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Arctic Amplification: Process Drivers and Sources of Uncertainty

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Arctic Impacts in pictures

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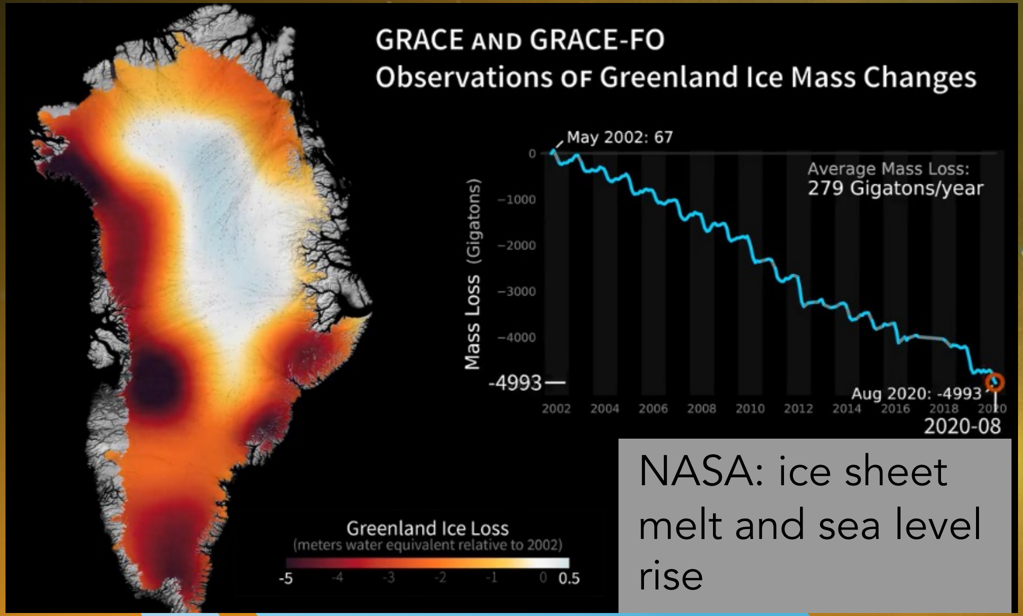
Marine food web

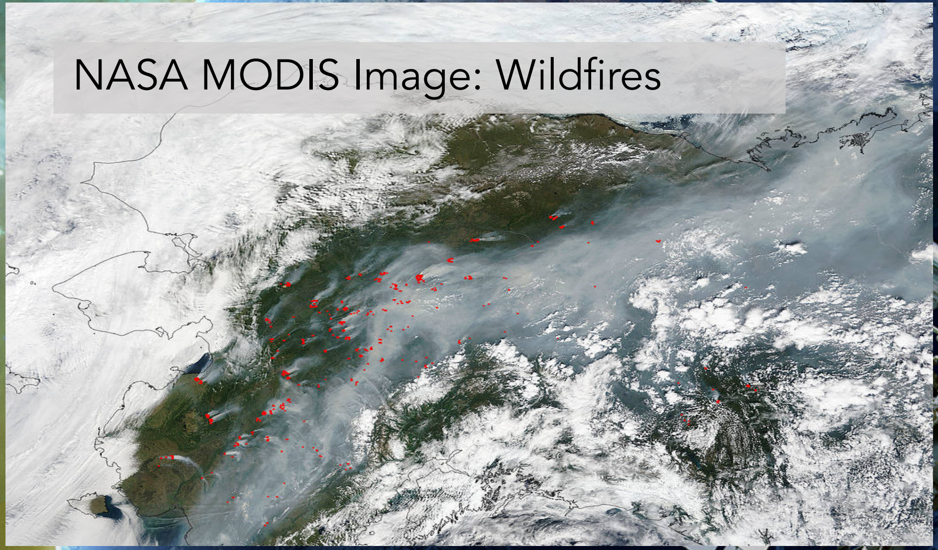
NASA Image: Thermokarst and permafrost thaw

Source: cnn.com

What can scientists do?



NASA: ice sheet melt and sea level rise



NASA MODIS Image: Wildfires

Reducing uncertainty in Arctic processes and models

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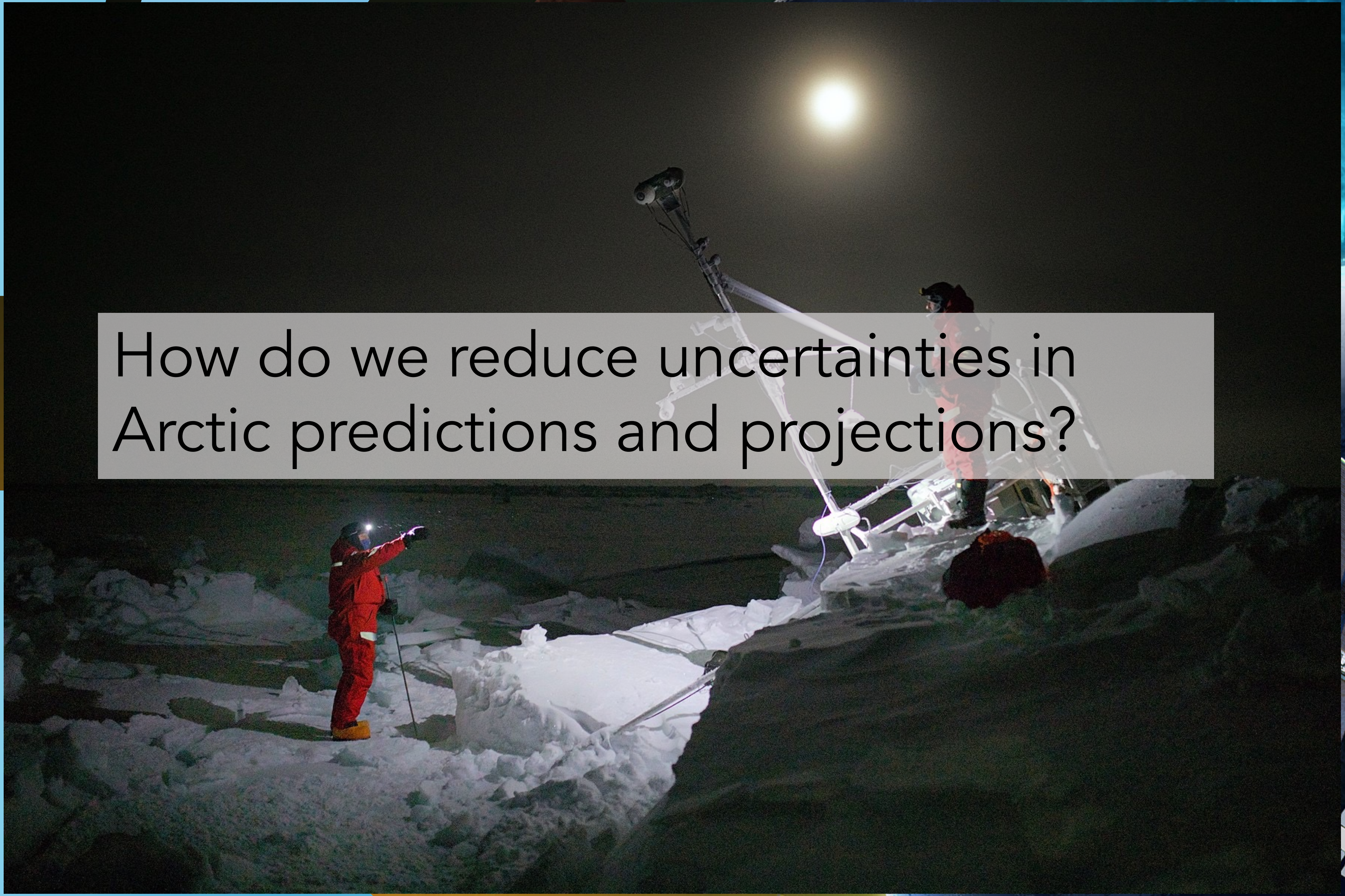

How do we reduce uncertainties in Arctic predictions and projections?

What is Arctic Amplification?

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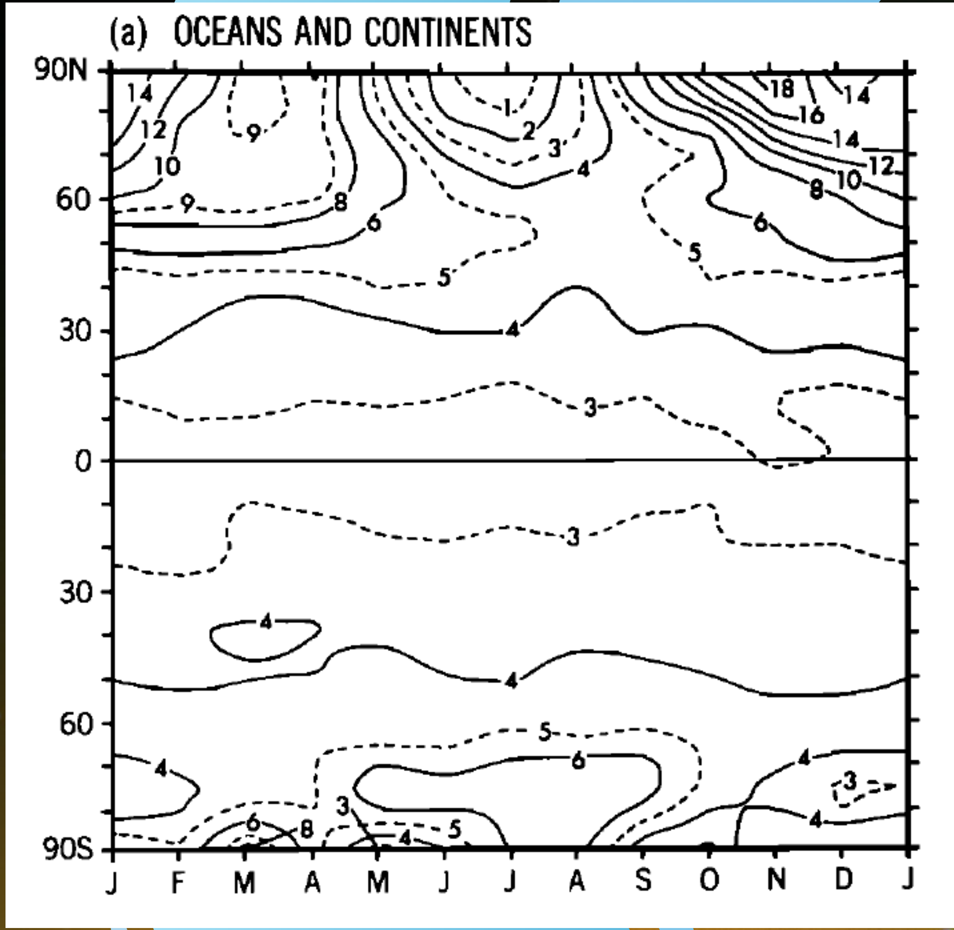
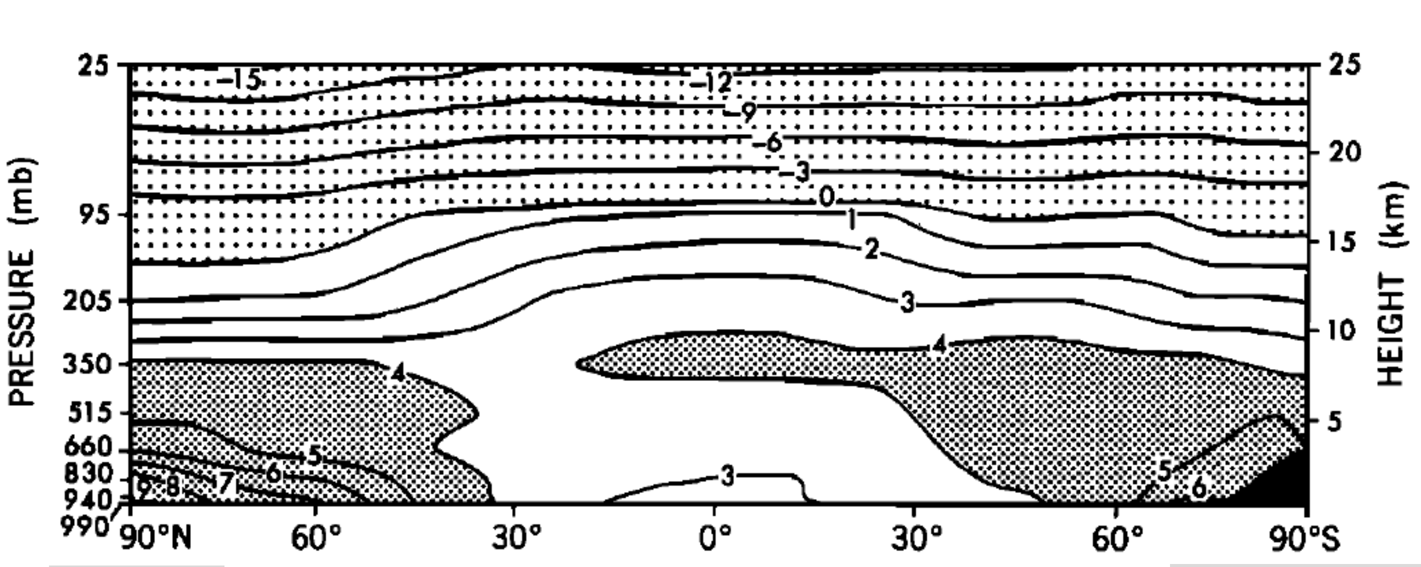


Arctic Amplification is the phenomenon where the Arctic is more sensitivity to a climate perturbation than the global average.



Arctic

Antarctic

Manabe and Stouffer (1980)

Larger Arctic Warming concentrated in fall and winter and near the surface.

