

# High-Latitude Hydroclimatology: Modeling the Cryosphere

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# Importance of High-Latitude Hydroclimatology

- Why do polar regions play a significant role in global climate?
  - The high albedo of snow and ice.
  - The large amount of freshwater stored in glaciers.
  - The large amount of carbon stored in permafrost.



# Importance of High-Latitude Hydroclimatology

- This lecture:
  - **The high albedo of snow and ice.**
  - **The large amount of carbon stored in permafrost.**
- Next lecture:
  - The large amount of freshwater stored in glaciers.



# Learning Goals

- Understand the role of the cryosphere in the climate system.
- Understand what polar amplification means.
- Understand why subgrid-scale parameterizations are used in climate models.

# The High-Latitude Cryosphere: Sea Ice and Polar Snow

- Sea ice and polar snow influence global climate by reflecting sunlight, and acting as insulators that prevent heat exchange between the ocean and the atmosphere.
- Snow accumulation and melt affect the mass balance of polar ice sheets, which in turn influence global sea levels.



# High-latitude regions are especially sensitive to climate change

- Why do high latitude regions experience more pronounced warming than other areas?
  - **Snow and ice *reflect* more solar radiation than other surfaces.**



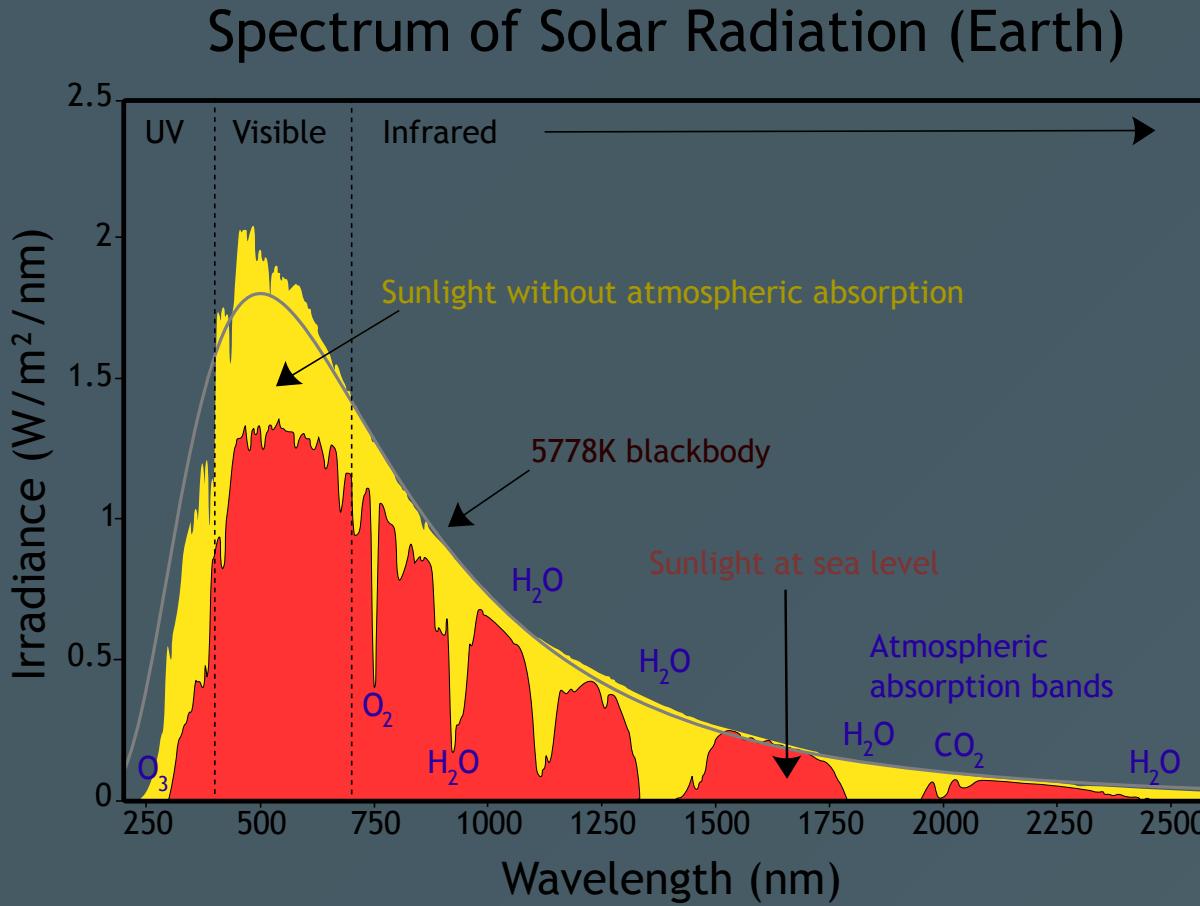
Photo: Matt Cooper

# What is albedo and why does it matter?

$$\text{albedo} = \frac{\text{reflected solar radiation}}{\text{incoming solar radiation}}$$

- Incoming solar radiation can be direct and diffuse (e.g., cloudy sky)
- Albedo generally increases when the sun is closer to the horizon (when the solar zenith angle is greater)
- “reflected” means integrated over all angles

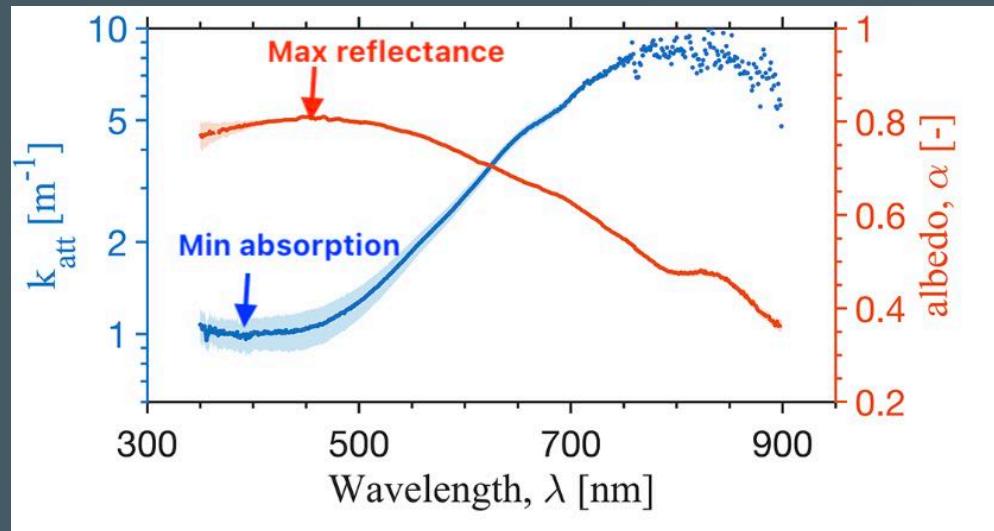
# Solar radiation peaks in the visible spectrum



By Robert A. Rohde [CC BY-SA 3.0](#)

# Snow reflectance peaks in the visible spectrum

- Pure ice is nearly transparent to blue light
- Almost all energy is absorbed at wavelengths in the red and beyond
- Unless the snow/ice is "dirty" ...

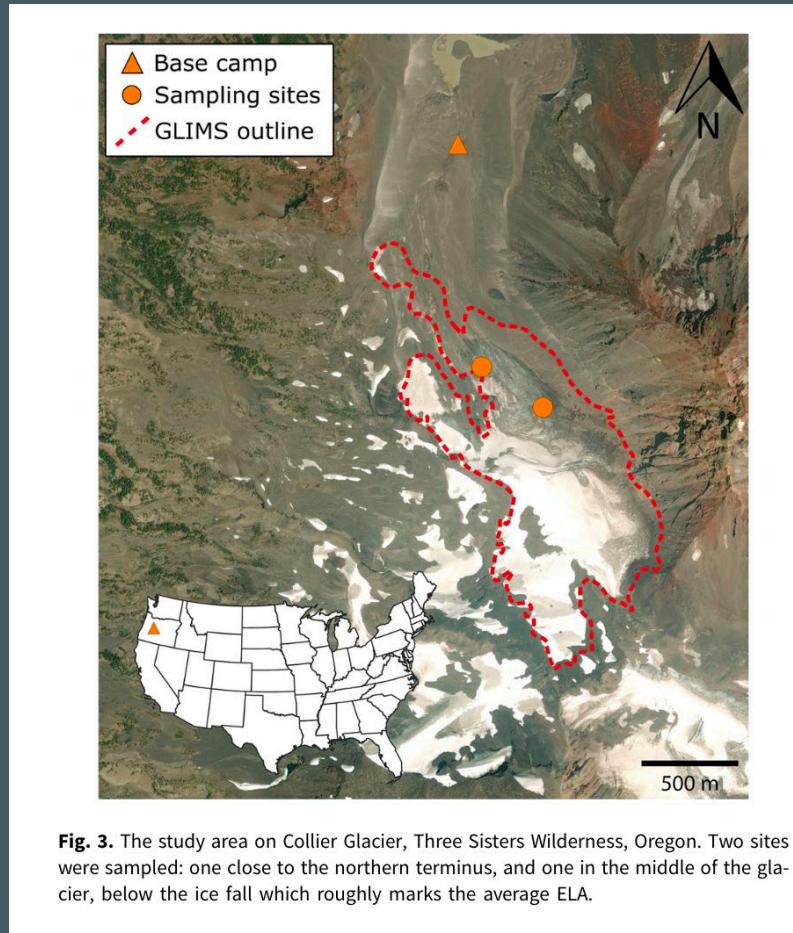


# A small change in albedo causes a large relative increase in absorbed sunlight

	albedo	absorbed (1-albedo)	
Start with:	0.8	0.2	
Lower by 20%:	0.64	0.36	<b>80% Increase</b>

