Greenhouse Gases

EES 3310/5310

Global Climate Change

Jonathan Gilligan

Class #5: Wednesday, January 15 2020

Office Hours

Rescheduled for today only: 11:10–12:00.

In general: If you have questions, my scheduled office hours are times you can just drop in with questions. No appointment necessary. I can make appointments for other times if necessary.

Lab #2 Assignment, Part 1:

General Principles:

Start at the top and work down:

1. Balance budget at boundary to space
   - Get “skin temperature” (top layer)
2. Balance budget at top layer of atmosphere
   - Get temp. of next layer down (2nd from top)
3. Balance budget at next layer of atmosphere
   - Get temp. of next layer down (3rd from top)
4. …
5. Balance budget at bottom layer of atmosphere
   - This gives surface (ground) temperature.

As long as the albedo and the solar constant don’t change, ***the skin temperature is always the same*** for all models: 254 K.

— *Understanding the Forecast*, p. 25.

“Balance the Budget”

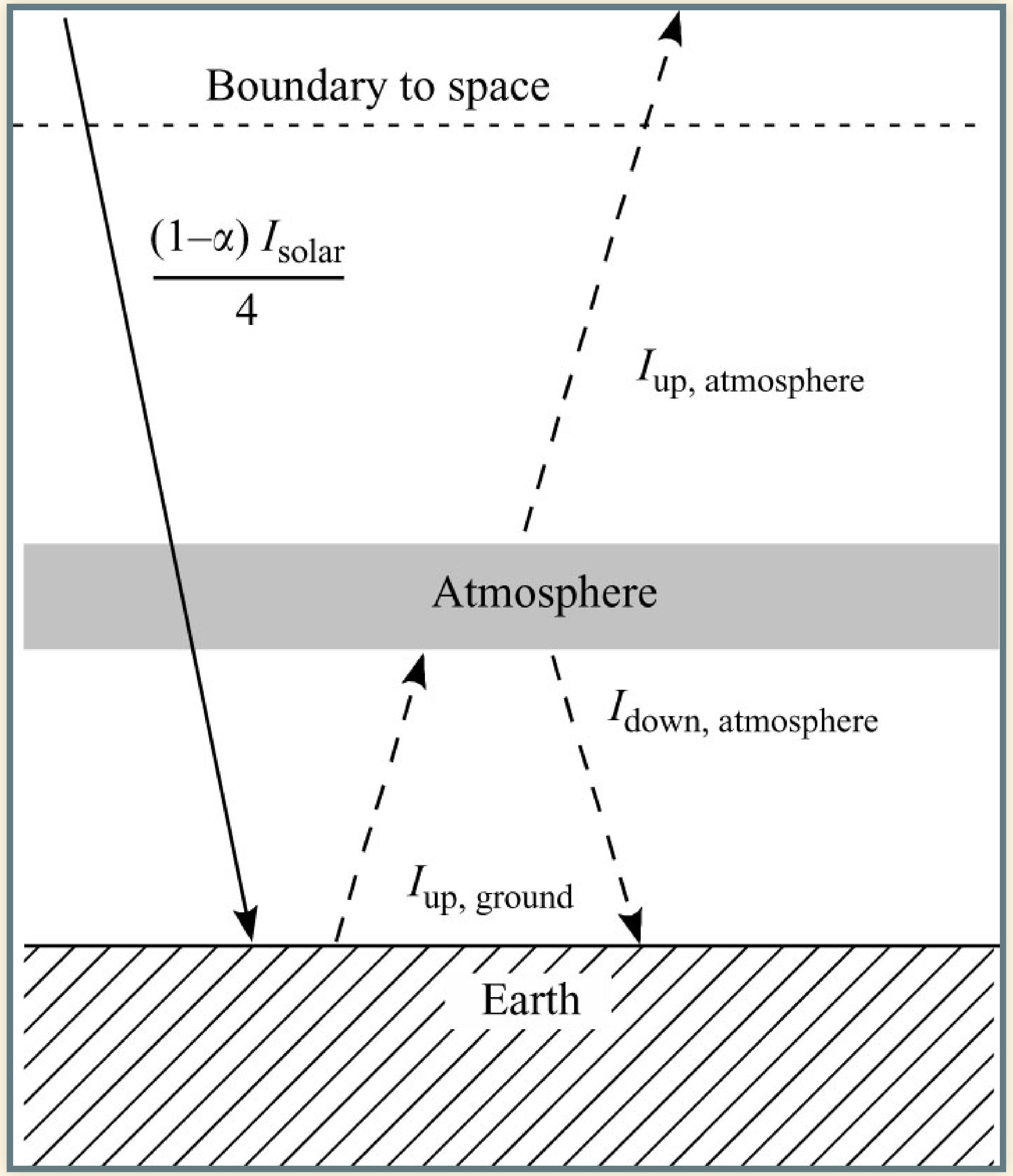
$$\text{Heat}_{\text{in}} = \text{Heat}_{\text{out}}$$

- Nature balances the budget automatically.
- We use this fact to find the ground temperature.
- If you know that $\text{Heat}_{\text{in}} = \text{Heat}_{\text{out}}$, you can figure out the intensities you don’t know.
- If you know the intensity of heat going out of something, you know its temperature.

1-Layer Model Review

Clarification

- When **shortwave radiation** hits surface:
  - Fraction α is *reflected*.
  - Fraction $1 - \alpha$ is *absorbed*.
- When **longwave radiation** hits surface or layer of atmosphere:
  - 100% is *absorbed*.
- When radiation is absorbed:
  - It transforms from **radiative energy** to **thermal energy**.
  - It stops behaving like *radiation*.
  - It becomes *vibrations of the molecules* in the dirt, water, or atmosphere.
- Separately from radiation being absorbed:
  - **Thermal radiation** is emitted from hot objects.
- Greenhouse effect *is not longwave radiation **reflecting** off atmosphere*
  - **Longwave radiation** is absorbed by atmosphere
  - **Radiation** changes into **thermal energy** in air molecules.
    - Air molecules get *hotter*.
  - Later, **air molecules** give off **thermal radiation**
    - This radiation is *different* from the radiation they absorbed.



1-Layer Model in Brief

Start at top:

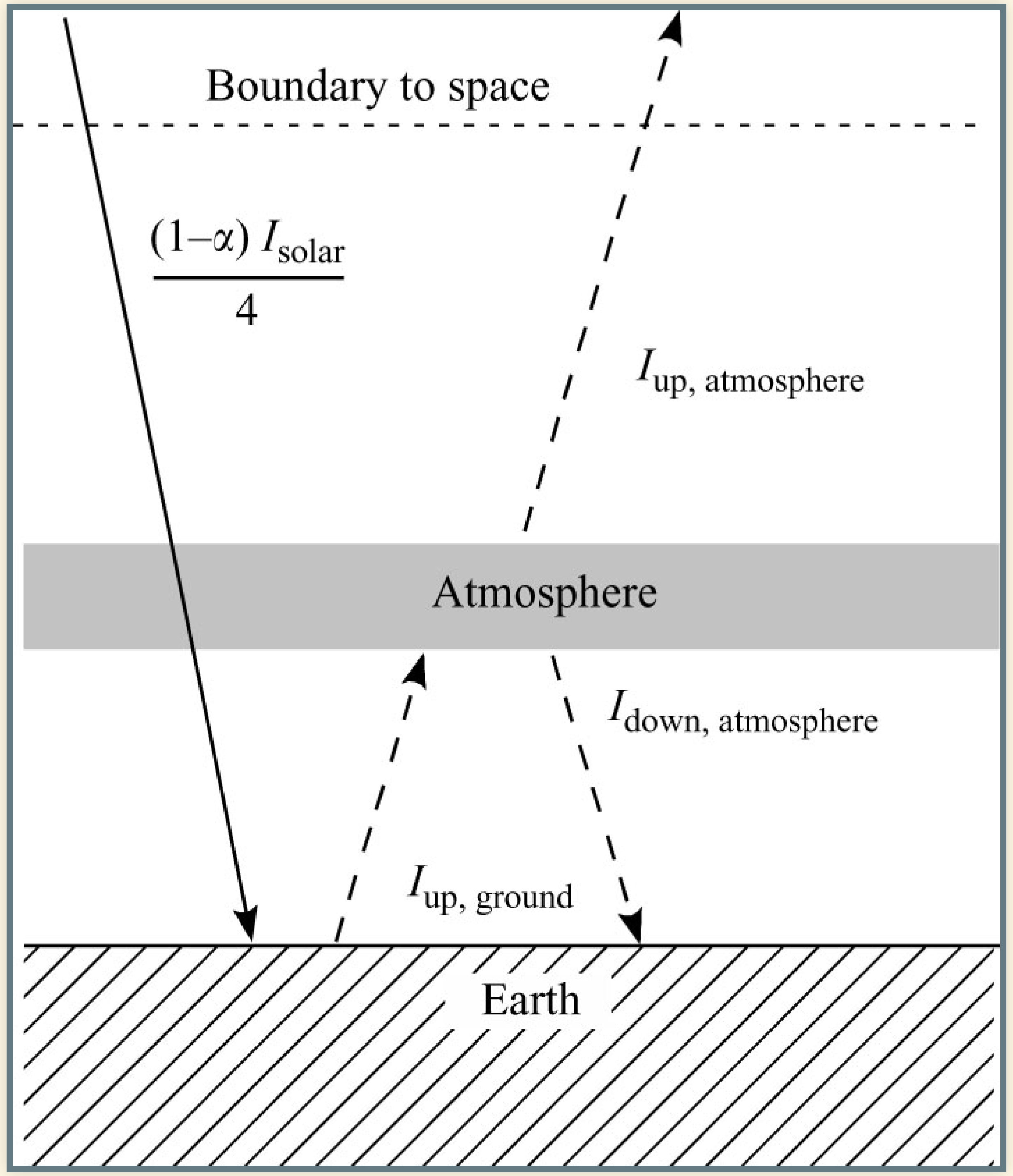
- Balance heat budget at boundary to space.

$$\frac{(1-\alpha) I_{\text{solar}}}{4} = \epsilon \sigma T_{\text{atmos}}^4$$

  - Same as bare-rock model: $T_{\text{atmos}} = 254\ K$.
    - *skin temperature*
- Balance budget at atmosphere:

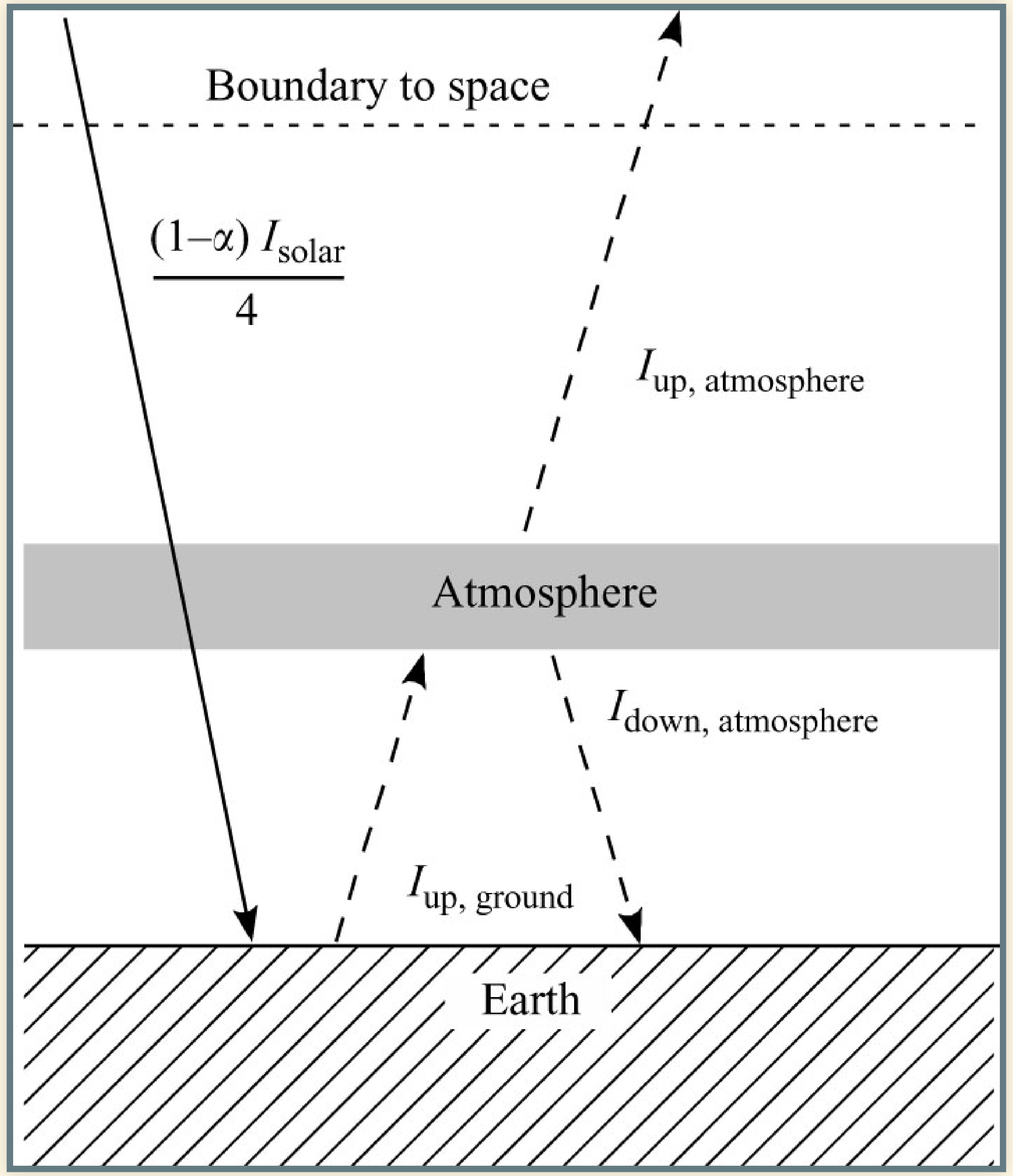
$$\begin{aligned} \epsilon \sigma T_{\text{ground}}^4 &= 2 \epsilon \sigma T_{\text{atmos}}^4 \\ T_{\text{ground}}^4 &= 2 T_{\text{atmos}}^4 \\ T_{\text{ground}} &= \sqrt[4]{2}\ T_{\text{atmos}} \end{aligned}$$

  - **Ground temp**: $T_{\text{ground}} = \sqrt[4]{2}\ T_{\text{skin}} = 302\ K$.



1-Layer Model: Heat Balance Details

- Numbers:
  - $I_{\text{solar}} = 1350 \; W/m^2$
  - $I_{\text{in}} = (1-\alpha) I_{\text{solar}}/4 = 236 \; W/m^2$
  - $I_{\text{down,atm}} = I_{\text{up,atm}} = I_{\text{in}} = 236 \; W/m^2$
  - $I_{\text{up,ground}} = 2 I_{\text{up,atm}} = 472 \; W/m^2$
- Balance:
  - Space:
    - in $= I_{\text{in}} = 236 \; W/m^2$,
    - out $= I_{\text{up,atm}} = 236 \; W/m^2$.
  - Atmosphere:
    - in $= I_{\text{up,ground}} = 472 \; W/m^2$,
    - out $= 2 I_{\text{up,atm}} = 472 \; W/m^2$.
  - Ground:
    - in $= I_{\text{in}} + I_{\text{down,atm}} = 472 \; W/m^2$,
    - out $= I_{\text{up,ground}} = 472 \; W/m^2$.

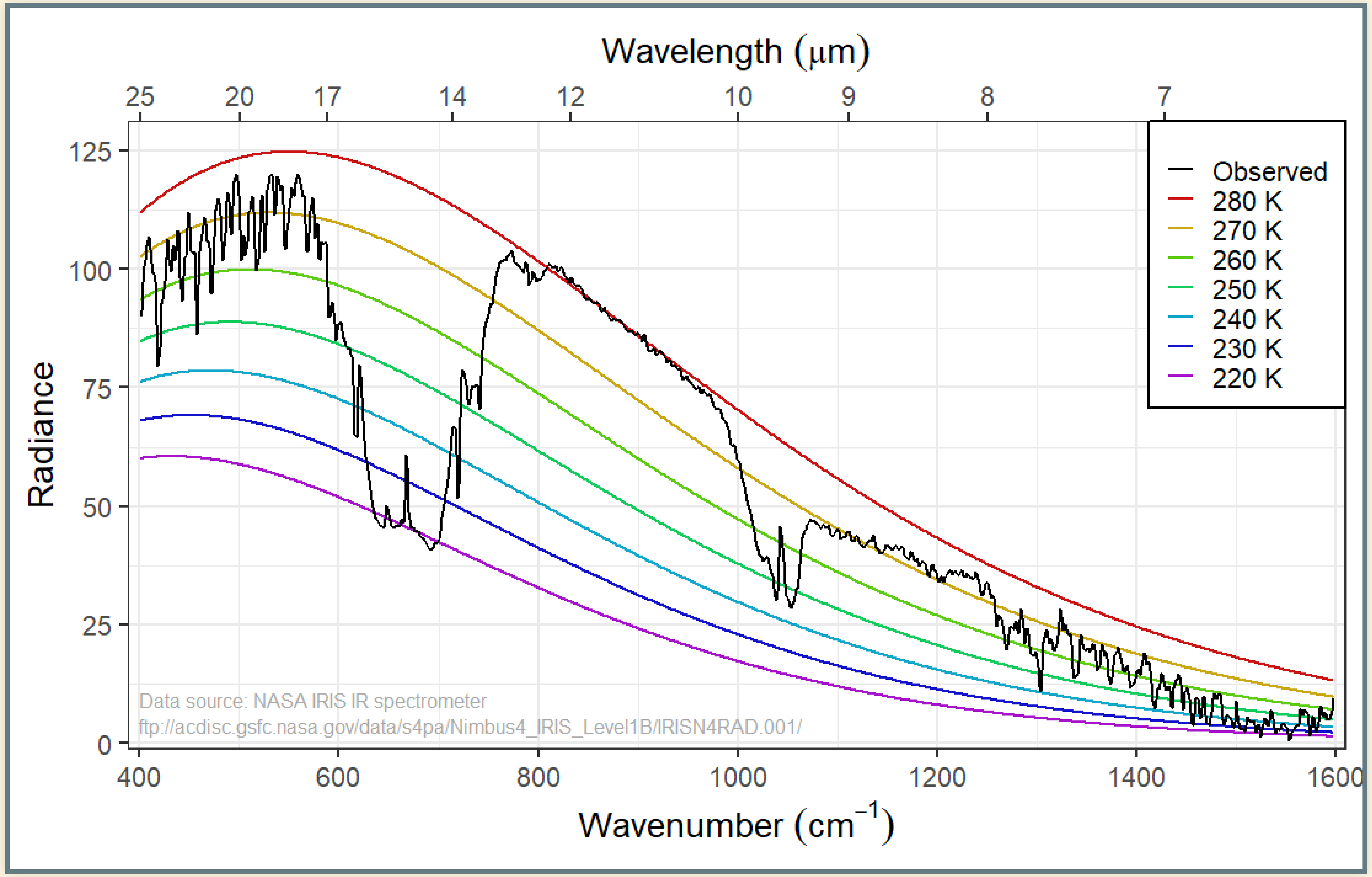


Greenhouse Gases

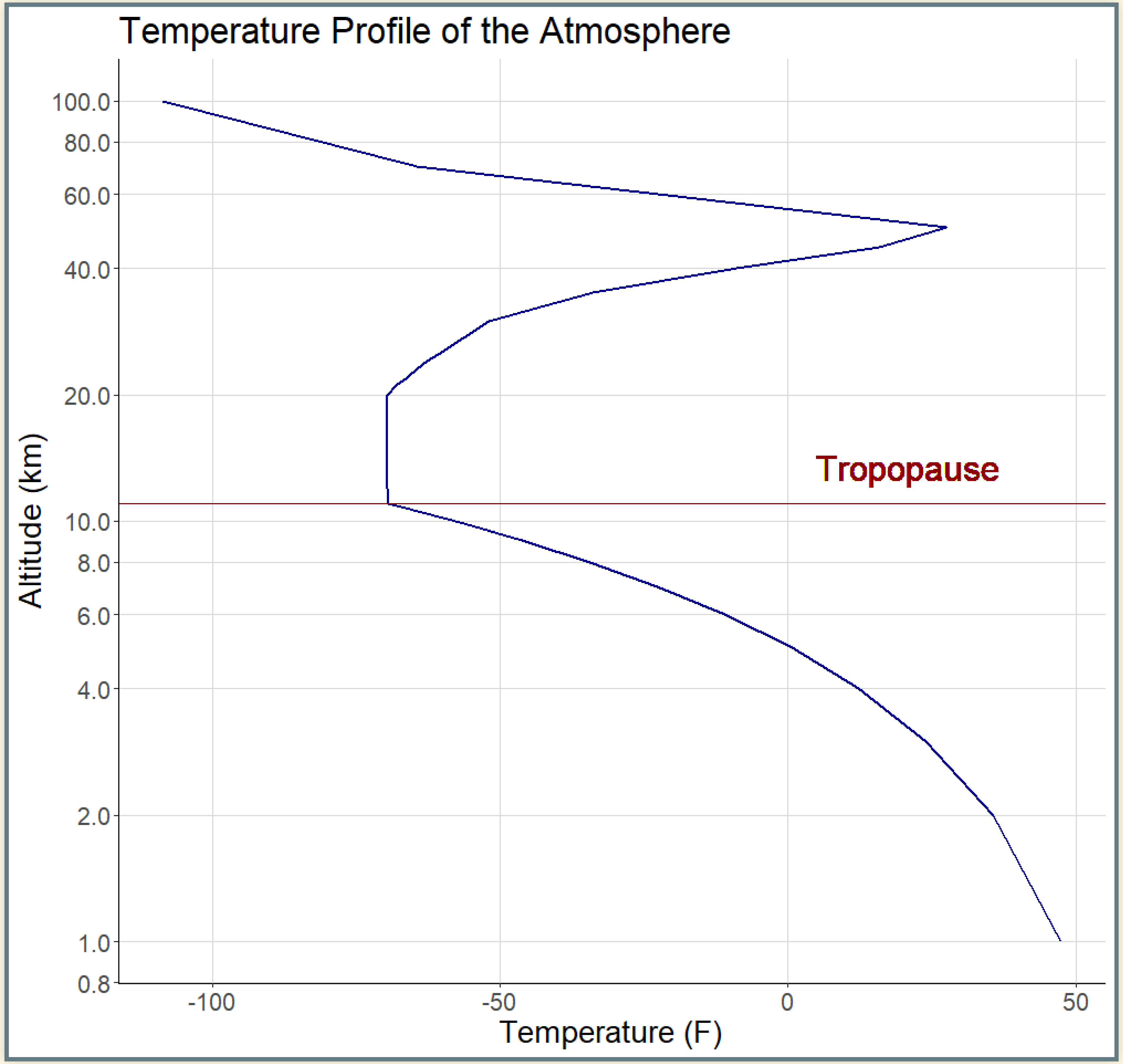
Greenhouse Gases

Layer model was too simple:

- Emissivity ε, varies with wavelength
- Temperature varies with altitude

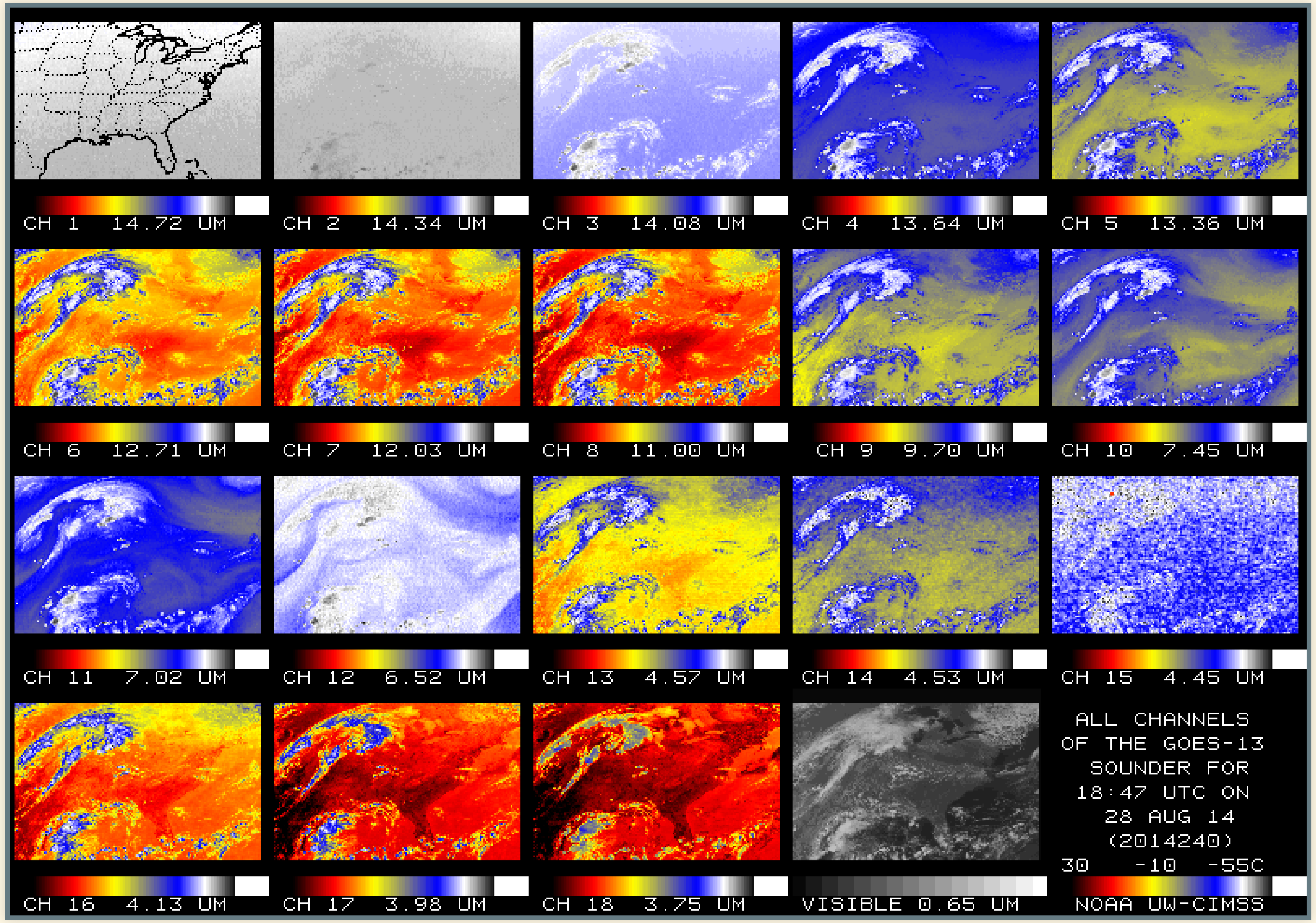


Temperature in the Atmosphere



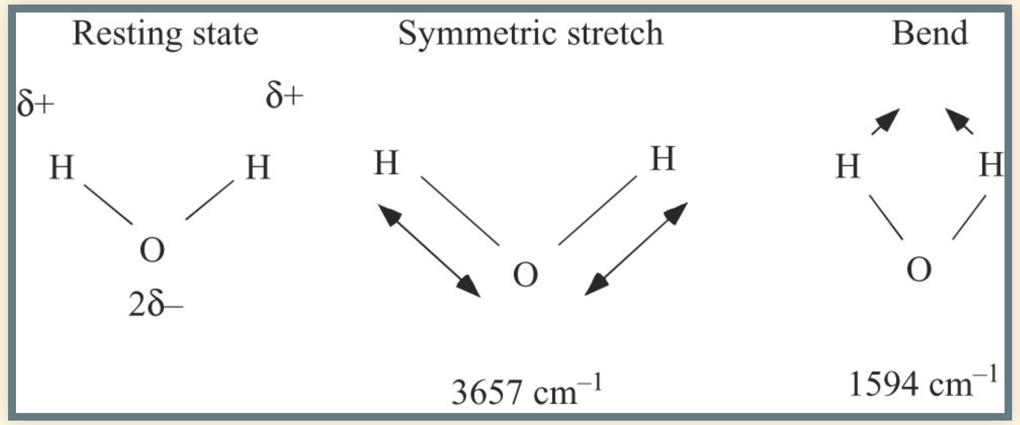
Longwave Light in the Atmosphere

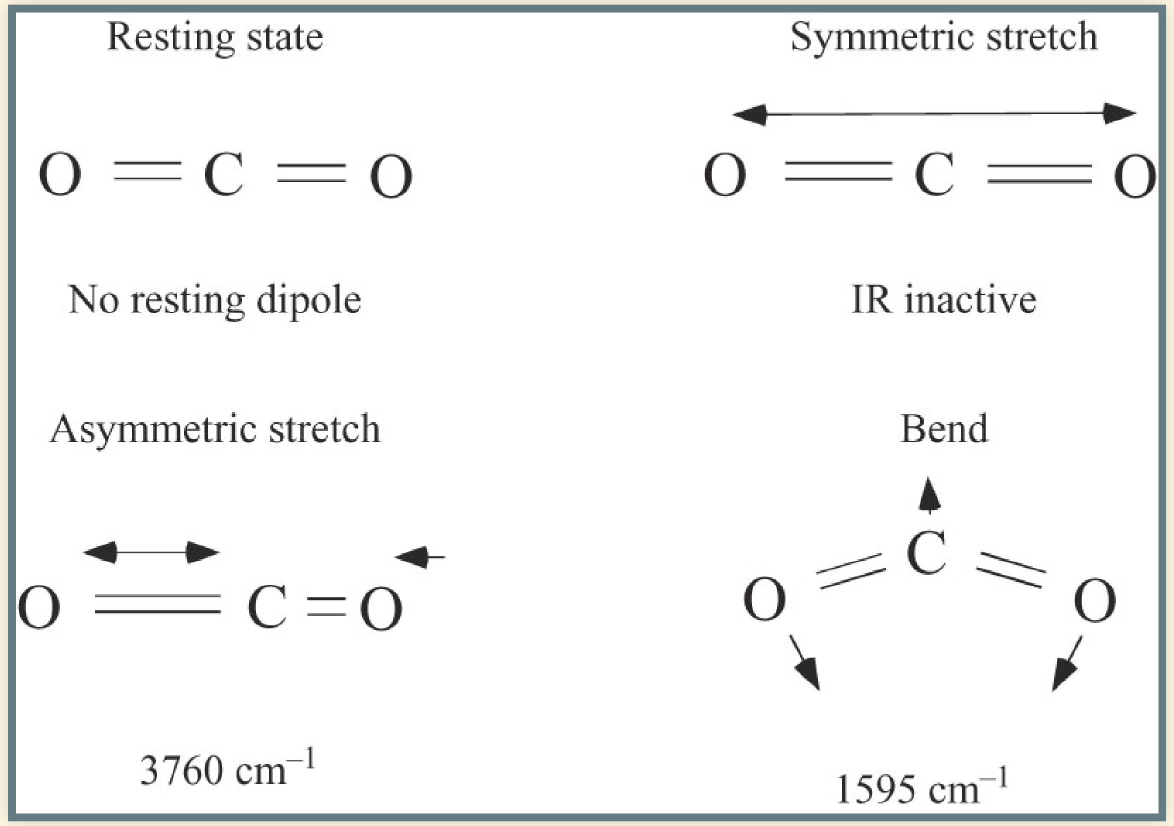
Earth seen by GOES satellite



Understanding Greenhouse Gases

Molecular Structure

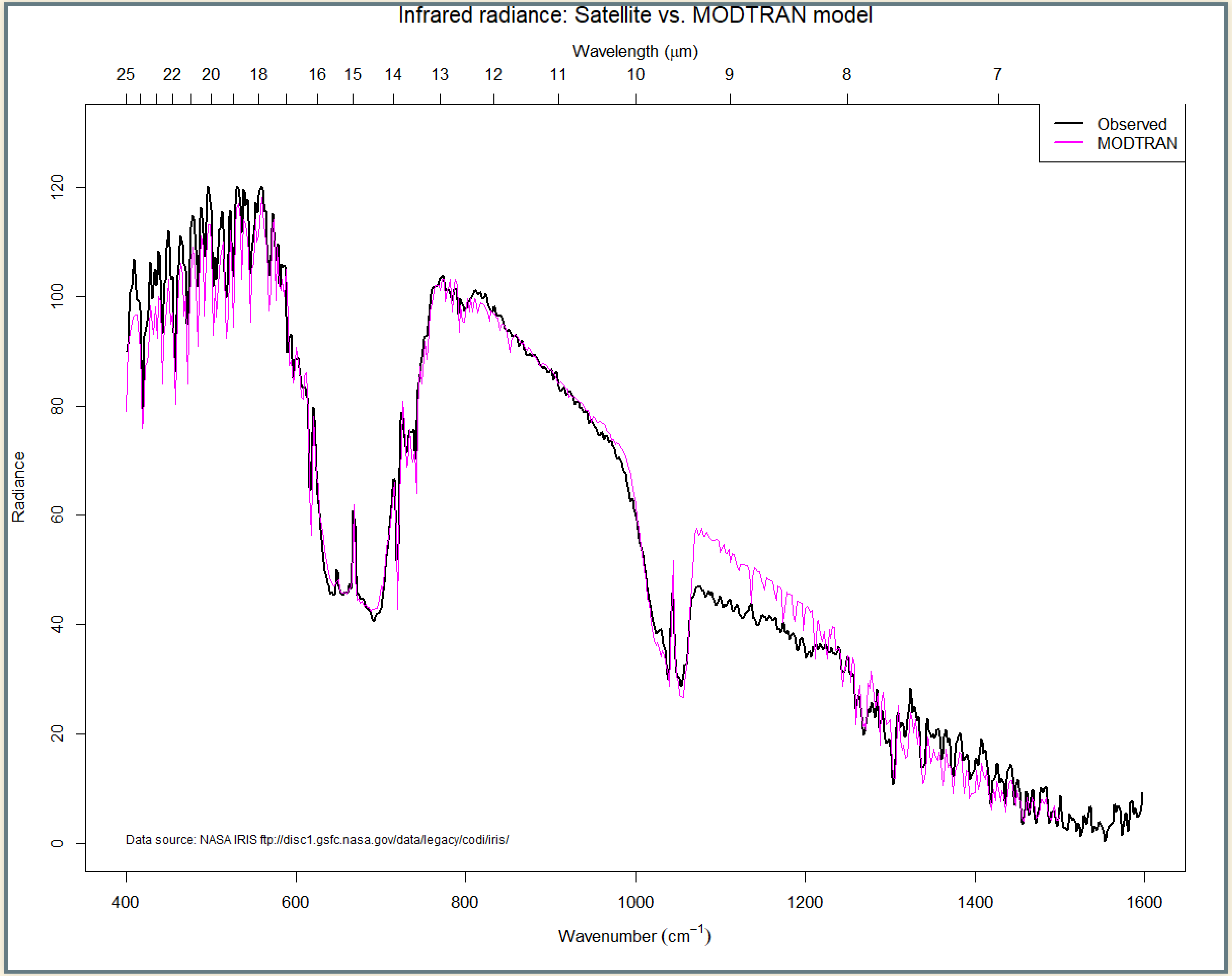




- Single atoms & two-atom molecules with the same atom (O_2, N_2) have little or no longwave absorption
- Molecules with:
  - two different atoms (CO, NO) absorb (simple stretch)
  - three or more atoms (CO_2, O_3, H_2O) absorb strongly (multiple stretching & bending modes)
  - More atoms, more different kinds → stronger absorption (CH_4, $C_2F_3Cl_3$ aka CFC 113)

Models and Observations

Models and Observations



Checking MODTRAN model: It looks very similar to real life.

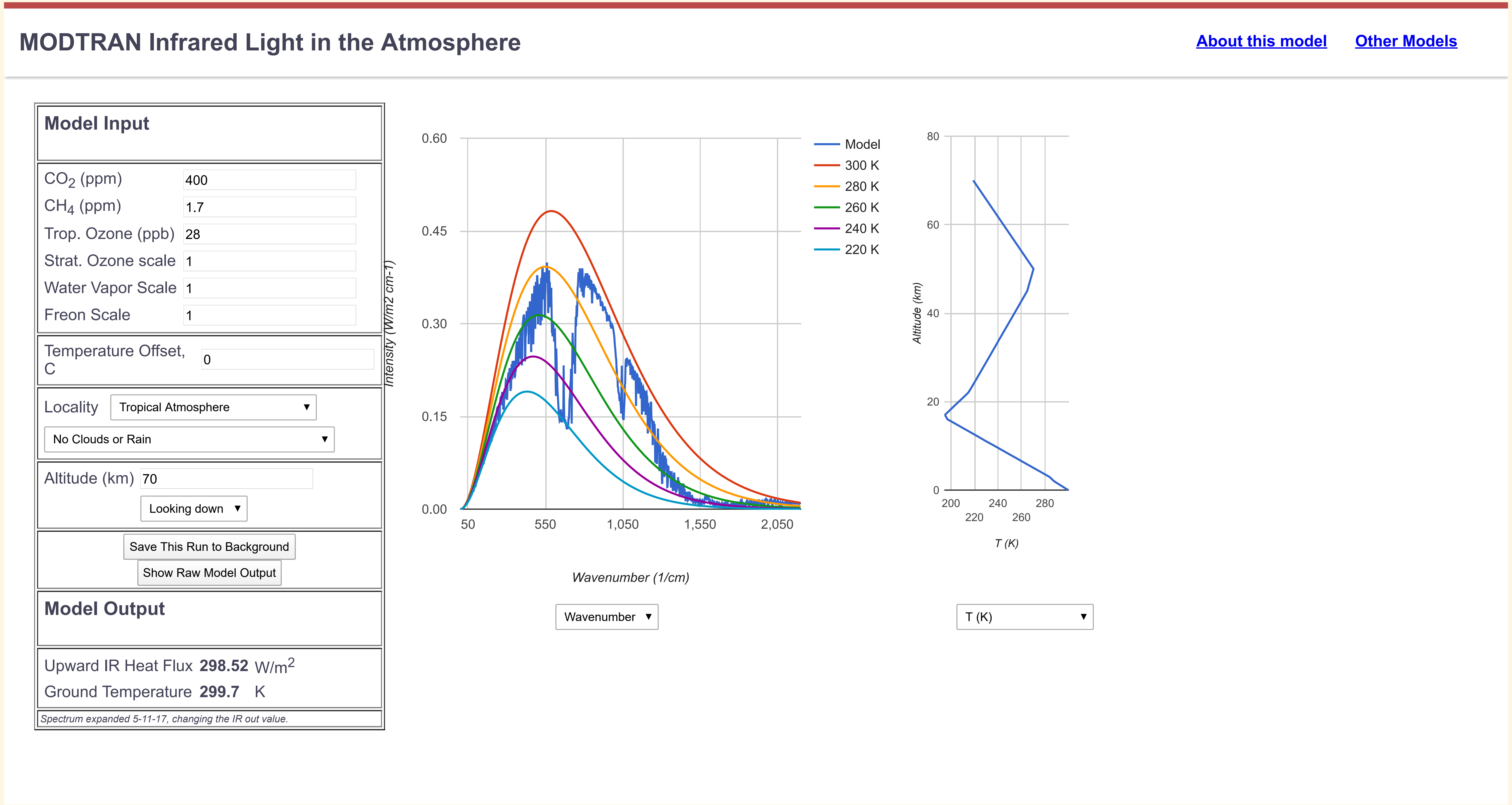
MODTRAN Computer Model

What is MODTRAN?

- Pure radiative calculation
  - Air does not move:
    - No wind or convection
- Only calculates infrared heat flux
  - Does not give equilibrium ground temperature
- Only calculates one spot
  - Does not give global averages
- You specify:
  - Ground temperature
  - Composition of atmosphere
- Modtran computes:
  - Longwave radiation at different altitudes
  - Total radiation to space

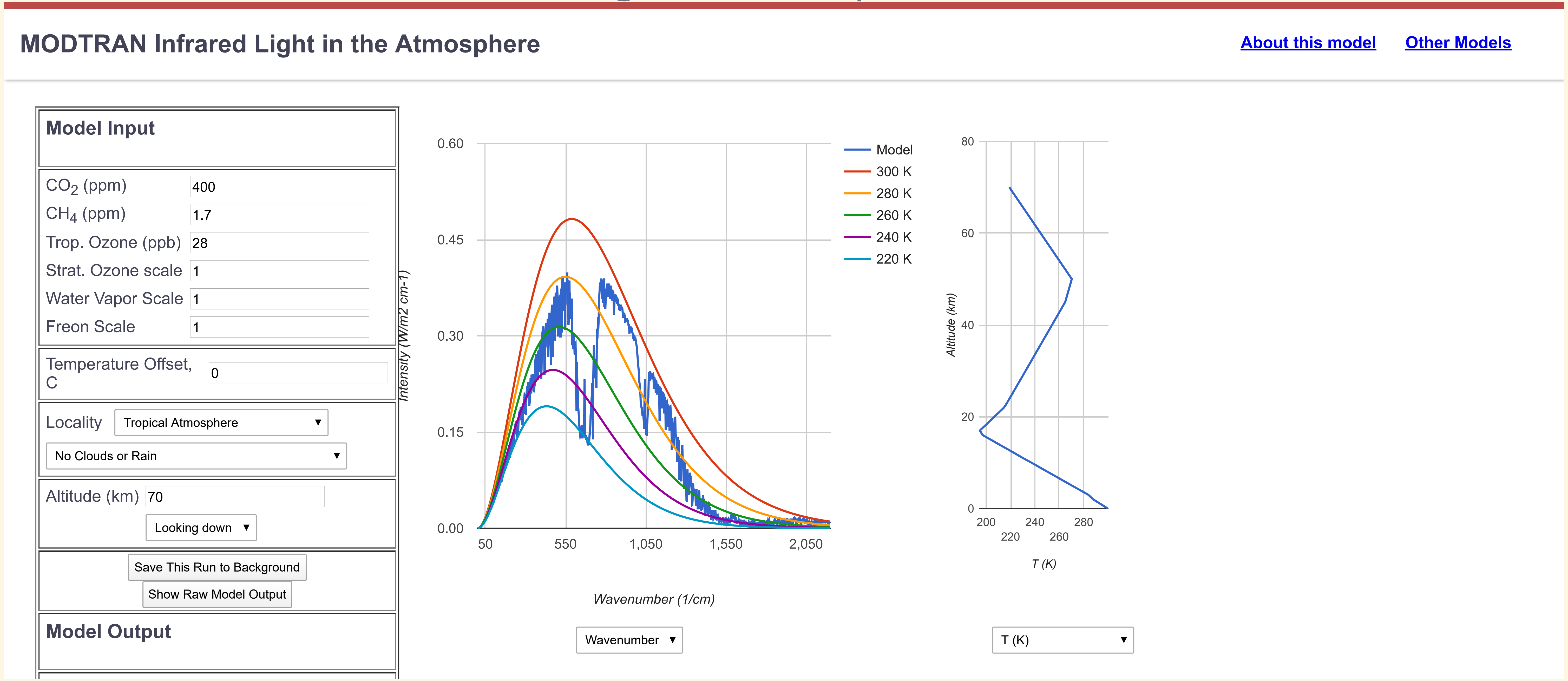
Running MODTRAN

- Go to http://climatemodels.uchicago.edu/modtran/
- Next

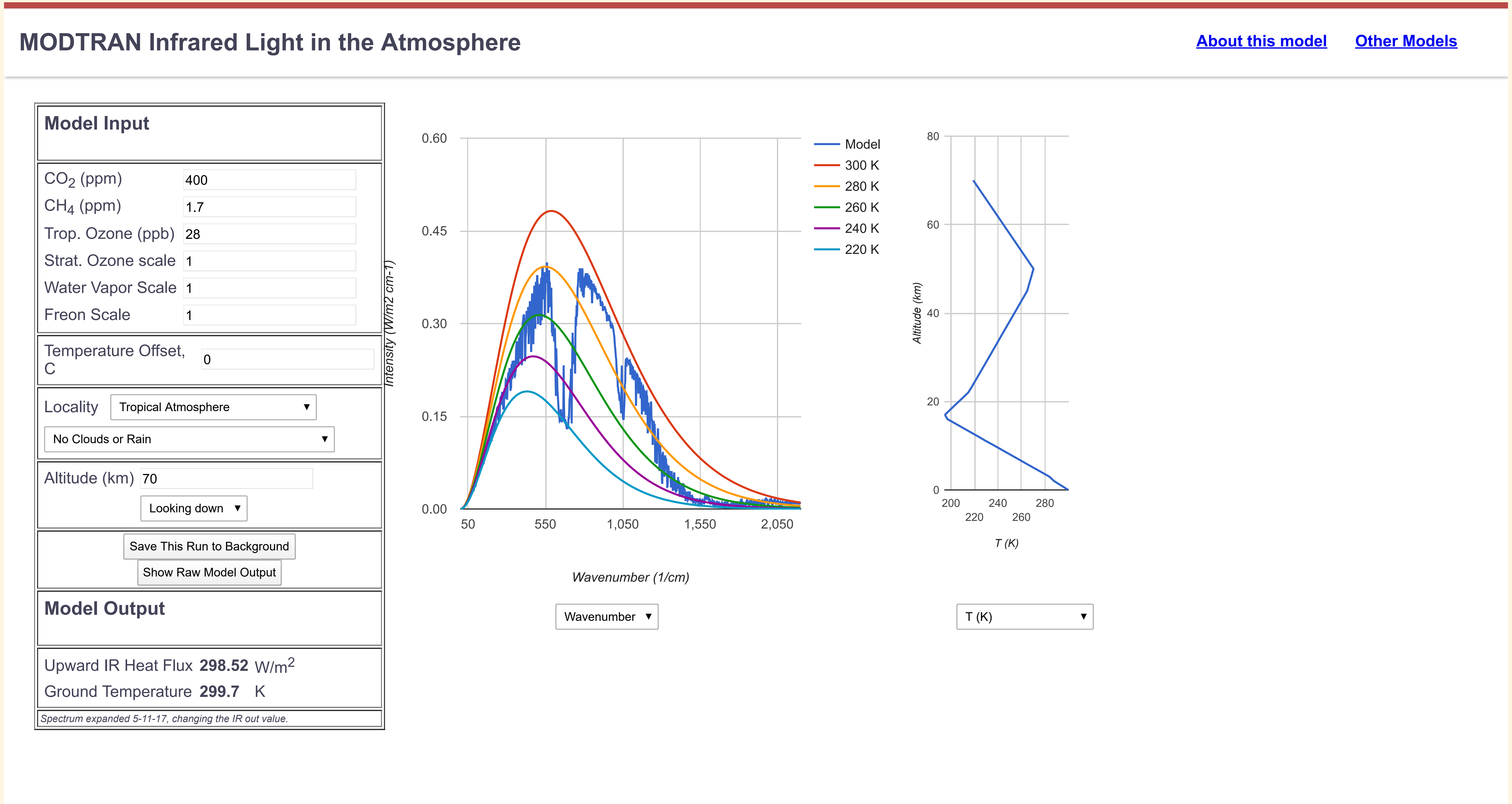


Exercise: Double CO_2

- Set Locality to "1976 U.S. Standard Atmosphere"
- Click "Save This Run to Background"
- Note the Upward IR heat flux
- Double the amount of CO_2
- Adjust T offset until new heat flux = background flux
- What is the new ground temperature?

