

# Climate Feedbacks

EES 3310/5310

Global Climate Change

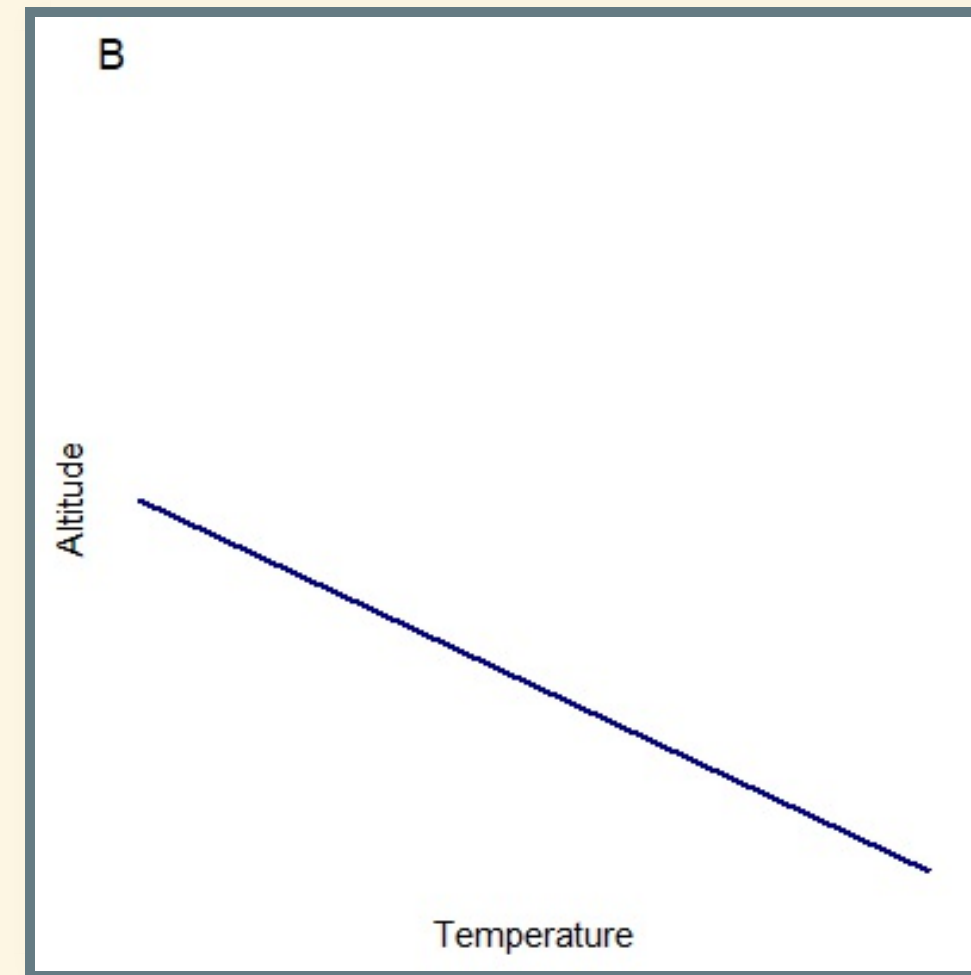
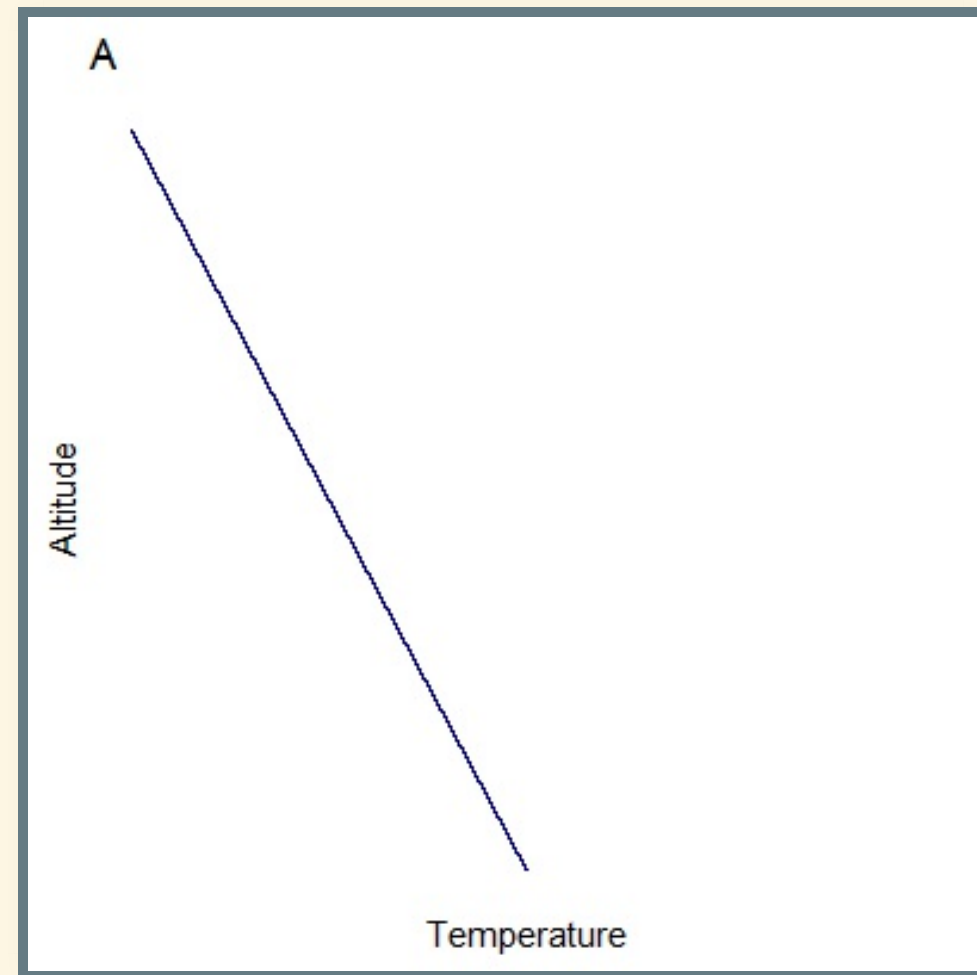
Jonathan Gilligan

