Climate Feedbacks

EES 3310/5310

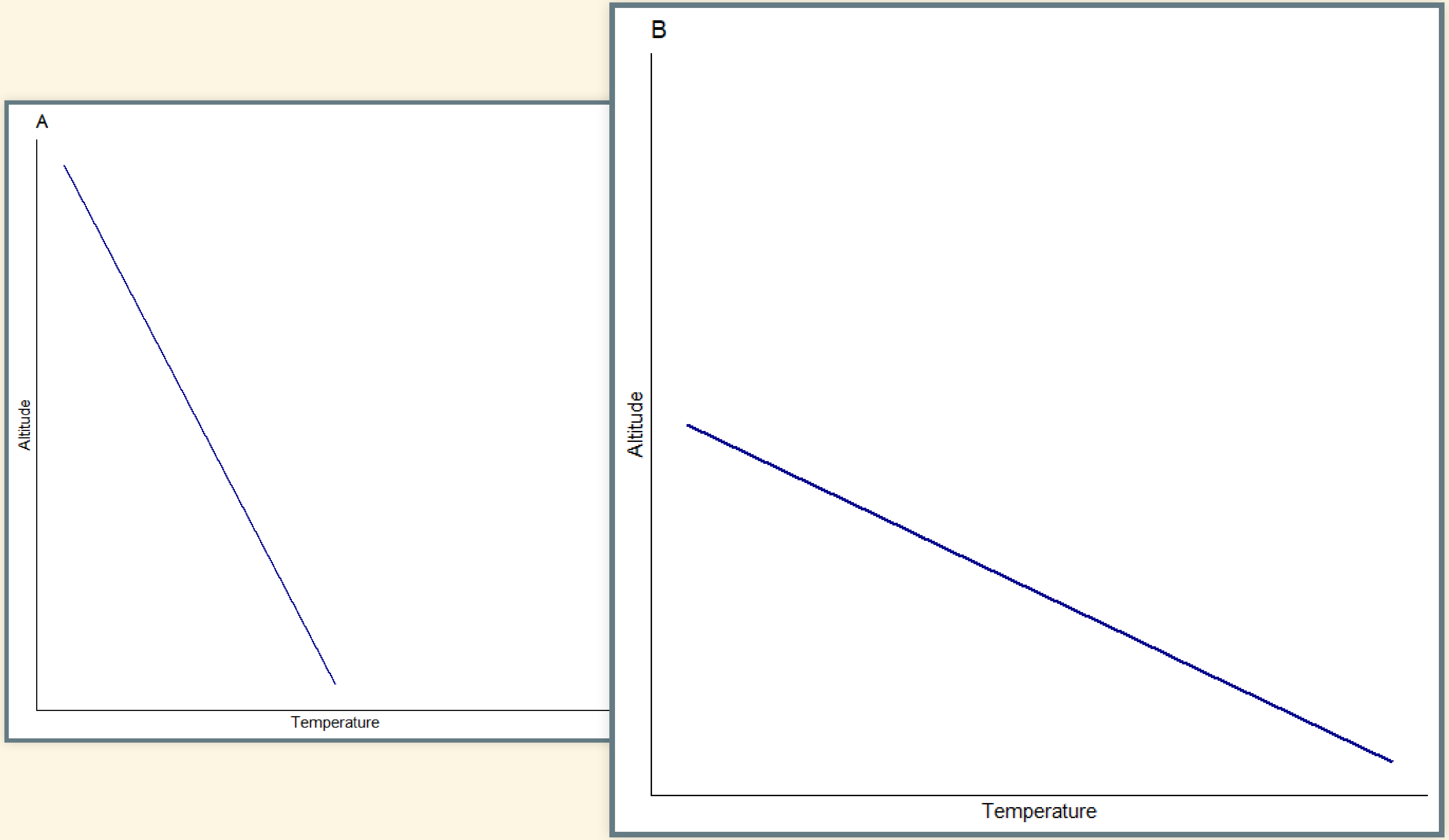
Global Climate Change

Jonathan Gilligan

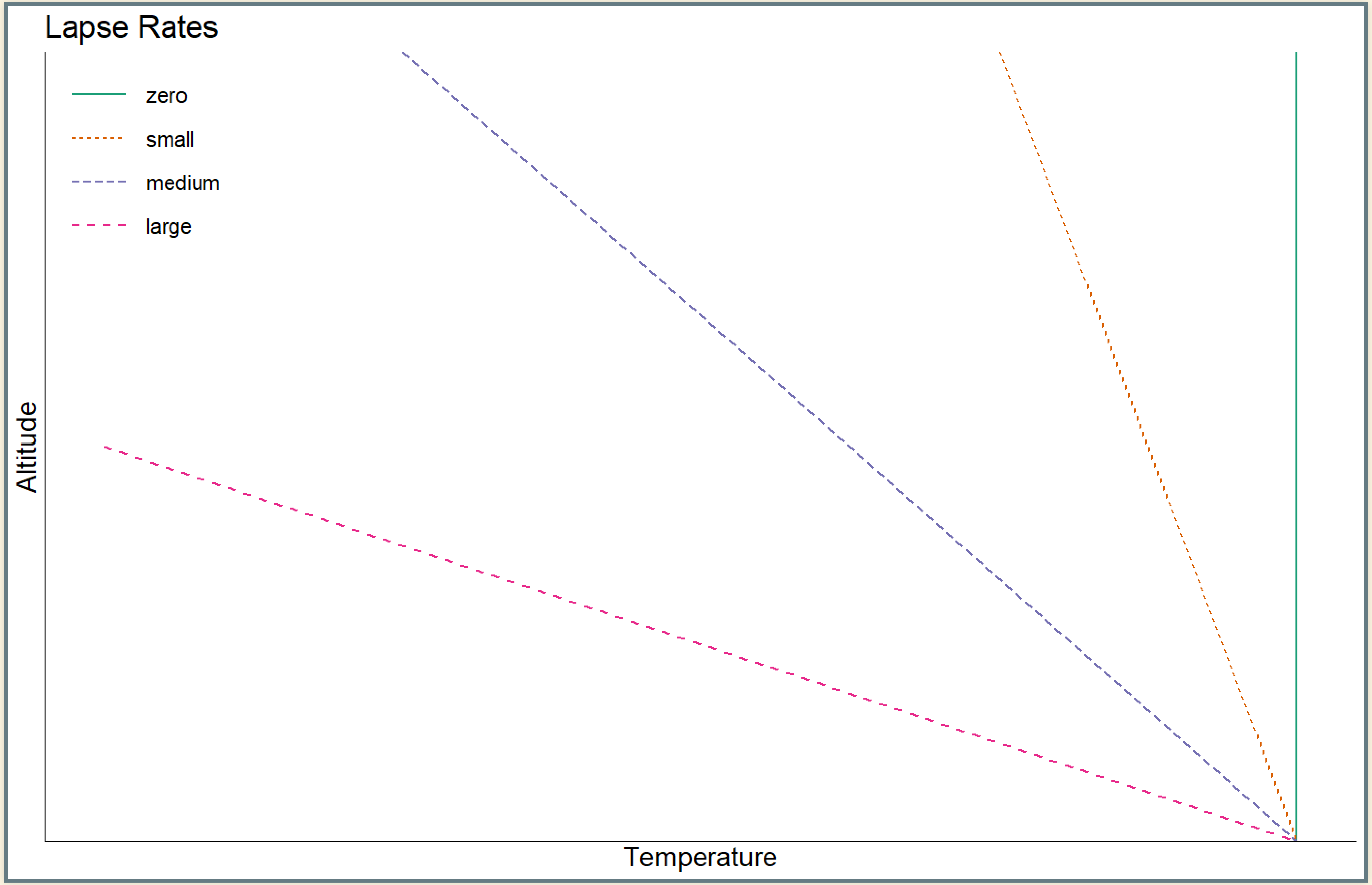
Class #8: Friday, January 24 2020

Lapse Rates

Which lapse rate is greater?



Lapse Rates



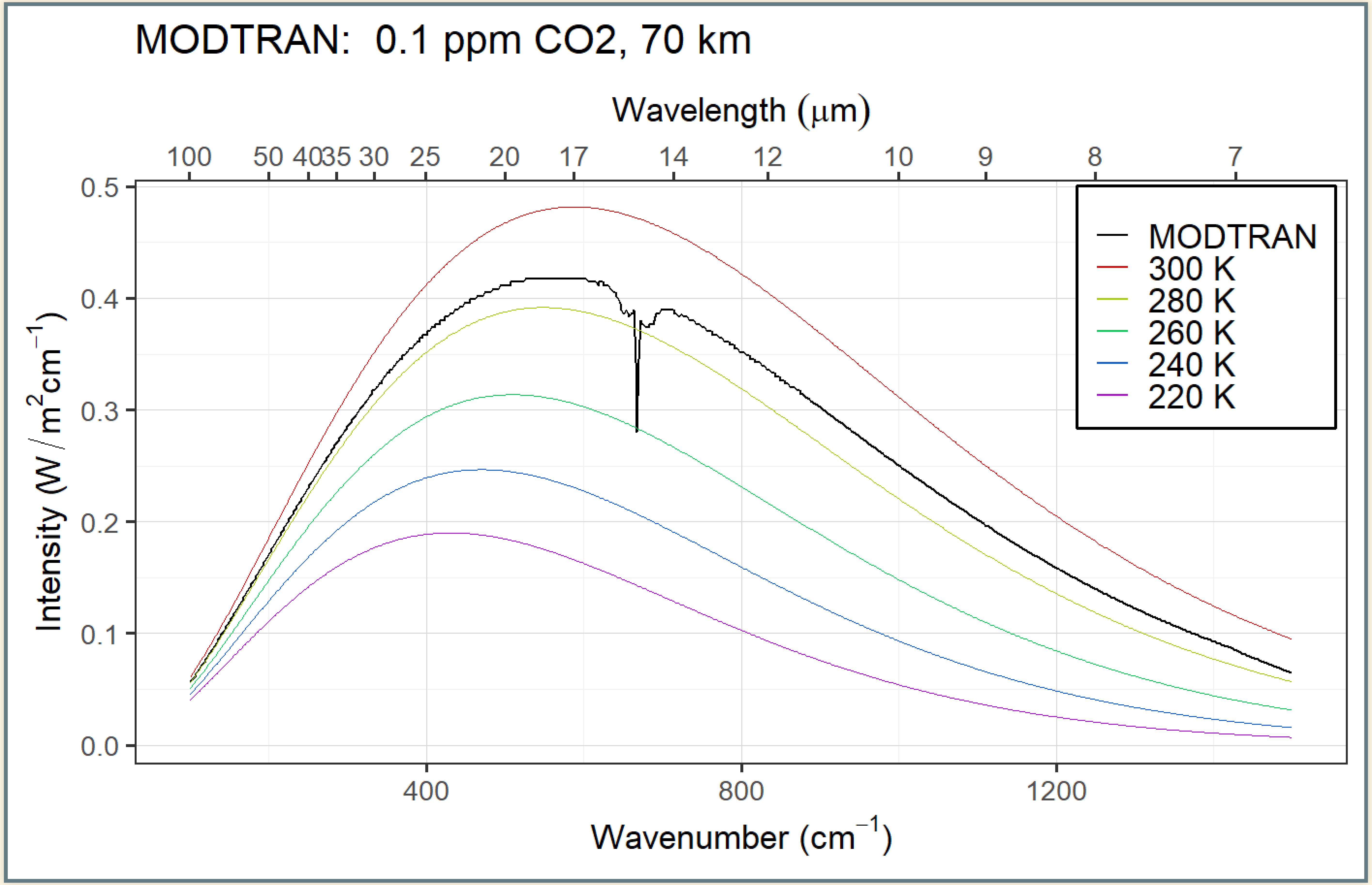
Vertical Structure and Saturation

Set up MODTRAN:

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

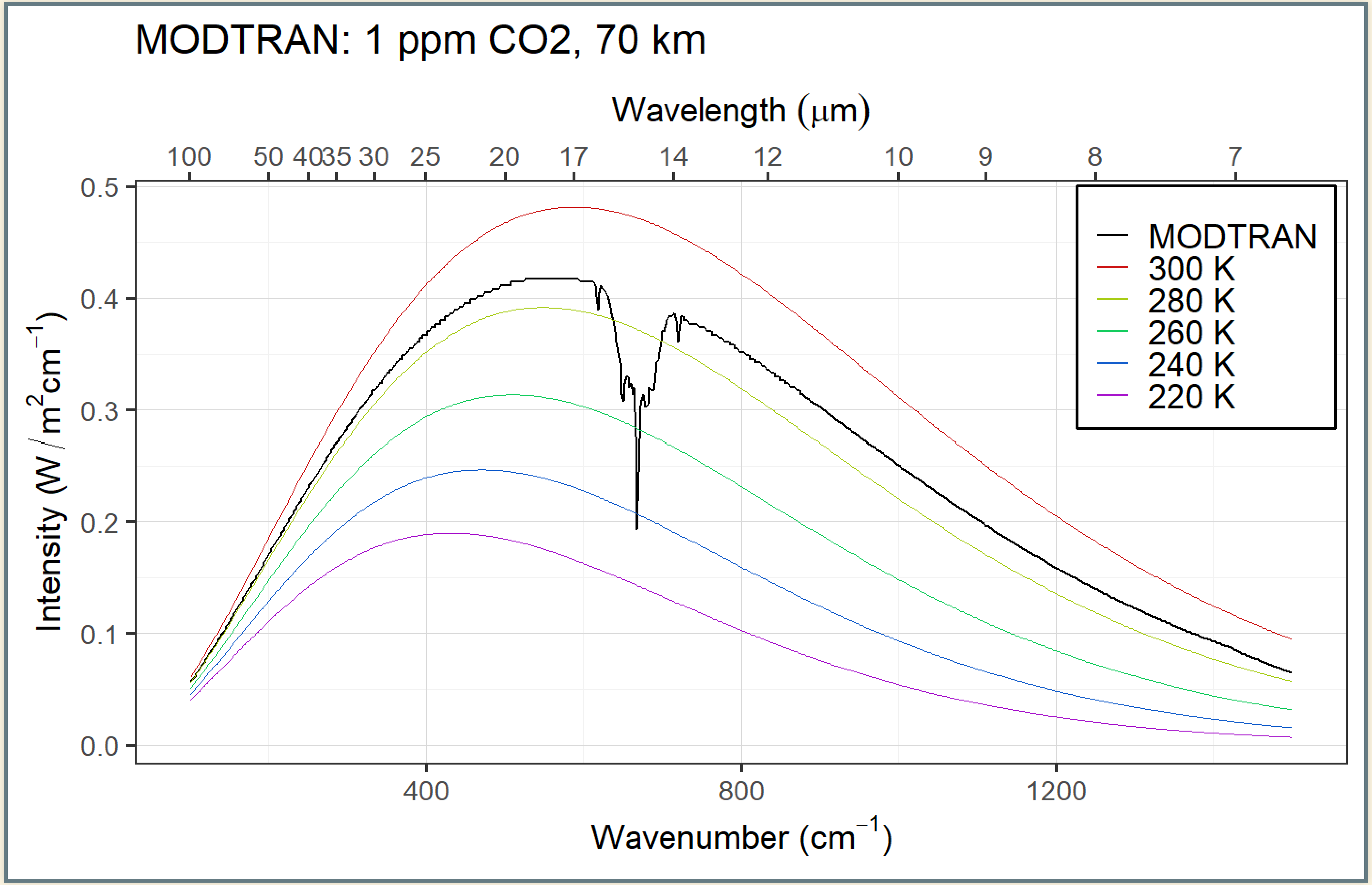
- Set altitude to **70 km** and location to “1976 U.S. Standard Atmosphere”.
- Set CO_2 to 0.1 ppm, all other gases to zero.
- Now increase by factors of 10 (1, 10, 100, 1000, 10000)

0.1 ppm CO_2



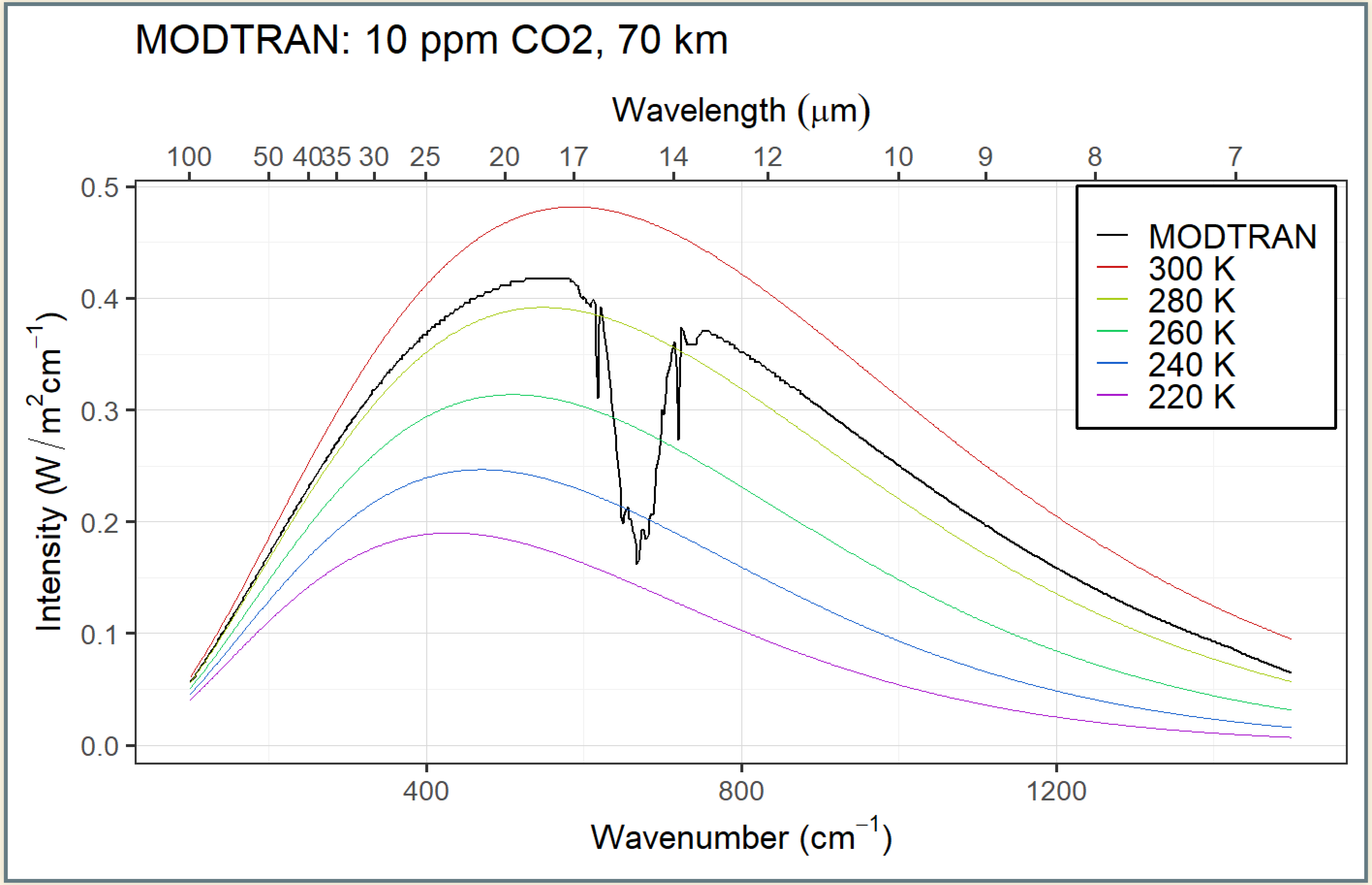
MODTRAN: 0.1 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K
400
800
1200
Wavenumber (cm⁻¹)