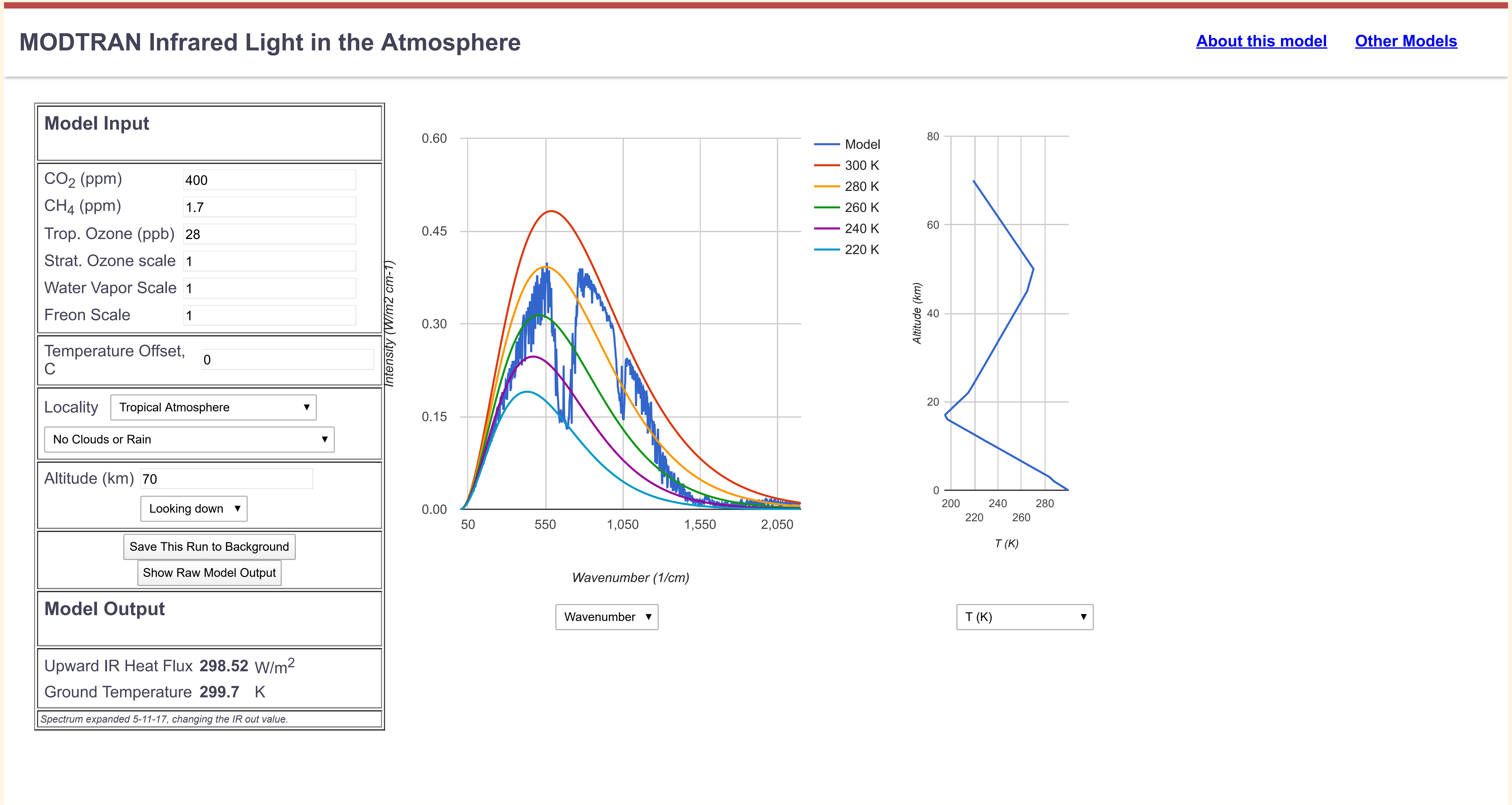


Exercise: Double CO_2



Different Gases

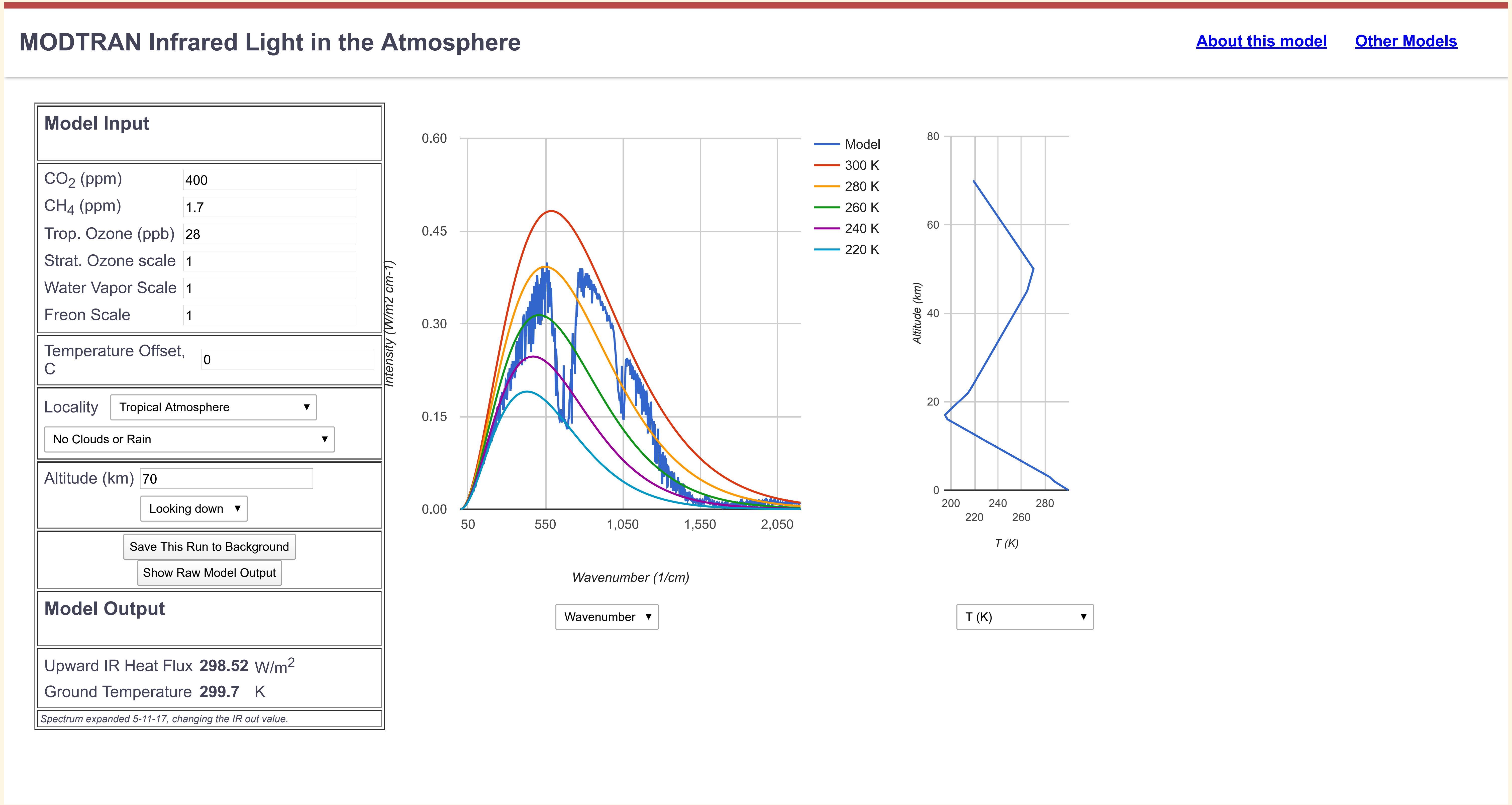
Different Gases



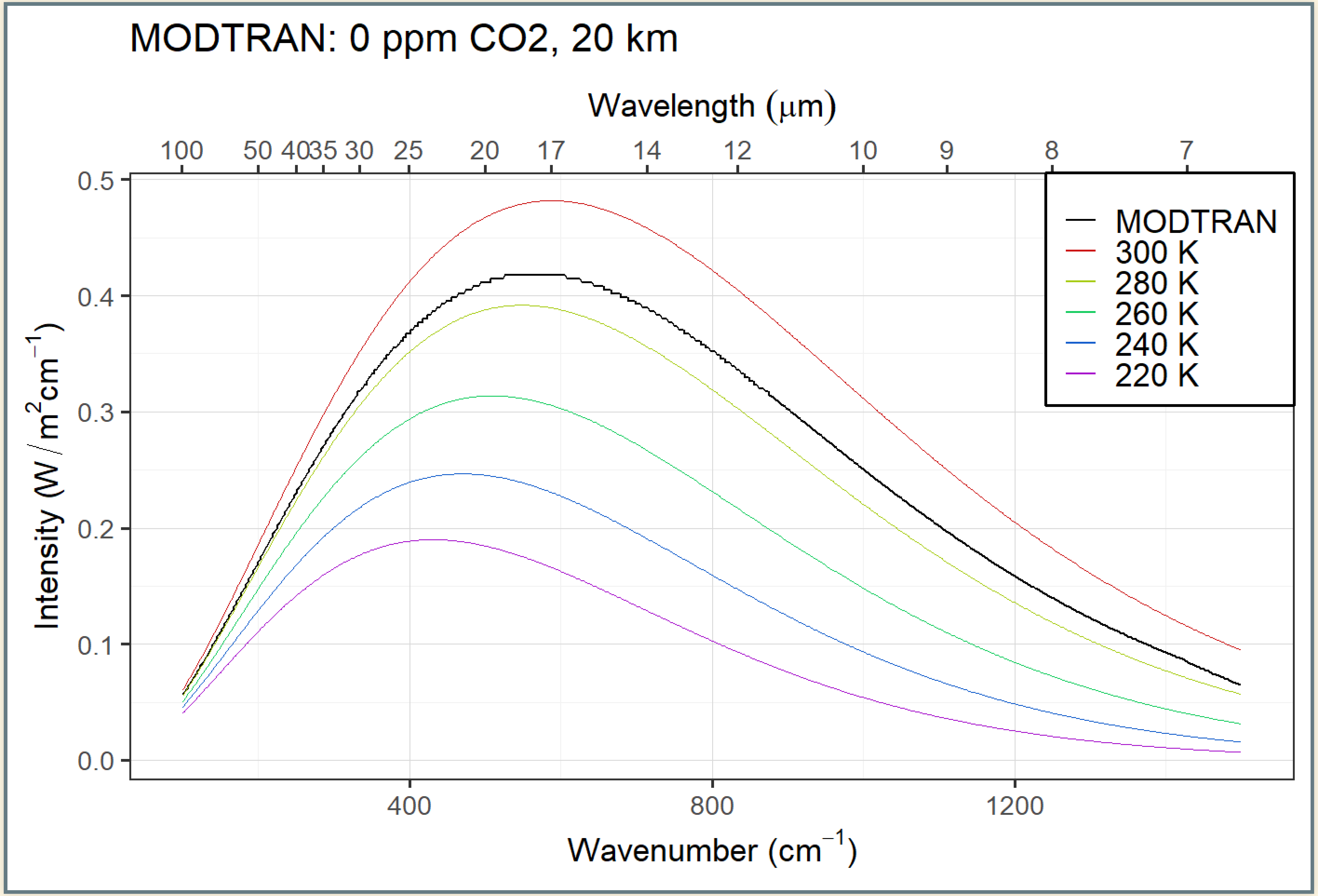
Band Saturation

Set up MODTRAN:

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

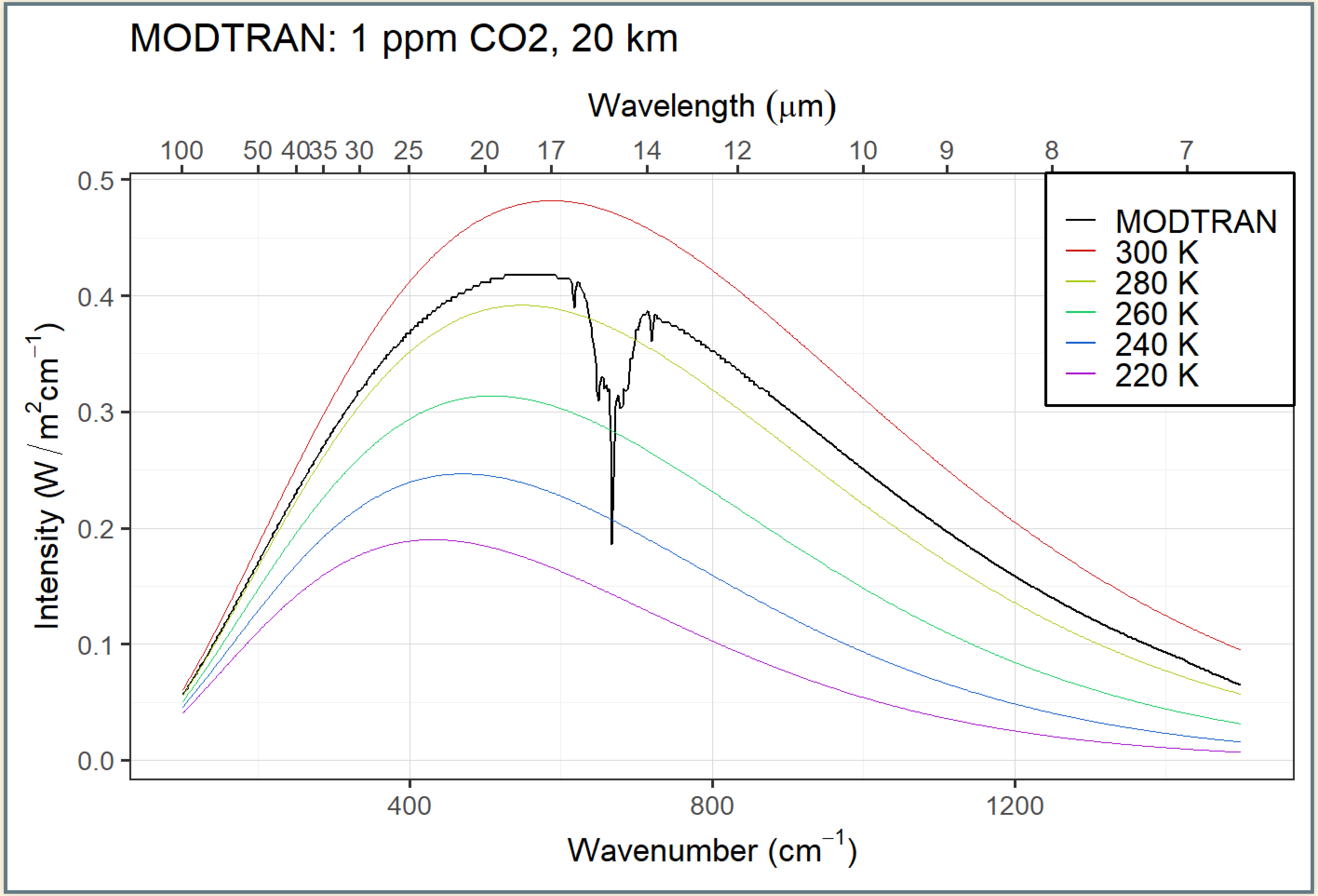


No CO_2



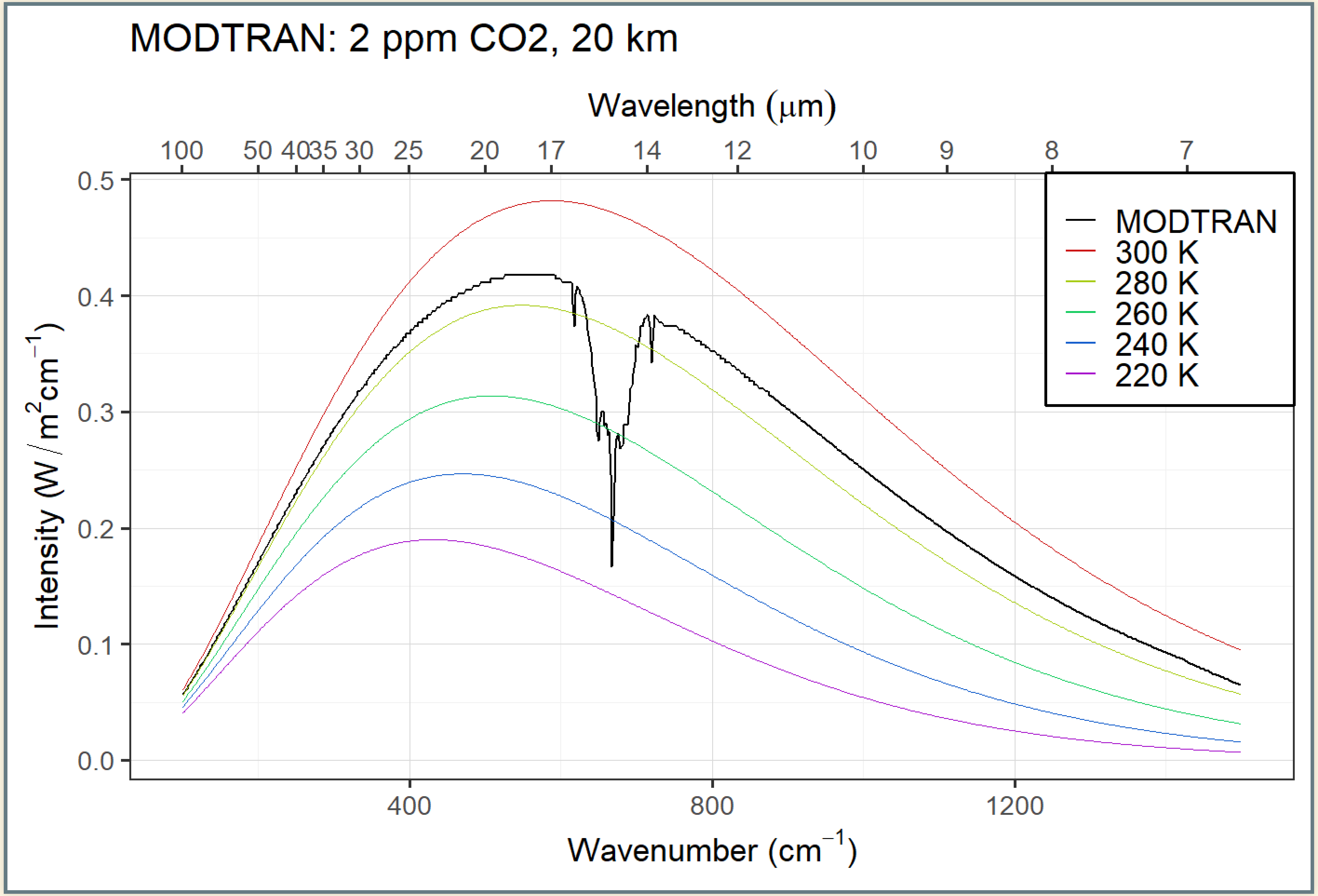
MODTRAN: 0 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

1 ppm CO_2



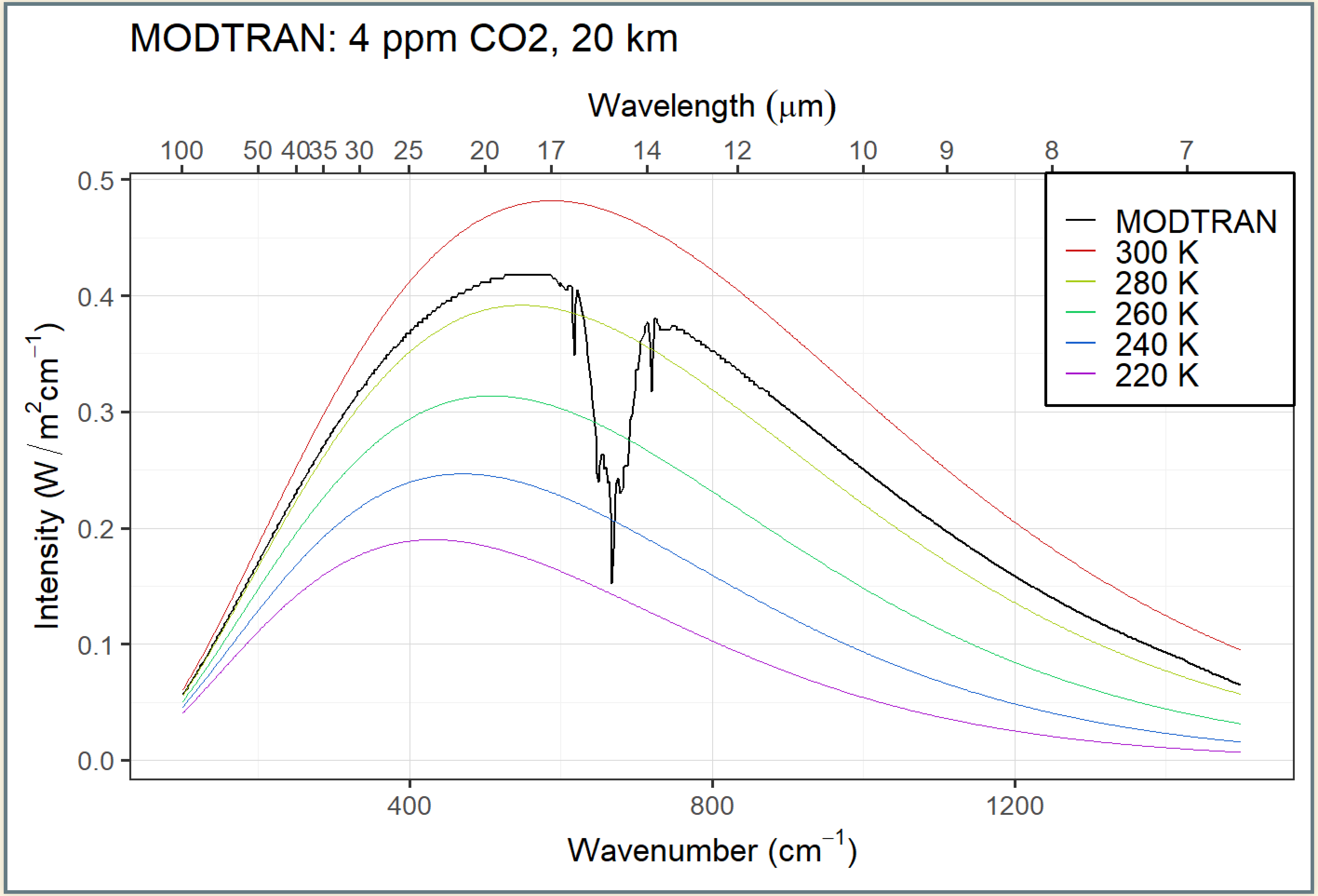
MODTRAN: 1 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m2cm−1)
400
800
1200
Wavenumber (cm−1)
MODTRAN
300 K
280 K
260 K
240 K
220 K

