Review of the Greenhouse Effect

EES 3310/5310

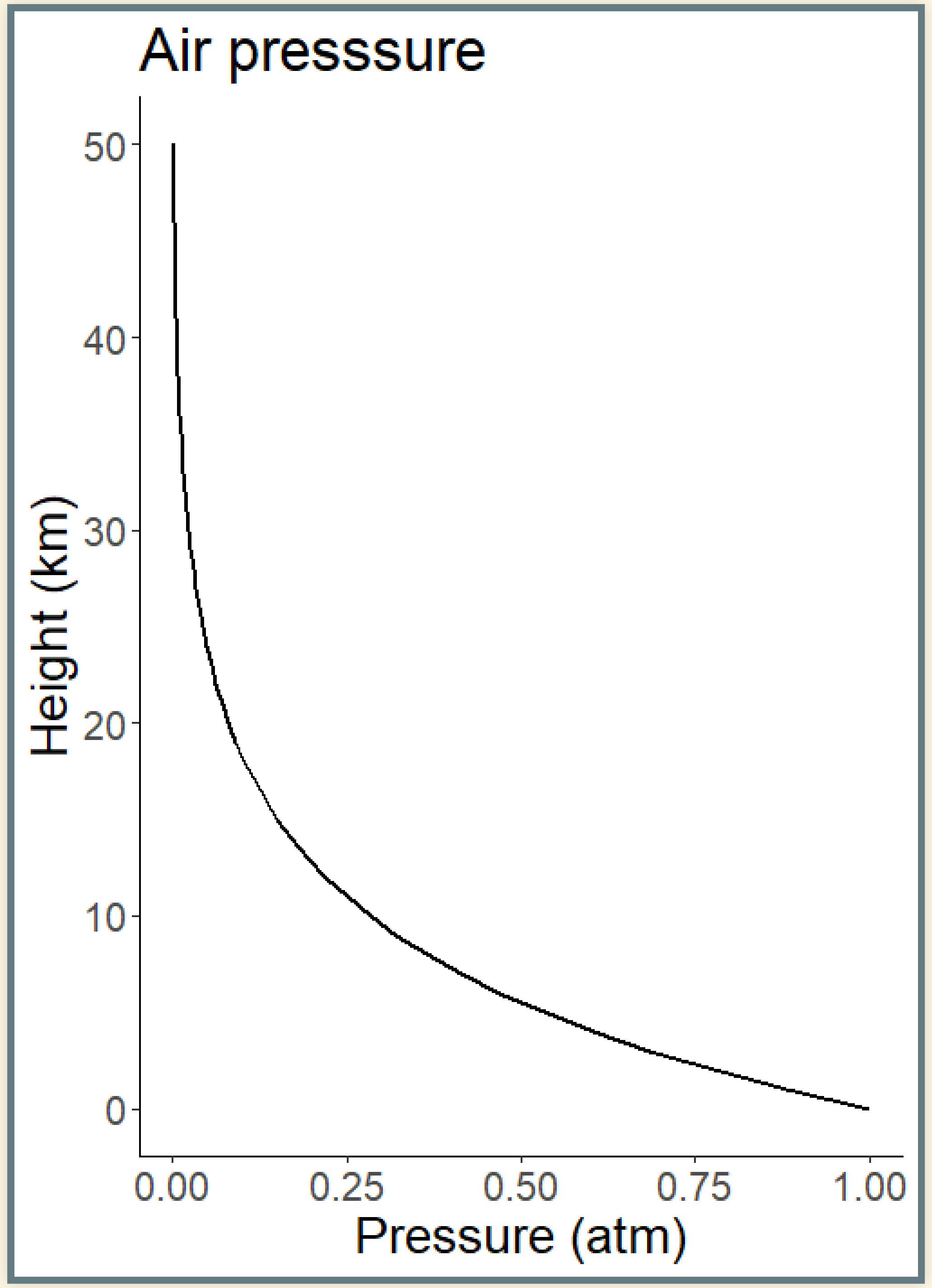
Global Climate Change

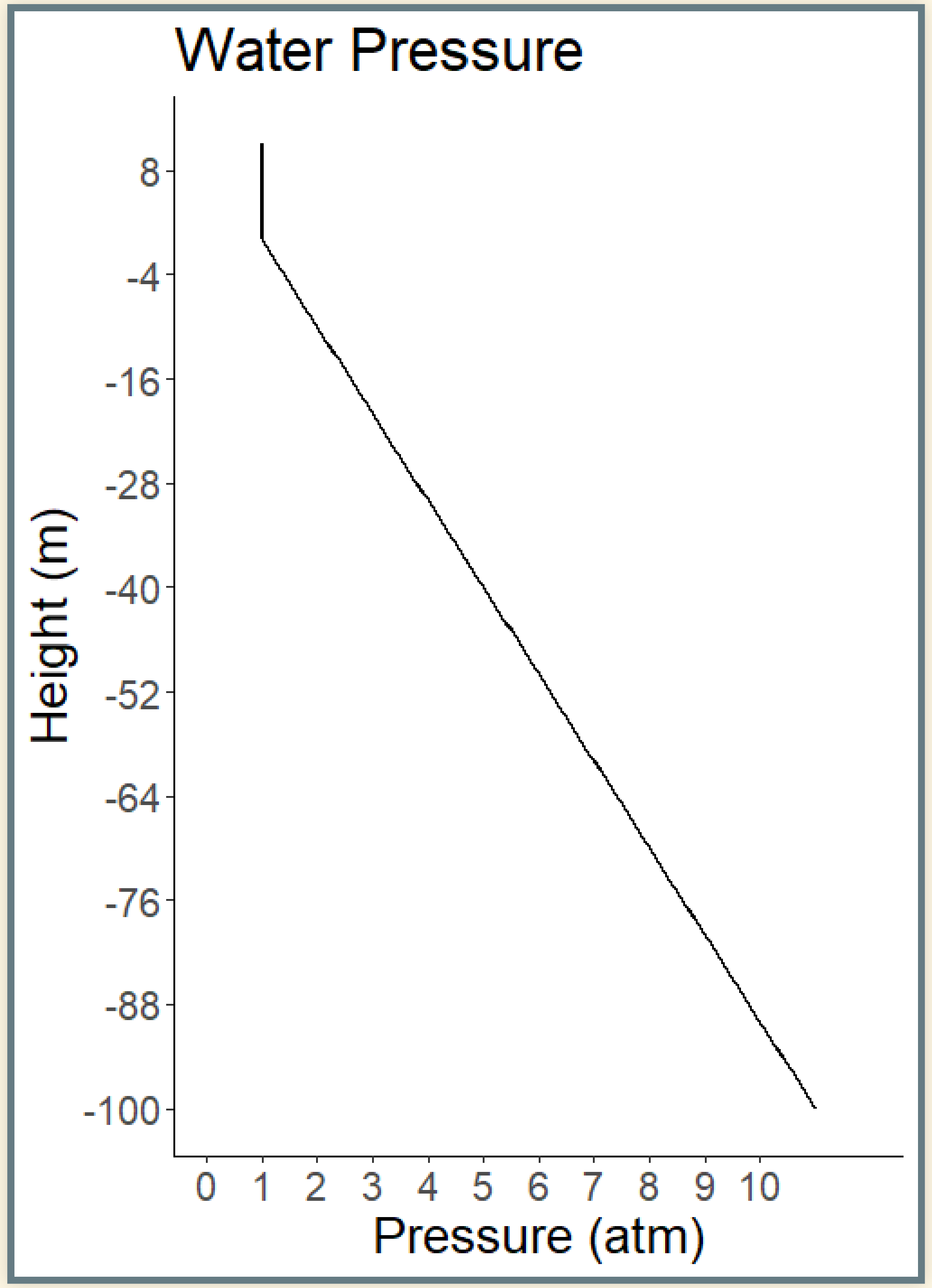
Jonathan Gilligan

Class #7: Wednesday, January 22 2020

Atmospheric Pressure

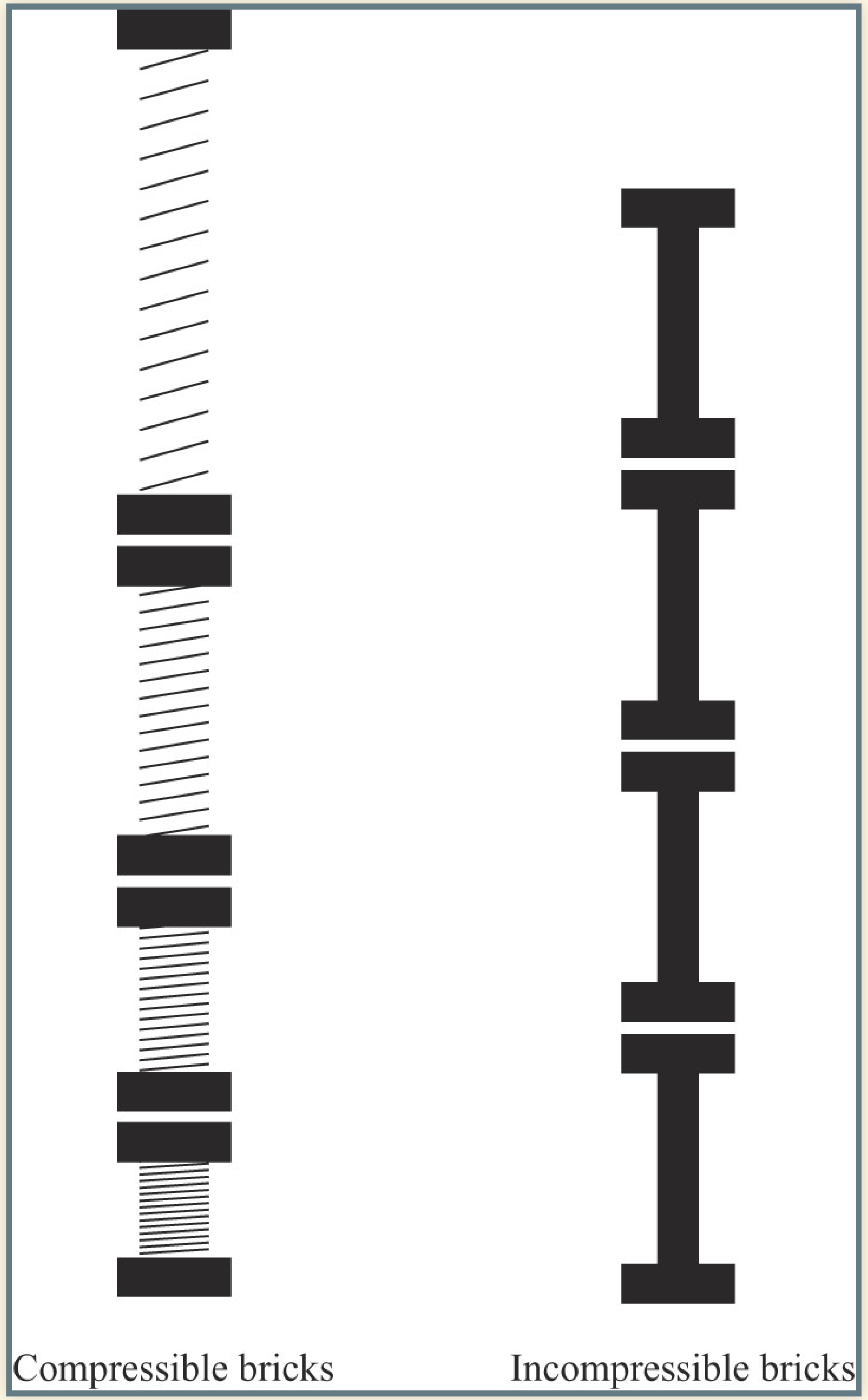
Air vs. Water


Air presssure
Height (km)
50
40
30
20
10
0
0.00
0.25
0.50
0.75
1.00
Pressure (atm)


Water Pressure
Height (m)
8
-4
-16
-28
-40
-52
-64
-76
-88
-100
0
1
2
3
4
5
6
7
8
9
10
Pressure (atm)

Air vs. Water

- Pressure = weight of everything overhead.
- Air is compressible, water isn't.
- 1 meter height of water weighs 1000 kg/m^2
- 1 meter height of dry air at sea-level density weighs 1.3 kg/m^2
- 1 m height of dry air 10 km above sea level weighs 0.4 kg/m^2

