Temperature Structure of the Atmosphere

EES 3310/5310

Global Climate Change

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Class #6: Monday, January 31 2022

Review Question

What is the “atmospheric window”?

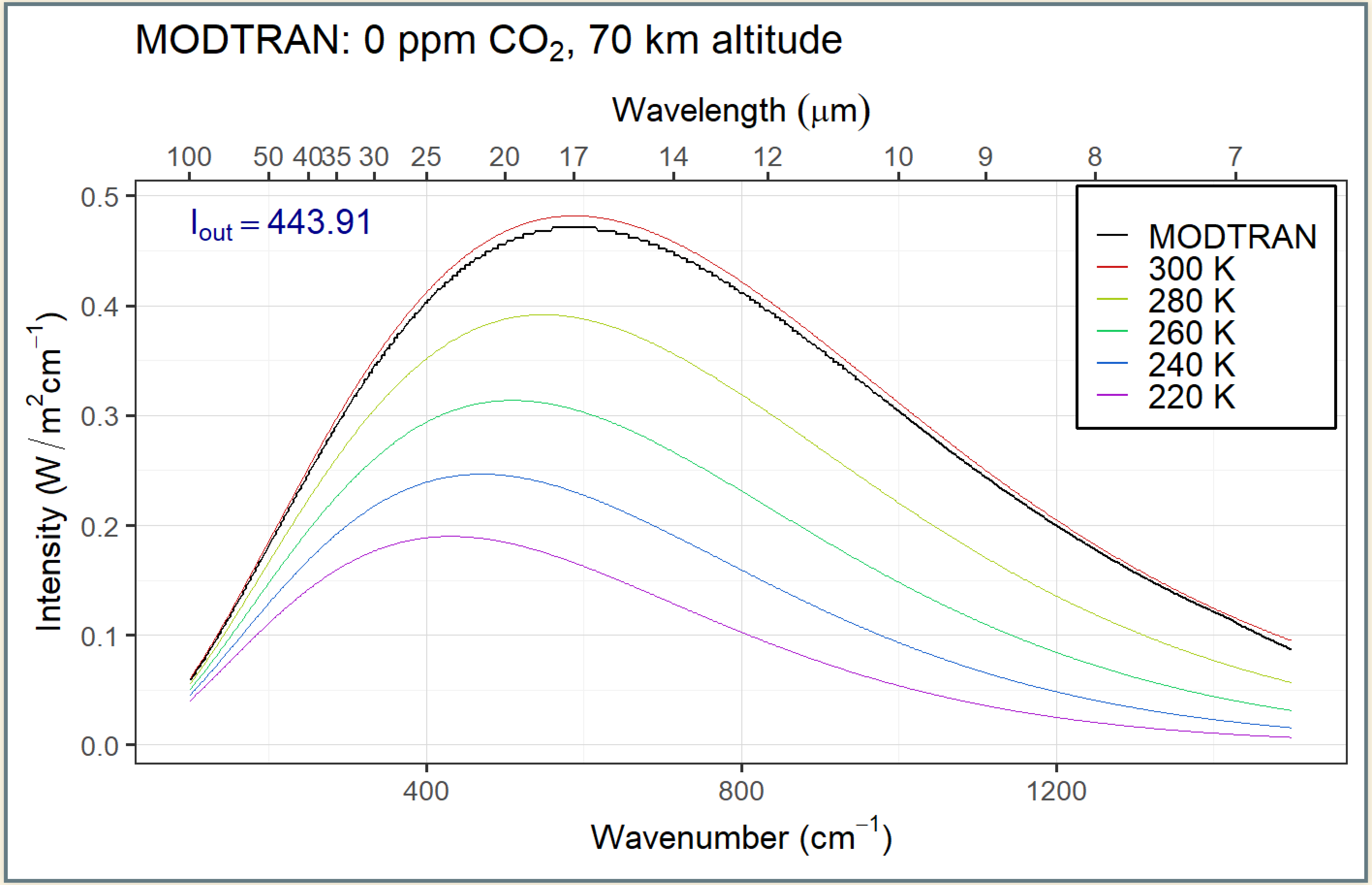
1. Regions where there are few clouds to block radiation.
2. Desert regions with very little water vapor.
3. Tropical regions with low CO_2 concentrations.
4. A range of wavelengths where no greenhouse gases absorb much.

Measuring Greenhouse Effect:

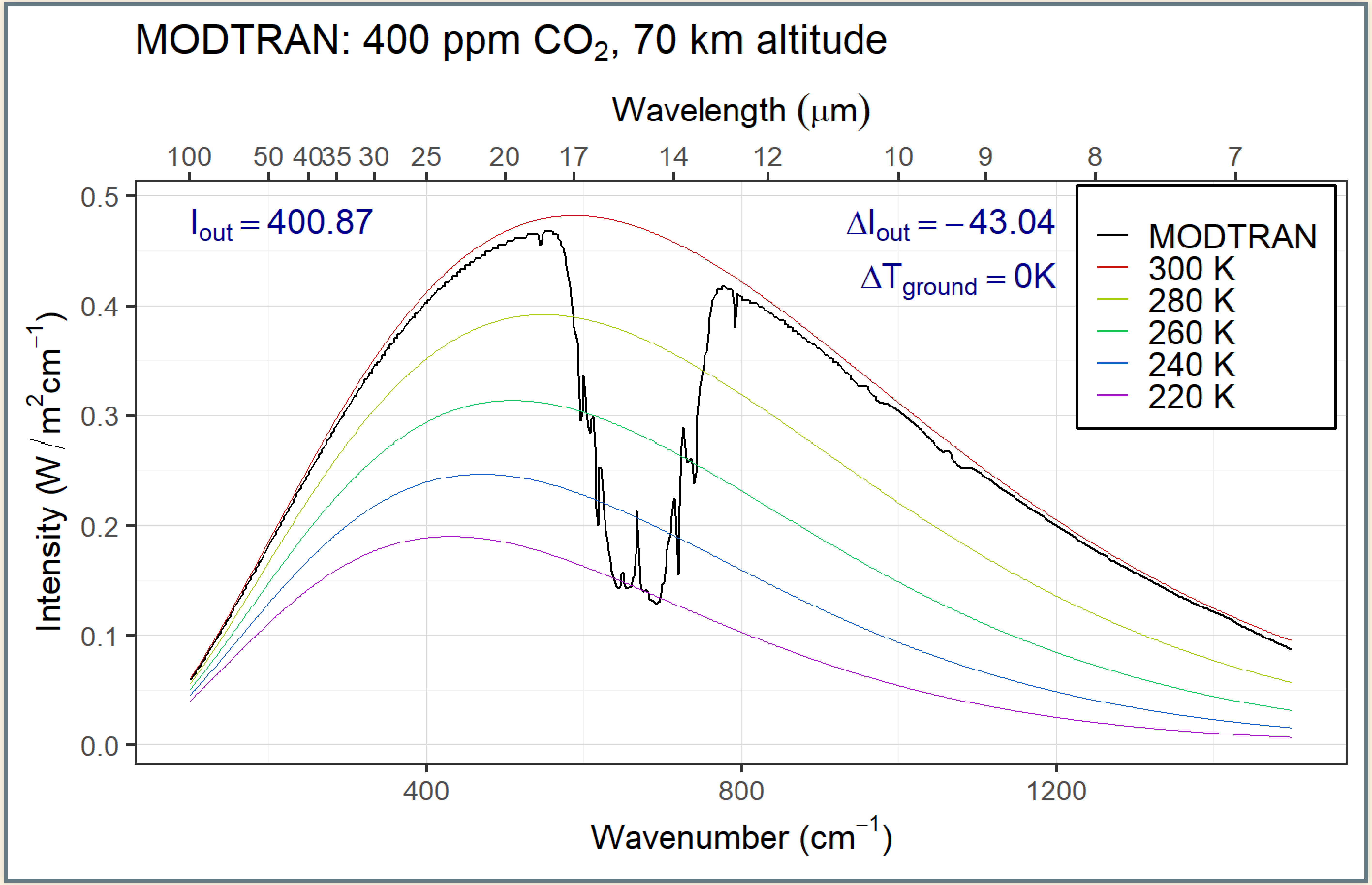
Measuring Greenhouse Effect:

- Go to MODTRAN, set CO_2 to 0 ppm, and set all other gases to zero.
- Set altitude to 70 km and location to “Tropical Atmosphere”.
- Press “Save this run to background”
- Note I_{out}
- Set CO_2 to 400 ppm and note the change in I_{out}
- Adjust the temperature offset to make the difference in $I_{\text{out}}(\text{New} - \text{BG})$ equal zero.

No Greenhouse Gases

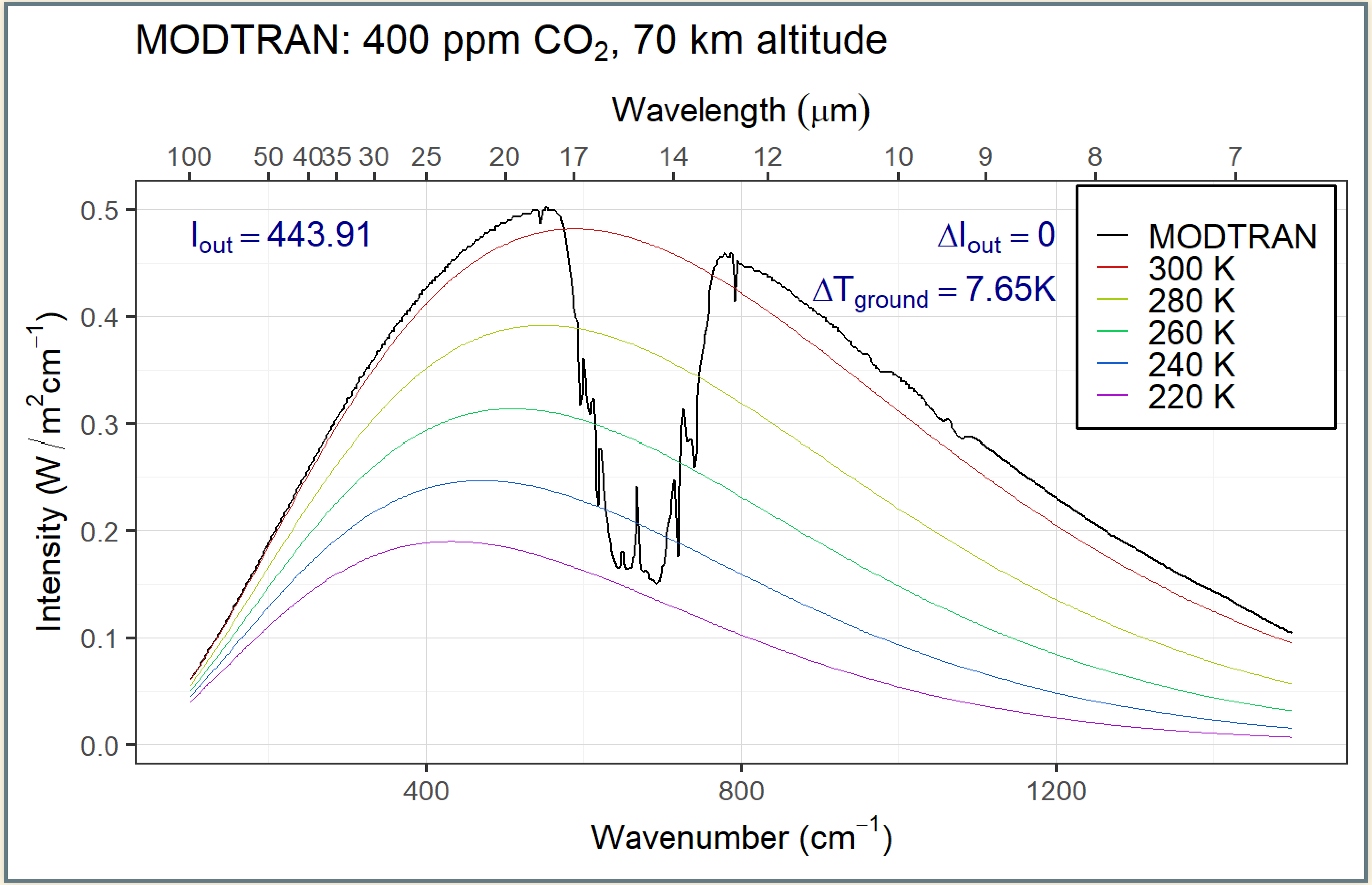


400 ppm



MODTRAN: 400 ppm CO2, 70 km altitude
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
Iout = 400.87
ΔIout = −43.04
ΔTground = 0K
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m2cm−1)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm−1)

Adjust temperature

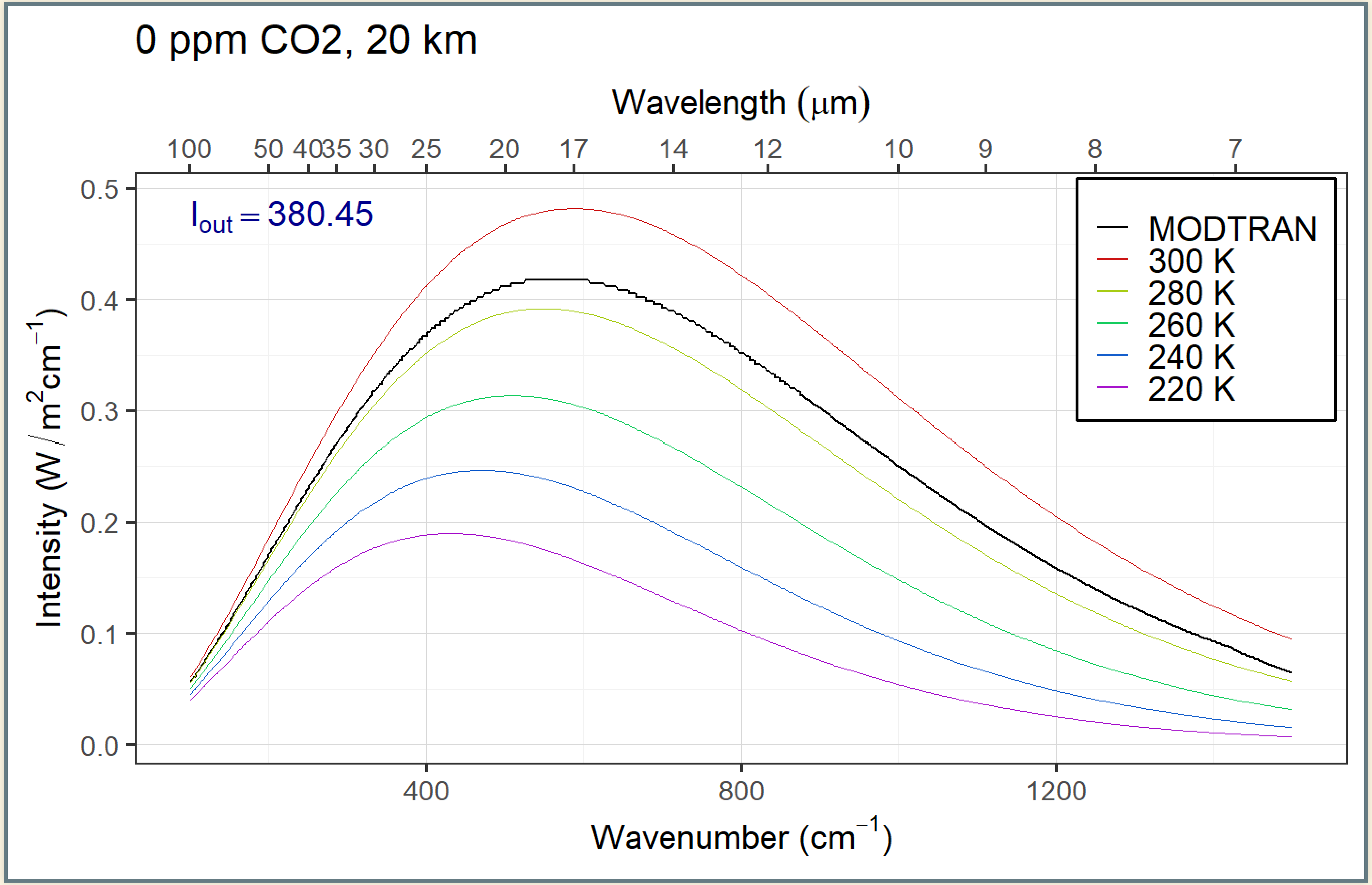


Band Saturation

Set up MODTRAN:

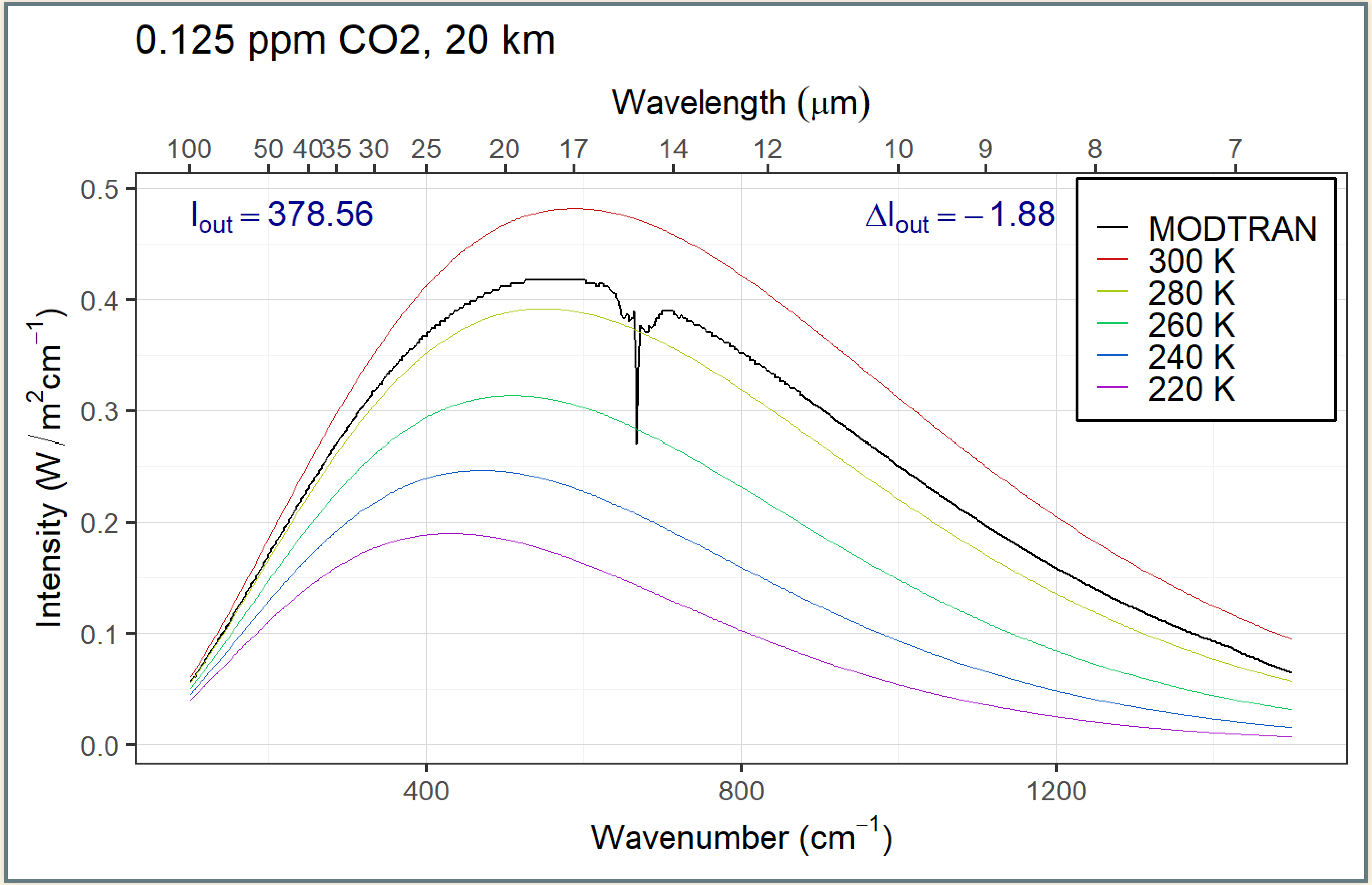
- Set “Location” to “1976 U.S. Standard Atmosphere”
- Set All greenhouse gases to zero
- Set altitude to 20 km