2 ppm CO_2

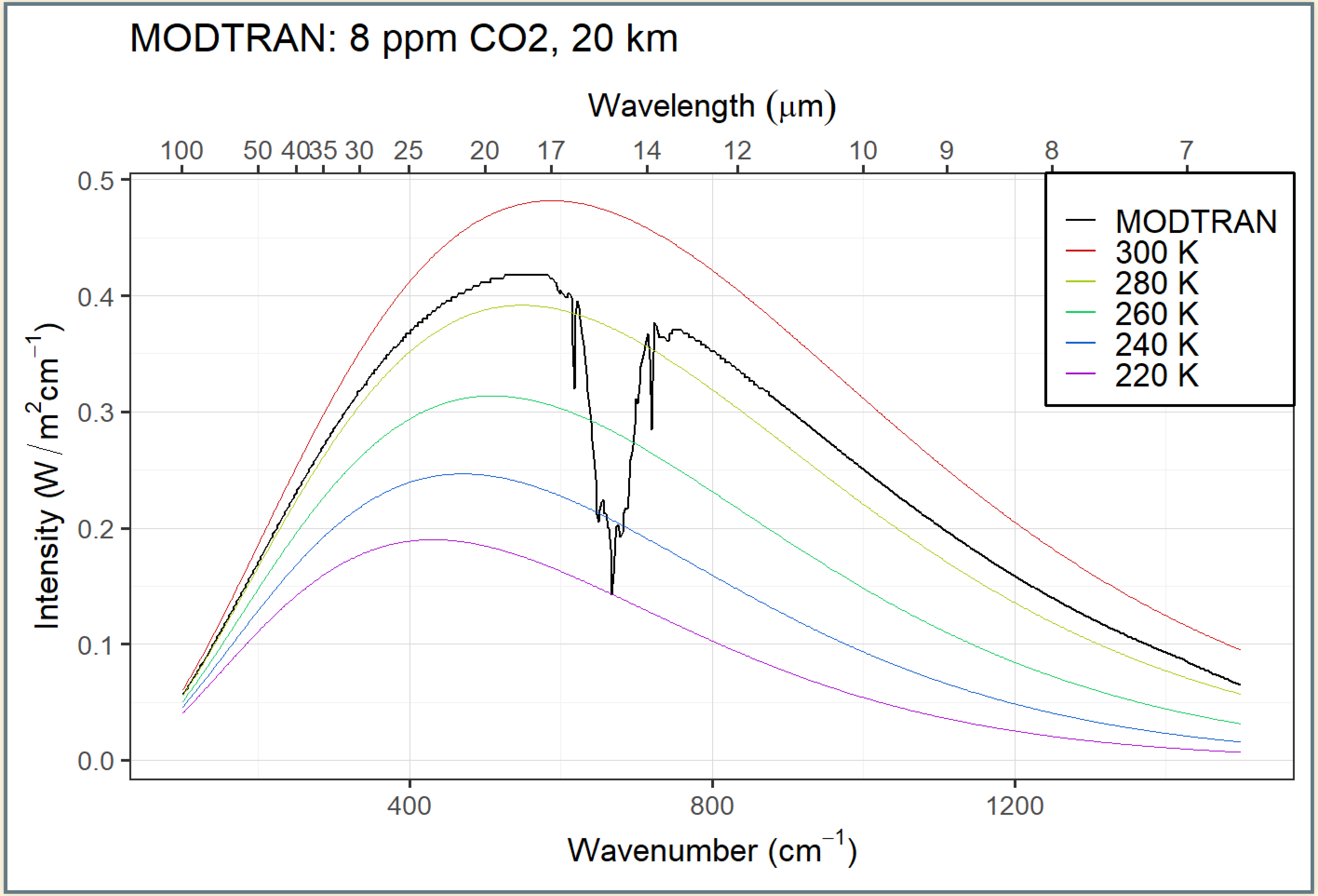


MODTRAN: 2 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
Intensity (W / m²cm⁻¹)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

4 ppm CO_2

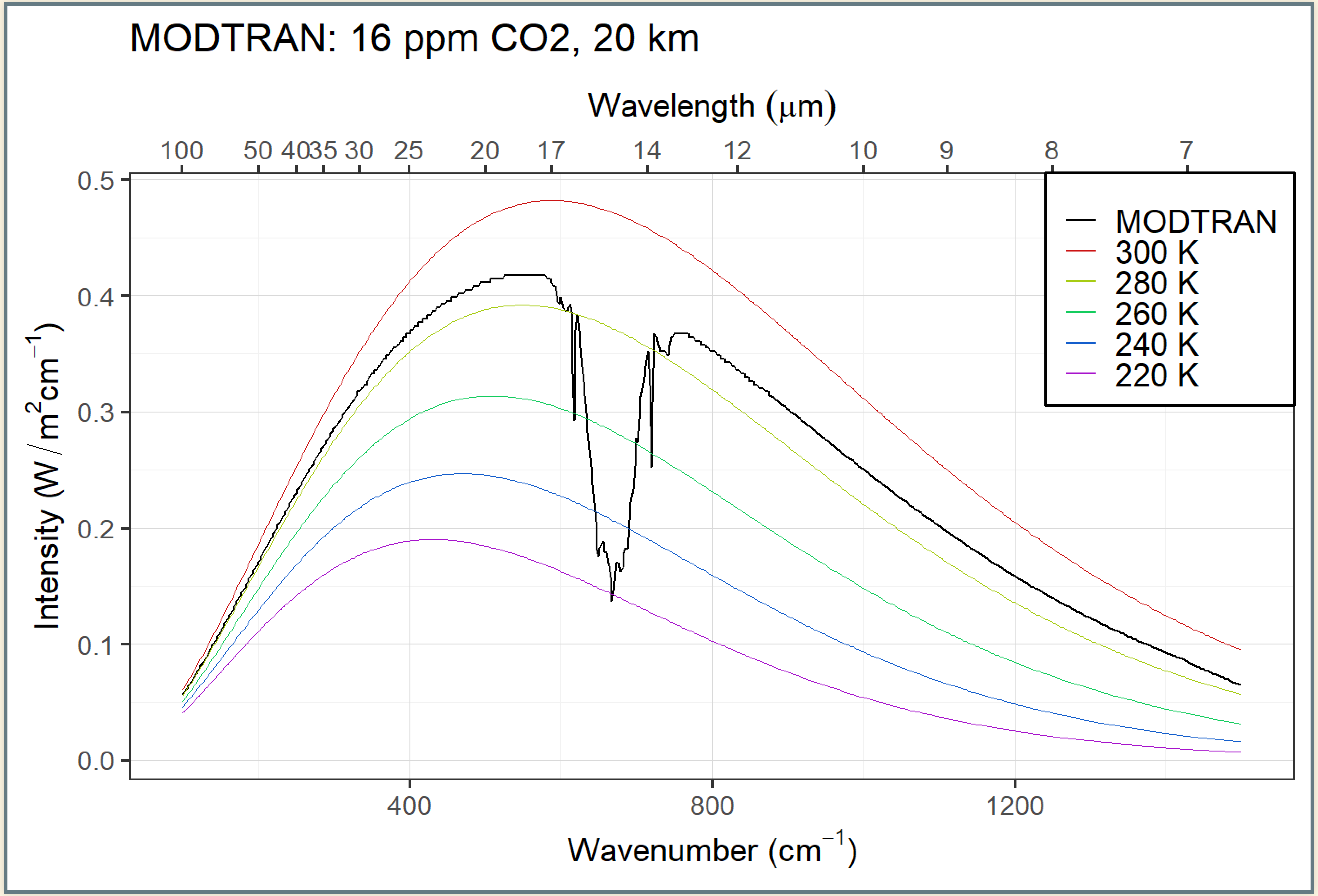

MODTRAN: 4 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

8 ppm CO_2

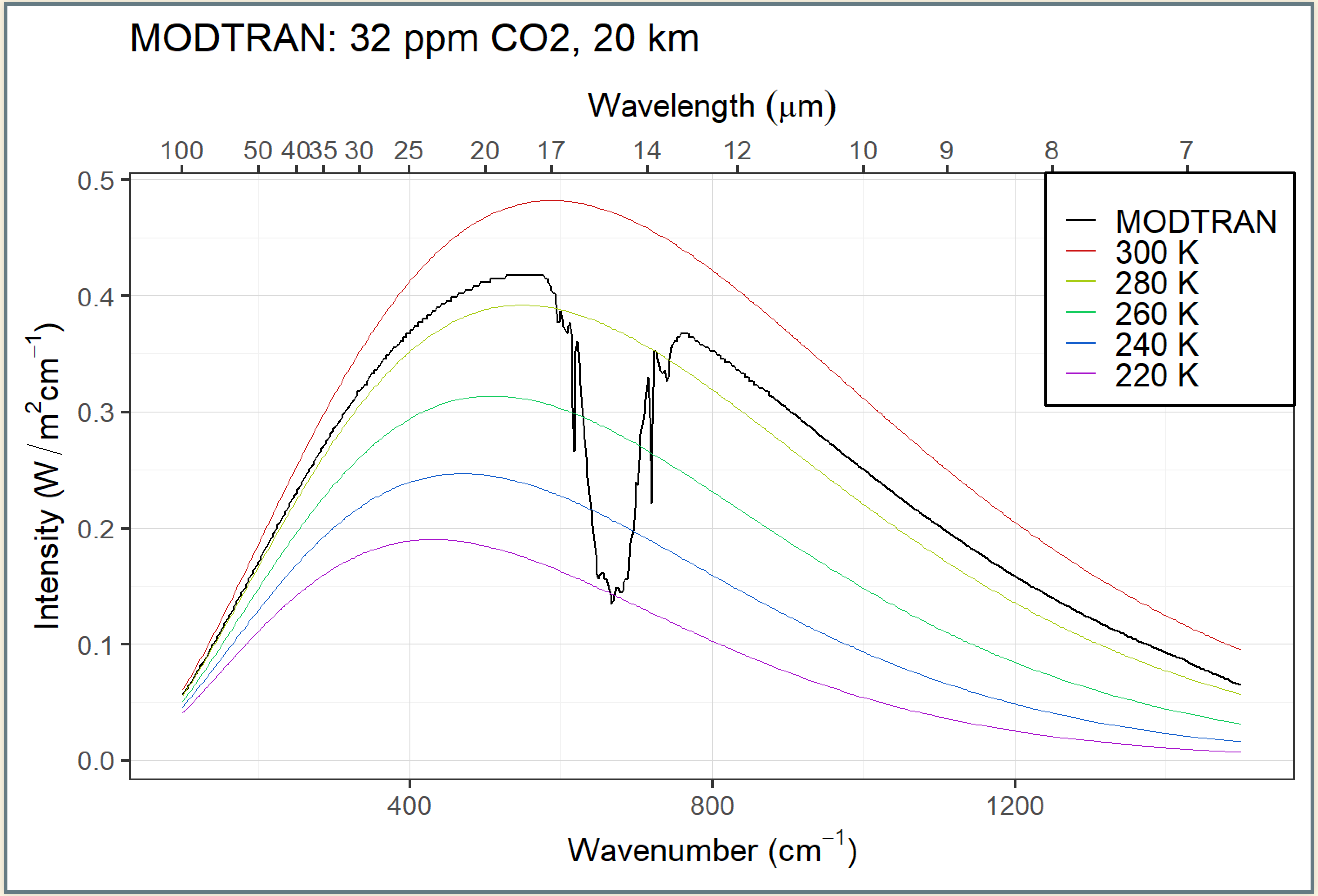


MODTRAN: 8 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m2cm−1)
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm−1)

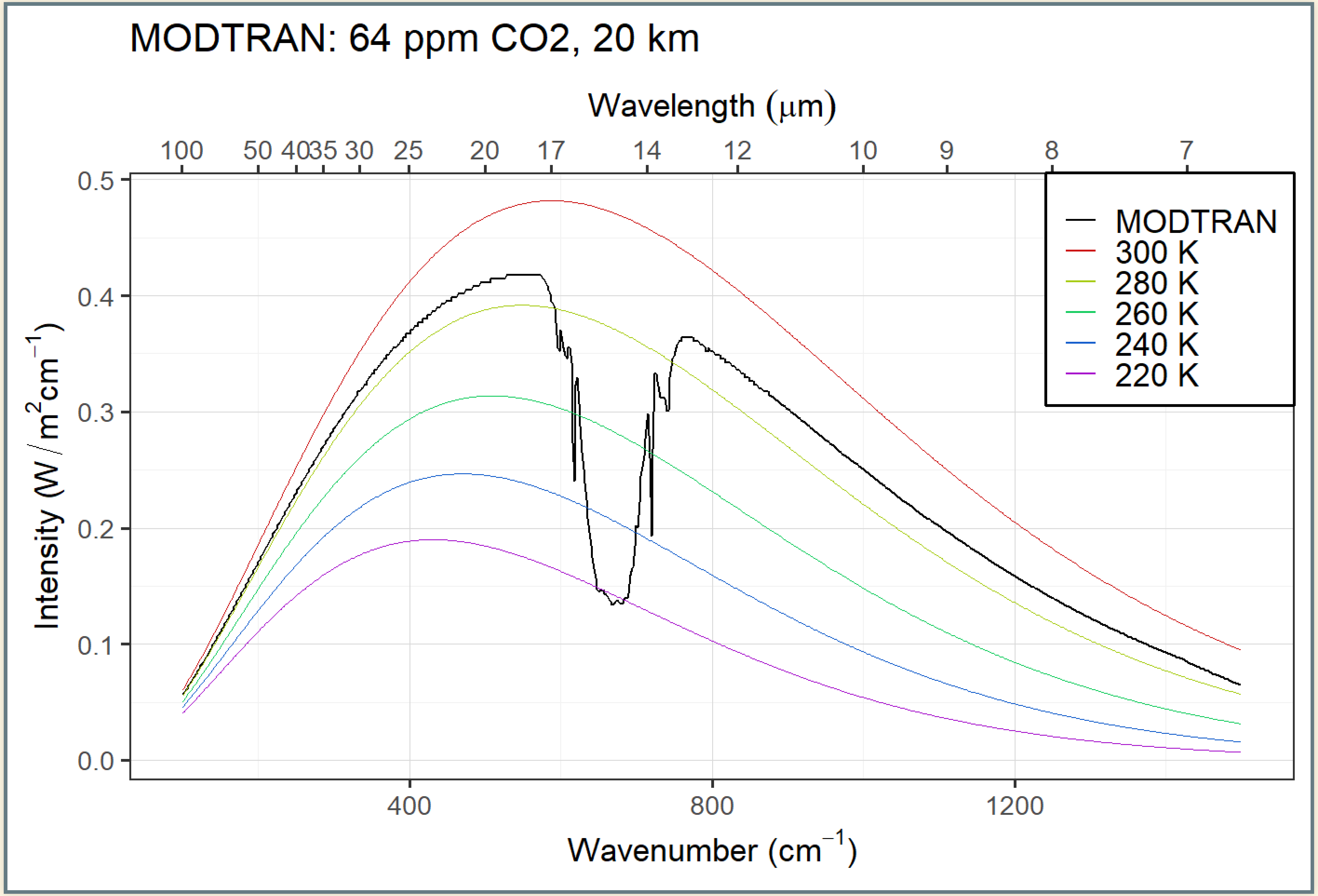
16 ppm CO_2


MODTRAN: 16 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
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

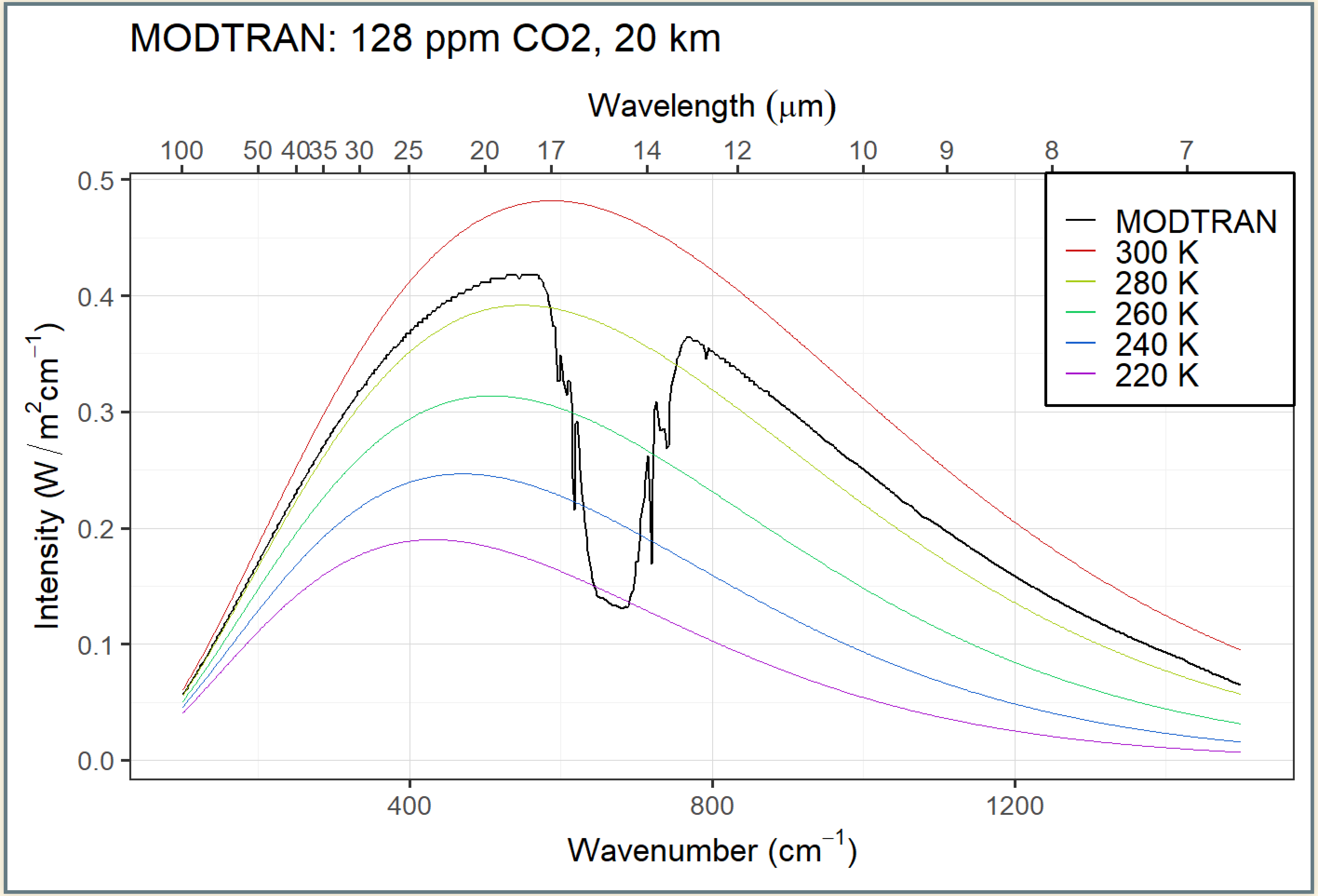
32 ppm CO_2


MODTRAN: 32 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
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)

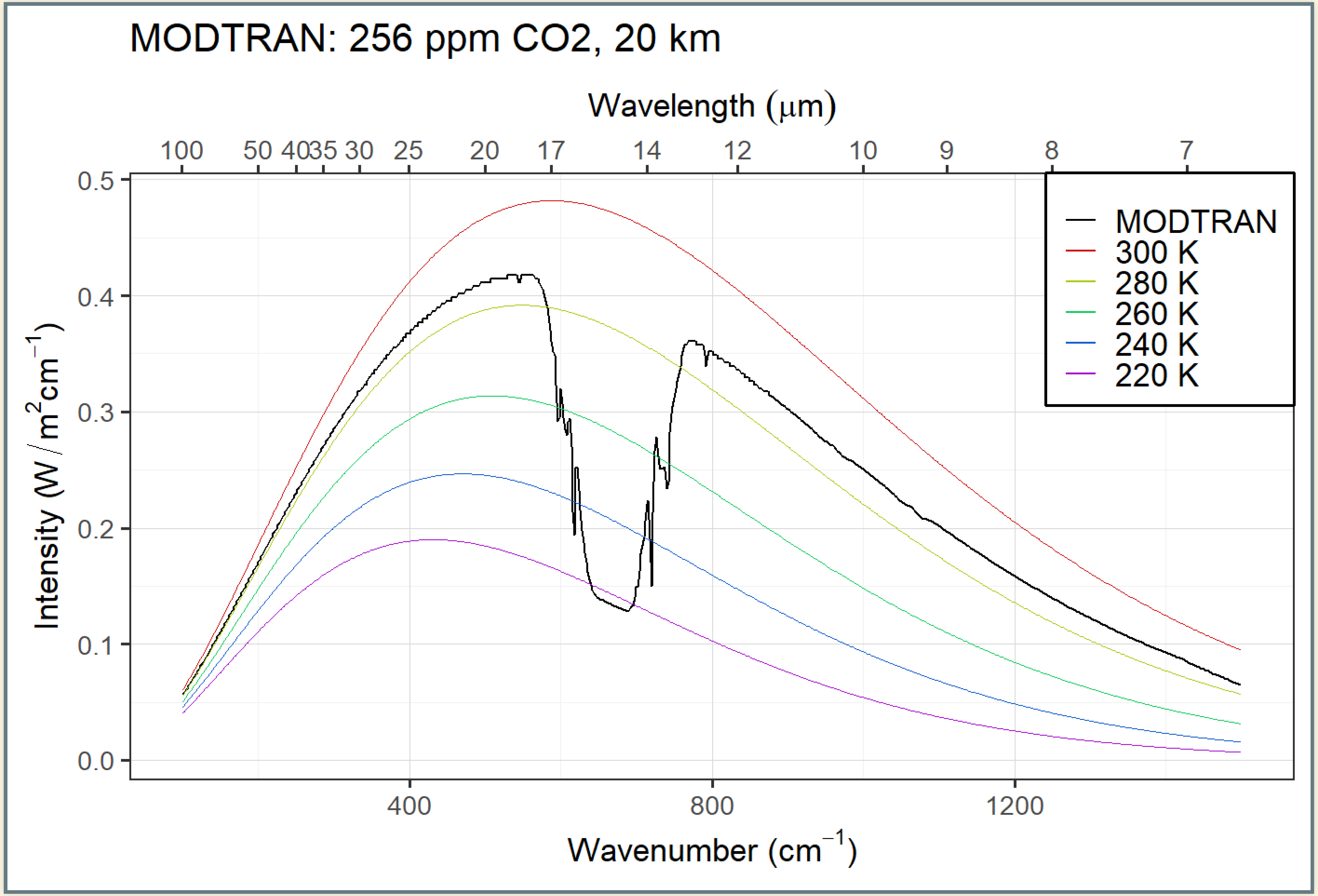
64 ppm CO_2


MODTRAN: 64 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
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

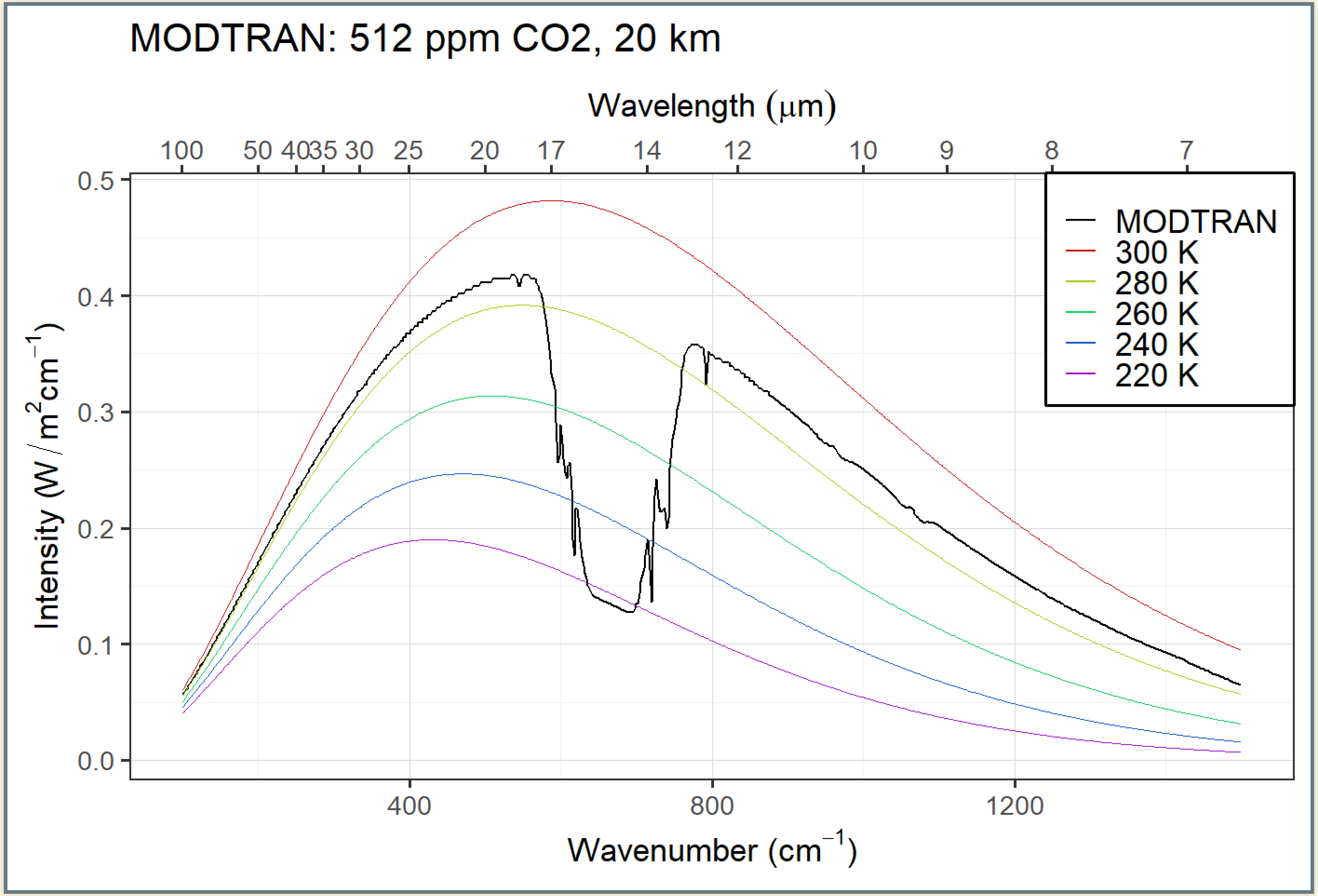
128 ppm CO_2


MODTRAN: 128 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
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

