# Climate Feedbacks

EES 3310/5310

Global Climate Change

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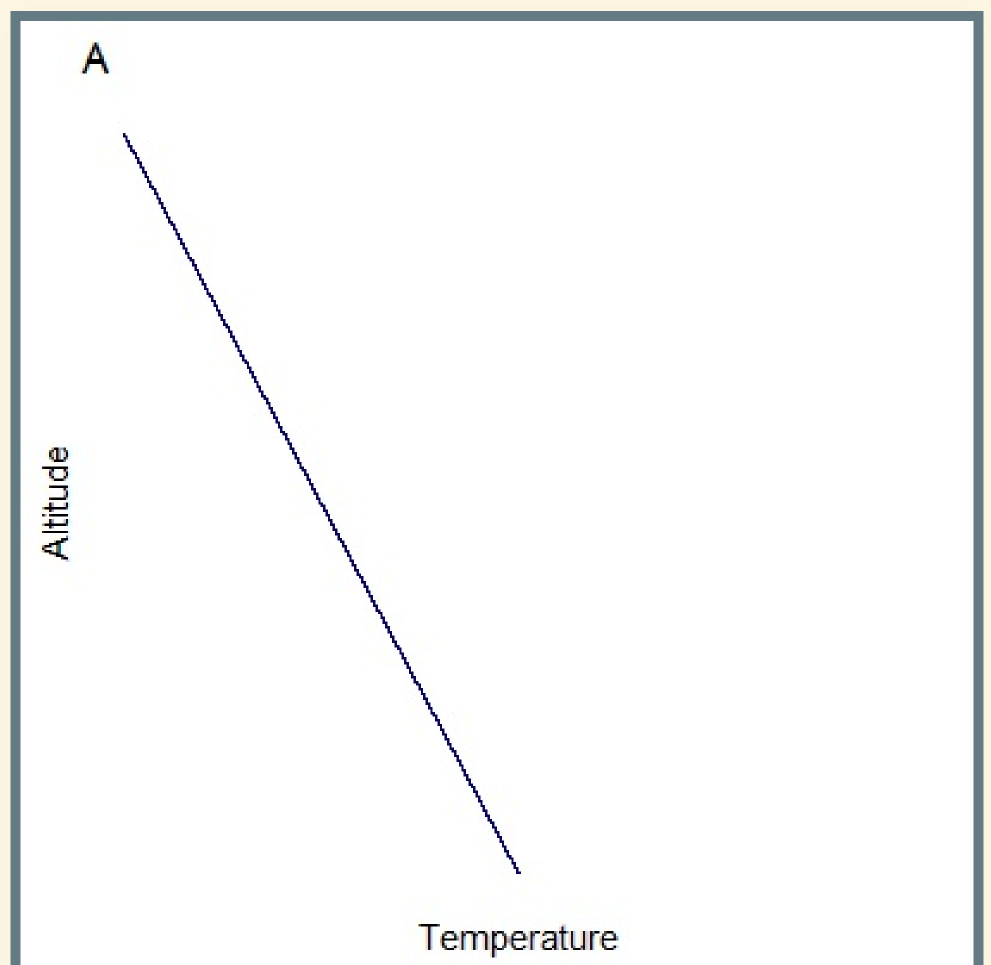
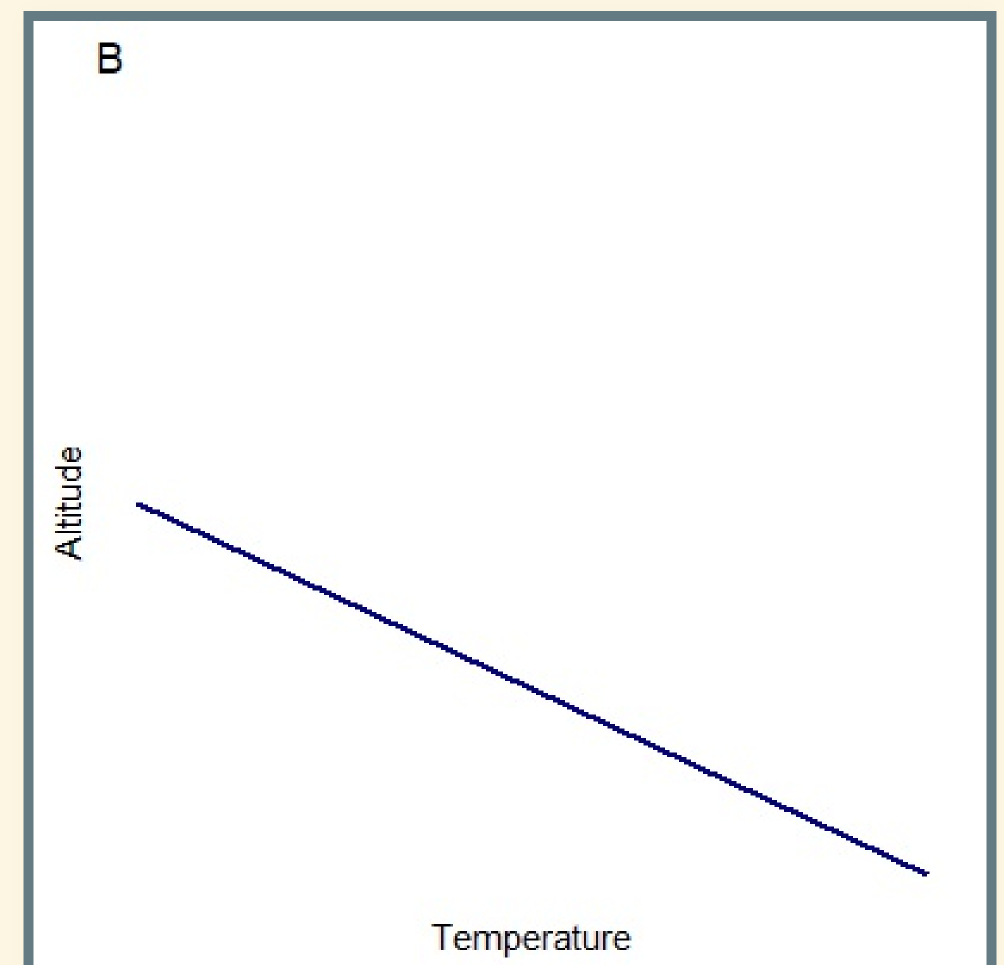
Class #8: Friday Sept. 7 2018