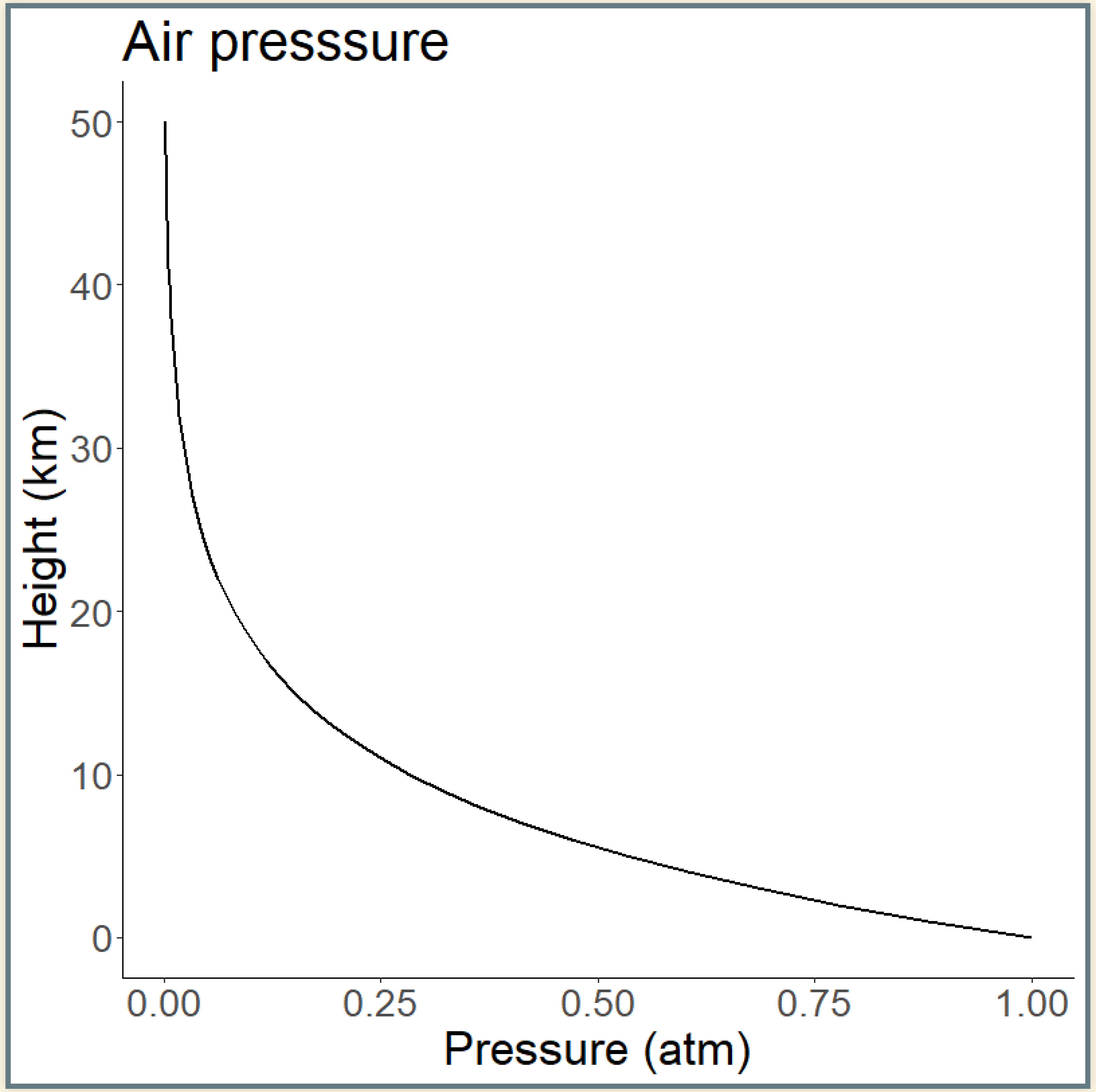


Air Pressure

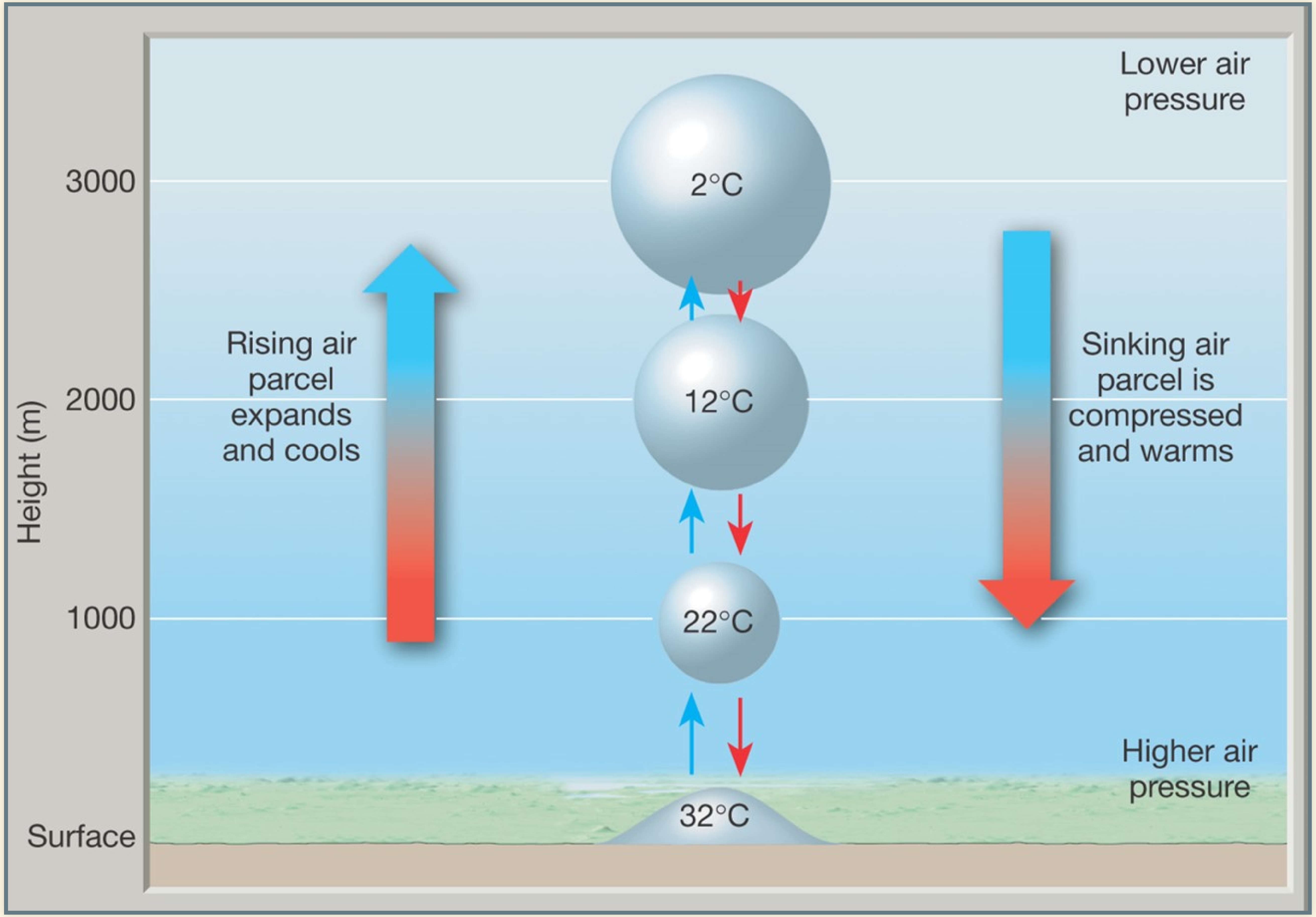
- Pressure at height h:

$$P(h) = P_0 \, e^{-h/8.0\text{km}}$$
$$= P_0 \, 2^{-h/5.5\text{km}}$$
$$= P_0 \left(\frac{1}{2}\right)^{h/5.5\text{km}}$$

  - Half the air is below 5.5 km.
  - 3/4 is below 11 km
  - 7/8 is below 16.5 km
- **NOTE:** The number 5.5 km is not exact, but it's consistent with the textbook.



Why is the air cooler higher up?

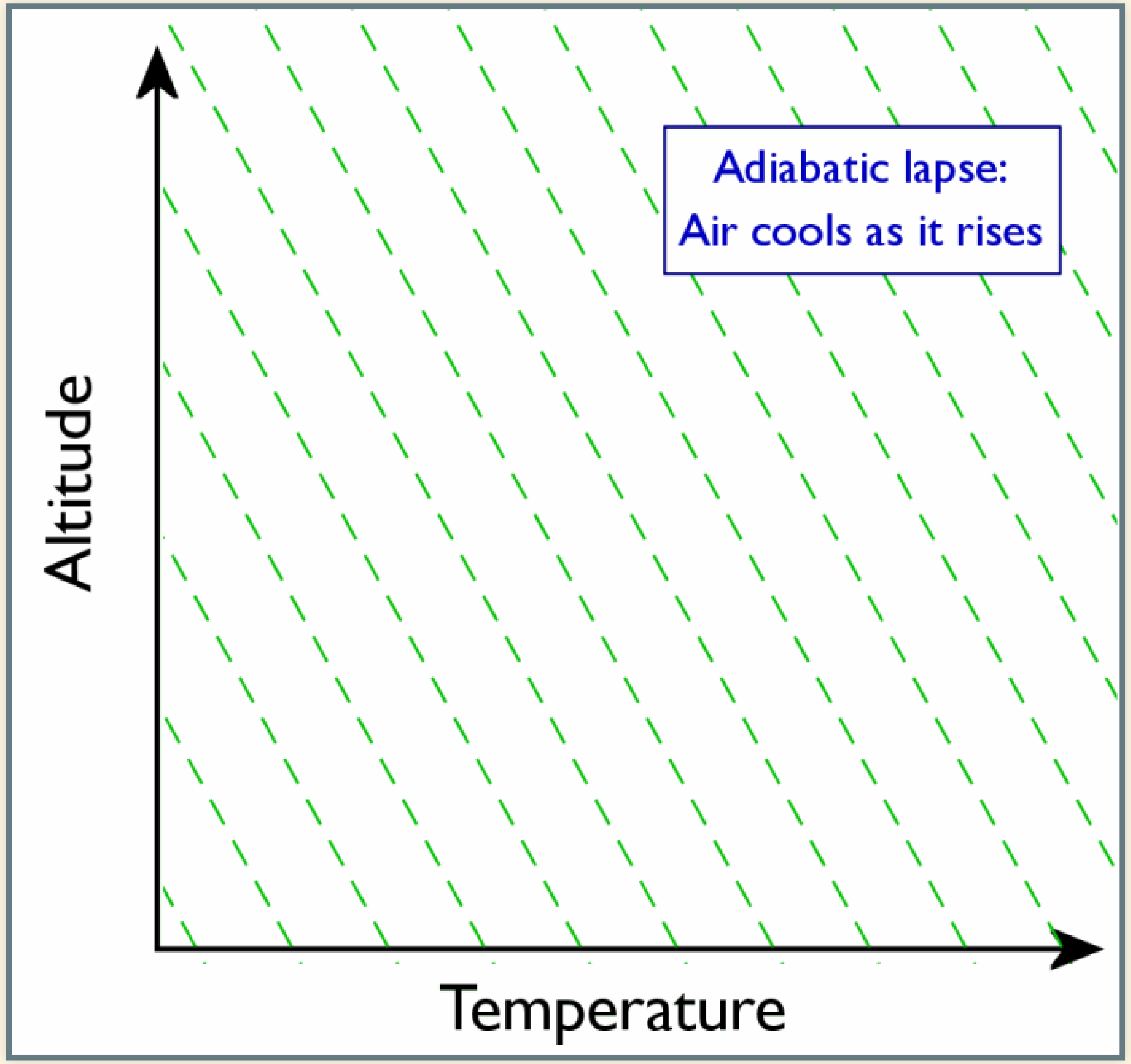


Terminology

- **Environmental Lapse**
  - Measured temperature of actual atmosphere
  - Compares one bit of air at one height with another bit at another height.
  - Changes from one time and place to another.
- **Adiabatic Lapse**
  - Change in a single parcel of air as it moves up or down
  - "**Adiabatic**" means no heat flowing in or out
    - **Adiabatic changes are reversible**
    - **Heat flow** is irreversible

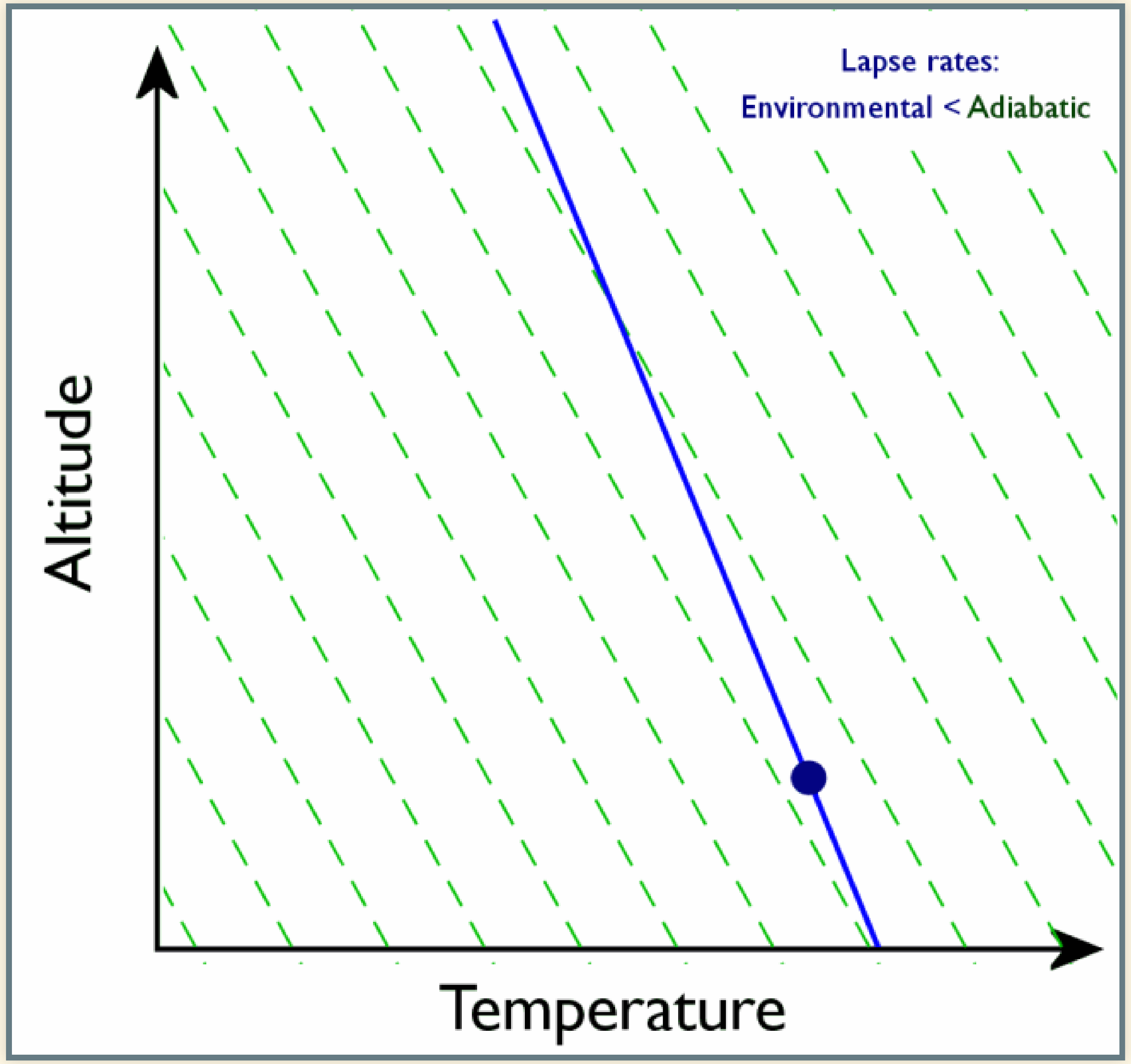
Overview of Convection

Overview of convection



- Closer to vertical = smaller lapse rate (vertical = zero)
- Closer to horizontal = larger lapse rate