Observed Surface Temperature Change

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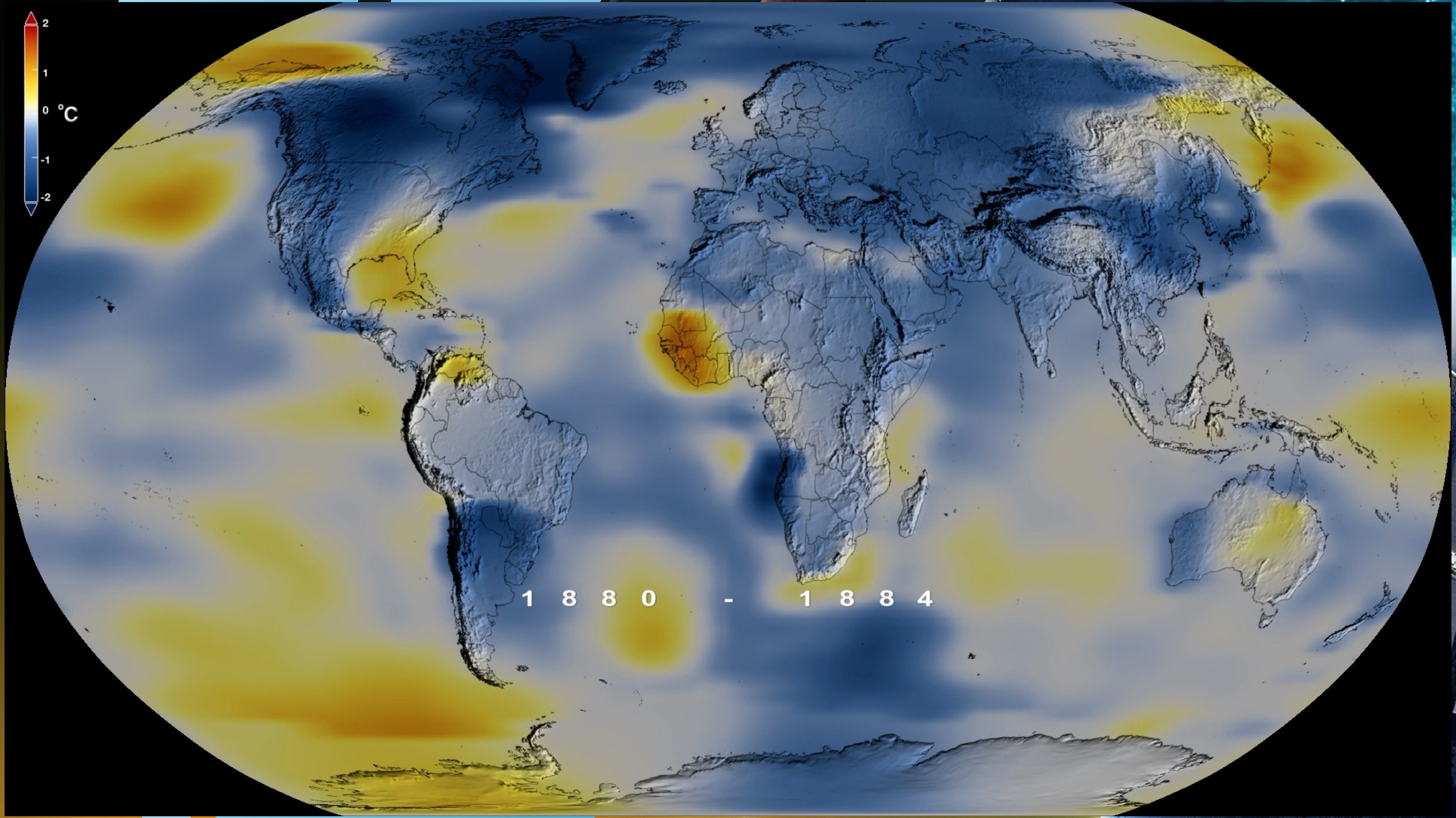
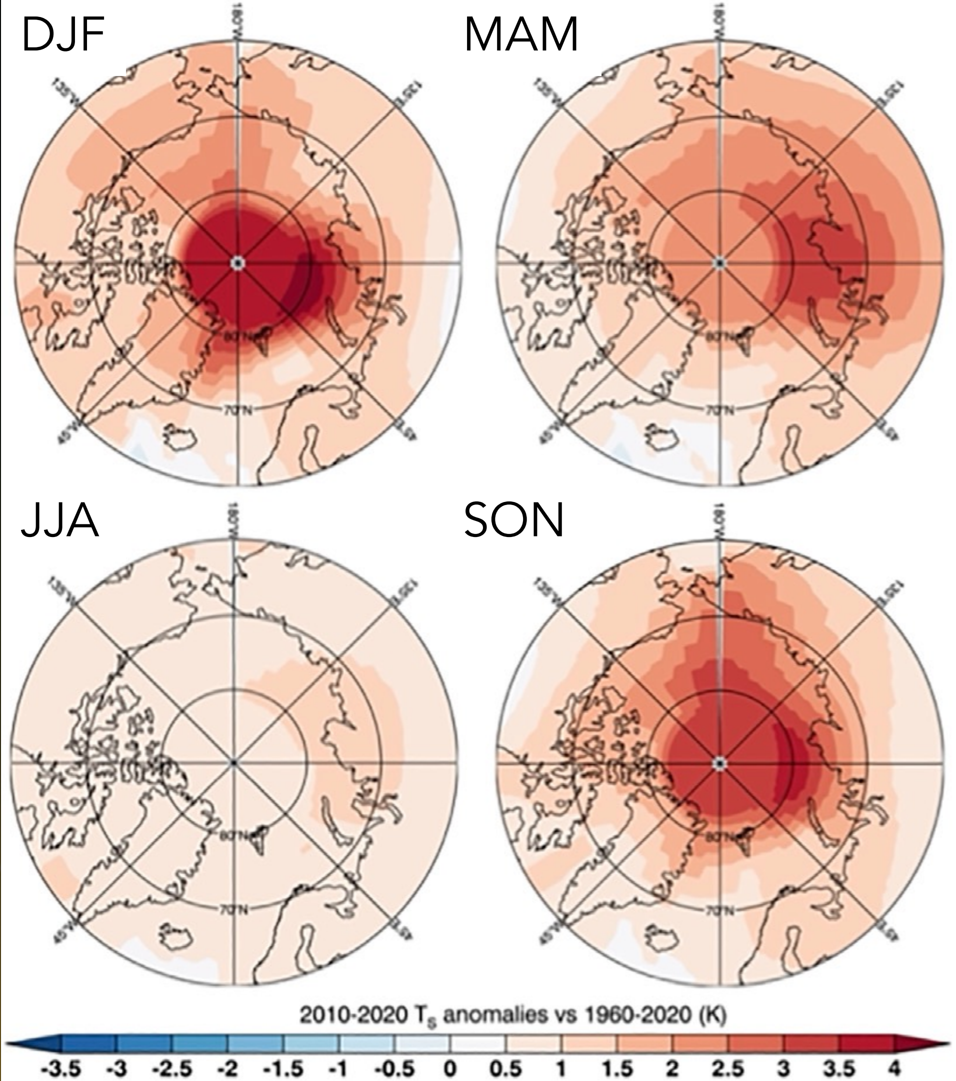
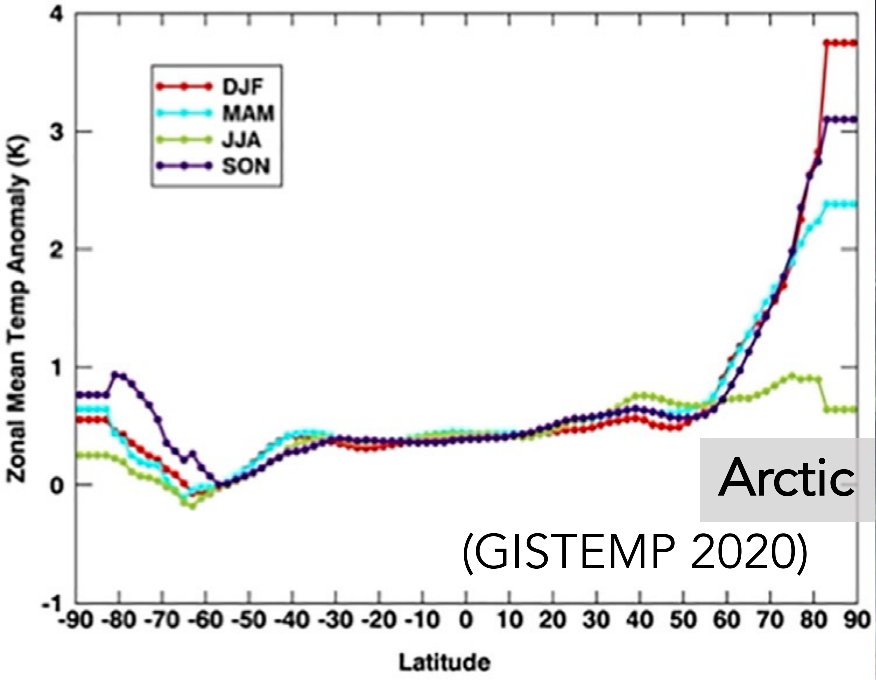
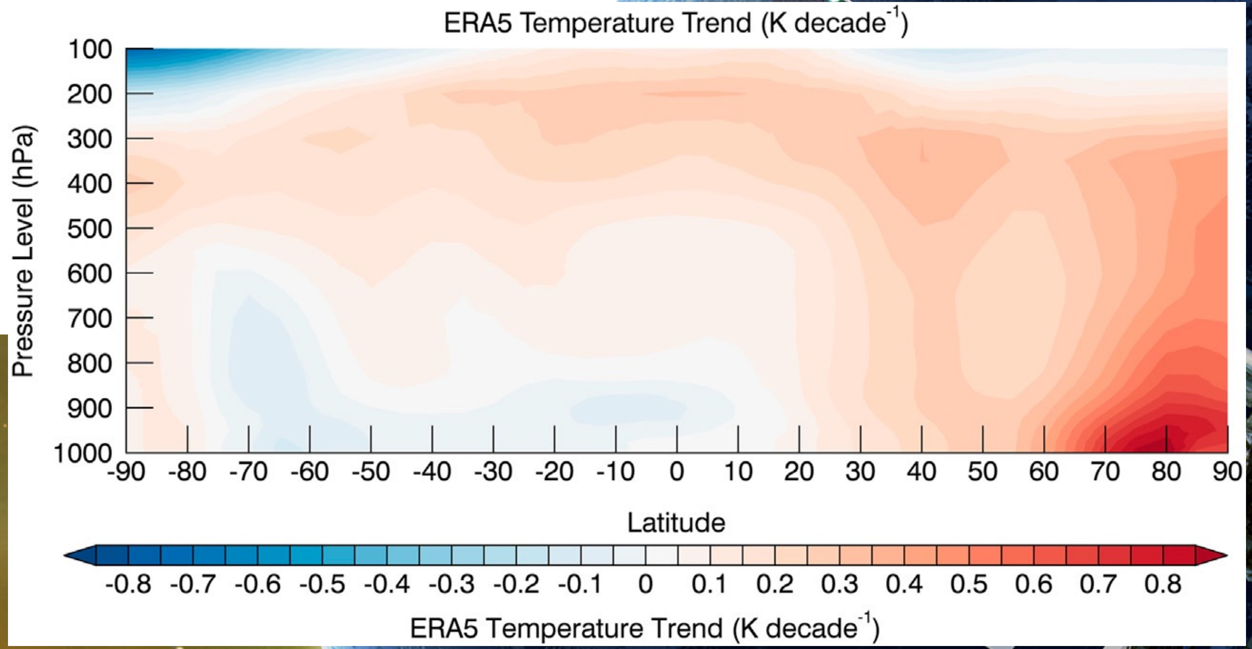


Features of AA: Observational Evidence

Observations show the fall/winter maximum and the surface-based profile of warming.







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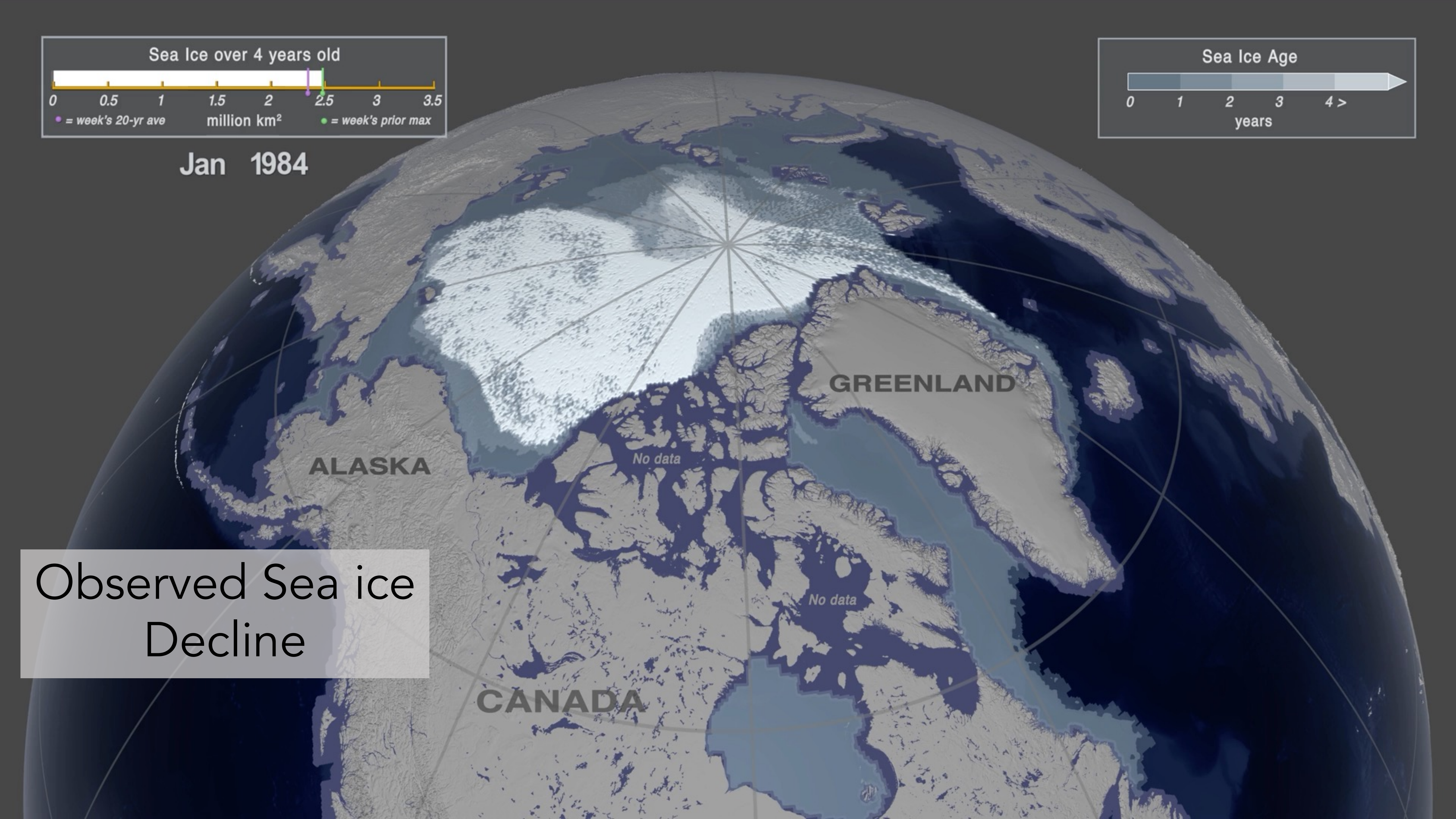
Observed Sea ice Decline



Historical Origins and Tools

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The Arctic Amplification (AA) Concept: Arrhenius (1896)