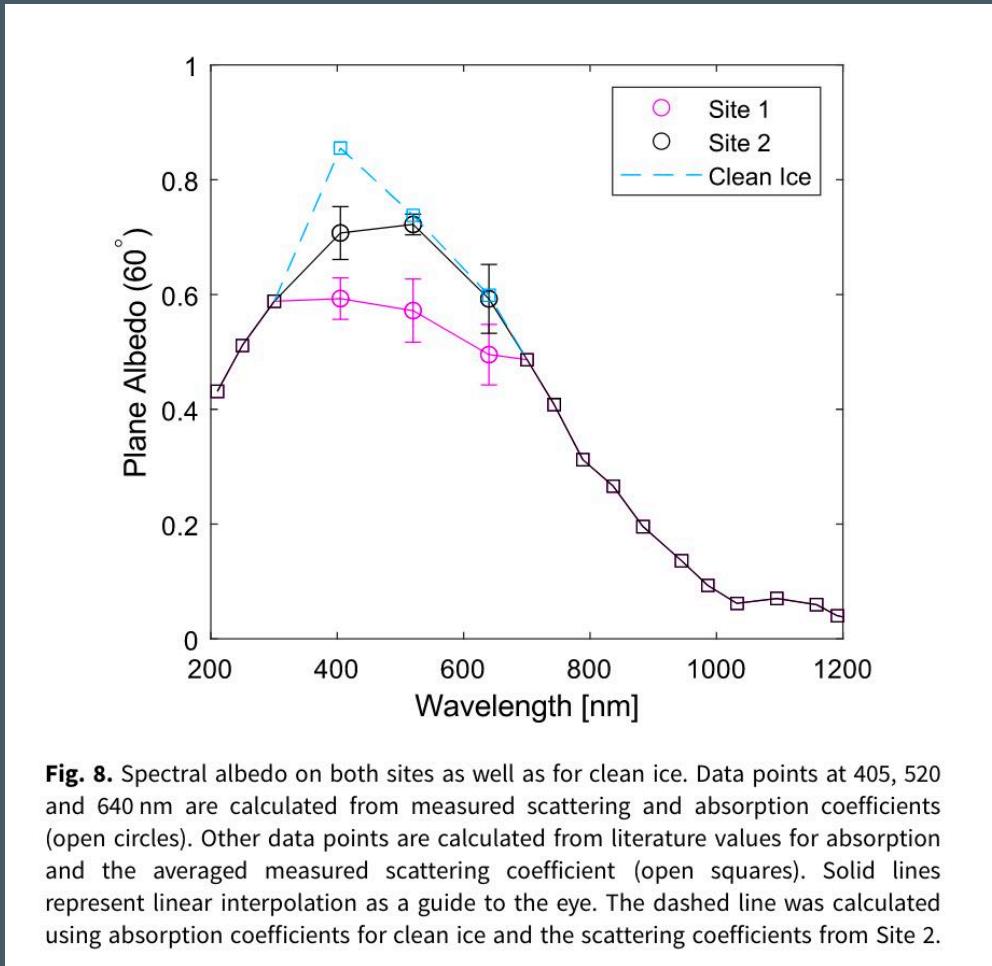
credit: Jeff Dozier

# What makes ice albedo decrease?

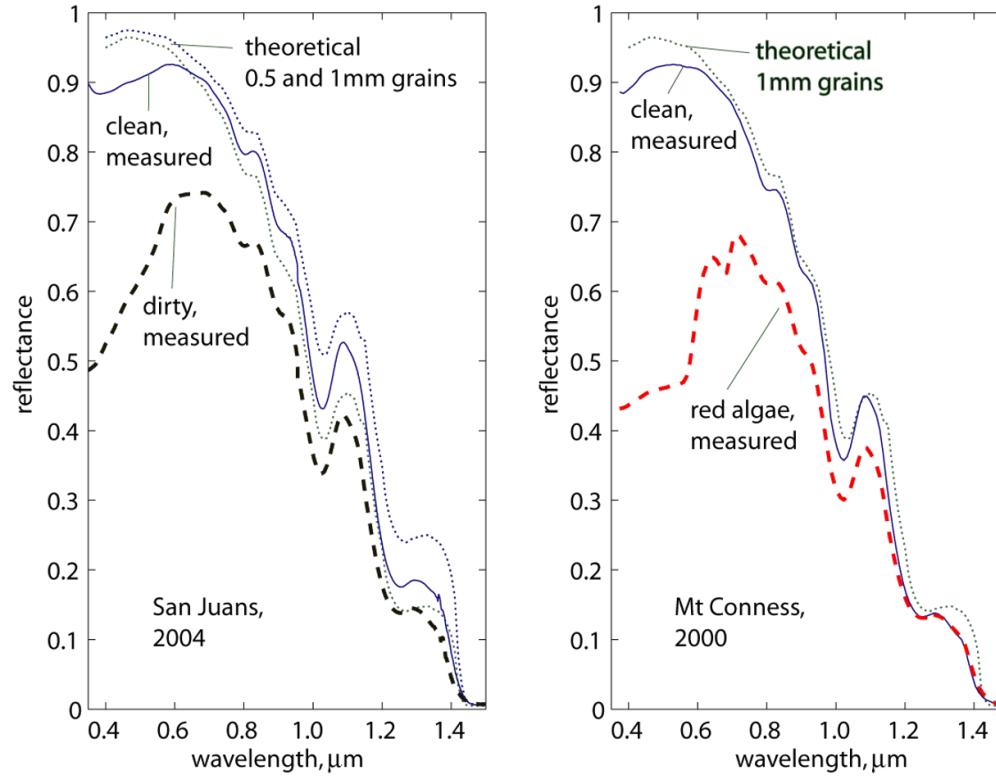


Allgaier, Cooper, and others 2022, The Journal of Glaciology

# Spectral reflectance of dirty glacial ice



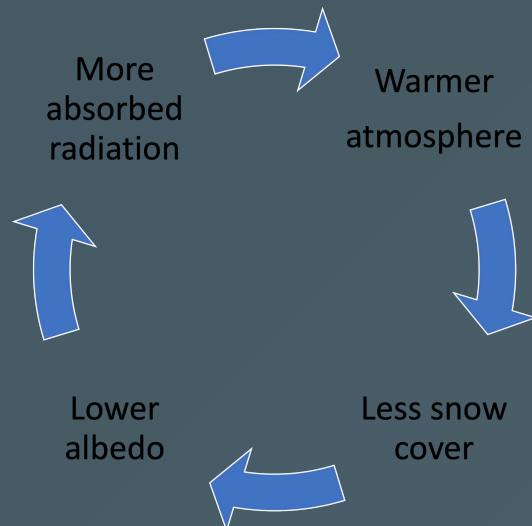
# Spectral reflectance of dirty snow and snow with red algae

