Feedbacks

EES 2110
Introduction to Climate Change
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Class #11: Friday, February 03 2023

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**, 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

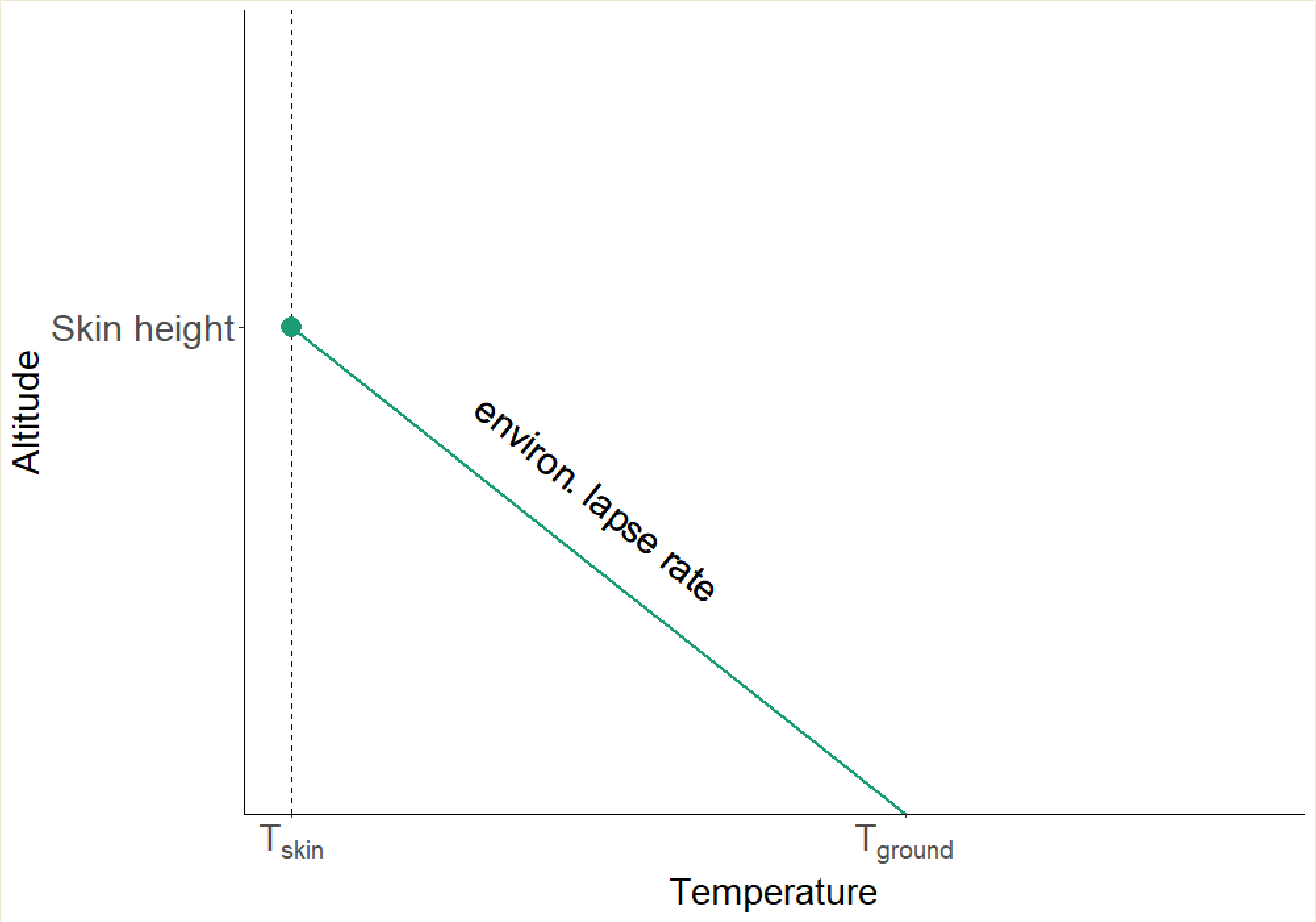
- Temperature rises ($\Delta T > 0$)
  - Ice recedes
  - Albedo gets smaller
  - More sunlight absorbed
  - $\Delta Q > 0$
  - $\displaystyle\frac{\Delta Q}{\Delta T} > 0$
    - Positive feedback

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

Water-vapor

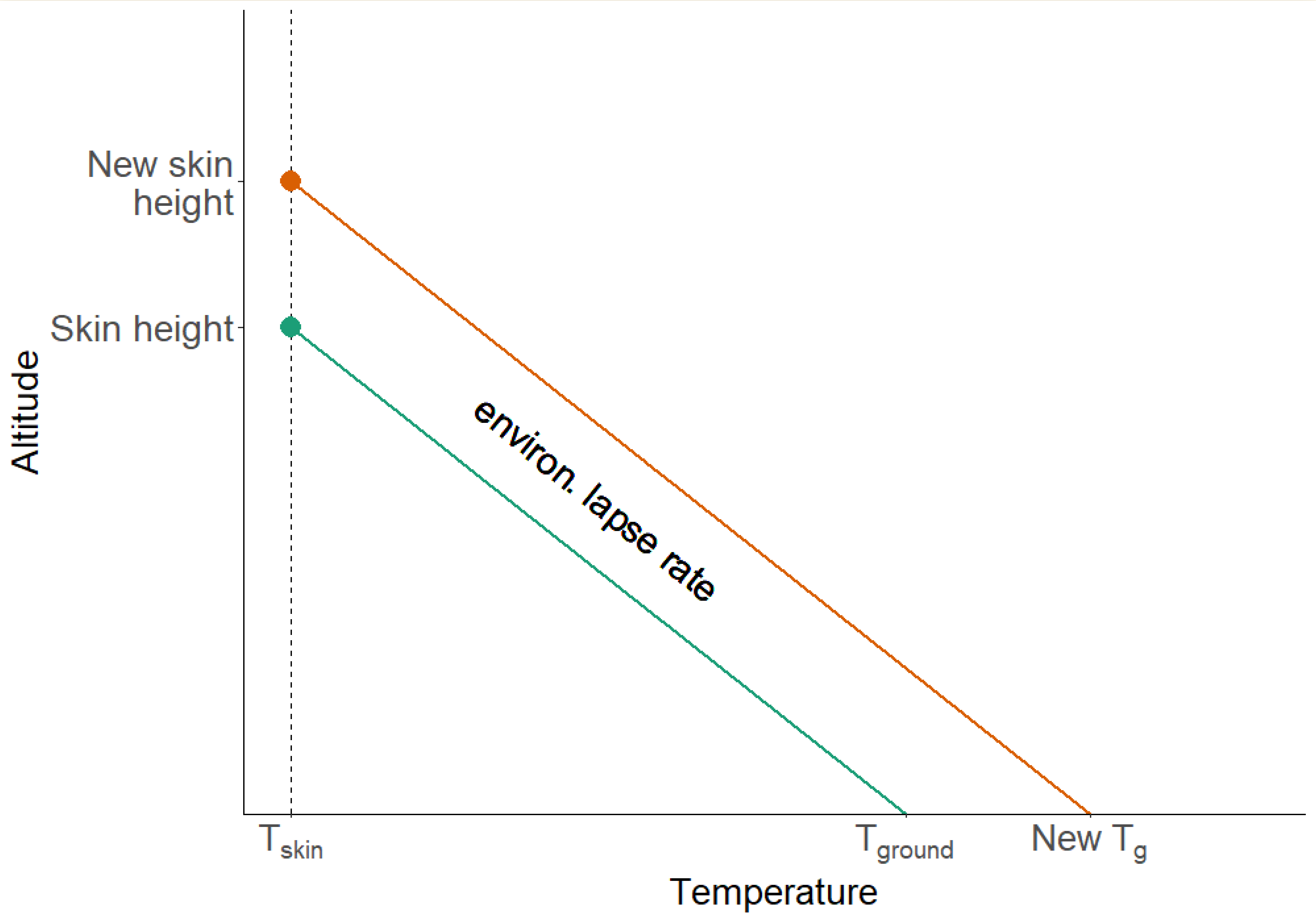
- Temperature rises
- What happens to humidity?
  - Humidity rises: more water vapor
- How does this affect ΔQ?
  - More water vapor $\rightarrow$ bigger greenhouse effect
  - I_{out} gets smaller
  - $\Delta Q = \Delta(I_{\text{in}} - I_{\text{out}}) > 0$
  - Positive $\Delta T \rightarrow \text{Positive}~\Delta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