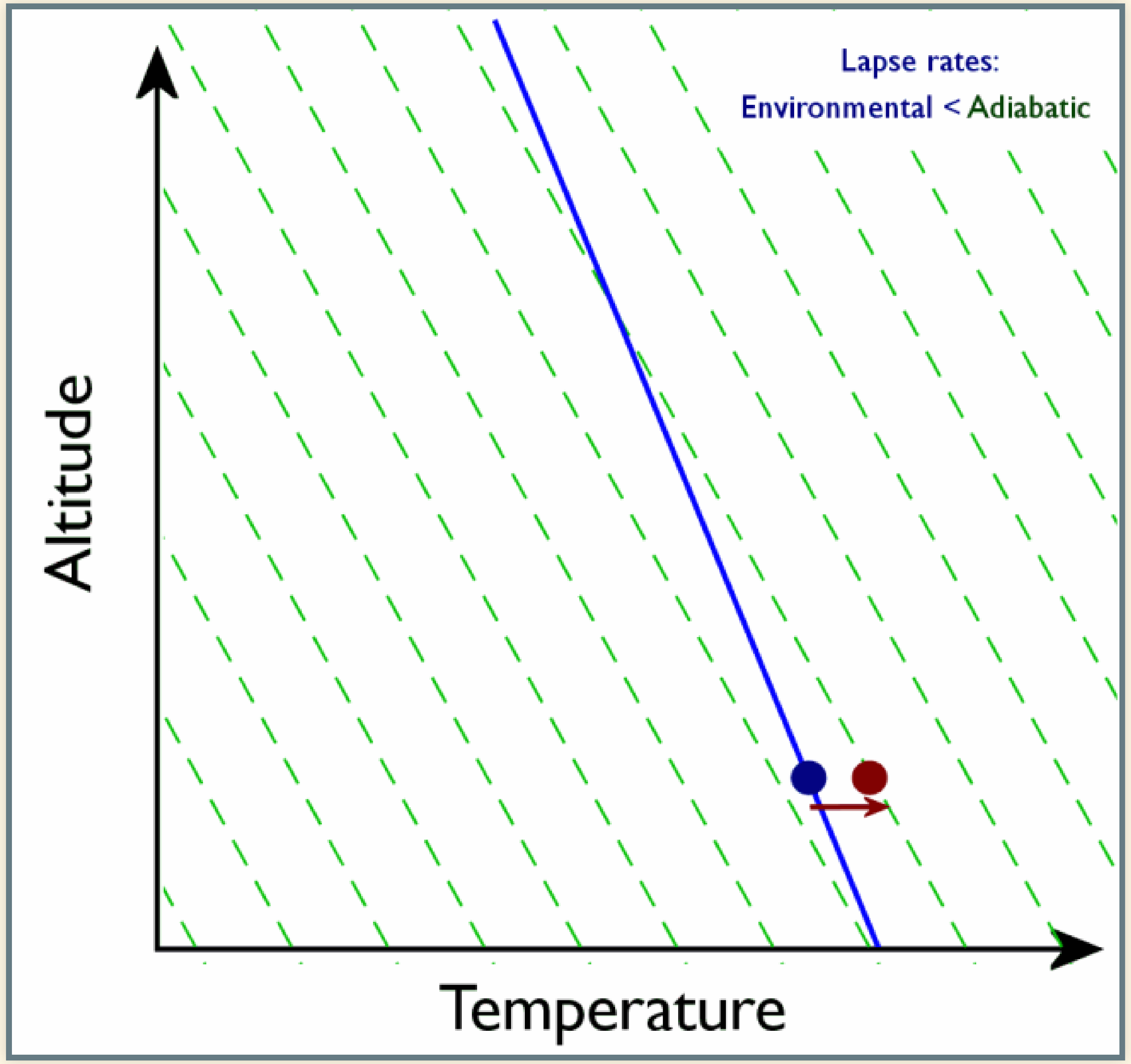
Stable Atmosphere
Initial State



- green = adiabatic lapse
- blue = environmental lapse < adiabatic

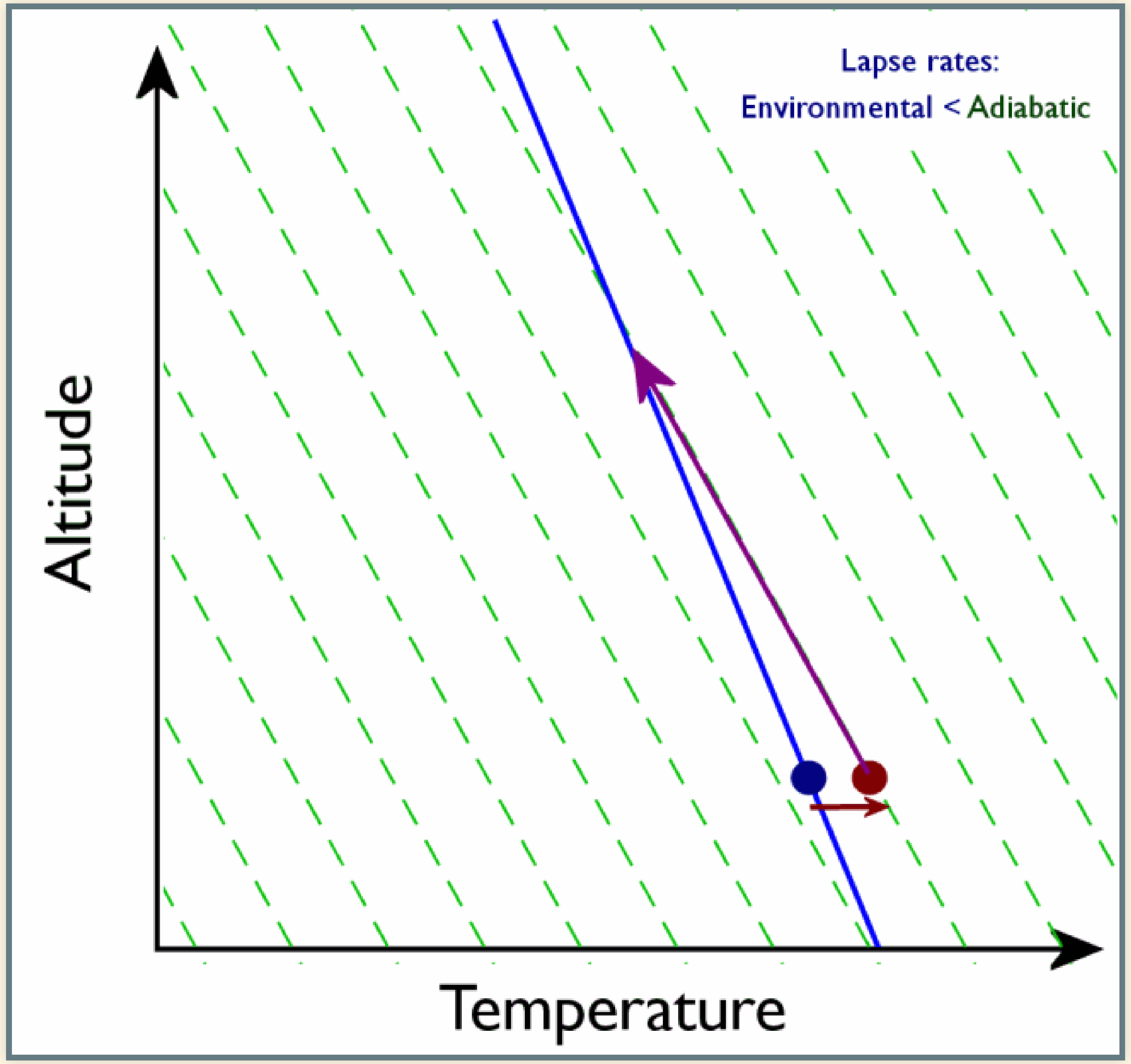
Stable Atmosphere

Parcel is heated



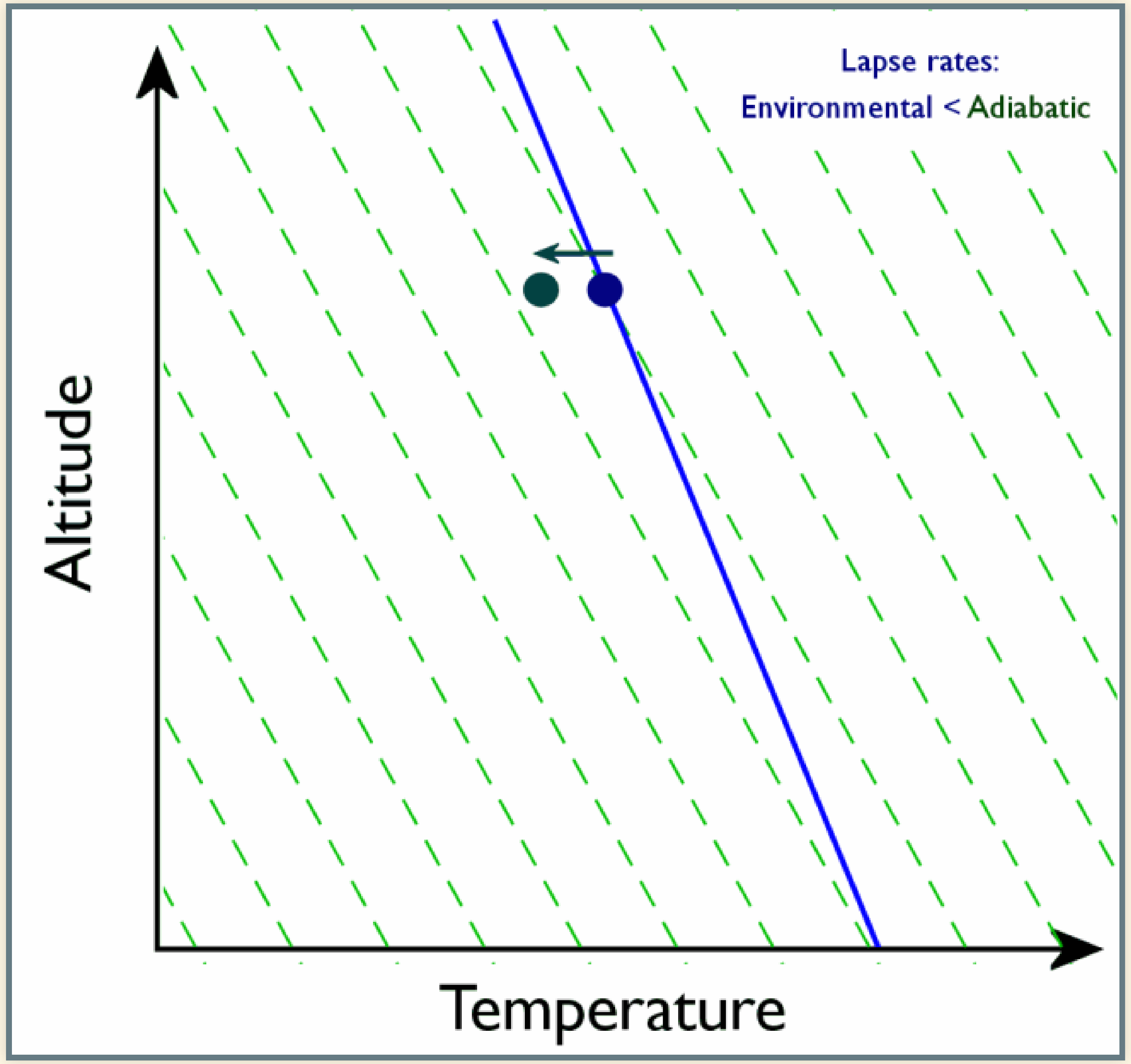
Stable Atmosphere

Rises to new equilibrium



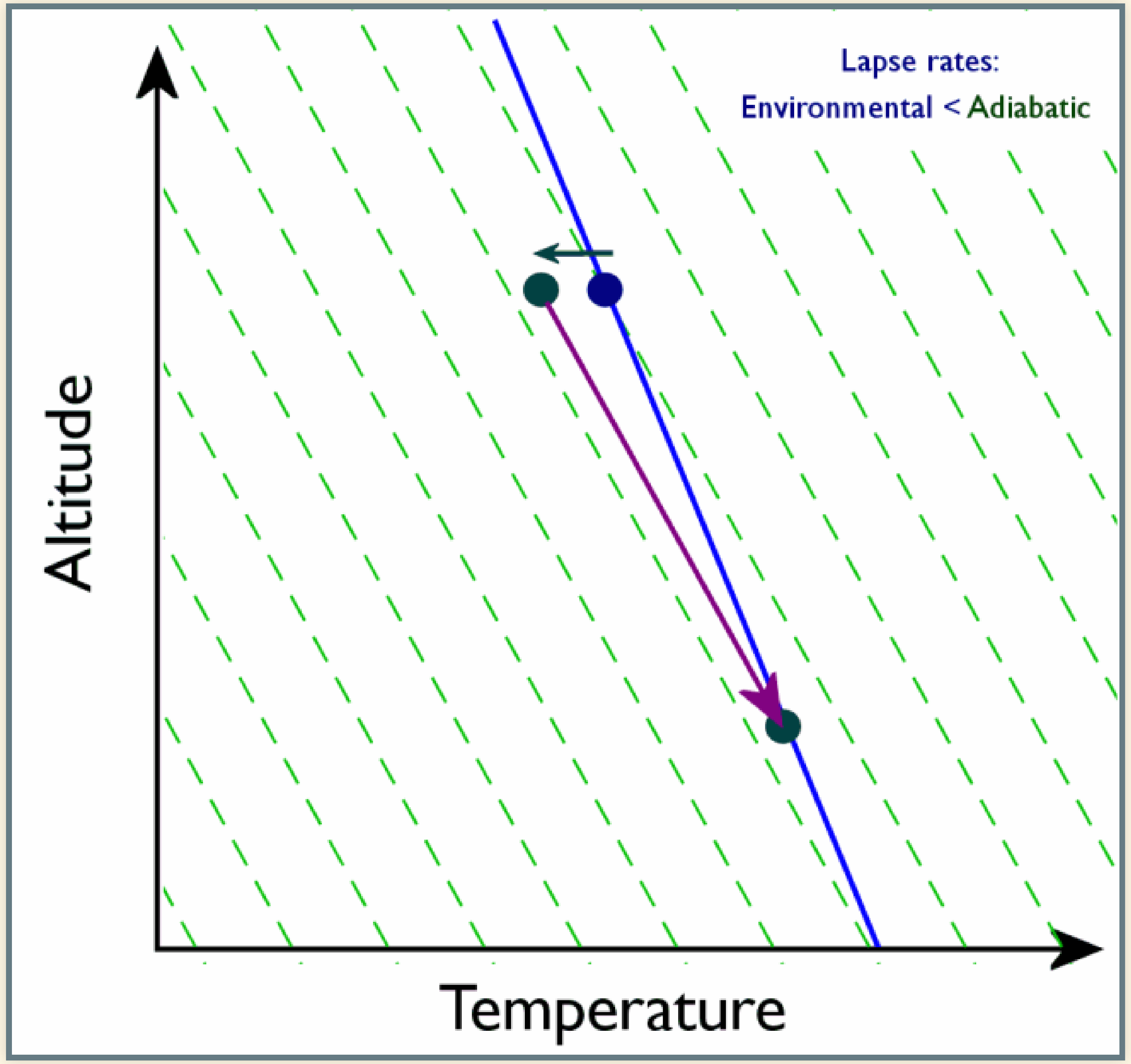
Stable Atmosphere

Parcel is cooled



Stable Atmosphere

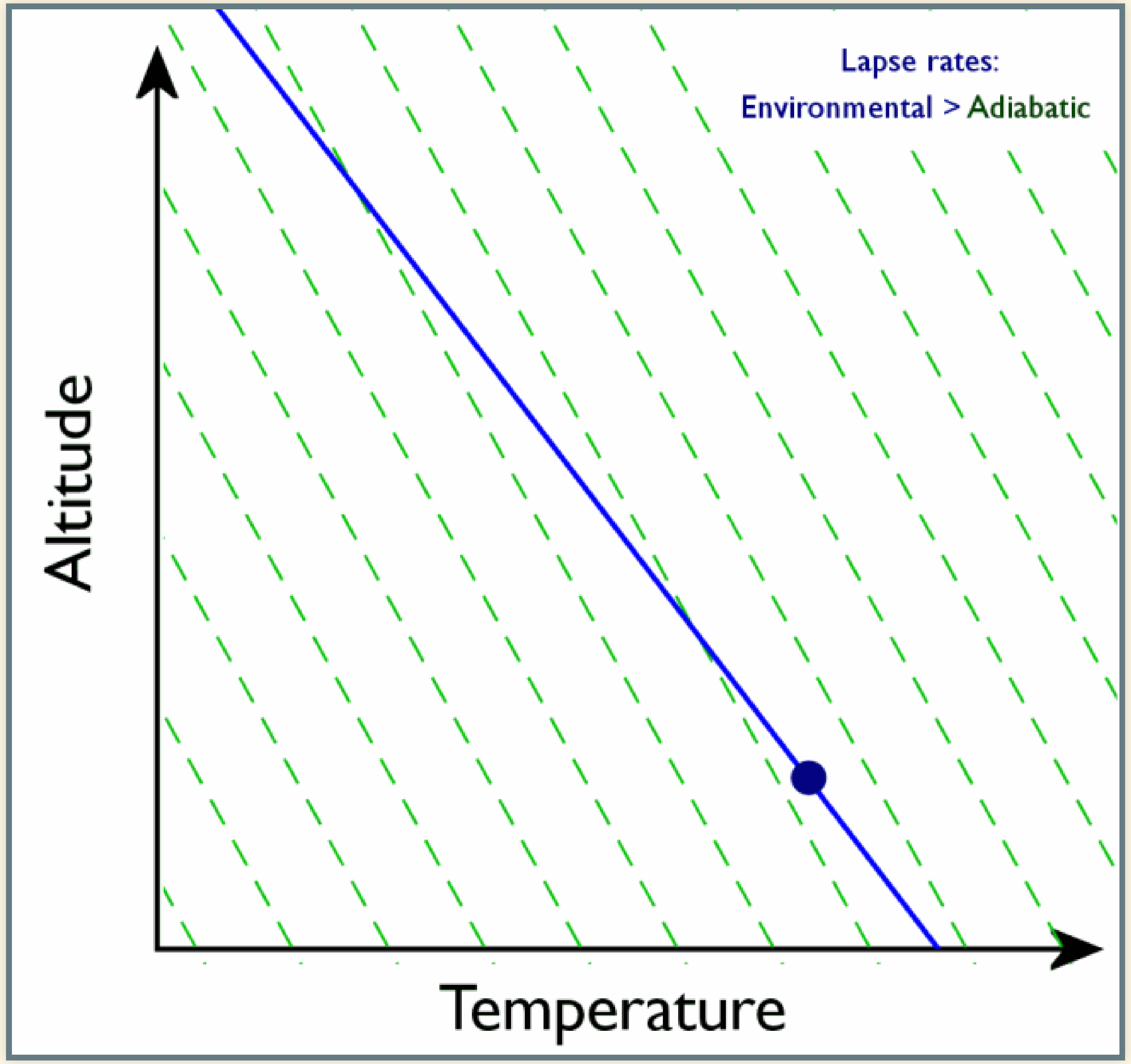
Sinks to new equilibrium



Unstable Atmosphere

Unstable Atmosphere

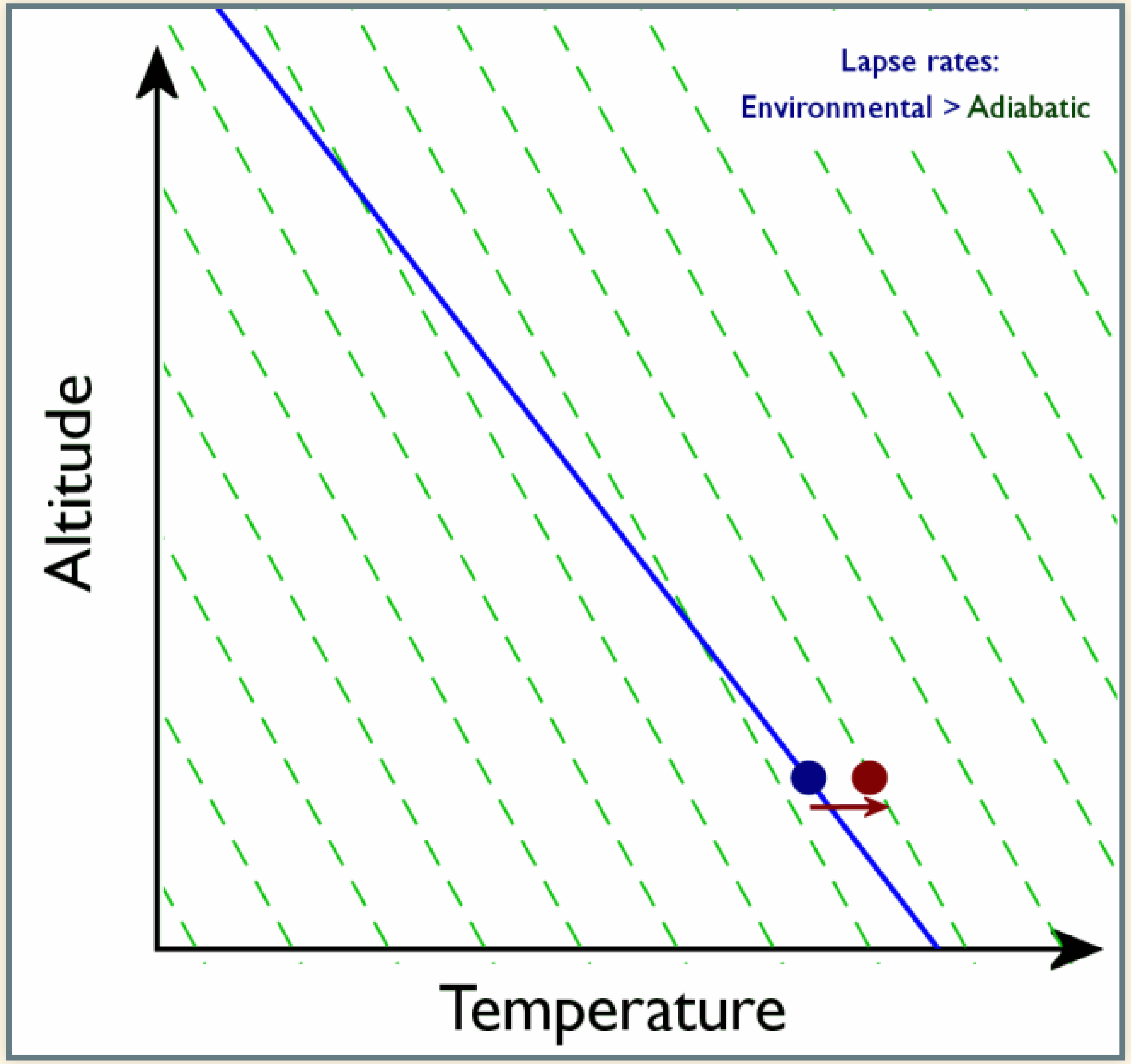
Initial State



- green = adiabatic lapse
- blue = environmental lapse > adiabatic

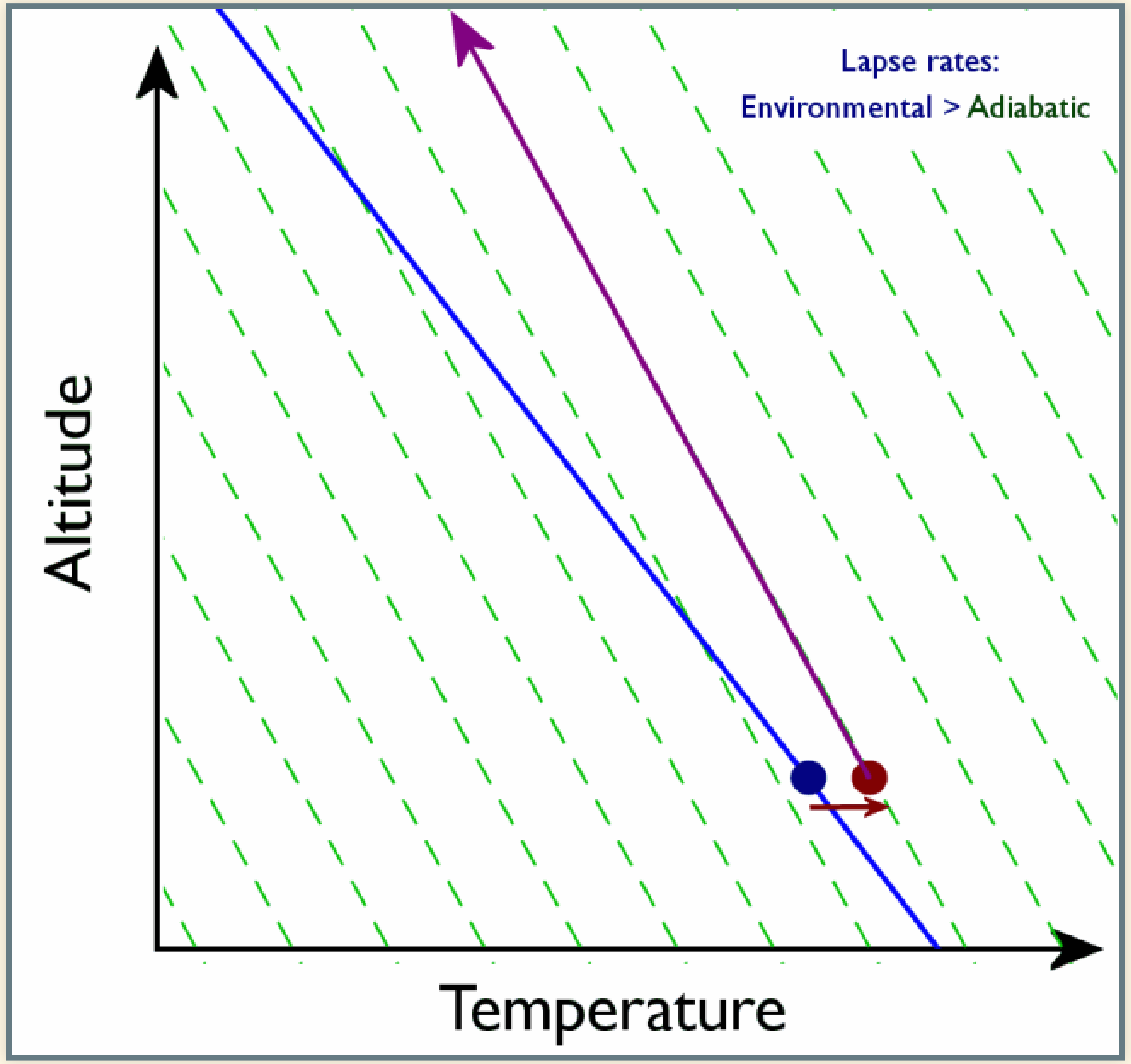
Unstable Atmosphere

Parcel is heated



