

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”

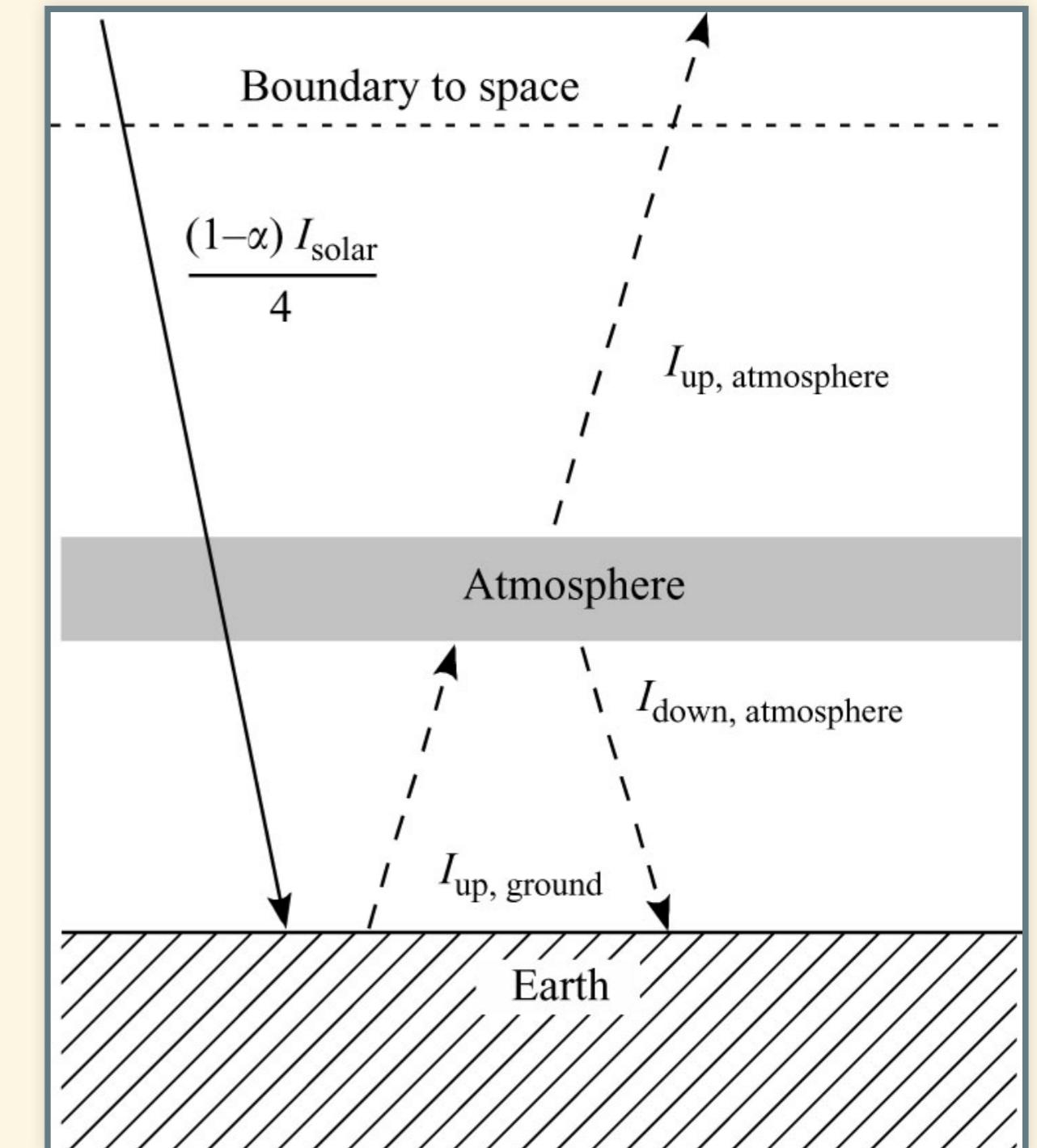
$$\text{Heat}_{\text{in}} = \text{Heat}_{\text{out}}$$

- 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.

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

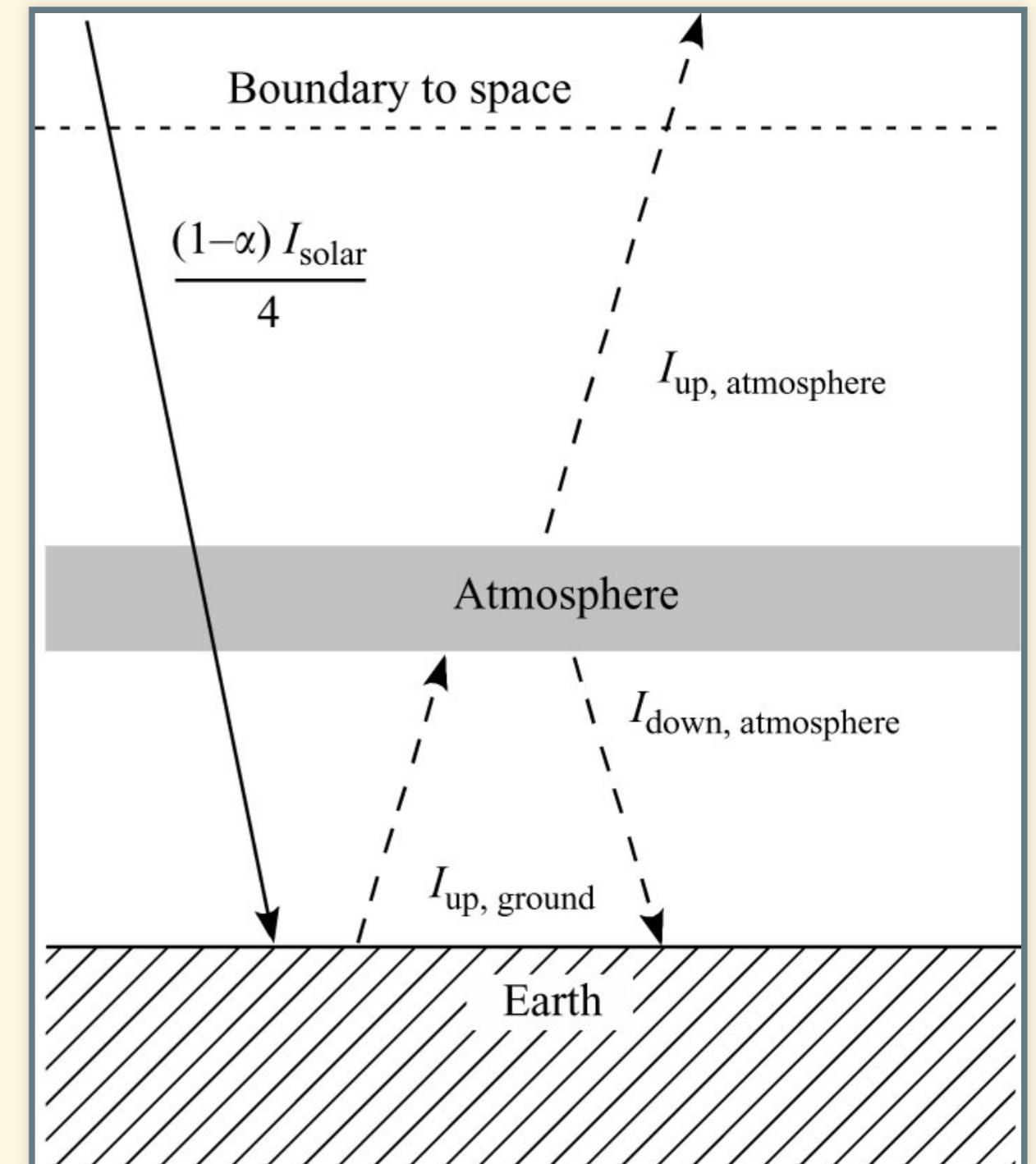
- Same as bare-rock model: $T_{\text{atmos}} = 254 \text{ K}$.
 - *skin temperature*
- Balance budget at atmosphere:

$$\epsilon \sigma T_{\text{ground}}^4 = 2 \epsilon \sigma T_{\text{atmos}}^4$$

$$T_{\text{ground}}^4 = 2 T_{\text{atmos}}^4$$

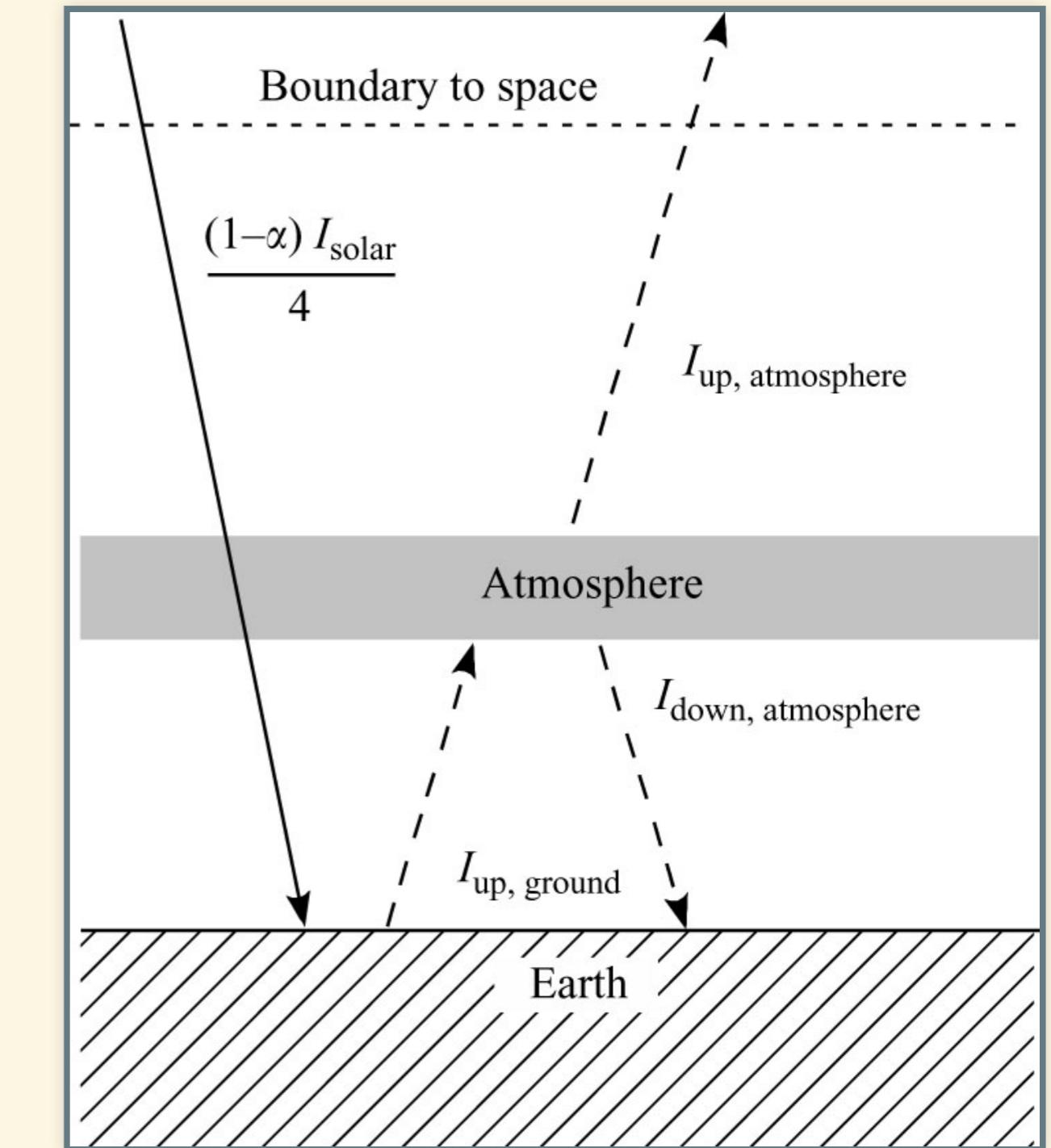
$$T_{\text{ground}} = \sqrt[4]{2} T_{\text{atmos}}$$

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



1-Layer Model: Heat Balance Details

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

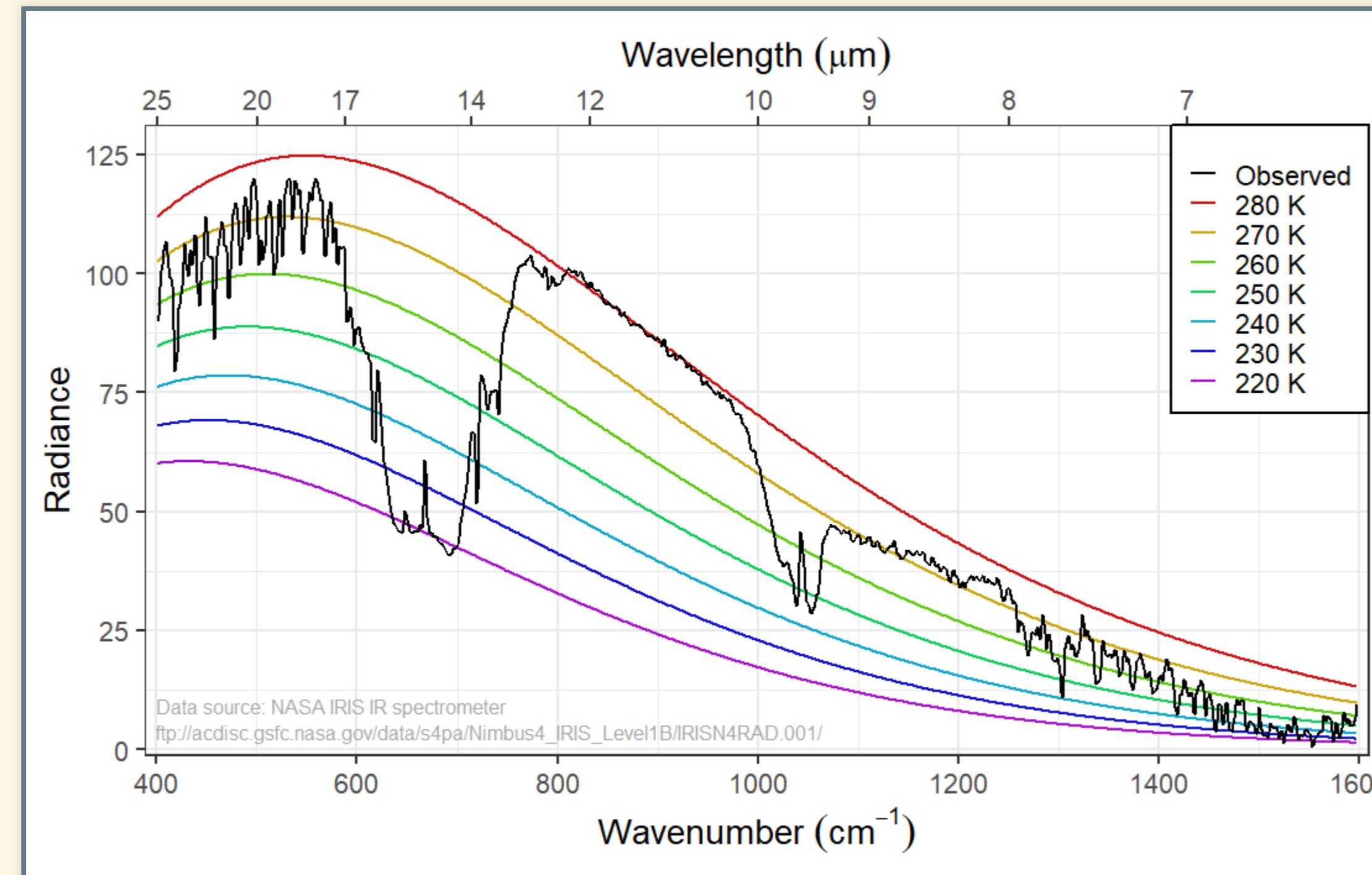


Greenhouse Gases

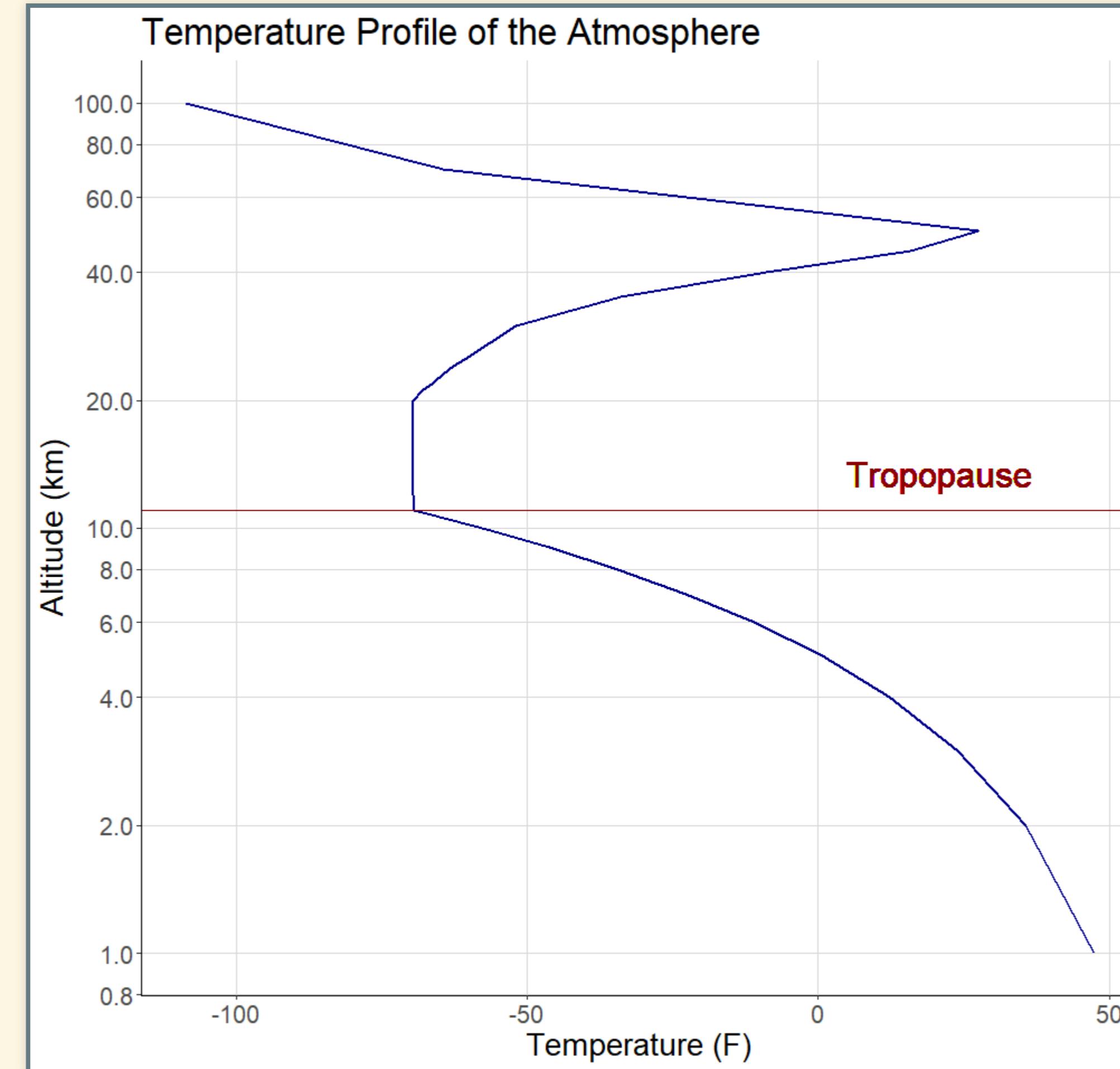
Greenhouse Gases

Layer model was too simple:

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

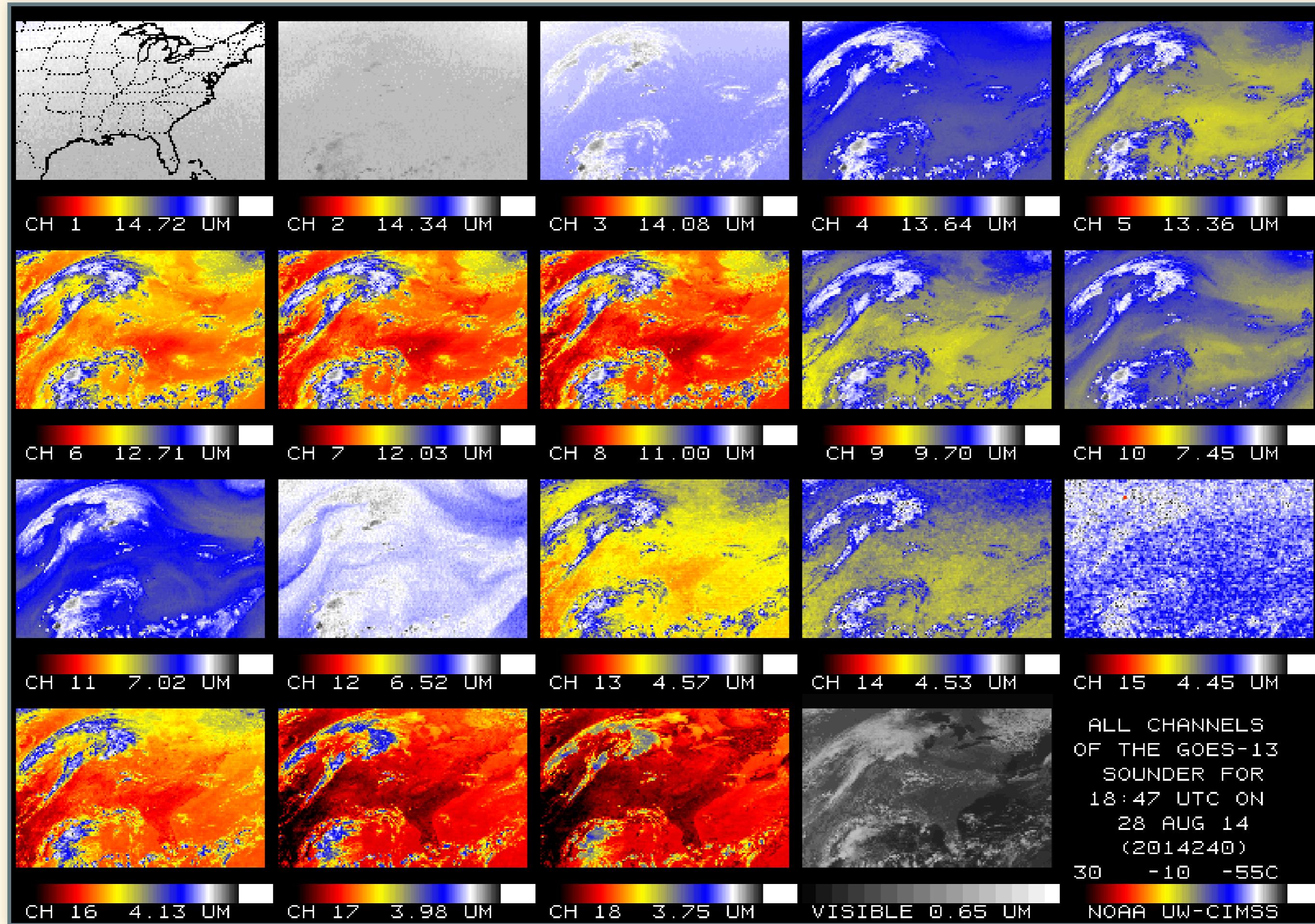


Temperature in the Atmosphere



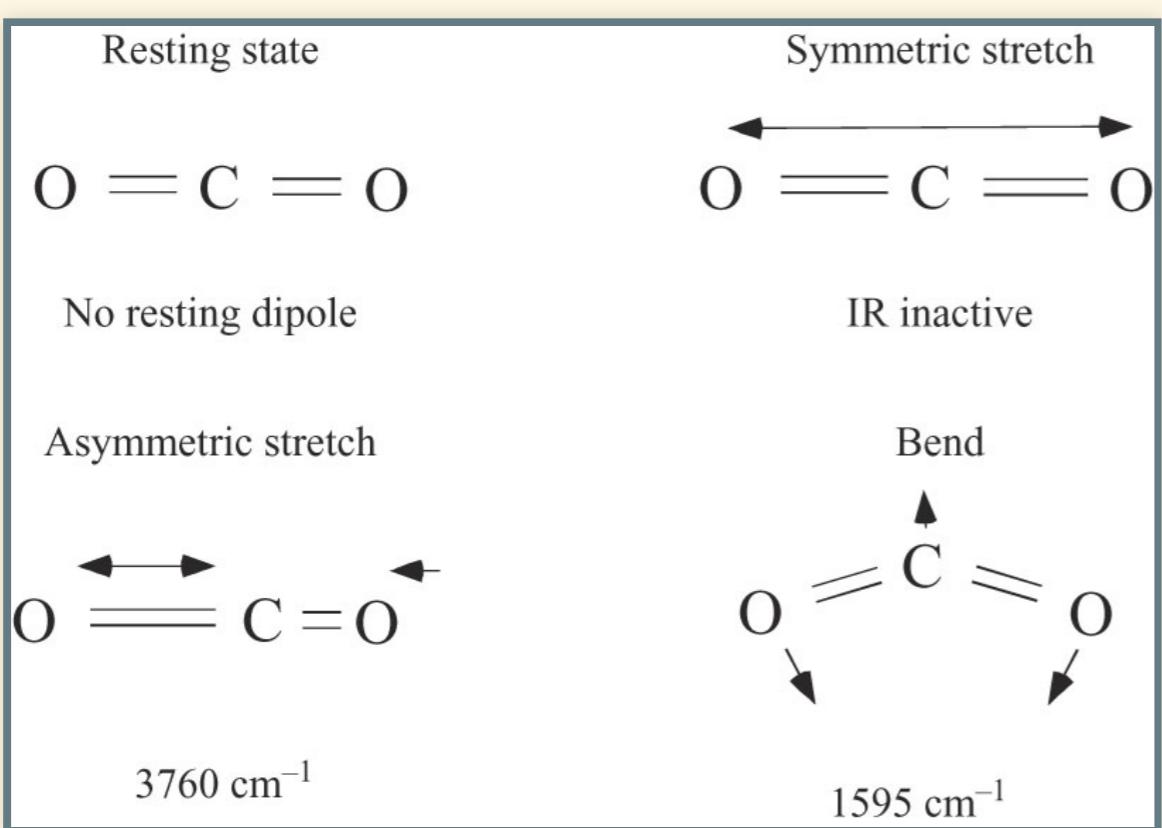
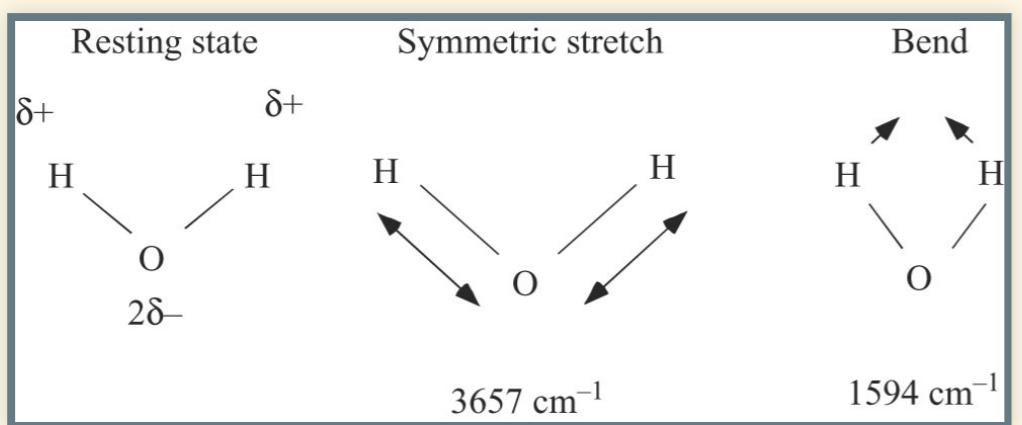
Longwave Light in the Atmosphere

Earth seen by GOES satellite



Understanding Greenhouse Gases

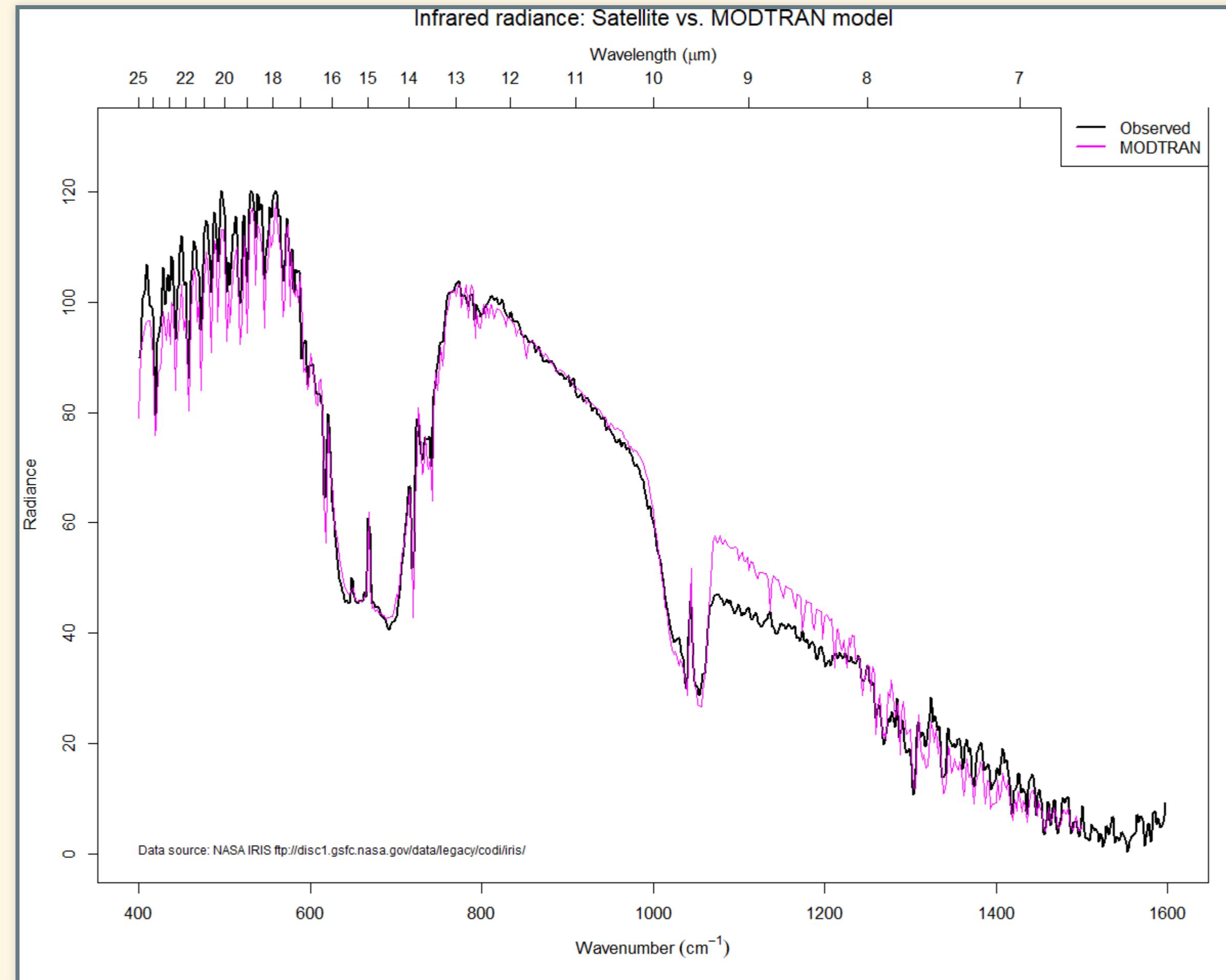
Molecular Structure



- 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 ($\text{CO}_2, \text{O}_3, \text{H}_2\text{O}$) absorb strongly (multiple stretching & bending modes)
 - More atoms, more different kinds → stronger absorption ($\text{CH}_4, \text{C}_2\text{F}_3\text{Cl}_3$ aka CFC 113)

Models and Observations

Models and Observations



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

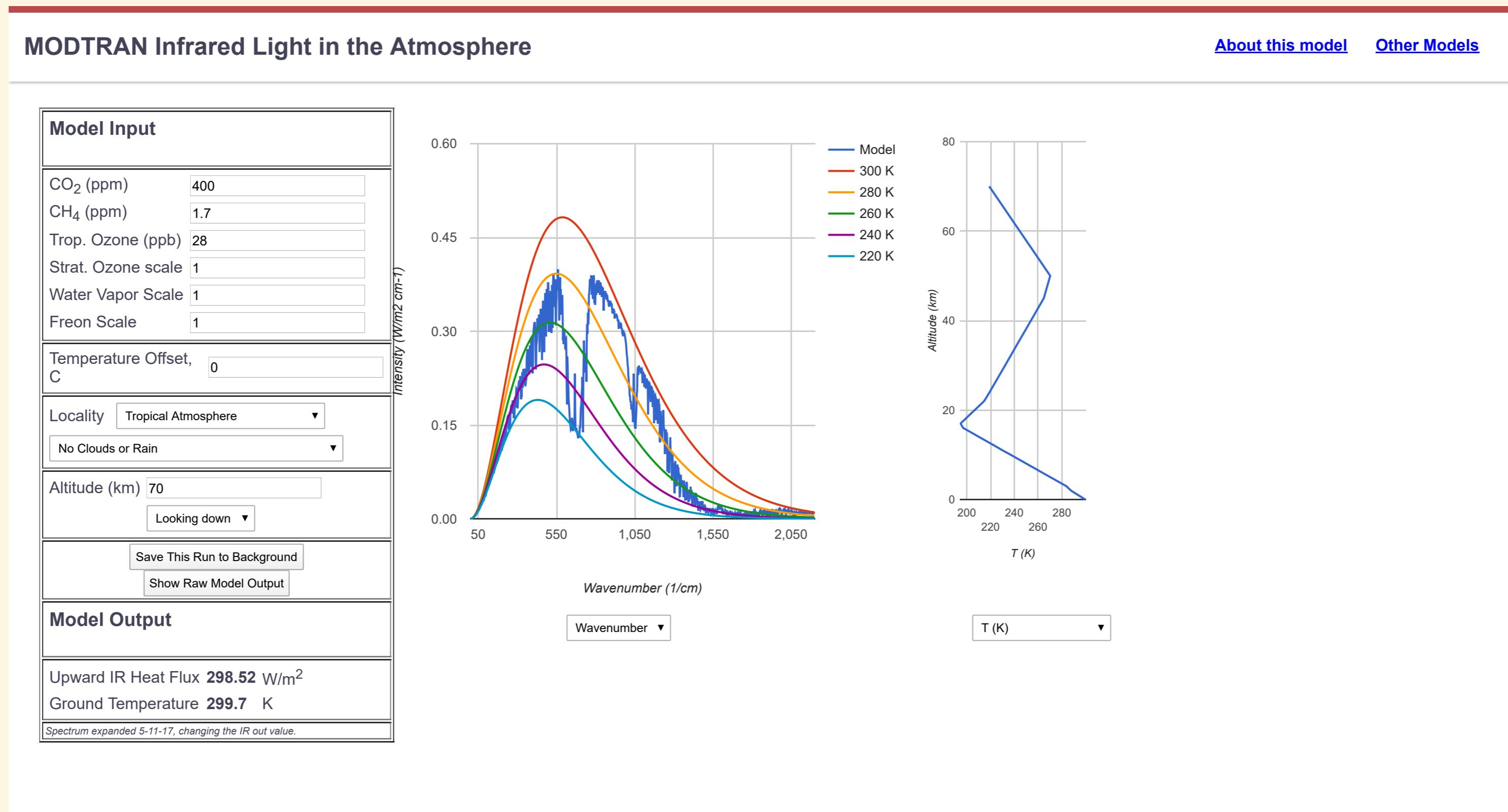
MODTRAN Computer Model

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

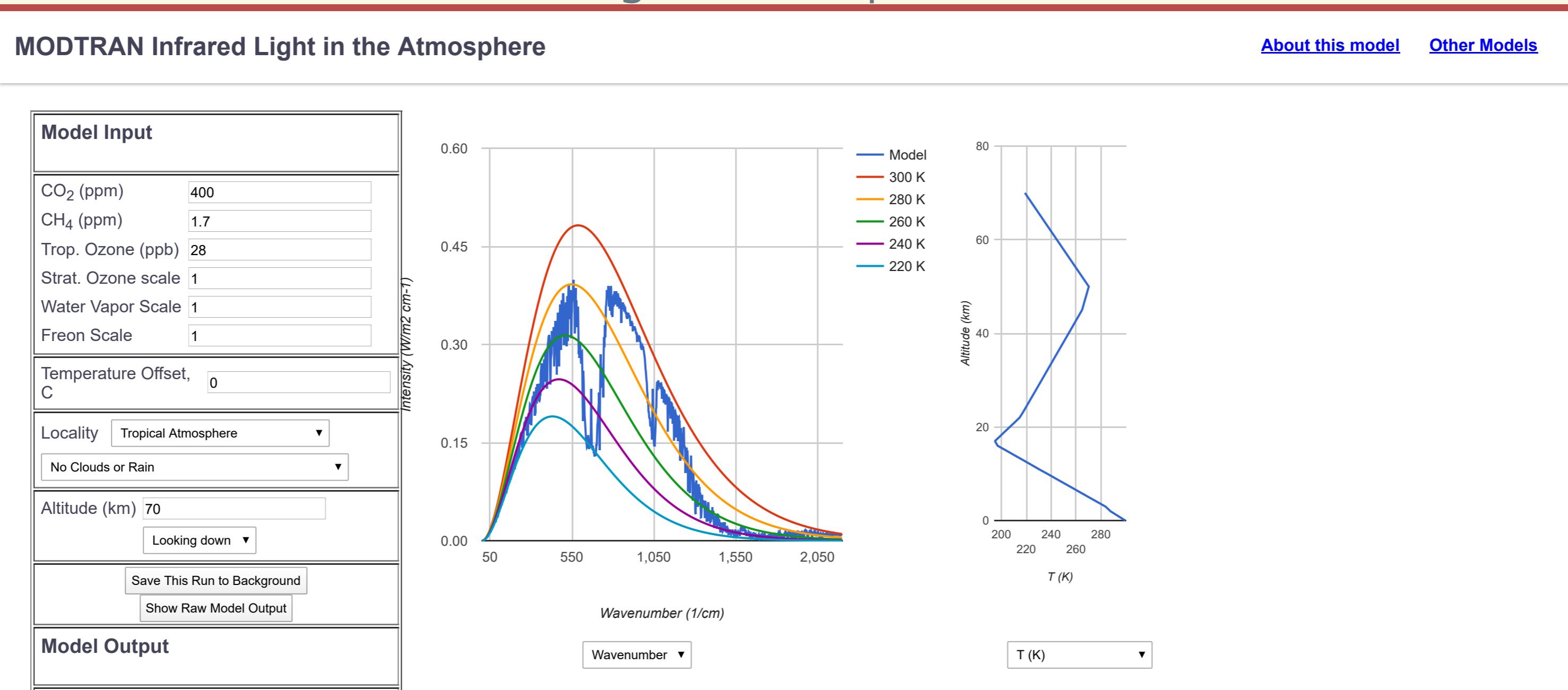
Running MODTRAN

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



Exercise: Double CO₂

- Set Locality to “1976 U.S. Standard Atmosphere”
- Click “Save This Run to Background”
- Note the Upward IR heat flux
- Double the amount of CO₂
- Adjust T offset until new heat flux = background flux
- What is the new ground temperature?



Exercise: Double CO₂

MODTRAN Infrared Light in the Atmosphere

[About this model](#) [Other Models](#)

Model Input

CO ₂ (ppm)	400
CH ₄ (ppm)	1.7
Trop. Ozone (ppb)	28
Strat. Ozone scale	1
Water Vapor Scale	1
Freon Scale	1

Temperature Offset, C

Locality Tropical Atmosphere

No Clouds or Rain

Altitude (km) 70

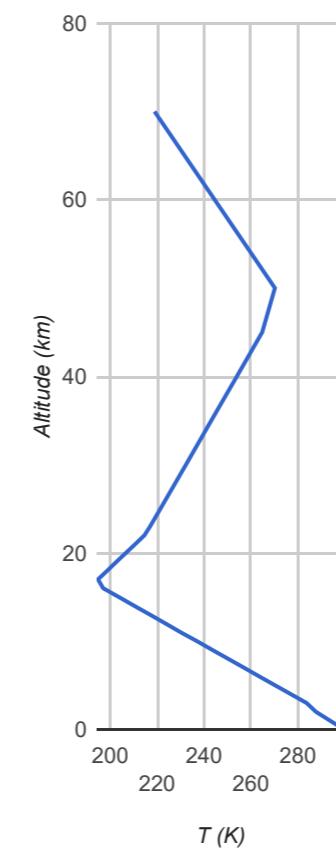
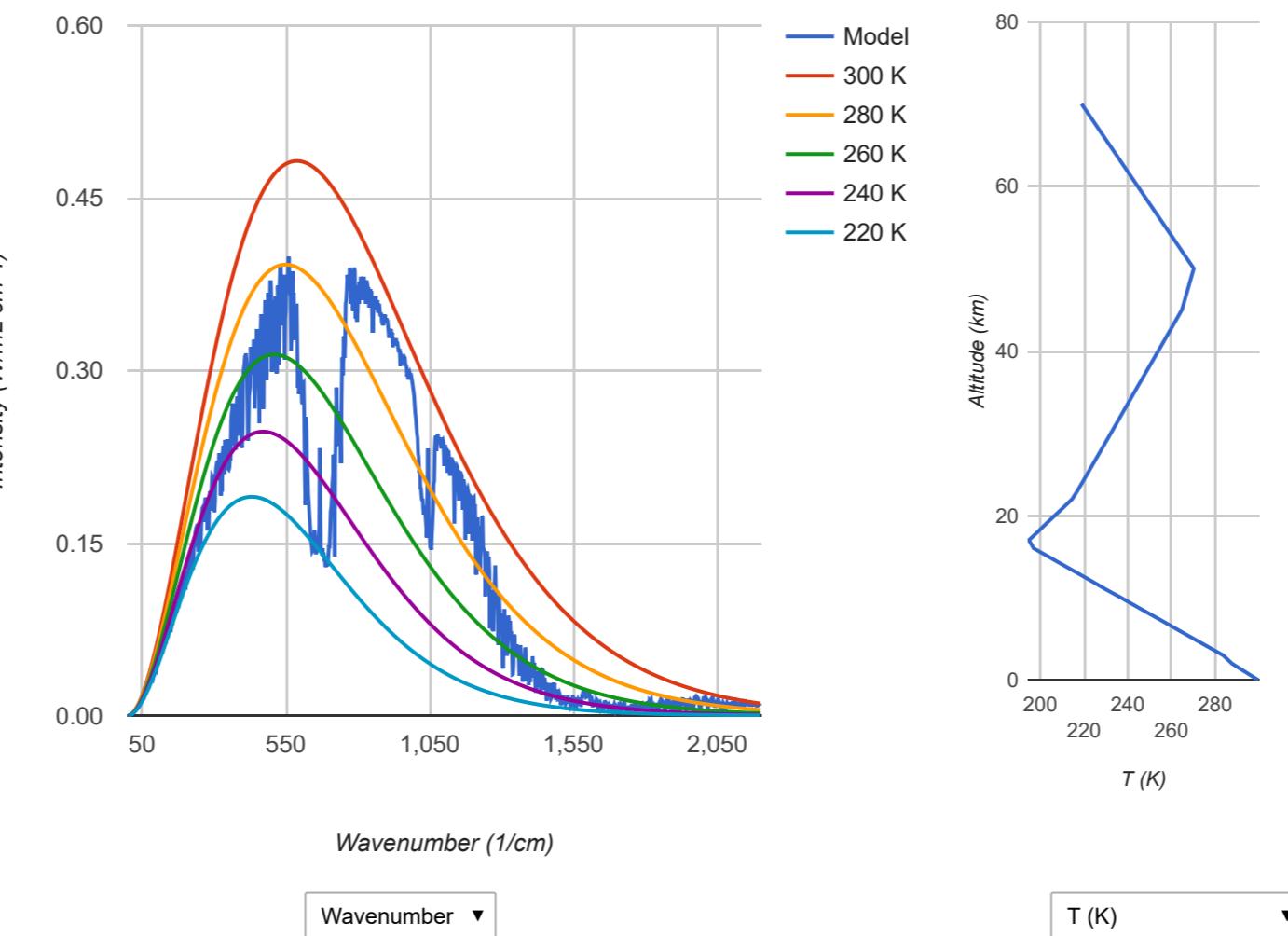
Looking down

Model Output

Upward IR Heat Flux **298.52** W/m²

Ground Temperature **299.7** K

Spectrum expanded 5-11-17, changing the IR out value.