Class #8: Friday Sept. 7 2018

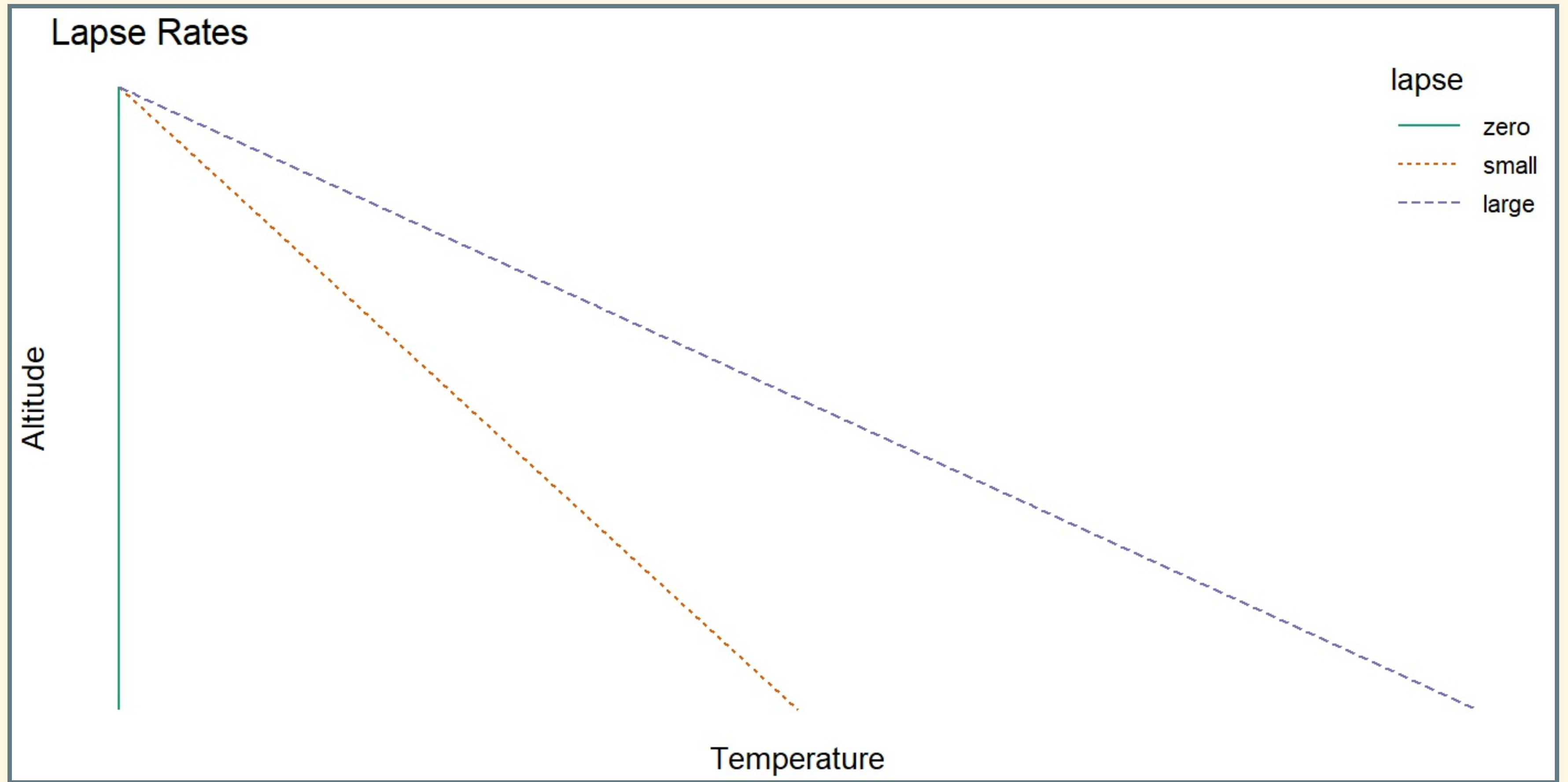


# Lapse Rates

# Which lapse rate is greater?



# Lapse Rates

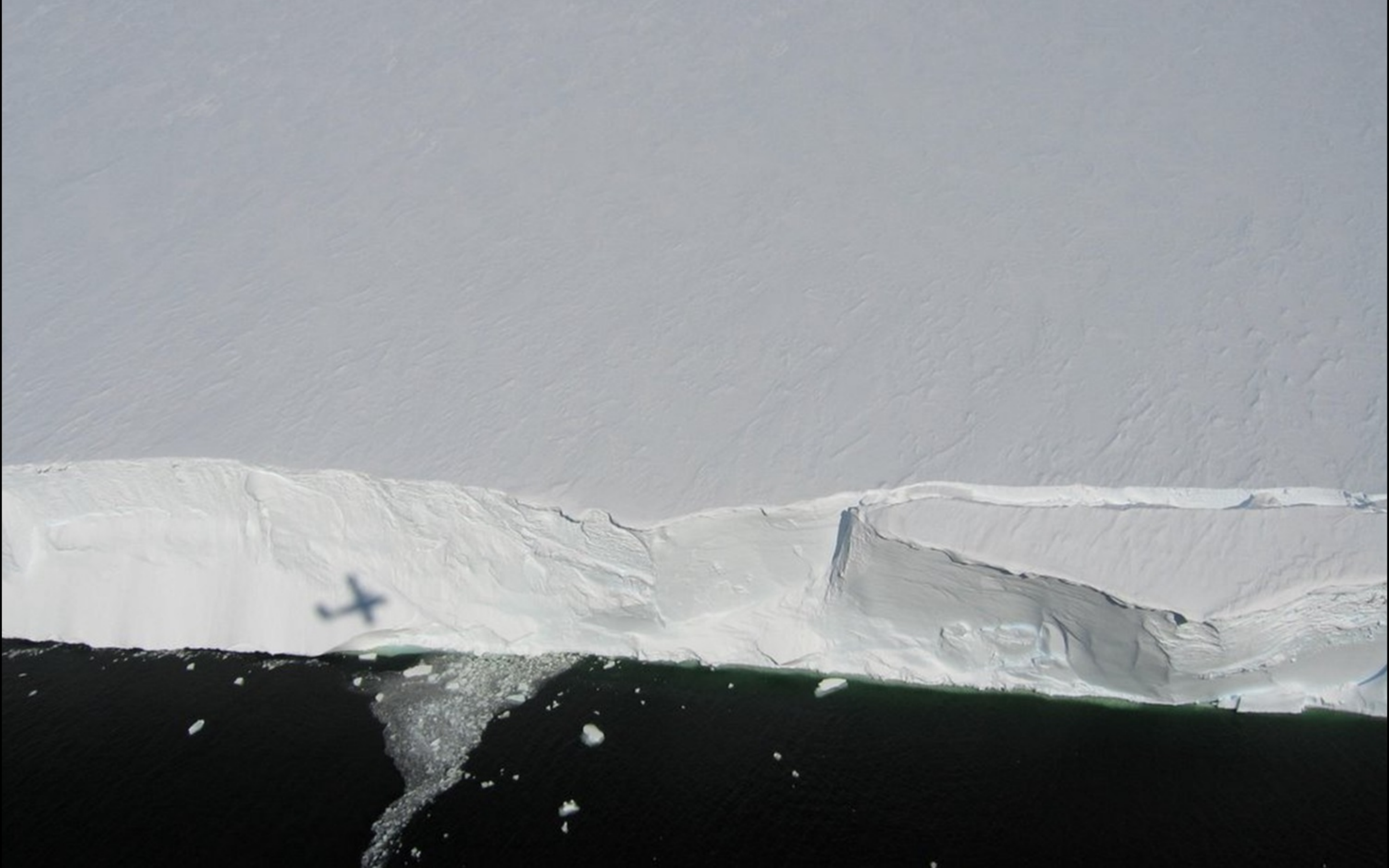


# Feedback

# 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  $Q \rightarrow Q_{\text{forcing}} > 0$ 
  - What happens?
- **Response:**  $T_{\text{ground}} \rightarrow T_0 + \Delta T$ 
  - **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