Unstable Atmosphere

Rises without stopping



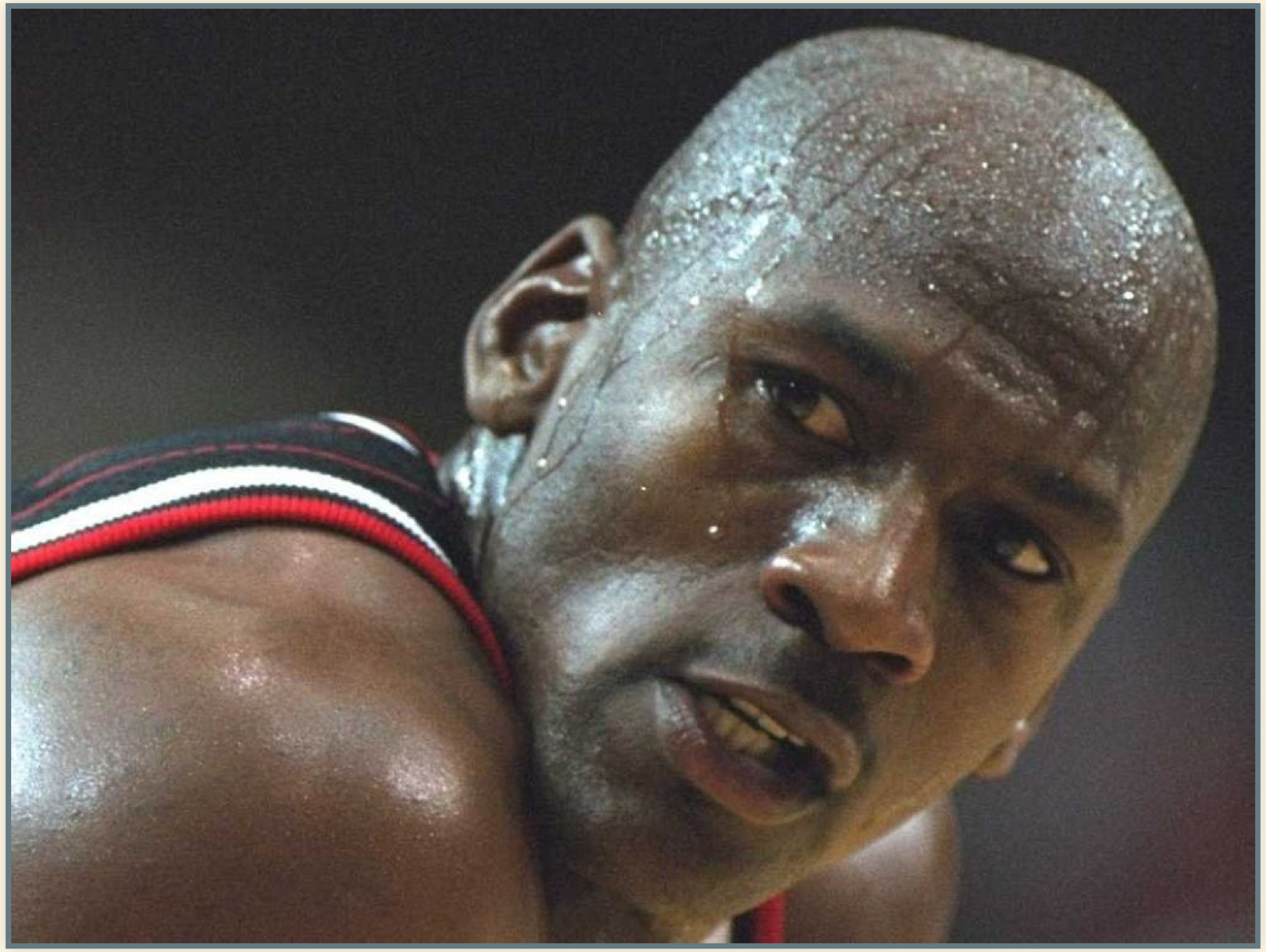
Summary of Stability

Summary of stability:

- Stable conditions:
  - Adiabatic Lapse > Environmental Lapse
- Unstable conditions:
  - Adiabatic Lapse < Environmental Lapse
- Why is stability important?
  - A stable atmosphere does not move heat around
  - An unstable atmosphere undergoes **convection**:
    - Hot air rises, cold air sinks
    - Redistributes heat

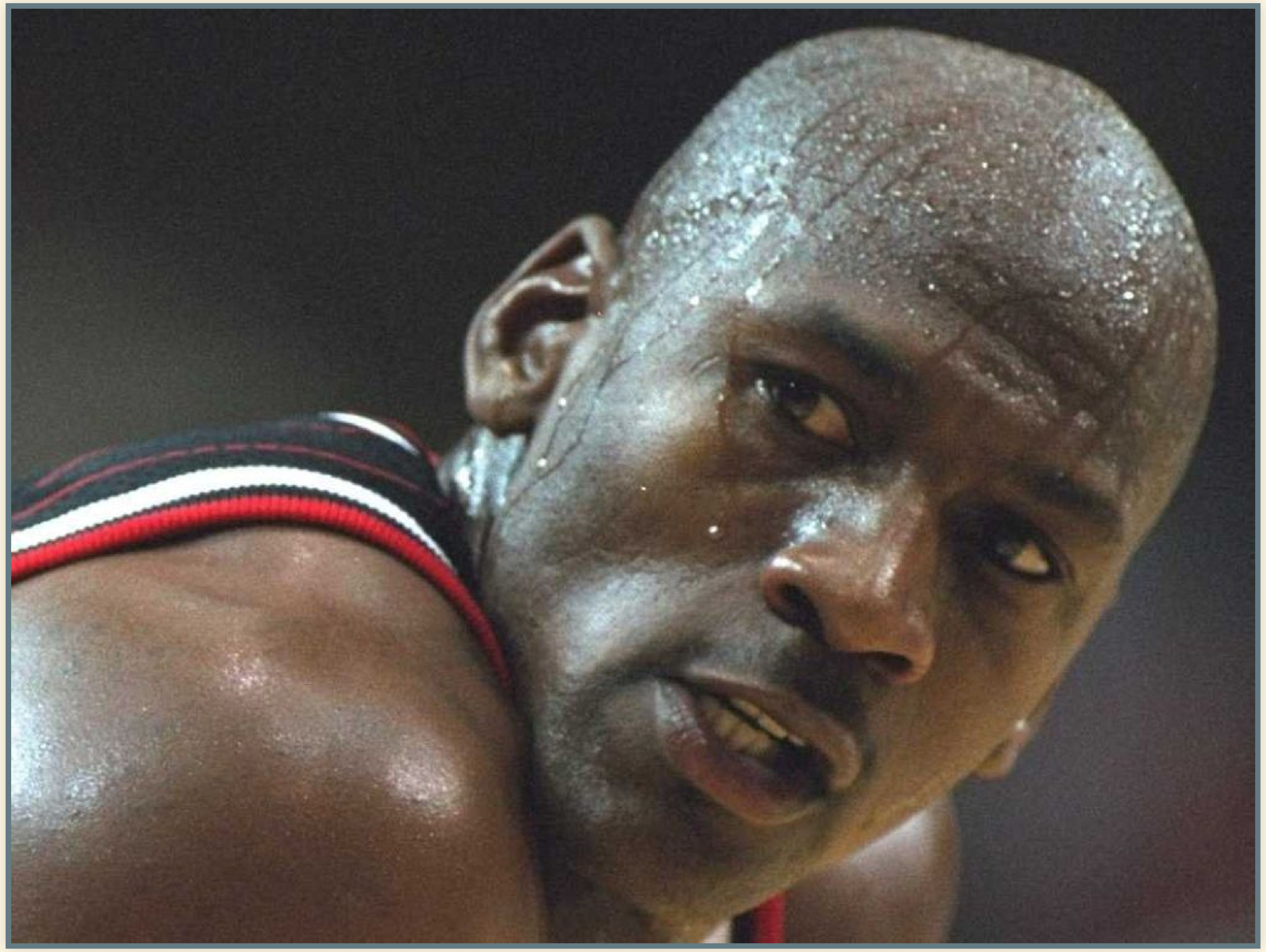
Moist Convection

Sweating



I’m not out there sweating for three hours every day just to find out what it feels like to sweat. — Michael Jordan

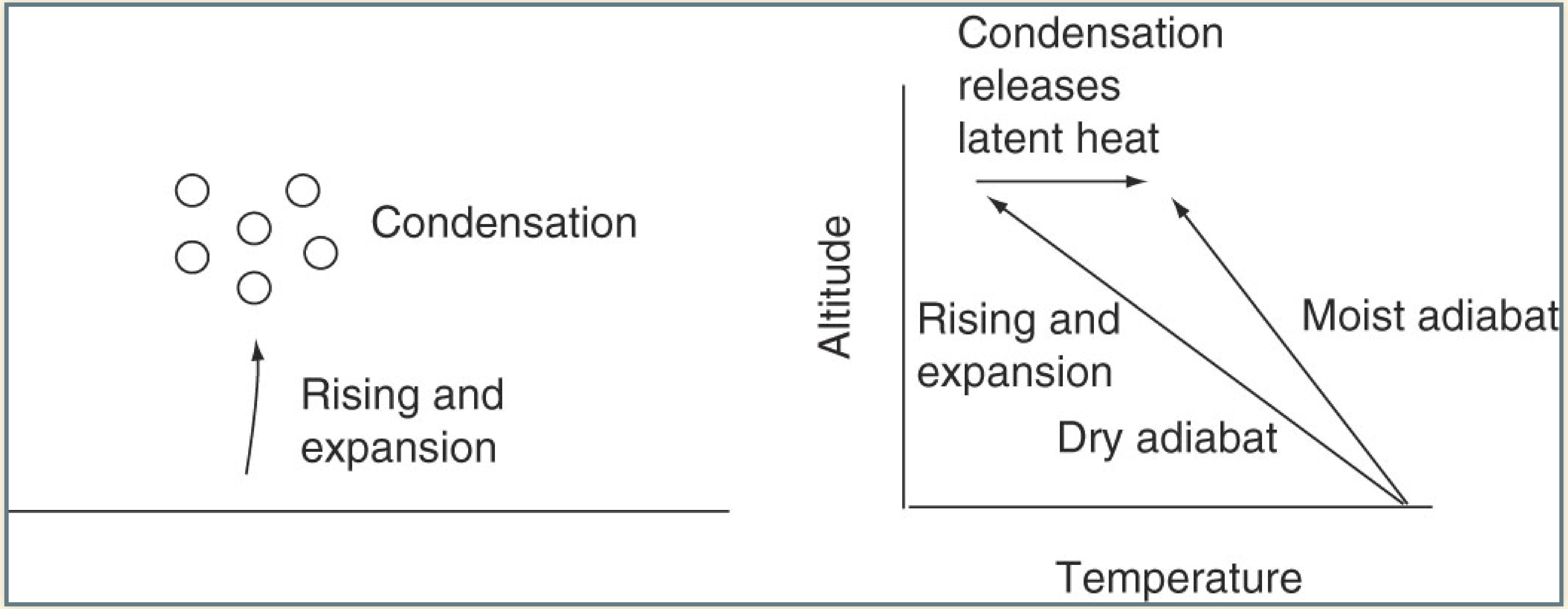
What *Does* It Feel Like to Sweat?