Greenhouse effect



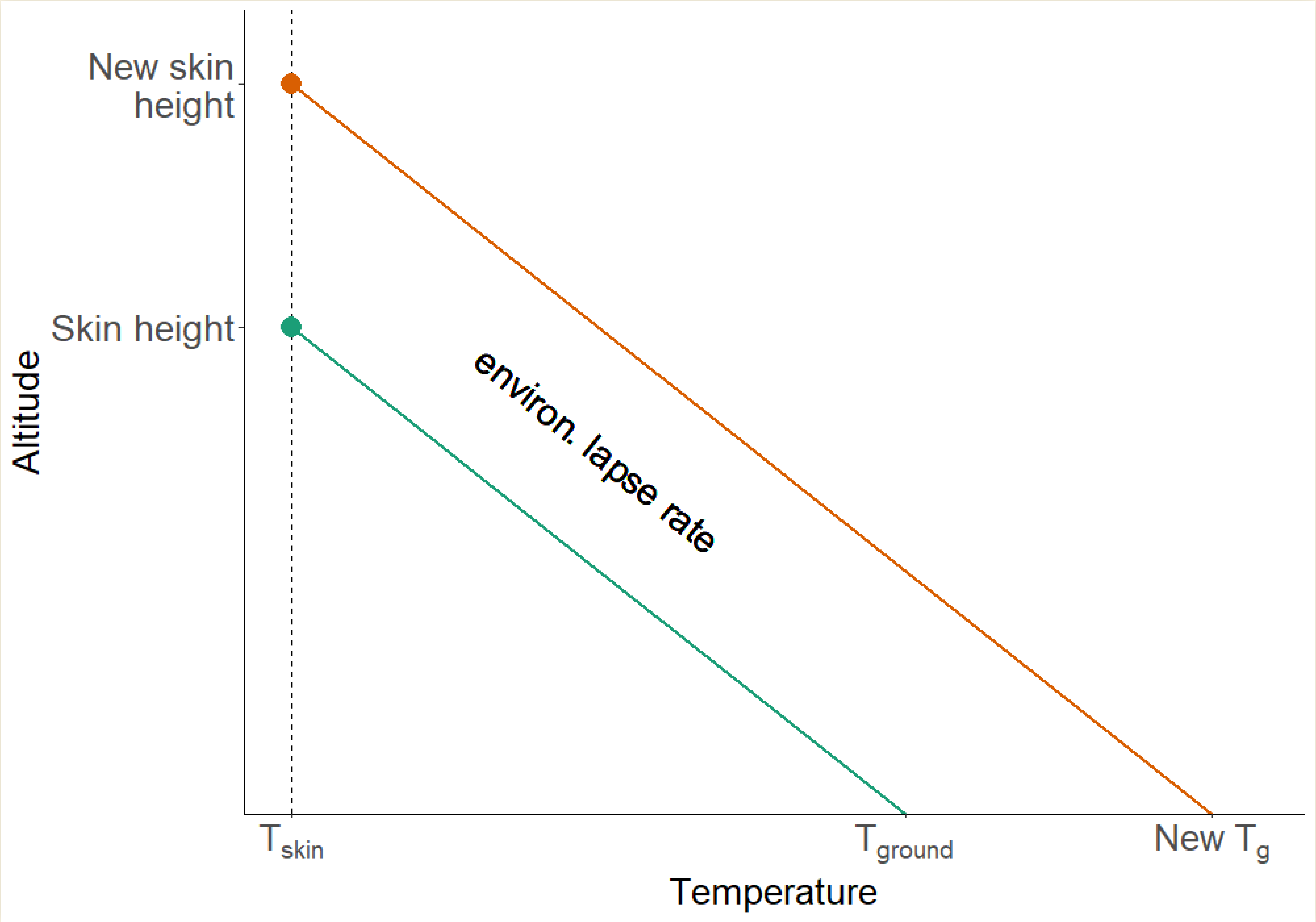
- Ground temp: $T_{\text{ground}} = T_{\text{skin}} + h_{\text{skin}} \times \text{env. lapse}$

Global warming



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

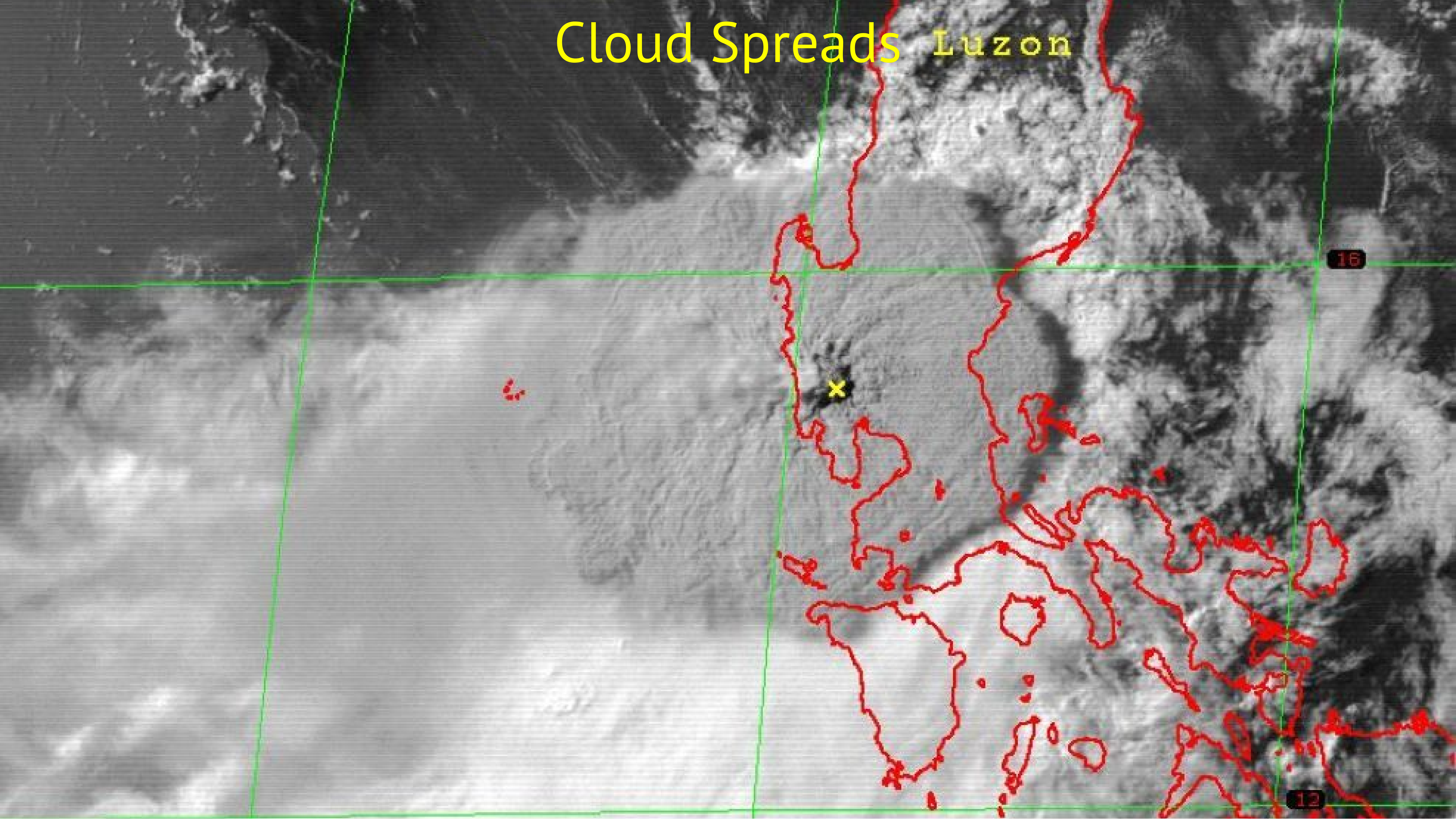
Water Vapor Feedback



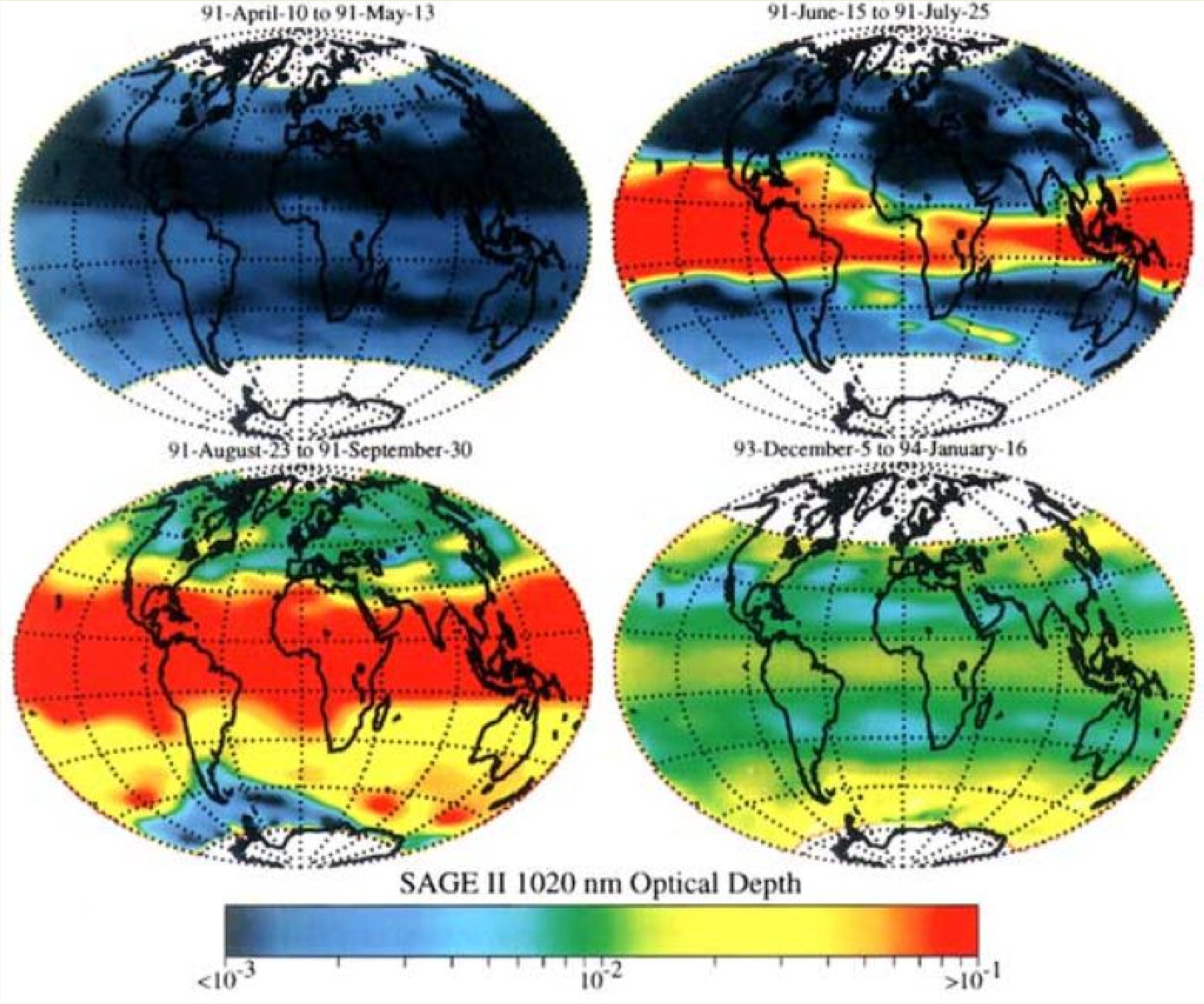
- Rising temperature $\rightarrow$ greater humidity
- Greater humidity $\rightarrow$ skin height rises even higher
- $\Delta T_{\text{ground}} = \Delta h_{\text{skin}} \times \text{Lapse}$