No CO_2



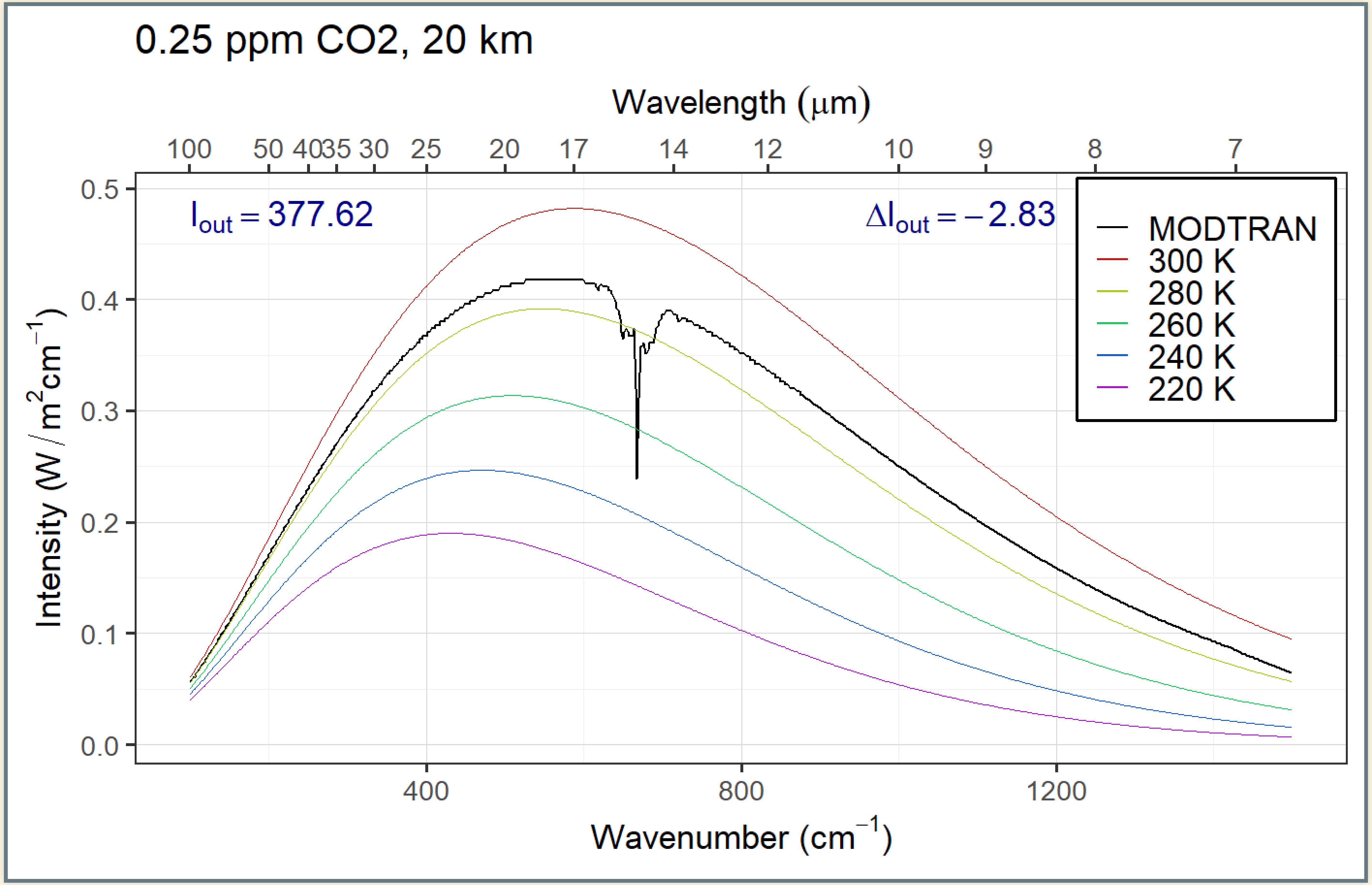
0 ppm CO2, 20 km
Wavelength (μm)
100 50 40 35 30 25 20 17 14 12 10 9 8 7
Intensity (W / m²cm⁻¹)
0.0 0.1 0.2 0.3 0.4 0.5
I_out = 380.45
MODTRAN
300 K
280 K
260 K
240 K
220 K
400 800 1200
Wavenumber (cm⁻¹)

0.125 ppm CO_2



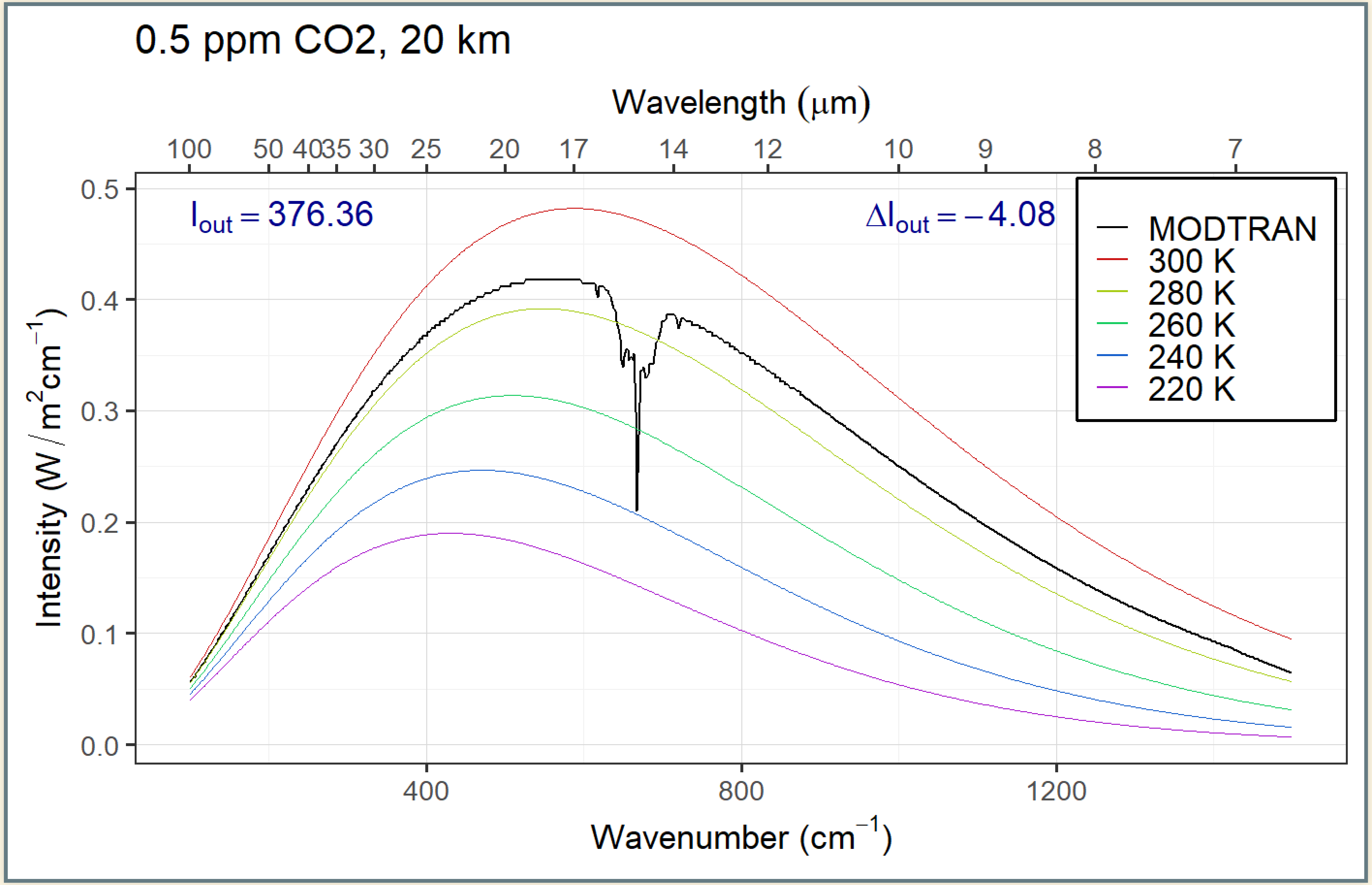
0.125 ppm CO2, 20 km
Wavelength (μm)
100 50 40 35 30 25 20 17 14 12 10 9 8 7
$I_{out} = 378.56$
$\Delta I_{out} = -1.88$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W/m^2cm^{-1})
0.0 0.1 0.2 0.3 0.4 0.5
400 800 1200
Wavenumber (cm^{-1})

0.25 ppm CO_2



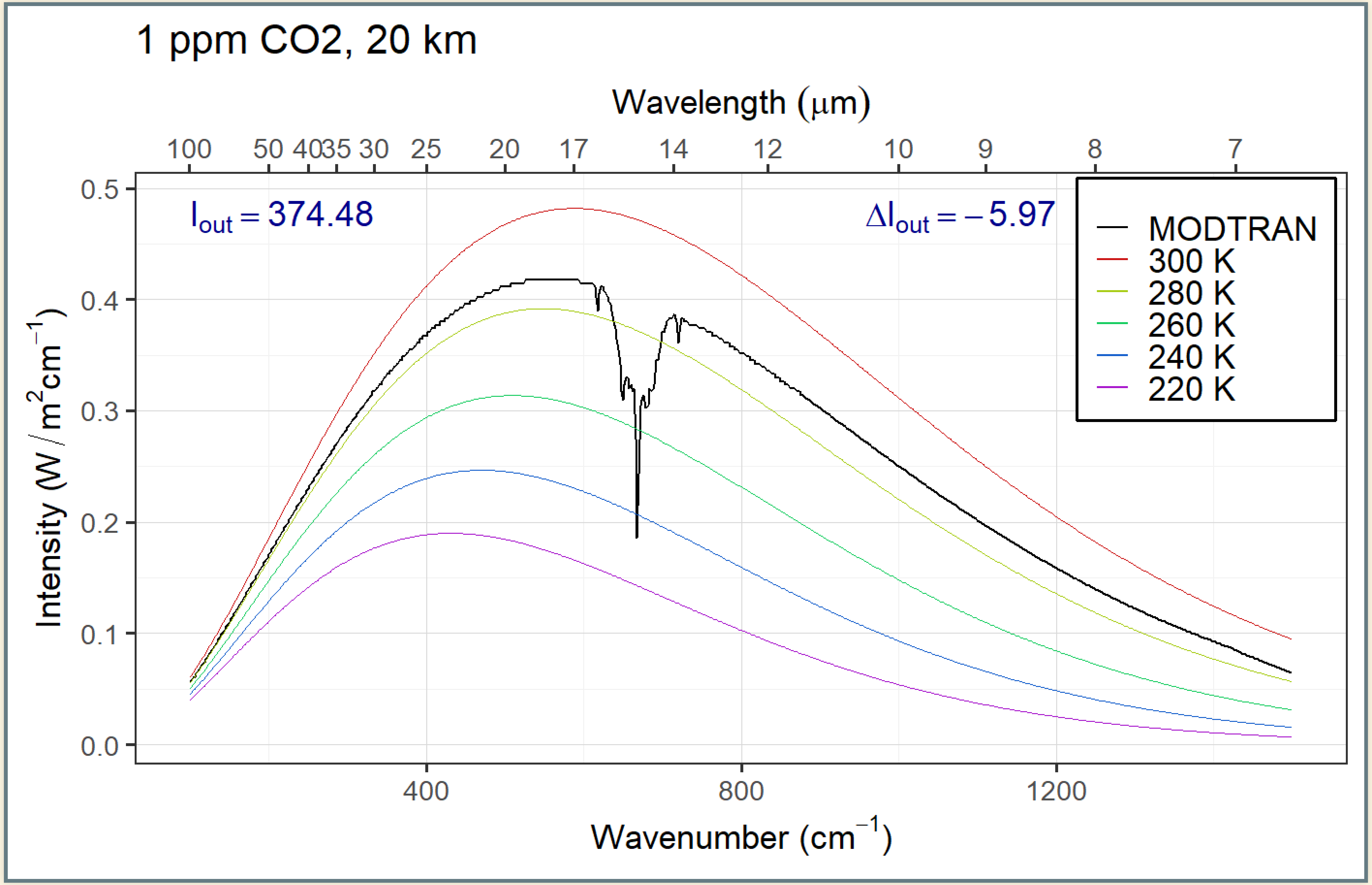
0.25 ppm CO2, 20 km
Wavelength (μm)
100 50 40 35 30 25 20 17 14 12 10 9 8 7
$I_{out} = 377.62$
$\Delta I_{out} = -2.83$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W/m^2 cm^{-1}$)
0.0 0.1 0.2 0.3 0.4 0.5
400 800 1200
Wavenumber (cm^{-1})

0.5 ppm CO_2



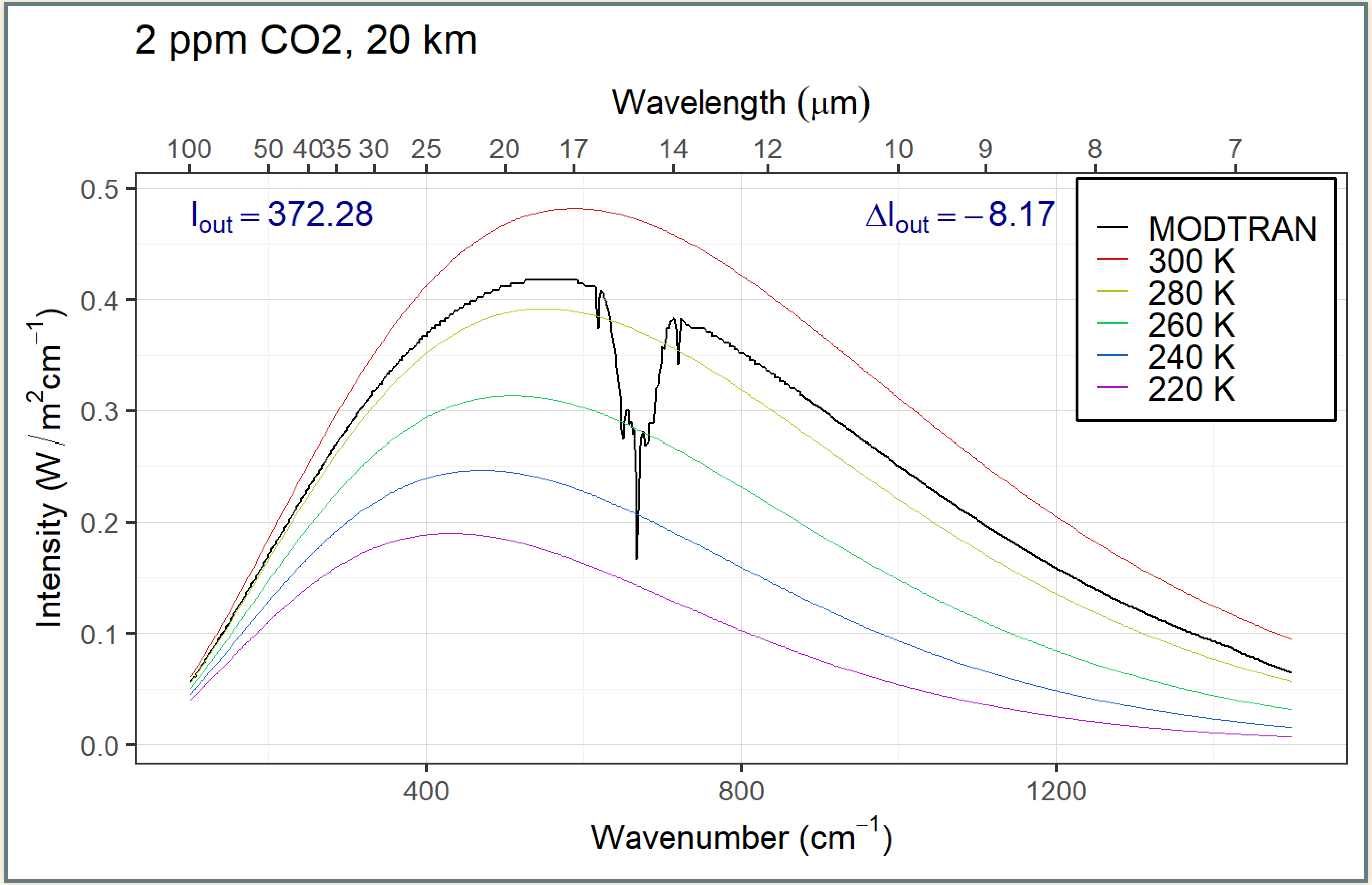
0.5 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 376.36$
$\Delta I_{out} = -4.08$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W / m^2 cm^{-1}$)
0.0
0.1
0.2
0.3
0.4
0.5
400
800
1200
Wavenumber (cm^{-1})

1 ppm CO_2

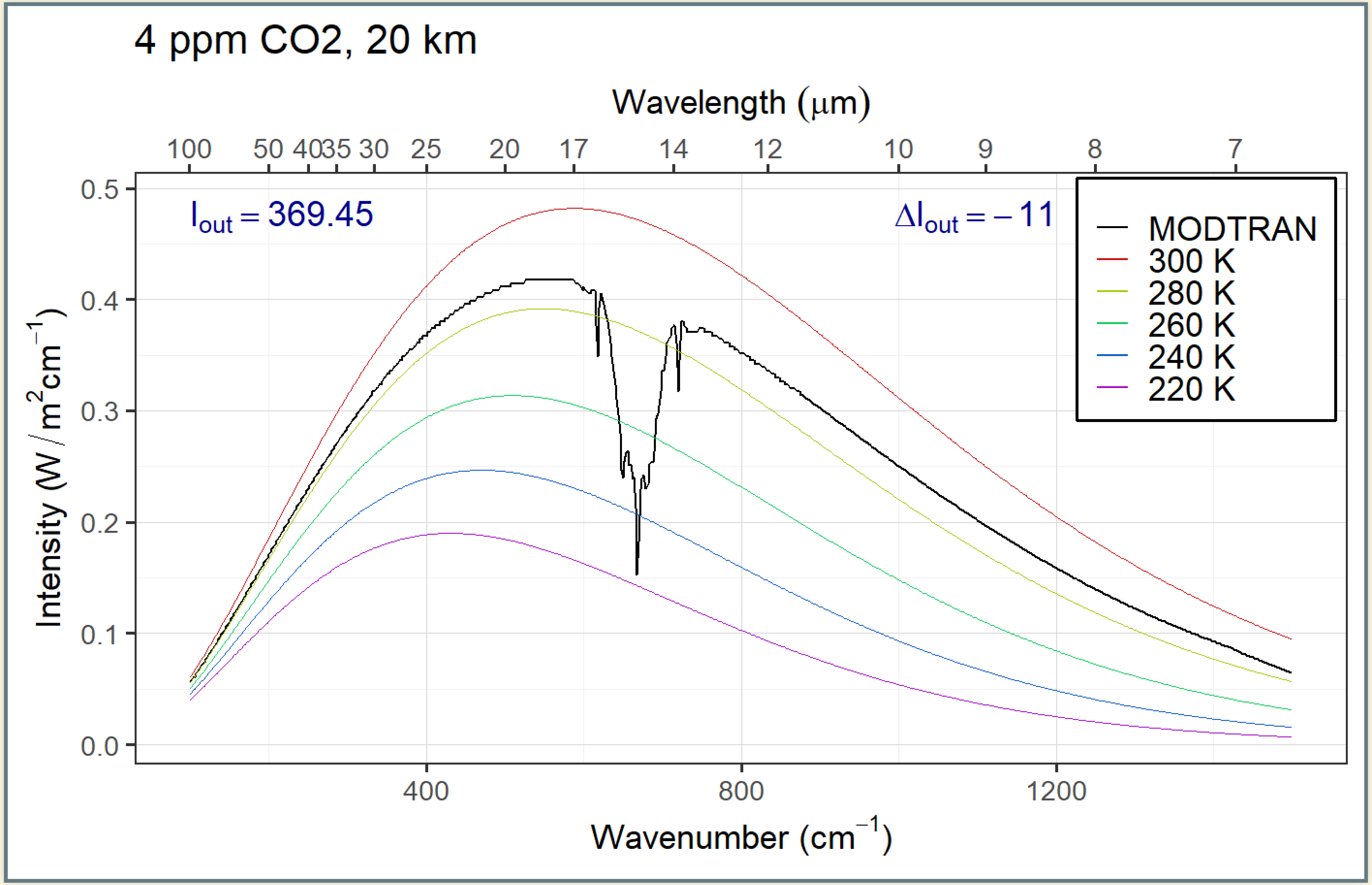


1 ppm CO2, 20 km
Wavelength (μm)
100 50 40 35 30 25 20 17 14 12 10 9 8 7
$I_{out} = 374.48$
$\Delta I_{out} = -5.97$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m²cm⁻¹)
0.0 0.1 0.2 0.3 0.4 0.5
400 800 1200
Wavenumber (cm⁻¹)