1 ppm CO_2



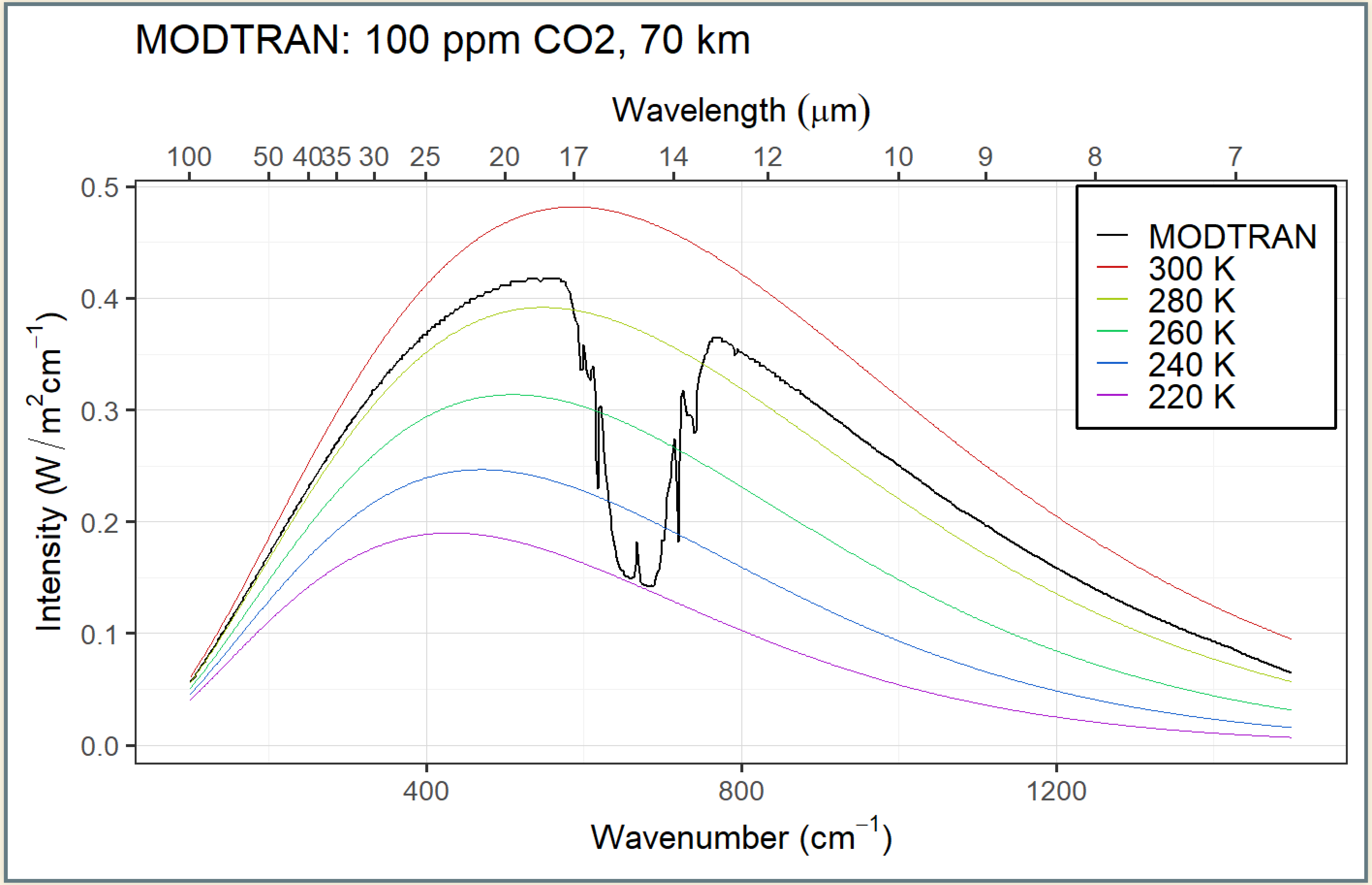
MODTRAN: 1 ppm CO2, 70 km
Wavelength (μm)
100 50 40 35 30 25 20 17 14 12 10 9 8 7
0.5 0.4 0.3 0.2 0.1 0.0
Intensity (W / m²cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K
400 800 1200
Wavenumber (cm⁻¹)

10 ppm CO_2



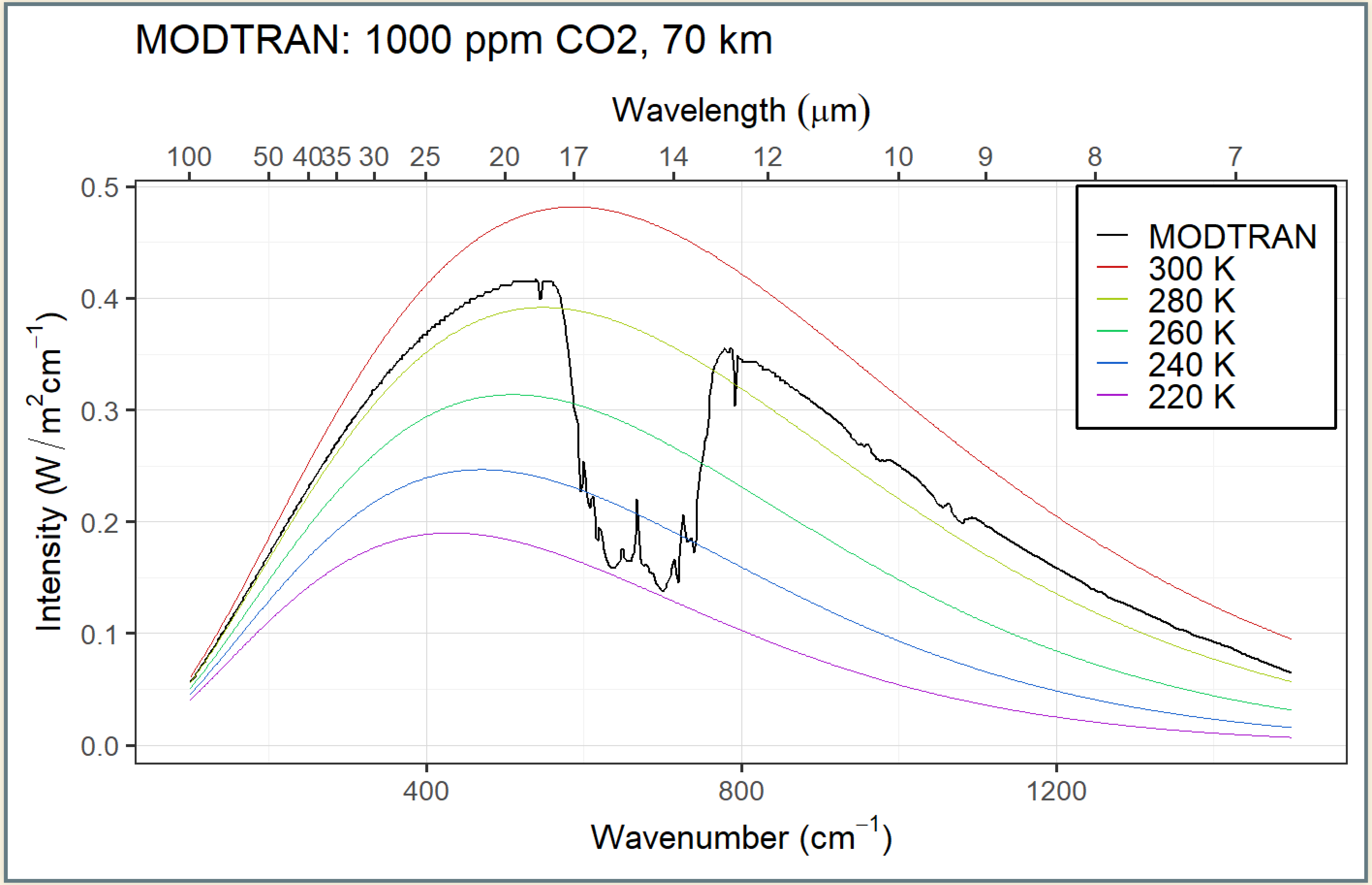
MODTRAN: 10 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

100 ppm CO_2



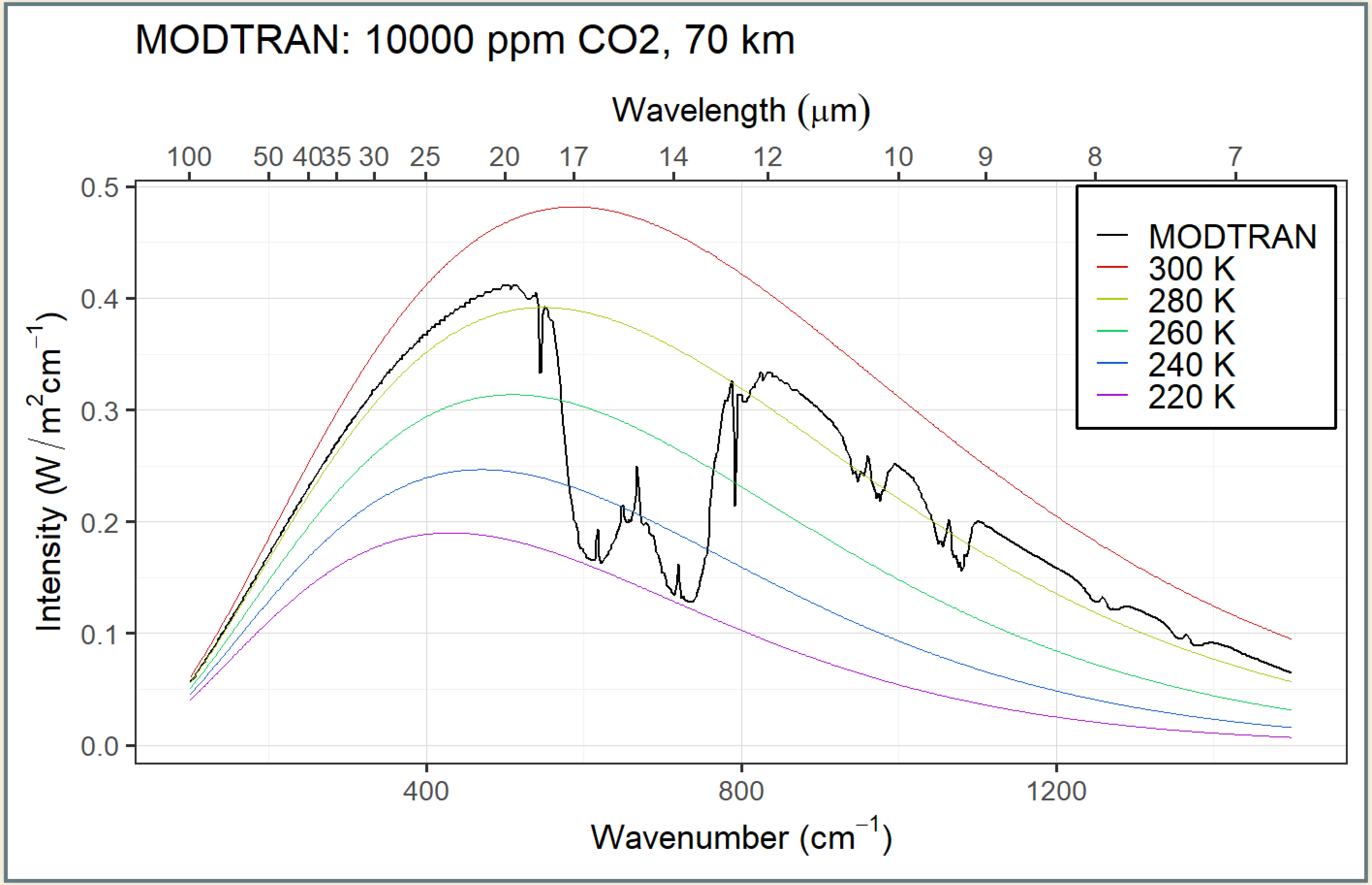
MODTRAN: 100 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
Intensity (W / m²cm⁻¹)
0.5
0.4
0.3
0.2
0.1
0.0
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

1000 ppm CO_2

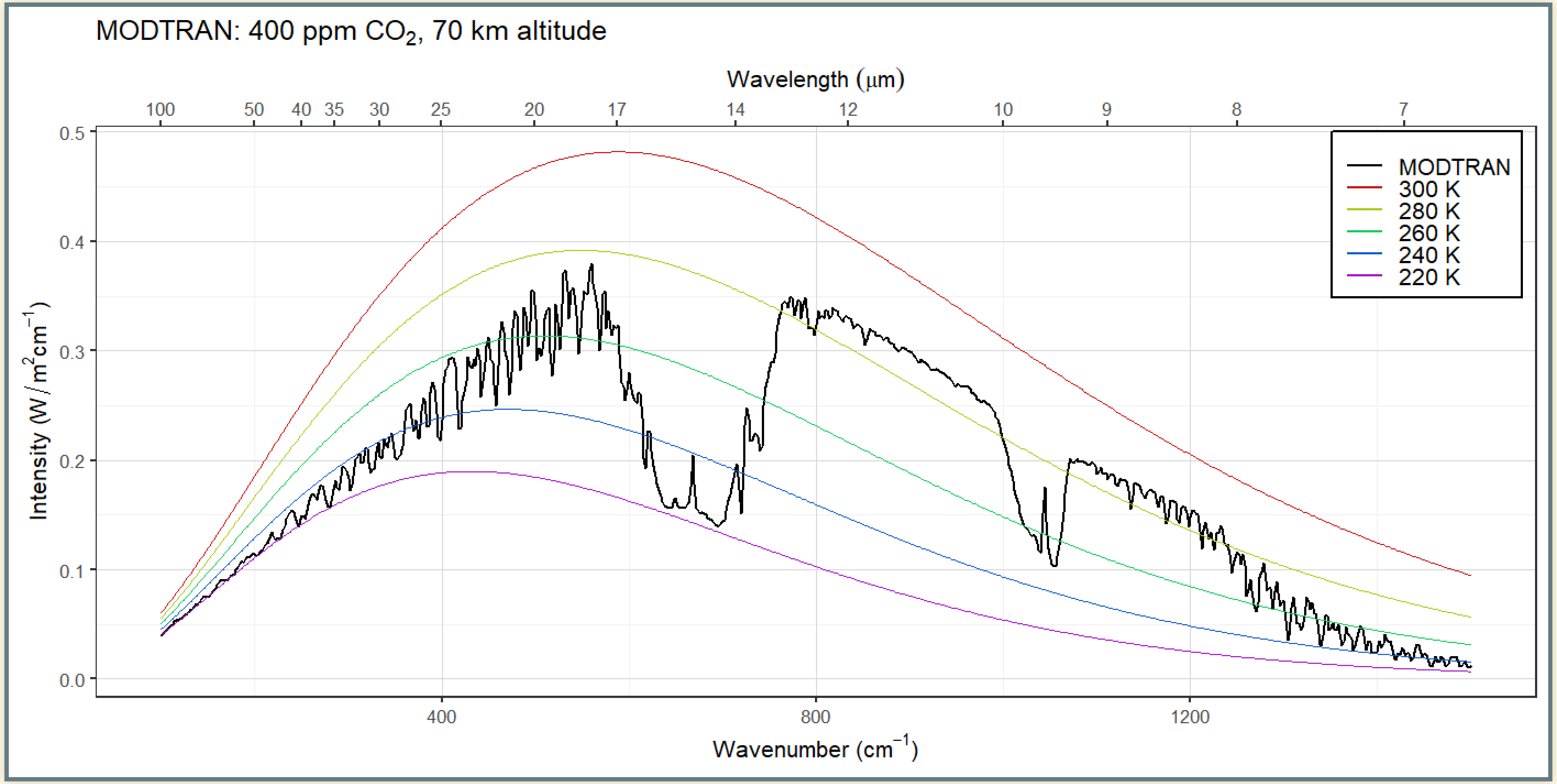


MODTRAN: 1000 ppm CO2, 70 km
Wavelength (μm)
100
50
40
35
30
25
20
17
14
12
10
9
8
7
0.5
0.4
0.3
0.2
0.1
0.0
Intensity (W / m²cm⁻¹)
400
800
1200
Wavenumber (cm⁻¹)
MODTRAN
300 K
280 K
260 K
240 K
220 K