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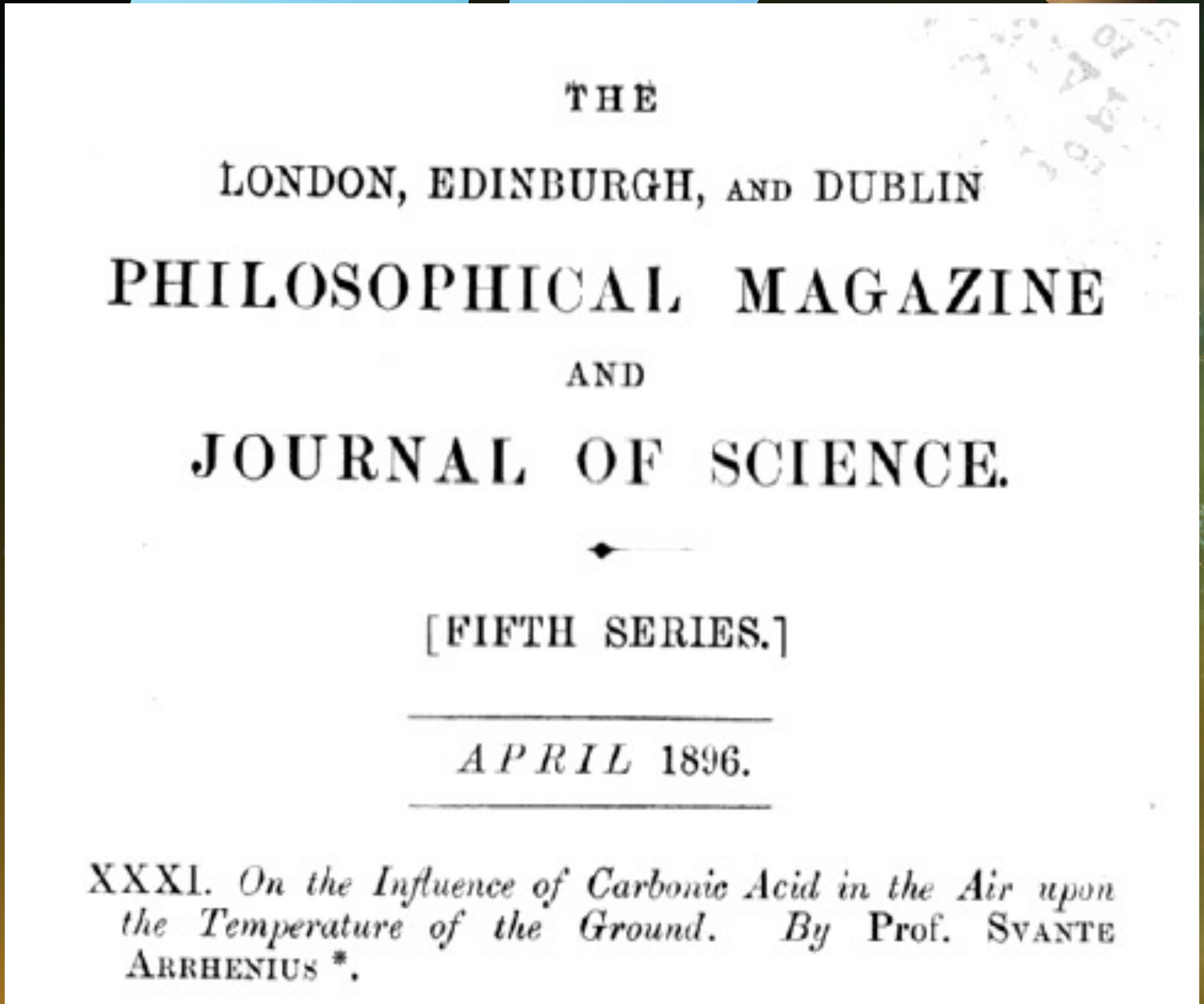

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* By Prof. SVANTE ARRHENIUS *.

- Arrhenius (1896) provided one of the earliest descriptions of Arctic Amplification.
- Origins of AA came within the context of explaining glacial/inter-glacial periods.
- **Key Mechanism**: Surface albedo changes due to the north-south progression of the snow-ice line.
- Energy balance calculations demonstrated the impact of surface albedo.

Sea Ice Albedo Feedback

Energy Balance Models (EBMs)

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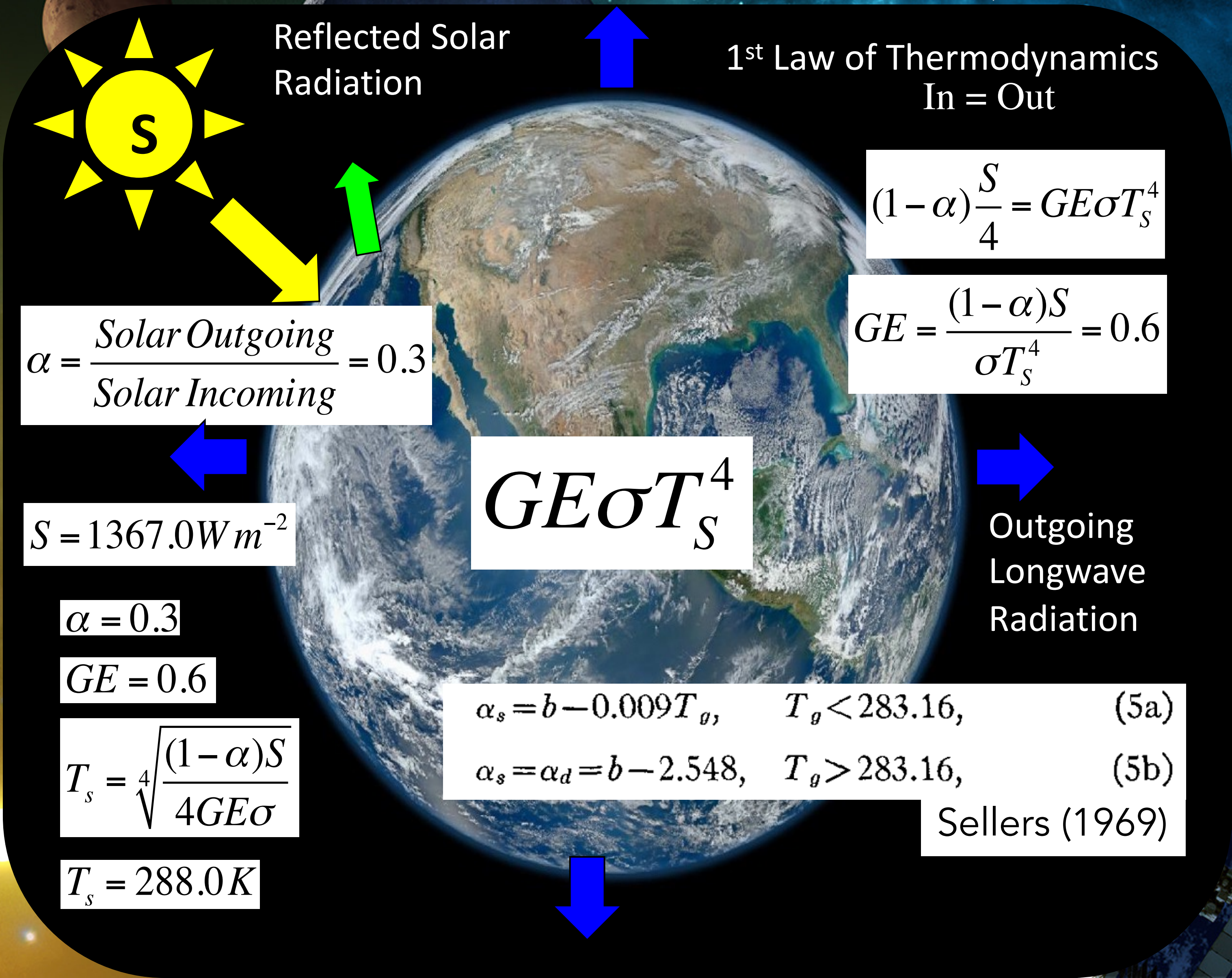
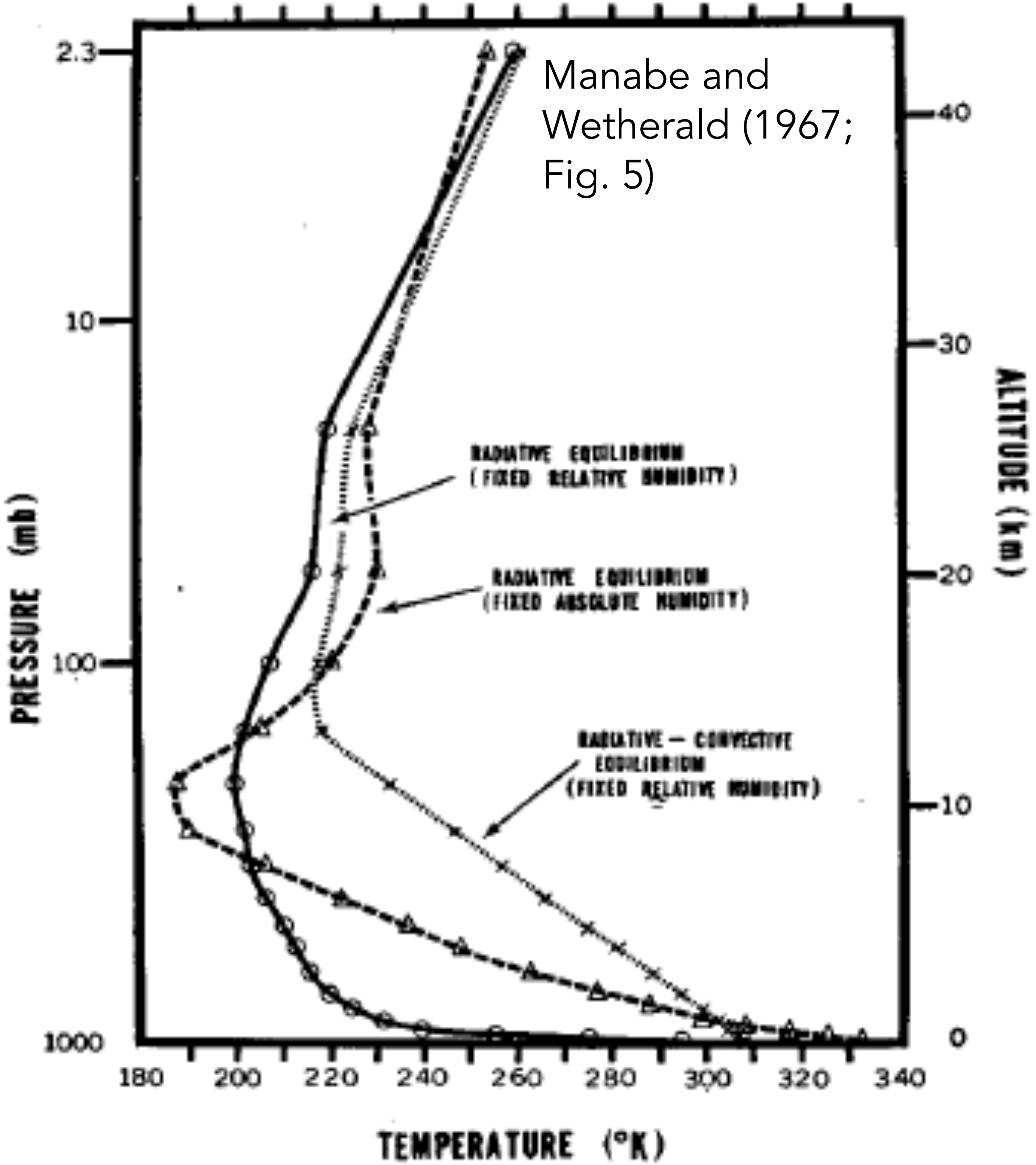
- EBMs are simplified models of climate models that describe the relationship between surface temperature and Earth's energy budget.
- EBMs are a conceptual tool to understand the relationship climate sensitivity and forcing.
- Budyko (1966), Rakipova (1966) used EBMs to quantify the influence of surface albedo on surface temperature.



Manabe and Wetherald (1967): Inclusion of Vertical Heat transport

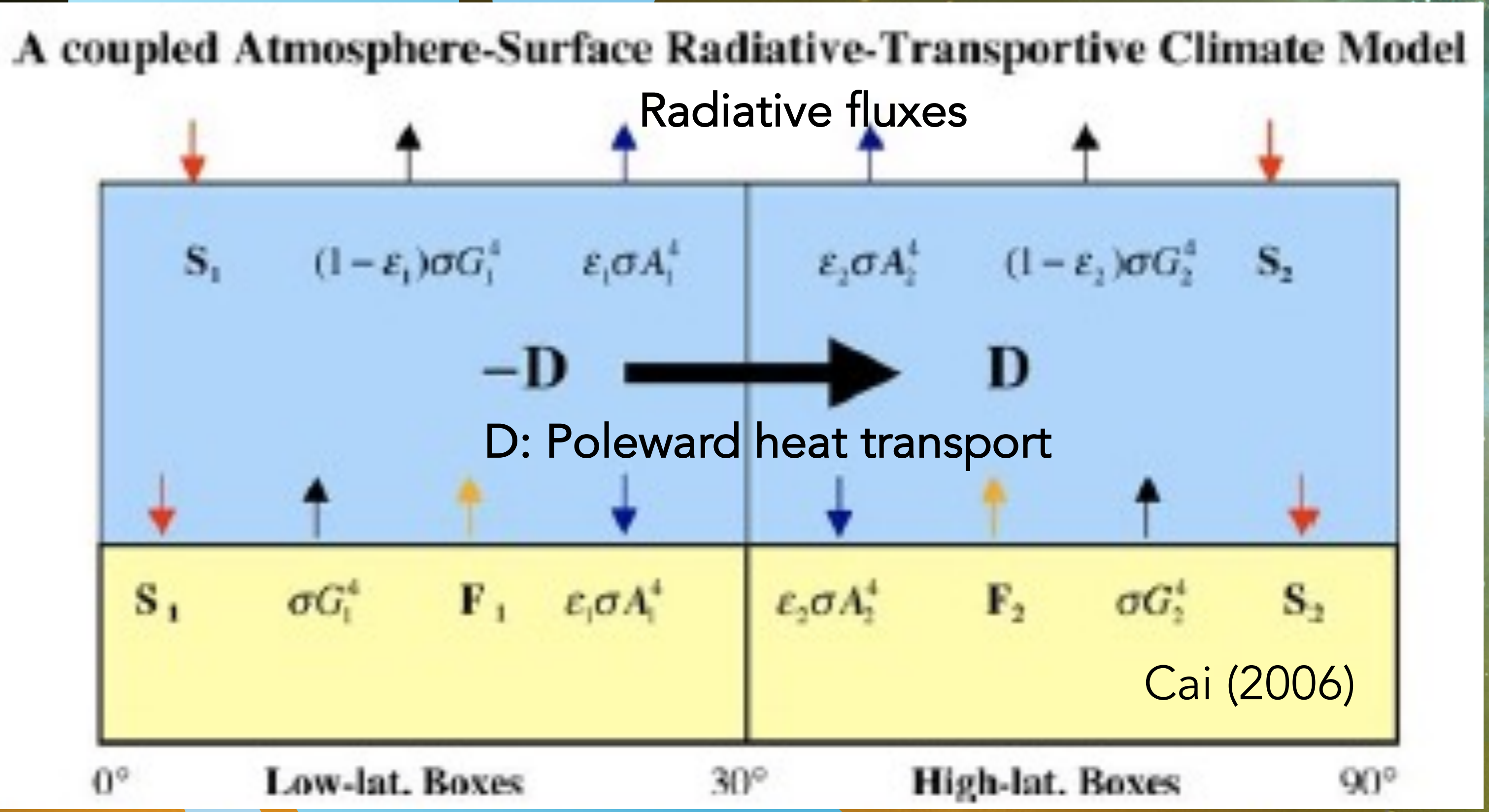
- Introduced the concept of radiative convective equilibrium.
- Found that the damping of vertical heat transport by strong stability at high latitudes caused a surface albedo perturbation to have a larger effect on near-surface atmospheric temperature than at higher altitudes (Fig. 19).



