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.**

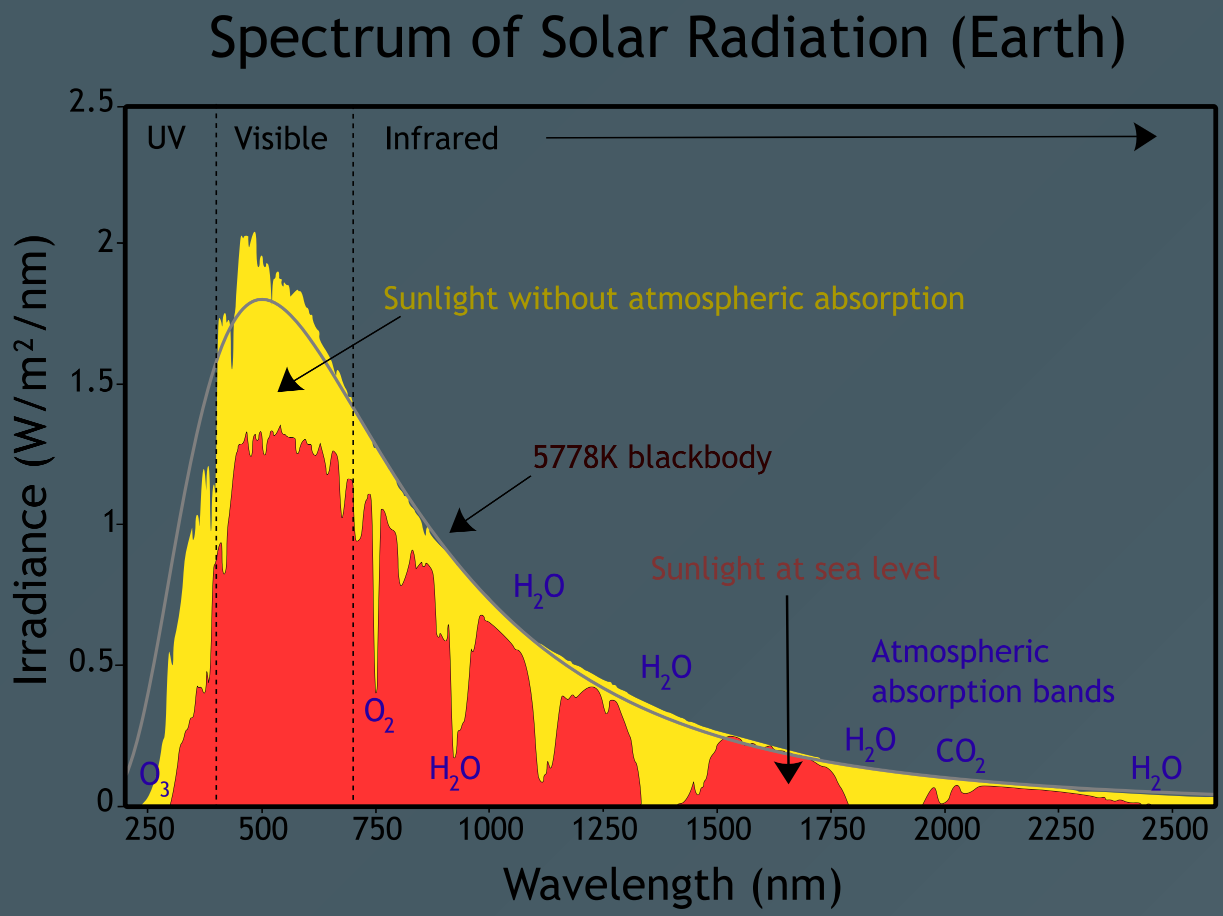
Photo: Matt Cooper

What is albedo and why does it matter?

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

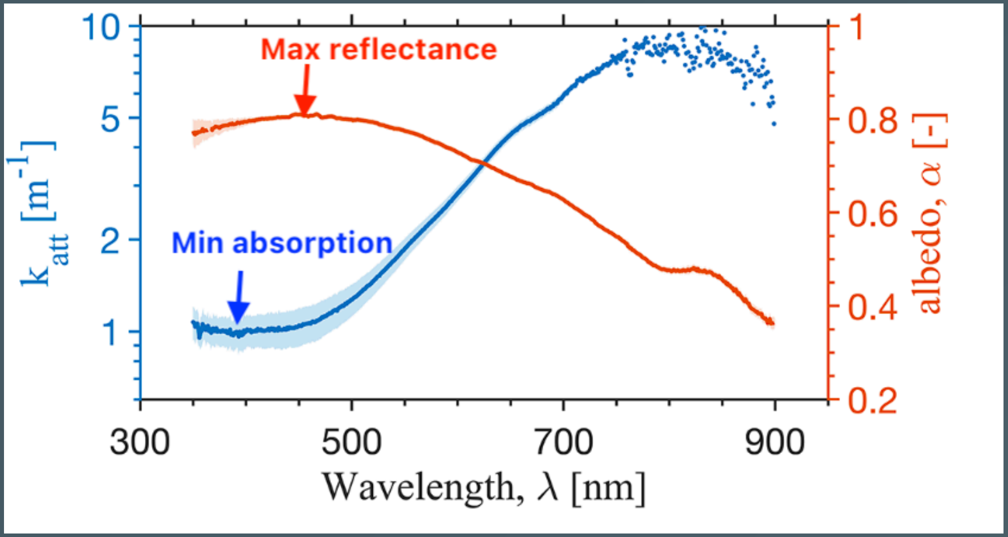
- Incoming solar radiation can be direct and diffuse (e.g., cloudy sky)
- Albedo generally increases when the sun is closer to the horizon (when the solar zenith angle is greater)
- “reflected” means integrated over all angles

Solar radiation peaks in the visible spectrum



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" ...



Cooper et al. 2021, The Cryosphere

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	**80% Increase**

credit: Jeff Dozier

What makes ice albedo decrease?

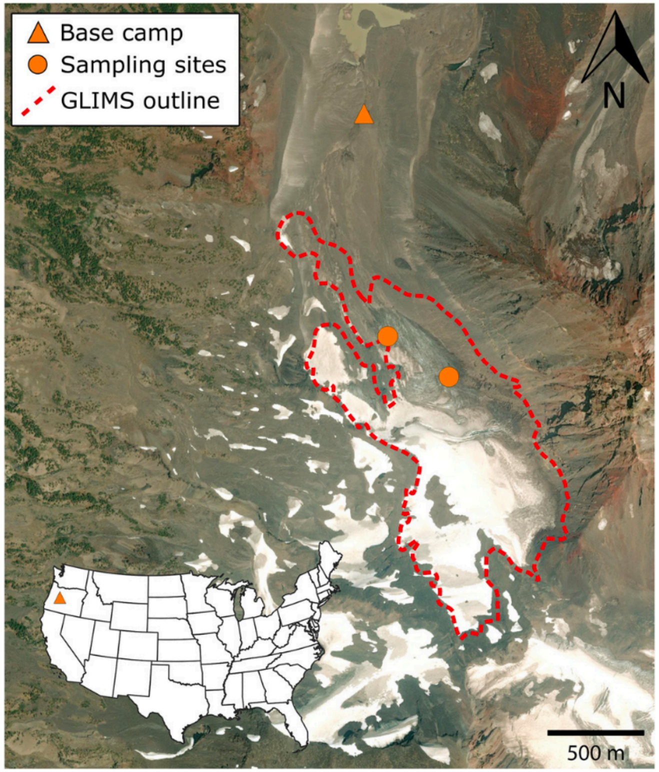


Fig. 3. The study area on Collier Glacier, Three Sisters Wilderness, Oregon. Two sites were sampled: one close to the northern terminus, and one in the middle of the glacier, below the ice fall which roughly marks the average ELA.