Interlude: Volcanic & Nuclear Winter

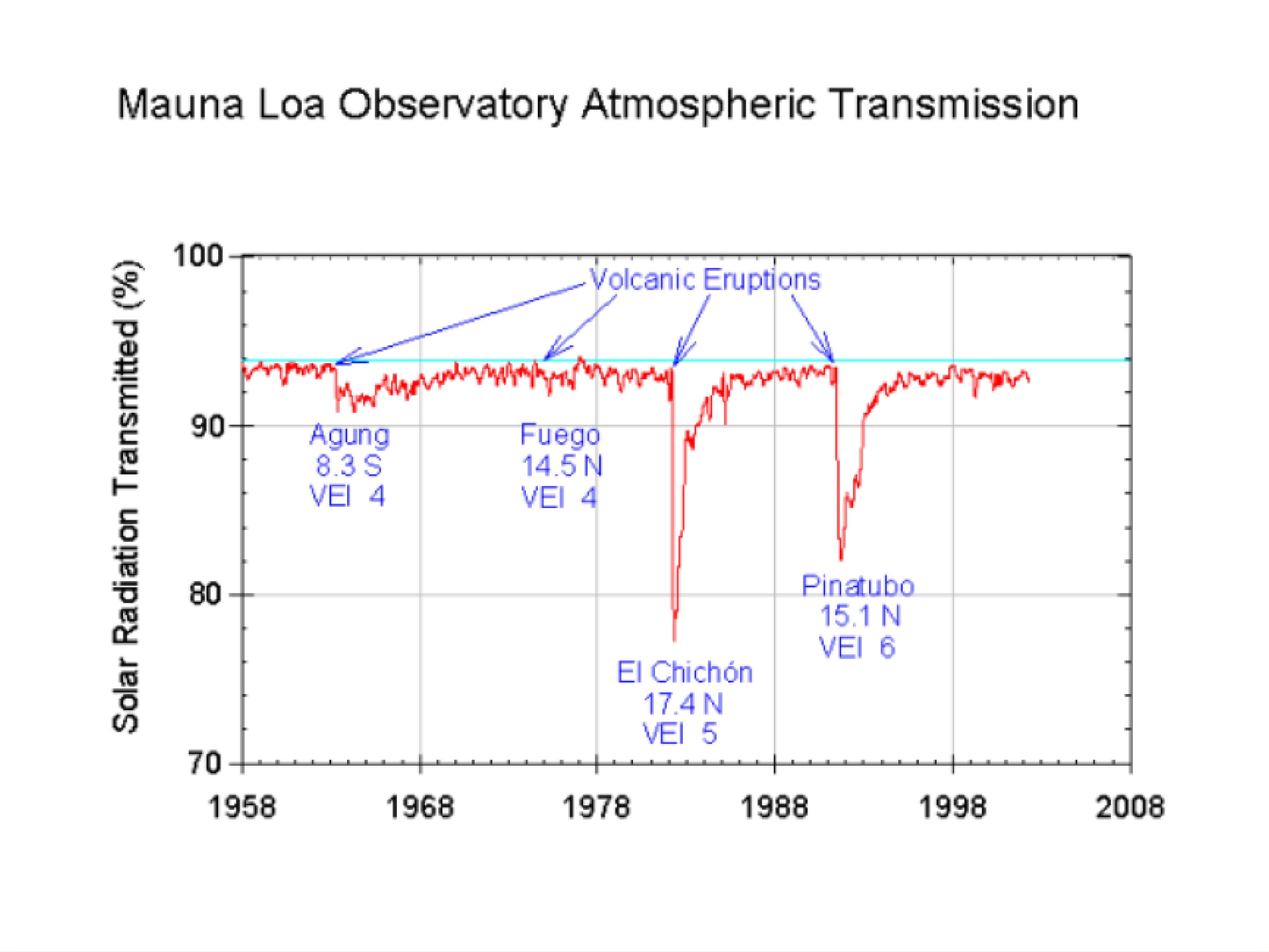
Mt. Pinatubo, Philippines, 1991


Cloud Spreads
Luzon
16
12

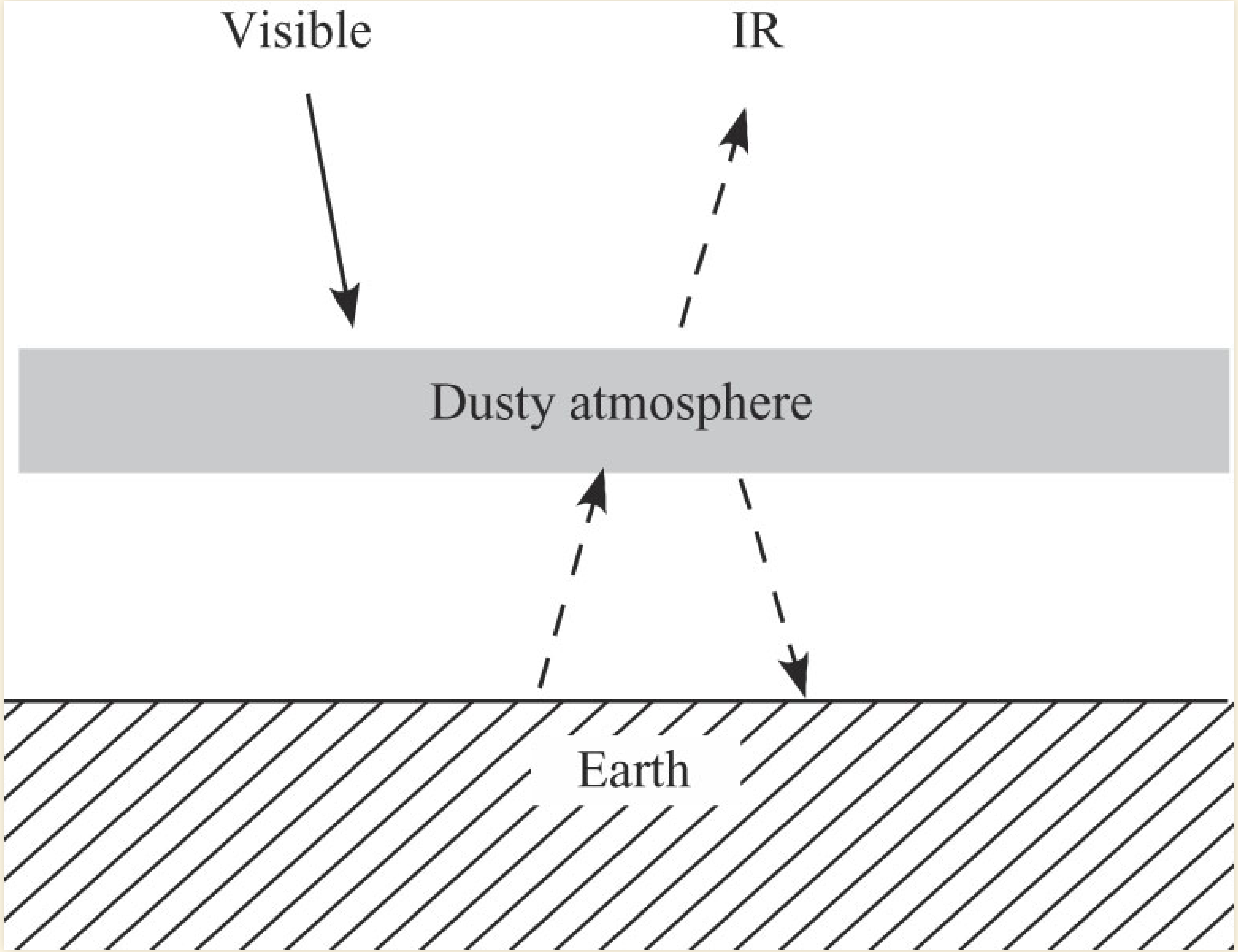
Around the planet



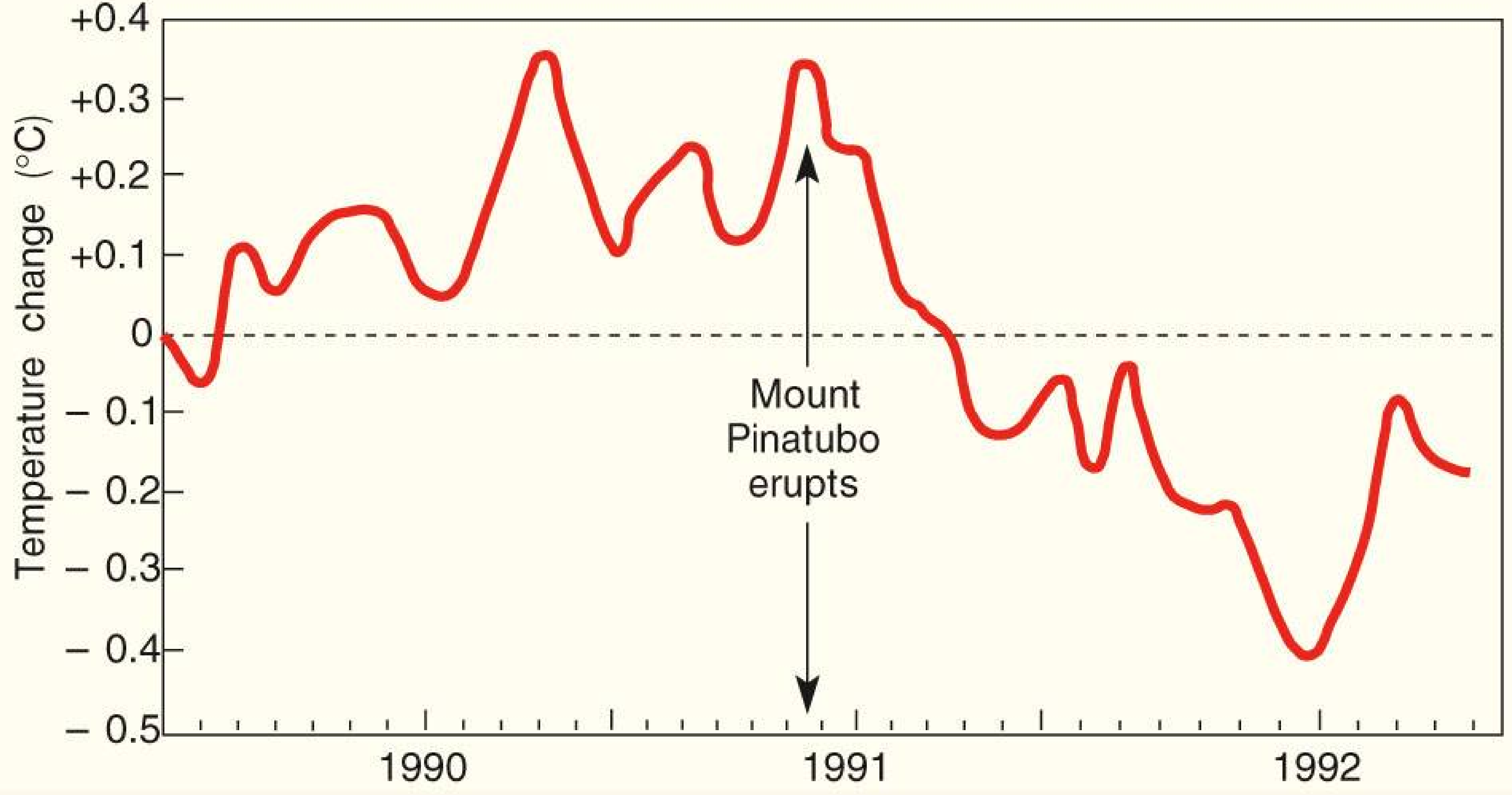