Manabe and Wetherald (1967; Fig. 5)

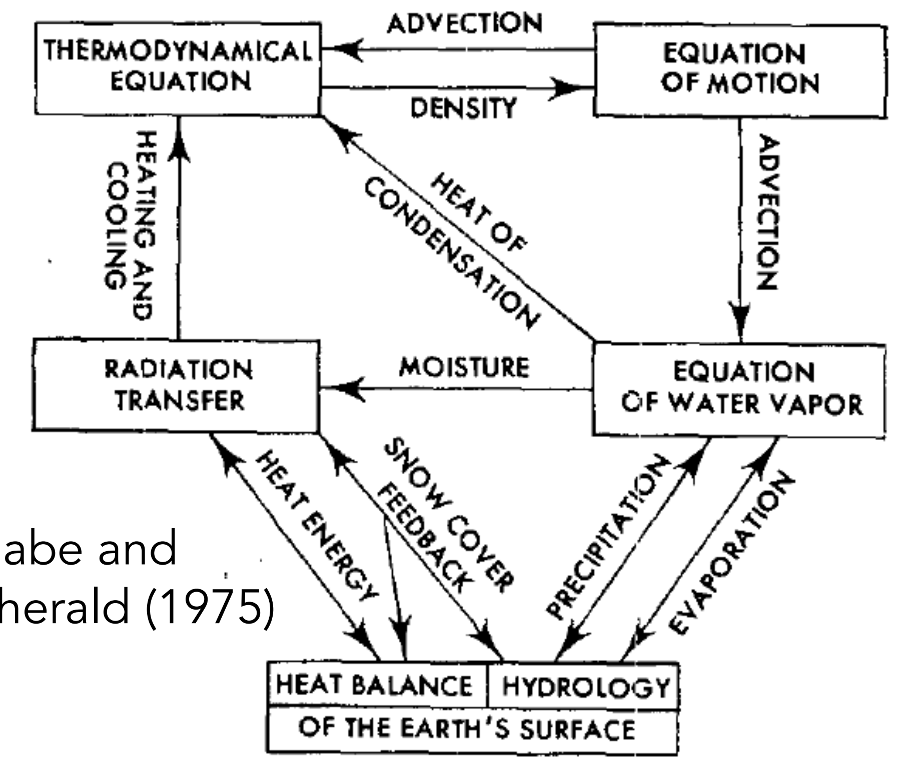
Advanced EBMs: Inclusion of horizontal heat transport

- Sellers (1969) provides an example:
- Horizontal heat transport is included in a zonally-averaged EBMs as a horizontal diffusion proportional to the meridional temperature gradient.
- Sellers (1969) found that the Arctic surface temperature and response are very sensitivity to the representation of poleward heat transport.

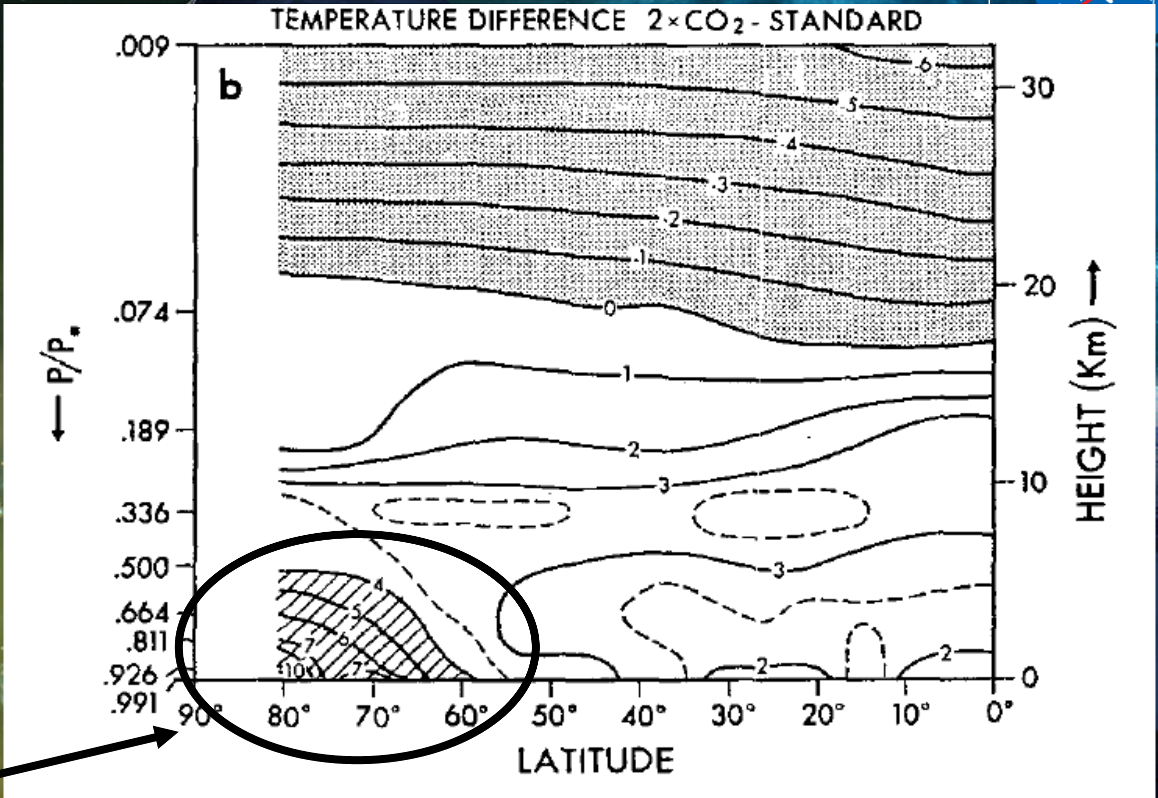


- It became clear that to understand Arctic Amplification, poleward heat transport should be resolved to understand the role of the mean circulation and eddies.

Applying a General Circulation Model to Arctic Amplification



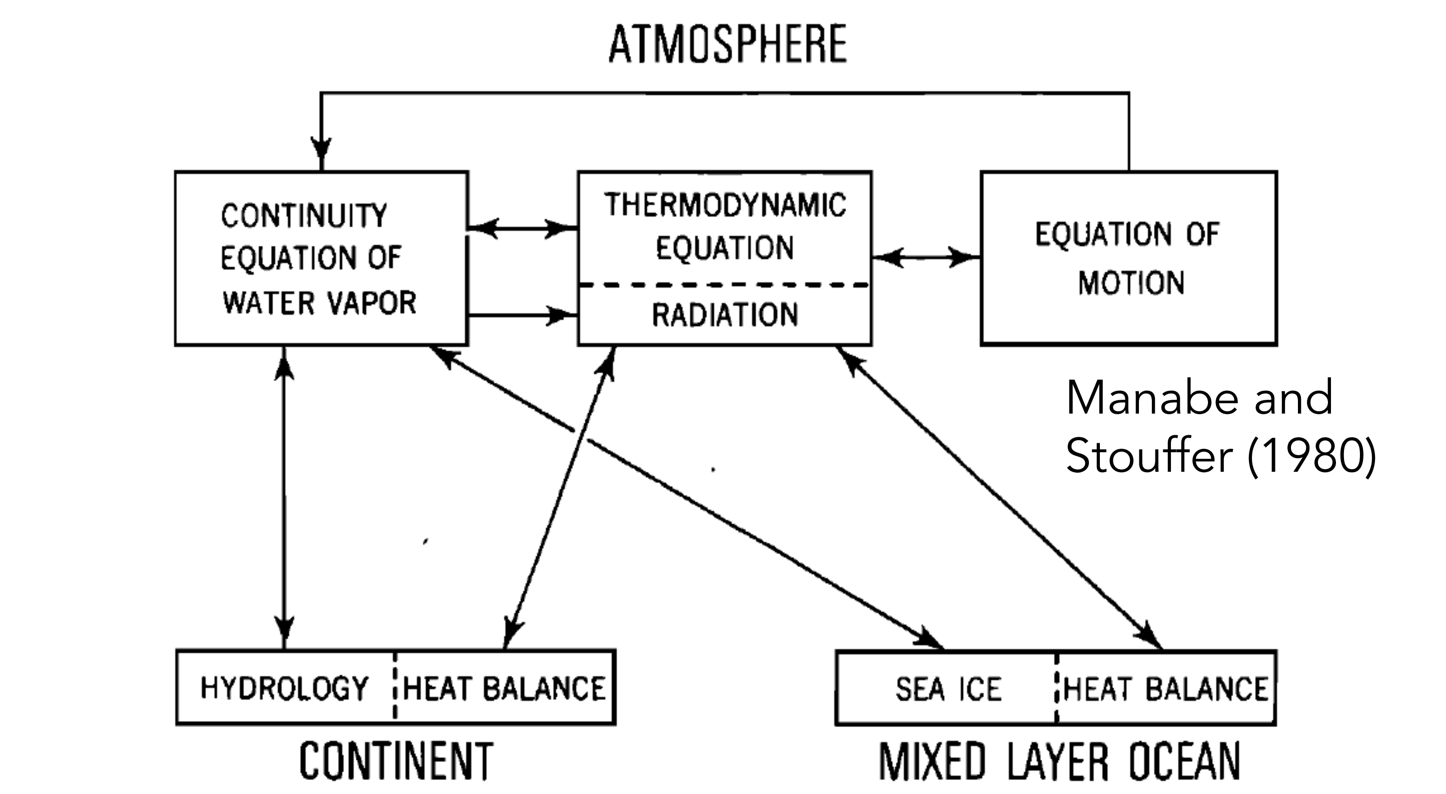
Manabe and Wetherald (1975)



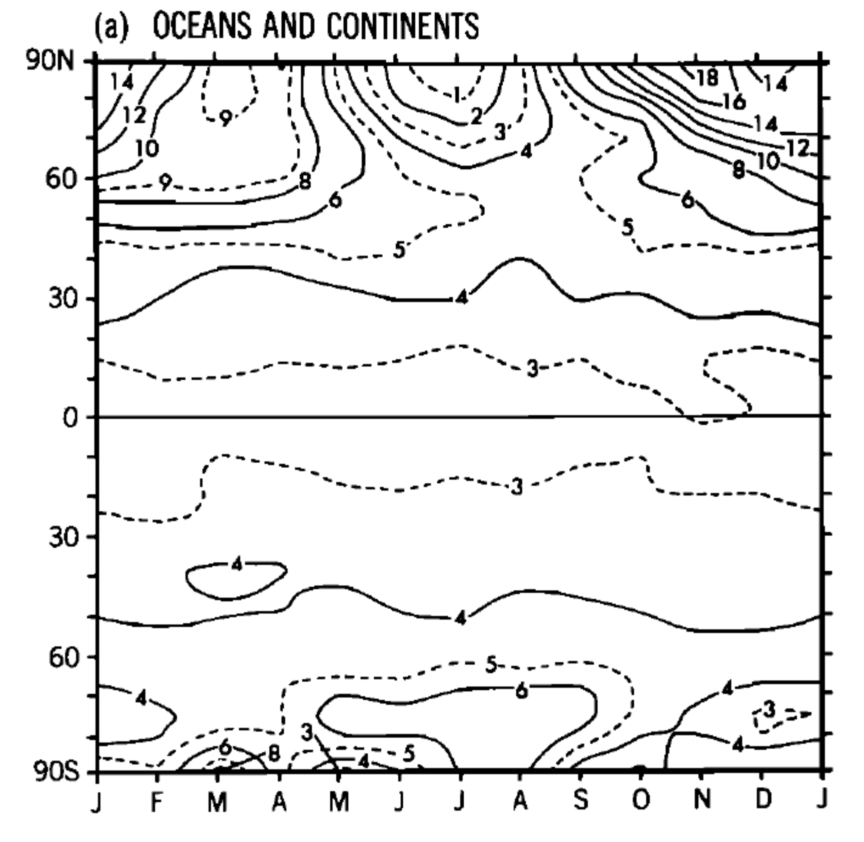
Key Results:

- Surface-based vertical structure of Arctic Amplification.
- Found a compensation between the increased latent heat and decreased poleward sensible heat transport resulting in a near-zero change in the total atmosphere poleward heat transport.

A modern explanation for Arctic Amplification



Manabe and Stouffer (1980)



- First study using a GCM with an ocean mixed layer, enabling an annual cycle of solar insolation. No poleward ocean heat transport.
- Key Results:
  - Fall/winter warming maximum and weak warming in summer.
  - Seasonality due to the summer-to-fall energy transfer by ocean heat storage.

MS1980 explanation: Modern Foundation

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- The key ideas written by MS80 remain the foundation of AA theory.
- Key Ideas:
    - Surface albedo feedback due to reduced sea ice cover drives increased absorption of sunlight during summer.
    - Extra energy does not cause substantial summer warming due to the large heat capacity of the ocean mixed layer and melting ice.
    - Energy accumulated and stored in the Arctic Ocean surface during summer delays fall sea ice freeze-up and thinner sea ice, increasing surface turbulent fluxes and conductive heat flux
    - Leading to enhanced lower tropospheric warming in fall and winter with a bottom-heavy profile, further enhanced by stable stratification confining warming to near-surface layers.
    - Seasonality attributed to the seasonal energy transfer.