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

Spectral reflectance of dirty glacial ice

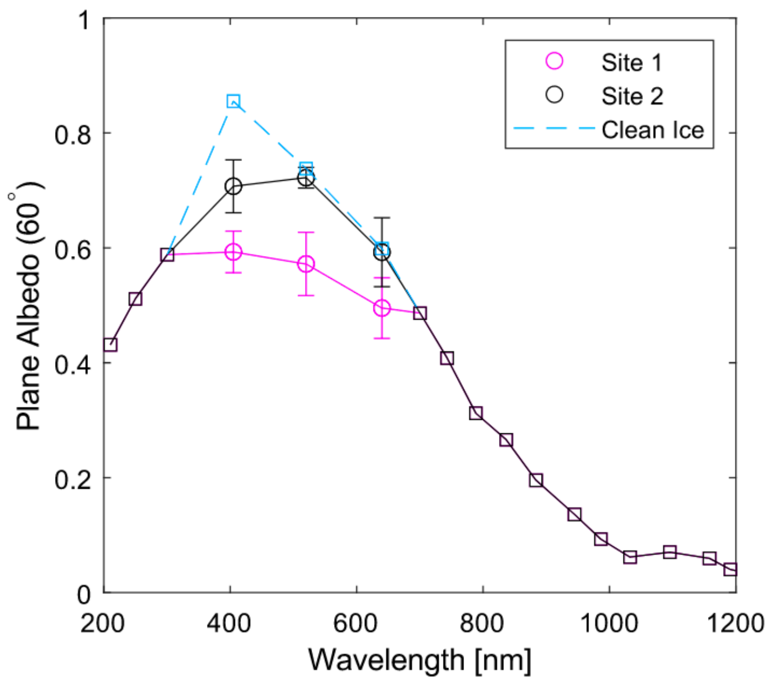
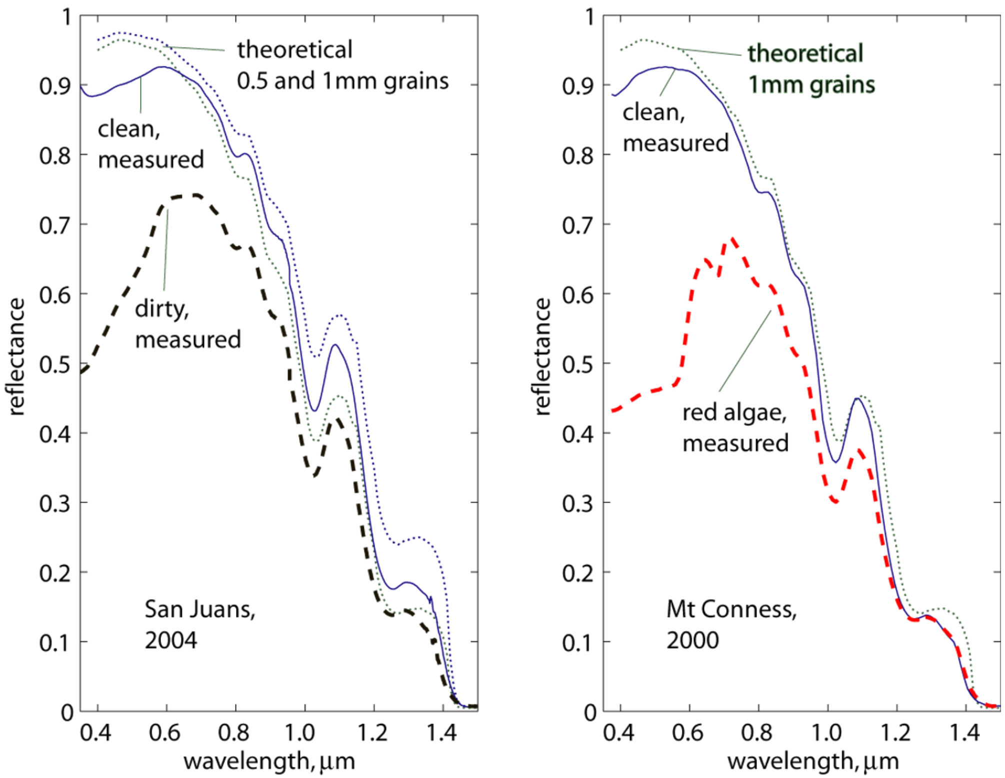


Fig. 8. Spectral albedo on both sites as well as for clean ice. Data points at 405, 520 and 640 nm are calculated from measured scattering and absorption coefficients (open circles). Other data points are calculated from literature values for absorption and the averaged measured scattering coefficient (open squares). Solid lines represent linear interpolation as a guide to the eye. The dashed line was calculated using absorption coefficients for clean ice and the scattering coefficients from Site 2.

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

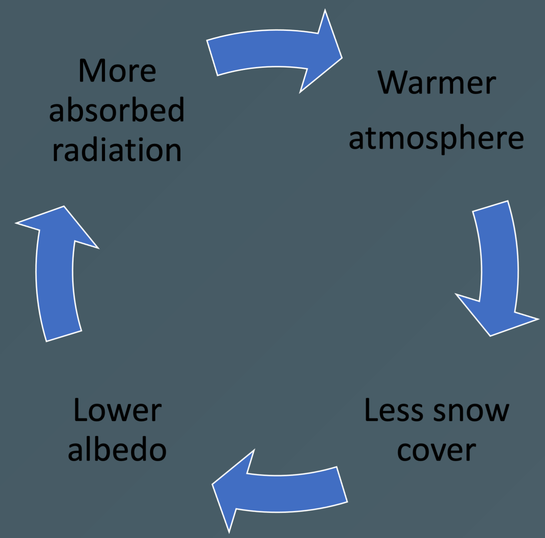
Spectral reflectance of dirty snow and snow with red algae