Cloud blocks sunlight



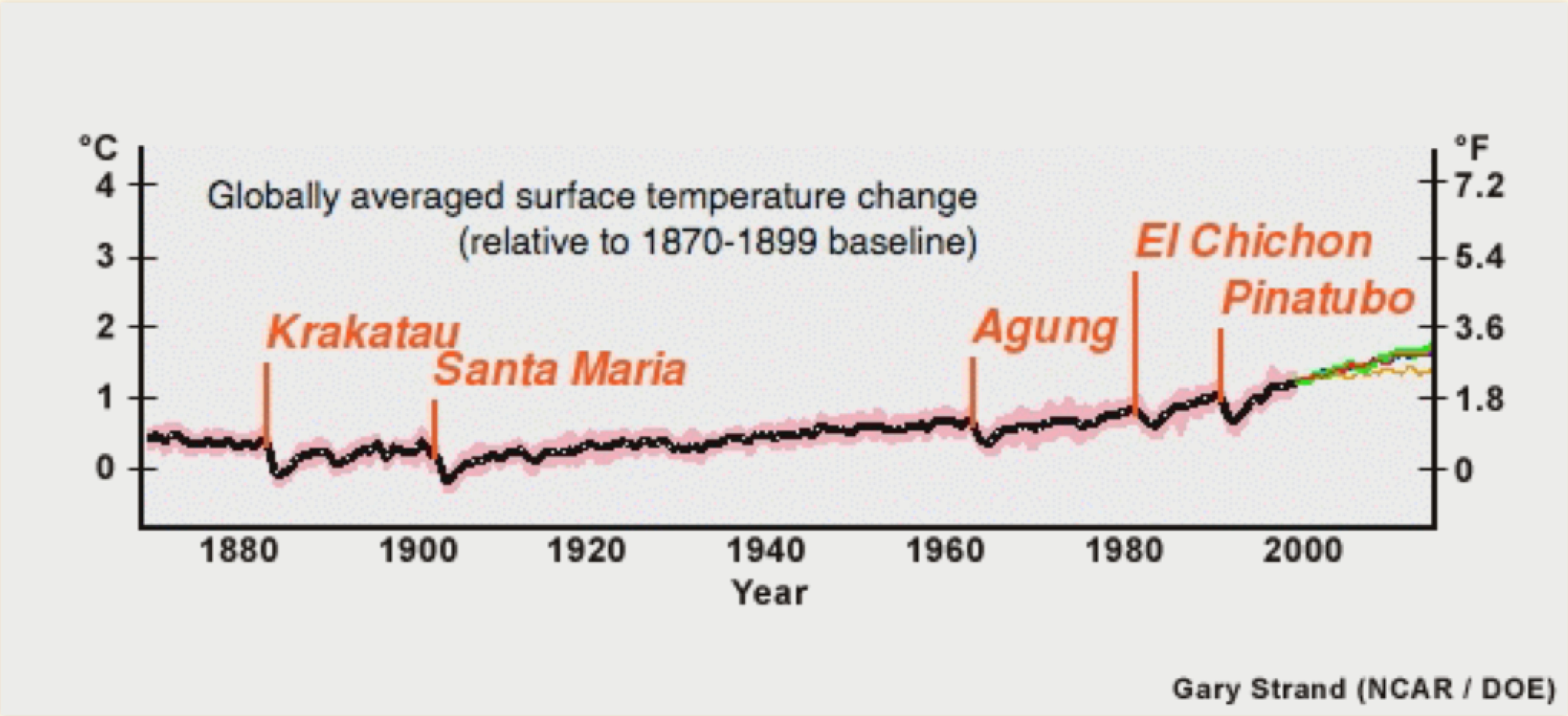
Exercise 3-3



Temperature drops

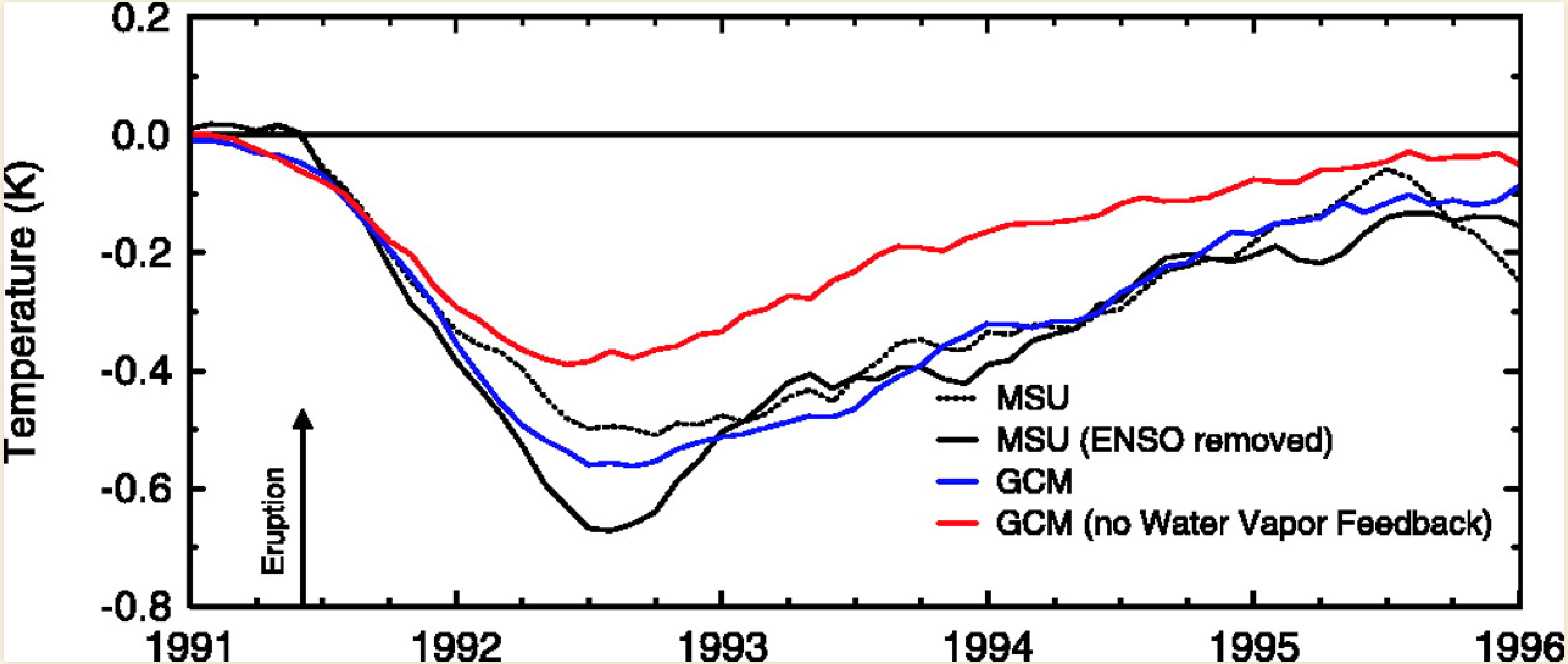


Volcanoes and Temperature



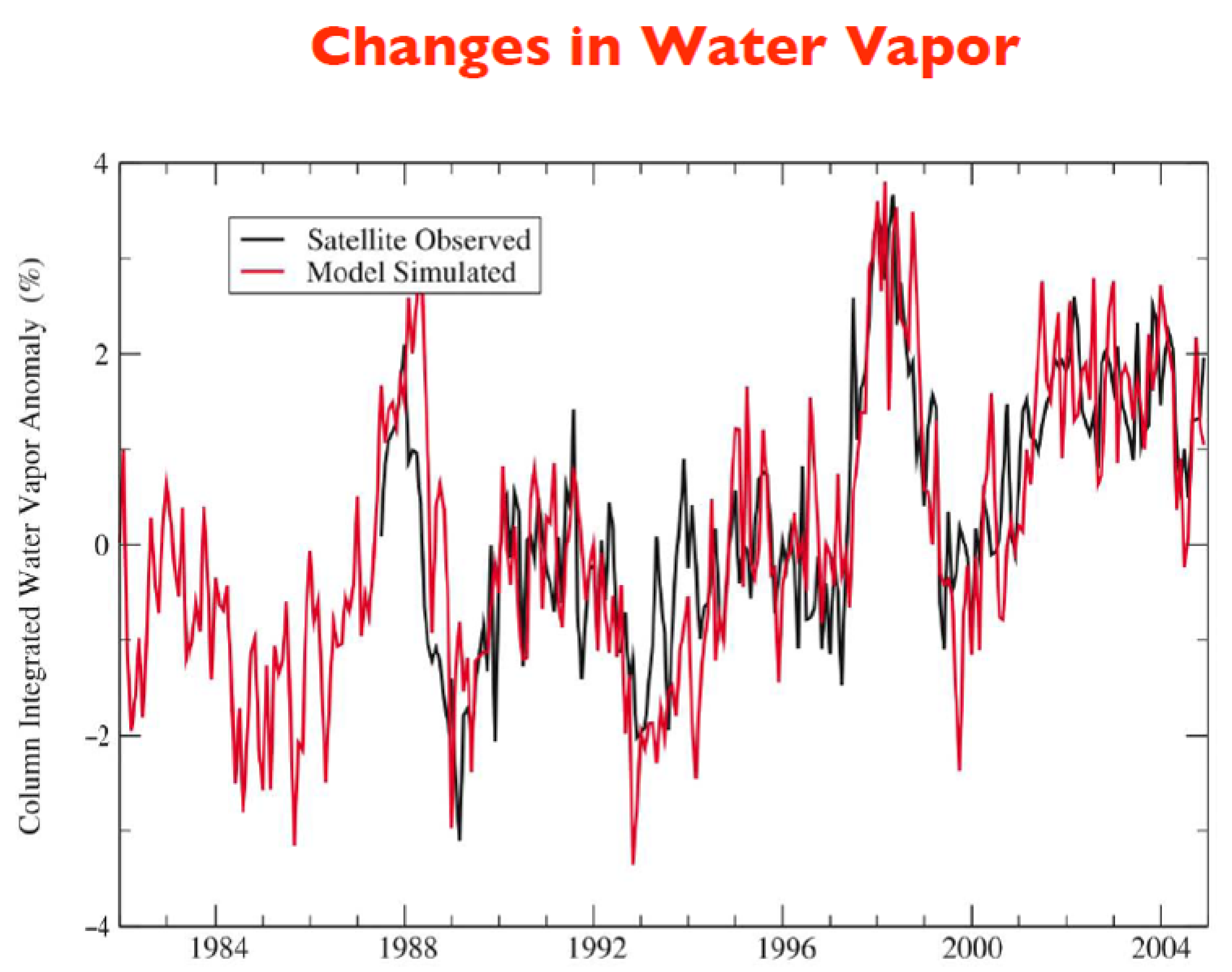
1816:
The Year Without a Summer