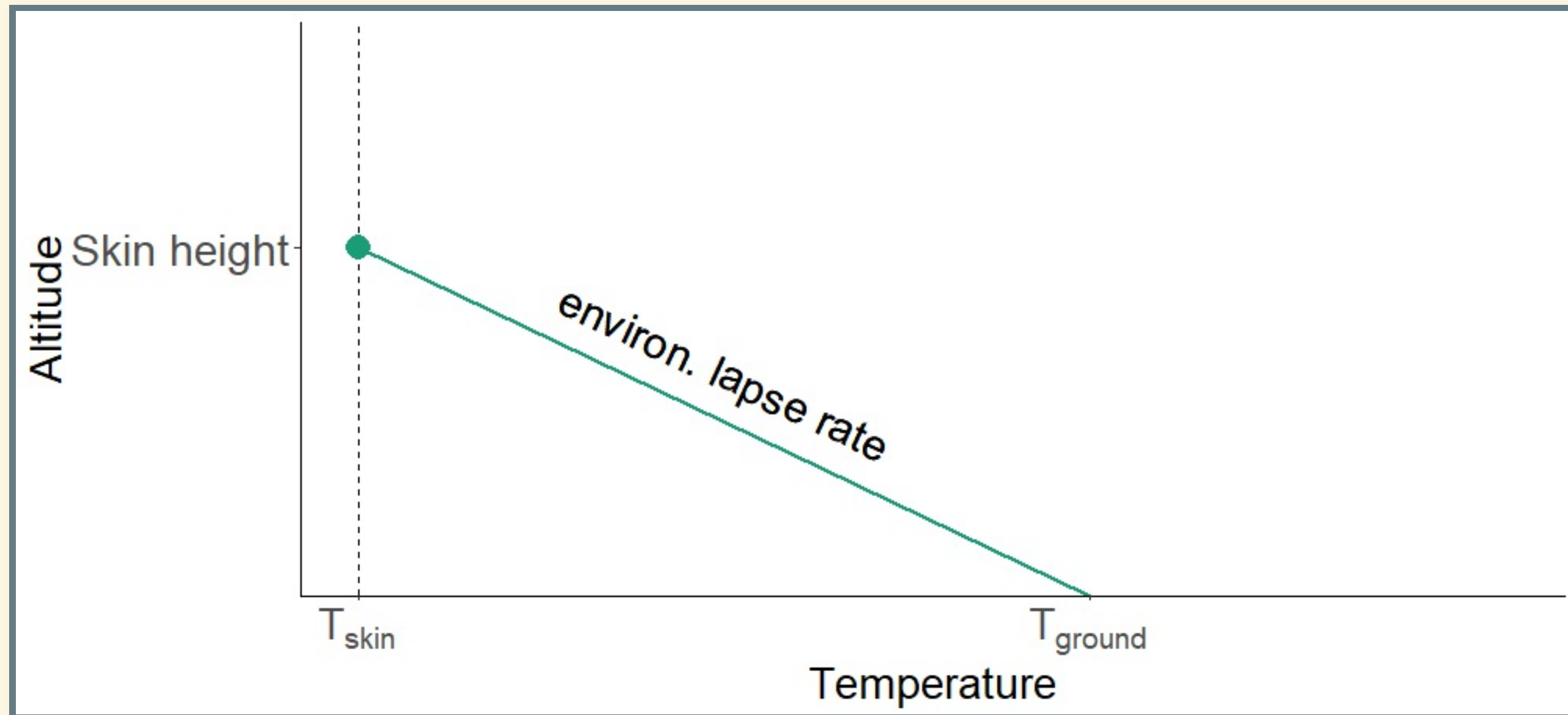




# Water-vapor

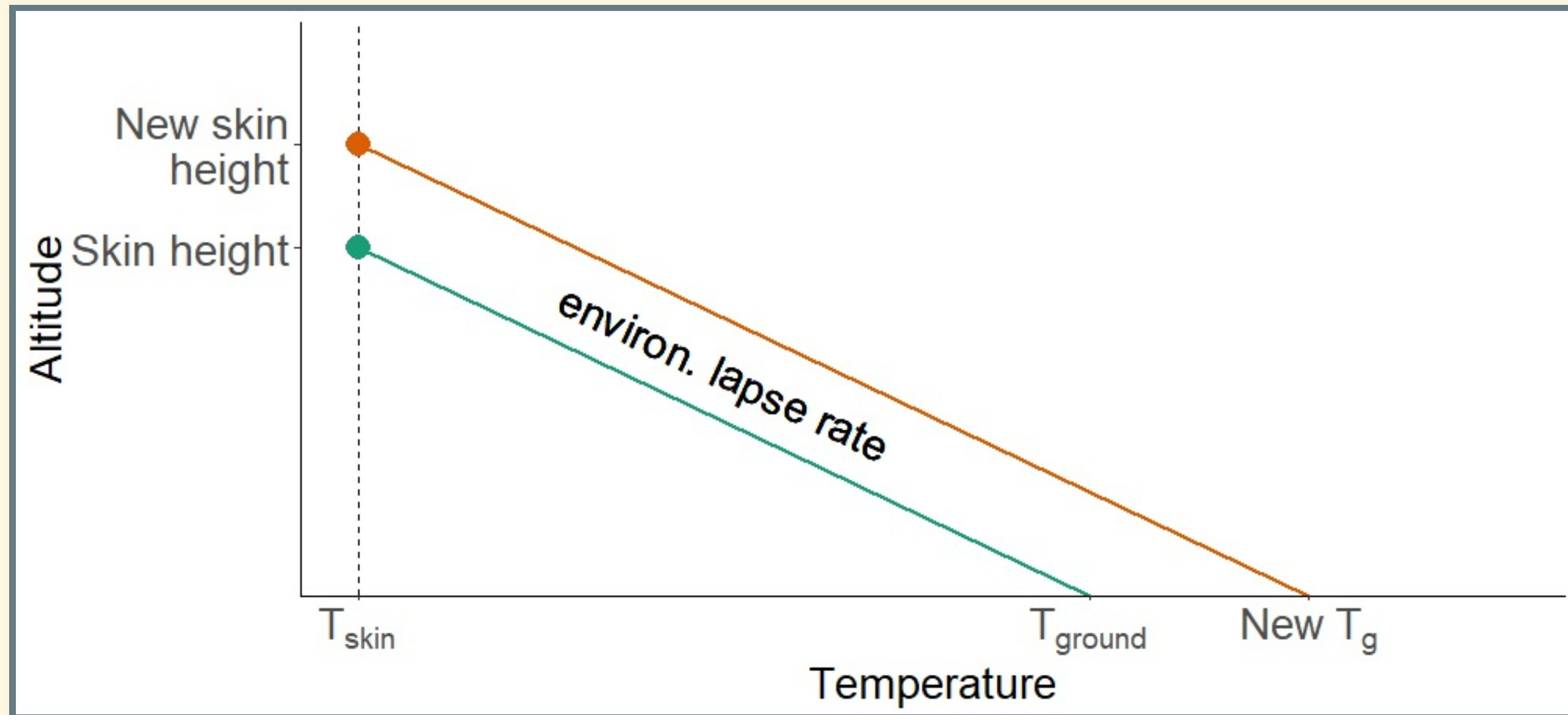
- Temperature rises
- What happens to humidity?
  - Humidity rises: more water vapor
- How does this affect  $\Delta Q$ ?
  - More water vapor  $\rightarrow$  bigger greenhouse effect
  - $I_{\text{out}}$  gets smaller
  - $\Delta Q = \Delta(I_{\text{in}} - I_{\text{out}}) > 0$
  - **Positive**  $\Delta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

# Greenhouse effect



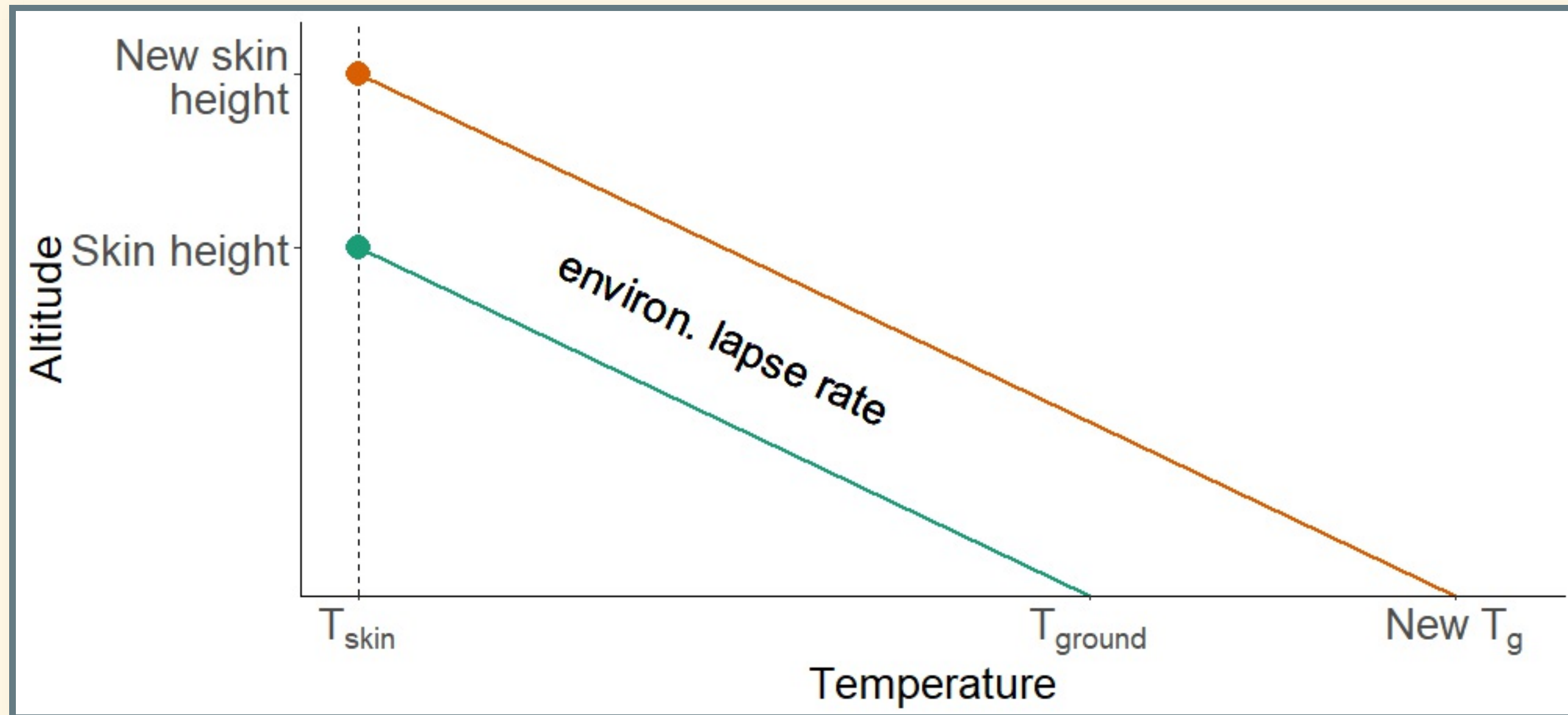
- Ground temp:  $T_{\text{ground}} = T_{\text{skin}} + h_{\text{skin}} \times \text{env. lapse}$

# Global warming



- Greater  $\text{CO}_2 \rightarrow$  greater skin height.
- Warming:  $\Delta T_{\text{ground}} = \Delta h_{\text{skin}} \times \text{env. lapse}$
- What does rising temperature do to water vapor?