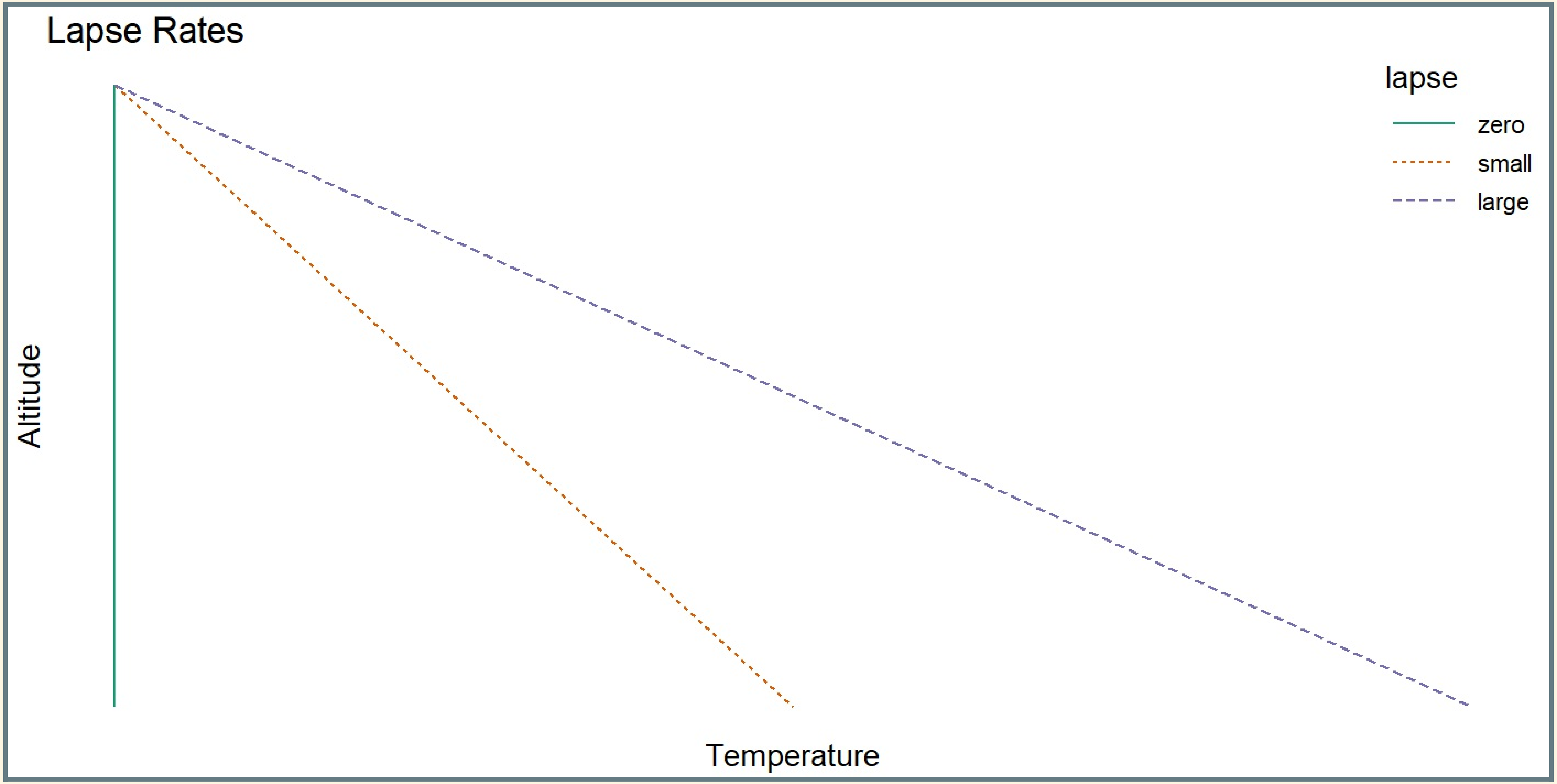
# Lapse Rates

# Which lapse rate is greater?



# Lapse Rates



# 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**, $\Delta T$ brings $I_{\text{out}}$ back to balance with $I_{\text{in}}$ .
  - **With feedback**, $\Delta T$ causes a new forcing, $\Delta Q_{\text{feedback}} = f \Delta T$
  - $\Delta Q_{\text{feedback}}$ causes further change in $T_{\text{ground}}$ .

# Examples of feedbacks

# Water-vapor

- Temperature rises
- What happens to humidity?
  - Humidity rises: more water vapor
- How does this affect $\Delta Q$?
  - More water vapor $\rightarrow$ bigger greenhouse effect
  - $I_{\text{out}}$ 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

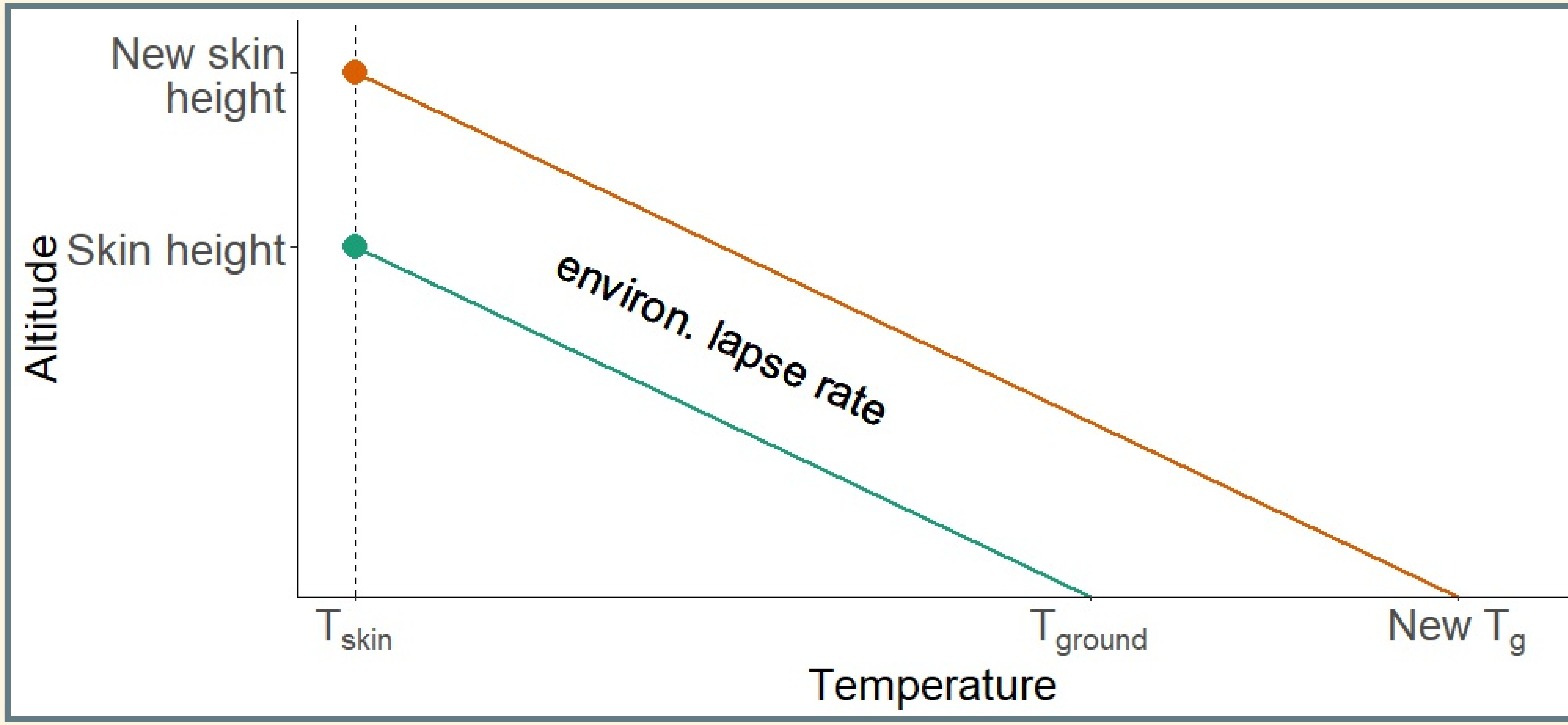
# Greenhouse effect

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

# Global warming

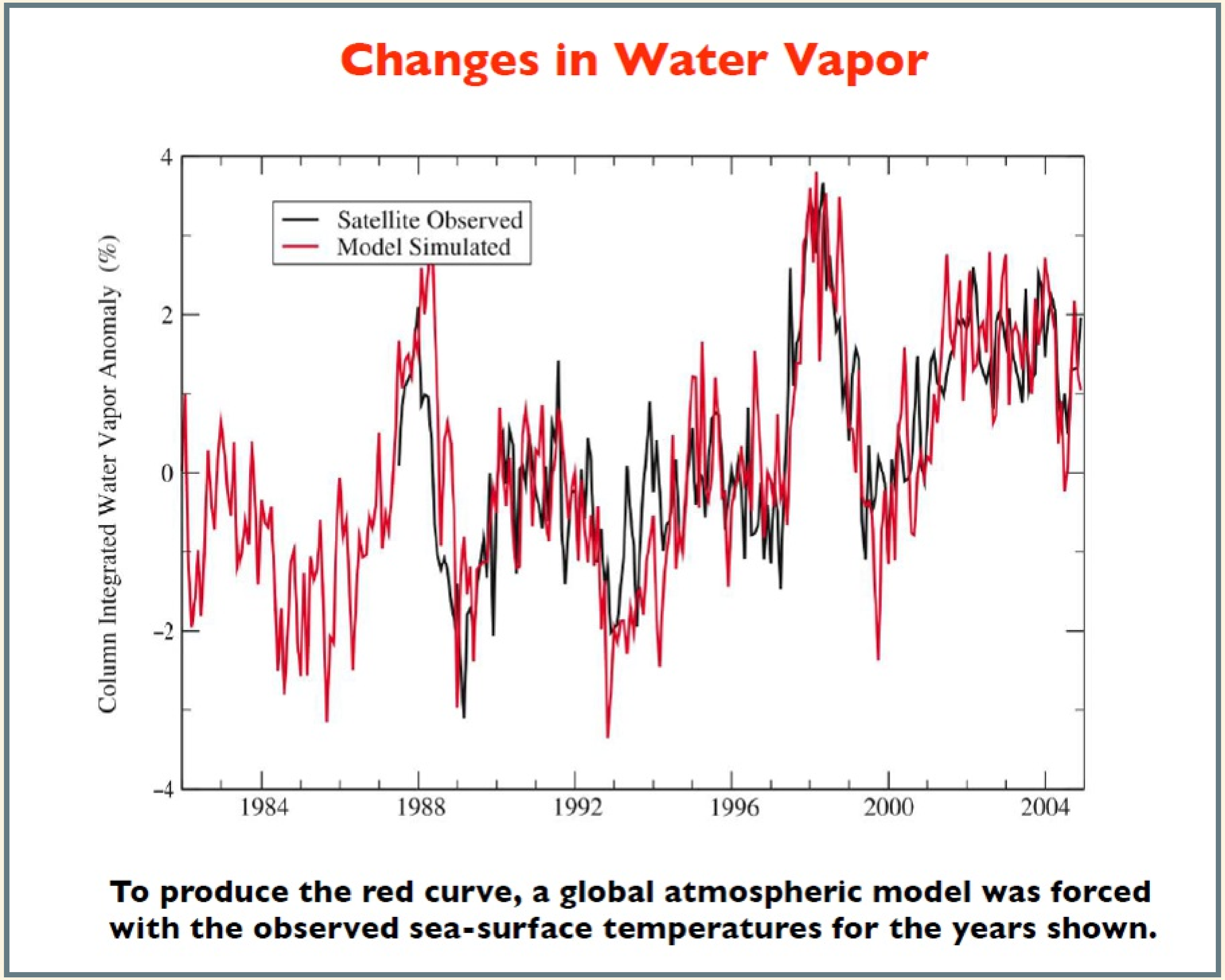
- Greater $CO_2 \rightarrow$ greater skin height.
- Warming: $\Delta T_{\mathrm{ground}} = \Delta h_{\mathrm{skin}} \times \text{env. lapse}$
- What does rising temperature do to water vapor?