Testing Theory of Water-Vapor Feedback



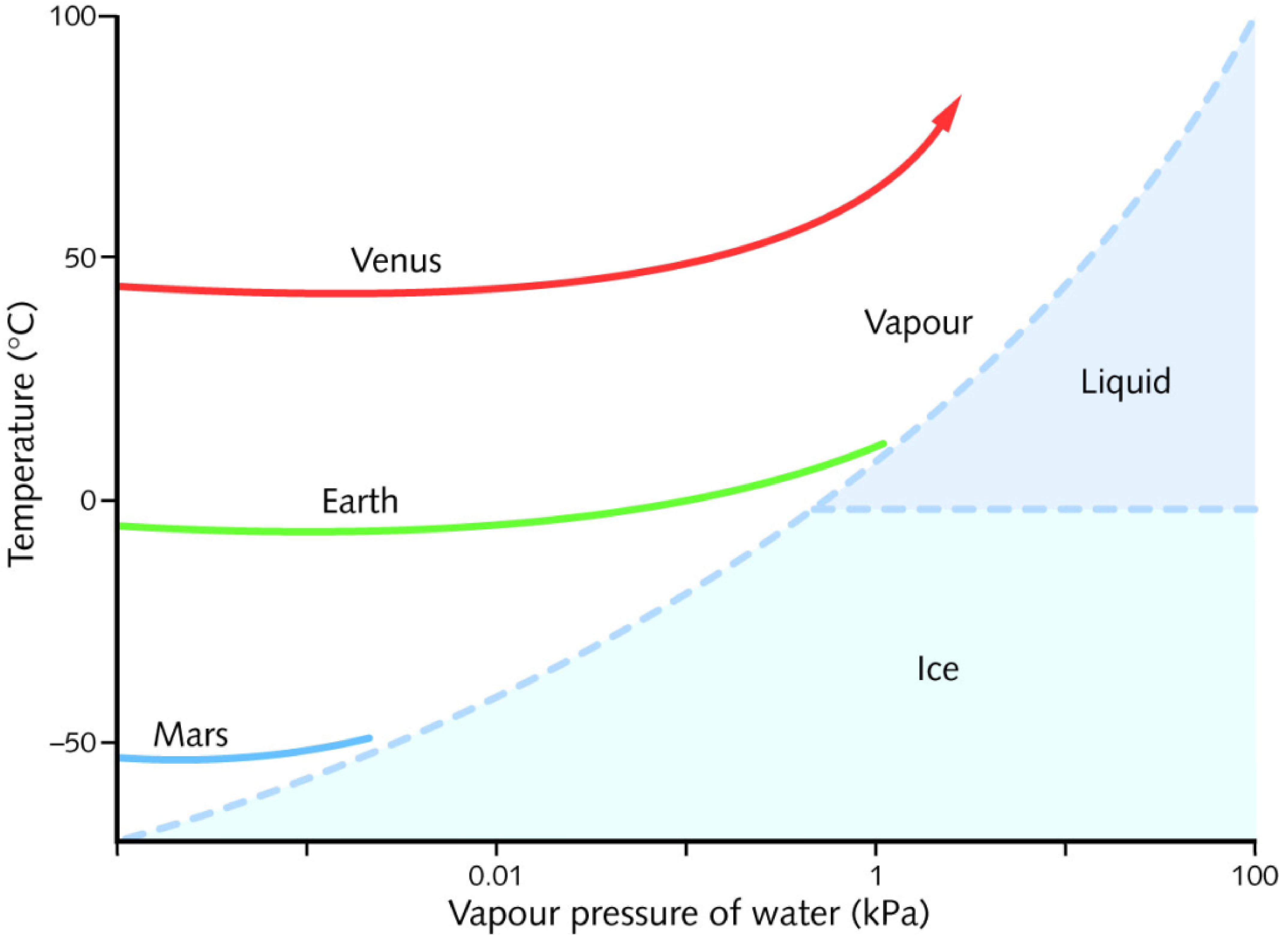
- Pinatubo erupts
- Model calculations with water vapor feedback correctly predict cooling
- Turn off water vapor feedback: incorrect predictions