Latent Heat

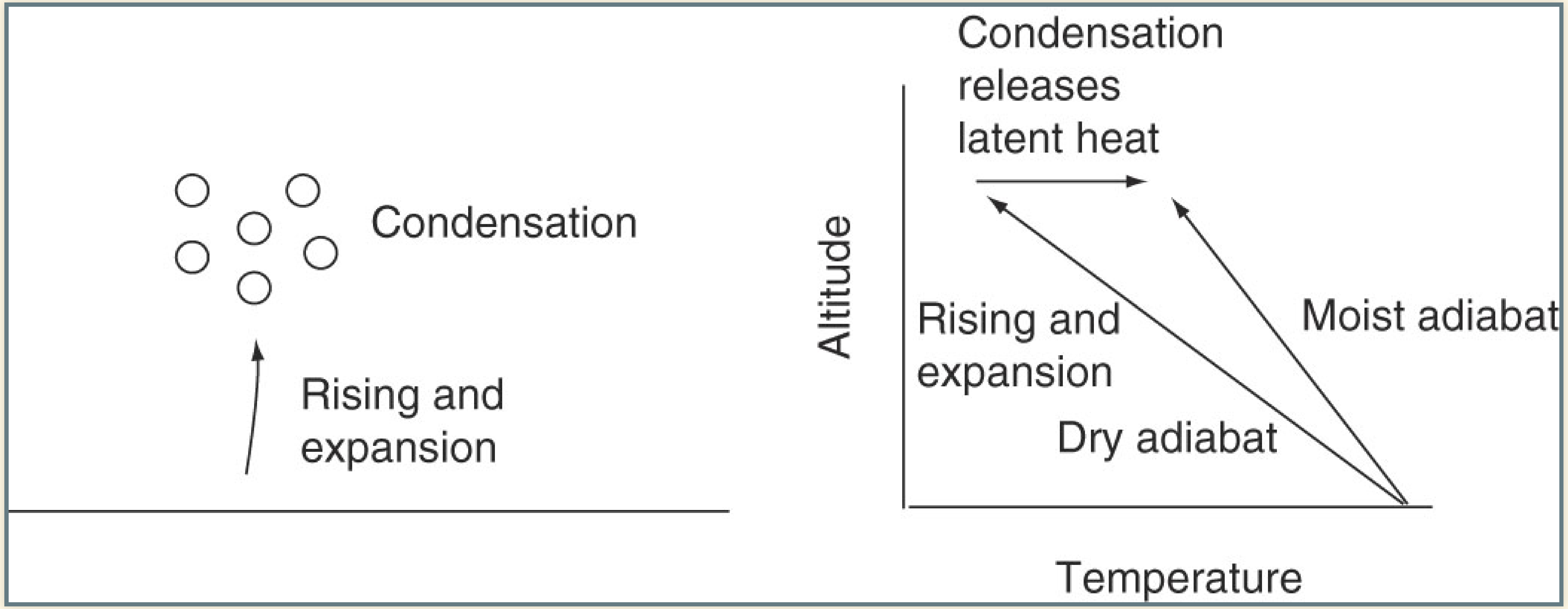
- When 1 gram of water **evaporates**, it absorbs 2,260 Joules of heat, **cools** its surroundings.
- When 1 gram of water **condenses**, it releases 2,260 Joules of heat, **warms** its surroundings.
- 2,260 Joules of heat will change the temperature of a kilogram of air by 2.2 K (4° F).

Moist Convection



- Dry air rises and cools
- Cooling $\Rightarrow$ water vapor condenses to liquid
- Condensation releases latent heat
- Latent heat warms air

Moist Convection



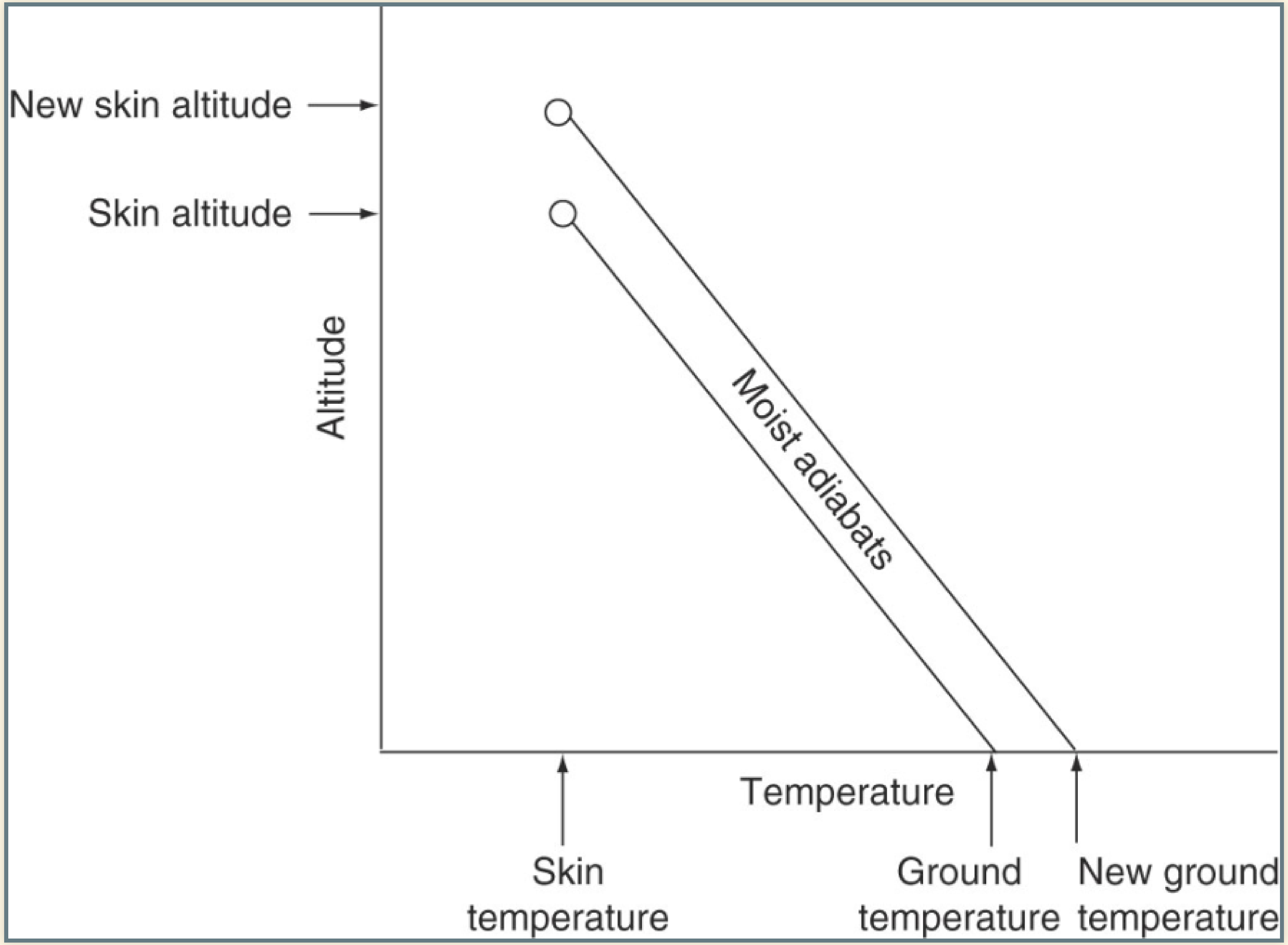
- Latent heat warms air
- Reduces adiabatic cooling
- Moist adiabatic lapse < Dry adiabatic lapse
- Smaller lapse = less stable
- **Humid air is less stable than dry air**

Perspective

- Stable:
  - Environmental lapse $\leq$ adiabatic lapse
- Unstable:
  - Environmental lapse > adiabatic lapse
- Adiabatic lapse:
  - Dry: 10 K/km
  - Moist: 4-8 K/km (depends on humidity)
- Pure radiative equilibrium (Layer models):
  - Would produce lapse of **16 K/km**: unstable
- Radiative-Convective equilibrium:
  - Convection modifies environmental lapse
  - Normal environmental lapse is roughly **6 K/km** (typical *moist adiabatic lapse rate*)

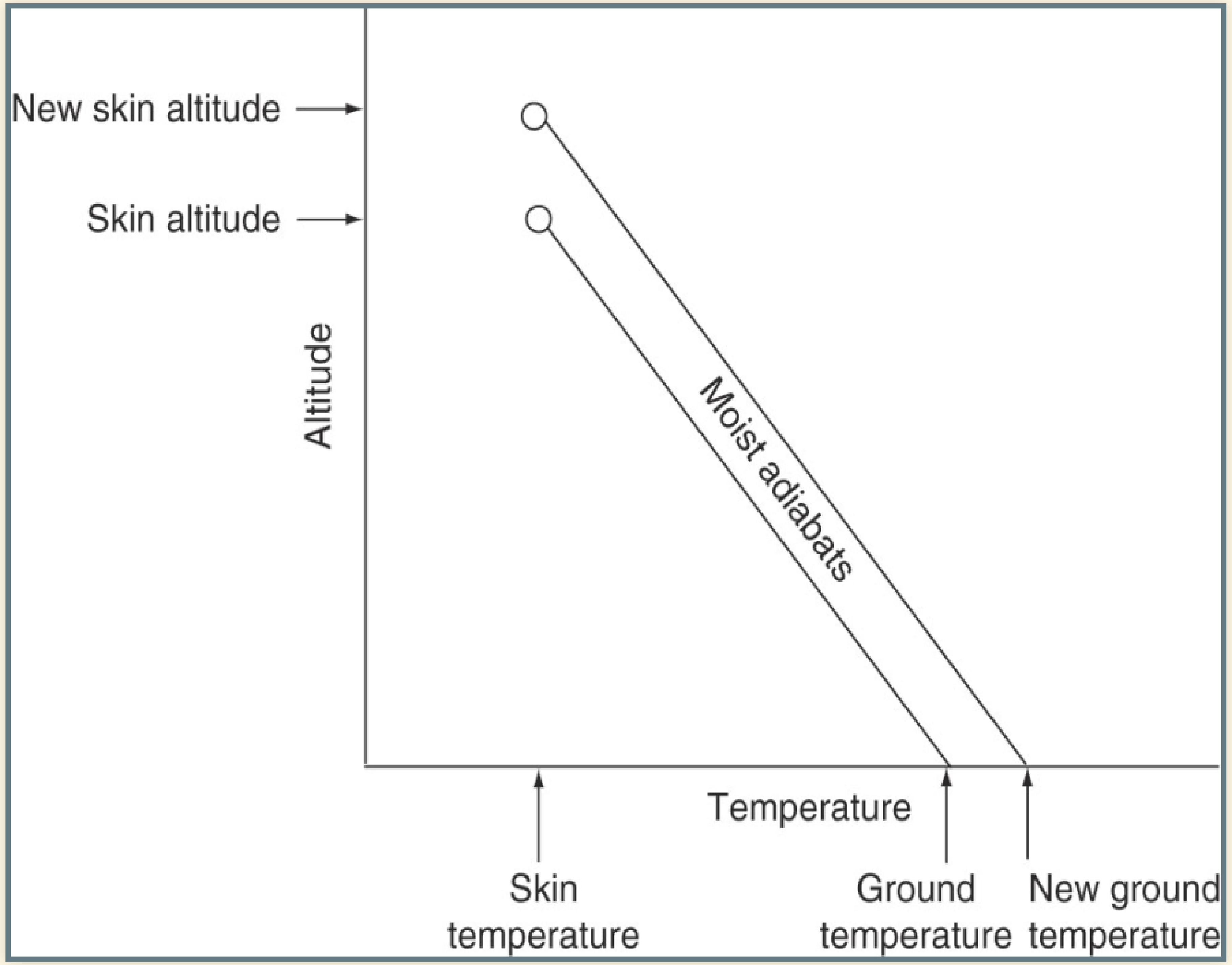
Greenhouse effect

Greenhouse effect



Greenhouse effect

1. $T_{\text{skin}} = 254$ K
2. $T_{\text{ground}} = T_{\text{skin}} + \textbf{lapse rate} \times h_{\text{skin}}$
3. Increase greenhouse gases
4. Skin height rises by Δh_{skin}
5. T_{ground} rises by $\textbf{lapse rate} \times \Delta h_{\text{skin}}$



Vertical Structure and Saturation

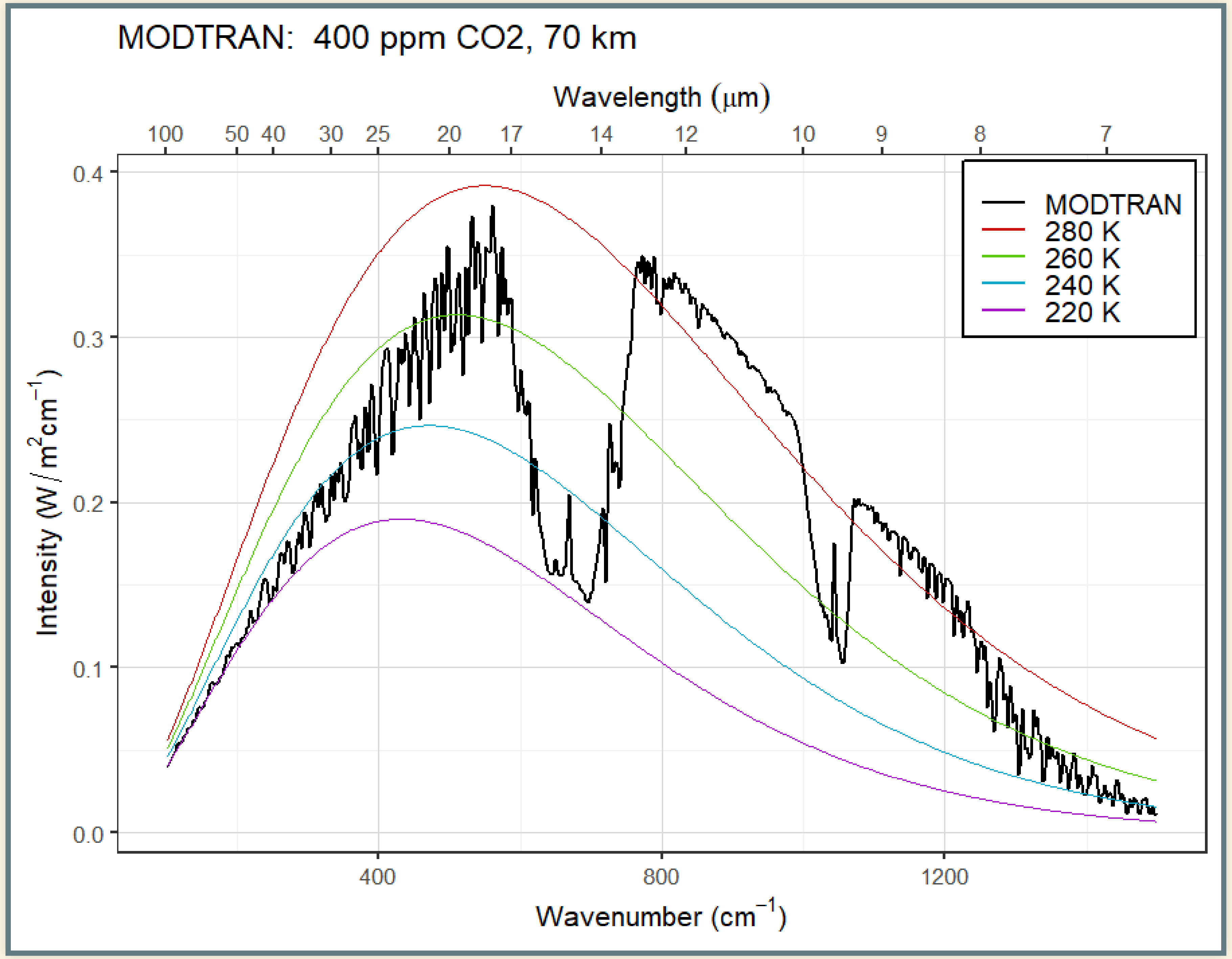
Set up MODTRAN:

Go to MODTRAN (http://climatemodels.uchicago.edu/modtran/)

- Set altitude to **70 km** and location to "1976 U.S. Standard Atmosphere".
- Leave all gases at their default values

Understanding MODTRAN Output

- **Black line:** brightness of longwave radiation *seen by a satellite* in space.
- **Colored curves:** brightness of longwave light emitted by *perfect black bodies* at different temperatures
- *Molecules overhead* absorb radiation from *molecules below*.
- To be seen from space, *there can't be too many absorbing molecules overhead*.
- **More absorption**: emission must be coming from *higher up*:
  - Higher up = colder = less intensity (dimmer)
- **Less absorption:** emission comes from *lower down*:
  - Lower down = warmer = greater intensity (brighter)