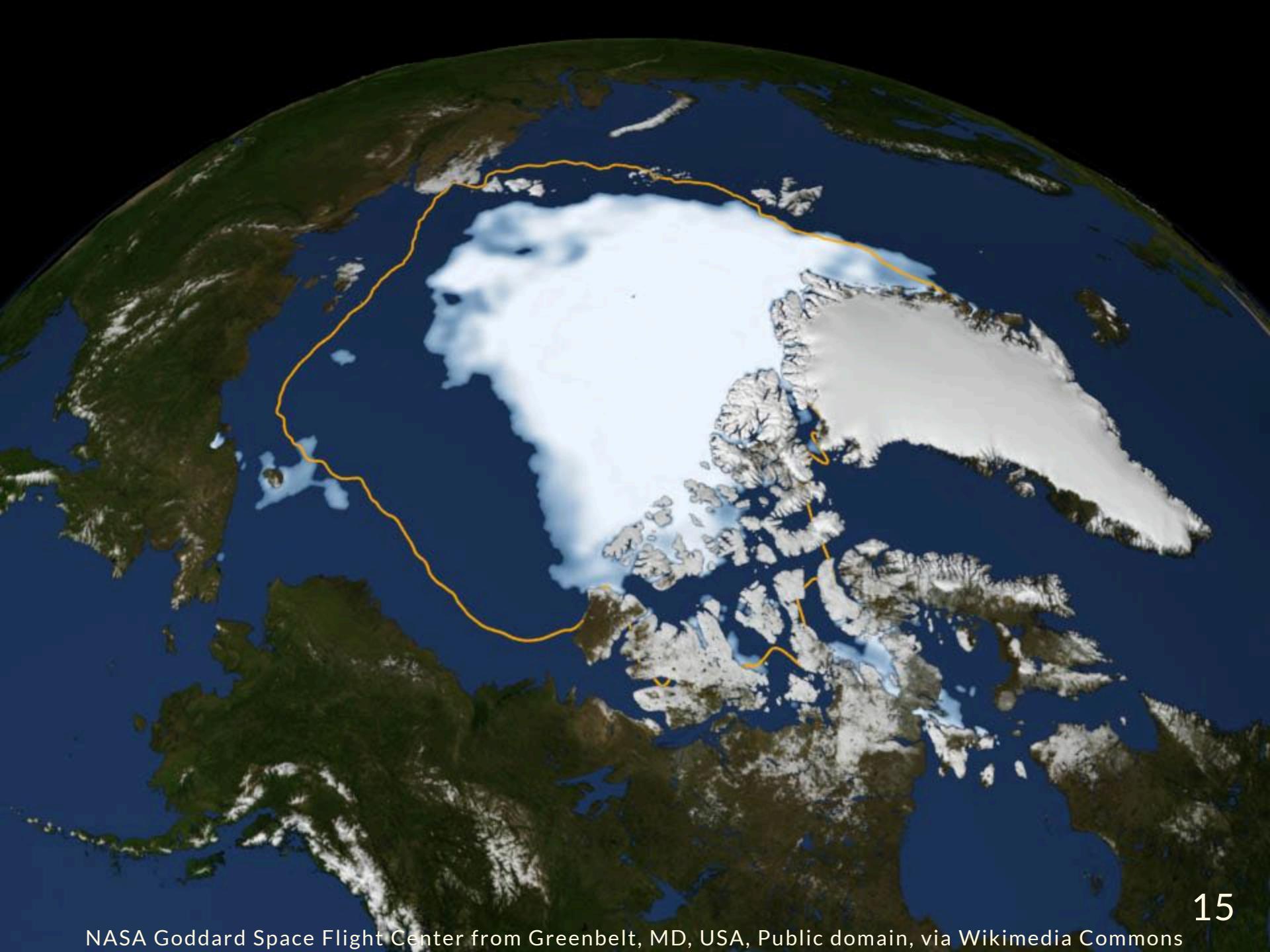


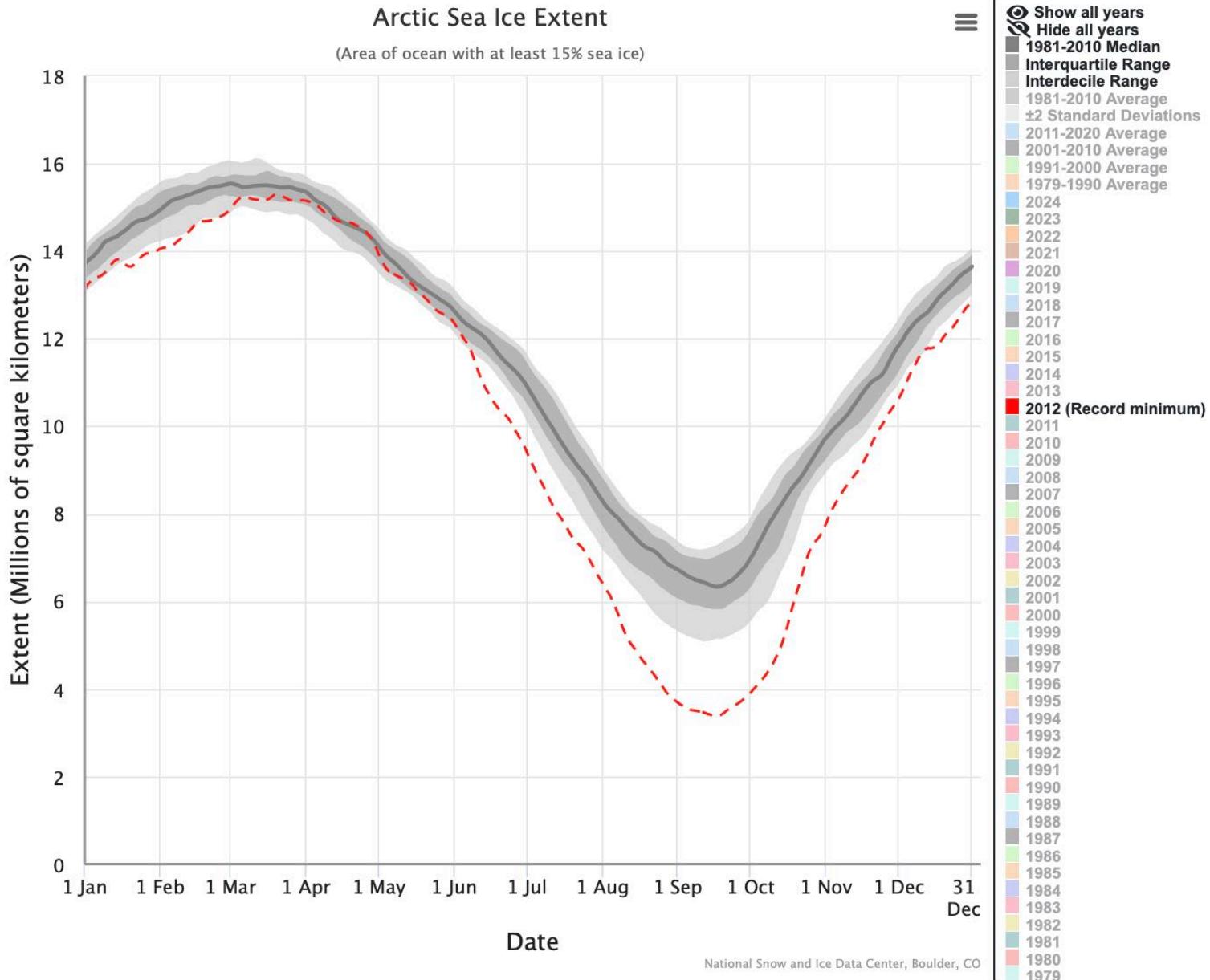
Painter et al. 2001

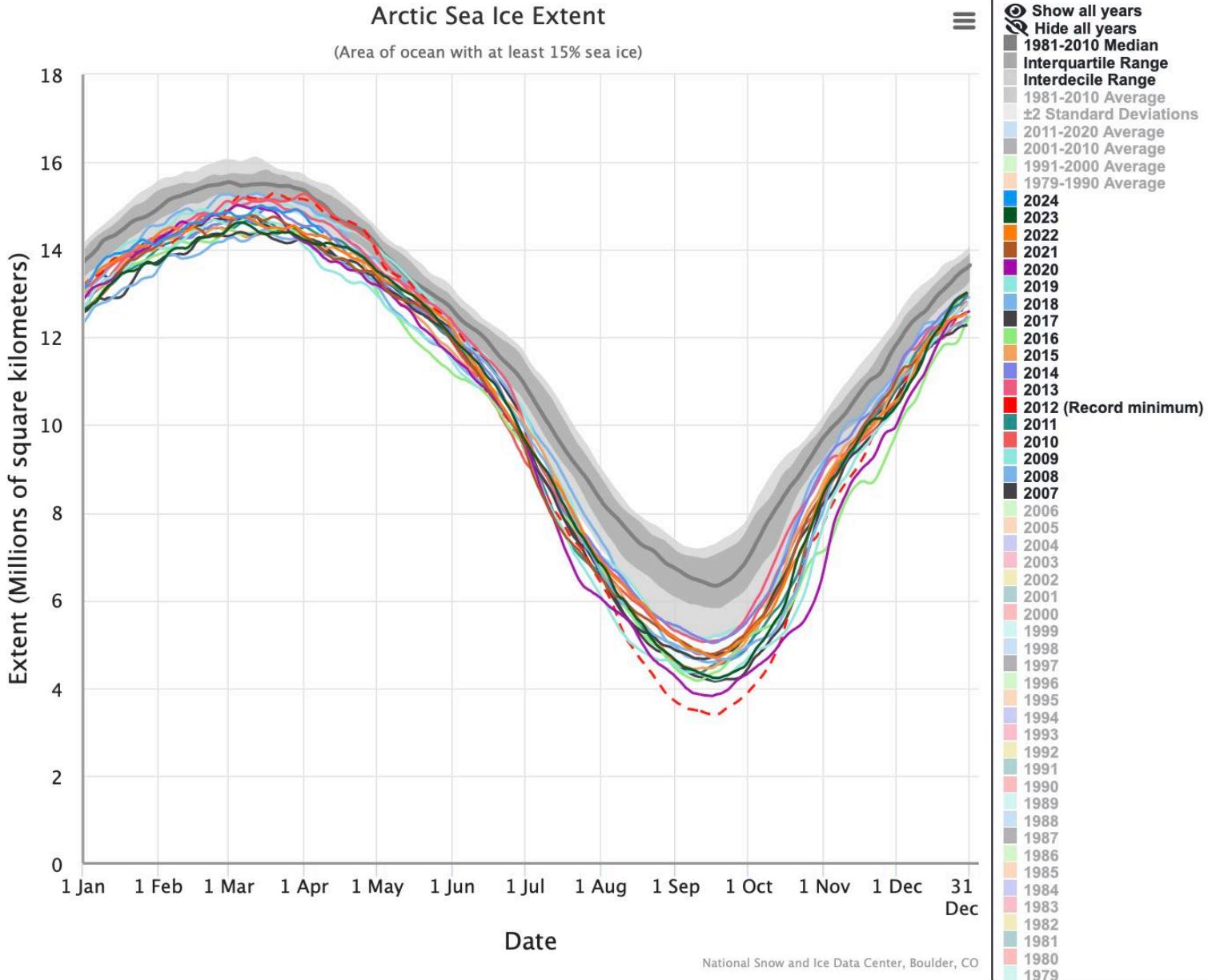
# High-latitude regions are especially sensitive to climate change

- Why do high latitude regions experience more pronounced warming than other areas?
- *Snow and ice reflect more solar radiation than other surfaces.*
  - **As earth warms, snow cover decreases and absorbed solar radiation increases, which causes more warming, more snow melt, and more absorption of solar radiation, leading to a positive feedback loop.**