2 ppm CO_2

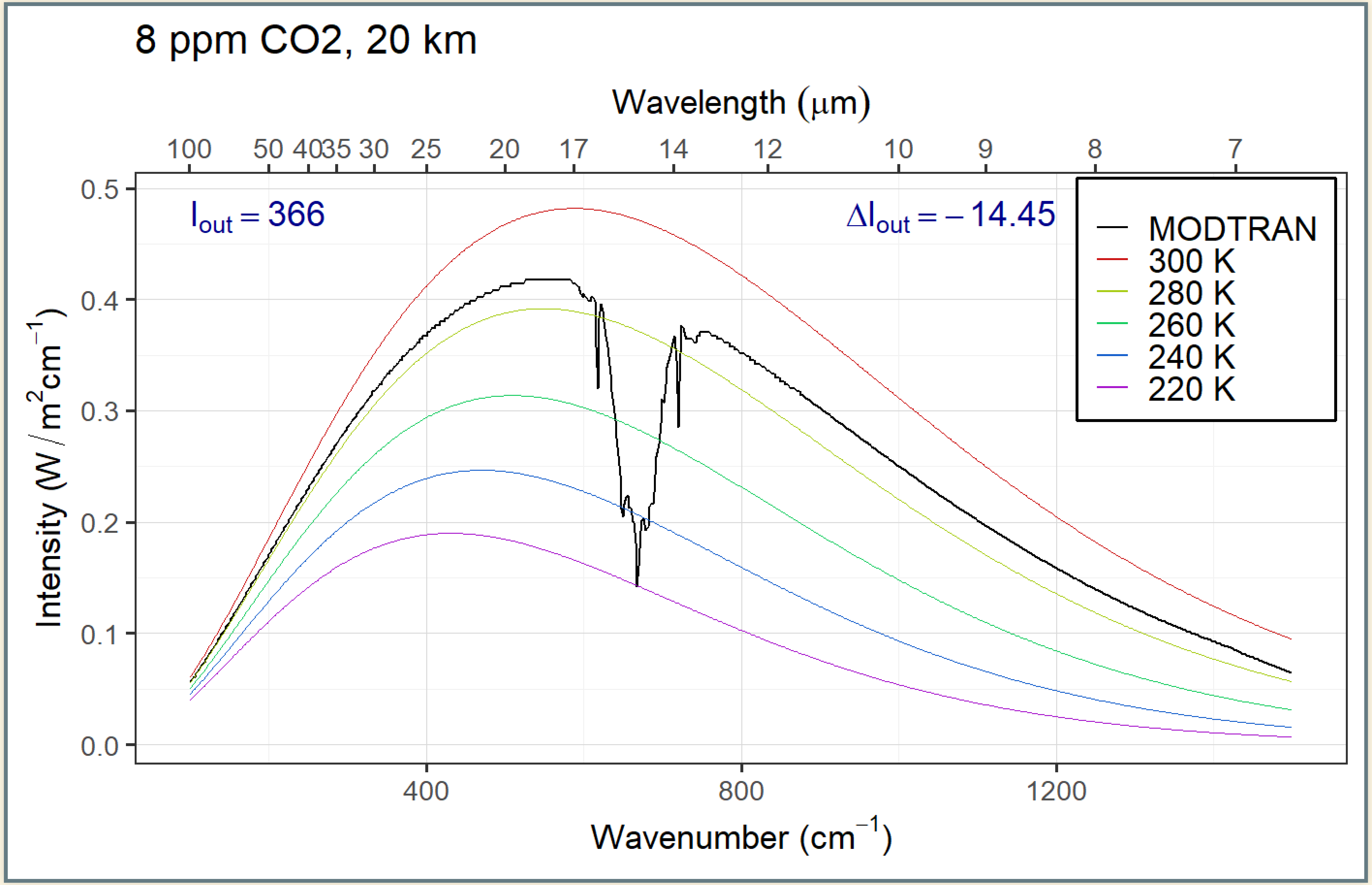

2 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 372.28$
$\Delta I_{out} = -8.17$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W / m^2 cm^{-1}$)
0.0
0.1
0.2
0.3
0.4
0.5
400
800
1200
Wavenumber (cm^{-1})

4 ppm CO_2



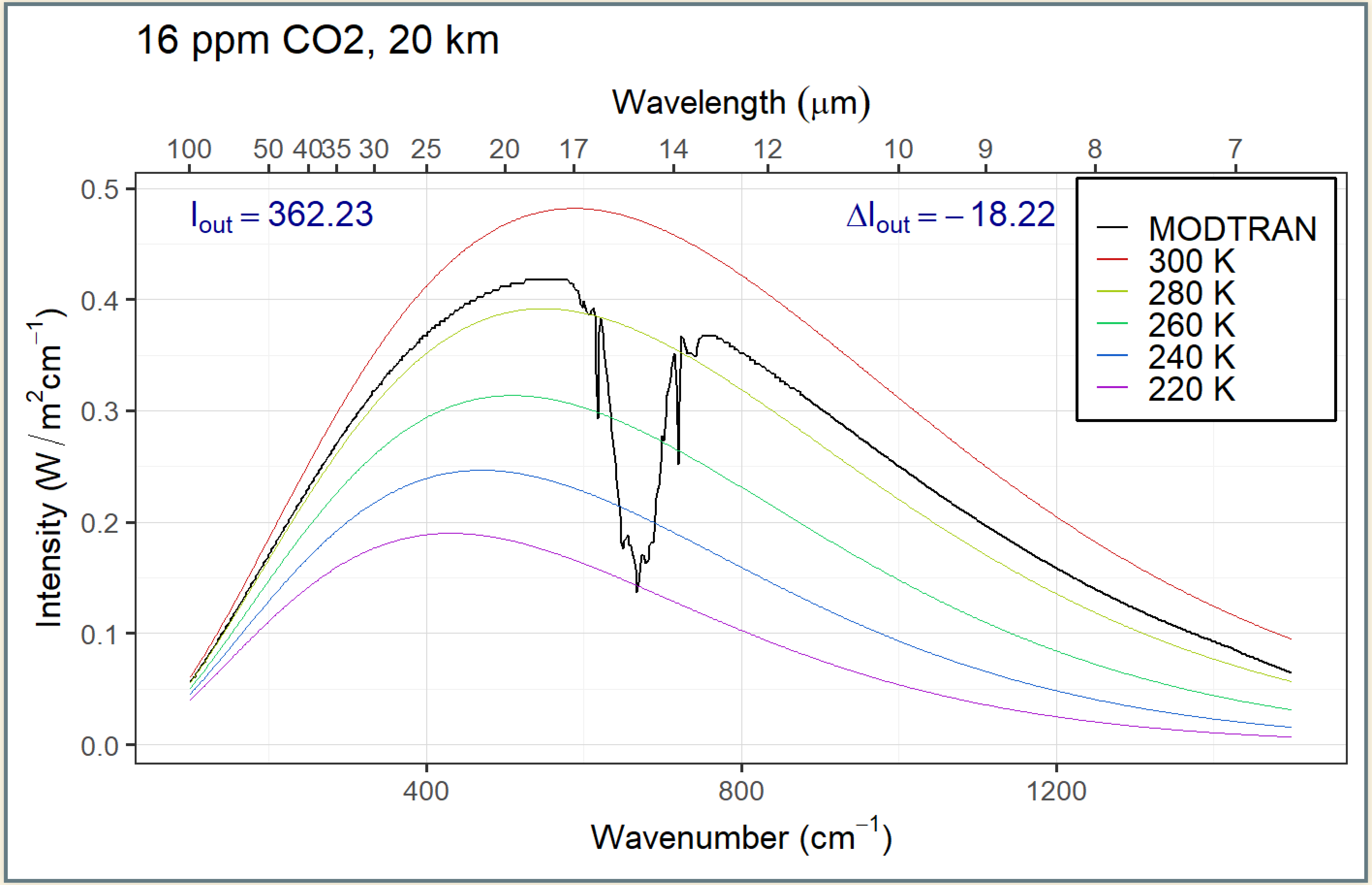
4 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
Intensity (W / m²cm⁻¹)
0.5
0.4
0.3
0.2
0.1
0.0
I_out = 369.45
ΔI_out = −11
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm⁻¹)

8 ppm CO_2



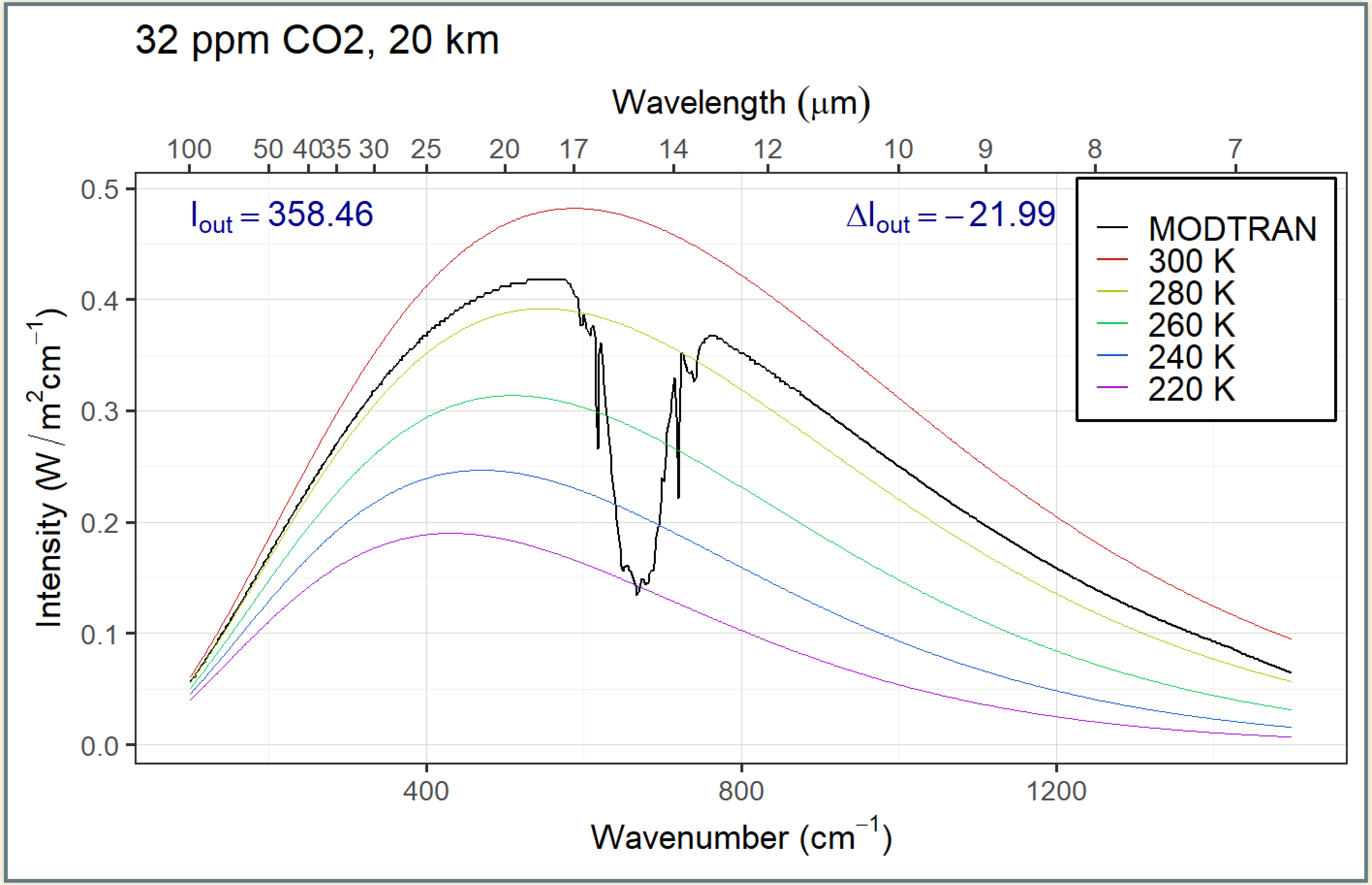
8 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
I_out = 366
ΔI_out = −14.45
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm⁻¹)

16 ppm CO_2

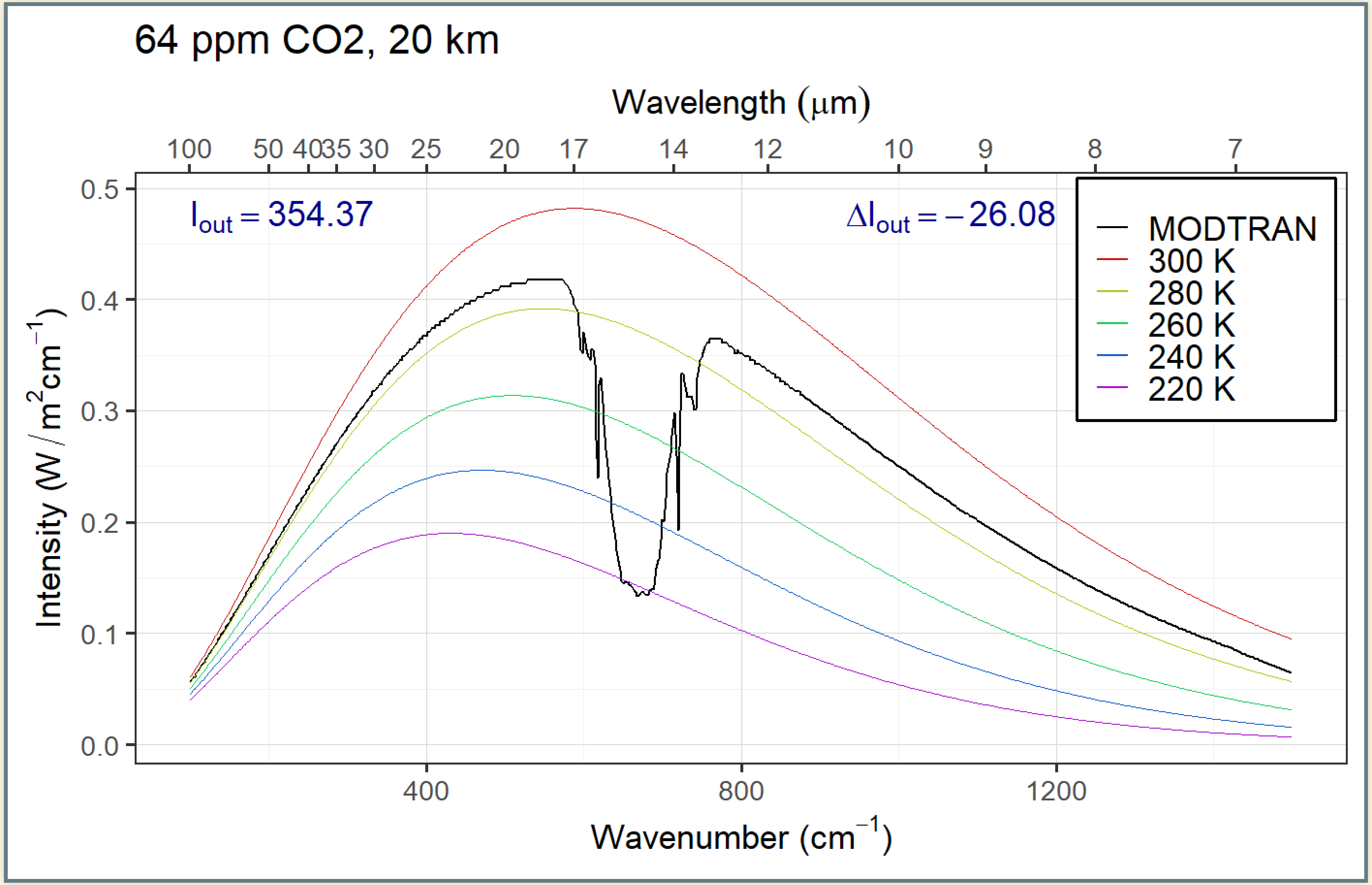


16 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
I_out = 362.23
ΔI_out = – 18.22
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm⁻¹)

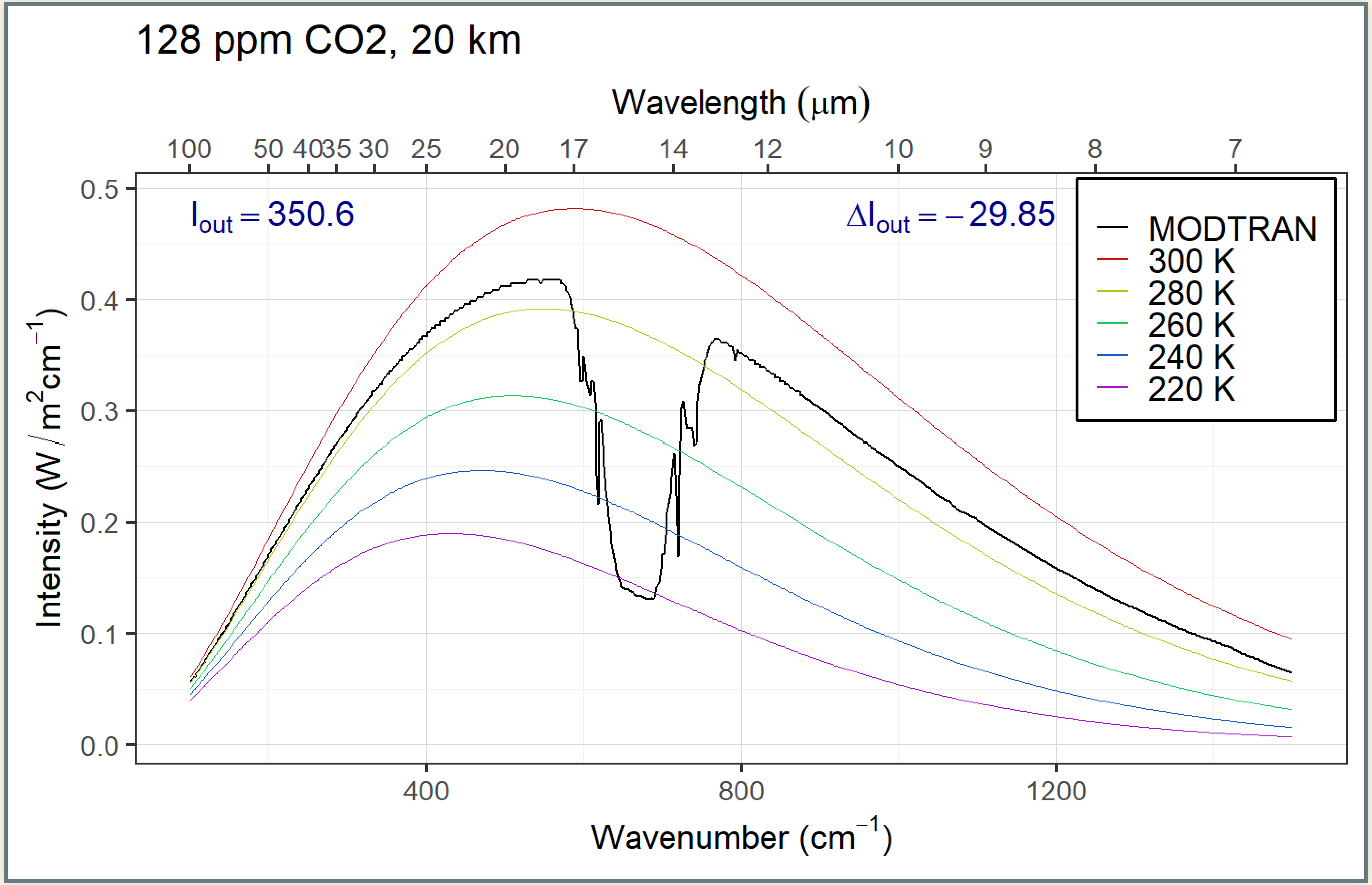
32 ppm CO_2


32 ppm CO2, 20 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
I_out = 358.46
ΔI_out = −21.99
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm⁻¹)