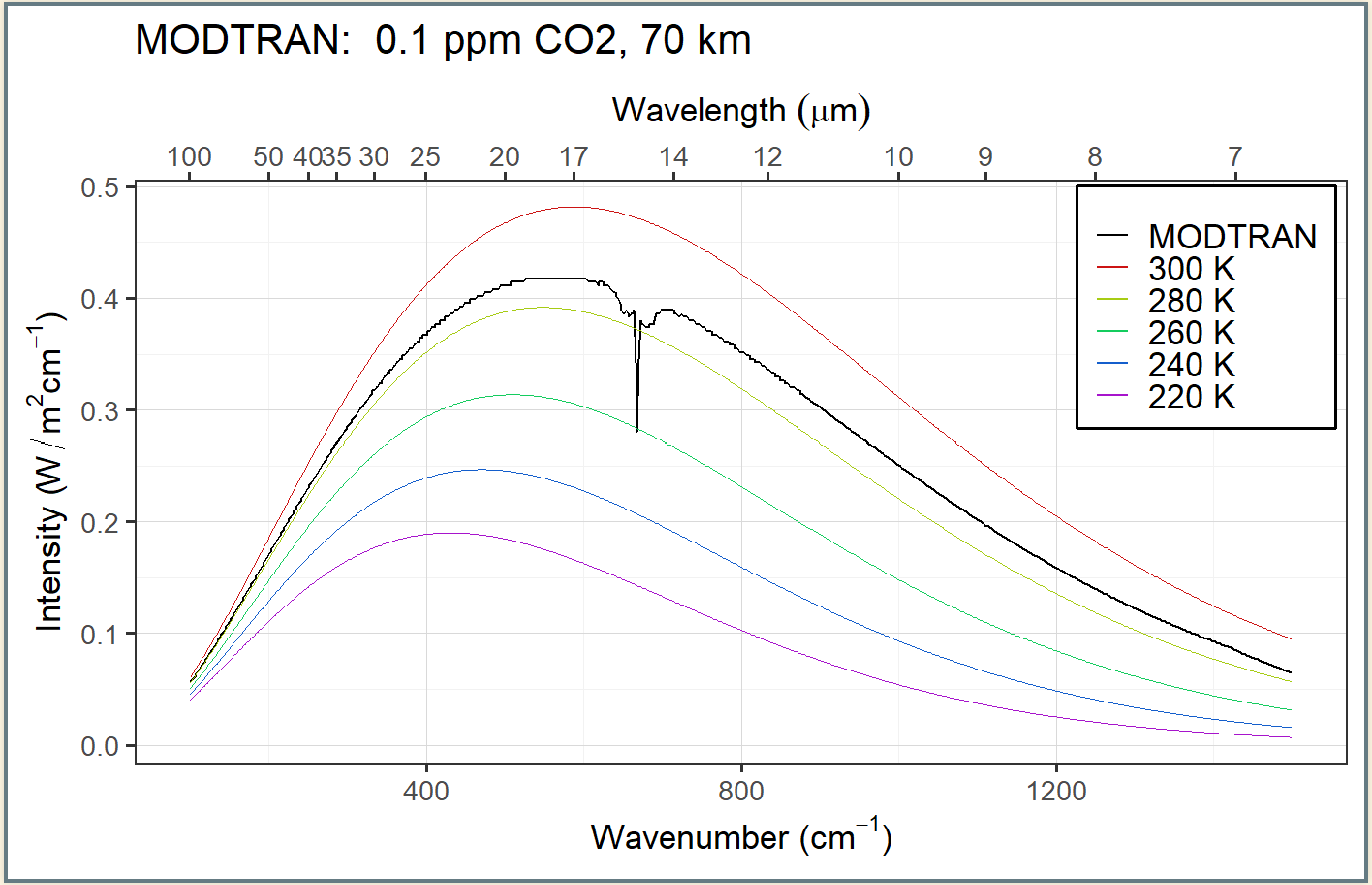


Vertical Structure and Band Saturation

Go to MODTRAN (http://climatemodels.uchicago.edu/modtran/)

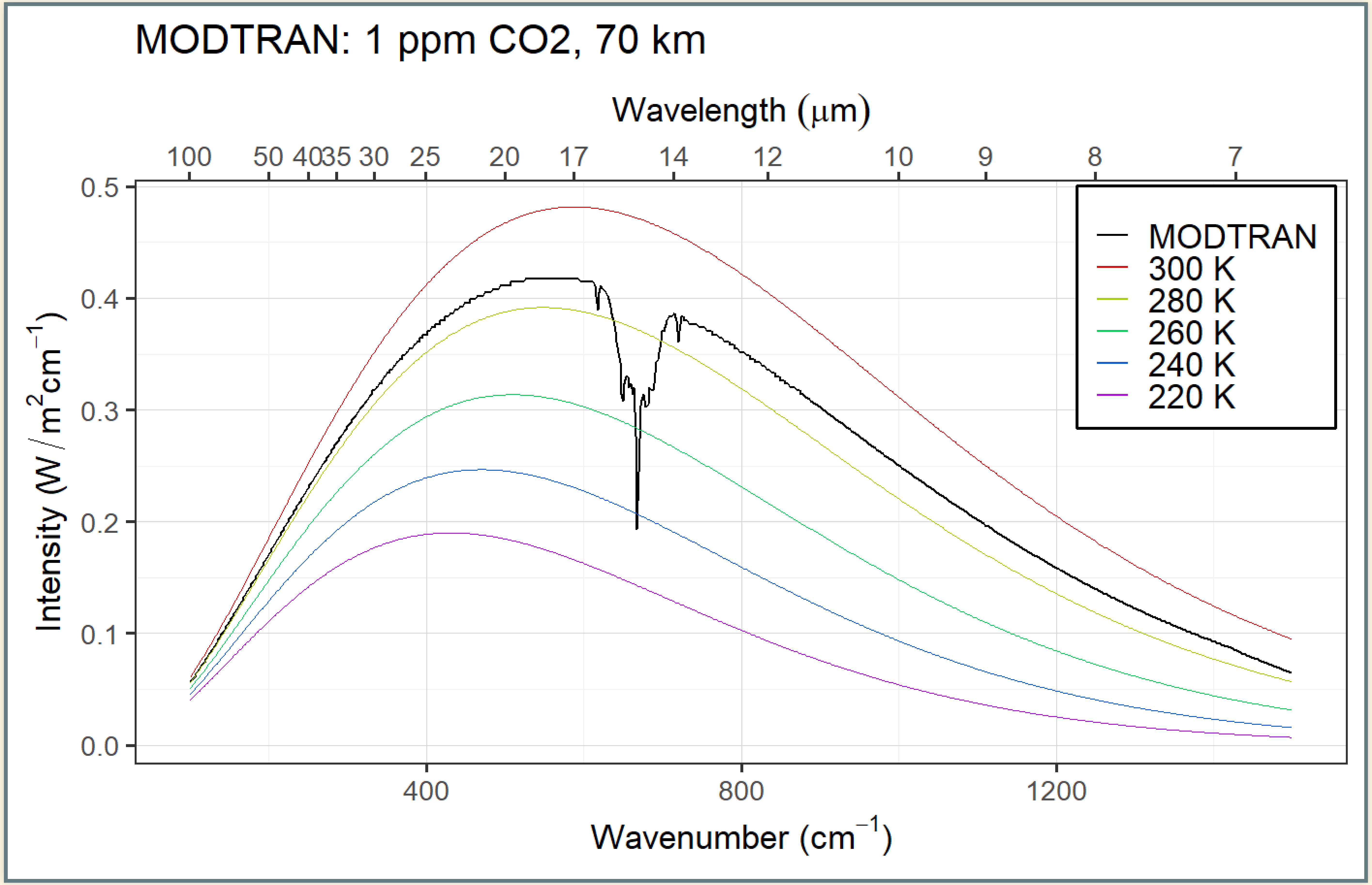
- Set altitude to **70 km** and location to “1976 U.S. Standard Atmosphere”.
- Set CO_2 to 1 ppm, all other gases to zero.
- Now increase by factors of 10 (10, 100, 1000, ...)

0.1 ppm CO_2



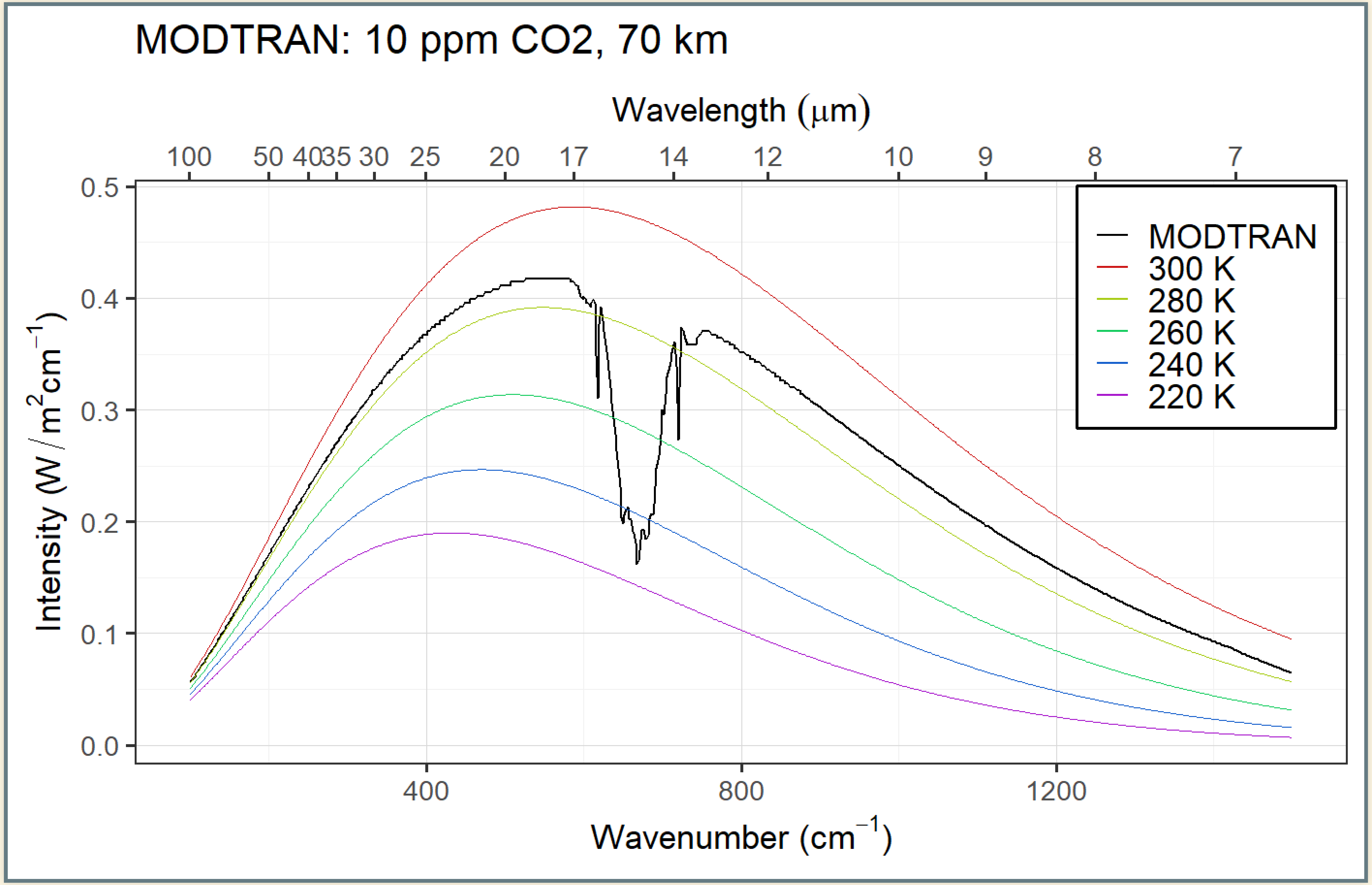
MODTRAN: 0.1 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m2cm−1)
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm−1)

1 ppm CO_2



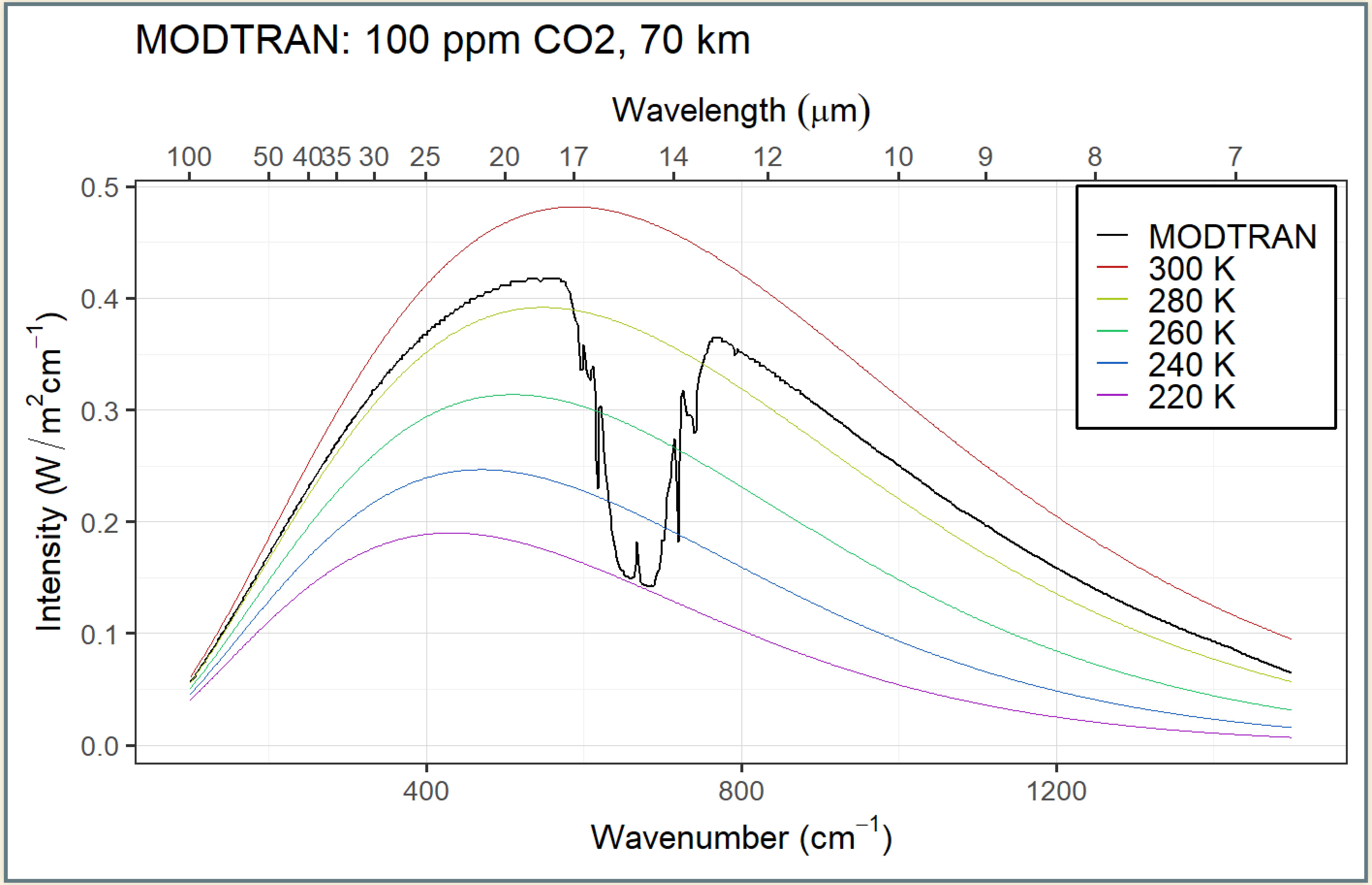
MODTRAN: 1 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
Intensity (W / m²cm⁻¹)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

10 ppm CO_2



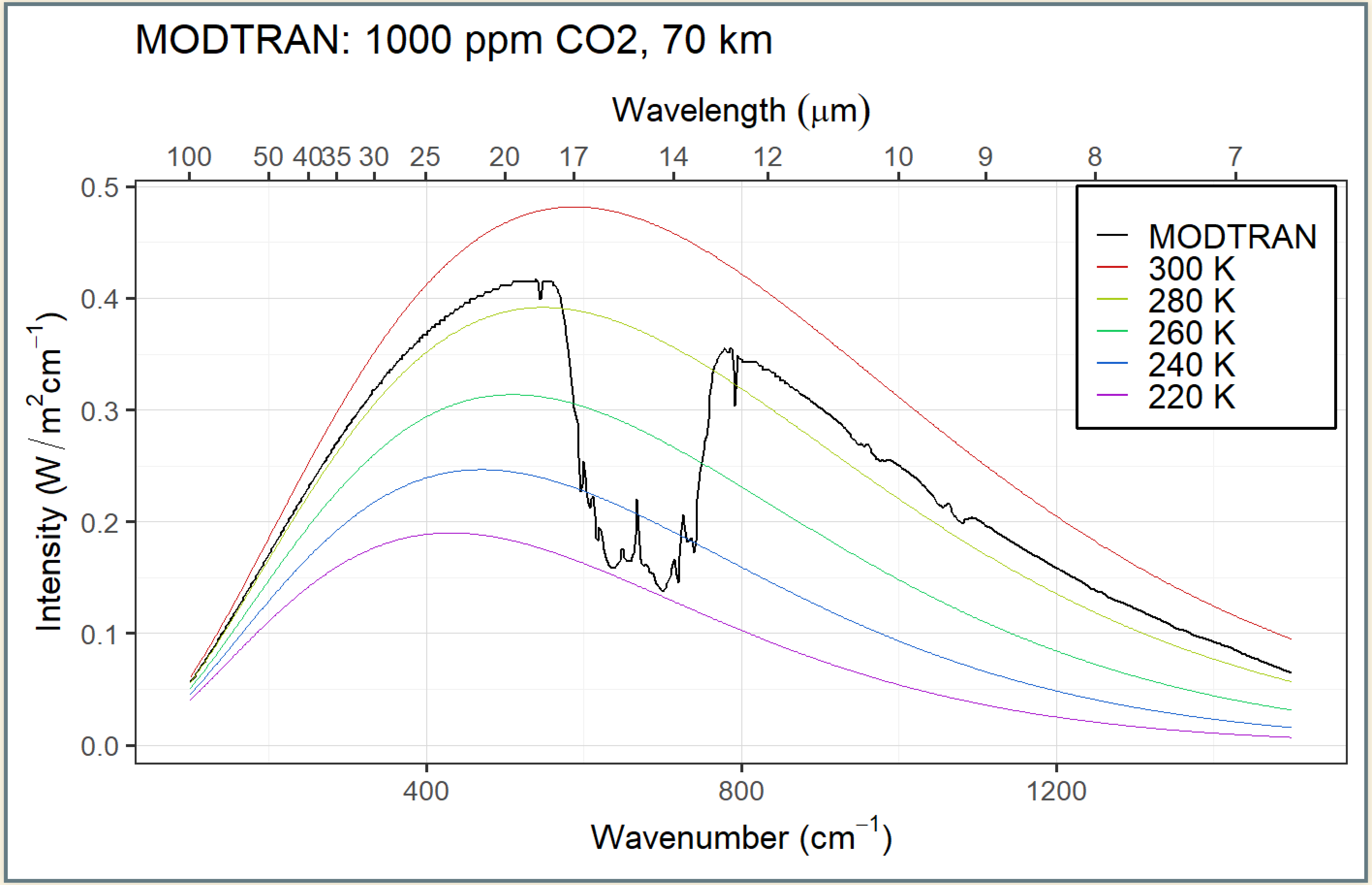
MODTRAN: 10 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm⁻¹)