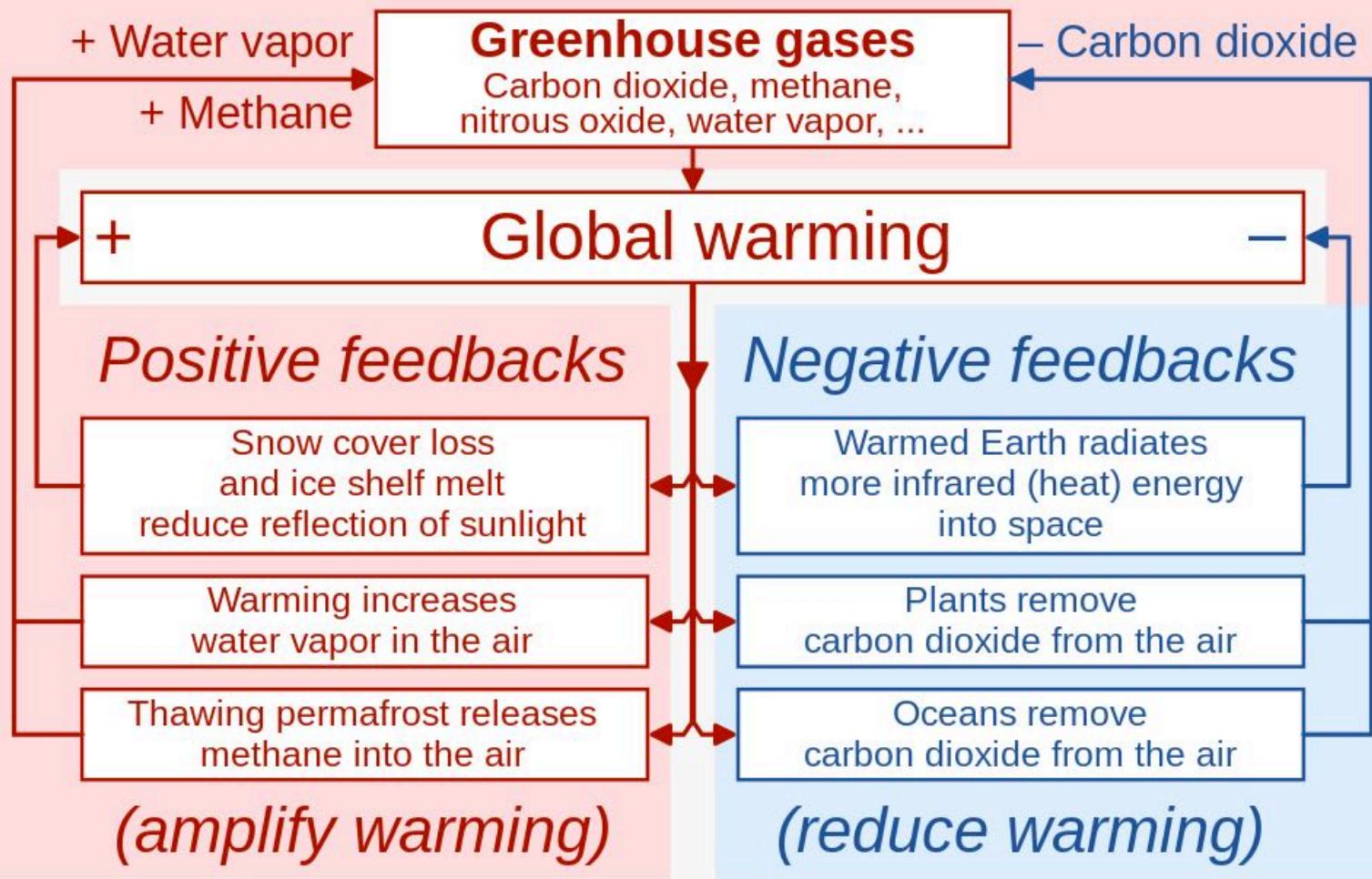






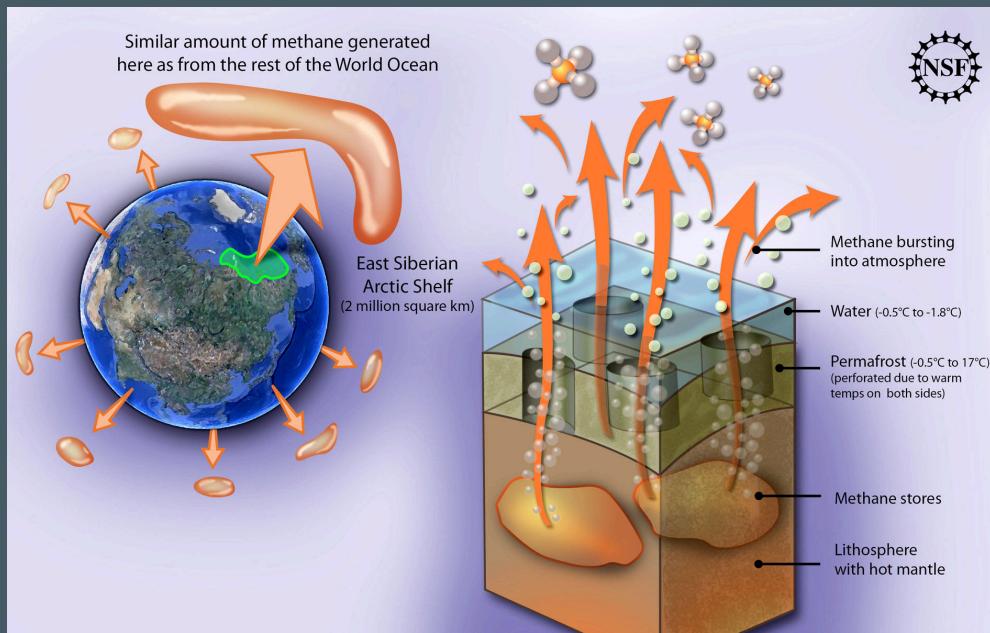


# Climate change feedbacks



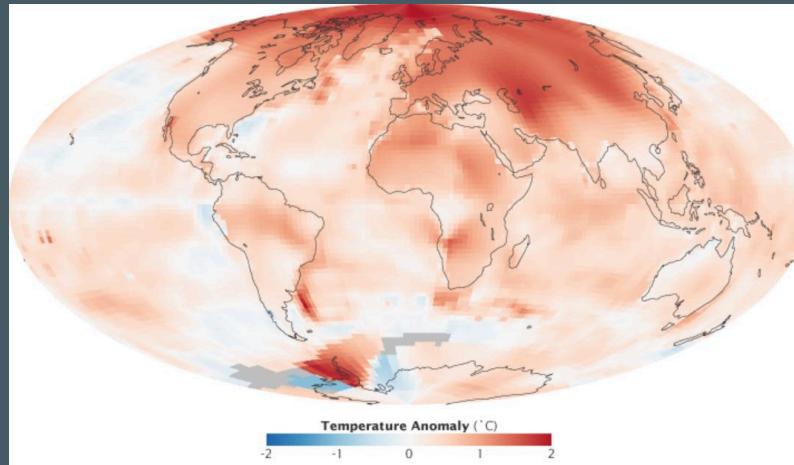
# Polar Amplification

- Polar amplification refers to the increased rate of warming in the Arctic and Antarctic compared to the global average.
- This phenomenon is caused by various positive feedback mechanisms, such as the ice-albedo feedback and the release of greenhouse gases from thawing permafrost.



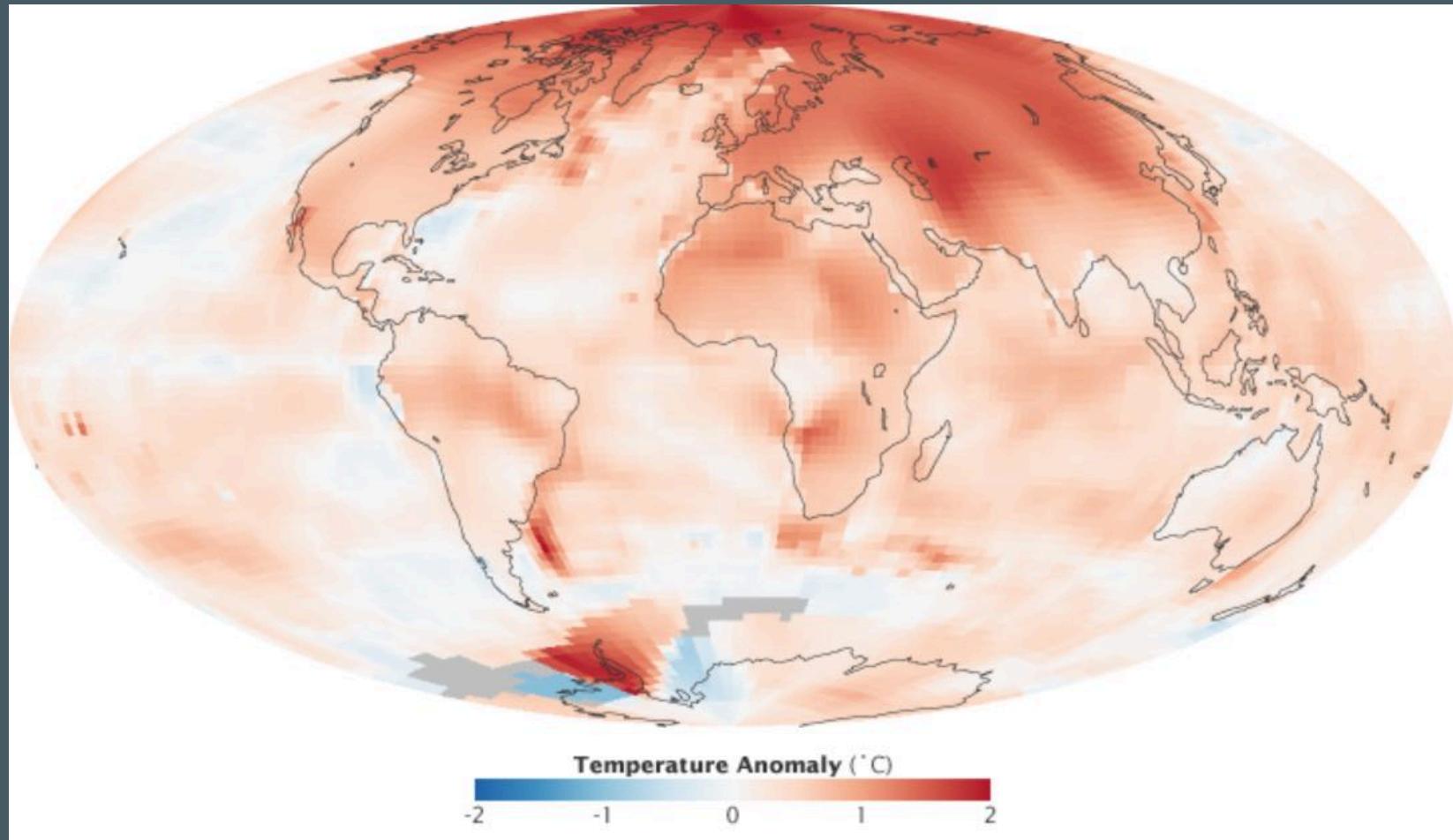
# Polar Amplification

- High-latitude regions warm faster than the global average
  - Arctic: 2.5°C
  - Antarctic: 1.5°C
  - Global: 1.1°C
- Factors: Ice-albedo feedback, changes in atmospheric and oceanic circulation, and increased greenhouse gases.



