Temperature Structure of the Atmosphere

EES 2110

Introduction to Climate Change

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Class #7: Wednesday, January 25 2023

Visible Radiation in Colored Water

Visible Radiation in Colored Water

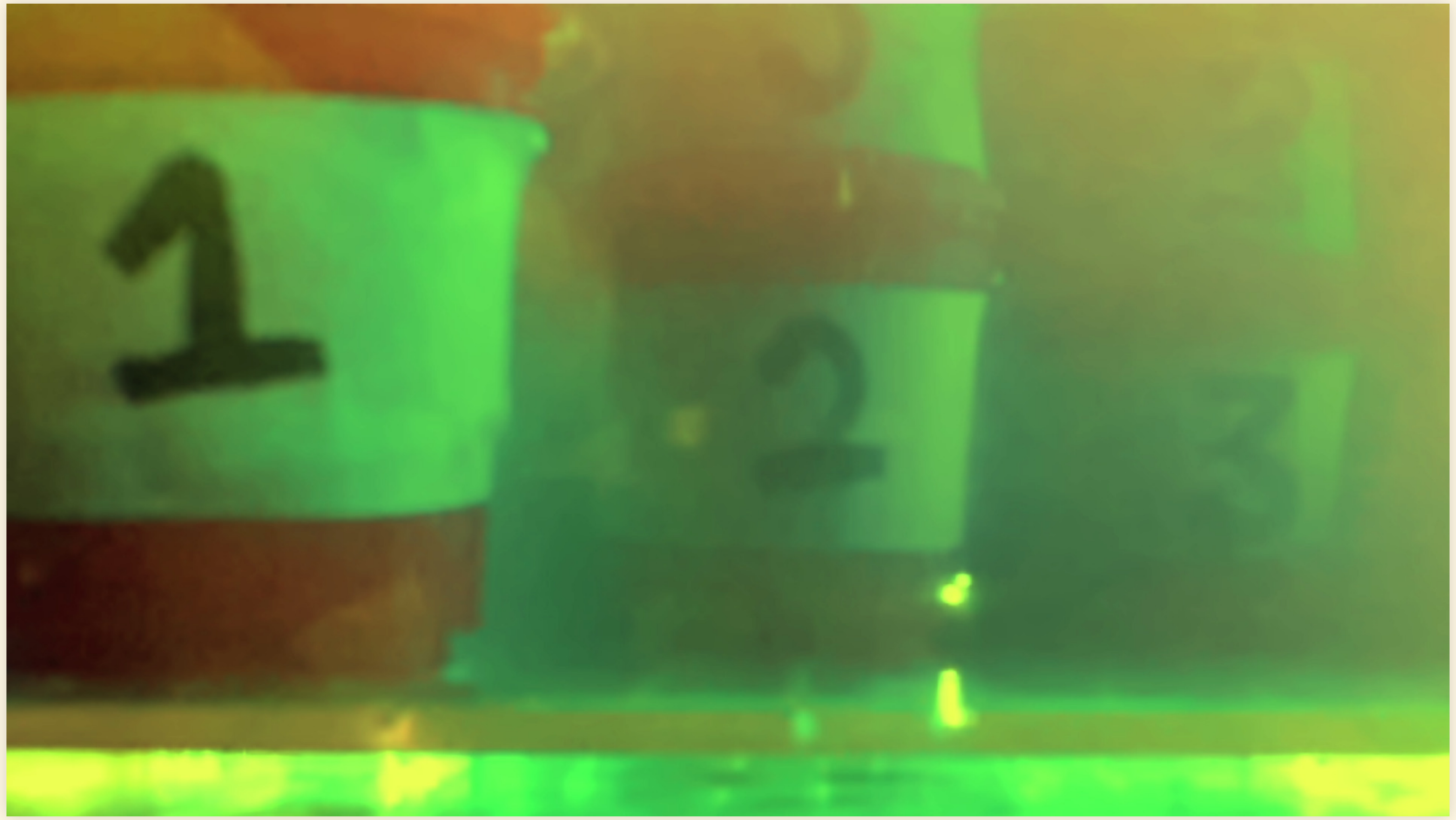
- To better understand the concept of how different parts of the atmosphere look to a satellite at different frequencies in the longwave spectrum,
  - Consider looking through colored water at different frequencies in the visible spectrum
- Here are three cups with black-on-white labels
  - The cups are in an empty tank

- Full visible spectrum

Visible Radiation in Colored Water

- Here are three cups with black-on-white labels
- The tank is filled with water, colored green with food-coloring

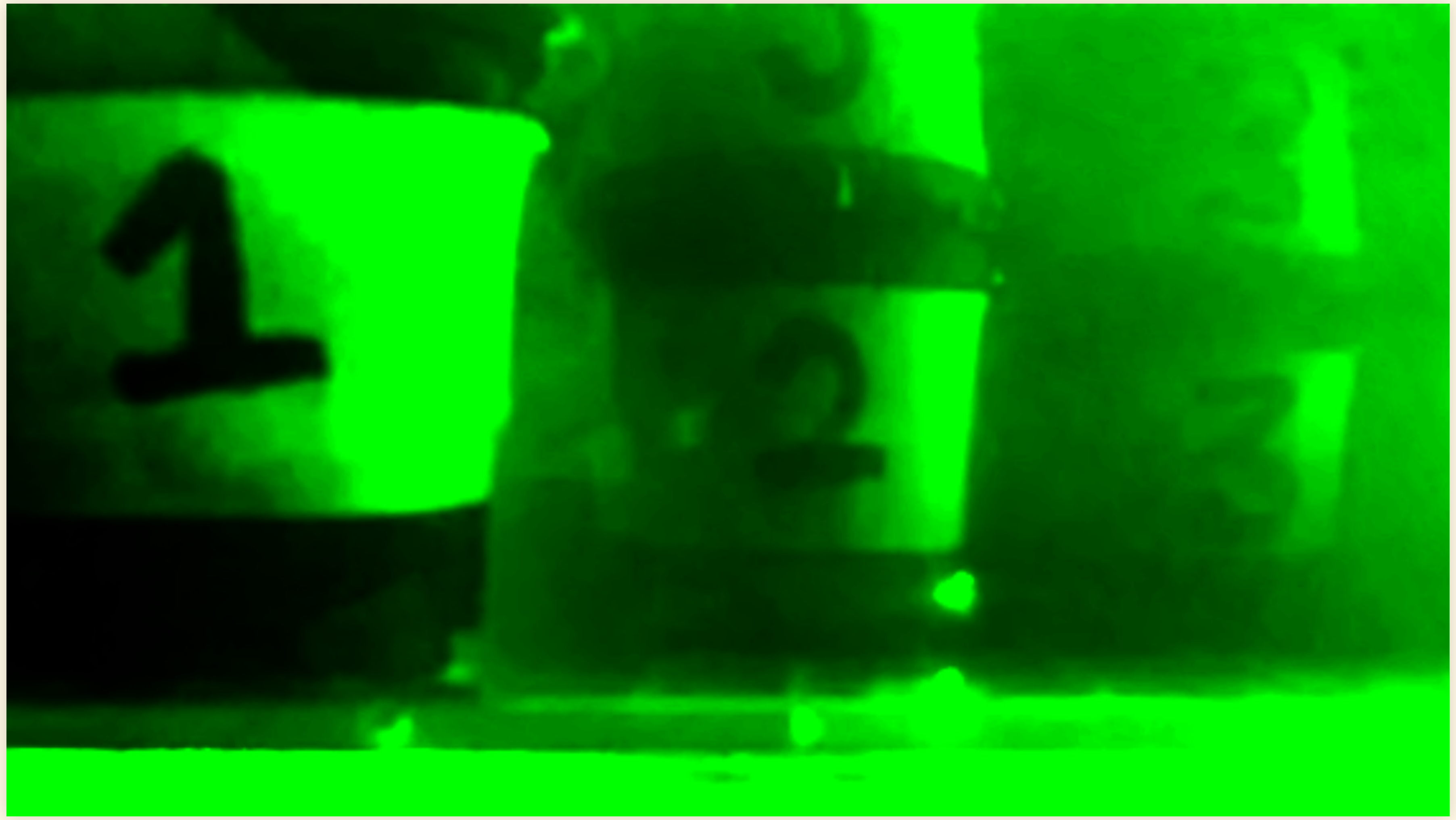
- Full visible spectrum



Visible Radiation in Colored Water

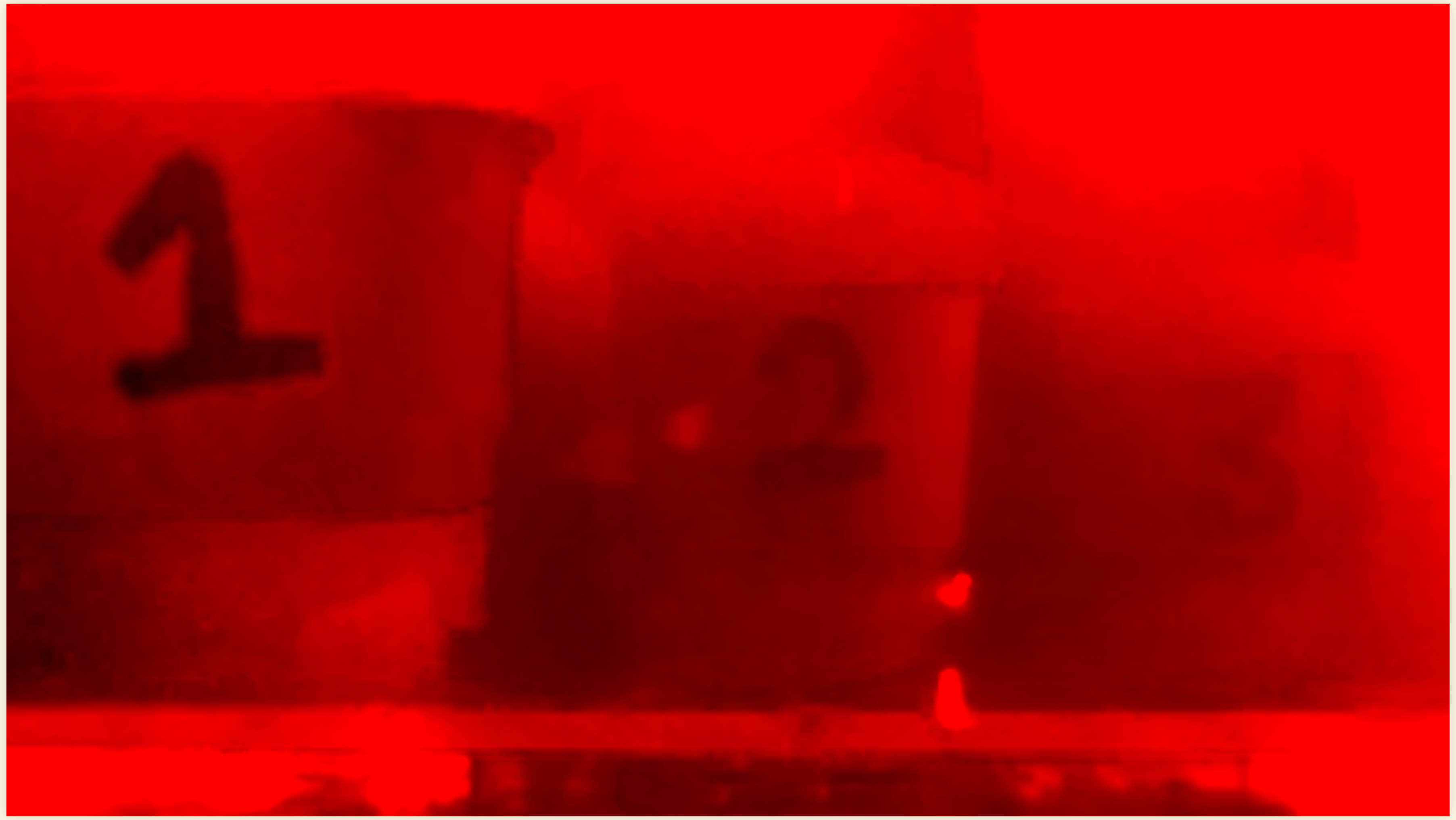
- Here are three cups with black-on-white labels
- The tank is filled with water, colored green with food-coloring

- Only the green frequencies



Visible Radiation in Colored Water

- Here are three cups with black-on-white labels
- The tank is filled with water, colored green with food-coloring
- Only the red frequencies

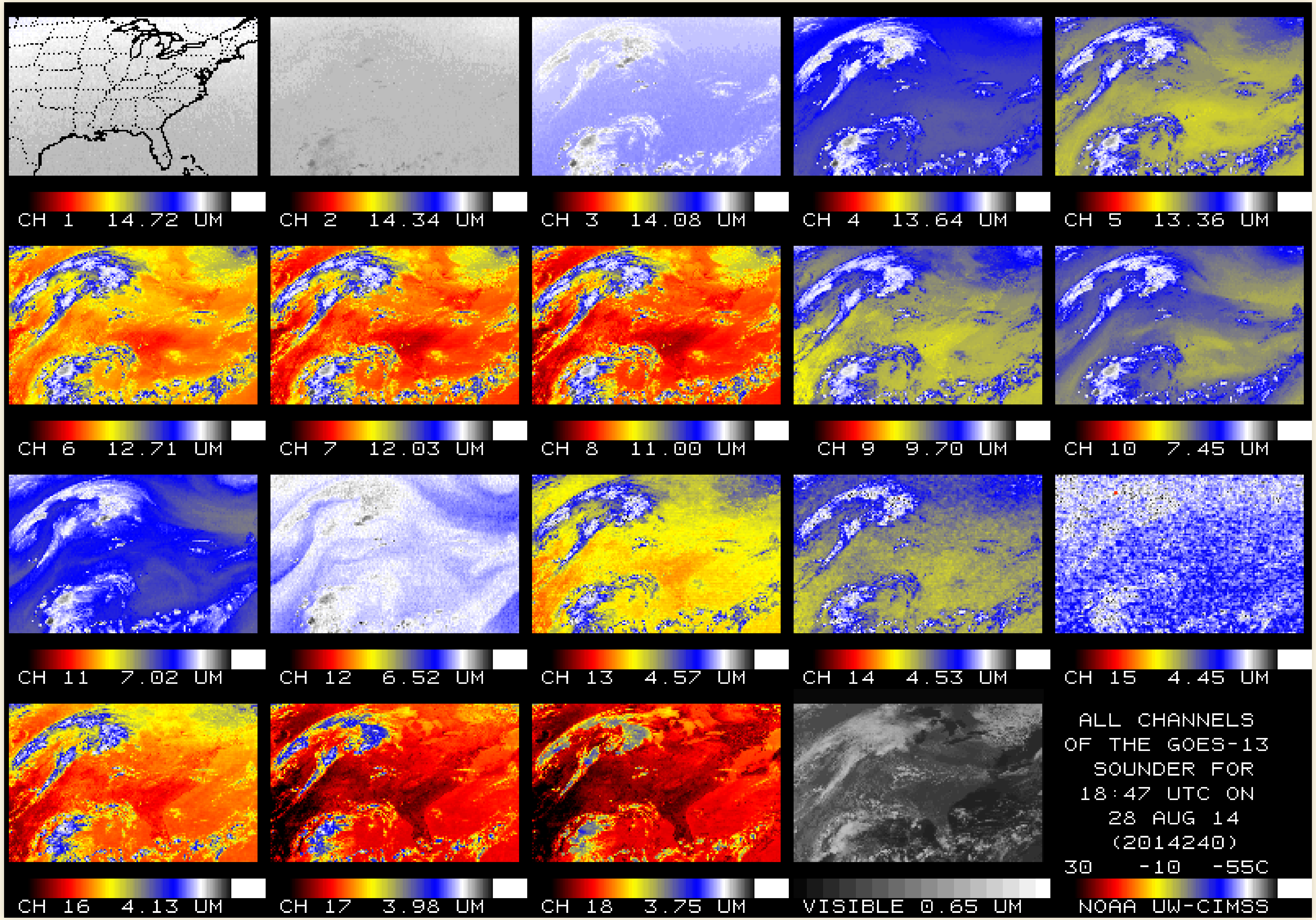


Visible Radiation in Colored Water

- Here are three cups with black-on-white labels
- The tank is filled with water, colored green with food-coloring

- Only the blue frequencies

Compare to Longwave Radiation in Atmosphere

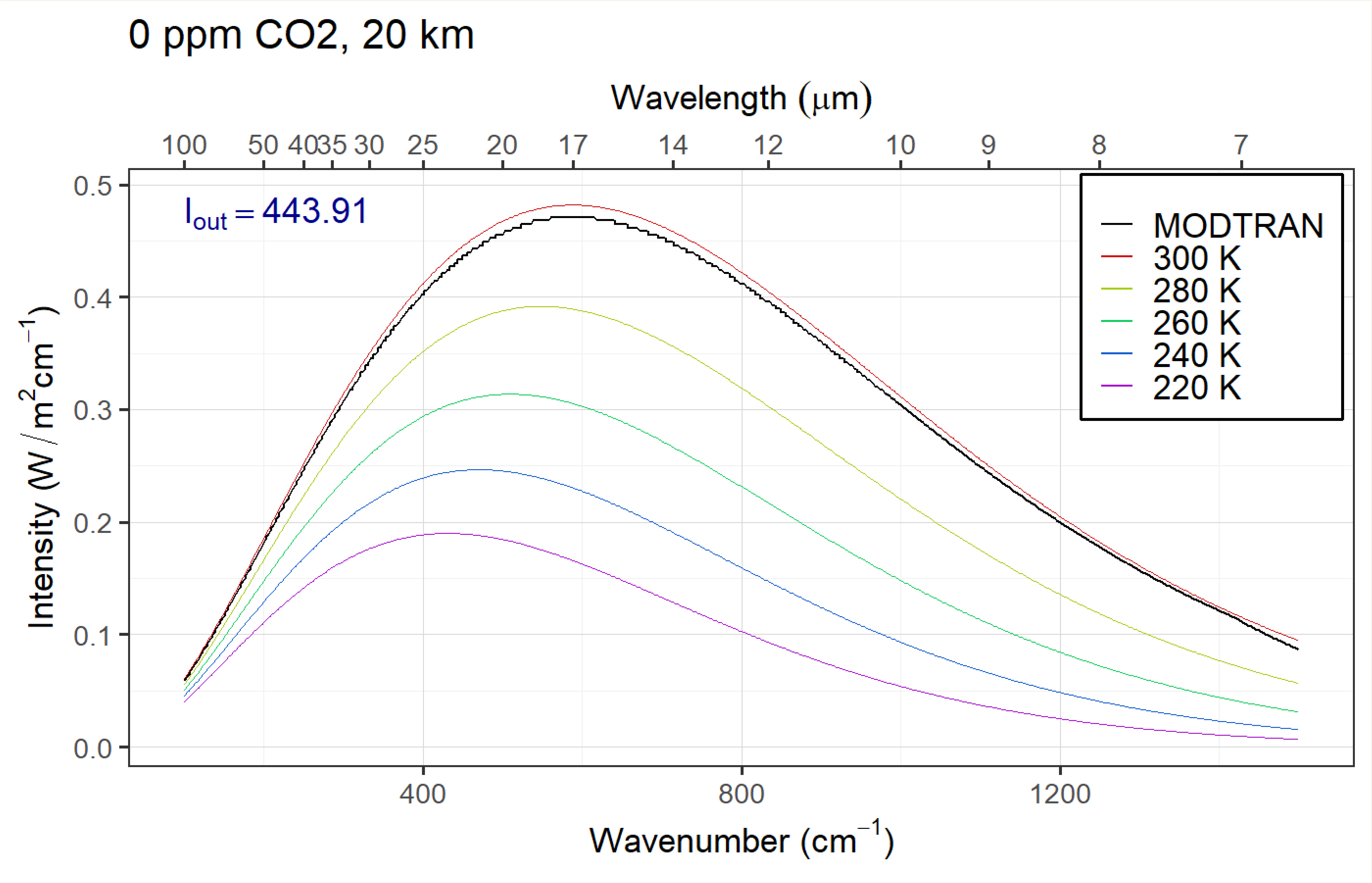


Band Saturation

Band Saturation:

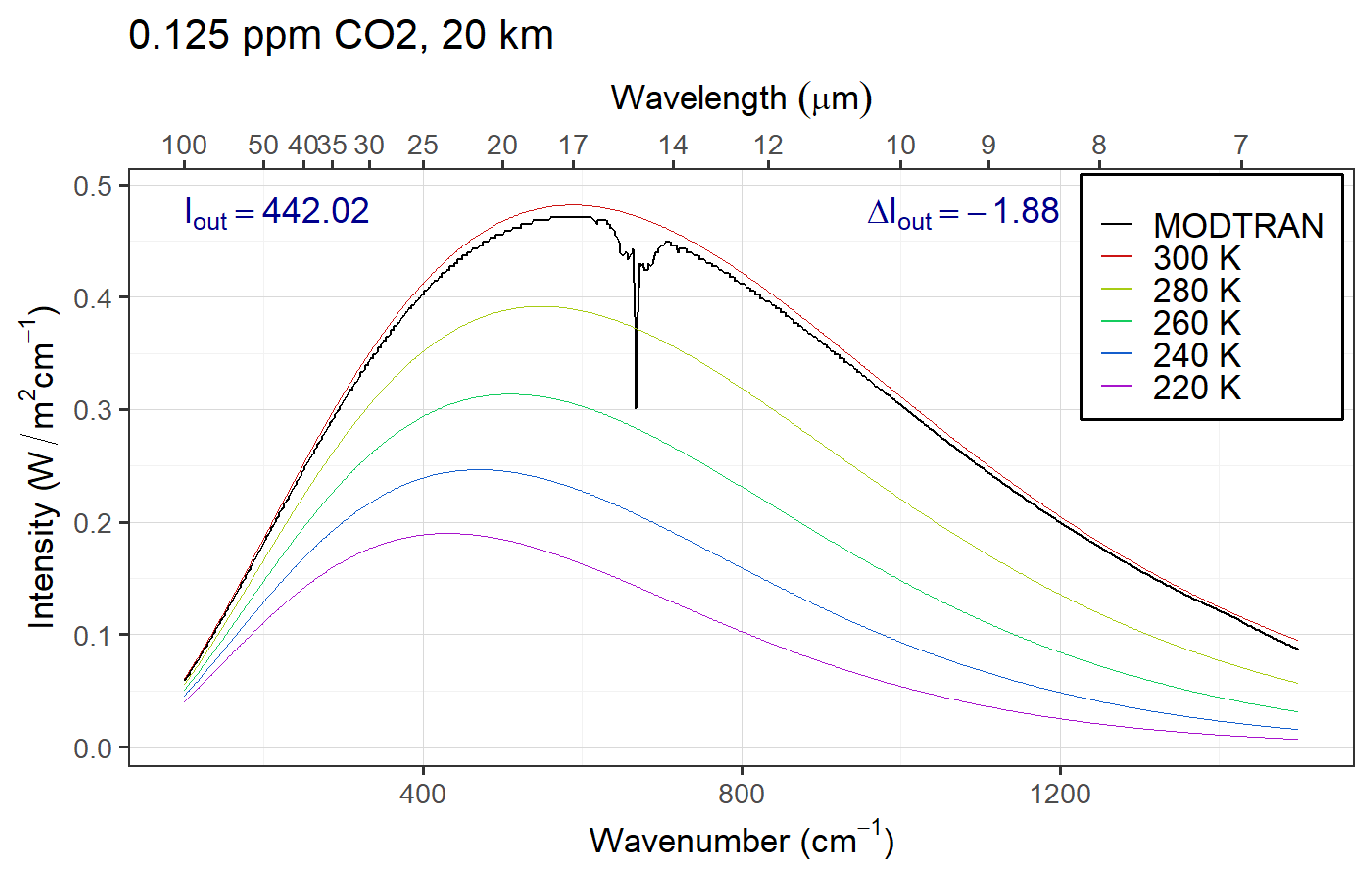
- Set All greenhouse gases to zero
- Set altitude to 20 km
- Start with a small concentration of CO2 and then keep doubling it

No CO_2



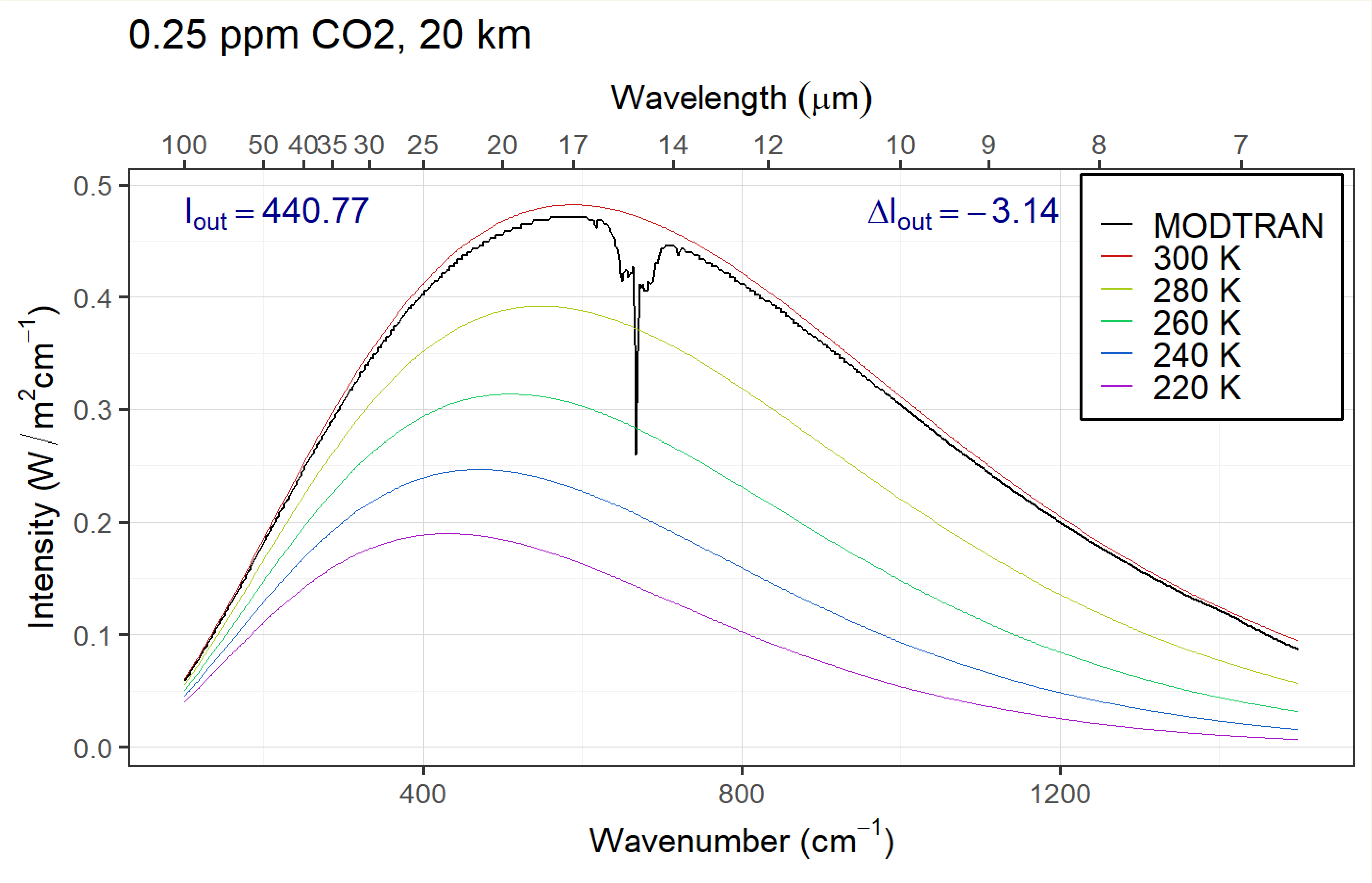
0 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 443.91$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W / m^2 cm^{-1}$)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

0.125 ppm CO_2



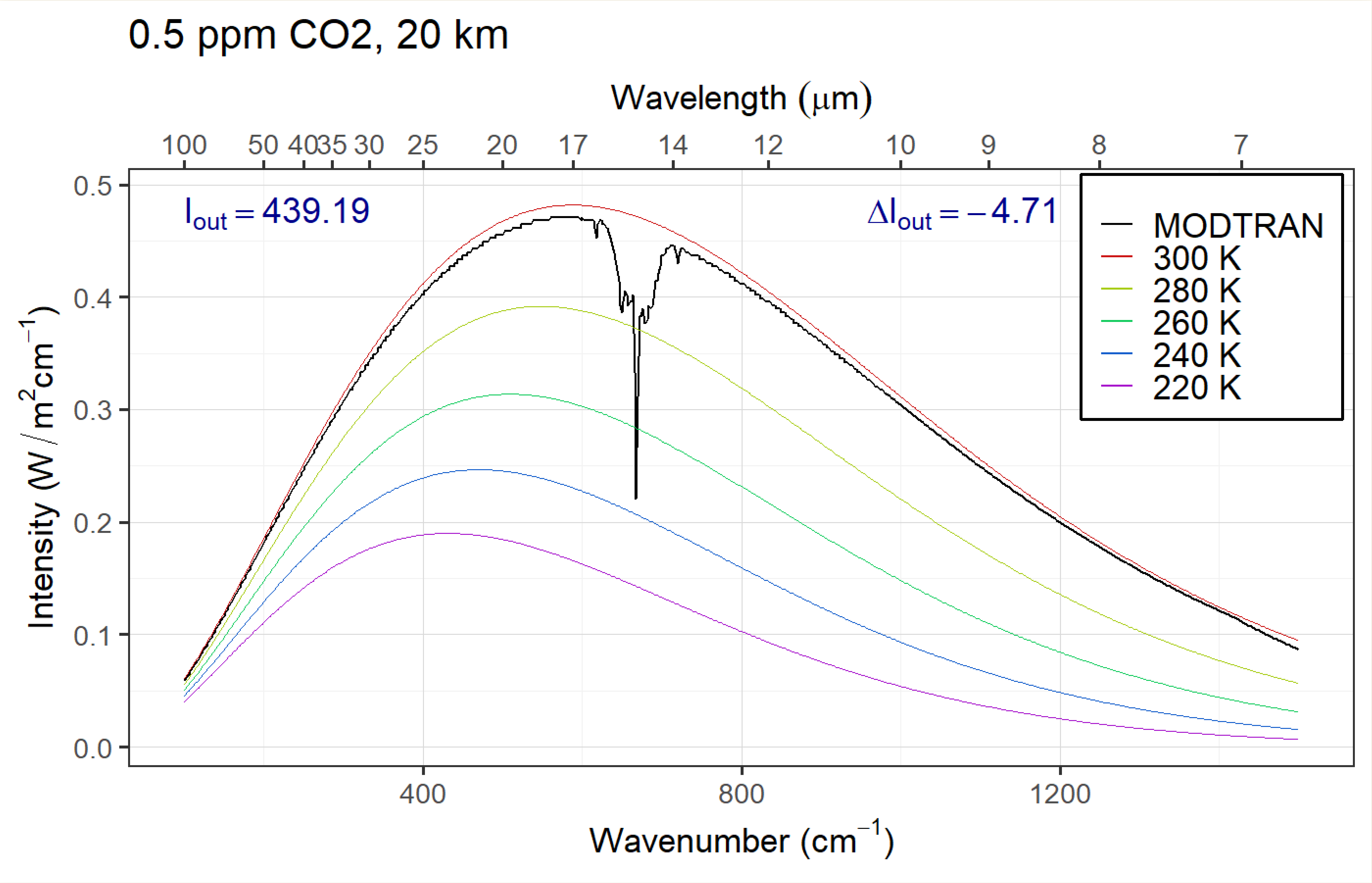
0.125 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
I_out = 442.02
ΔI_out = − 1.88
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm⁻¹)

0.25 ppm CO_2



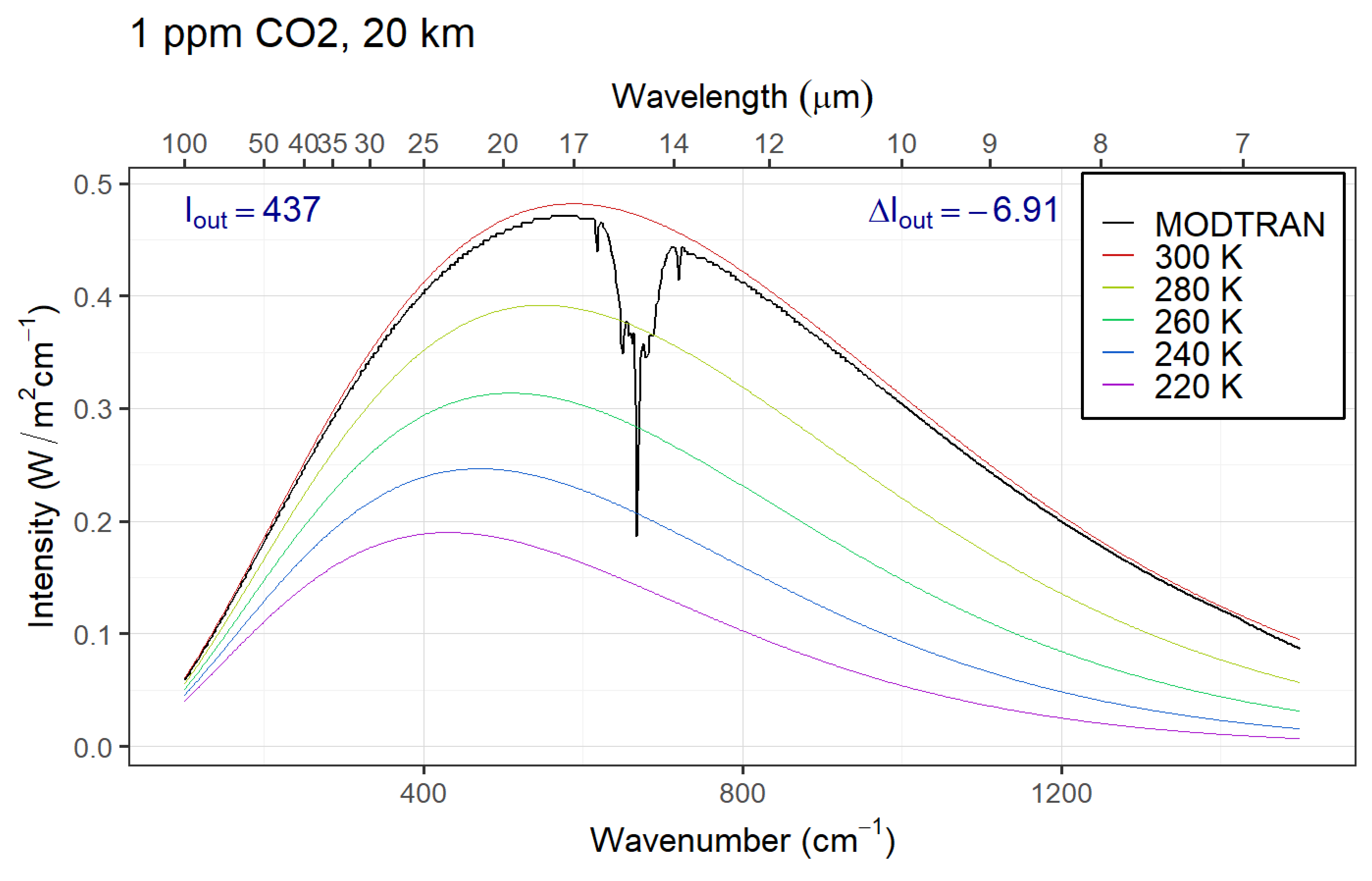
0.25 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 440.77$
$\Delta I_{out} = -3.14$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W/m^2cm^{-1})
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

0.5 ppm CO_2



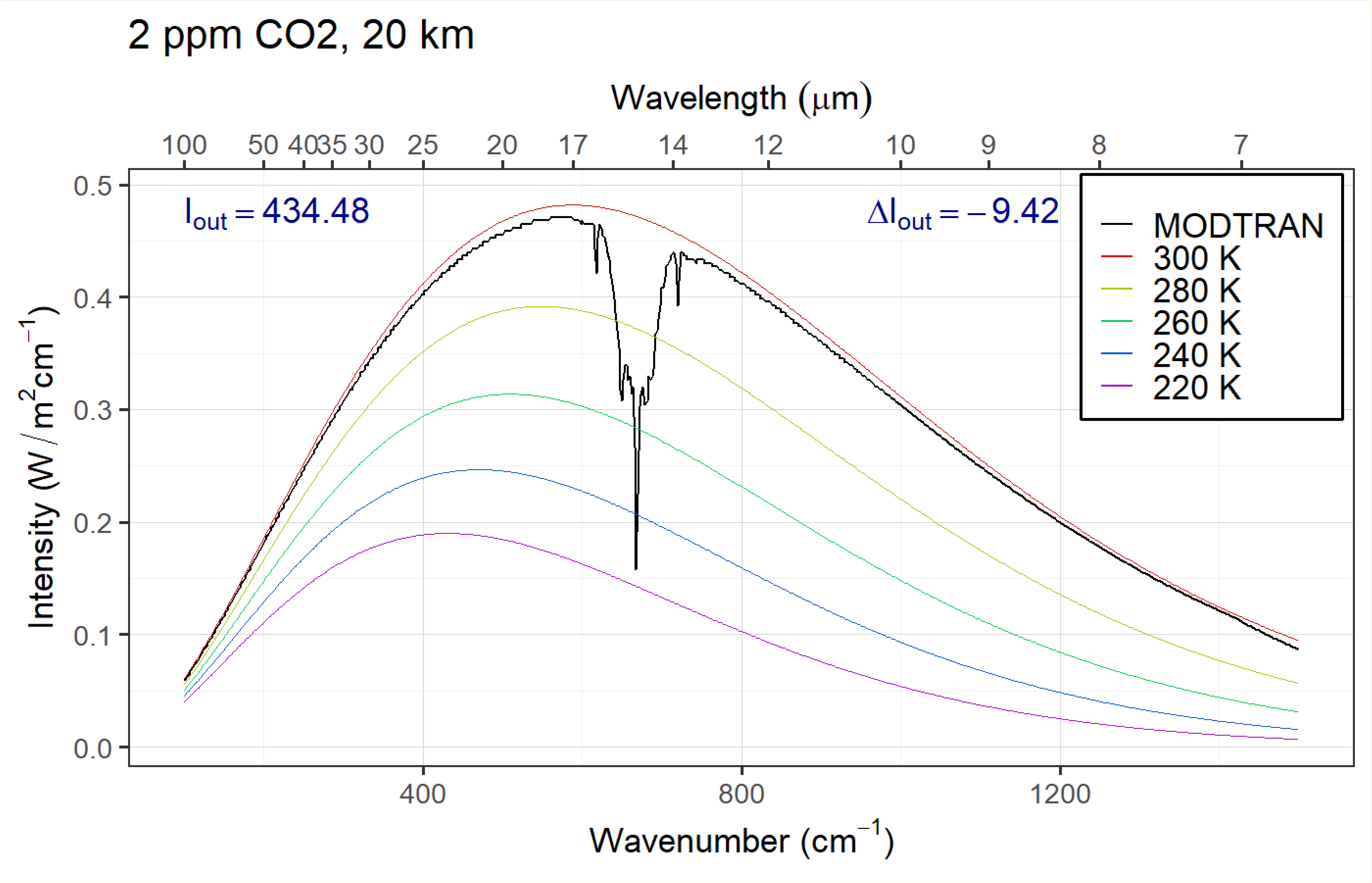
0.5 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 439.19$
$\Delta I_{out} = -4.71$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m²cm⁻¹)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm⁻¹)

