Temperature Structure of the Atmosphere

EES 3310/5310

Global Climate Change

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Class #6: Friday, January 17 2020

Review Question

What is the “atmospheric window”?

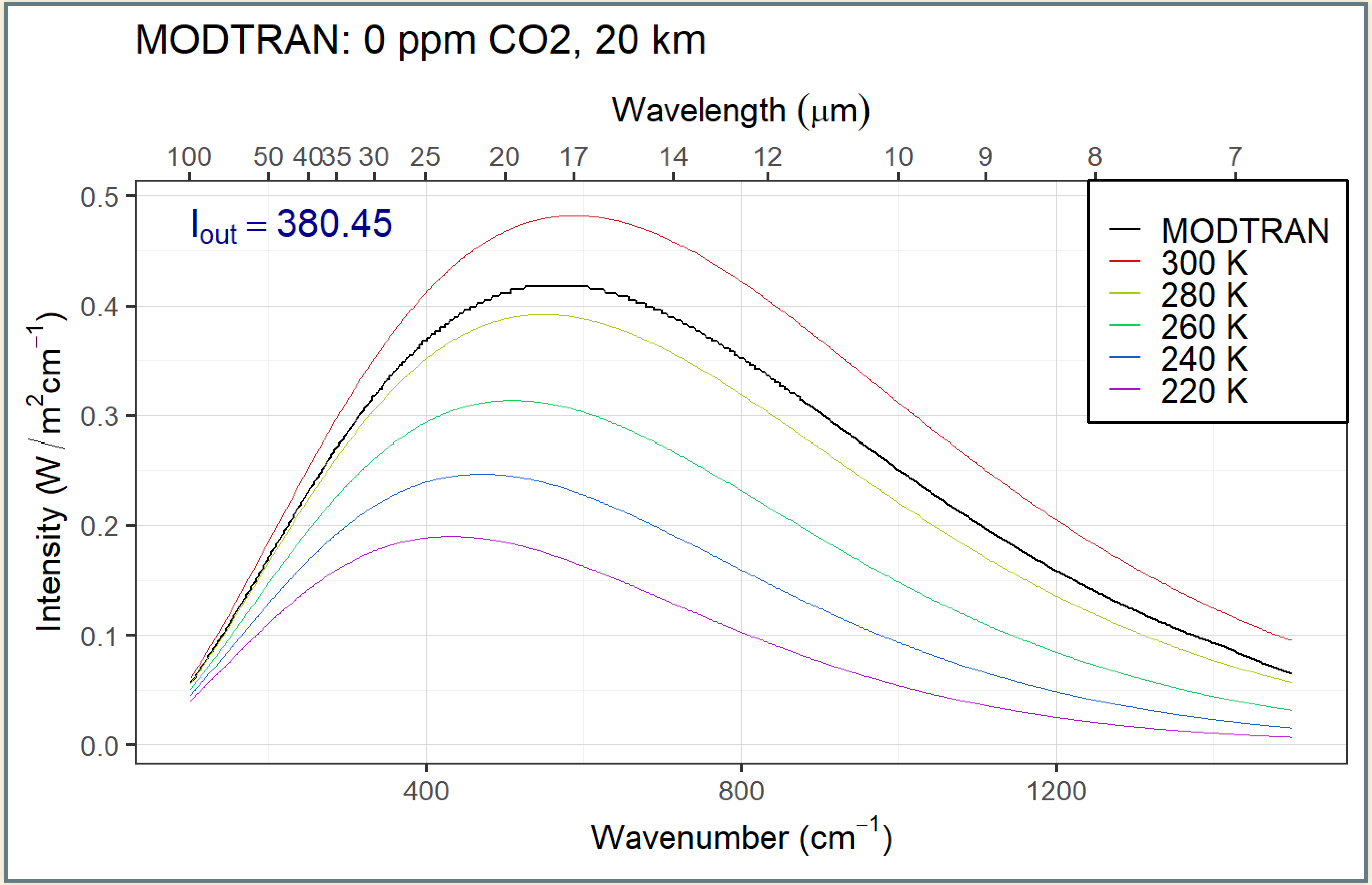
1. Regions where there are few clouds to block radiation.
2. Desert regions with very little water vapor.
3. Tropical regions with low CO_2 concentrations.
4. A range of wavelengths where no greenhouse gases absorb much.

Measuring Band Saturation

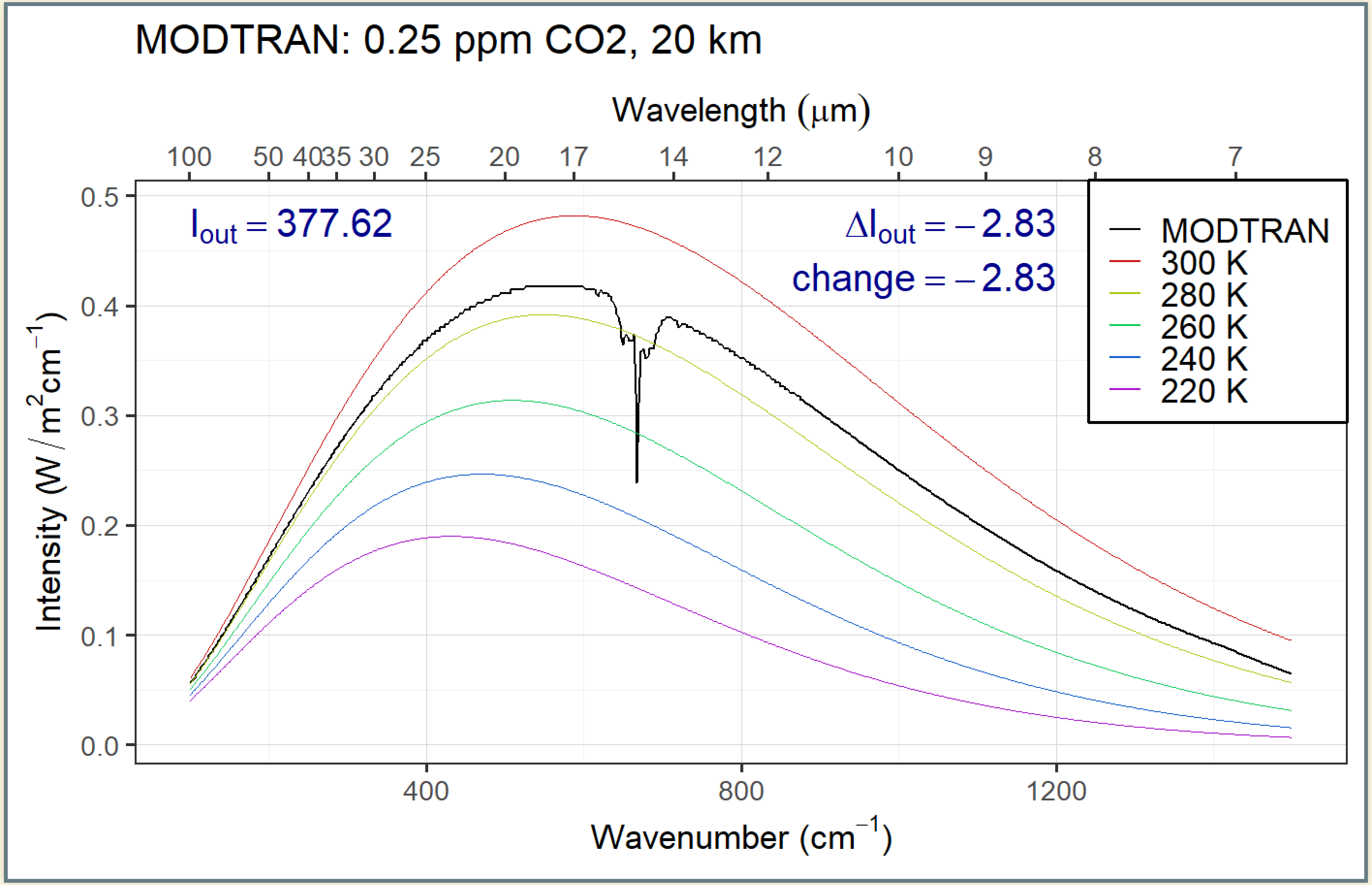
Set up MODTRAN:

- Go to MODTRAN, set CO_2 to 0.25 ppm, and set all other gases to zero.
- Set altitude to 20 km and location to “1976 US Standard Atmosphere”.
- Press “Save this run to background”
- Note I_{out}
- Double CO_2 and note the change in I_{out}
- Keep doubling CO_2 until you get to 1024 ppm.
- Do you notice anything about the changes in I_{out}?

0 ppm CO_2

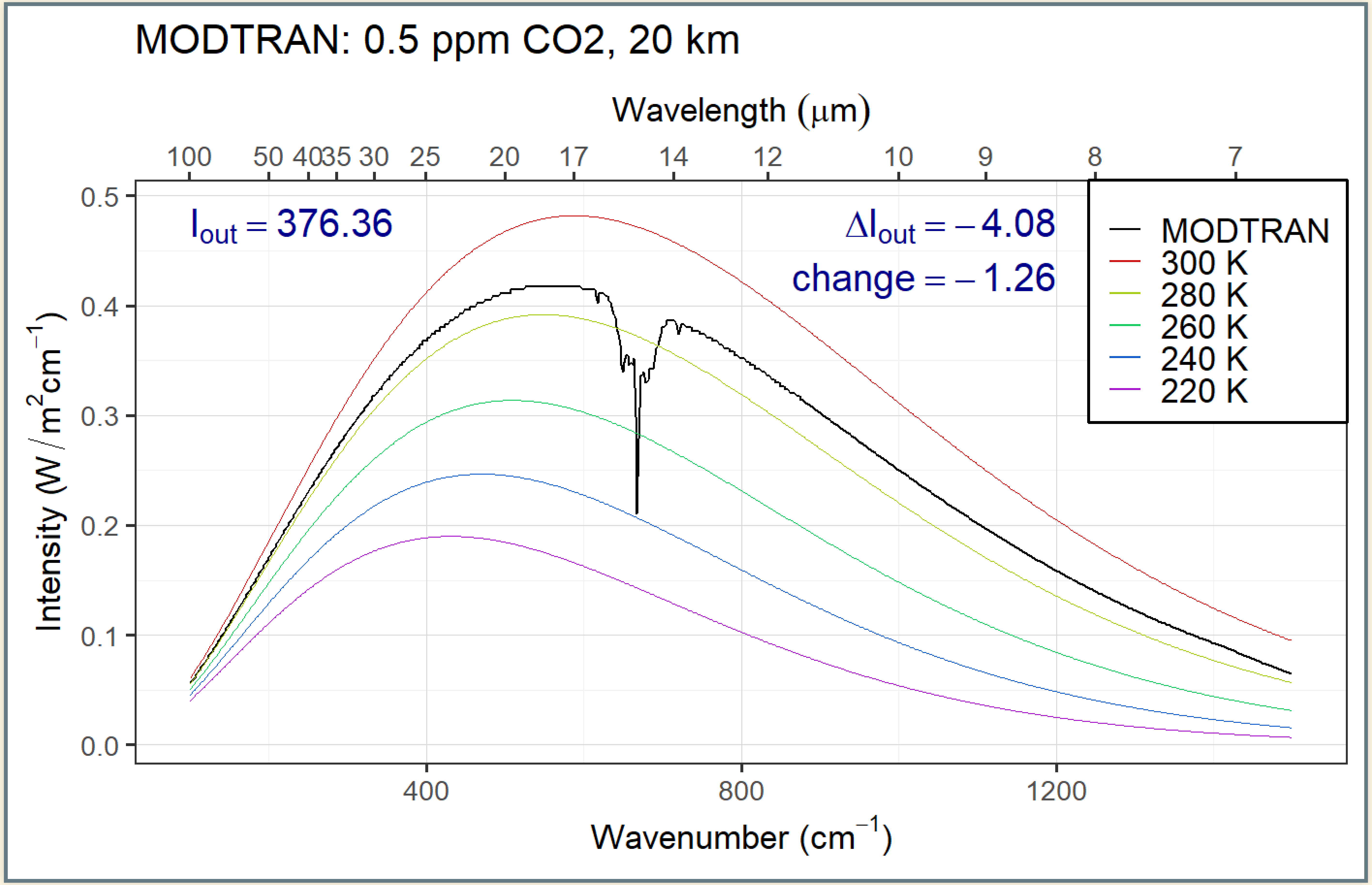

MODTRAN: 0 ppm CO2, 20 km
Wavelength (μm)
100 50 40 35 30 25 20 17 14 12 10 9 8 7
$I_{out} = 380.45$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W/m^2cm^{-1})
0.0 0.1 0.2 0.3 0.4 0.5
400 800 1200
Wavenumber (cm^{-1})

0.25 ppm CO_2

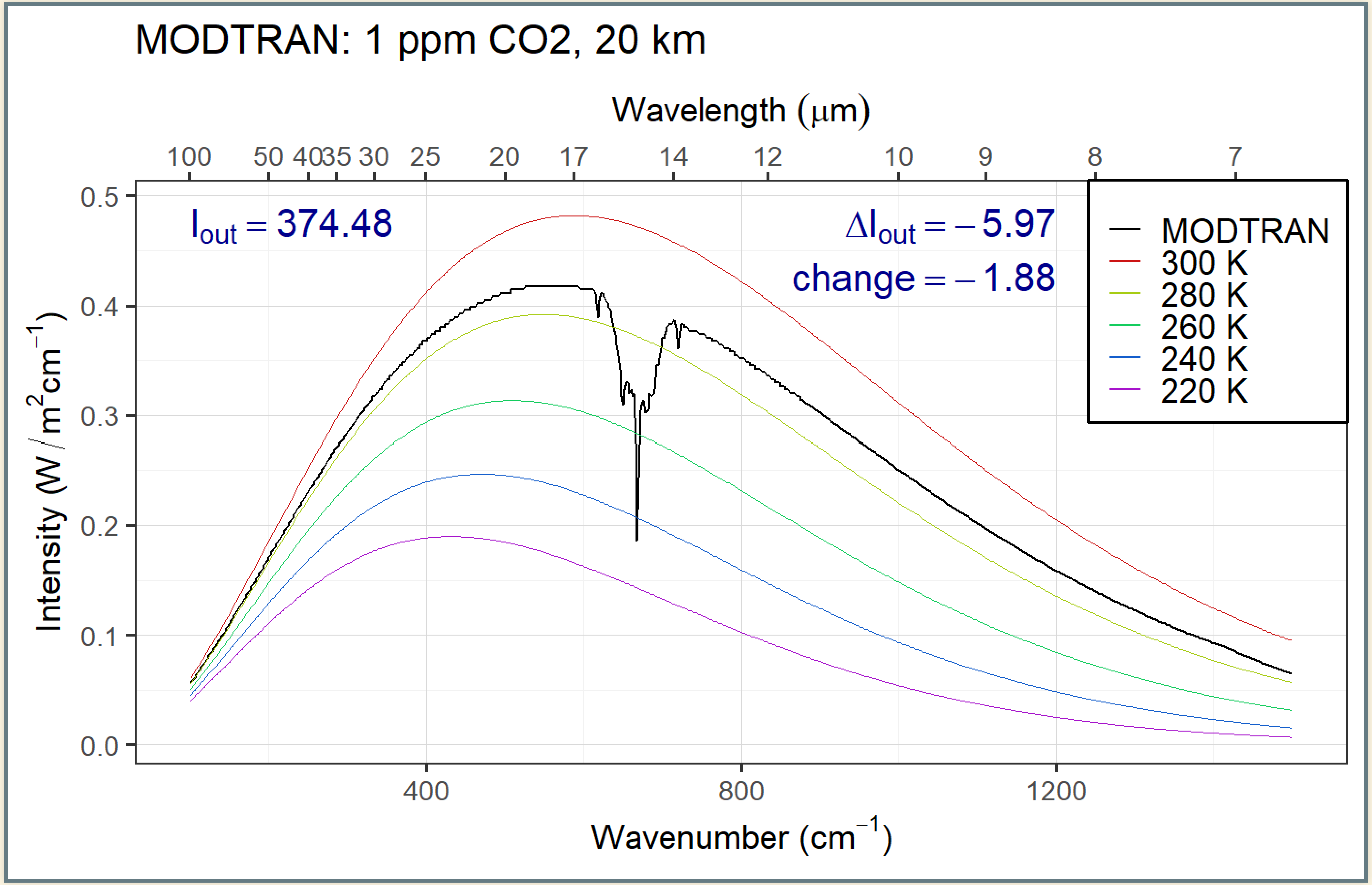


MODTRAN: 0.25 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 377.62$
$\Delta I_{out} = -2.83$
$change = -2.83$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity $(W/m^2 cm^{-1})$
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

0.5 ppm CO_2

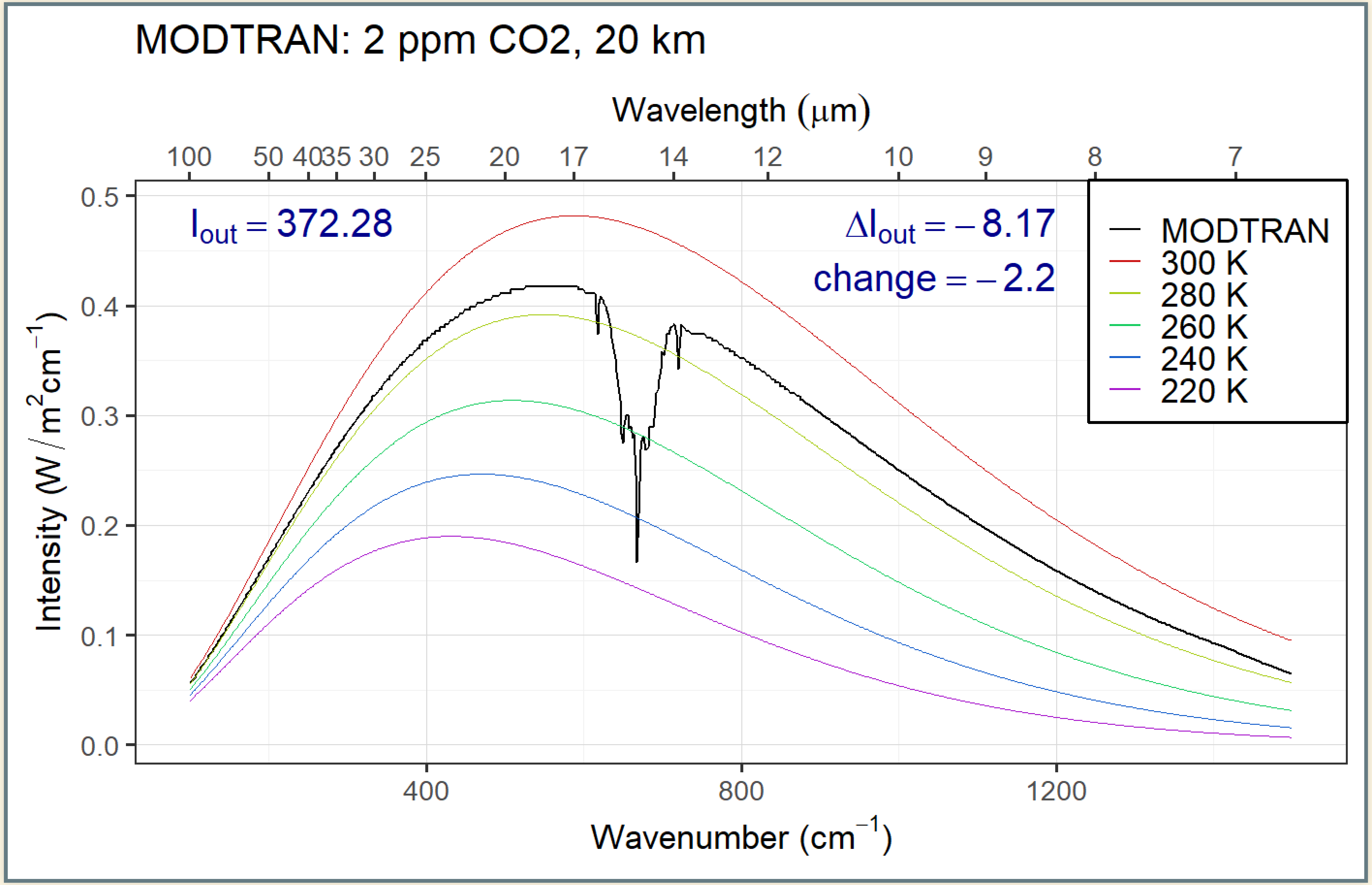

MODTRAN: 0.5 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 376.36$
$\Delta I_{out} = -4.08$
change = −1.26
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m²cm⁻¹)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm⁻¹)

1 ppm CO_2



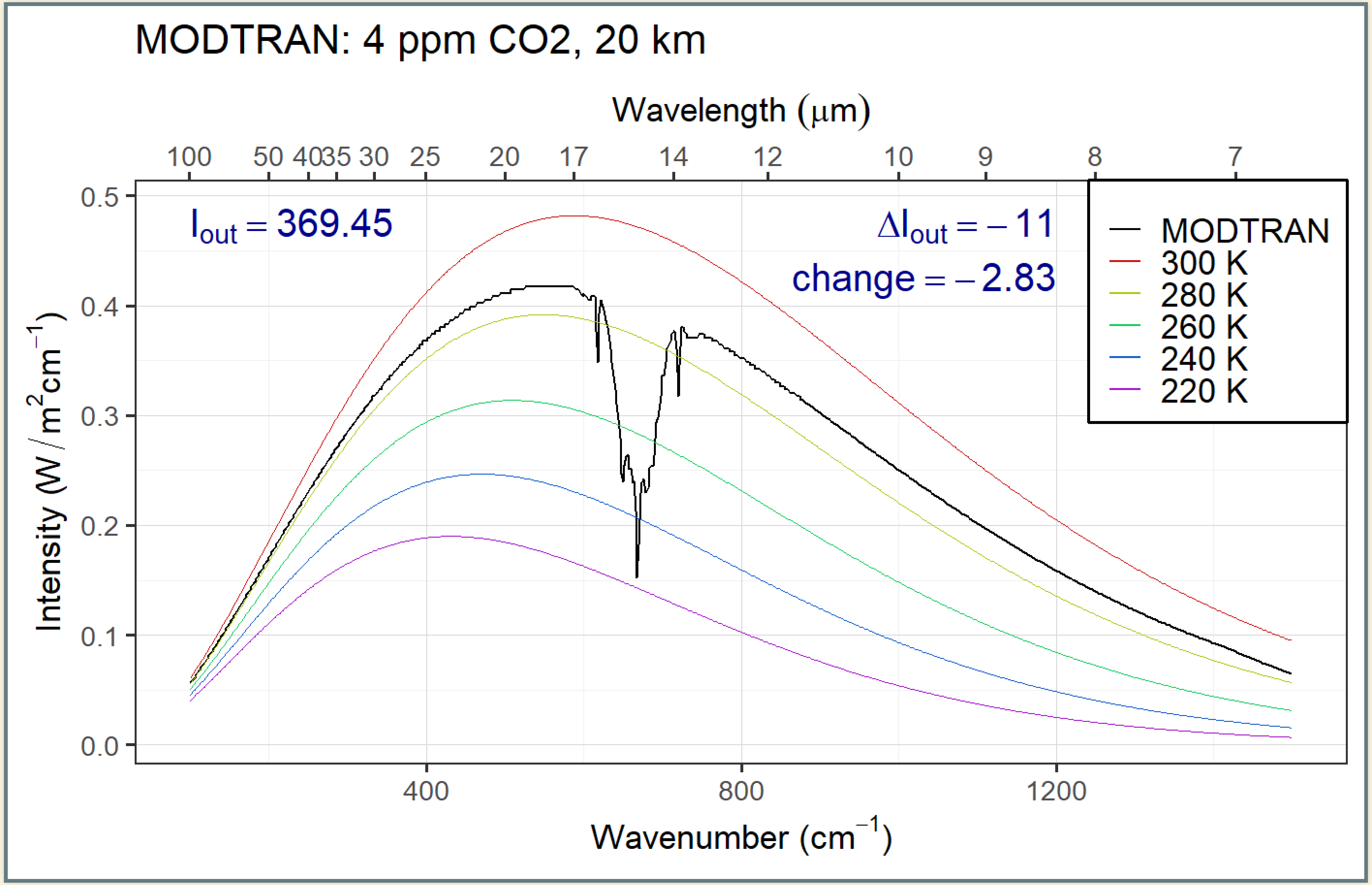
MODTRAN: 1 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
I_out = 374.48
ΔI_out = −5.97
change = −1.88
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm⁻¹)