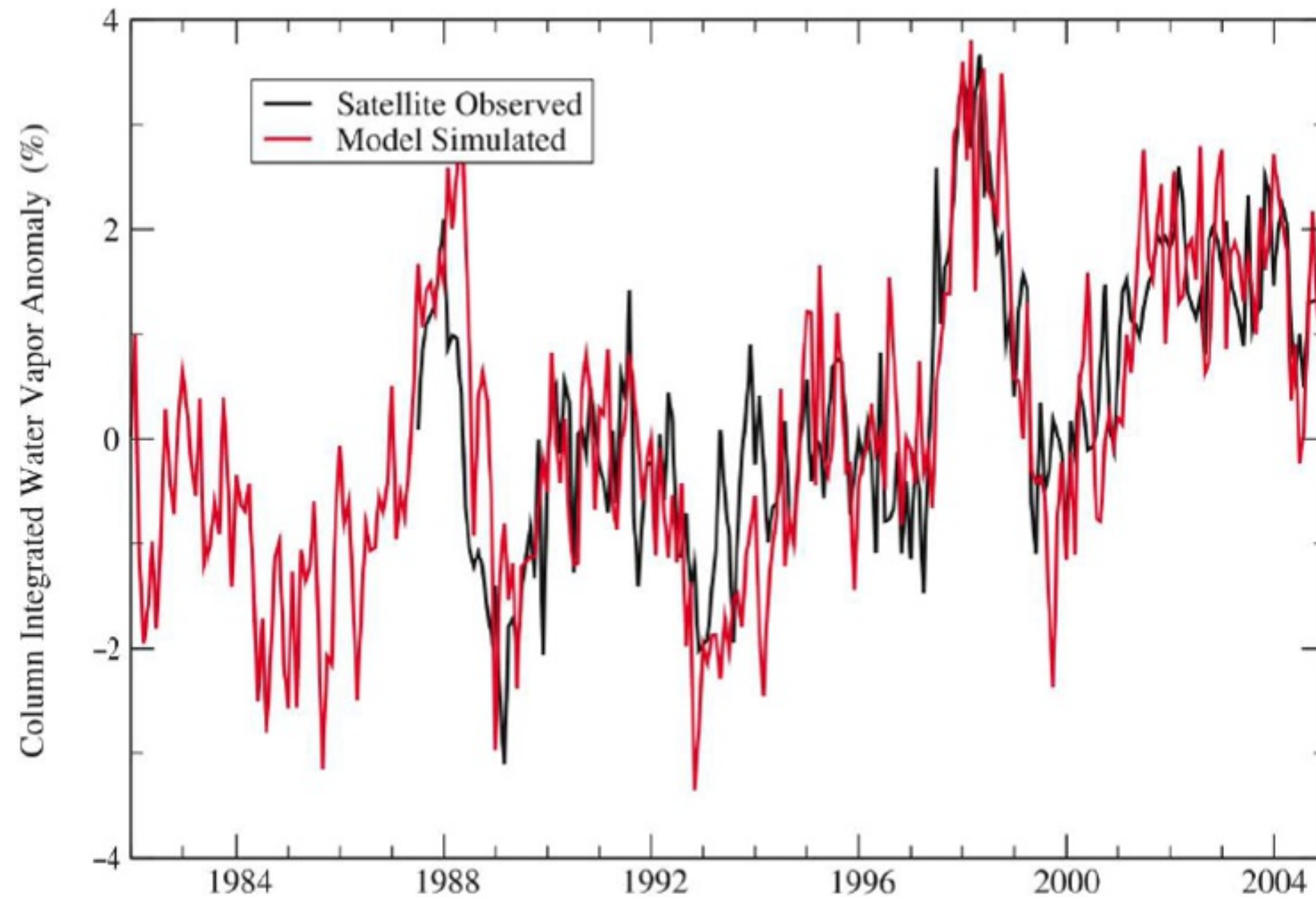
# Water Vapor Feedback



- 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

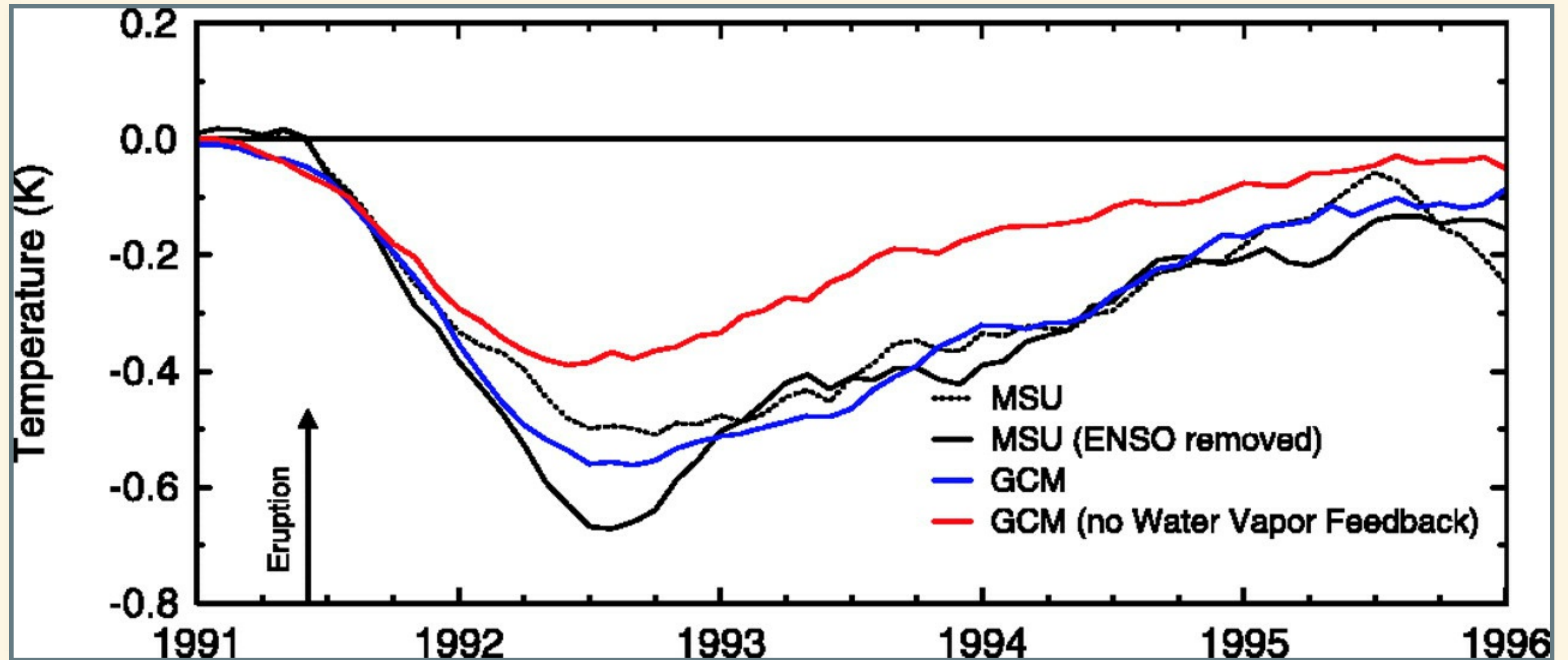
## Changes in Water Vapor



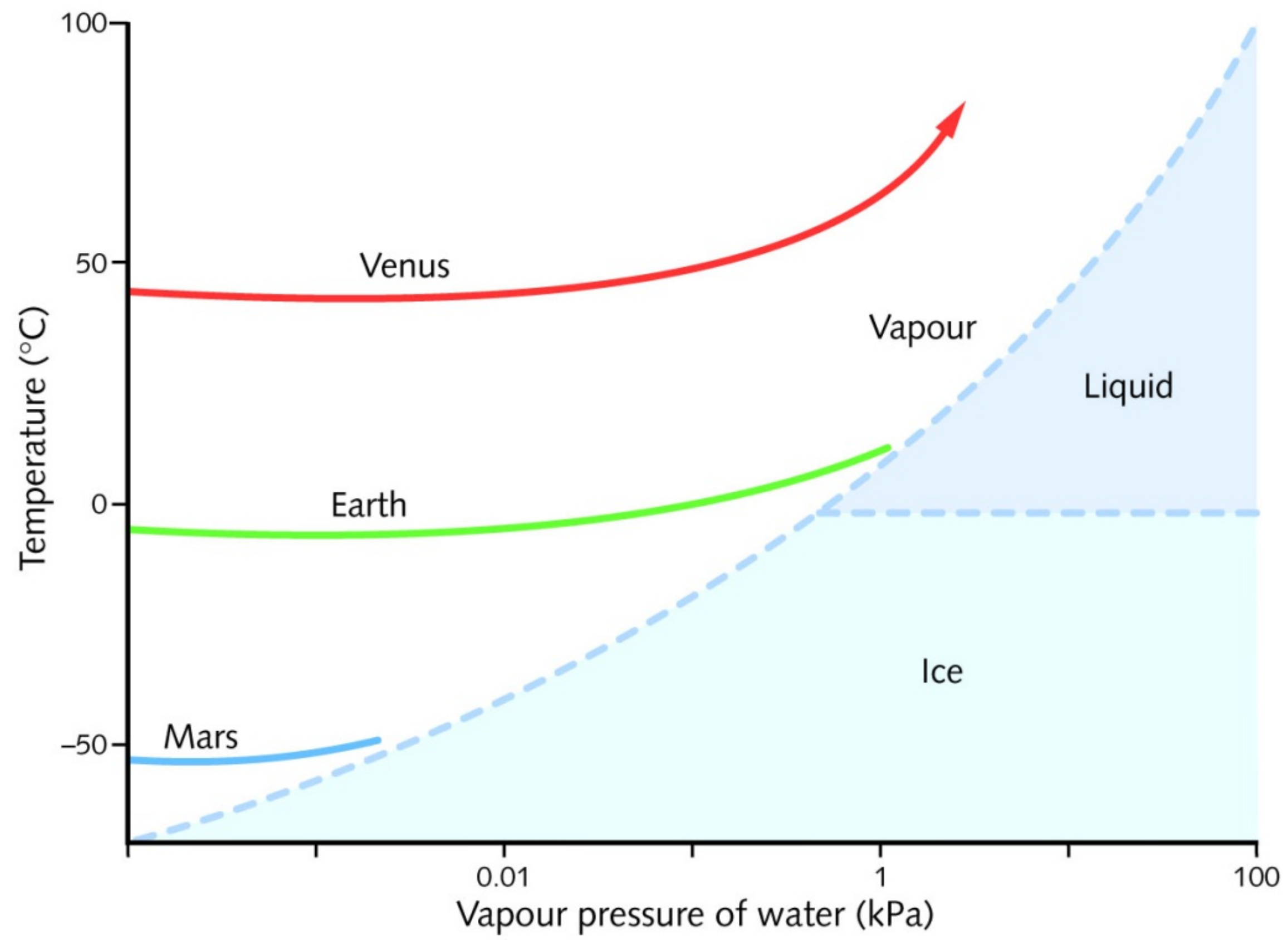
**To produce the red curve, a global atmospheric model was forced with the observed sea-surface temperatures for the years shown.**