1 ppm CO_2

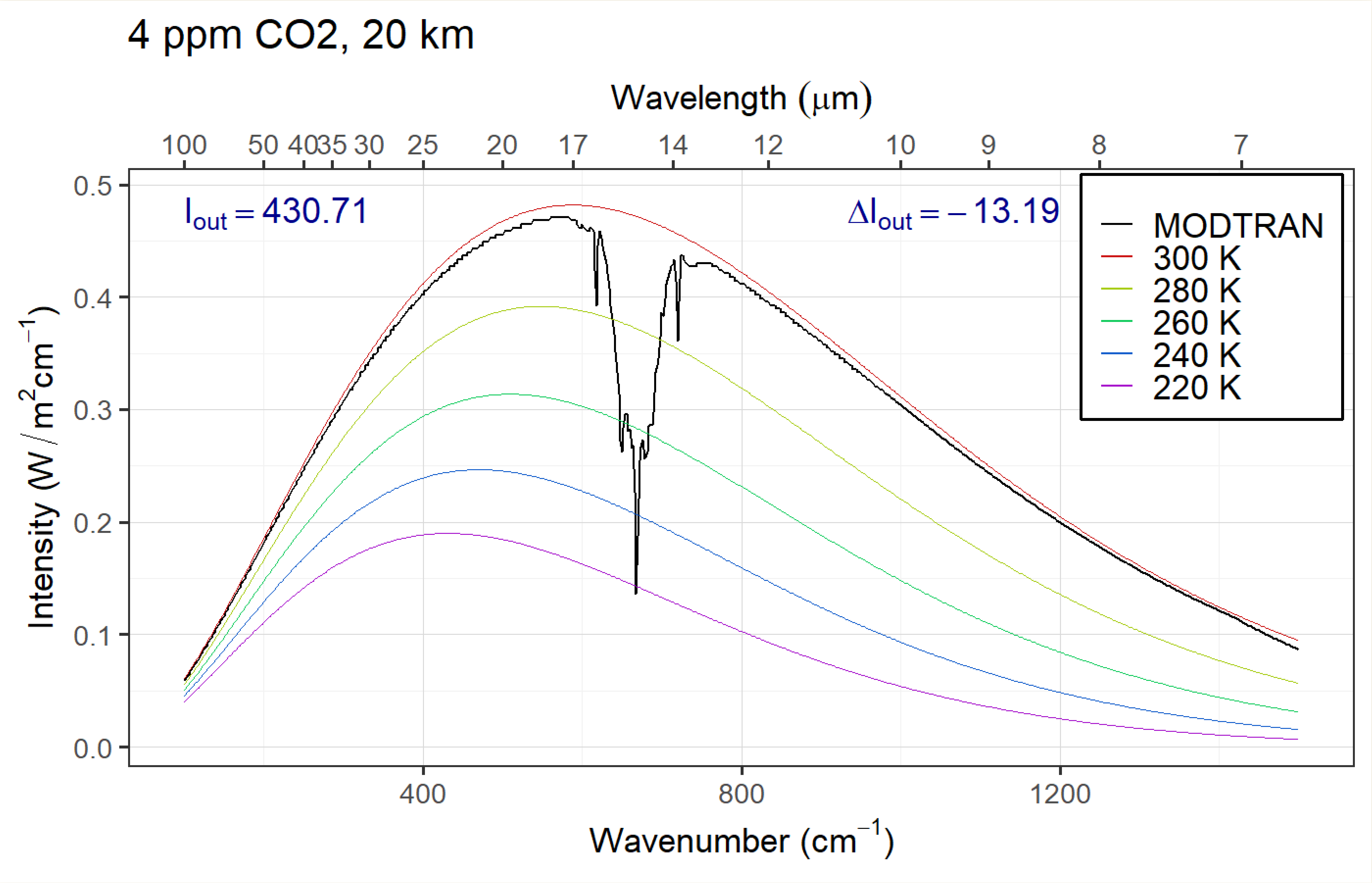


1 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 437$
$\Delta I_{out} = -6.91$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W / m^2 cm^{-1}$)
0.0
0.1
0.2
0.3
0.4
0.5
400
800
1200
Wavenumber (cm^{-1})

2 ppm CO_2

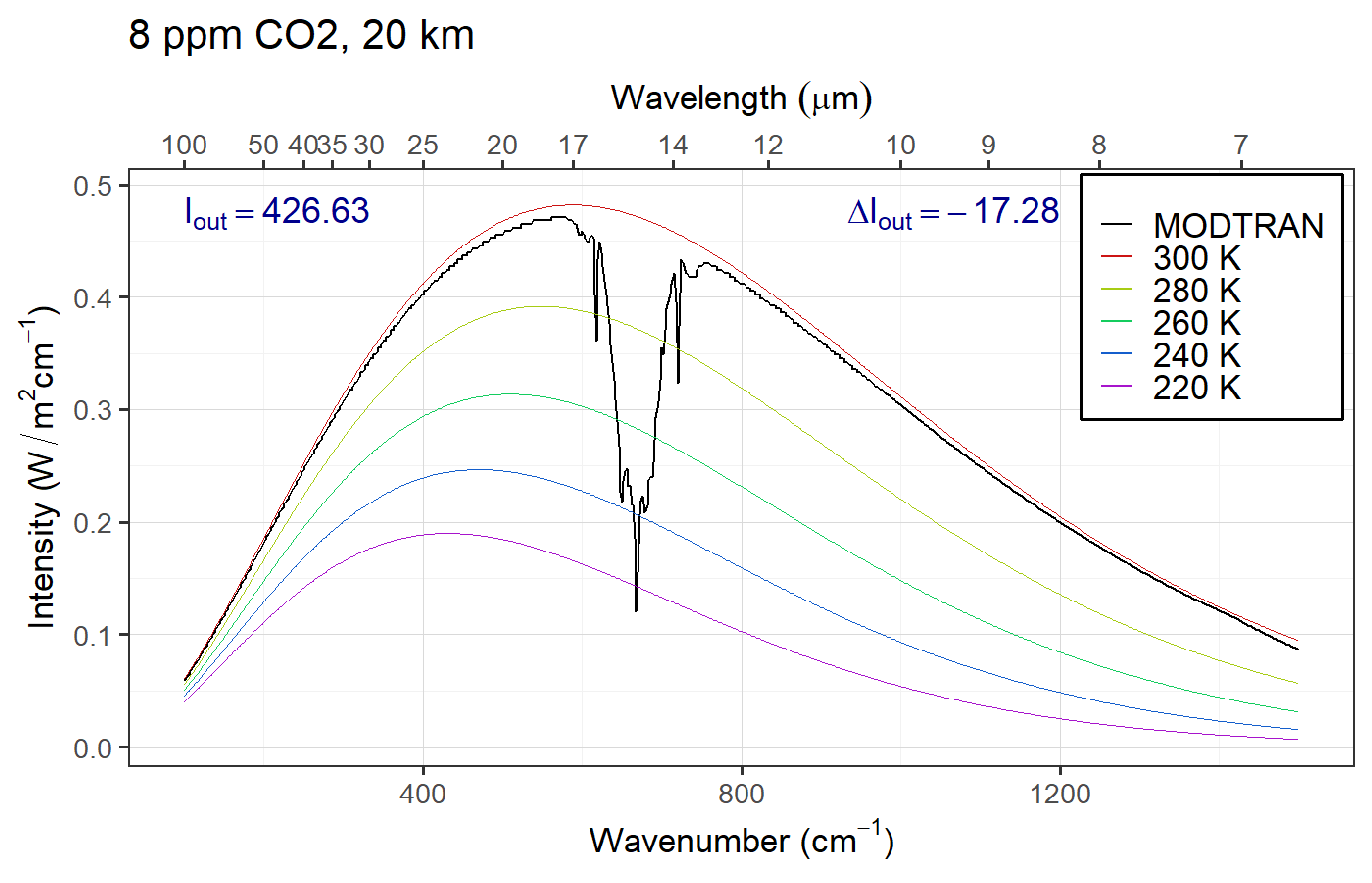

2 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 434.48$
$\Delta I_{out} = -9.42$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W/m^2 cm^{-1}$)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

4 ppm CO_2



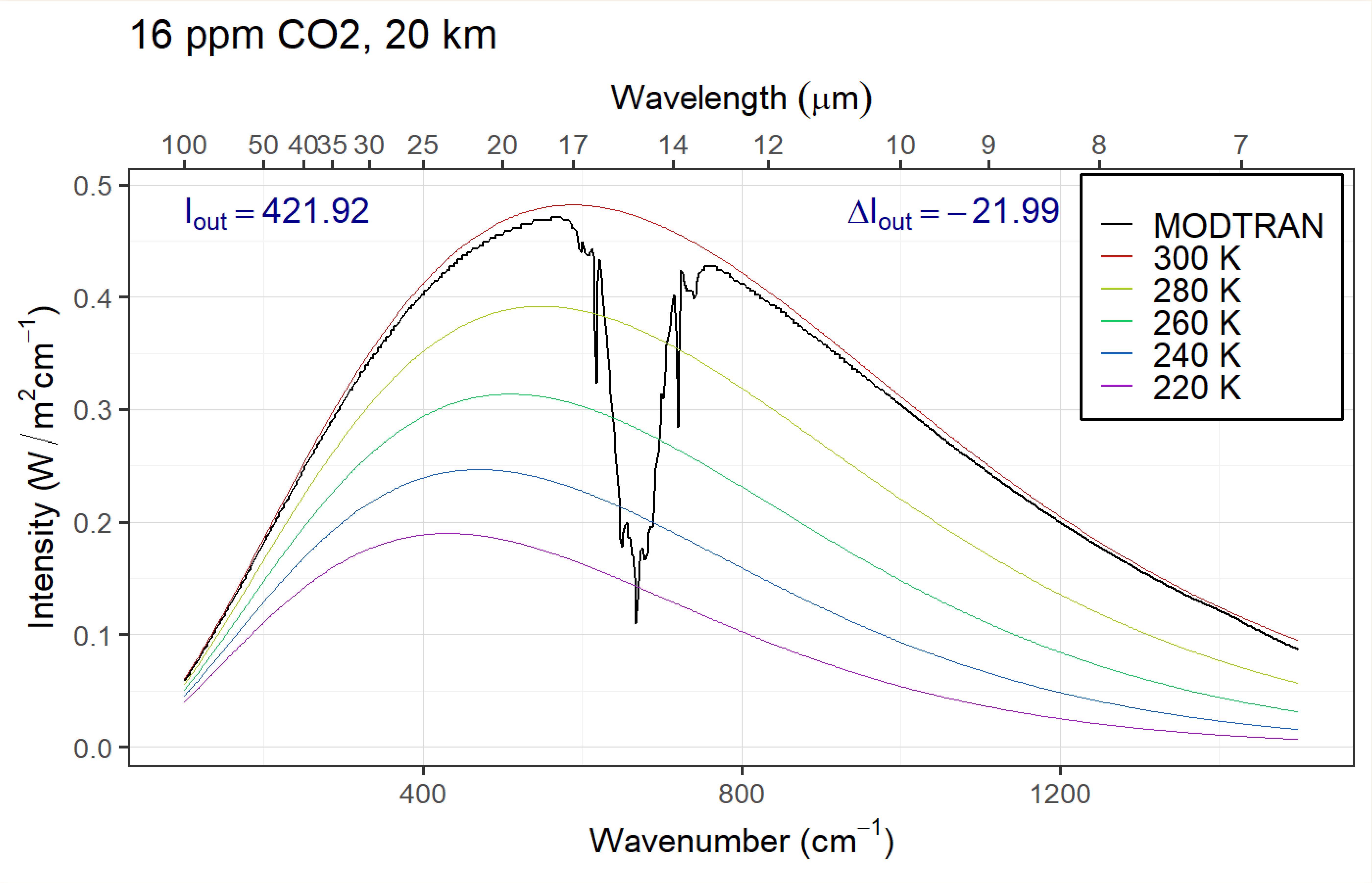
4 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 430.71$
$\Delta I_{out} = -13.19$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m²cm⁻¹)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm⁻¹)

8 ppm CO_2



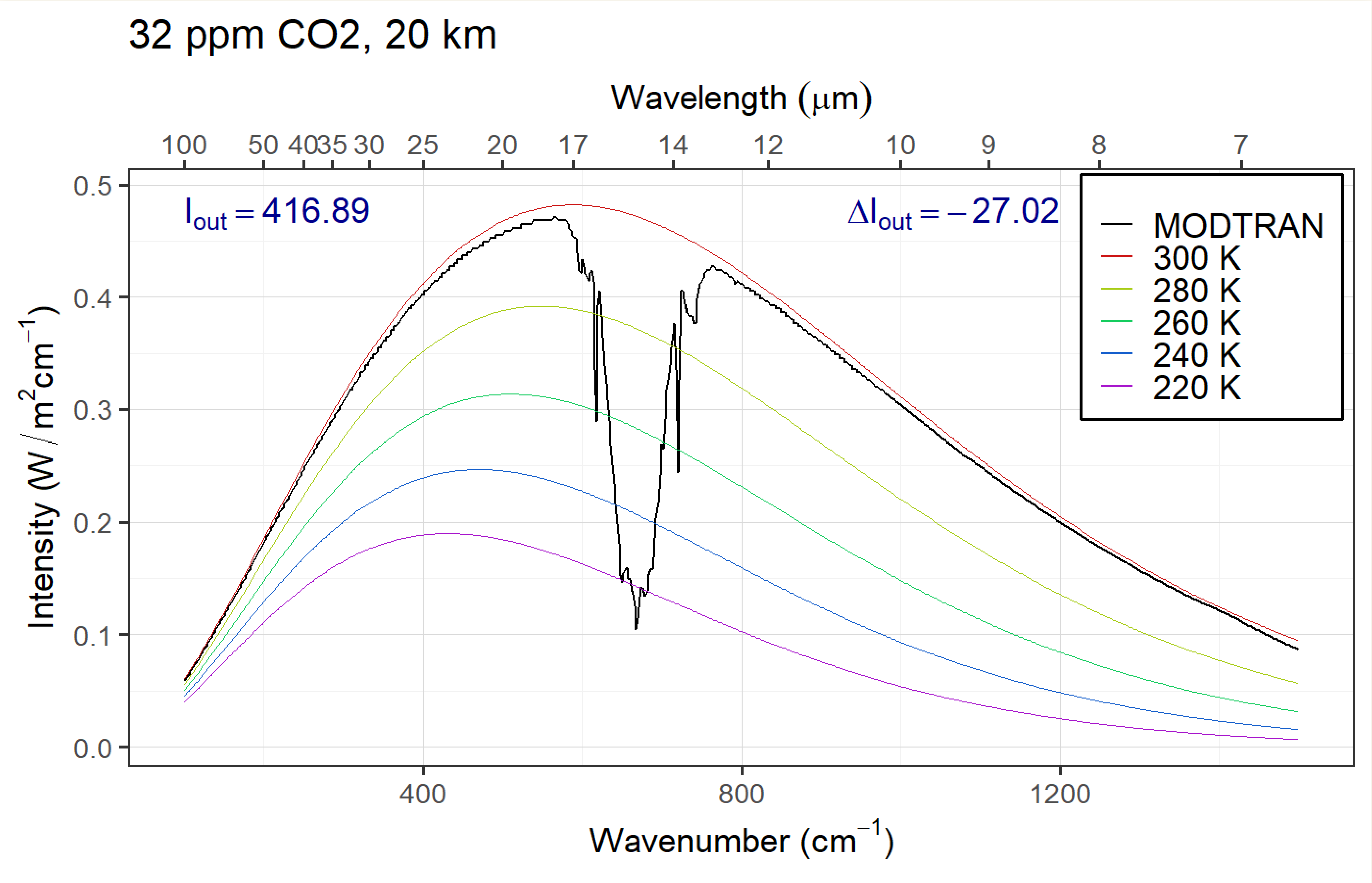
8 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 426.63$
$\Delta I_{out} = -17.28$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W / m^2 cm^{-1}$)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