2 ppm CO_2



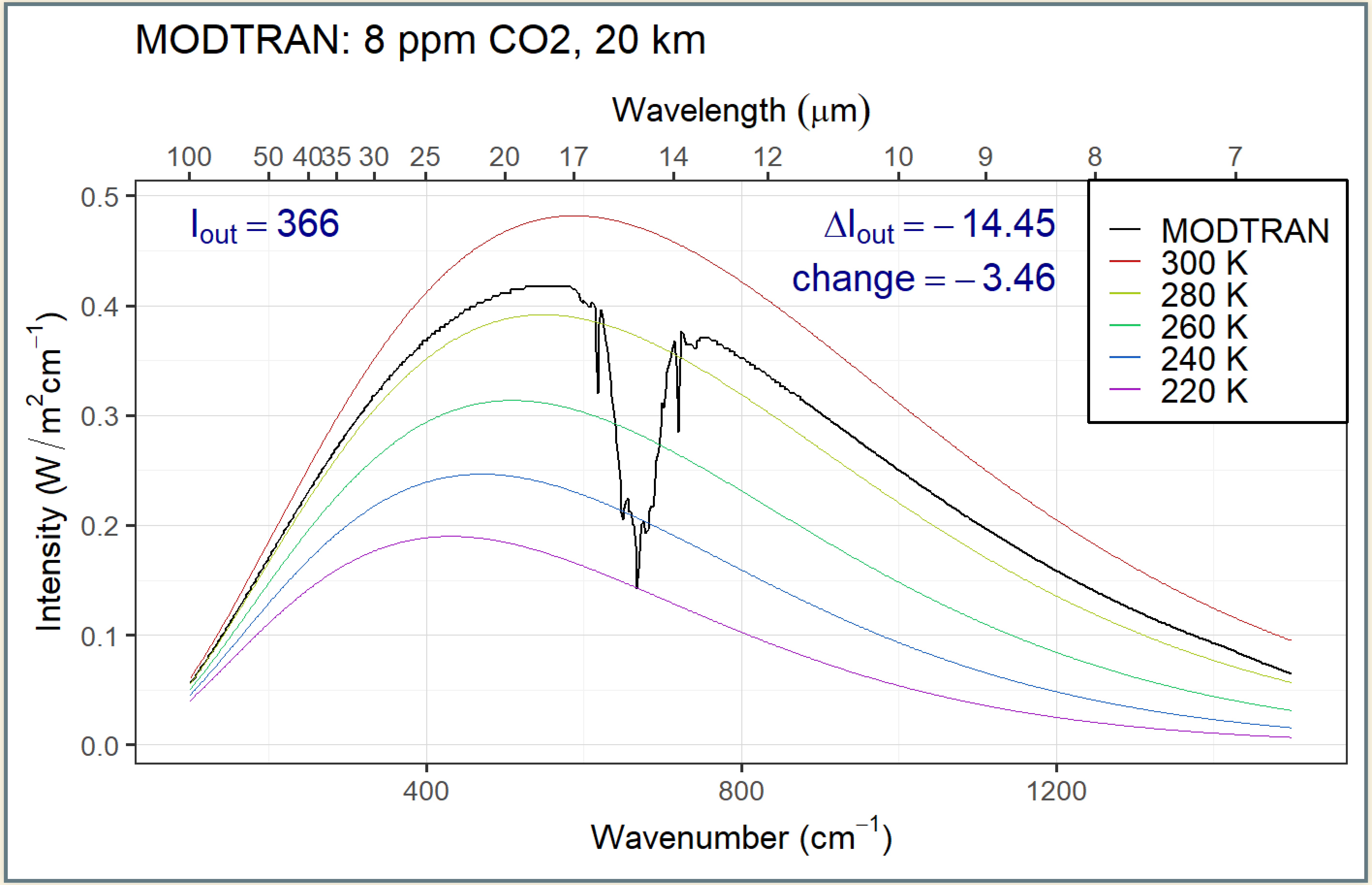
MODTRAN: 2 ppm CO2, 20 km
Wavelength (μm)
100 50 40 35 30 25 20 17 14 12 10 9 8 7
$I_{out} = 372.28$
$\Delta I_{out} = -8.17$
change = −2.2
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W/m^2cm^{-1})
0.0 0.1 0.2 0.3 0.4 0.5
400 800 1200
Wavenumber (cm^{-1})

4 ppm CO_2



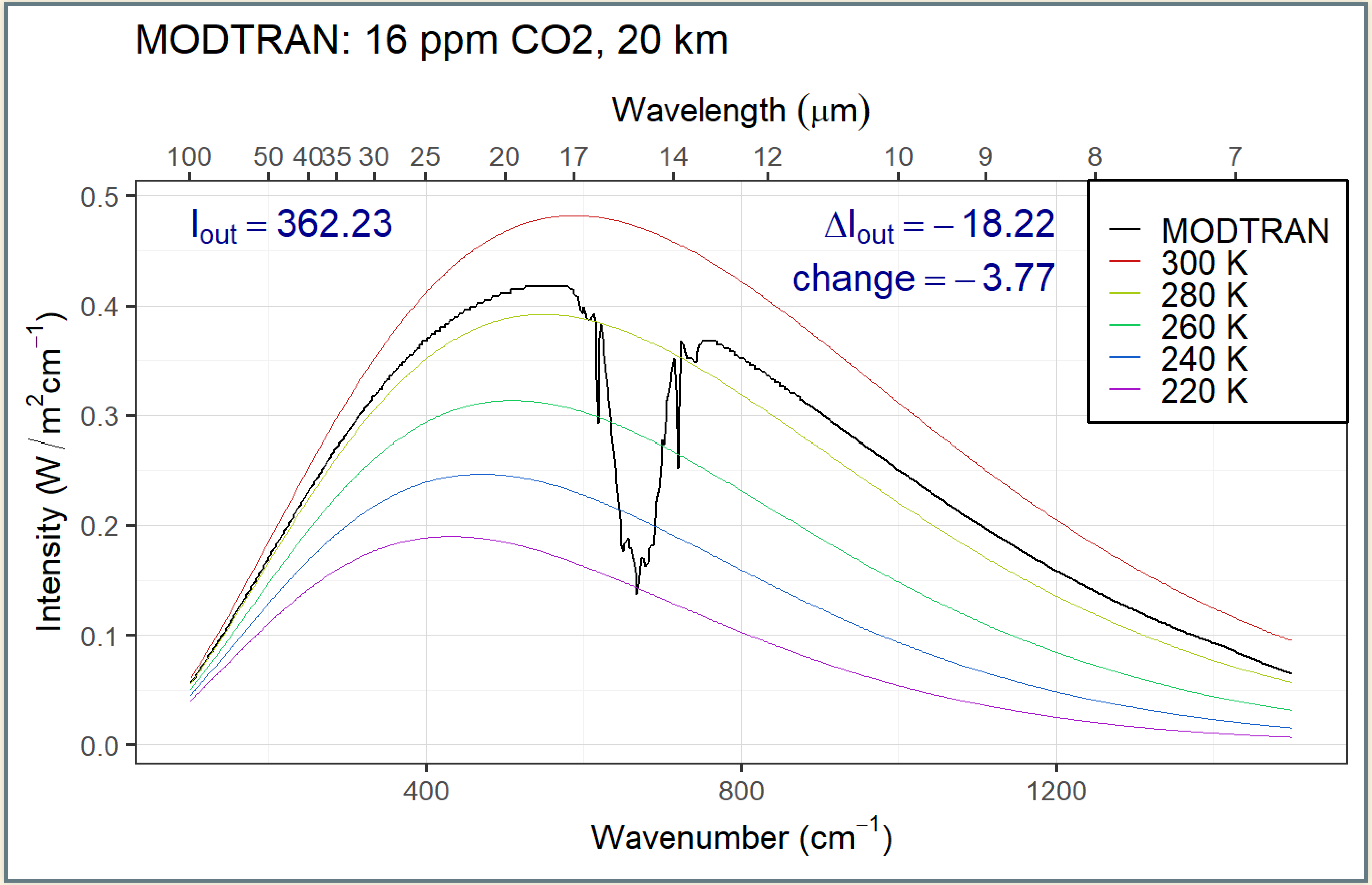
MODTRAN: 4 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 369.45$
$\Delta I_{out} = -11$
change = −2.83
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m²cm⁻¹)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm⁻¹)

8 ppm CO_2



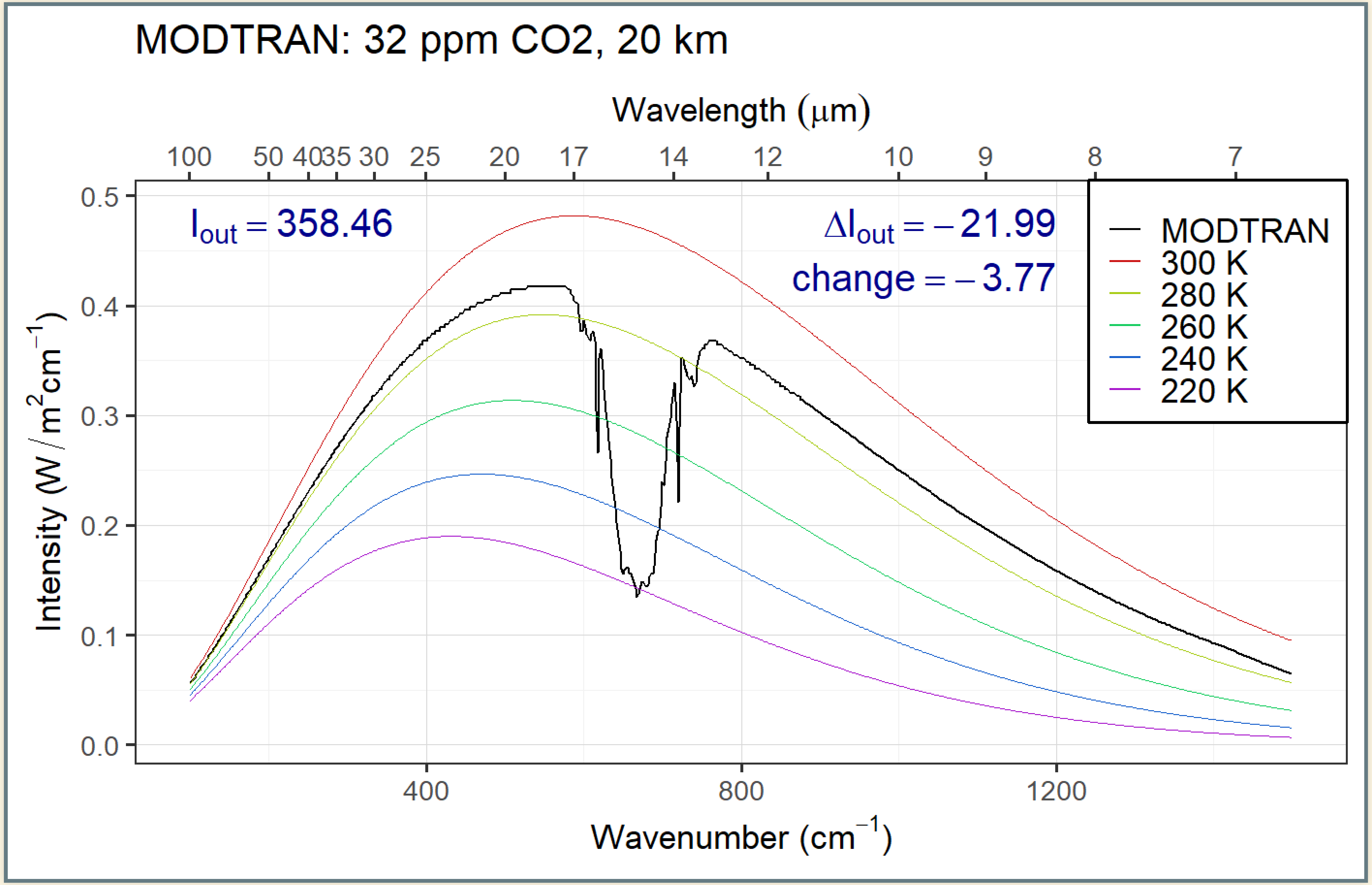
MODTRAN: 8 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 366$
$\Delta I_{out} = -14.45$
change = −3.46
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m²cm⁻¹)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm⁻¹)

16 ppm CO_2



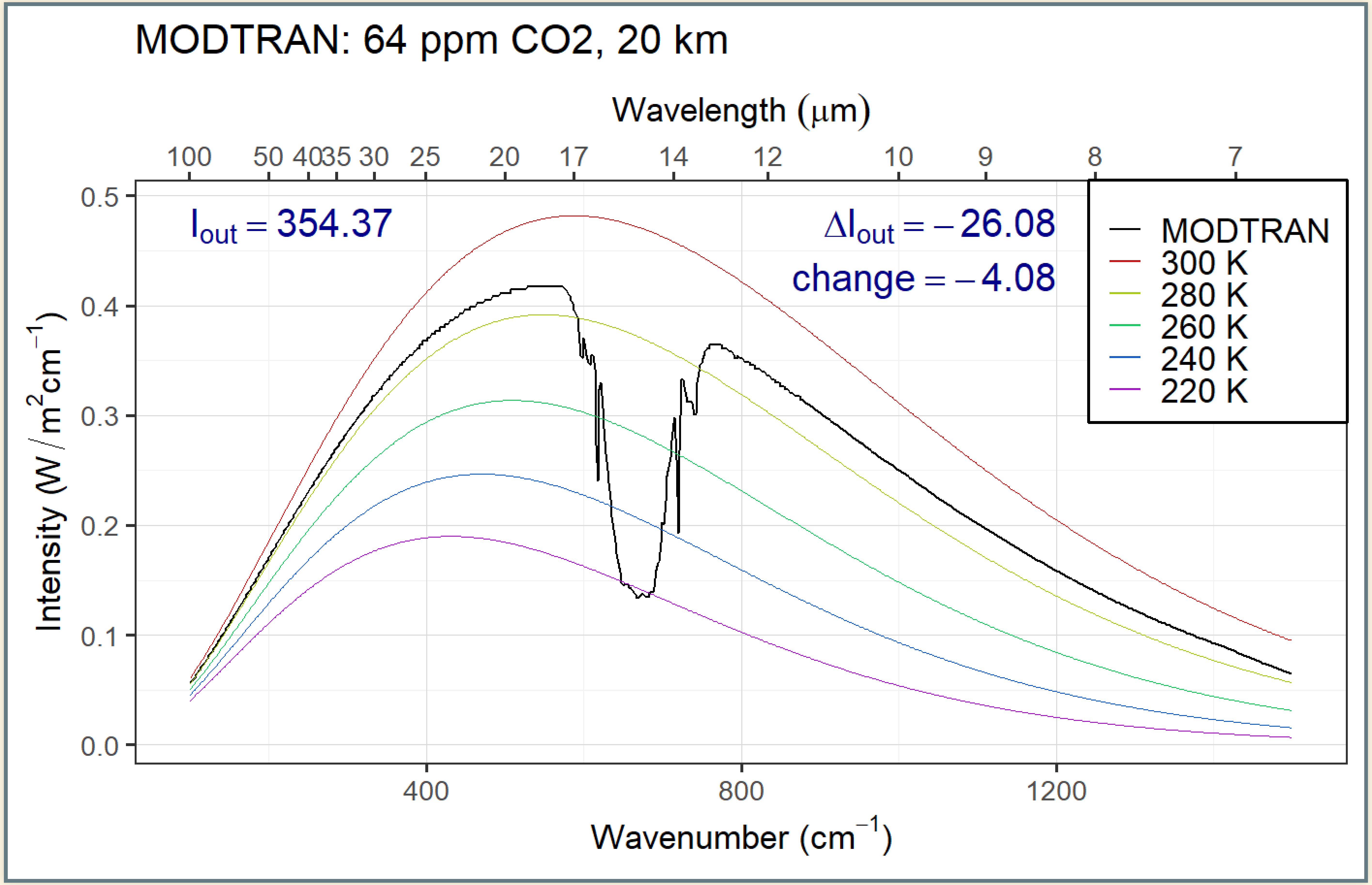
MODTRAN: 16 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 362.23$
$\Delta I_{out} = -18.22$
change = −3.77
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W / m^2 cm^{-1}$)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

32 ppm CO_2

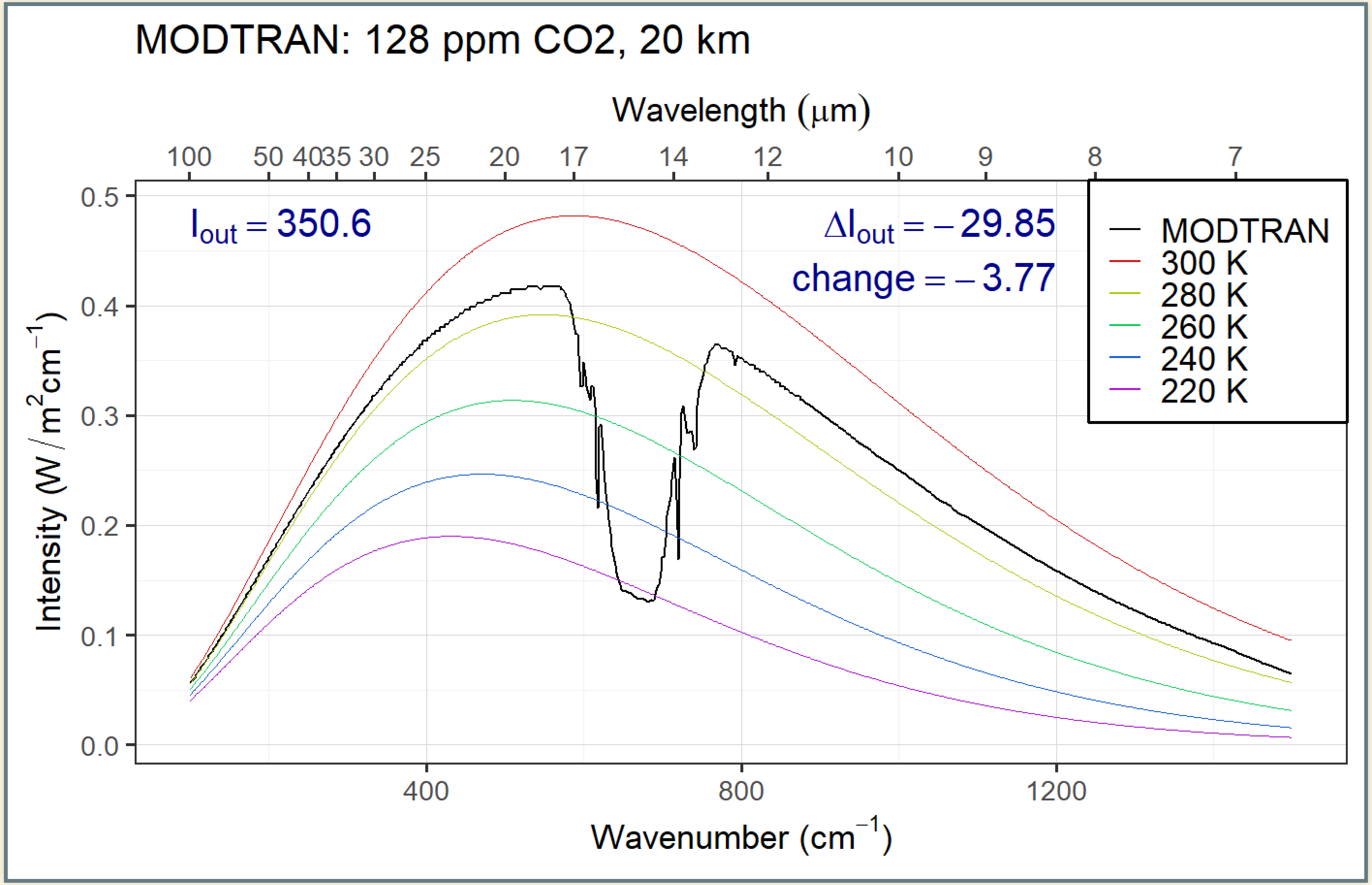


MODTRAN: 32 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 358.46$
$\Delta I_{out} = -21.99$
$change = -3.77$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W / m^2 cm^{-1}$)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

64 ppm CO_2

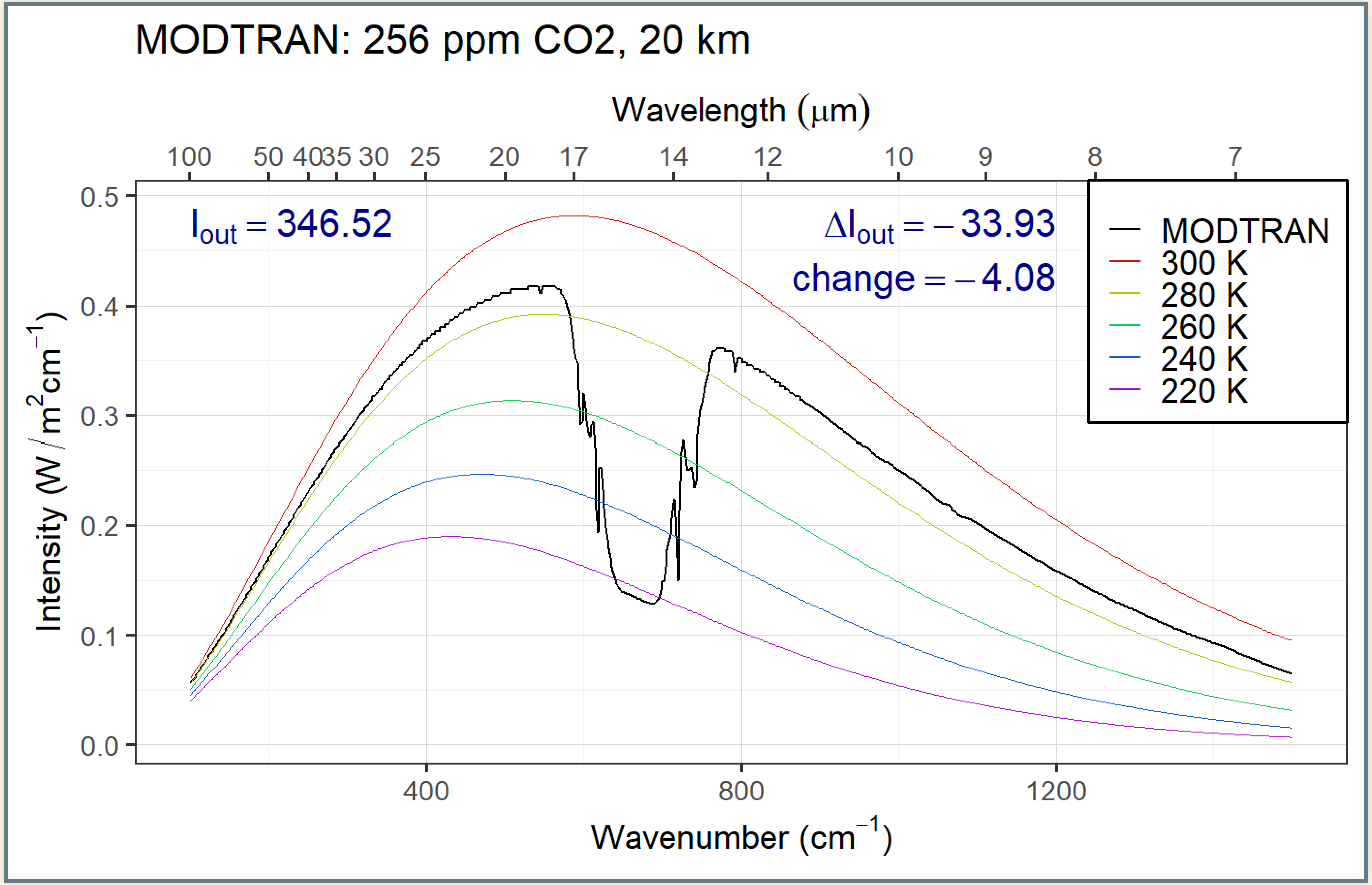

MODTRAN: 64 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 354.37$
$\Delta I_{out} = -26.08$
change = −4.08
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W/m^2cm^{-1})
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