# Water Vapor Feedback

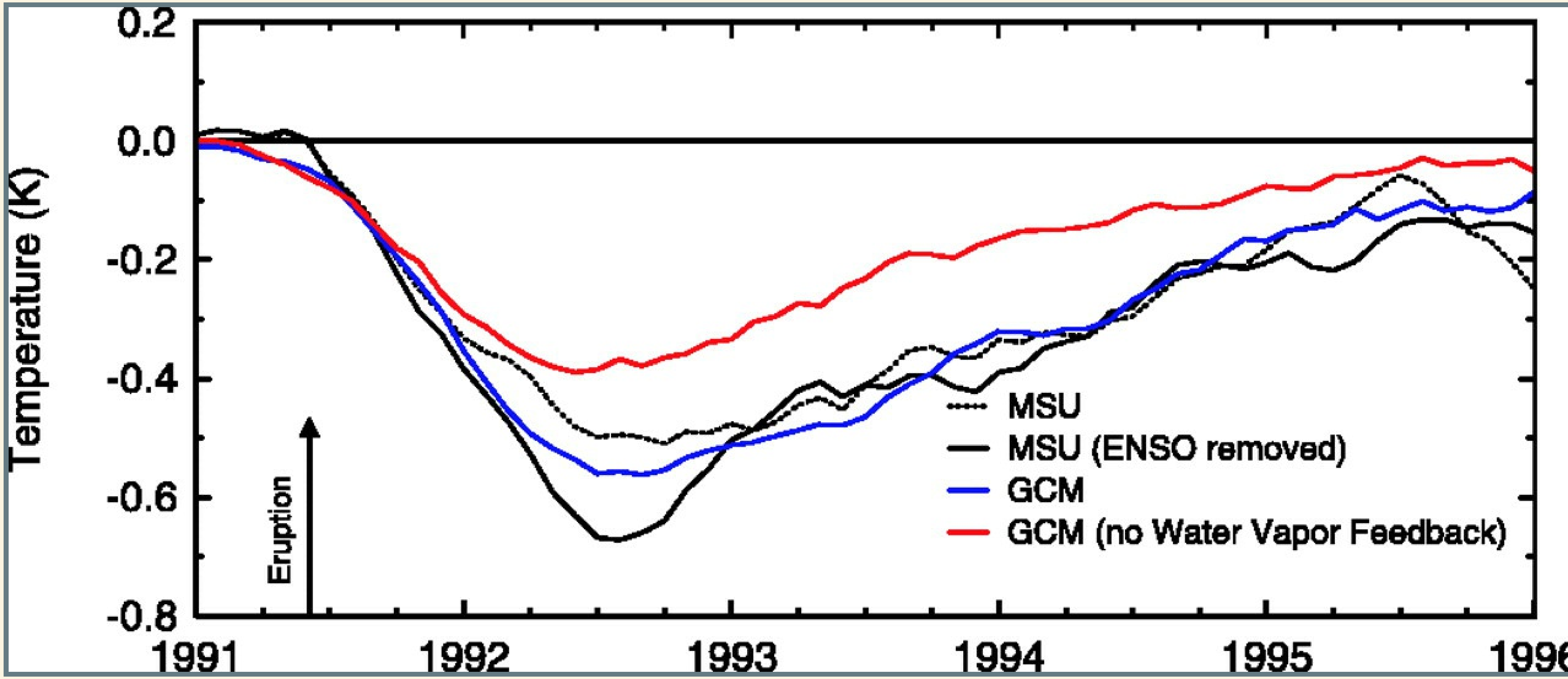



- Rising temperature $\rightarrow$ greater humidity
- Greater humidity $\rightarrow$ skin height rises even higher
- $\Delta T_{\text{ground}} = \Delta h_{\text{skin}} \times \text{Lapse}$