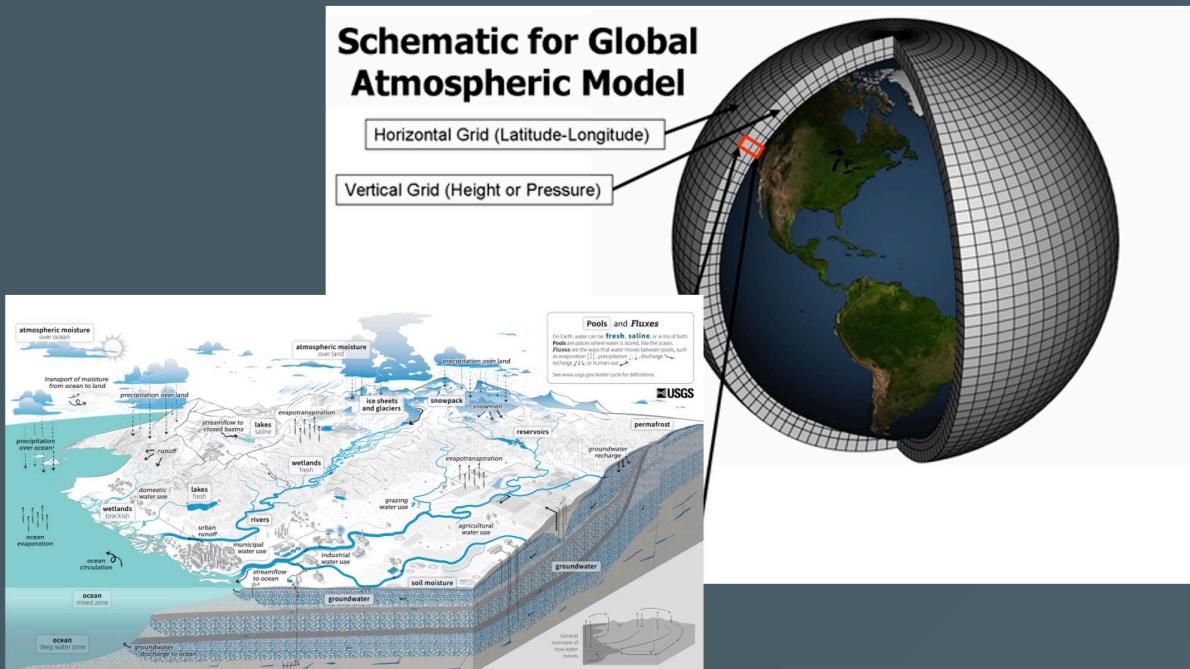
[https://commons.wikimedia.org/wiki/File:GISS\\_temperature\\_2000-09.png](https://commons.wikimedia.org/wiki/File:GISS_temperature_2000-09.png)

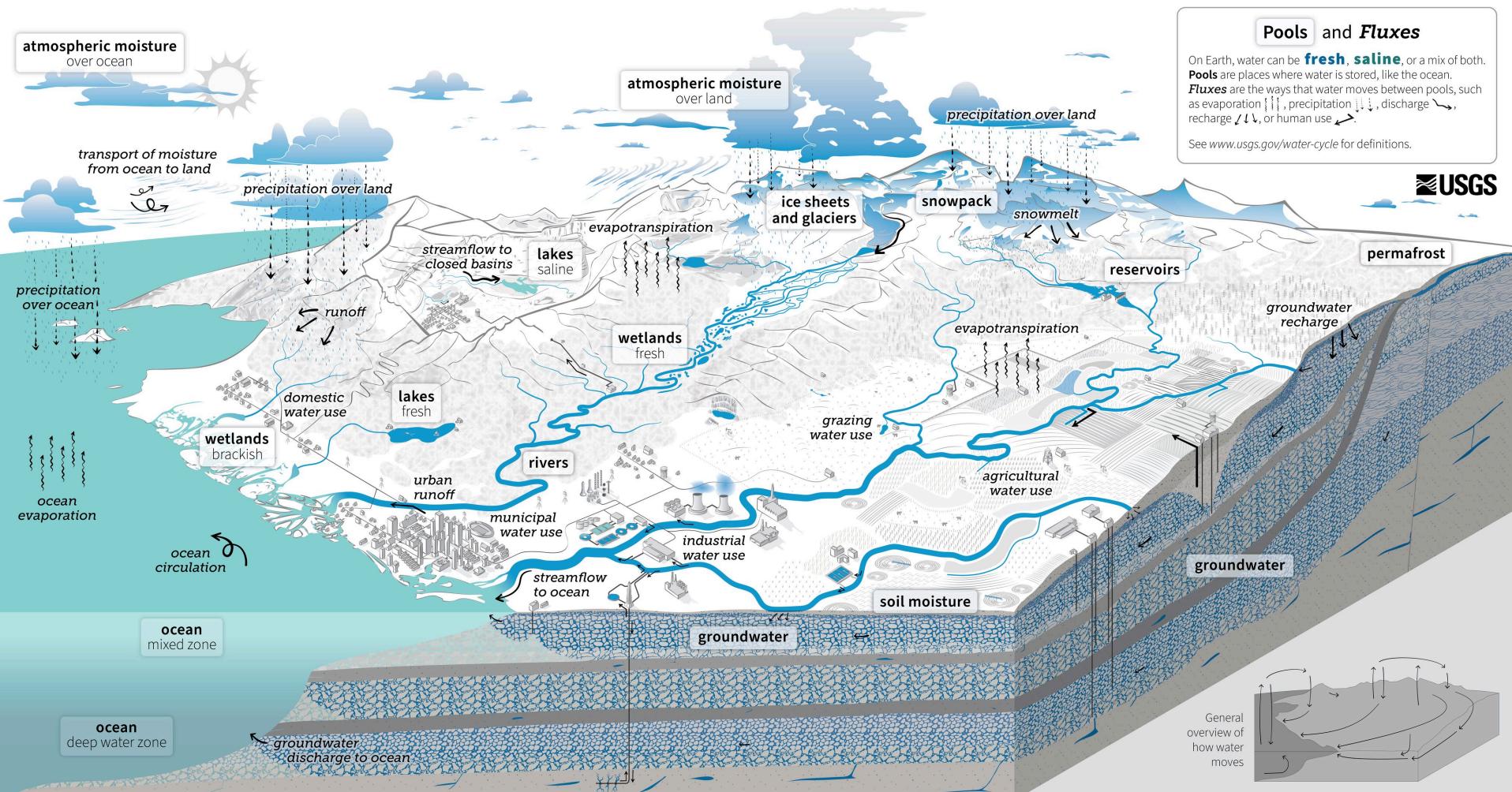
**Question: why are the northern latitudes warming more than the southern latitudes?**



# Global Climate Models for Hydroclimatology

- Climate models are essential tools for studying and predicting hydroclimatic processes in high-latitude regions.
- Accurately representing high-latitude processes in climate models is challenging due to the complex interactions between the atmosphere, ocean, and cryosphere.





# Permafrost Hydrology

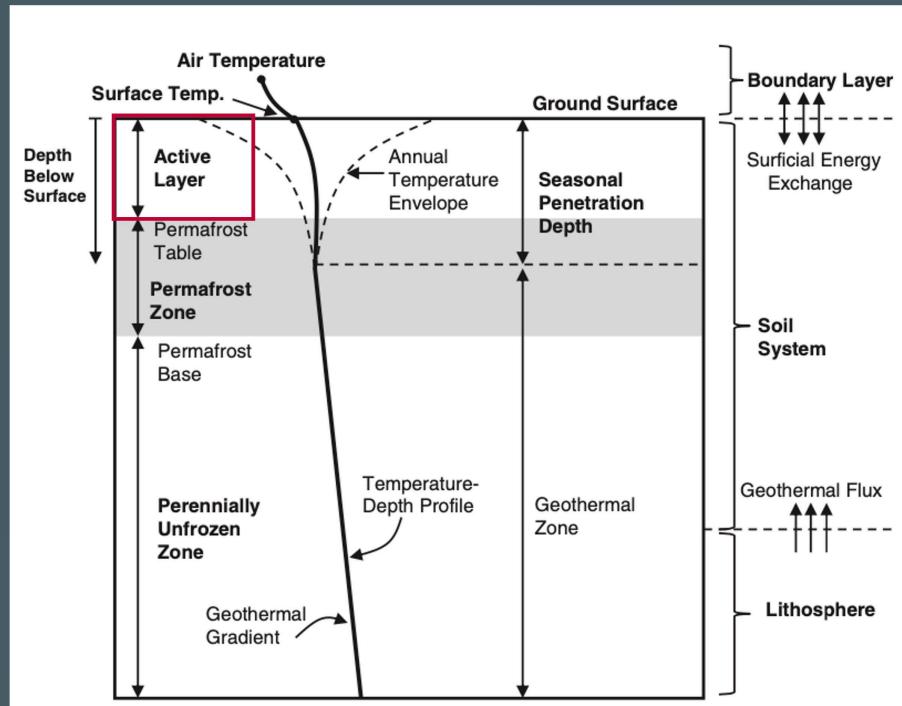
- Permafrost is permanently frozen ground, and it affects the storage and movement of water in high-latitude regions.
- Thawing permafrost can release significant amounts of carbon dioxide and methane, both potent greenhouse gases, exacerbating climate change (permafrost-carbon feedback).