10,000 ppm CO_2

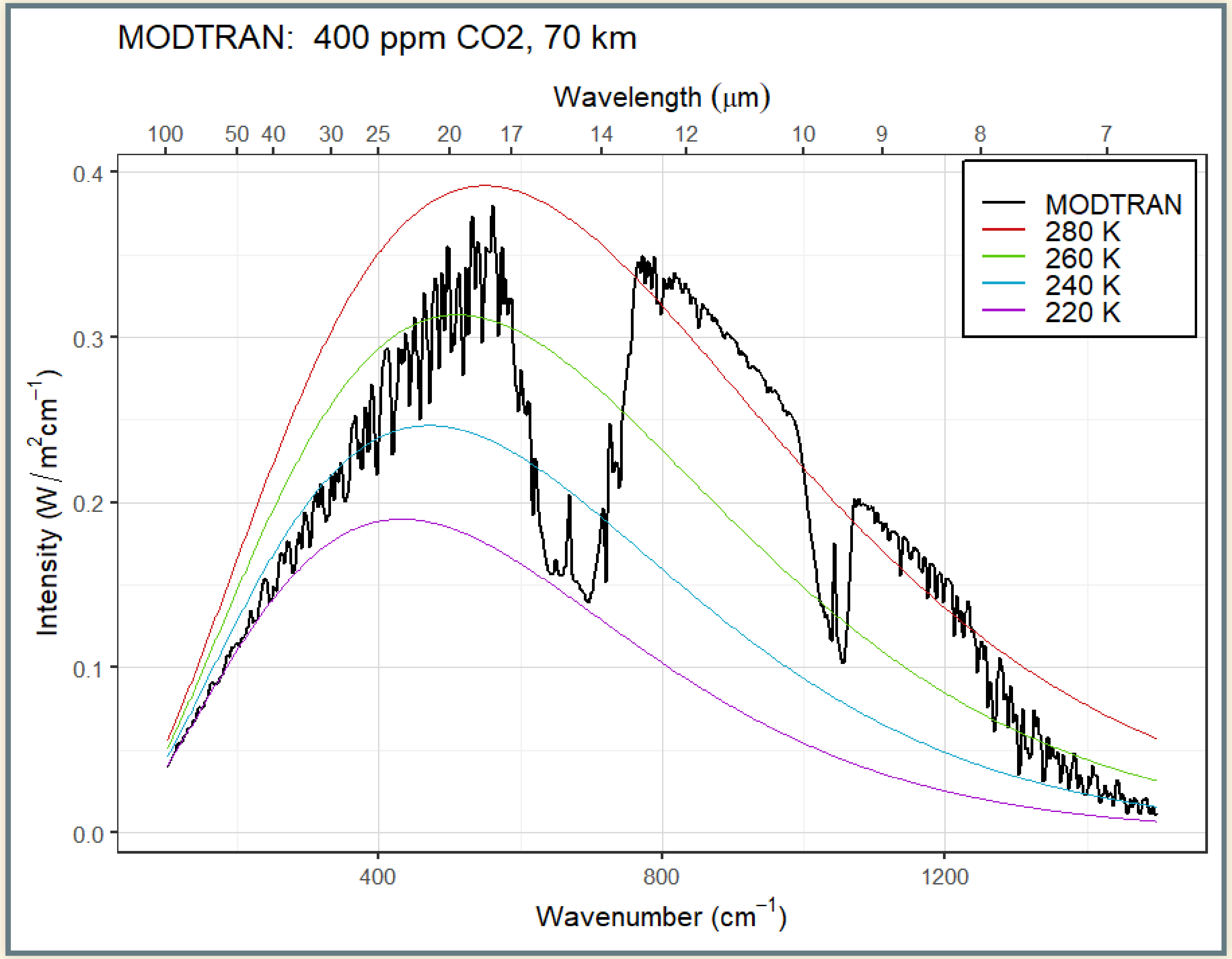


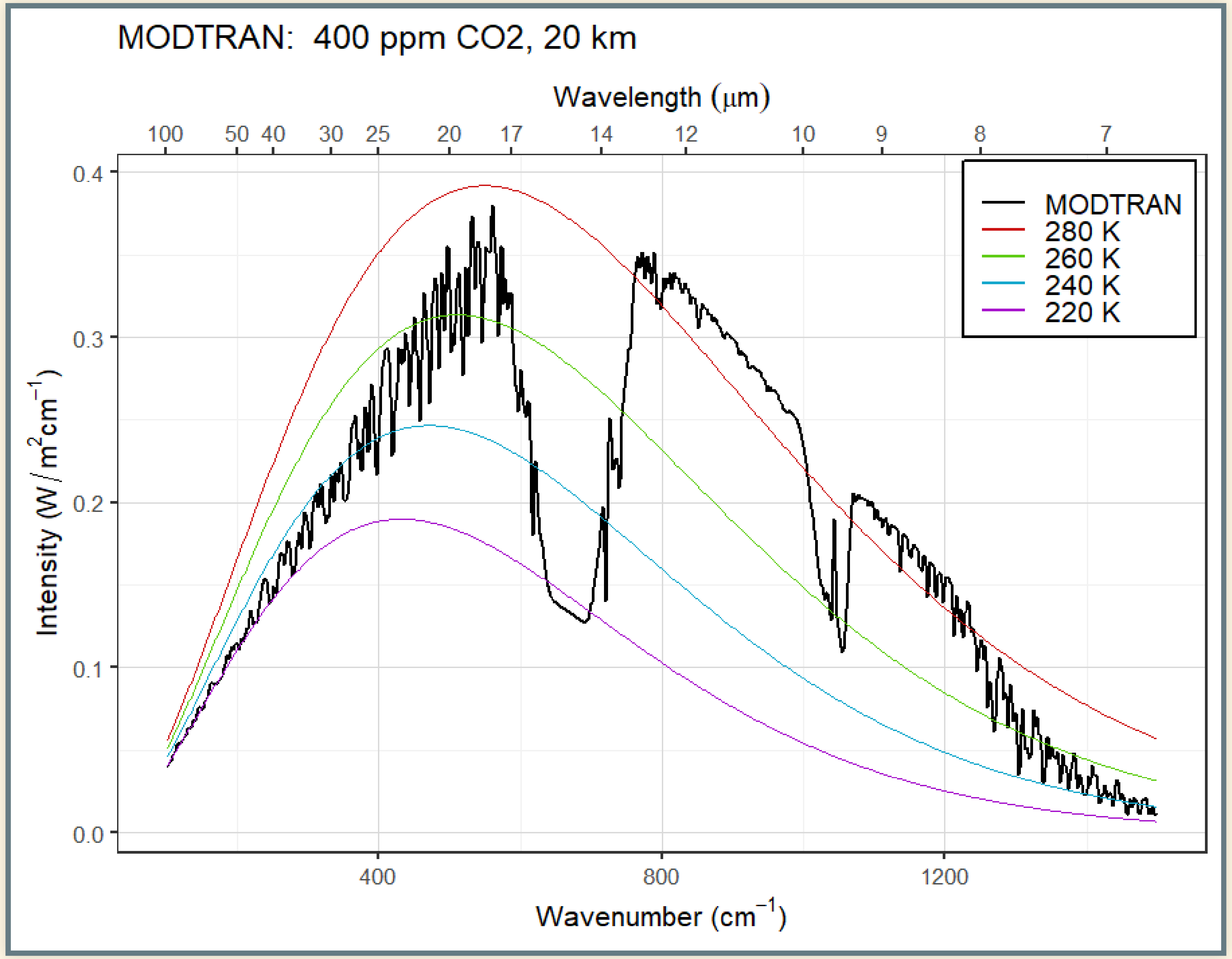
Question



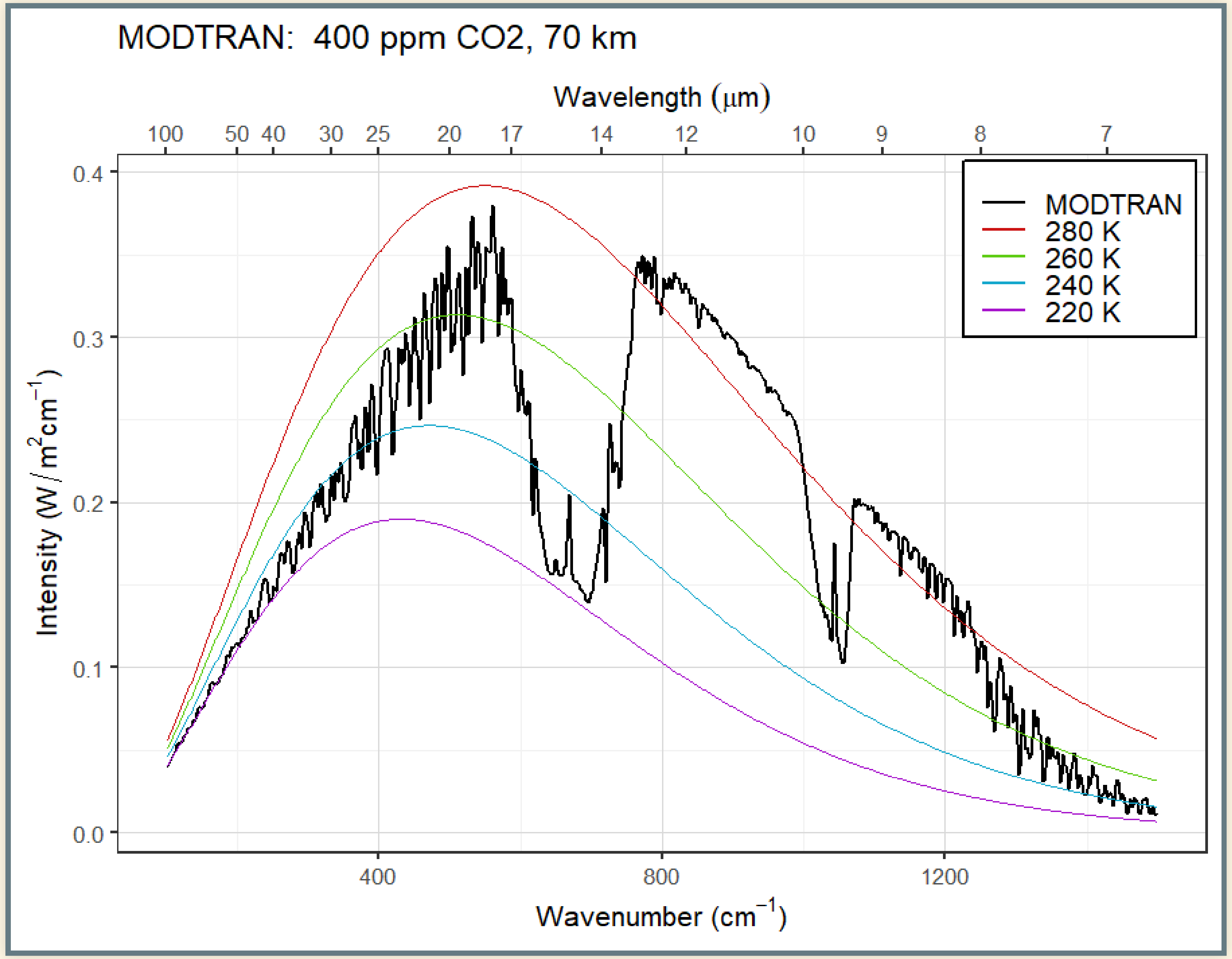
- Why do we see the spike in the middle of the CO_2 absorption feature?

Answer

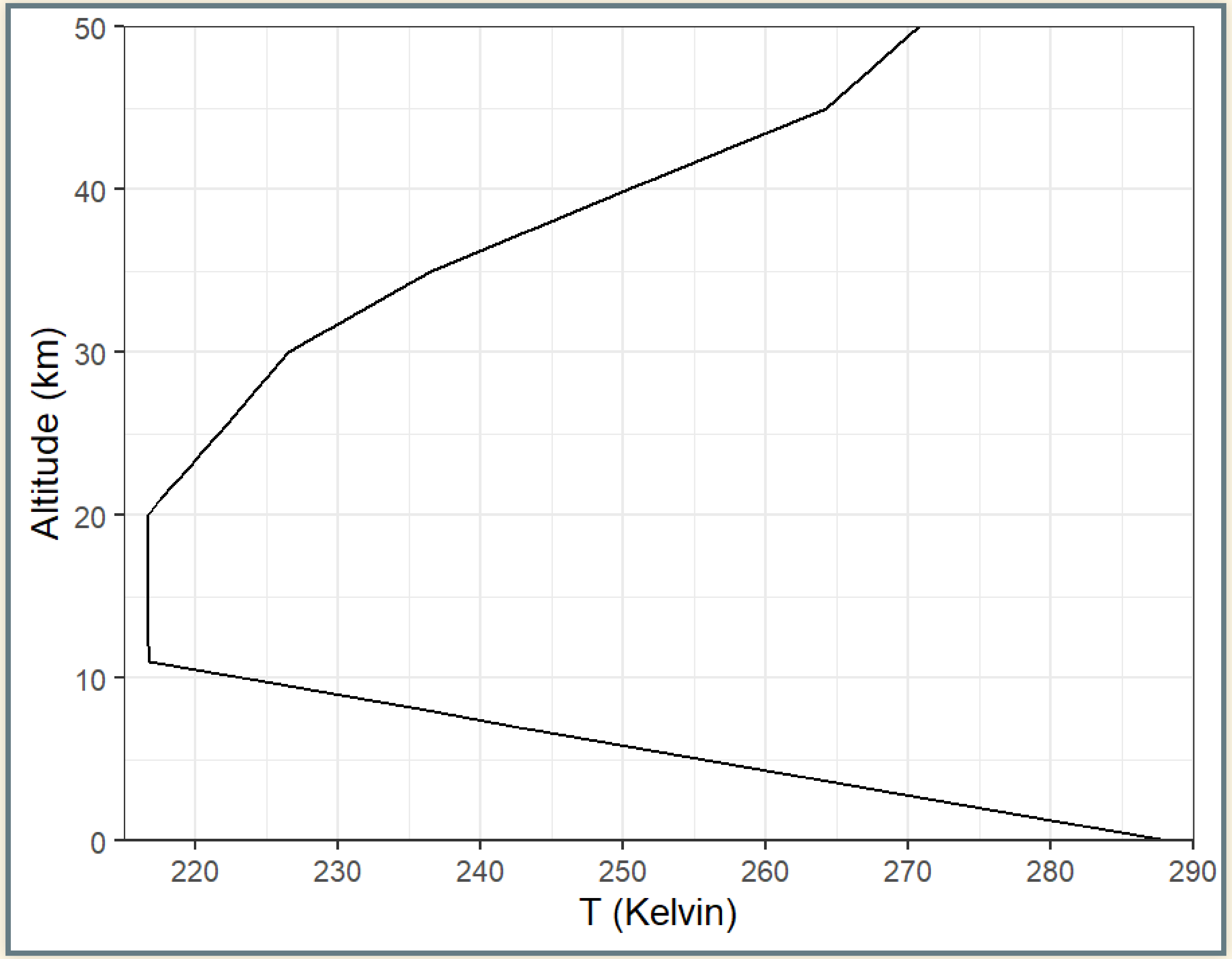

MODTRAN: 400 ppm CO2, 70 km
Wavelength (μm)
100 50 40 30 25 20 17 14 12 10 9 8 7
Intensity (W / m2cm-1)
0.0 0.1 0.2 0.3 0.4
400 800 1200
Wavenumber (cm-1)
MODTRAN
280 K
260 K
240 K
220 K


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

Answer

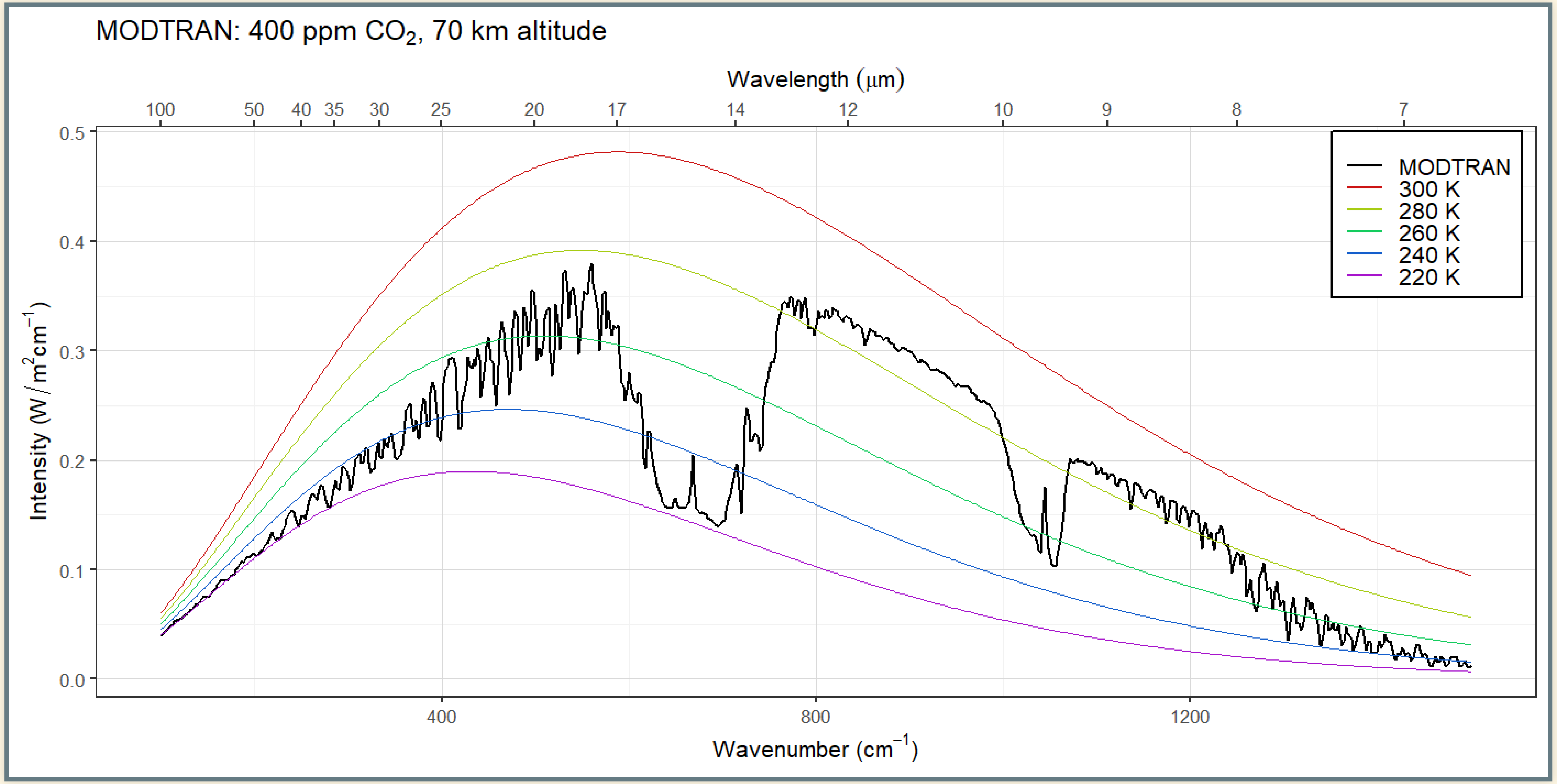


MODTRAN: 400 ppm CO2, 70 km
Wavelength (μm)
100 50 40 30 25 20 17 14 12 10 9 8 7
Intensity (W / m2cm-1)
0.4 0.3 0.2 0.1 0.0
MODTRAN
280 K
260 K
240 K
220 K
400 800 1200
Wavenumber (cm-1)



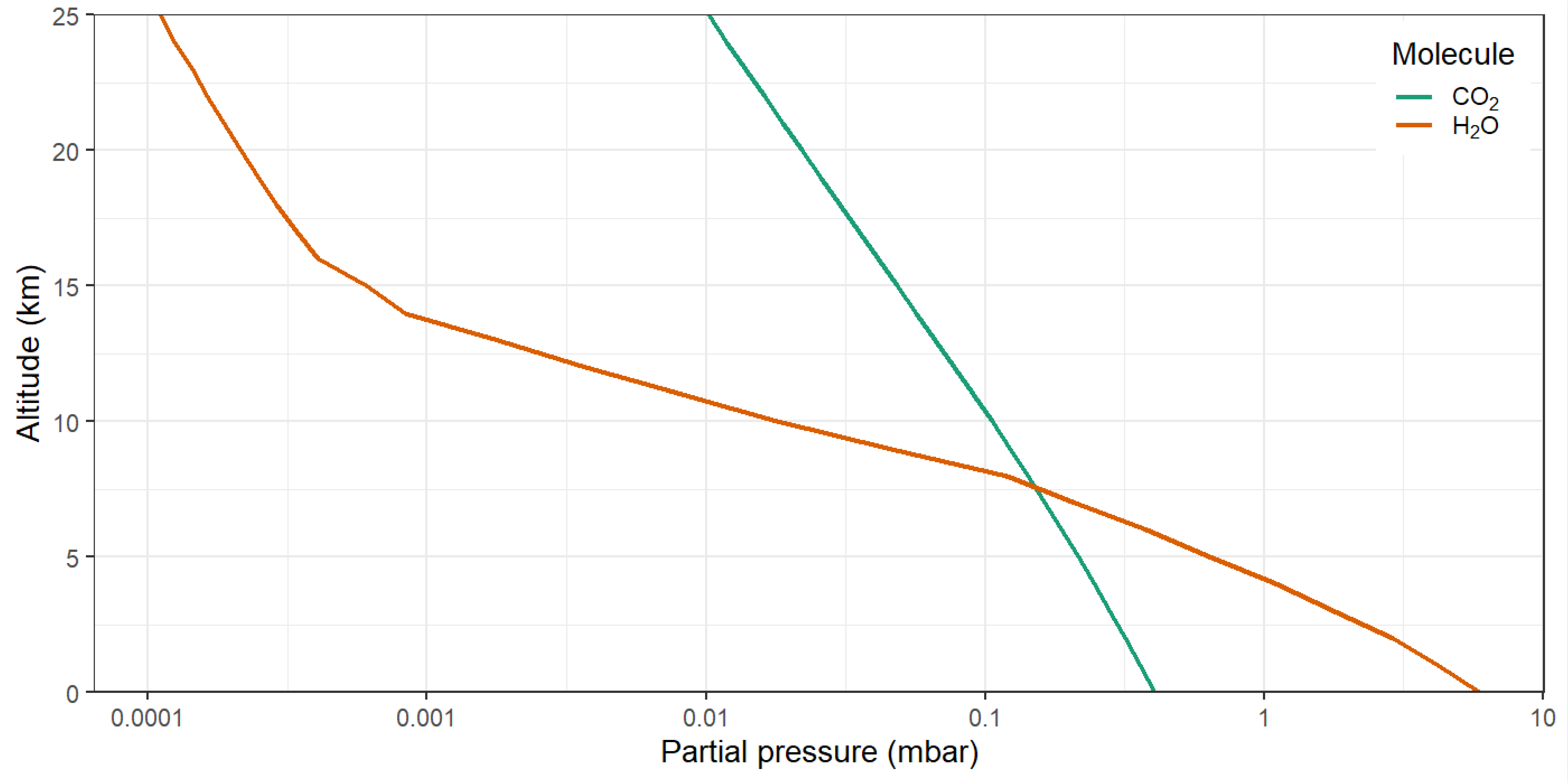
Altitude (km)
50 40 30 20 10 0
220 230 240 250 260 270 280 290
T (Kelvin)

Question



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

Answer



- Near the ground, there is much more water vapor (10 times more)
- Above about 7 km, there is much more CO_2 (100 times more at 20 km)
  - Water vapor concentrations become small enough to be transparent to space at a much lower altitude than CO_2

Review Perspective

Review Perspective

1. **Start with bare-rock temperature**
   - This becomes skin temperature
2. **Add simple atmosphere:**
   - Completely absorbs longwave radiation
   - Top of atmosphere: skin temperature (same as bare-rock)
   - Atmosphere insulates surface $\Rightarrow$ surface heats up
   - More layers $\Rightarrow$ bigger greenhouse effect
3. **Realistic longwave absorption:**
   - Atmosphere is not a black body
4. **Radiative-Convective equilibrium:**
   - Pure radiative equilibrium would have *huge* lapse
   - Big lapse is unstable $\Rightarrow$ convection
     - Convection mixes hot & cold air $\Rightarrow$ modifies environmental lapse
     - Reduces greenhouse effect

Feedback

Feedback

- Q is net heat flow into the earth:
  - $Q = I_{\text{in}} - I_{\text{out}}$,
- **At Start:** $Q = I_{\text{in}} - I_{\text{out}} = 0$,
  - $T_{\text{ground}} = T_0$.
- **Forcing:** change $Q \to Q_{\text{forcing}} > 0$
  - What happens?
- **Response:** $T_{\text{ground}} \to T_0 + \Delta T$
  - **Normally**, ΔT brings I_{out} back to balance with I_{in}.
  - **With feedback**, ΔT causes a new forcing, $\Delta Q_{\text{feedback}} = f \Delta T$
  - $\Delta Q_{\text{feedback}}$ causes further change in T_{ground}.

