Review of the Greenhouse Effect

EES 3310/5310

Global Climate Change

Jonathan Gilligan

Class #7: Wednesday, February 2 2022

Black History Month:
Great Black Climate Scientists

Warren M. Washington

- Born 1936, Portland OR
- B.S., 1958 (physics) Oregon State University
- Ph.D., 1964 (meteorology) Pennsylvania State University
- Scientist at National Center for Atmospheric Research (NCAR) since 1963
  - One of the first developers of global climate models
  - Pioneer in using parallel supercomputers for climate modeling
  - Head of Climate Section, 1974–1987
  - Director of Climate and Global Dynamics Division, 1987–1995

Warren Washington looking at microfilm of climate model results in 1973. (Photo by UCAR, Ginger Hein)

Warren Washington

- Honors:
  - President American Meteorological Society (1994)
  - Chair of National Science Board (2000–2006)
  - National Academy of Engineering, since 2002
  - Shared 2007 Nobel Peace Prize
  - 2010 National Medal of Science
  - 2019 Tyler Prize for Environmental Achievement
  - Many more…

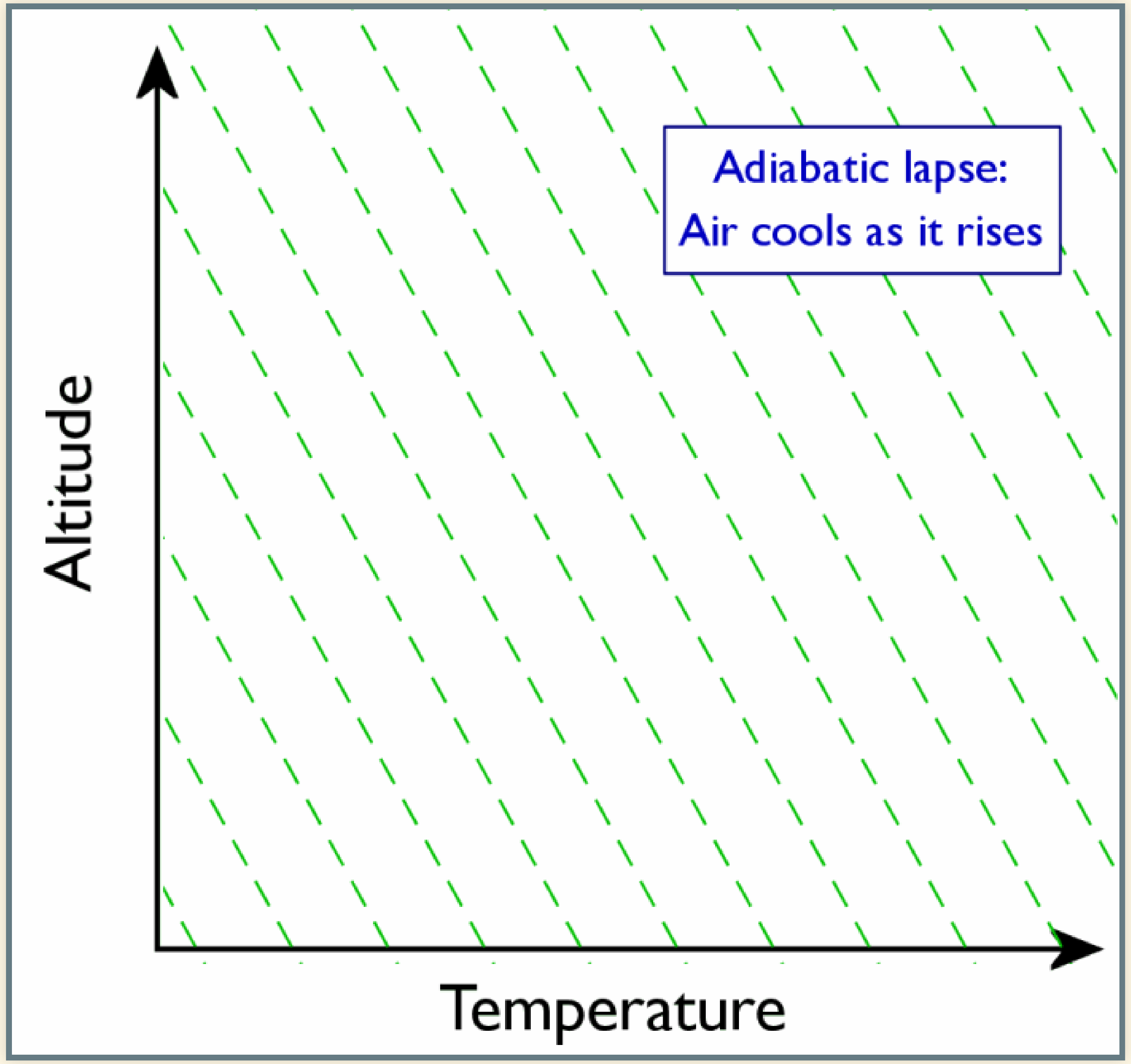
Review of Lapse Rates and Stability

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

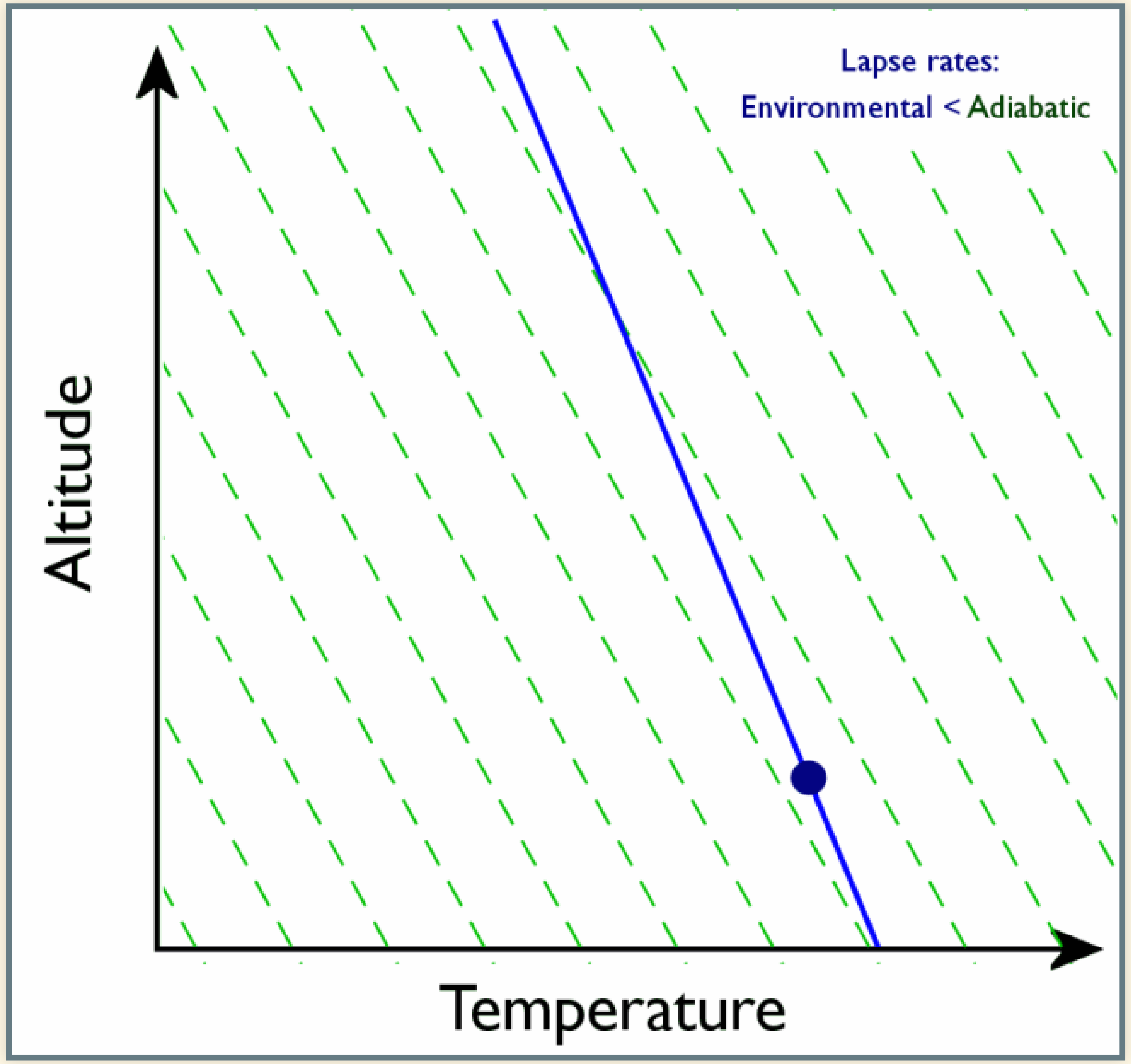
Overview of Convection

Overview of convection



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

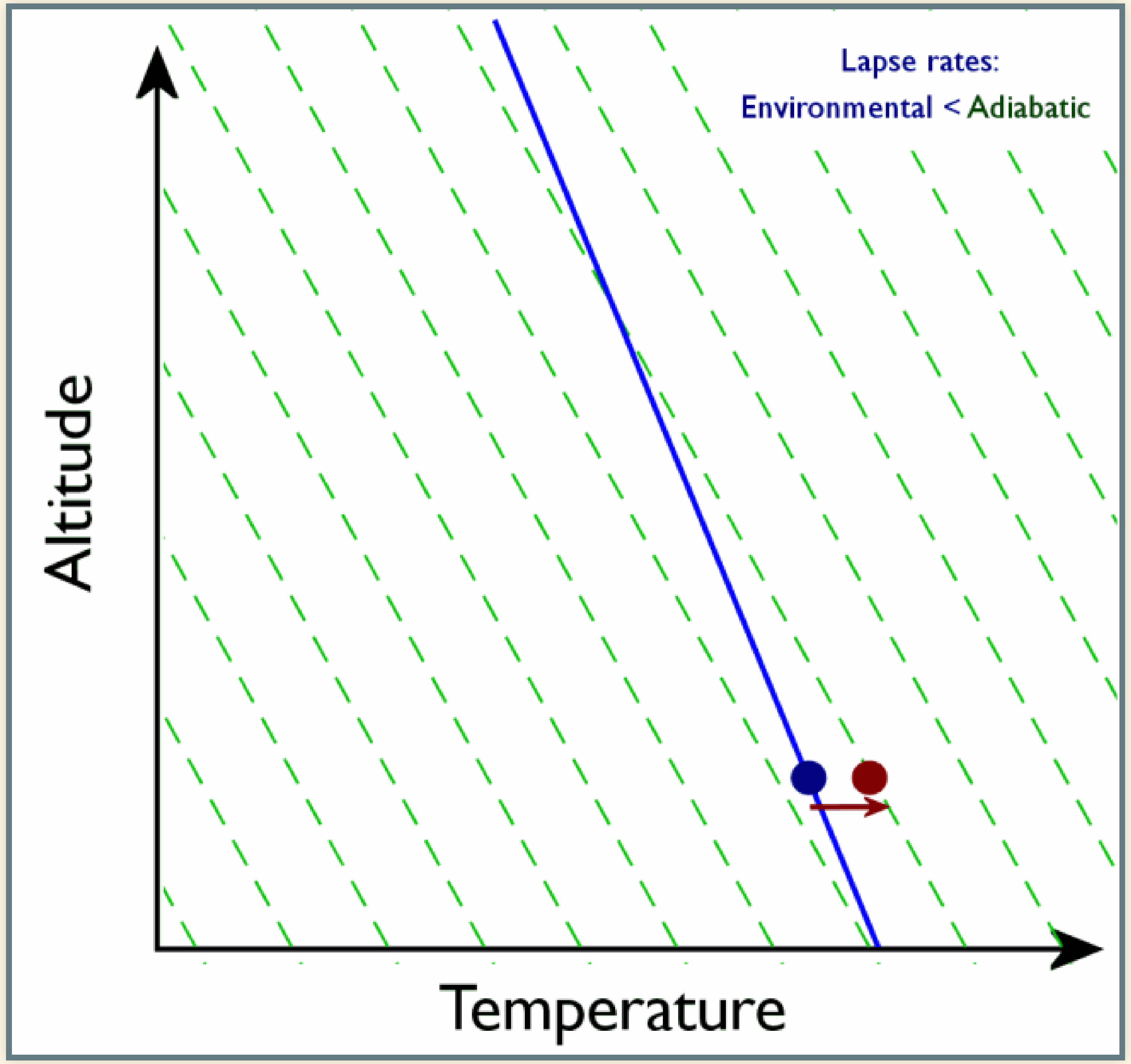
Stable Atmosphere
Initial State



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

