 K

Vocabulary note:

- "radiative temperature"
- "skin temperature"
- "bare rock temperature"

all mean the same thing.

Earth, Mars, Venus

	Earth	Mars	Venus
Solar constant	1350 W/m^2	600 W/m^2	2604 W/m^2
Albedo	0.30	0.17	0.71
$T_{radiative}$	254 K	216 K	240 K
Actual $T_{surface}$	295 K	240 K	700 K
One-Layer $T_{surface}$	302 K	257 K	286 K
Difference	7 K	17 K	−414 K

One-layer model works pretty well for Earth.

Not so well for Mars

Terribly for Venus.

Earth, Mars, Venus

	Earth	**Mars**	**Venus**
Solar constant	1350 W/m^2	600 W/m^2	2604 W/m^2
Albedo	0.30	0.17	0.71
$T_{radiative}$	254 K	216 K	240 K
Actual $T_{surface}$	295 K	240 K	700 K
One-Layer $T_{surface}$	302 K	257 K	286 K
Difference	7 K	17 K	−414 K
Atmospheric pressure	1013 mb	6 mb	92,000 mb