Different Gases

Different Gases

MODTRAN Infrared Light in the Atmosphere

[About this model](#) [Other Models](#)

Model Input

CO ₂ (ppm)	400
CH ₄ (ppm)	1.7
Trop. Ozone (ppb)	28
Strat. Ozone scale	1
Water Vapor Scale	1
Freon Scale	1

Temperature Offset, C: 0

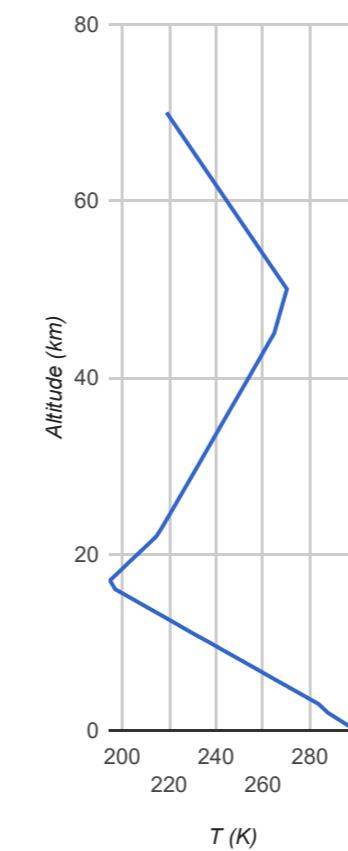
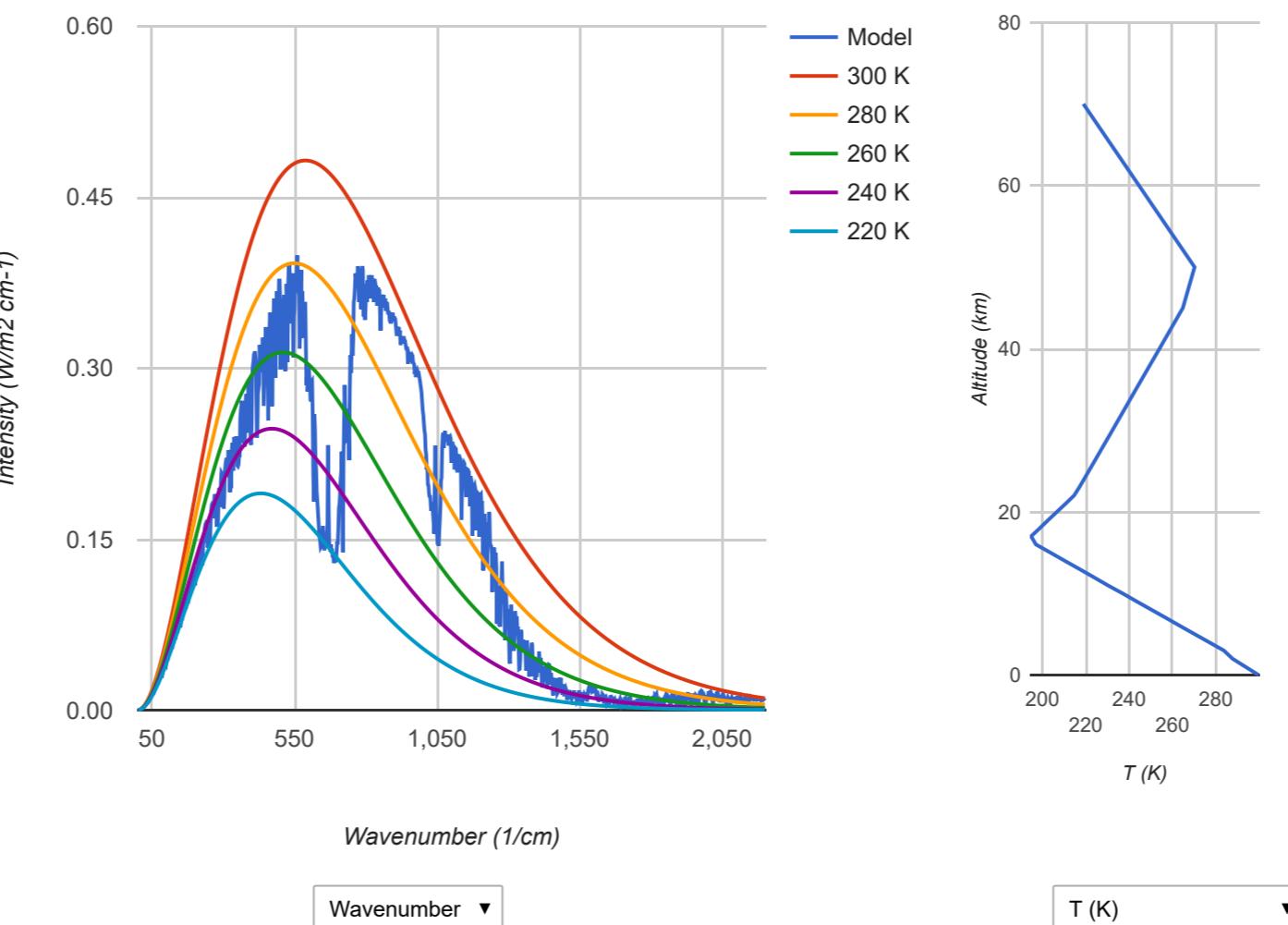
Locality: Tropical Atmosphere
No Clouds or Rain

Altitude (km): 70
Looking down

Model Output

Upward IR Heat Flux **298.52 W/m²**
Ground Temperature **299.7 K**

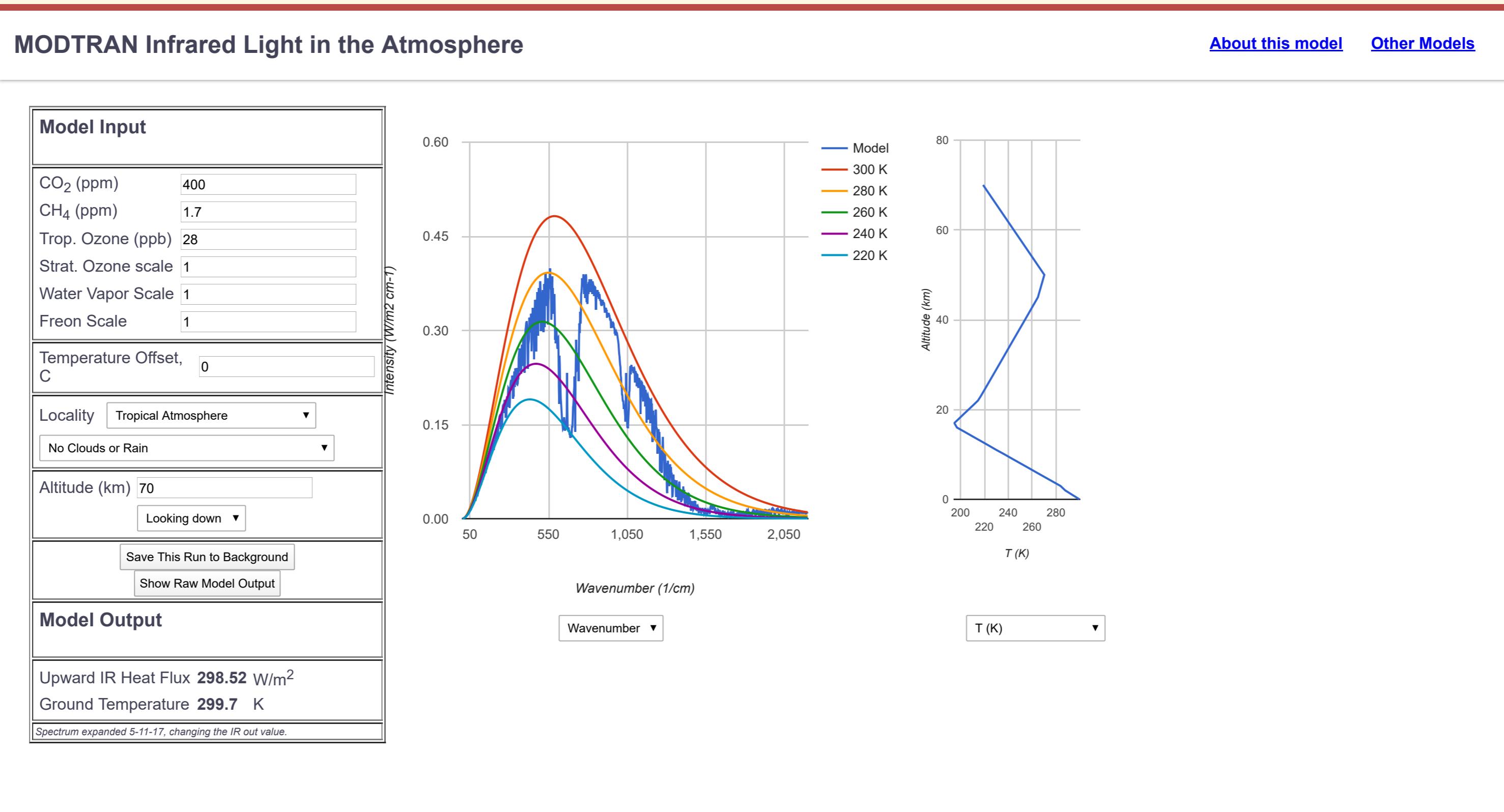
Spectrum expanded 5-11-17, changing the IR out value.



Band Saturation

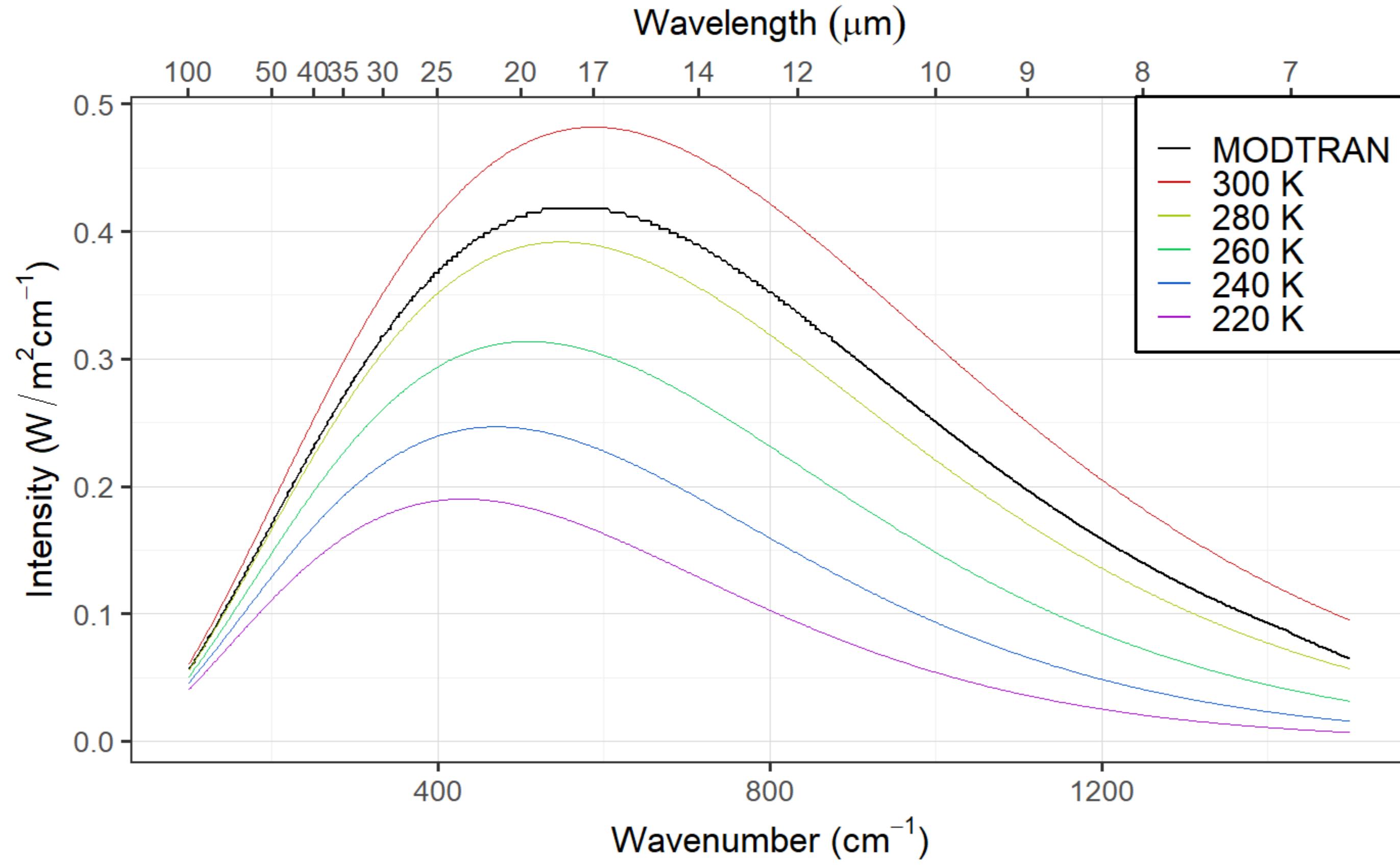
Set up MODTRAN:

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



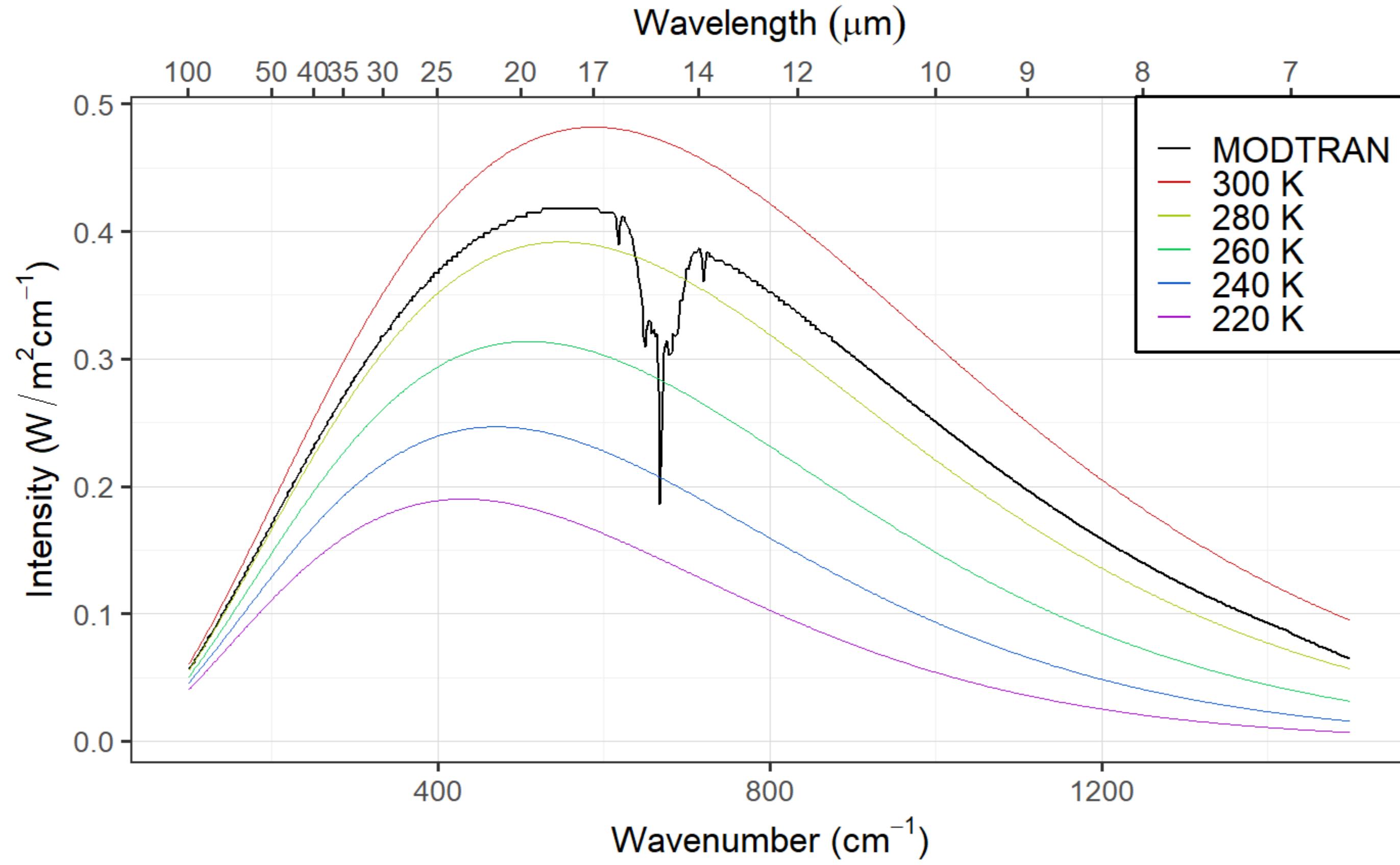
No CO₂

MODTRAN: 0 ppm CO₂, 20 km



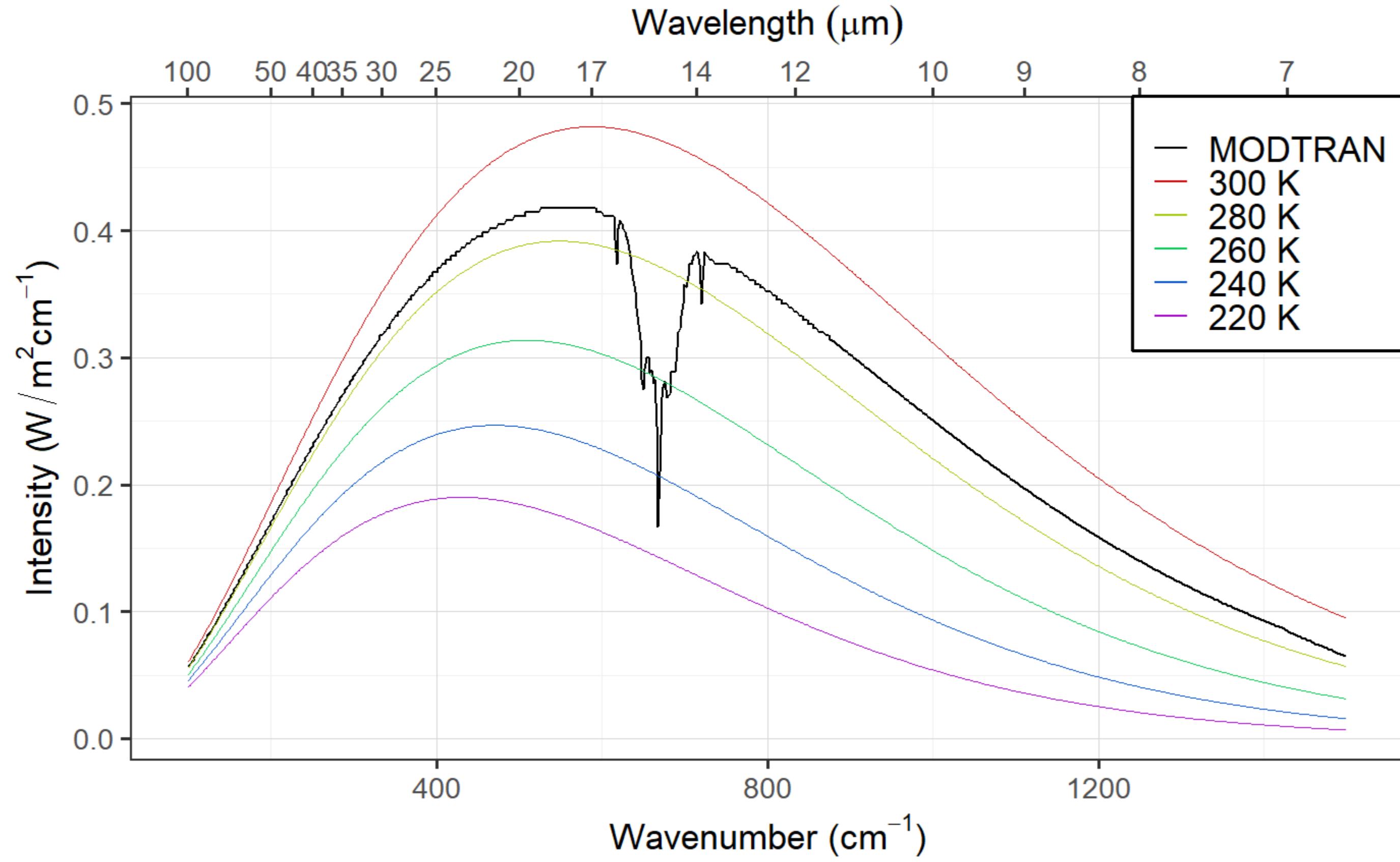
1 ppm CO₂

MODTRAN: 1 ppm CO₂, 20 km



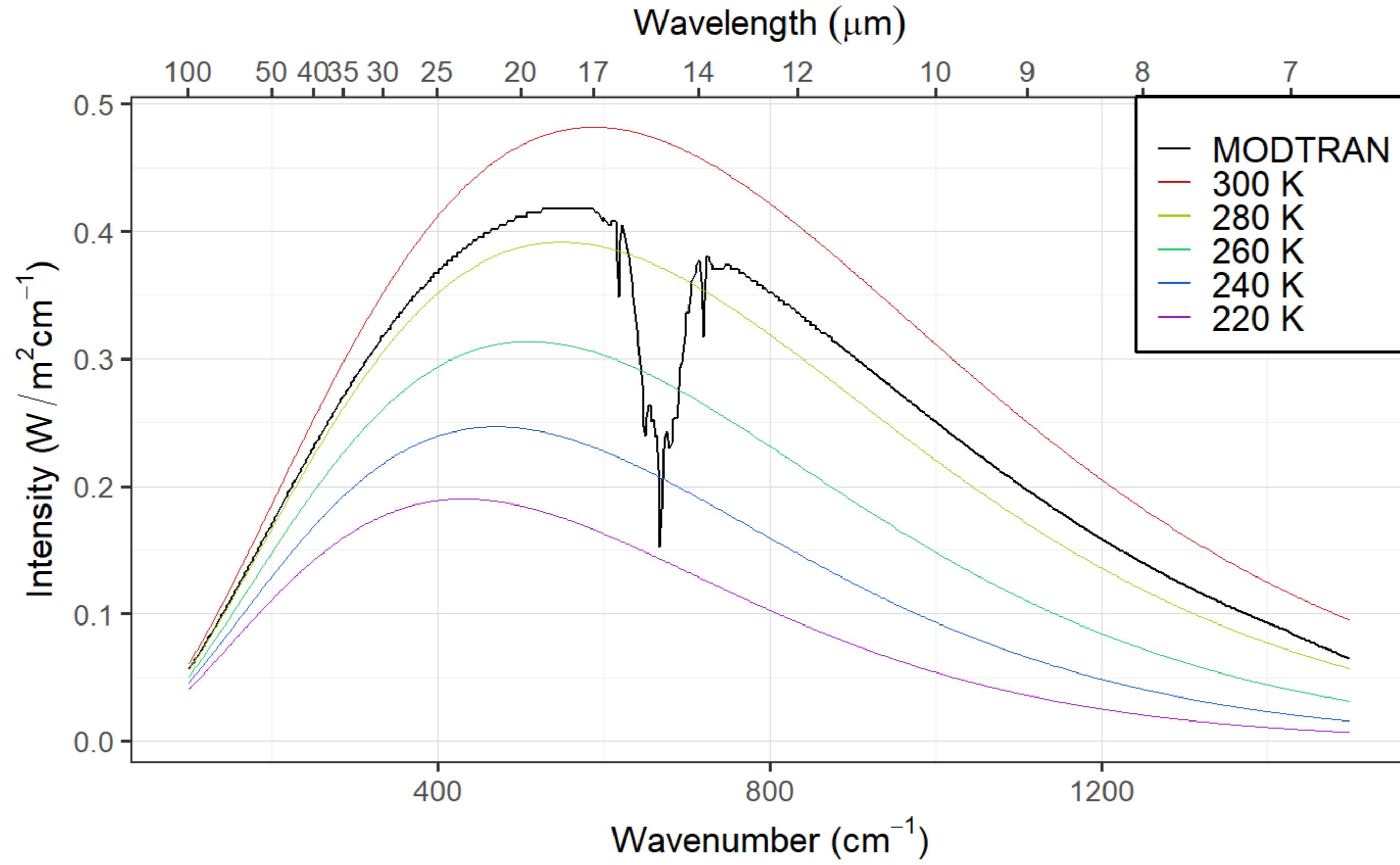
2 ppm CO₂

MODTRAN: 2 ppm CO₂, 20 km



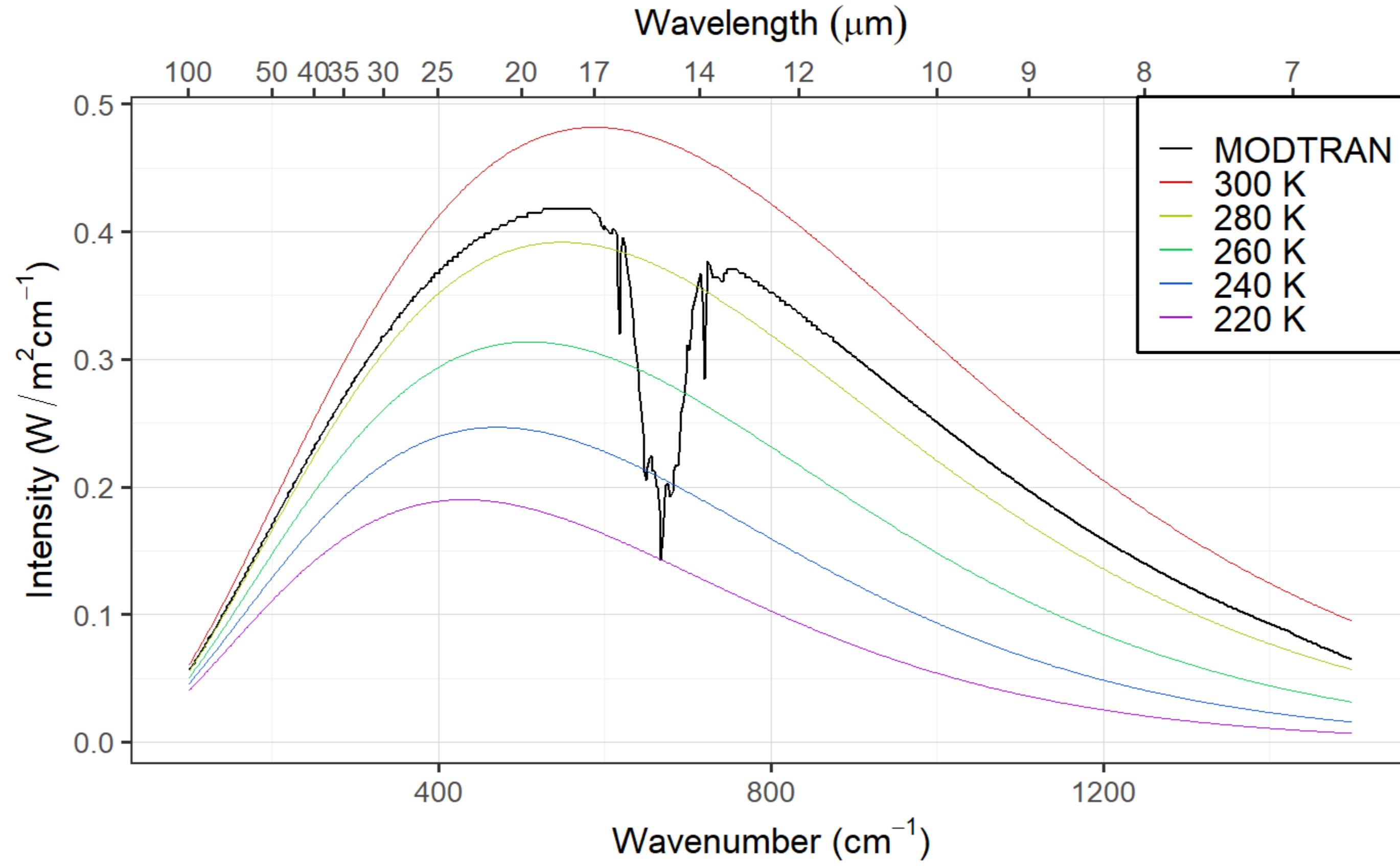
4 ppm CO₂

MODTRAN: 4 ppm CO₂, 20 km



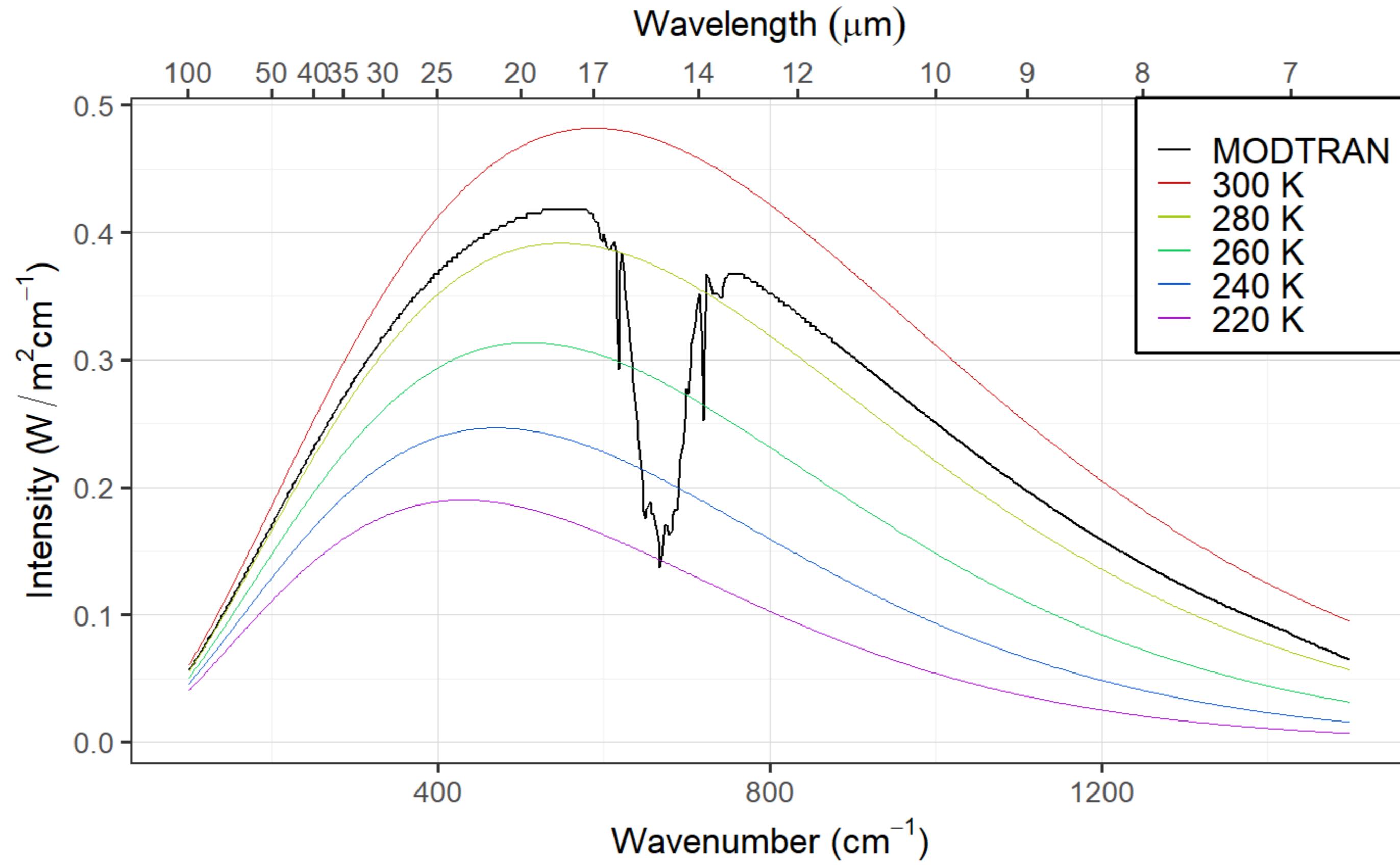
8 ppm CO₂

MODTRAN: 8 ppm CO₂, 20 km



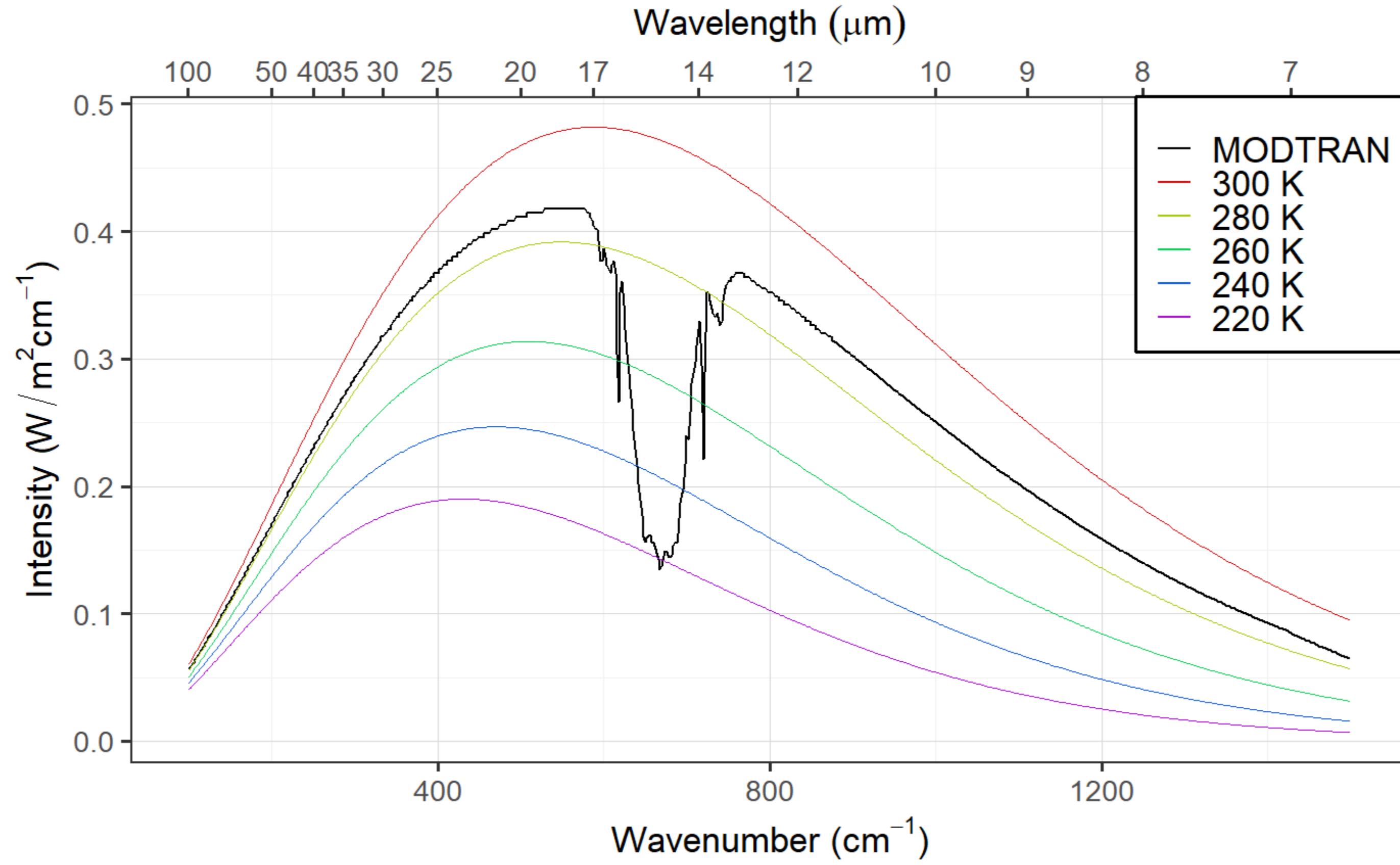
16 ppm CO₂

MODTRAN: 16 ppm CO₂, 20 km



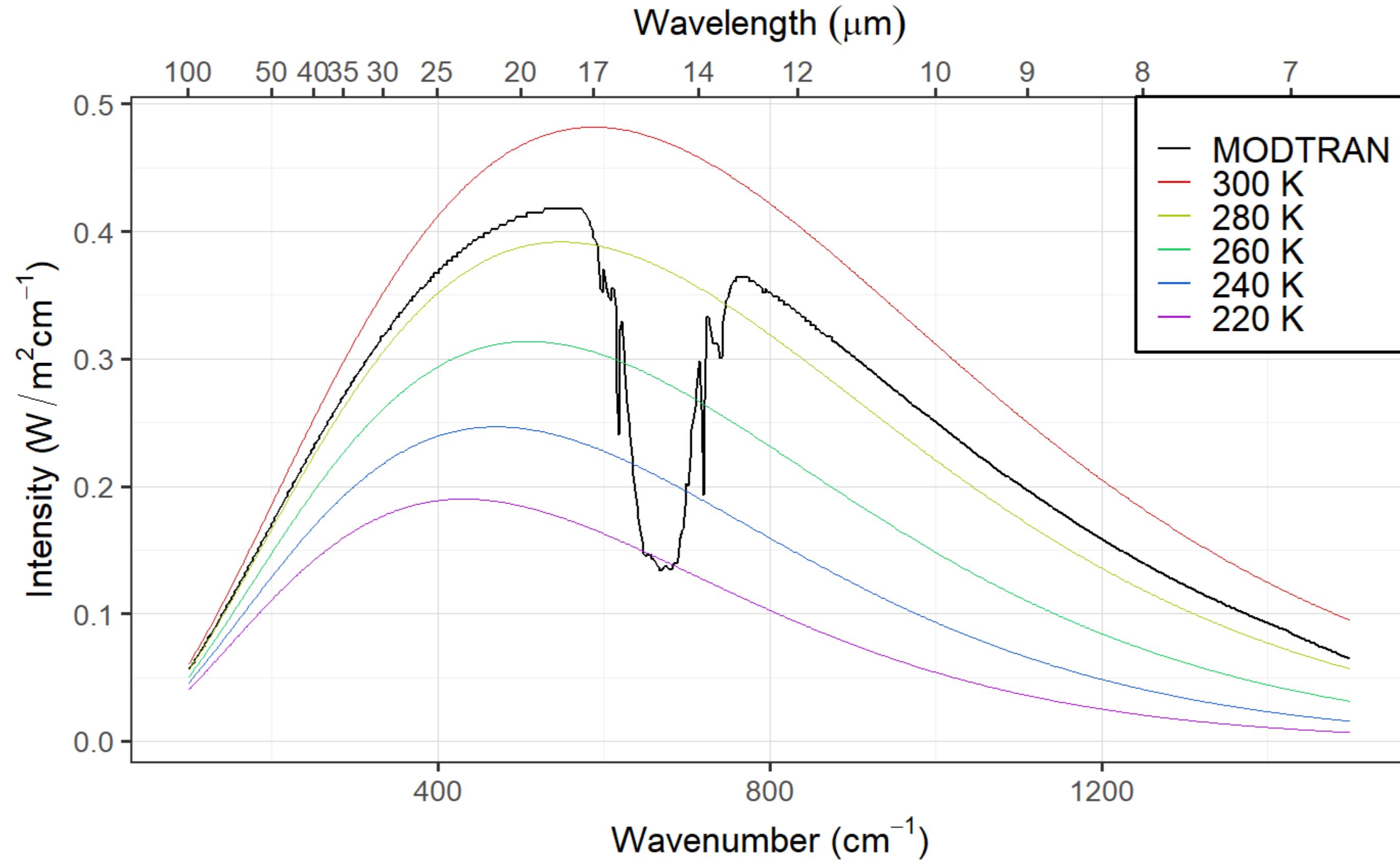
32 ppm CO₂

MODTRAN: 32 ppm CO₂, 20 km



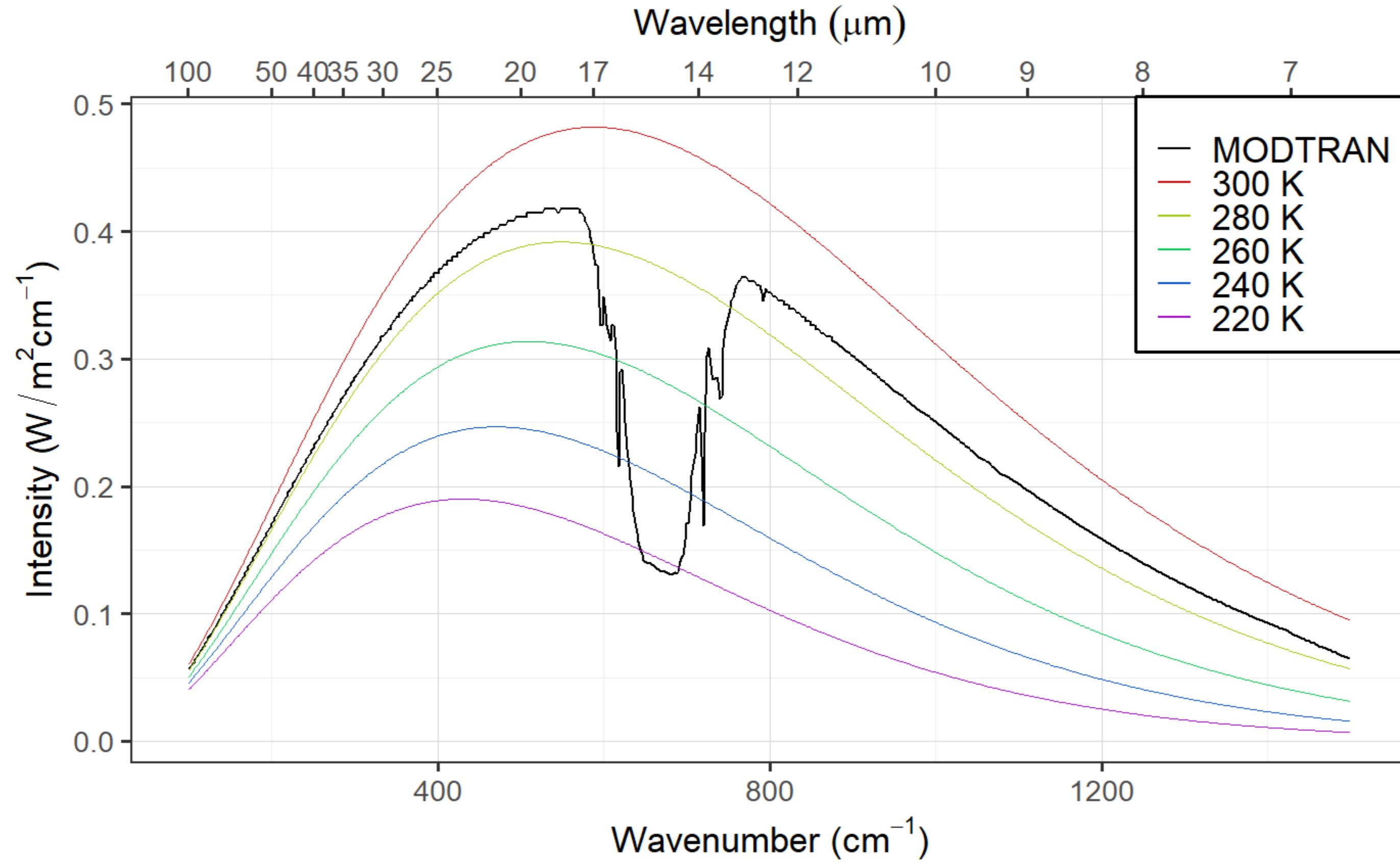
64 ppm CO₂

MODTRAN: 64 ppm CO₂, 20 km