# Testing Theory of Water-Vapor Feedback

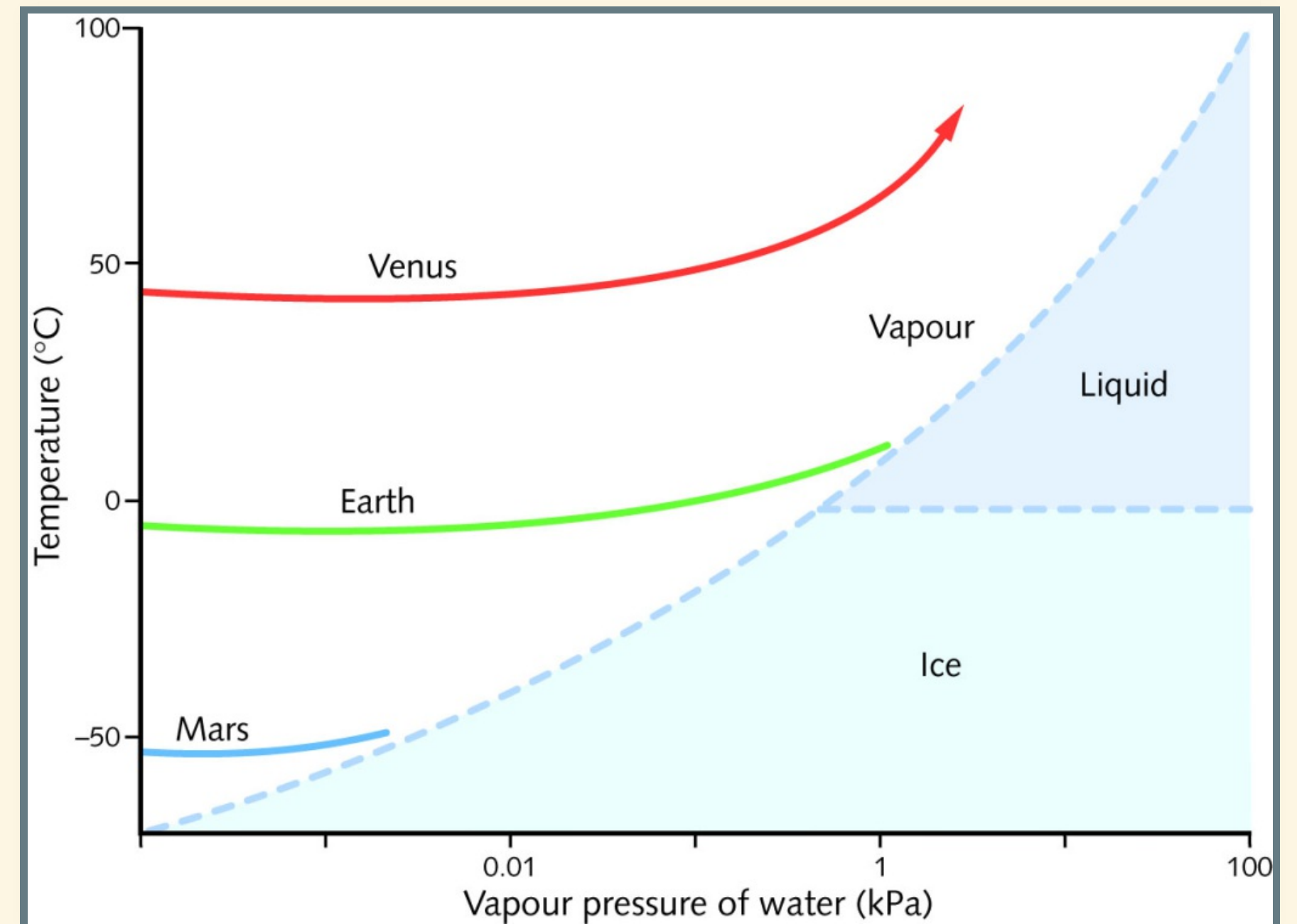


- Pinatubo erupts
- Model calculations with water vapor feedback correctly predict cooling
- Turn off water vapor feedback: incorrect predictions



# Runaway Greenhouse

- 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.

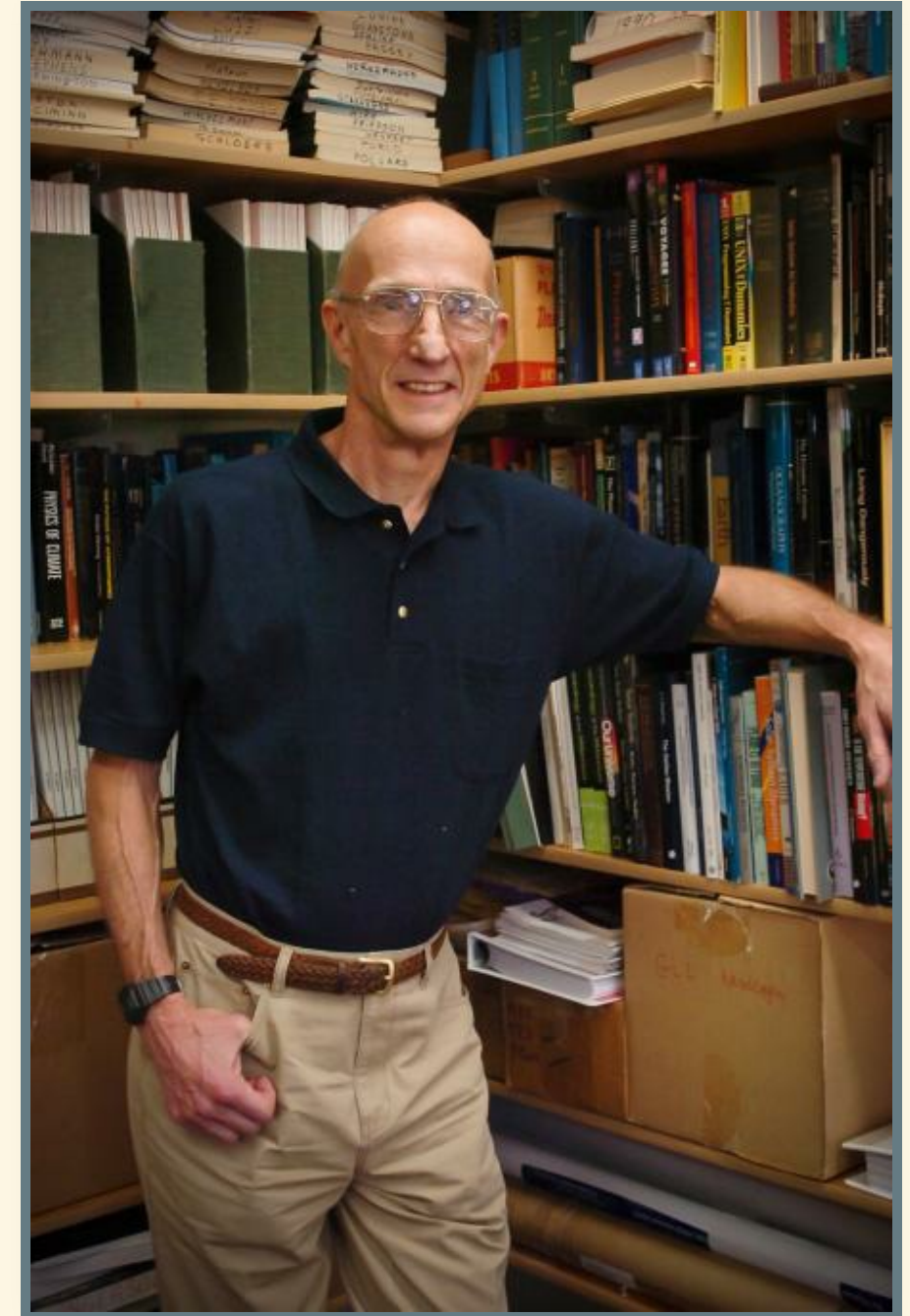




# Andrew Ingersoll & Runaway Greenhouse

1967: First class he ever taught

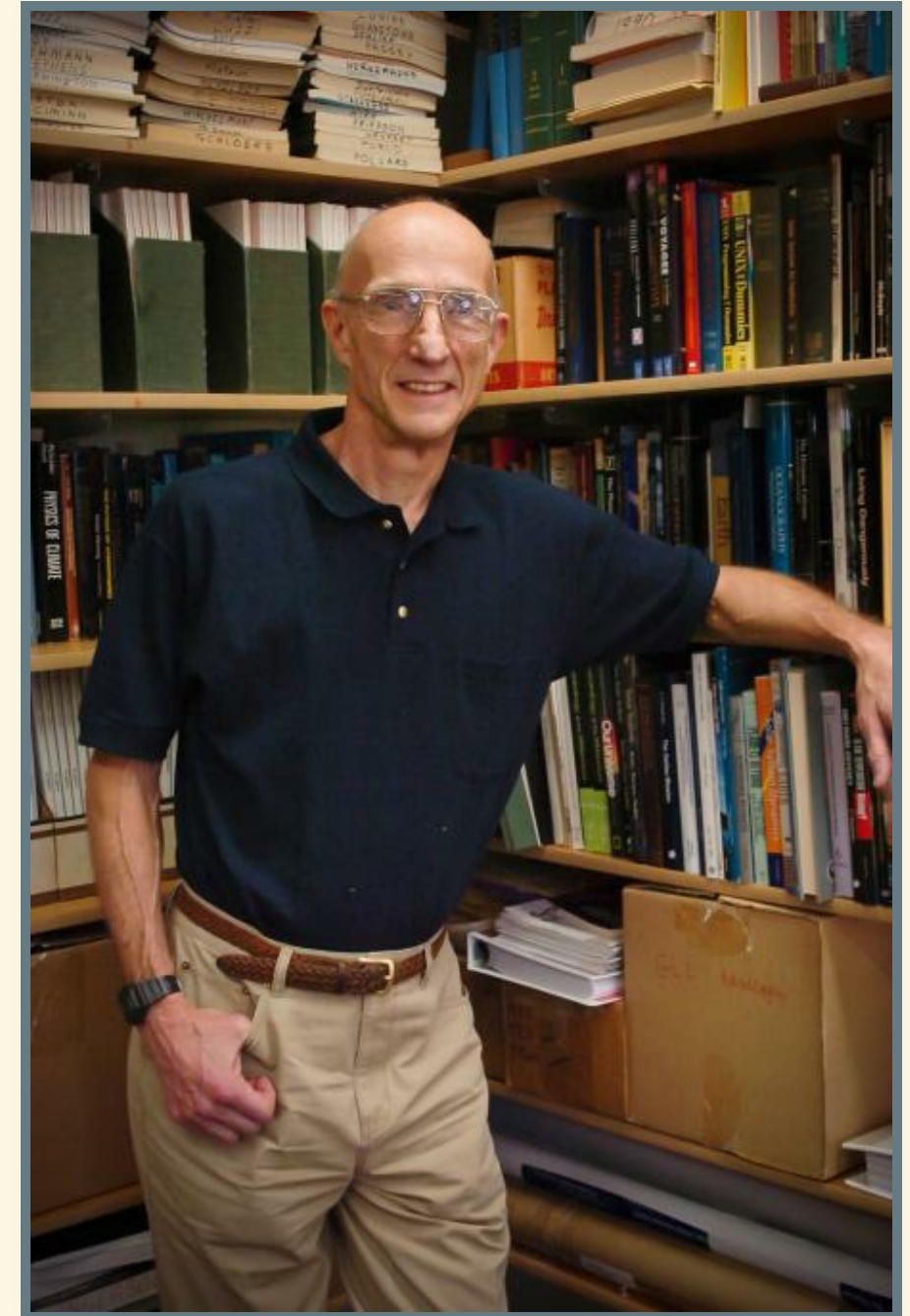
- Assigned homework:
  - Calculate water vapor feedback
- Students couldn't solve problem
- Fixed problem so students could solve it
- It worked for Earth, but not Venus
- Hmmmm ...
- It would work for Venus if all the oceans boiled dry.