64 ppm CO_2

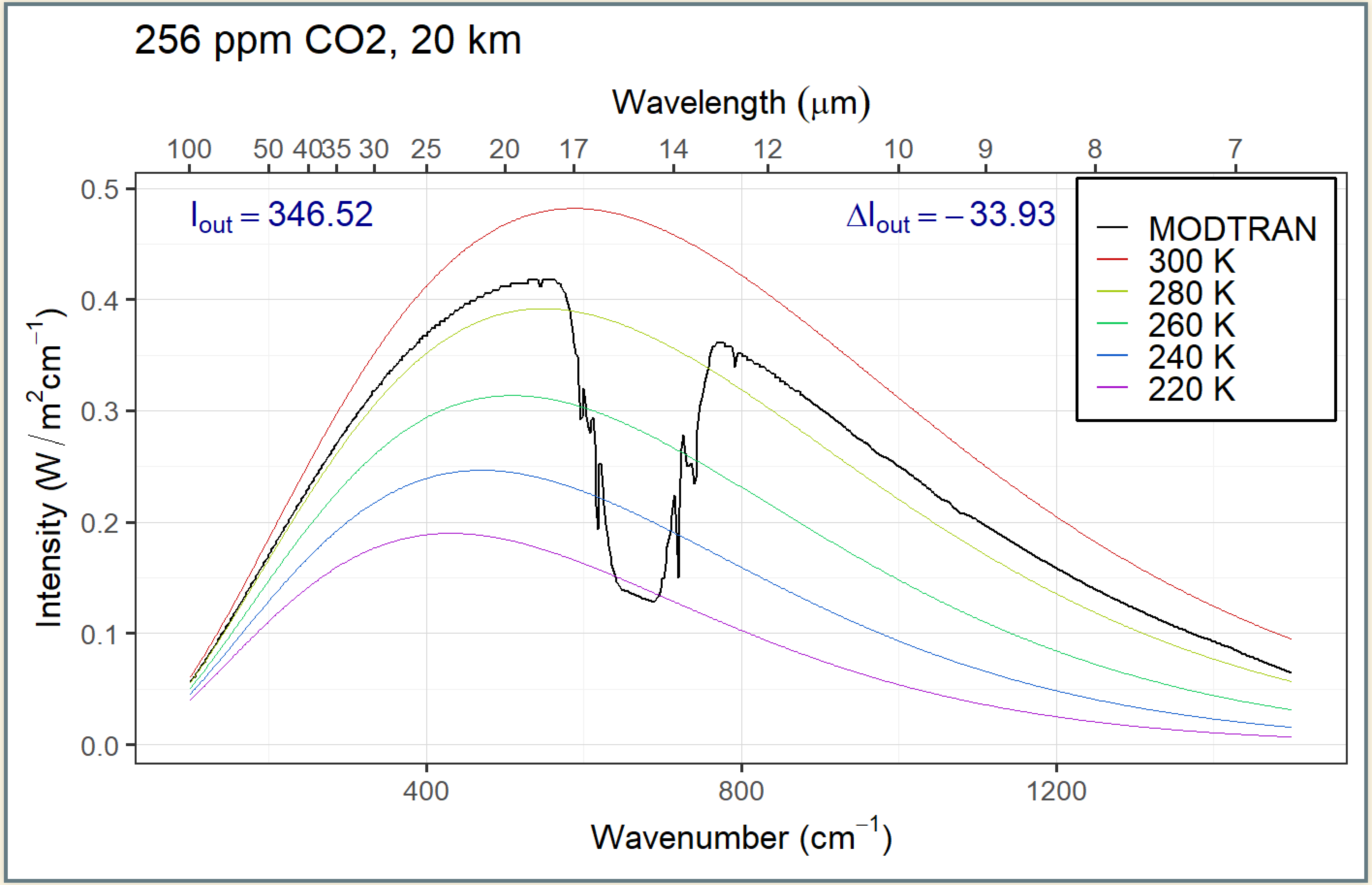

64 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 354.37$
$\Delta I_{out} = -26.08$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m^{2}cm^{-1})
0.0
0.1
0.2
0.3
0.4
0.5
400
800
1200
Wavenumber (cm^{-1})

128 ppm CO_2



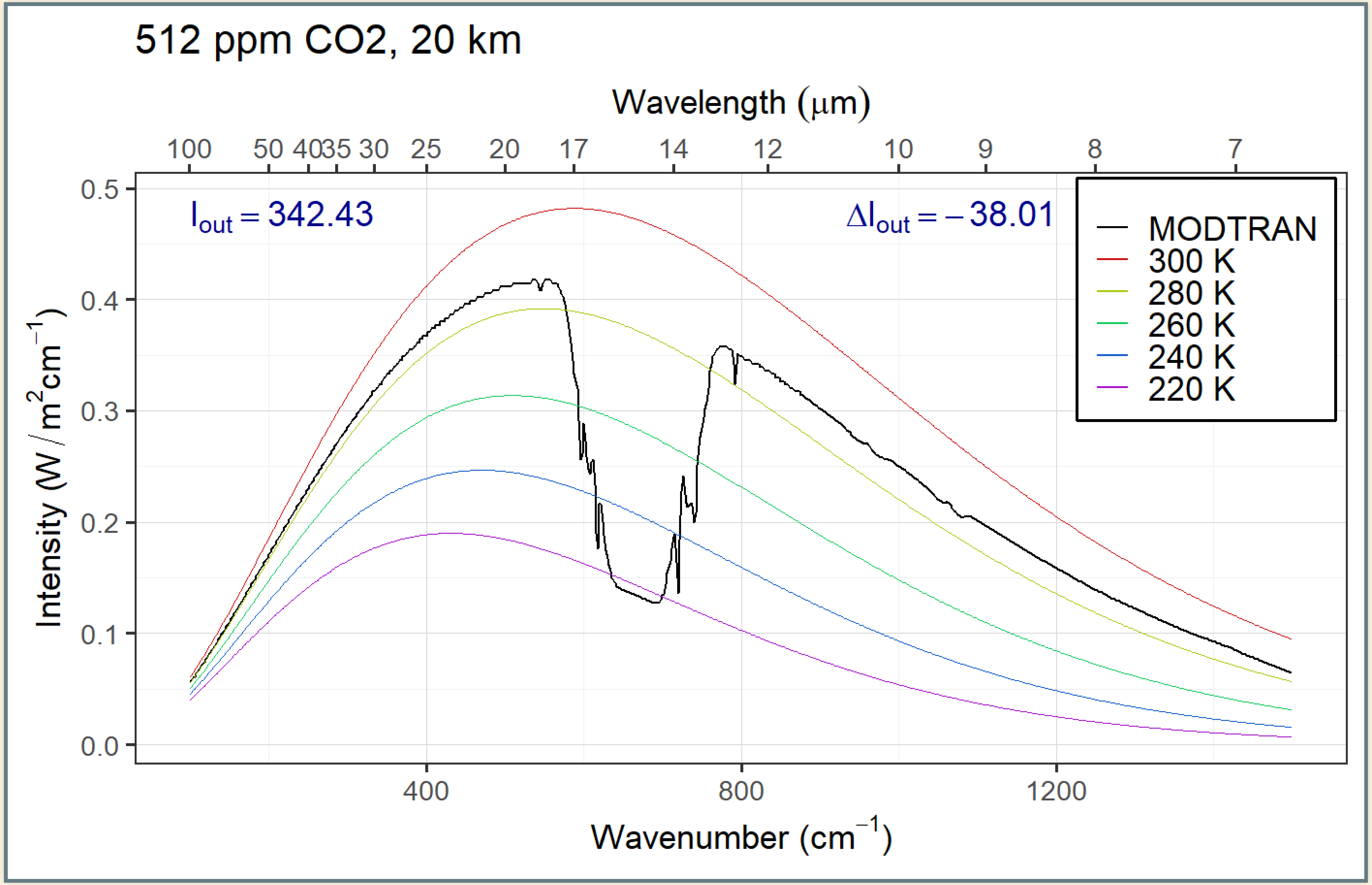
128 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 350.6$
$\Delta I_{out} = -29.85$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m^{2}cm^{-1})
0.0
0.1
0.2
0.3
0.4
0.5
400
800
1200
Wavenumber (cm^{-1})

256 ppm CO_2



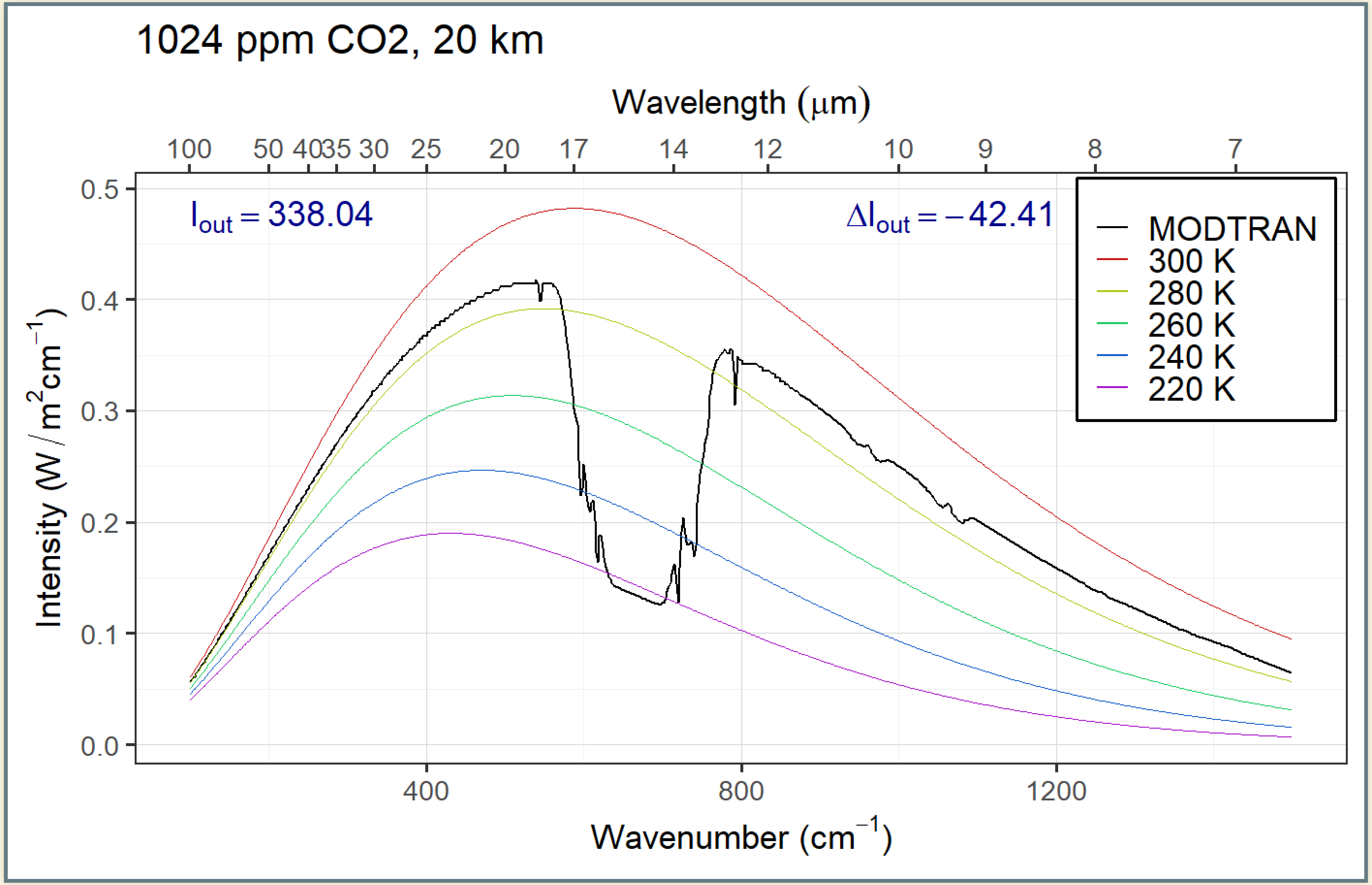
256 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 346.52$
$\Delta I_{out} = -33.93$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity $(W / m^2 cm^{-1})$
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

512 ppm CO_2

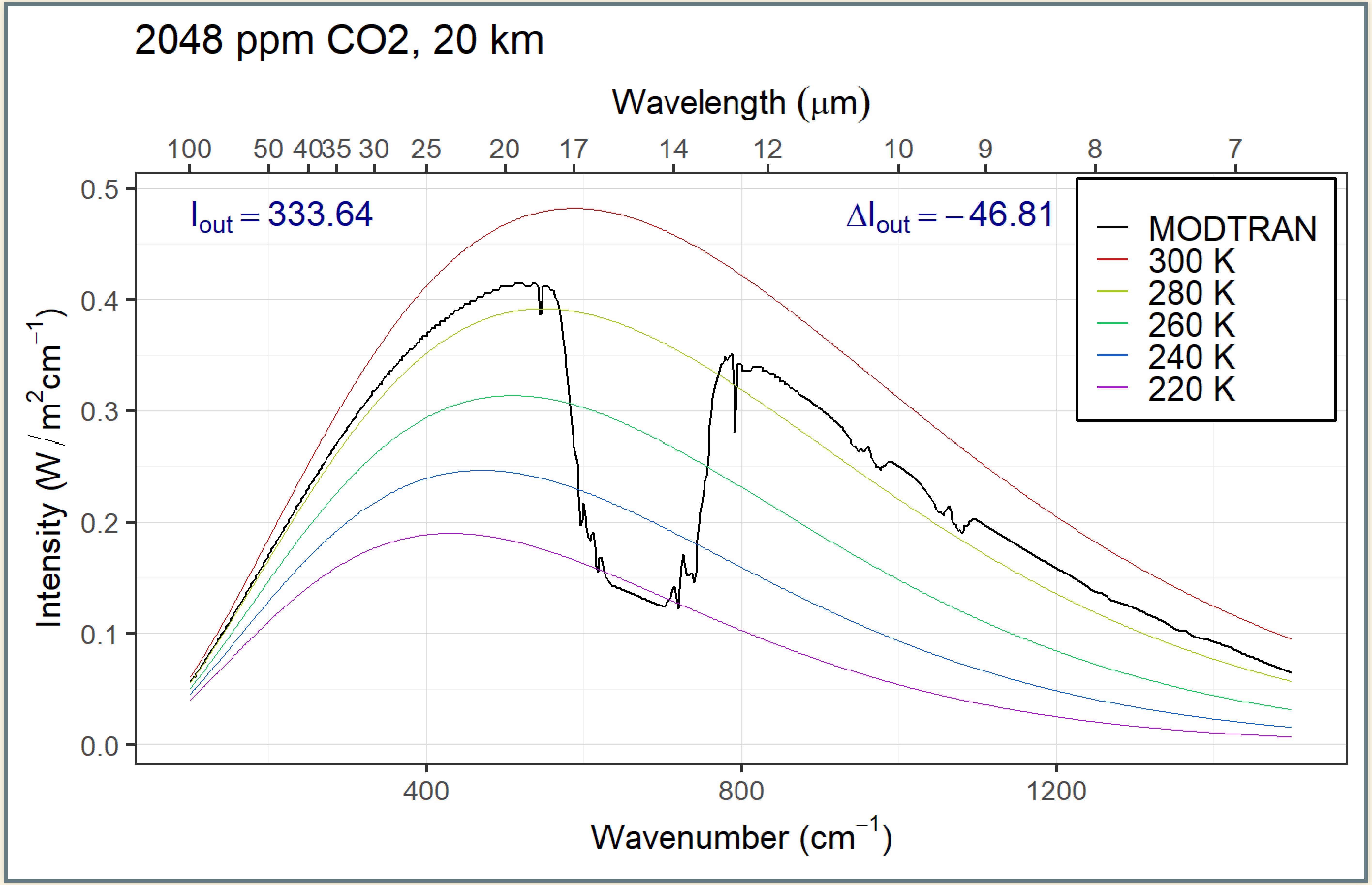


512 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m^{2}cm^{-1})
$I_{out} = 342.43$
$\Delta I_{out} = -38.01$
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm^{-1})

1024 ppm CO_2

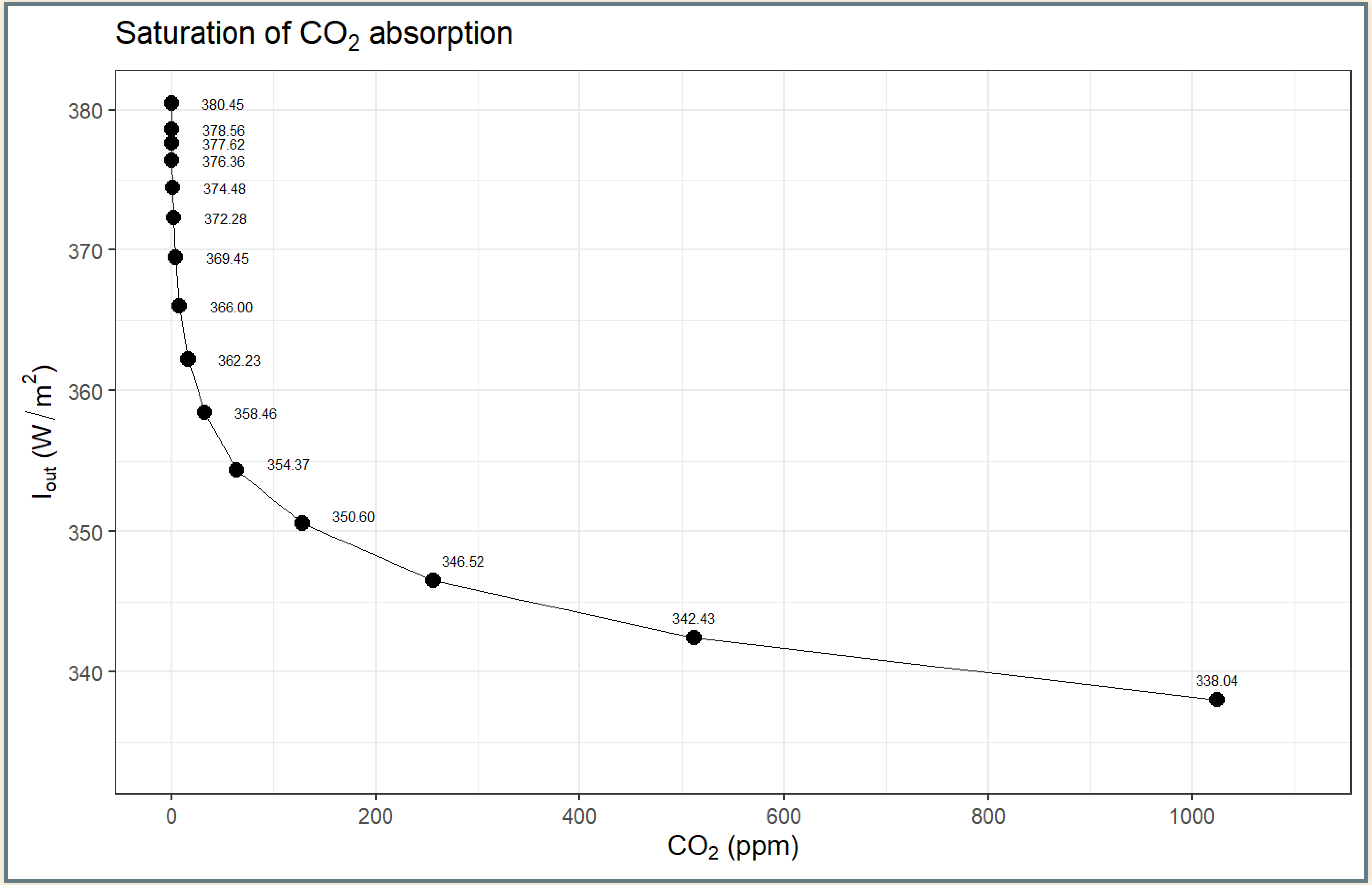

1024 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 338.04$
$\Delta I_{out} = -42.41$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W/m^2 cm^{-1}$)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