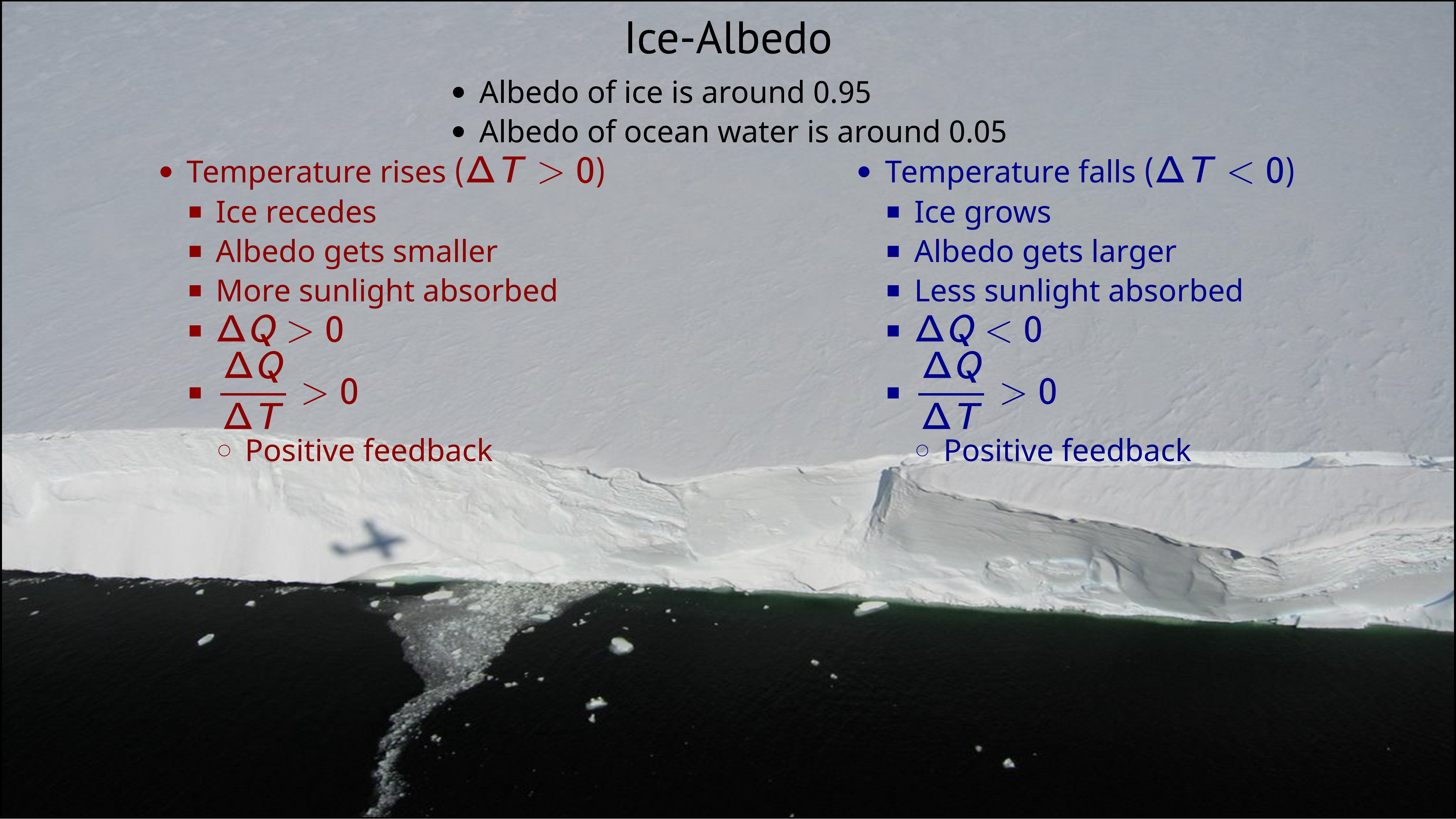
Examples of feedbacks

Ice-Albedo

- Albedo of ice is around 0.95
- Albedo of ocean water is around 0.05

- Temperature rises ($\Delta T > 0$)
  - Ice recedes
  - Albedo gets smaller
  - More sunlight absorbed
  - $\Delta Q > 0$
  - $\dfrac{\Delta Q}{\Delta T} > 0$
    - Positive feedback

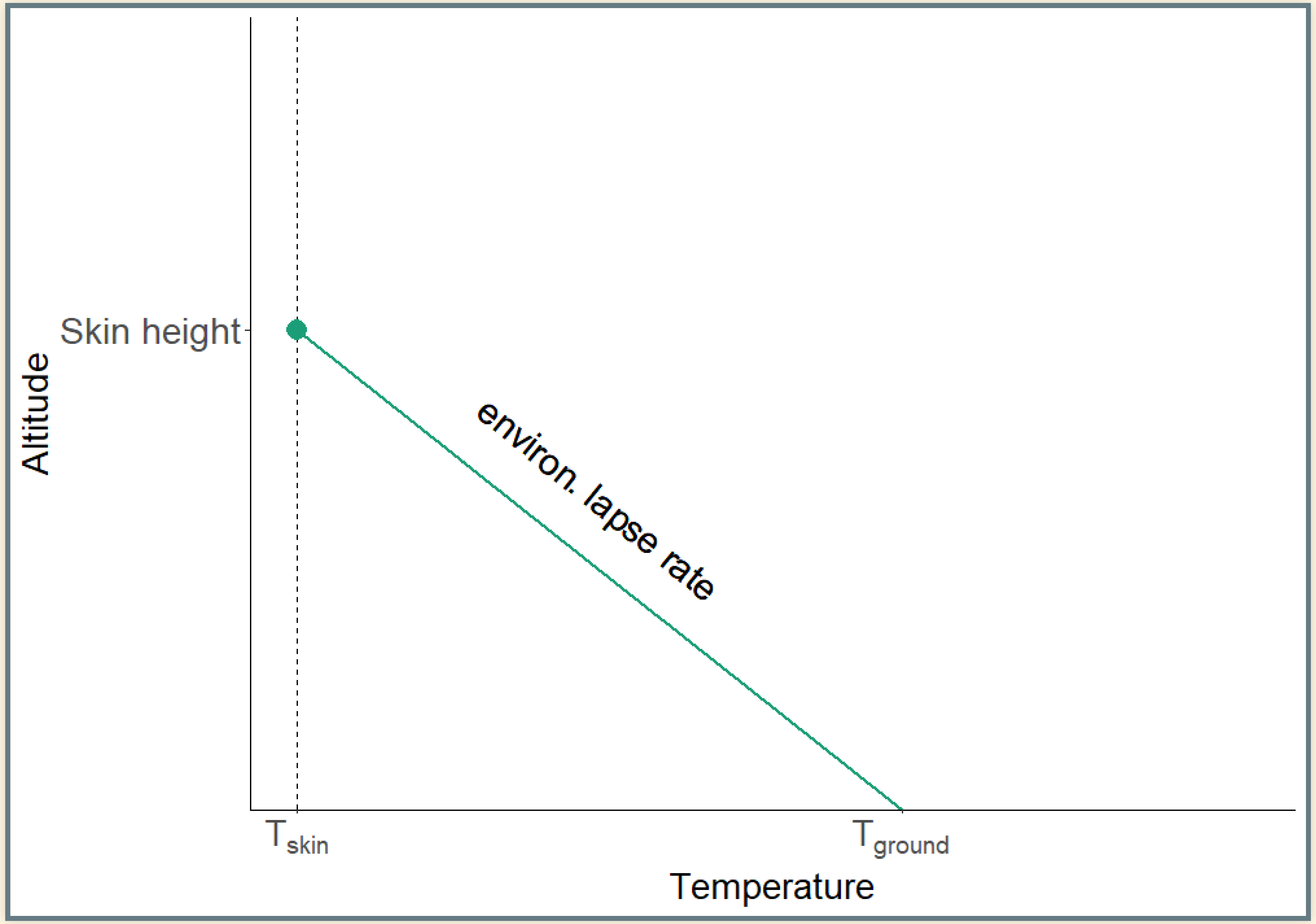
- Temperature falls ($\Delta T < 0$)
  - Ice grows
  - Albedo gets larger
  - Less sunlight absorbed
  - $\Delta Q < 0$
  - $\dfrac{\Delta Q}{\Delta T} > 0$
    - Positive feedback



Water-vapor

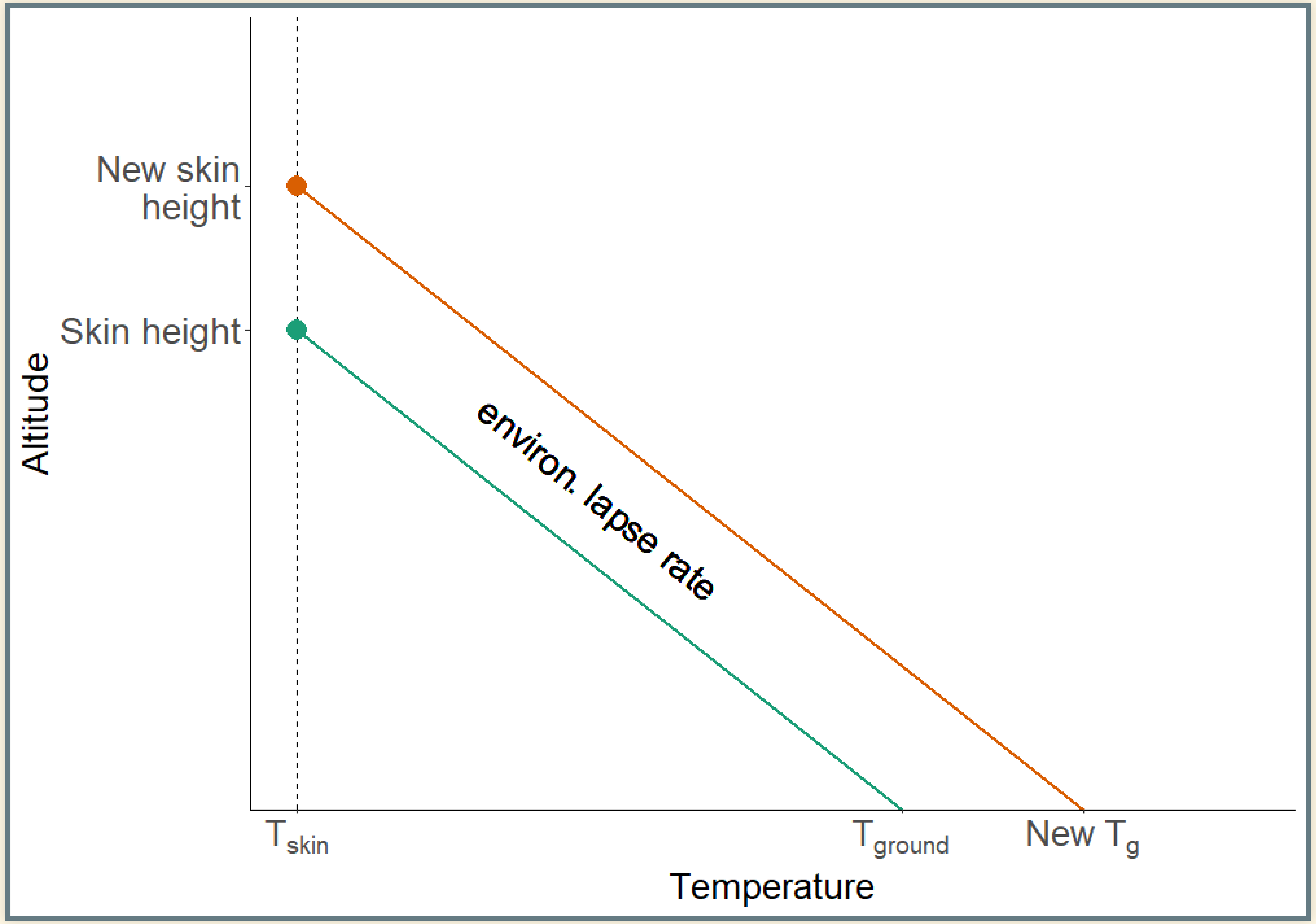
- Temperature rises
- What happens to humidity?
  - Humidity rises: more water vapor
- How does this affect ΔQ?
  - More water vapor $\rightarrow$ bigger greenhouse effect
  - I_{out} gets smaller
  - $\Delta Q = \Delta(I_{\text{in}} - I_{\text{out}}) > 0$
  - Positive $\Delta T \rightarrow \text{Positive } \Delta Q$
    - $f = \Delta Q / \Delta T > 0$: positive feedback

Greenhouse effect



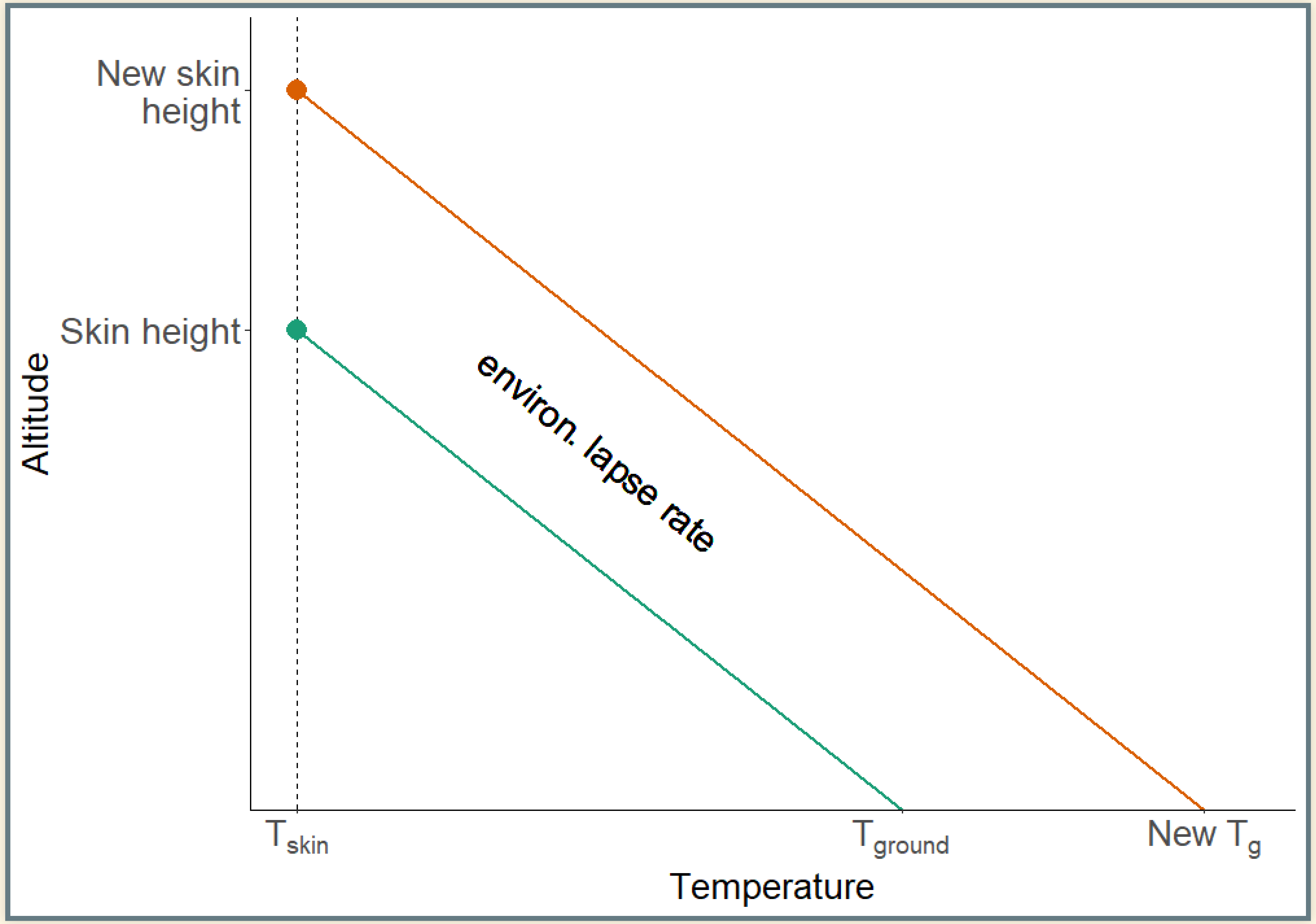
- Ground temp: $T_{\text{ground}} = T_{\text{skin}} + h_{\text{skin}} \times \text{env. lapse}$

Global warming



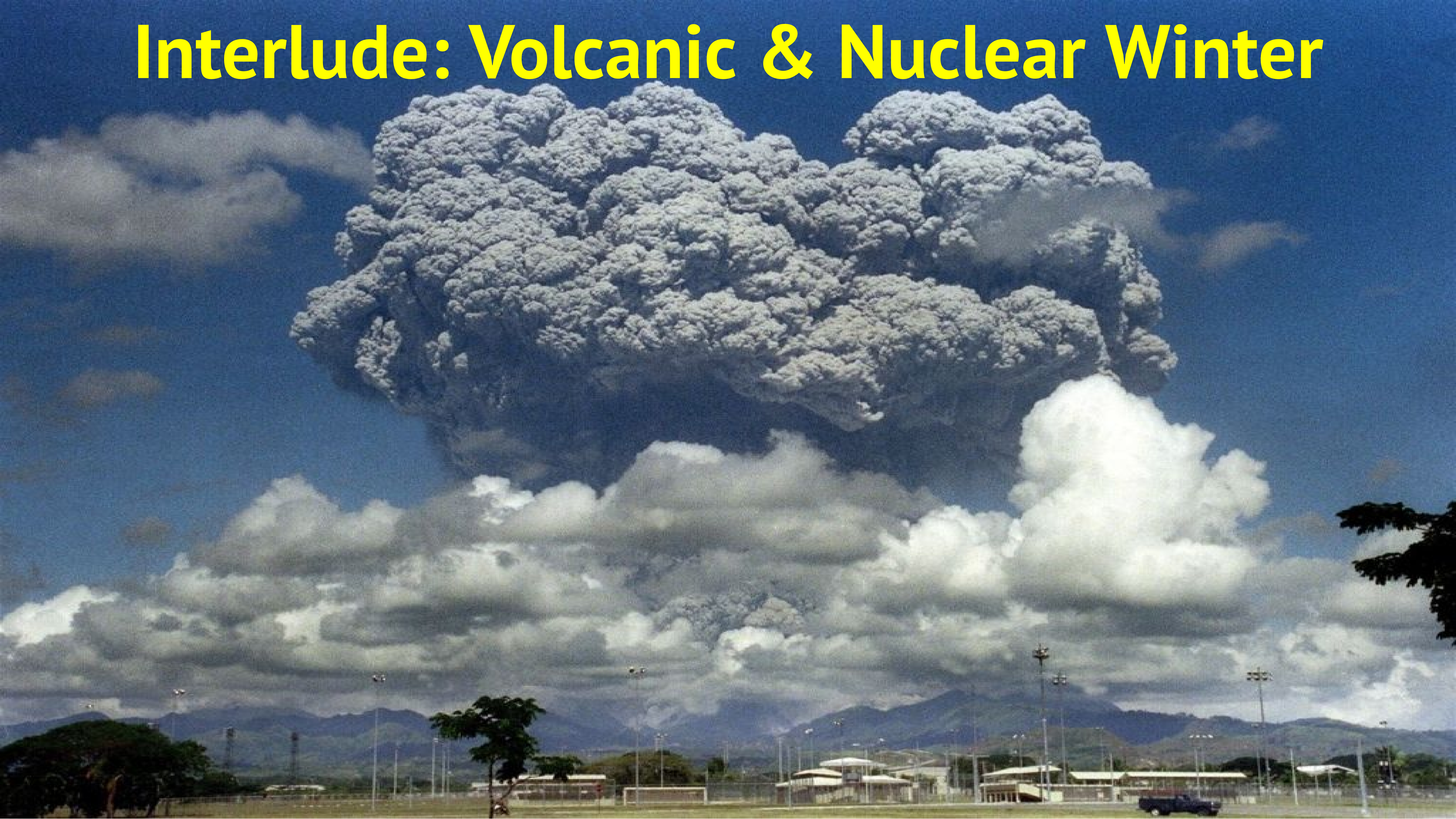
- Greater $CO_2 \longrightarrow$ greater skin height.
- Warming: $\Delta T_{\text{ground}} = \Delta h_{\text{skin}} \times$ env. lapse
- What does rising temperature do to water vapor?