16 ppm CO_2



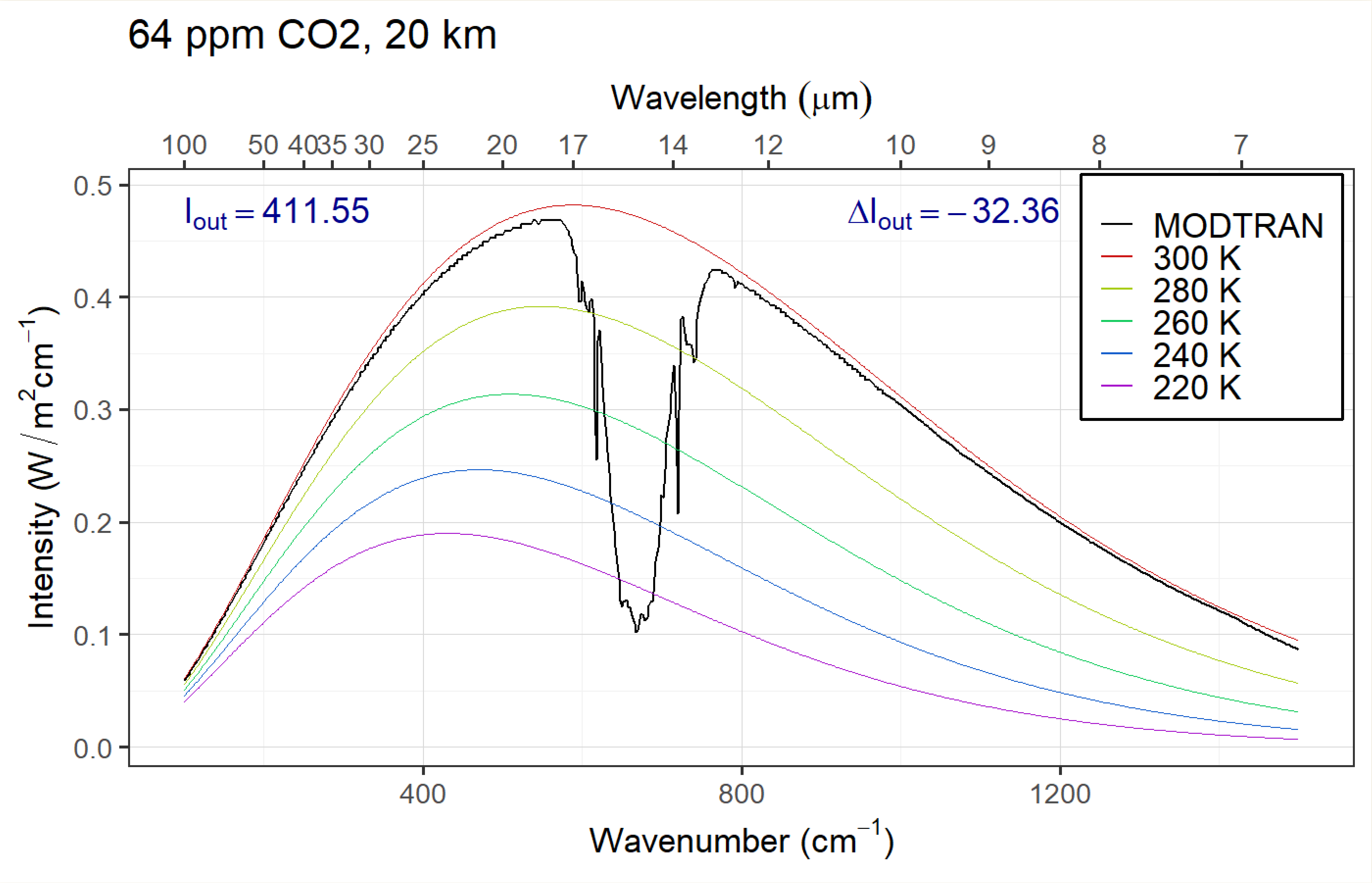
16 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 421.92$
$\Delta I_{out} = -21.99$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W/m^2cm^{-1})
0.0
0.1
0.2
0.3
0.4
0.5
400
800
1200
Wavenumber (cm^{-1})

32 ppm CO_2



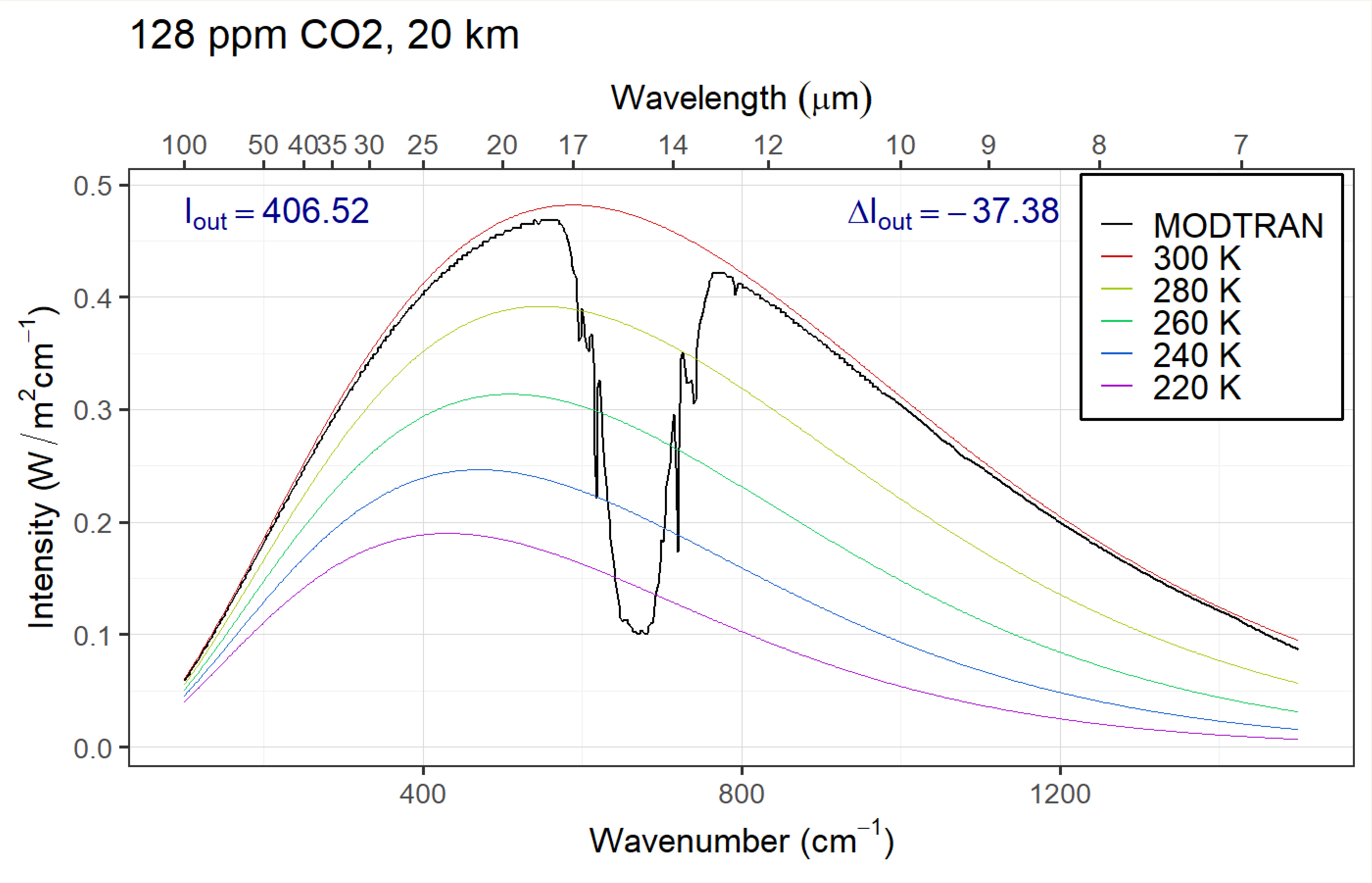
32 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 416.89$
$\Delta I_{out} = -27.02$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity $(W/m^2 cm^{-1})$
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

64 ppm CO_2



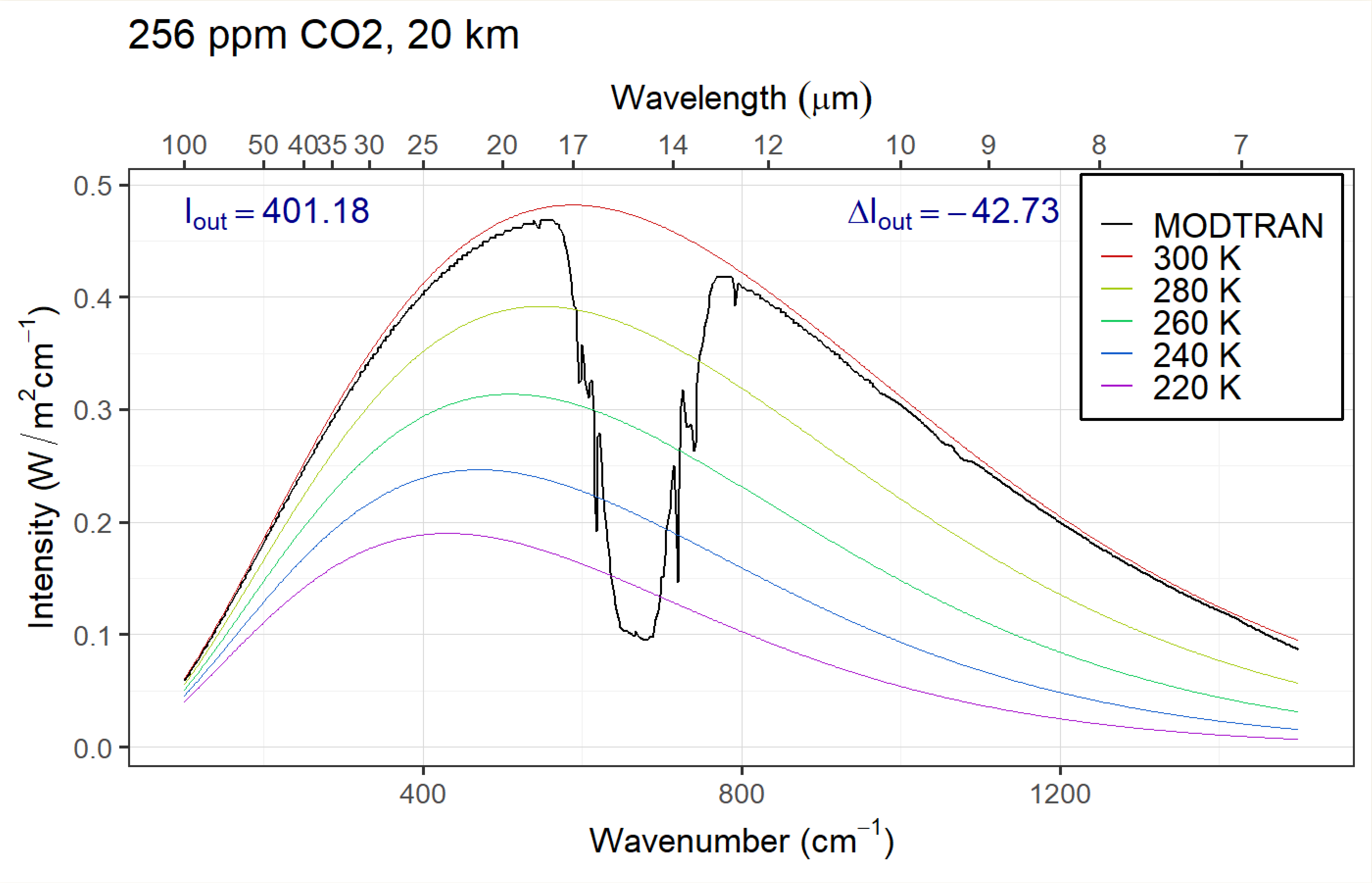
64 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 411.55$
$\Delta I_{out} = -32.36$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W/m^2 cm^{-1}$)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

128 ppm CO_2



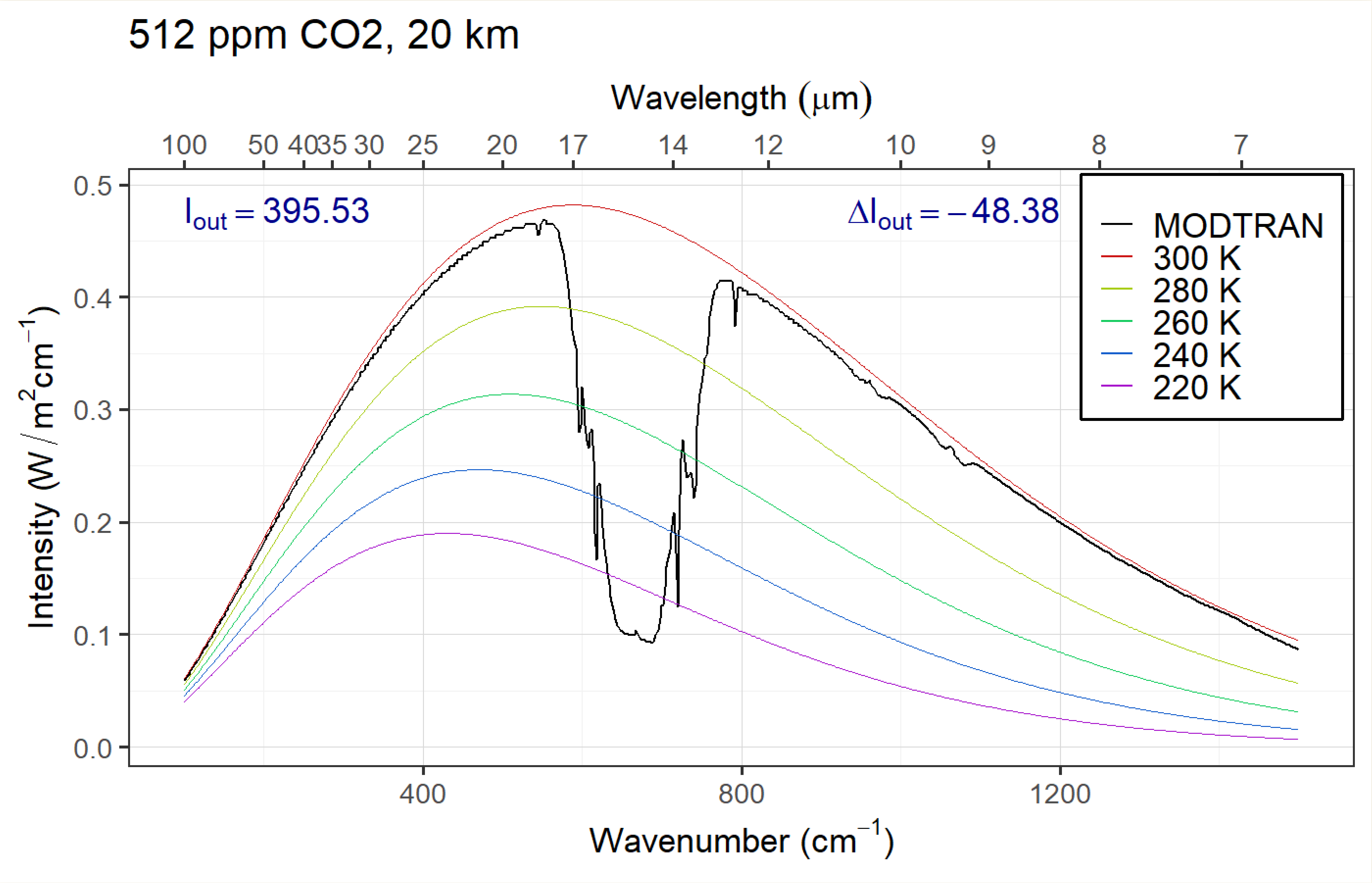
128 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 406.52$
$\Delta I_{out} = -37.38$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity $(W / m^2 cm^{-1})$
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

256 ppm CO_2



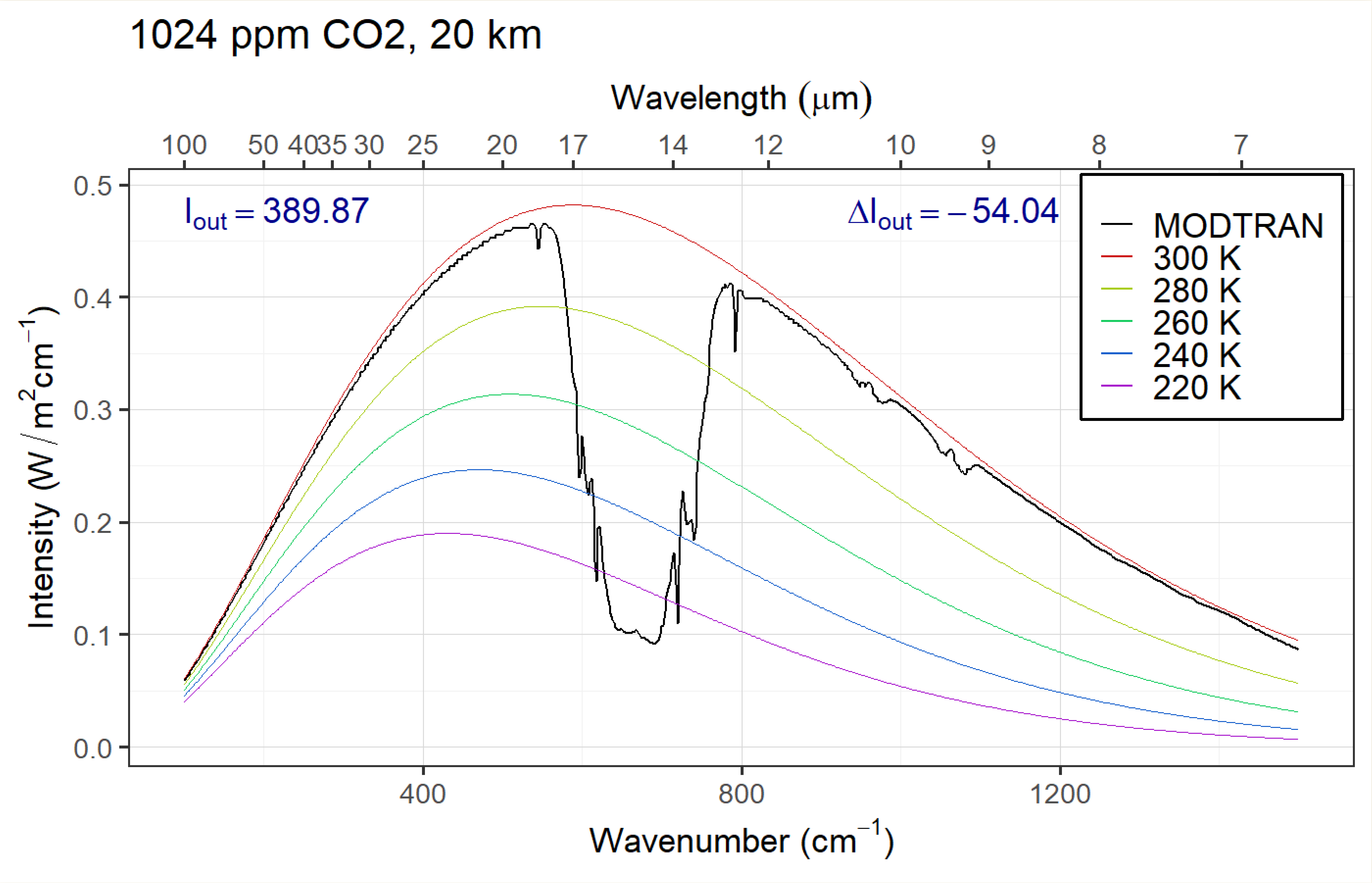
256 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 401.18$
$\Delta I_{out} = -42.73$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity $(W/m^2 cm^{-1})$
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