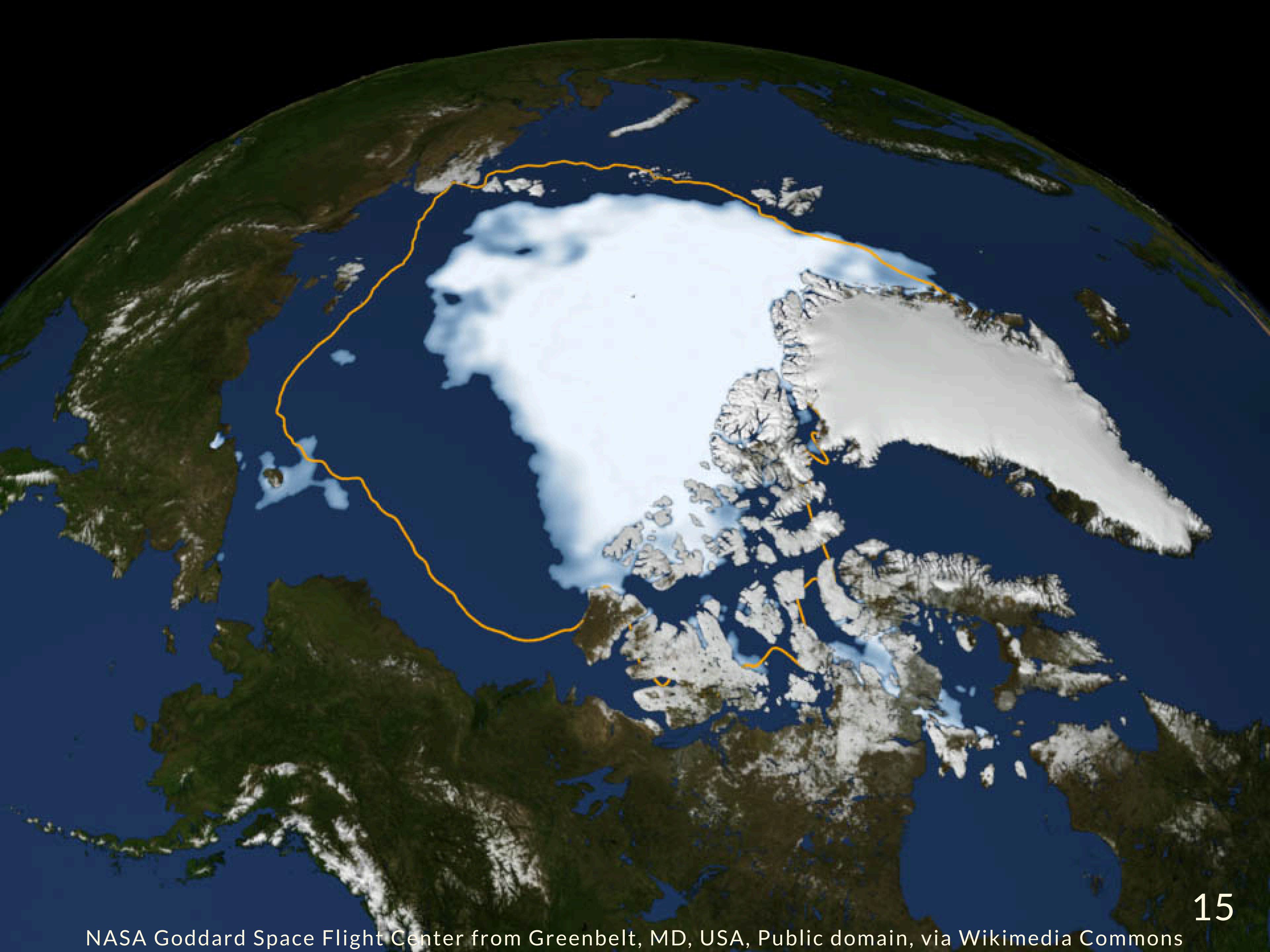


Painter et al. 2001

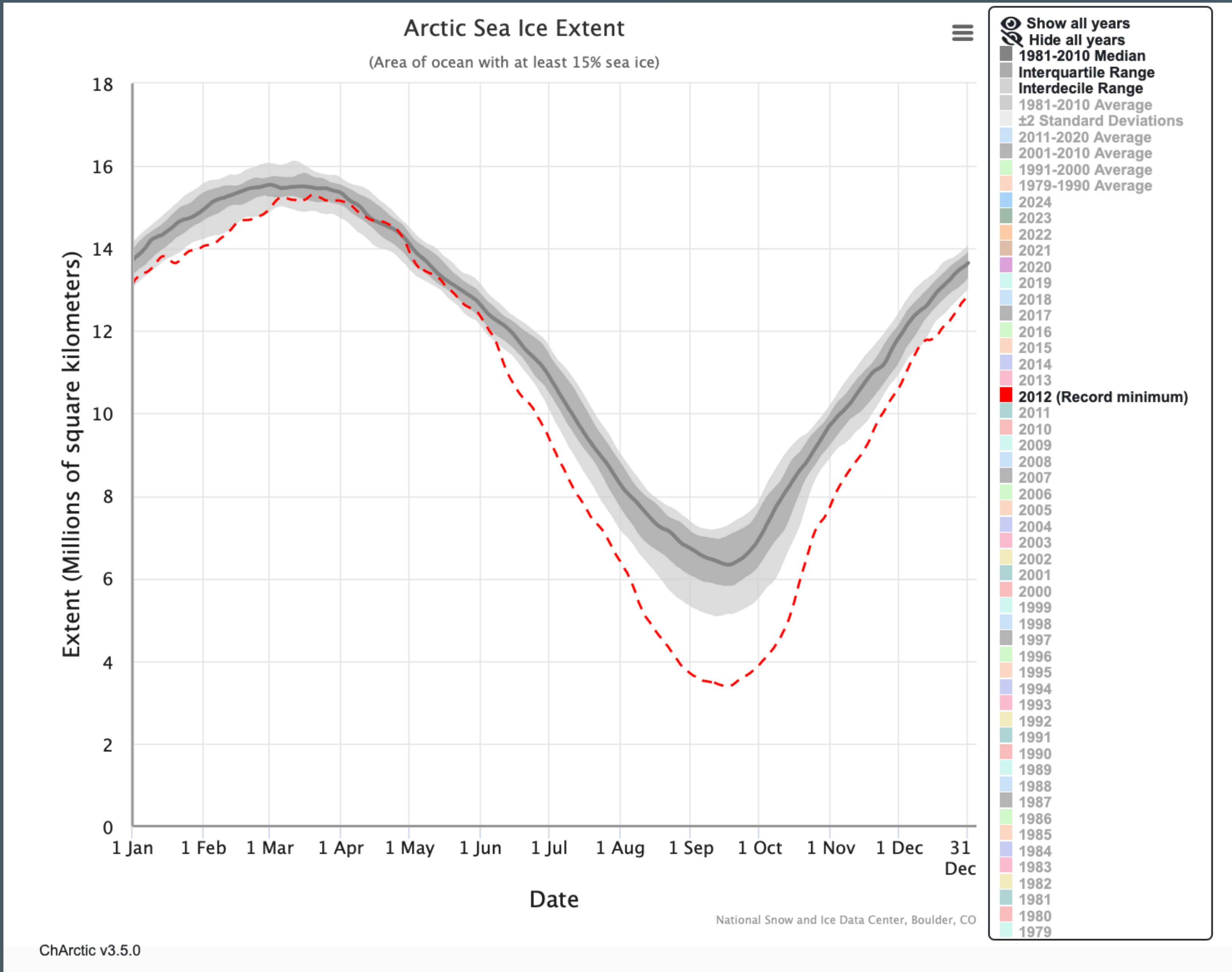
High-latitude regions are especially sensitive to climate change

- 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.**





NASA Goddard Space Flight Center from Greenbelt, MD, USA, Public domain, via Wikimedia Commons



Arctic Sea Ice Extent
(Area of ocean with at least 15% sea ice)
Extent (Millions of square kilometers)
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10
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1 Mar
1 Apr
1 May
1 Jun
1 Jul
1 Aug
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1 Oct
1 Nov
1 Dec
31 Dec
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National Snow and Ice Data Center, Boulder, CO
ChArctic v3.5.0
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Hide all years
1981-2010 Median
Interquartile Range
Interdecile Range
1981-2010 Average
±2 Standard Deviations
2011-2020 Average
2001-2010 Average
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1979-1990 Average
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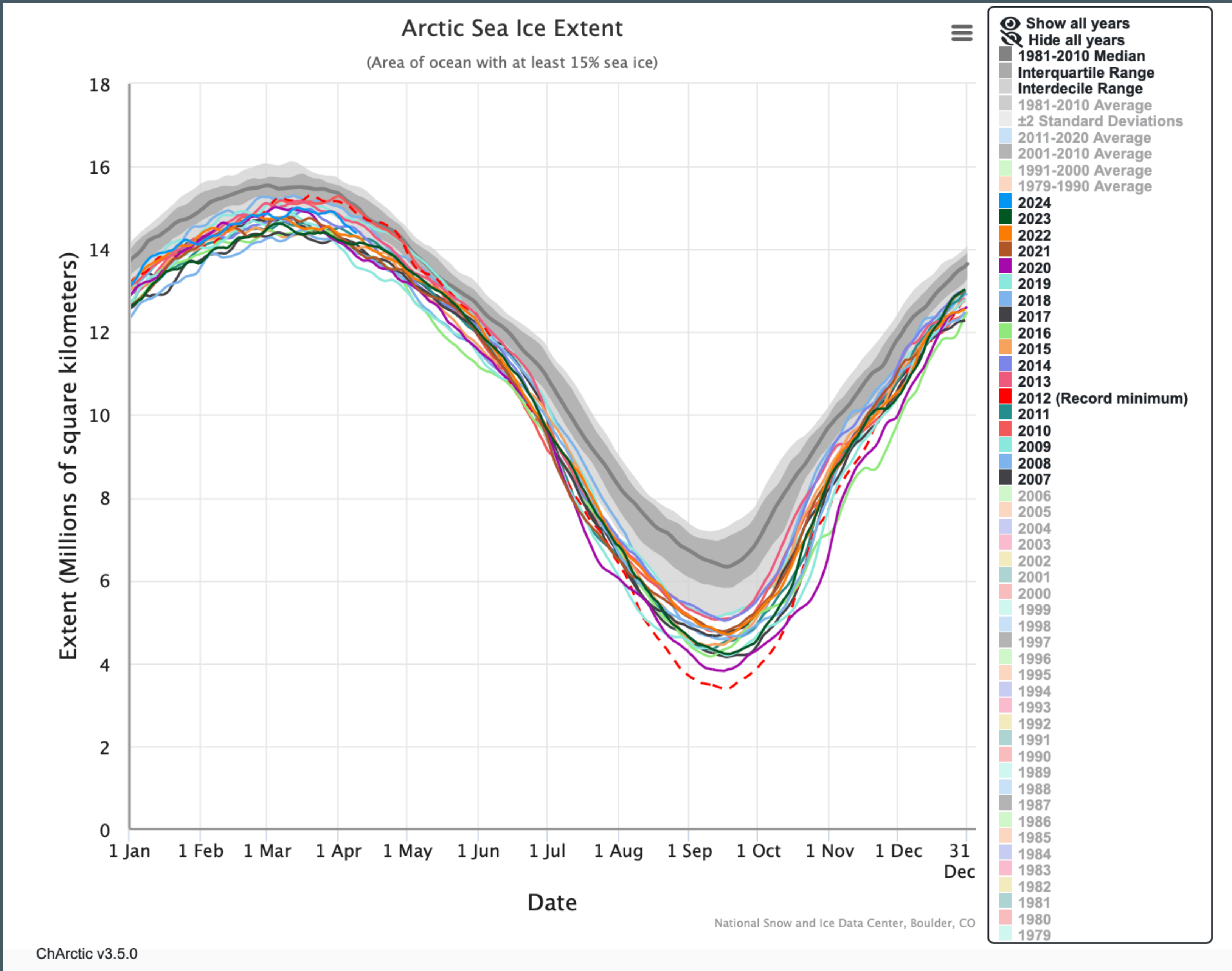
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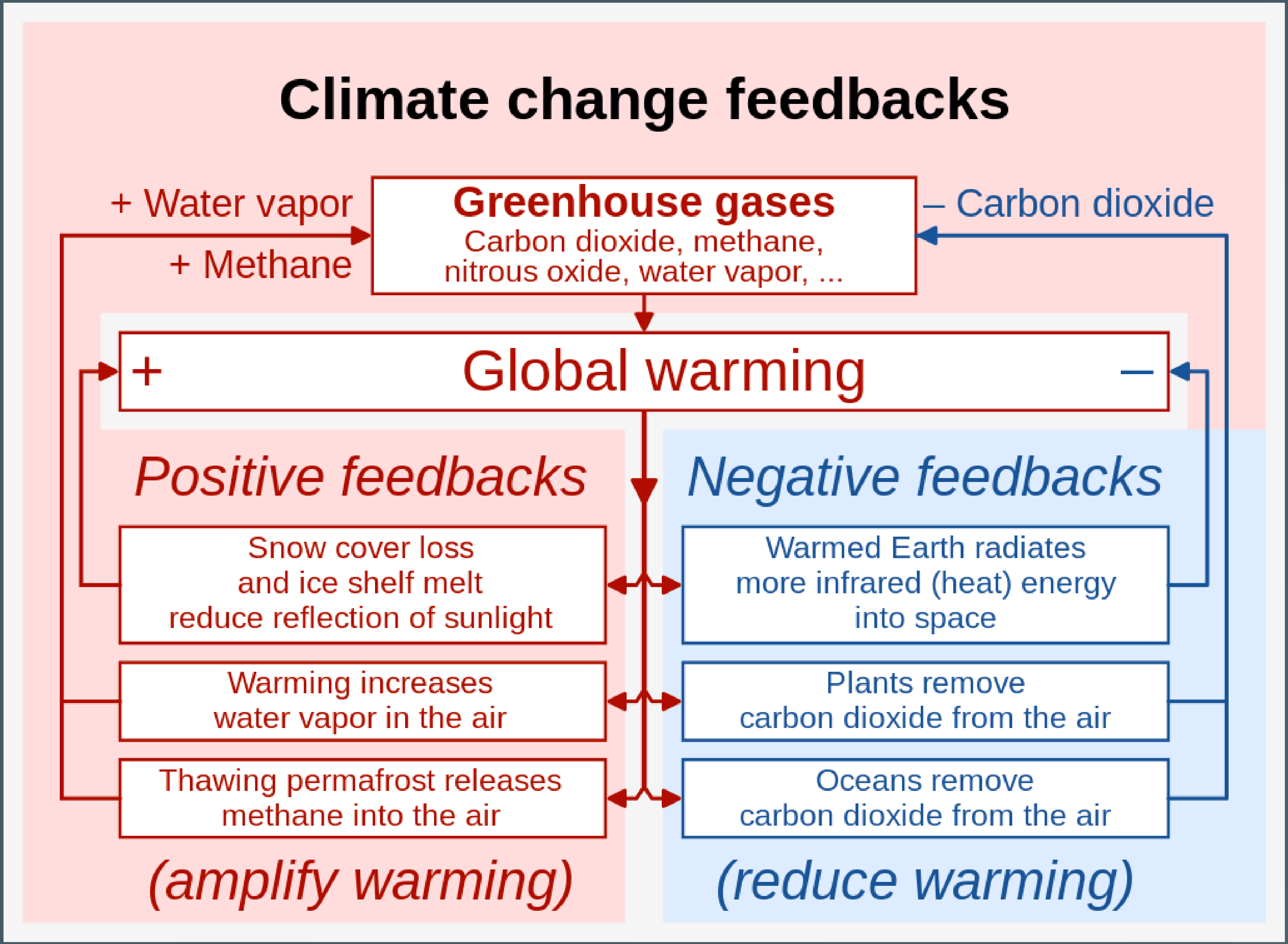
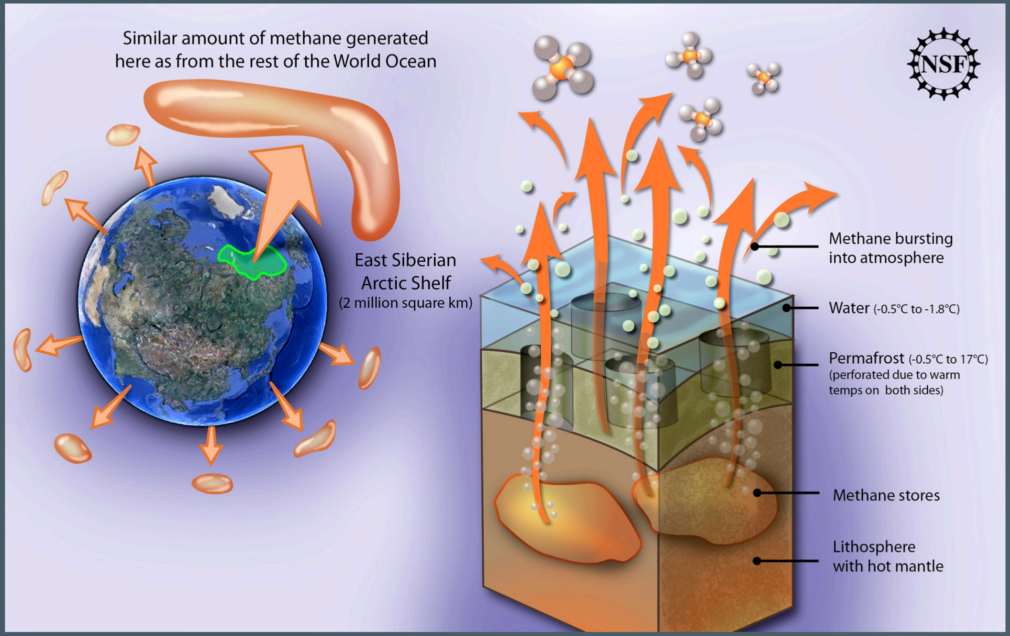