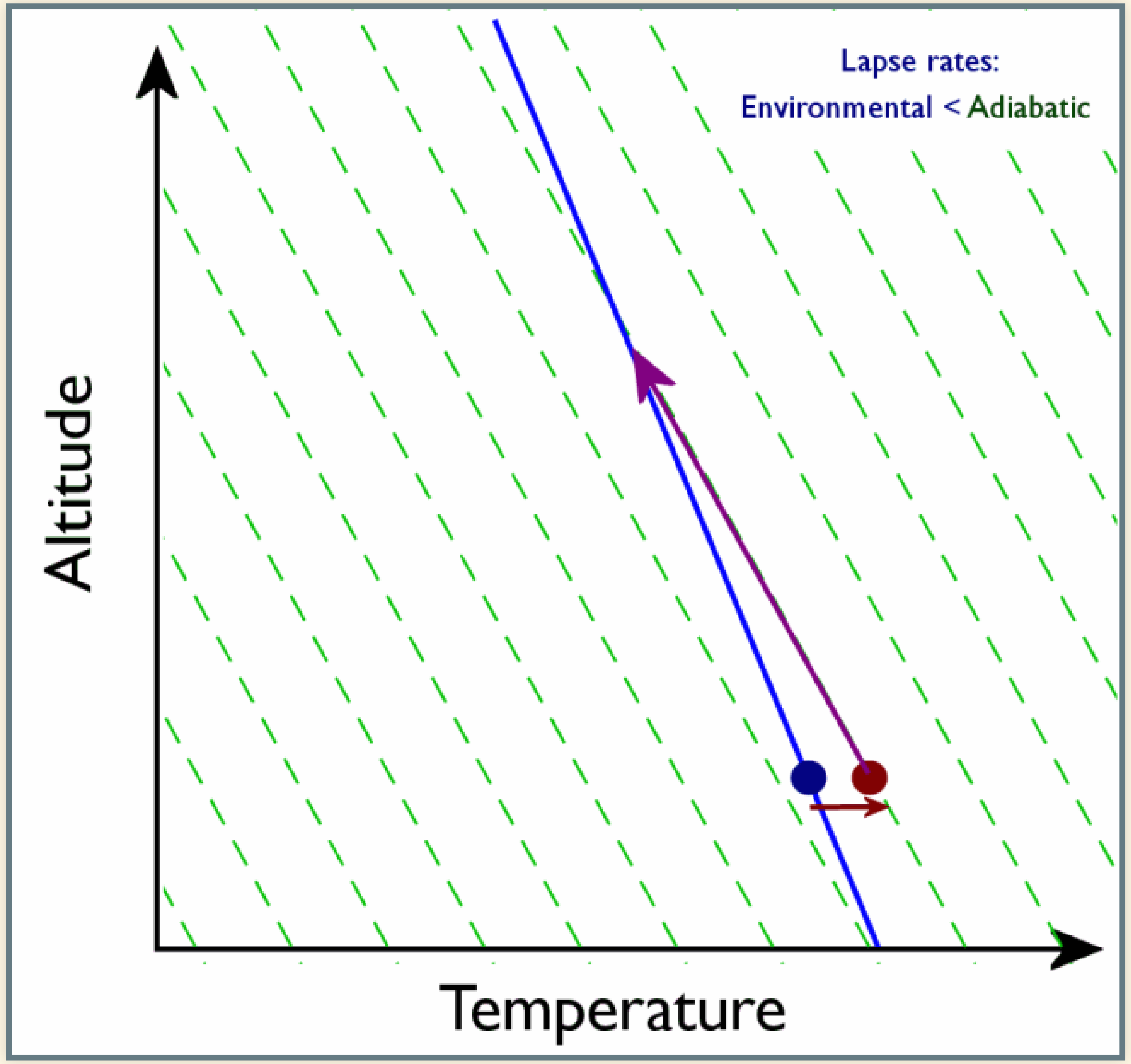
Stable Atmosphere

Parcel is heated



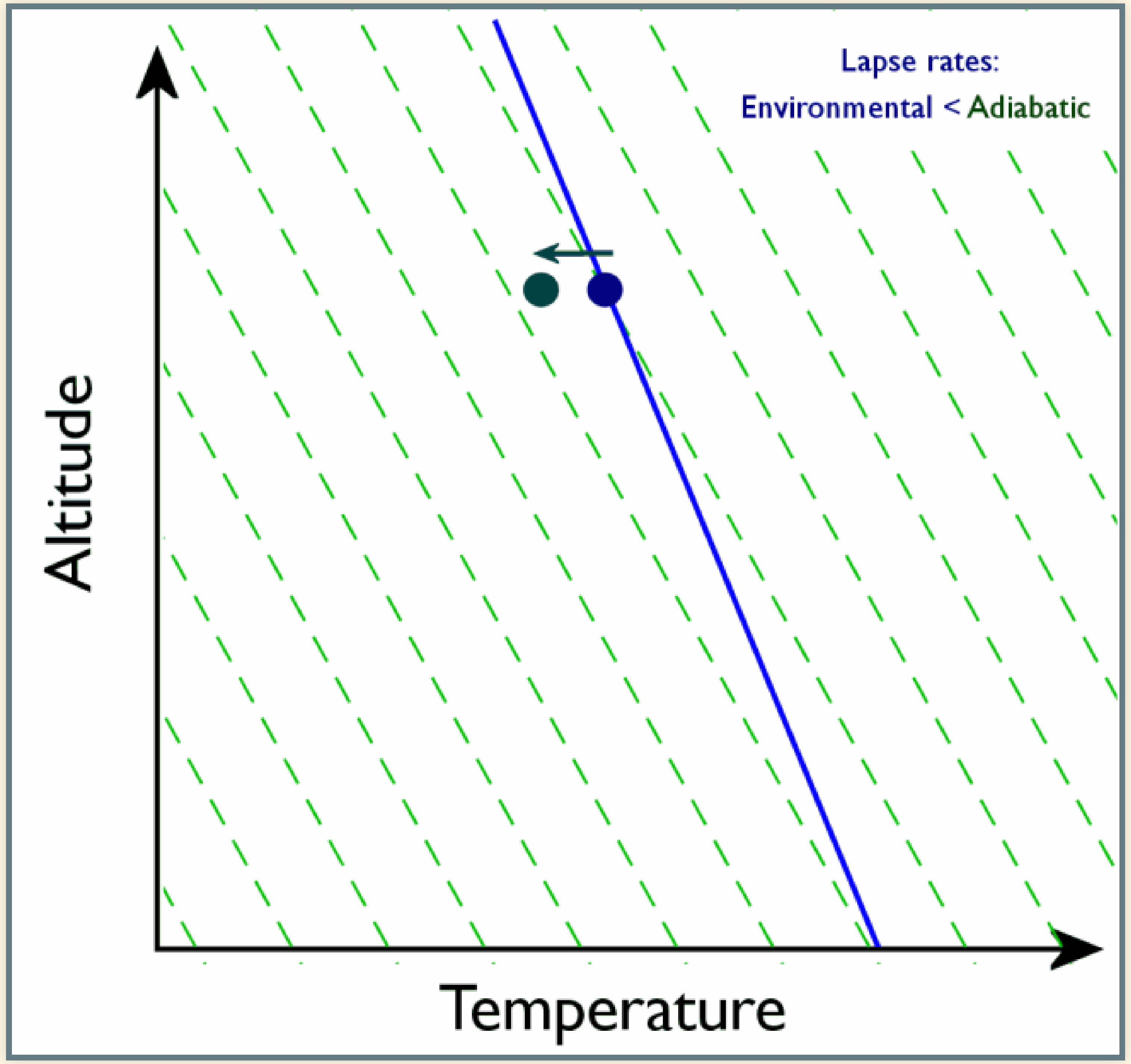
Stable Atmosphere

Rises to new equilibrium



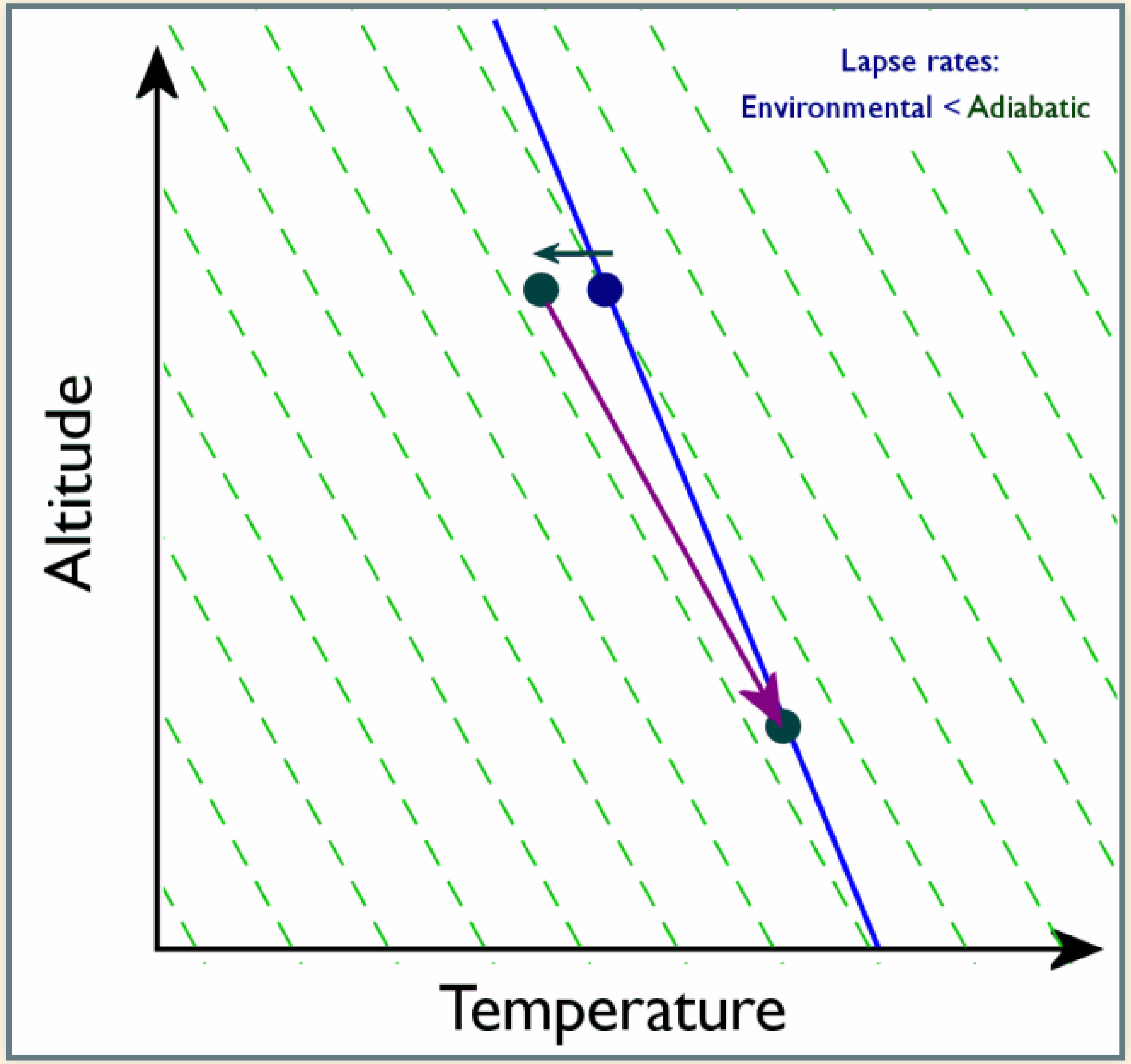
Stable Atmosphere

Parcel is cooled



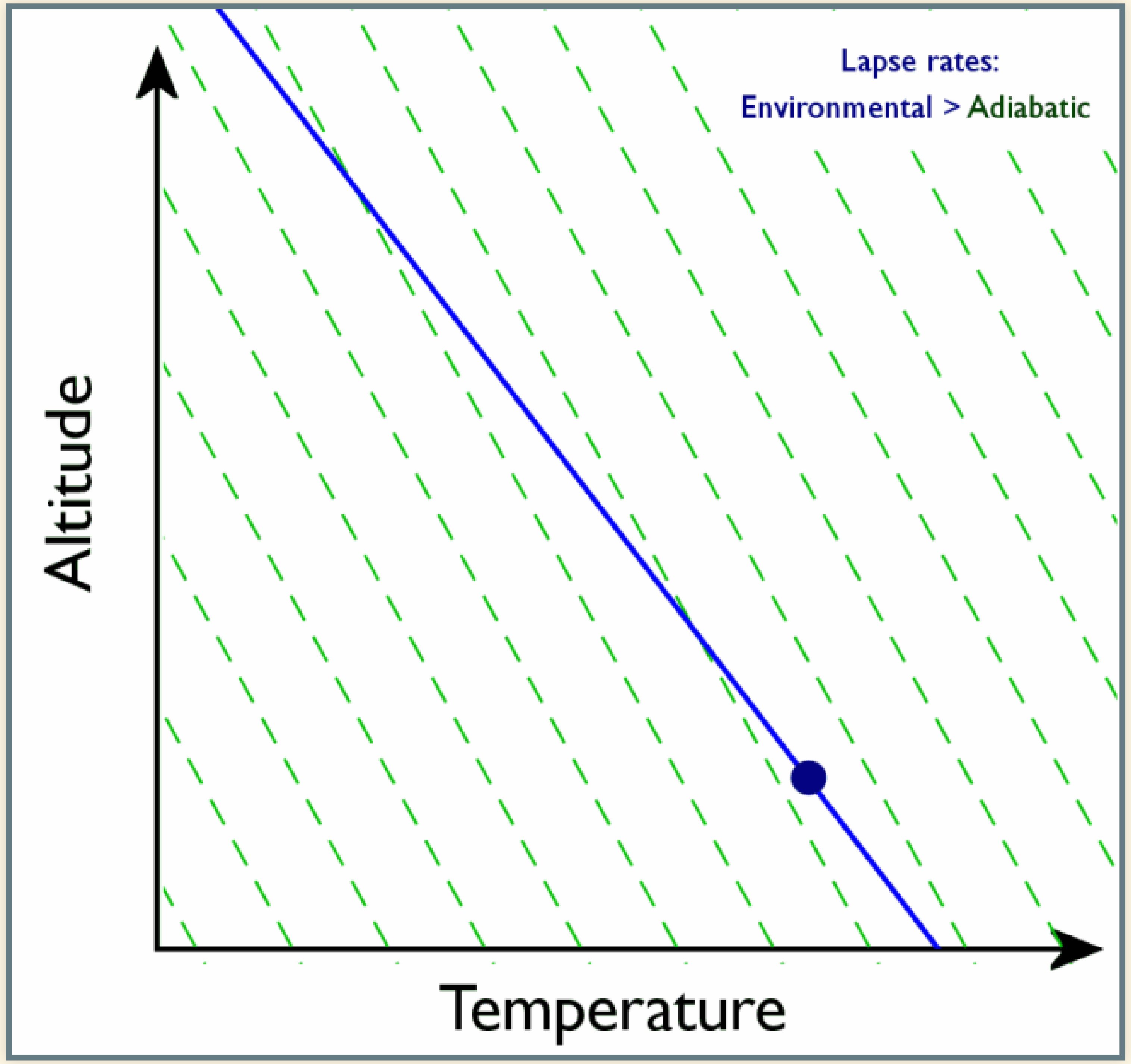
Stable Atmosphere

Sinks to new equilibrium



Unstable Atmosphere

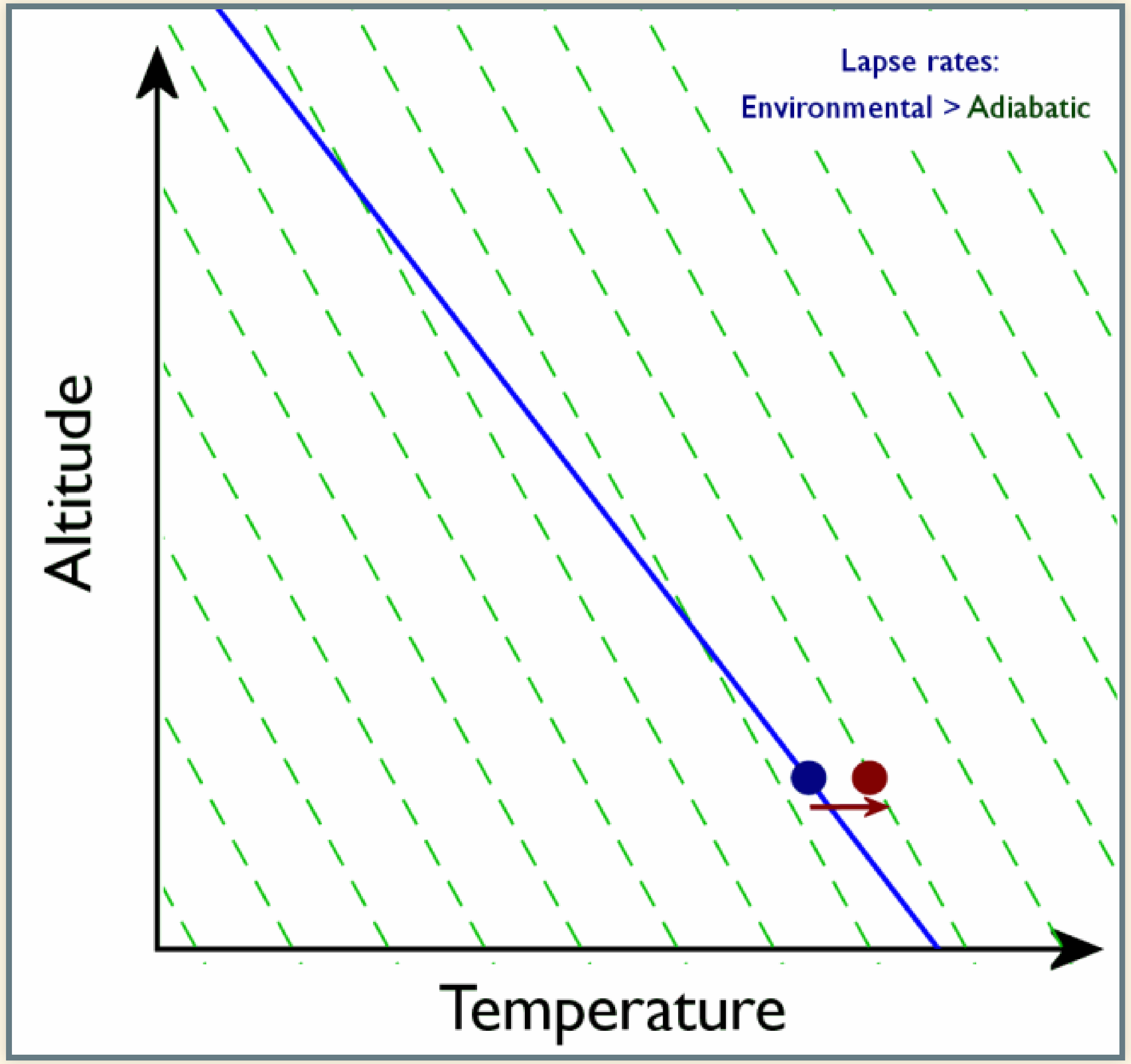
Unstable Atmosphere
Initial State



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

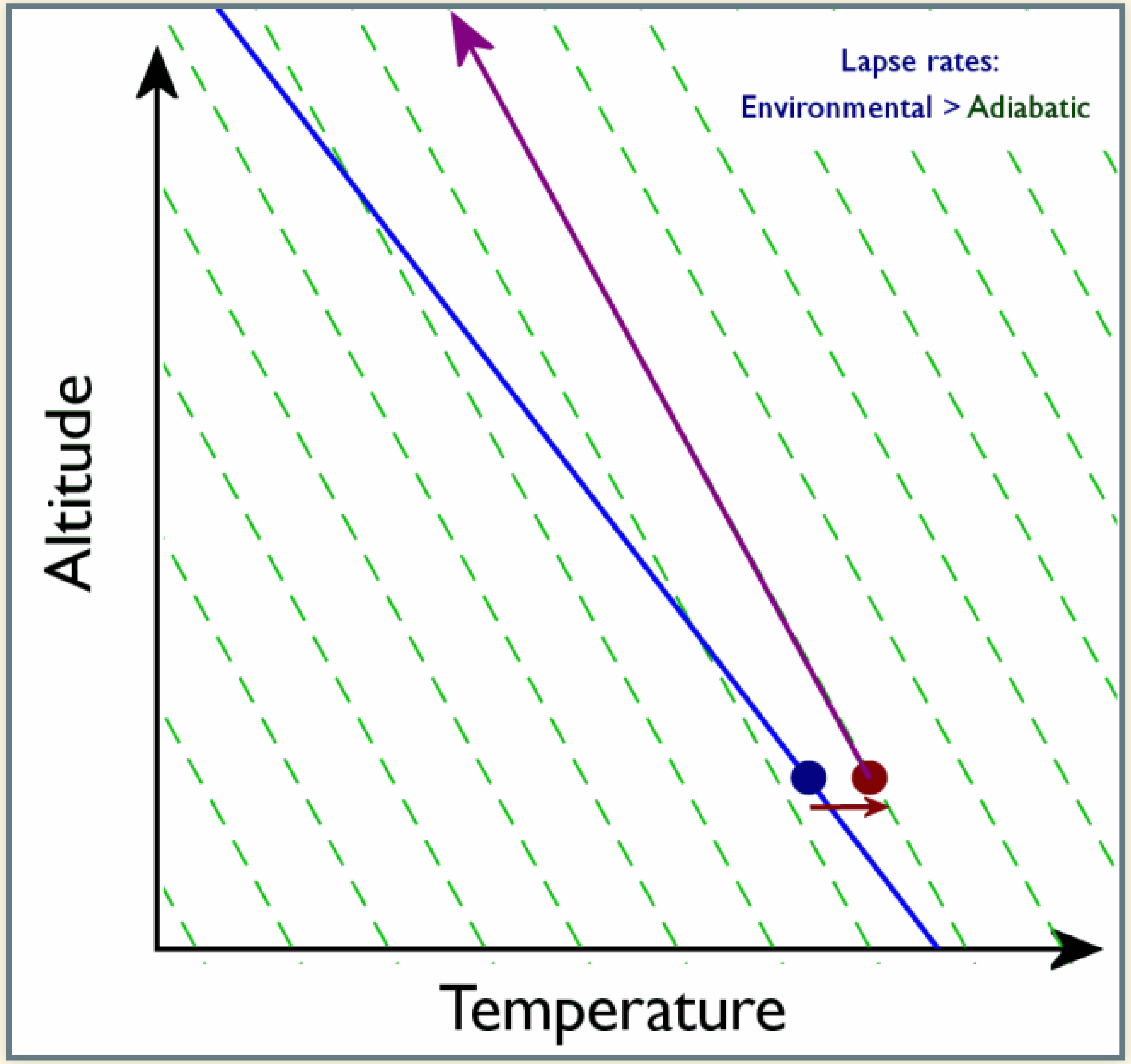
Unstable Atmosphere

Parcel is heated



Unstable Atmosphere

Rises without stopping



Summary of Stability

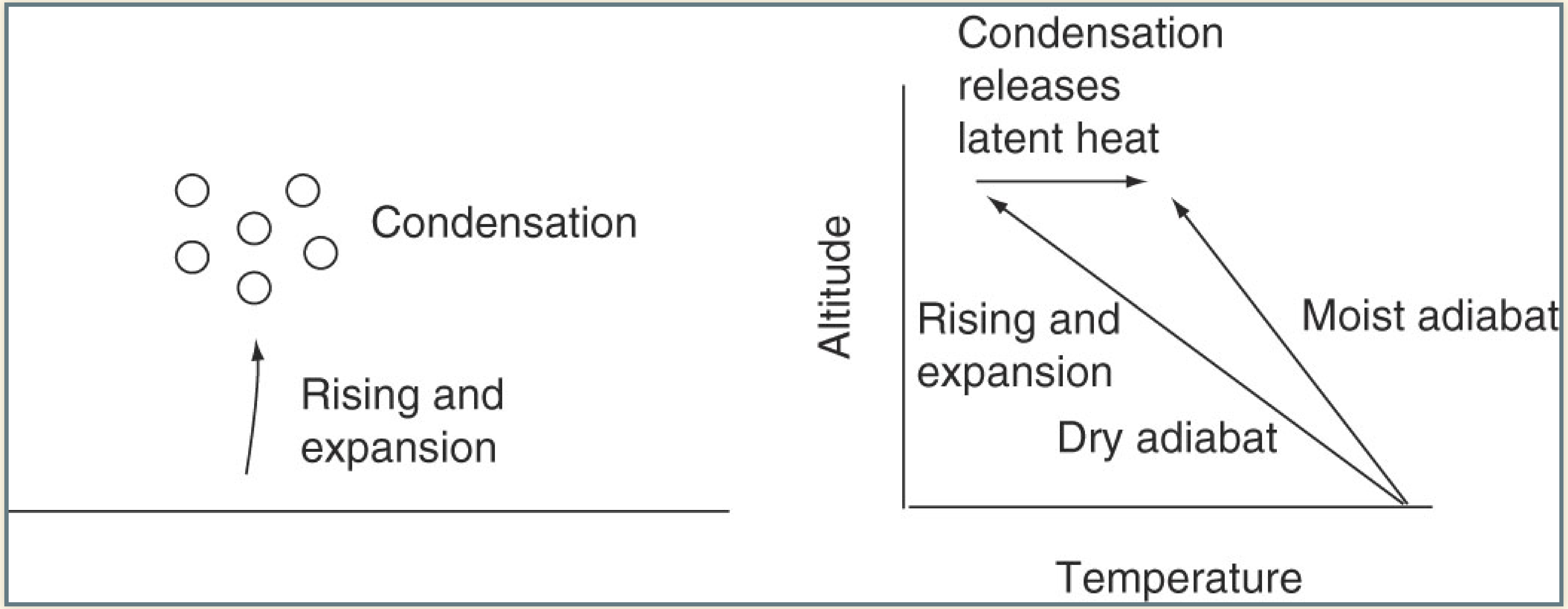
Summary of stability:

- 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

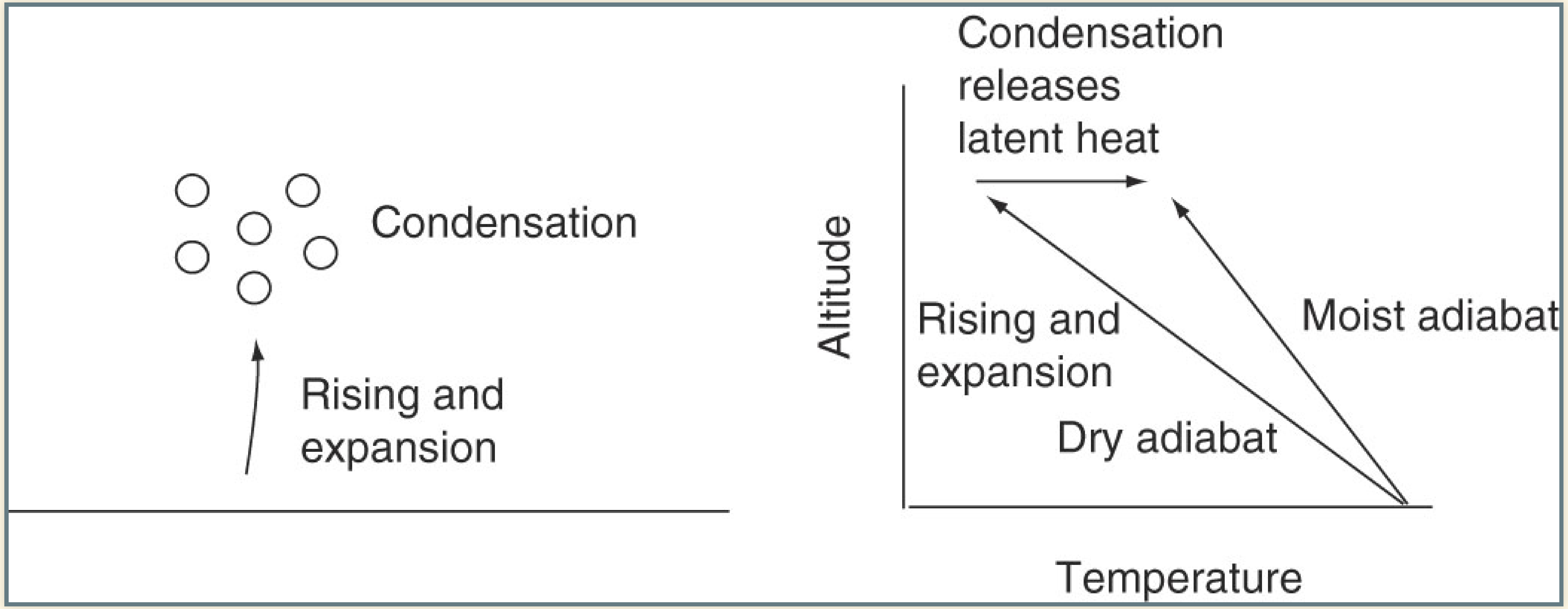
Moist Convection

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
- Heat reduces adiabatic cooling
- Moist adiabatic lapse < Dry adiabatic lapse
- Smaller lapse = less stable
- **Humid air is less stable than dry air**

Perspective

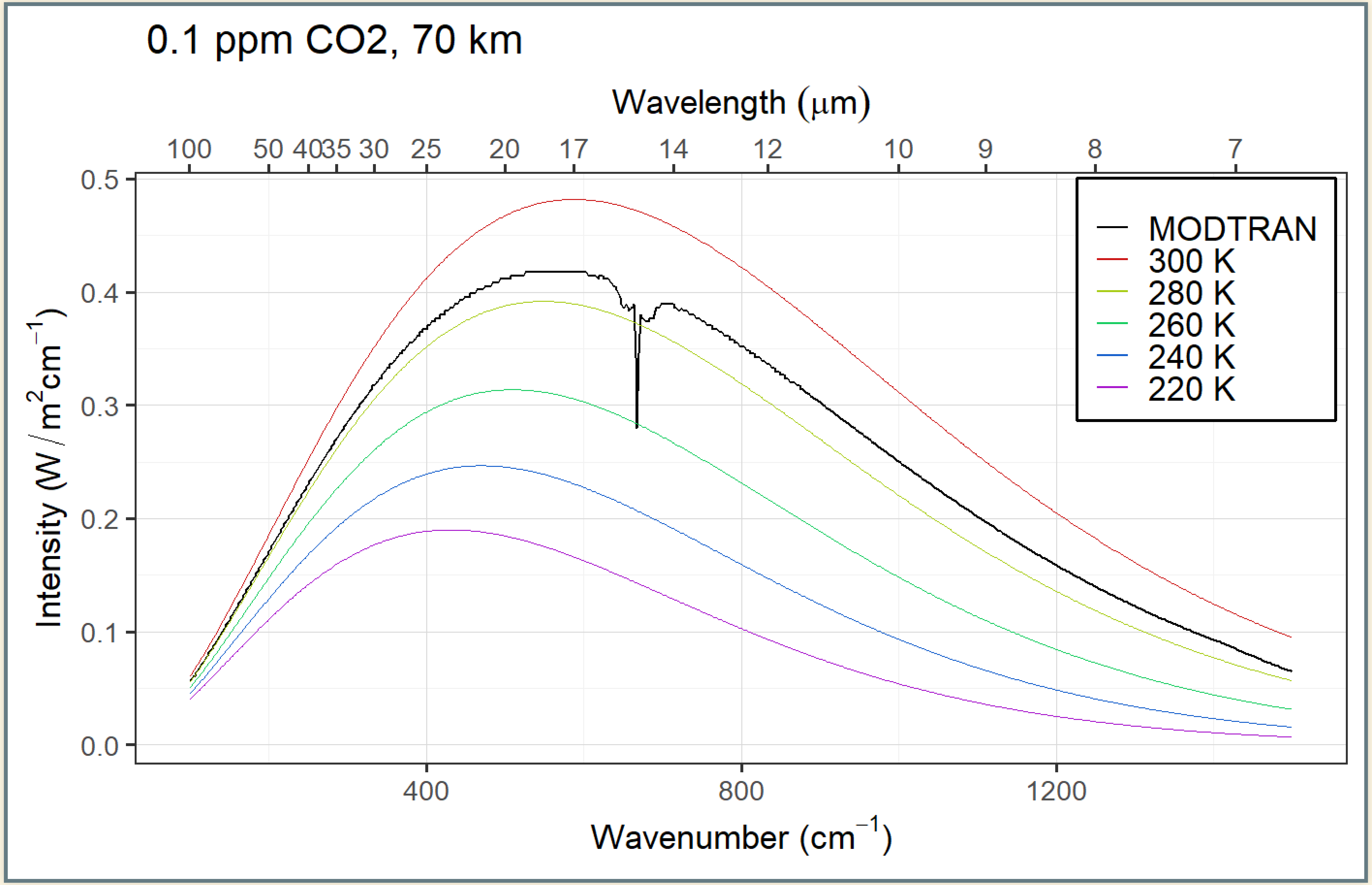
- Stable:
  - Environmental lapse $\leq$ adiabatic lapse
- Unstable:
  - Environmental lapse > adiabatic lapse
- Adiabatic lapse:
  - Dry: 10 K/km
  - Moist: 4-8 K/km (depends on humidity)
- Pure radiative equilibrium:
  - Would produce lapse of **16 K/km**: unstable
- Radiative-Convective equilibrium: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

Vertical Structure and Saturation

Set up MODTRAN:

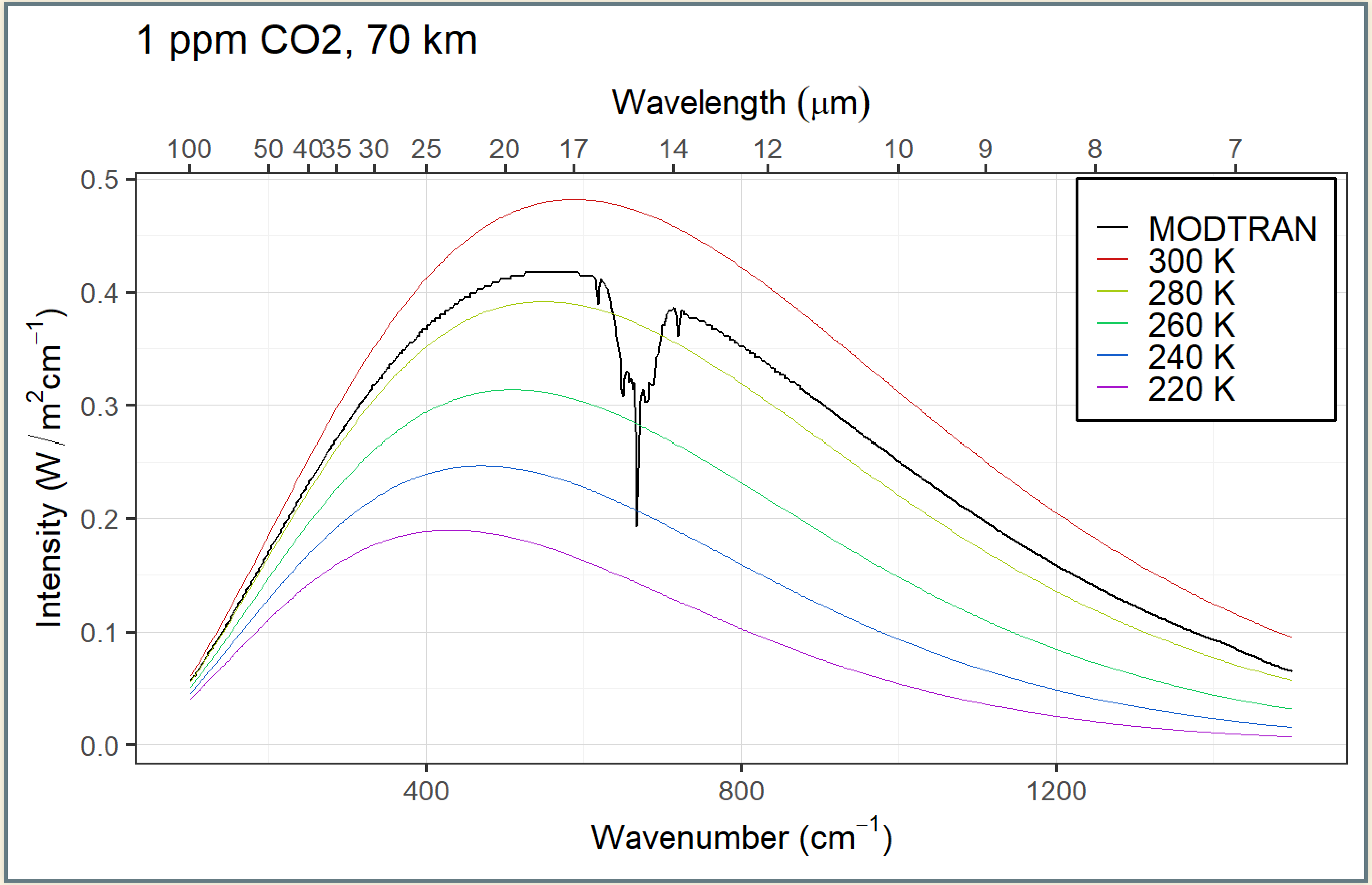
- Open MODTRAN http://climatemodels.uchicago.edu/modtran/
- Set location to “1976 U.S. Standard Atmosphere”.
- Set altitude to **70 km**.
- Set CO_2 to 0.1 ppm, all other gases to zero.
- Now increase CO_2 by factors of 10 (1, 10, 100, 1000, 10000)
- Notice differences between **70 km** and **20 km**.