128 ppm CO_2



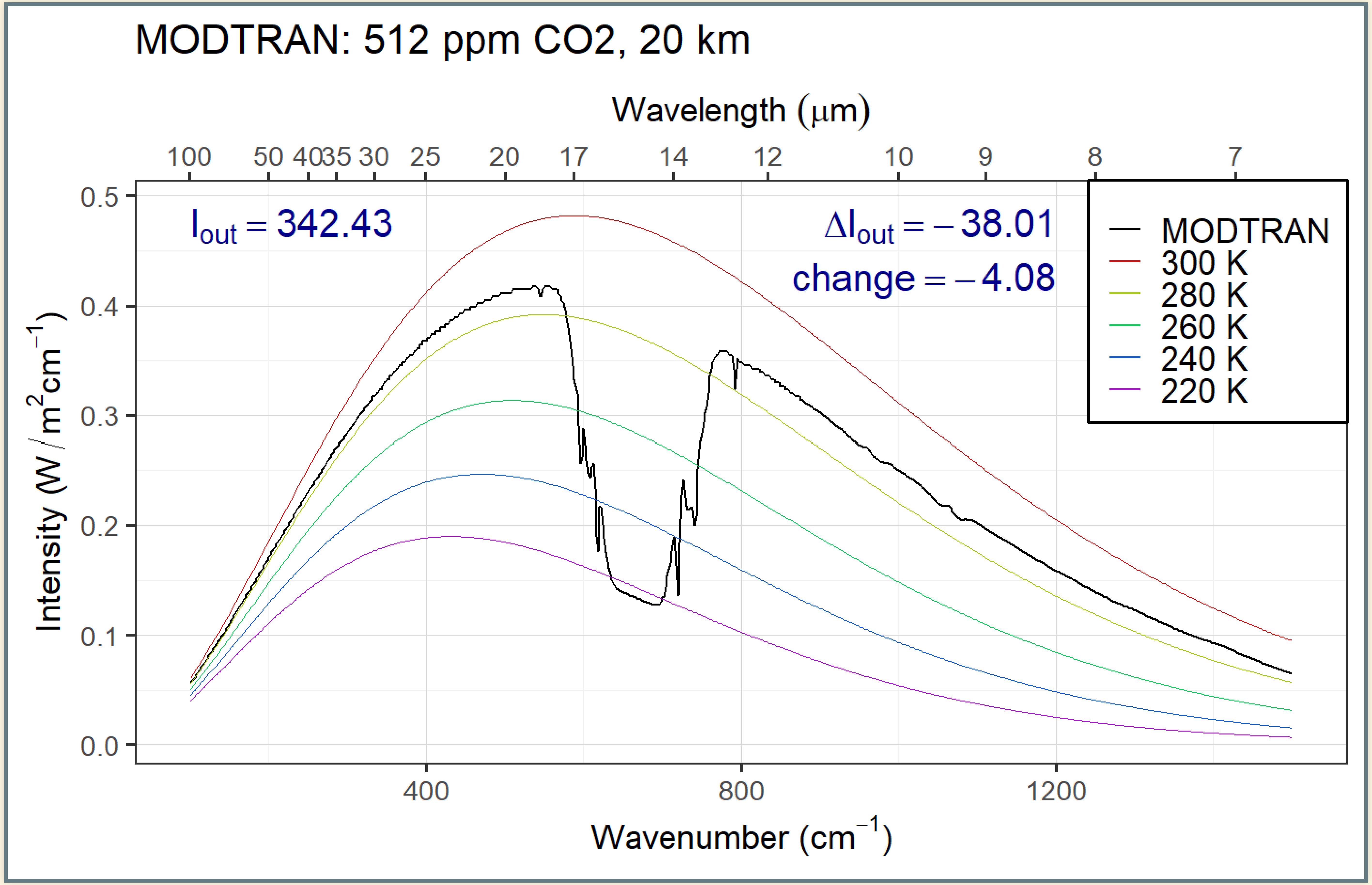
MODTRAN: 128 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 350.6$
$\Delta I_{out} = -29.85$
change = −3.77
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m²cm⁻¹)
0.0
0.1
0.2
0.3
0.4
0.5
400
800
1200
Wavenumber (cm⁻¹)

256 ppm CO_2

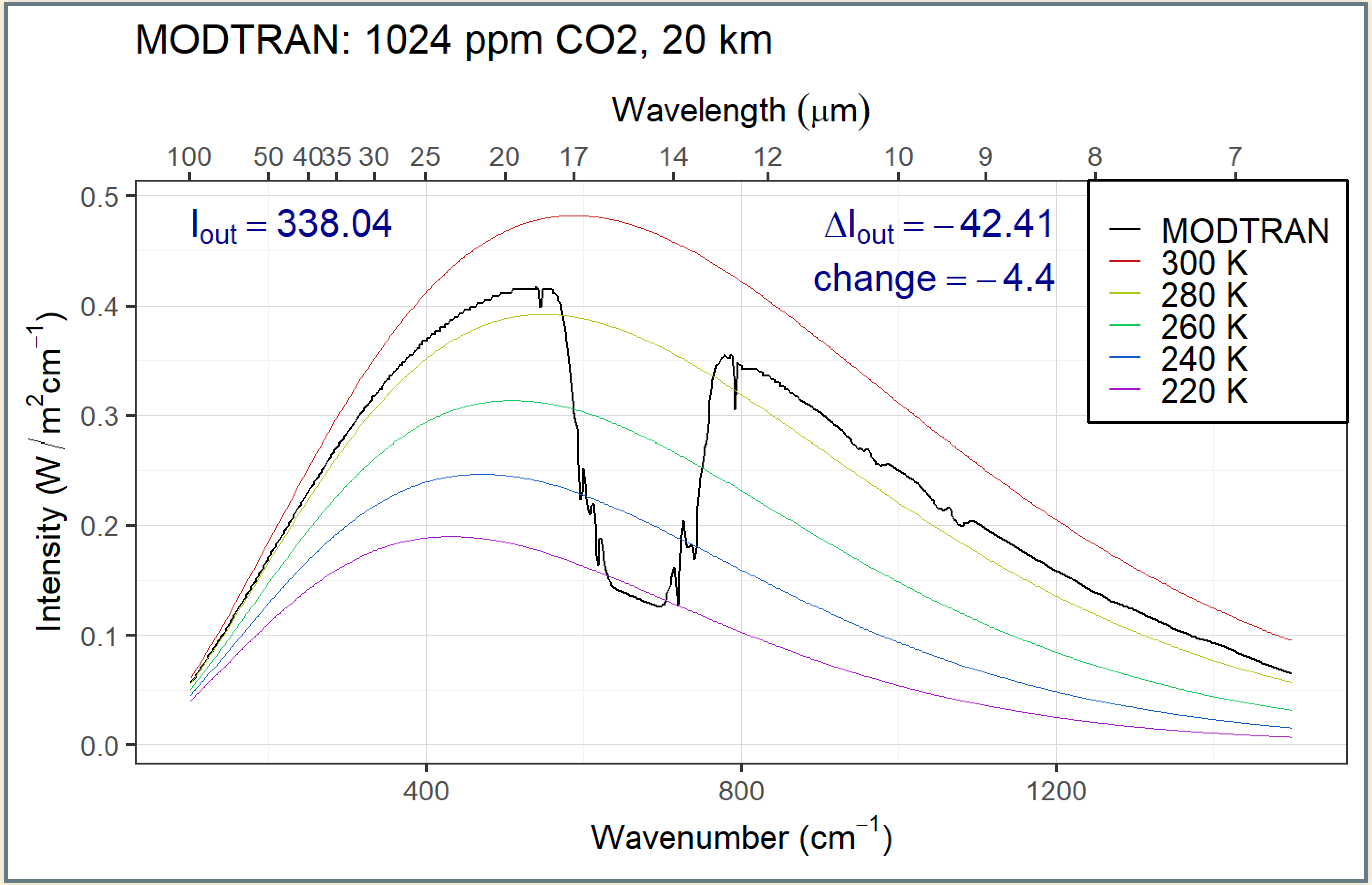


MODTRAN: 256 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 346.52$
$\Delta I_{out} = -33.93$
$change = -4.08$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m²cm⁻¹)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm⁻¹)

512 ppm CO_2

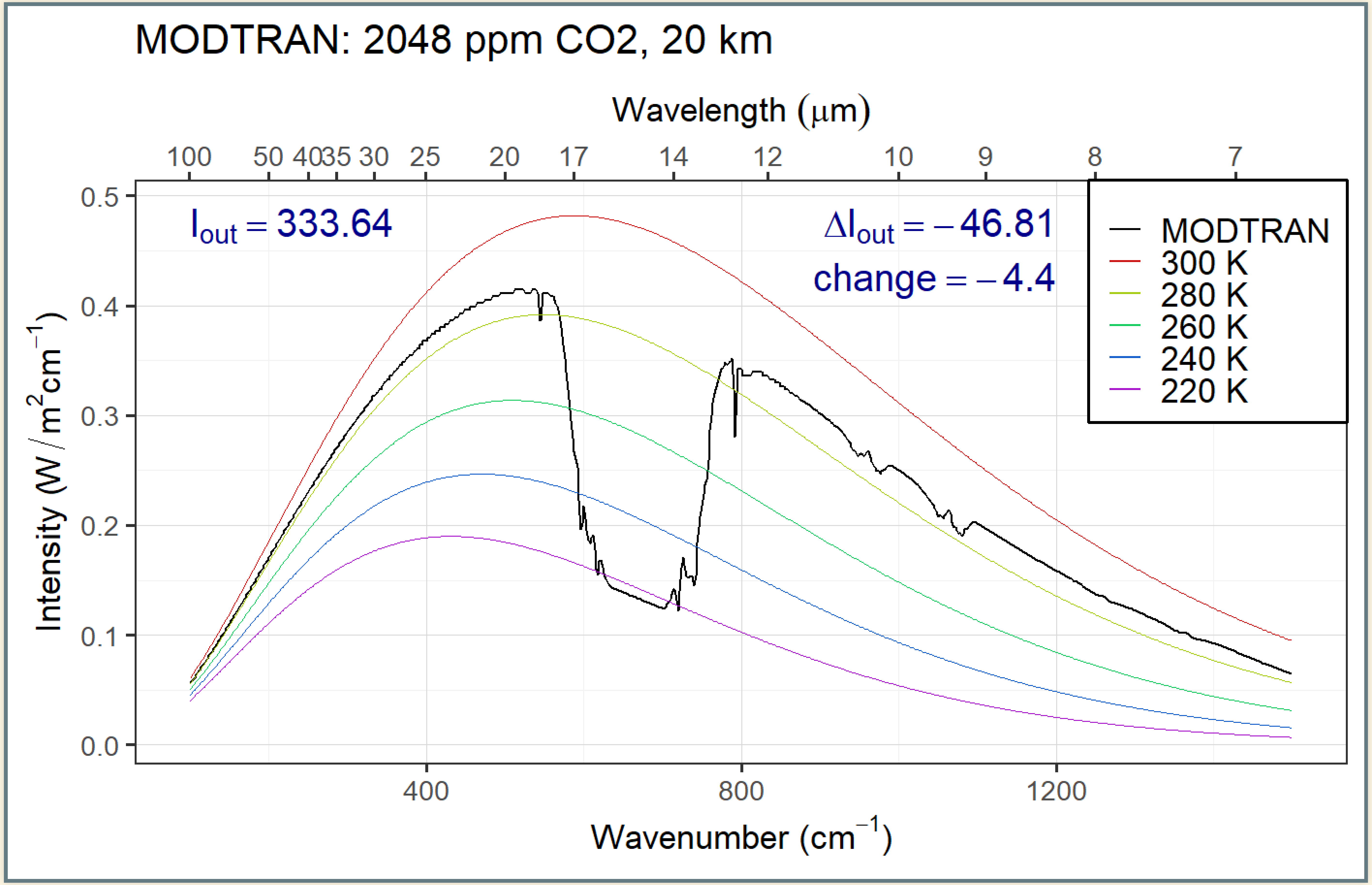

MODTRAN: 512 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 342.43$
$\Delta I_{out} = -38.01$
$\text{change} = -4.08$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W/m^2cm^{-1})
0.0
0.1
0.2
0.3
0.4
0.5
400
800
1200
Wavenumber (cm^{-1})

1024 ppm CO_2



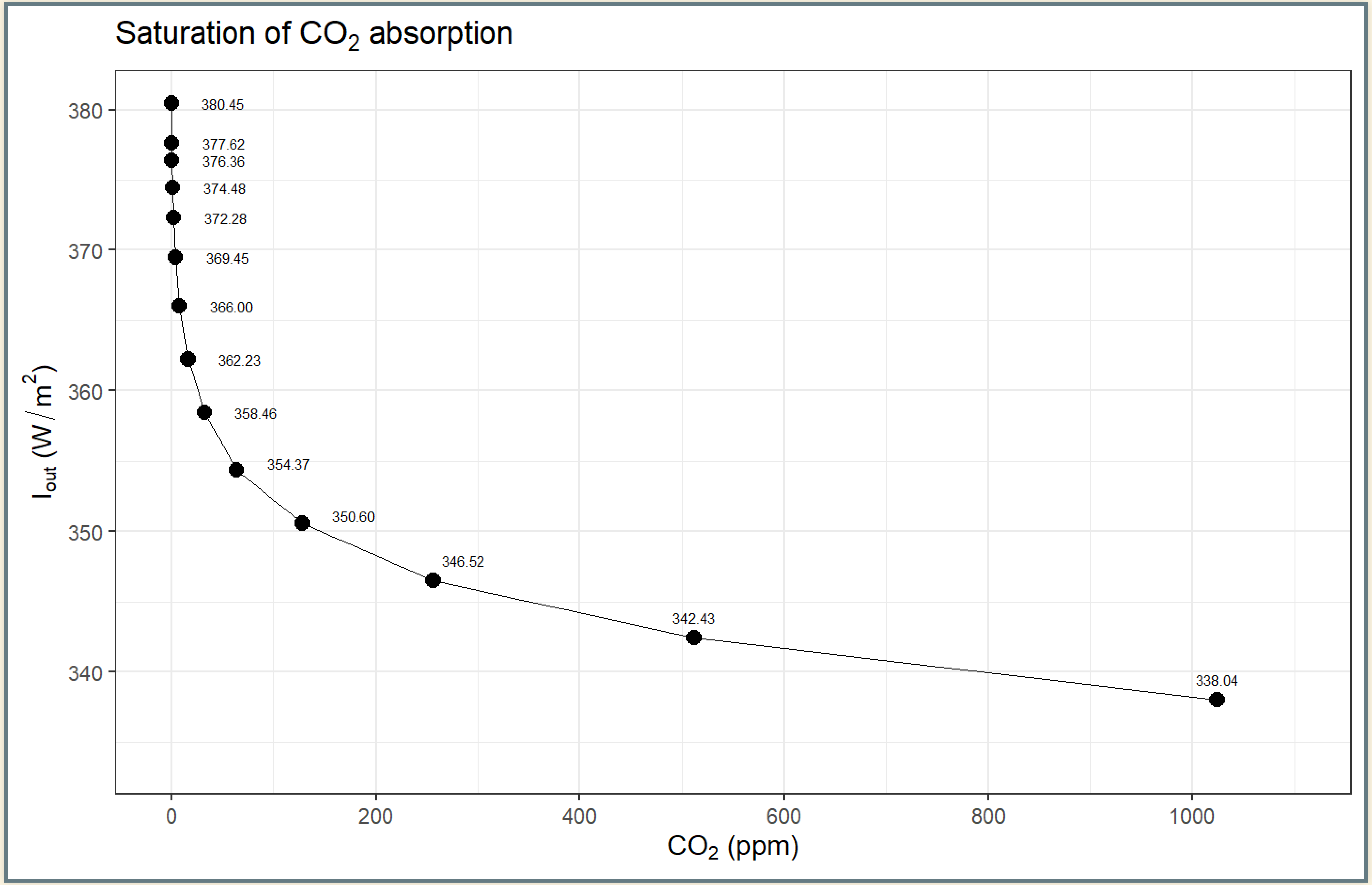
MODTRAN: 1024 ppm CO2, 20 km
Wavelength (μm)
100 50 40 35 30 25 20 17 14 12 10 9 8 7
$I_{out} = 338.04$
$\Delta I_{out} = -42.41$
change = −4.4
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m²cm⁻¹)
0.0 0.1 0.2 0.3 0.4 0.5
400 800 1200
Wavenumber (cm⁻¹)

2048 ppm CO_2

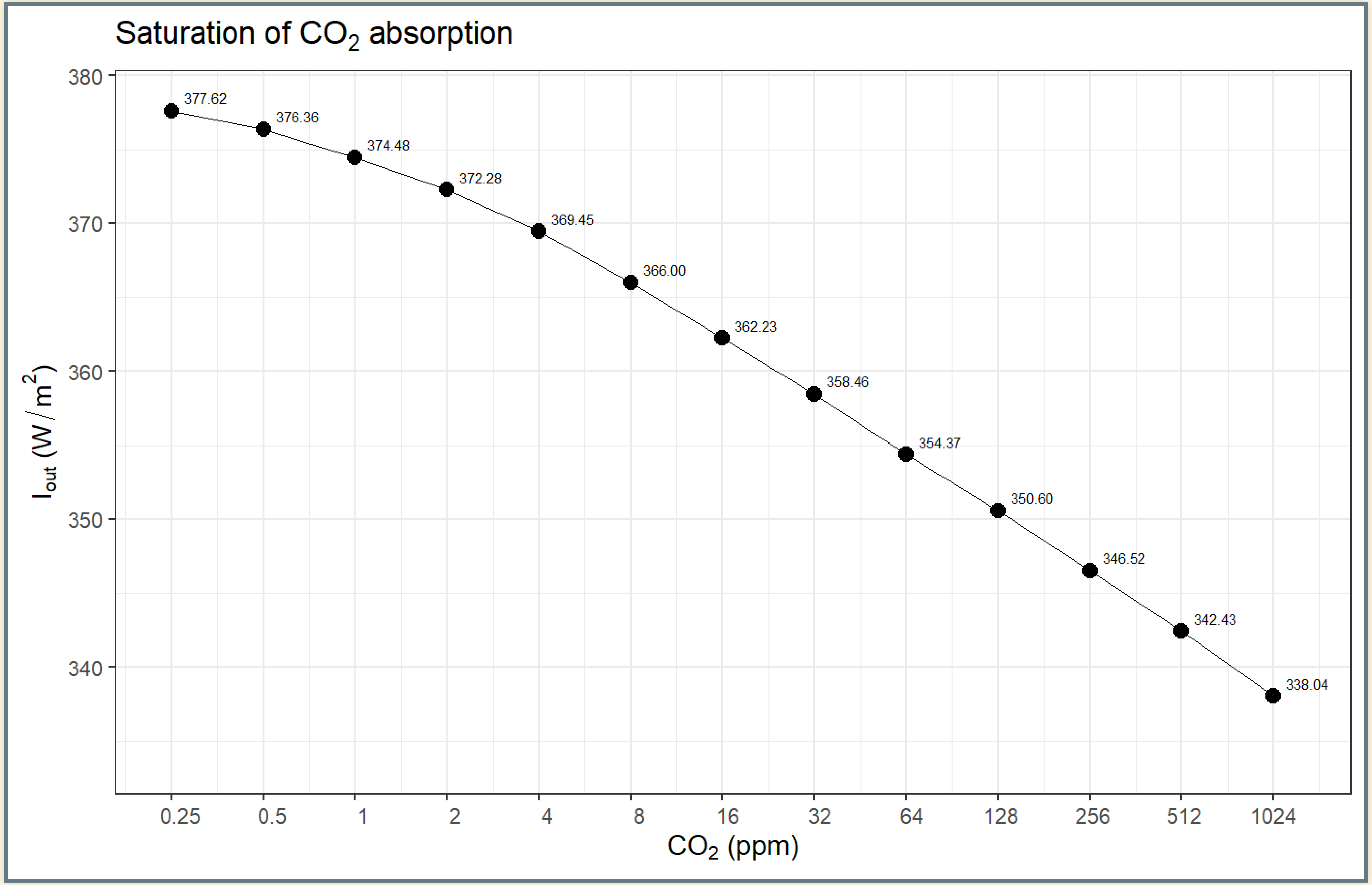


MODTRAN: 2048 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 333.64$
$\Delta I_{out} = -46.81$
$change = -4.4$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W/m^2cm^{-1})
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

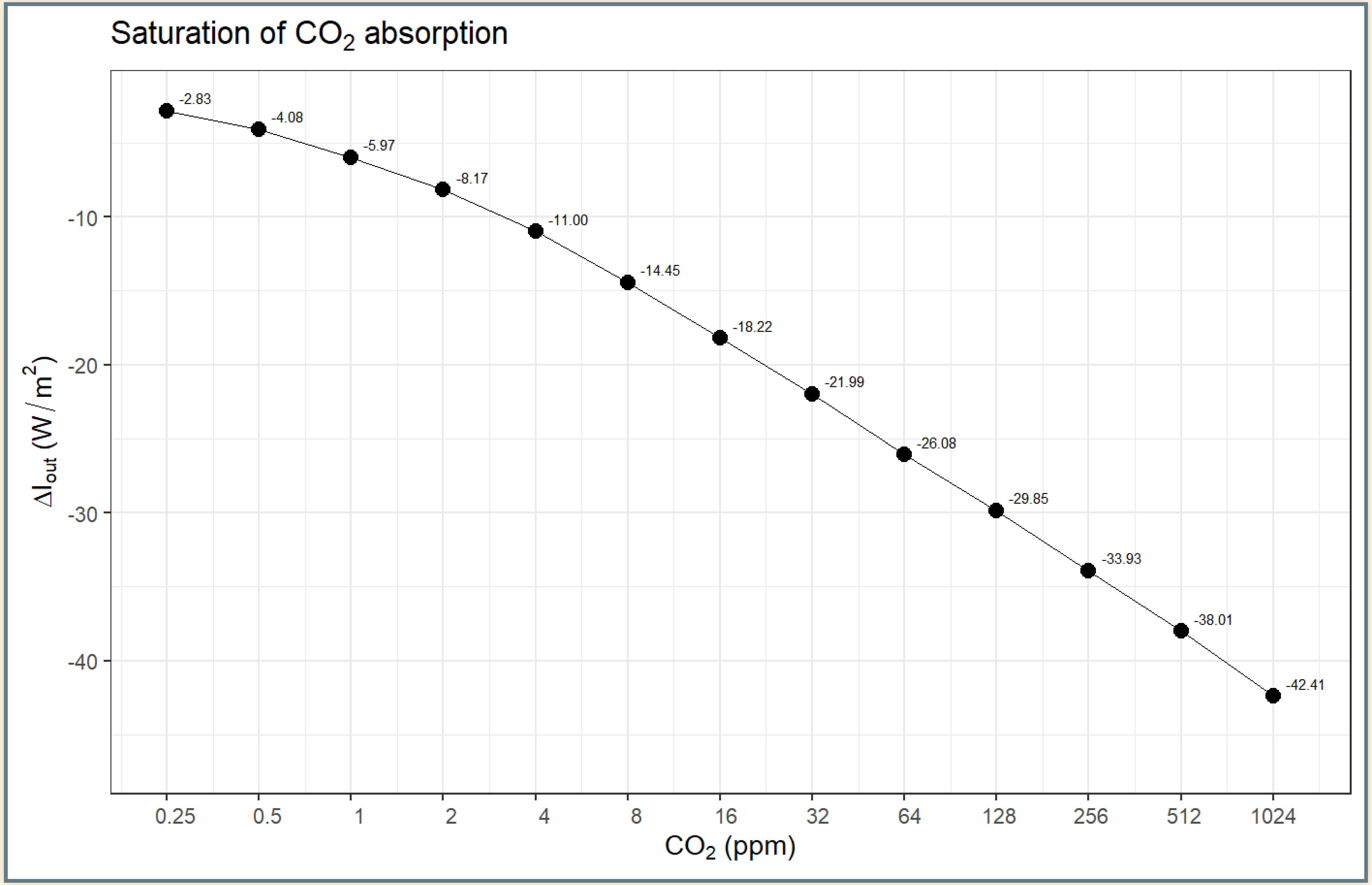
Band Saturation (I_{out})



I_{out} (CO_2 on log scale)