Climate change feedbacks
+ Water vapor
+ Methane
Greenhouse gases
Carbon dioxide, methane,
nitrous oxide, water vapor, ...
– Carbon dioxide
Global warming
+
–
Positive feedbacks
Snow cover loss
and ice shelf melt
reduce reflection of sunlight
Warming increases
water vapor in the air
Thawing permafrost releases
methane into the air
(amplify warming)
Negative feedbacks
Warmed Earth radiates
more infrared (heat) energy
into space
Plants remove
carbon dioxide from the air
Oceans remove
carbon dioxide from the air
(reduce warming)

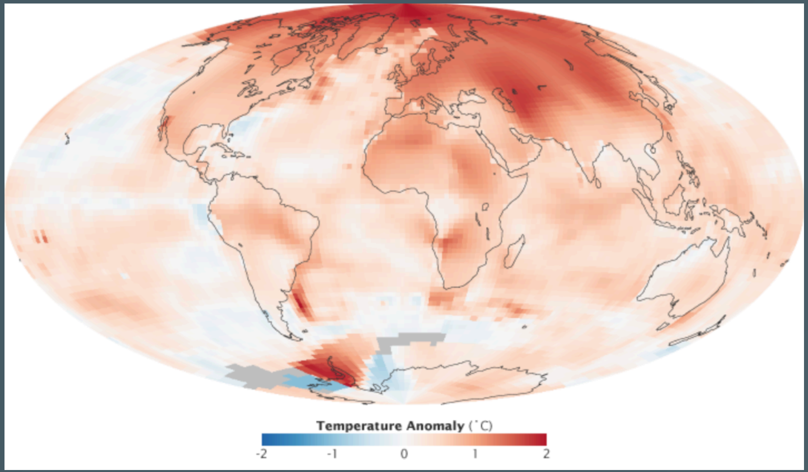
Polar Amplification

- 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.