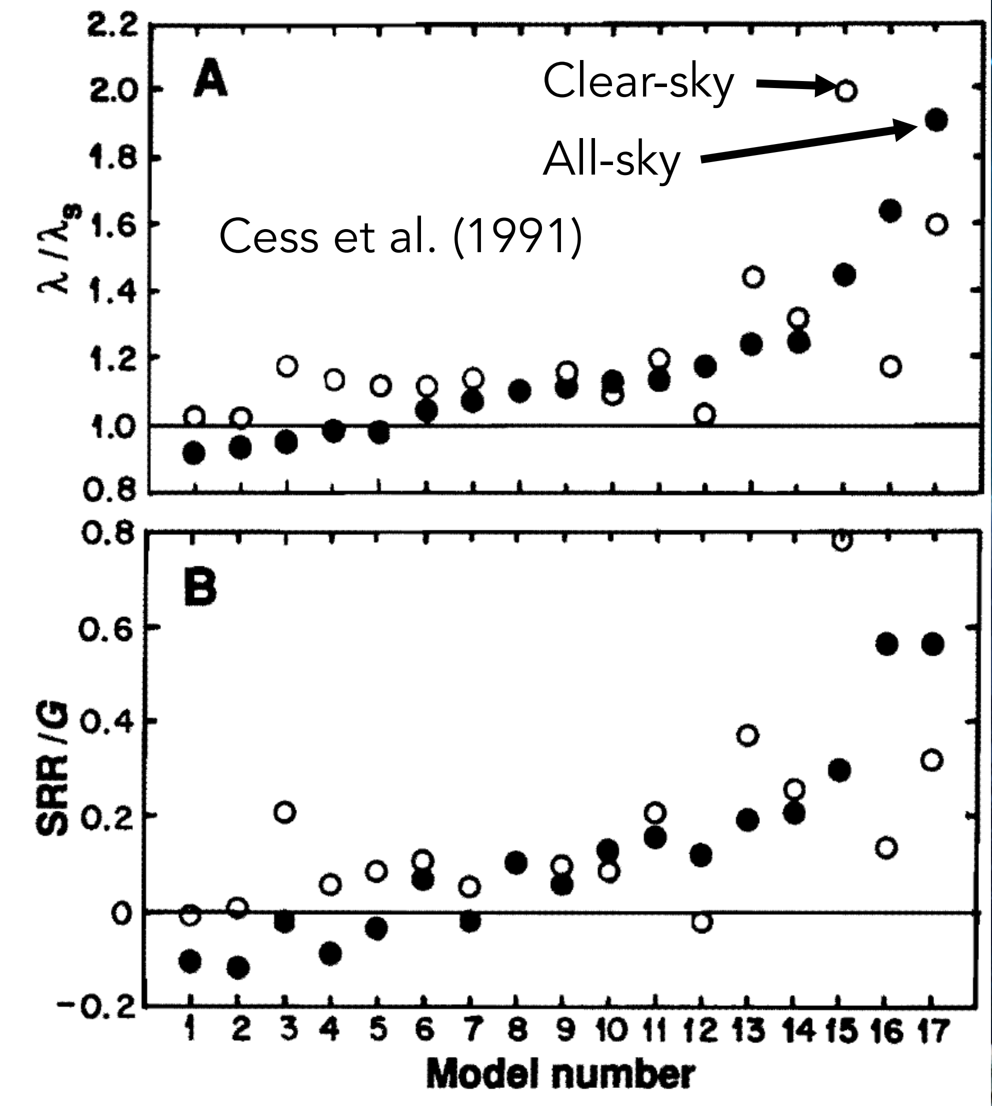
Washington and Meehl Paper: Poleward ocean heat transport

- Washington and Meehl (1984;1986;1989) performed model simulations and wrote a series of paper with increasingly complex representations of the ocean
- Experimental design
  - Swamp Ocean: no heat storage, no transport
  - Mixed Layer ocean: heat storage, no transport
  - Fully coupled ocean: heat storage and transport

- Including ocean heat transport influences the model simulation by:
  - Warming the Arctic surface temperature base climate
  - Changing the regional sea ice distribution
  - Weakening the surface albedo feedback
  - Reducing climate sensitivity

Emergence of Multi-model Intercomparisons

- Emergence of Model Intercomparison Projects: Cess et al.(1989; 1990; 1991).
- The principal utility of MIPs is to understand how and why models differ.
- The first large-scale, coordinated climate model intercomparison occurred in the late 1980s (Cess et al. 1989).
- The key result was a three-fold difference in global climate sensitivity between models, attributed mainly to cloud feedback differences.

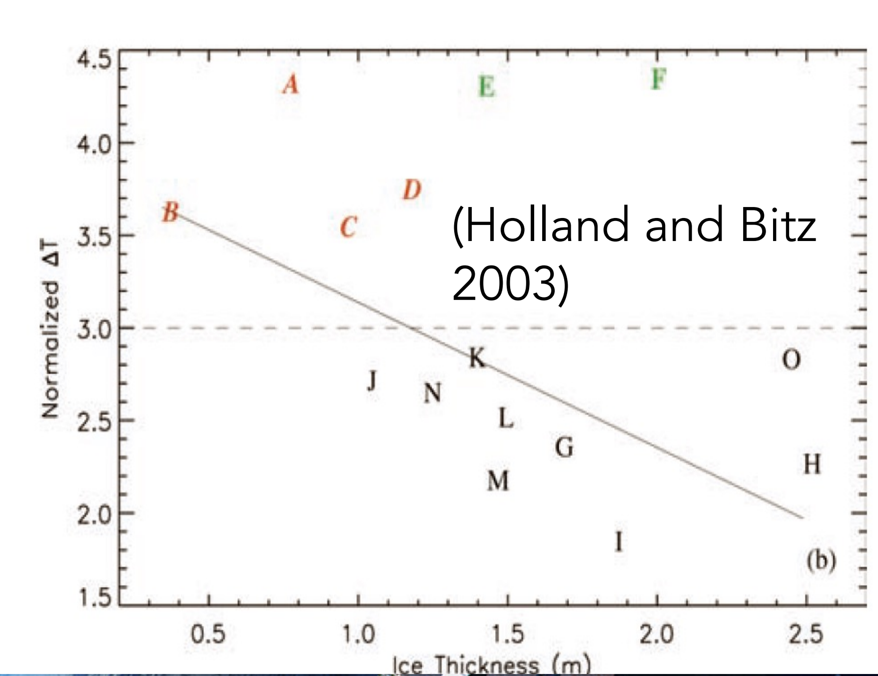


- Cess et al. (1991) reported a substantial spread in the model simulated snow-ice albedo feedbacks, related to clouds.

Improved computational capabilities and MIPs: 1990s

- The continued MIPs revealed sea ice thickness, ocean heat transport, and clouds as key sources of inter-model differences in AA.

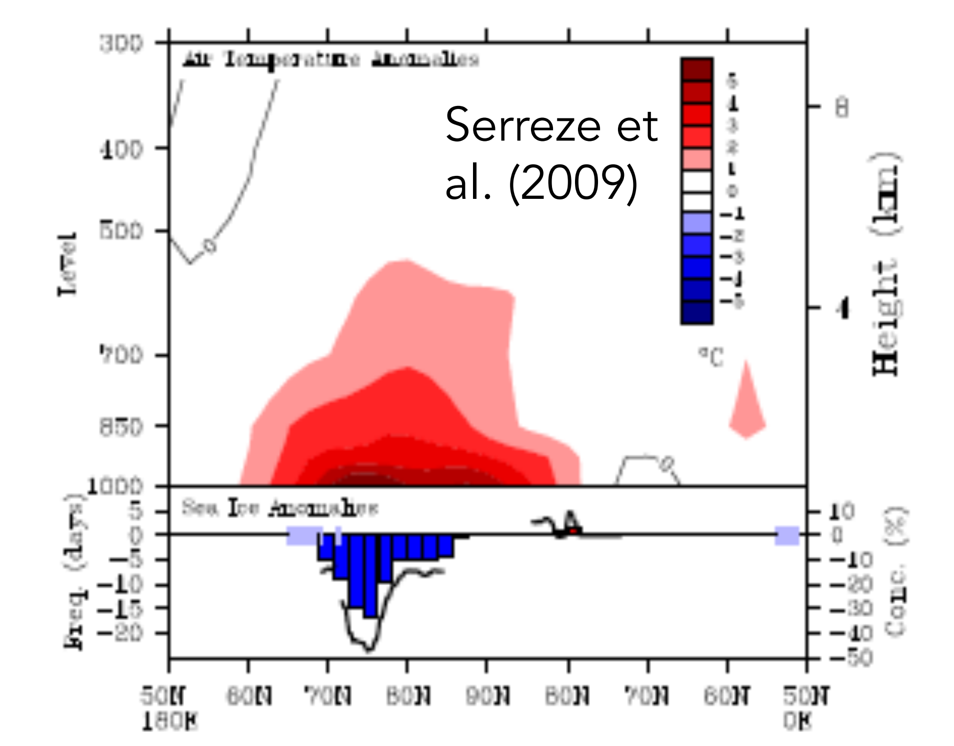
- Transient climate change experiments emerged (e.g., 1% per yr CO_2 increase; (Washington and Meehl 1989; Manabe et al. 1991; Washington and Meehl 1996; Meehl et al. 2000)
  - Bryan et al. (1982) made the first attempt, finding different high and low-latitude transient responses.
  - The Arctic response was analysis in additional transient experiments illustrating (1)
    - The influence of the ocean circulation
    - The spatial distribution of Arctic warming
      - Slower warming over the ocean and in regions of deep water forming
      - Faster warming over land



These studies did not change the underlying understanding of the physical drivers of polar amplification.

Modern Paradigm Shifts: 2000s

- This decade saw Arctic Amplification emerge as a unique research topic
- Paradigm shift: Use of Observations.
    - Studies emerged using multi-decadal records to evaluate temperature, snow cover, and sea ice trends, verifying early predictions of AA
    - This use is in sharp contrast to the 1980s when the limited observations restricted their use to control climate tuning.
- Multi-decadal observations enabled the first studies of emergent constraints—relationships between an uncertain aspect of climate projections and an observable quantity (e.g., Hall and Qu 2006).

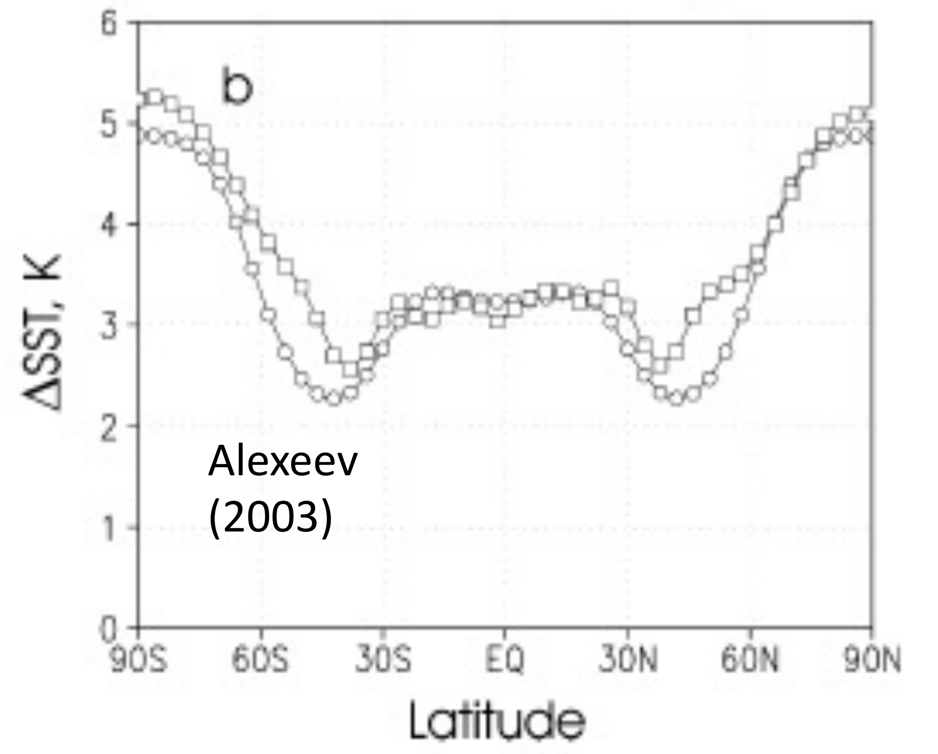


Serreze et al. (2009)

Verified AA characteristics:

- Fall/winter maximum
- Bottom-heavy structure
- Prominence of surface albedo feedback
- Importance of strong static stability

Paradigm Shift: AA without surface albedo feedback



- Several early 2000s studies altered the trajectory of Arctic Amplification studies.
- Alexeev (2003): illustrated polar amplification in an aquaplanet model in the absence of sea ice.
- Hall (2004): used feedback suppression to show polar amplification without an active surface albedo feedback.
- These results were at odds with earlier work
  - Differences with Ingram et al. (1989) are traced to a model setup prohibiting seasonal energy transfer by the ocean.
  - Differences with Rind et al. (1995) are unclear.

- Studies argue that poleward heat transport produces polar amplification due to an increased efficiency, as poleward traveling air is warmer and moister than before (Alexeev et al., 2005; Cai 2005; Cai 2006).
- These area remains an active area of study.

Current and Ongoing work: Era of Model-Observation Synergy

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- New satellite data sets and more sophisticated meteorological reanalysis have been enabling factors (e.g, Screen and Simmonds 2010; Boisvert and Stroeve 2014; Kay and Gettelman 2009; Taylor et al. 2015)
- Reemergence of Idealized modeling setups (e.g., Feldl and Merlis 2021)
- Single-model Large Ensembles (Kay et al 2015)
- New feedback and model diagnostics
- First Polar Amplification MIP
- Key outcomes:
  - Confirmation of the sea ice-atmosphere-ocean coupling process (Screen and Simmonds 2012; Boeke and Taylor 2018; Dai et al. 2019)
  - Importance of episodic variability and air-mass transformation
  - Improved quantification of the influence of internal variability Arctic climate trends.

Feedback Diagnostics

- **Purpose:** to quantify the relationship between a climate feedback process and its important to the simulated climate change.