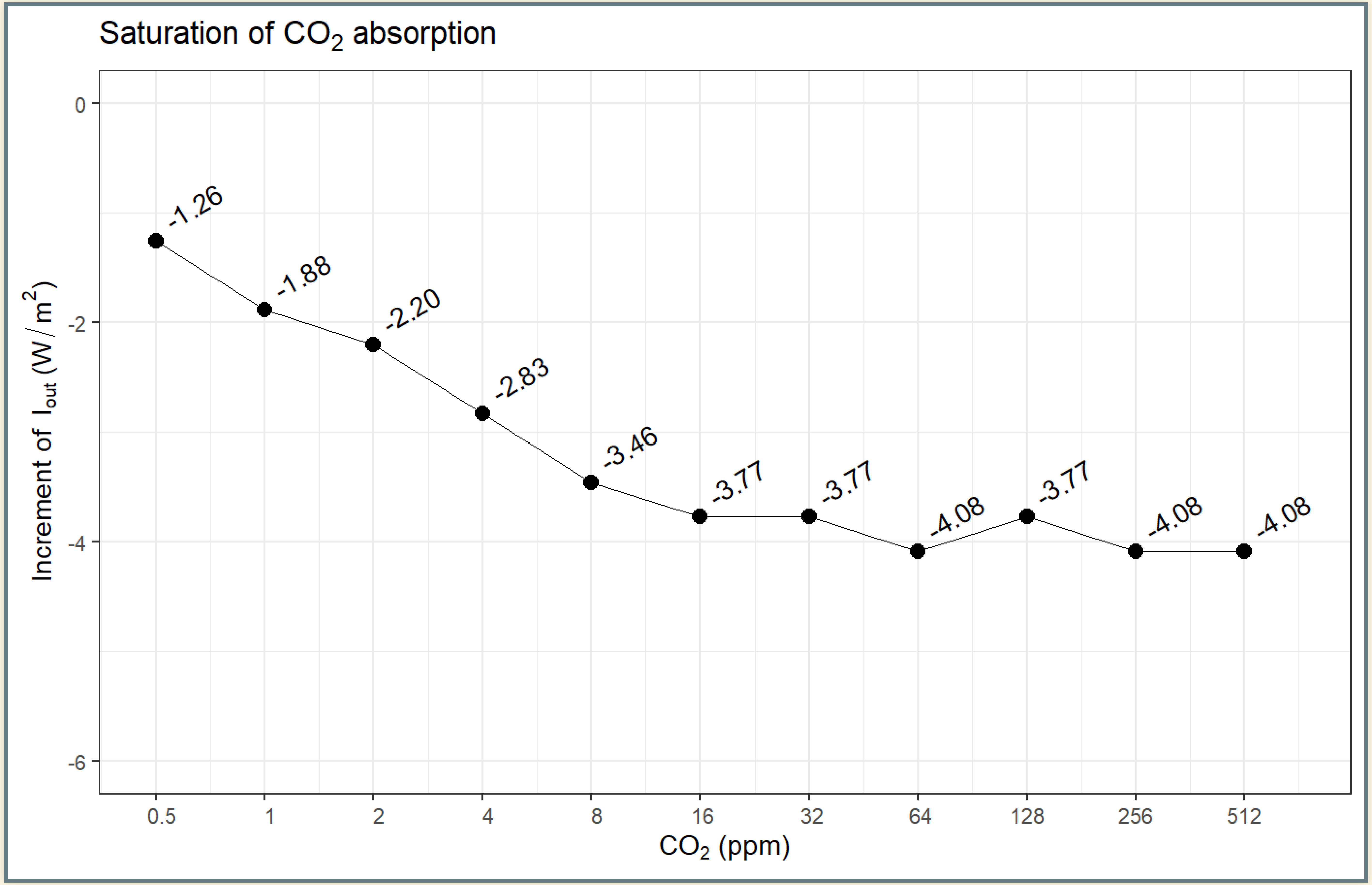
ΔI_{out}



Saturation of CO2 absorption
-2.83
-4.08
-5.97
-8.17
-11.00
-14.45
-18.22
-21.99
-26.08
-29.85
-33.93
-38.01
-42.41
-10
-20
-30
-40
ΔIout (W / m2)
0.25
0.5
1
2
4
8
16
32
64
128
256
512
1024
CO2 (ppm)

Change in I_{out} from no CO_2

Increments of I_{out}



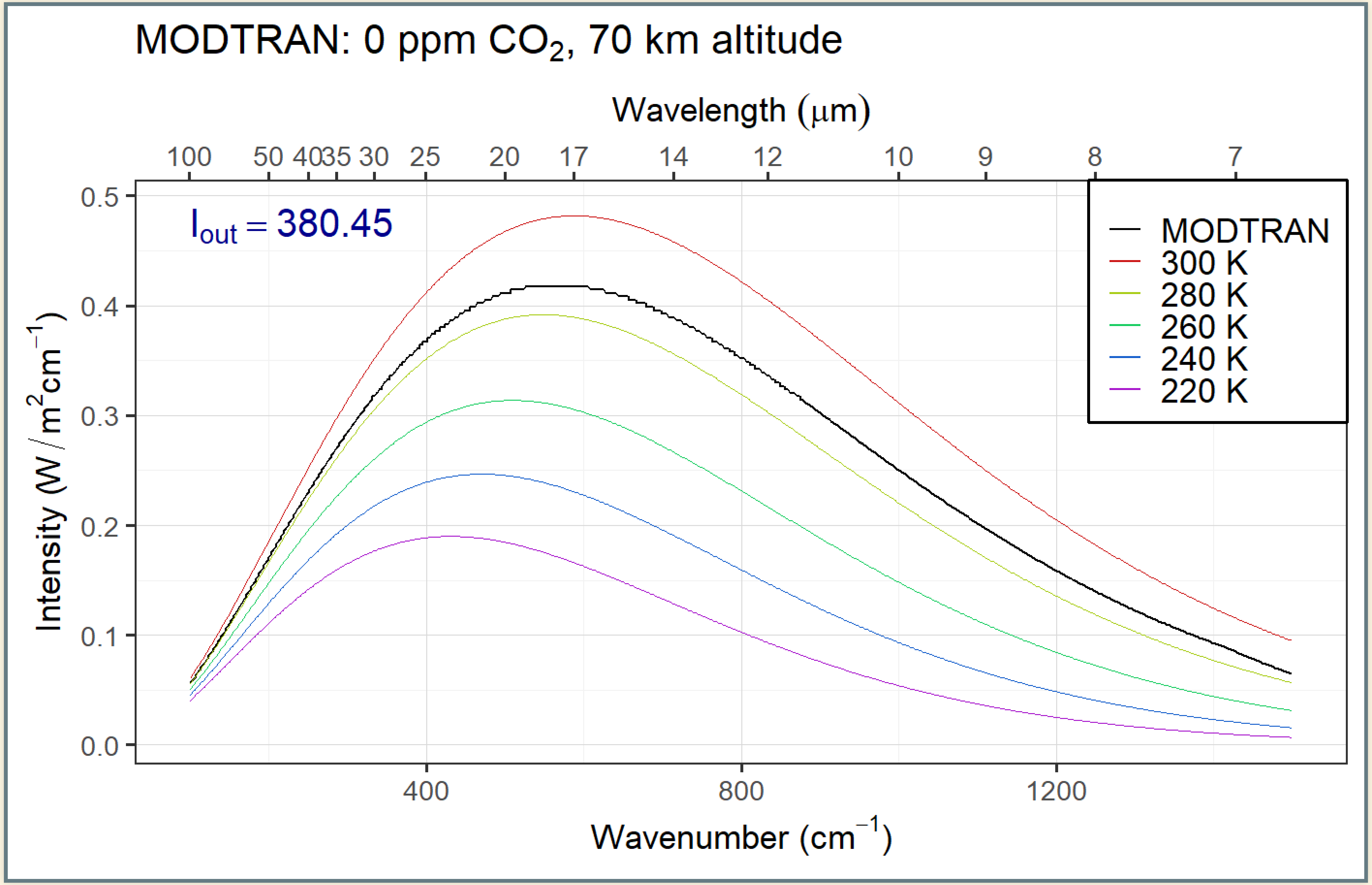
Change in I_{out} from previous I_{out}

Measuring Greenhouse Effect:

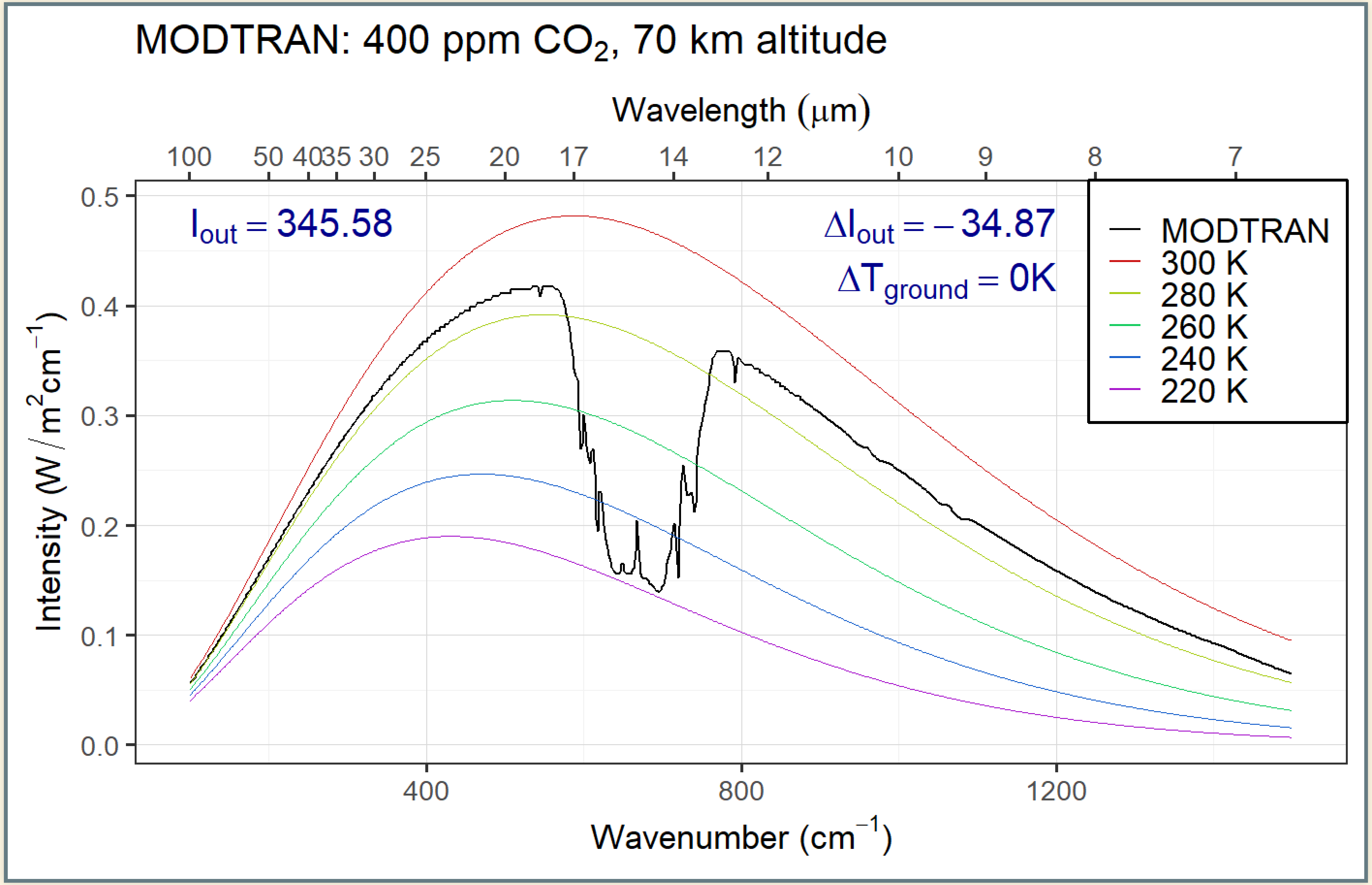
Measuring Greenhouse Effect:

- Go to MODTRAN, set CO_2 to 0 ppm, and set all other gases to zero.
- Set altitude to 70 km and location to “1976 US Standard 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.

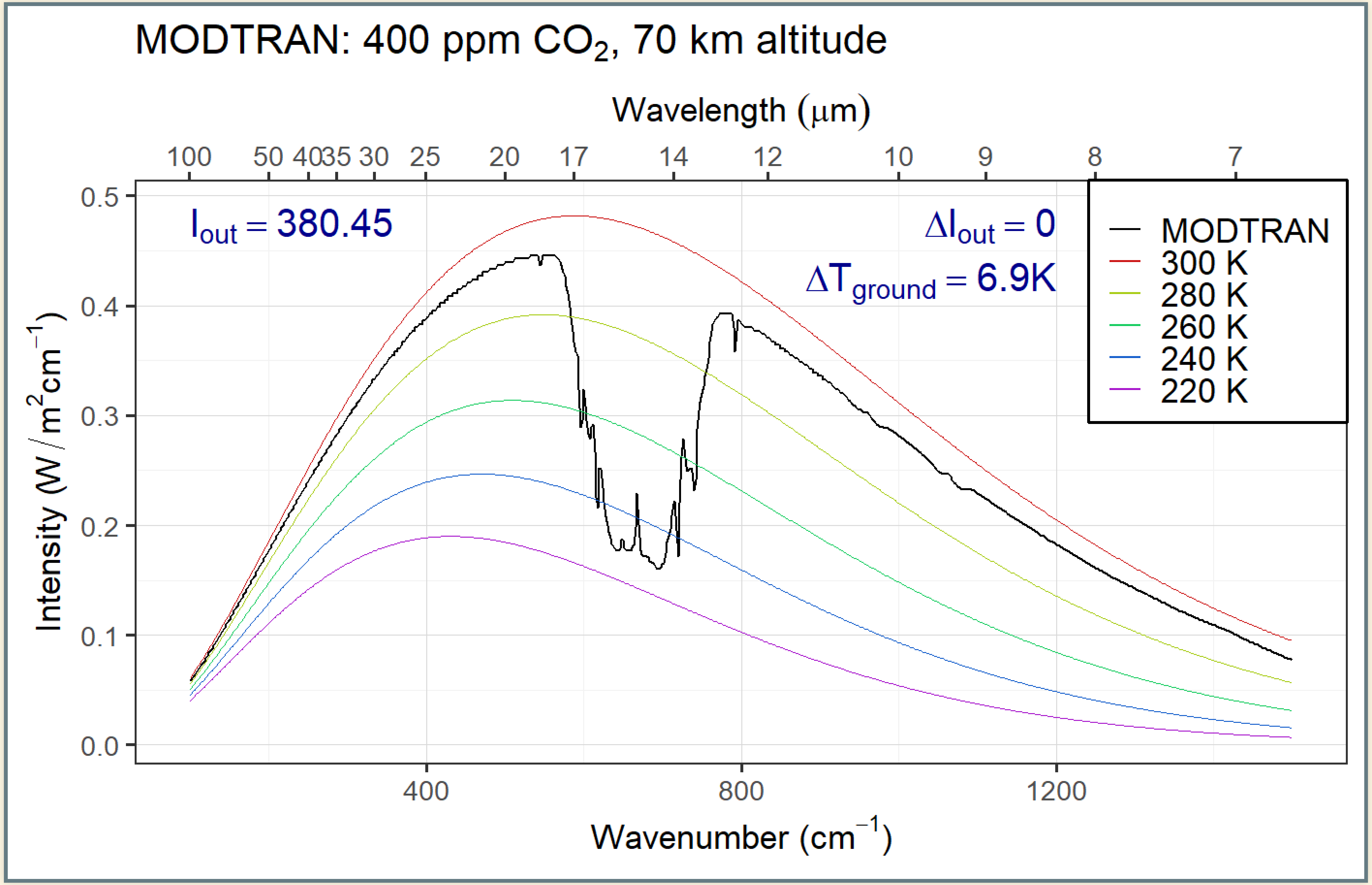
No Greenhouse Gases



400 ppm


MODTRAN: 400 ppm CO_2, 70 km altitude
Wavelength (μm)
100 50 40 35 30 25 20 17 14 12 10 9 8 7
$I_{out} = 345.58$
$\Delta I_{out} = -34.87$
$\Delta T_{ground} = 0K$
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})

Adjust temperature



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

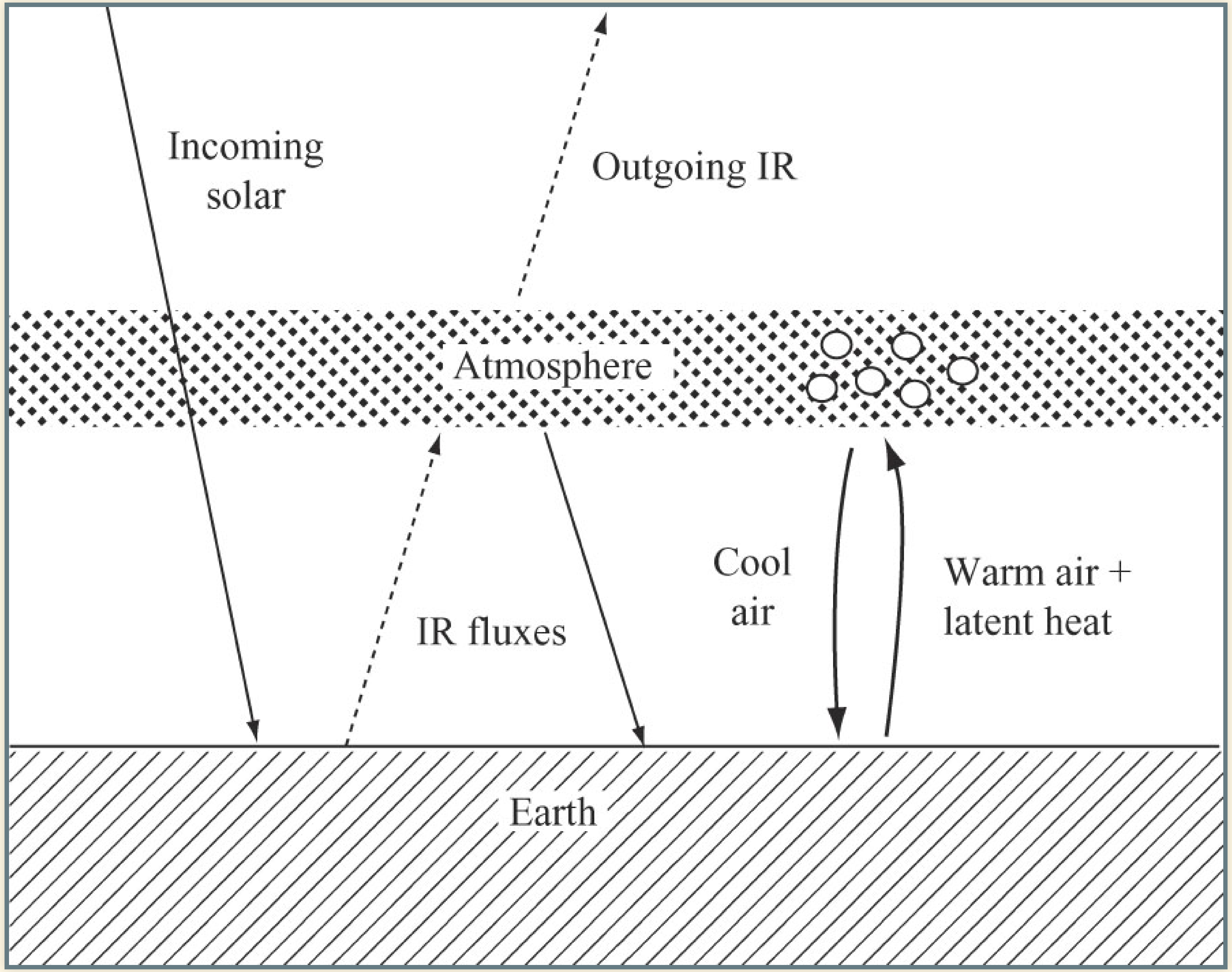
1. Purely radiative (no convection)
   - Each layer has uniform temperature
     a. Single-layer, uniform spectrum (Mon. 1/13)
        - Absorbs 100% longwave light
     b. Multi-layer, uniform spectrum (Lab #2)
        - More layers $\Rightarrow$ greater greenhouse effect.
     c. Realistic spectrum (Wed. 1/15 & today)
        - More realistic
        - Harder to do calculations (need computer)
2. Introduce convection (Today & Wednesday)
   - 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

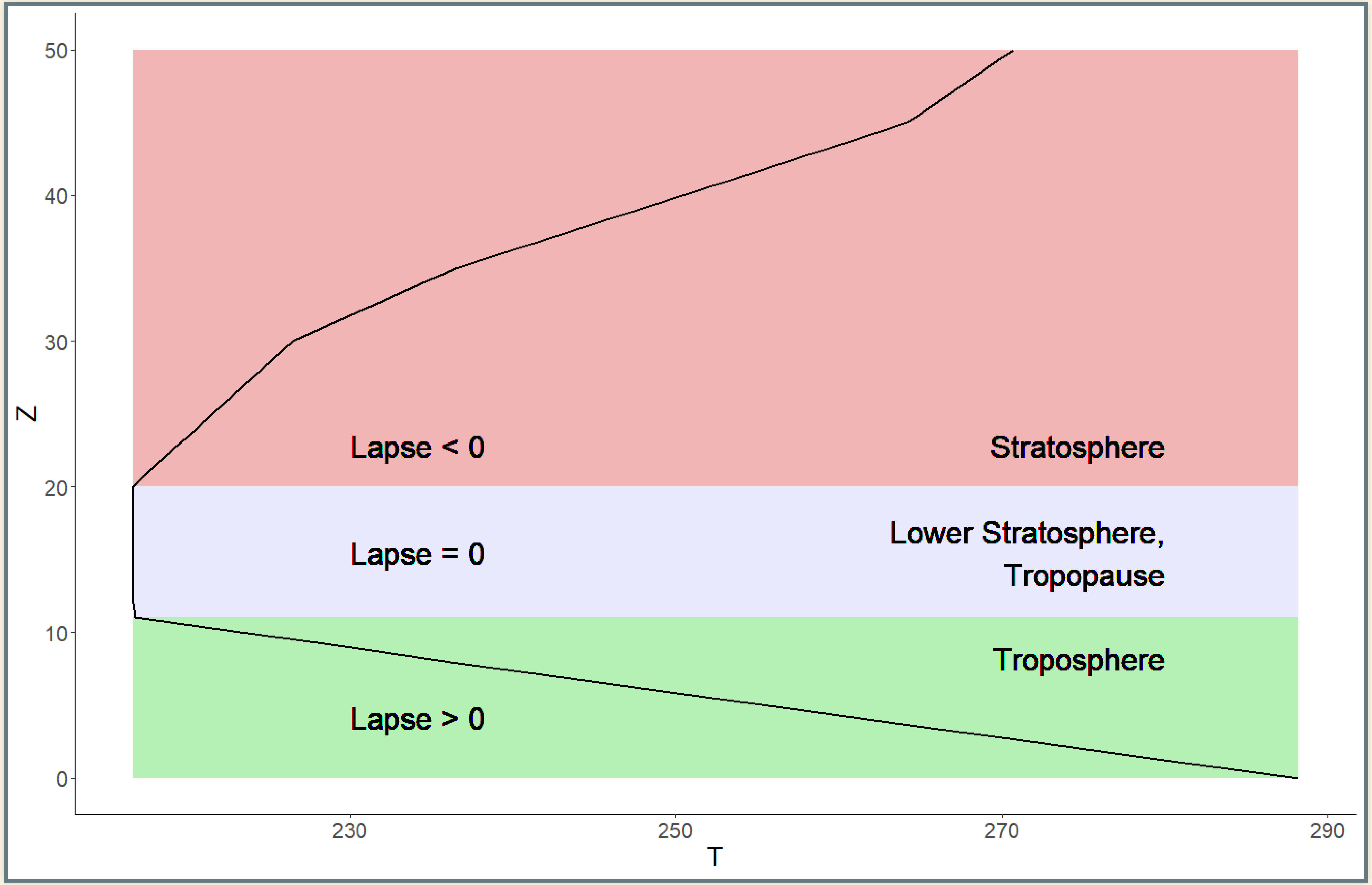
Greenhouse effect

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:

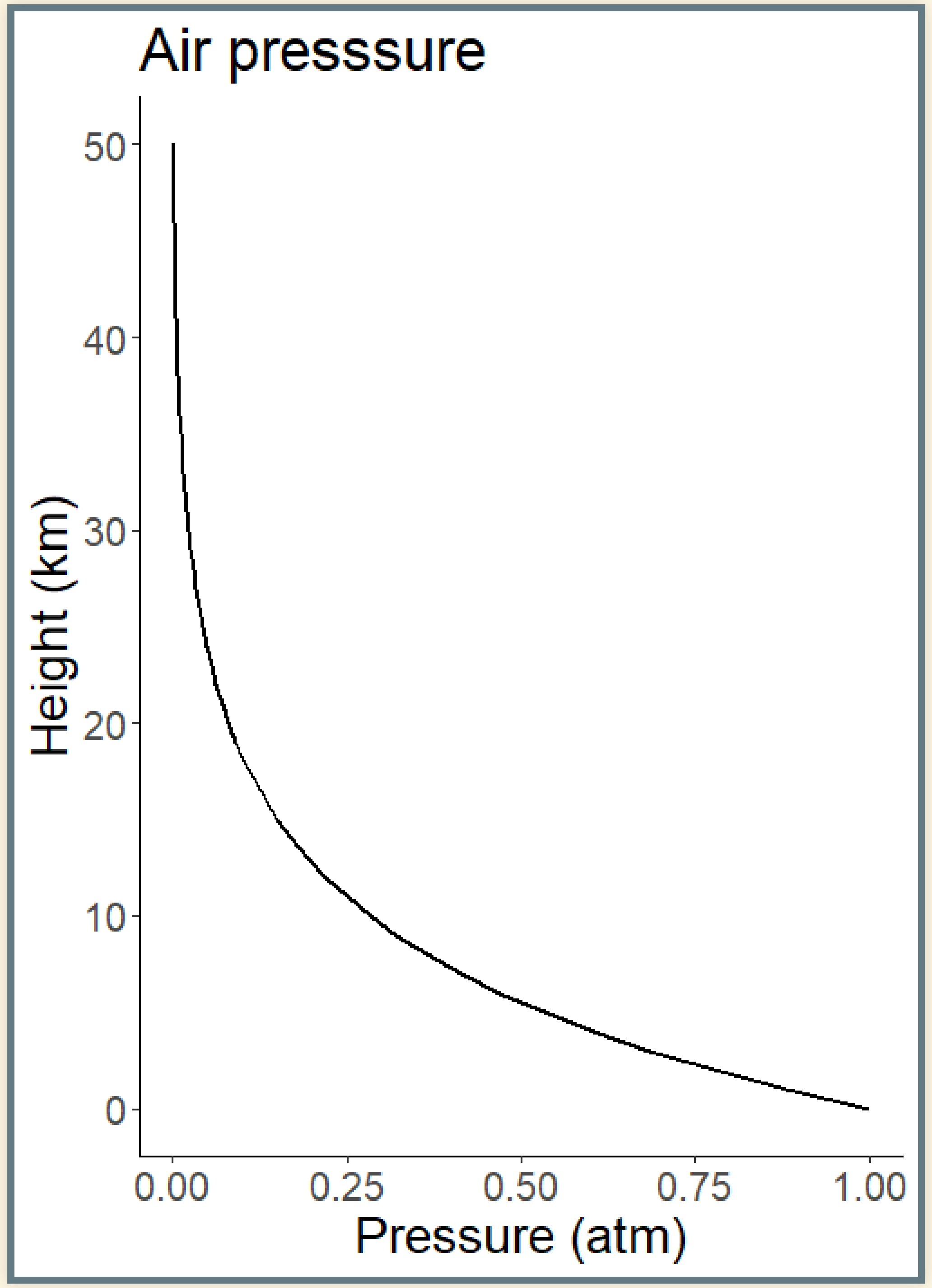


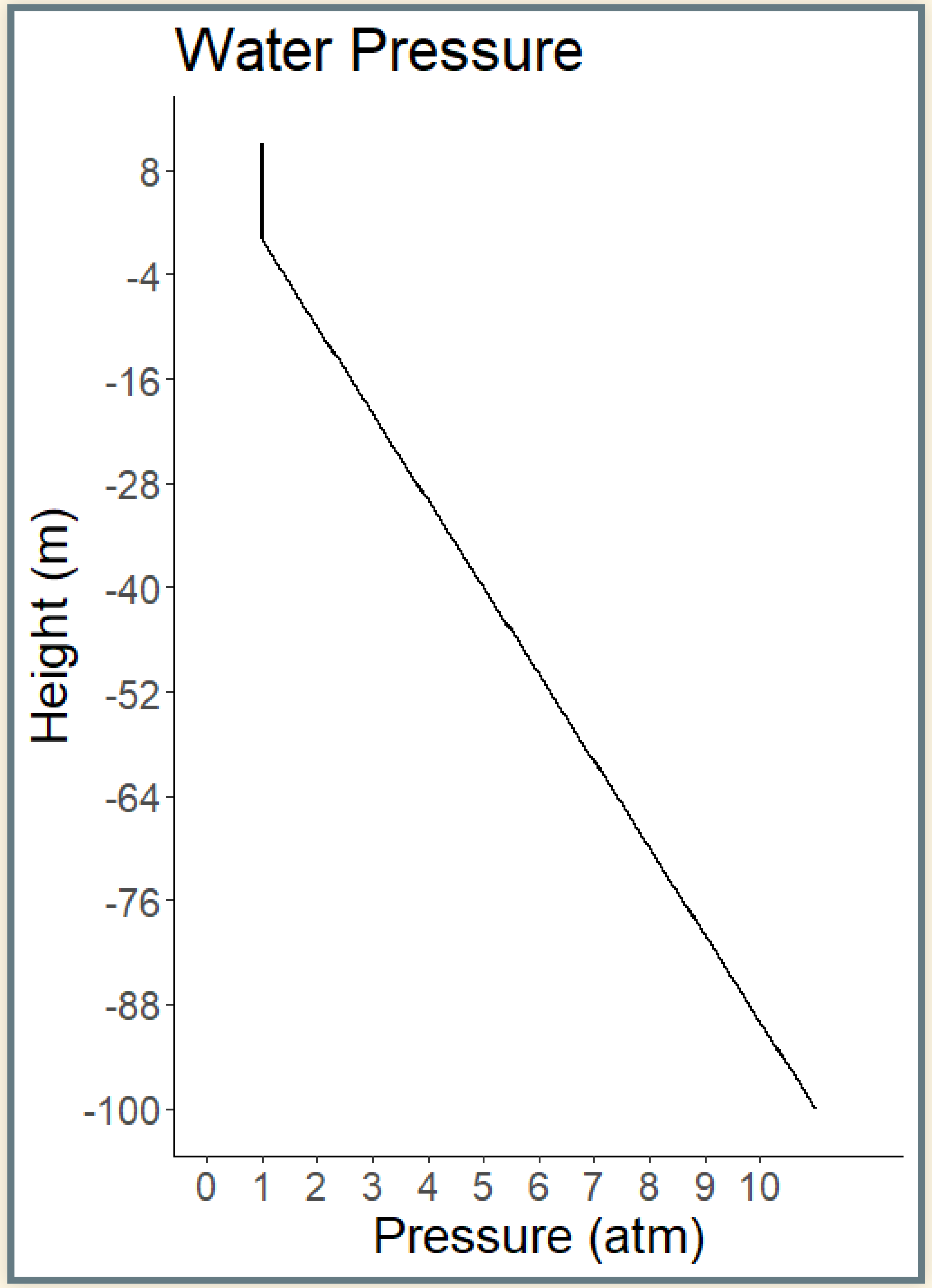
Vertical Structure

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

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

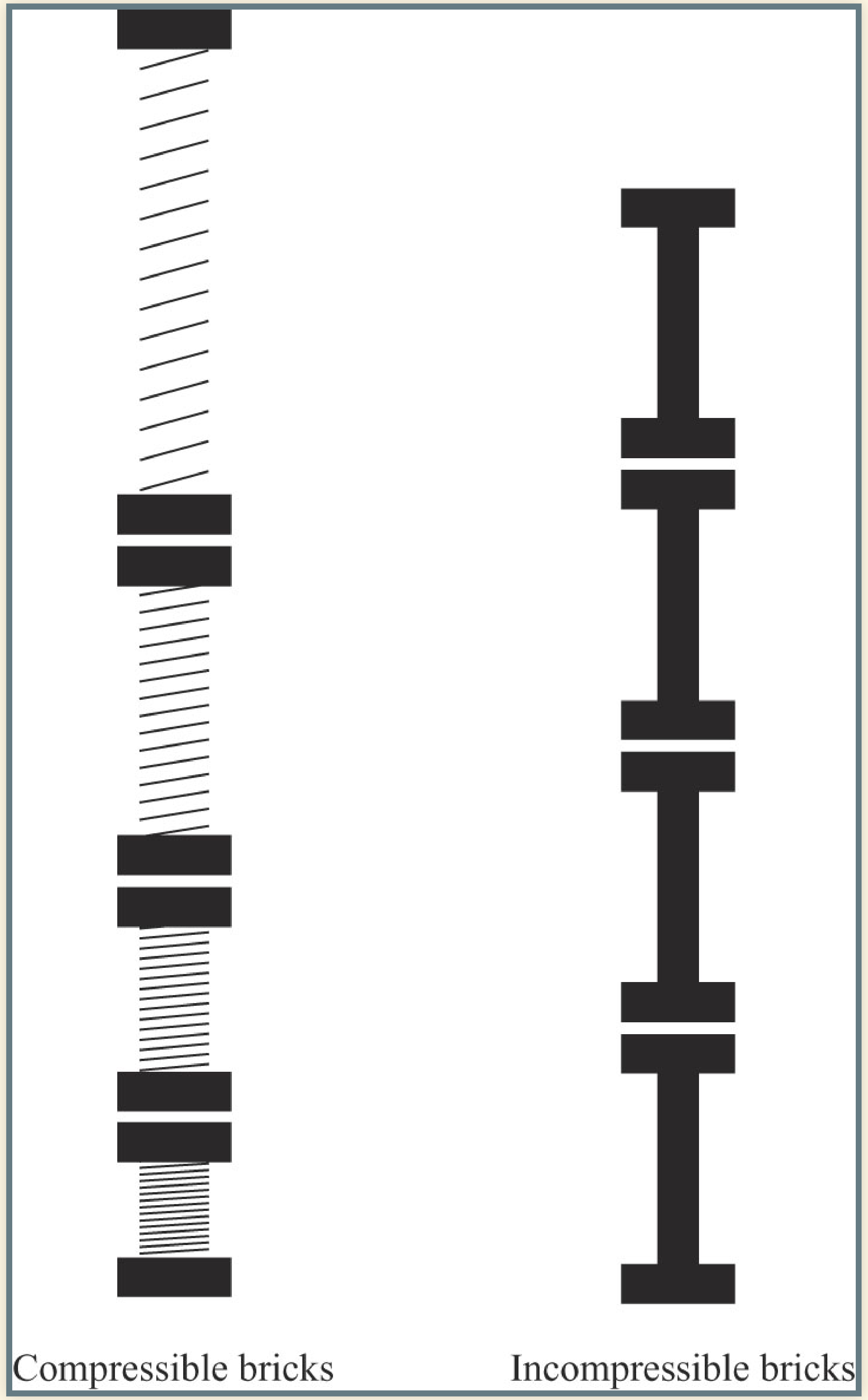
Air vs. Water


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 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

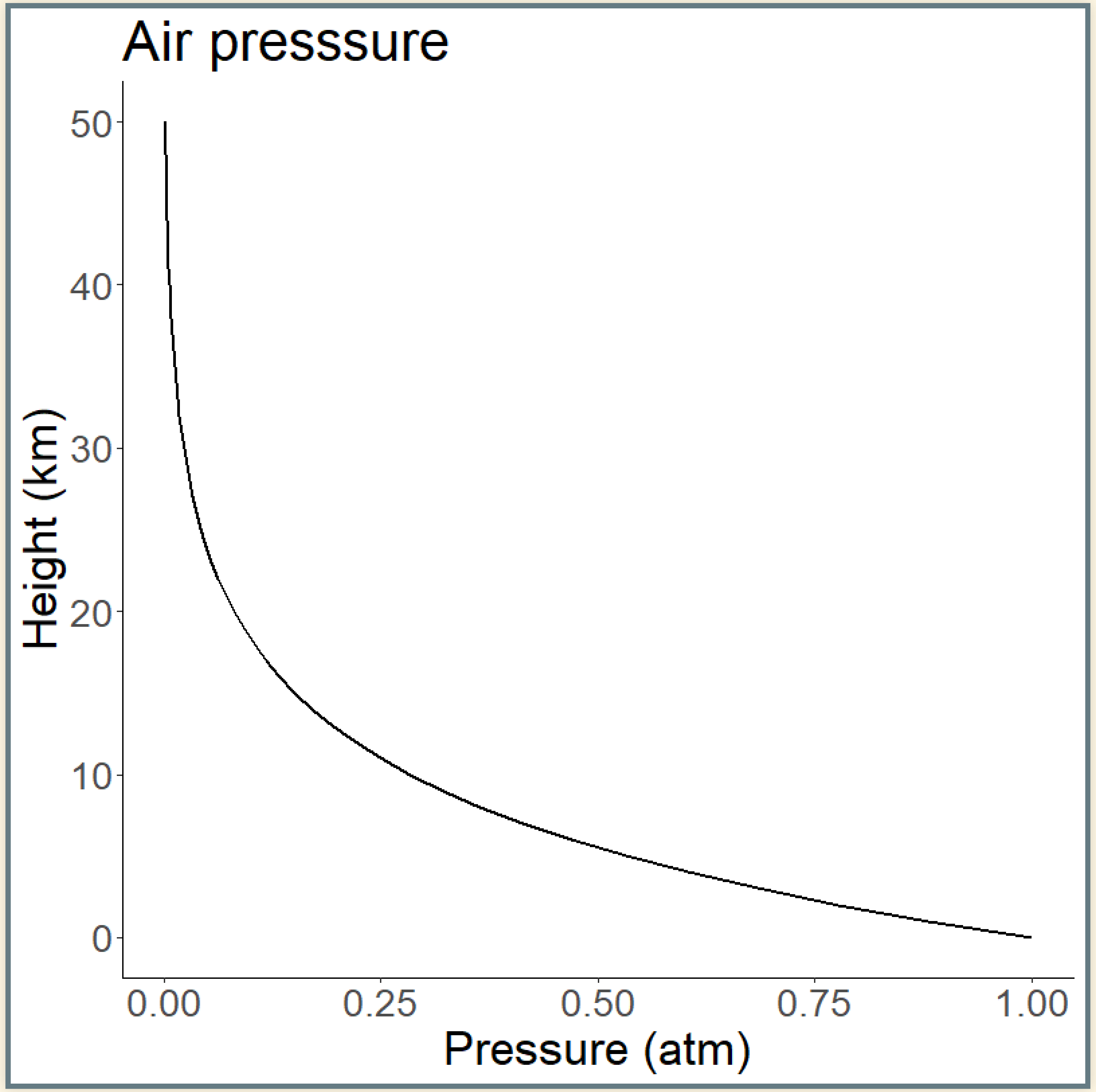


Air Pressure

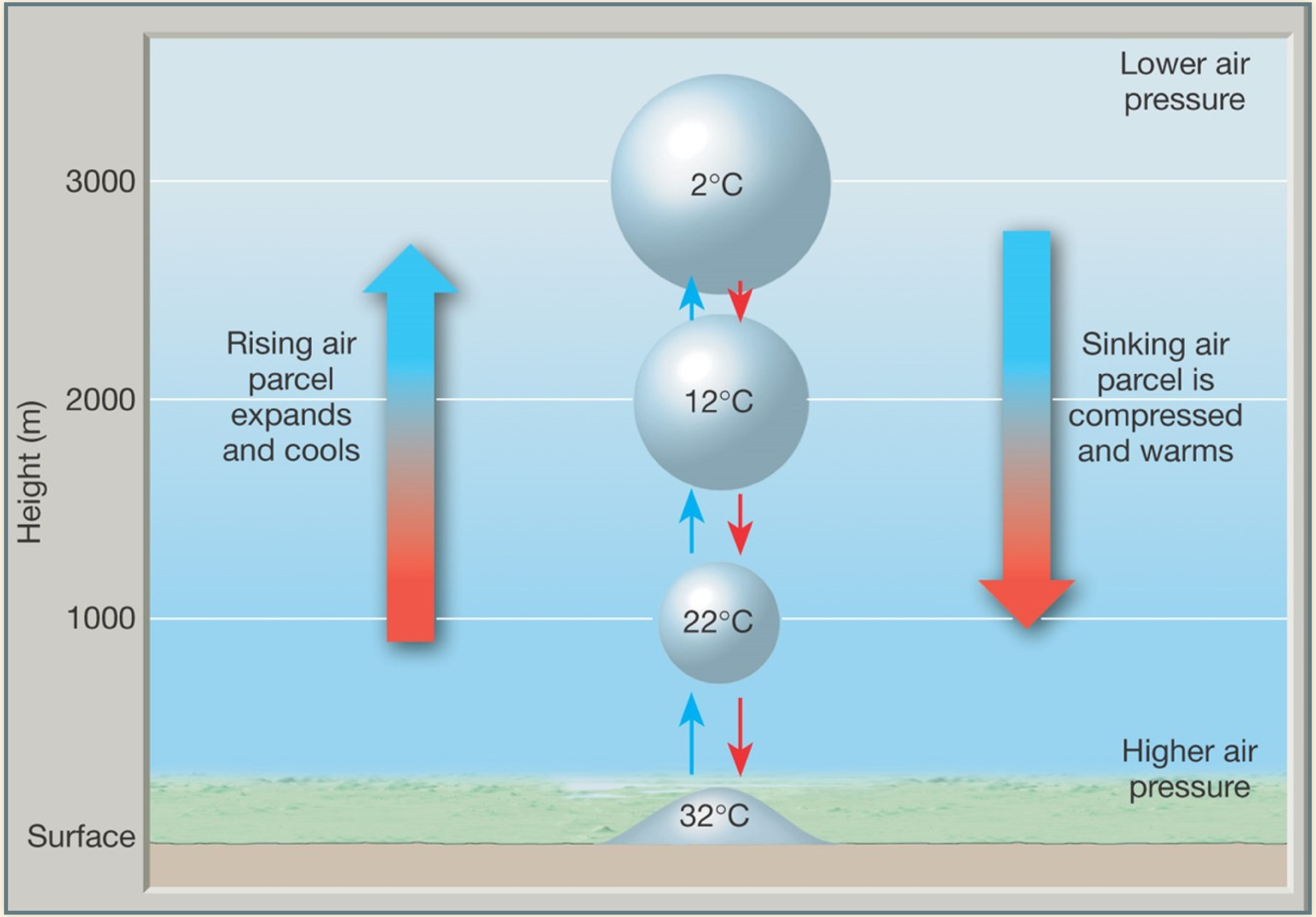
- Pressure at height h:

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

  - 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?