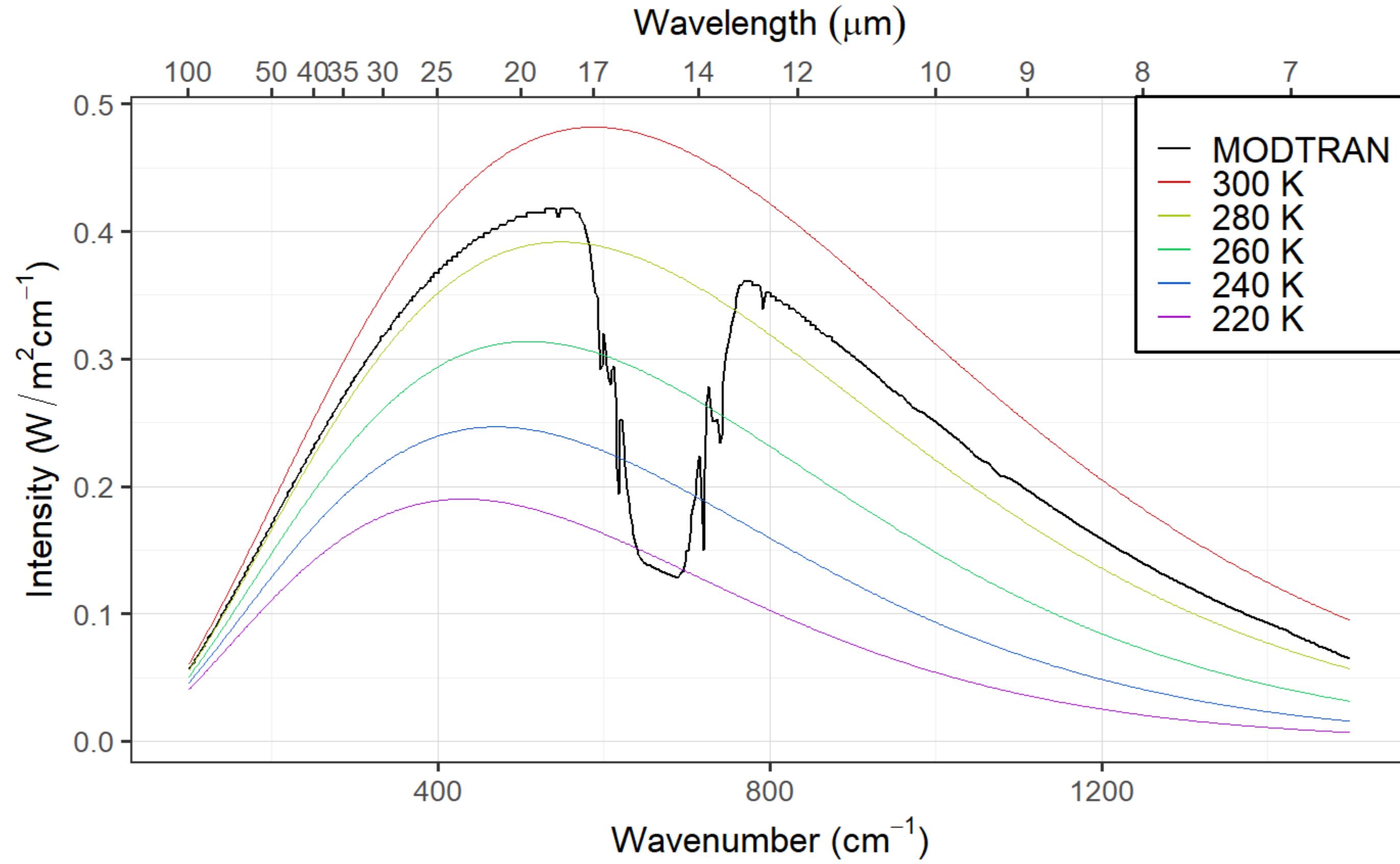
128 ppm CO₂

MODTRAN: 128 ppm CO₂, 20 km



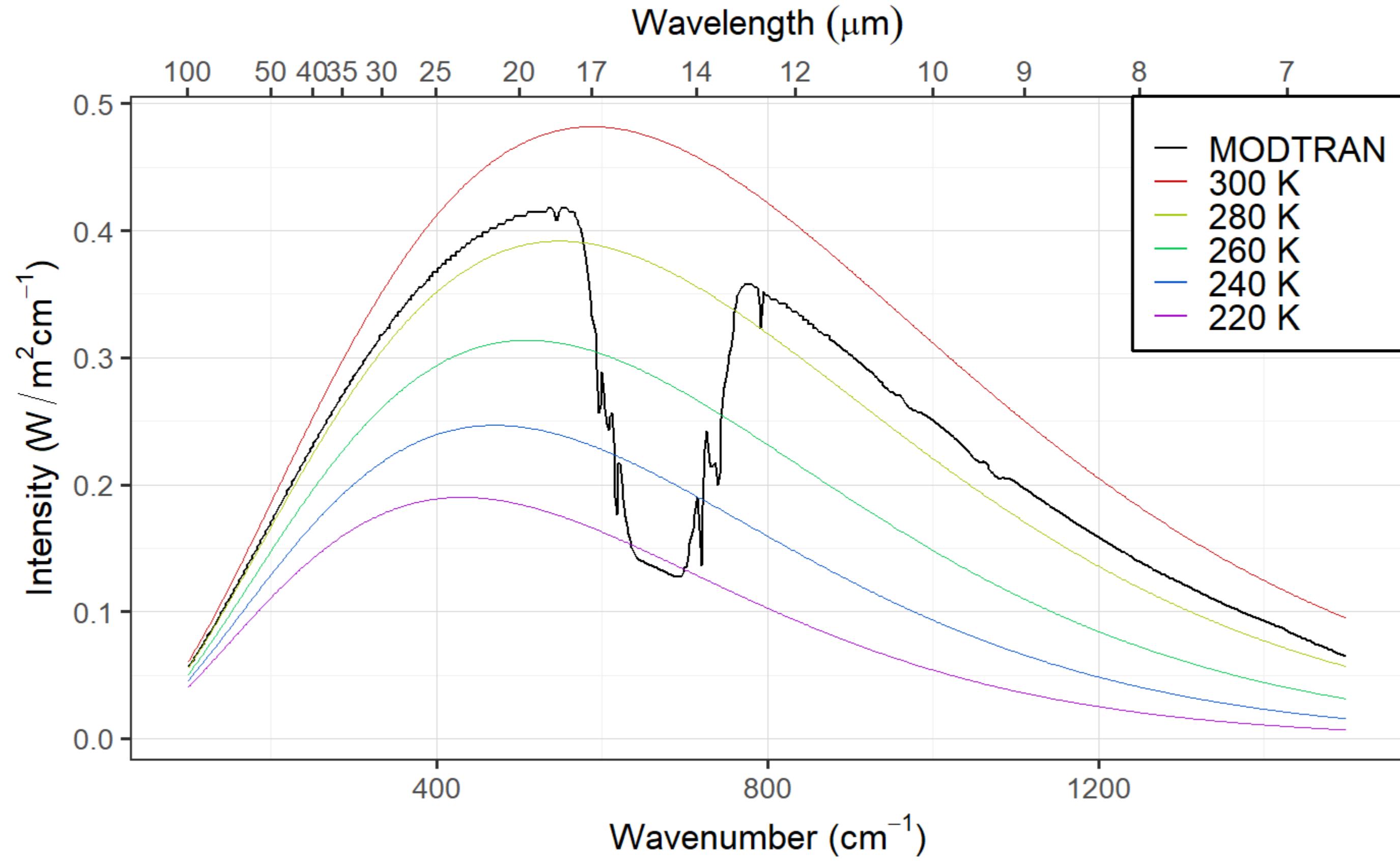
256 ppm CO₂

MODTRAN: 256 ppm CO₂, 20 km



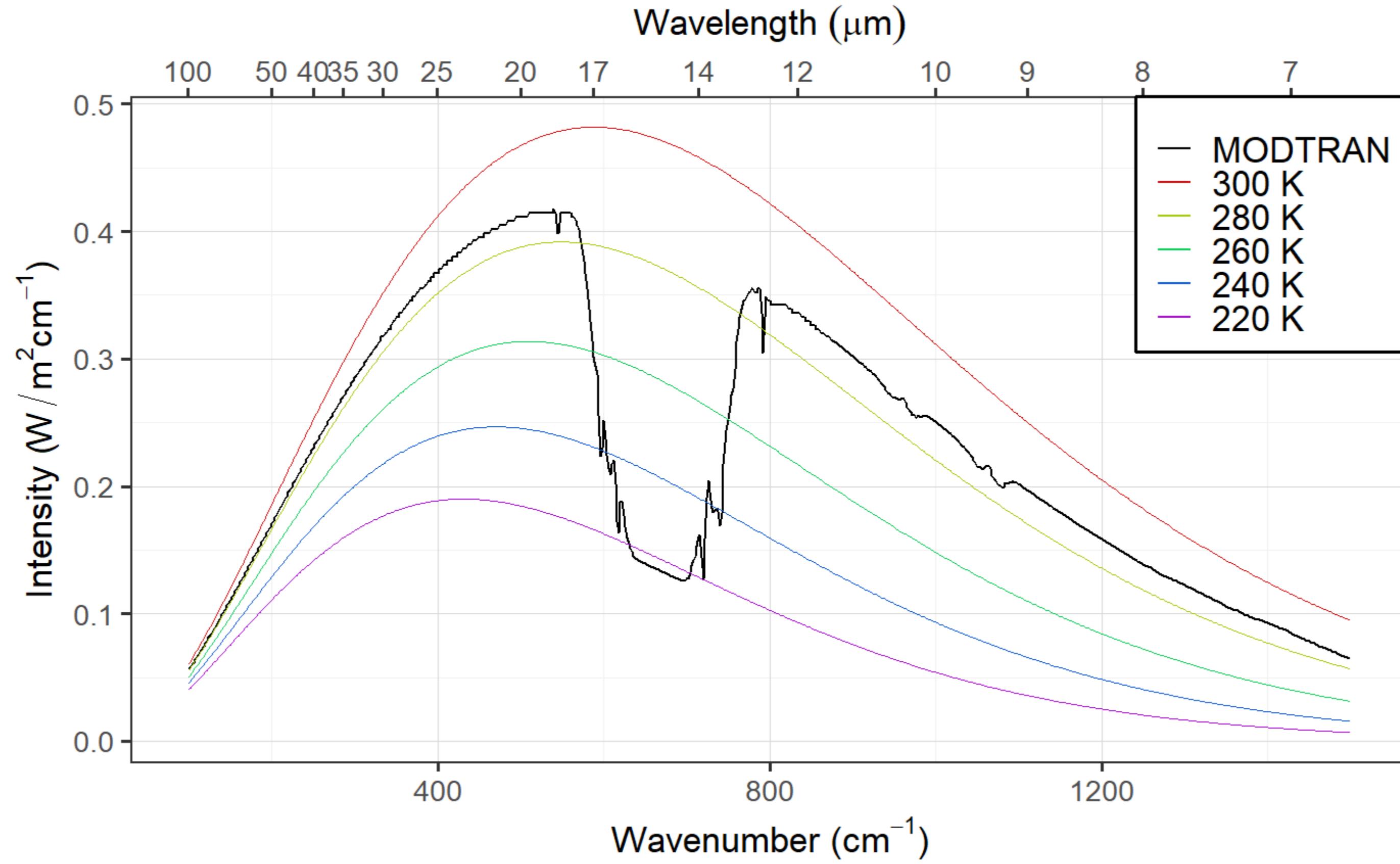
512 ppm CO₂

MODTRAN: 512 ppm CO₂, 20 km



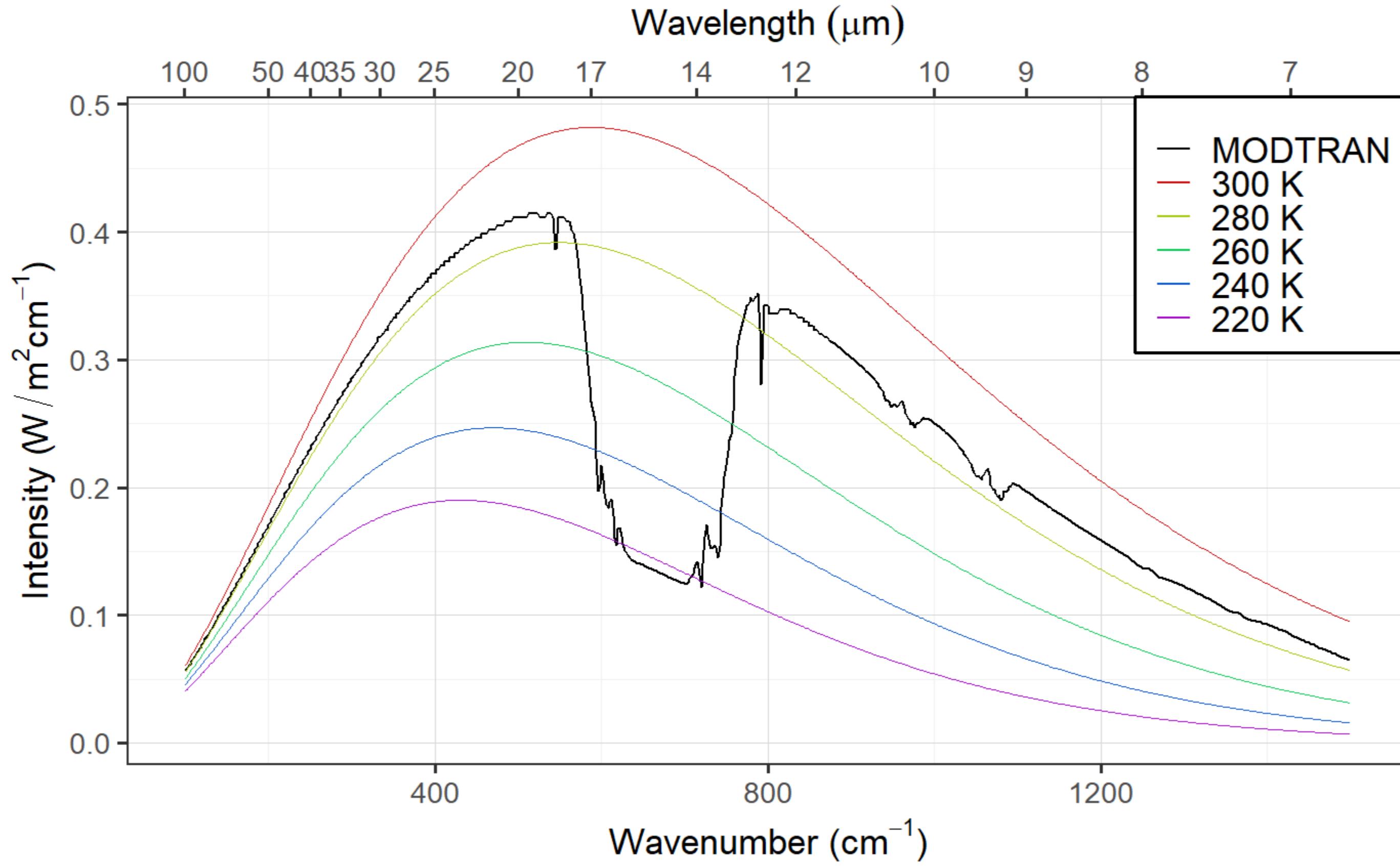
1024 ppm CO₂

MODTRAN: 1024 ppm CO₂, 20 km



2048 ppm CO₂

MODTRAN: 2048 ppm CO₂, 20 km



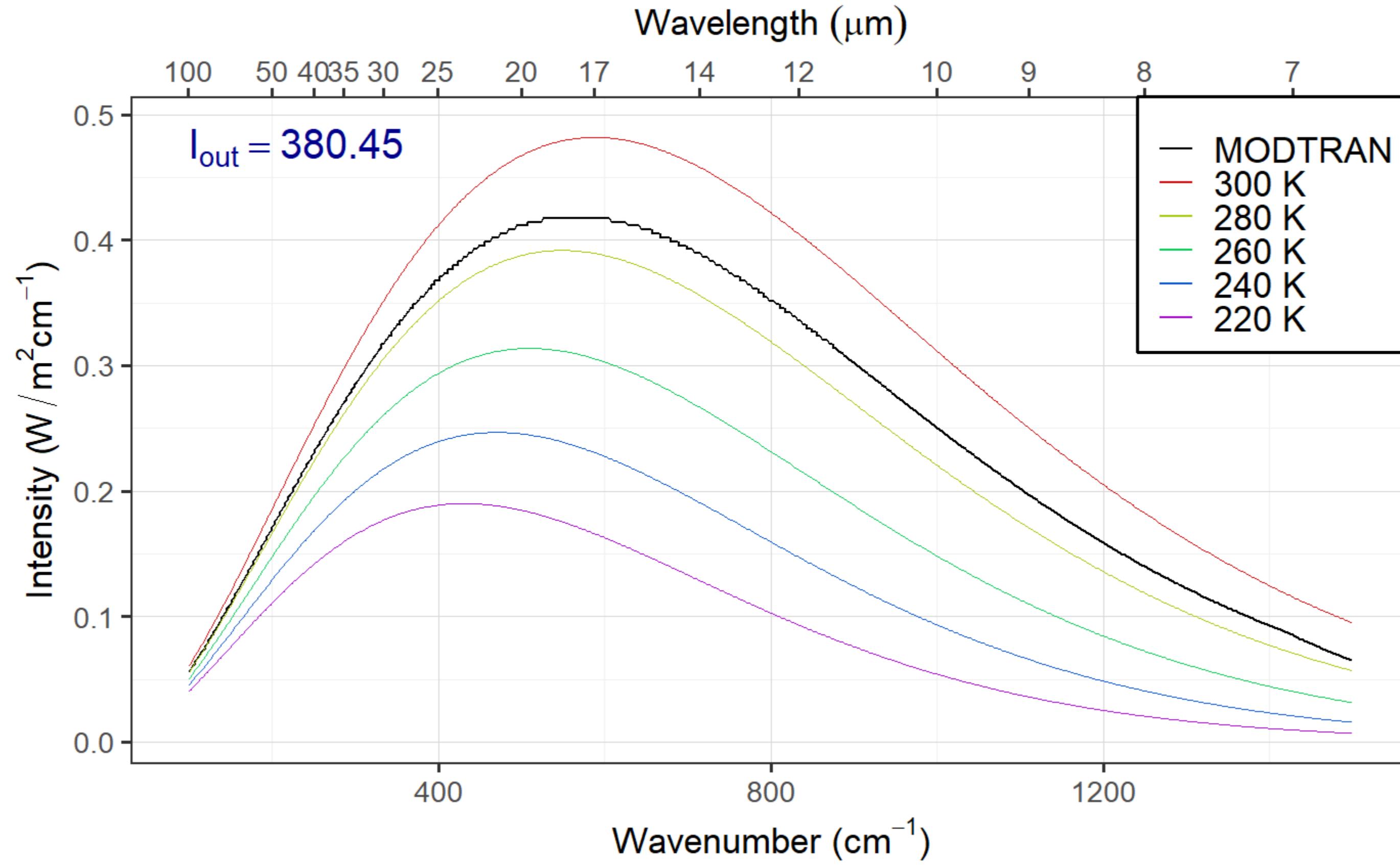
Measuring Band Saturation

Set up MODTRAN:

- Go to MODTRAN, set CO₂ 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 CO₂ and note the change in I_{out}
- Keep doubling CO₂ until you get to 1600 ppm.
- Do you notice anything about the changes in I_{out} ?