Water Vapor Feedback

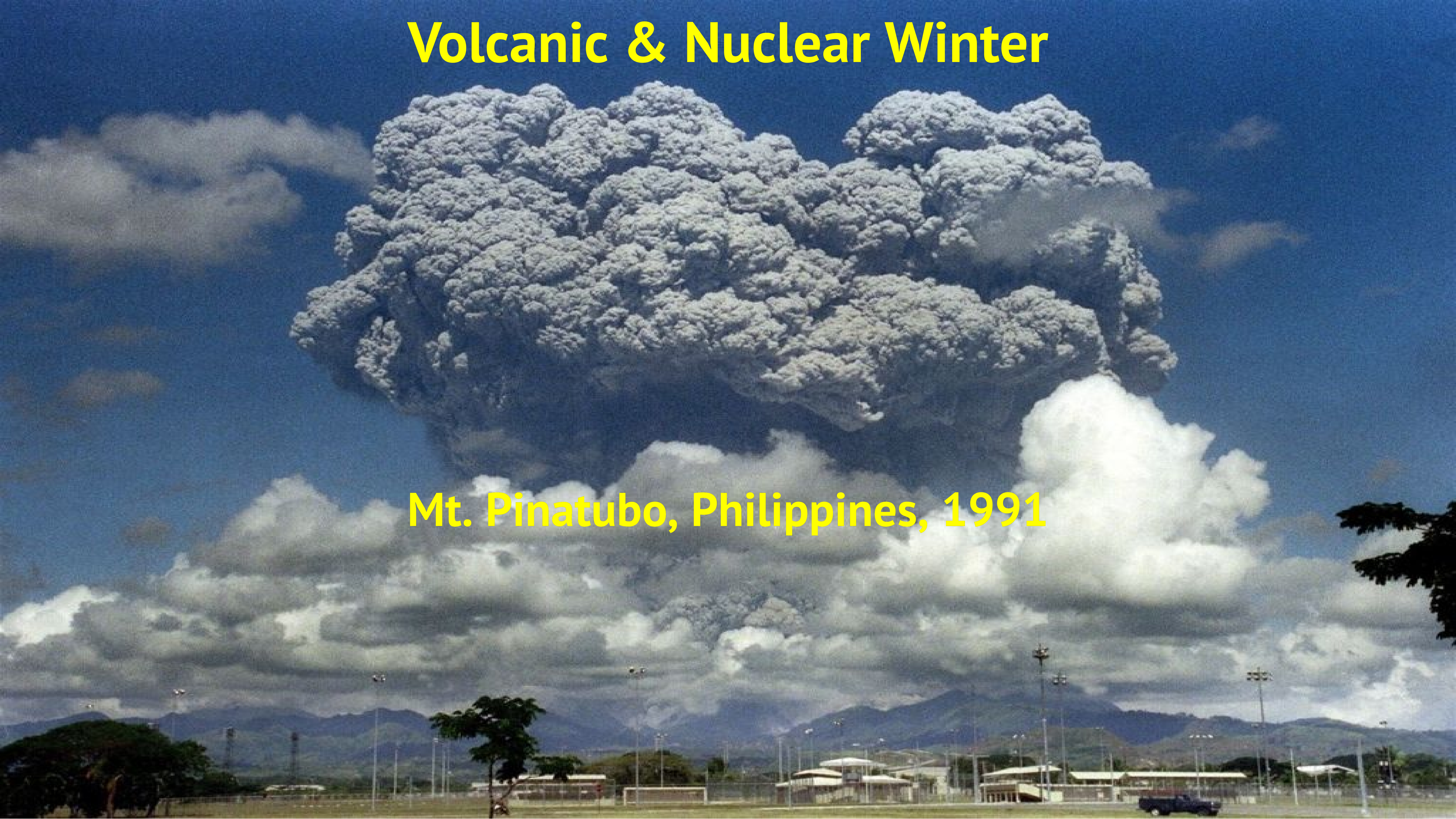


- Rising temperature $\longrightarrow$ greater humidity
- Greater humidity $\longrightarrow$ skin height rises even higher
- $\Delta T_{\text{ground}} = \Delta h_{\text{skin}} \times \text{Lapse}$