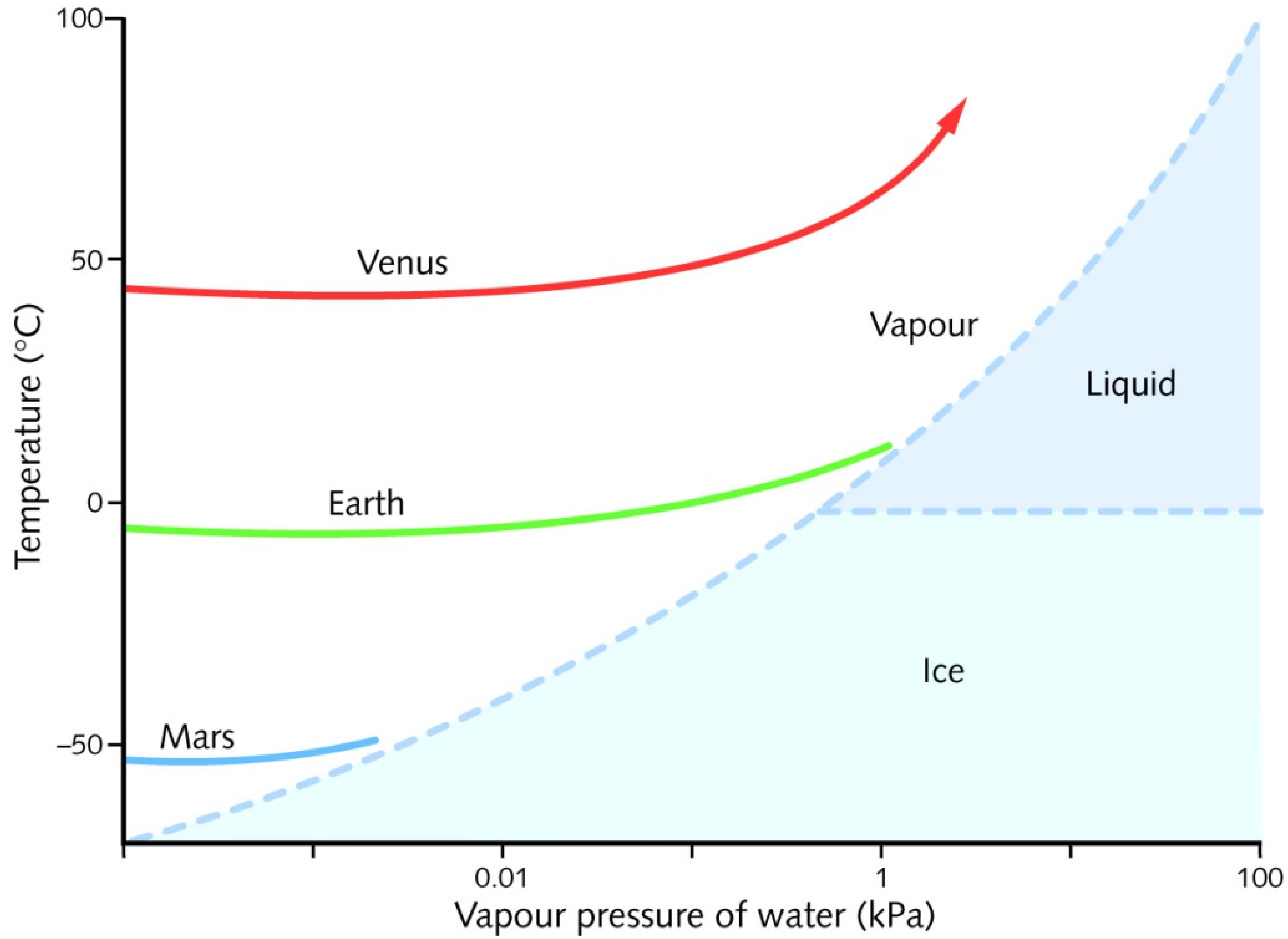
# Testing Theory



# Testing Theory of Water-Vapor Feedback

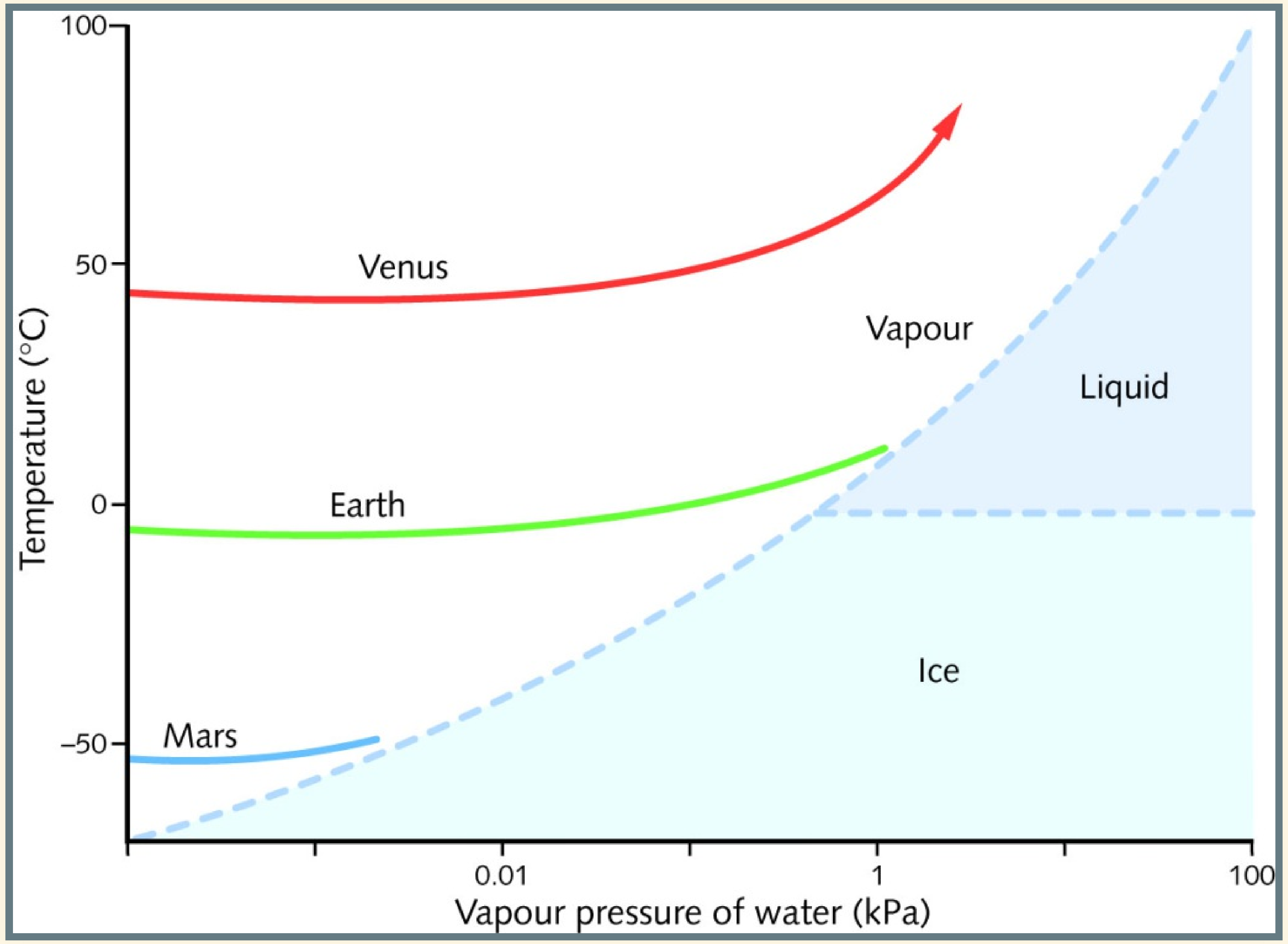



- Pinatubo erupts
- Model calculations with water vapor feedback correctly predict cooling
- Turn off water vapor feedback: incorrect predictions


100
50
0
–50
Temperature (°C)
Venus
Vapour
Liquid
Earth
Ice
Mars
0.01
1
100
Vapour pressure of water (kPa)

# Runaway Greenhouse

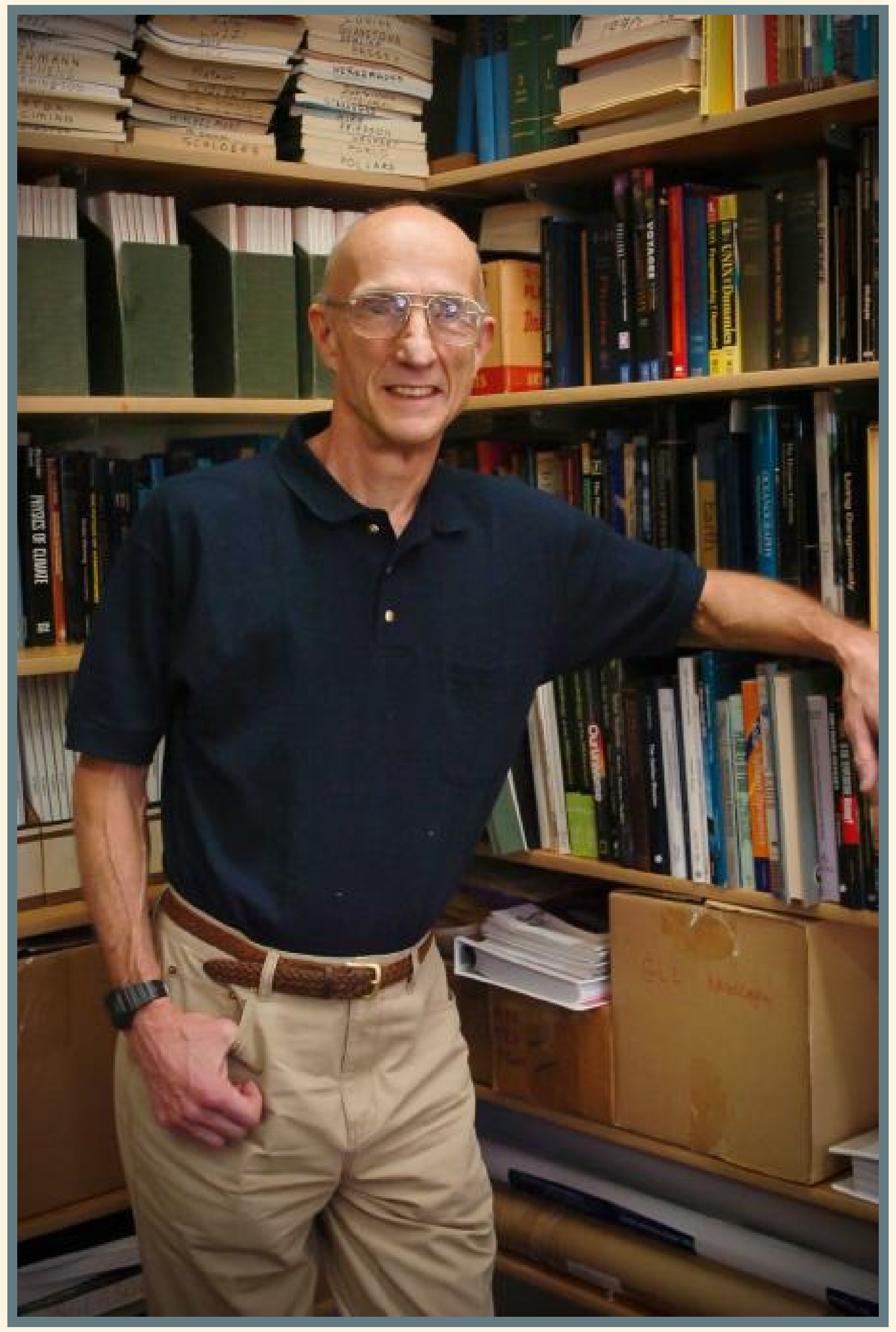
- Equilibrium vapor pressure: $p_{\text{eq}}(T)$
- Actual vapor pressure $p$
- If $p_{\text{eq}}(T) > p$, then $p$ will rise.
- Rising $p \to$ rising $T \to$ rising $p_{\text{eq}}(T)$.
- Equilibrium when $p = p_{\text{eq}}(T)$,
- If vapor pressure curve does not hit equilibrium with water or ice, greenhouse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