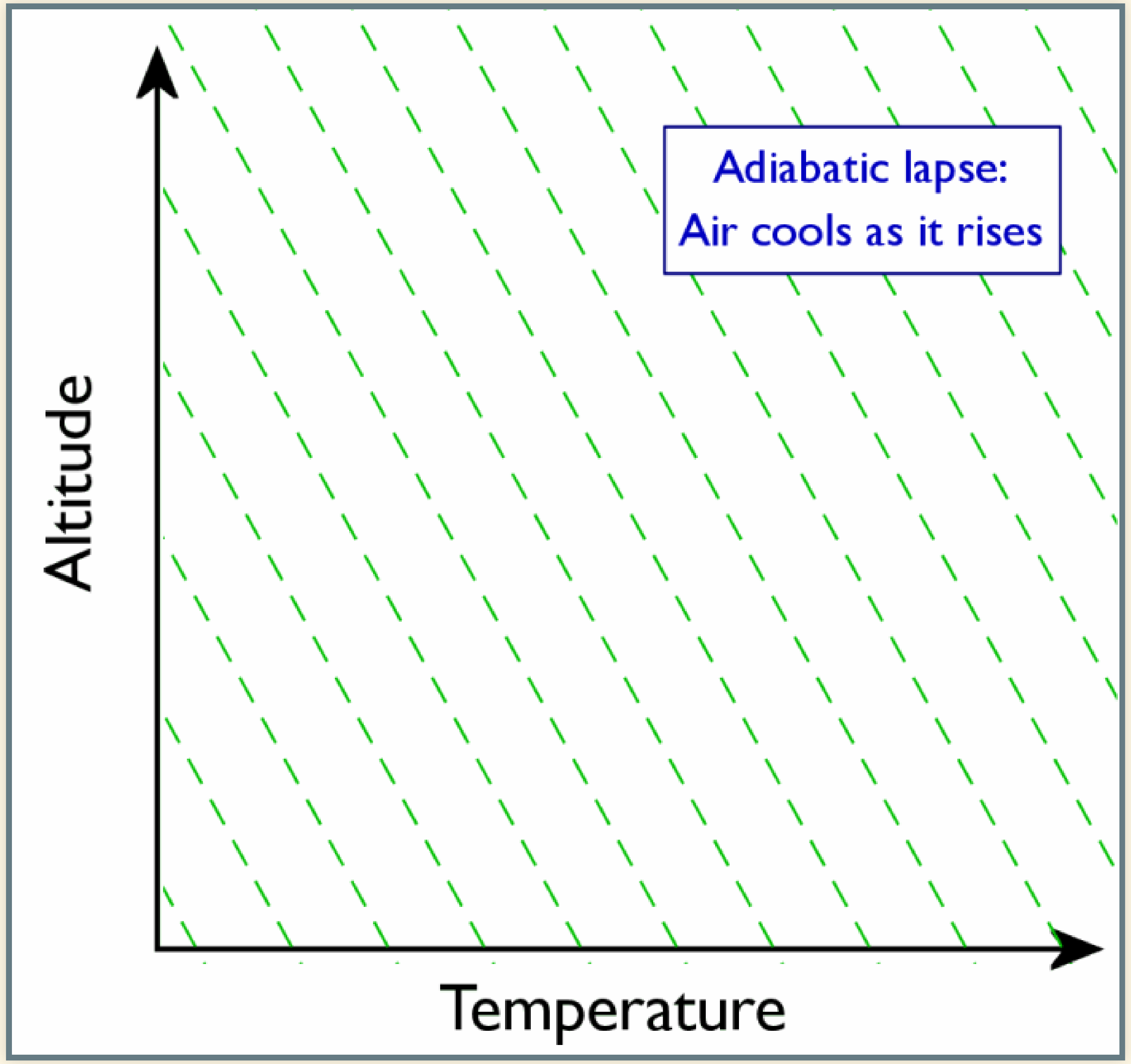


Terminology

- **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

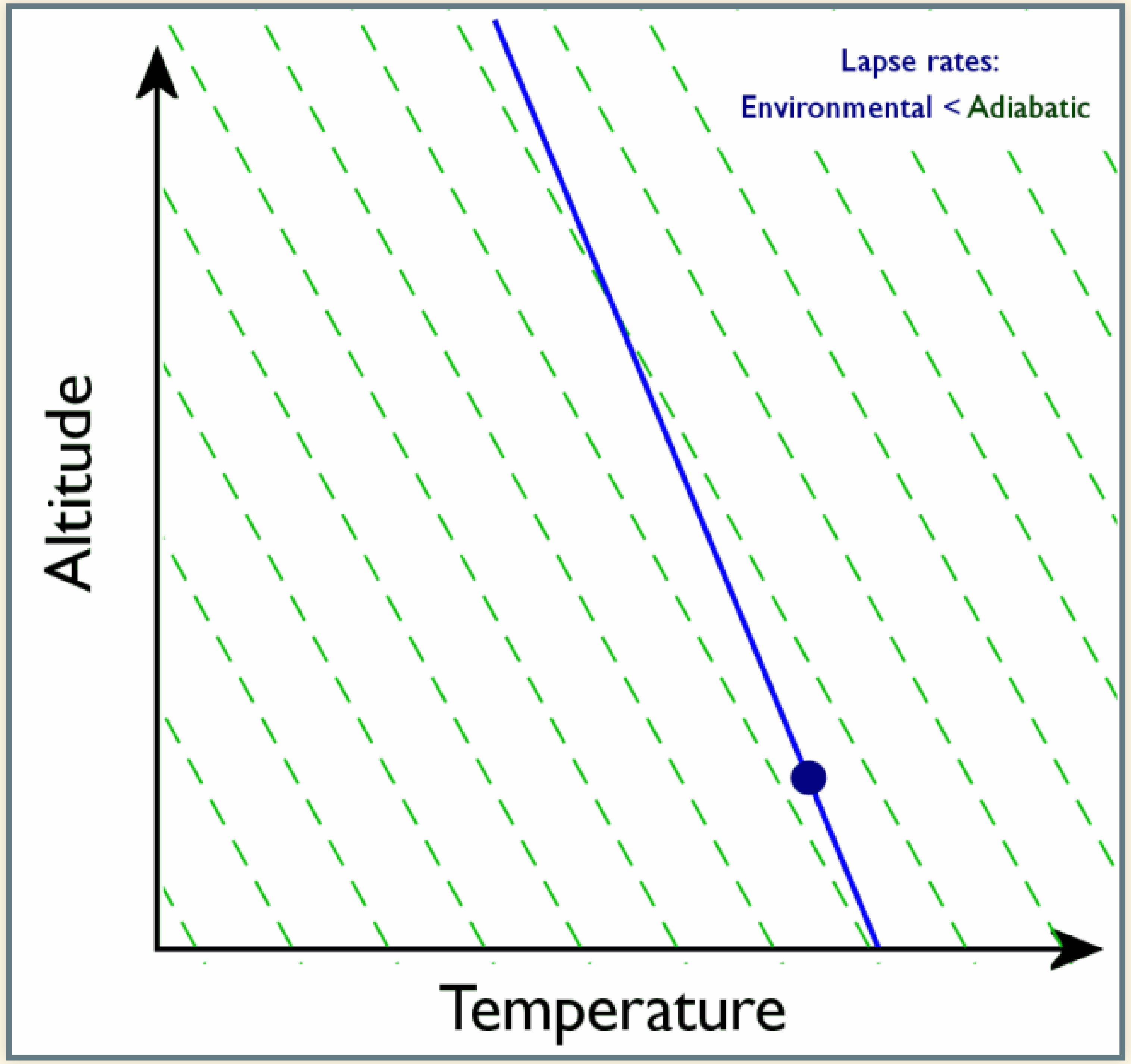
Overview of convection



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

Stable Atmosphere

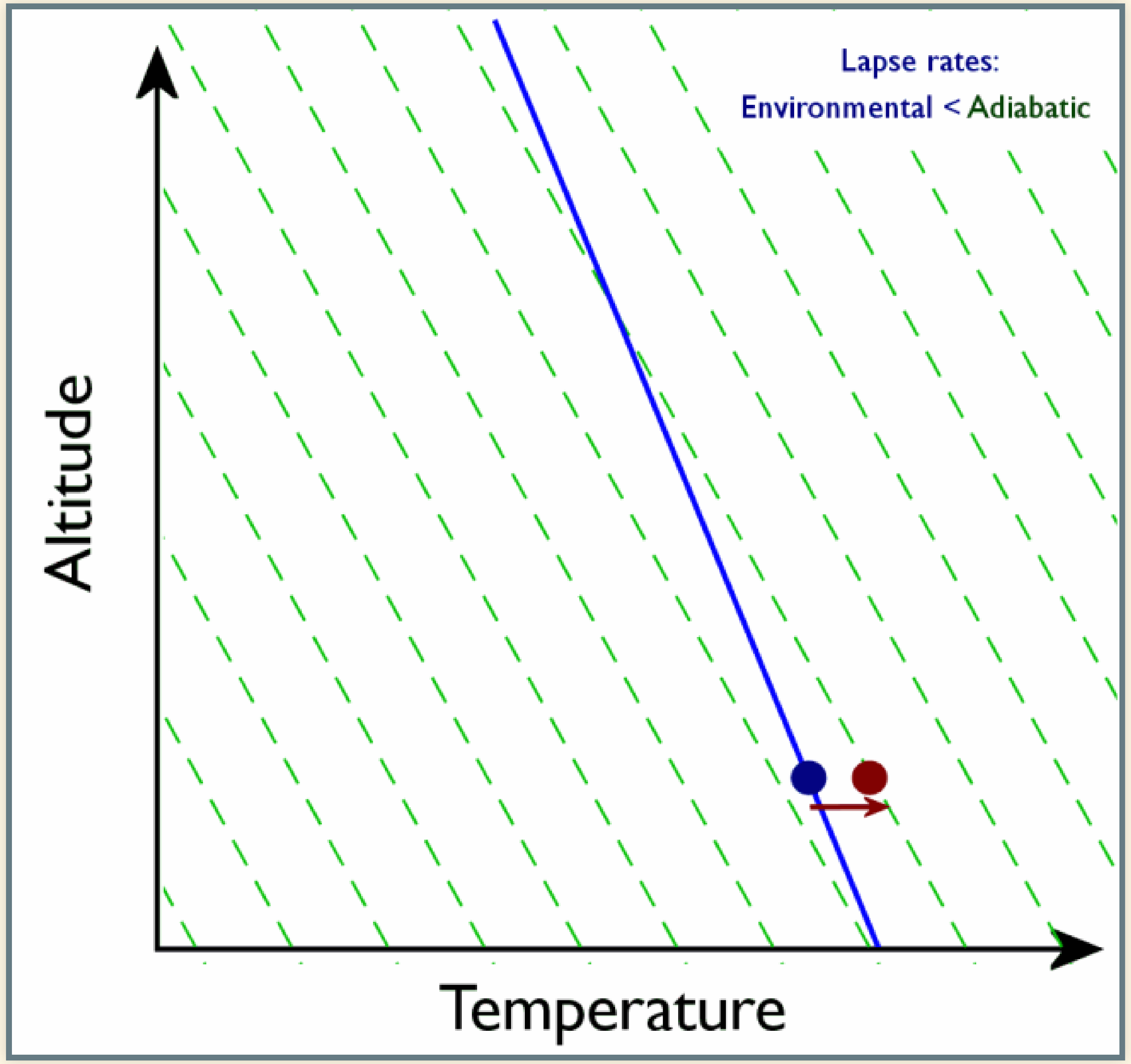
Initial State



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

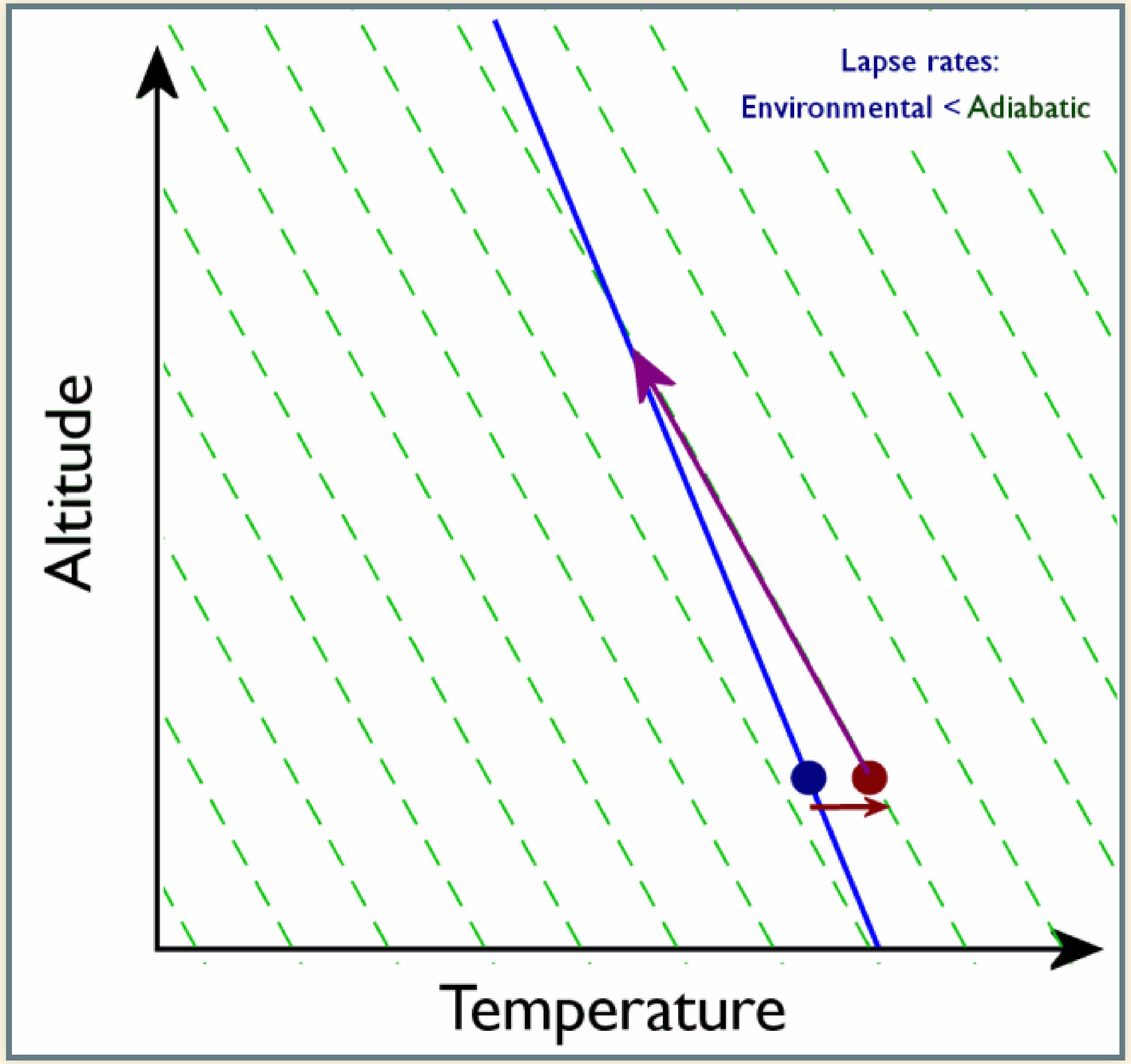
Stable Atmosphere

Parcel is heated



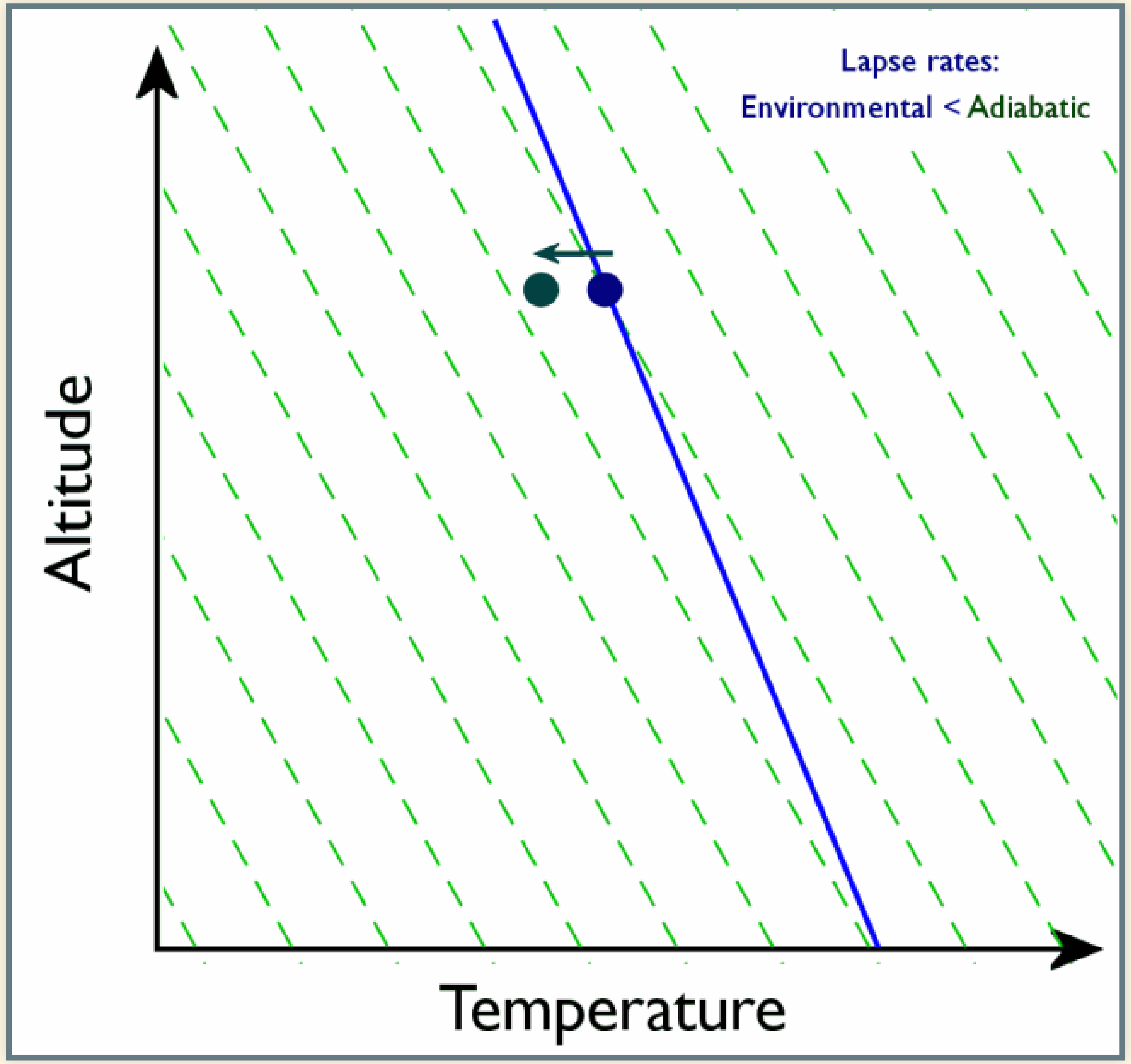
Stable Atmosphere

Rises to new equilibrium



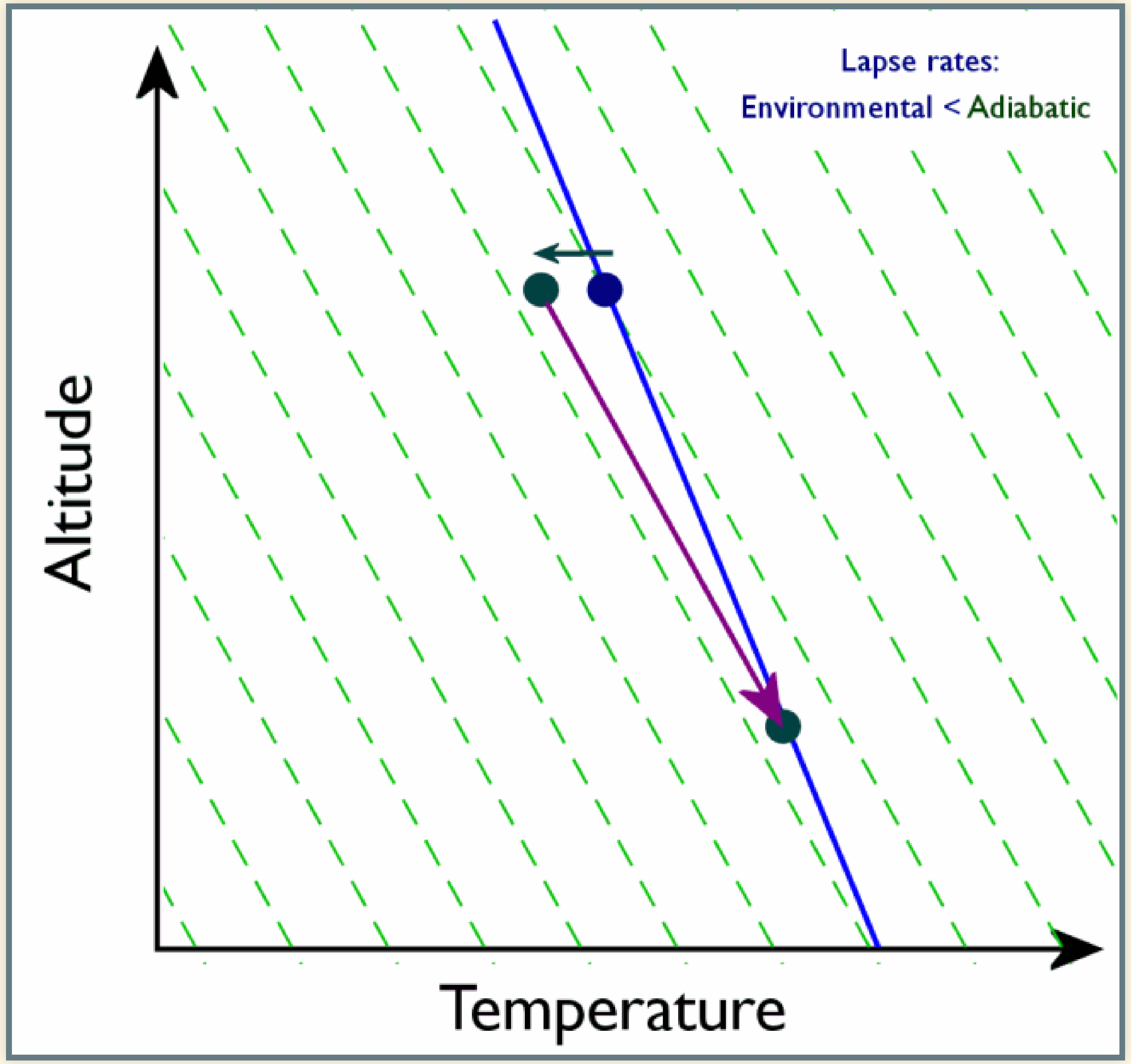
Stable Atmosphere

Parcel is cooled



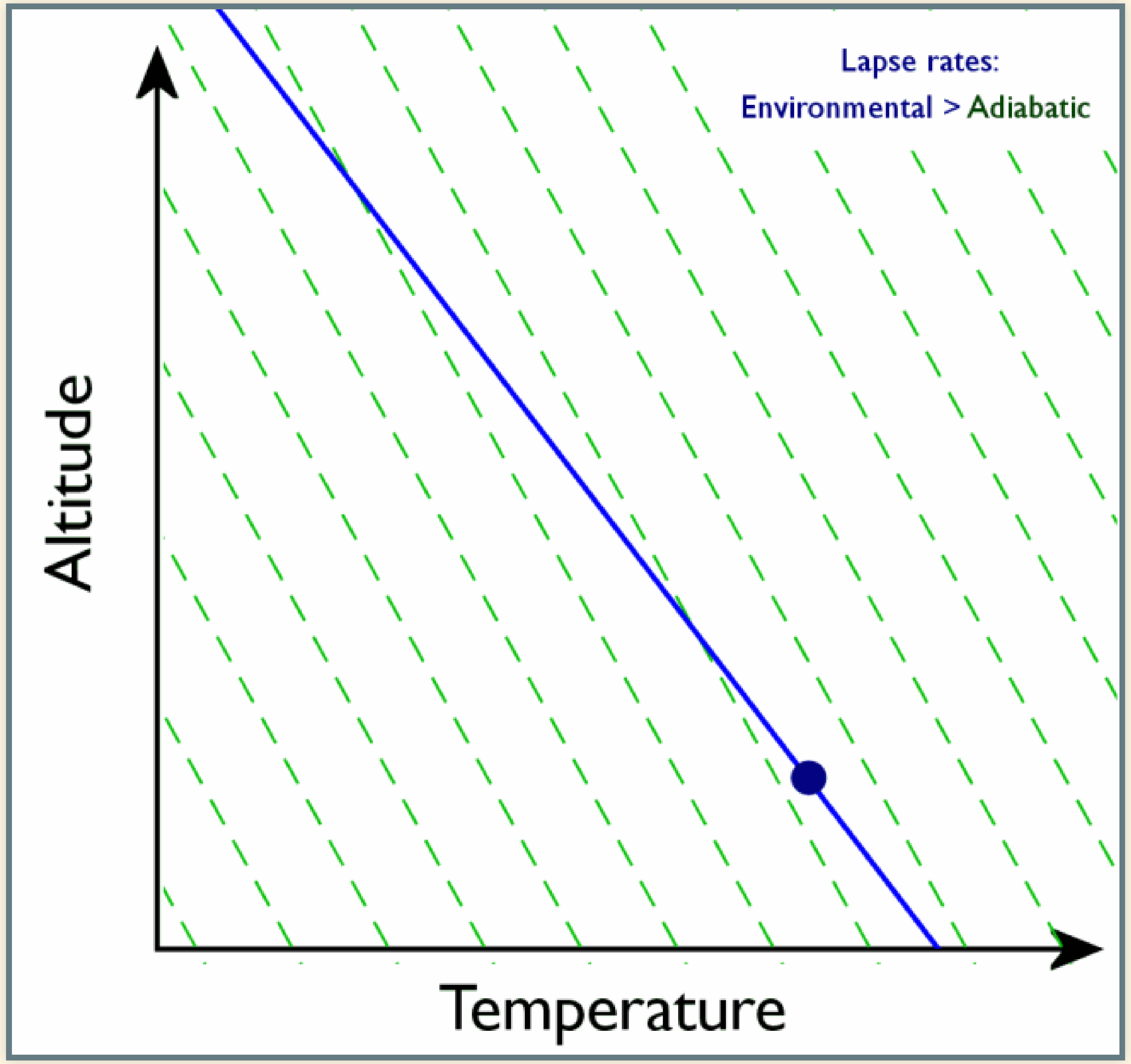
Stable Atmosphere

Sinks to new equilibrium



Unstable Atmosphere

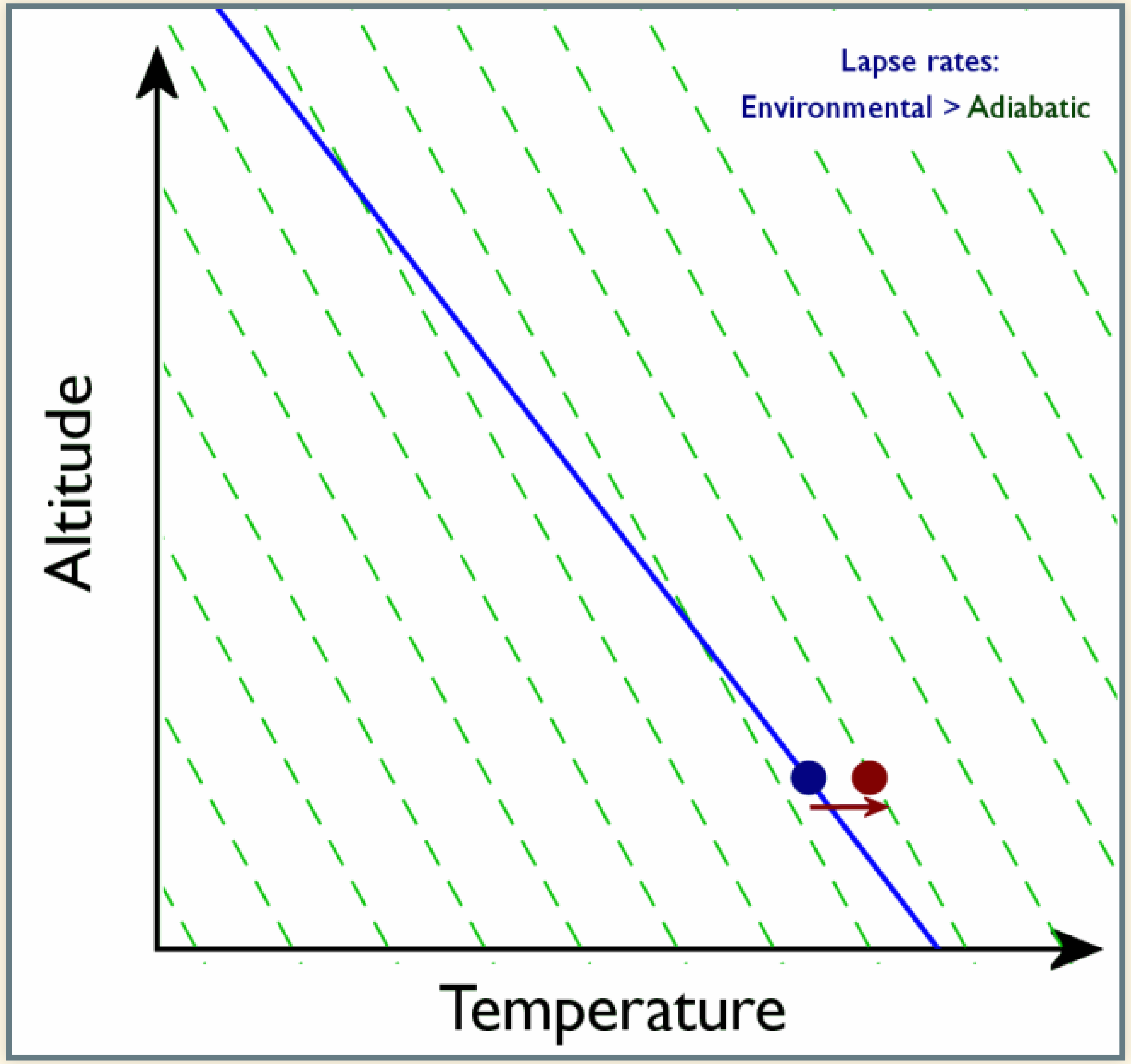
Unstable Atmosphere
Initial State



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

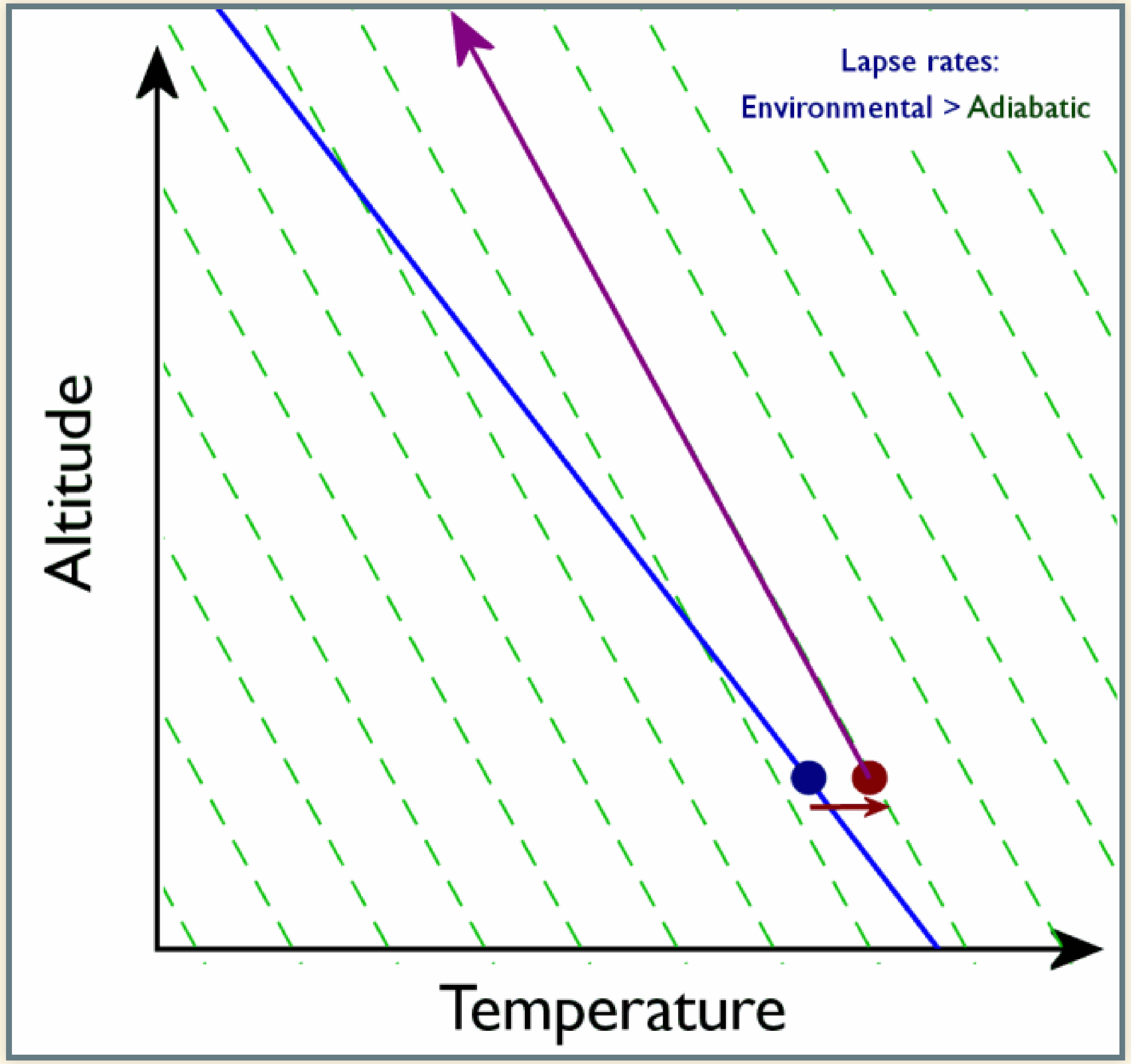
Unstable Atmosphere

Parcel is heated



Unstable Atmosphere

Rises without stopping