0.1 ppm CO_2

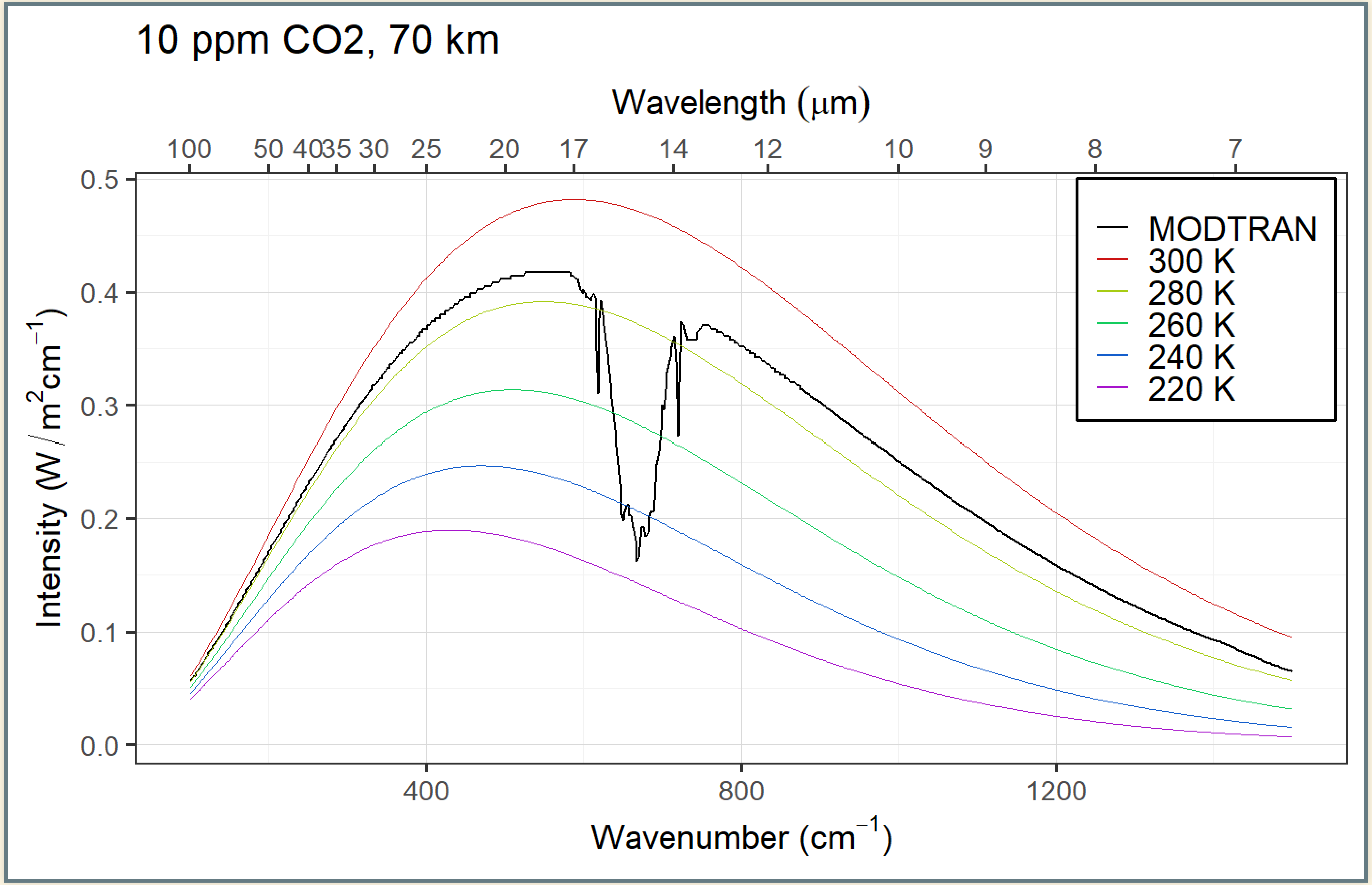


0.1 ppm CO2, 70 km
Wavelength (µm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
Intensity (W / m²cm⁻¹)
0.5
0.4
0.3
0.2
0.1
0.0
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm⁻¹)

1 ppm CO_2

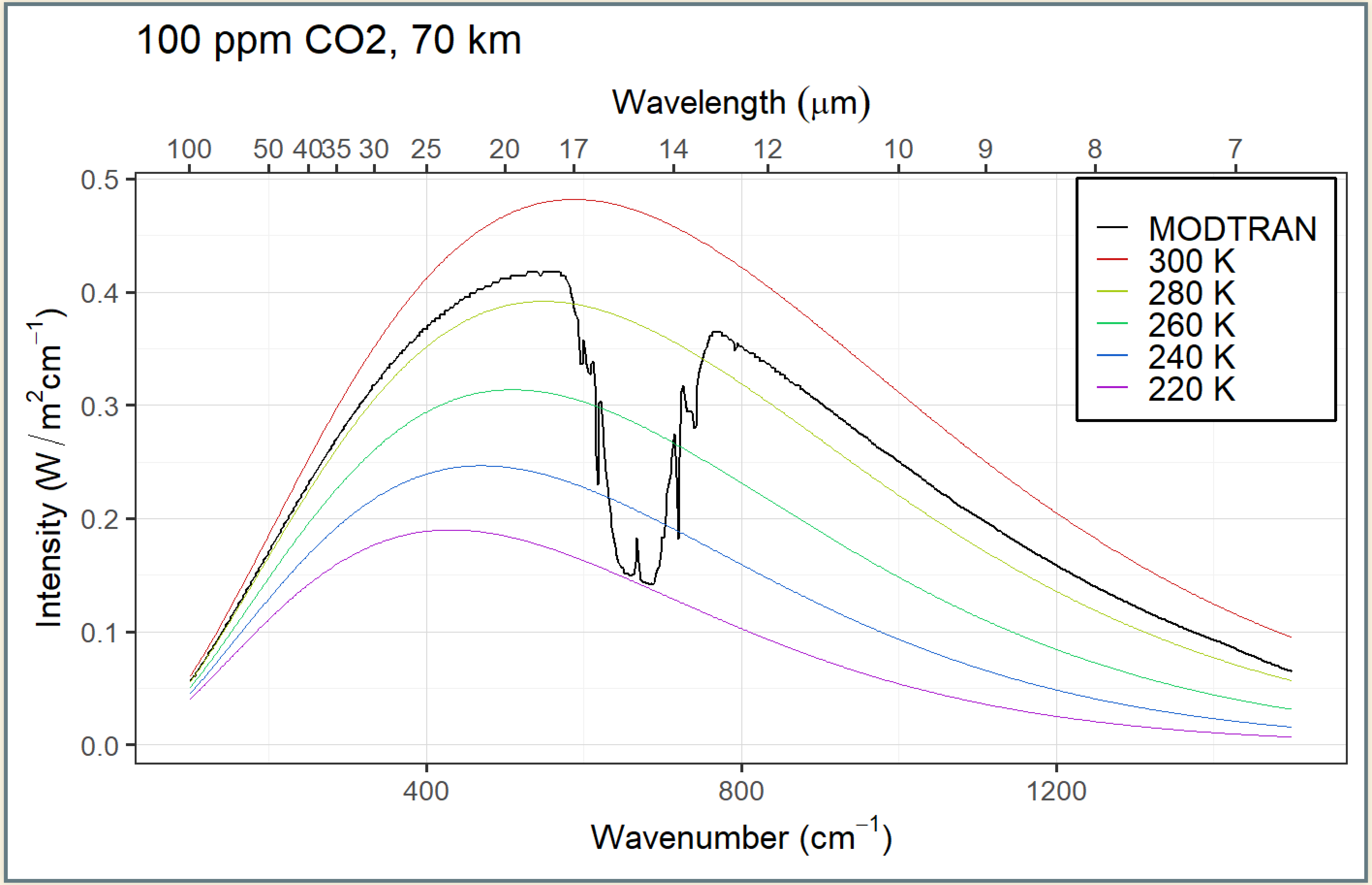

1 ppm CO2, 70 km
Wavelength (µm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

10 ppm CO_2



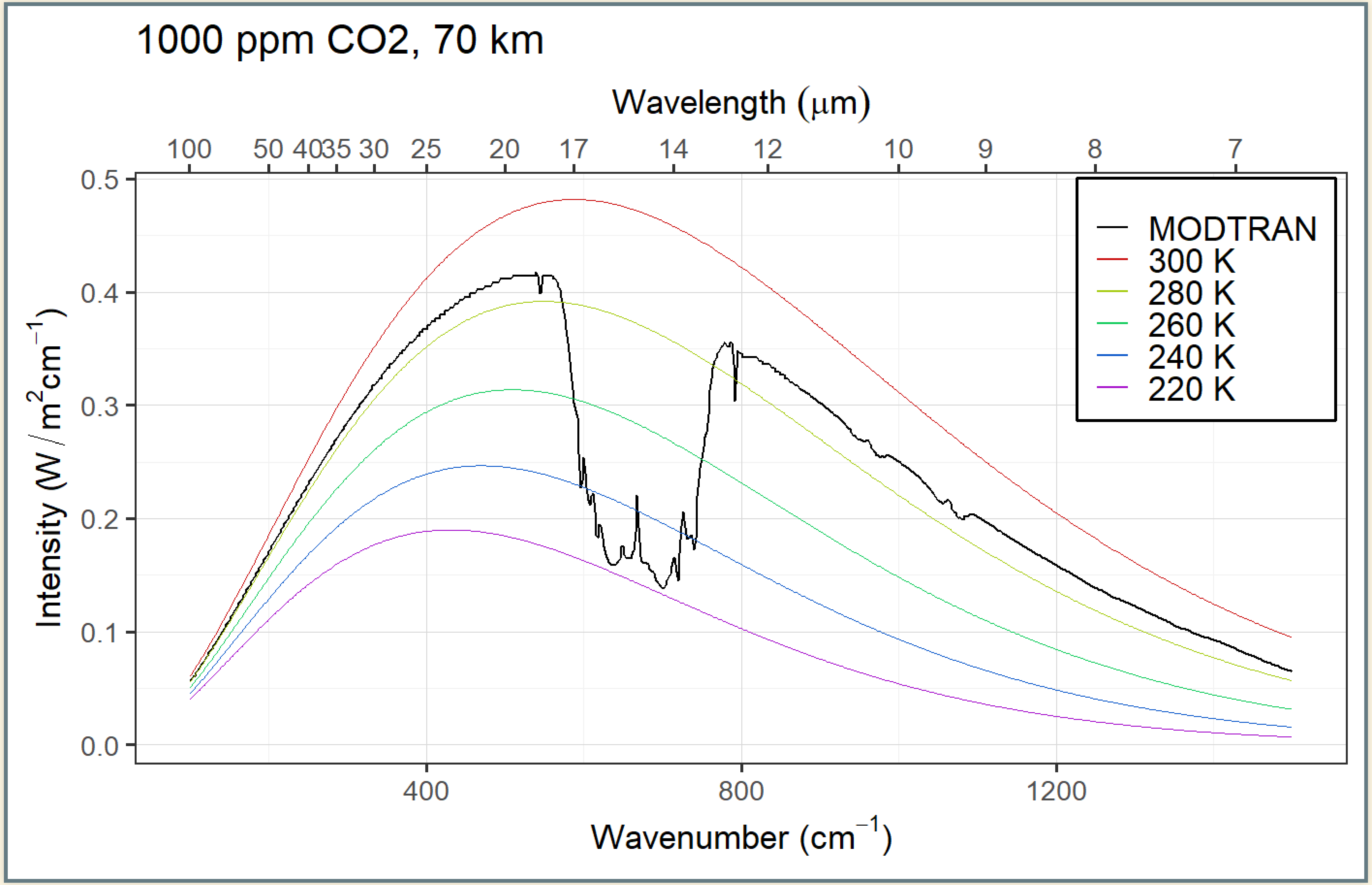
10 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm⁻¹)

100 ppm CO_2



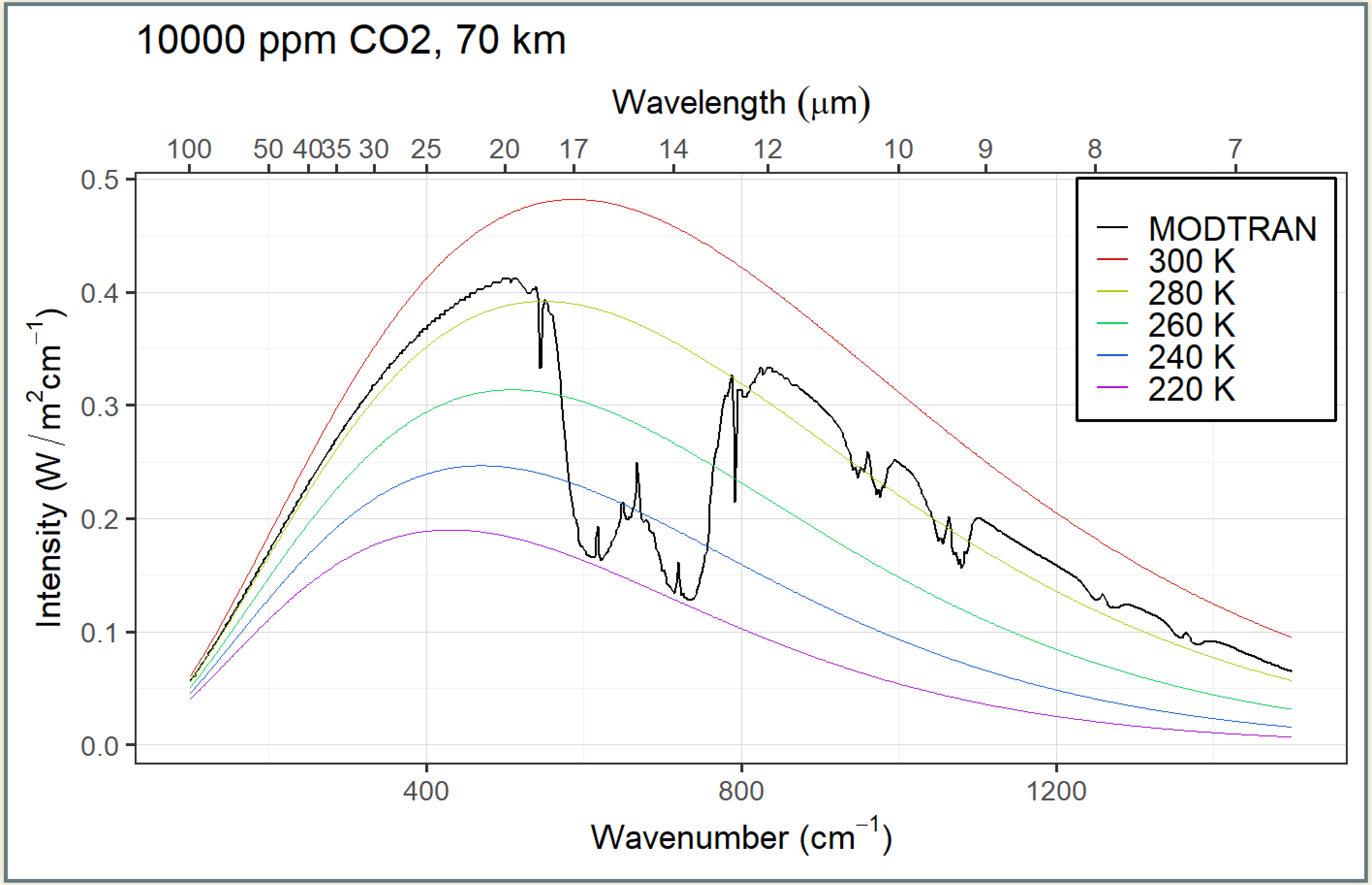
100 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