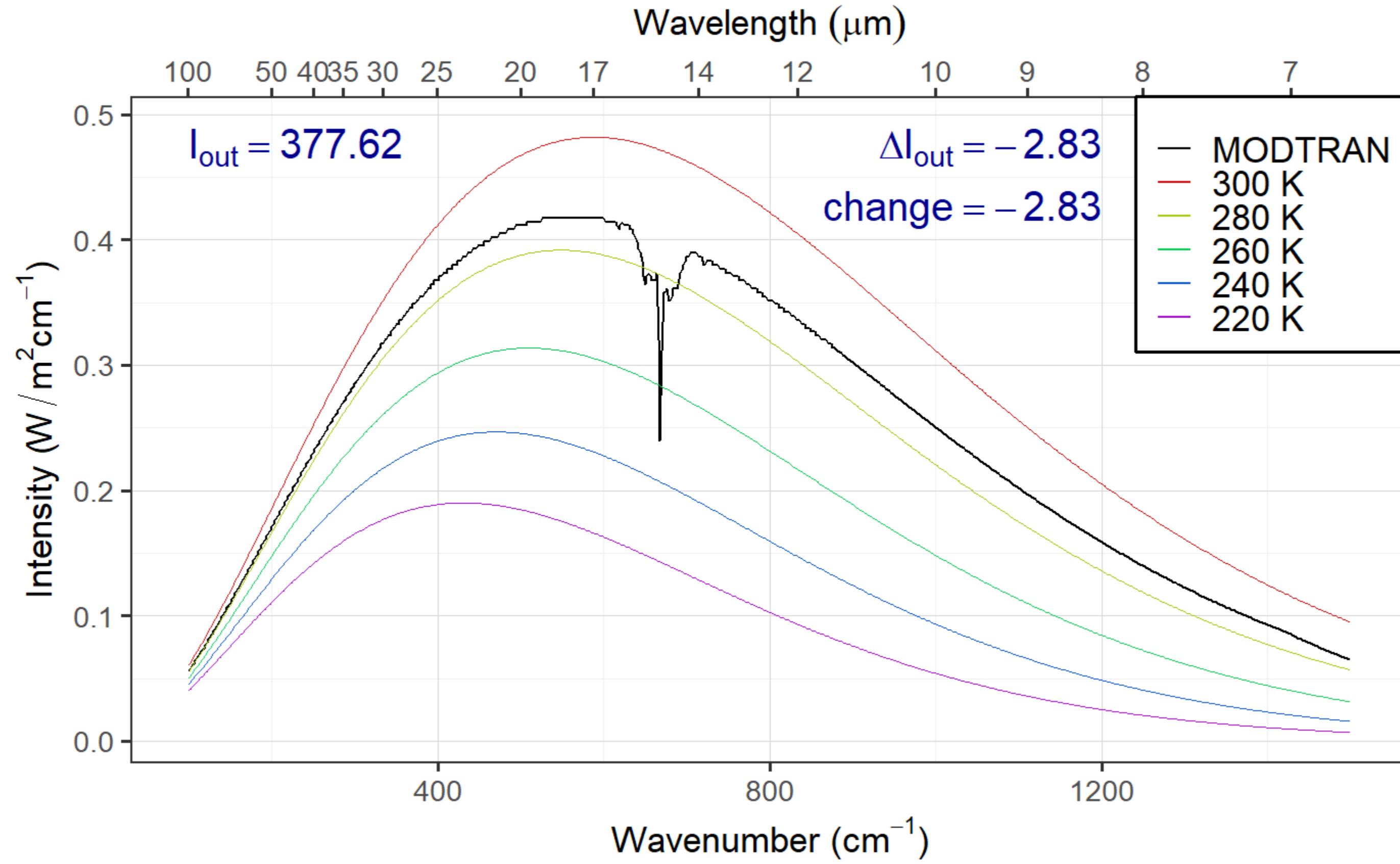
0 ppm CO₂

MODTRAN: 0 ppm CO₂, 20 km



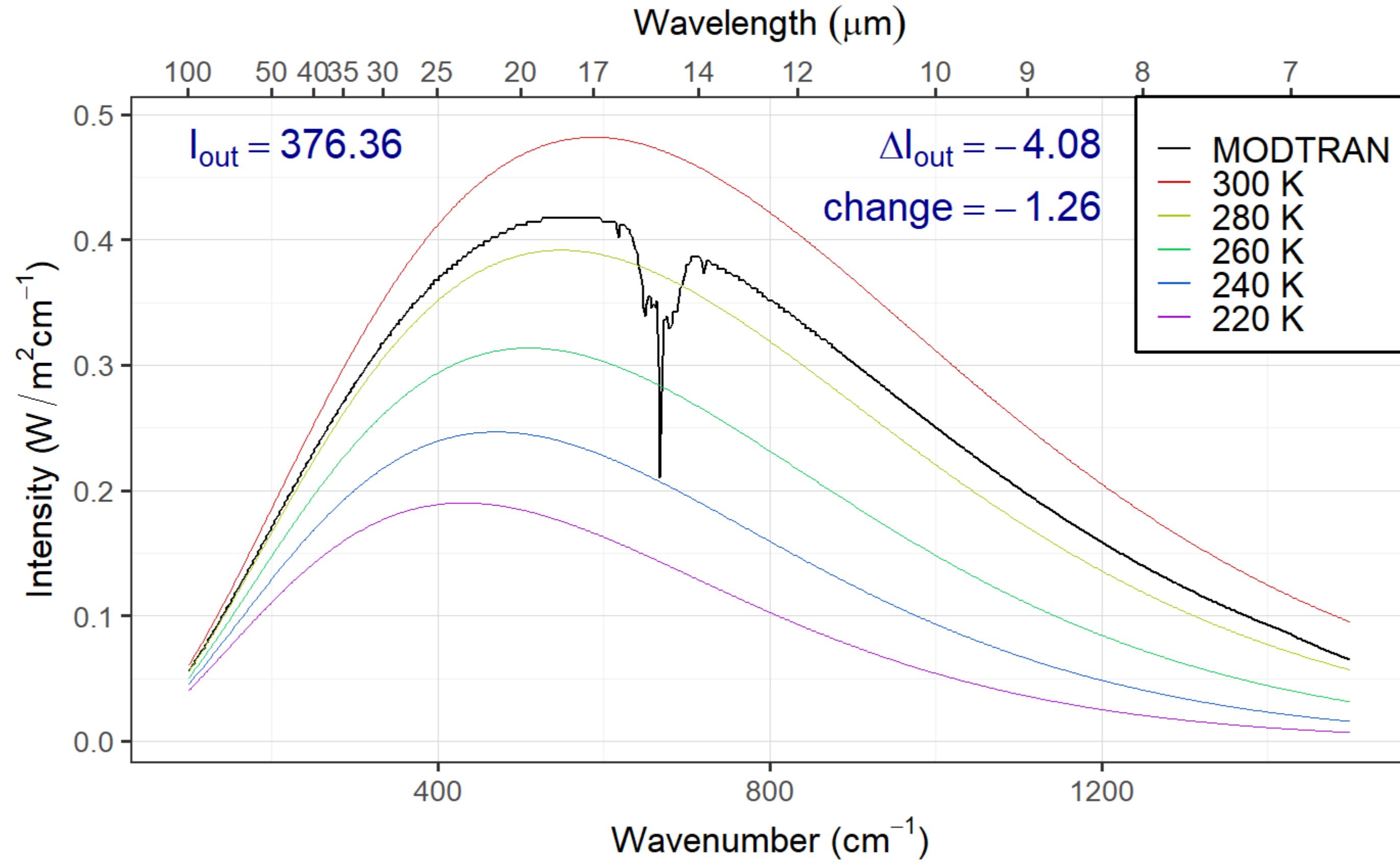
0.25 ppm CO₂

MODTRAN: 0.25 ppm CO₂, 20 km



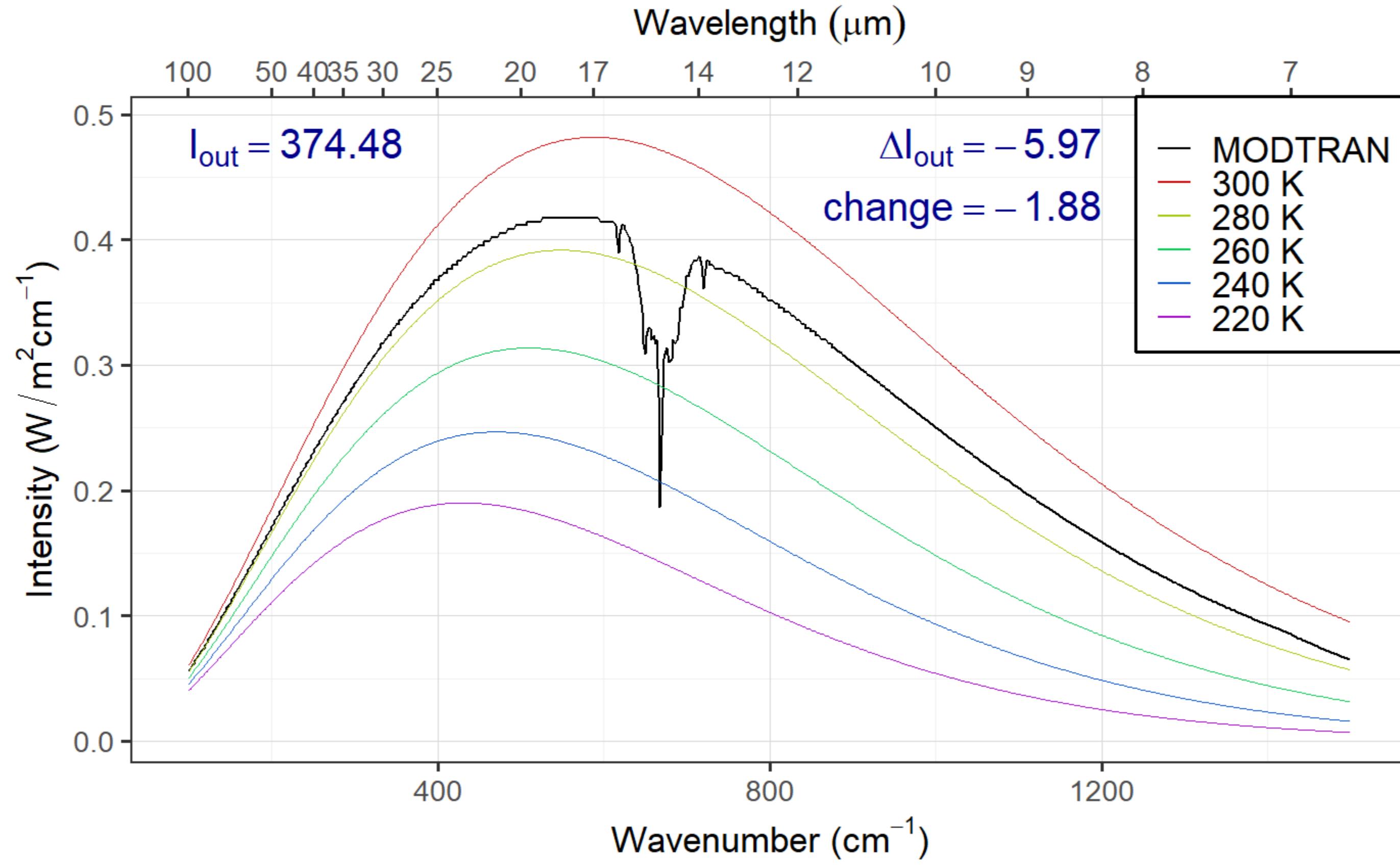
0.5 ppm CO₂

MODTRAN: 0.5 ppm CO₂, 20 km



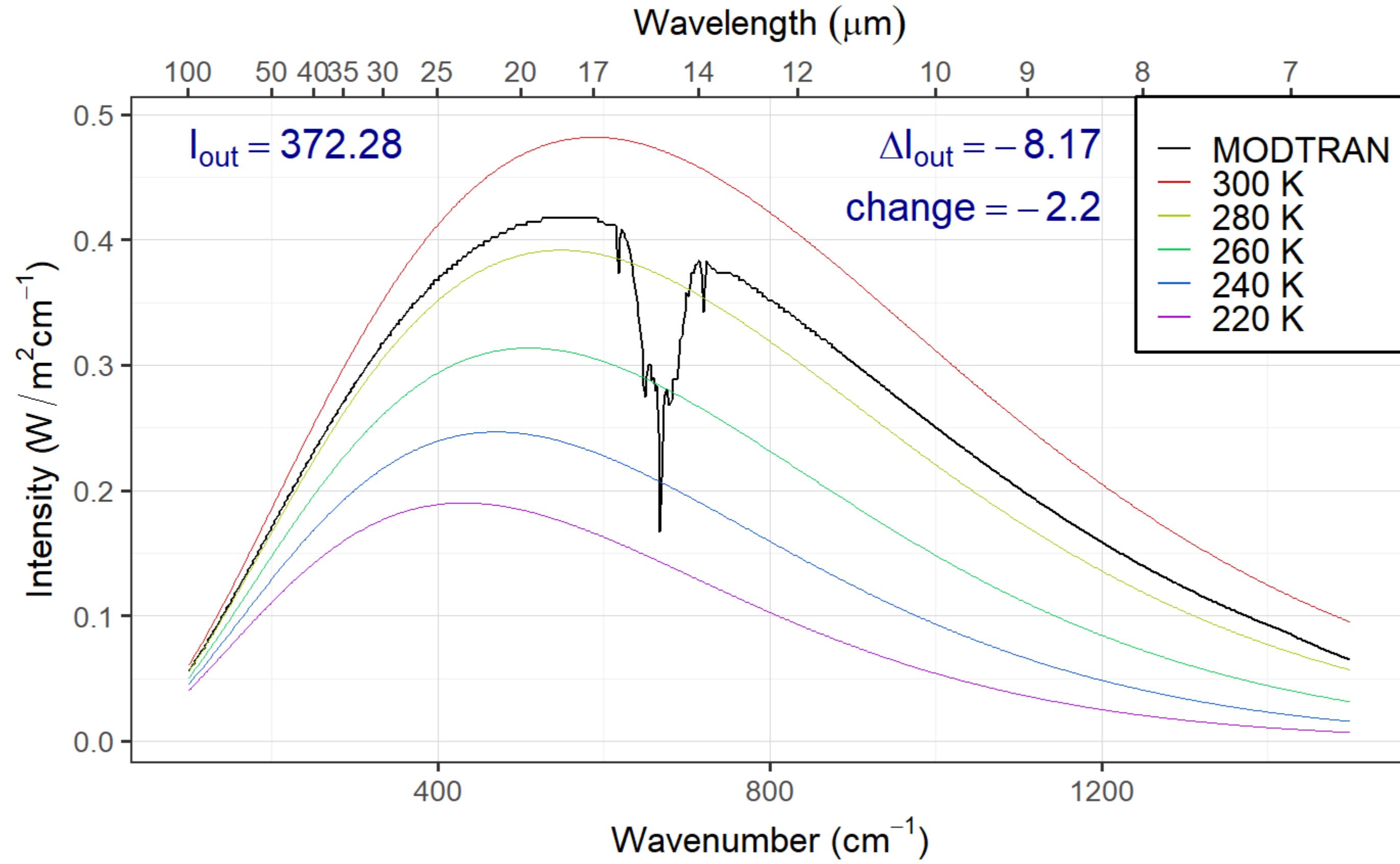
1 ppm CO₂

MODTRAN: 1 ppm CO₂, 20 km



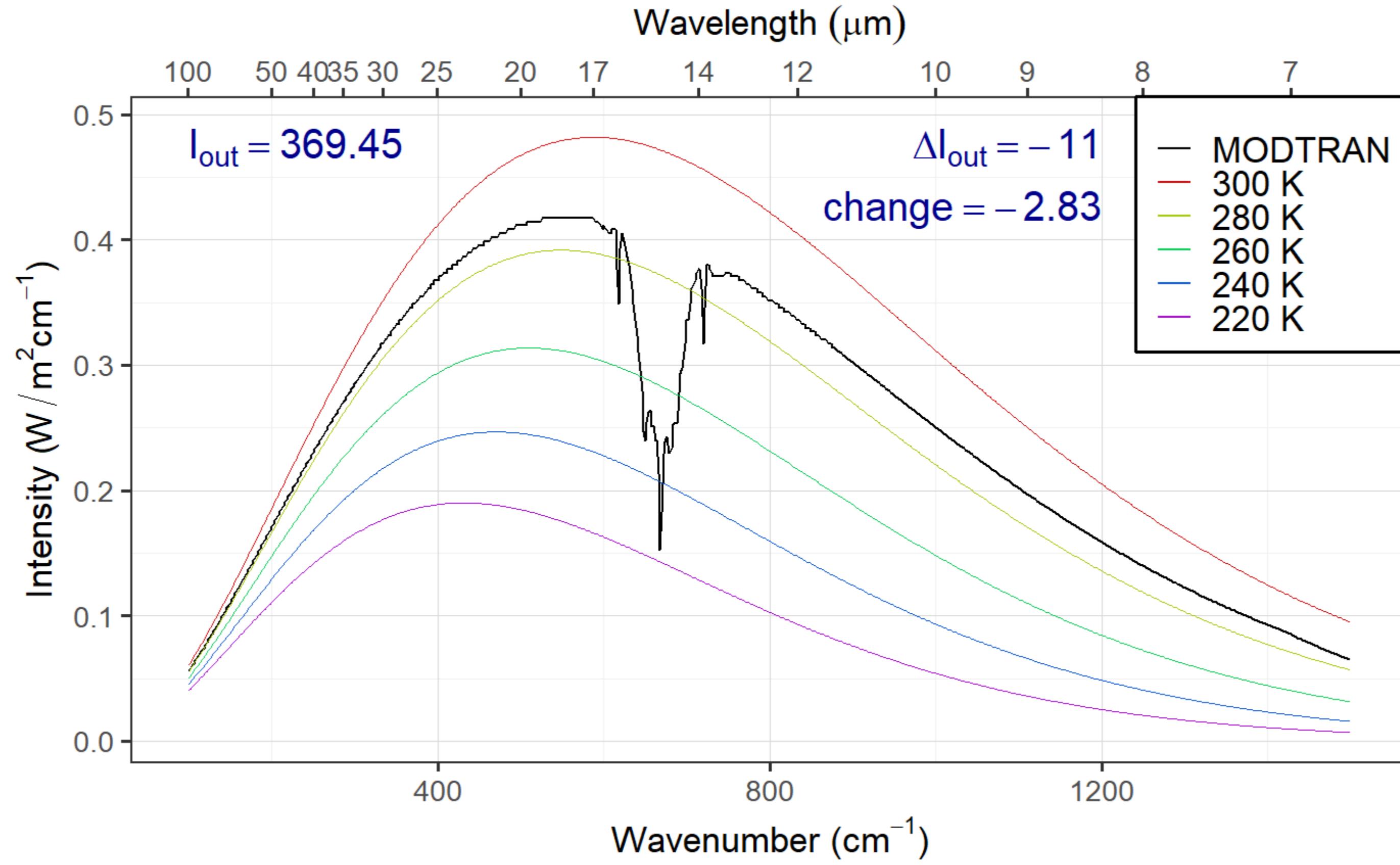
2 ppm CO₂

MODTRAN: 2 ppm CO₂, 20 km



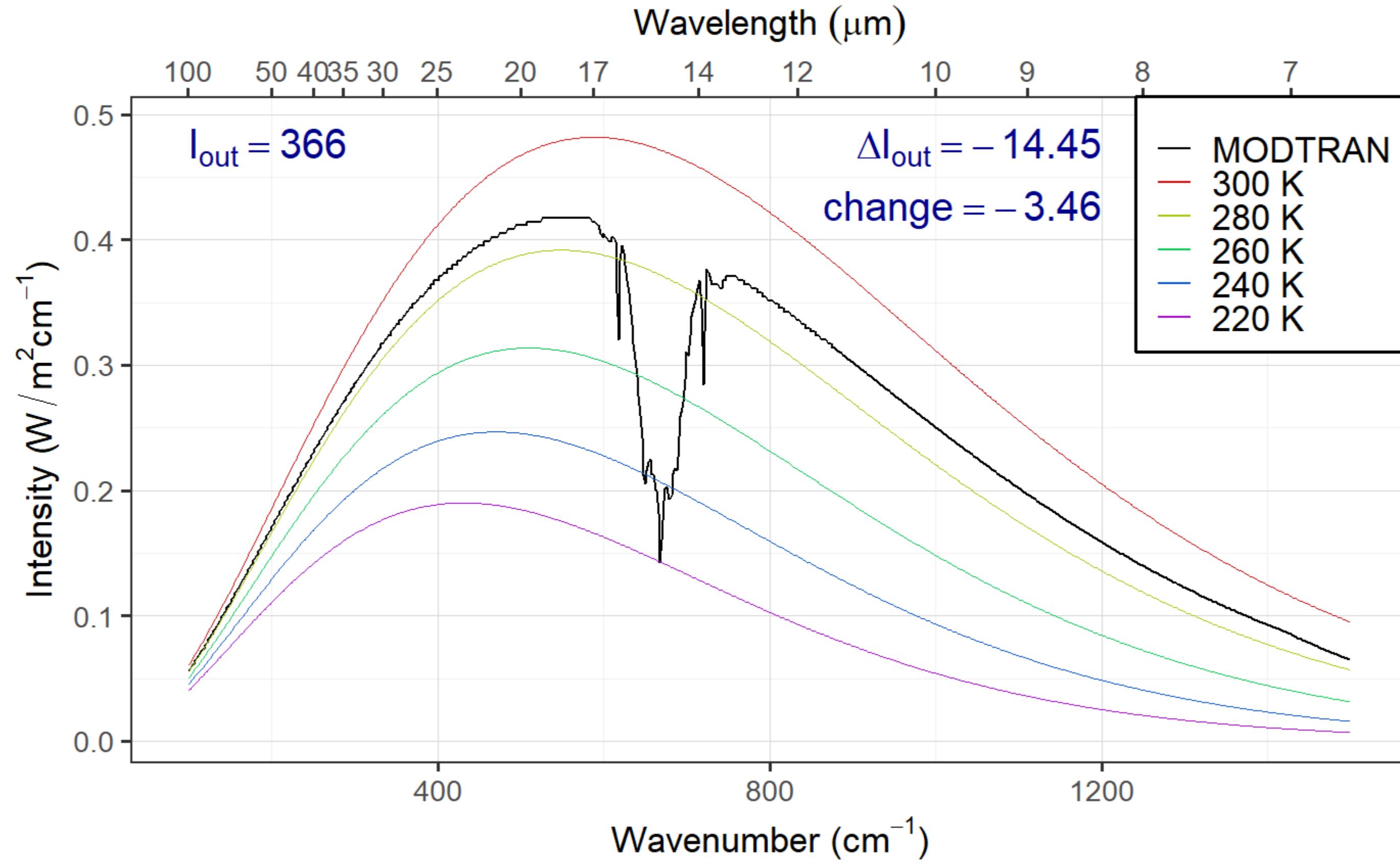
4 ppm CO₂

MODTRAN: 4 ppm CO₂, 20 km



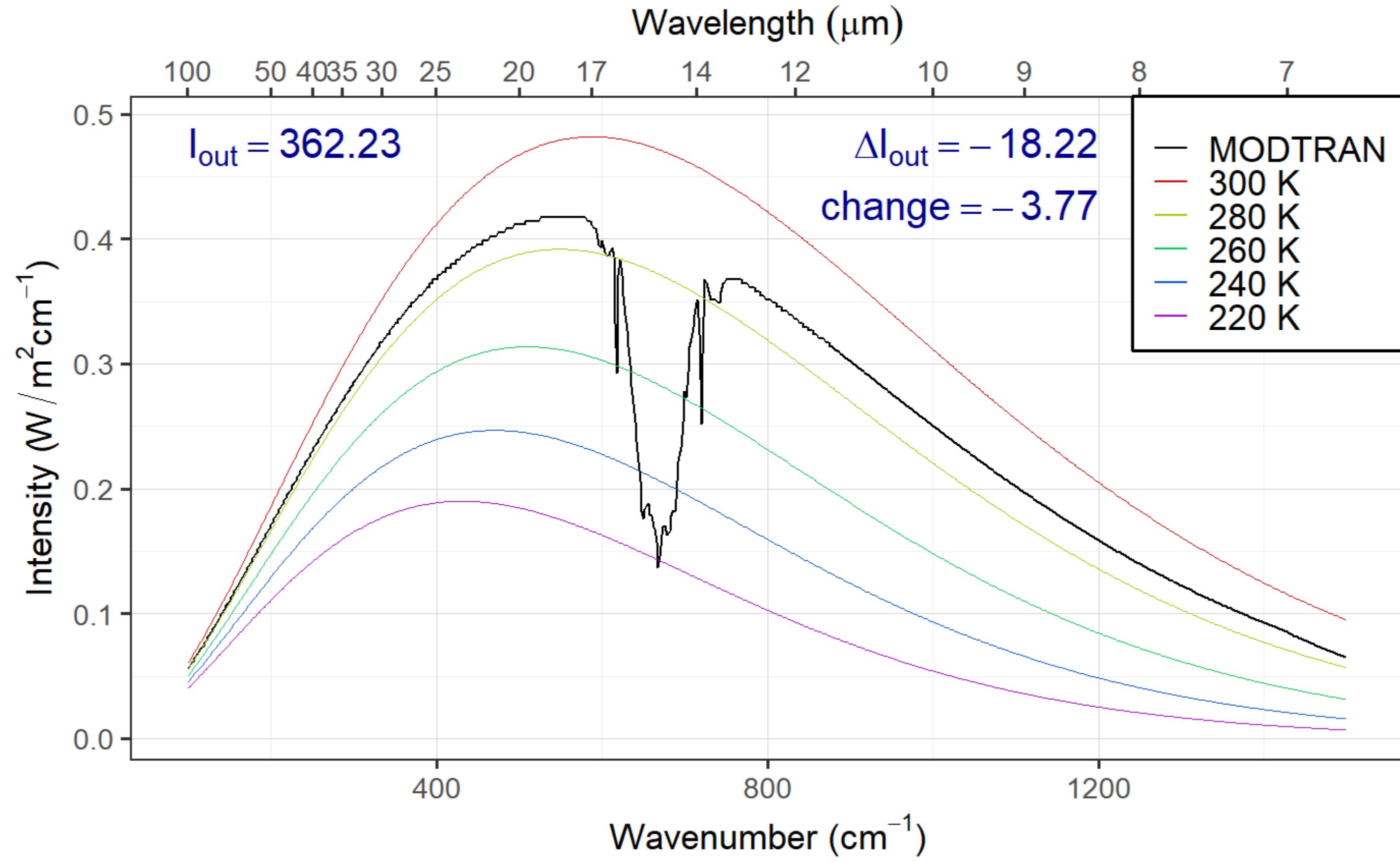
8 ppm CO₂

MODTRAN: 8 ppm CO₂, 20 km



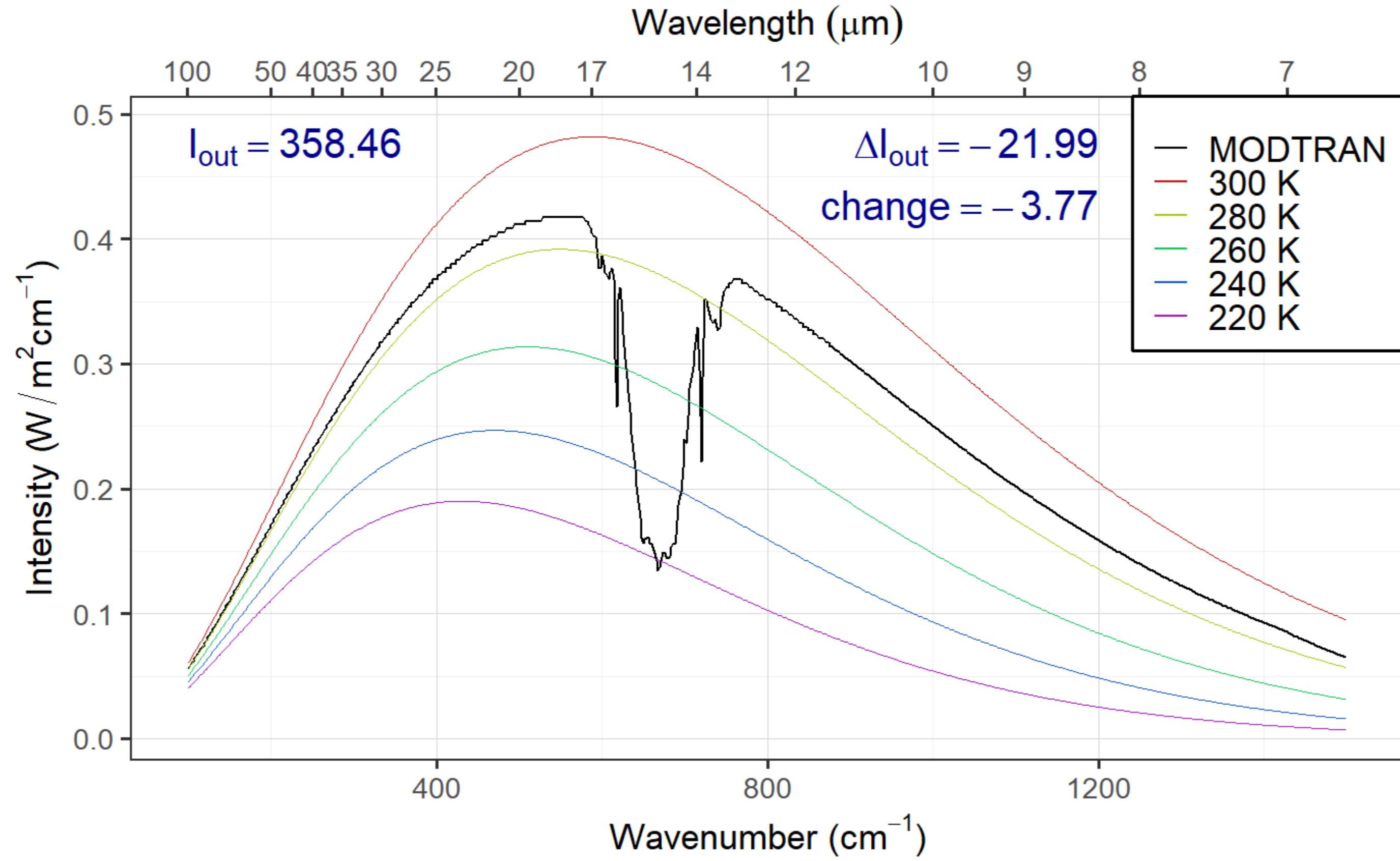
16 ppm CO₂

MODTRAN: 16 ppm CO₂, 20 km