512 ppm CO_2



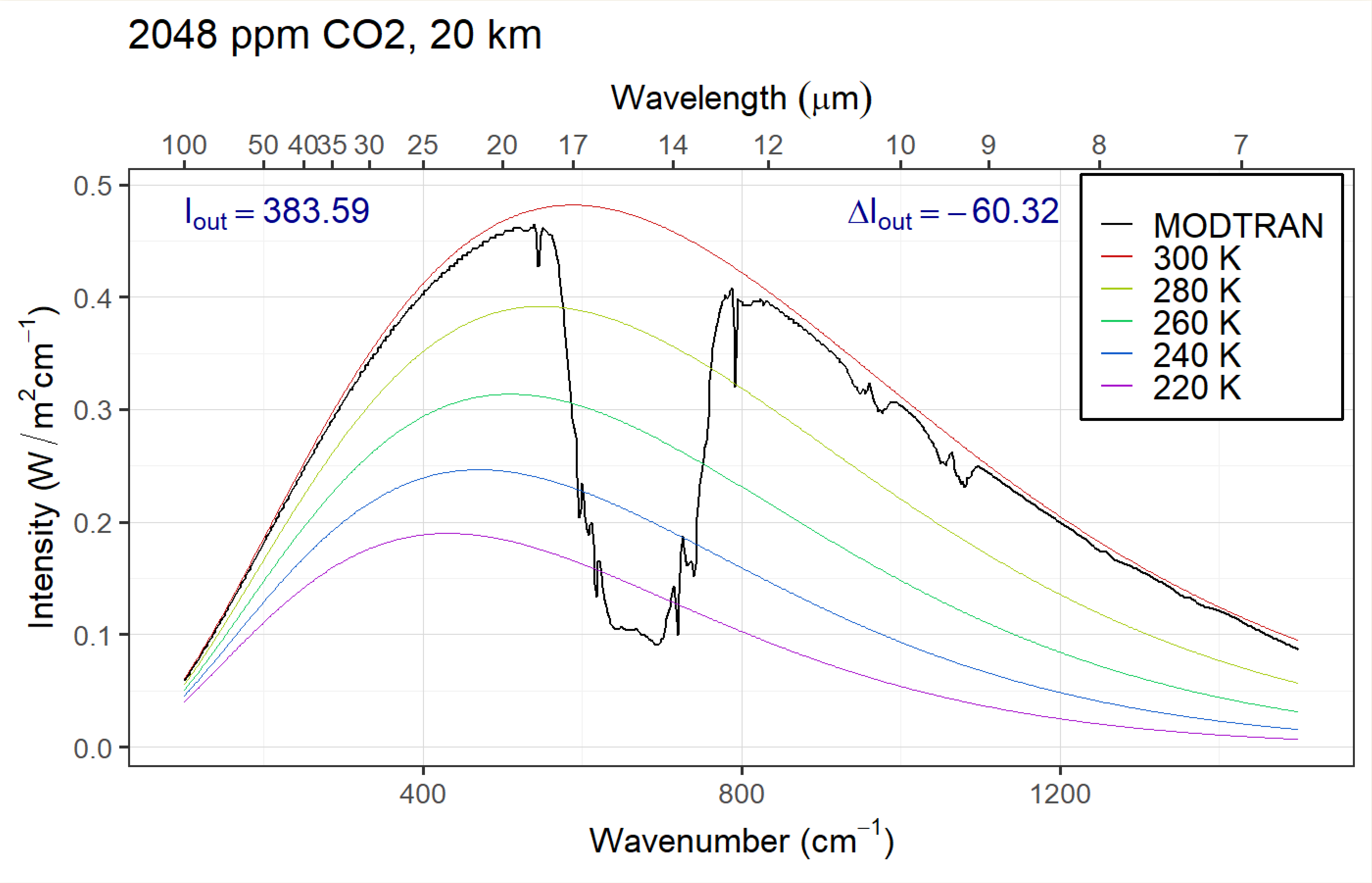
512 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 395.53$
$\Delta I_{out} = -48.38$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity $(W / m^2 cm^{-1})$
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

1024 ppm CO_2



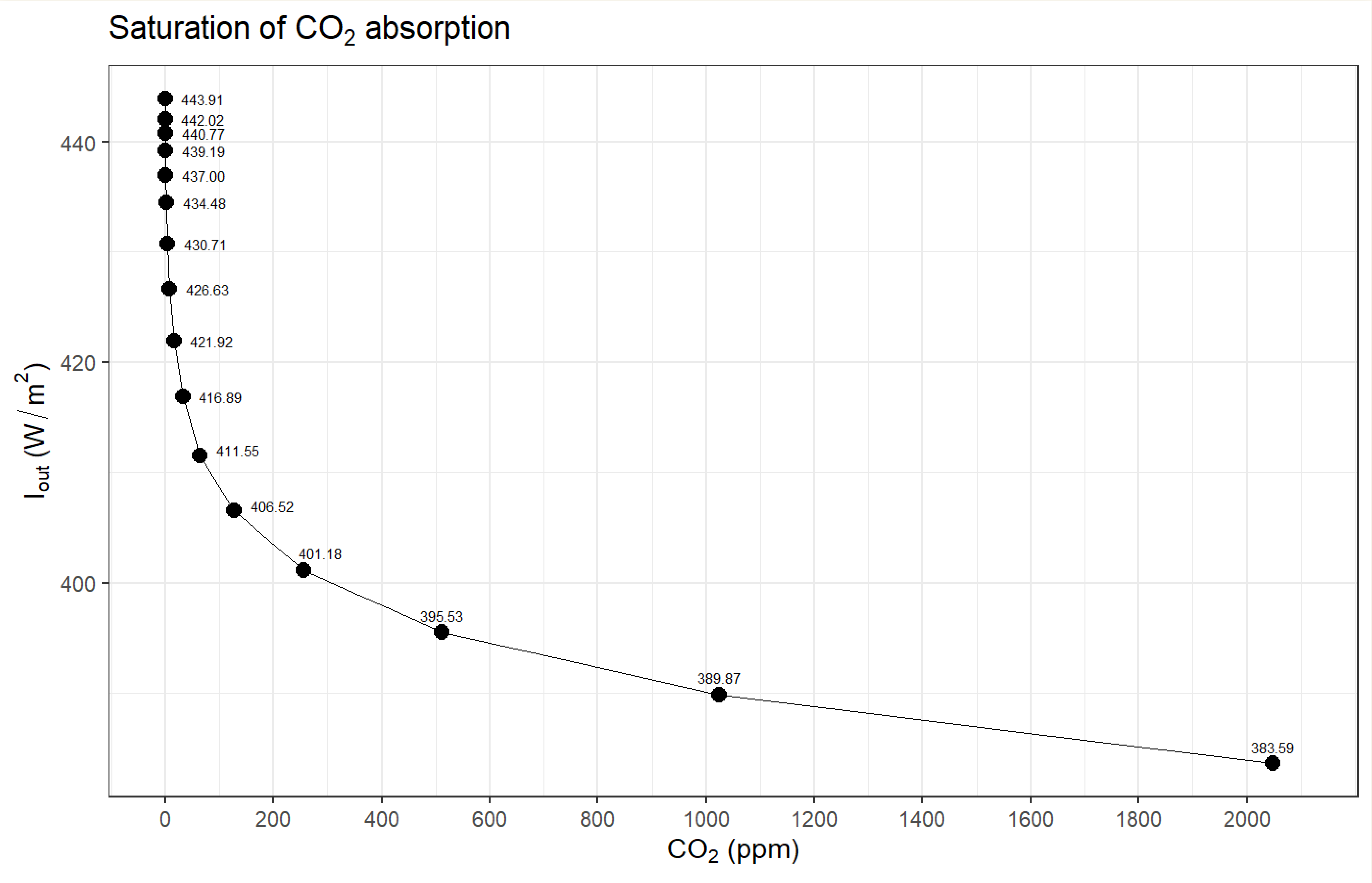
1024 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 389.87$
$\Delta I_{out} = -54.04$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W/m^2 cm^{-1}$)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

2048 ppm CO_2

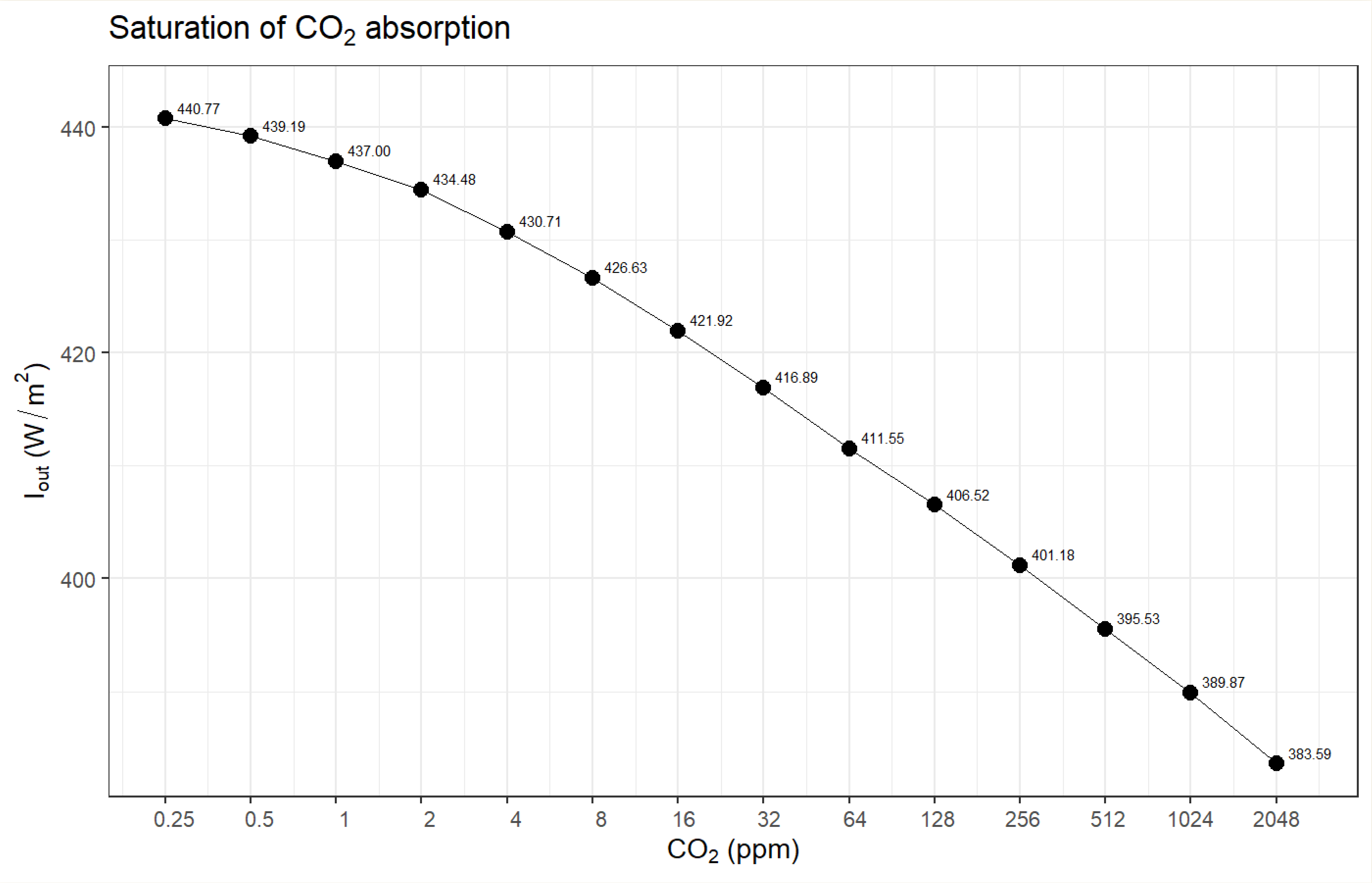


2048 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 383.59$
$\Delta I_{out} = -60.32$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W/m^2cm^{-1})
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

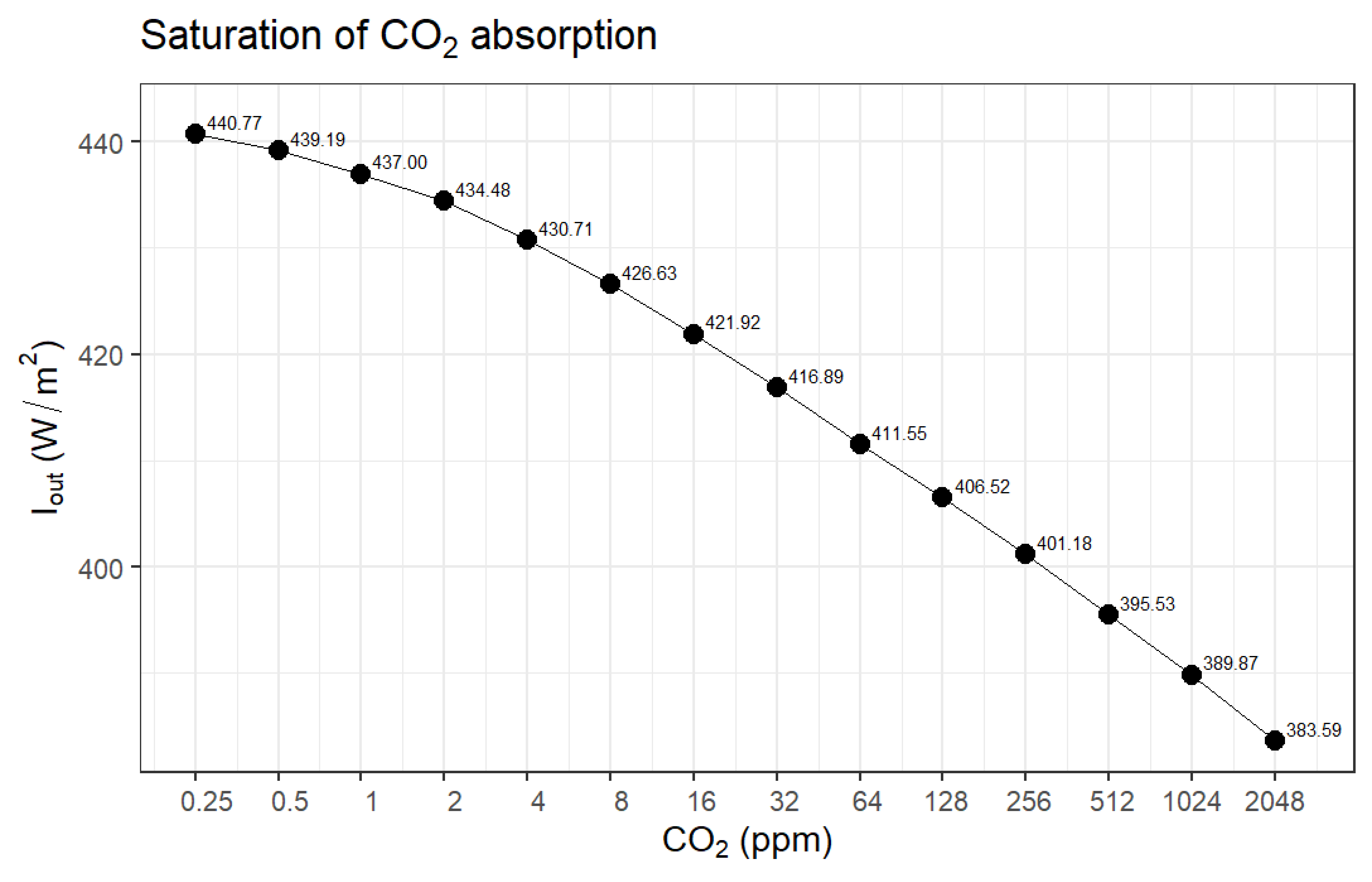
Band Saturation (I_{out})



I_{out} (CO_2 on log scale)



Saturation



- When absorption is saturated,
  - You get the same change in I_{out} every time you double CO_2.

Calculating Global Warming

Calculating Global Warming

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

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 methane molecule = dozens of CO_2 molecules
  - 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

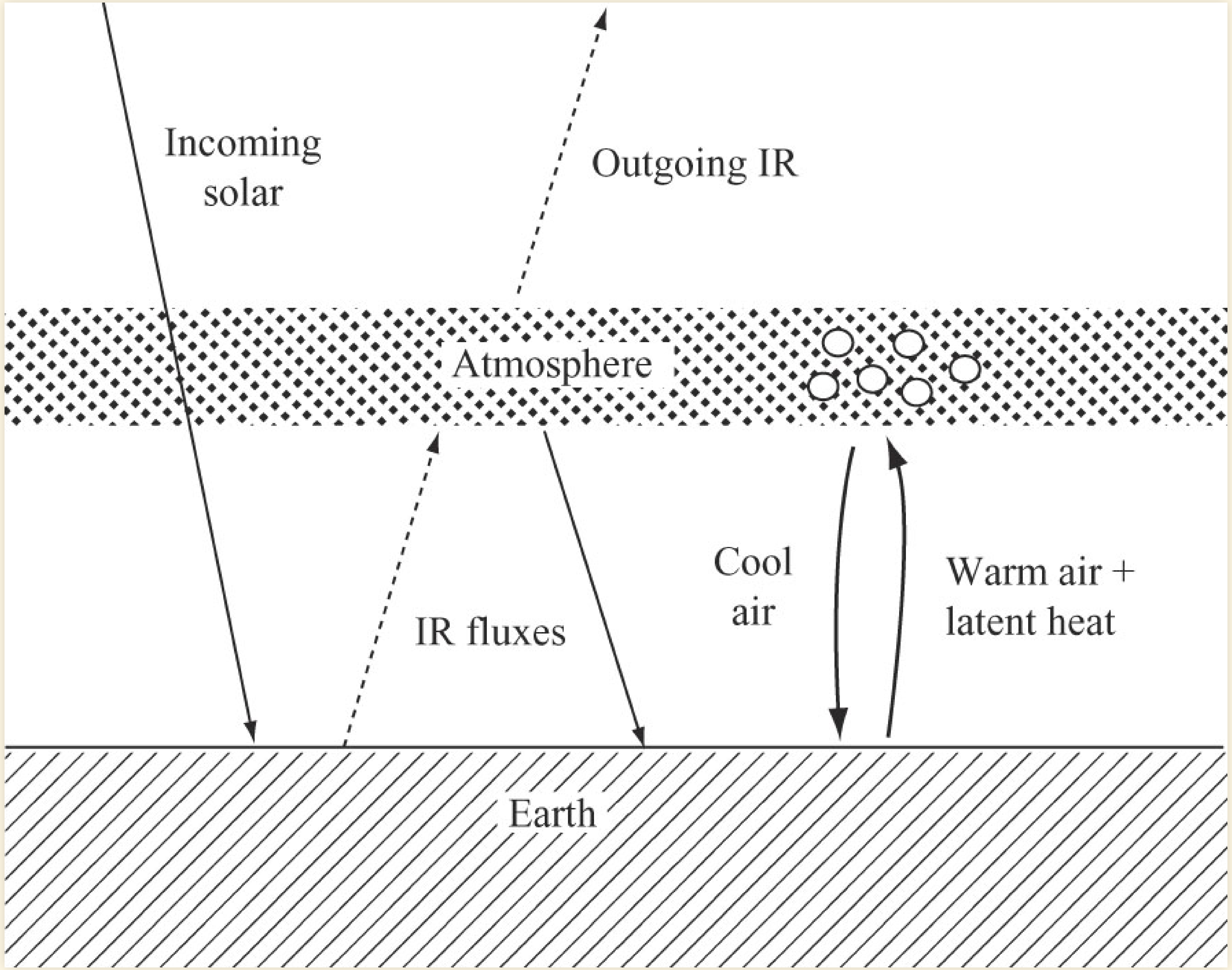
1. Purely radiative (no convection)
    - Each layer has uniform temperature
        a. Single-layer, uniform spectrum (Wed. 1/18)
            - Absorbs 100% longwave light
        b. Multi-layer, uniform spectrum
            - More layers $\Rightarrow$ greater greenhouse effect.
        c. Realistic spectrum (Fri. 1/20 & Mon. 1/23)
            - More realistic
            - Harder to do calculations (need computer)
2. Introduce convection (Today & Fri. 1/27)
    - 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