1000 ppm CO_2

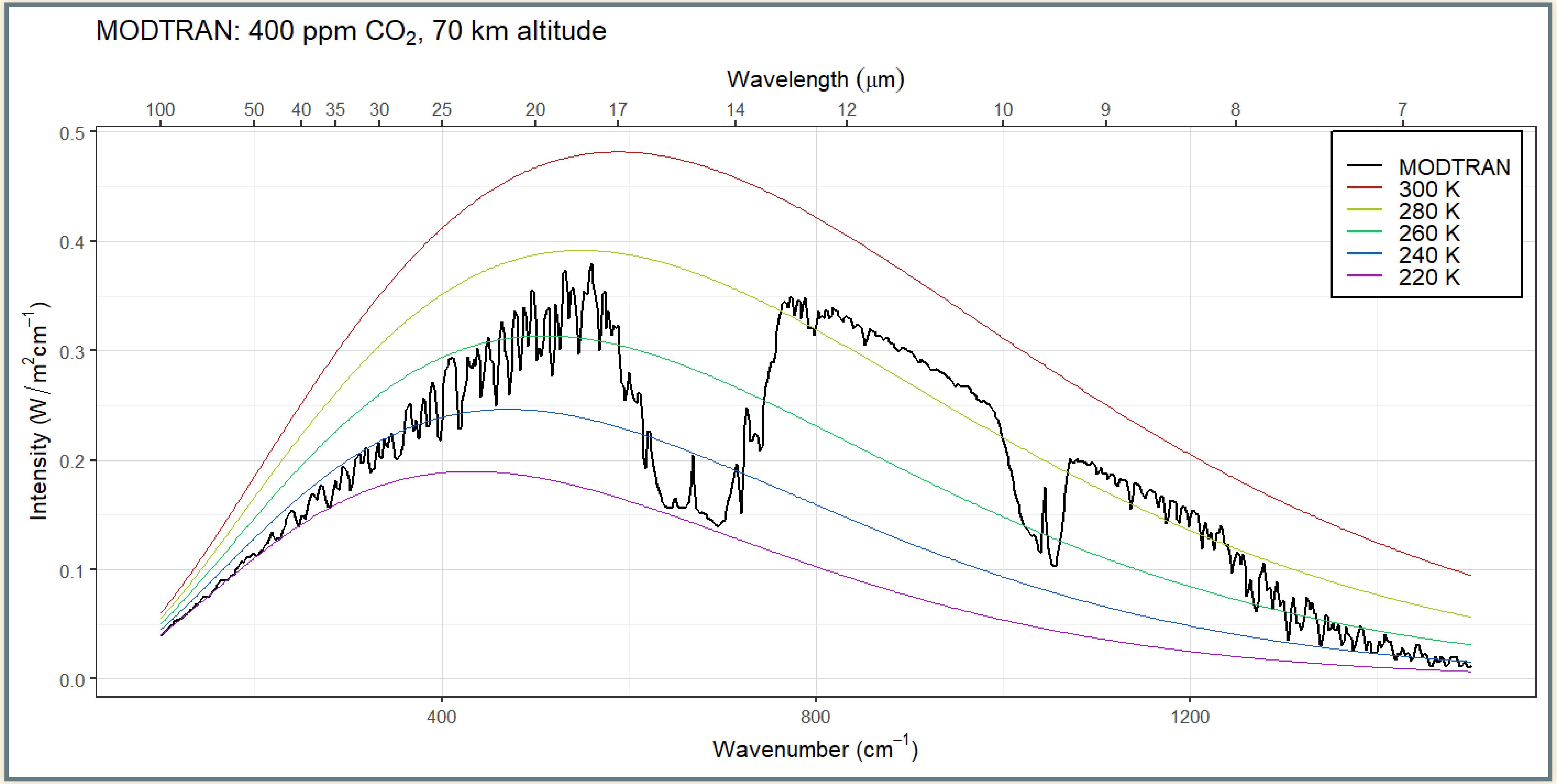


1000 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

10,000 ppm CO_2

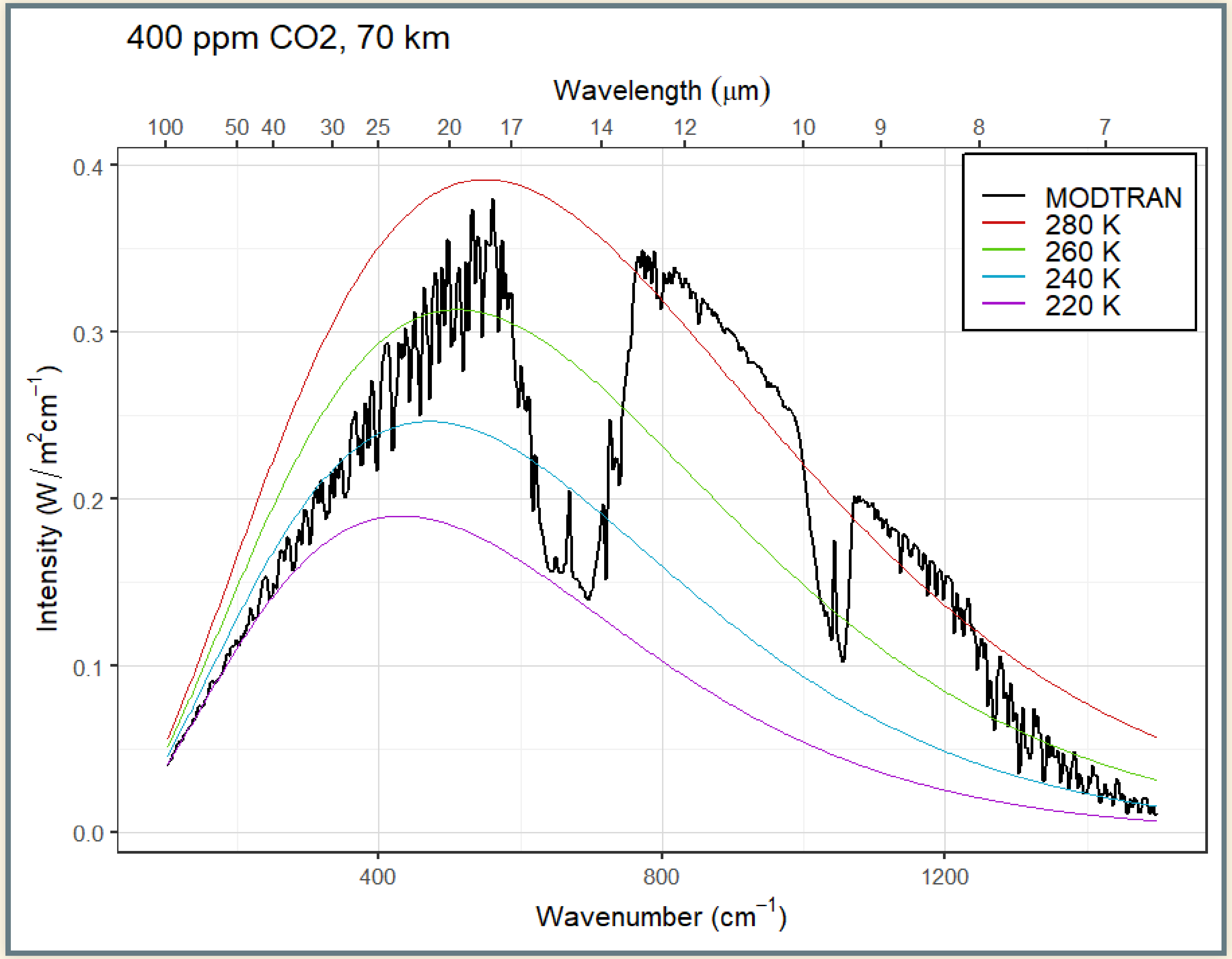


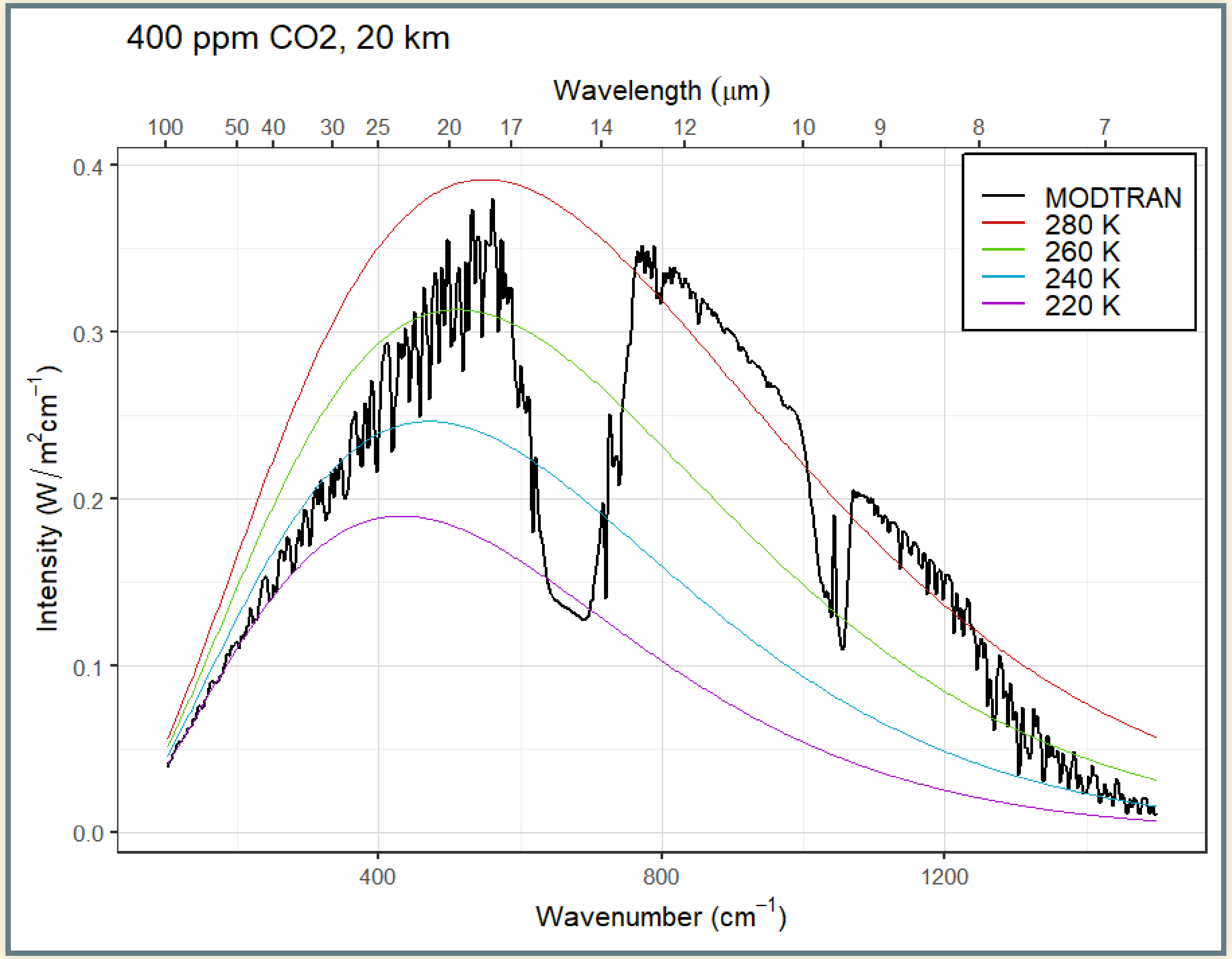
Question



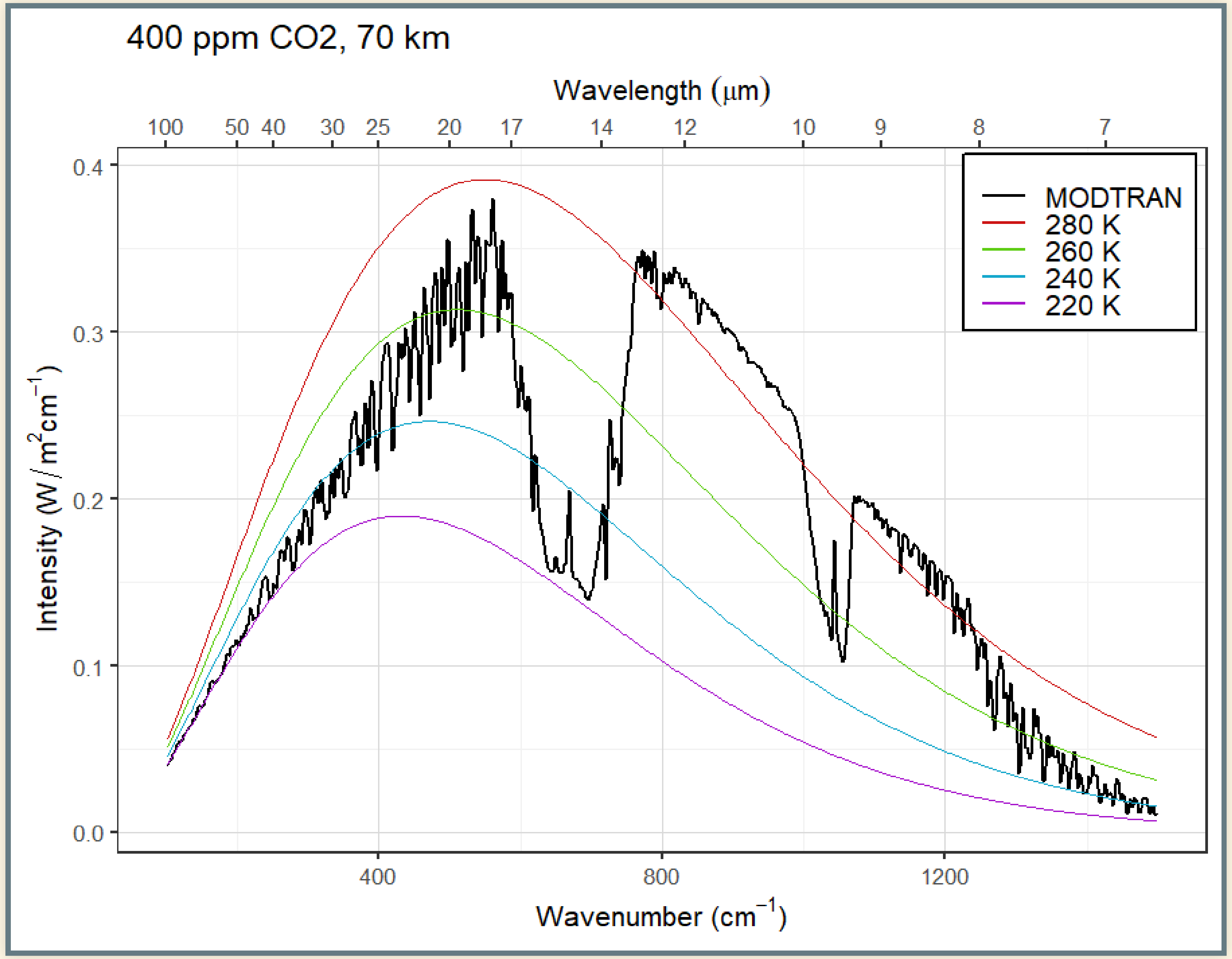
- Why do we see the spike in the middle of the CO_2 absorption feature?

Answer

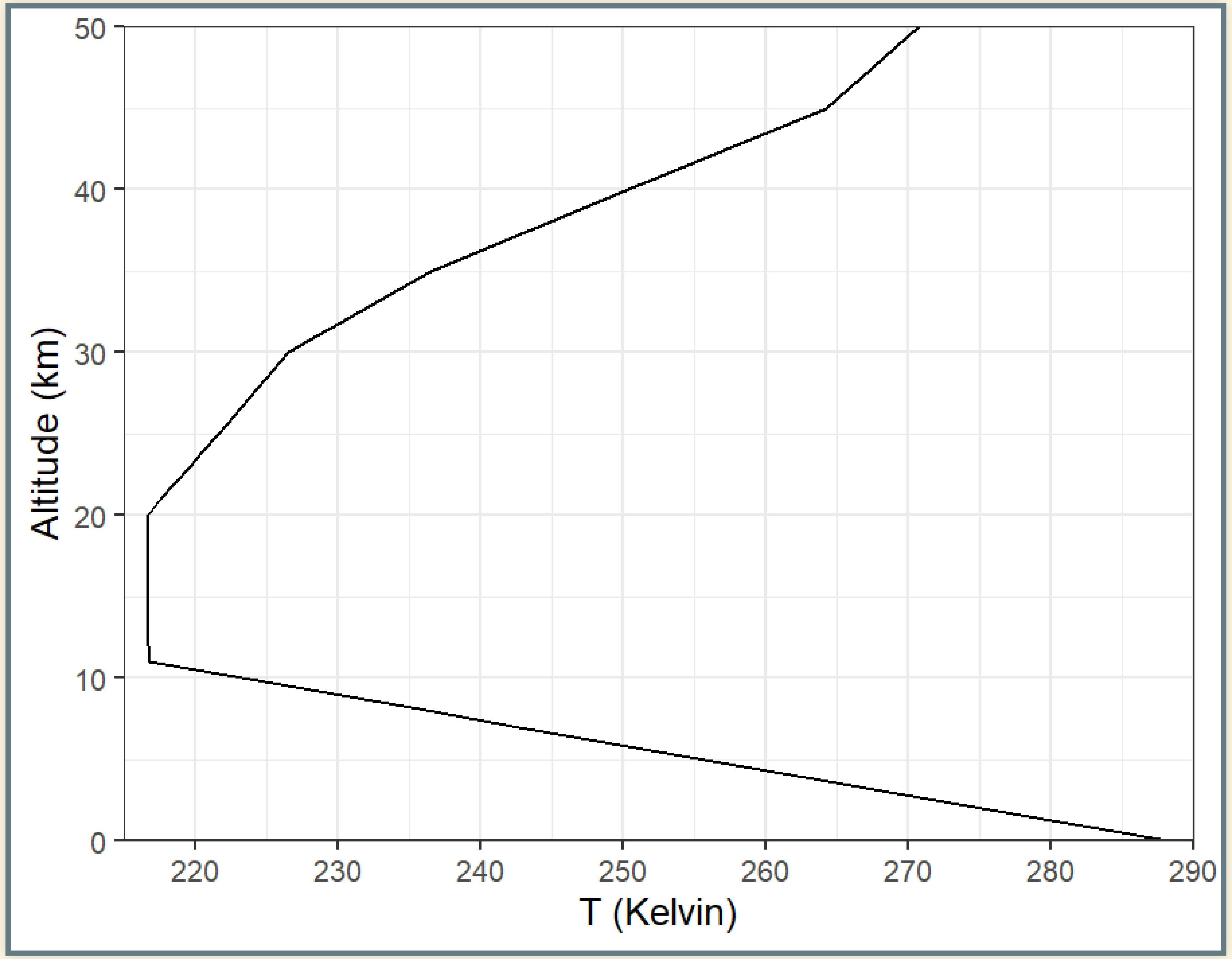

400 ppm CO2, 70 km
Wavelength (μm)
100 50 40 30 25 20 17 14 12 10 9 8 7