# Andrew Ingersoll & Runaway Greenhouse

## 1967: First class he ever taught

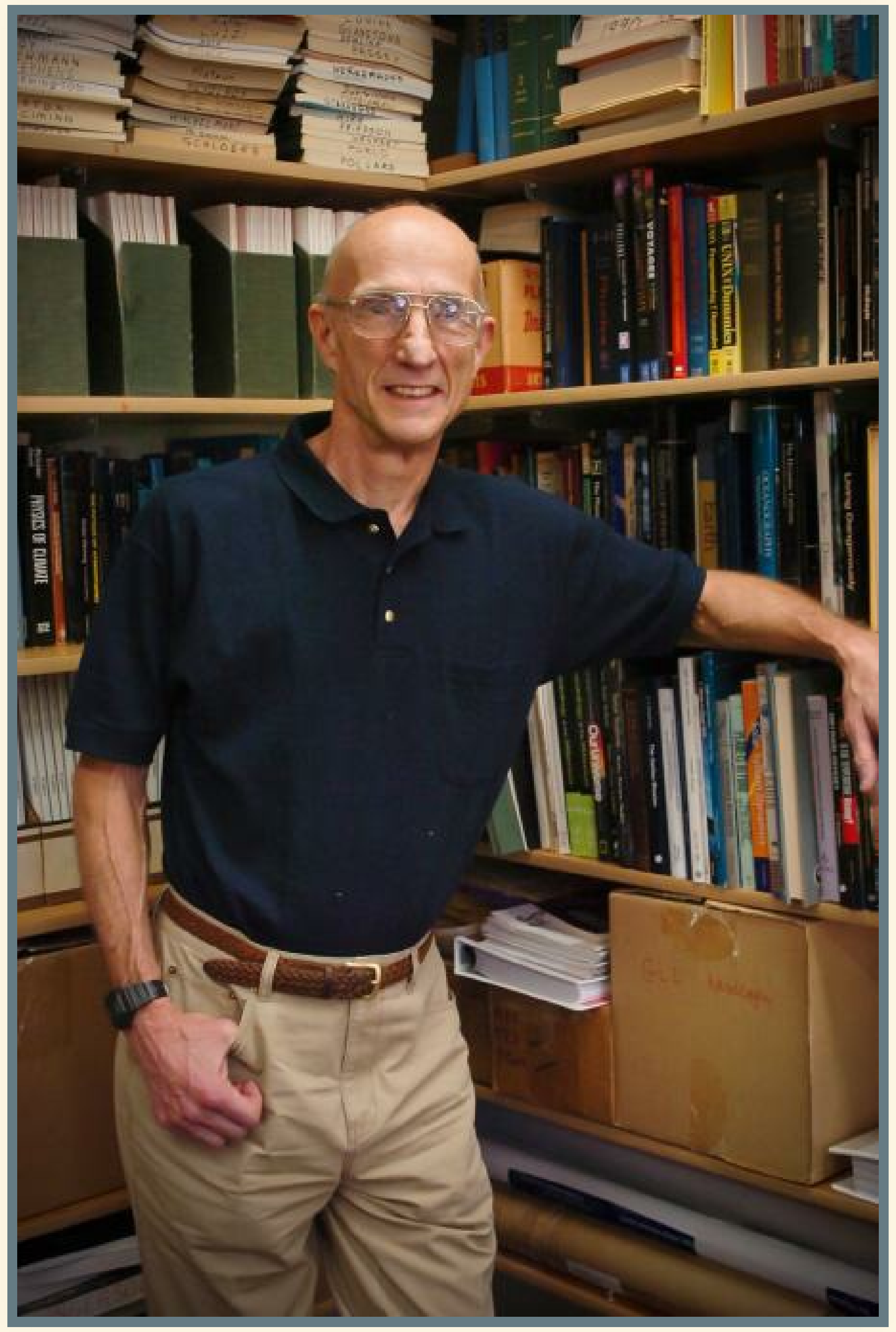
- Assigned homework:
  - Calculate water vapor feedback
- Students couldn't solve problem
- Fixed problem so students could solve it
- It worked for Earth, but not Venus
- Hmmmm …
- It would work for Venus if all the oceans boiled dry.