Interlude: Volcanic & Nuclear Winter

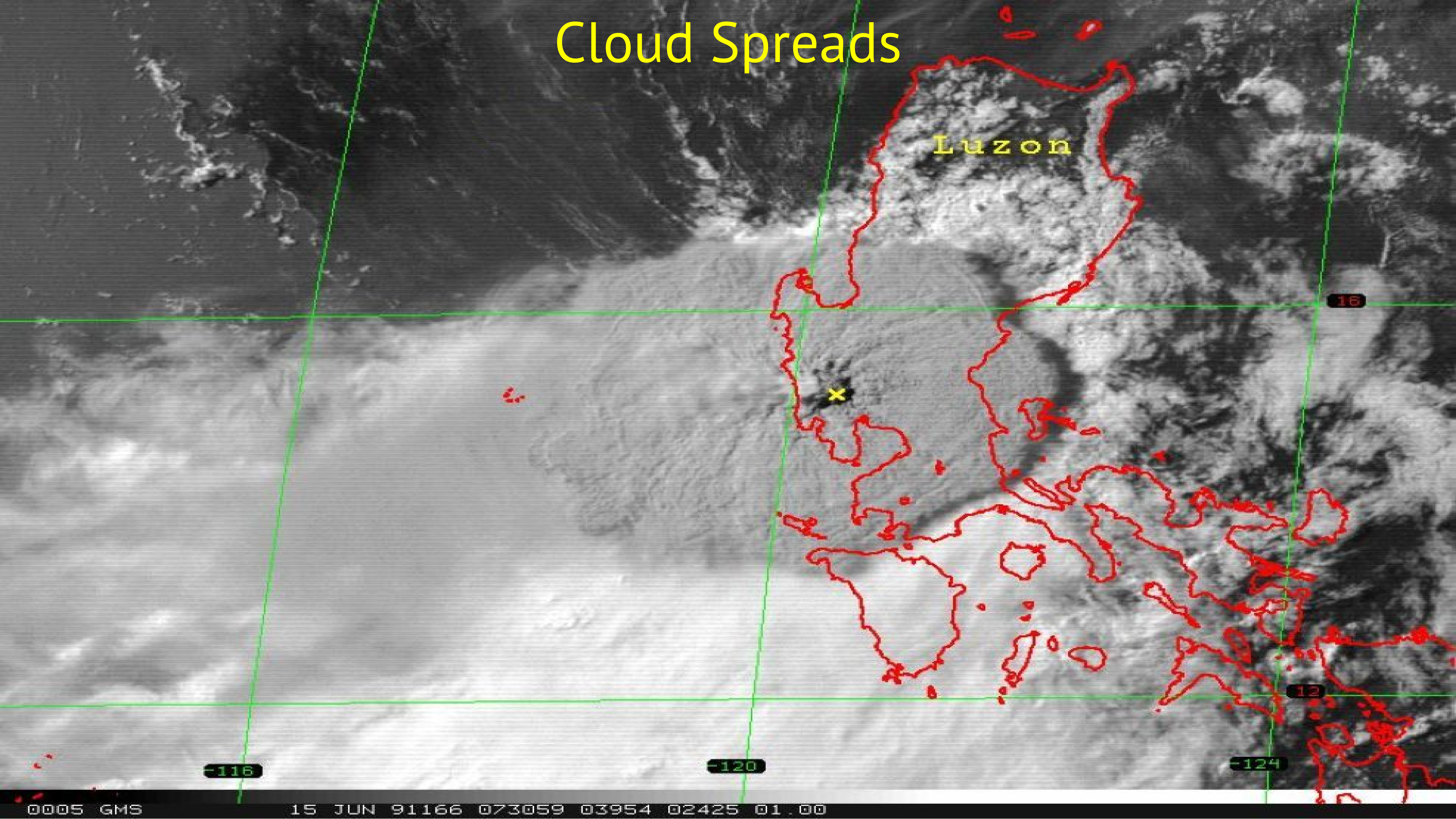


Volcanic & Nuclear Winter

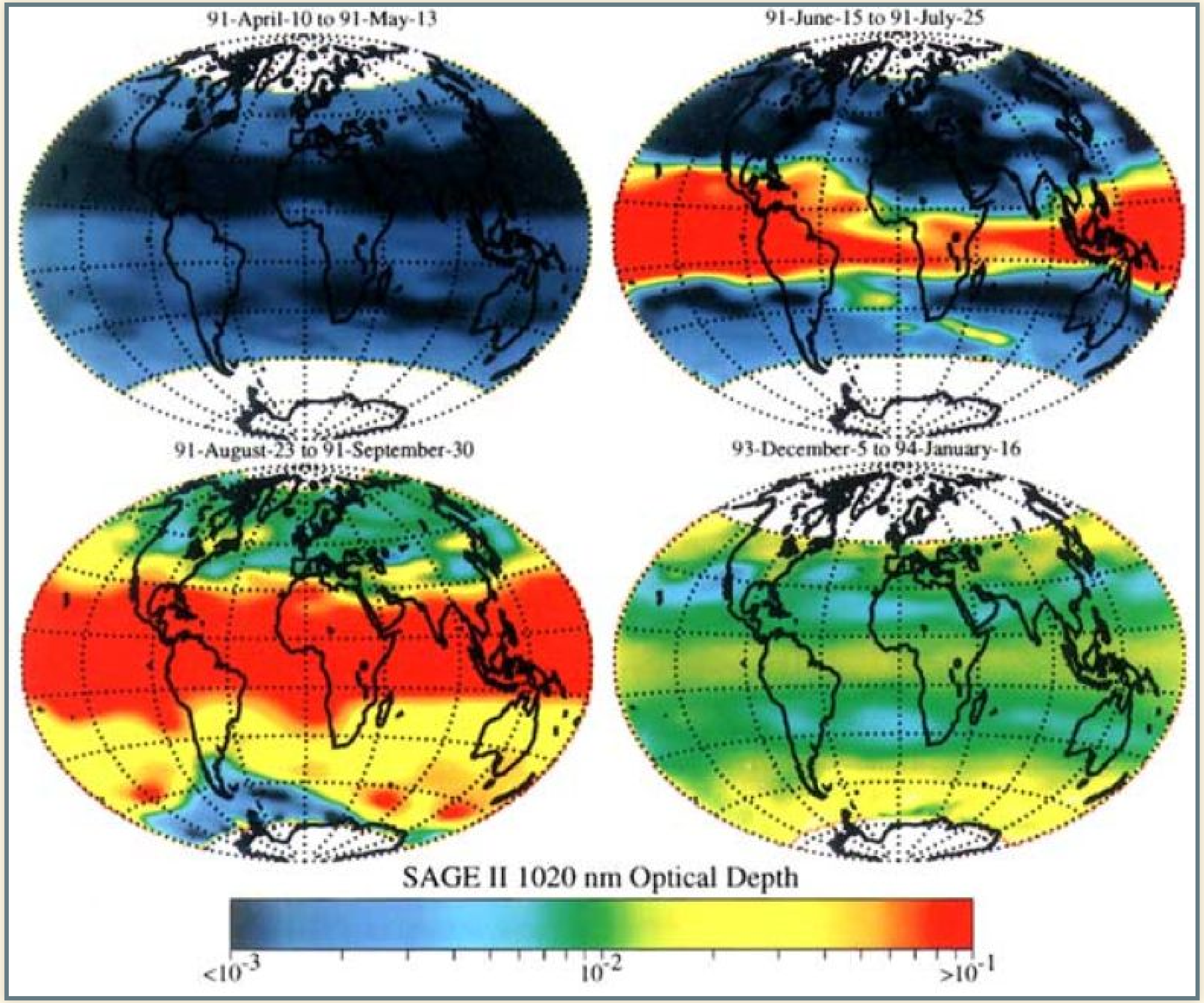


Mt. Pinatubo, Philippines, 1991

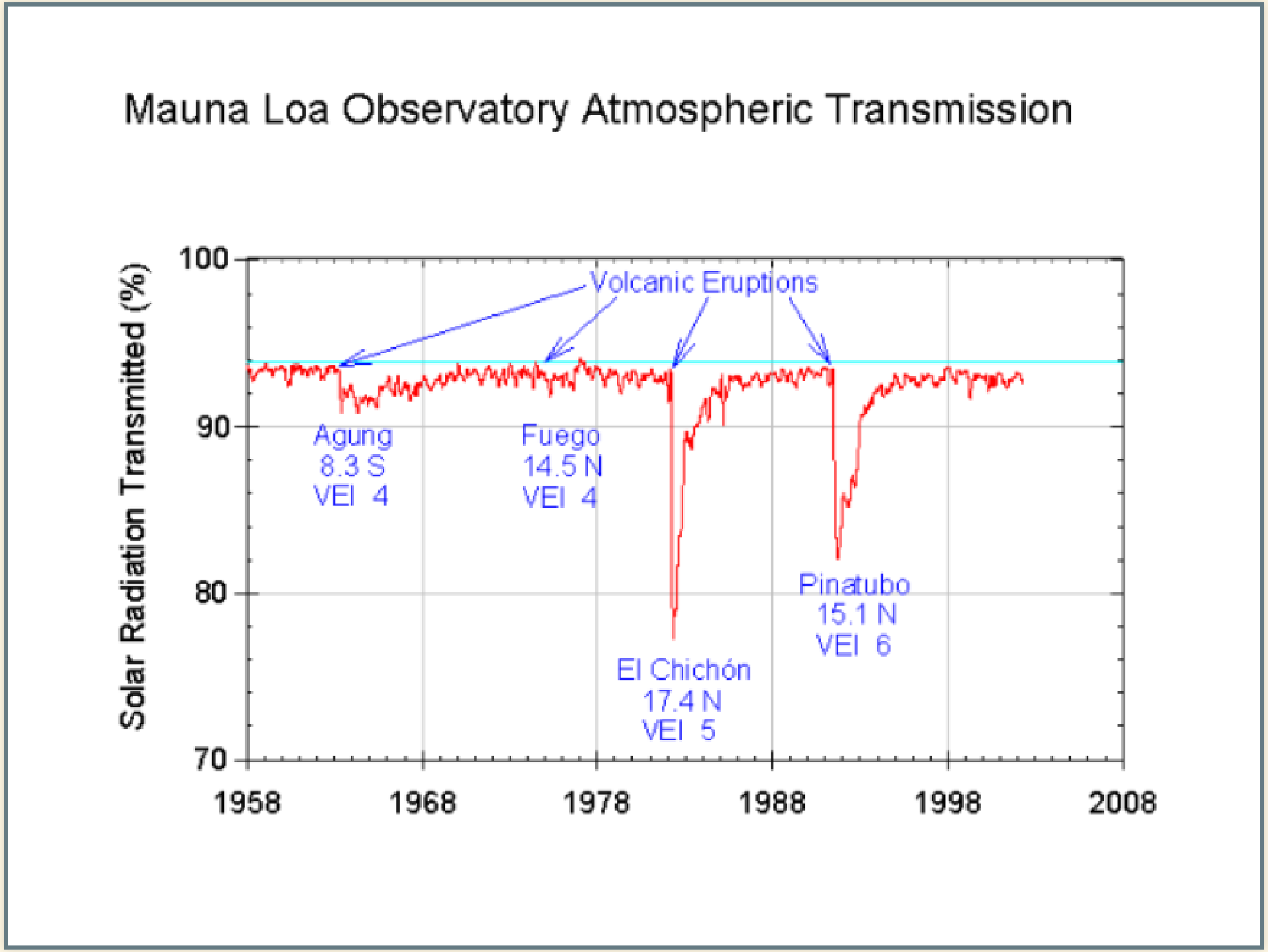
Cloud Spreads



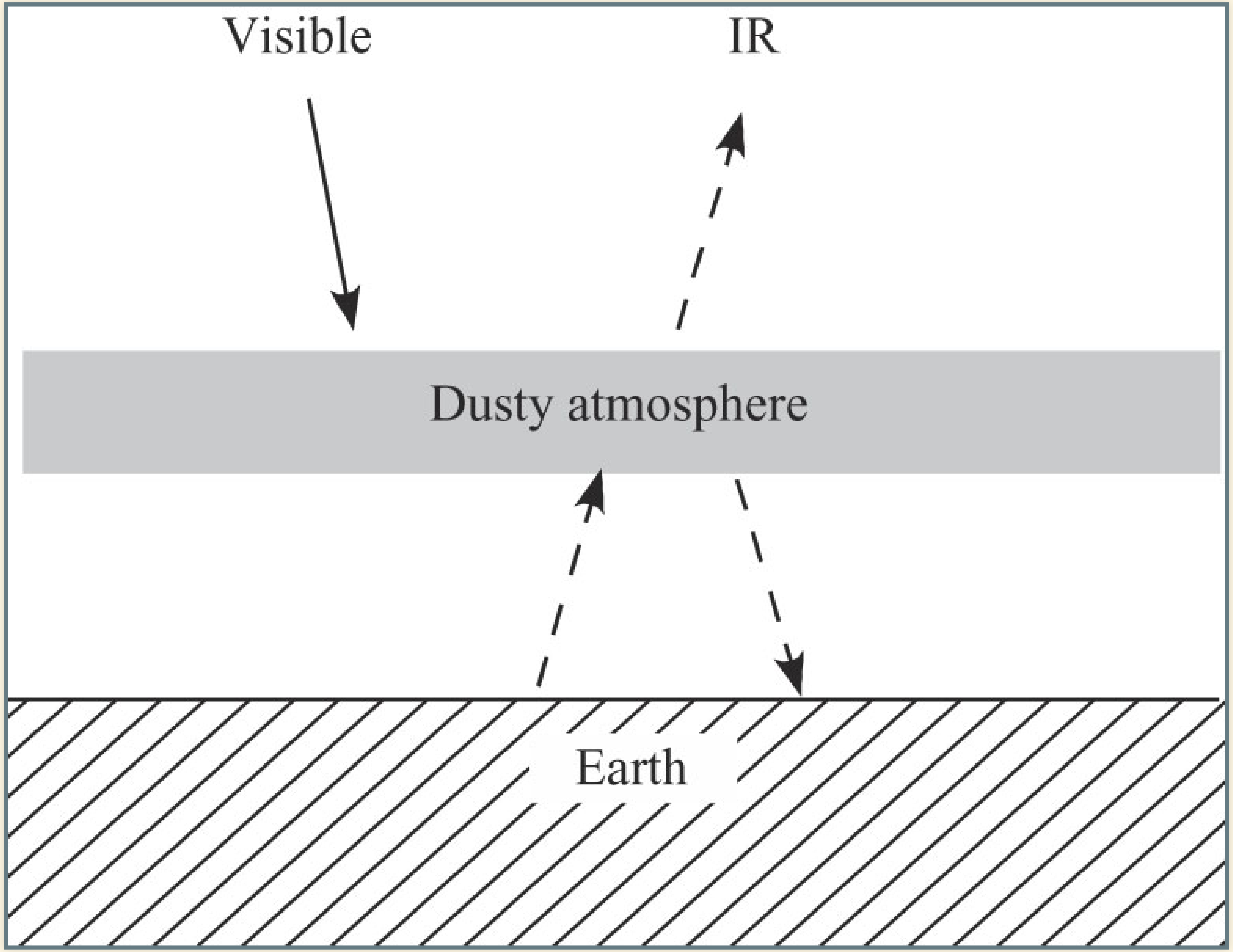
Around the planet



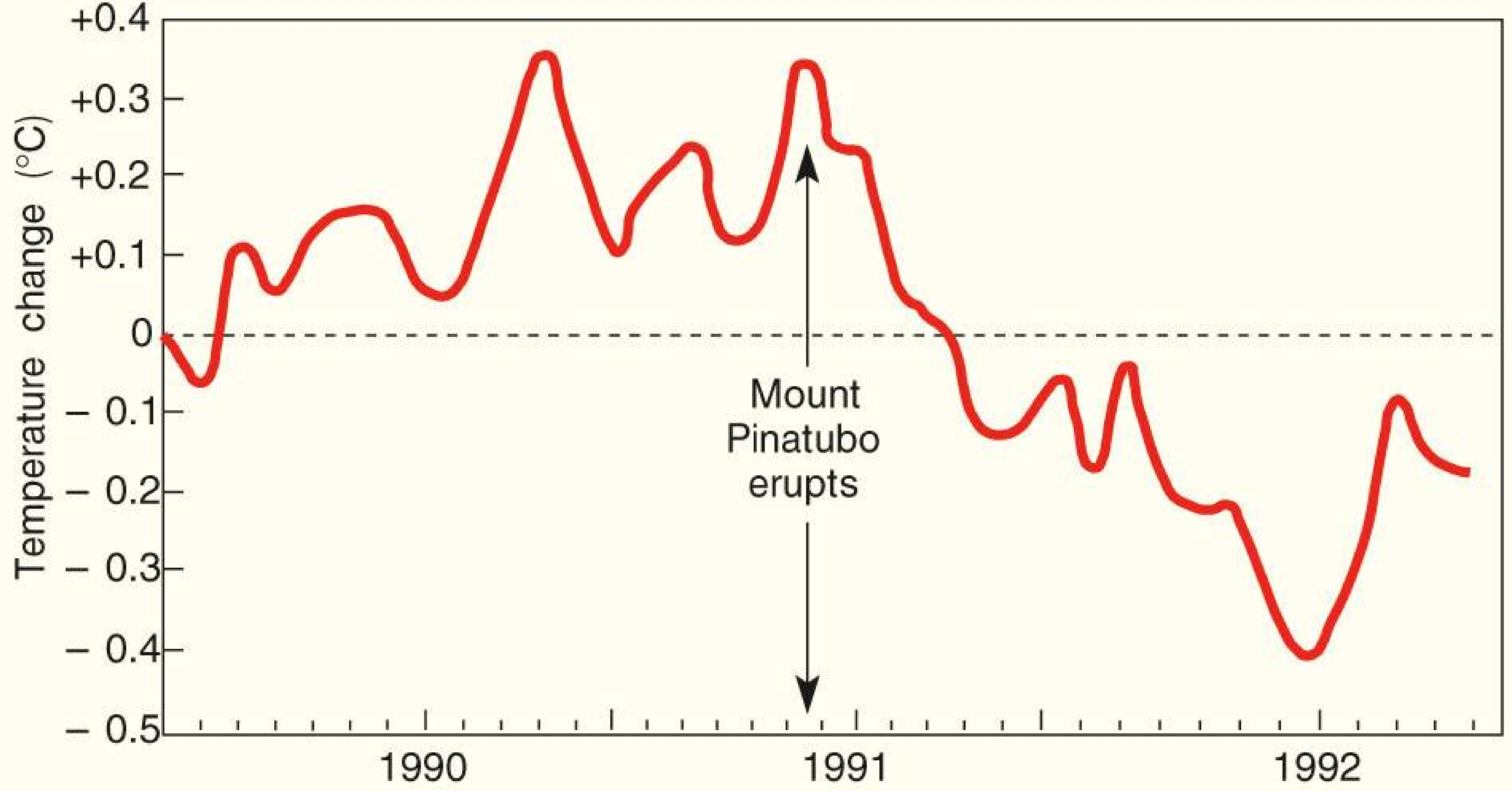
Cloud blocks sunlight



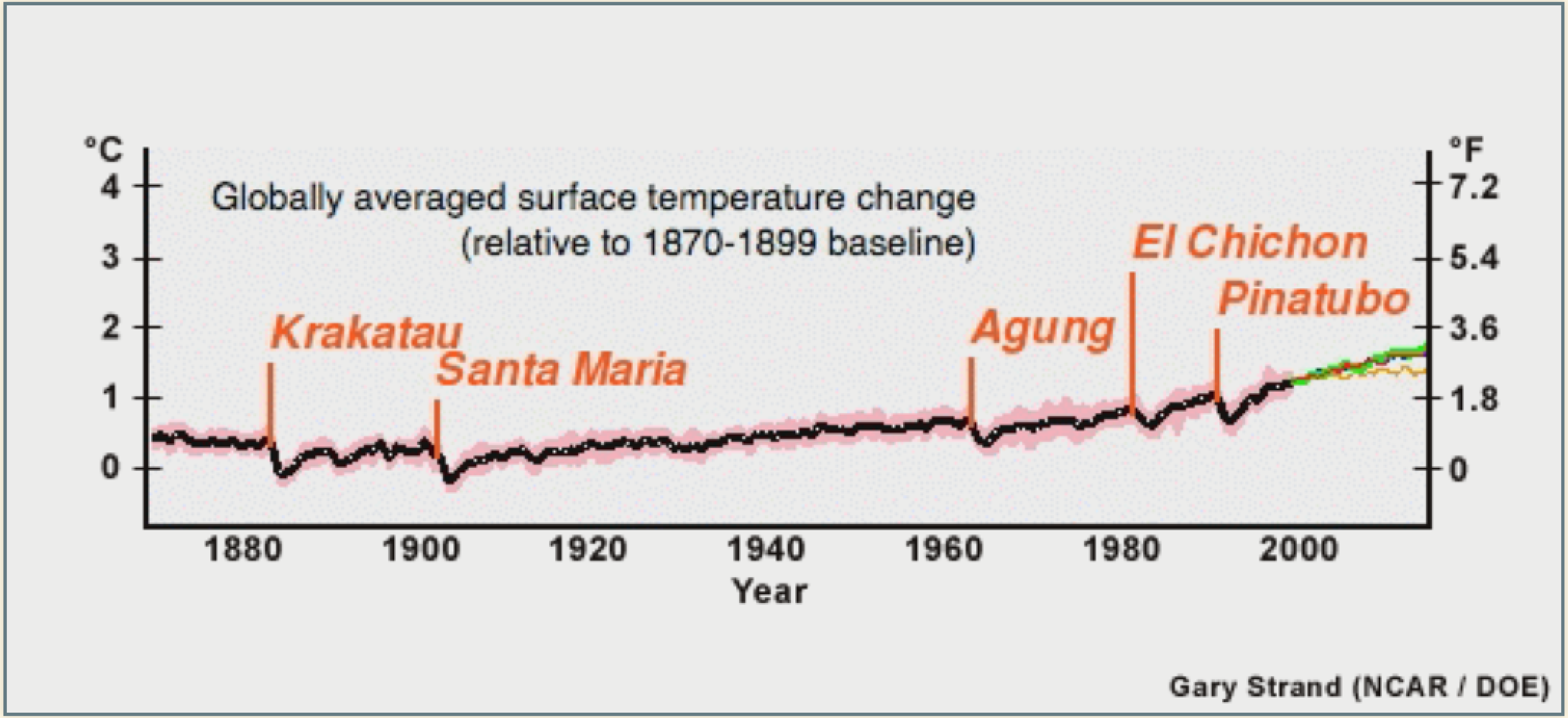
Exercise 3-3



Temperature drops



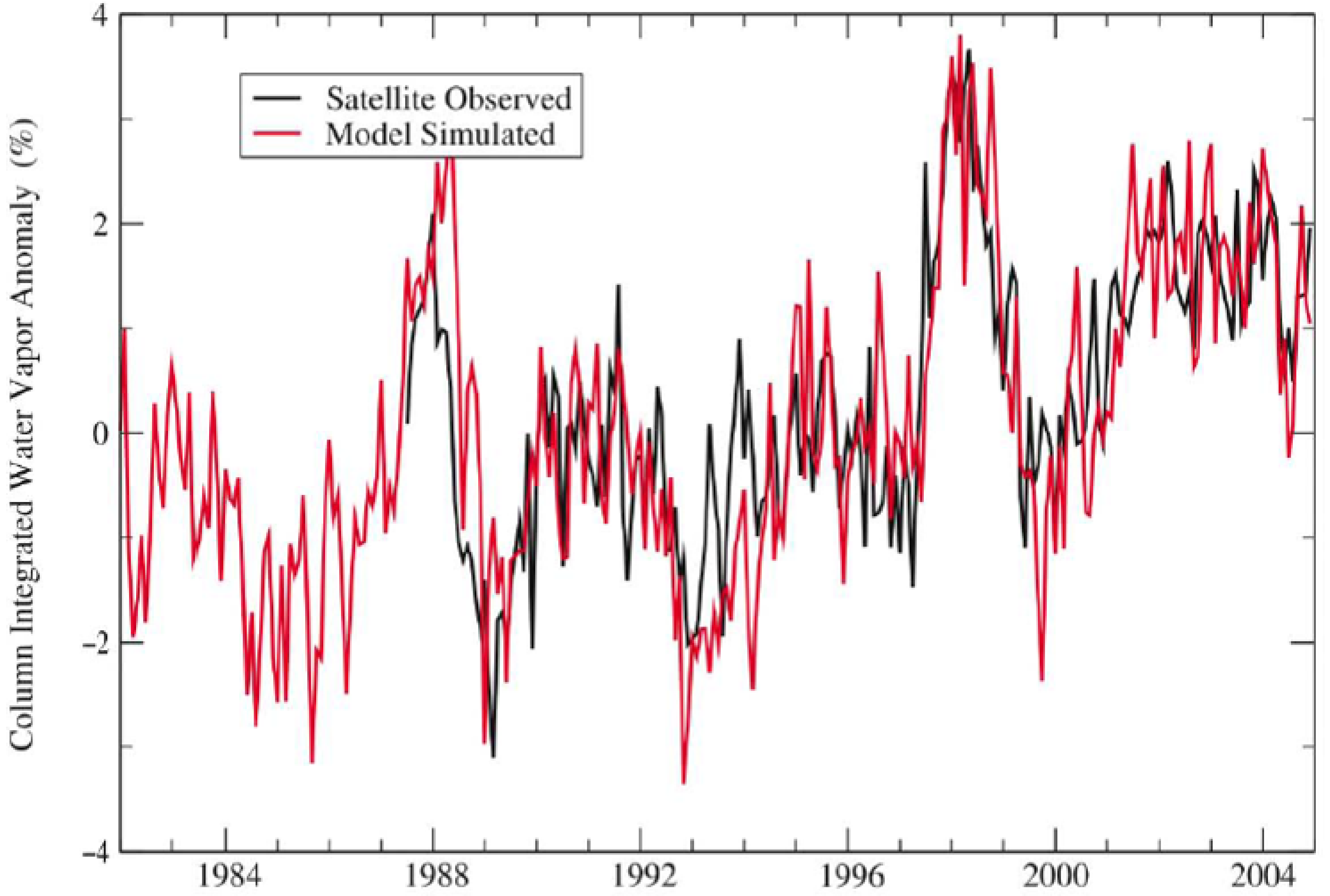
Volcanoes and Temperature



1816:
The Year Without a Summer

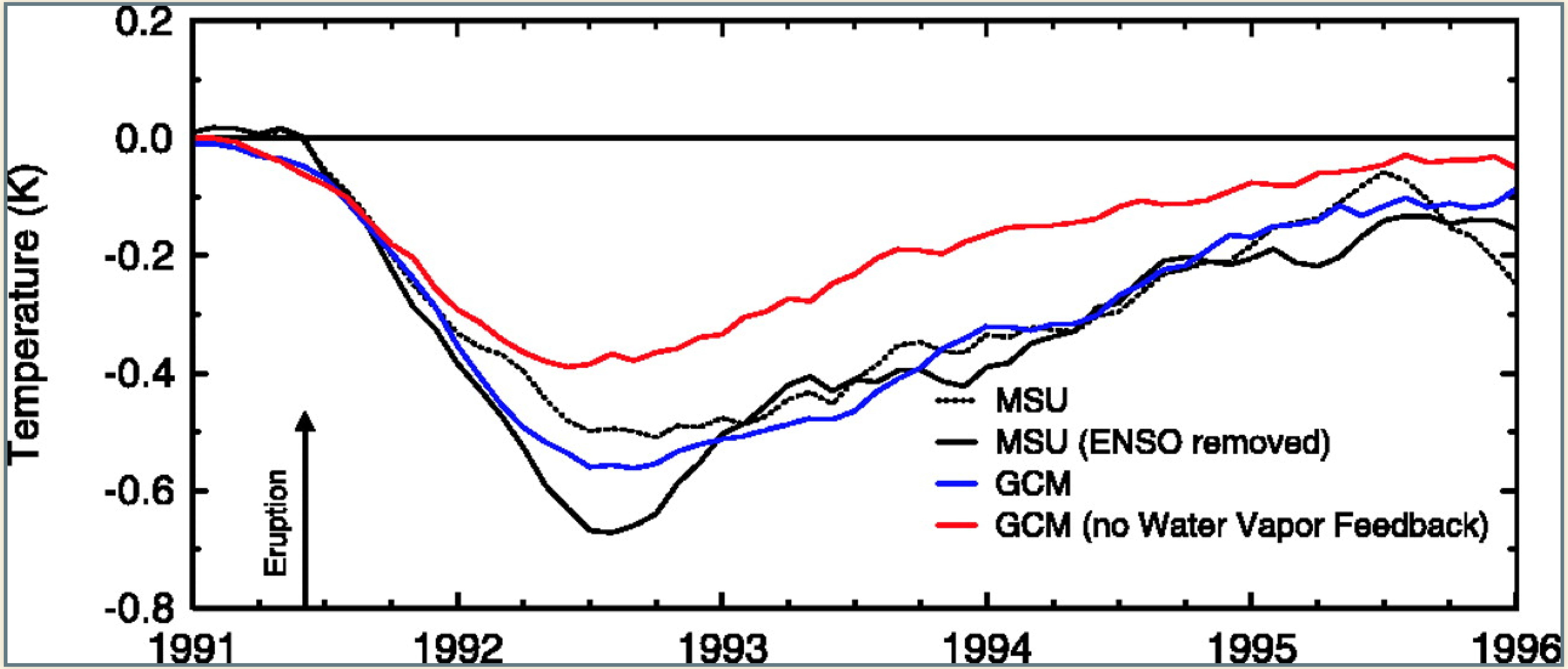
Testing Theory of Water-Vapor Feedback

Changes in Water Vapor



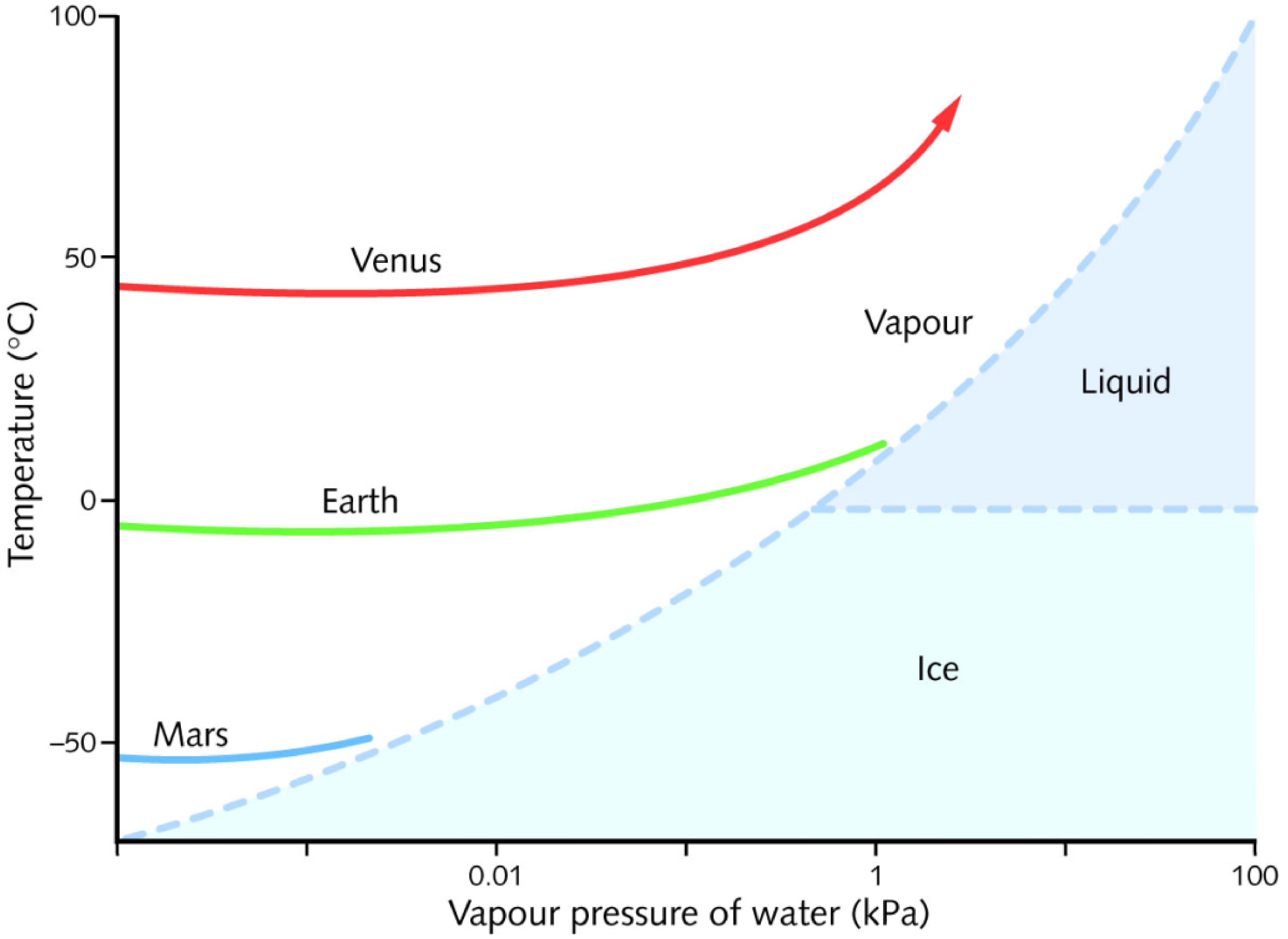
To produce the red curve, a global atmospheric model was forced with the observed sea-surface temperatures for the years shown.

Testing Theory of Water-Vapor Feedback



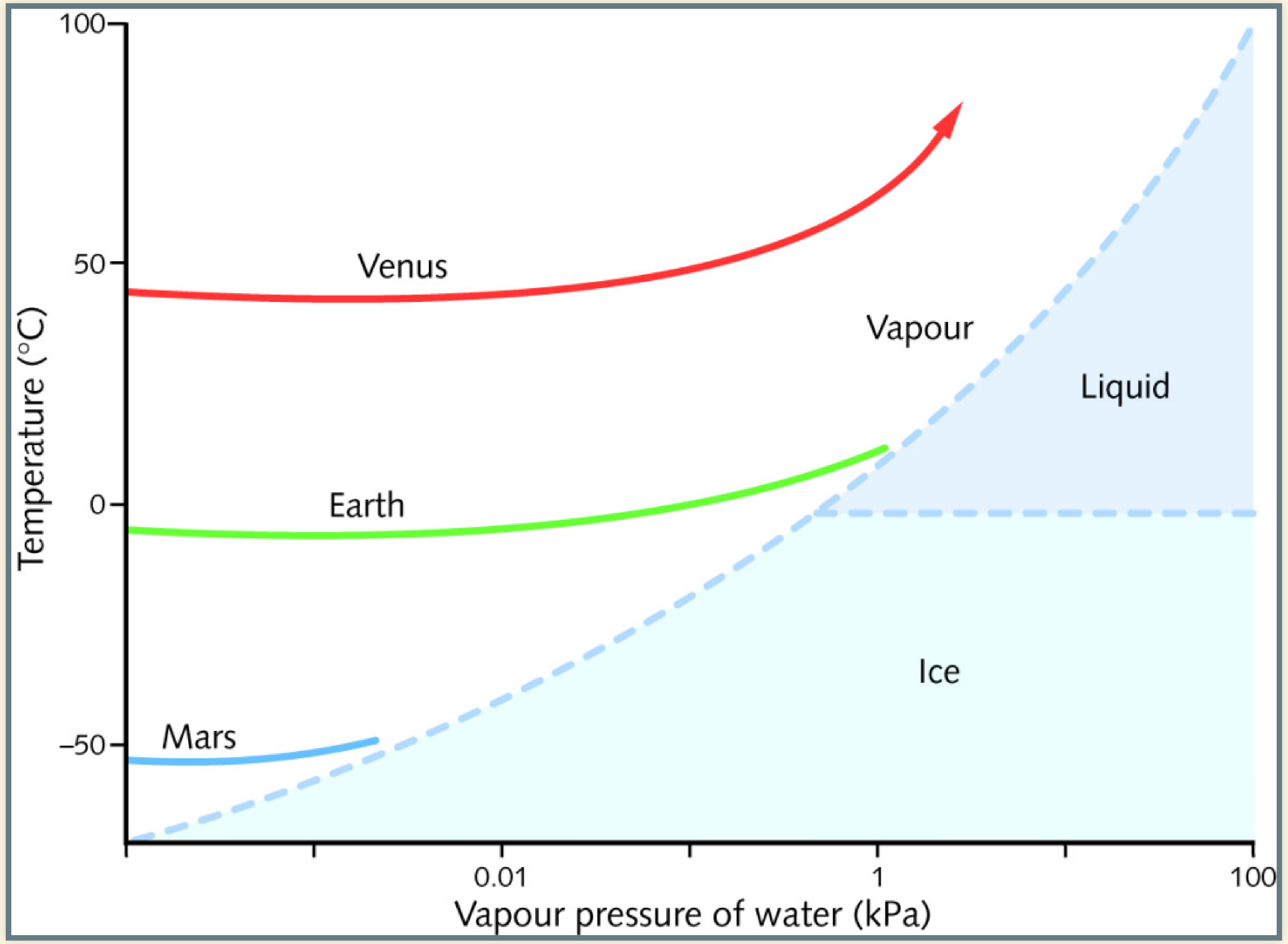
- Pinatubo erupts
- Model calculations with water vapor feedback correctly predict cooling
- Turn off water vapor feedback: incorrect predictions