2048 ppm CO_2

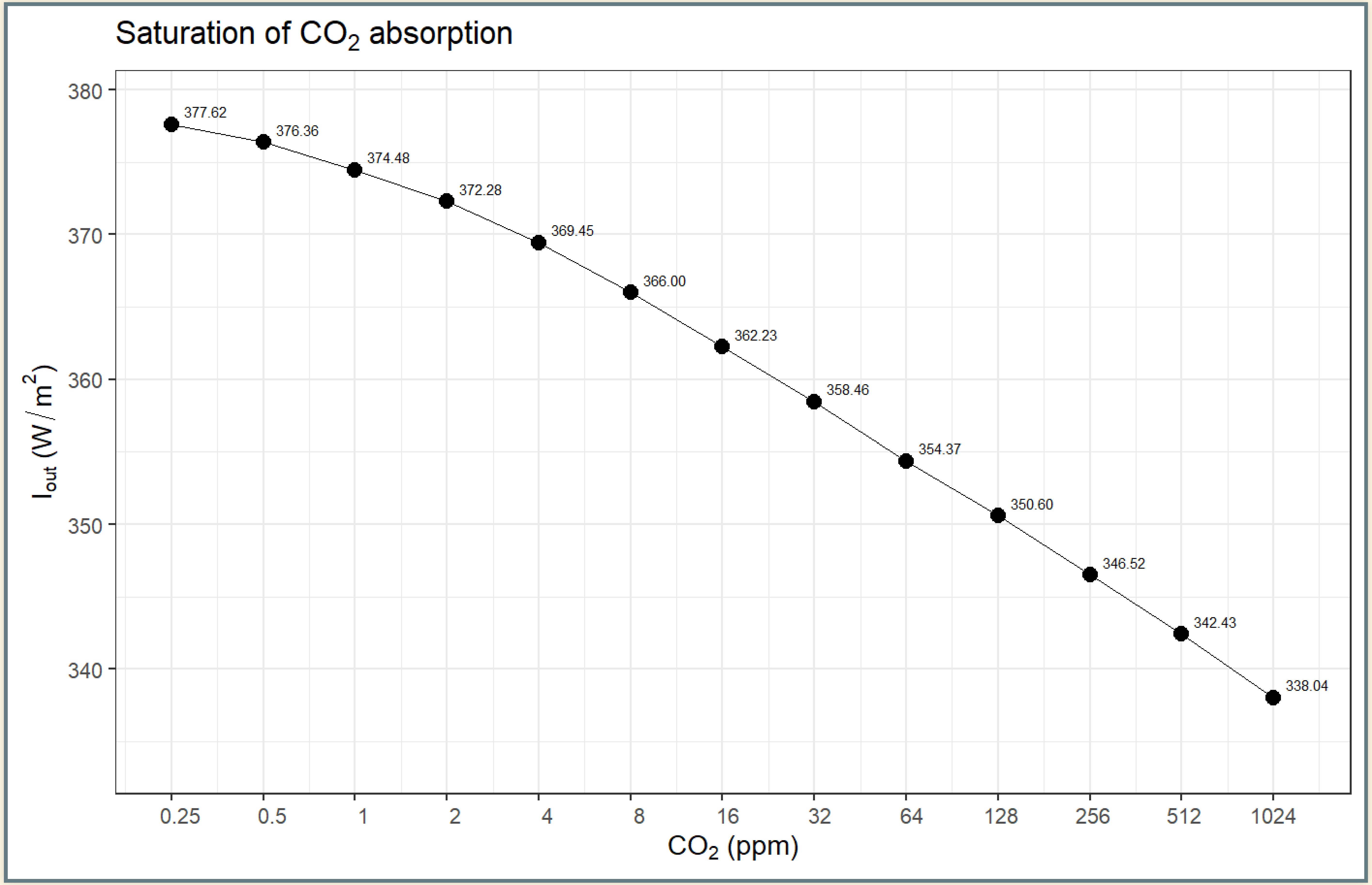


2048 ppm CO2, 20 km
Wavelength (μm)
100 50 40 35 30 25 20 17 14 12 10 9 8 7
$I_{out} = 333.64$
$\Delta I_{out} = -46.81$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W/m^2cm^{-1})
0.0 0.1 0.2 0.3 0.4 0.5
400 800 1200
Wavenumber (cm^{-1})

Band Saturation (I_{out})



I_{out} (CO_2 on log scale)



Calculating Global Warming

Calculating Global Warming

- "Climate sensitivity" = ΔT_{2x}
  - Temperature rise for doubled CO_2.
  - Uncertain (because of feedbacks)
  - Best estimate: $\Delta T_{2x} \sim$ 3.2K (range 2.0–4.5 K)
- Every time you double CO_2, T rises by ΔT_{2x}.
- For arbitrary change in CO_2:

$$\Delta T = \Delta T_{2x} \times \frac{\ln\left(\frac{\text{new } pCO_2}{\text{old } pCO_2}\right)}{\ln 2}$$

Global Warming Potential

- Absorption by CO_2 and water vapor are very saturated
- Absorption in the atmospheric window is not saturated
- Therefore, molecule-for-molecule, gases that absorb in the window have a much bigger effect on the climate than adding more CO_2.
  - One chlorofluorocarbon molecule = thousands of CO_2 molecules
- Global Warming Potential (GWP) of *x* = how many CO_2 molecules cause the same warming as one molecule of *x*

Evolving theory of greenhouse effect

Greenhouse effect

1. Purely radiative (no convection)
   - Each layer has uniform temperature
     a. Single-layer, uniform spectrum (Wed. 1/26)
        - Absorbs 100% longwave light
     b. Multi-layer, uniform spectrum (Lab #3)
        - More layers $\Rightarrow$ greater greenhouse effect.
     c. Realistic spectrum (Fri. 1/28 & today)
        - More realistic
        - Harder to do calculations (need computer)
2. Introduce convection (Today & Wed. 2/2)
   - Temperature changes with height
   - Convection moves heat up and down
   - Radiative-convective models are very accurate
     - But require computers

The Vertical Structure of the Atmosphere

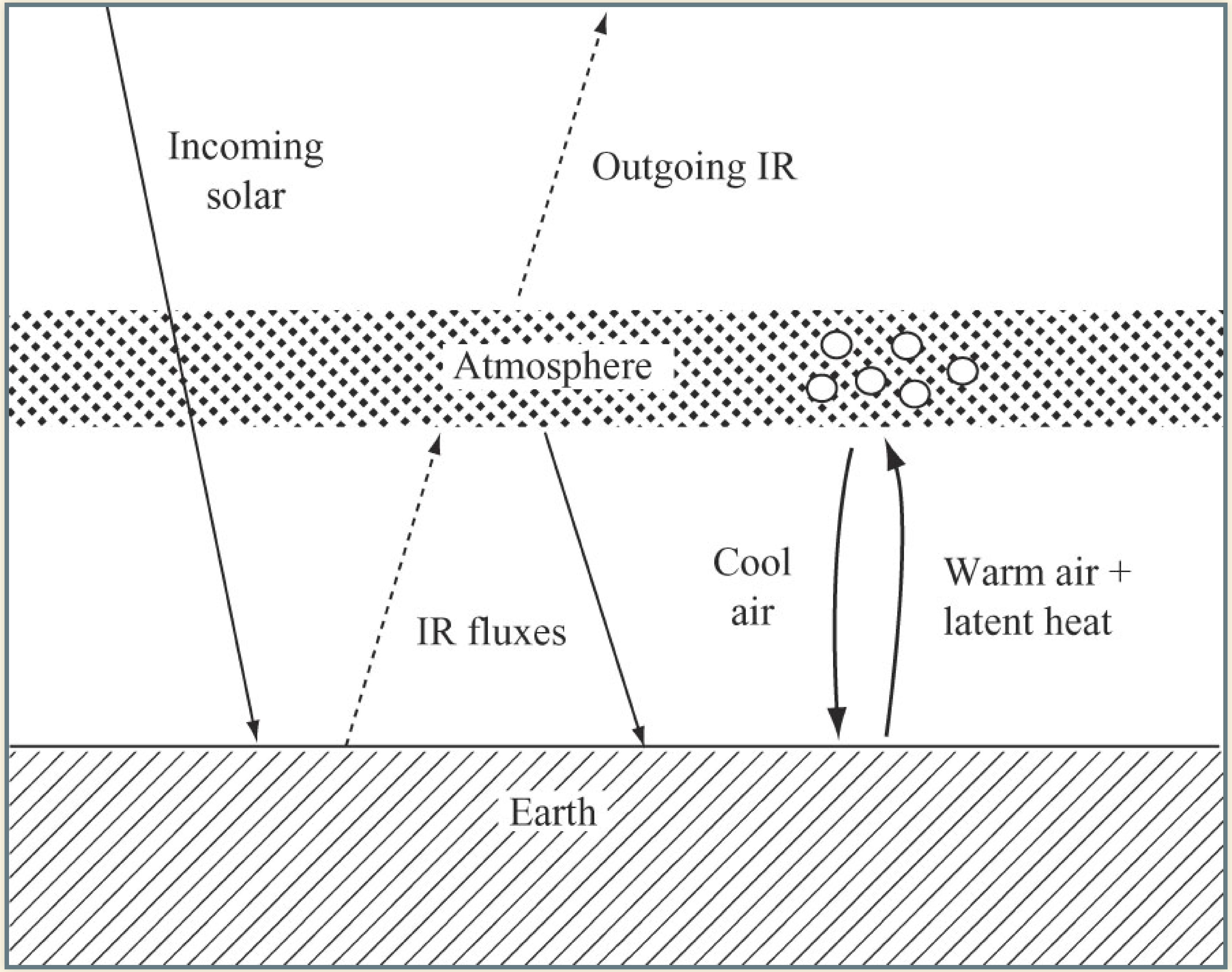
Greenhouse effect

1. Purely radiative (no convection)
   - Each layer has uniform temperature
     a. Single-layer, uniform spectrum
        - Absorbs 100% longwave light

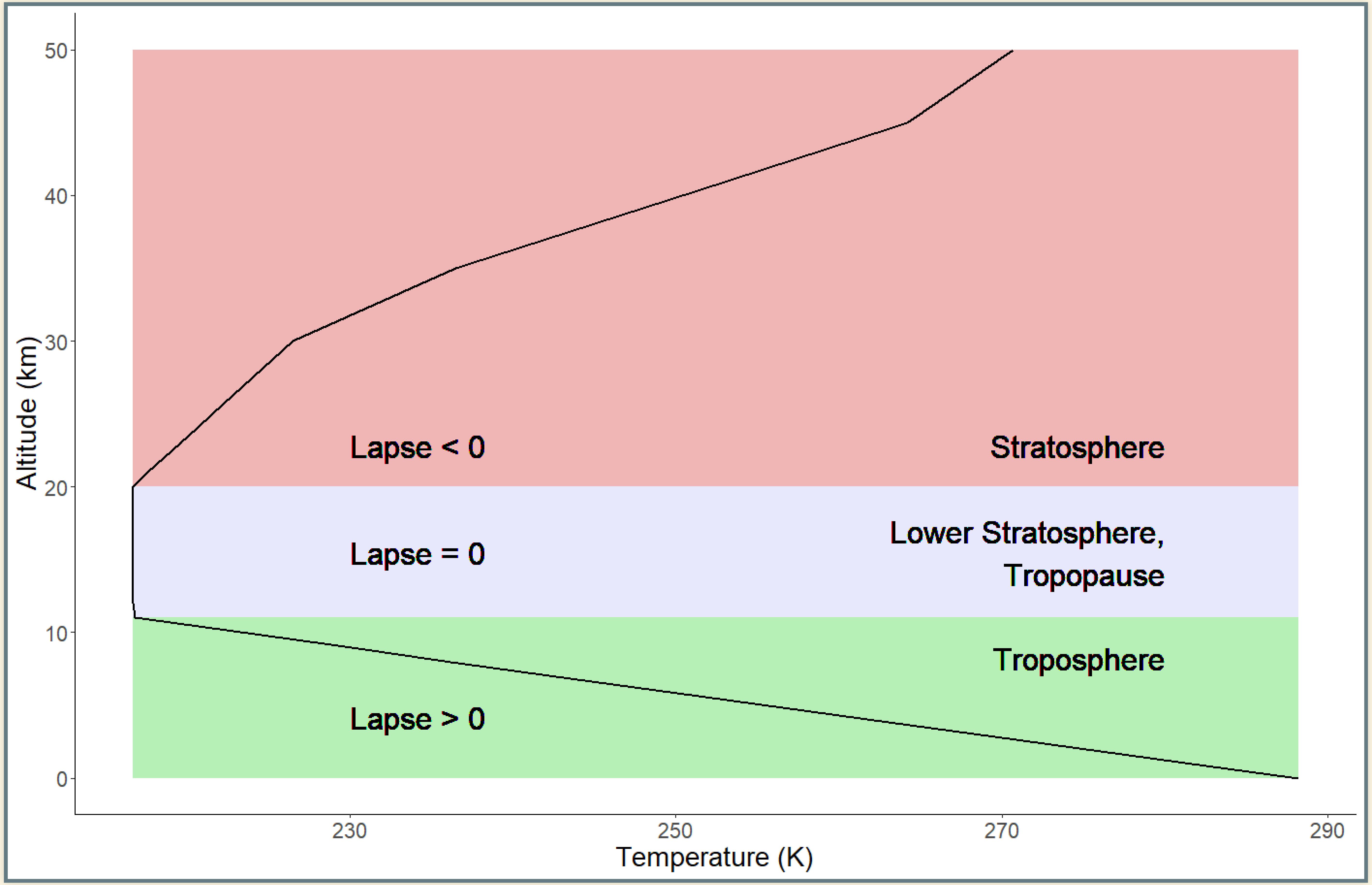
     b. Multi-layer, uniform spectrum
        - More layers $\Rightarrow$ greater greenhouse effect.

     c. Realistic spectrum
        - More realistic
        - Harder to do calculations (need computer)
2. Convection:
   - Temperature changes with height
   - Convection moves heat up and down
   - Radiative-convective models are very accurate
     - But require computers

Radiative-Convective Equilibrium



Normal Atmosphere:

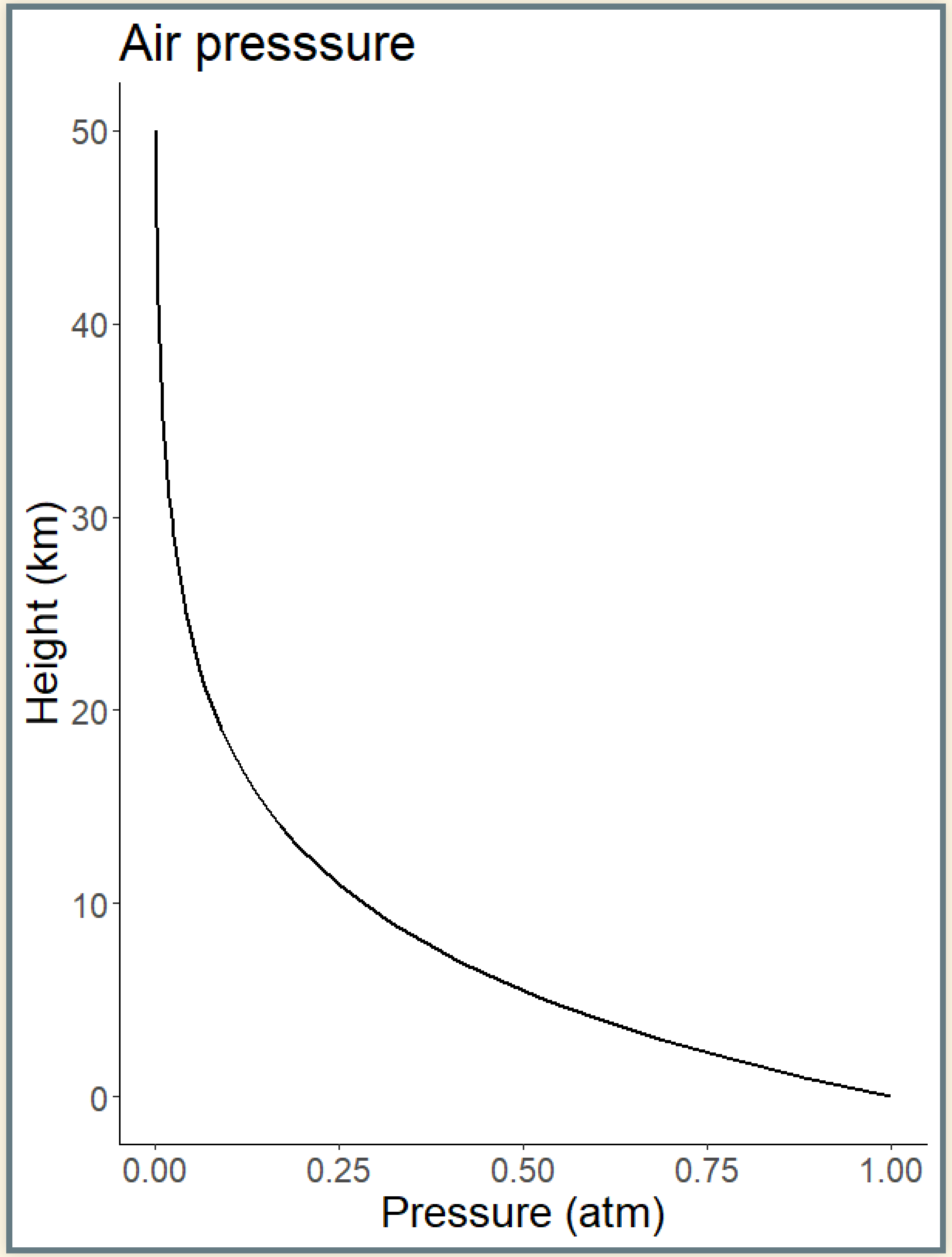


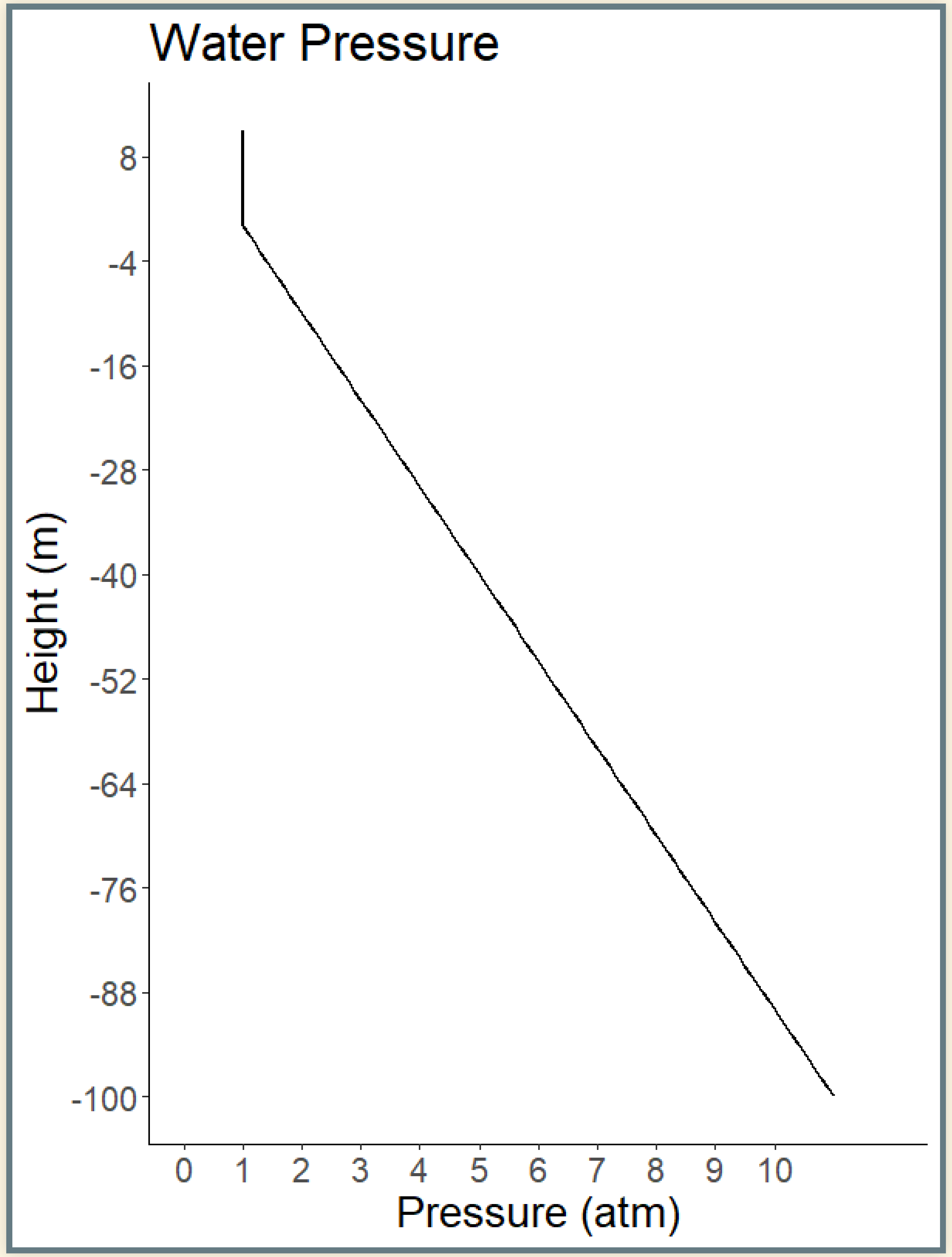
Vertical Structure

$$\text{Lapse rate} = \frac{-\Delta T}{\Delta \text{height}}$$

- Positive lapse rate: Air overhead is cooler (normal for troposphere)
- Negative lapse rate: Air overhead is warmer (abnormal, “inversion”)