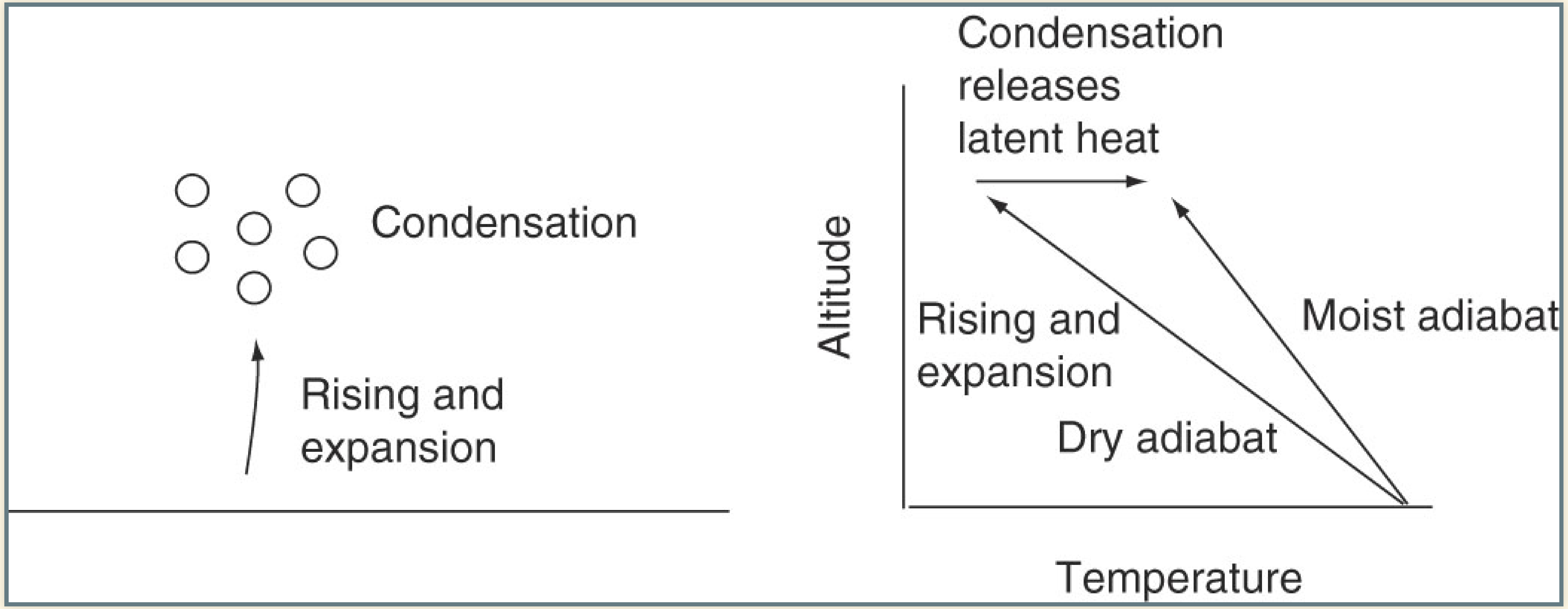
Summary of Stability

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

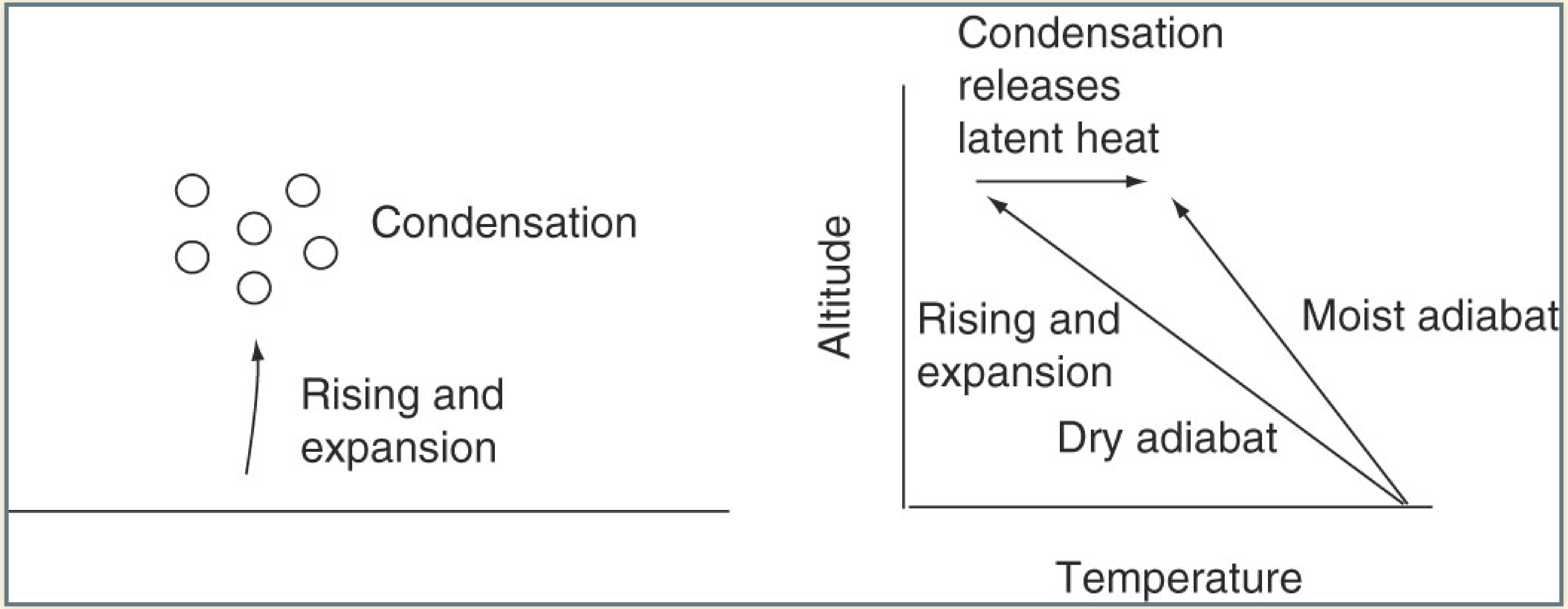
Moist Convection

Moist Convection



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

Moist Convection



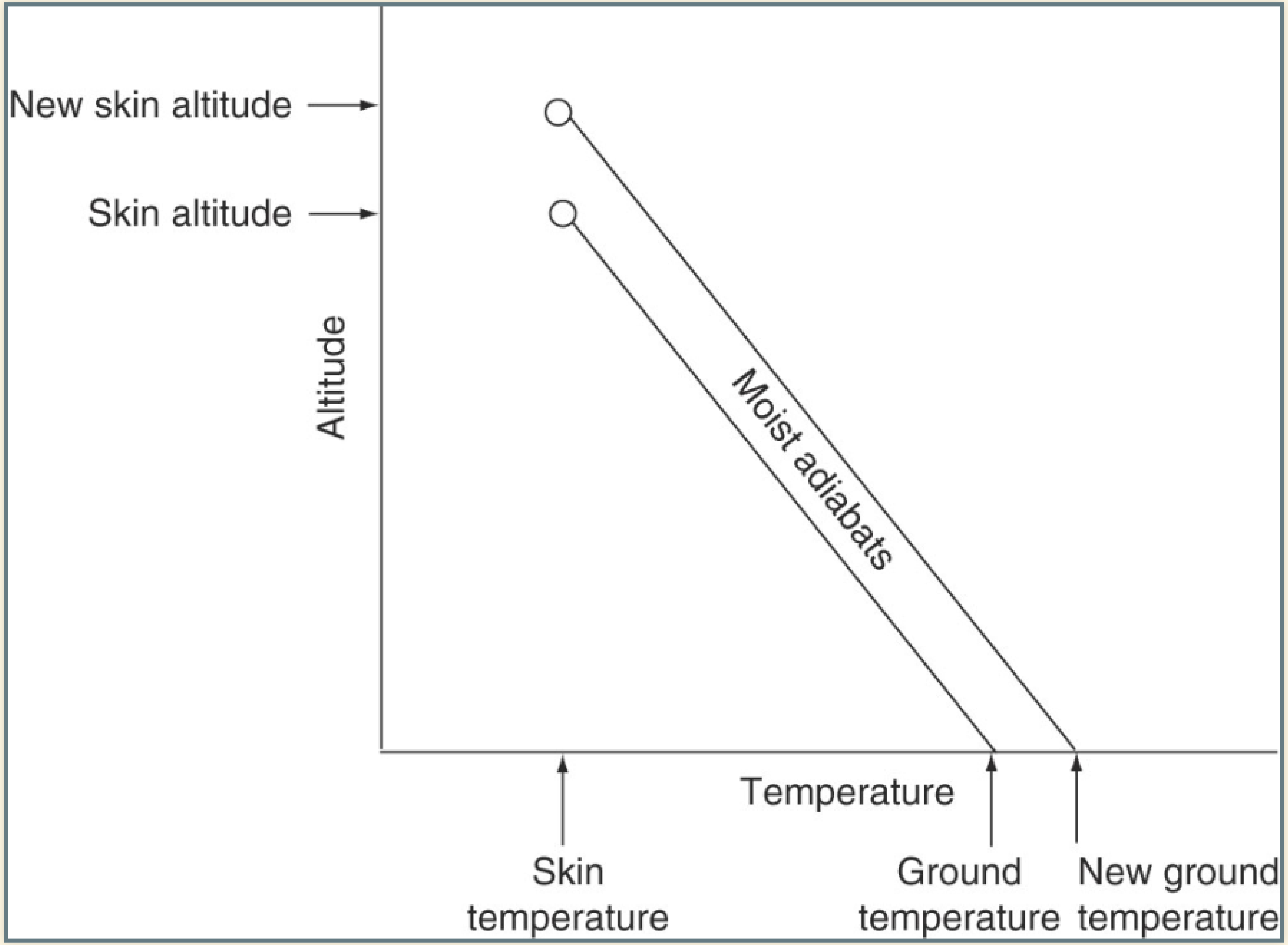
- Latent heat warms air
- Reduces adiabatic cooling
- Moist adiabatic lapse < Dry adiabatic lapse
- Smaller lapse = less stable
- **Humid air is less stable than dry air**

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:
  - 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*)

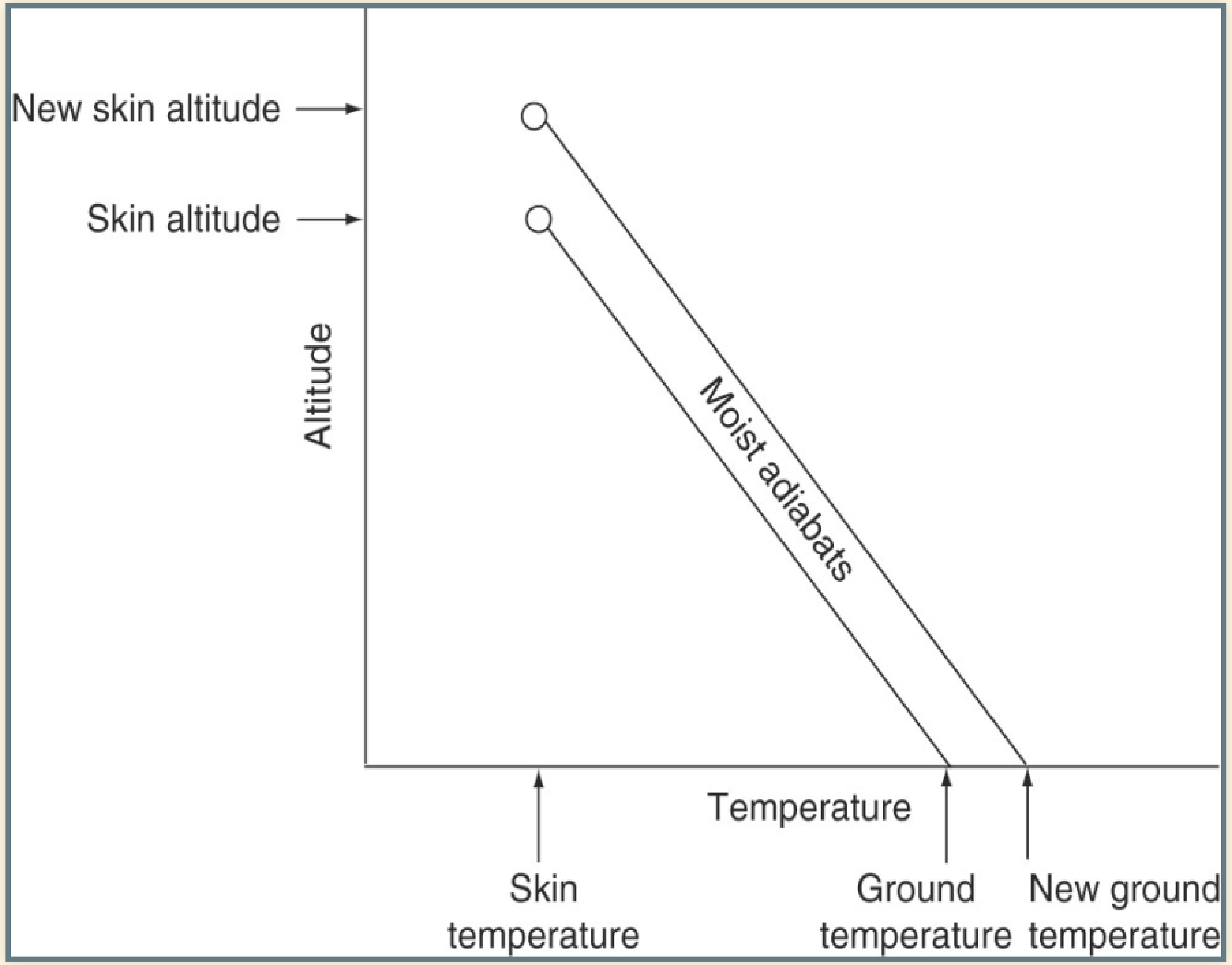
Greenhouse effect

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 $\textbf{lapse rate} \times \Delta h_{\text{skin}}$



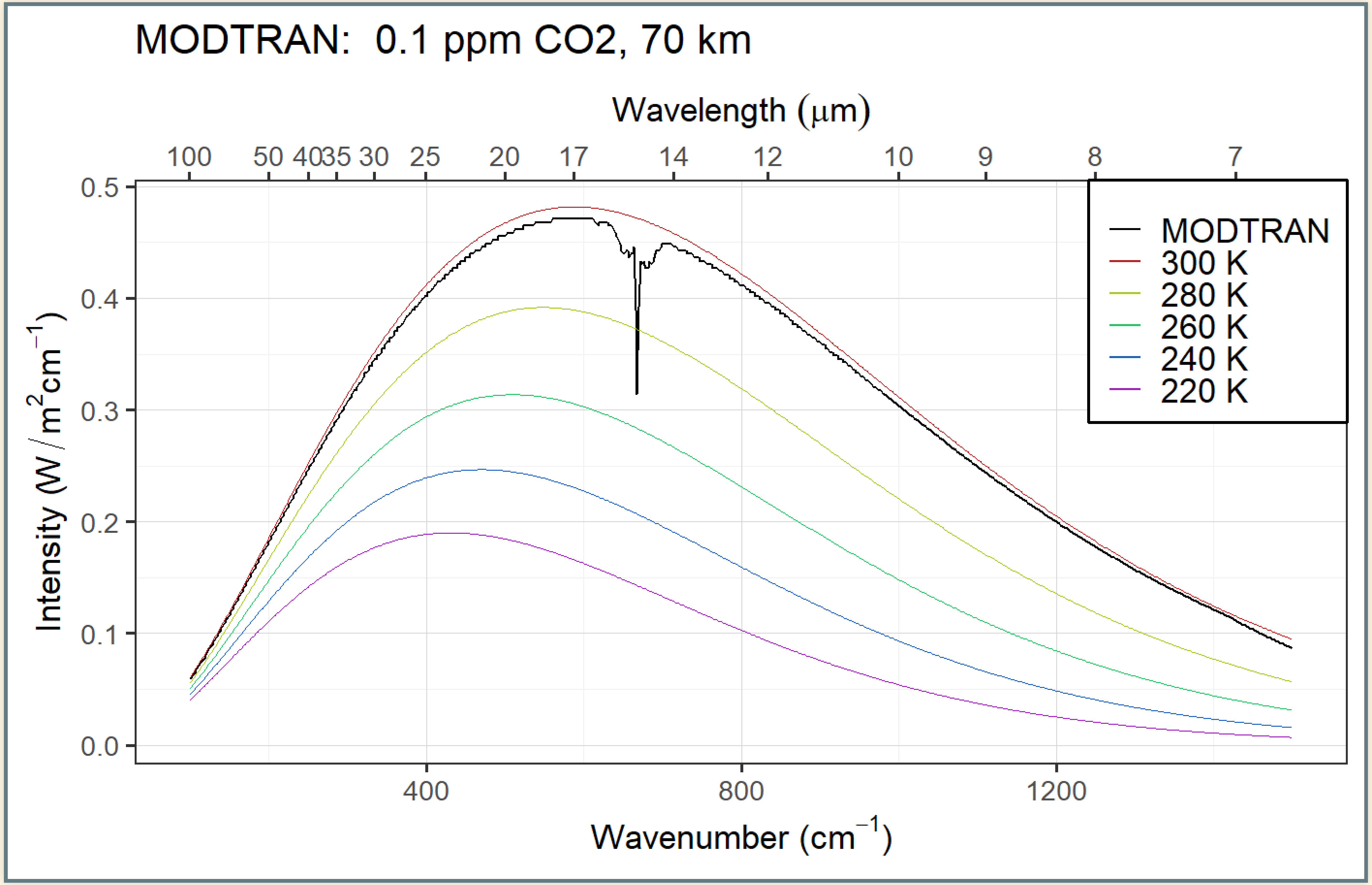
Vertical Structure and Saturation

Set up MODTRAN:

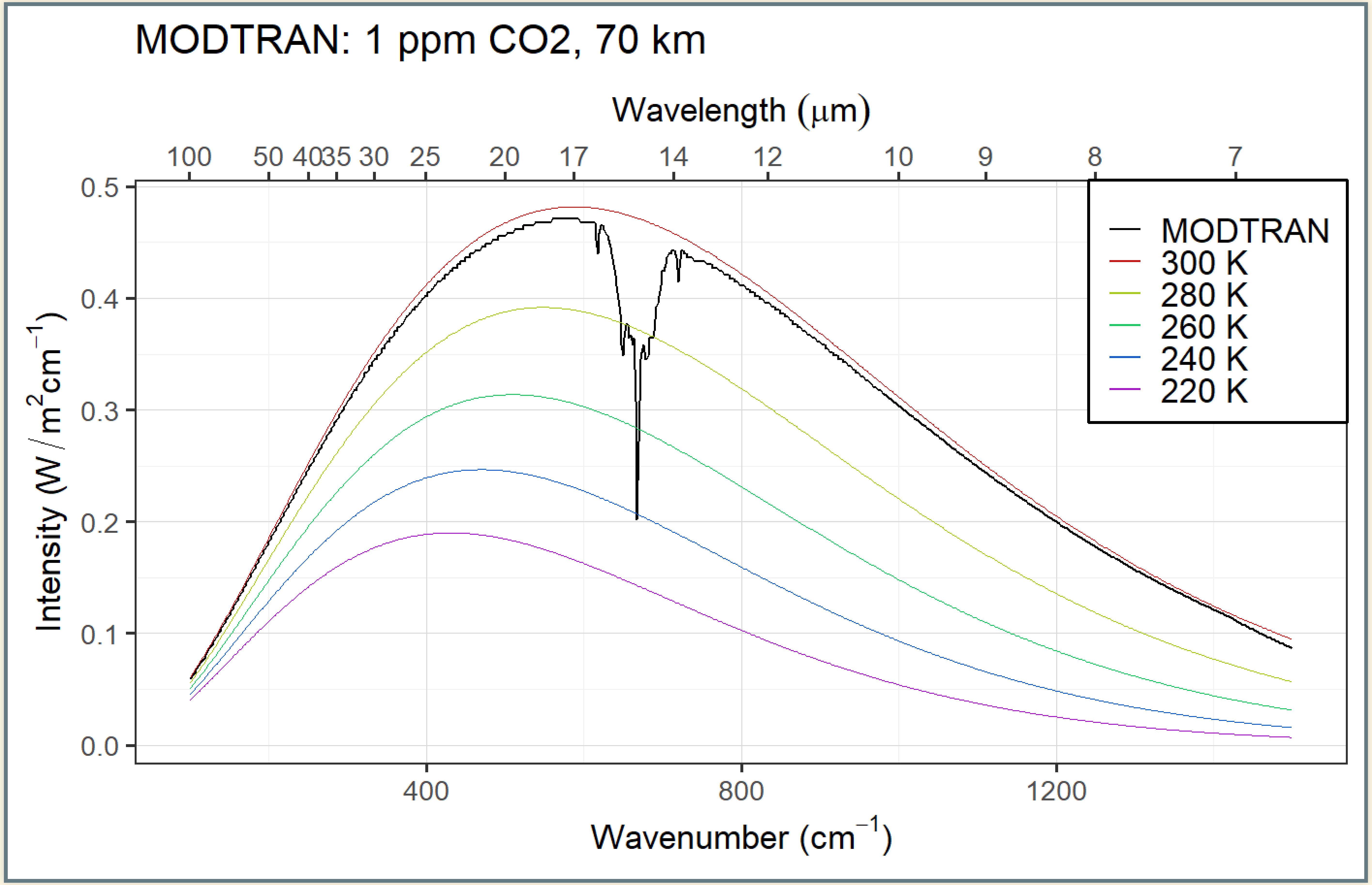
Go to MODTRAN (http://climatemodels.uchicago.edu/modtran/)