100 ppm CO_2



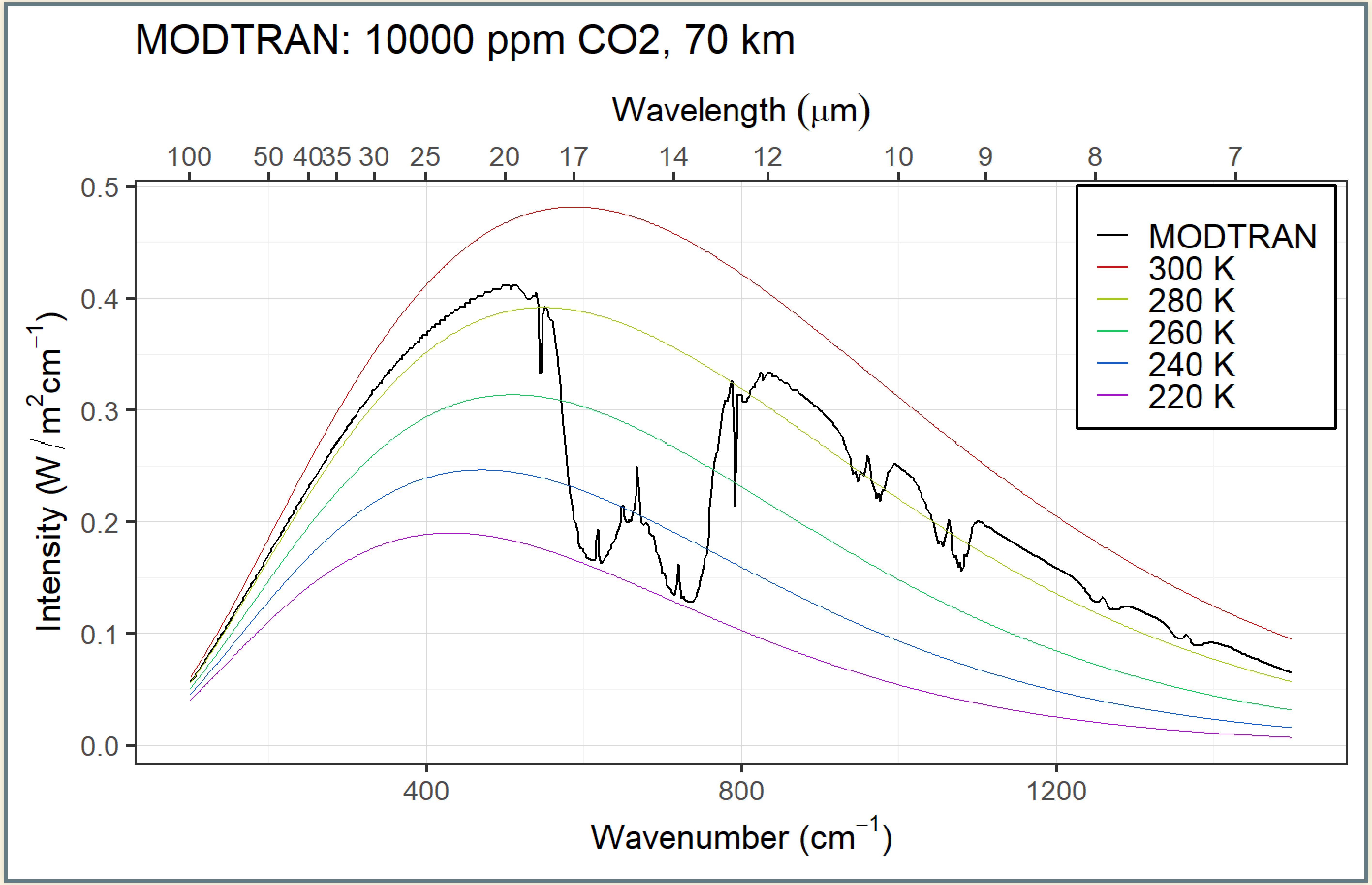
MODTRAN: 100 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m2cm−1)
400
800
1200
Wavenumber (cm−1)
MODTRAN
300 K
280 K
260 K
240 K
220 K

1000 ppm CO_2

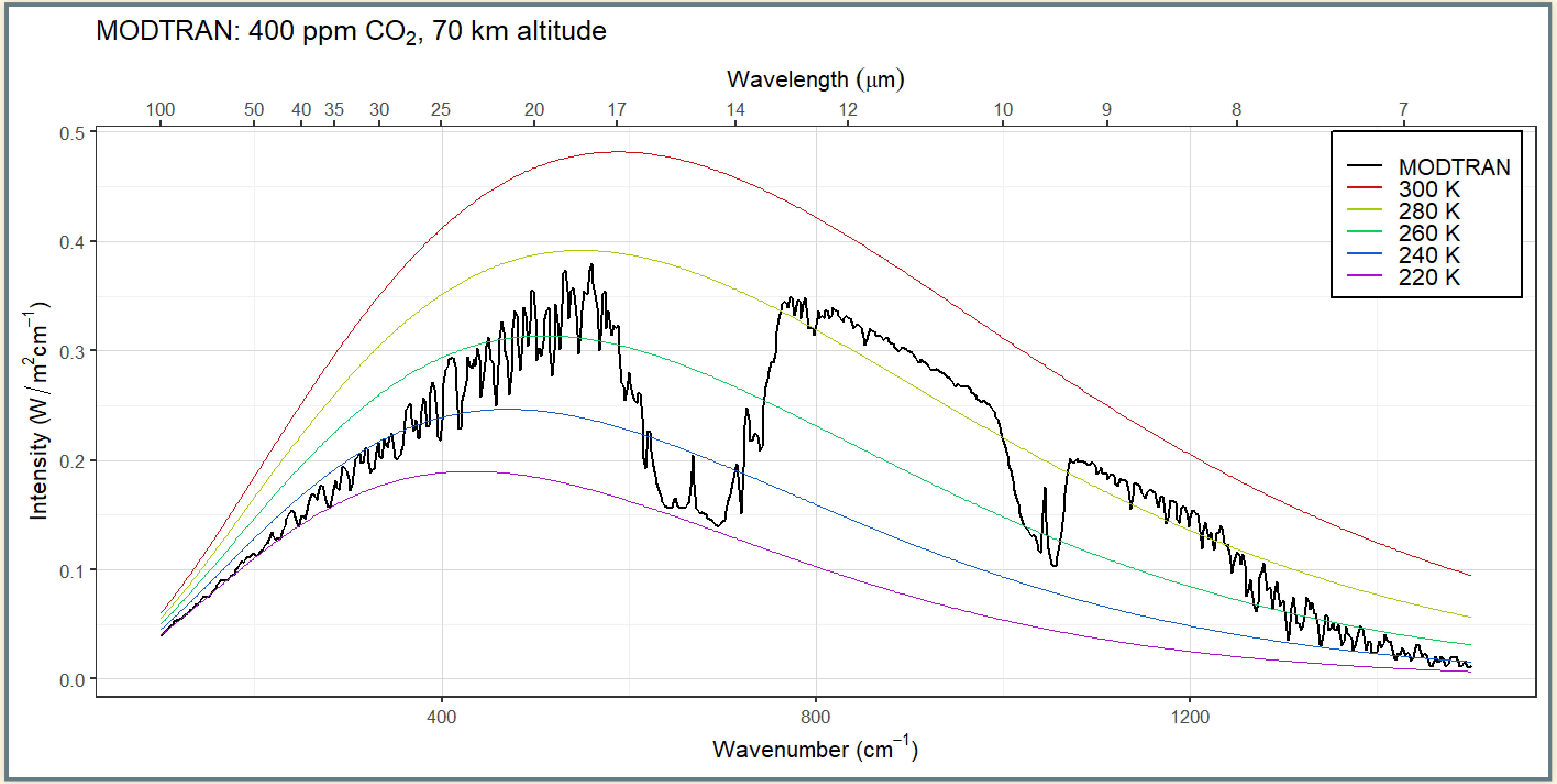


MODTRAN: 1000 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
Intensity (W / m²cm⁻¹)
0.0
0.1
0.2
0.3
0.4
0.5
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