Runaway Greenhouse



Runaway Greenhouse

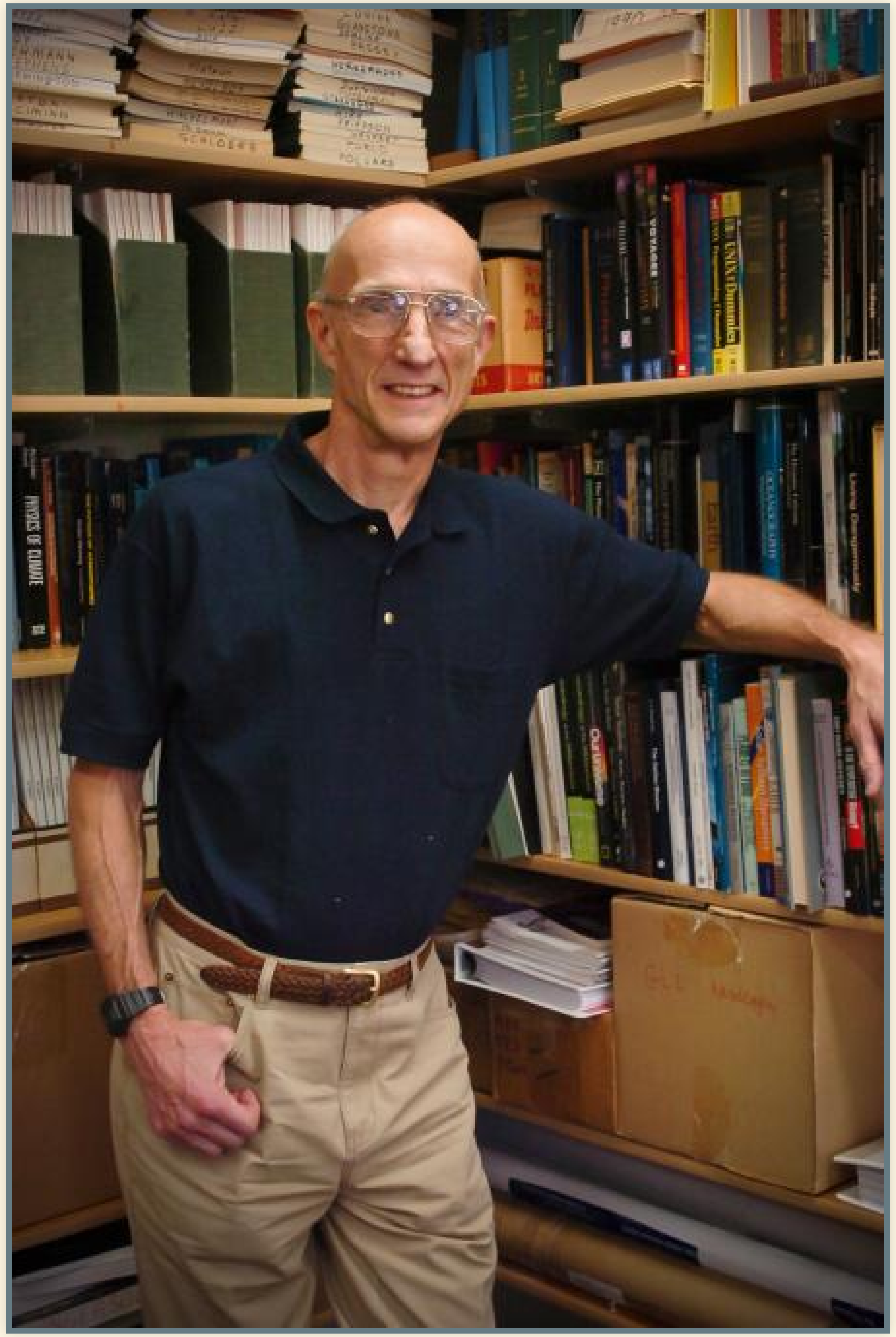
- Equilibrium vapor pressure: $p_{\text{eq}}(T)$
- Actual vapor pressure p
- If $p_{\text{eq}}(T) > p$, then p will rise.
- Rising $p \rightarrow$ rising $T \rightarrow$ rising $p_{\text{eq}}(T)$.
- Equilibrium when $p = p_{\text{eq}}(T)$,
- If vapor pressure curve does not hit equilibrium with water or ice, greenhouse will run away:
  - Water will keep evaporating until oceans are dry.



Andrew Ingersoll & Runaway Greenhouse

1967: First class he ever taught

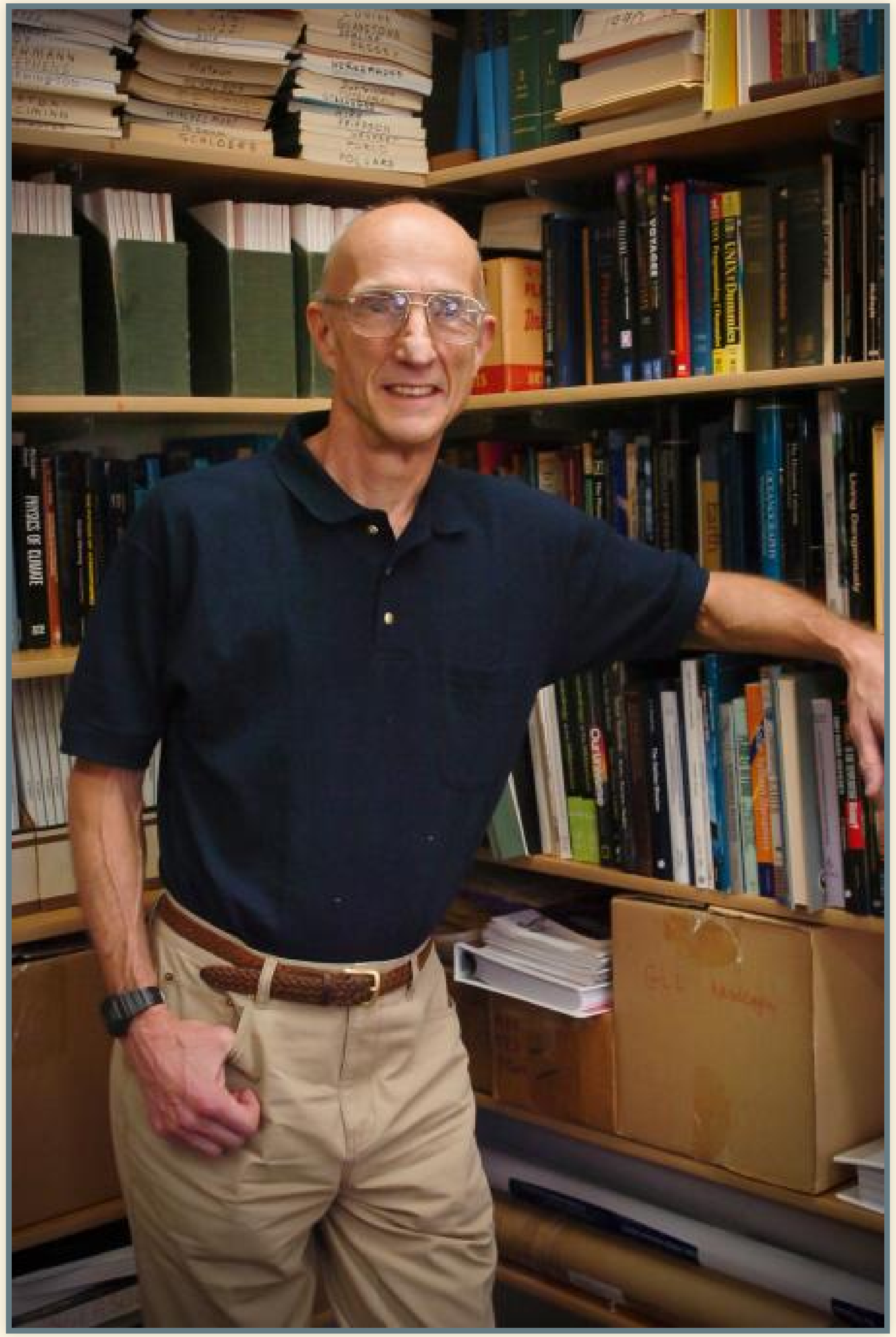
- Assigned homework:
  - Calculate water vapor feedback
- Students couldn't solve problem
- Fixed problem so students could solve it
- It worked for Earth, but not Venus
- Hmmmm …
- It would work for Venus if all the oceans boiled dry.



Andrew Ingersoll & Runaway Greenhouse

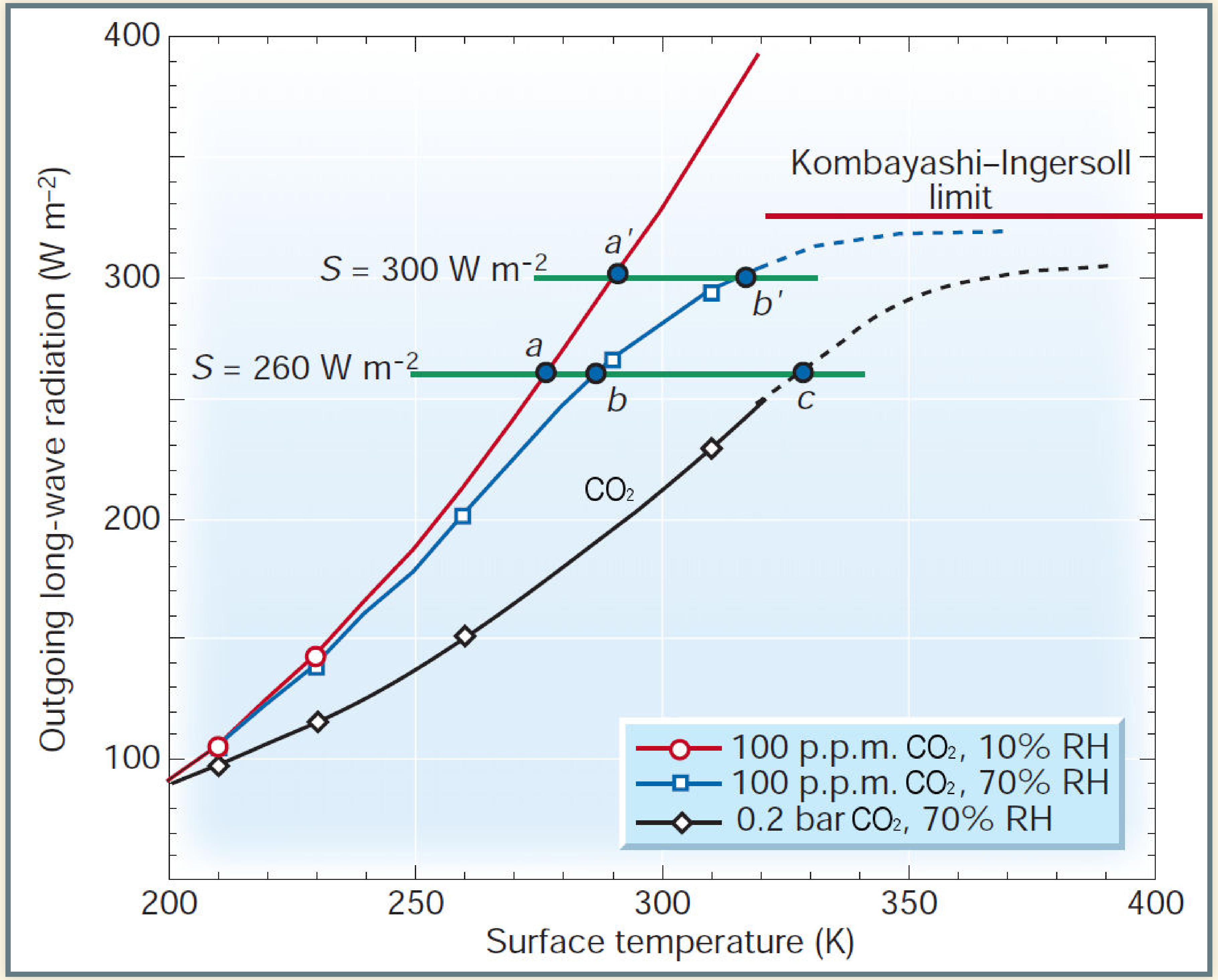
Wrote up results for publication

- Rejected by journal
- Submitted to another journal
  - Rejected again
- Submitted to a third journal
  - Accepted
- Now a classic paper
  - Cited more than 200 times



Kombayashi-Ingersoll Limit

- Outgoing long-wave has to balance incoming sunlight
- no feedback, feedback, feedback + high CO_2
- Brighter sun → hotter → more water vapor
- Kombayashi-Ingersoll limit:
  - Sunlight below limit, there is a stable equilibrium with liquid water
  - Sunlight above limit, oceans boil dry



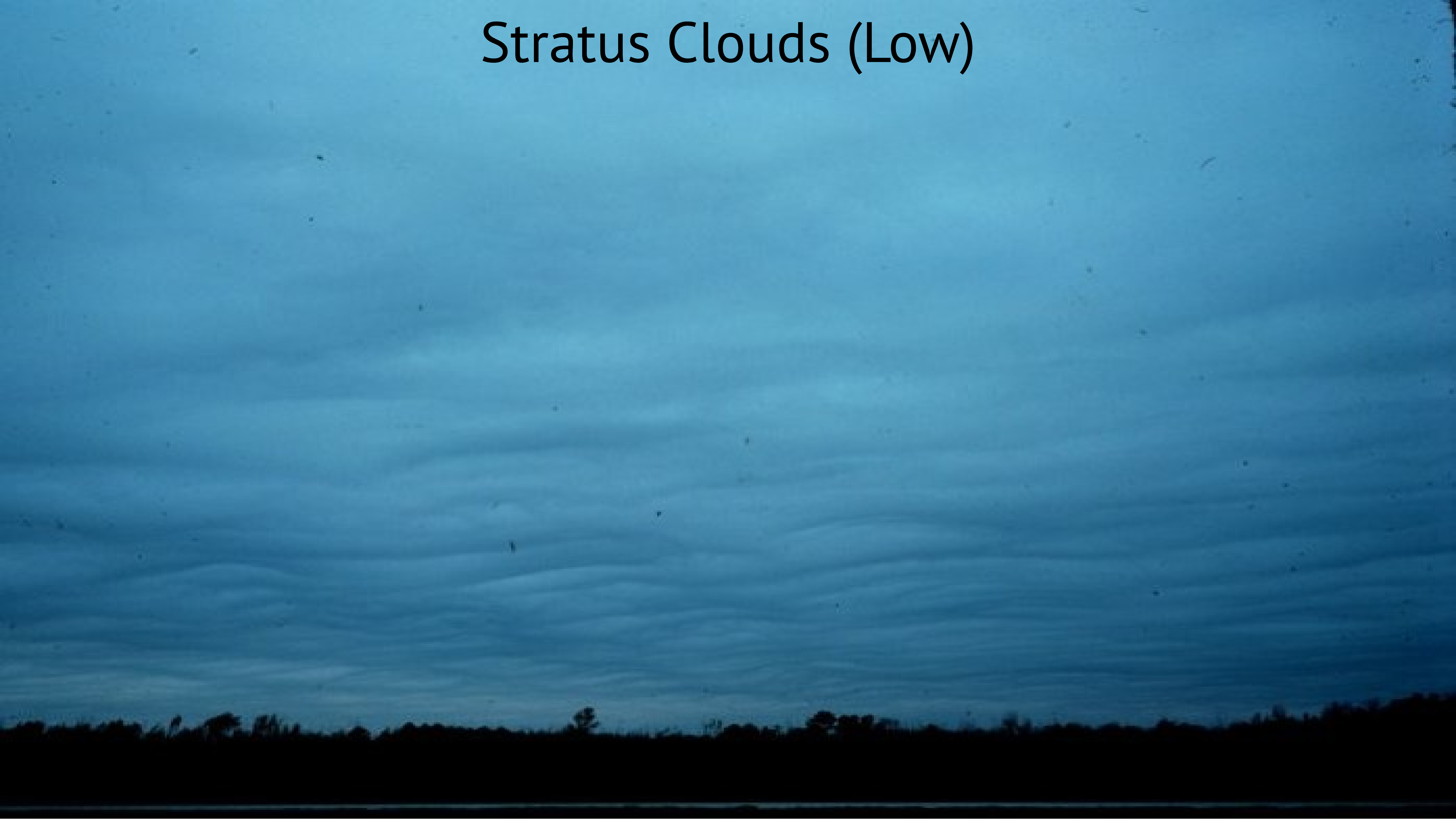
Cloud Feedbacks

Cloud Feedbacks

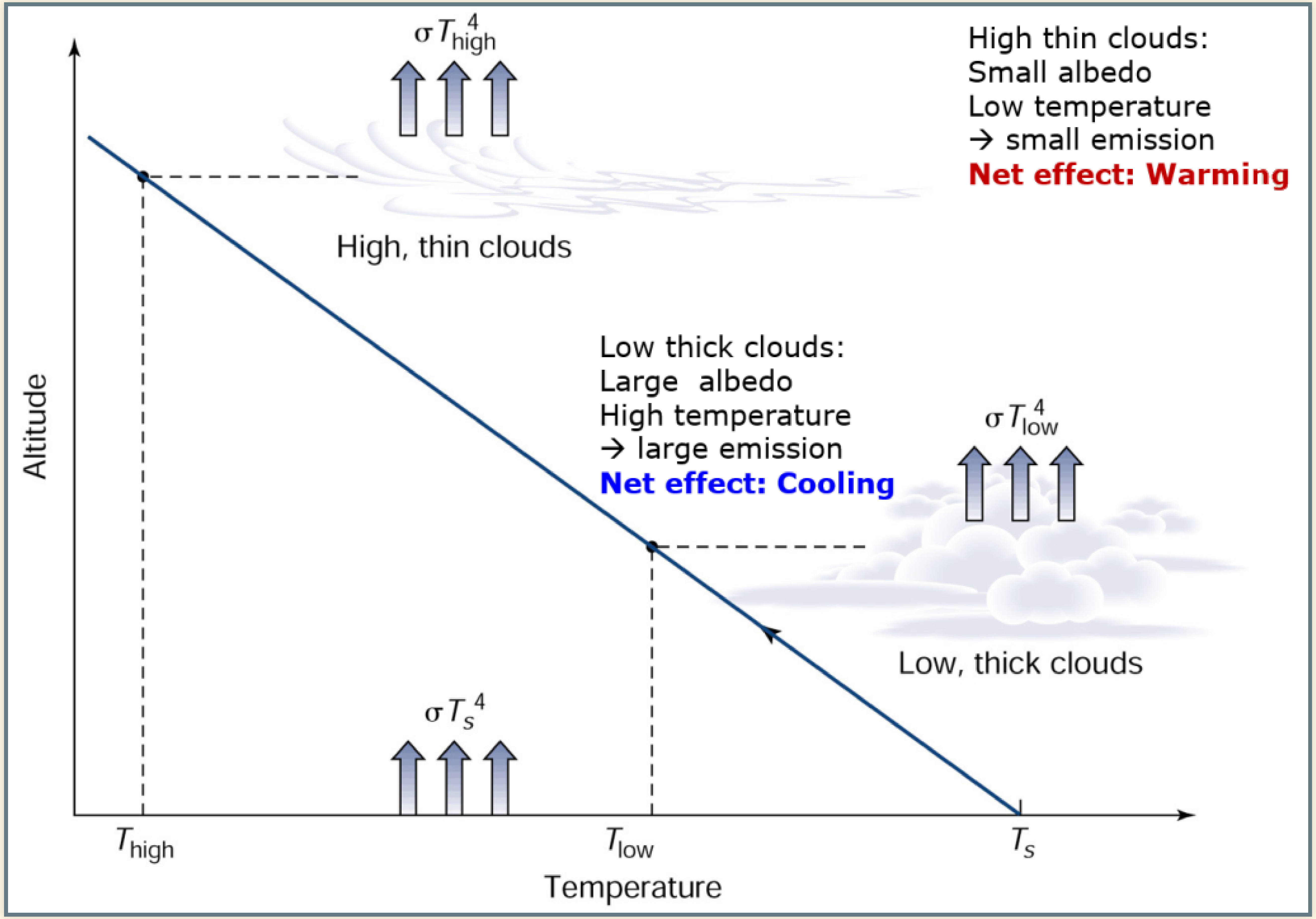
- What effect do clouds have on climate?
- What effects does climate have on clouds?
- Warmer $\rightarrow$ more clouds
- More clouds:
  - Higher albedo
    - (cools earth: negative feedback)
  - High emissivity: blocks longwave light
    - (warms earth: positive feedback)
- Which effect is bigger?