Additional Tests



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

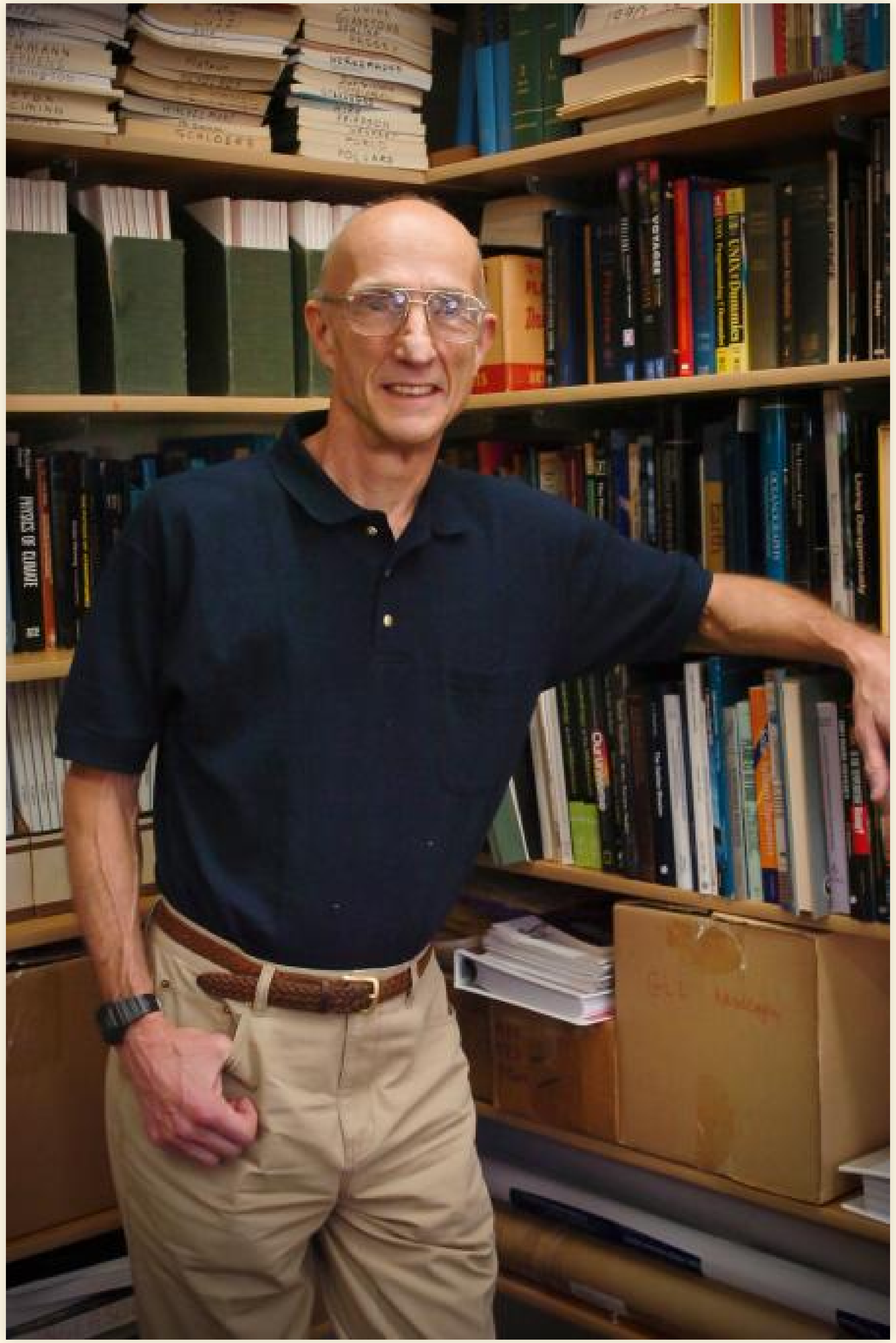
Runaway Greenhouse



Andrew Ingersoll & Runaway Greenhouse

1967: First class he ever taught

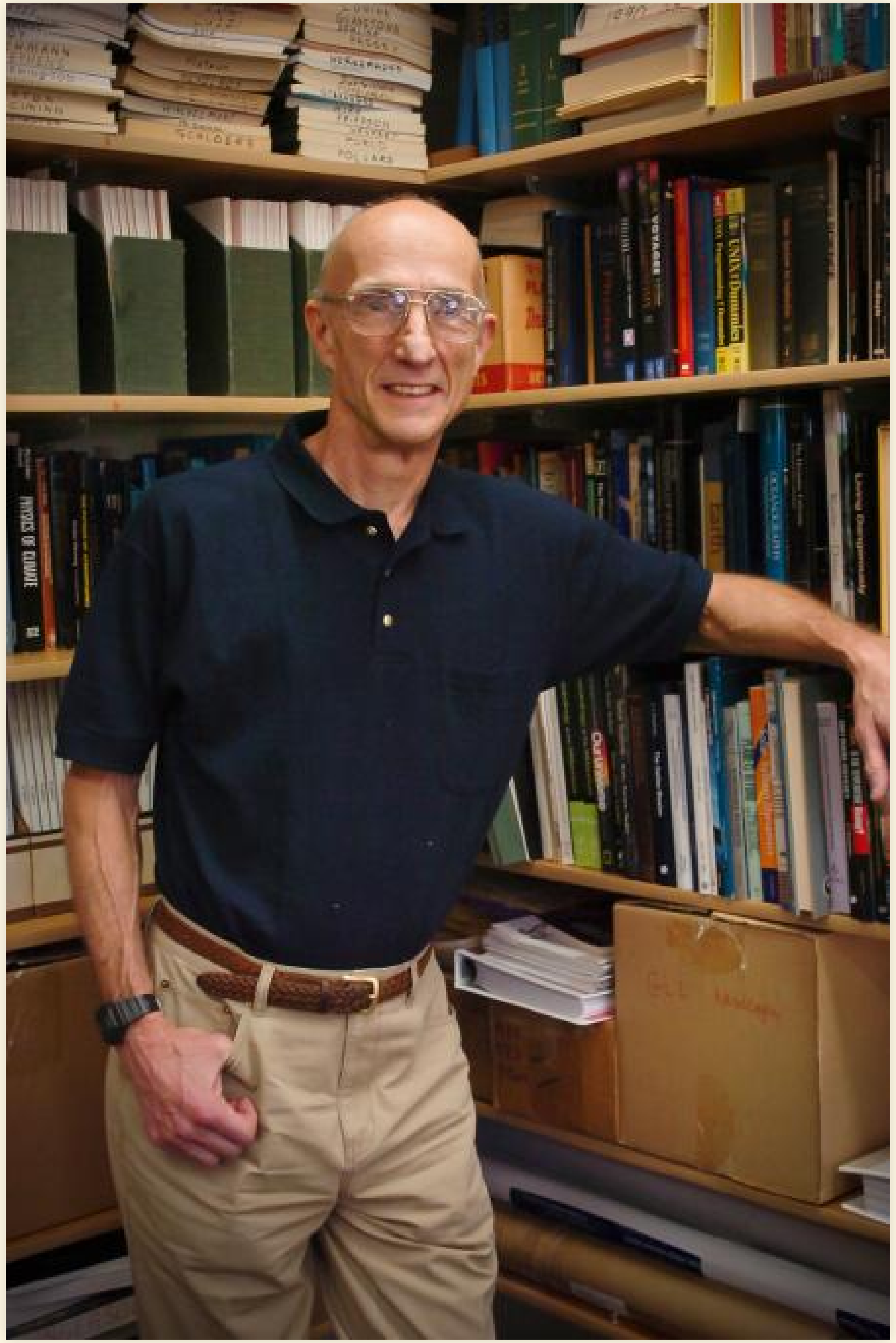
- Assigned homework:
  - Calculate water vapor feedback
- Students couldn't solve problem
- Fixed problem so students could solve it
- It worked for Earth, but not Venus
- Hmmmm …
- It would work for Venus if all the oceans boiled dry.



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 $\rightarrow$ hotter $\rightarrow$ more water vapor
- Water vapor absorbs outgoing radiation
- Absorption $\rightarrow$ hotter $\rightarrow$ more vapor
- Kombayashi-Ingersoll limit:
  - Sunlight below limit, there is a stable equilibrium with liquid water
  - Sunlight above limit, oceans boil dry