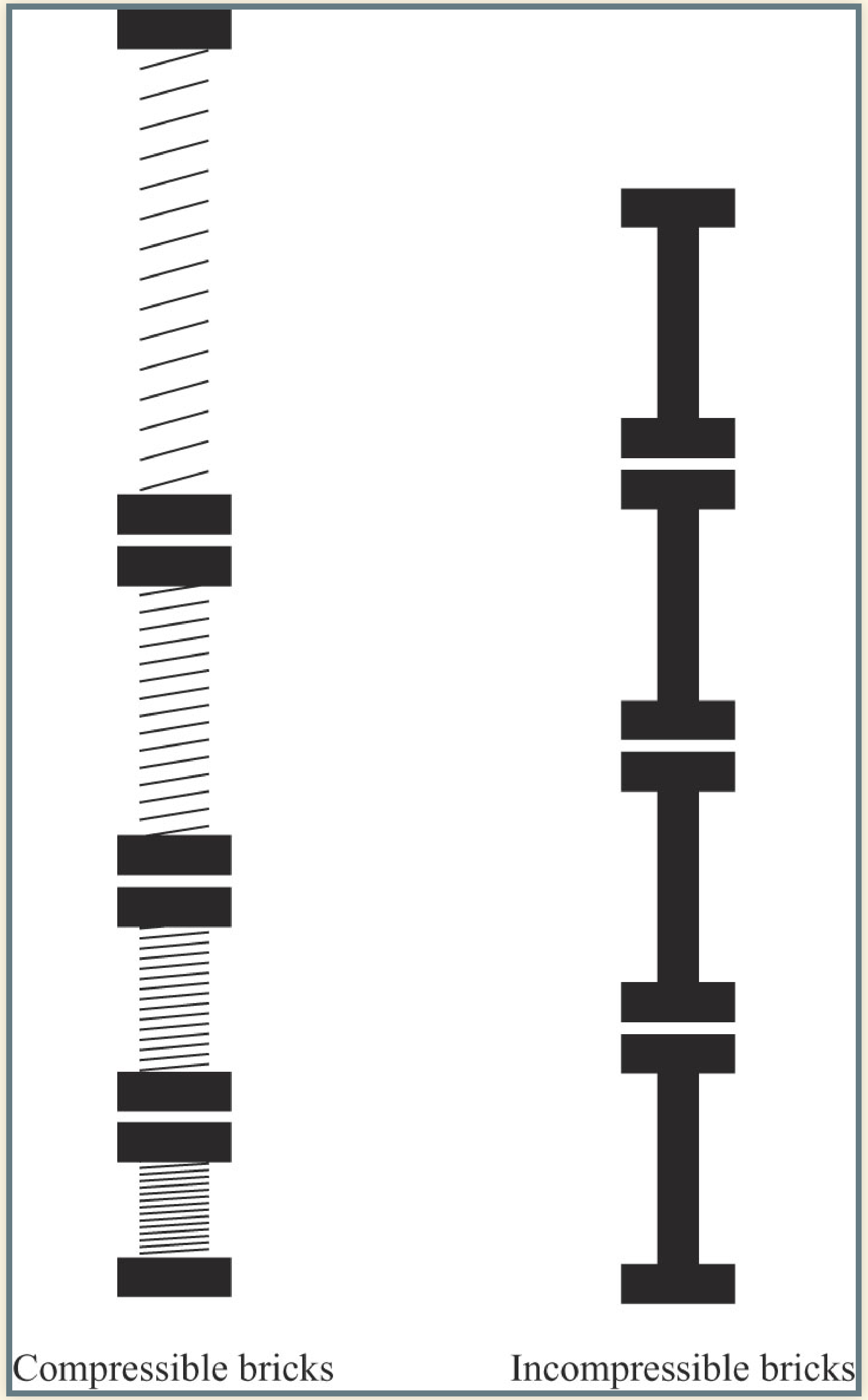
Air vs. Water


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 cubic meter of water weighs 1000 kg
- 1 cubic meter of dry air at sea-level density weighs 1.3 kg
- 1 cubic meter of dry air 10 km above sea level weighs 0.4 kg



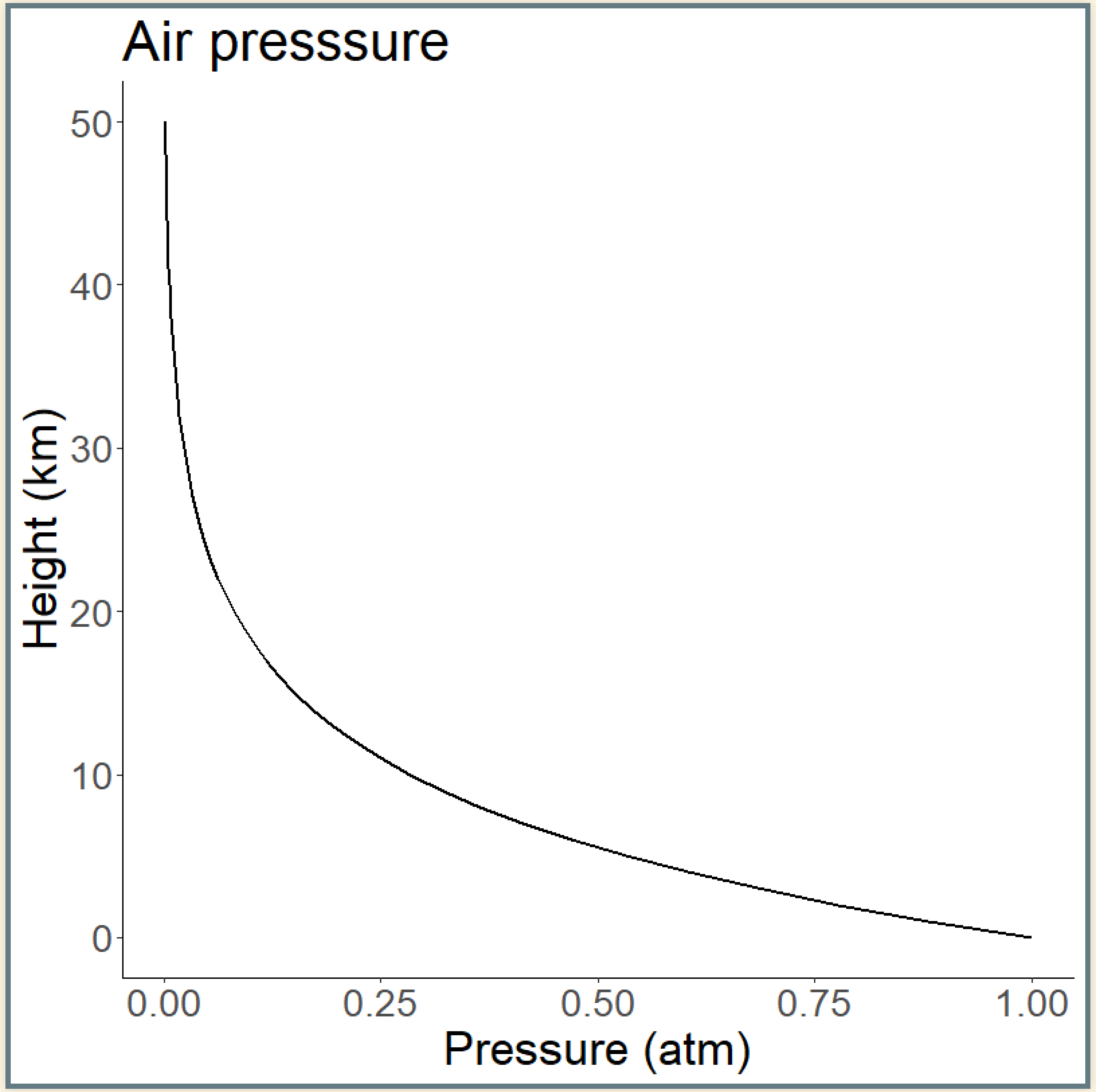
Air Pressure

- Pressure at height ***h***:

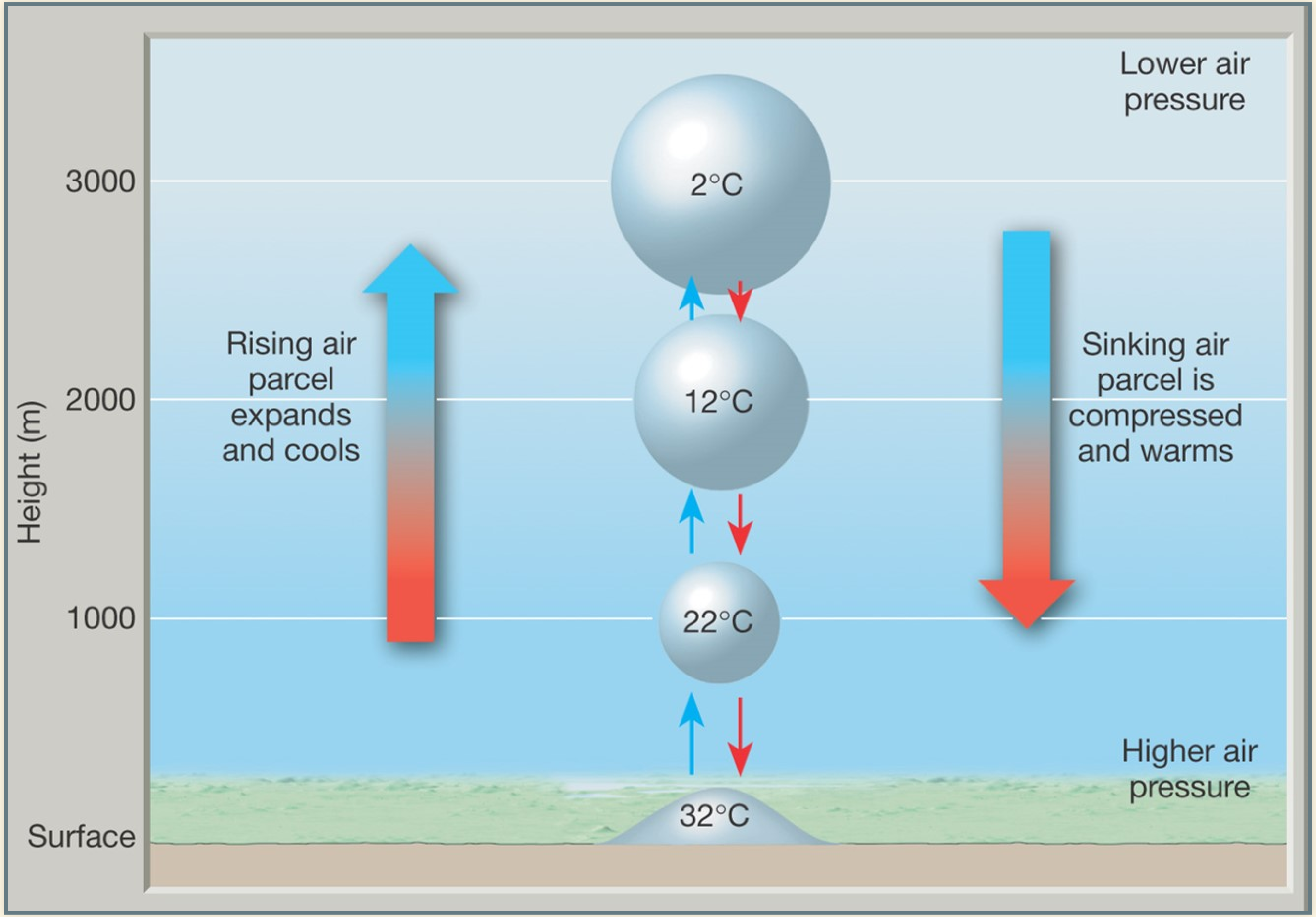
$$
\begin{aligned}
P(h) &= P_0\, e^{-h/8.0\mathrm{km}} \\
&= P_0\, 2^{-h/5.5\mathrm{km}} \\
&= P_0 \left(\frac{1}{2}\right)^{h/5.5\mathrm{km}}
\end{aligned}
$$

  - Half the air in the atmosphere 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?