256 ppm CO_2

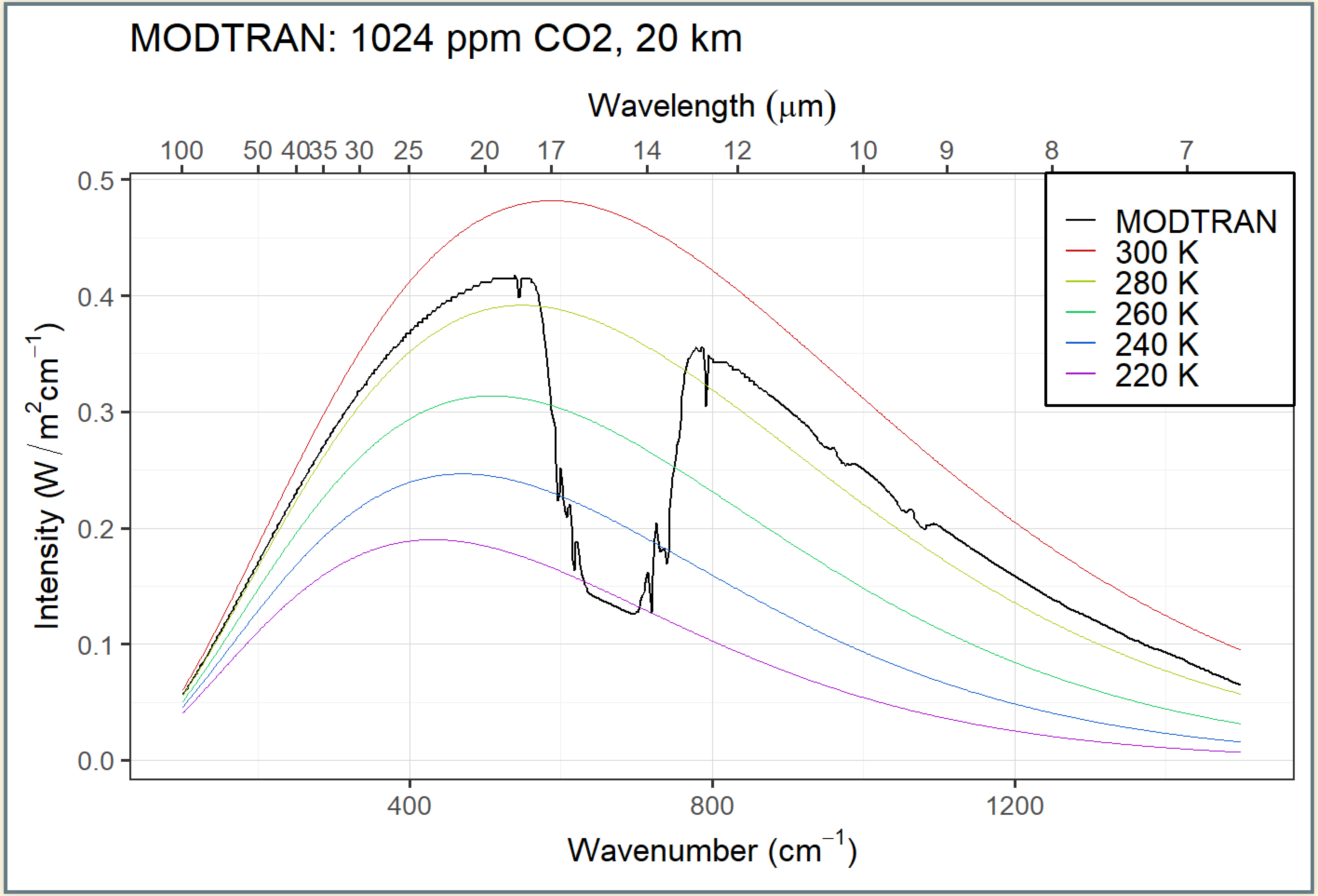

MODTRAN: 256 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

512 ppm CO_2

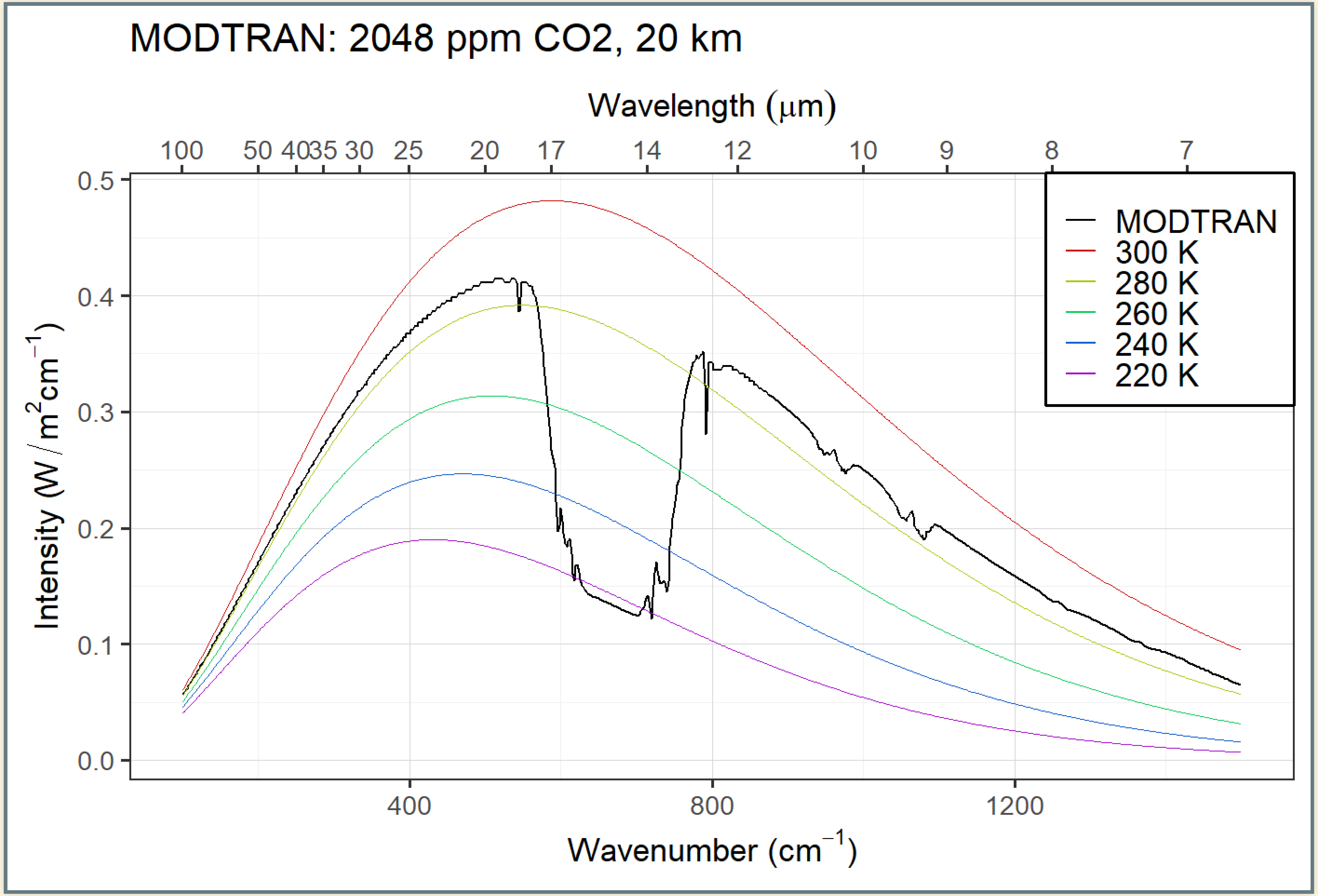


MODTRAN: 512 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m2cm−1)
400
800
1200
Wavenumber (cm−1)
MODTRAN
300 K
280 K
260 K
240 K
220 K

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
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)

2048 ppm CO_2

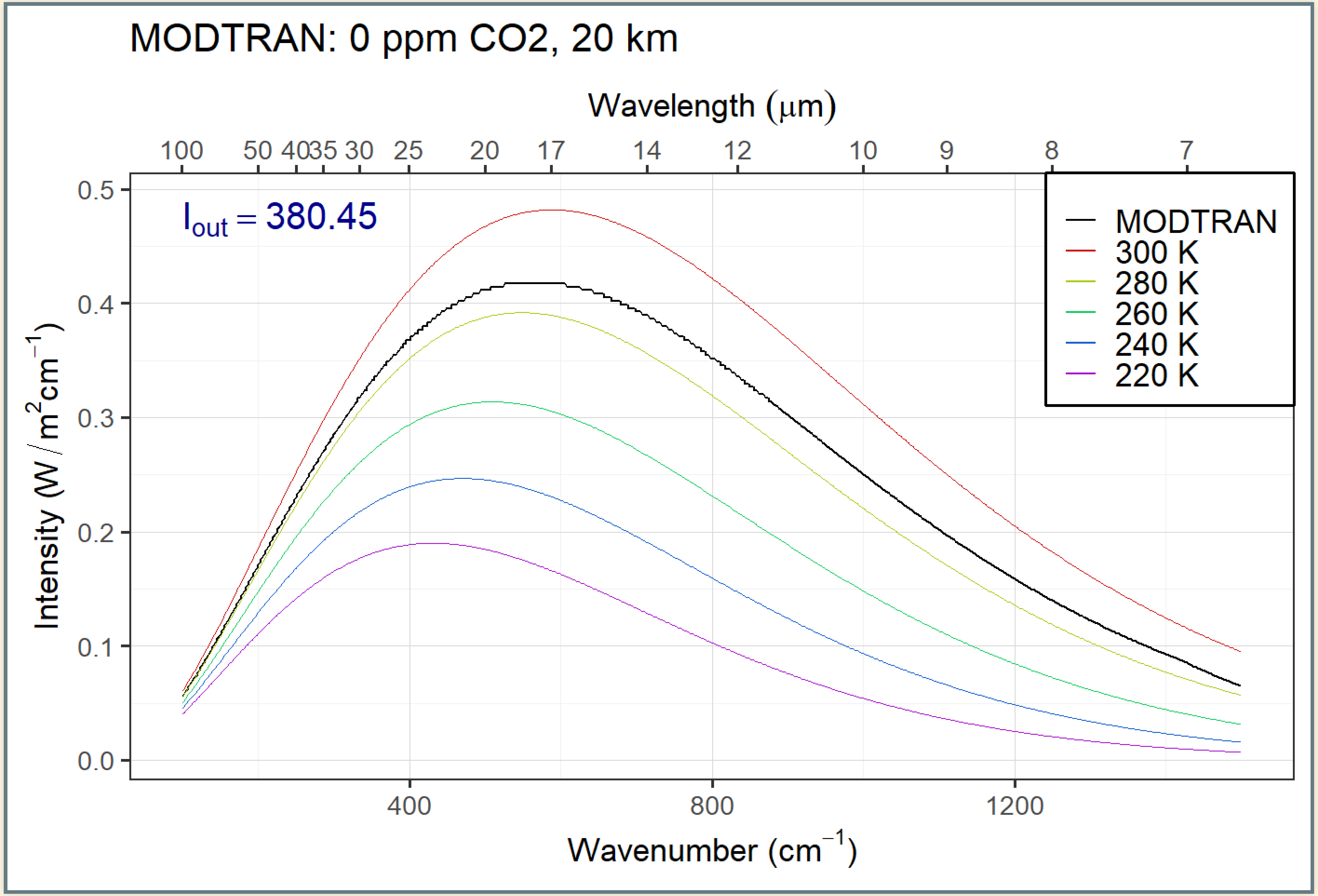

MODTRAN: 2048 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m2cm−1)
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm−1)

Measuring Band Saturation

Set up MODTRAN:

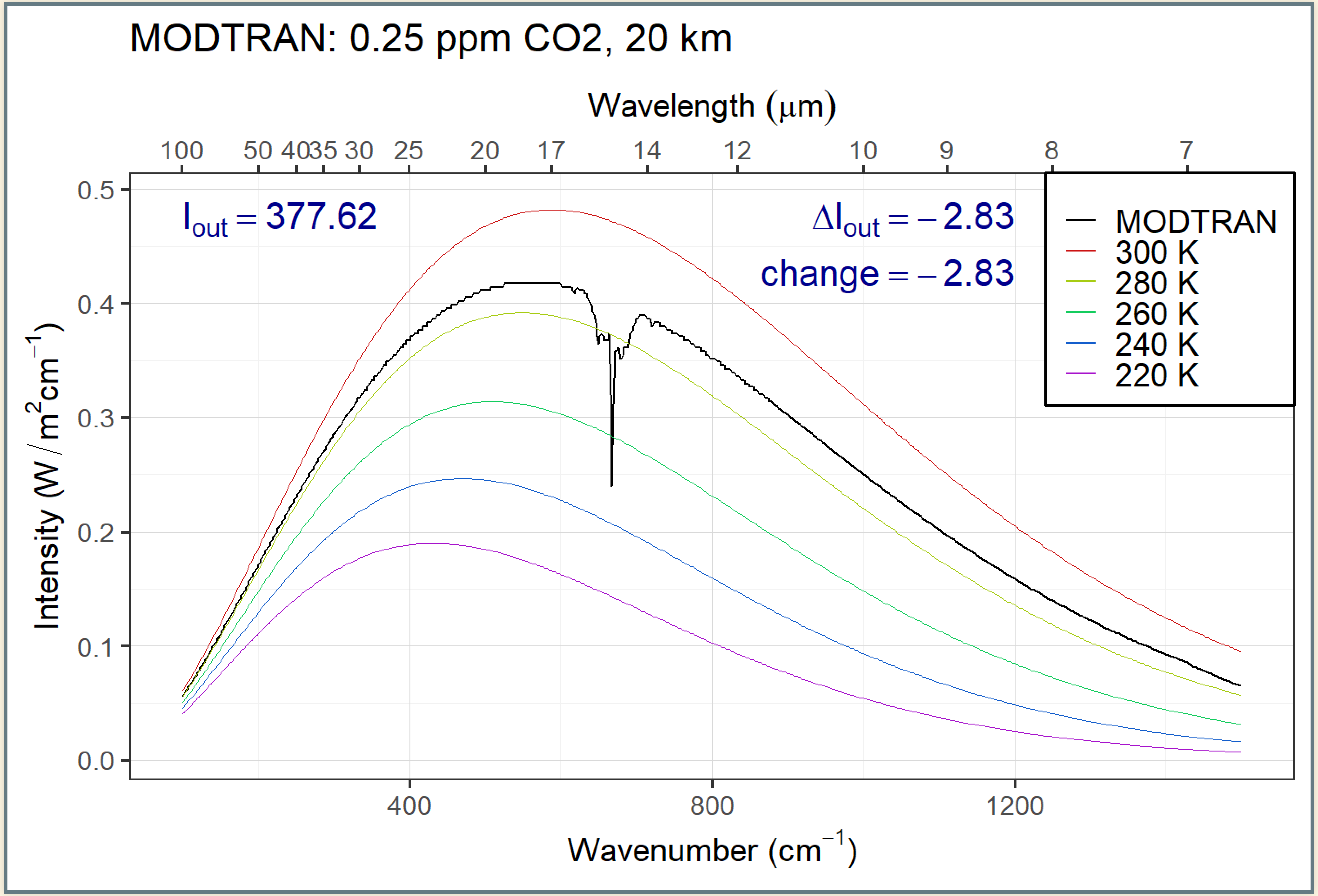
- Go to MODTRAN, set CO_2 to 100 ppm, and set all other gases to zero.
- Set altitude to 20 km and location to “1976 US Standard Atmosphere”.
- Press “Save this run to background”
- Note I_{out}
- Double CO_2 and note the change in I_{out}
- Keep doubling CO_2 until you get to 1600 ppm.
- Do you notice anything about the changes in I_{out}?

0 ppm CO_2



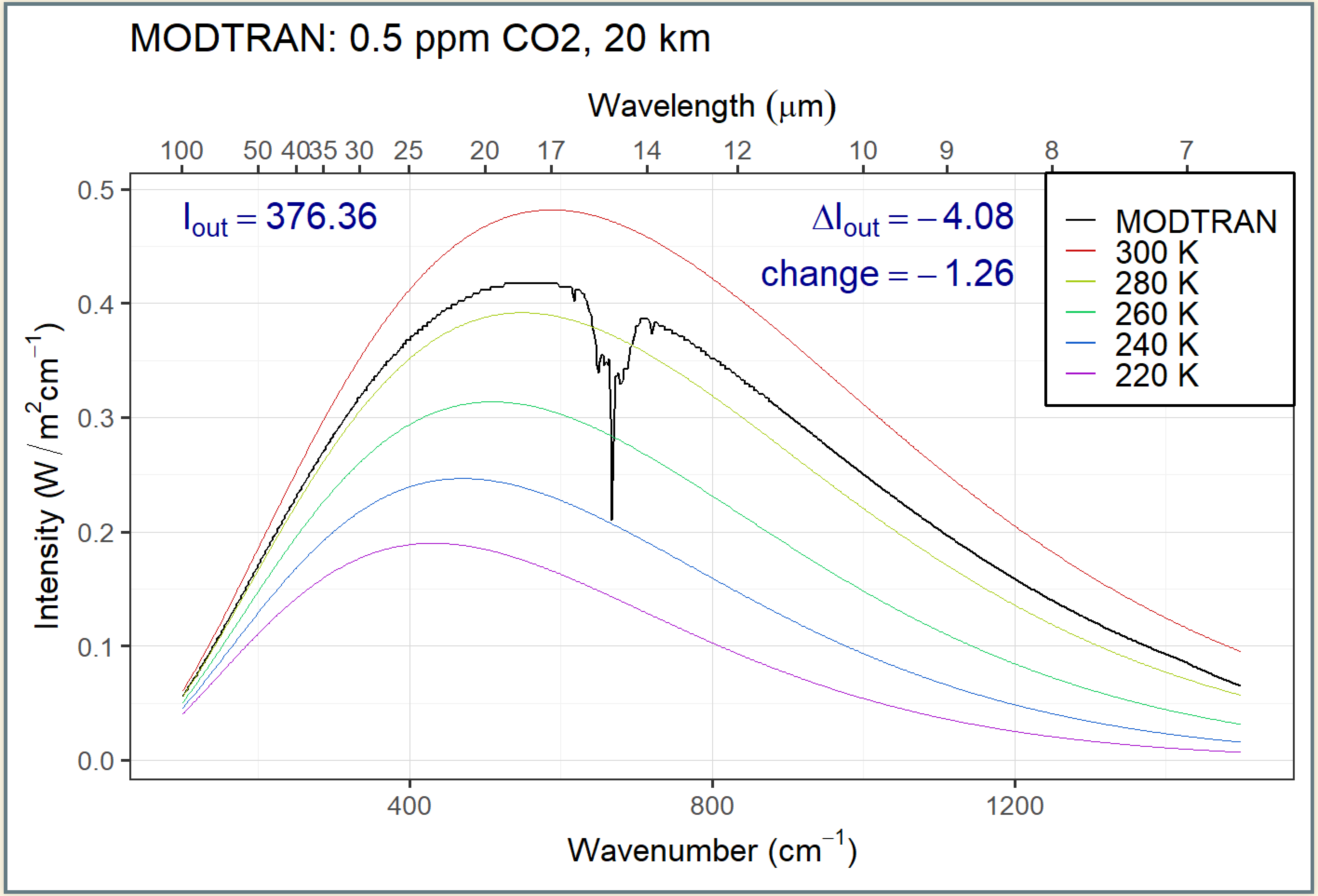
MODTRAN: 0 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 380.45$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W / m^2 cm^{-1}$)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

0.25 ppm CO_2

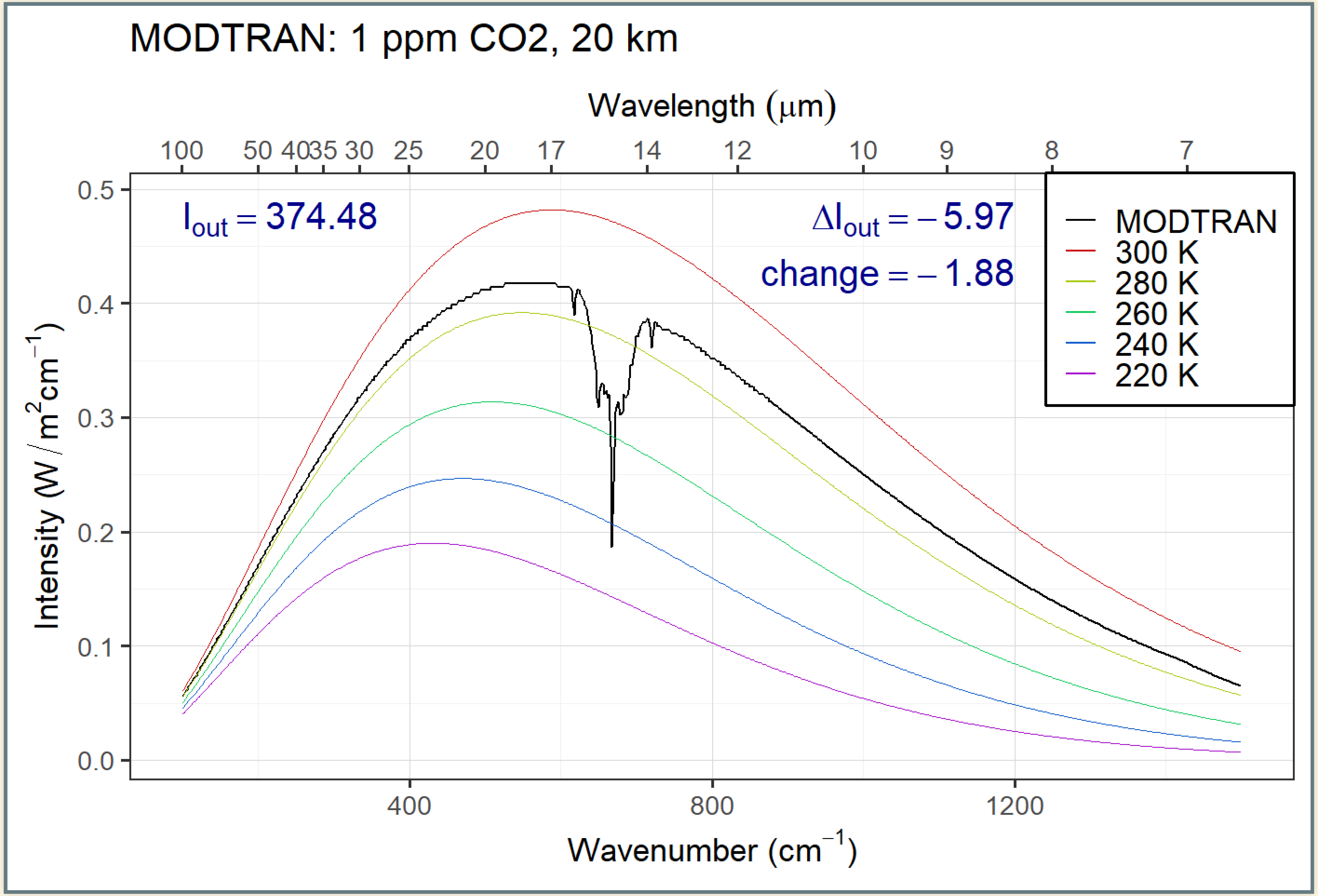


MODTRAN: 0.25 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 377.62$
$\Delta I_{out} = -2.83$
$change = -2.83$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W/m^2cm^{-1})
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