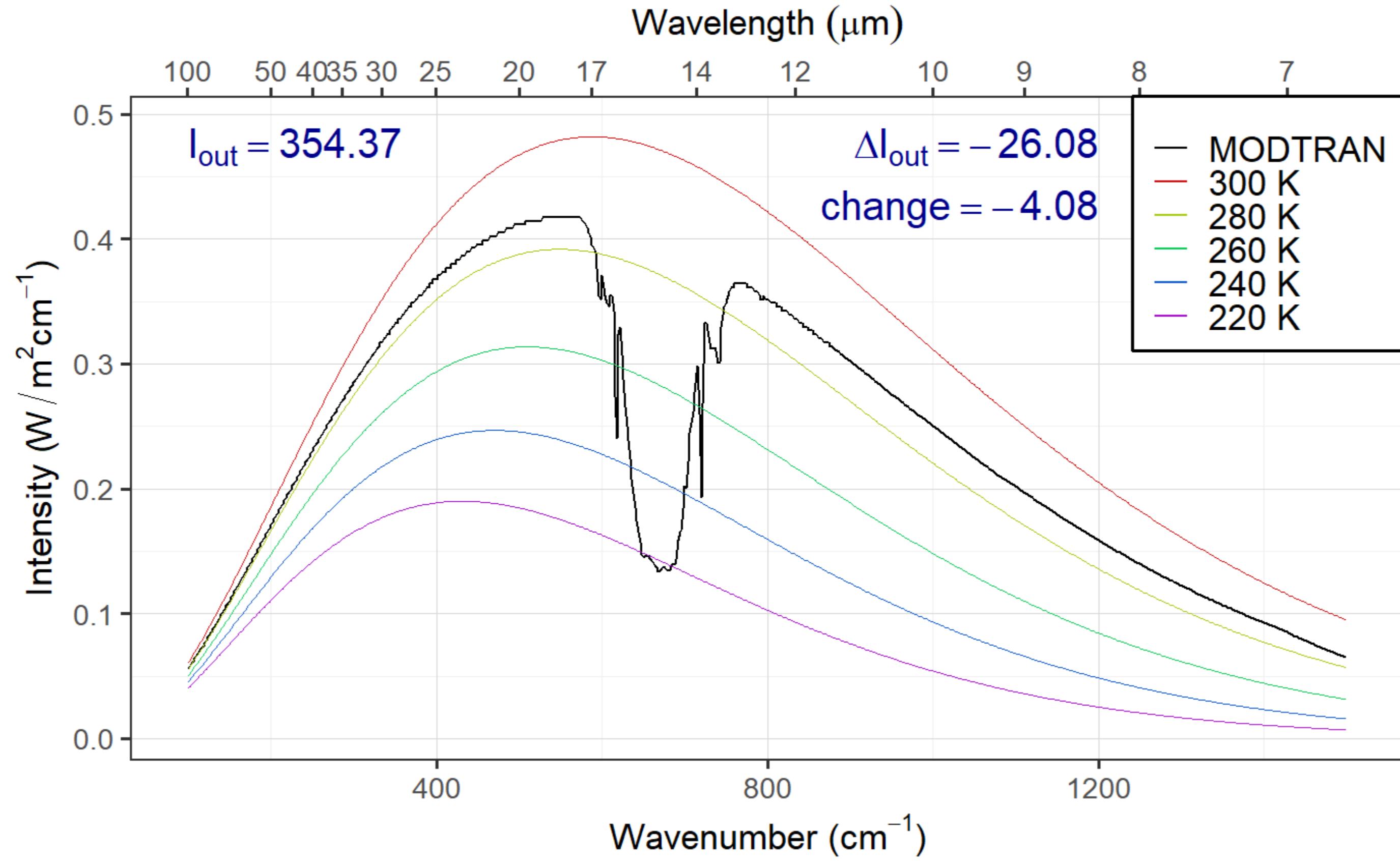
32 ppm CO₂

MODTRAN: 32 ppm CO₂, 20 km



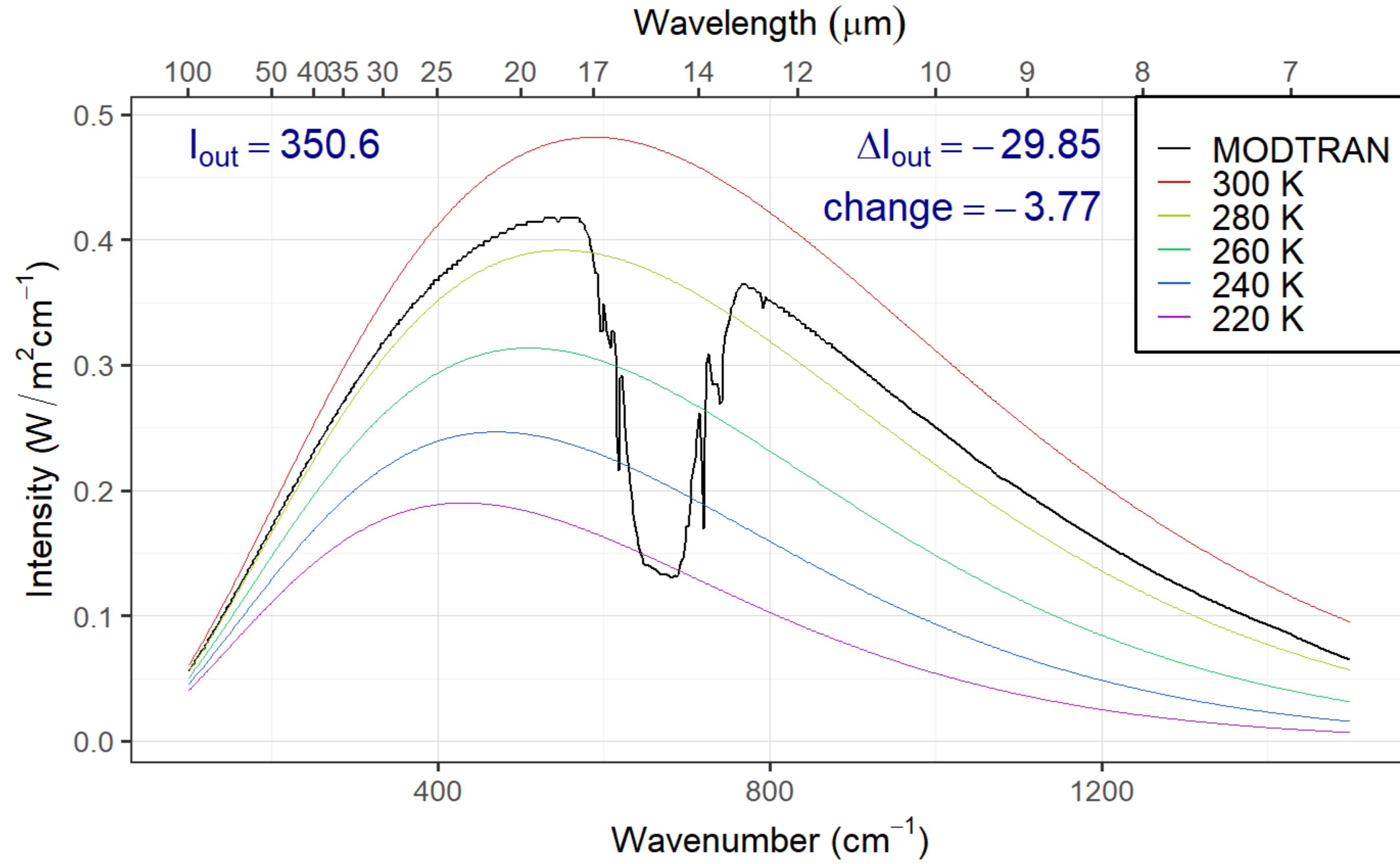
64 ppm CO₂

MODTRAN: 64 ppm CO₂, 20 km



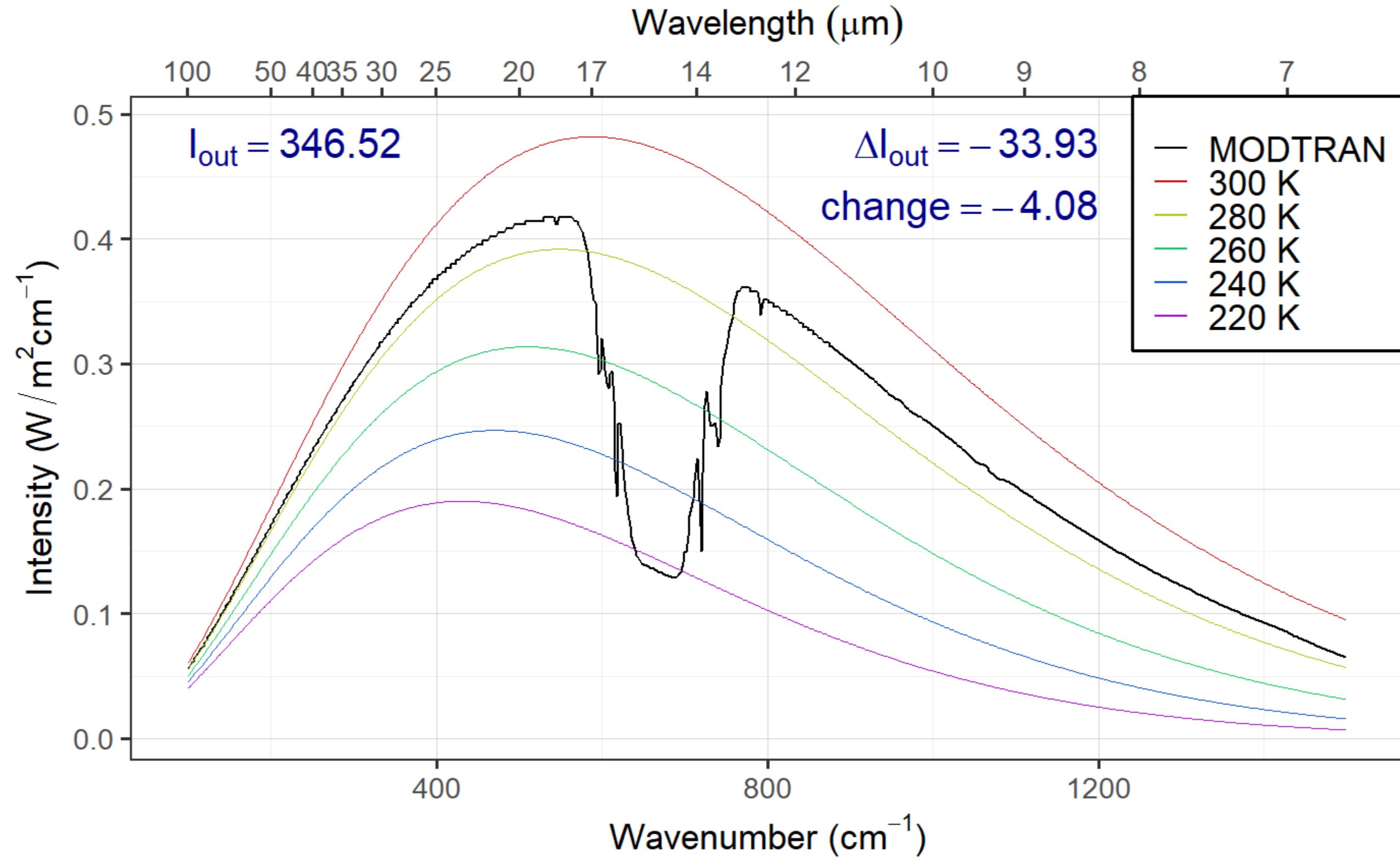
128 ppm CO₂

MODTRAN: 128 ppm CO₂, 20 km



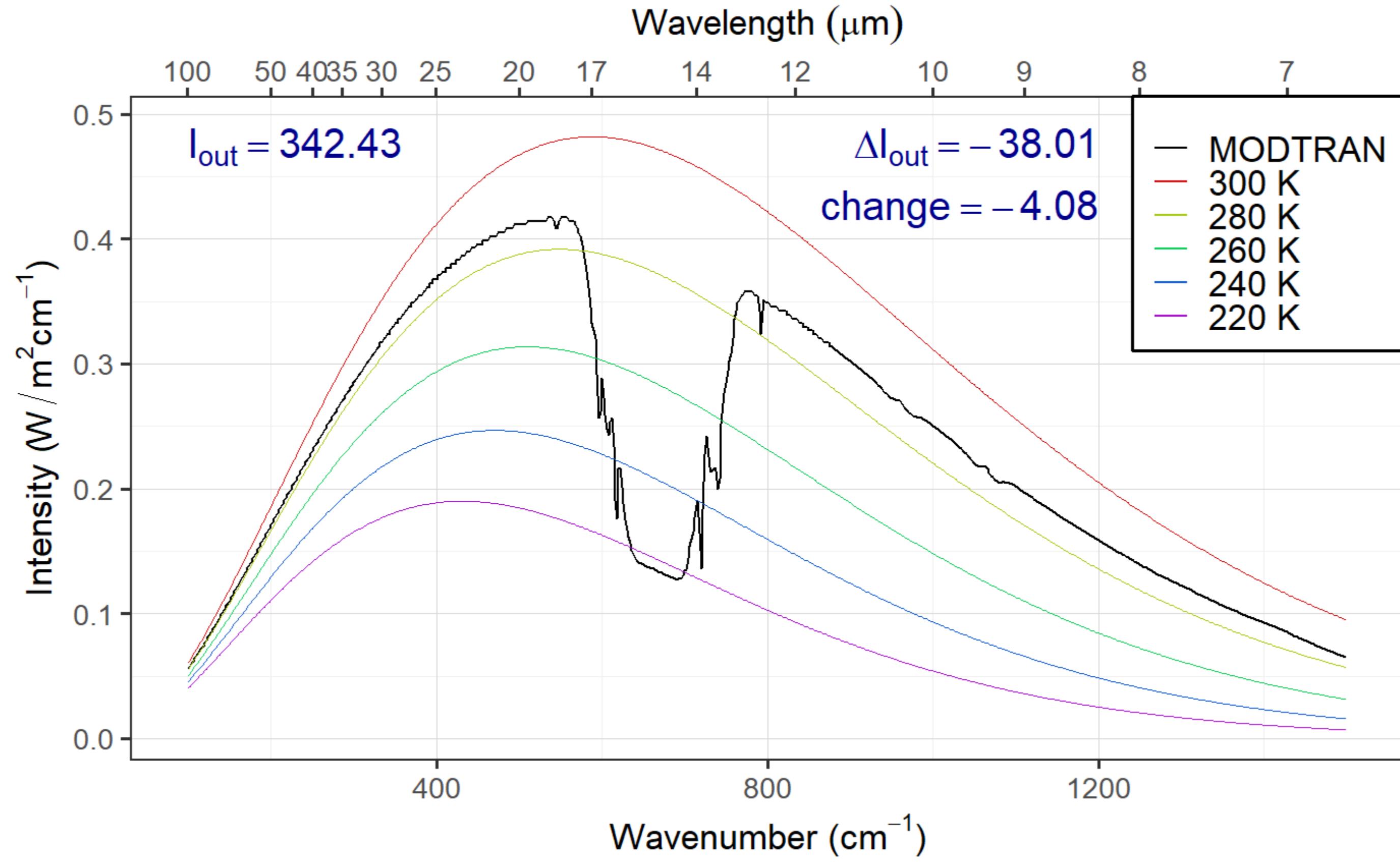
256 ppm CO₂

MODTRAN: 256 ppm CO₂, 20 km



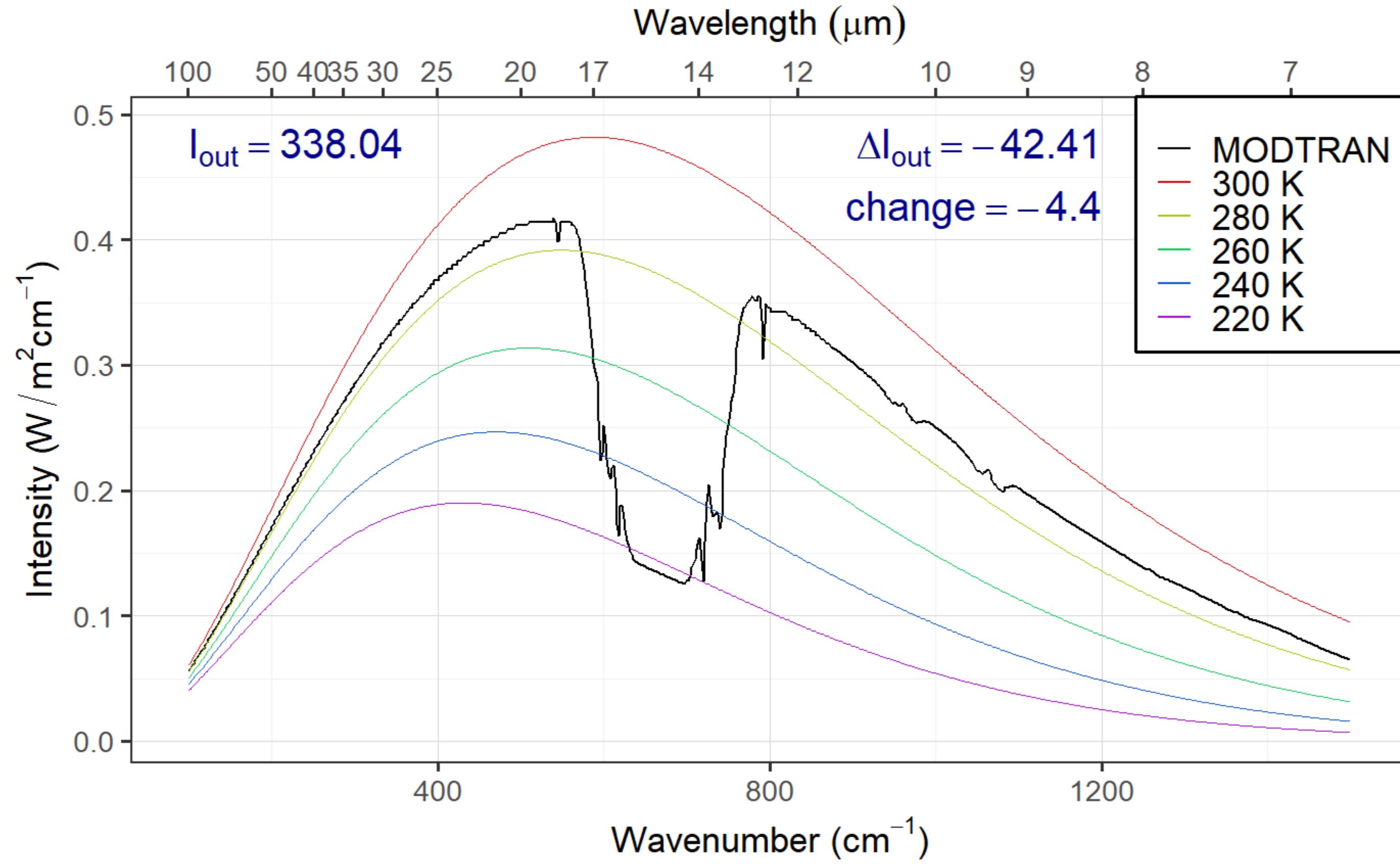
512 ppm CO₂

MODTRAN: 512 ppm CO₂, 20 km



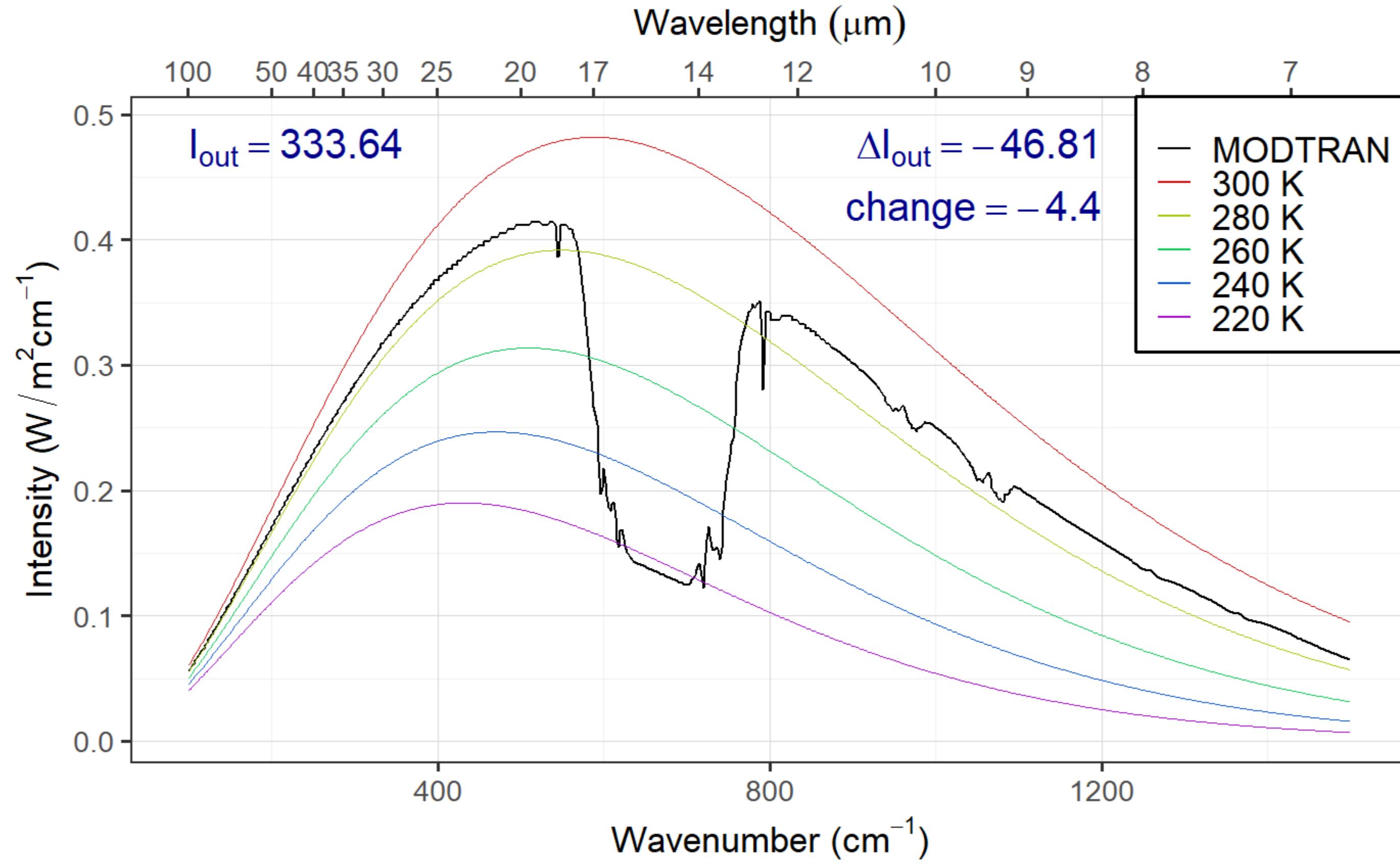
1024 ppm CO₂

MODTRAN: 1024 ppm CO₂, 20 km

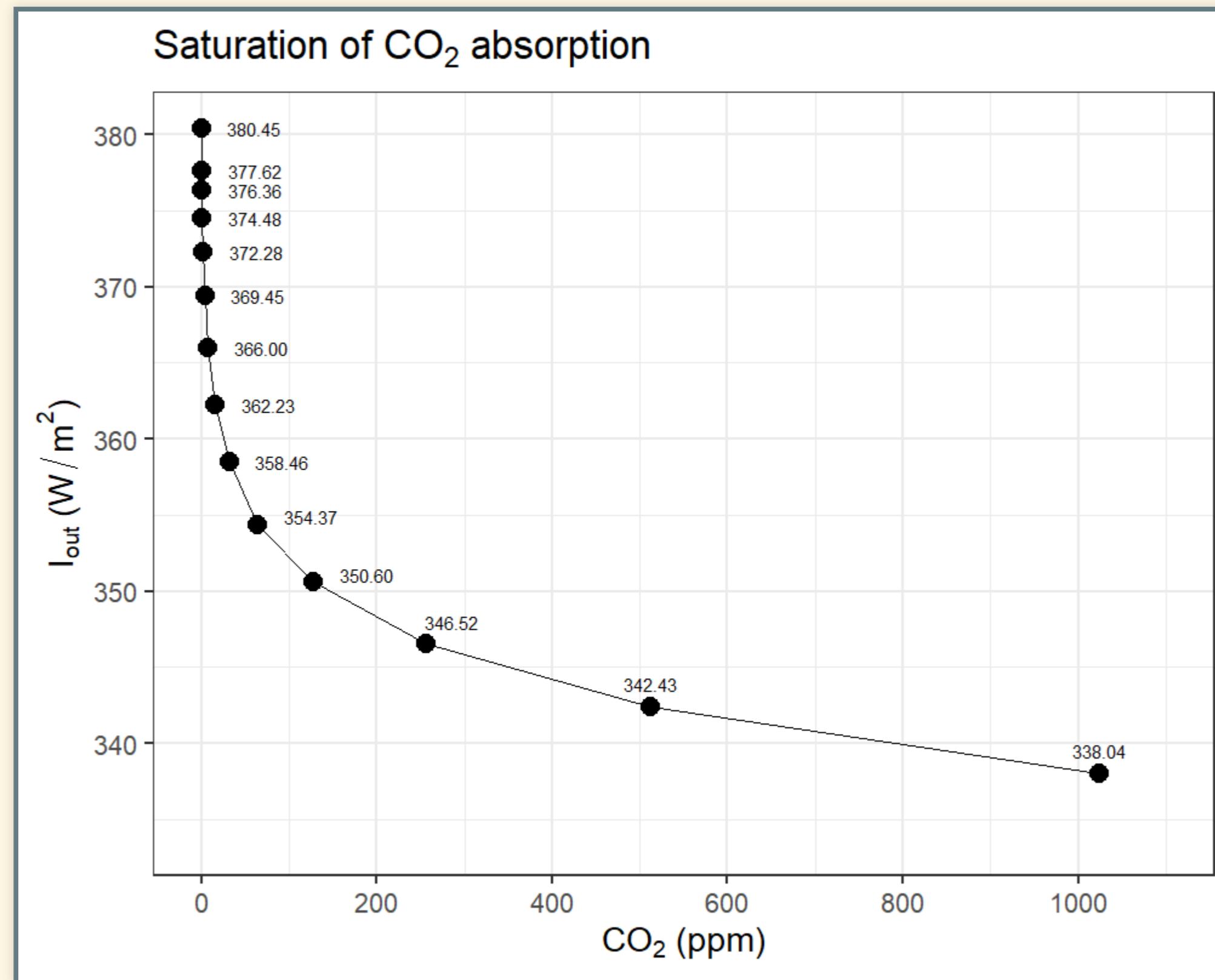


2048 ppm CO₂

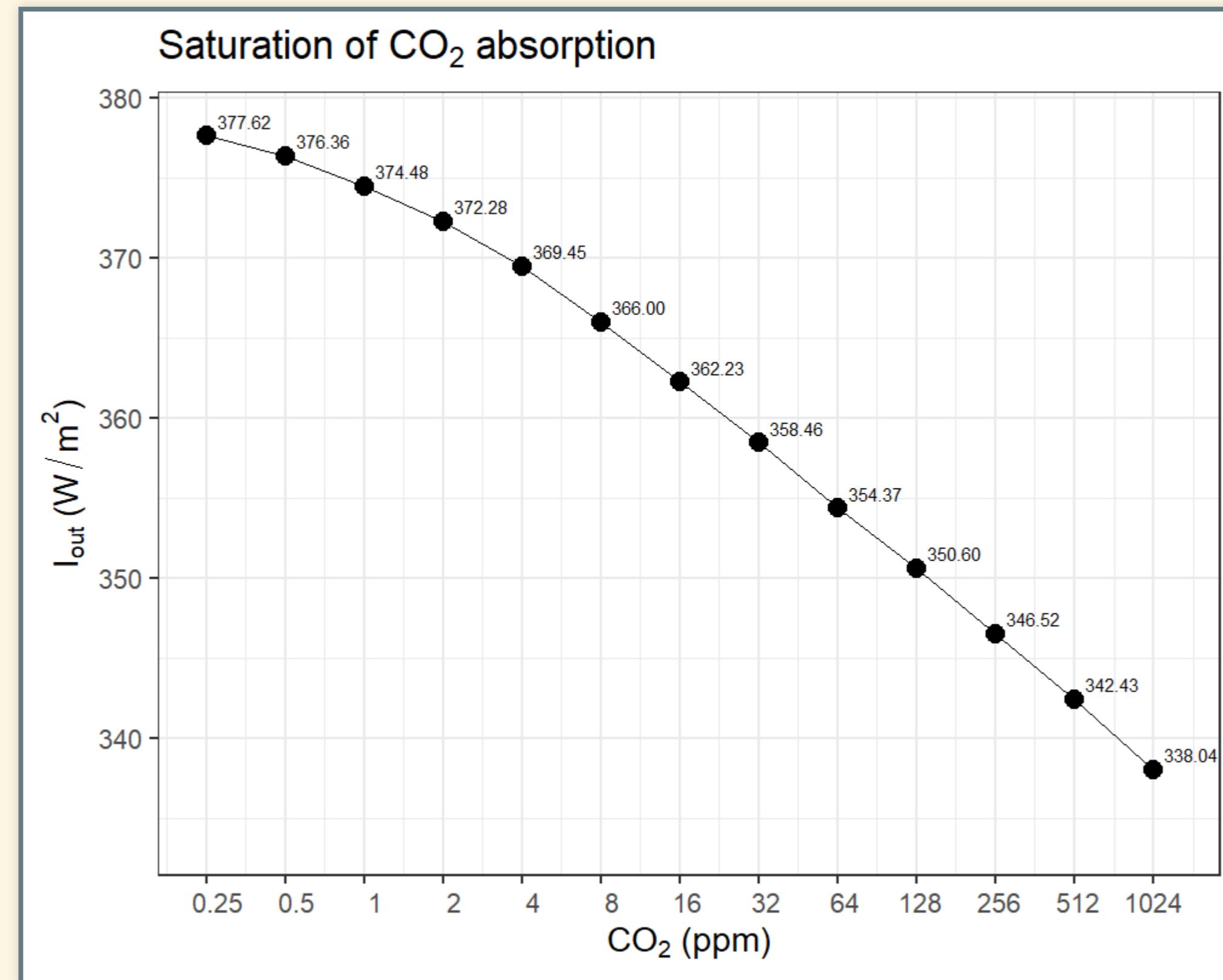
MODTRAN: 2048 ppm CO₂, 20 km



Band Saturation (I_{out})