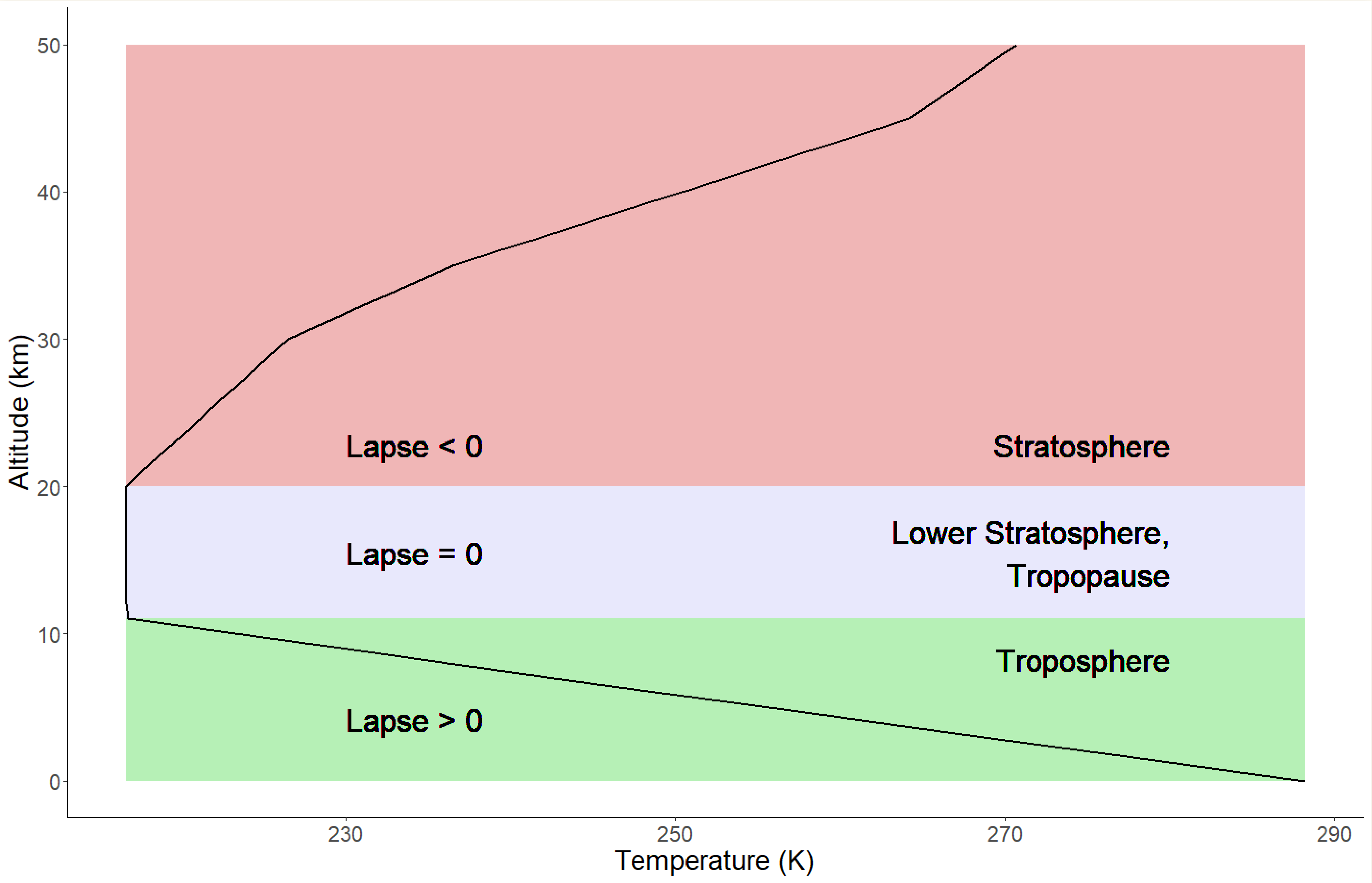
Greenhouse effect

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:



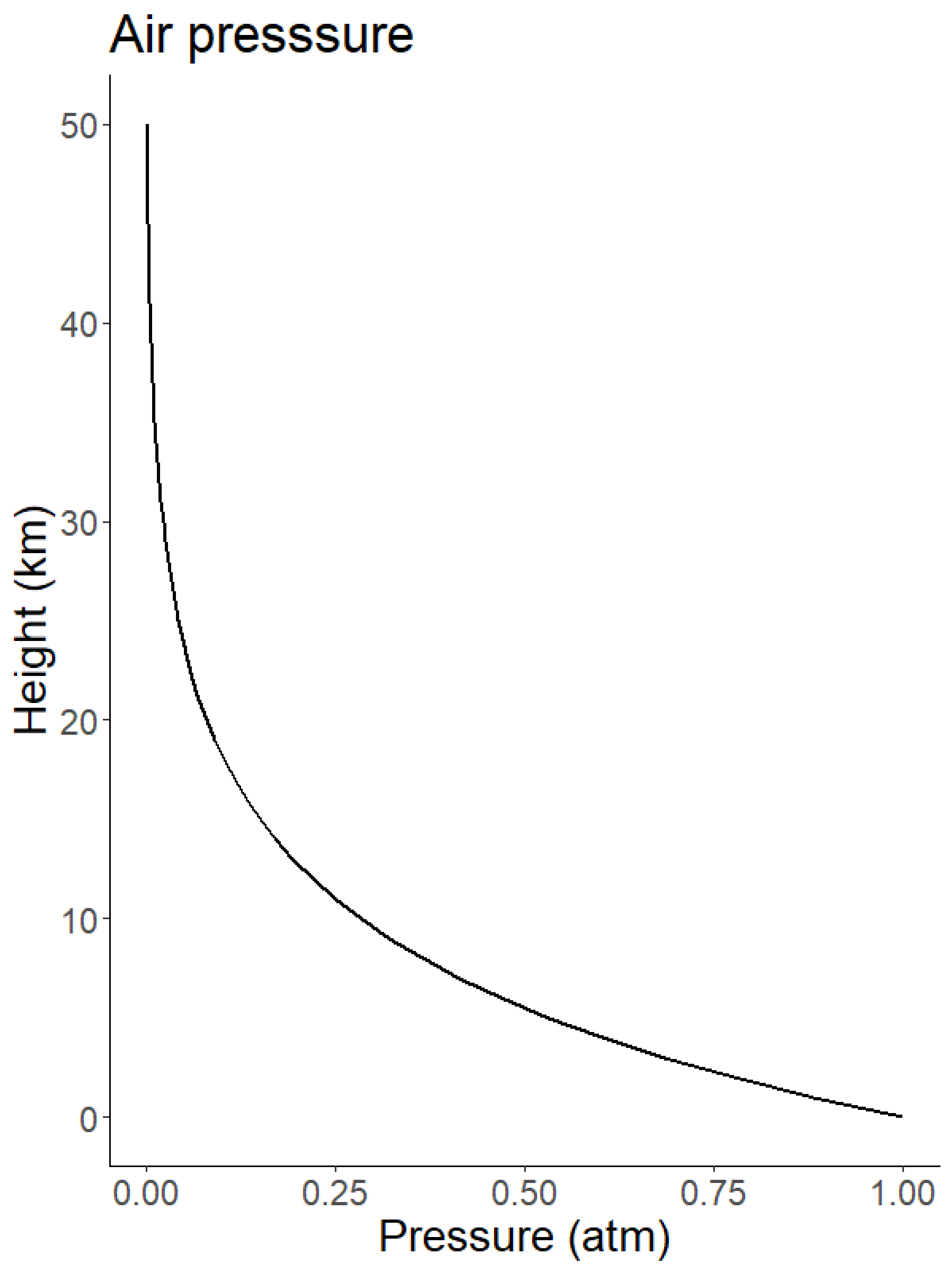
Vertical Structure

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

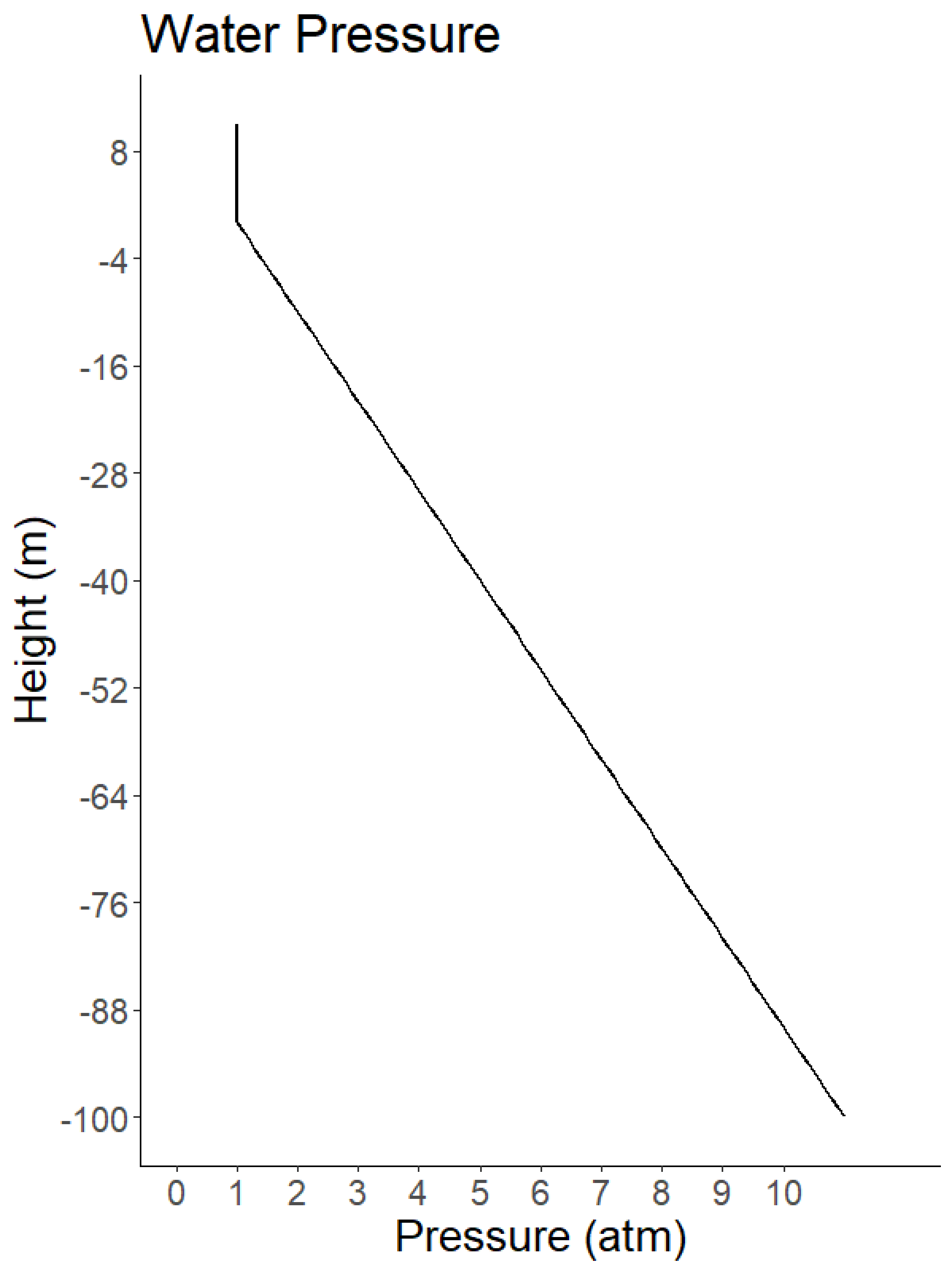
Δ means "change"

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

Air vs. Water



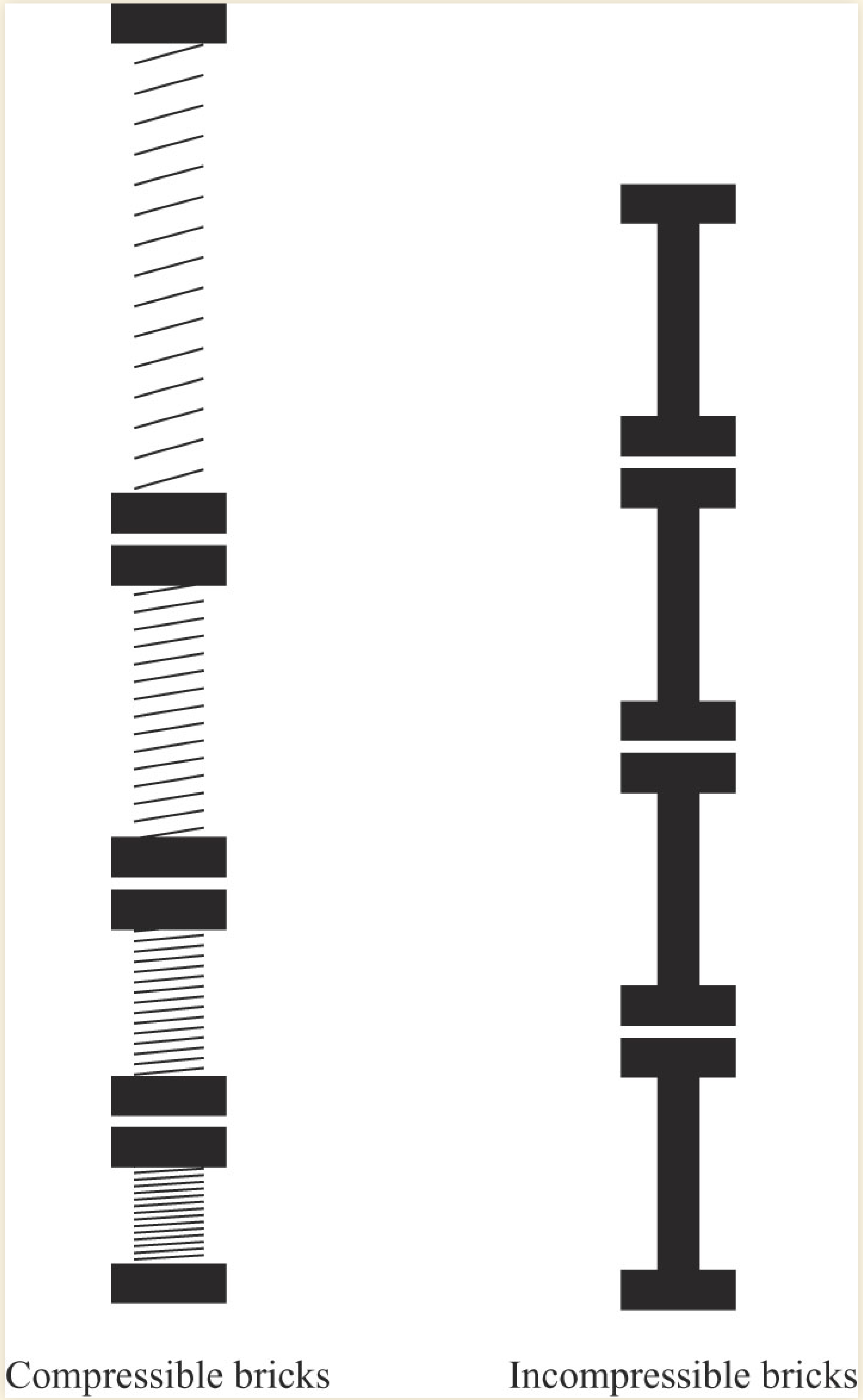
Air presssure
Height (km)
50
40
30
20
10
0
0.00
0.25
0.50
0.75
1.00
Pressure (atm)