10,000 ppm CO_2

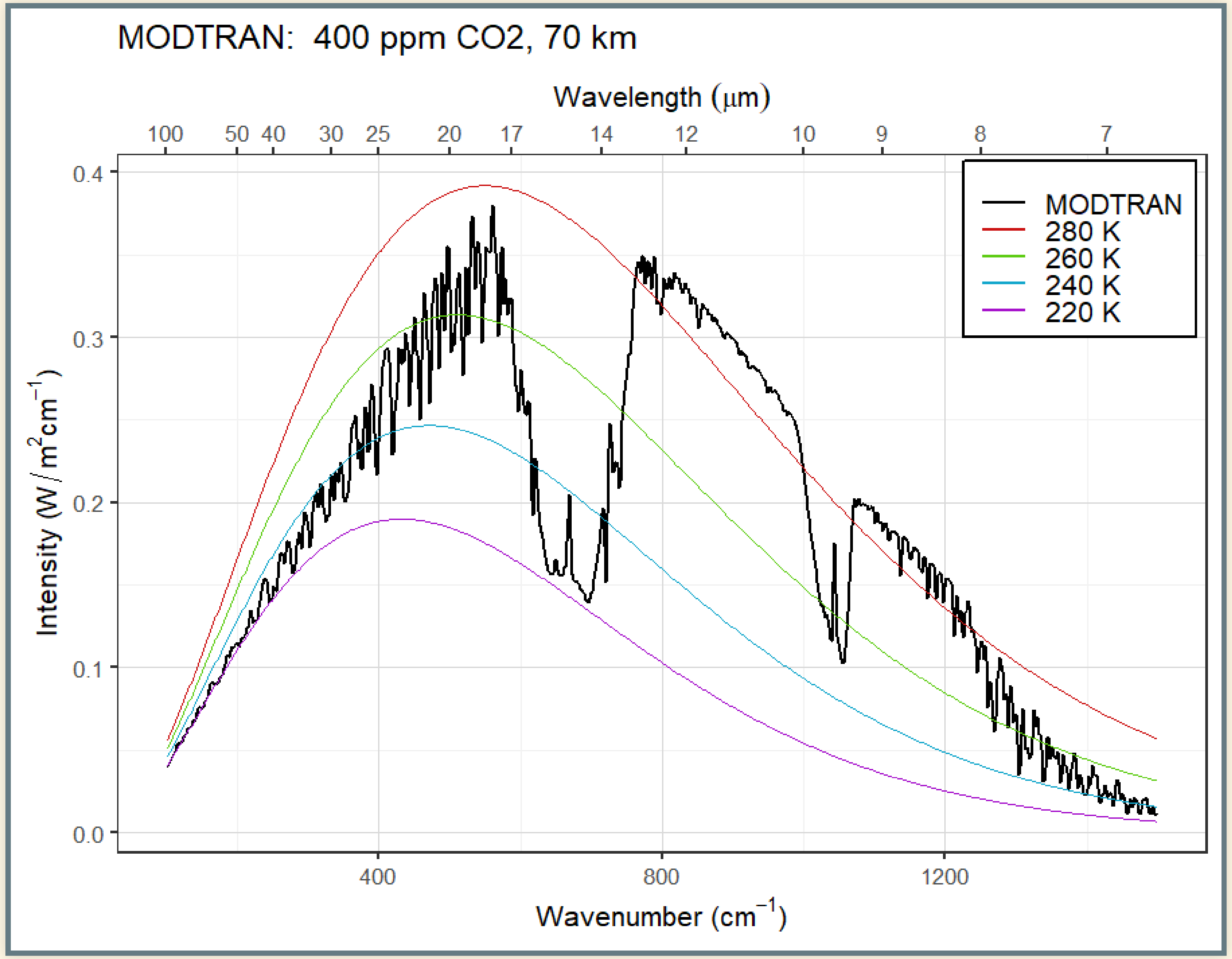


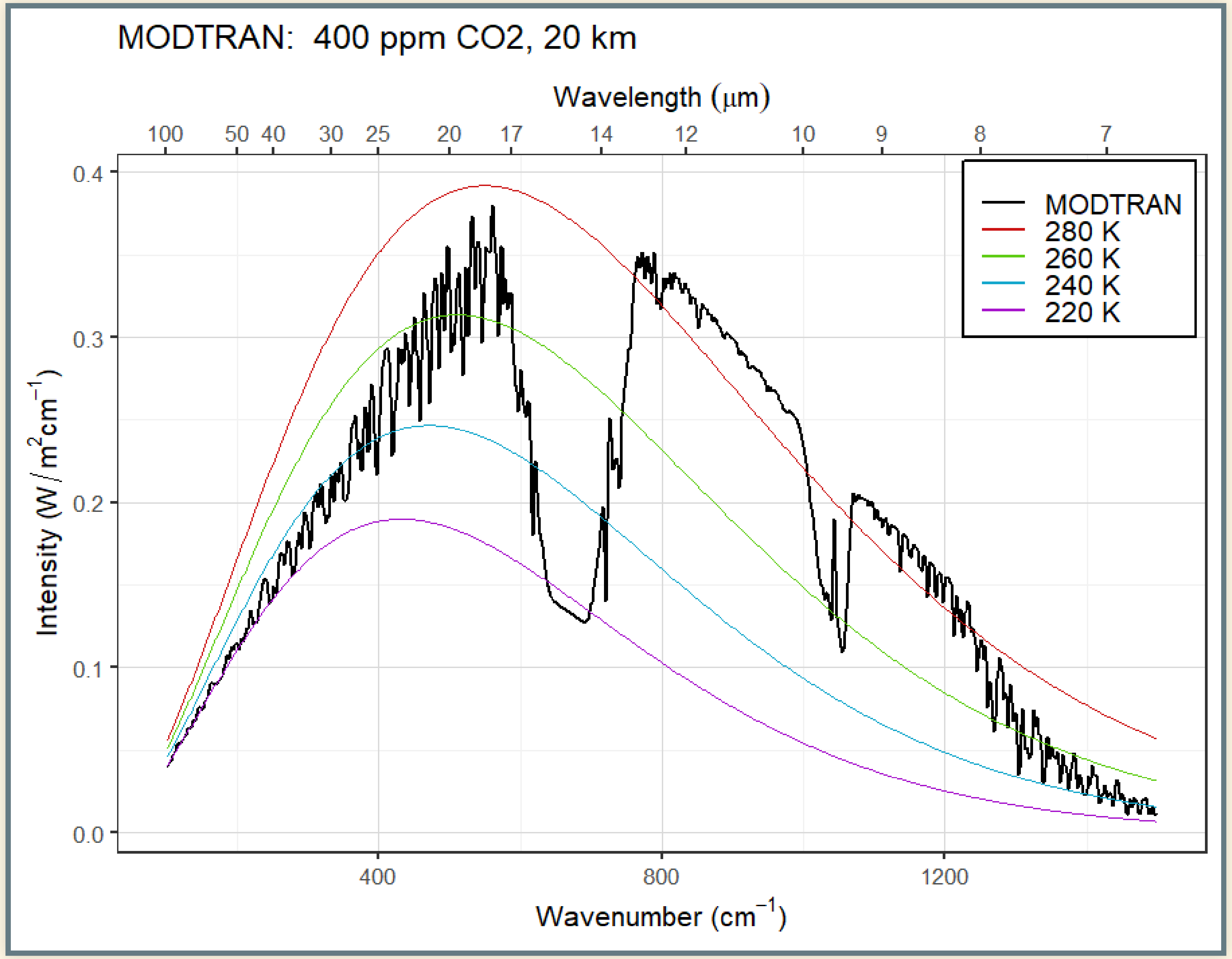
Question



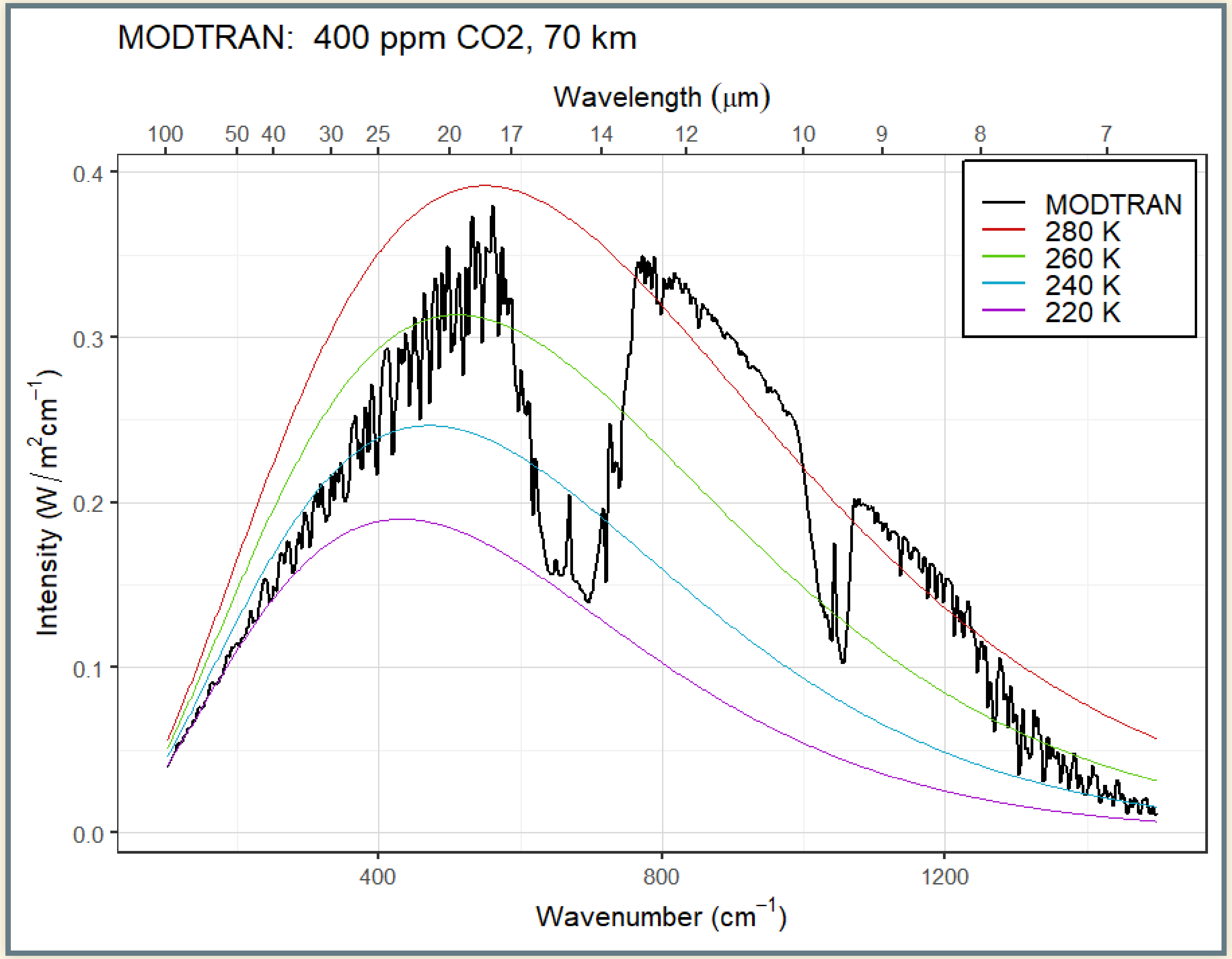
- Why do we see the spike in the middle of the CO_2 absorption feature?

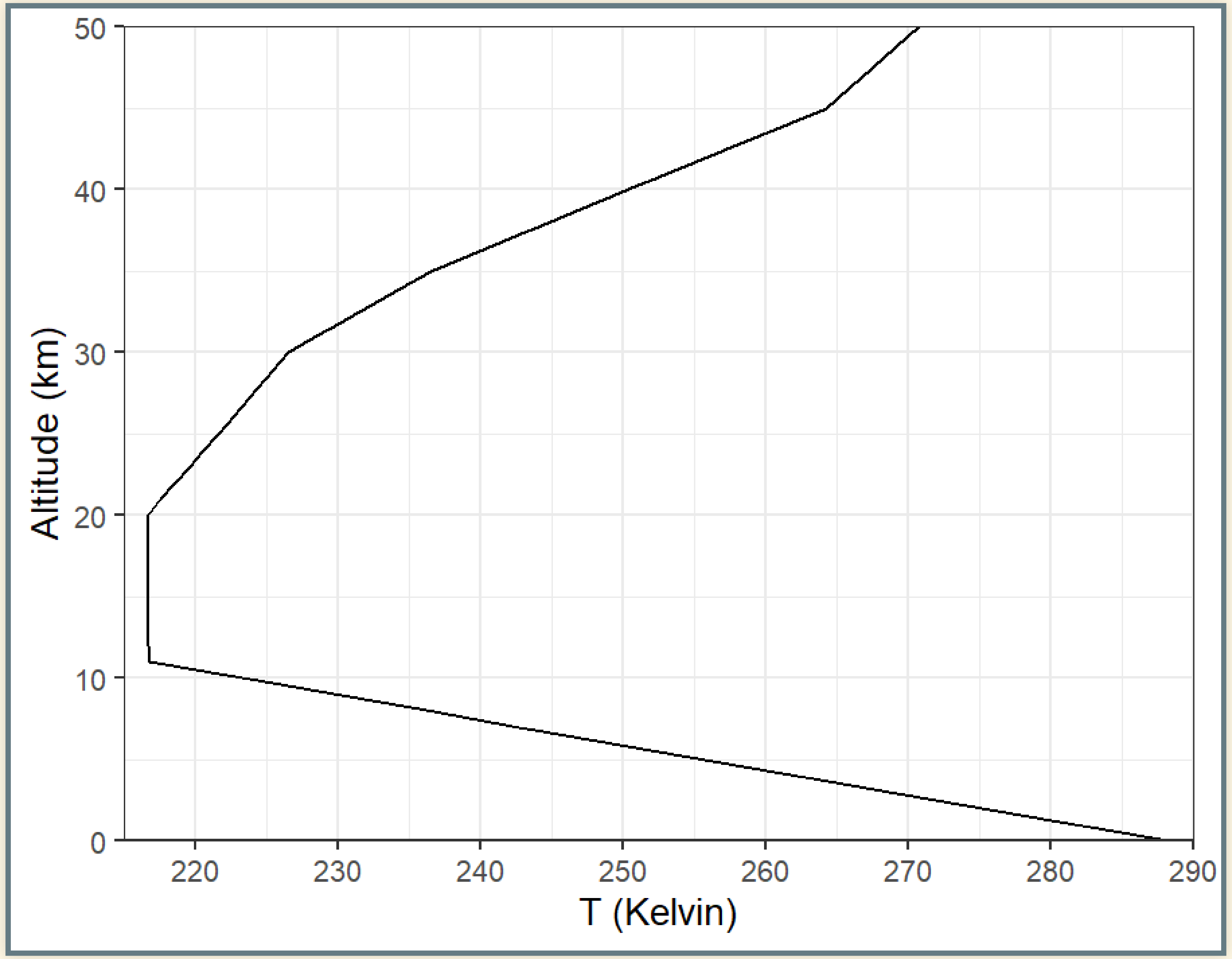
Answer


MODTRAN: 400 ppm CO2, 70 km
Wavelength (μm)
100 50 40 30 25 20 17 14 12 10 9 8 7
Intensity (W / m2cm−1)
0.0 0.1 0.2 0.3 0.4
400 800 1200
Wavenumber (cm−1)
MODTRAN
280 K
260 K
240 K
220 K

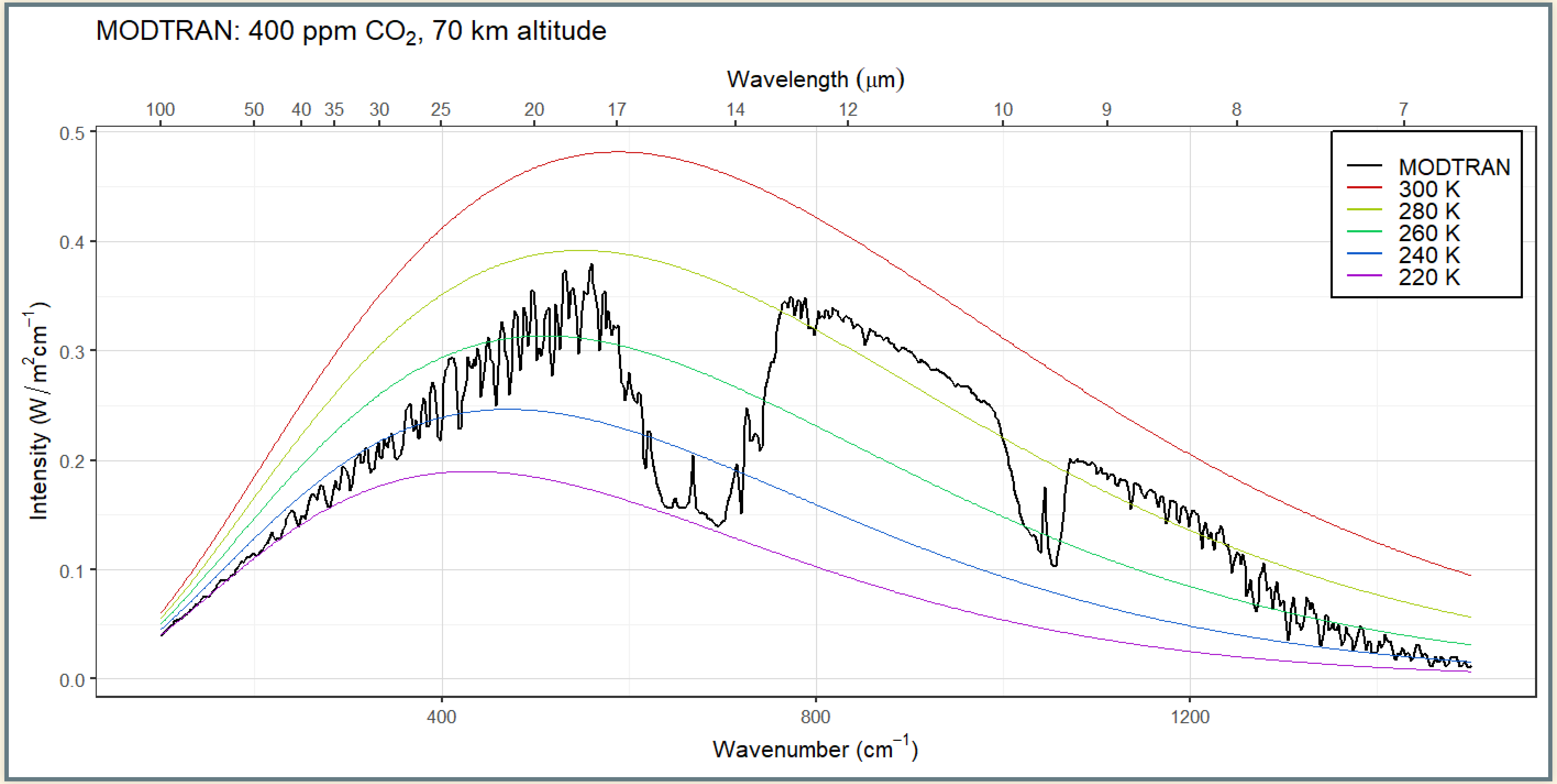

MODTRAN: 400 ppm CO2, 20 km
Wavelength (μm)
100 50 40 30 25 20 17 14 12 10 9 8 7
Intensity (W / m2cm−1)
0.0 0.1 0.2 0.3 0.4
400 800 1200
Wavenumber (cm−1)
MODTRAN
280 K
260 K
240 K
220 K

Answer


MODTRAN: 400 ppm CO2, 70 km
Wavelength (μm)
100 50 40 30 25 20 17 14 12 10 9 8 7
Intensity (W / m^{2}cm^{-1})
0.0 0.1 0.2 0.3 0.4
400 800 1200
Wavenumber (cm^{-1})
MODTRAN
280 K
260 K
240 K
220 K

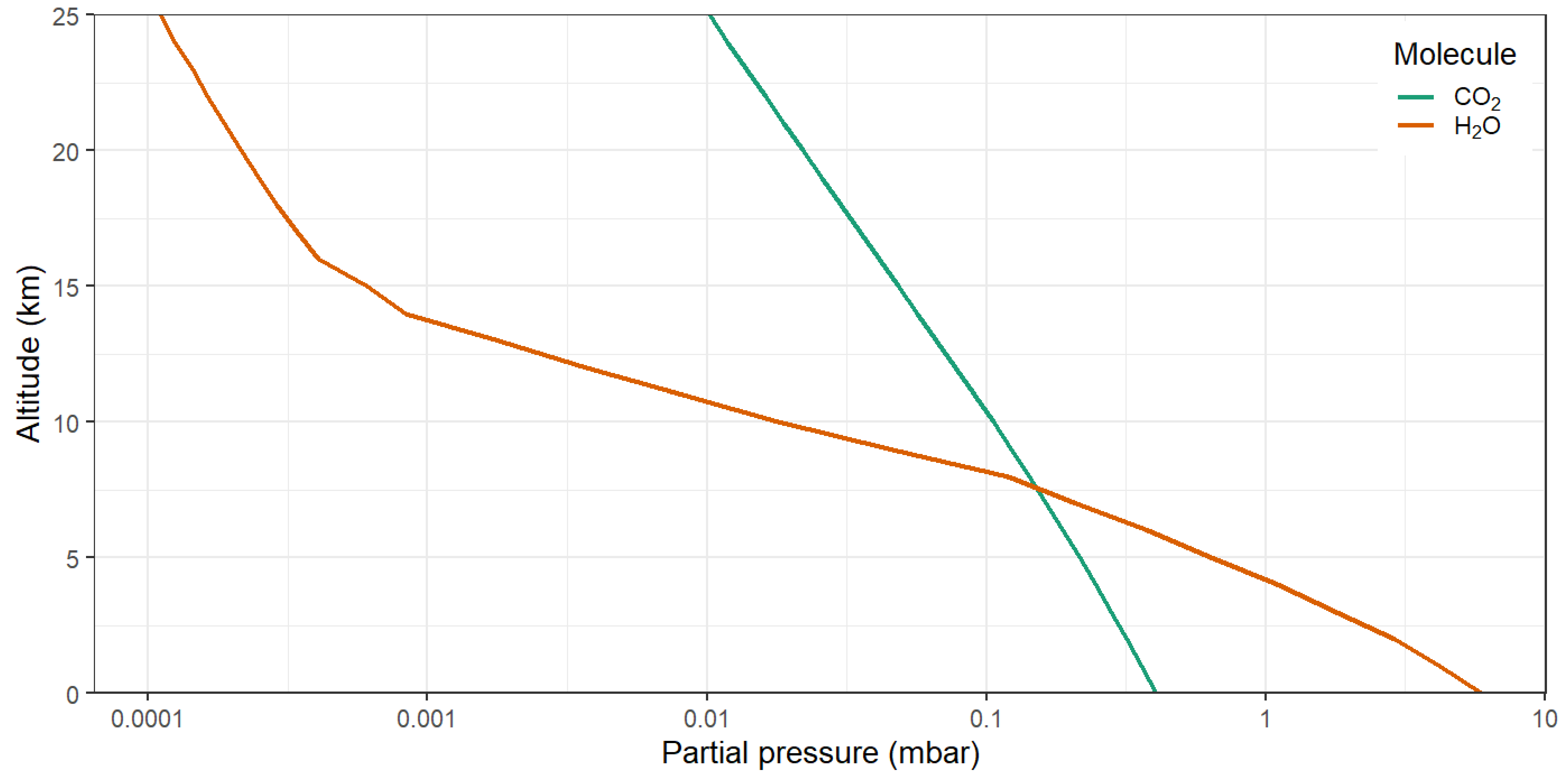

Altitude (km)
0 10 20 30 40 50
220 230 240 250 260 270 280 290
T (Kelvin)

Question



- Water vapor absorption is completely saturated.
  - Why does water vapor emit at warmer temperatures than CO_2?

Answer



- Near the ground, there is much more water vapor (10 times more)
- Above about 7 km, there is much more CO_2 (100 times more at 20 km)
  - Water vapor concentrations become small enough to be transparent to space at a much lower altitude than CO_2

Review Perspective

Review Perspective

1. **Start with bare-rock temperature**
   - This becomes skin temperature
2. **Add simple atmosphere:**
   - Completely absorbs longwave radiation
   - Top of atmosphere: skin temperature (same as bare-rock)
   - Atmosphere insulates surface $\Rightarrow$ surface heats up
   - More layers $\Rightarrow$ bigger greenhouse effect
3. **Realistic longwave absorption:**
   - Atmosphere is not a black body
4. **Radiative-Convective equilibrium:**
   - Pure radiative equilibrium would have *huge* lapse
   - Big lapse is unstable $\Rightarrow$ convection
     - Convection mixes hot & cold air $\Rightarrow$ modifies environmental lapse
     - Reduces greenhouse effect