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

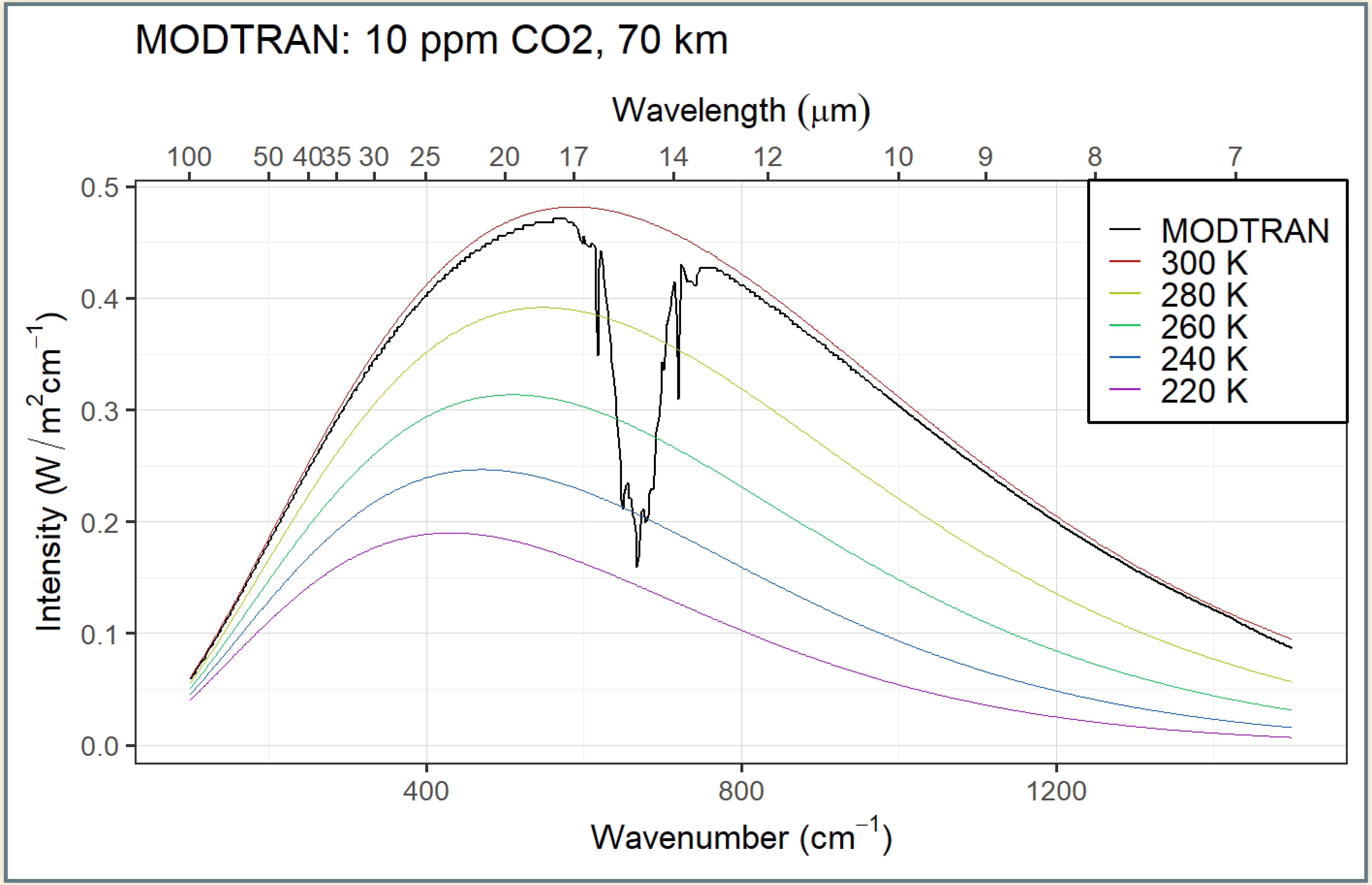
0.1 ppm CO_2


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

1 ppm CO_2

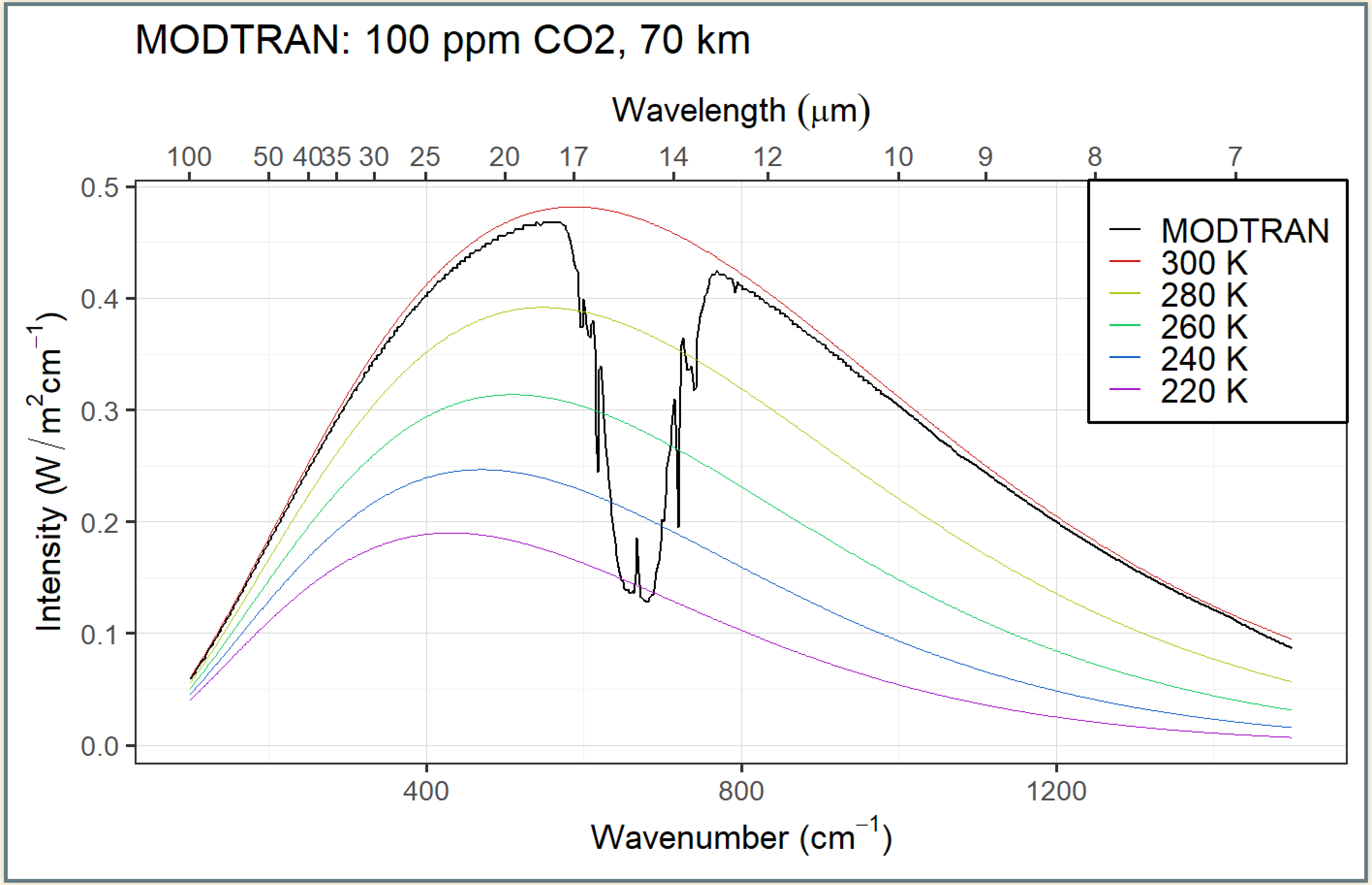

MODTRAN: 1 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m2cm−1)
400
800
1200
Wavenumber (cm−1)
MODTRAN
300 K
280 K
260 K
240 K
220 K

10 ppm CO_2

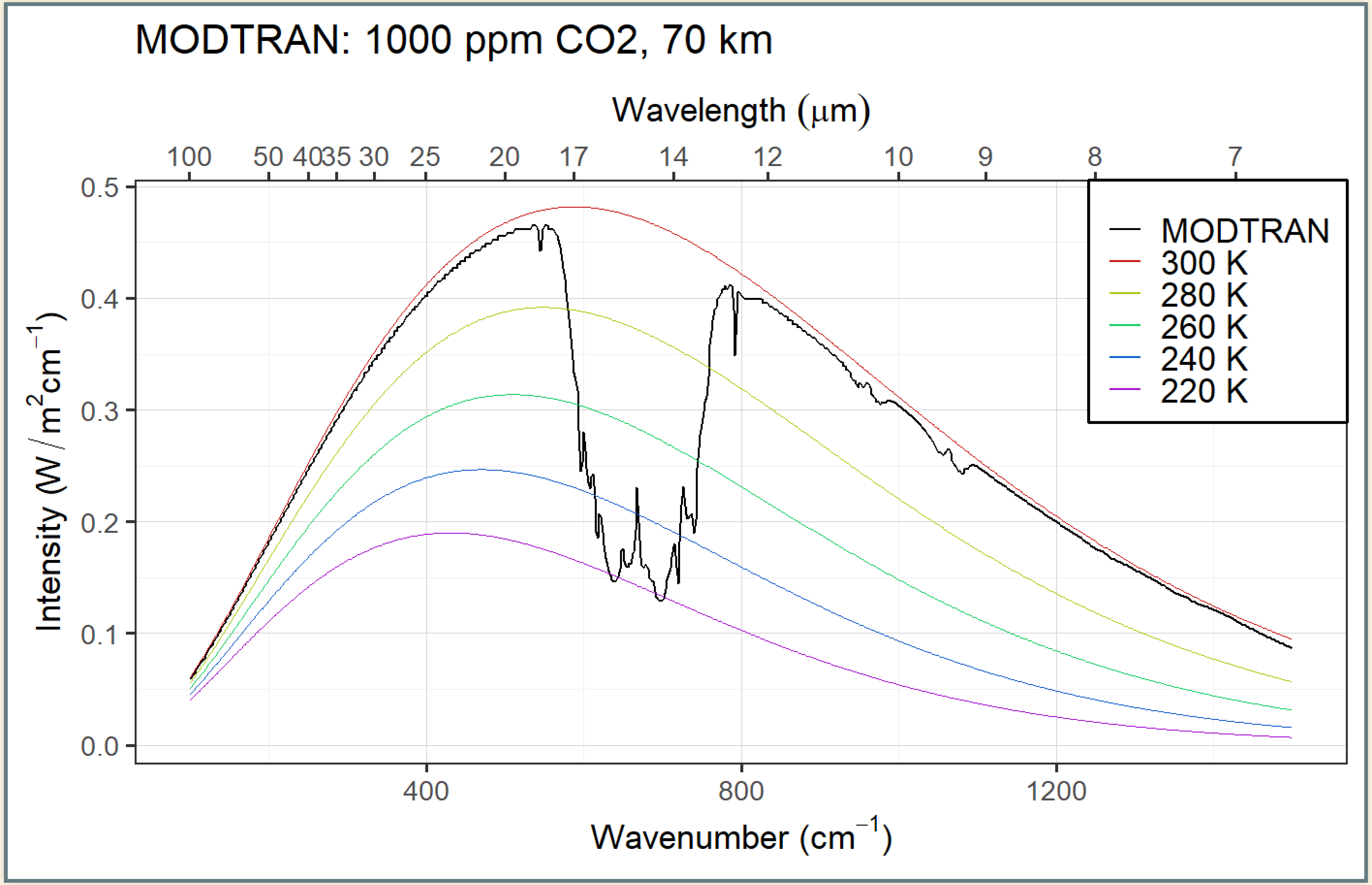


MODTRAN: 10 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

100 ppm CO_2

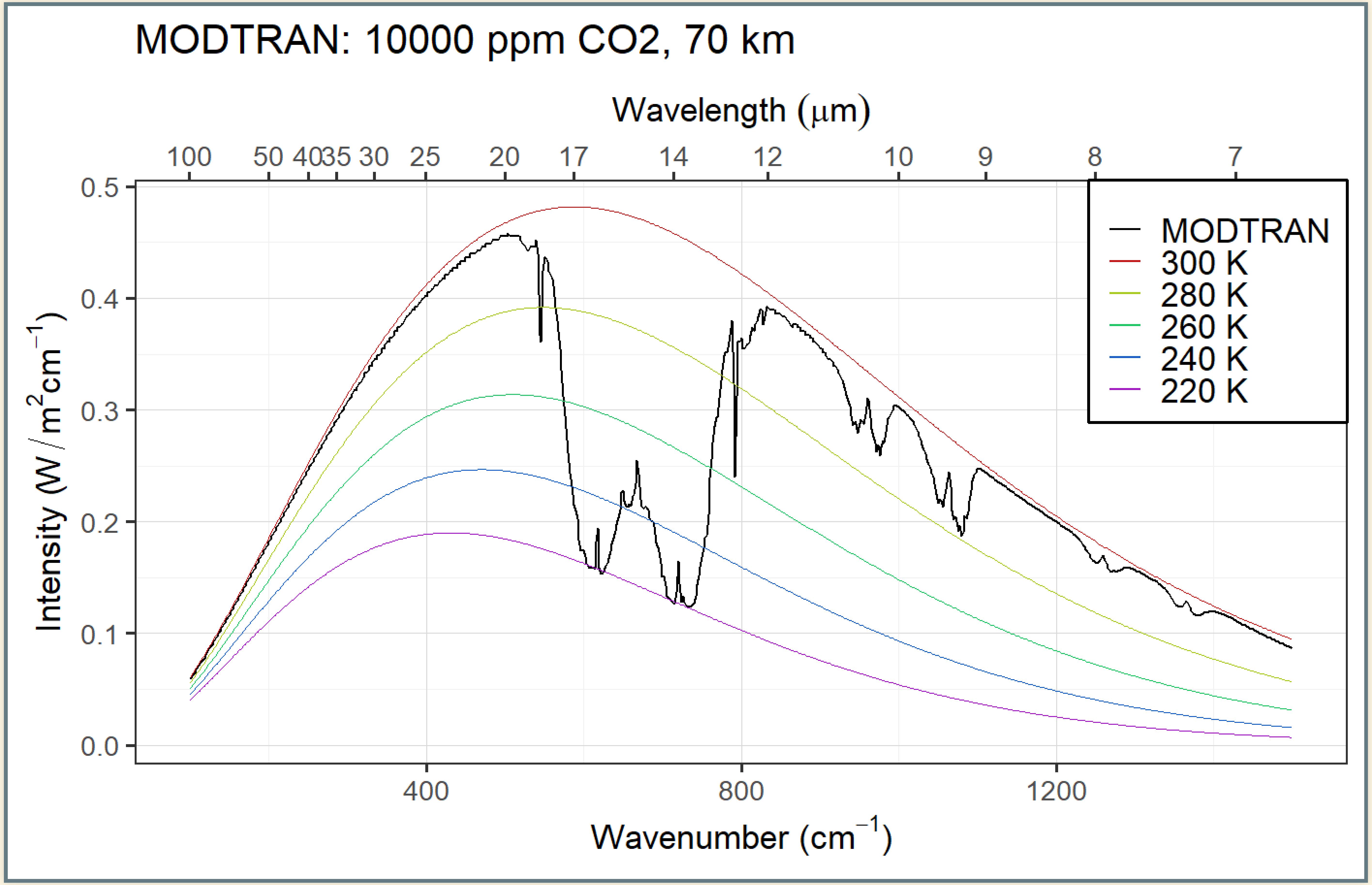

MODTRAN: 100 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

1000 ppm CO_2

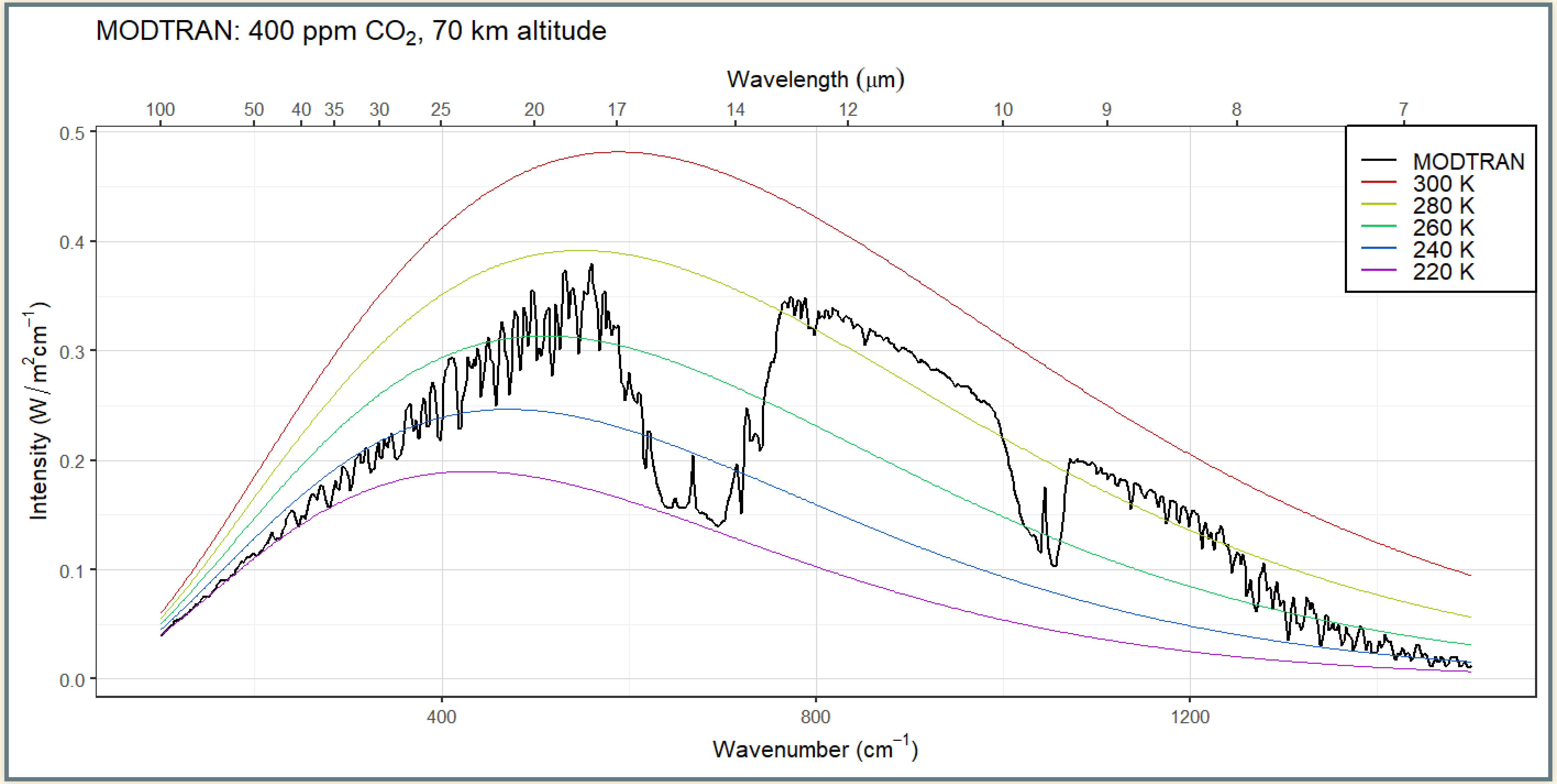


MODTRAN: 1000 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm⁻¹)

10,000 ppm CO_2

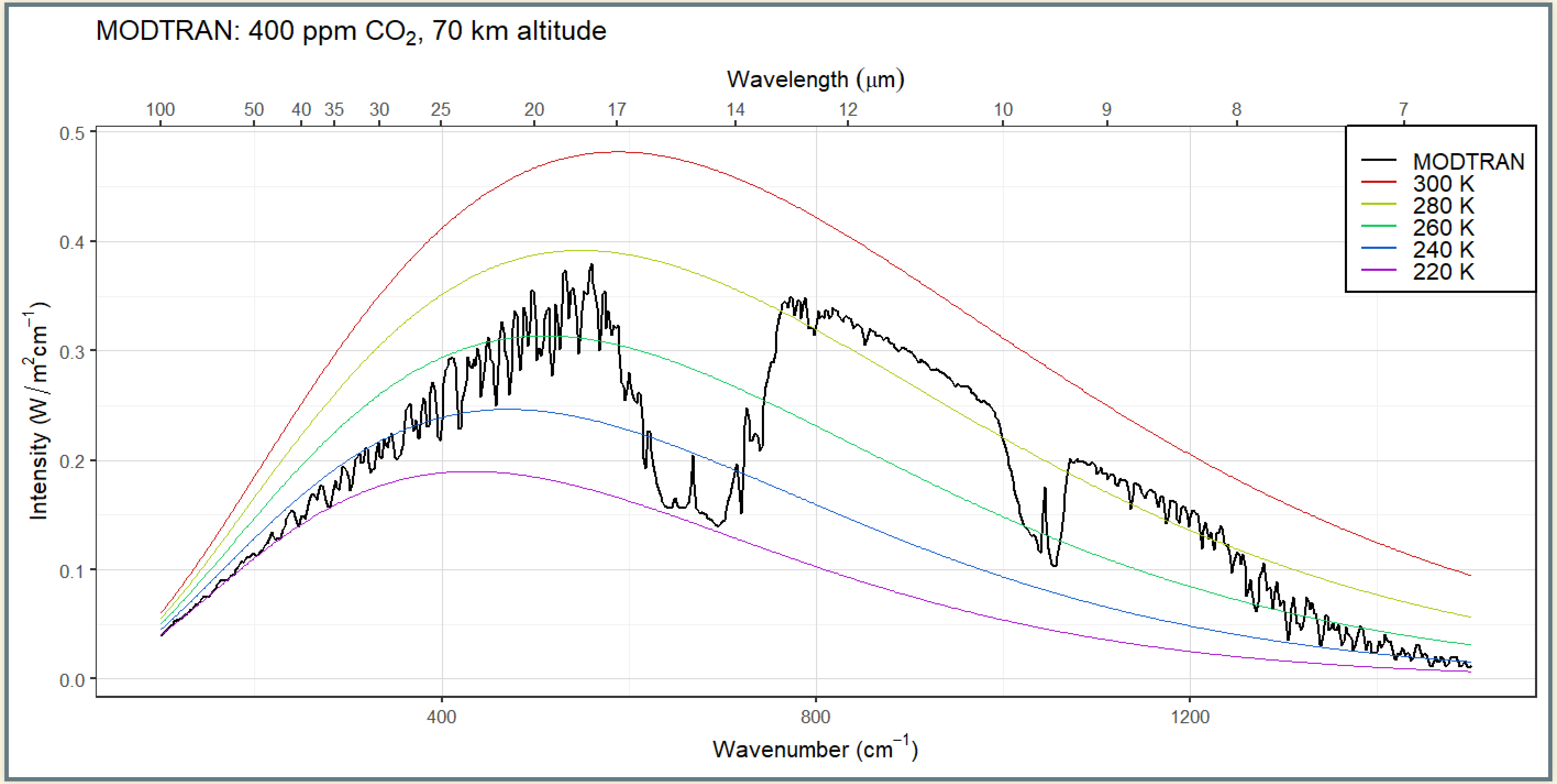


Question



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

Question



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