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

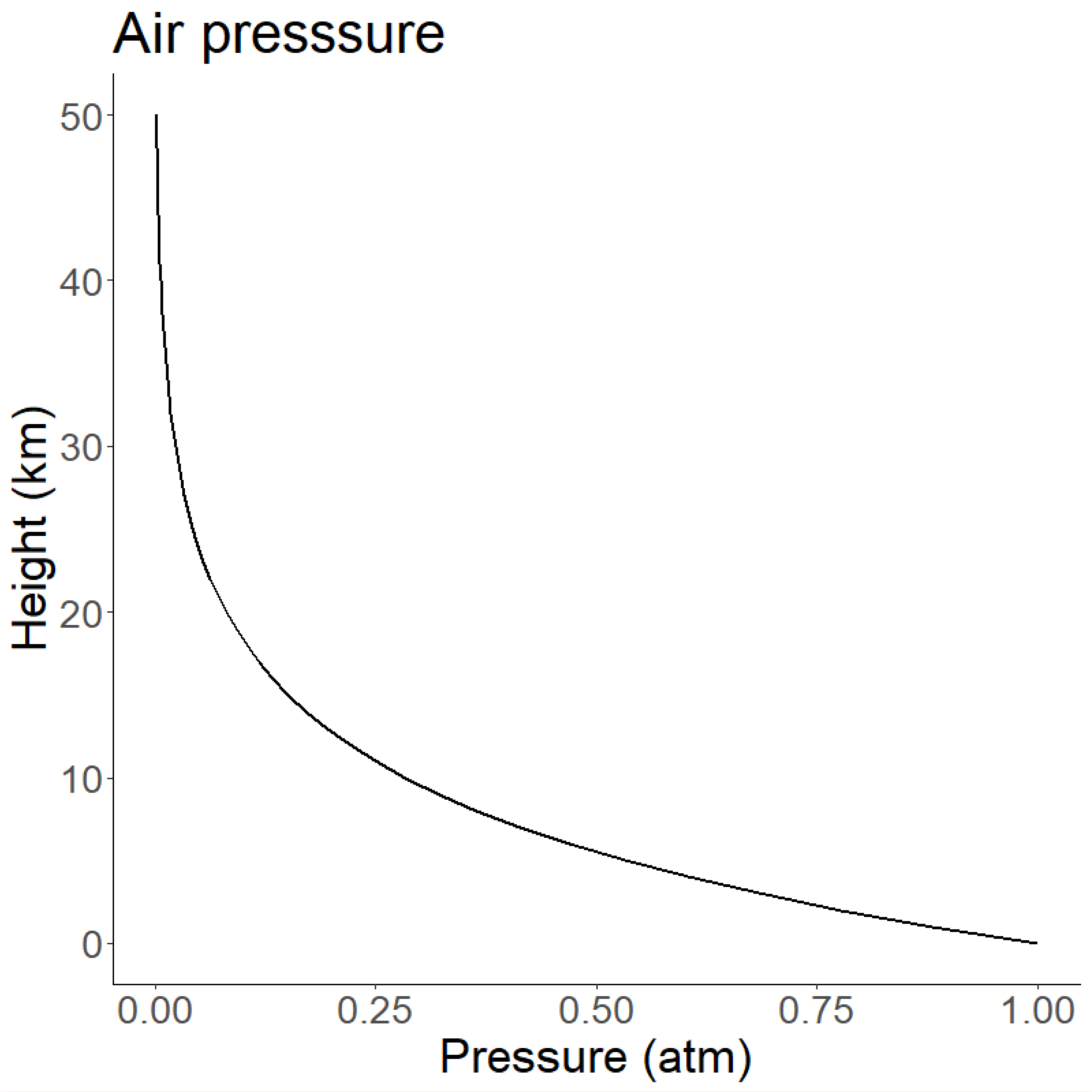


Air Pressure

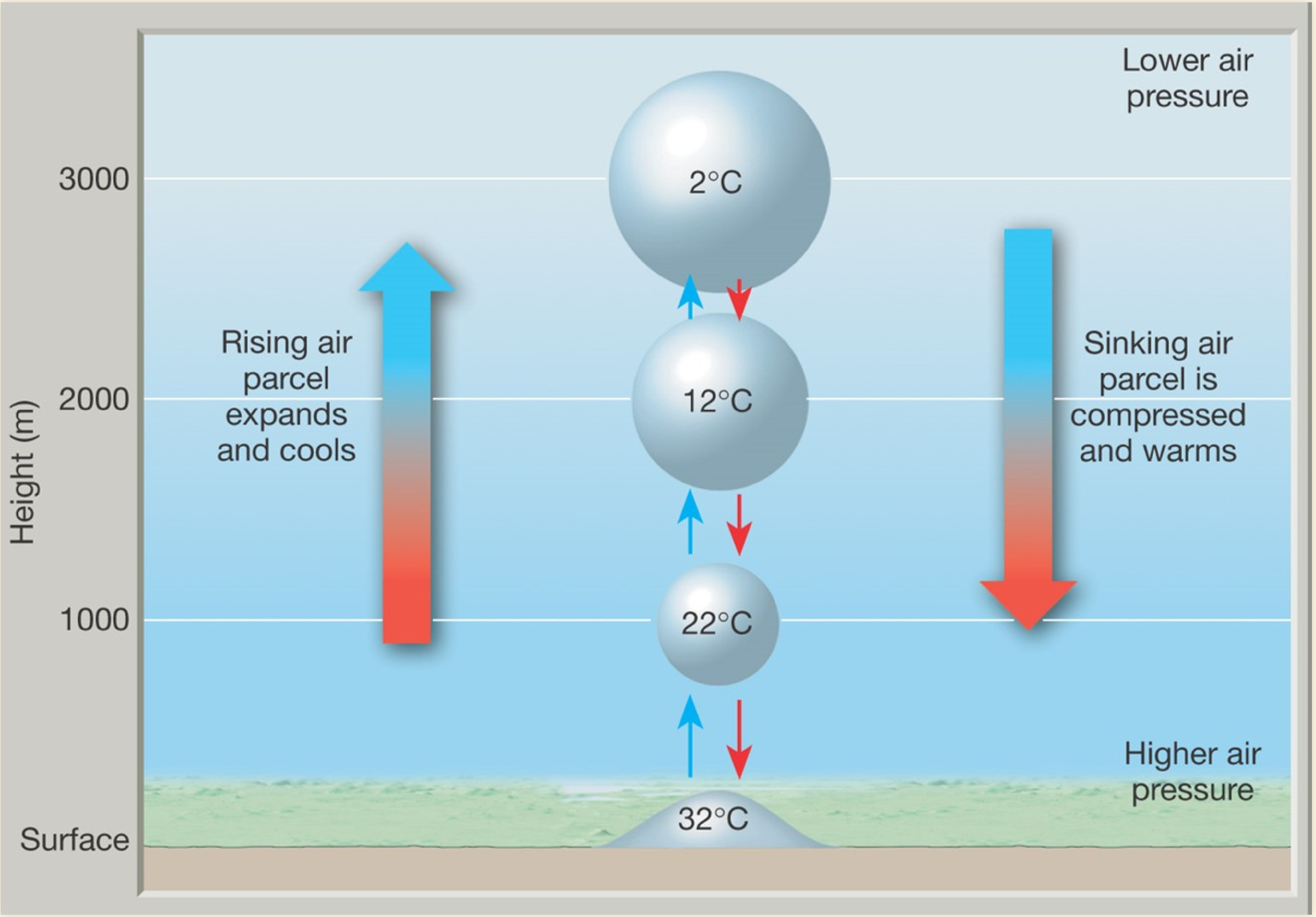
- Pressure at height *h*:

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

  - Every time you go up 5.5 km, the pressure drops by half
  - 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?

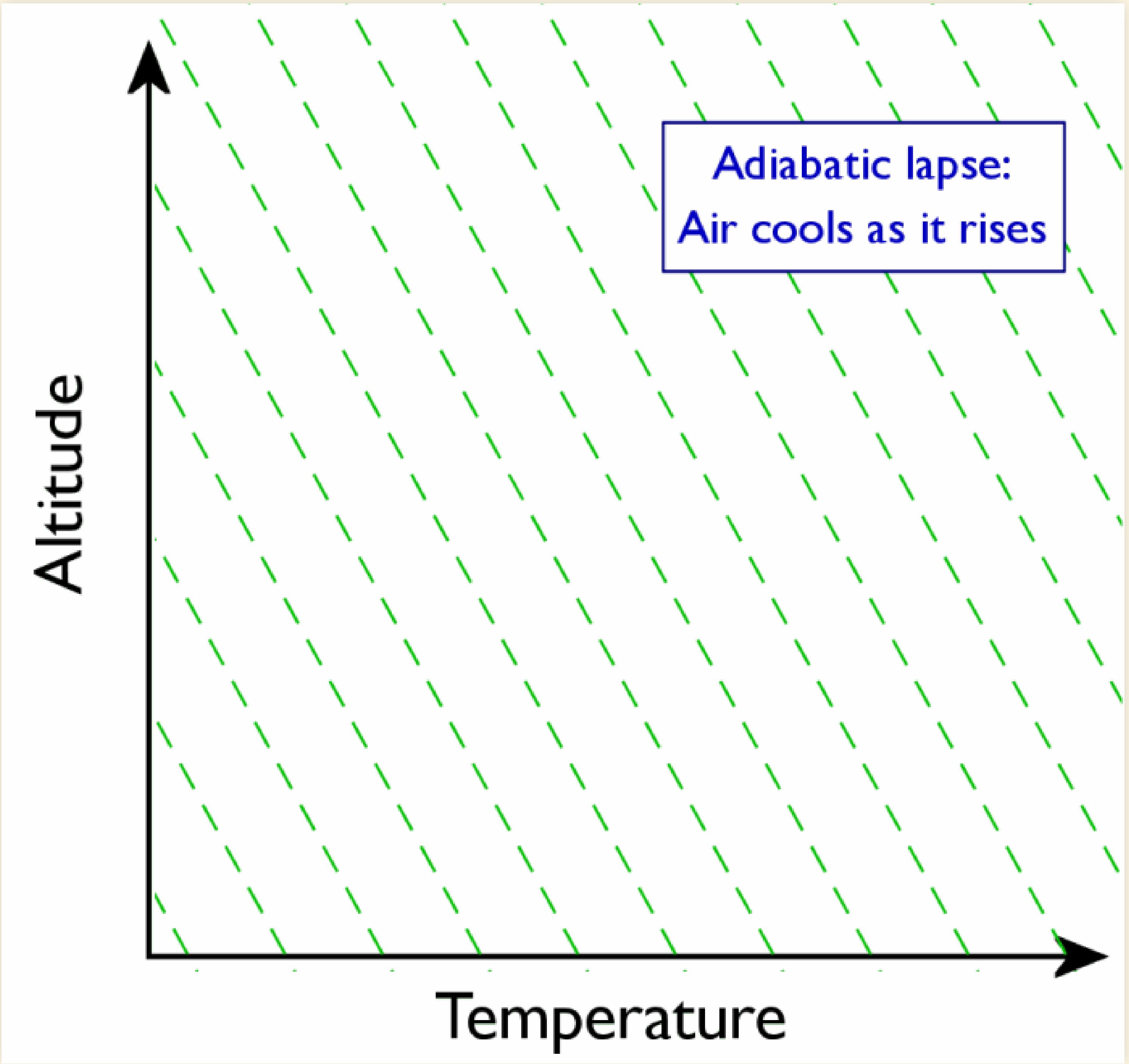


Terminology

- **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

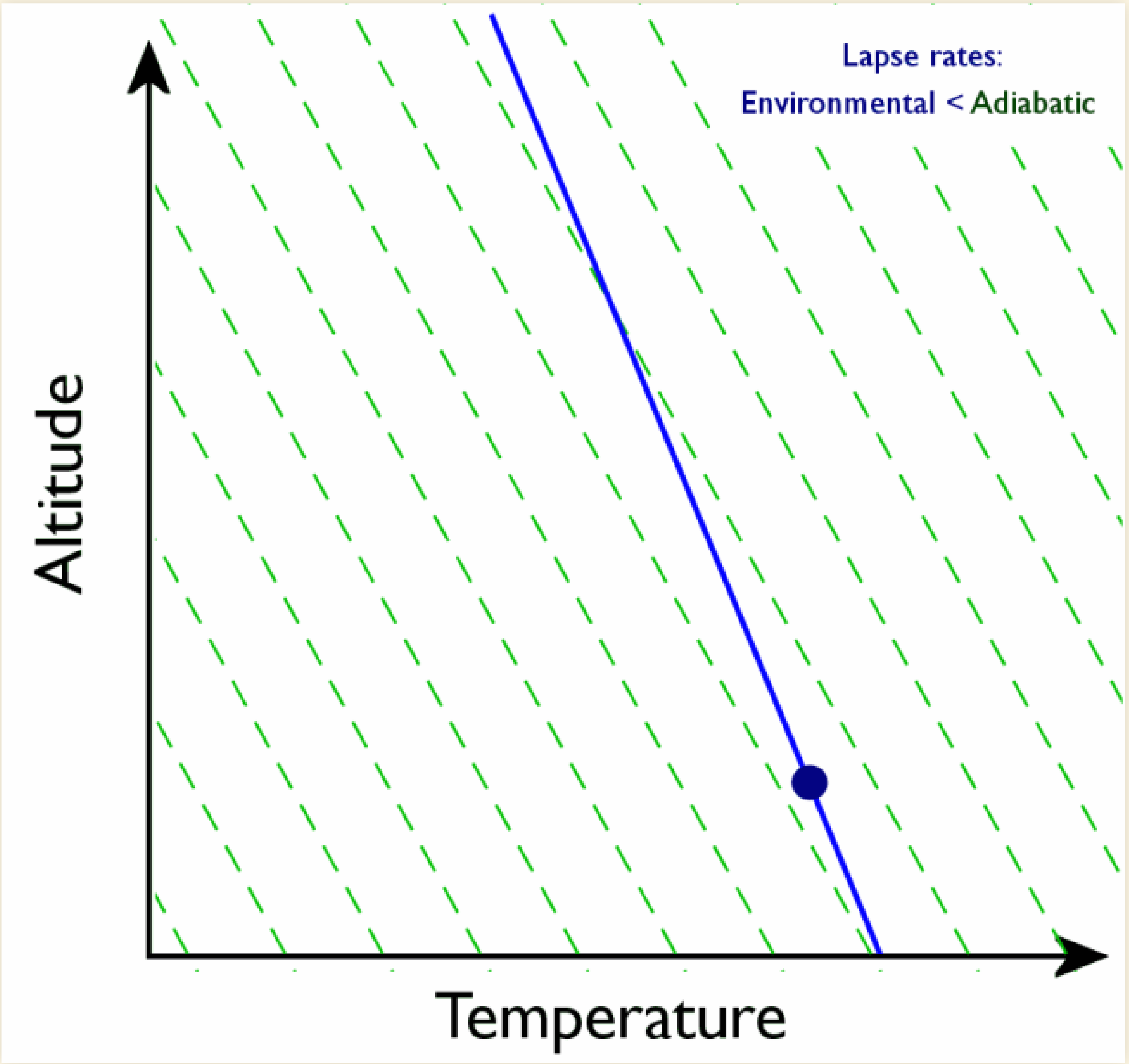
Overview of Convection

Overview of convection



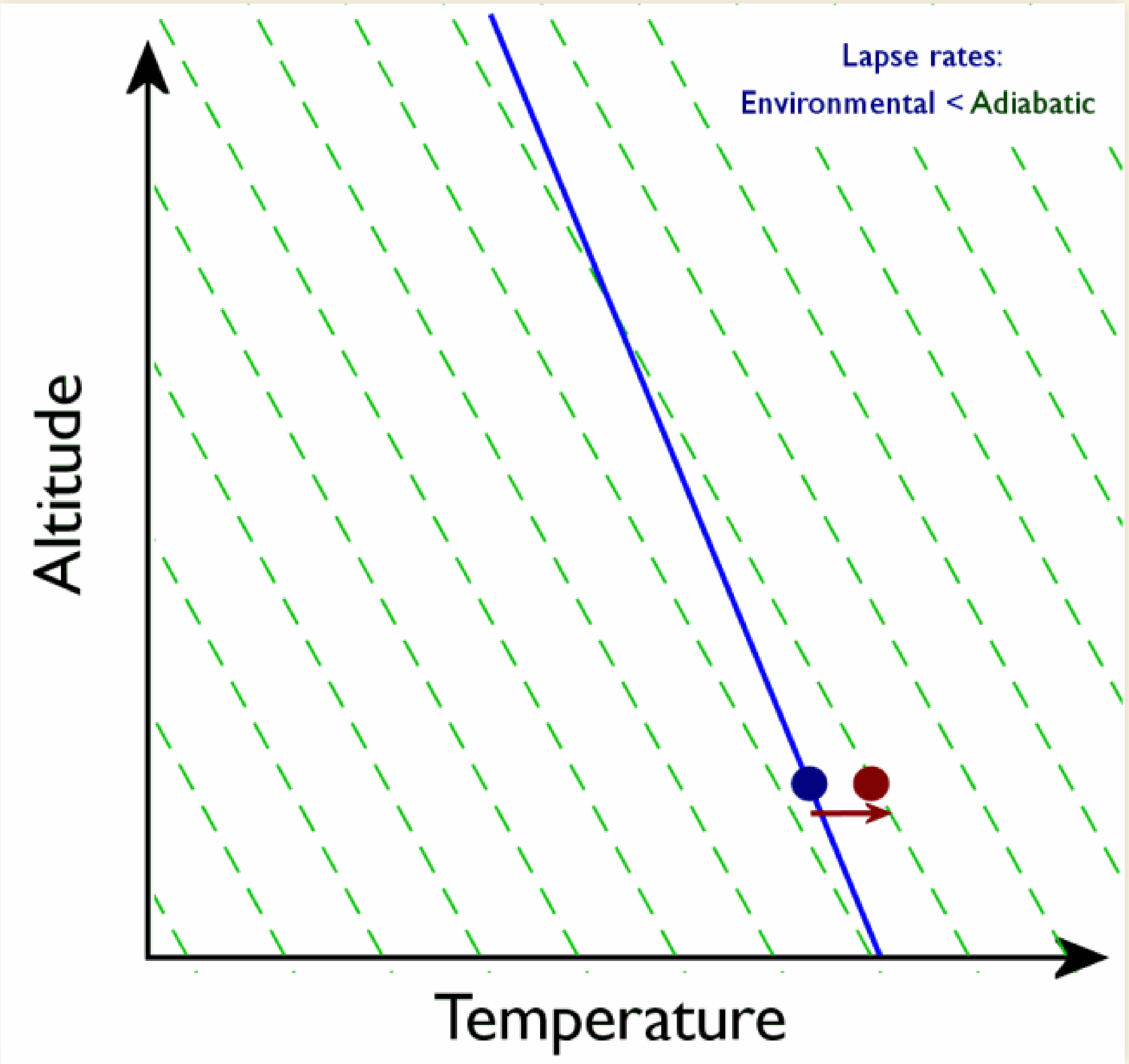
- Closer to vertical = smaller lapse rate (vertical = zero)
- Closer to horizontal = larger lapse rate

Stable Atmosphere
Initial State



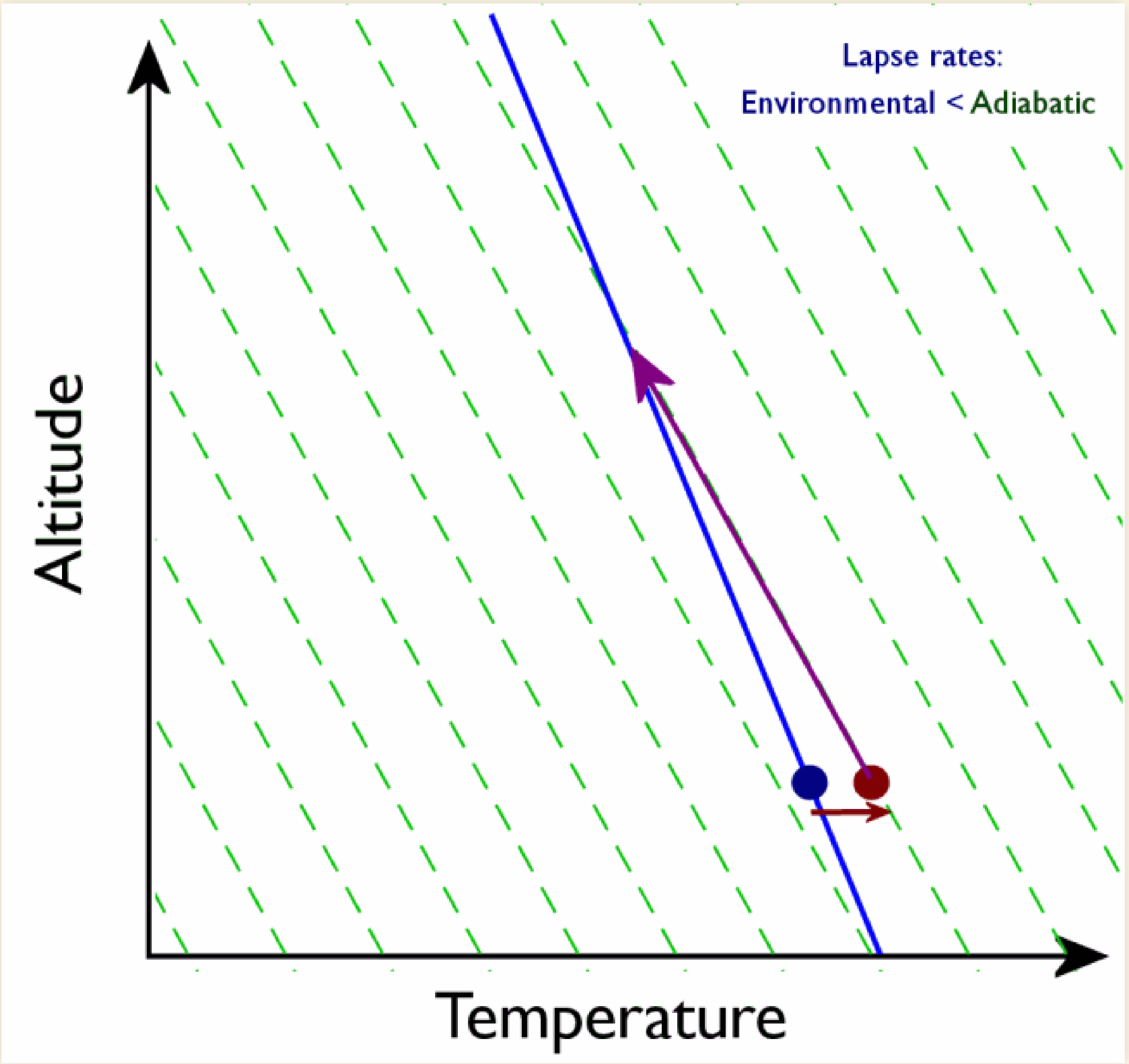
- green = adiabatic lapse
- blue = environmental lapse < adiabatic