# Andrew Ingersoll & Runaway Greenhouse

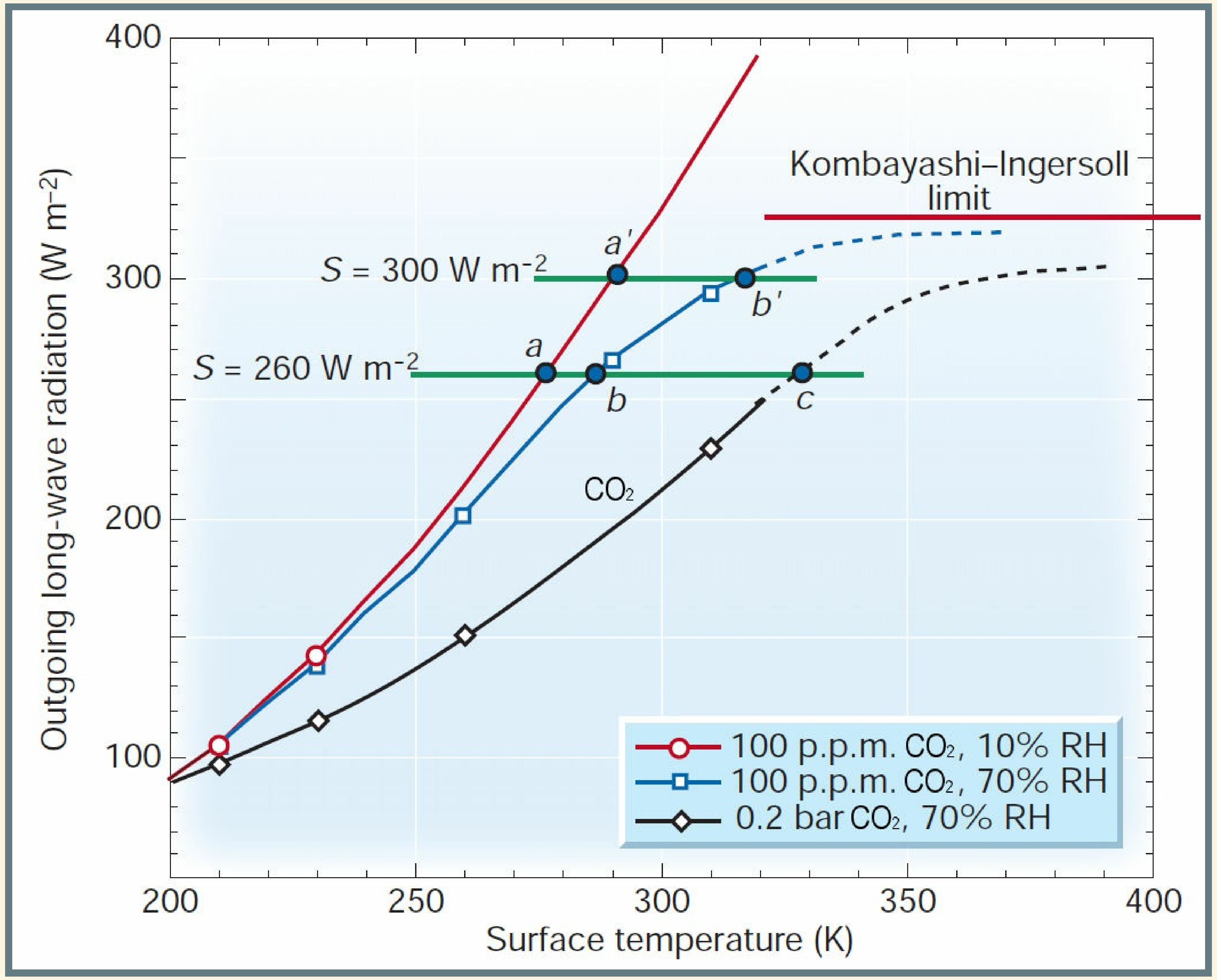
## Wrote up results for publication

- 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

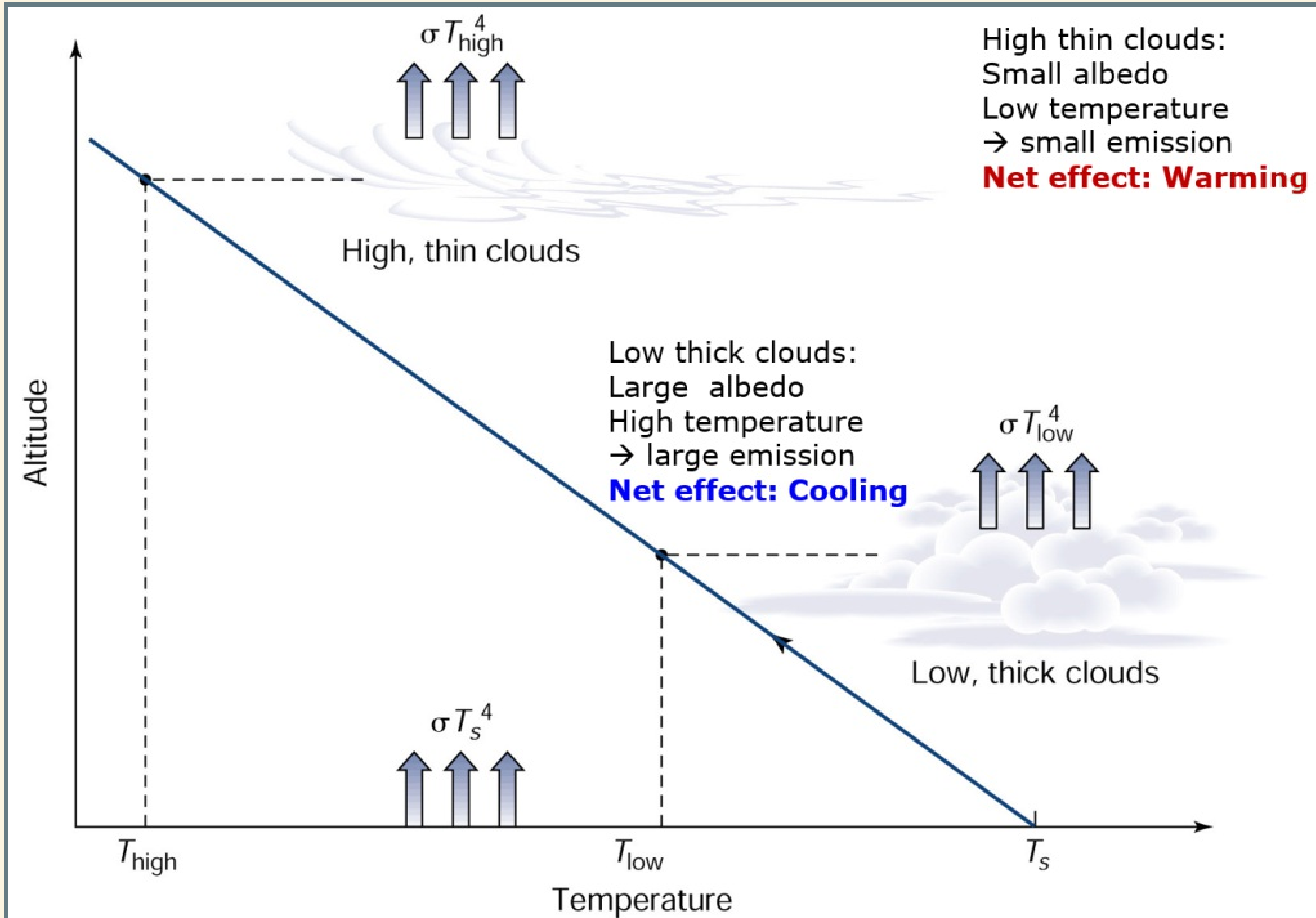
- Outgoing long-wave has to balance incoming sunlight
- Brighter sun → hotter surface → more water vapor
- Kombayashi-Ingersoll limit:
  - Sunlight below limit, there is a stable equilibrium with liquid water
  - Sunlight above limit, oceans boil dry



# Cloud Feedbacks

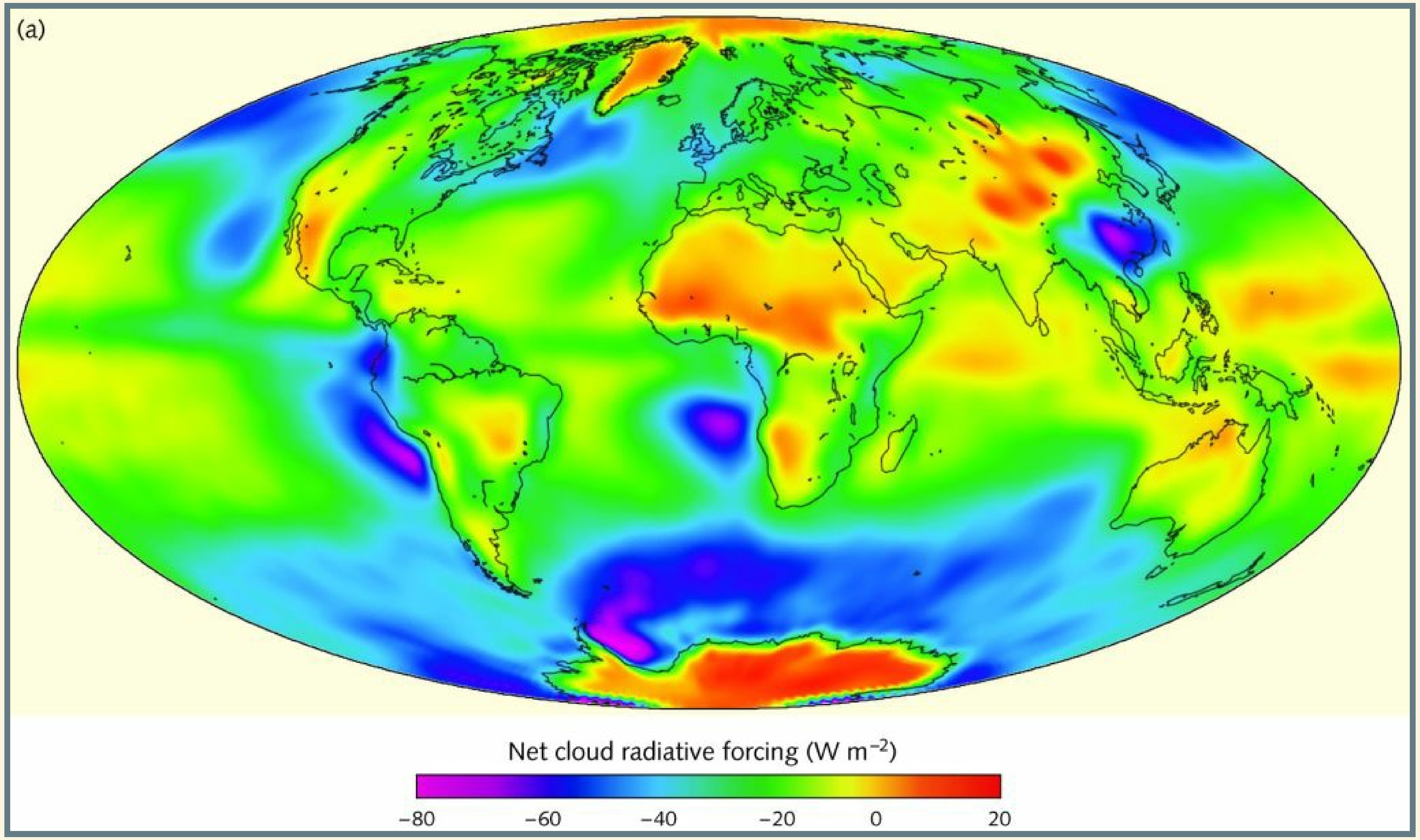
- What effect do clouds have on climate?
- What effects does climate have on clouds?
- Warmer $\rightarrow$ more clouds
- More clouds:
  - Higher albedo
    - (cools earth: negative feedback)
  - High emissivity: blocks longwave light
    - (warms earth: positive feedback)
- Which effect is bigger?