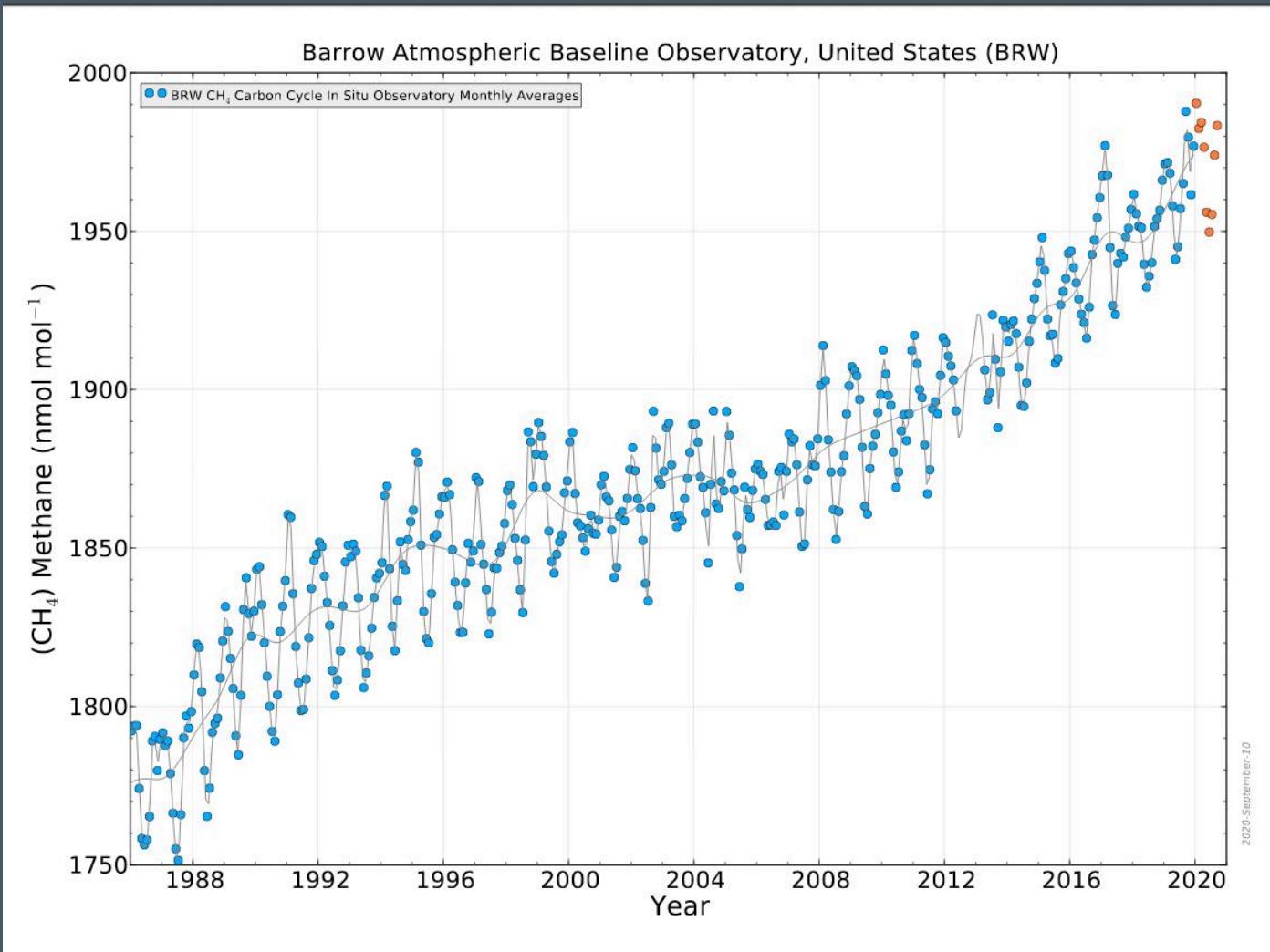
# Permafrost Hydrology

- Permafrost stores large amounts of carbon and water.
- Thawing permafrost affects hydrology, ecosystems, and infrastructure.

diagram: Kurylyk et al (2014) ESR



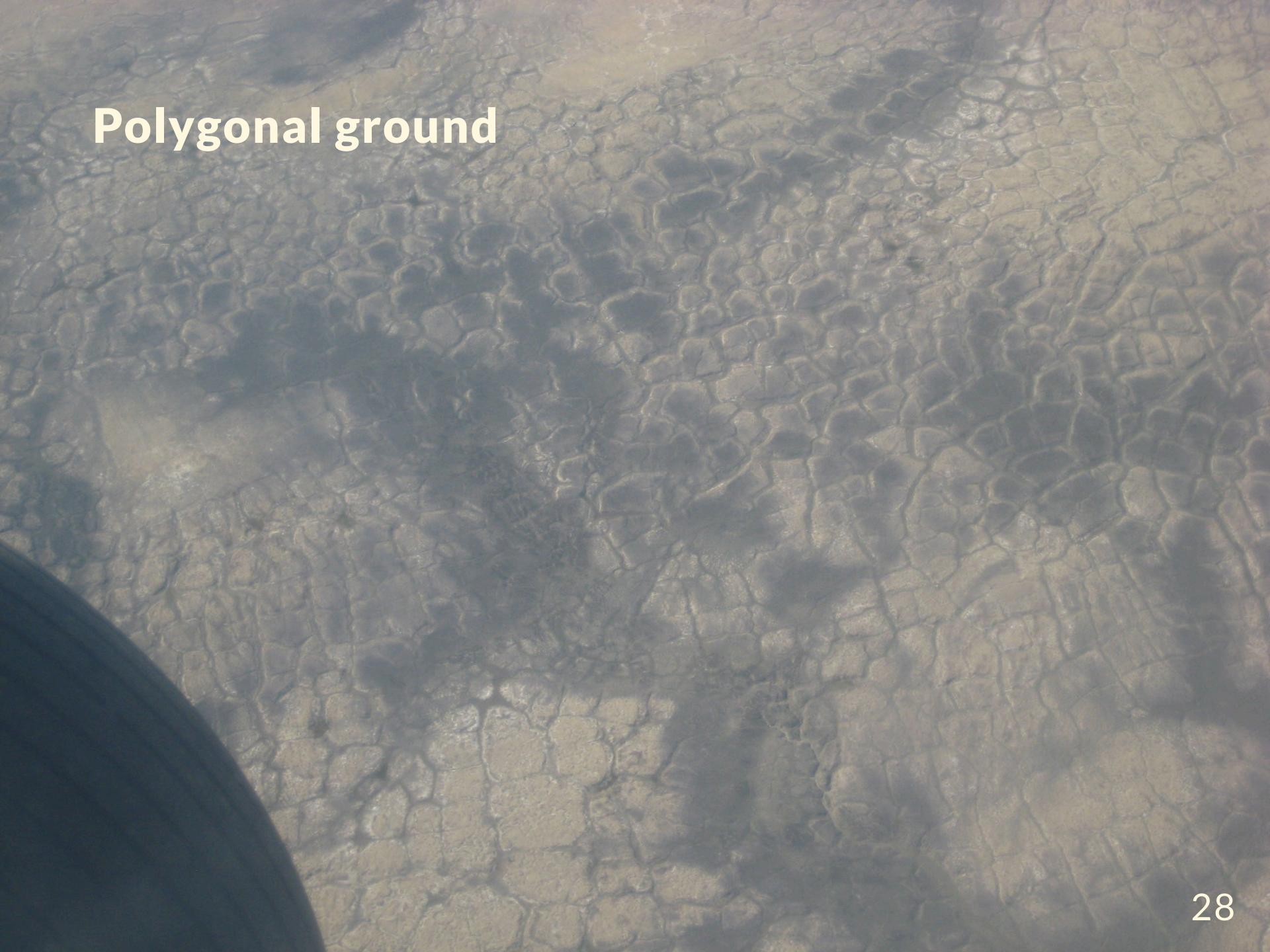
# Arctic methane emissions



# Permafrost Hydrology

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An aerial photograph of a vast, arid landscape. The terrain is characterized by a dense network of deep, irregular cracks and polygons, creating a pattern reminiscent of dry mud or ancient龟壳 (tortoise shell). The colors are muted, with shades of brown, tan, and light grey dominating the scene. In the upper left corner, a small, dark, circular object, possibly a satellite or a lens cap, is visible. The horizon line is flat and distant, under a clear, pale sky.