Cloud Feedbacks

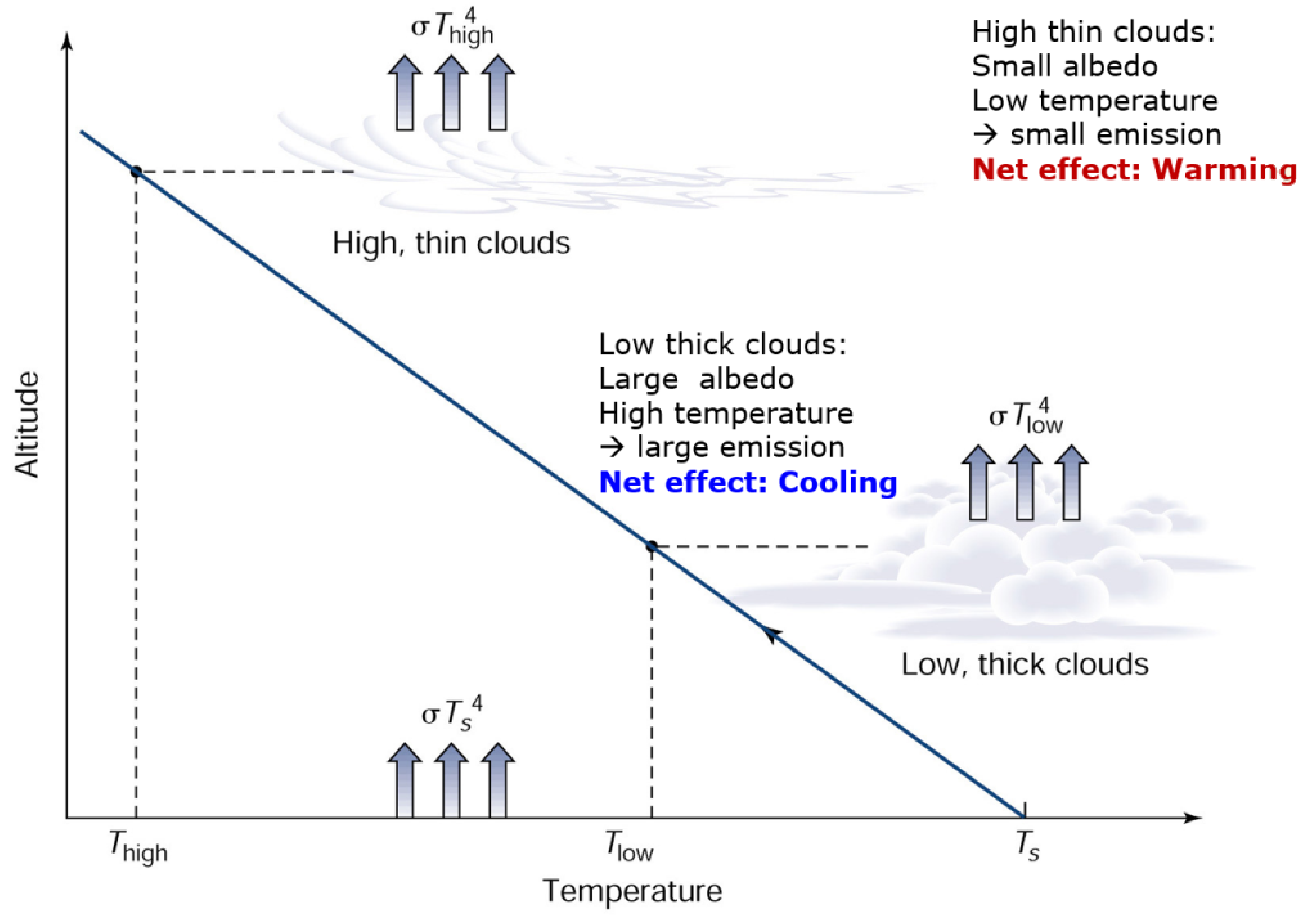
Cloud Feedbacks

- 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)

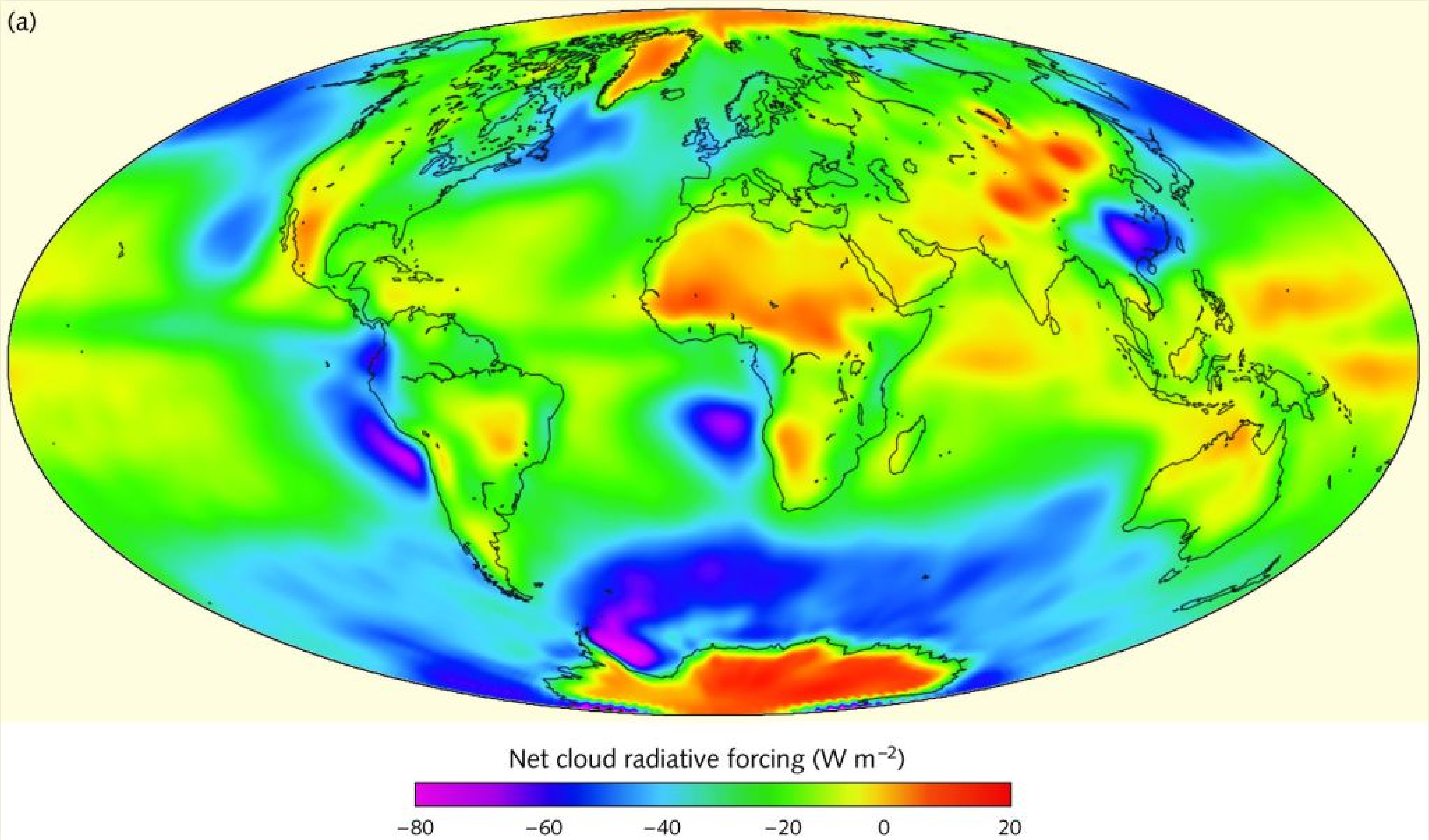
Stratus Clouds (Low)