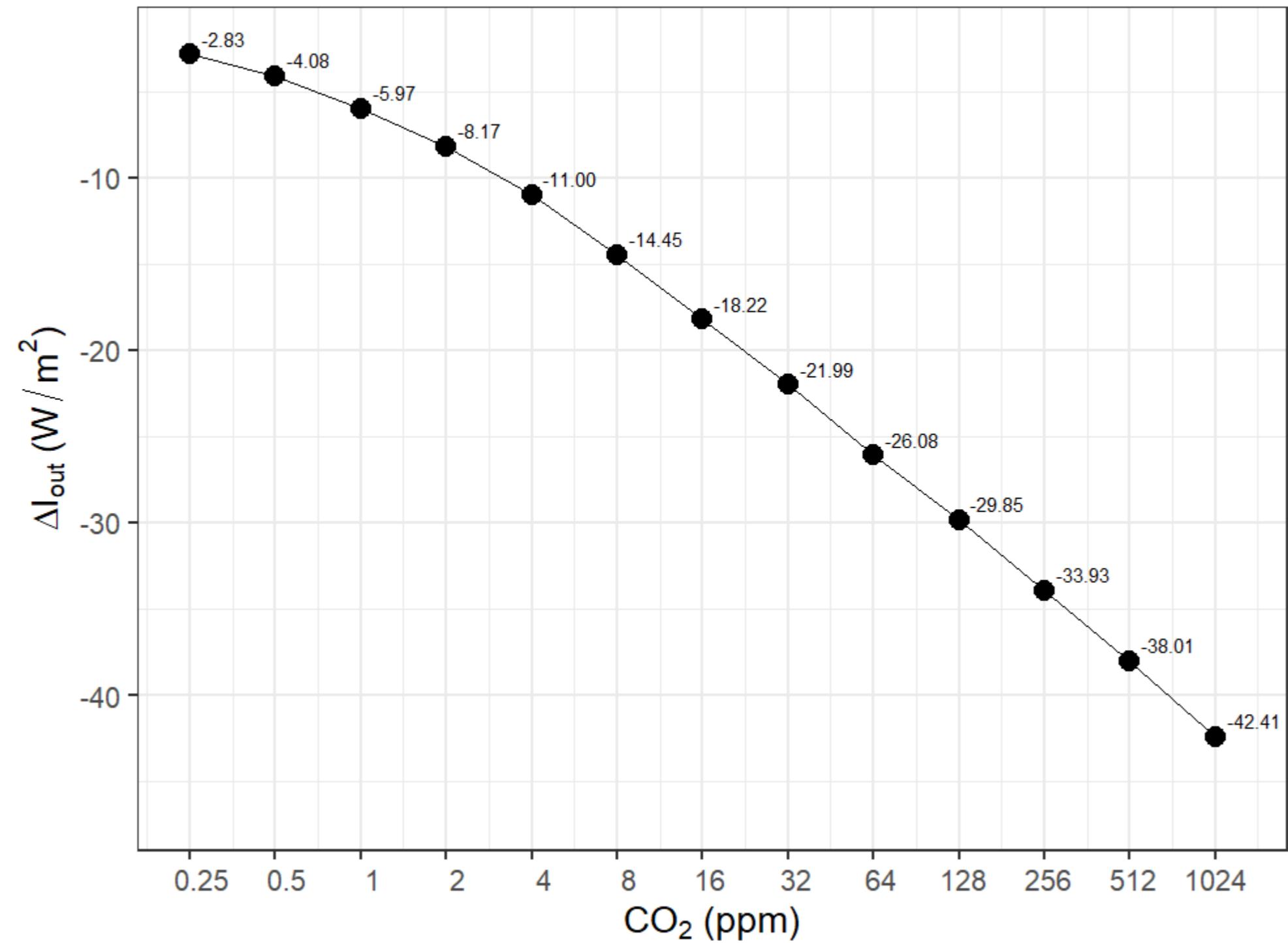


I_{out} (CO_2 on log scale)



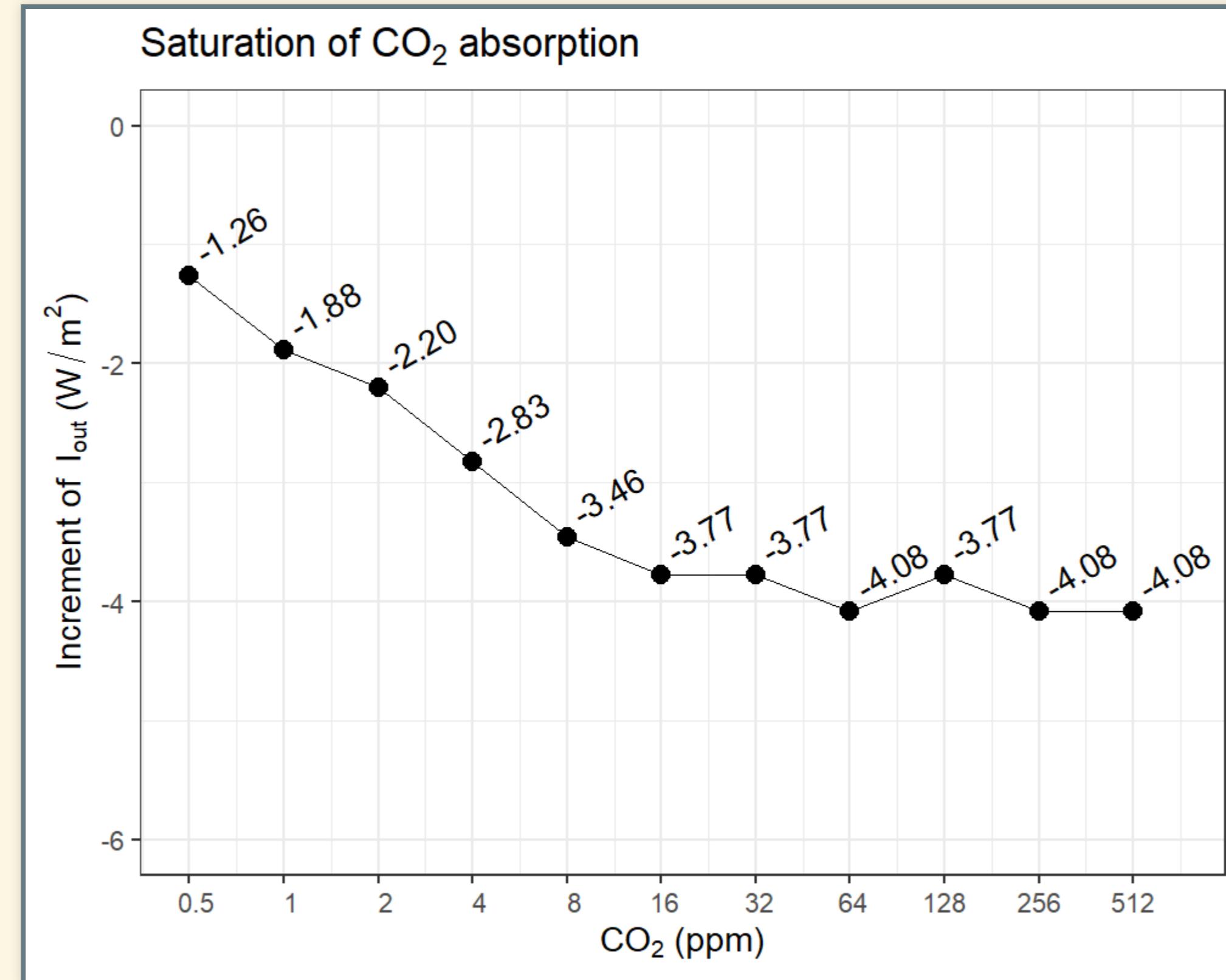
ΔI_{out}

Saturation of CO₂ absorption



Change in I_{out} from no CO₂

Increments of I_{out}



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

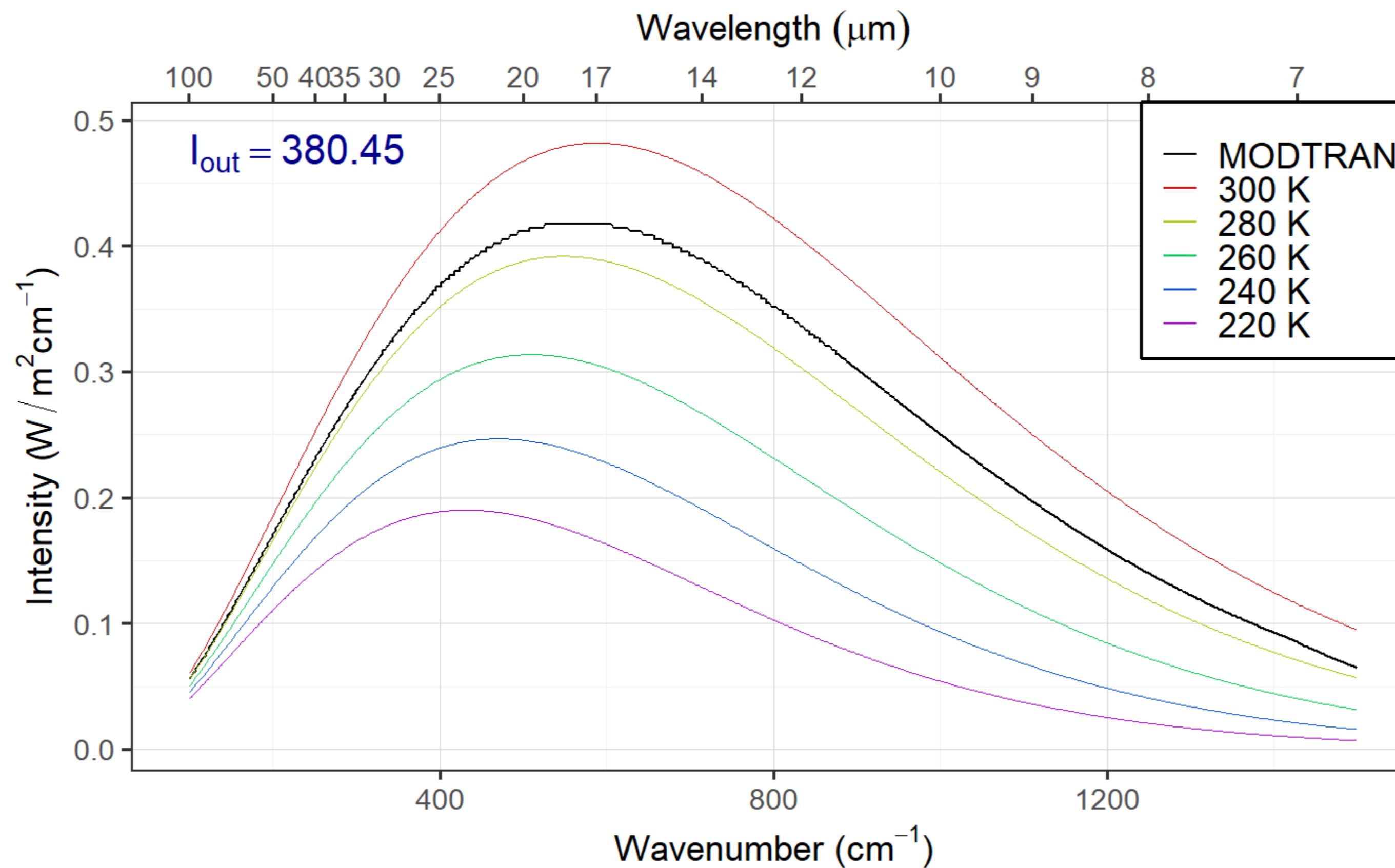
Measuring Greenhouse Effect:

Measuring Greenhouse Effect:

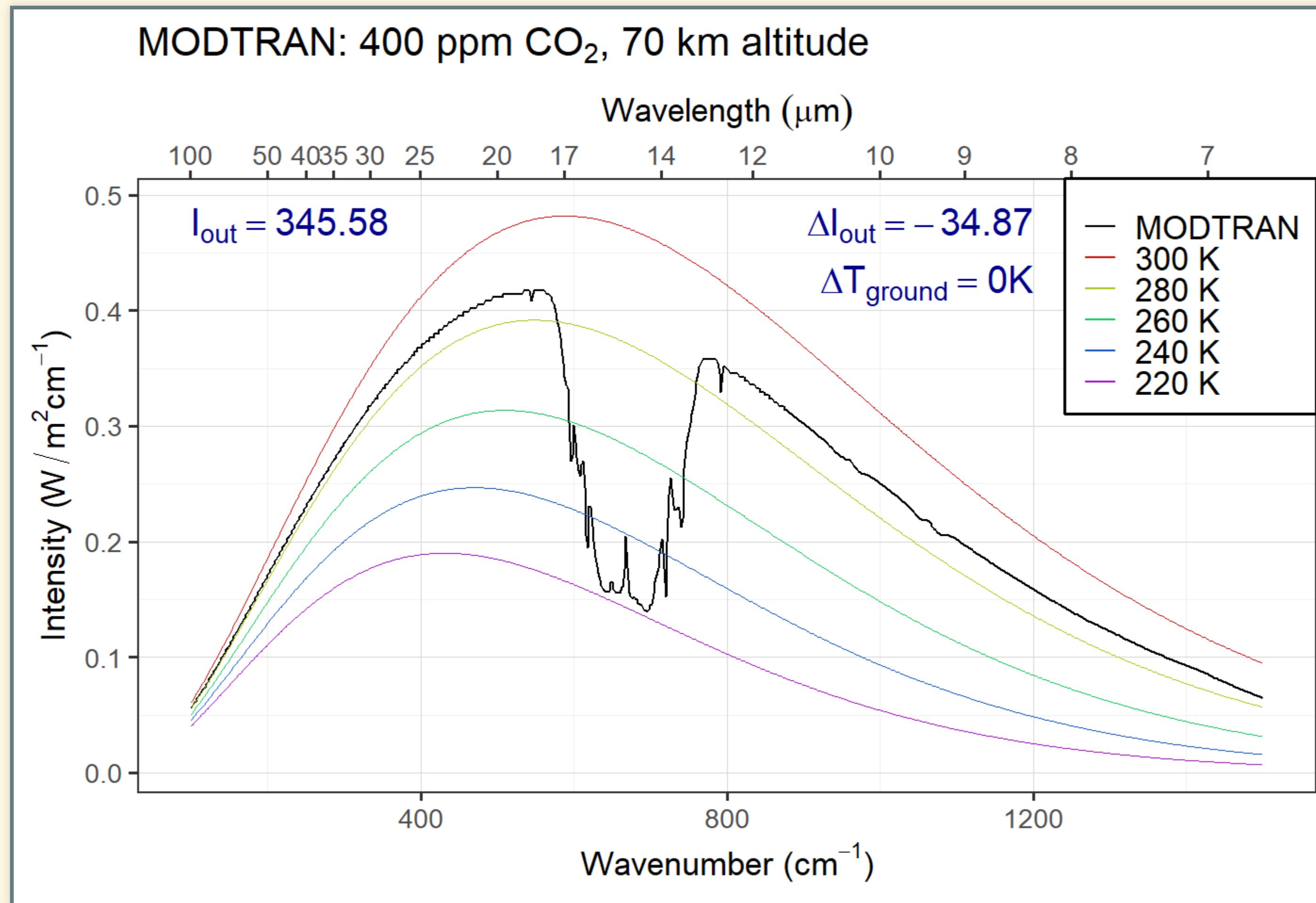
- Go to MODTRAN, set CO₂ to 0 ppm, and set all other gases to zero.
- Set altitude to 70 km and location to “1976 US Standard Atmosphere”.
- Press “Save this run to background”
- Note I_{out}
- Set CO₂ to 400 ppm and note the change in I_{out}
- Adjust the temperature offset to make the difference in $I_{\text{out}}(\text{New} - \text{BG})$ equal zero.

No Greenhouse Gases

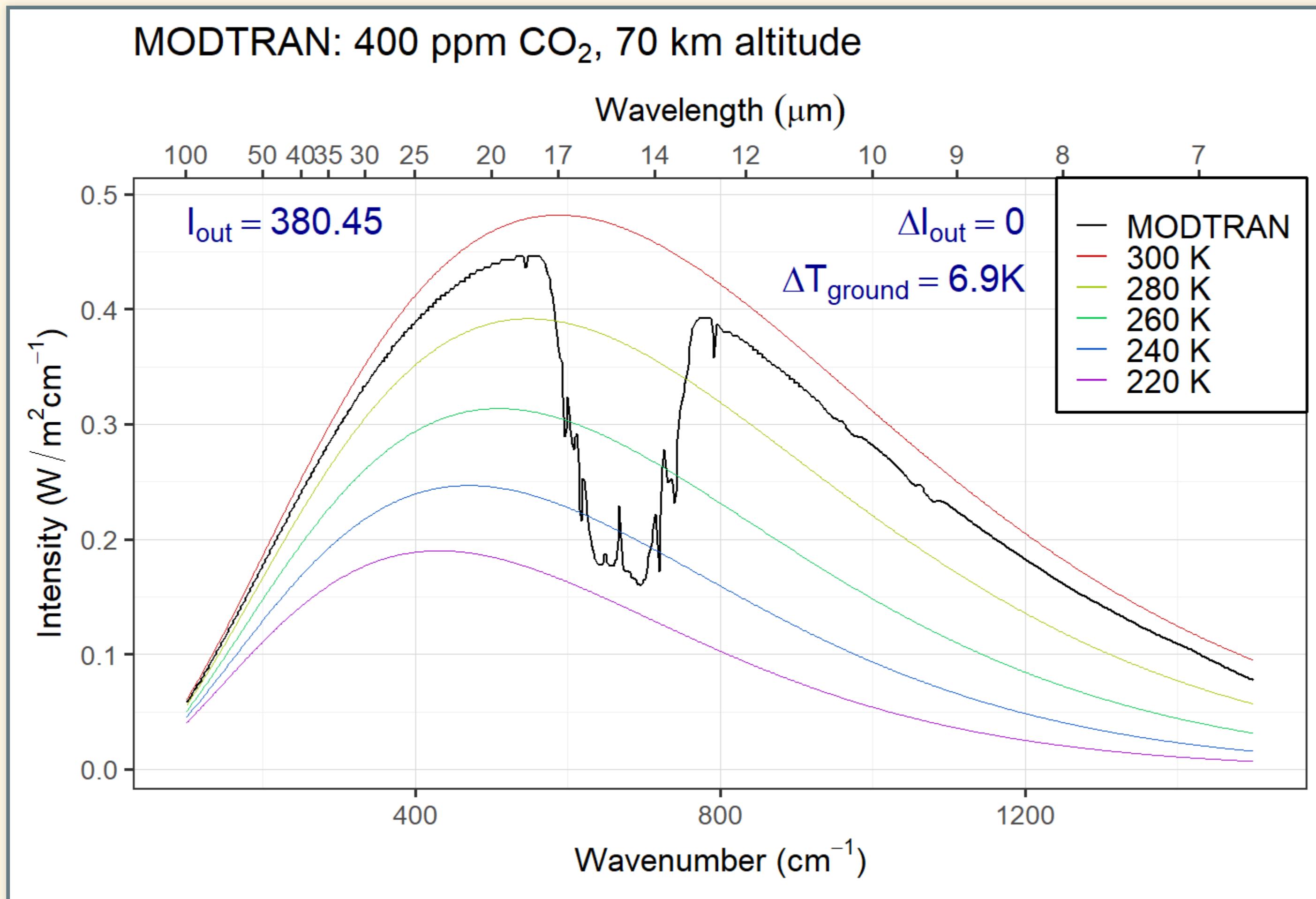
MODTRAN: 0 ppm CO₂, 70 km altitude



400 ppm



Adjust temperature



Calculating Global Warming

Calculating Global Warming

- “Climate sensitivity” = ΔT_{2x}
 - Temperature rise for doubled CO₂.
 - Uncertain (because of feedbacks)
 - Best estimate: $\Delta T_{2x} \sim 3.2\text{K}$ (range 2.0–4.5 K)
- Every time you double CO₂, T rises by ΔT_{2x} .
- For arbitrary change in CO₂:

$$\Delta T = \Delta T_{2x} \times \frac{\ln\left(\frac{\text{new } p\text{CO}_2}{\text{old } p\text{CO}_2}\right)}{\ln 2}$$

Global Warming Potential

- Absorption by CO₂ 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 CO₂.
 - One chlorofluorocarbon molecule = thousands of CO₂ molecules
- Global Warming Potential (GWP) of x = how many CO₂ molecules cause the same warming as one molecule of x