Diagnosis framework	Strengths	Weaknesses	Example References
Global/Regional TOA (or surface) energy budget decomposition	• Easy to apply to comprehensive model output and model intercomparisons • Compares all the feedbacks	• Assumes linearity and does not provide insights into how different feedbacks are coupled • Lapse rate feedback conceptually unclear at high latitudes in TOA frameworks	Pithan and Mauritsen (2014)
Coupled Feedback Response Analysis Method (CFRAM)	• 3D analysis of feedback contributions • Resolves process contributions to vertical warming profile	• Does not provide insights into how different feedbacks are coupled • Computationally expensive	Taylor et al. (2013)
Mechanism denial	• Tests how a given process interacts with different feedbacks	• Hard to implement in comprehensive models • Modifies the reference climate state	Graversen and Wang (2009)
Idealized forcing	• Compares roles of local and remote forcings and feedbacks	• Separation between local and remote is sometimes unclear	Stuecker et al. (2018)
Sea ice forcing	• Tests the importance of sea ice for Arctic warming	• Differing assumptions regarding conservation of energy and melt water	Screen et al. (2018)
Neural network	• Captures nonlinear feedbacks either due to large perturbation or coupling effects, e.g. cloud-masking of the albedo and water vapor feedbacks	• The valid value range and accuracy of predicted feedbacks depends on the training dataset	Zhu et al. (2019)

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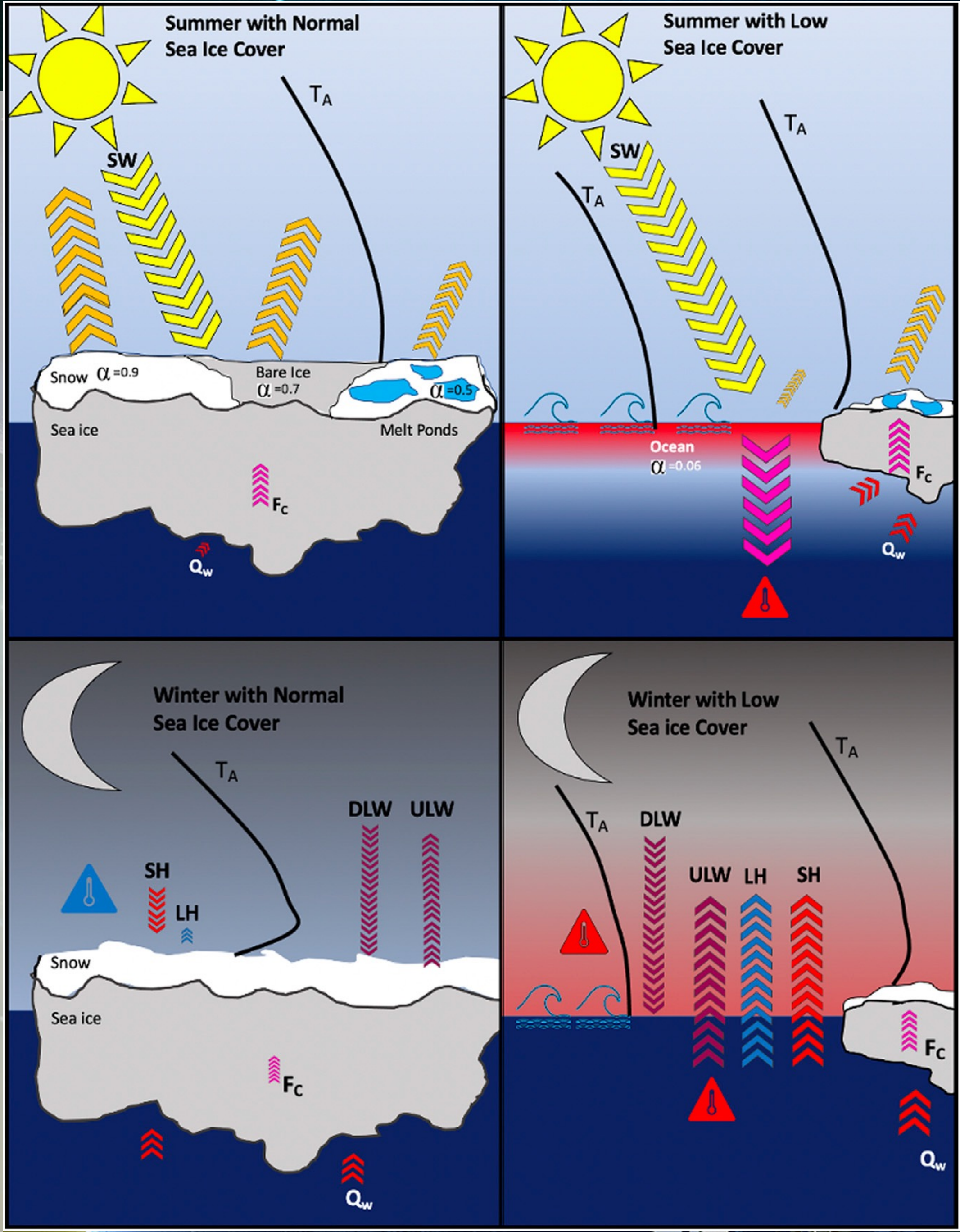
Processes and Key characteristics

Sea ice and Snow Feedbacks

- Sea ice and snow feedbacks:
  - Surface albedo—sea ice and snow cover reductions in response to warming decrease in surface albedo and increased solar absorption, an **amplifying feedback**.
  - Sea ice insulation—warms and/or moistens atmosphere
    - sea ice reductions facilitate increased turbulent energy exchanges (sensible and latent heat) from the Arctic ocean to the atmosphere.
    - Thinner sea ice facilitates a great conductance of heat from ocean-to-atmosphere through sea ice.
- **Key uncertain and unresolved processes:**
  - Sea ice and snow albedo—continuously evolve due to variability in sea ice and snow coverage, thickness, melt ponds, floe size, and topography. These processes are incompletely understood and and climate model parameterizations are poorly constrained by data.
  - Dependence between sea ice cover, thermodynamic structure, and clouds.
  - Mechanical sea ice break-up—Less sea ice cover promotes more ocean wave leading to sea ice break-up
- **Key Need: Accurate data of sea ice and snow properties with surface energy budget fluxes under a range of conditions.**



Temperature Feedbacks:

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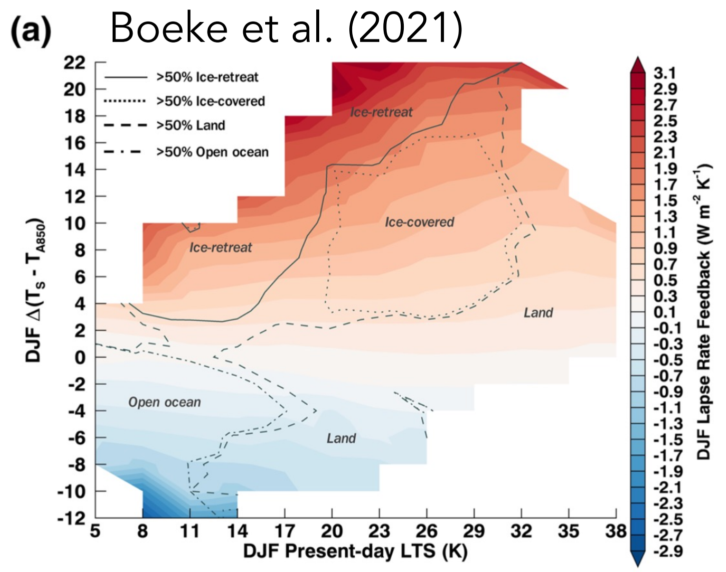
- Temperature feedbacks stem from the sensitivity of OLR to temperature.
- Planck feedback (vertically uniform)—the contribution to AA originates from the non-linearity of blackbody radiation (Stefan-Boltzman Law) with temperature. Negative at all latitudes and less negative at high latitudes. However, this effect is small (Henry and Merlis 2019).
- Lapse Rate feedback (vertically non-uniform)—contribution to AA stems from the change in sign of the feedback with latitude
    - Convection "pins" the tropical temperature profile to the moist adiabatic lapse rate, resulting in the atmosphere warms more than the surface, increasing OLR—a negative feedback.
    - The high latitude atmosphere is close to radiative-advective equilibrium (balance between radiative energy loss and advective energy gain) and the temperature profile is not "pinned" to the moist adiabatic lapse rate. Thus, the surface and atmospheric temperature changes are decoupled due to the strong static stability—a positive feedback.
    - The **high-latitude lapse rate feedback is a multi-process feedback** influenced by radiative, advective, and surface-atmosphere coupling processes.
- **Key uncertain and unresolved processes:** Influence of surface-atmosphere turbulent exchanges, episodic variability, and sea ice properties on temperature and humidity.

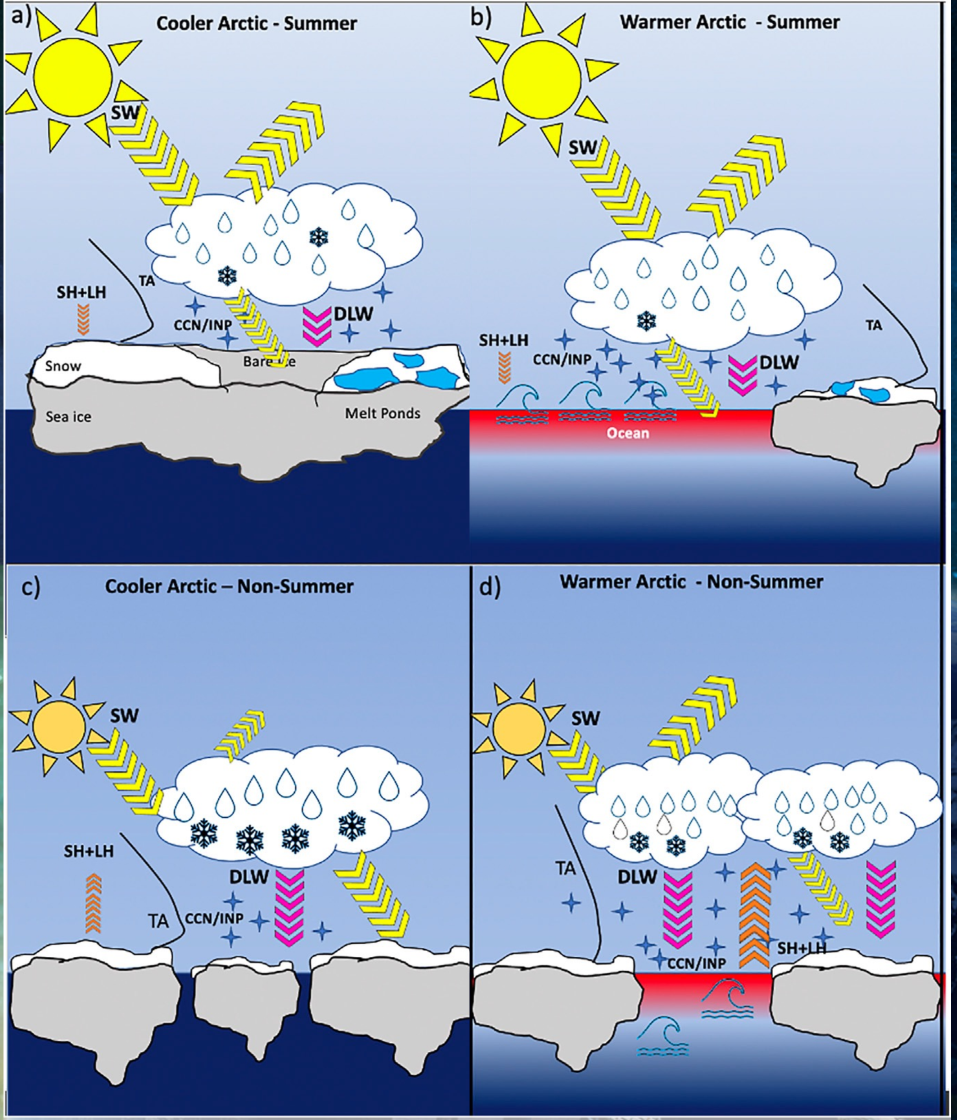


Key needs: Improved diagnostic framework linking the high-latitude lapse rate feedback to the contributing physical processes and data to understand the relationships between the sea ice-atmosphere-ocean coupling processes and episodic variability that set the atmospheric temperature structure.

Arctic Cloud Processes and Feedbacks

Arctic cloud feedback mechanisms:

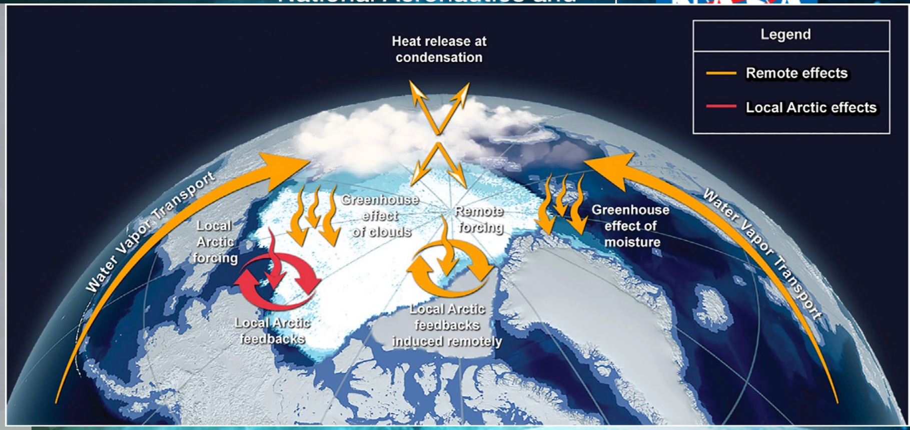
- **Cloud optical depth feedback**—dependence of cloud phase on temperature and the sensitivity of cloud albedo to phase.
  - Negative feedback—warmer temperatures reduce cloud ice and increase cloud liquid => greater cloud albedo.
  - Sensitive to amount of cloud ice in the base state climate
- **Cloud-Stability feedback**—dependence of cloud amount and optical depth on lower tropospheric stability
  - Arctic cloud fraction and optical thickness tend to increase with reduced lower tropospheric stability.
  - LTS is expected to decrease, increasing cloud fraction and optical depth—positive feedback, seasonally varying.
- **Cloud-surface coupling feedback**—dependence of cloud properties on surface turbulent fluxes.
  - Increased surface turbulent fluxes, promotes greater cloud fraction and optical depth.
  - Evidence suggests that cloud-sea ice feedback promotes surface warming in non-summer months
- **Cloud Masking**—modifies the strength of other feedbacks.
- **Key unresolved processes:** cloud microphysics and interactions with large-scale meteorology, ice nucleation mechanisms and ice-nucleating particle (INP) properties and sources.



Key needs: In situ data cloud microphysical data, specifically in mixed phase clouds, simultaneously with atmospheric, ocean, and sea ice state information and energy fluxes.

Remote Processes: Water vapor triple effect

- **Remote-induced warming**—any warming due to a non-Arctic change.
    - Warming resulting from changes in poleward heat transport .
    - Warming due to local feedbacks initiated remote effects are included, since local feedback are not actually local in nature.
- A range of studies show the that between 50 and 85% of the Arctic warming is due to remote processes.
- However, some studies argued that remote process cannot drive Arctic Amplification due to the weak changes or decreases in total heat transport due to the opposing response of SH vs. LH transports.
- Discrepancies between these studies are likely due to
    - The water vapor triple effect
    - Differing attribution of warming to local and remote processes
    - A focus on vertically integrated energy transport.
- **Water Vapor Triple Effect:**
    - The multiple influences of water vapor on the Arctic energy budget from condensation and greenhouse effects of moisture and clouds.
    - Graversen and Burtu (2016) found an order of magnitude larger warming per unit of energy due to the Arctic LH transport than DSE , due to the accompanying changes in specific humidity and clouds.
    - Thus, vertically integrated measures of PHT do not measure this full effect of dynamics.