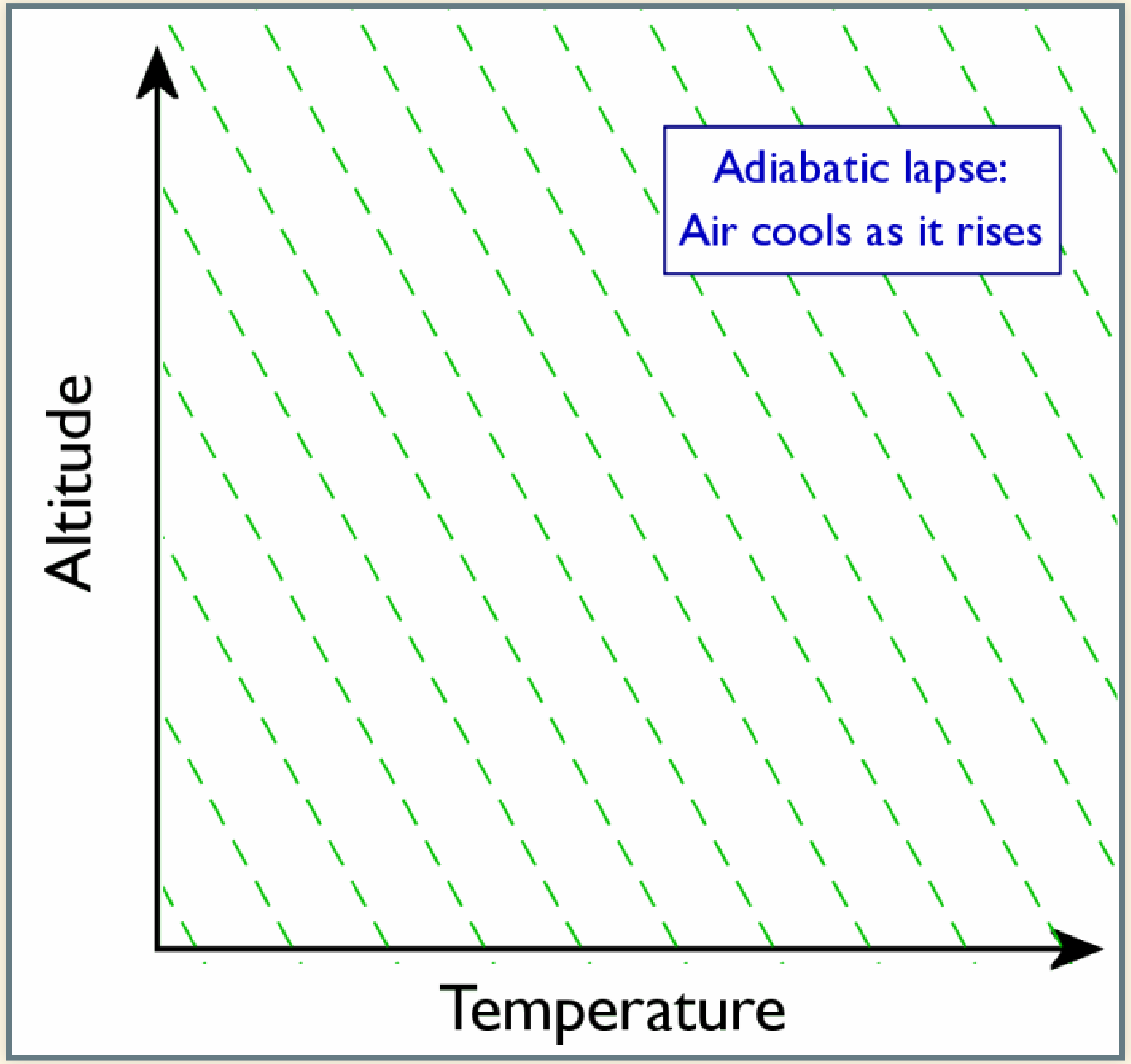


Terminology

- **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

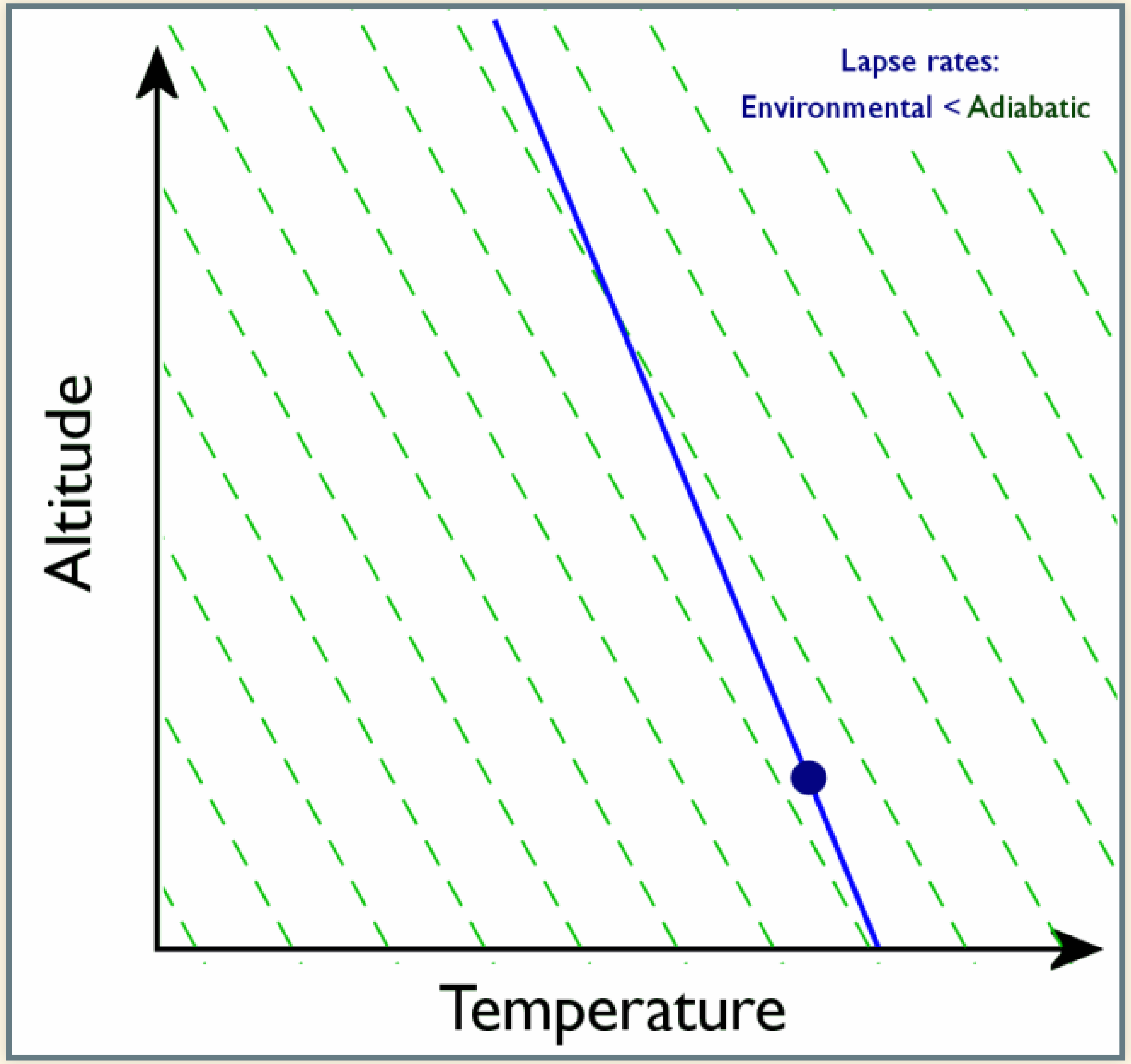
Overview of Convection

Overview of convection



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

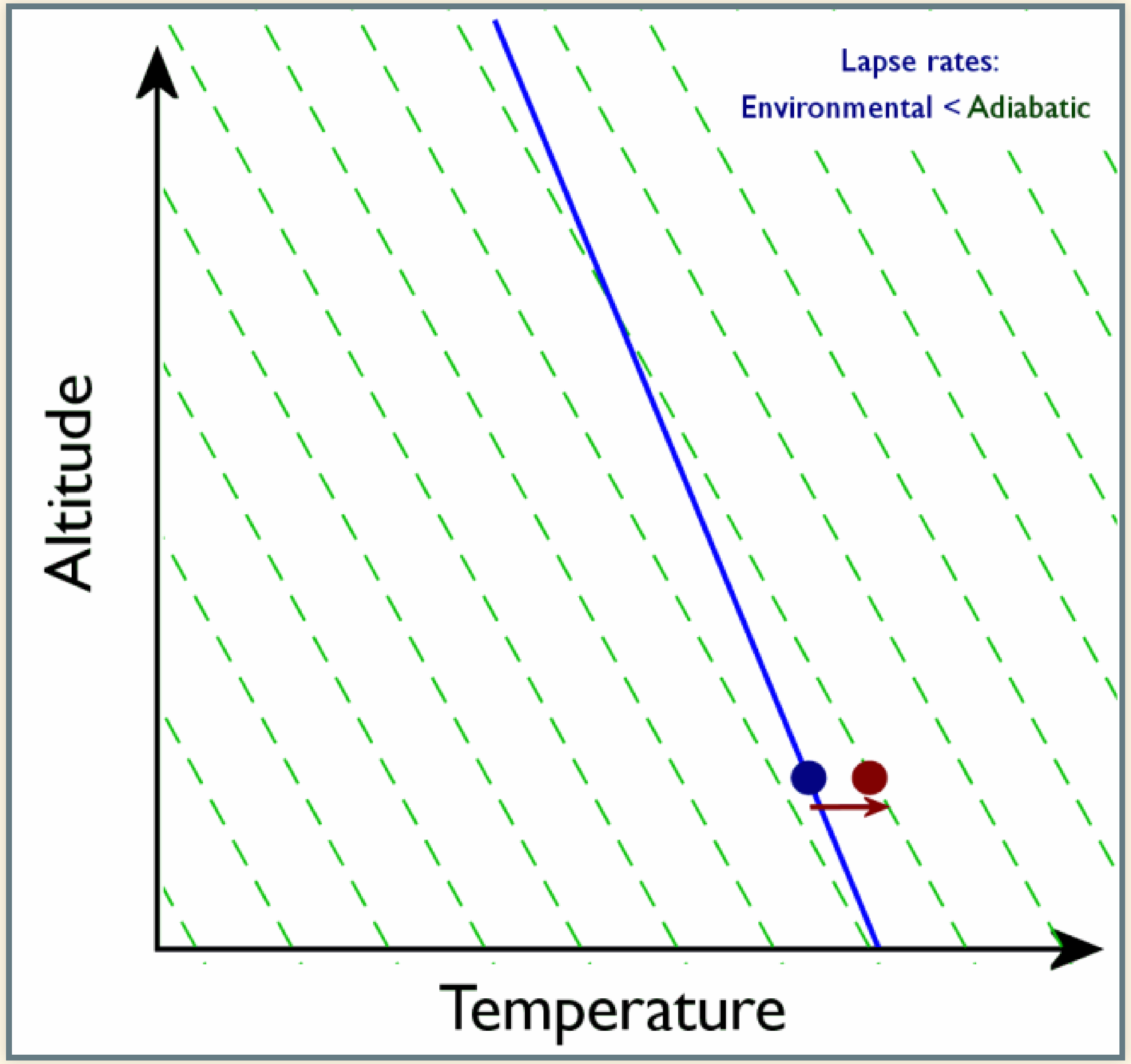
Stable Atmosphere
Initial State



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

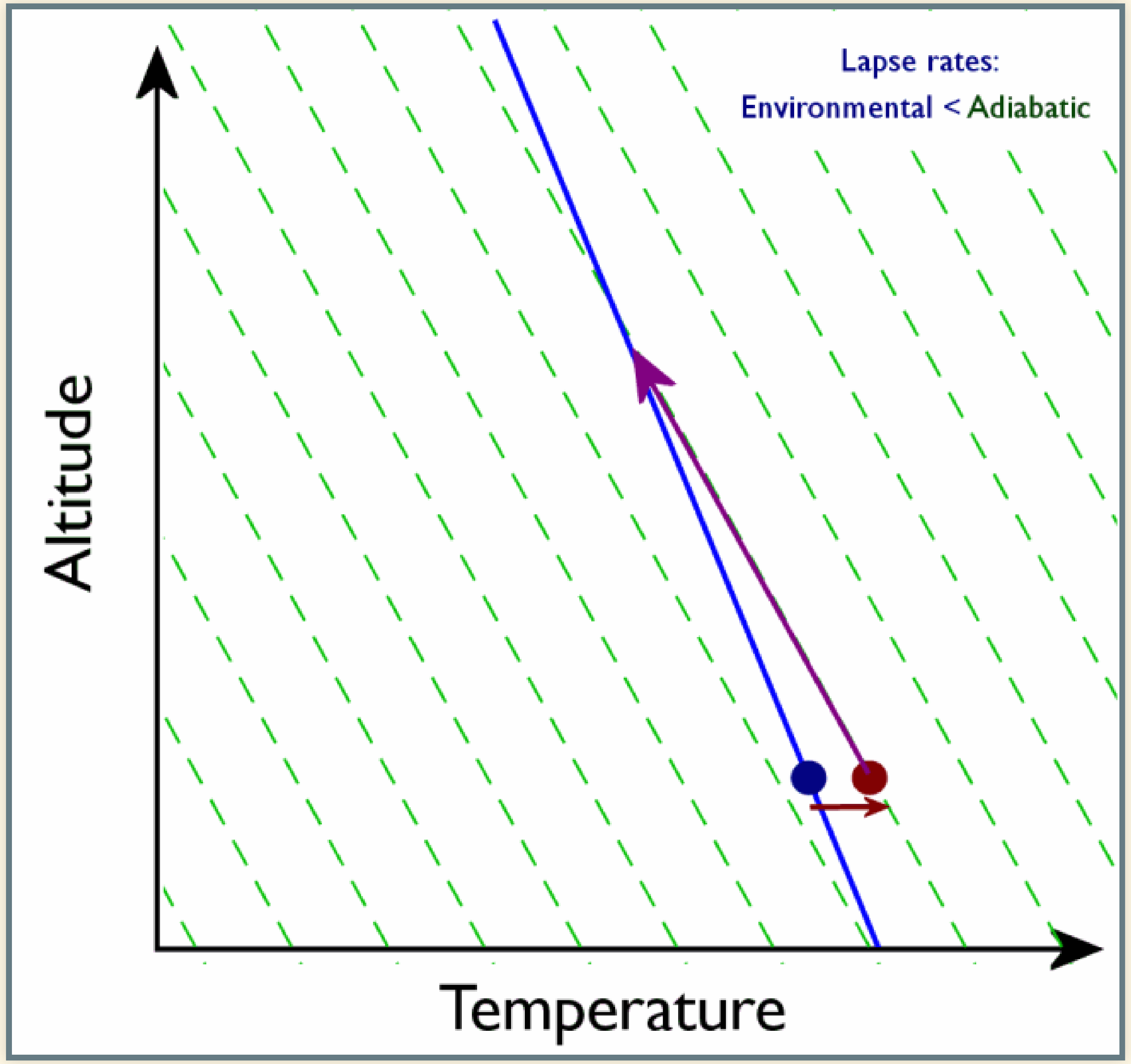
Stable Atmosphere

Parcel is heated



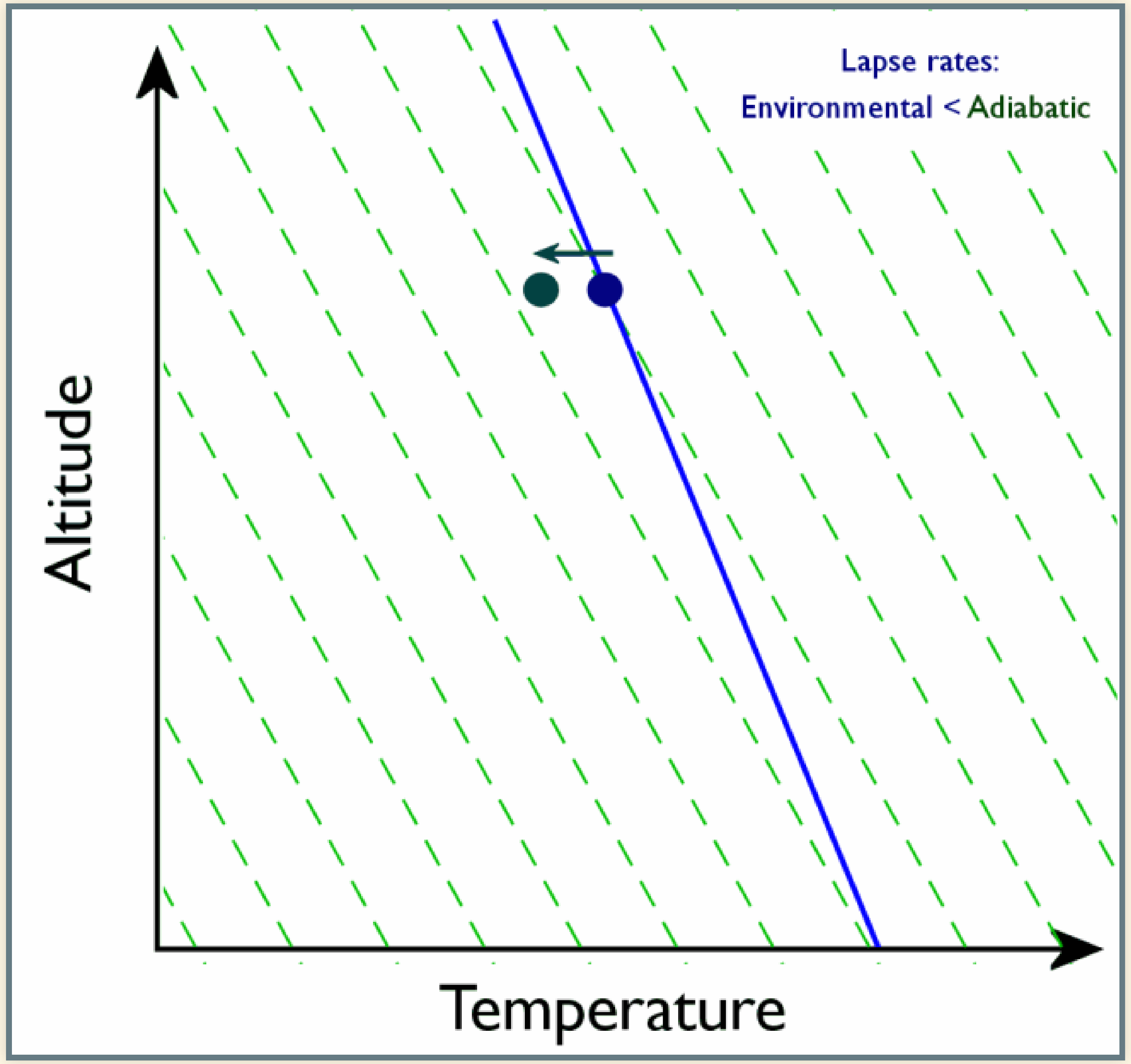
Stable Atmosphere

Rises to new equilibrium



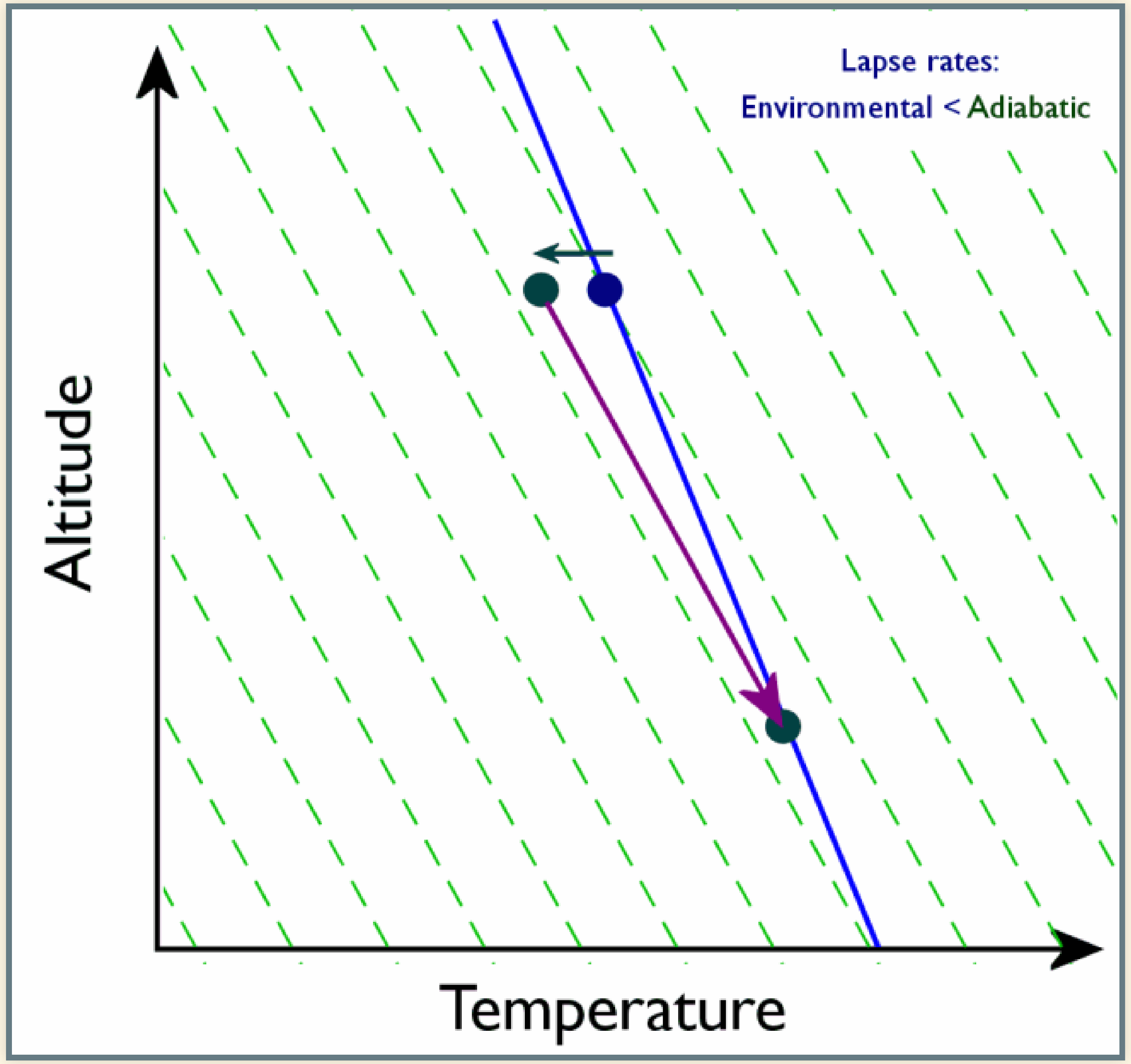
Stable Atmosphere

Parcel is cooled



Stable Atmosphere

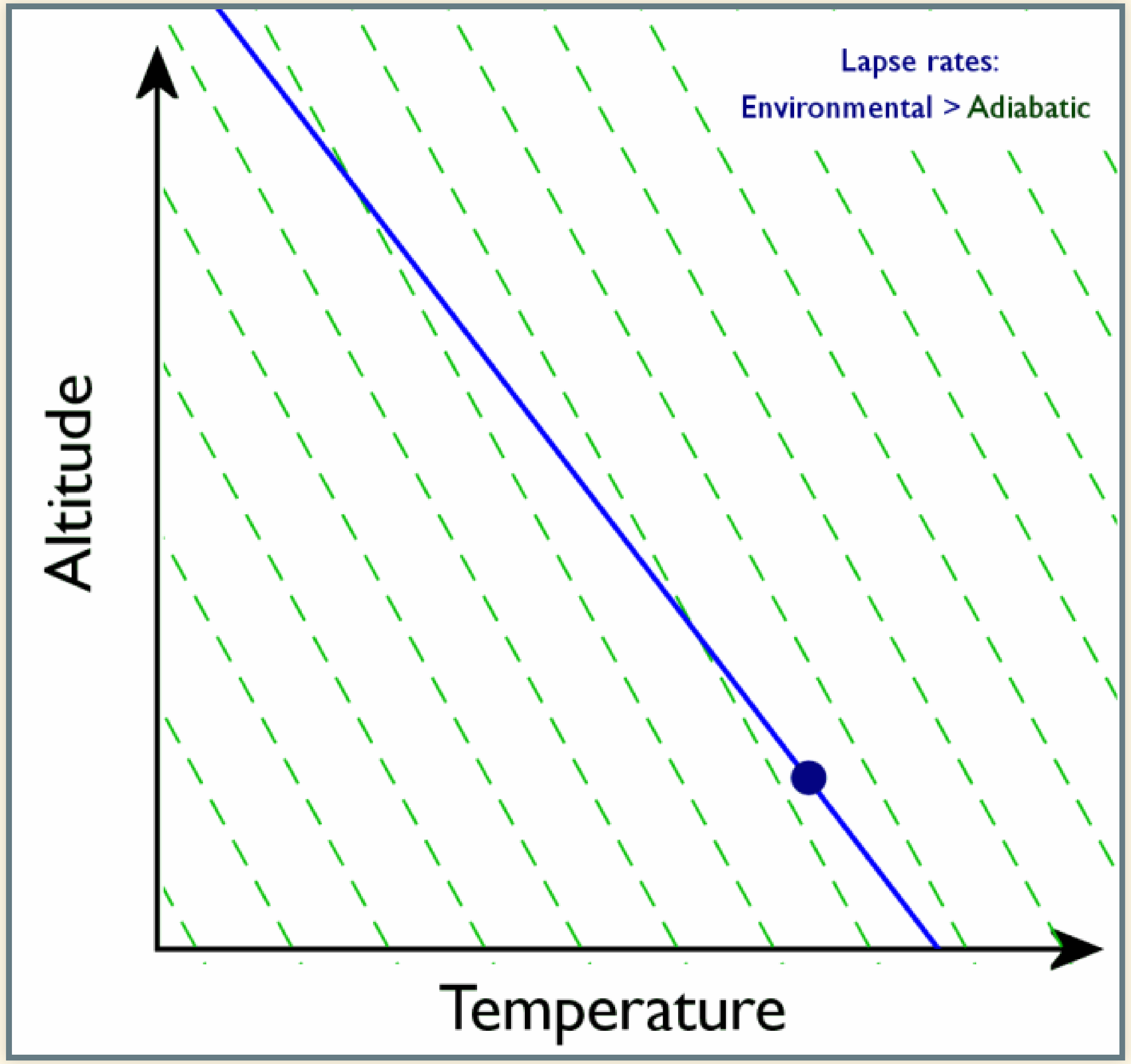
Sinks to new equilibrium



Unstable Atmosphere

Unstable Atmosphere

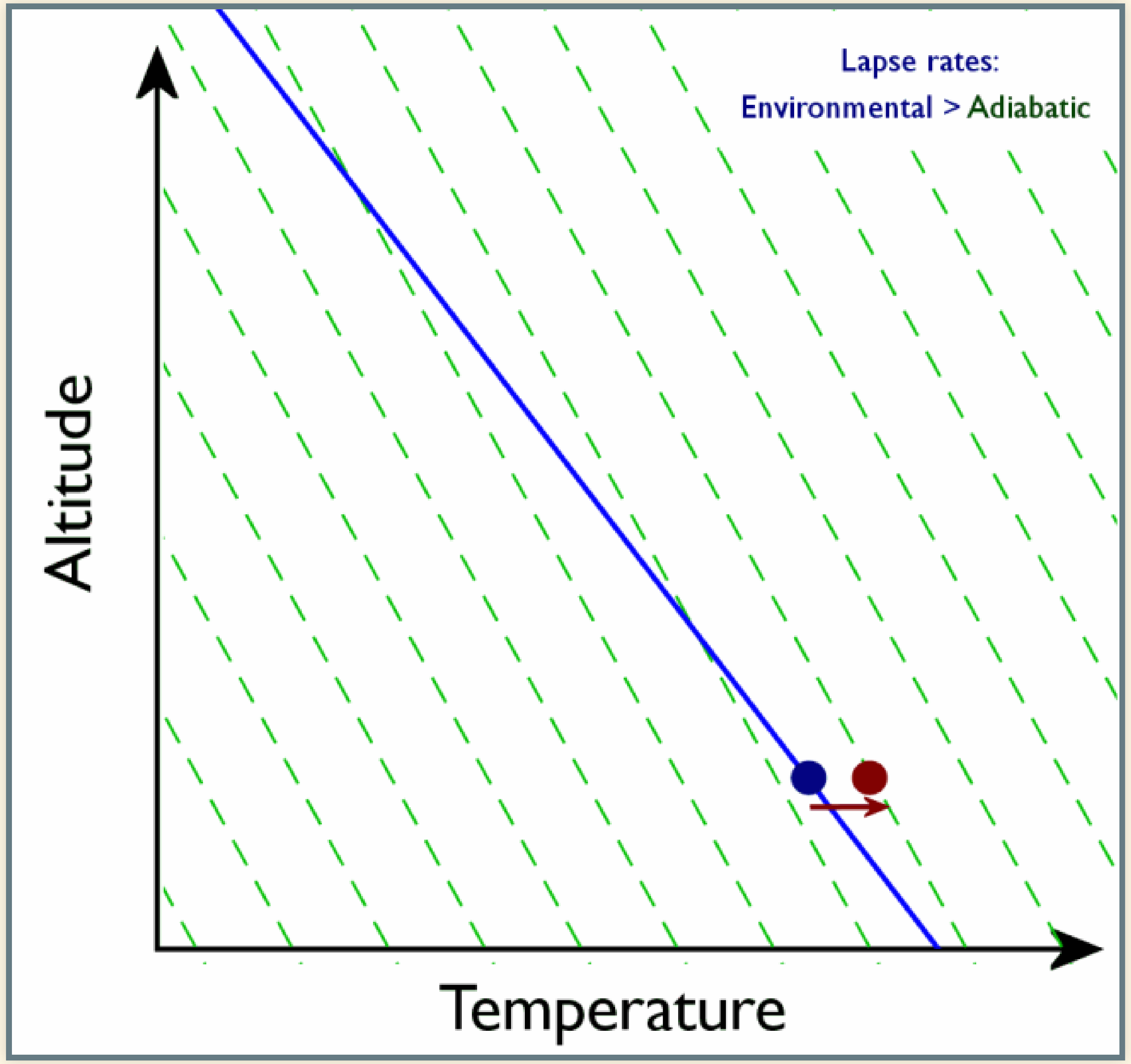
Initial State