Polygonal ground

Polygonal ground

# Permafrost Hydrology

- Thawing permafrost affects hydrology, ecosystems, and infrastructure



image: Ethan Coon, AMANZI-ATS

# Sub-grid parameterization

- How do we represent this complexity in models?
- Answer: sub-grid parameterizations

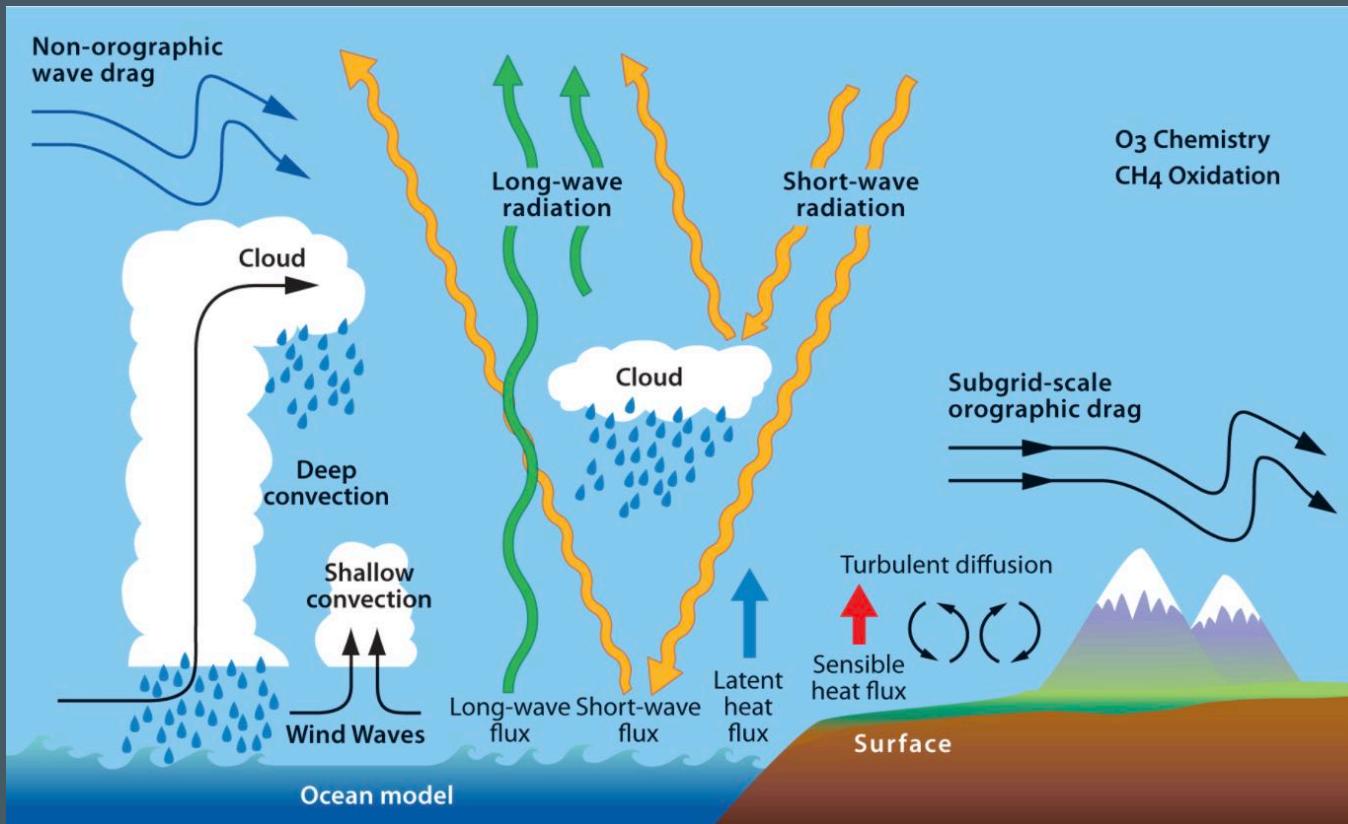
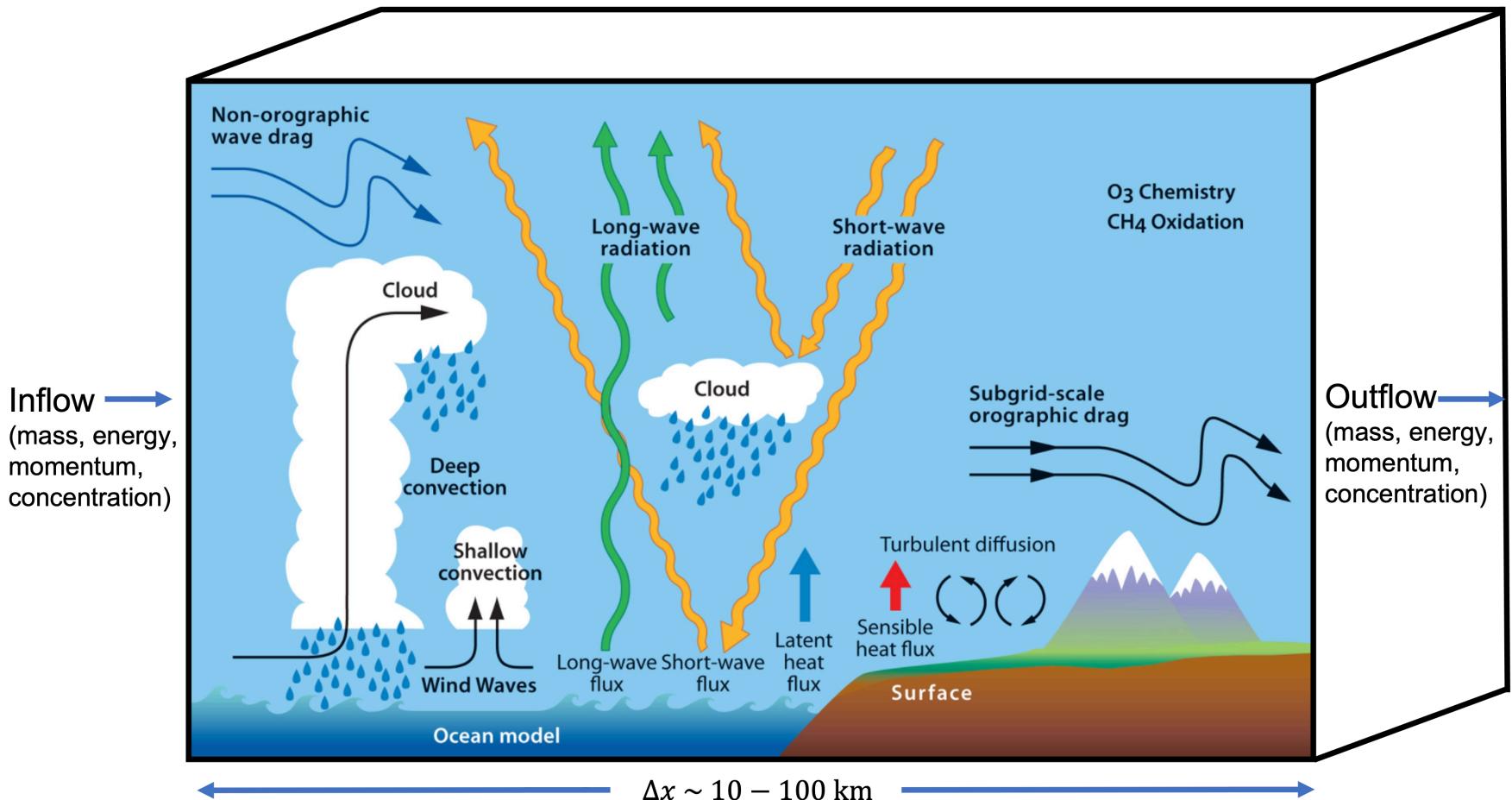


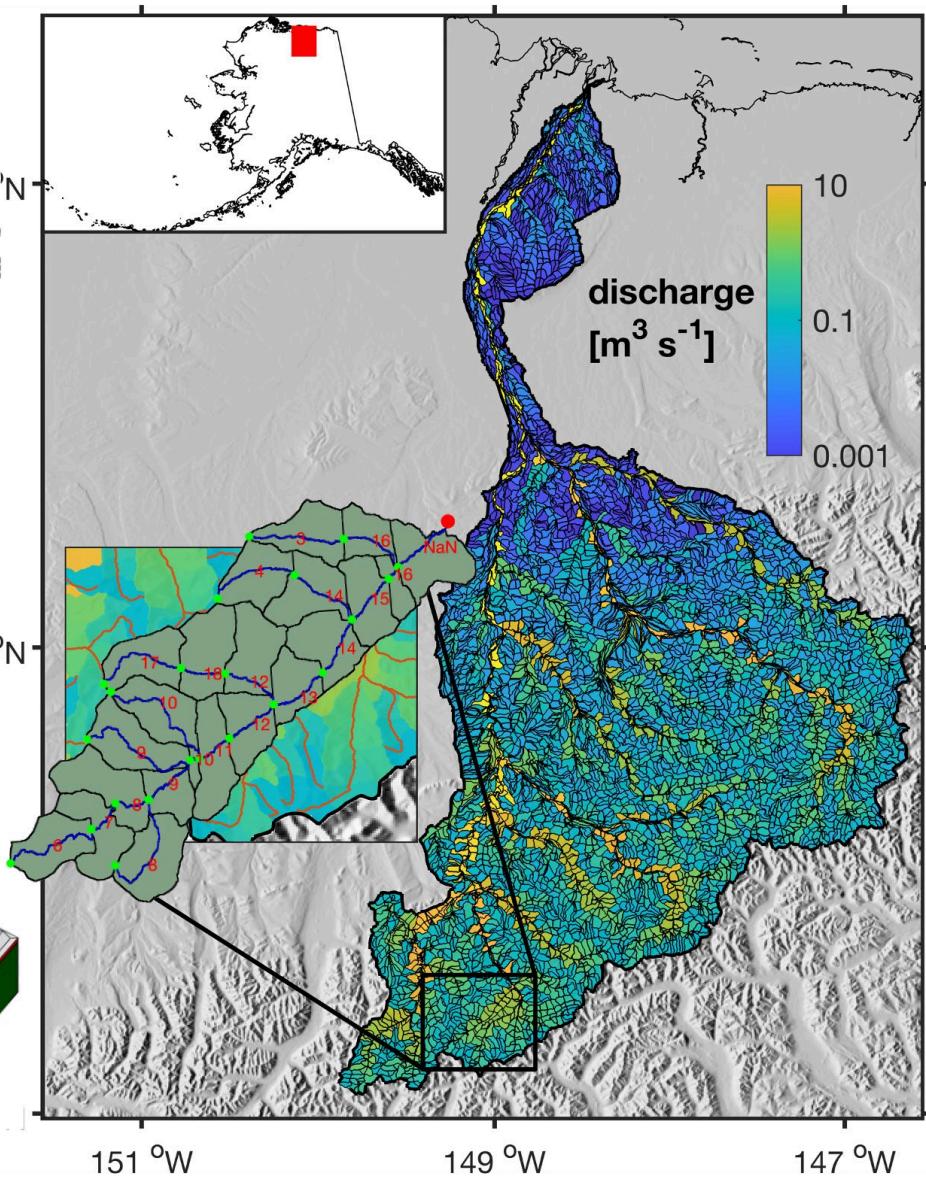
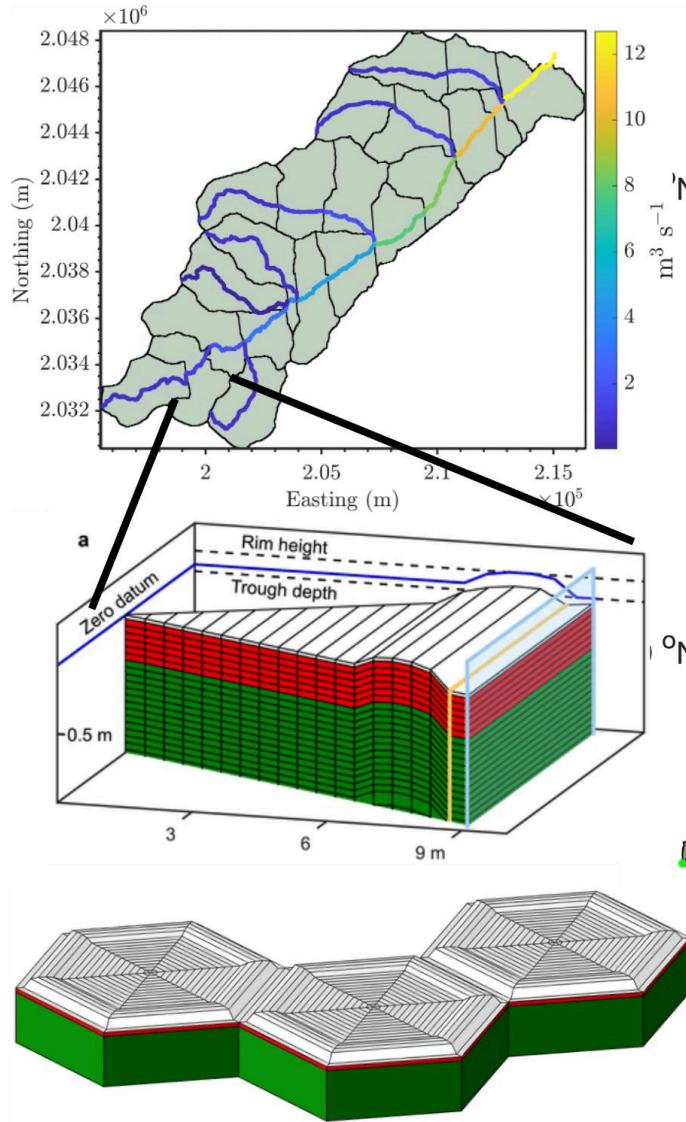
image: [https://www2.cesm.ucar.edu/working\\_groups/Atmosphere/parameterizations/](https://www2.cesm.ucar.edu/working_groups/Atmosphere/parameterizations/)