# Andrew Ingersoll & Runaway Greenhouse

Wrote up results for publication

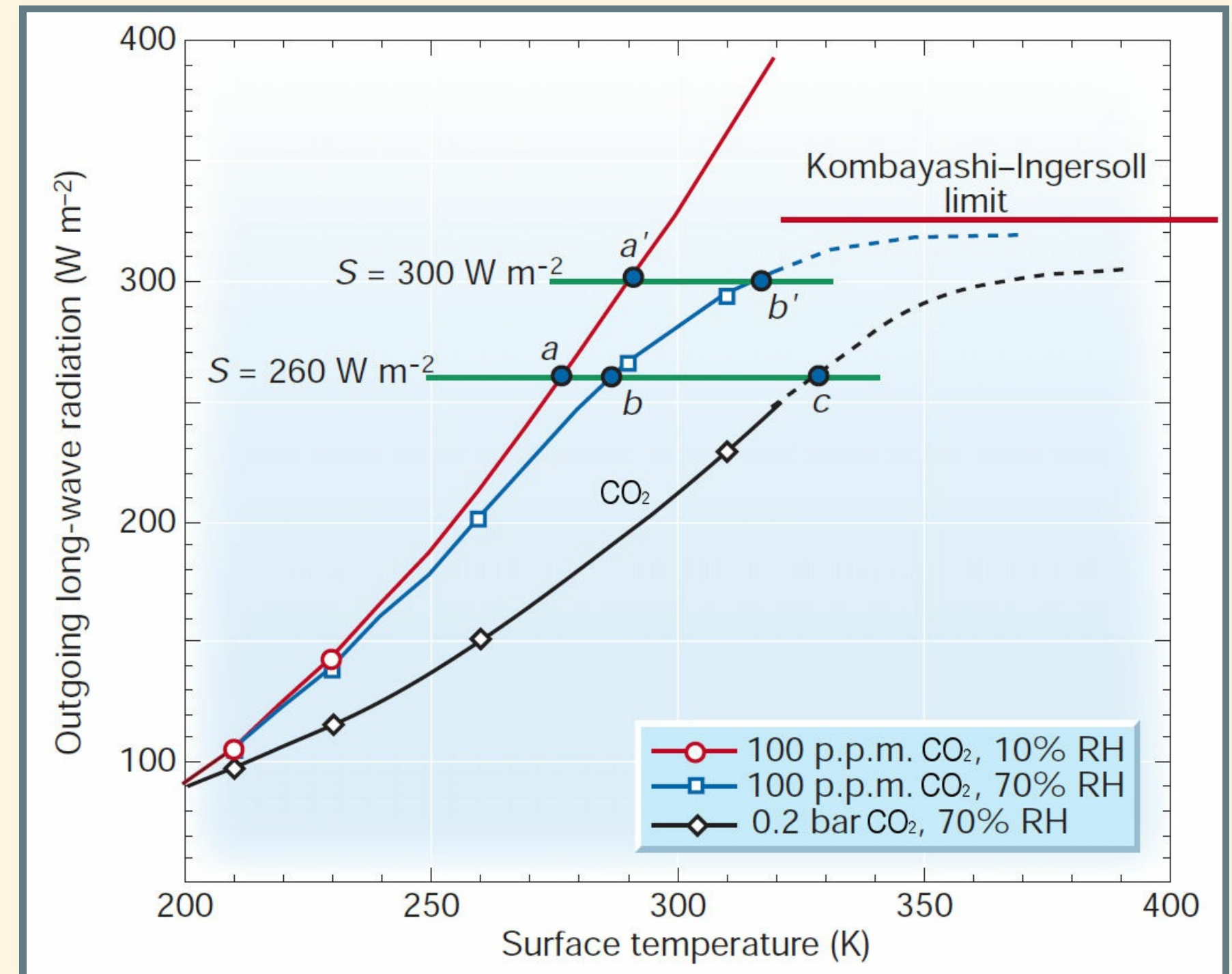
- Rejected by journal
- Submitted to another journal
  - Rejected again
- Submitted to a third journal
  - Accepted
- Now a classic paper
  - Cited more than 200 times





# Kombayashi-Ingersoll Limit

- Outgoing long-wave has to balance incoming sunlight
- 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

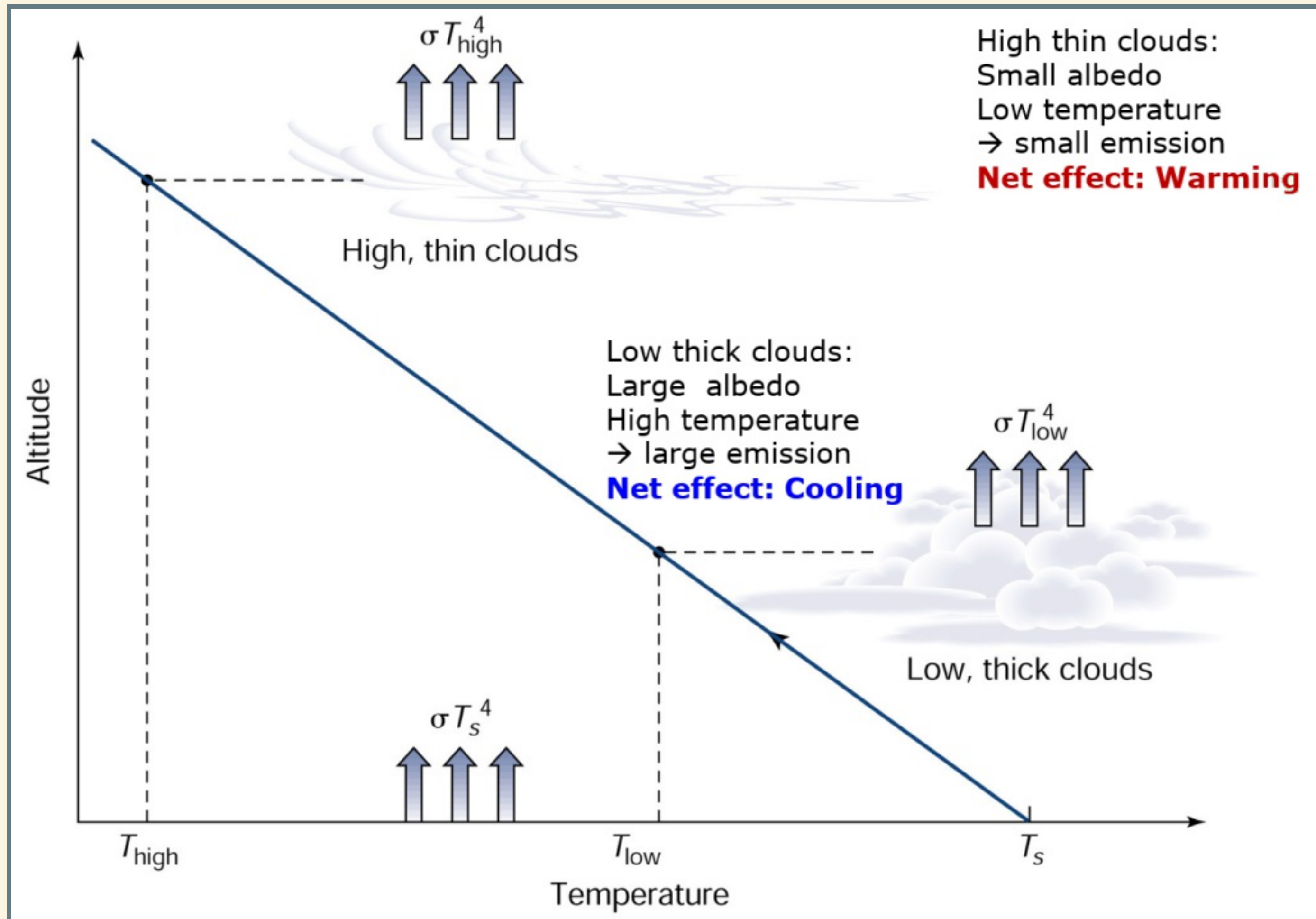
- What effect do clouds have on climate?
- What effects does climate have on clouds?
- Warmer → more clouds
- More clouds:
  - Higher albedo
    - (cools earth: negative feedback)
  - High emissivity: blocks longwave light
    - (warms earth: positive feedback)
- Which effect is bigger?