Cirrus Clouds (High)

Stratus Clouds (Low)

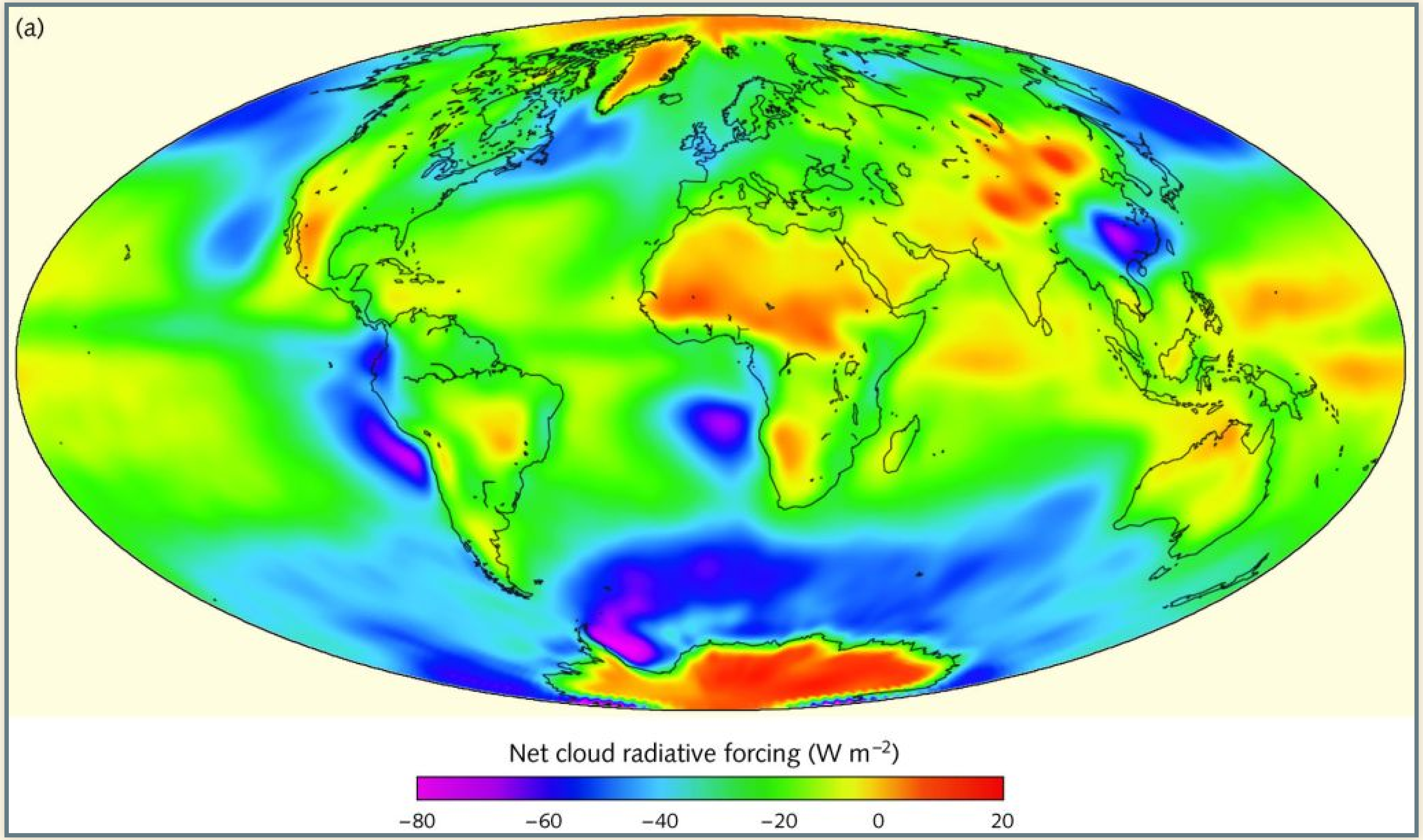


Cloud Feedbacks



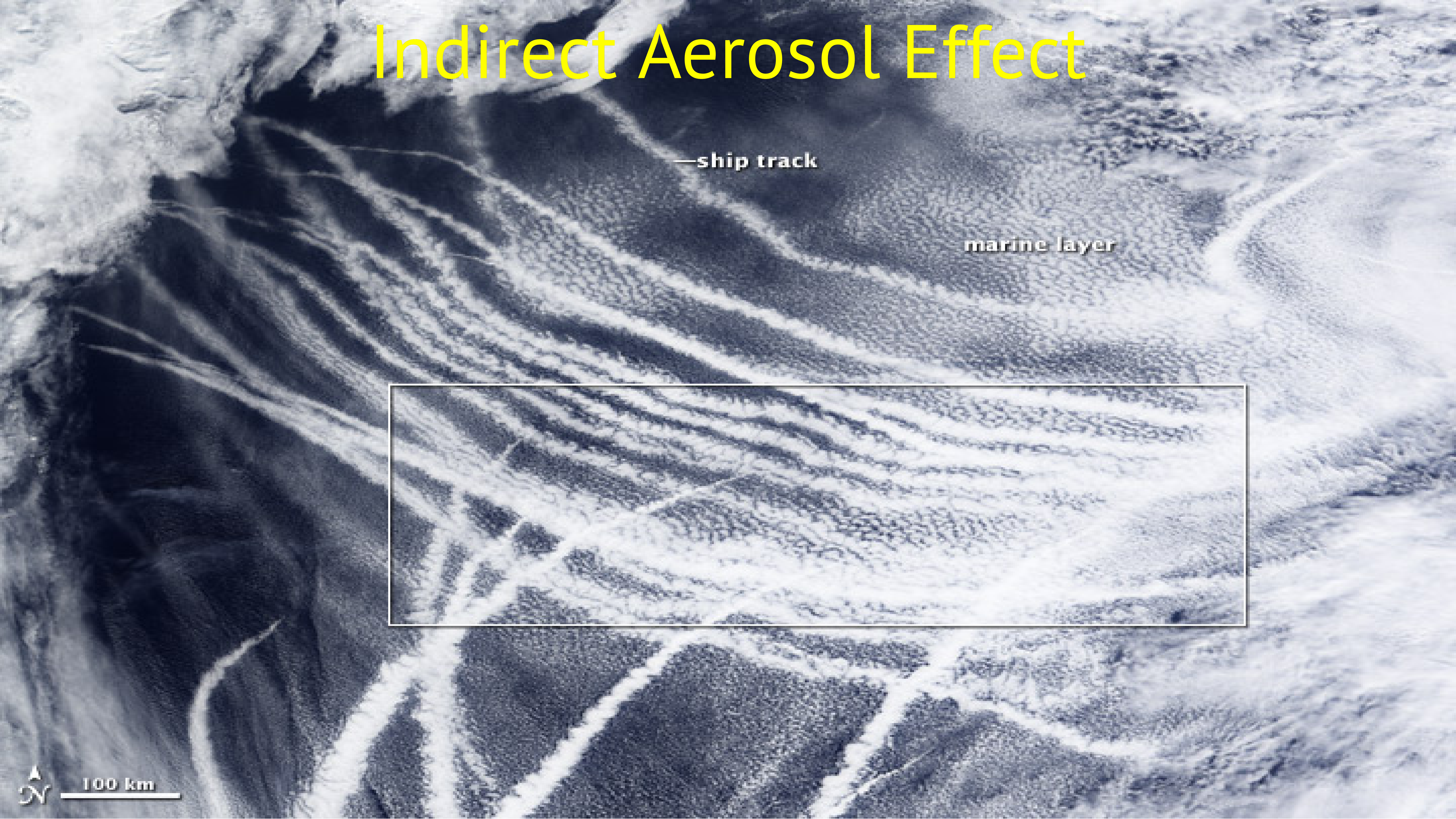
Satellite Measurements

Radiative forcing by clouds



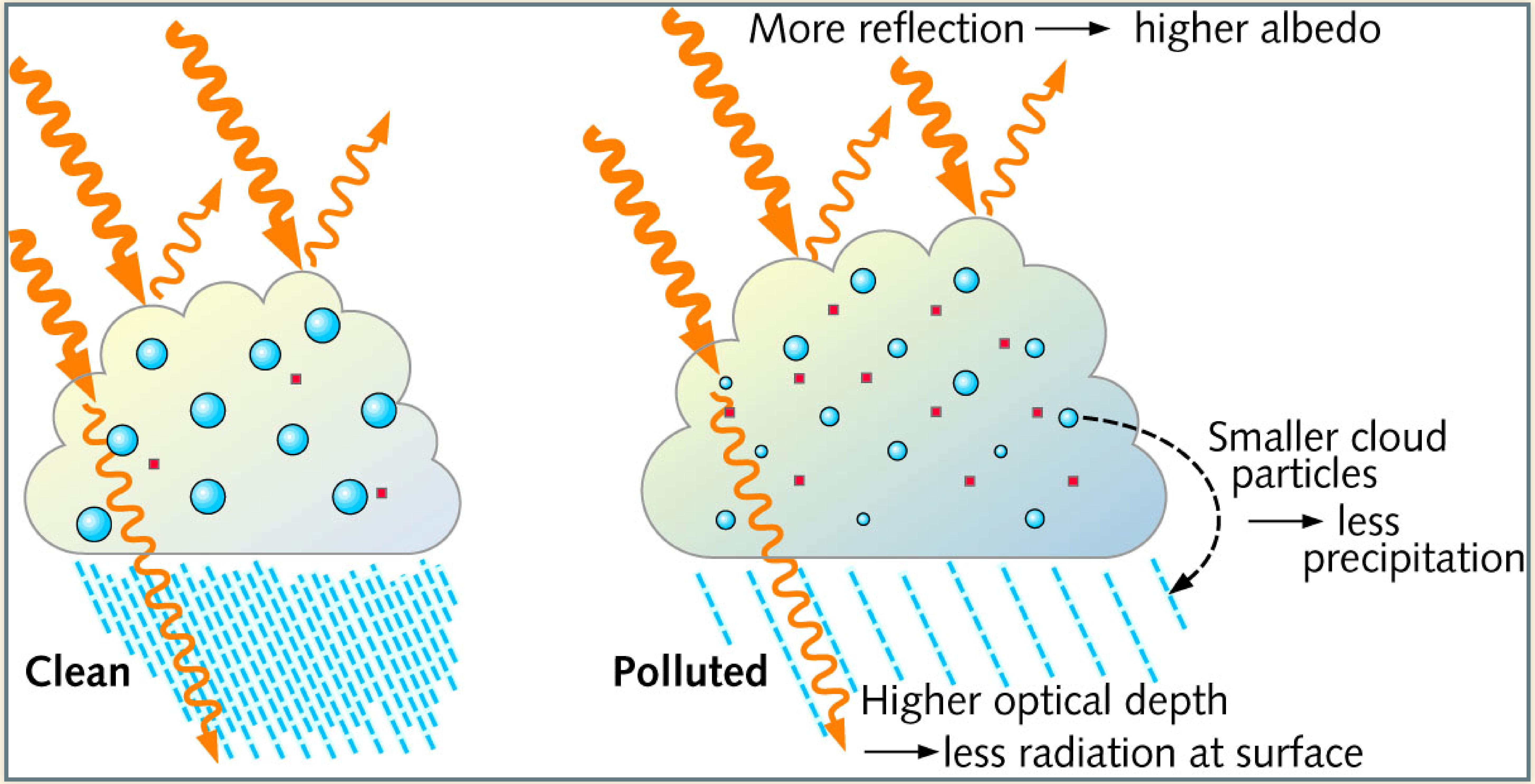
(negative = cooling, positive = warming)

Indirect Aerosol Effect

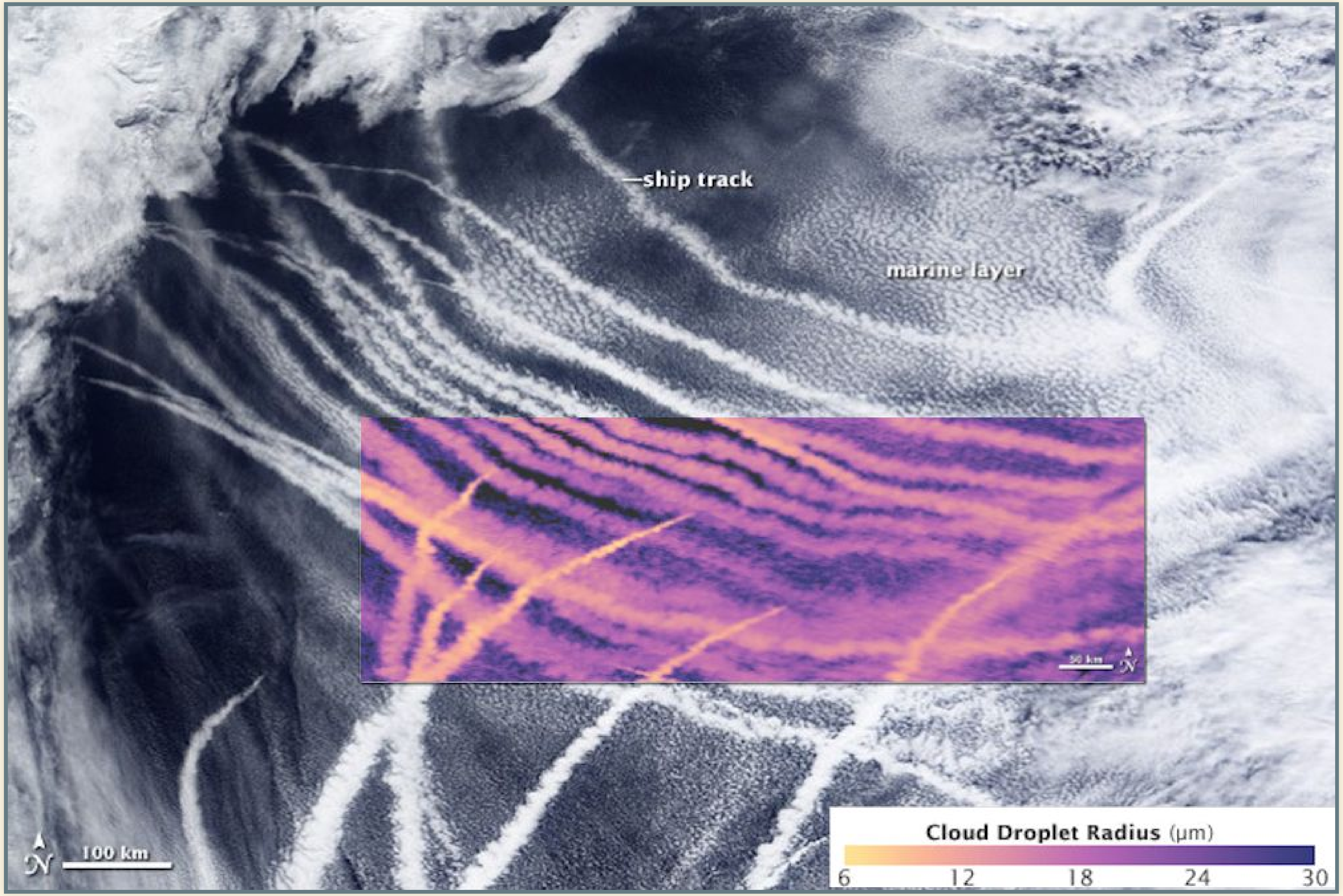


Indirect Aerosol Effect

- Aerosol particles $\longrightarrow$ more, smaller droplets
- Smaller droplets $\longrightarrow$ greater albedo, longer lifetime
- More droplets $\longrightarrow$ greater albedo, more absorption

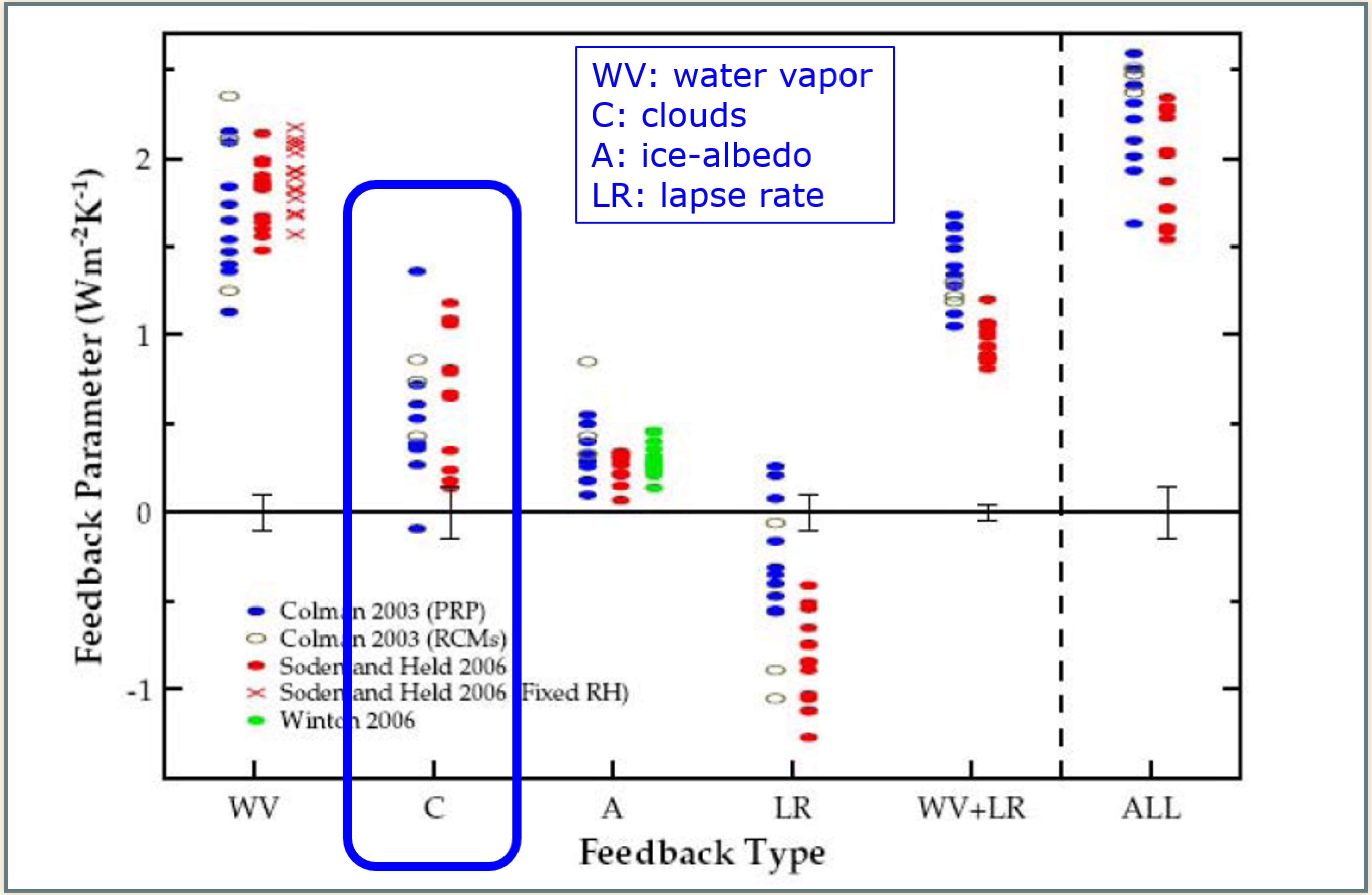


Indirect Aerosol Effect



Summary of Feedbacks

Summary of Feedbacks



Stefan-Boltzmann Feedback

- The biggest feedback in the climate system is the Stefan-Boltzmann feedback.
- Stefan-Boltzmann equation: $I = \varepsilon\sigma T^4$
  - $Q = Q_{\text{in}} - Q_{\text{out}}$
  - Higher temperature $\rightarrow$ more heat out to space
    - Q_{out} gets larger, so $\Delta Q < 0$
  - $\Delta T > 0 \rightarrow \Delta Q < 0$
  - $f = \dfrac{\Delta Q}{\Delta T} < 0$: negative feedback
- Creates stable climate

Stability of the Climate

- Most feedbacks we've discussed are positive:
  - Ice-albedo
  - Water vapor
  - Clouds (mostly)
- Why don't these positive feedbacks make the climate unstable?
  - (e.g., runaway greenhouse)
  - They are smaller than the negative Stefan-Boltzmann feedback
    - so the total feedback remains negative.
  - Positive feedbacks amplify warming:
    - More than we'd get with just Stefan-Boltzmann feedback,
    - But they are too small to destabilize the planet.
- Many scientists worry about a possible "tipping point":
  - Is there a temperature threshold where positive feedbacks become greater than Stefan-Boltzmann?
    - This would destabilize the climate.