Cloud Feedbacks



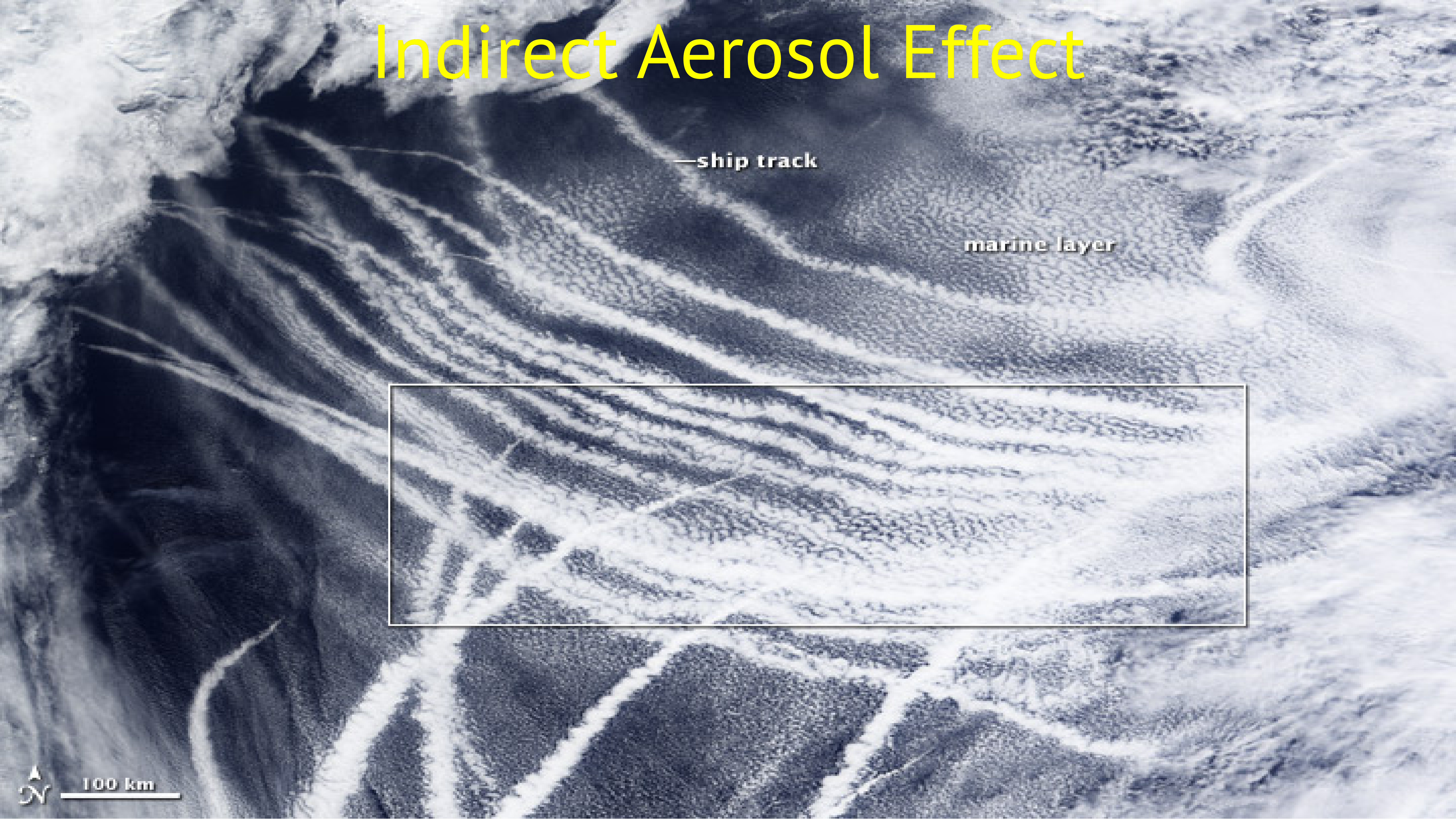
Satellite Measurements

Radiative forcing by clouds



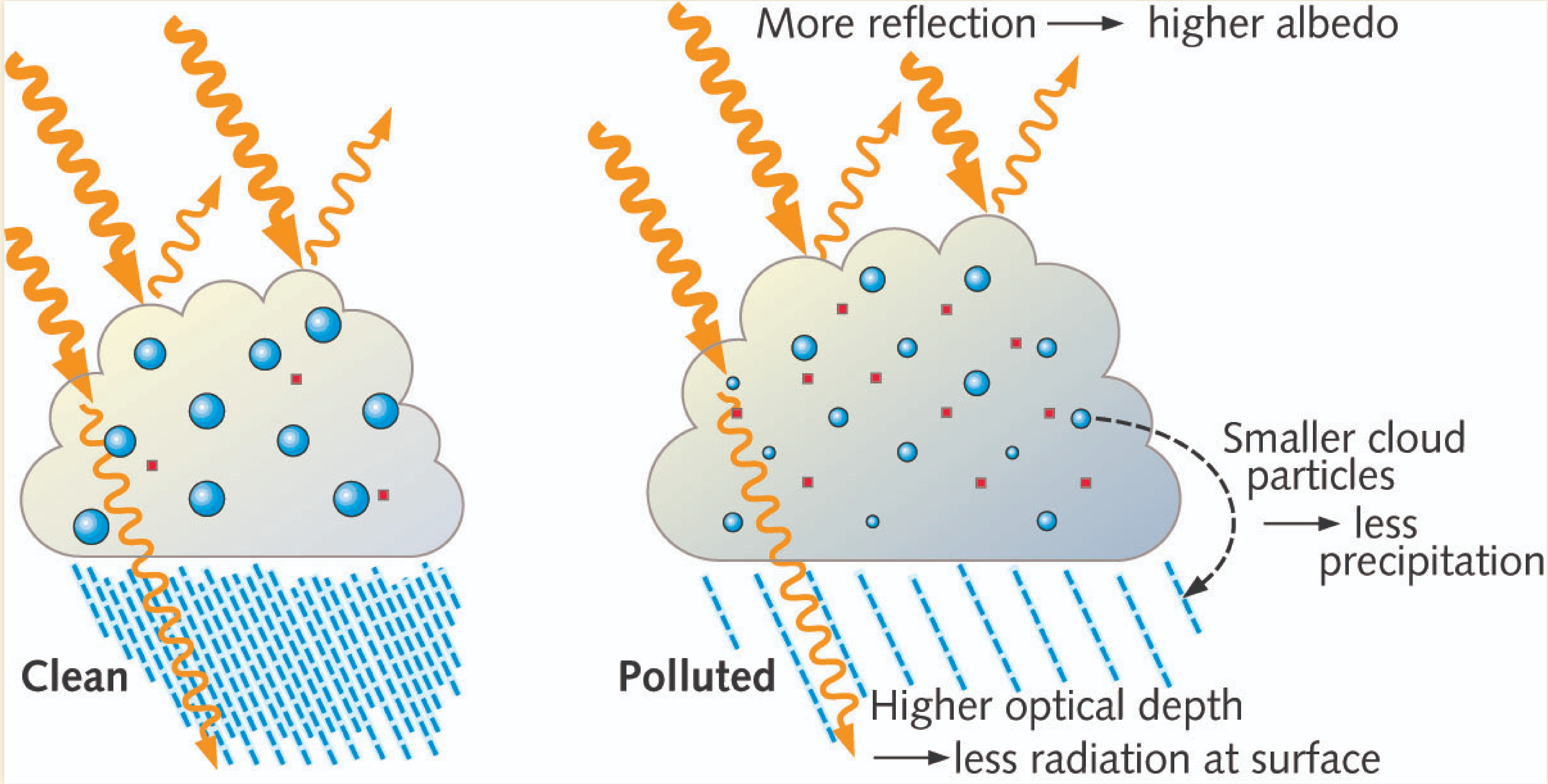
(negative = cooling, positive = warming)

Indirect Aerosol Effect

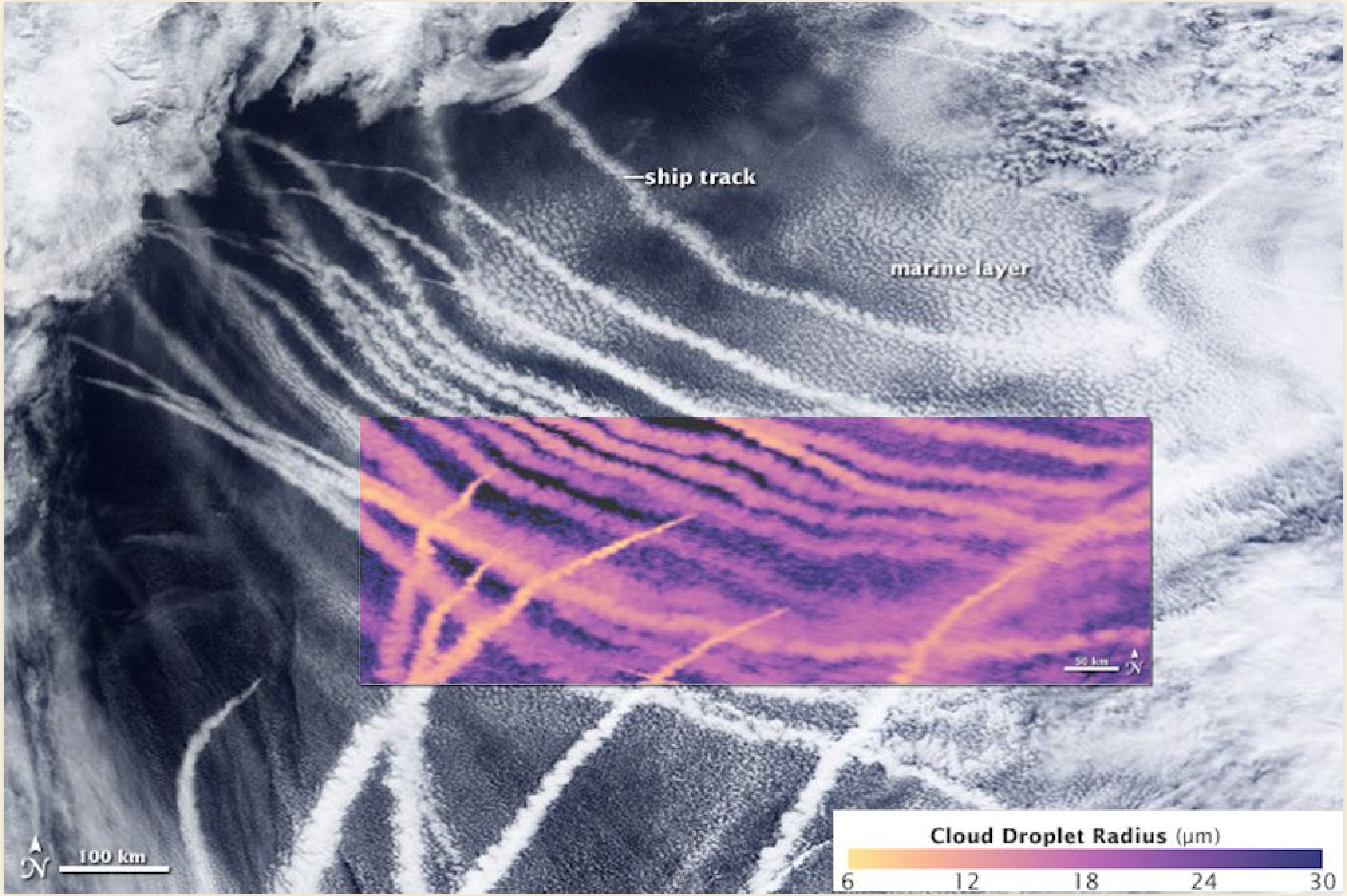


Indirect Aerosol Effect

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



Indirect Aerosol Effect



Summary of Feedbacks

Summary of Feedbacks

- Ice-Albedo has been extensively studied:
  - It’s known to be moderately positive.
- Water vapor has been studied:
  - It’s known to be strongly positive (factor of 2).
- There is some uncertainty about clouds:
  - Most likely they’re positive,
  - Strength is very uncertain

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 $\Delta Q < 0$
  - $\Delta T > 0 \rightarrow \Delta Q < 0$
  - $\displaystyle f = \frac{\Delta Q}{\Delta T} < 0$: 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.