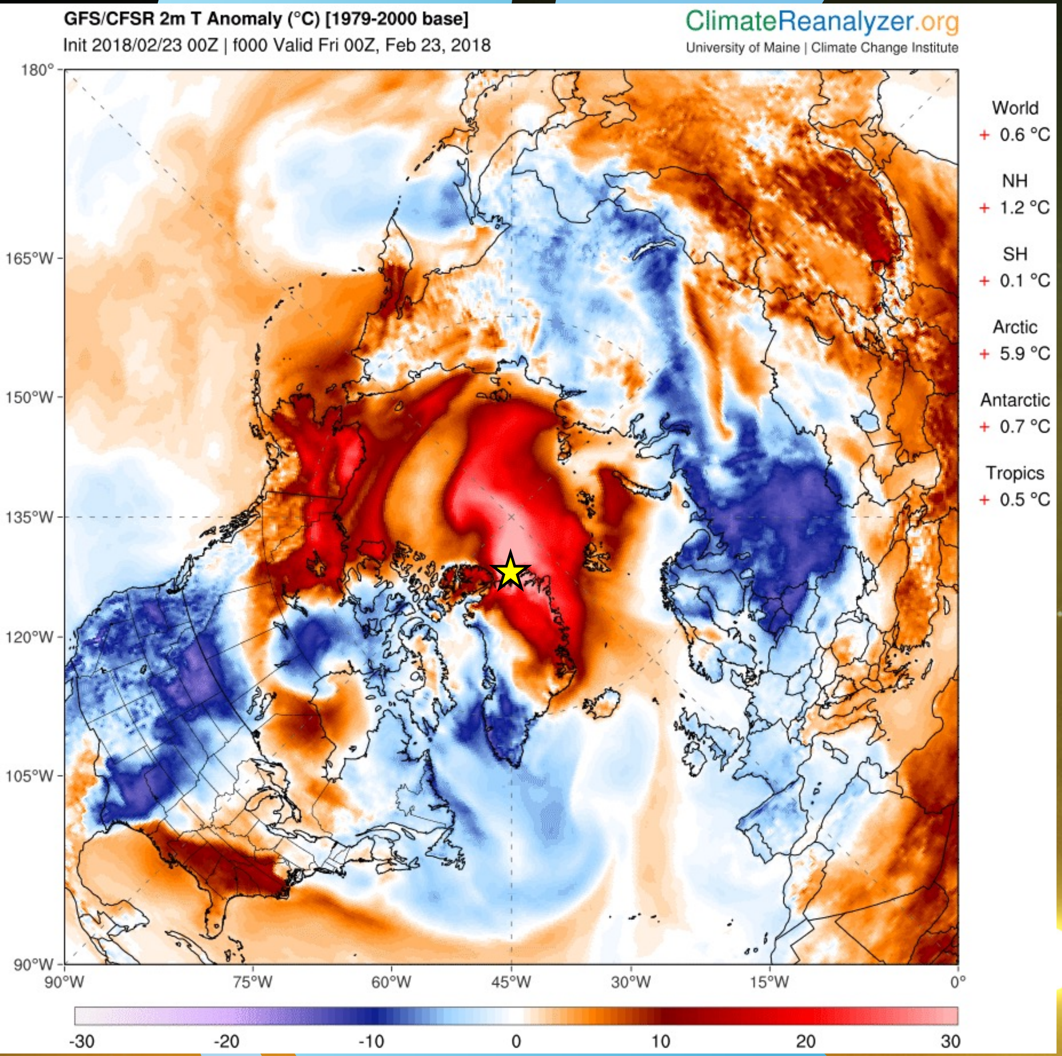


Important notes:

- Studies show that Low latitude warming is efficiently communicated to high latitudes, but high latitude warming is not efficiently communicated to lower latitudes.
- Teleconnections are important to consider and represent in models to capture the "efficient communication" of low-latitude warming to high latitudes.

Remote Processes: Episodic events

- Remote impacts occur via episodic events often associated with synoptic waves. These episodic events represent short timescale but extreme transports of heat and moisture into the Arctic.



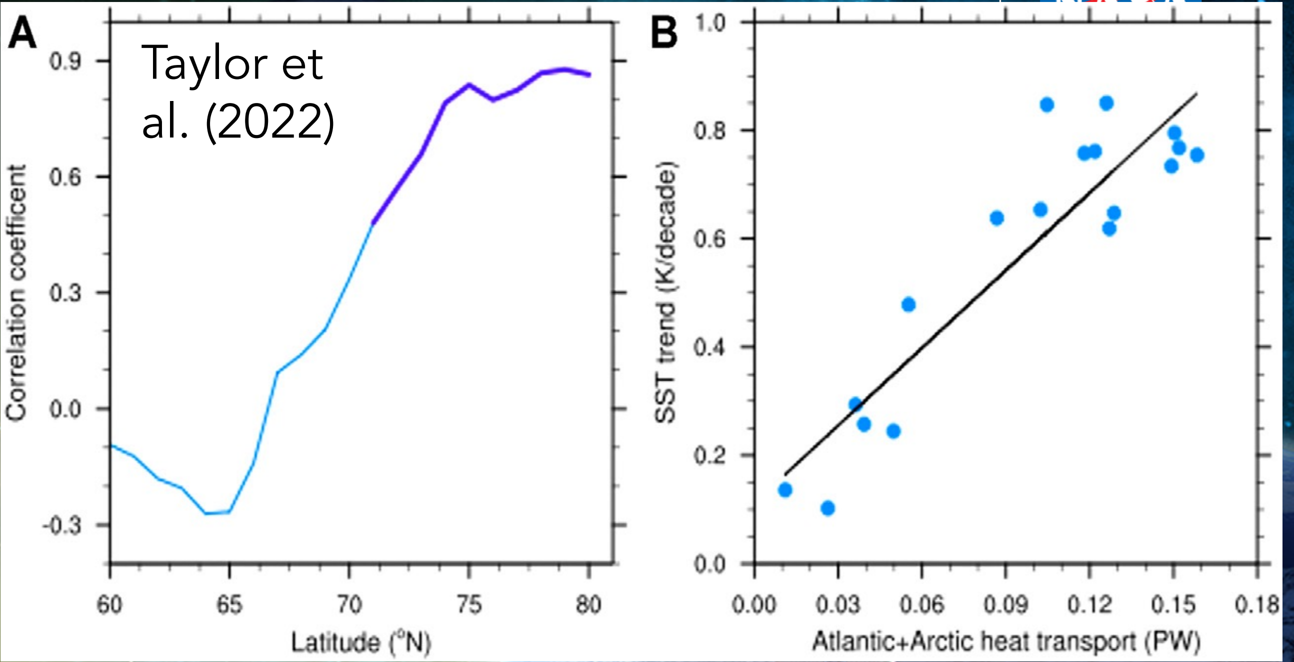
- These events bring warm moist airmasses into the Arctic, that over time transform into more Arctic airmasses.
- During this process corresponds to two different clouds and net SEB states (cloudy and radiatively balanced, clear and strong radiative cooling.
- Episodic variability can influence AA through:
  - Changes in the frequency of radiatively clear and cloudy states influencing the SEB and cloud feedback.
  - Changes in the properties of the incoming air masses could influence cloud processes
  - Non-linear effects of strongly meridional transports
  - Wind flow regime dependence of surface turbulent fluxes (e.g., off-sea ice vs. on-sea ice flow).
- Impacts on longer time scale via impacts on sea ice thickness

Key Need: A quantitative understanding of the Arctic system response to episodic heat and moisture transport events, air-mass transformation, and cloud formation, understanding of how episodic events rectify on the longer time scale.

Source:https://www.theweathernetwork.com/

Ocean Energy Transport Effects

- Changes in ocean heat transport influences Arctic climate by influence surface temperature and sea ice distribution and properties.
- Observations suggest that poleward transport has increased through the Fram Strait and Barents Sea in recent years and climate models also simulate increased poleward OHT.
- Ocean heat transport changes are thought to contribute to additional Arctic warming, however studies offer conflicting interpretations mainly due to the latitude band considered.



- Several mechanisms contribute to enhanced poleward OHT
  - Warmer Atlantic water results in greater OHT with the same mass transport.
  - Ocean circulation changes—e.g., a strengthened North Atlantic subpolar gyre causes increased OHT into the Barents sea decreasing sea ice and increasing oceanic heat release.
    - Studies suggest that feedbacks between the atmosphere and ocean can further enhance this heat transport.
  - Role of the AMOC is debated—a stronger weakening is linked to less Arctic warming. AMOC may be influenced/weakened by the melting sea ice.
- Panel (b) shows that OHT into the Arctic from the Atlantic correlates with projected Arctic warming, such that larger transport increases yields larger warming.

Conceptual Model

Conceptual model…putting all of this together

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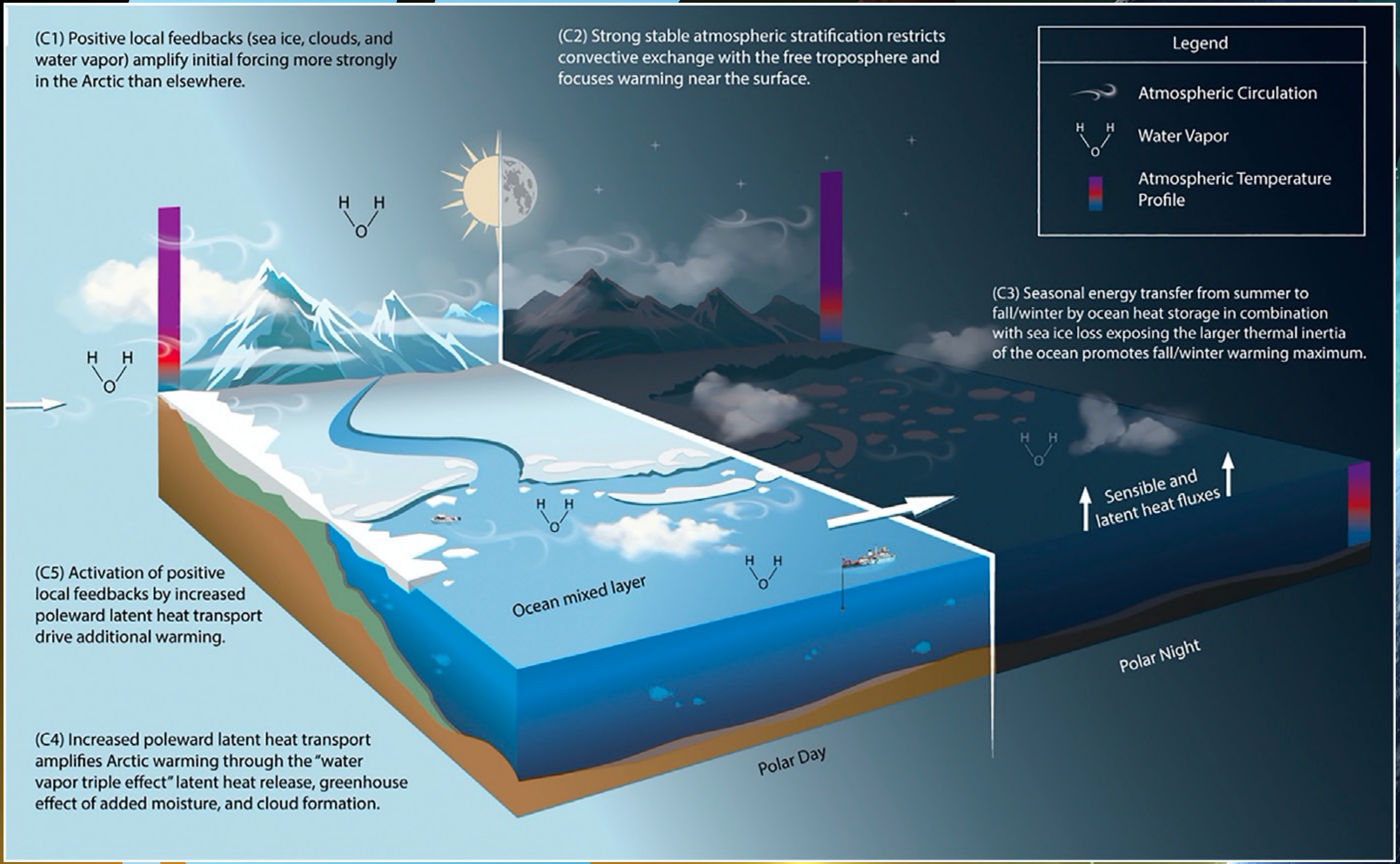

While improved understanding of individual process is critical for producing improved Arctic warming projects, our conceptual model highlights the **need to account for local feedback and remote process interactions** within the context of the annual cycle to be able to constrain the high-end of model projections.

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Recommendations

Recommendations:

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- Maintain and expand Arctic Observing System including both long-term ground-based and satellite observations and Arctic field expeditions. Vision: a permanent, floating Central Arctic Observatory.
- Reduce uncertainties in surface energy budget data: especially from space-based platforms.
- Quantitative understanding of the influence of individual parameterizations on simulations climate feedbacks: need model experimental protocols
- Coordinated intercomparison of surface turbulent fluxes and parameterization across contemporary climate models.
- A <u>WCRP-like working group</u> to rethink/redesign Arctic/Polar climate feedback diagnostic techniques.
- Research Foci:
  - Quantify how local feedback and remote process interactions influence the sea ice annual cycle.
  - Quantified understanding of how episodic heat and moisture transport events rectify onto climate change time scales.
- Regional climate change indicators integrated into policy frameworks.

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Conclusion

- Our understanding of Arctic Amplification has evolved substantially over the last 100 years from a single-process phenomenon to one now know to be a coupled atmosphere-sea ice-ocean process.
- The highly-coupled nature of the Arctic, the diverse surface properties, and the harsh conditions have presented humanity a great challenge to understand this fascinating region of Earth.
- We have learned a lot and have a lot to learn.
- One thing we know for sure is that the fate of this relatively small part of planet Earth has far outsized impacts on the society.
- An important step remains, we must raise the Arctic Amplification to a higher place on the climate science priority list to ensure that the surprises that the climate system has in store for us don't have unmanageable consequences.