# Cloud Feedbacks



# Satellite Measurements

## Radiative forcing by clouds

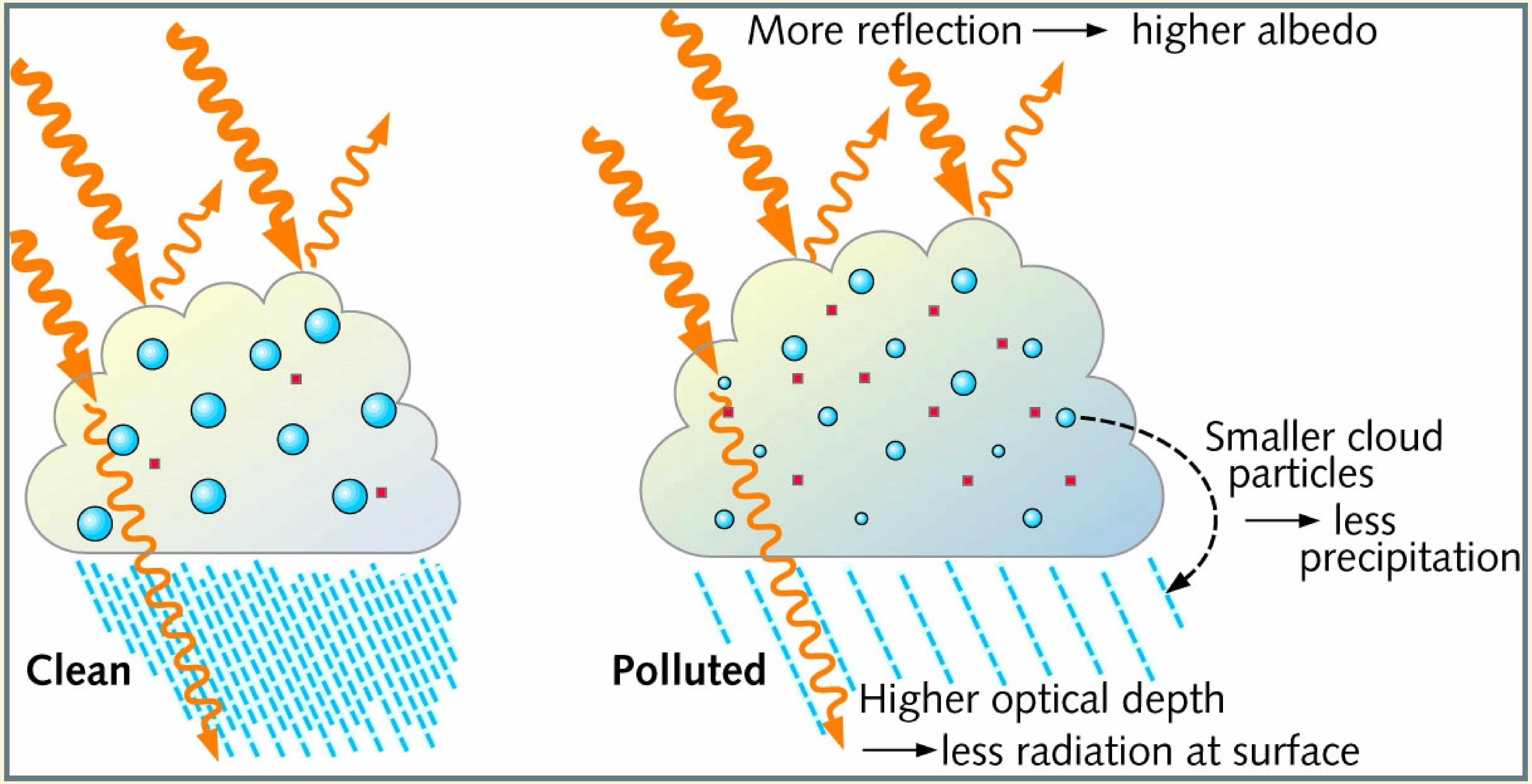



(negative = cooling, positive = warming)


ship track
marine layer
100 km

# Indirect Aerosol Effect

- Aerosol particles → more, smaller droplets
- Smaller droplets → greater albedo, longer lifetime
- More droplets → greater albedo, more absorption



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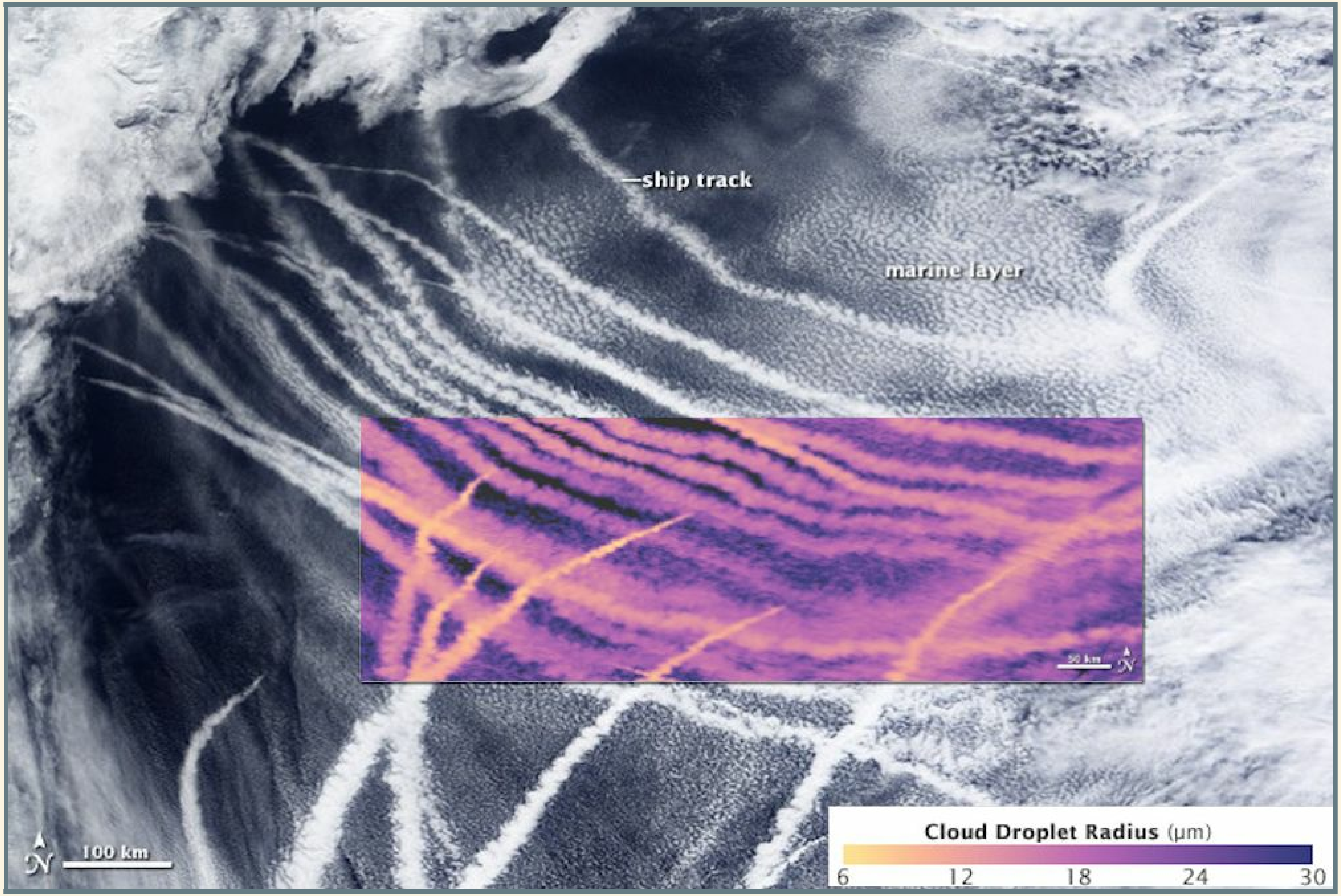