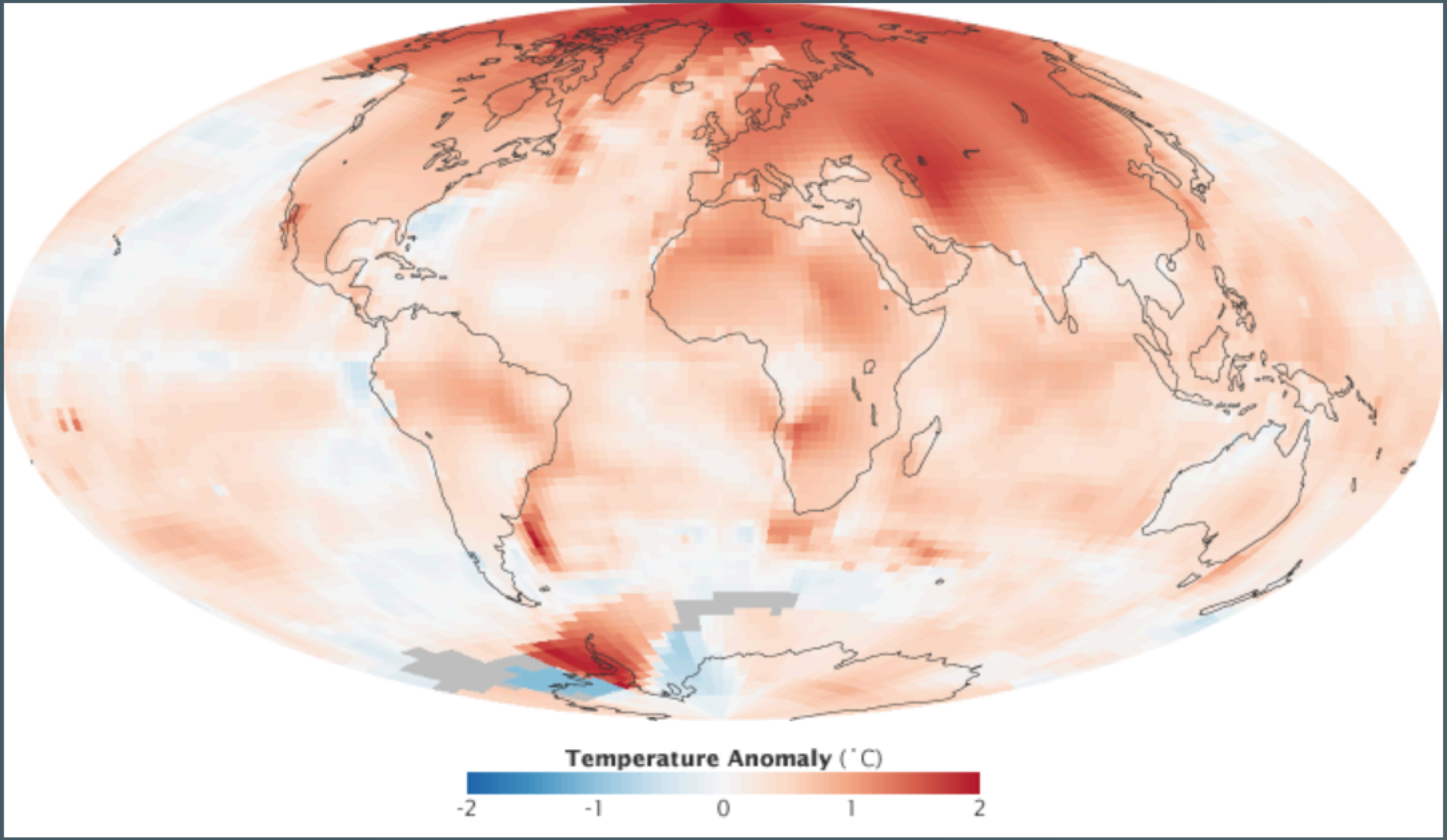
Polar Amplification

- 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.



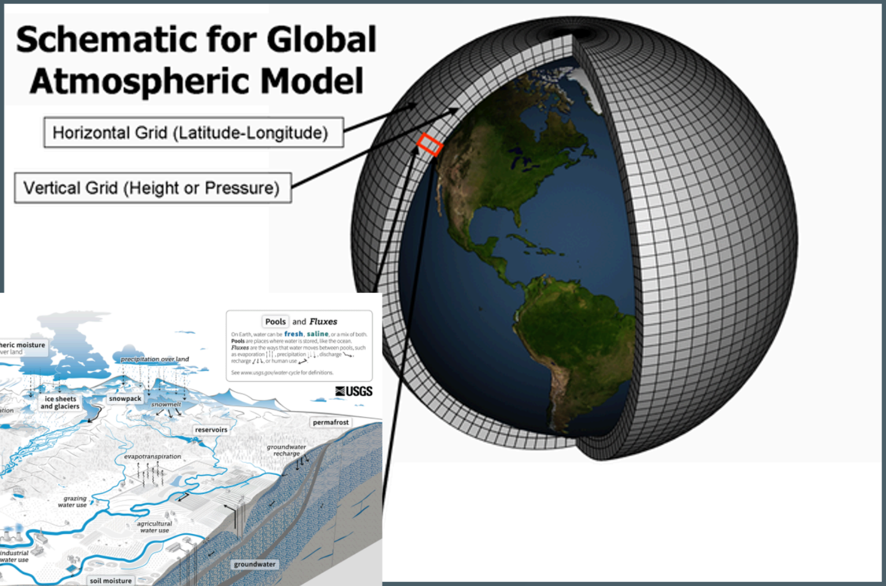
https://commons.wikimedia.org/wiki/File:GISS_temperature_2000-09.png

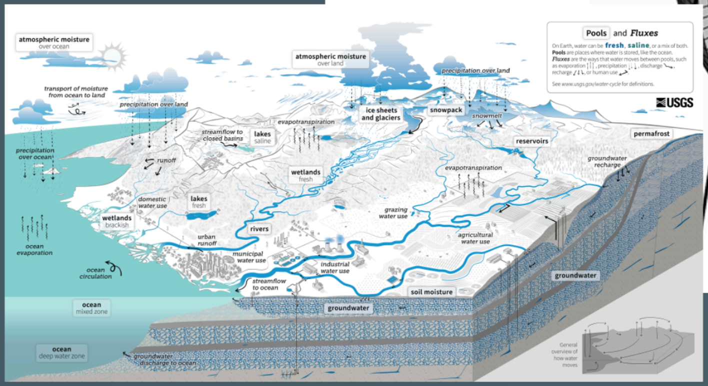
Question: why are the northern latitudes warming more than the southern latitudes?

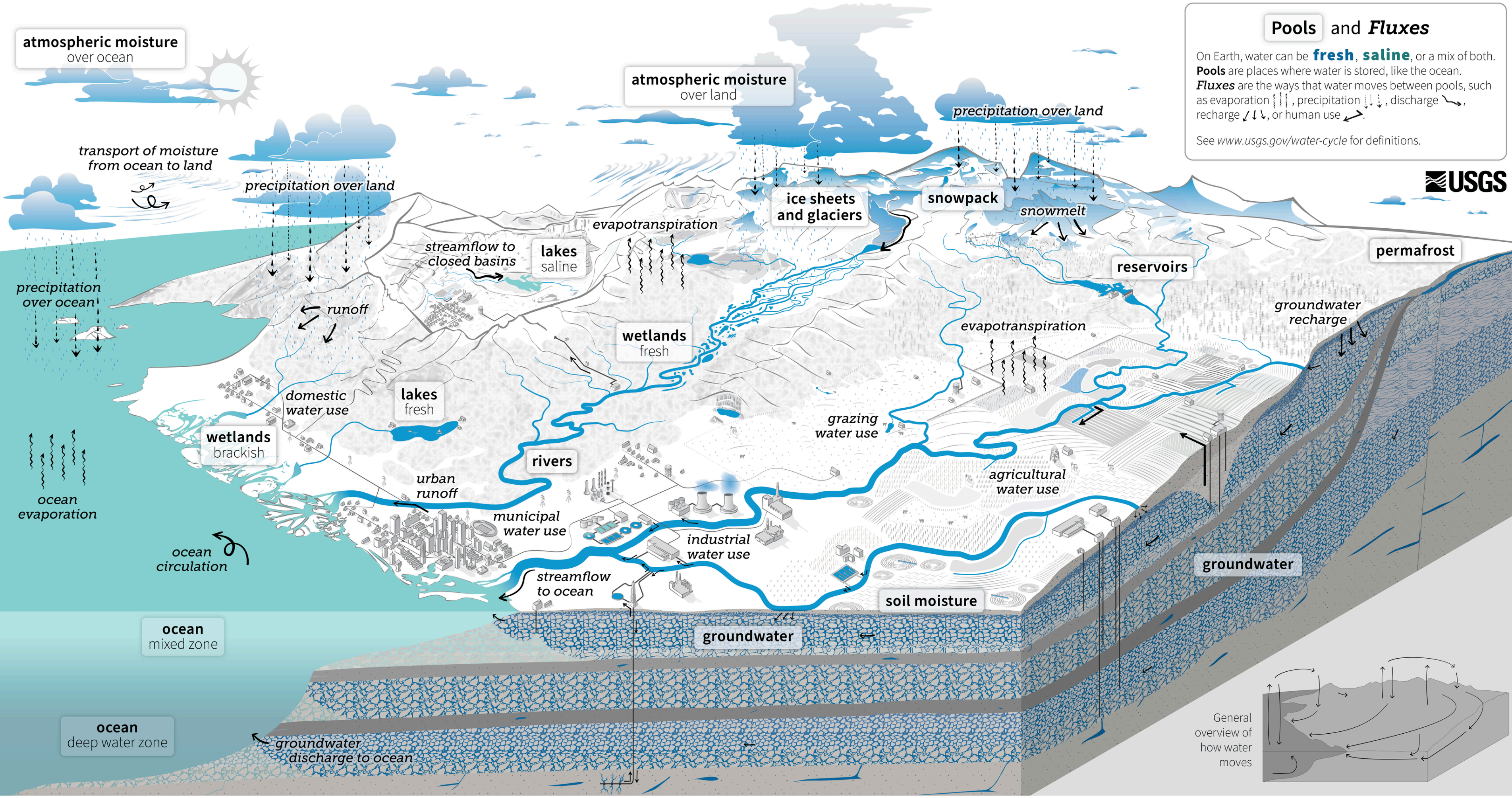


Global Climate Models for Hydroclimatology

- 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.