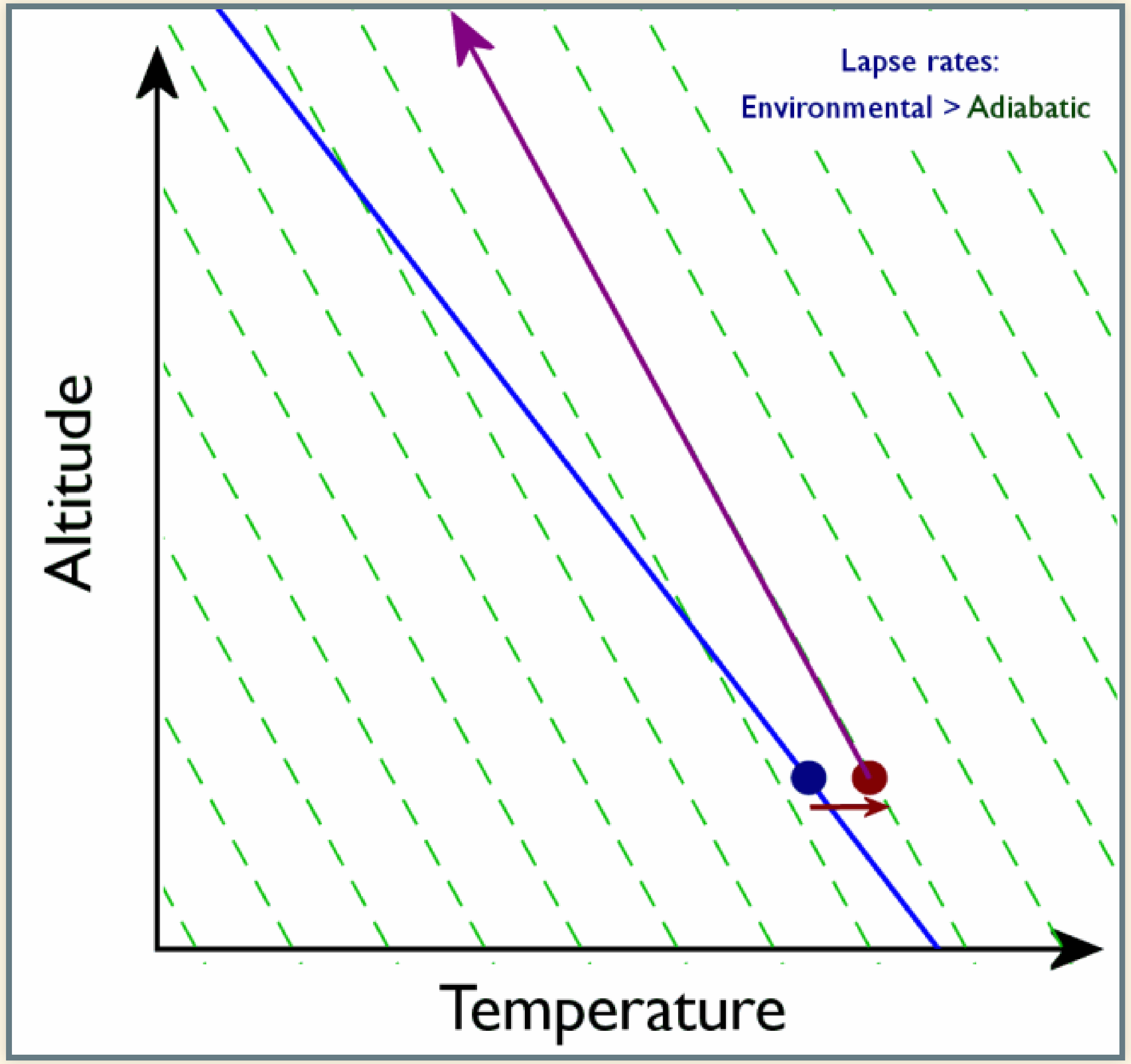
- green = adiabatic lapse
- blue = environmental lapse > adiabatic

Unstable Atmosphere

Parcel is heated



Unstable Atmosphere
Rises without stopping



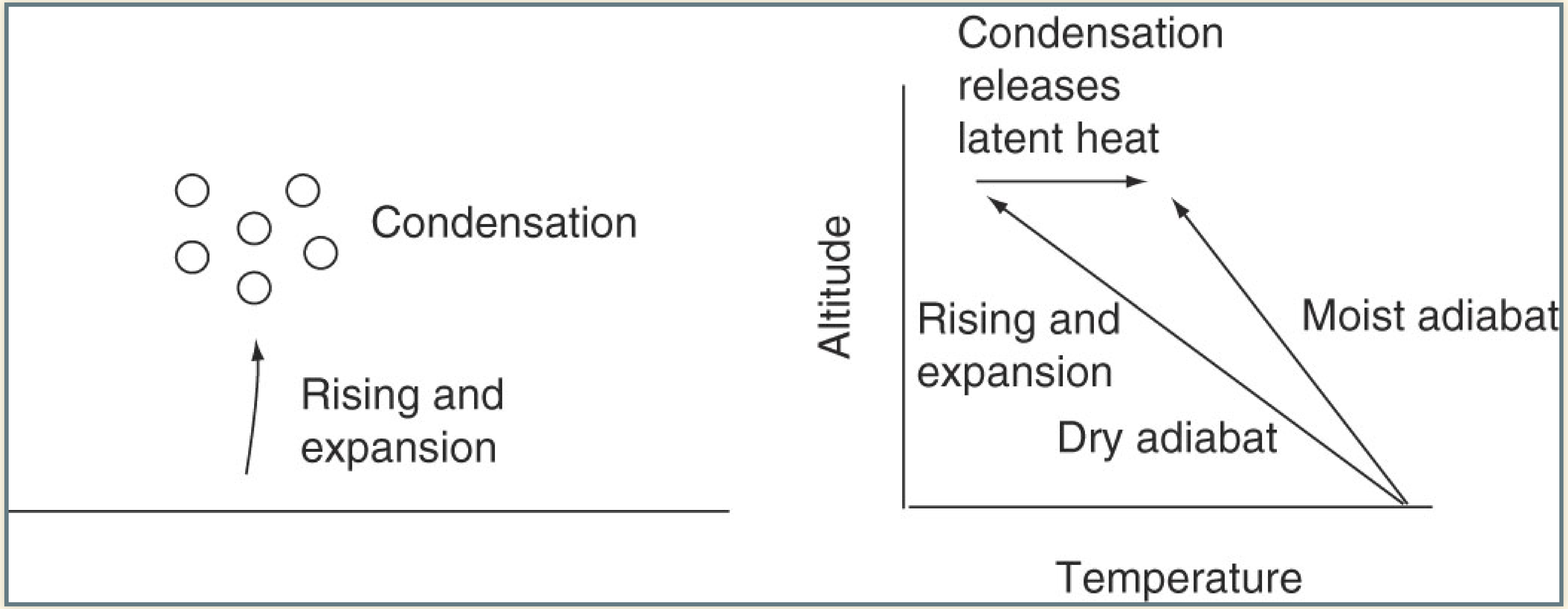
Summary of Stability

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

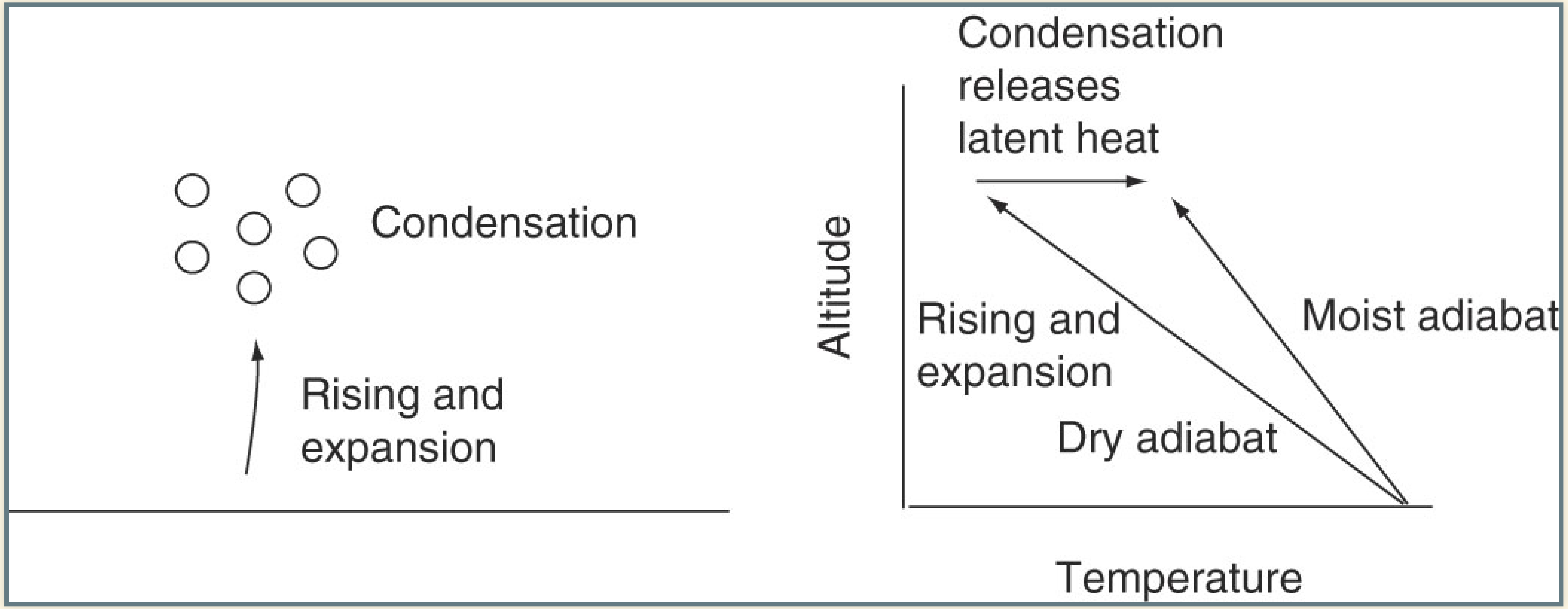
Moist Convection

Moist Convection



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

Moist Convection



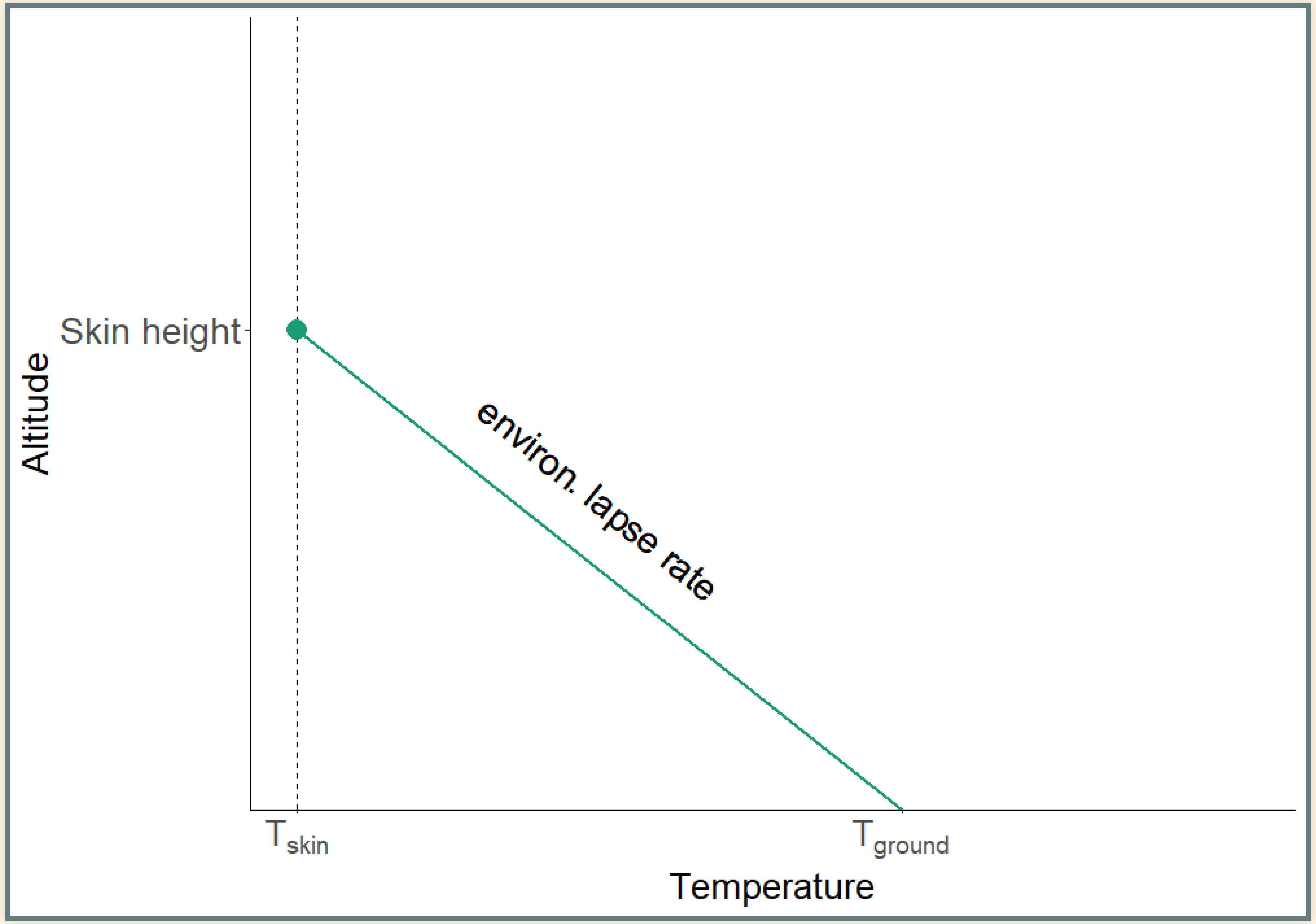
- Latent heat warms air
- Heat reduces adiabatic cooling
- Moist adiabatic lapse < Dry adiabatic lapse
- Smaller lapse = less stable
- **Humid air is less stable than dry air**

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*)

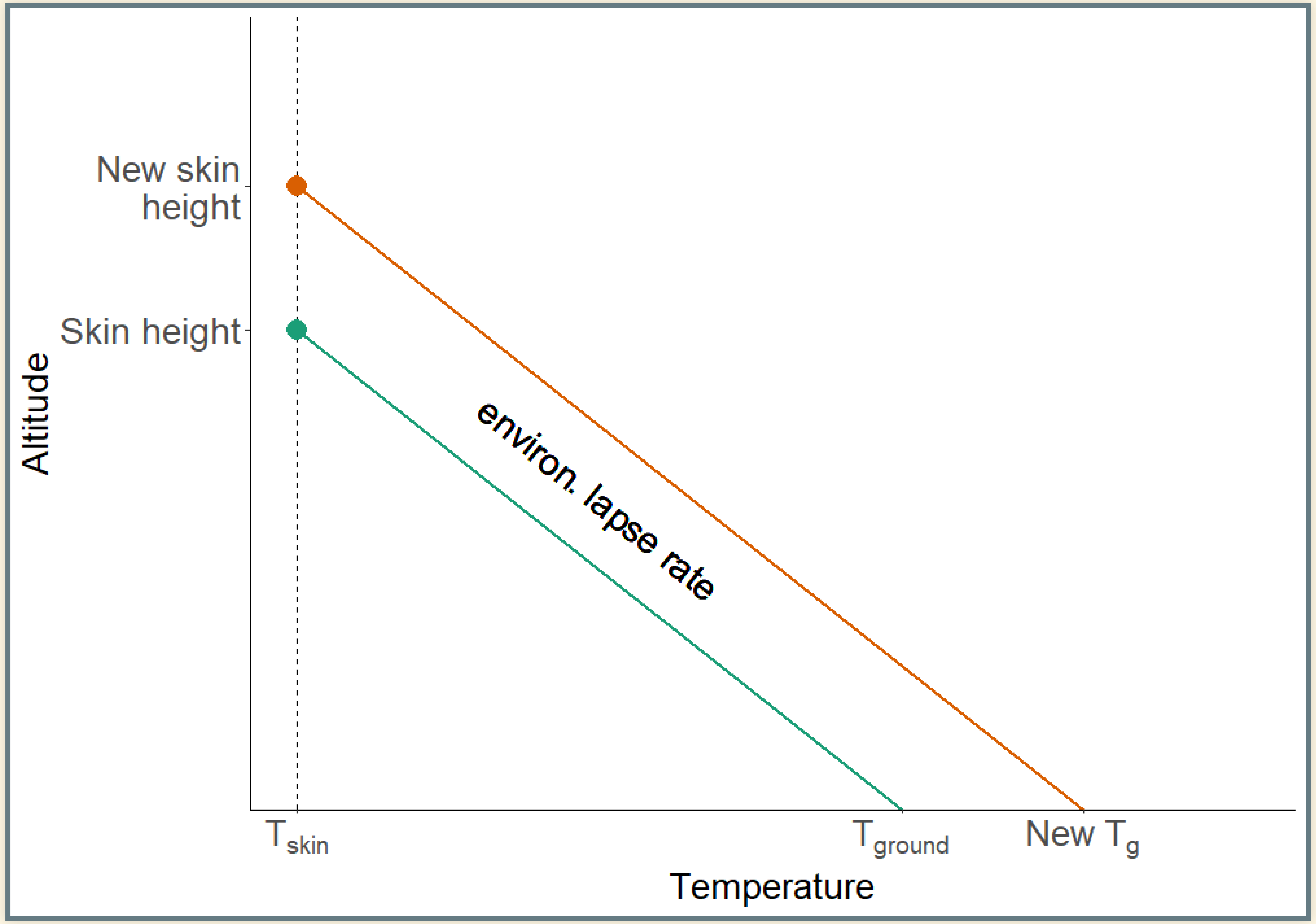
Greenhouse effect

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