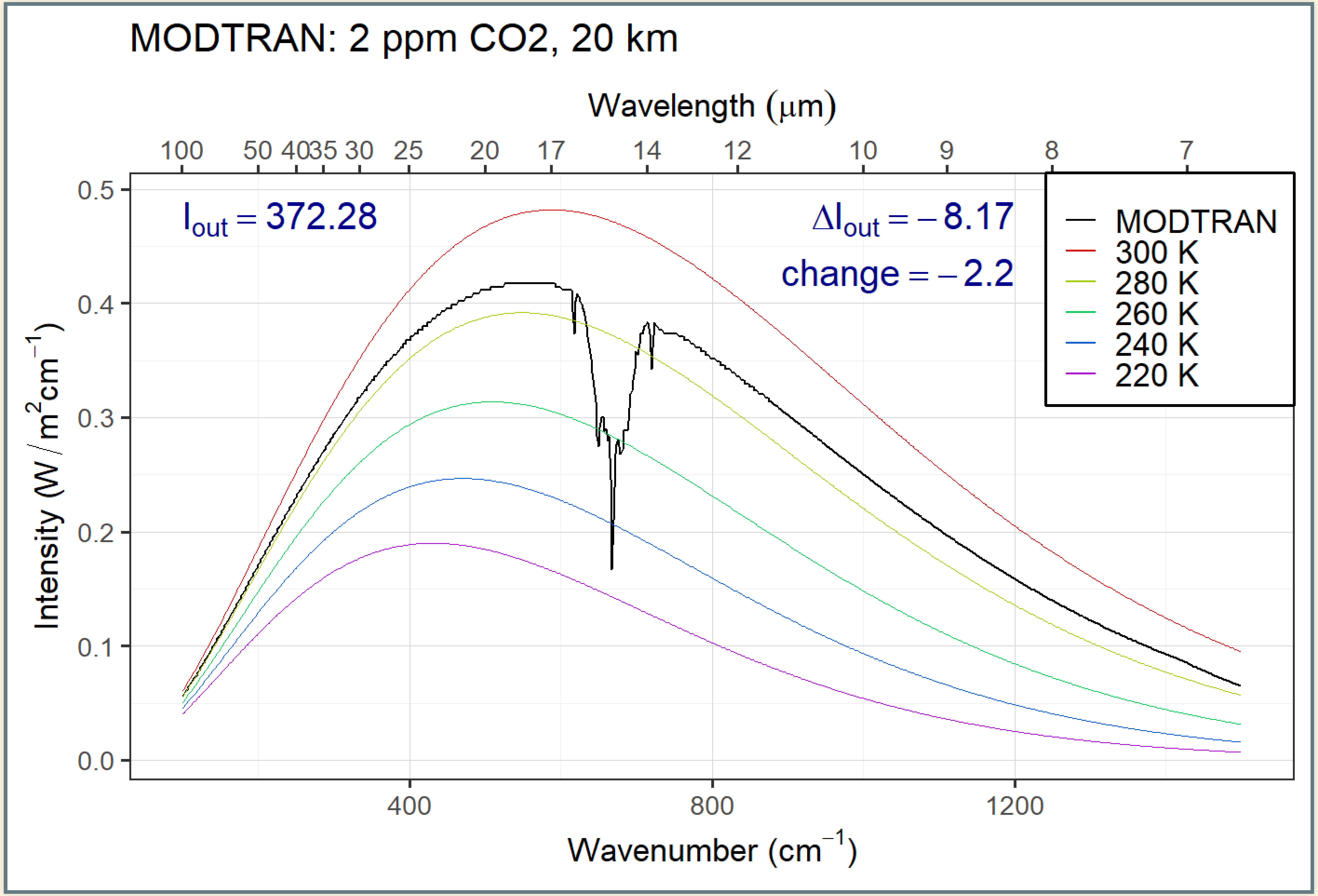
0.5 ppm CO_2


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 ($W / m^2 cm^{-1}$)
0.0 0.1 0.2 0.3 0.4 0.5
400 800 1200
Wavenumber (cm^{-1})

1 ppm CO_2

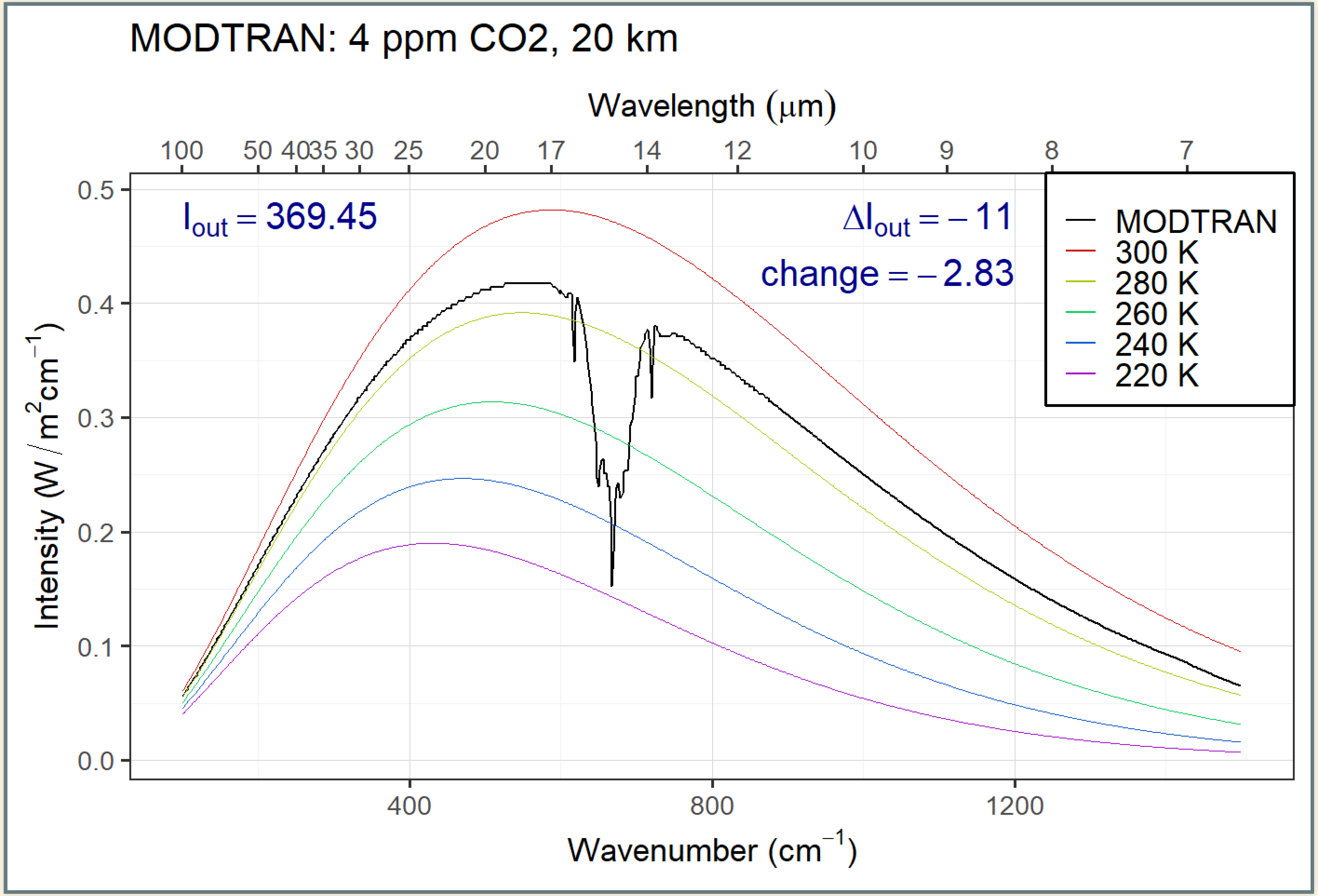

MODTRAN: 1 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m2cm−1)
Iout = 374.48
ΔIout = −5.97
change = −1.88
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm−1)

2 ppm CO_2

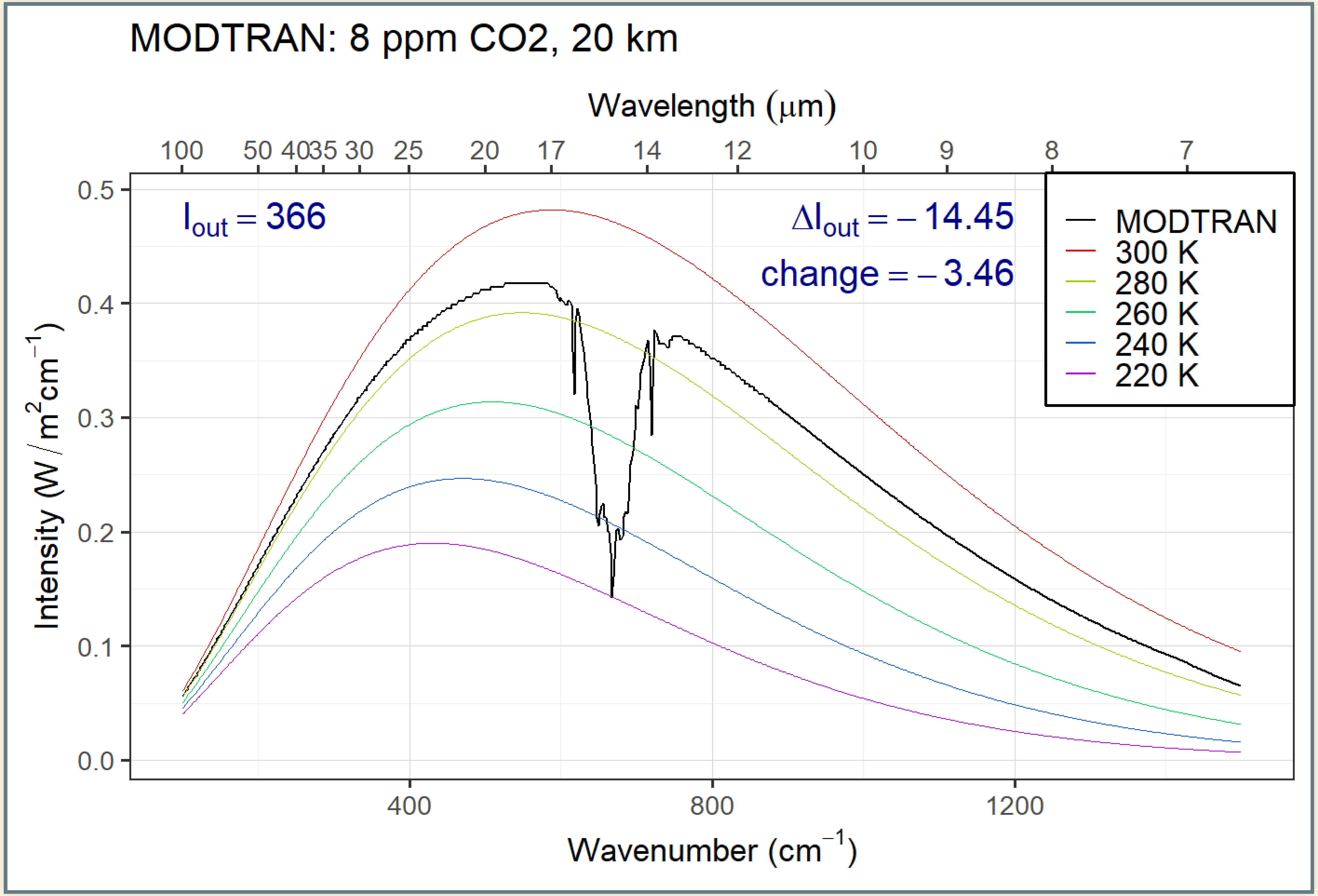


MODTRAN: 2 ppm CO2, 20 km
Wavelength (μm)
100 50 40 35 30 25 20 17 14 12 10 9 8 7
$I_{out} = 372.28$
$\Delta I_{out} = -8.17$
$change = -2.2$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m^{2}cm^{-1})
0.0 0.1 0.2 0.3 0.4 0.5
400 800 1200
Wavenumber (cm^{-1})

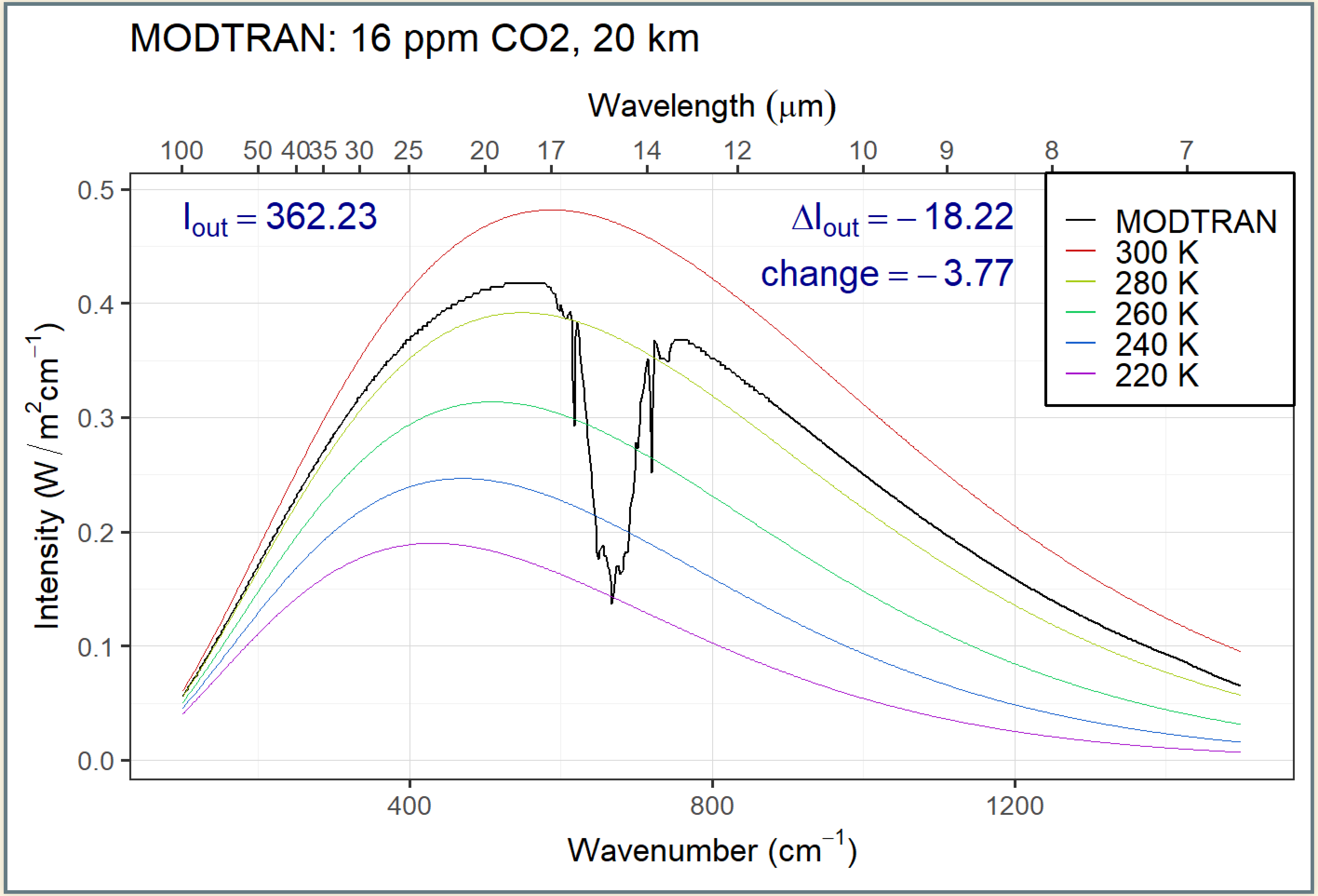
4 ppm CO_2


MODTRAN: 4 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)
Iout = 369.45
ΔIout = − 11
change = − 2.83
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm−1)

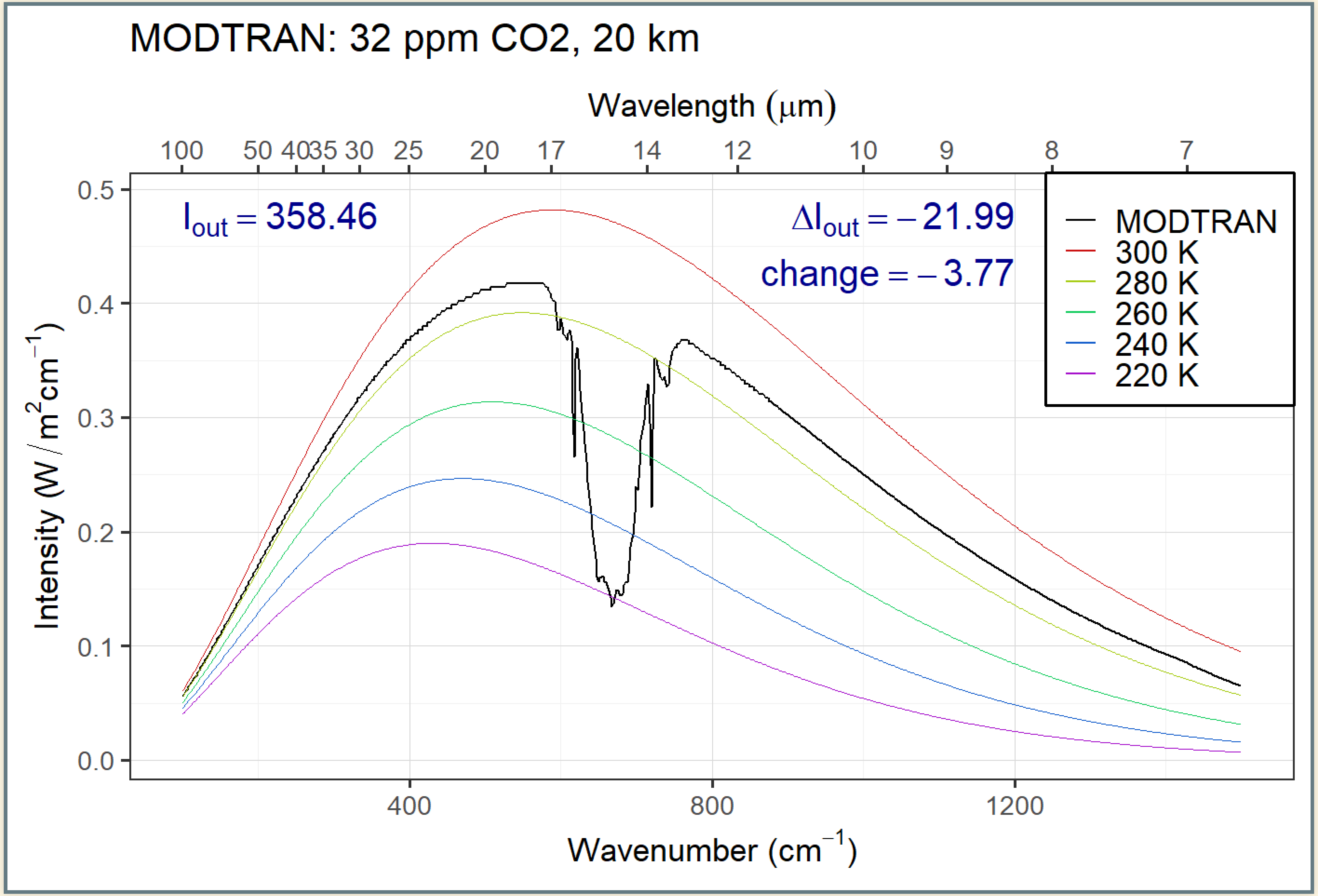
8 ppm CO_2


MODTRAN: 8 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
$I_{out} = 366$
$\Delta I_{out} = -14.45$
$change = -3.46$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W/m^2cm^{-1})
400
800
1200
Wavenumber (cm^{-1})

16 ppm CO_2

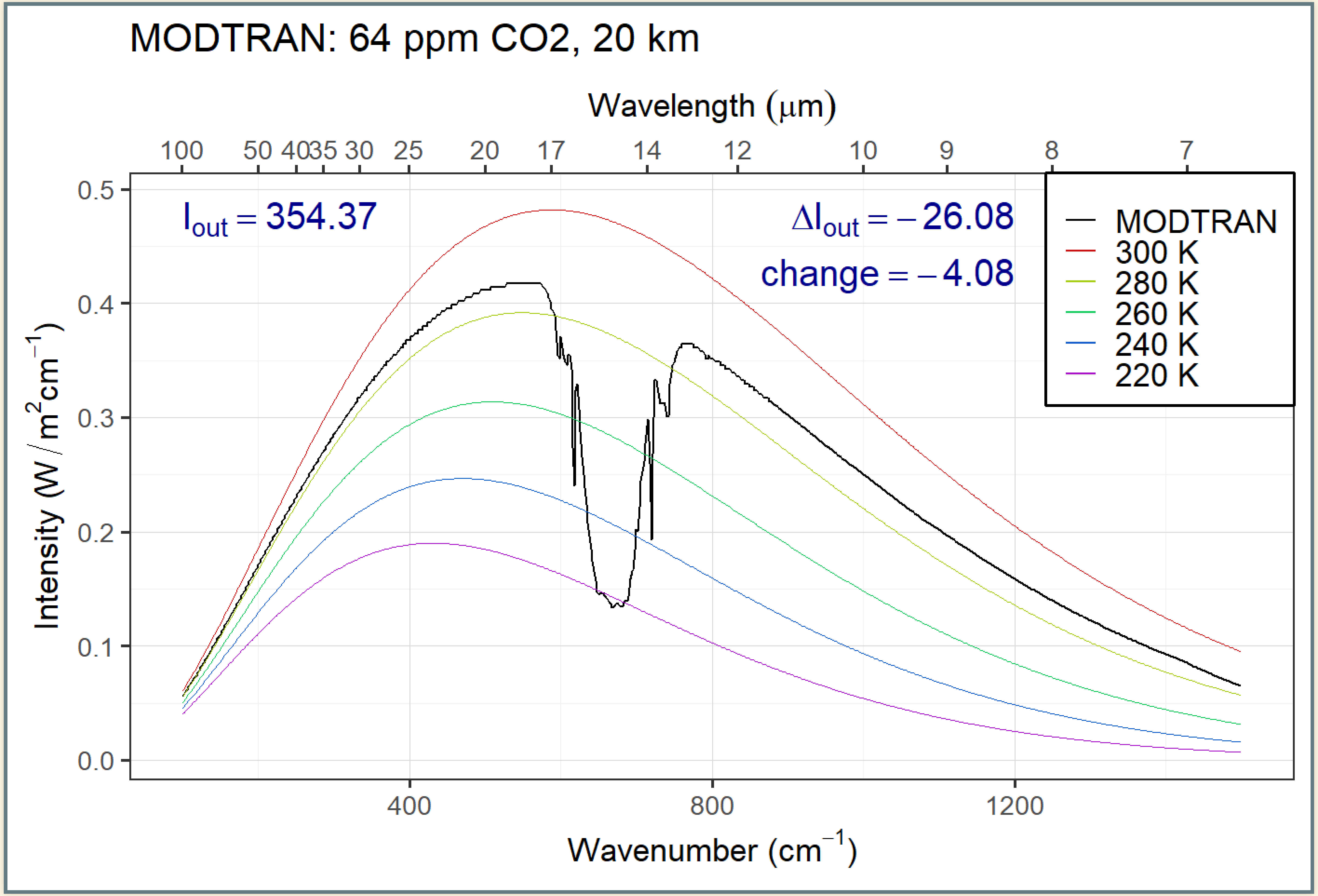

MODTRAN: 16 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
I_out = 362.23
ΔI_out = −18.22
change = −3.77
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm⁻¹)