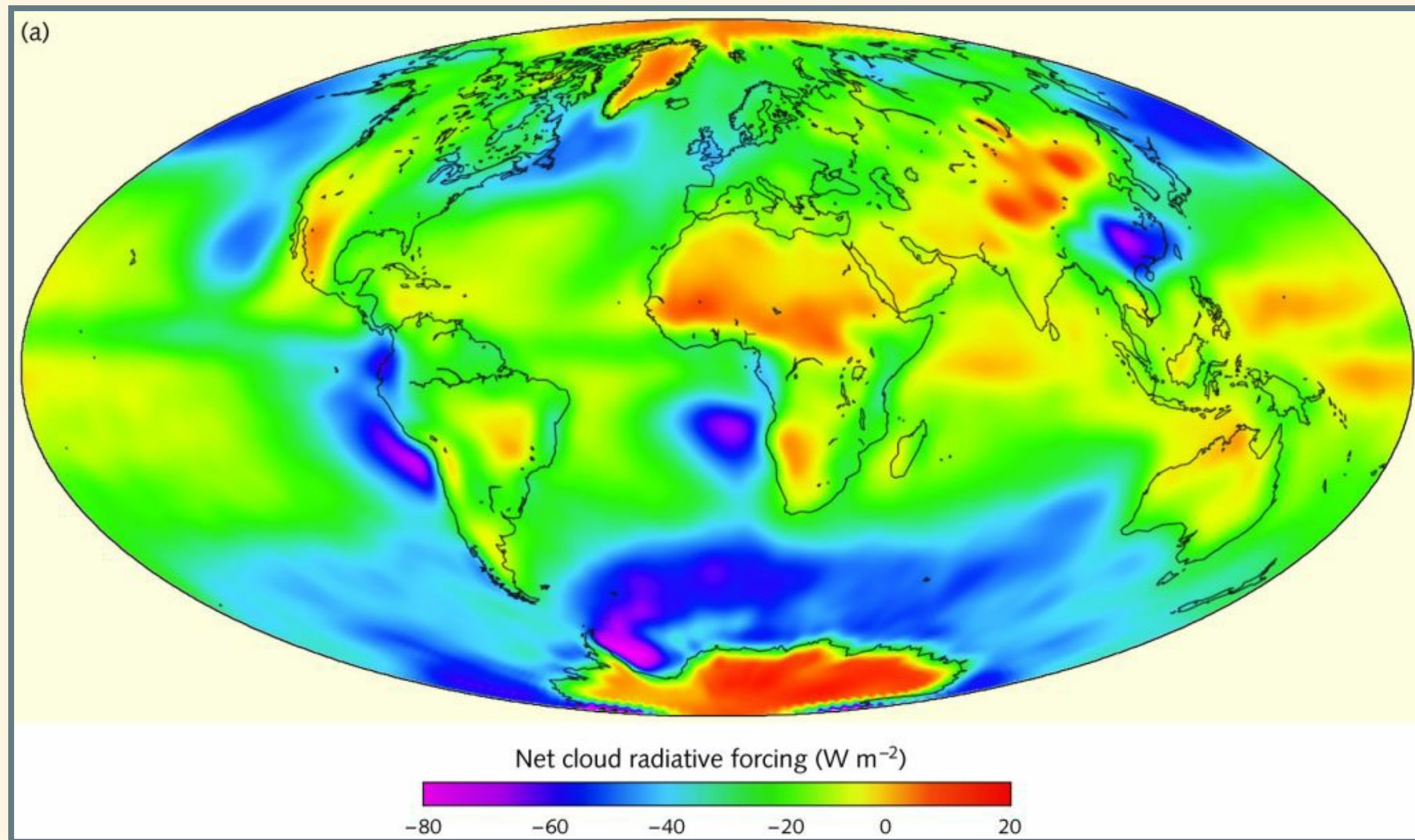
# Cloud Feedbacks



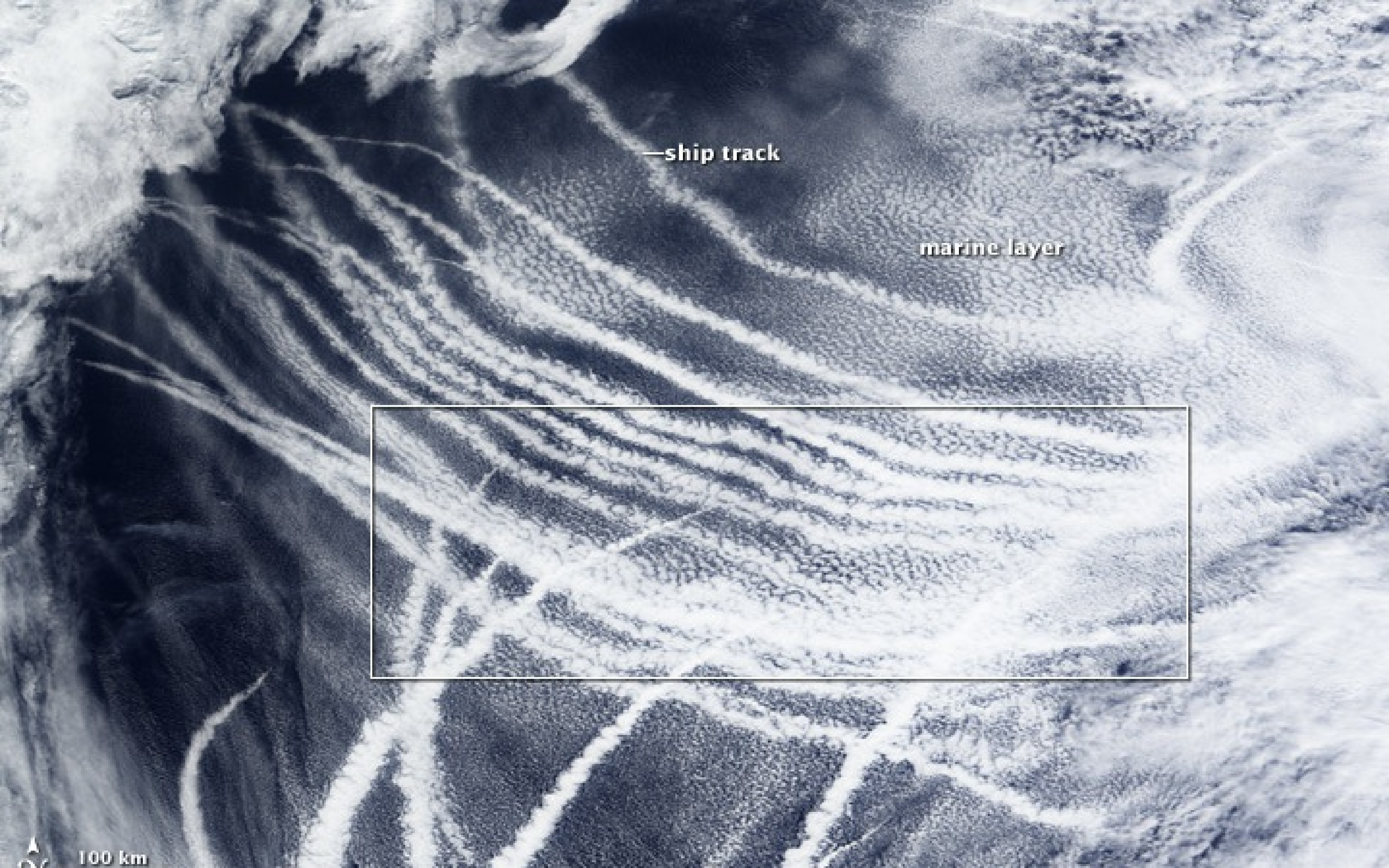


# Satellite Measurements

## Radiative forcing by clouds



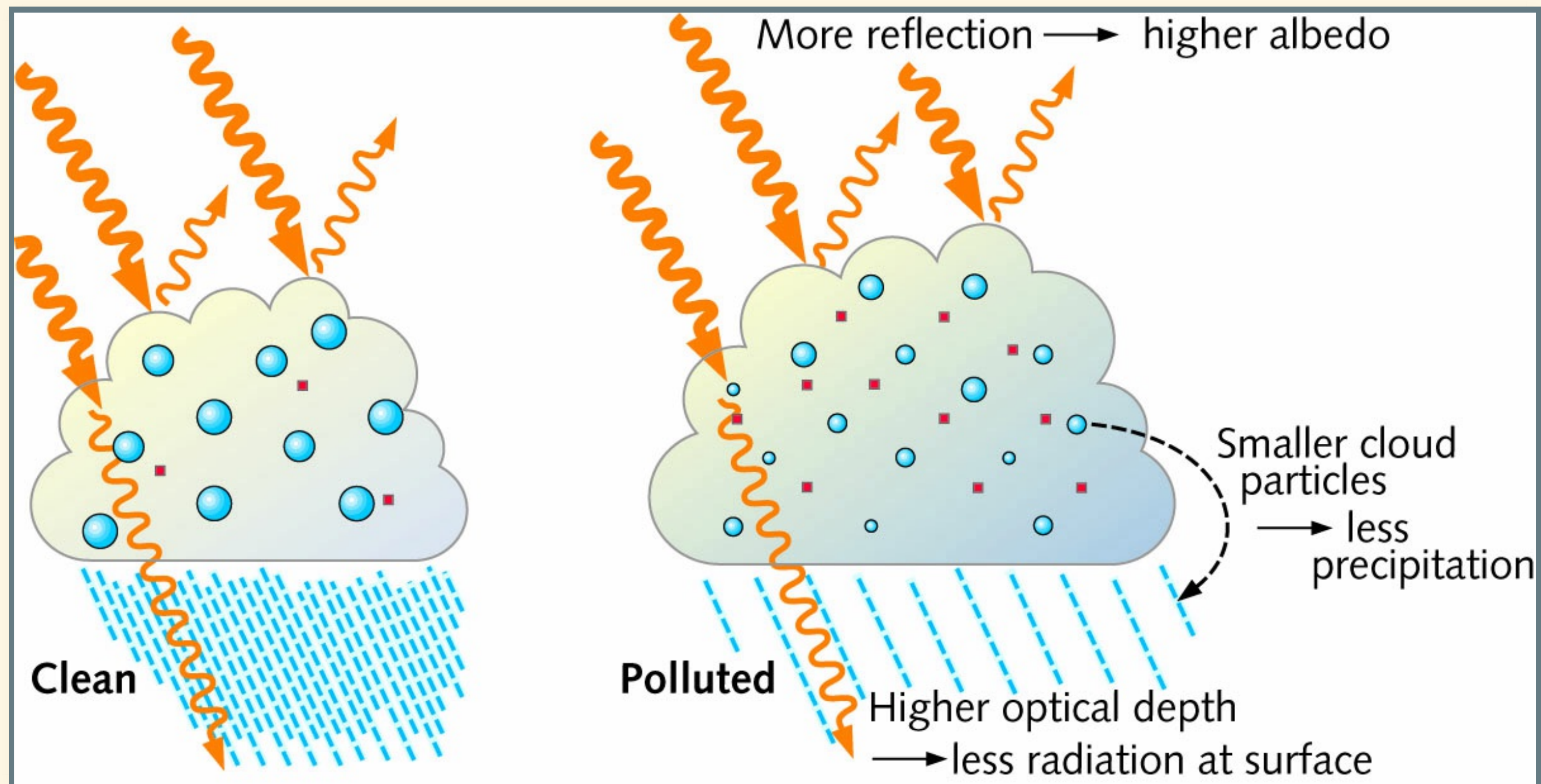
(negative = cooling, positive = warming)