atmospheric moisture over ocean
transport of moisture from ocean to land
precipitation over land
precipitation over ocean
runoff
atmospheric moisture over land
streamflow to closed basins
lakes saline
evapotranspiration
ice sheets and glaciers
snowpack
precipitation over land
snowmelt
reservoirs
permafrost
groundwater recharge
evapotranspiration
wetlands fresh
domestic water use
lakes fresh
wetlands brackish
ocean evaporation
rivers
urban runoff
grazing water use
agricultural water use
municipal water use
industrial water use
ocean circulation
streamflow to ocean
soil moisture
groundwater
ocean mixed zone
groundwater
ocean deep water zone
groundwater discharge to ocean
General overview of how water moves
Pools and *Fluxes*
On Earth, water can be **fresh**, **saline**, or a mix of both.
Pools are places where water is stored, like the ocean.
Fluxes are the ways that water moves between pools, such as evaporation, precipitation, discharge, recharge, or human use.
See *www.usgs.gov/water-cycle* for definitions.
USGS

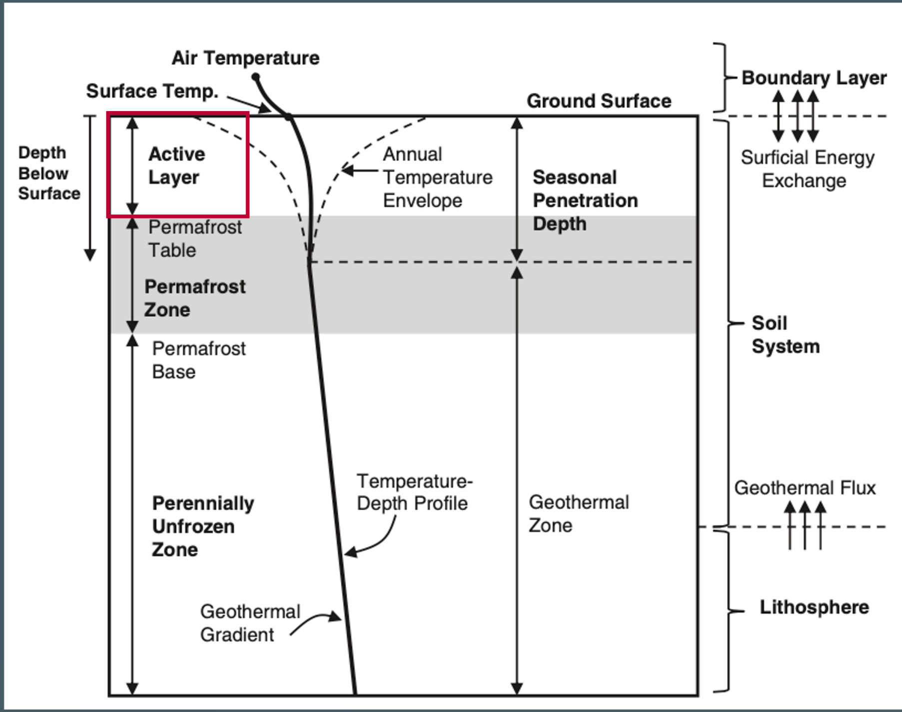
Permafrost Hydrology

- 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).

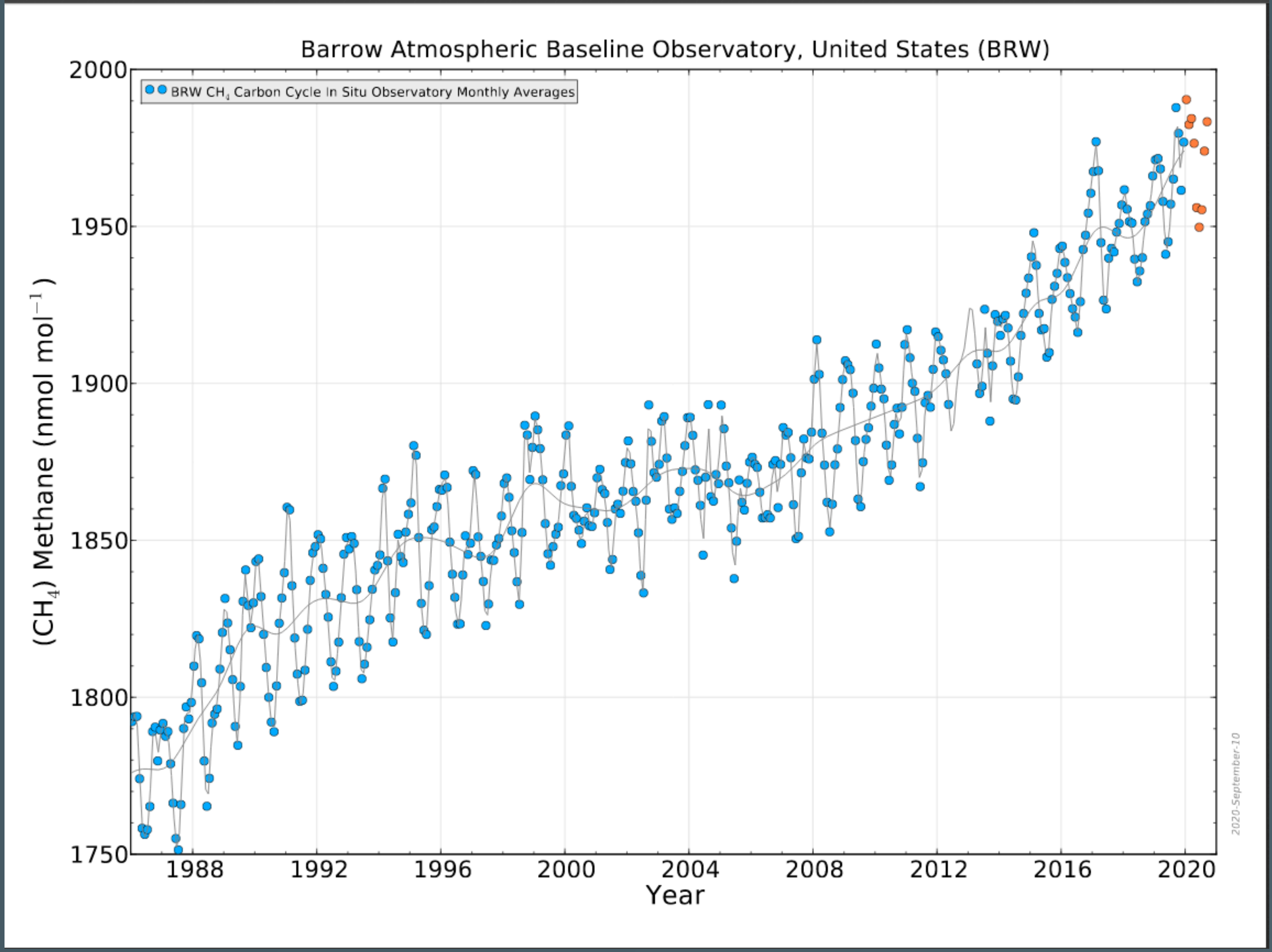

Permafrost Hydrology

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

diagram: Kurylyk et al (2014) ESR



Arctic methane emissions



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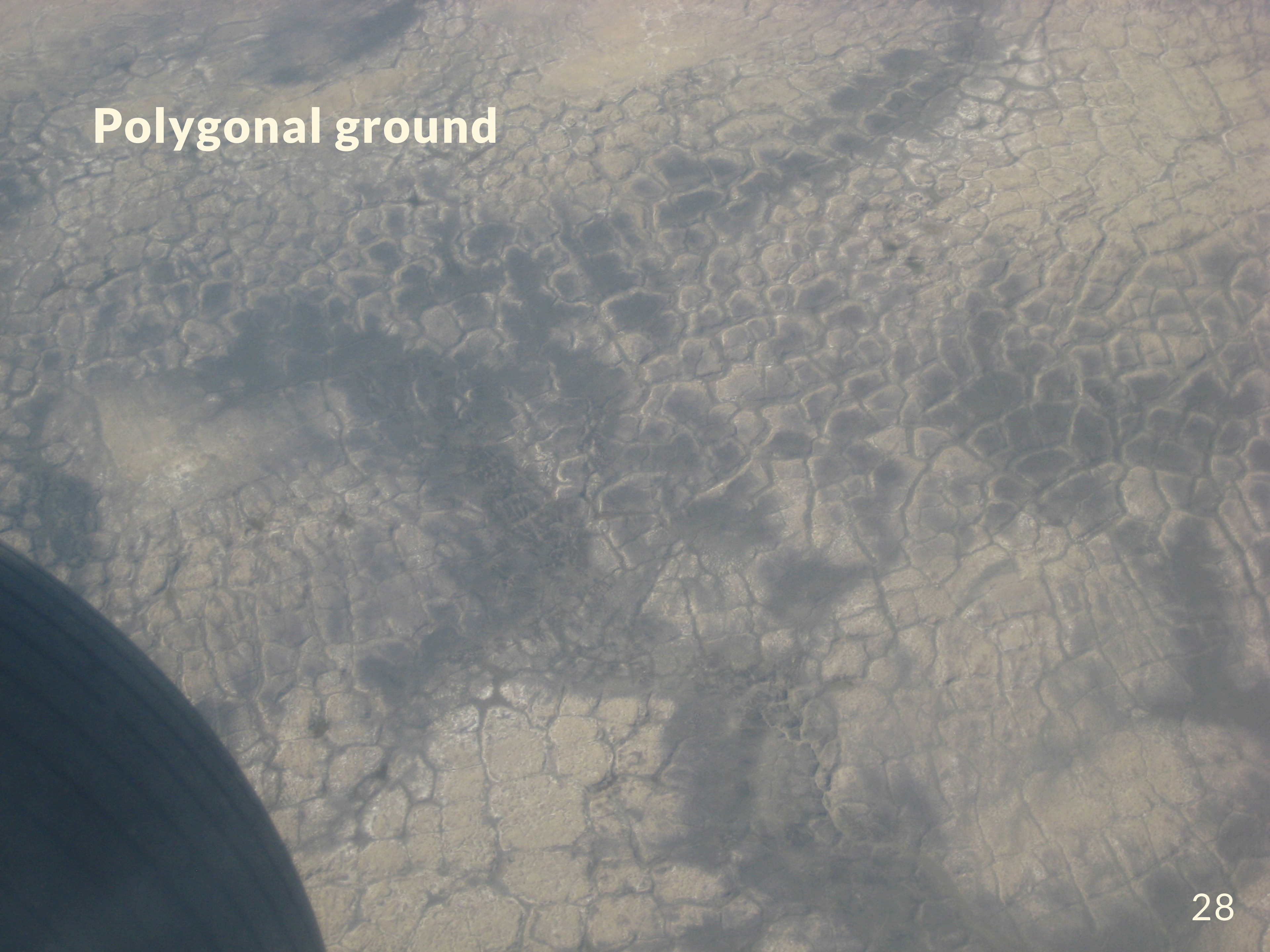
Polygonal ground