# Sub-grid parameterization



# Case Study: Representing permafrost in models





Gao and Coon, *The Cryosphere*. 2023; Abolt et al. *JGR*. 2020

# Sub-grid parameterization of soil ice content

- Represent the effect of soil ice content on lateral flow with parameter  $\Theta_{ice}$

## 2.7.5. Lateral Sub-surface Runoff

Lateral sub-surface runoff occurs when saturated soil moisture conditions exist within the soil column. Sub-surface runoff is

$$q_{drai} = \Theta_{ice} K_{baseflow} \tan(\beta) \Delta z_{sat}^{N_{baseflow}} , \quad (2.7.108)$$

where  $K_{baseflow}$  is a calibration parameter,  $\beta$  is the topographic slope, the exponent  $N_{baseflow} = 1$ , and  $\Delta z_{sat}$  is the thickness of the saturated portion of the soil column.

**Development of a simple groundwater model for use in climate models and evaluation with Gravity Recovery and Climate Experiment data**

Guo-Yue Niu,<sup>1</sup> Zong-Liang Yang,<sup>1</sup> Robert E. Dickinson,<sup>2</sup> Lindsey E. Gulden,<sup>1</sup> and Hua Su<sup>1</sup>

# Learning outcomes

- Understand the role of the cryosphere in the climate system.
- Understand what polar amplification means.
- Understand why subgrid-scale parameterizations are used in climate models.

# Learning outcomes

- Understand the role of the cryosphere in the climate system.
  - **High albedo of snow and ice.**
    - Large increases in absorbed heat as snow and ice melt
  - **Large amount of carbon stored in permafrost.**
    - Large increases in greenhouses gases as permafrost thaws

# Learning outcomes

- *Understand the role of the cryosphere in the climate system.*
- **Understand what polar amplification means.**
  - **The Arctic warming faster than the rest of the globe due to positive feedbacks in the climate system.**
  - **As the Arctic warms, snow cover declines, leading to more heat absorption, more warming, and more snow melt.**
  - **As the Arctic warms, permafrost melts, releasing carbon, leading to more warming, and more permafrost melt.**

# Learning outcomes

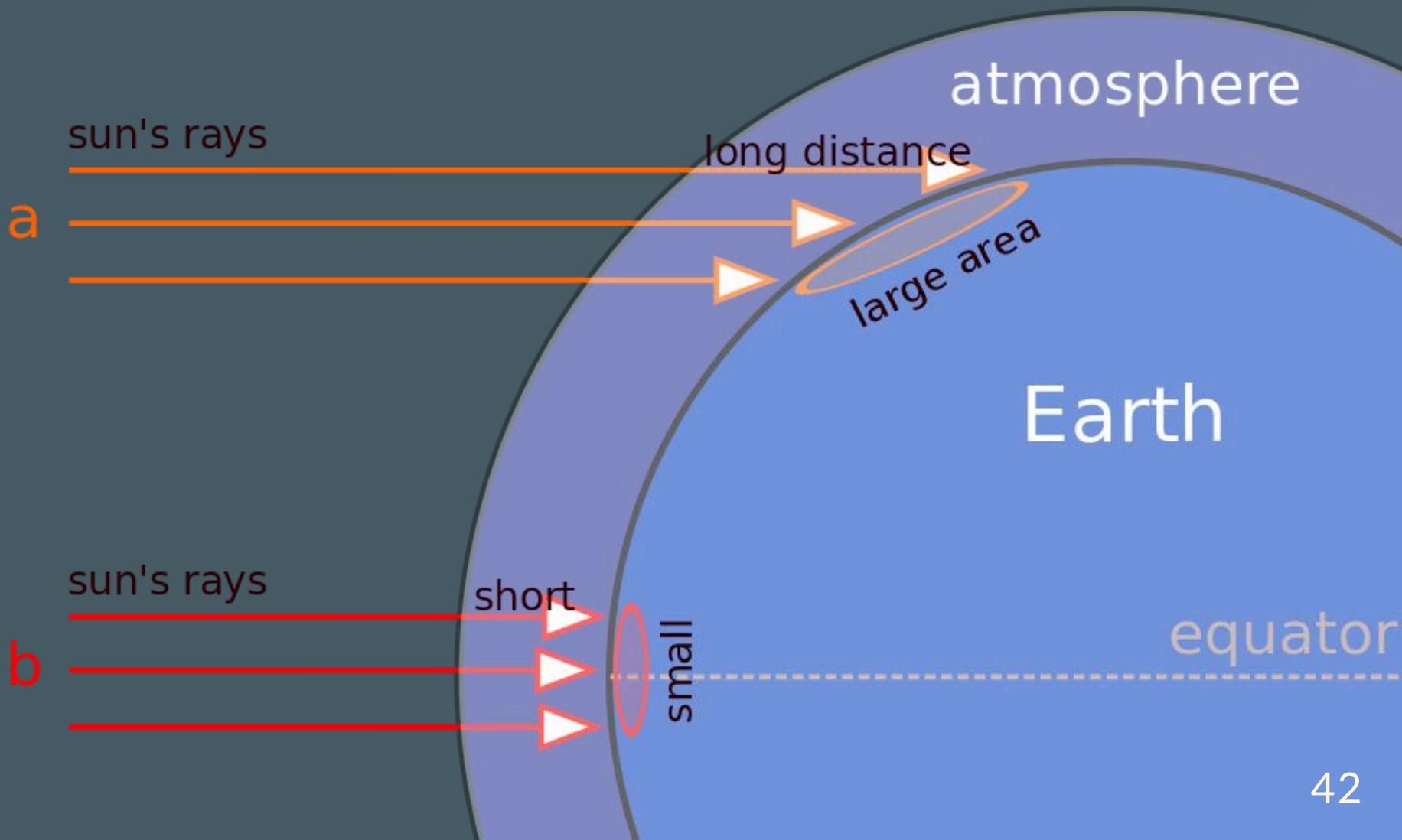
- *Understand the role of the cryosphere in the climate system.*
- *Understand what polar amplification means.*
- **Understand why sub-grid scale parameterizations are used.**
  - **Climate processes are complex, and it is not possible to represent them all in a climate model.**
  - **Sub-grid parameterizations capture the effects of processes that are not explicitly resolved in the model.**

# Recap and Takeaway Messages

- High-latitude hydroclimatology is critical for understanding global climate change.
- Climate models are essential tools for studying hydroclimatic processes.
- Polar amplification, sea ice, permafrost, and freshwater inputs play key roles.
- The accuracy of climate models is challenged by complex interactions between different components of the Earth system, and the necessity of representing them with sub-grid parameterizations.

A satellite photograph of Earth's Northern Hemisphere, centered on the Arctic region. The image shows a large expanse of white and light blue sea ice covering the Arctic Ocean and surrounding landmasses. The surrounding landmasses are green and brown, representing continents and islands. The horizon line is visible at the top of the image.

**Questions?**



- Observations show an earlier peak in spring
- Observations show fewer peaks in late summer