Intensity (W/m²cm⁻¹)
0.0 0.1 0.2 0.3 0.4
MODTRAN
280 K
260 K
240 K
220 K
400 800 1200
Wavenumber (cm⁻¹)


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
MODTRAN
280 K
260 K
240 K
220 K
400 800 1200
Wavenumber (cm⁻¹)

Answer

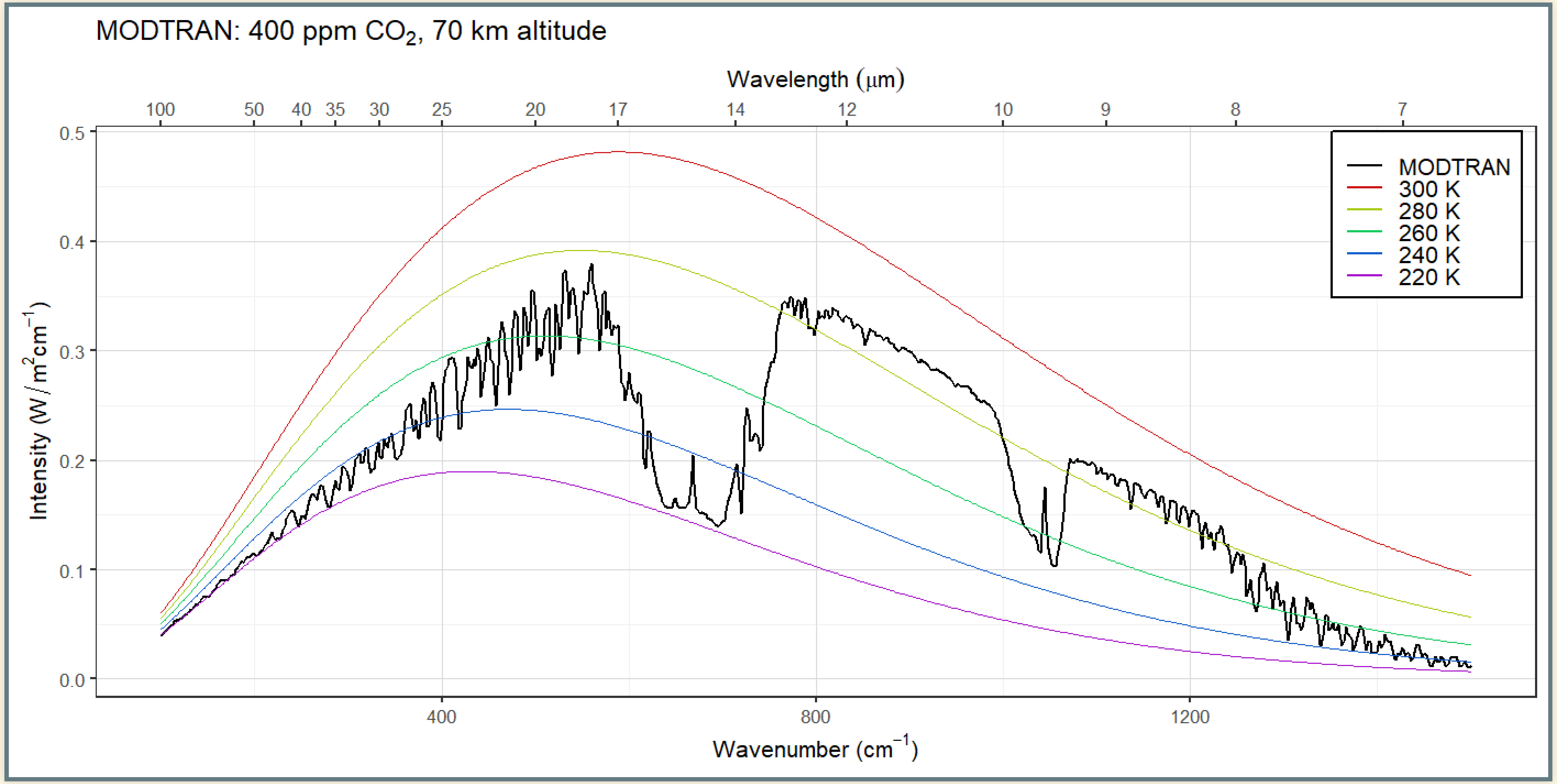


400 ppm CO2, 70 km
Wavelength (μm)
100 50 40 30 25 20 17 14 12 10 9 8 7
MODTRAN
280 K
260 K
240 K
220 K
Intensity (W/m²cm⁻¹)
0.0 0.1 0.2 0.3 0.4
400 800 1200
Wavenumber (cm⁻¹)