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

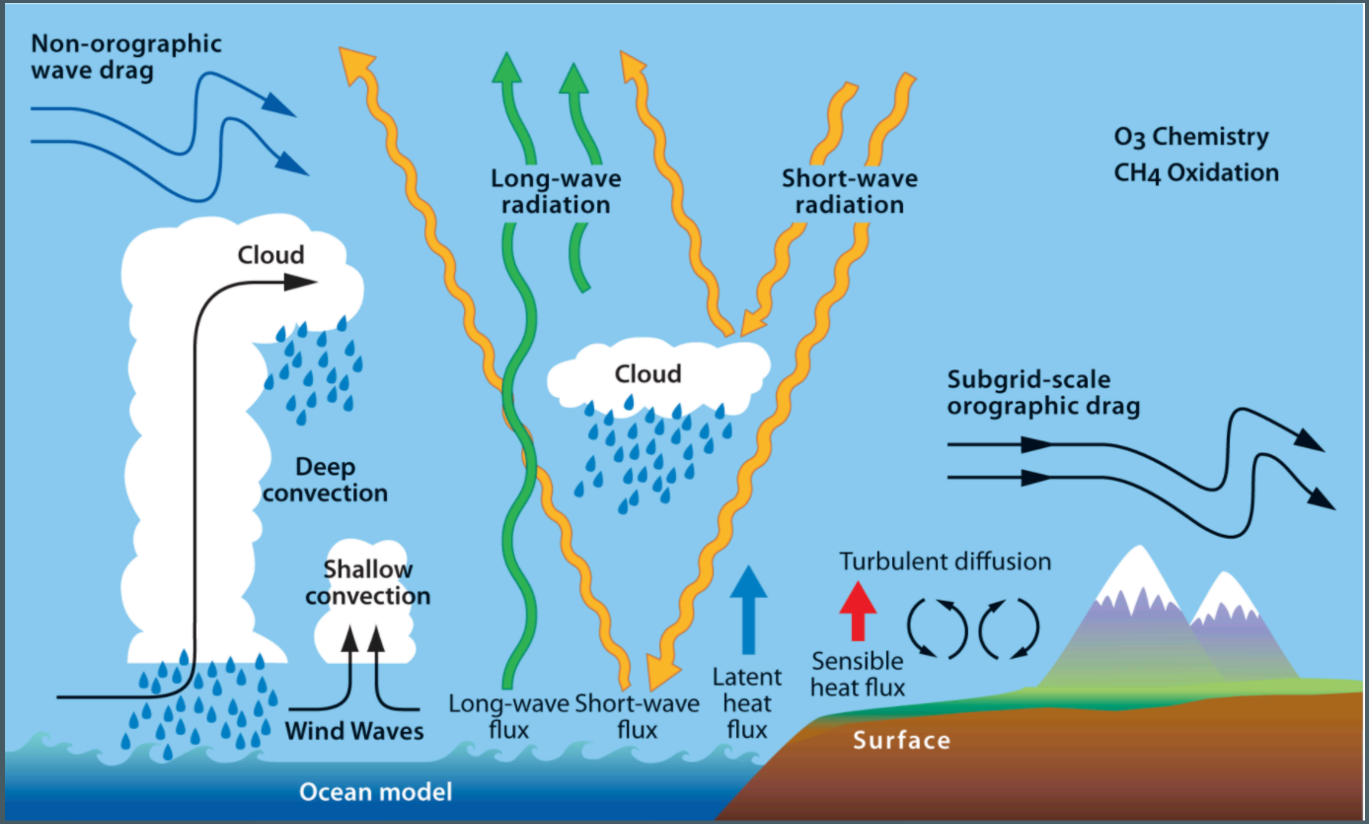
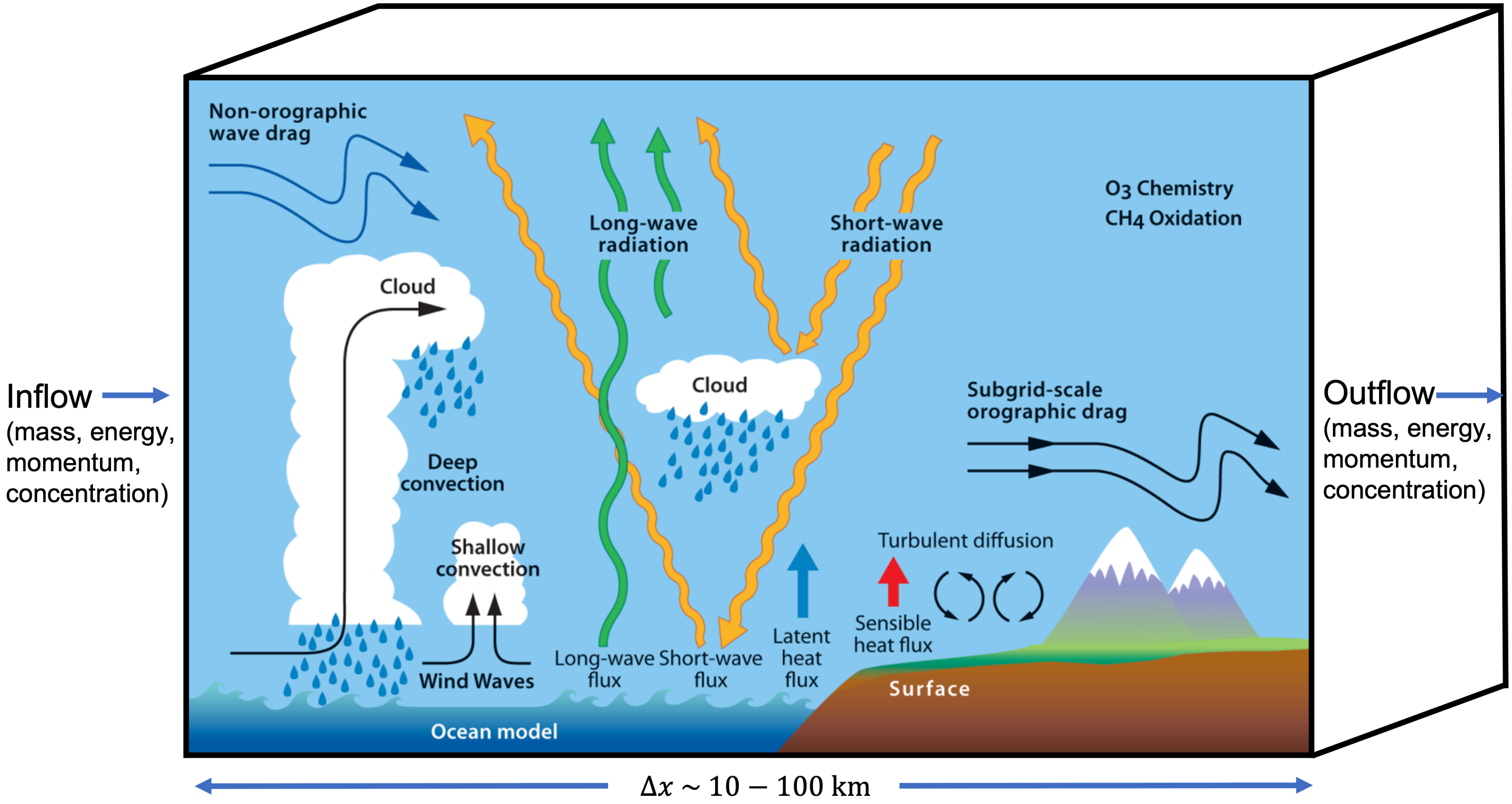
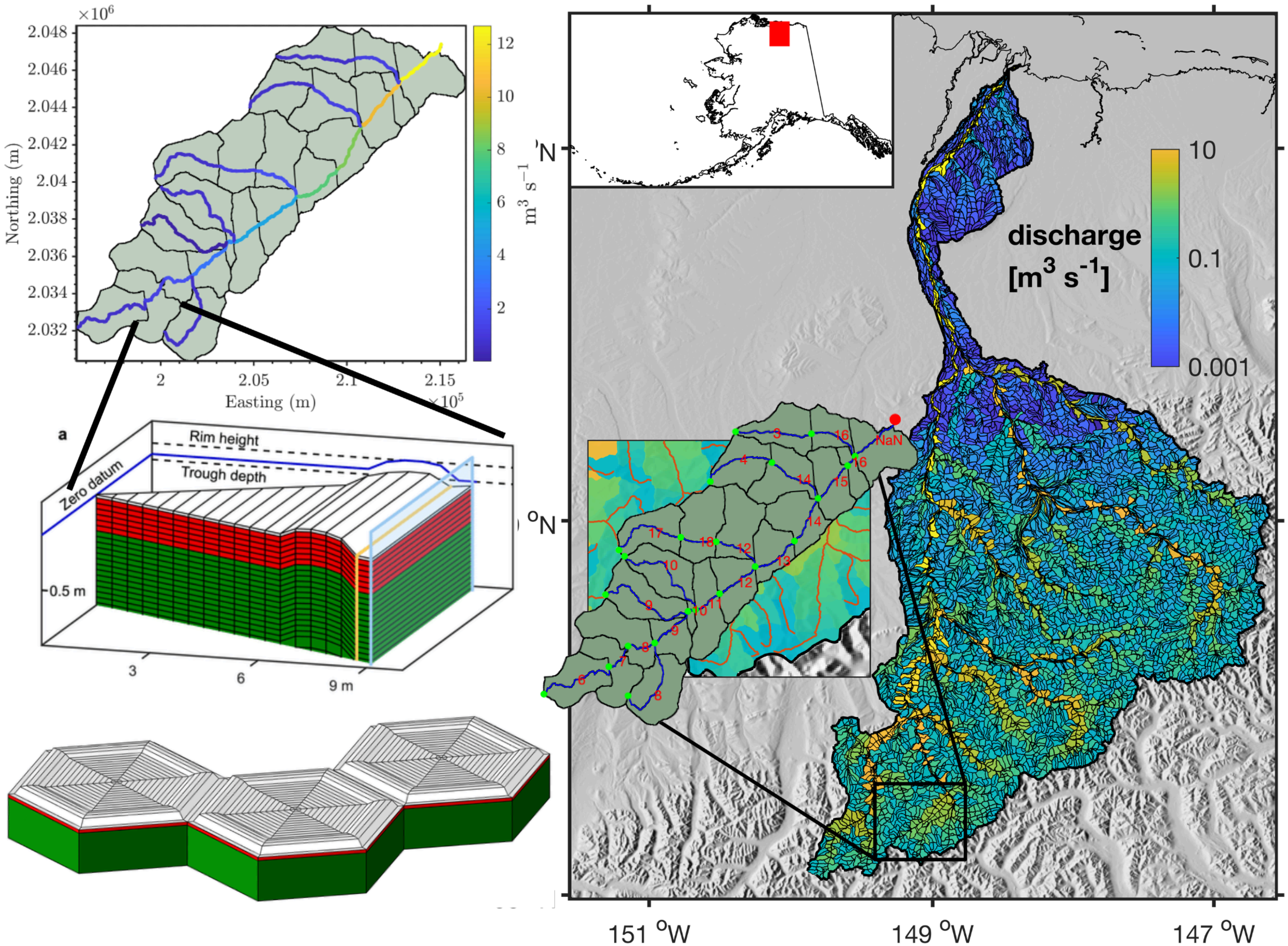