Stable Atmosphere
Parcel is heated



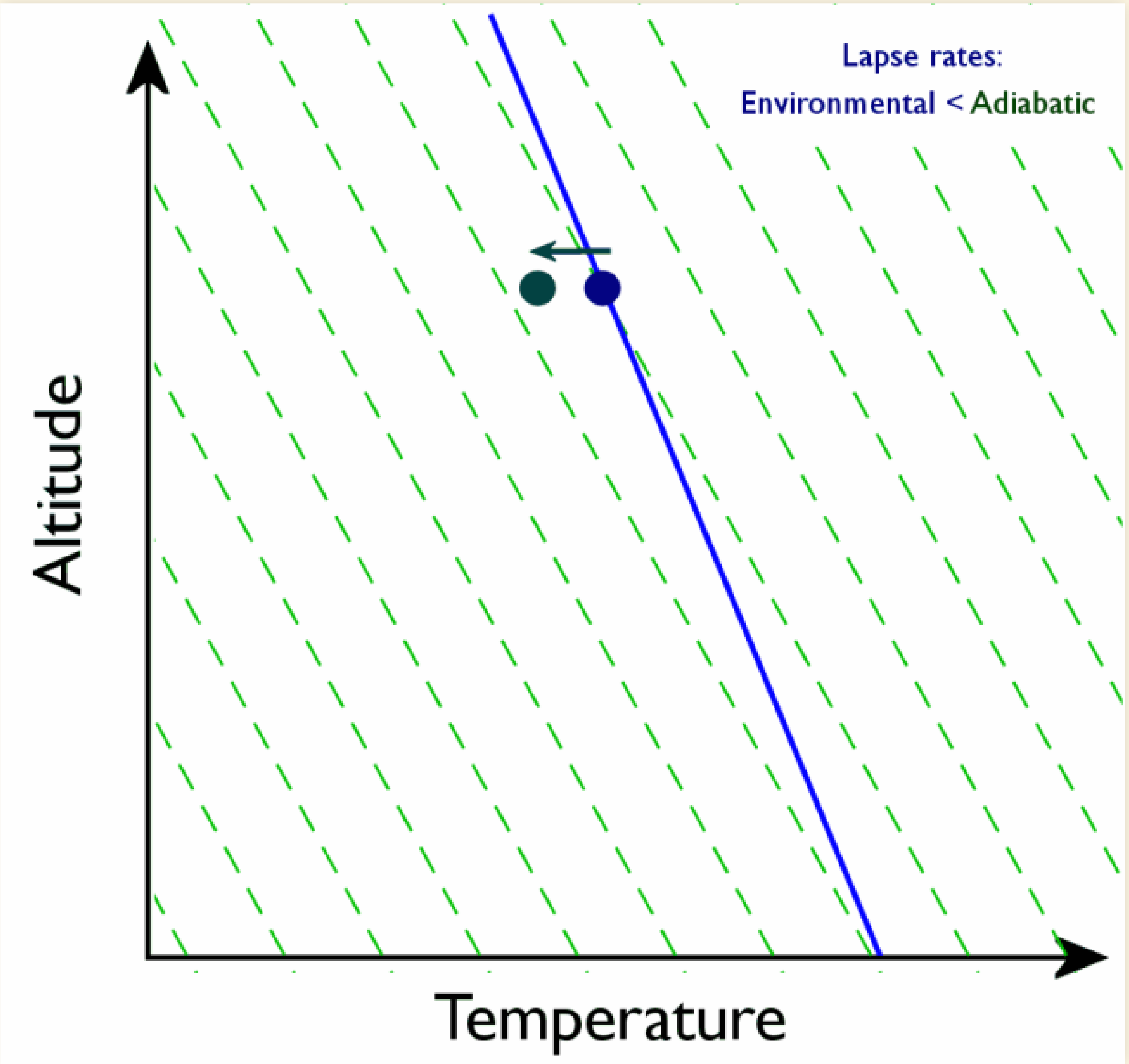
Stable Atmosphere

Rises to new equilibrium



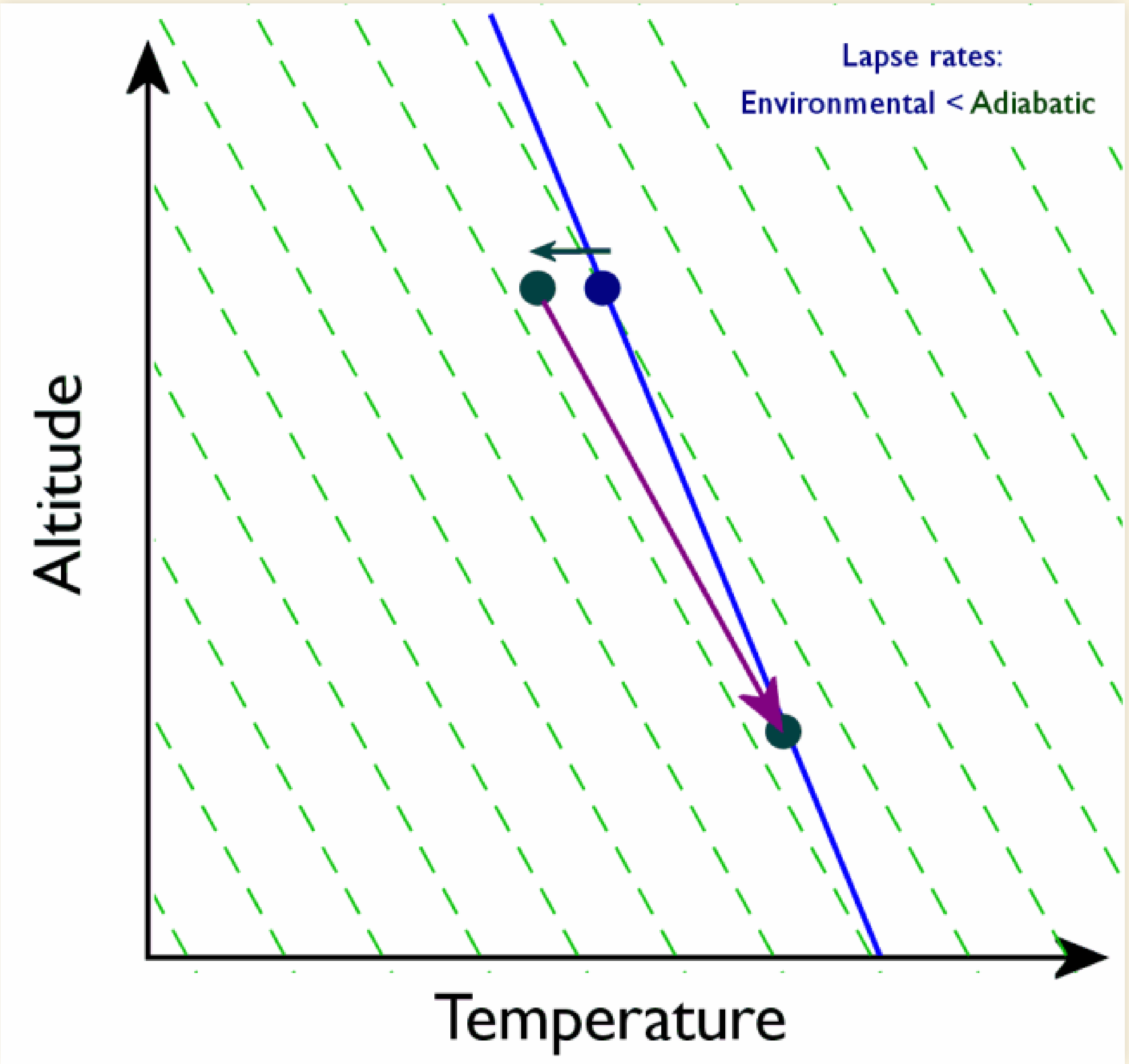
Stable Atmosphere

Parcel is cooled



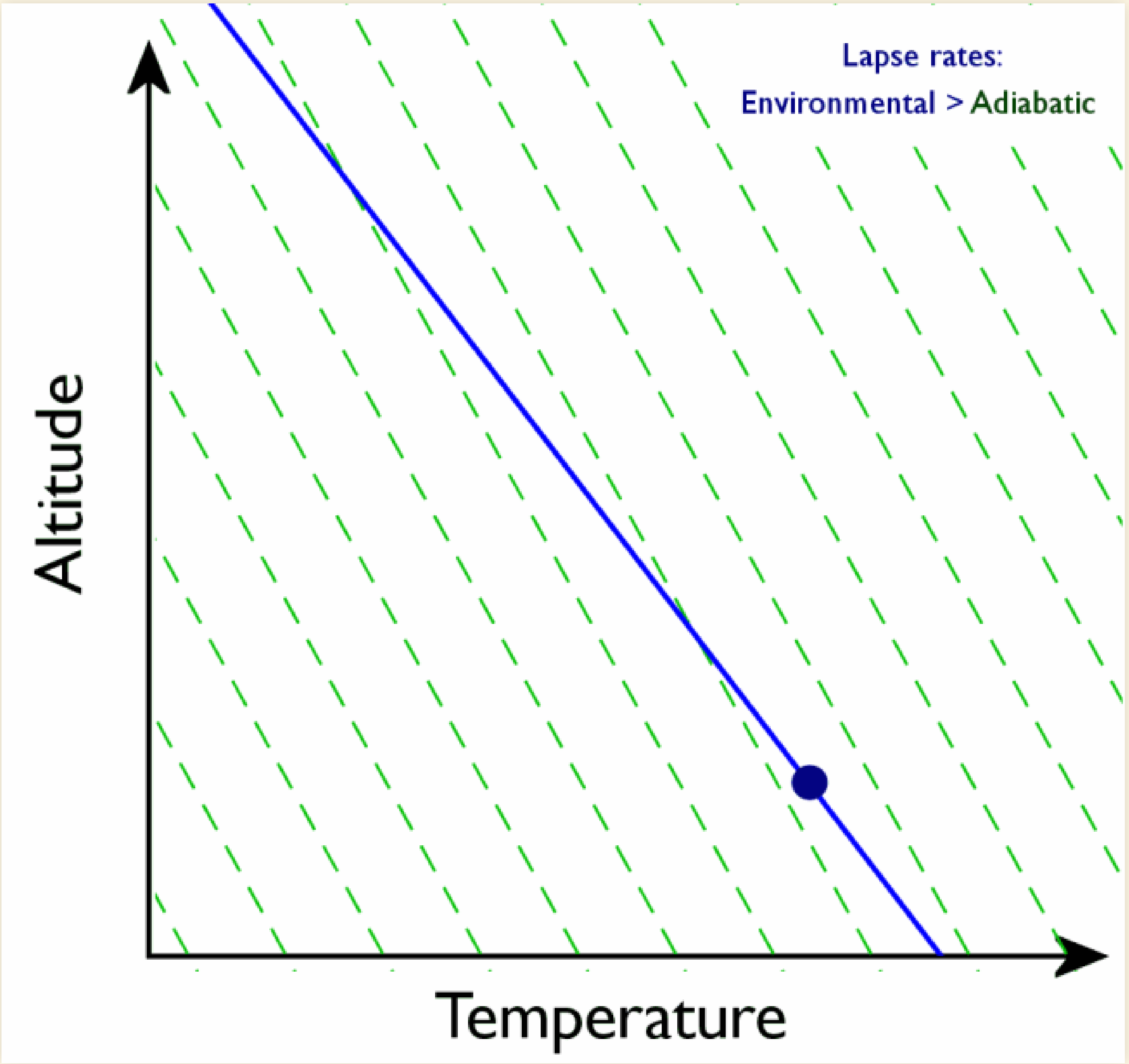
Stable Atmosphere

Sinks to new equilibrium



Unstable Atmosphere

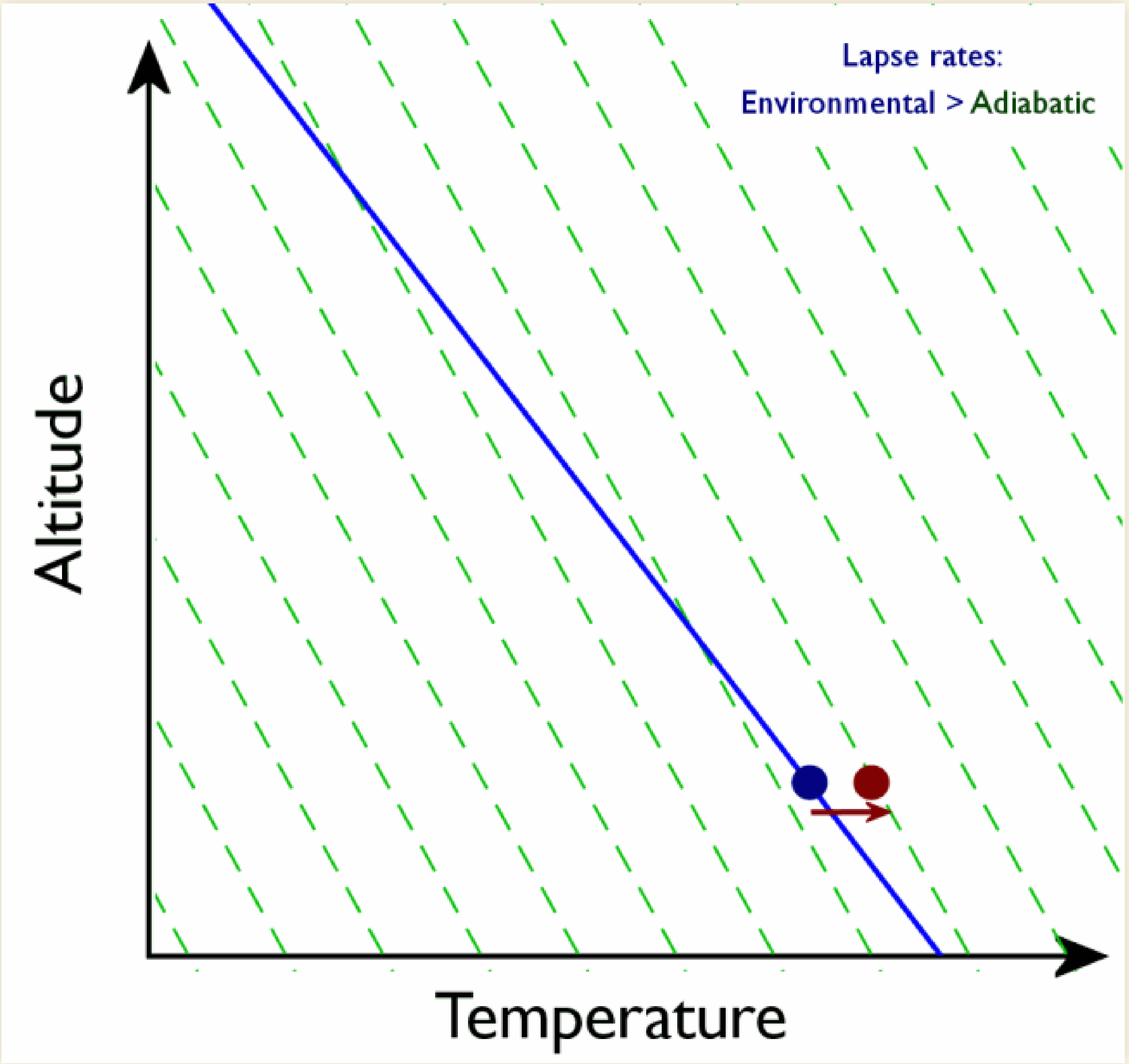
Unstable Atmosphere
Initial State



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

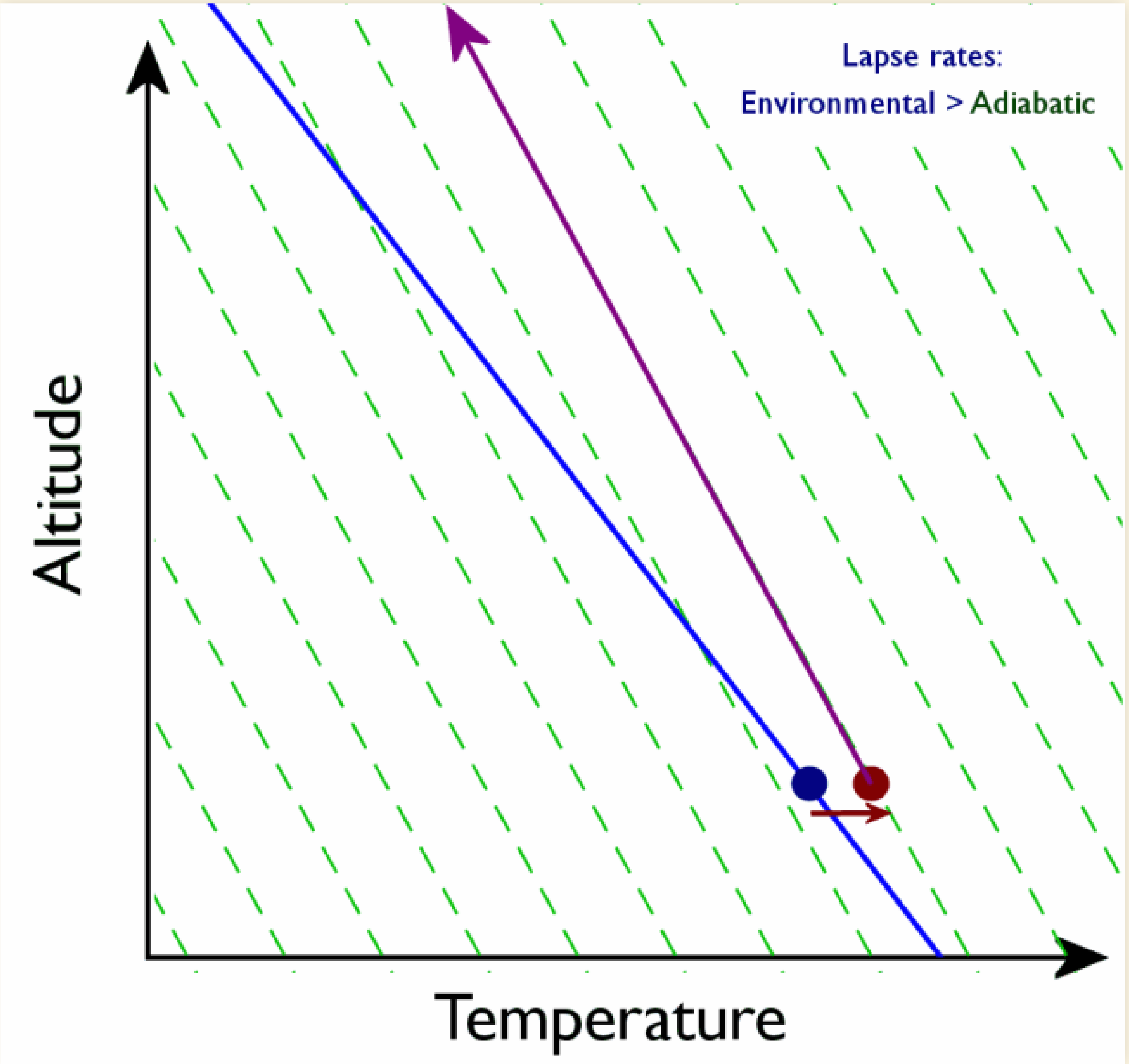
Unstable Atmosphere

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