32 ppm CO_2

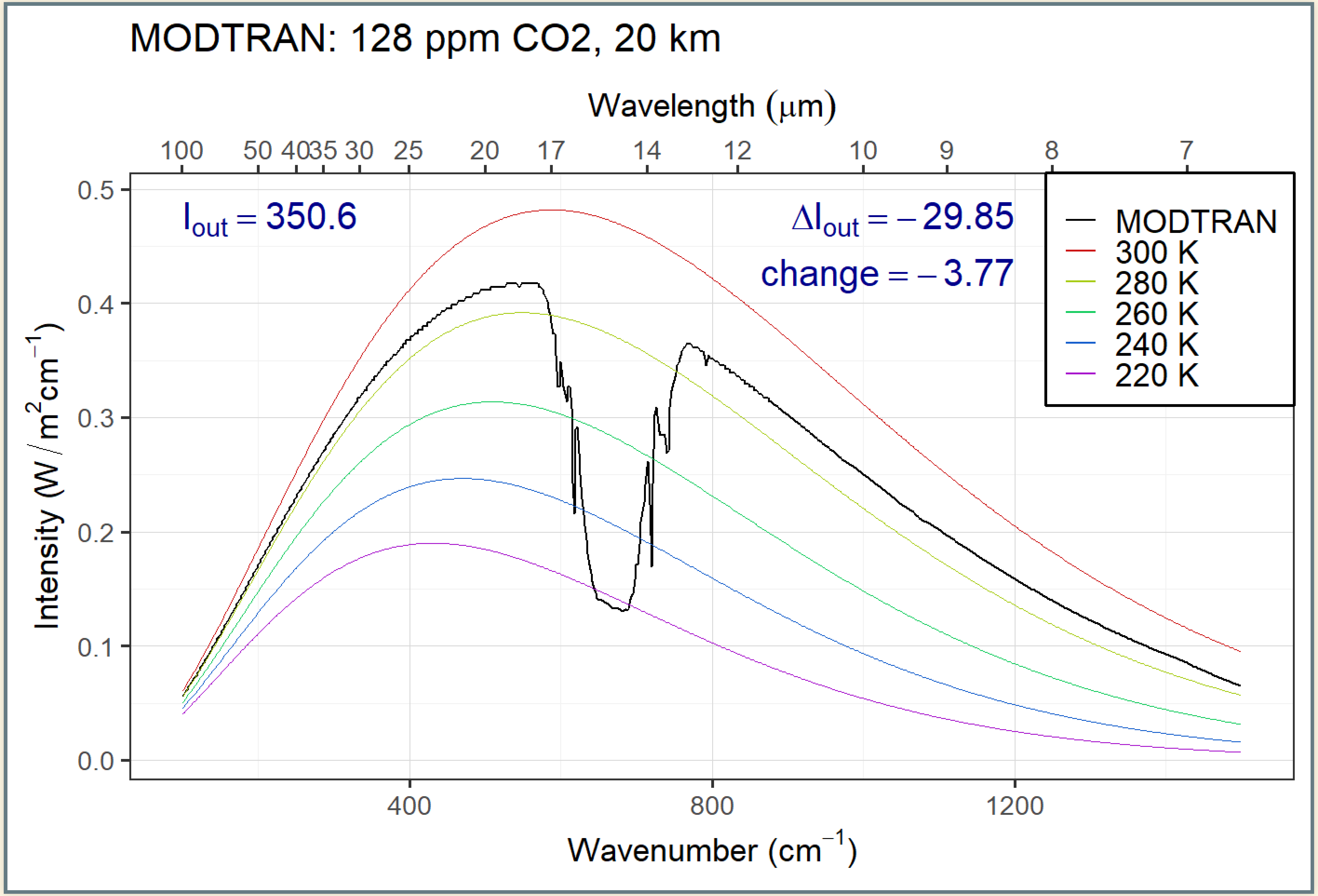


MODTRAN: 32 ppm CO2, 20 km
Wavelength (μm)
100 50 40 35 30 25 20 17 14 12 10 9 8 7
$I_{out} = 358.46$
$\Delta I_{out} = -21.99$
$change = -3.77$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W/m^2cm^{-1})
0.0 0.1 0.2 0.3 0.4 0.5
400 800 1200
Wavenumber (cm^{-1})

64 ppm CO_2

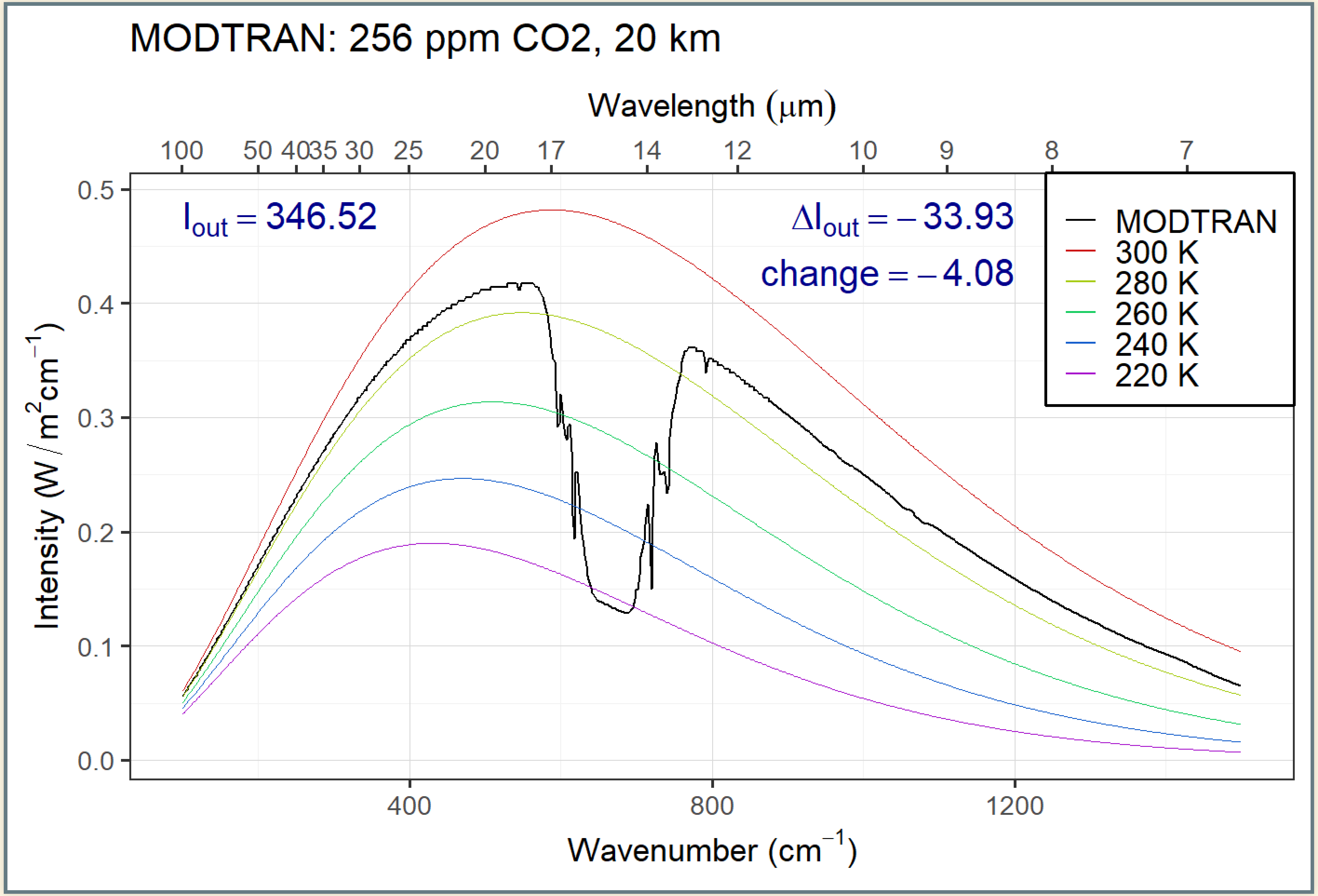

MODTRAN: 64 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 354.37$
$\Delta I_{out} = -26.08$
change = −4.08
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W / m^2 cm^{-1}$)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

128 ppm CO_2

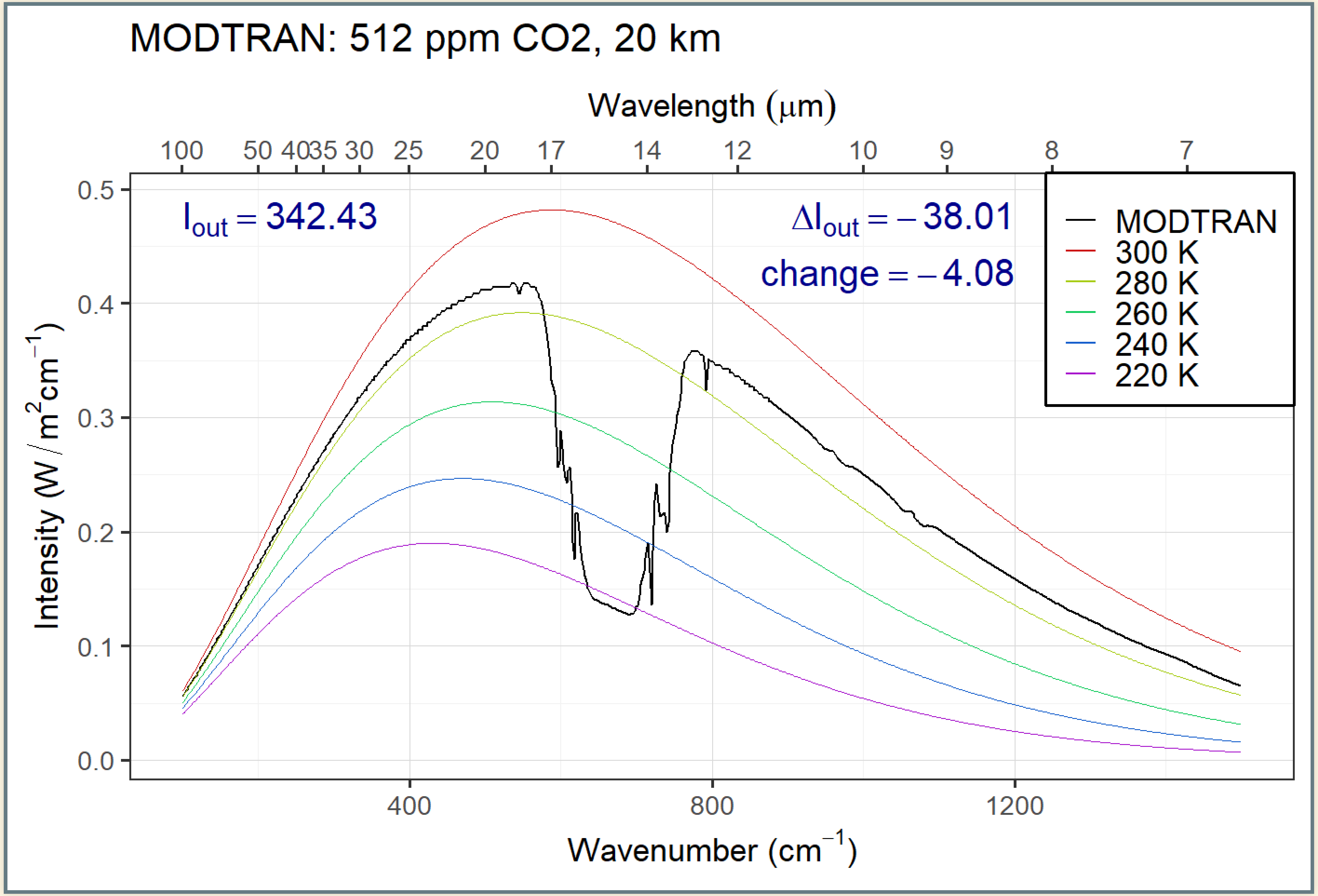


MODTRAN: 128 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
$I_{out} = 350.6$
$\Delta I_{out} = -29.85$
$change = -3.77$
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity ($W / m^2 cm^{-1}$)
400
800
1200
Wavenumber (cm^{-1})

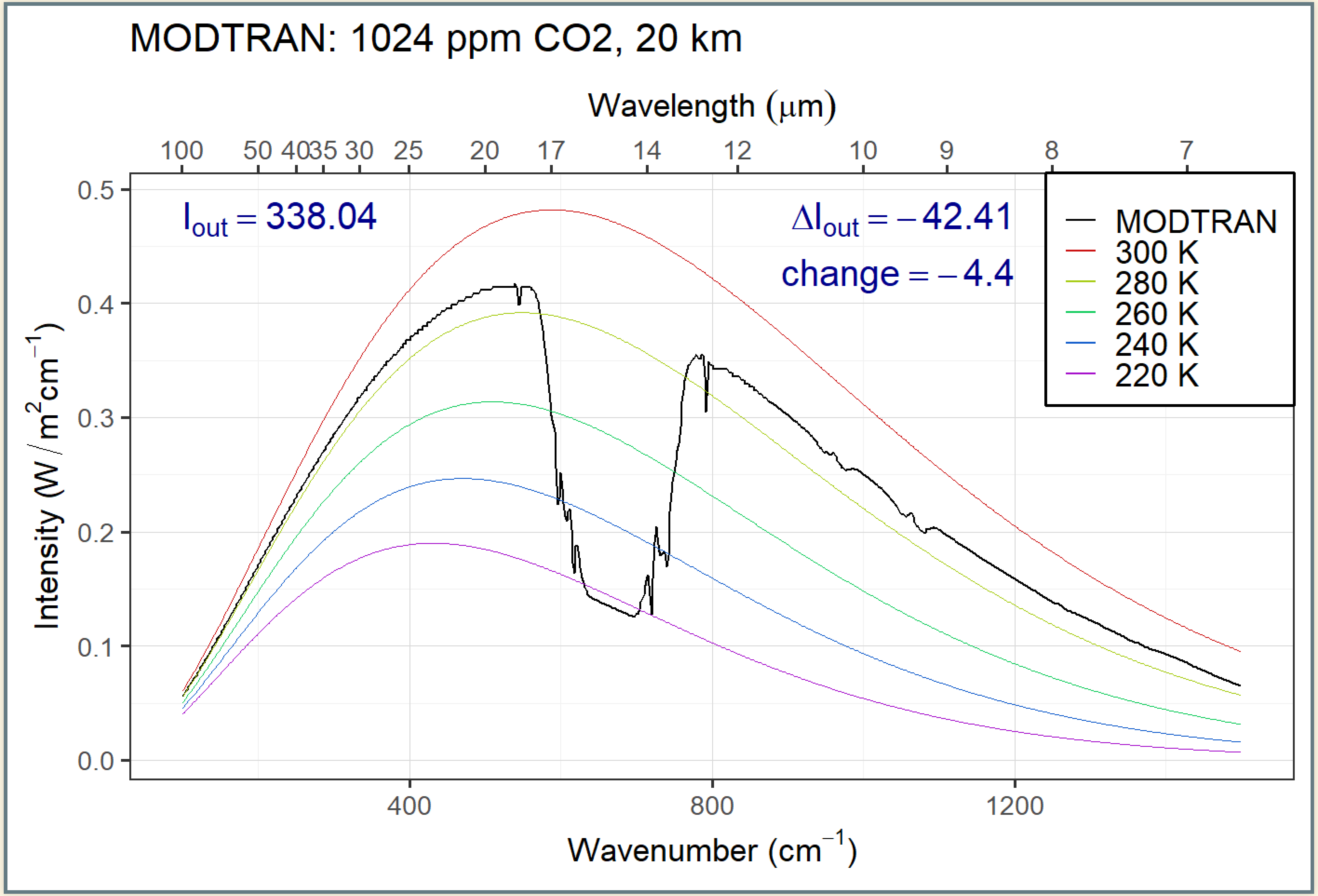
256 ppm CO_2


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/m^2cm^{-1})
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

512 ppm CO_2

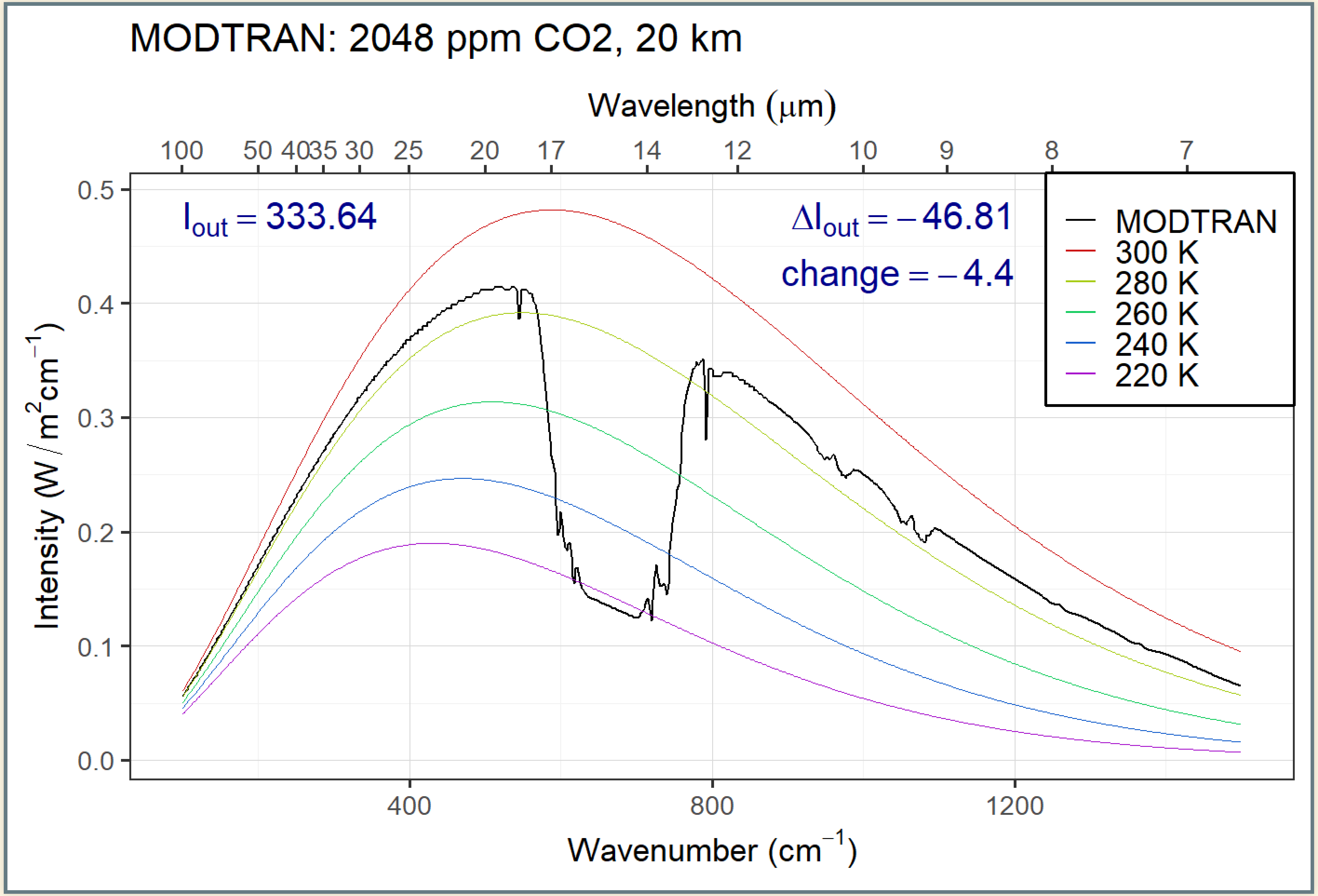

MODTRAN: 512 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 342.43$
$\Delta I_{out} = -38.01$
change = −4.08
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m^{2}cm^{-1})
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm^{-1})

1024 ppm CO_2

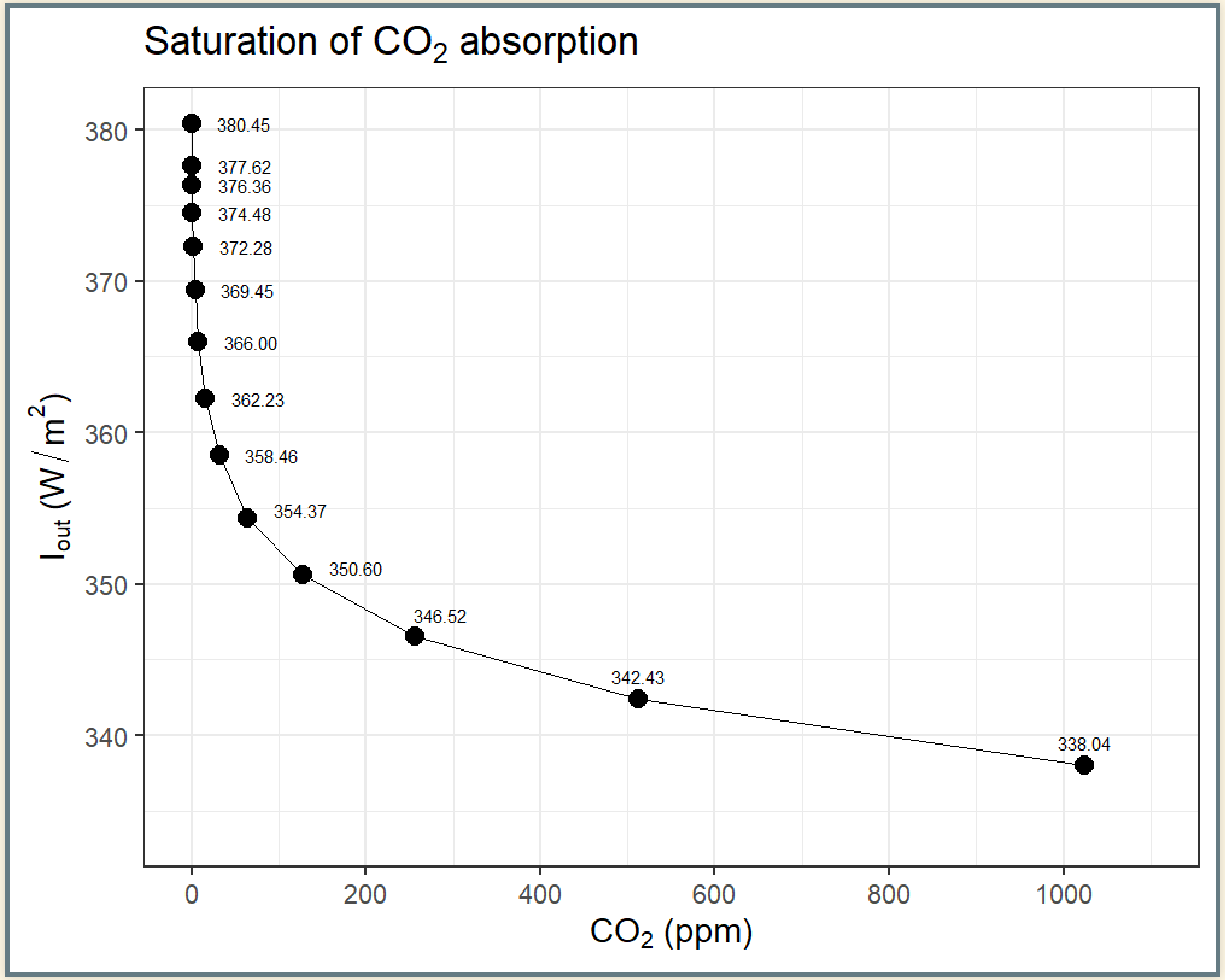


MODTRAN: 1024 ppm CO2, 20 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
$I_{out} = 338.04$
$\Delta I_{out} = -42.41$
change = −4.4
MODTRAN
300 K
280 K
260 K
240 K
220 K
Intensity (W / m²cm⁻¹)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm⁻¹)