image: https://www2.cesm.ucar.edu/working_groups/Atmosphere/parameterizations/

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 Θ_{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

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

where $K_{baseflow}$ is a calibration parameter, β is the topographic slope, the exponent $N_{baseflow}$ = 1, and Δz_{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,[1] Zong-Liang Yang,[1] Robert E. Dickinson,[2] Lindsey E. Gulden,[1] and Hua Su[1]

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.**

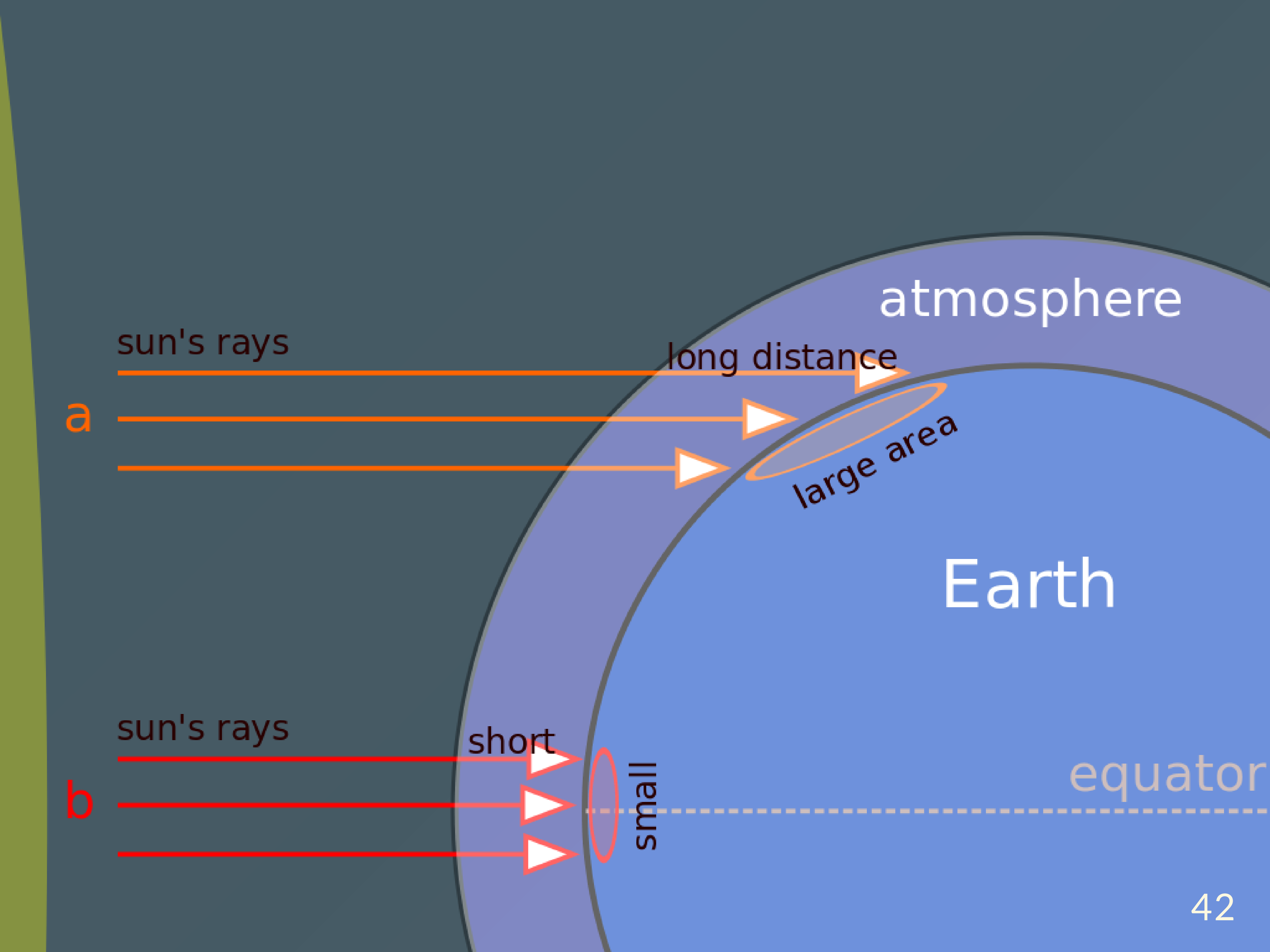
Learning outcomes

- *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.

Questions?


atmosphere
sun's rays
long distance
a
large area
Earth
sun's rays
short
b
small
equator

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