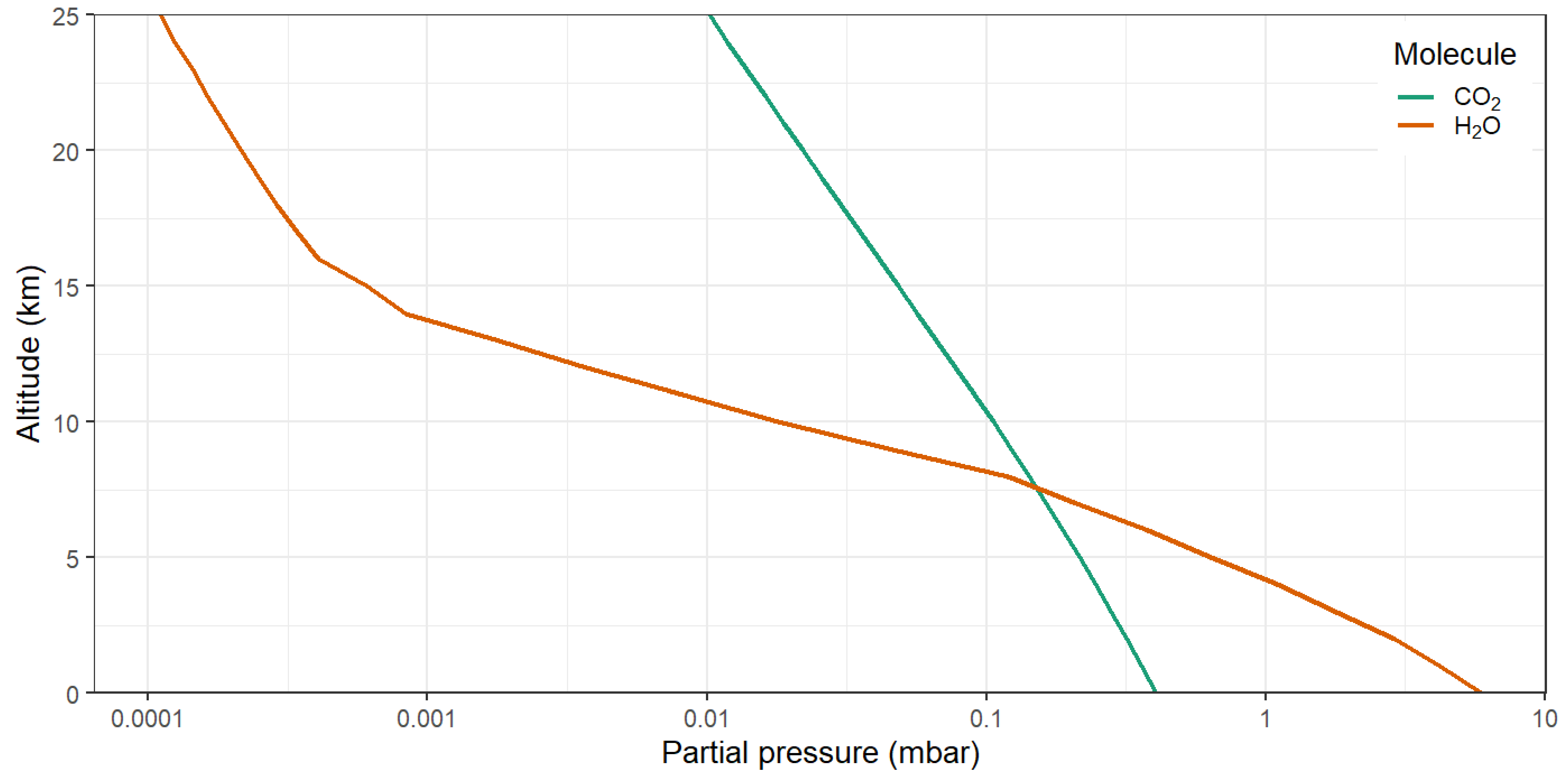
Altitude (km)
0 10 20 30 40 50
220 230 240 250 260 270 280 290
T (Kelvin)

Question



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

Answer



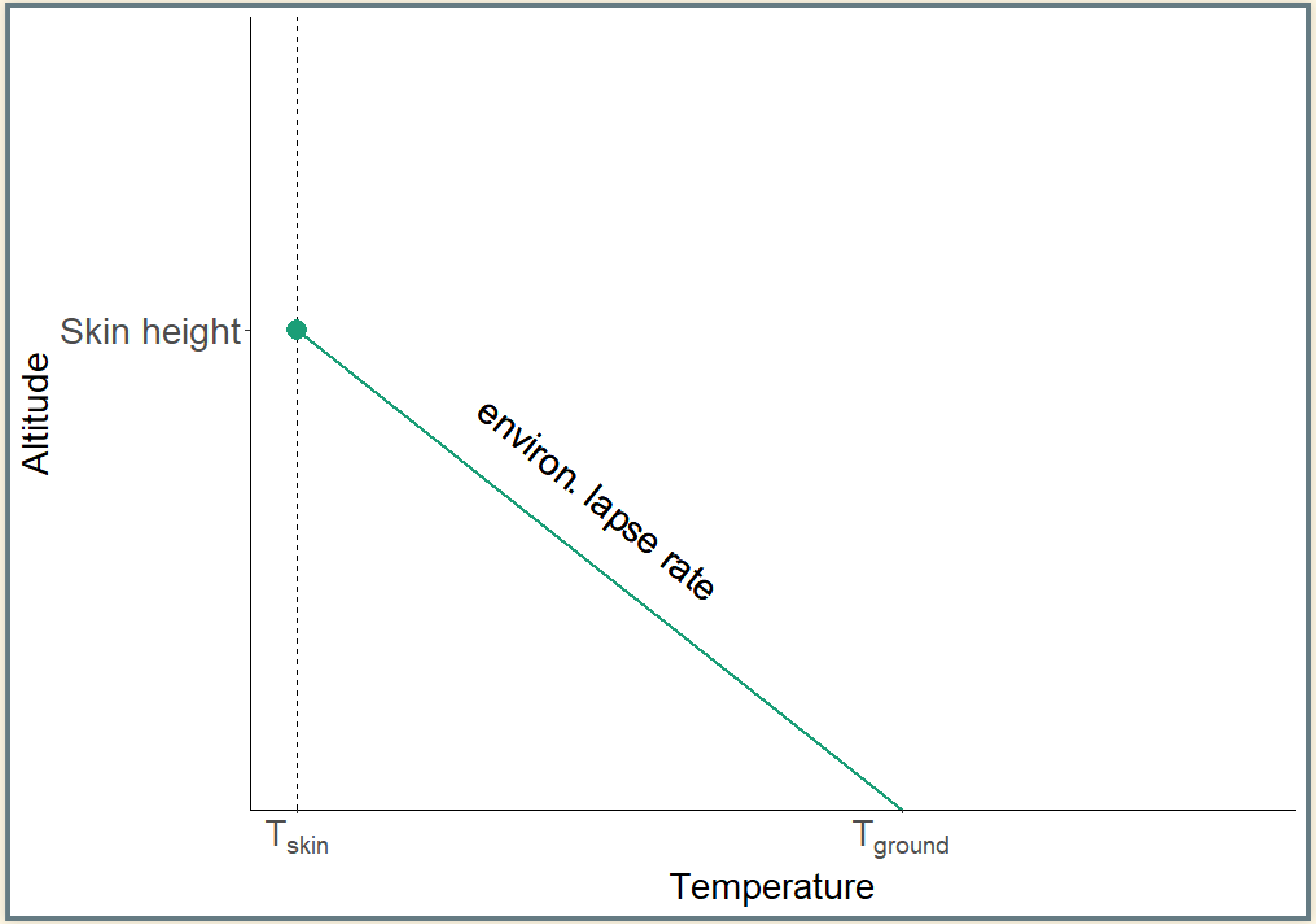
- Near the ground, there is much more water vapor (15 times more)
- Above about 7 km, there is much more CO_2 (100 times more at 20 km)
  - Water vapor concentrations become small enough to be transparent to space at a much lower altitude than CO_2

Convection and the Greenhouse Effect

Another Perspective on Band Saturation

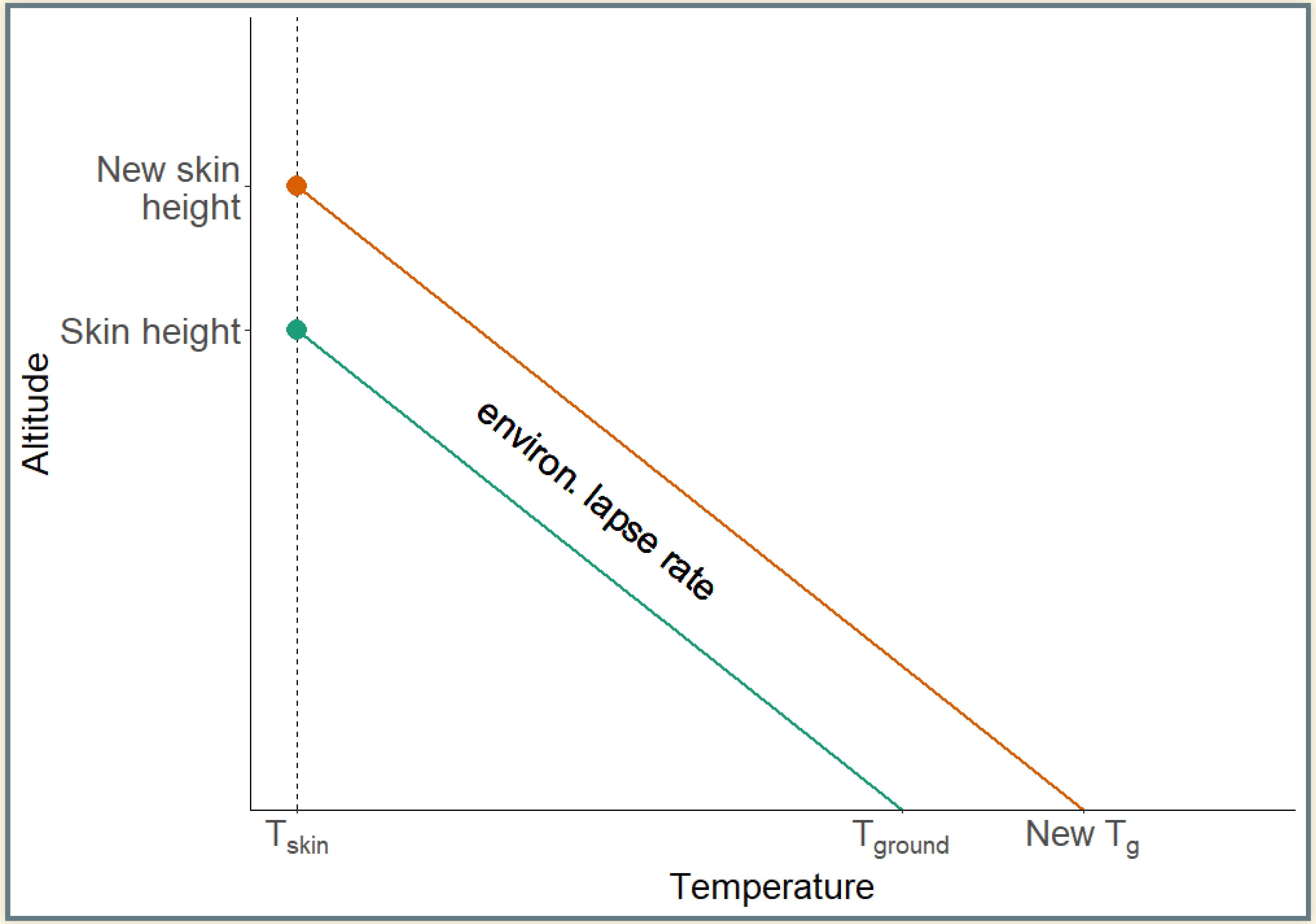
- Instead of thinking of saturation as increasing absorption ...
- Think of saturation as raising the skin height
  - Skin height = the height at which the atmosphere becomes transparent enough to radiate out to space
    - The height of the top of the atmospheric layer in a layer model
  - The atmosphere becomes opaque at a certain wavelength when there are more than a certain number of molecules per square meter of an absorbing gas overhead.
    - The higher you go, the fewer molecules are overhead and the more are below your feet.
    - The atmosphere gradually becomes more transparent, but we pretend that this happens suddenly at a certain height.
    - Pressure and density fall exponentially as you go higher, so this approximation is reasonable.
- After band saturation sets in, adding more greenhouse gas raises the skin height.

Saturation, Convection, and the Greenhouse Effect



- Skin temp: $T_{\text{skin}} = T_{\text{bare rock}} = 254$ K.
- Ground temp: $T_{\text{ground}} = T_{\text{skin}} + h_{\text{skin}} \times \text{ELR}$
  - ELR = Environmental Lapse Rate

Global warming



- Greater $CO_2 \longrightarrow$ greater skin height.
- Warming: $\Delta T_{\text{ground}} = \Delta h_{\text{skin}} \times$ env. lapse

Review of the Greenhouse Effect

Review of the Greenhouse Effect

1. **Start with bare-rock temperature**
   - This becomes skin temperature
2. **Add simple layer atmosphere:**
   - Completely black to longwave radiation
   - Top of atmosphere: skin temperature (same as bare-rock)
   - Atmosphere insulates surface ⇒ surface heats up
   - More layers ⇒ bigger greenhouse effect
3. **Realistic longwave absorption:**
   - Atmosphere is not black
   - Absorption depends on wavelength
4. **Radiative-Convective equilibrium:**
   - Pure radiative equilibrium would have *huge* environmental lapse rate
     - 16 K/km
   - Big lapse rate is unstable ⇒ convection
     - ELR (16 K/km) > ALR (6–10 K/km)
     - Convection mixes hot & cold air ⇒ reduces environmental lapse until it becomes stable
     - Reduces greenhouse effect
   - **Alternate perspective:**
     - Think of greenhouse effect in terms of raising the skin height instead of blocking heat flow.
     - T_{skin} is always T~bare rock~
     - $T_{ground} = T_{skin} + h_{skin} \times$ Environmental Lapse Rate

Questions & Discussion of Greenhouse Effect