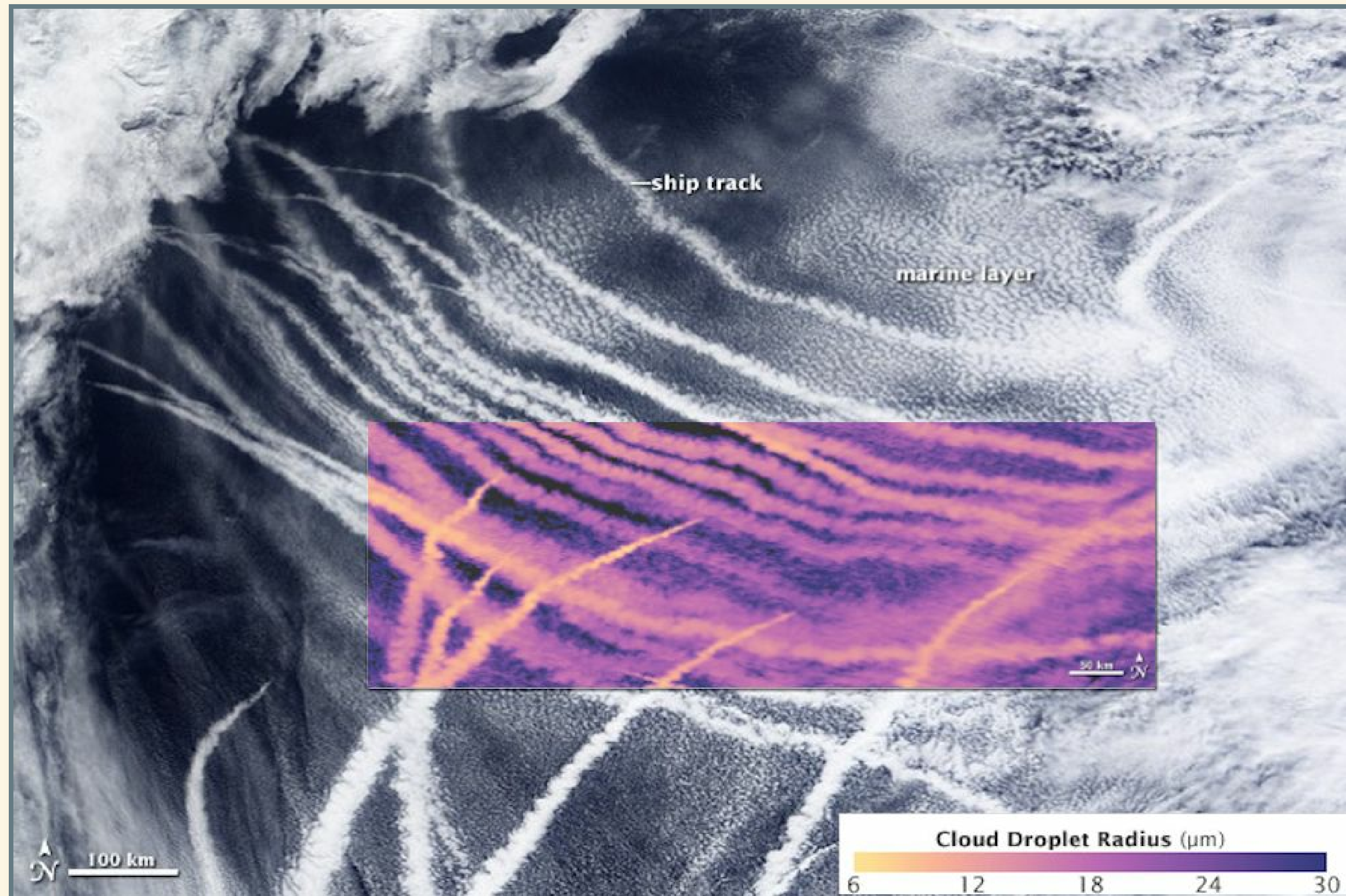


# Indirect Aerosol Effect

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



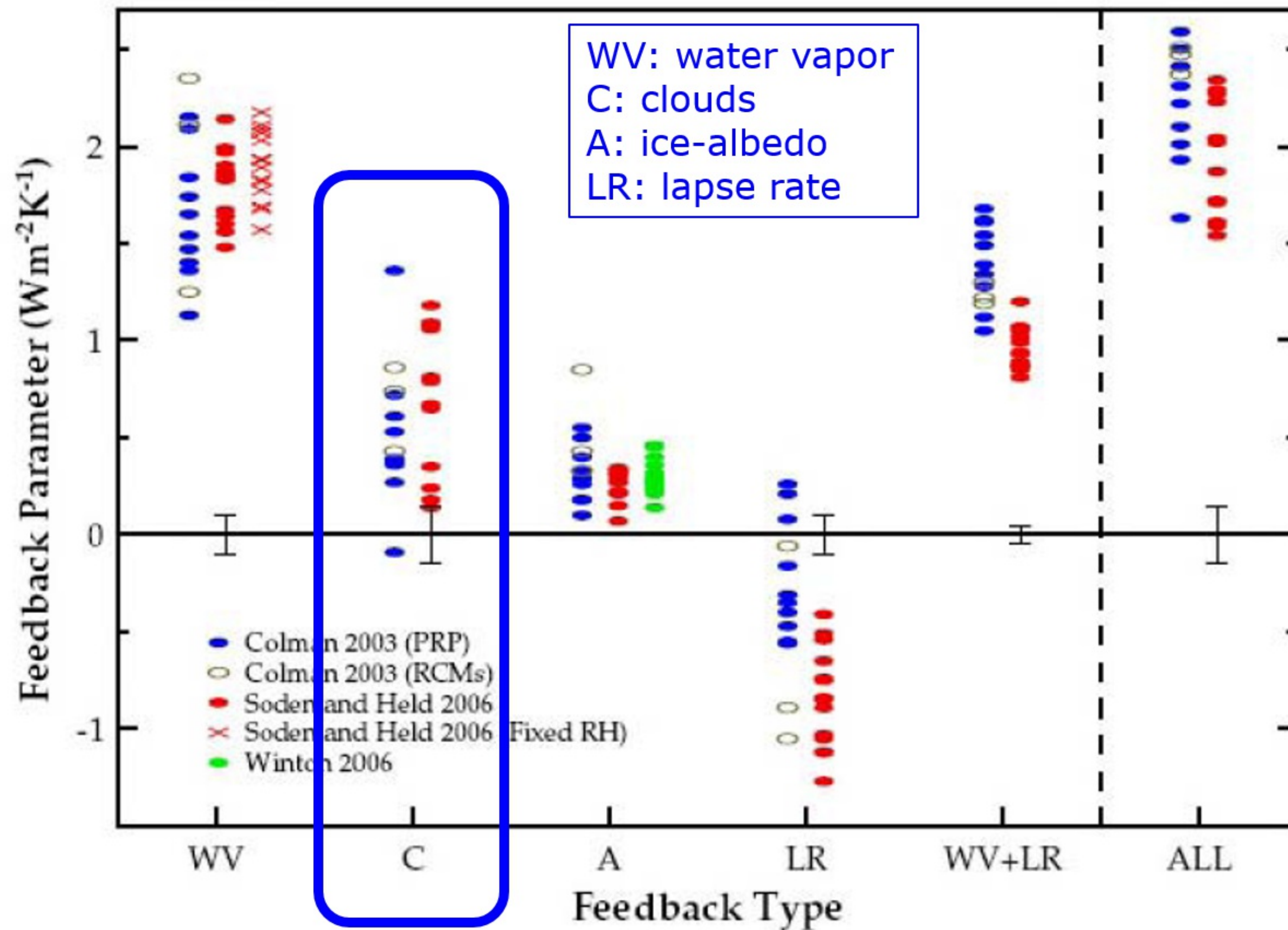
# Indirect Aerosol Effect



# Summary of Feedbacks



# Summary of Feedbacks



# 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  $Q \rightarrow Q_{\text{forcing}} > 0$ 
  - What happens?
- Response:  $T_{\text{ground}} \rightarrow T_0 + \Delta T$ 
  - 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  $Q \rightarrow Q_{\text{forcing}} > 0$

- Response:  $T_{\text{ground}} \rightarrow T_0 + \Delta T$

- Feedback:  $\Delta Q_{\text{feedback}} = f \Delta T$

- New equilibrium:

$$\Delta Q = -Q_{\text{forcing}}$$

$$Q = Q_{\text{forcing}} + \Delta Q$$

$$= Q_{\text{forcing}} - Q_{\text{forcing}} = 0$$

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

# 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:  $f = f_0 + f_1 + f_2 + \dots$
- $f_0 = f_{\text{SB}}$ : Stefan-Boltzmann
- Other feedbacks  $f_1, f_2, \dots$ :
  - 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

$$a = \frac{f_0}{f} = \frac{f_0}{f_0 + f_1 + f_2 + \dots}$$

$f_0 = f_{\text{SB}} = \text{Stefan-Boltzmann feedback}$

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

- $a > 1$ : 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.