# Summary of Feedbacks

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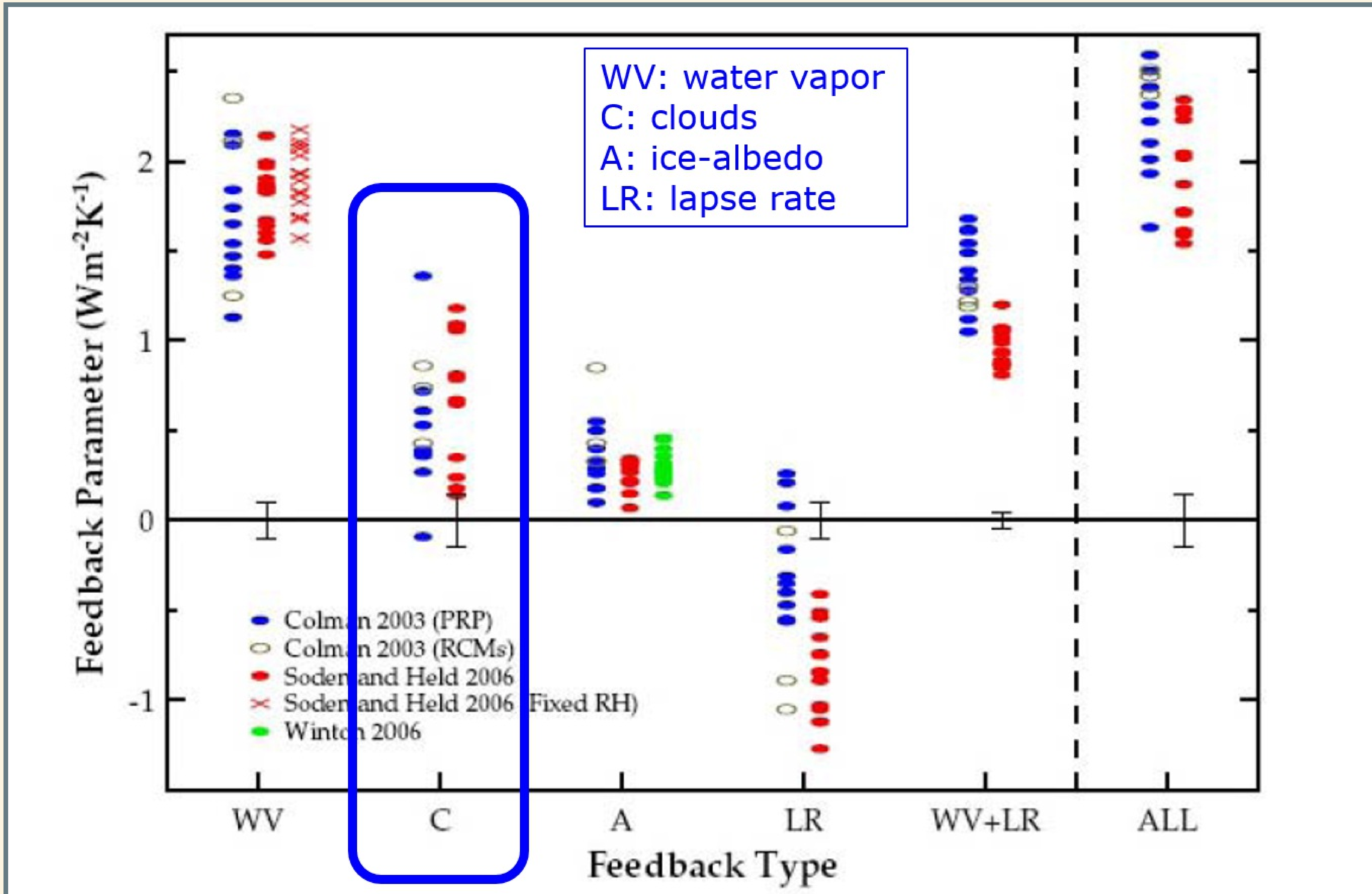

# Feedback Mathematics

# Feedback Mathematics

This mathematical section is for the graduate students.
Undergraduates will not be responsible for this material.

# Feedback Mathematics

- $Q$ is heat coming into the earth:
  - $Q = I_{\text{in}} - I_{\text{out}}$ ,
- Start out: $Q = I_{\text{in}} - I_{\text{out}} = 0$ ,
  - $T_{\text{ground}} = T_0$ .
- Forcing: change $Q \to Q_{\text{forcing}} > 0$
  - What happens?
- Response: $T_{\text{ground}} \to T_0 + \Delta T$
  - What happens to $Q$
- Feedback: $\Delta Q_{\text{feedback}} = f \Delta T$

# Stabilizing (Negative) Feedback

- Start out: $Q = I_{\text{in}} - I_{\text{out}} = 0$ ,
  - $T = T_0$
- Positive Forcing: change $Q \to Q_{\text{forcing}} > 0$
- Response: $T_{\text{ground}} \to T_0 + \Delta T$
- Feedback: $\Delta Q_{\text{feedback}} = f \Delta T$
  - New equilibrium:

$$\begin{aligned} \Delta Q &= -Q_{\text{forcing}} \\ Q &= Q_{\text{forcing}} + \Delta Q \\ &= Q_{\text{forcing}} - Q_{\text{forcing}} = 0 \end{aligned}$$

  - $\Delta T = \Delta Q / f = -Q_{\text{forcing}} / f$

# Stefan-Boltzmann Feedback

## Bare rock:

- $I_{\text{out}} = \epsilon \sigma T^4$
- $f_{\text{SB}} = -3.2\ \text{Wm}^{-2}\text{K}^{-1}$
- Forcing: $Q_{\text{forcing}} = I_{\text{in}} - I_{\text{out}} = +1\ \text{Wm}^{-2}$
  - Will this warm or cool the planet?
- $\Delta T = -Q_{\text{forcing}}/f$
- $$\Delta T = \frac{-1\ \text{Wm}^{-2}}{-3.2\ \text{Wm}^{-2}\text{K}^{-1}} = +0.32\ \text{K}$$
- Is Stefan-Boltzmann feedback positive or negative?
  - Negative because although temperature rises, SB feedback stabilizes it.

# Positive & Negative Feedback

# Positive & Negative Feedback

- Total feedback: $f = f_0 + f_1 + f_2 + \cdots$
- $f_0 = f_{SB}$: Stefan-Boltzmann
- Other feedbacks $f_1, f_2, \cdots$:
  - Positive ($f_i > 0$): amplifies temperature change
    - Warmings $\rightarrow$ hotter
    - Coolings $\rightarrow$ colder
  - Negative ($f_i < 0$): diminishes temperature change
    - Warmings $\rightarrow$ milder
    - Coolings $\rightarrow$ milder

# Amplification

$$
\begin{aligned}
a &= \frac{f_0}{f} = \frac{f_0}{f_0 + f_1 + f_2 + \cdots} \\
f_0 &= f_{\mathrm{SB}} = \text{Stefan-Boltzmann feedback}
\end{aligned}
$$

$$
\begin{aligned}
\Delta T &= \frac{-Q_{\text{forcing}}}{f} \\
&= a \times \frac{-Q_{\text{forcing}}}{f_0}
\end{aligned}
$$

- $a > 1$: net feedback is positive:
  - more severe warmings, coolings.
- $a < 1$: net feedback is negative:
  - milder warmings, coolings.

# 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)
  - Because they are smaller than the negative Stefan-Boltzmann feedback, so the total feedback remains negative.
  - Thus, positive feedbacks make global warming much greater than it would be with just the Stefan-Boltzmann feedback, but they’re not big enough to destabilize the planet.
- Many scientists worry that there may be a threshold of global warming where the positive feedbacks will become greater than Stefan-Boltzmann and destabilize the climate.