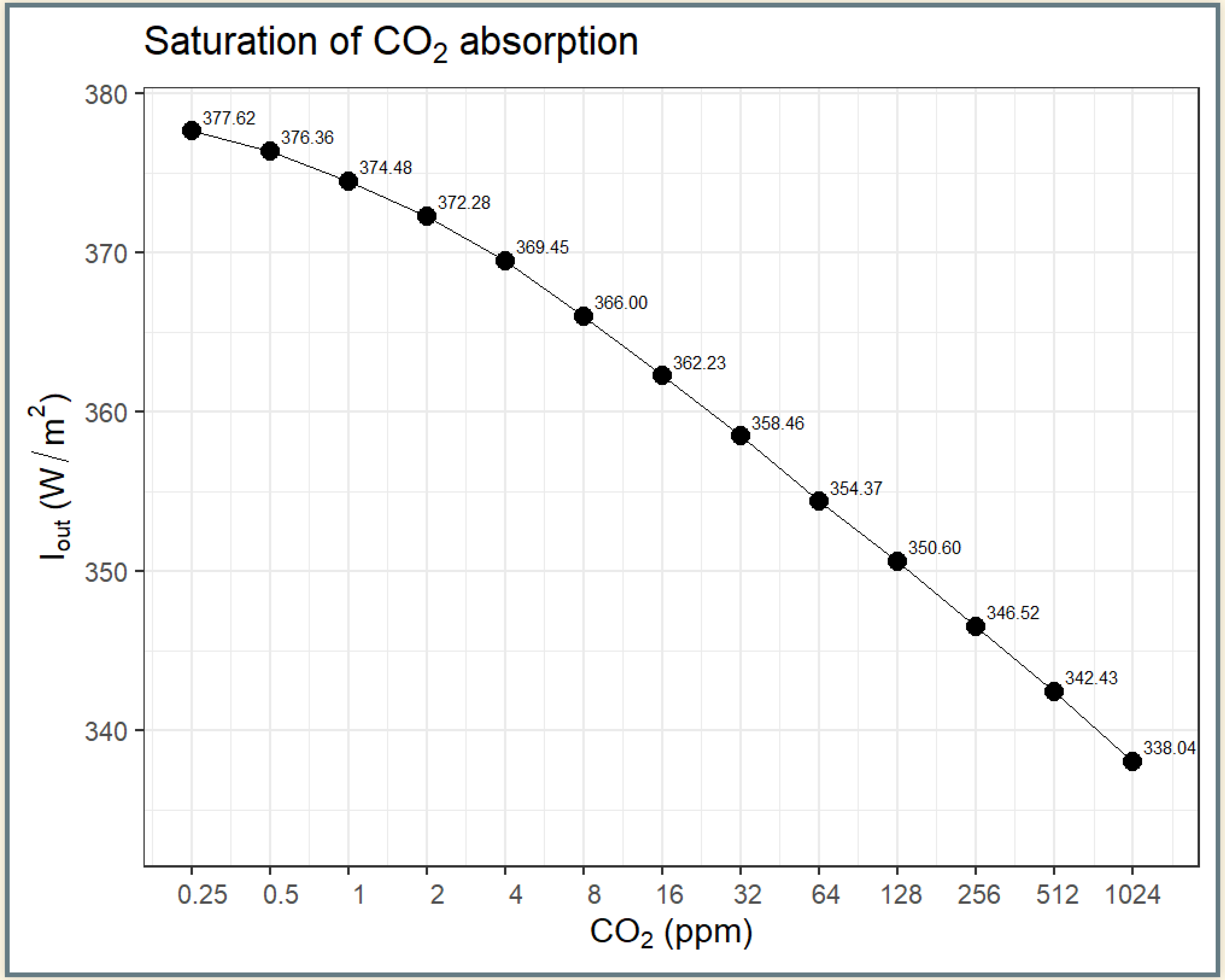
2048 ppm CO_2


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 / m²cm⁻¹)
0.0 0.1 0.2 0.3 0.4 0.5
400 800 1200
Wavenumber (cm⁻¹)

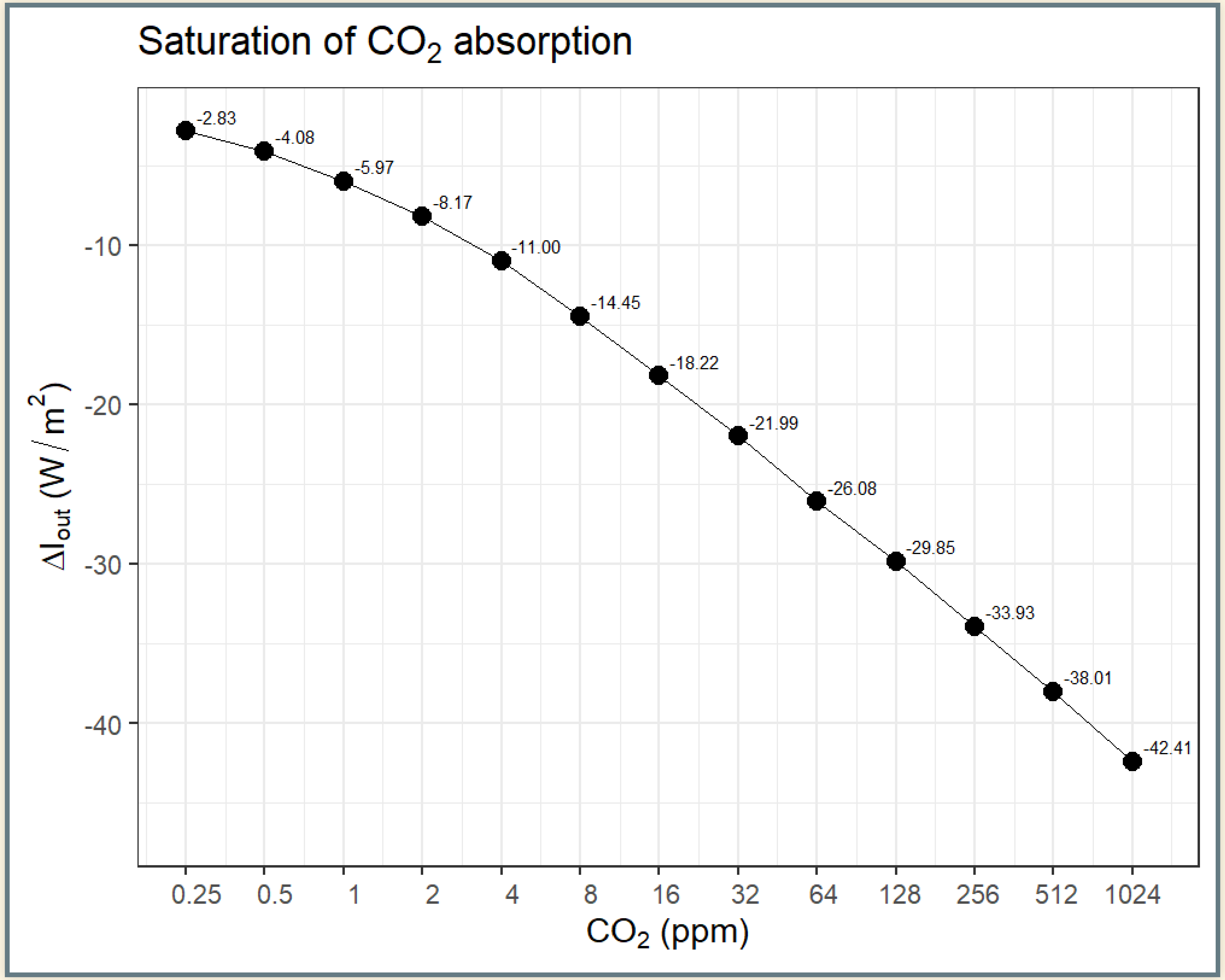
Band Saturation (I_{out})



I_{out} (CO_2 on log scale)

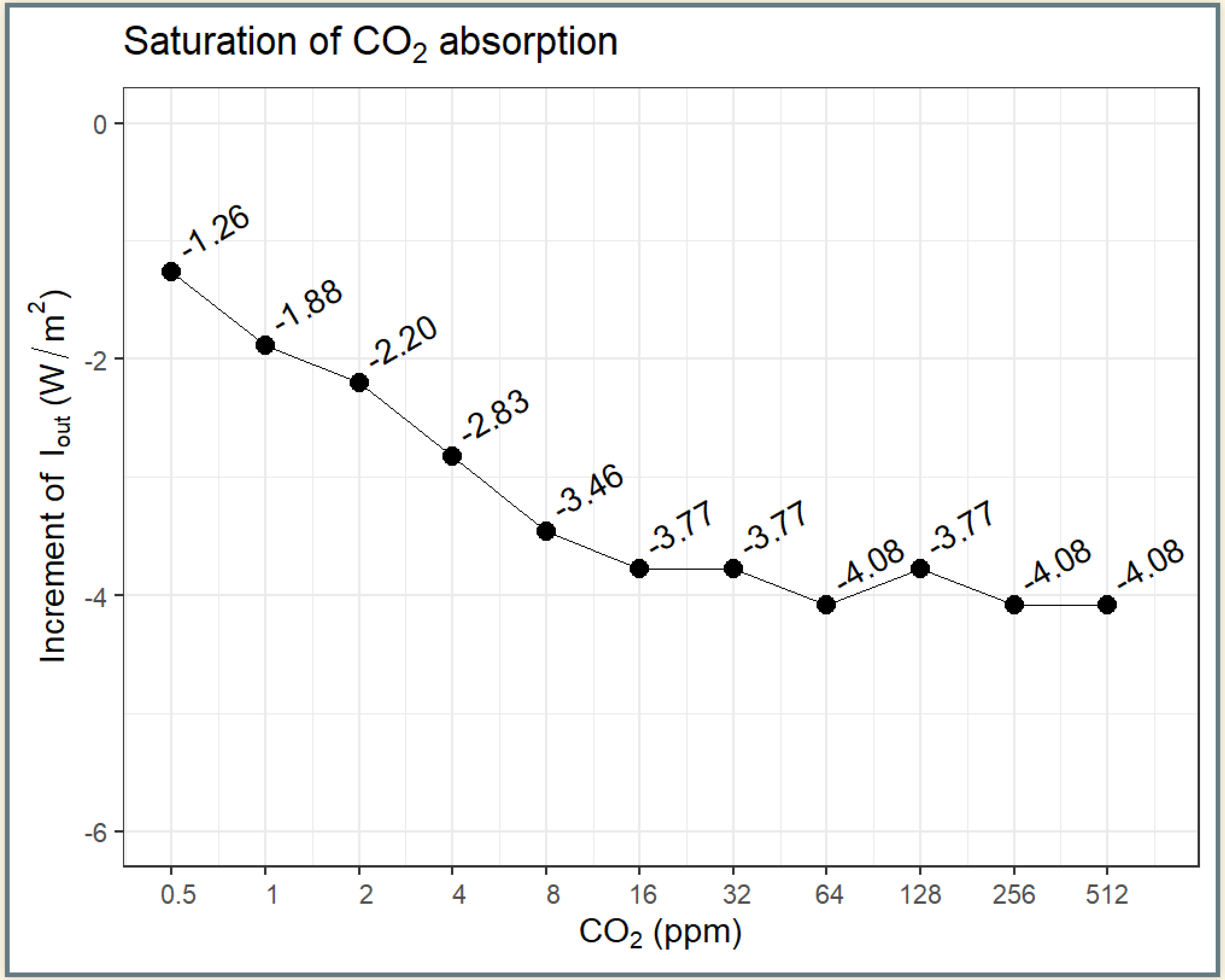


ΔI_{out}



Change in I_{out} from no CO_2

Increments of I_{out}



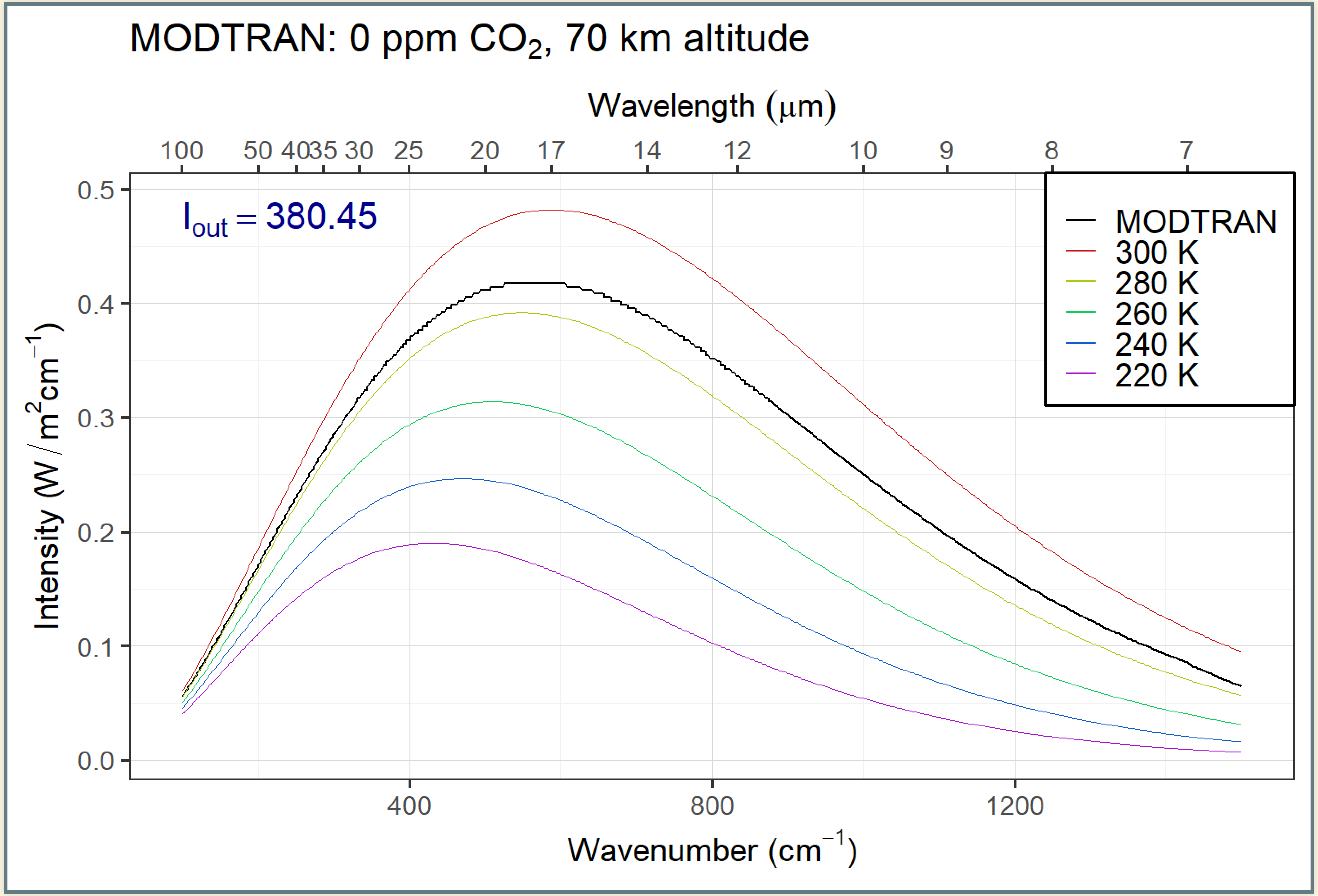
Change in I_{out} from previous I_{out}

Measuring Greenhouse Effect:

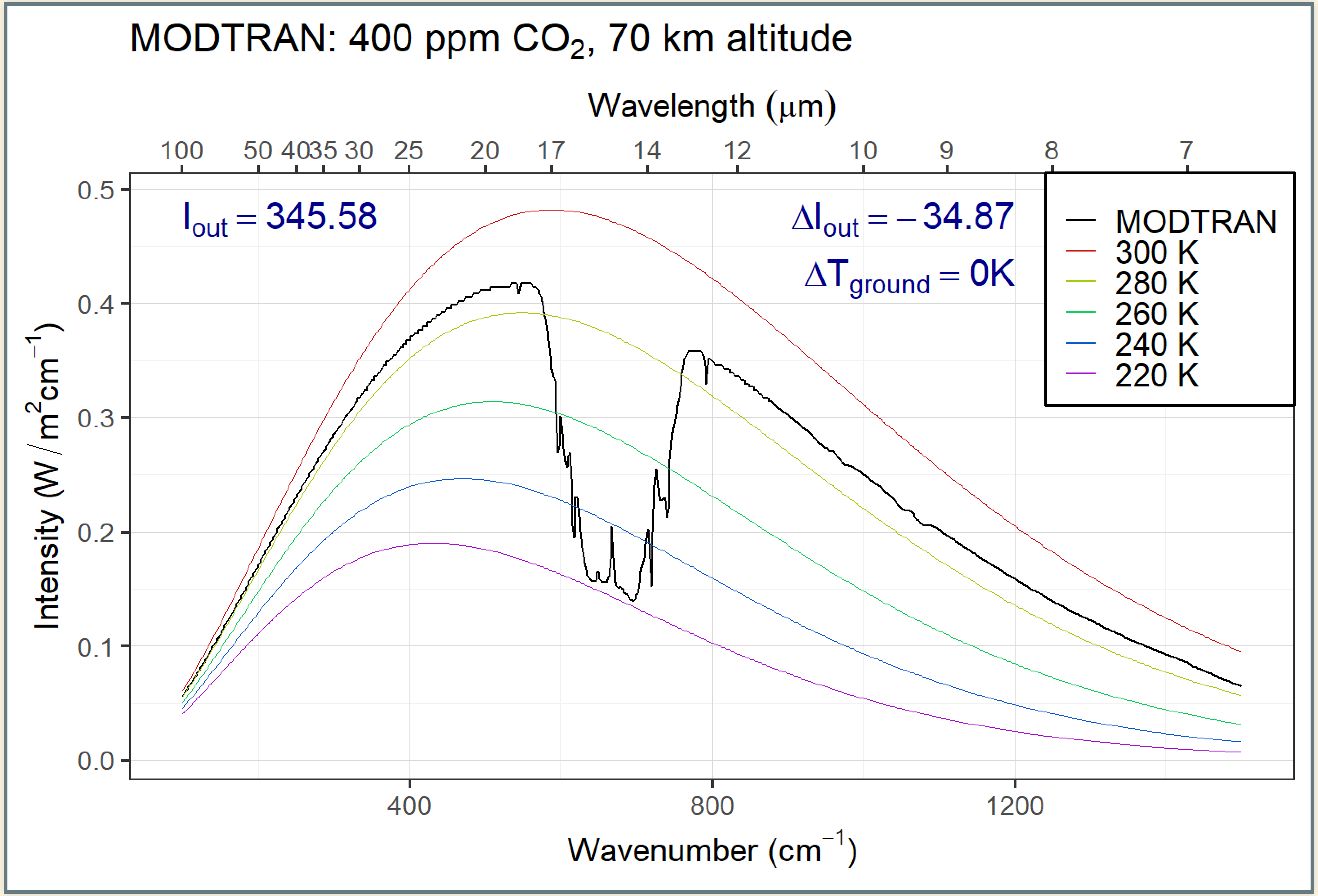
Measuring Greenhouse Effect:

- 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

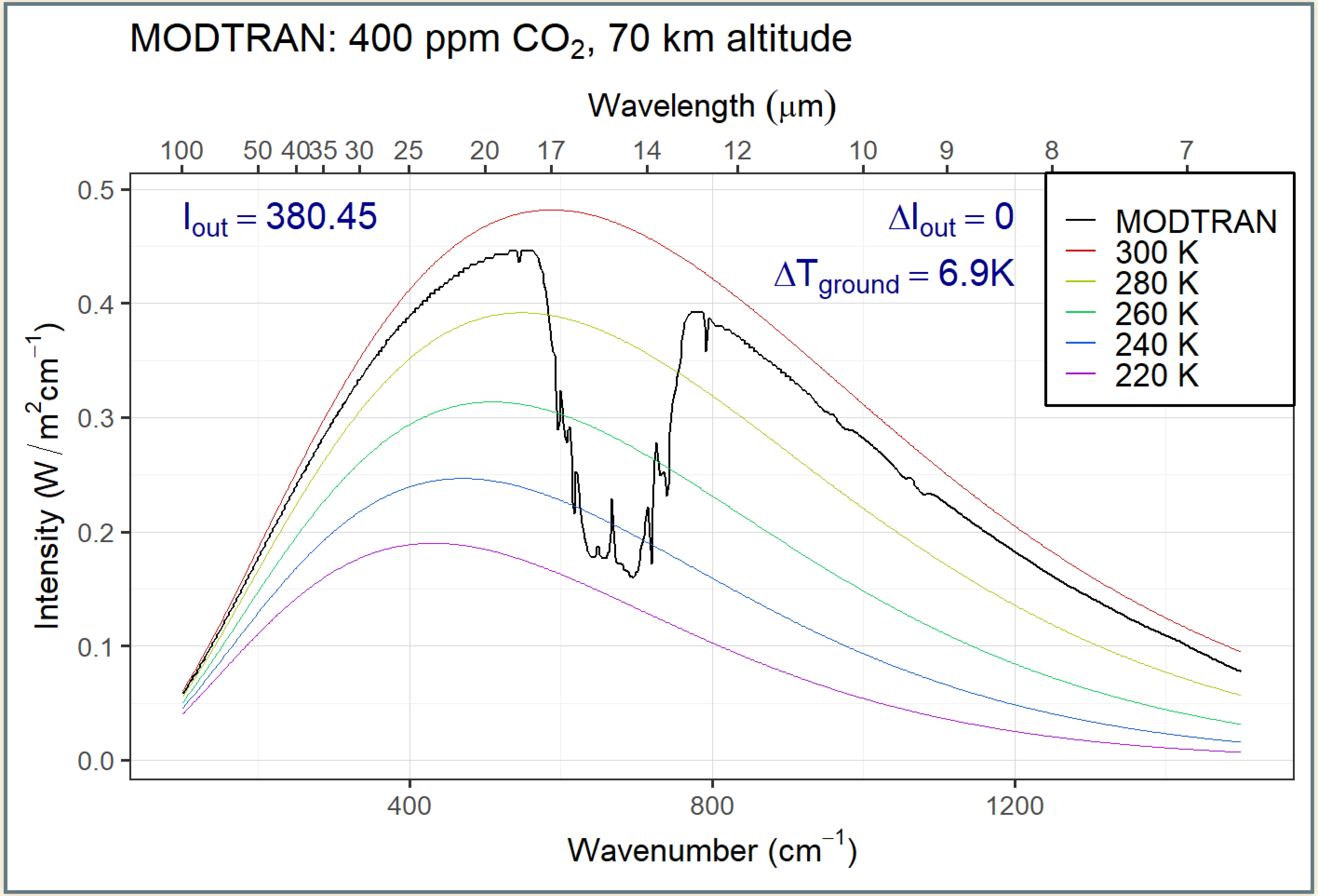


400 ppm



MODTRAN: 400 ppm CO2, 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^2cm^{-1})
0.5
0.4
0.3
0.2
0.1
0.0
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*