Back-up slides

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Influence of seasonal time scale energy transfer to climate change time scale:

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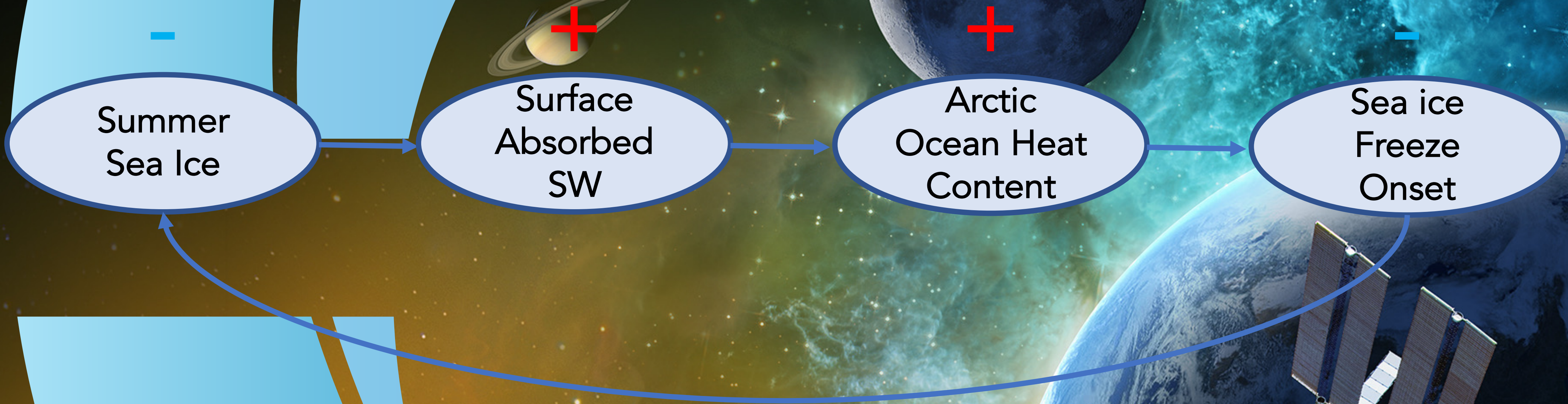
Interactions of the upper Arctic Ocean, sea ice, and atmosphere



Later fall sea ice freeze onset promotes increased LH and SH and greater LW downwelling radiation leading to less winter thickness growth.

Greater seasonal energy transfer, greater Arctic Amplification

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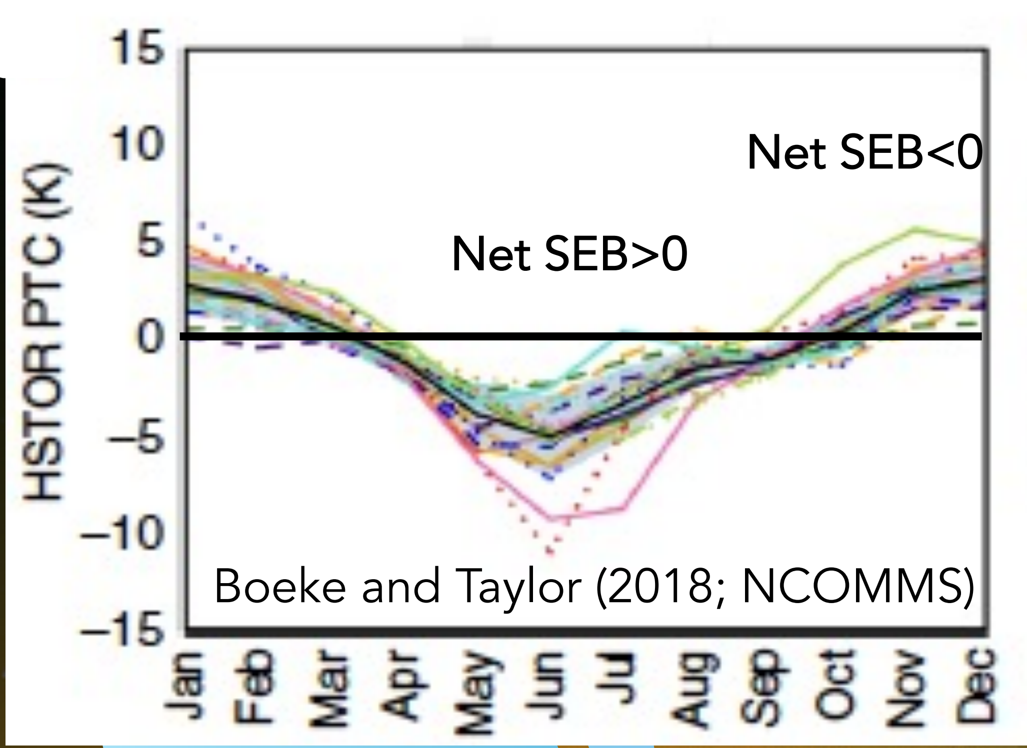
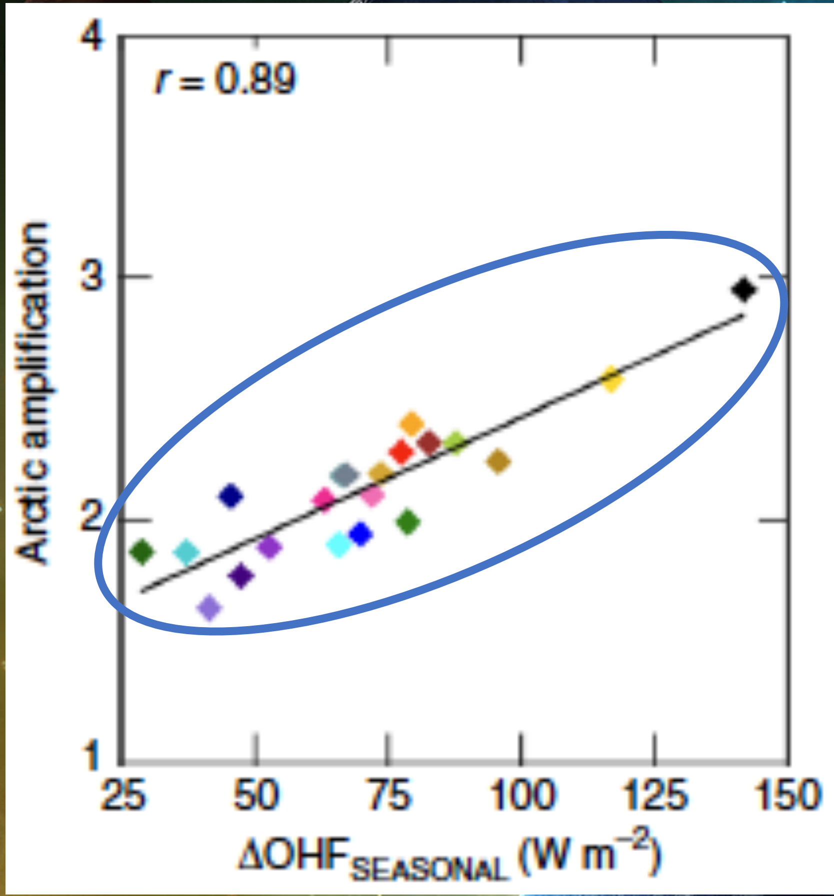
SEB=> Surface Energy Budget





Models with a greater increase in the seasonal amplitude of ocean heat storage produce greater Arctic Amplification.

The seasonal transfer of energy from summer to fall has a fingerprint on the centennial scale Arctic Amplification.

Processes driving the change in seasonal energy transfer

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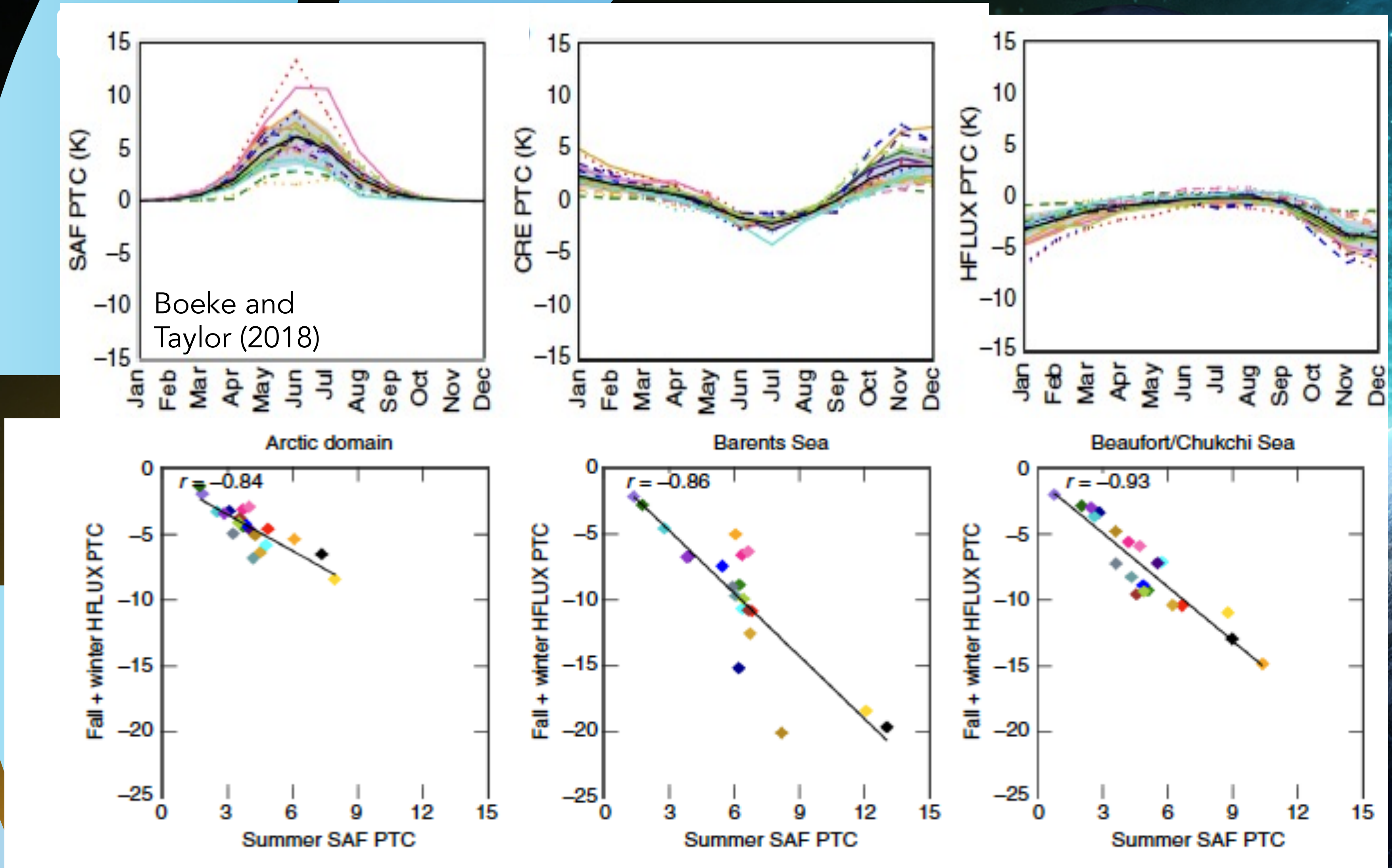

The seasonal transfer of energy results from the **summer surface albedo feedback** and **fall/winter increase in surface-to-atmosphere surface turbulent fluxes.**

Cross-scale interactions due to seasonal energy transfer are tied to cross-interface energy exchanges.

Seasonal energy transfer: Ocean Mixed Layer Depth Uncertainty

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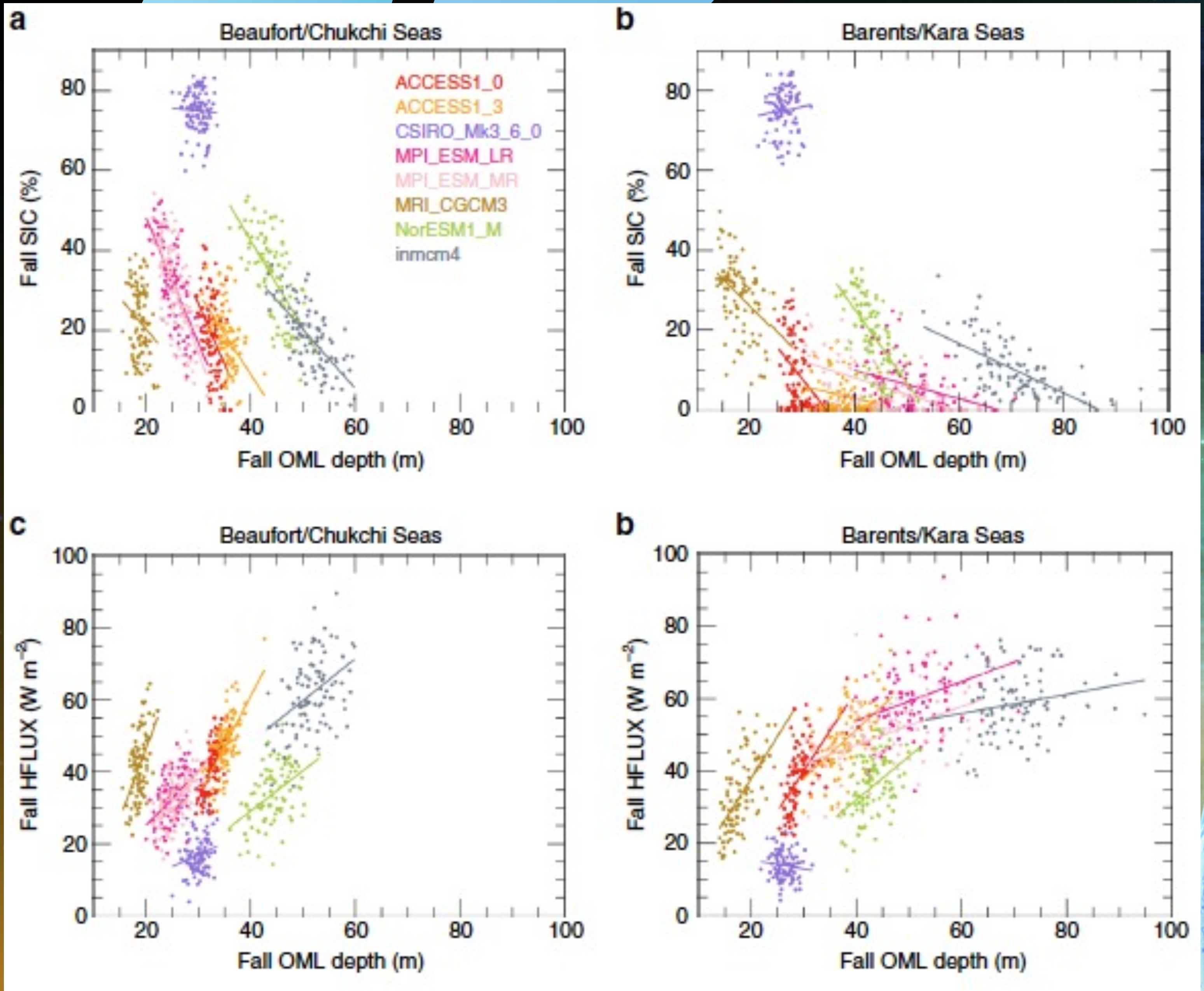

Ocean mixed layer depth and related processes influence the seasonal exchange of energy between the ocean, sea ice, and atmosphere.

Stark inter-model differences are found between the Arctic Ocean mixed layer depth and the relationships with sea ice and turbulent fluxes.

Seasonal energy transfer: Influence of Ocean heat transport

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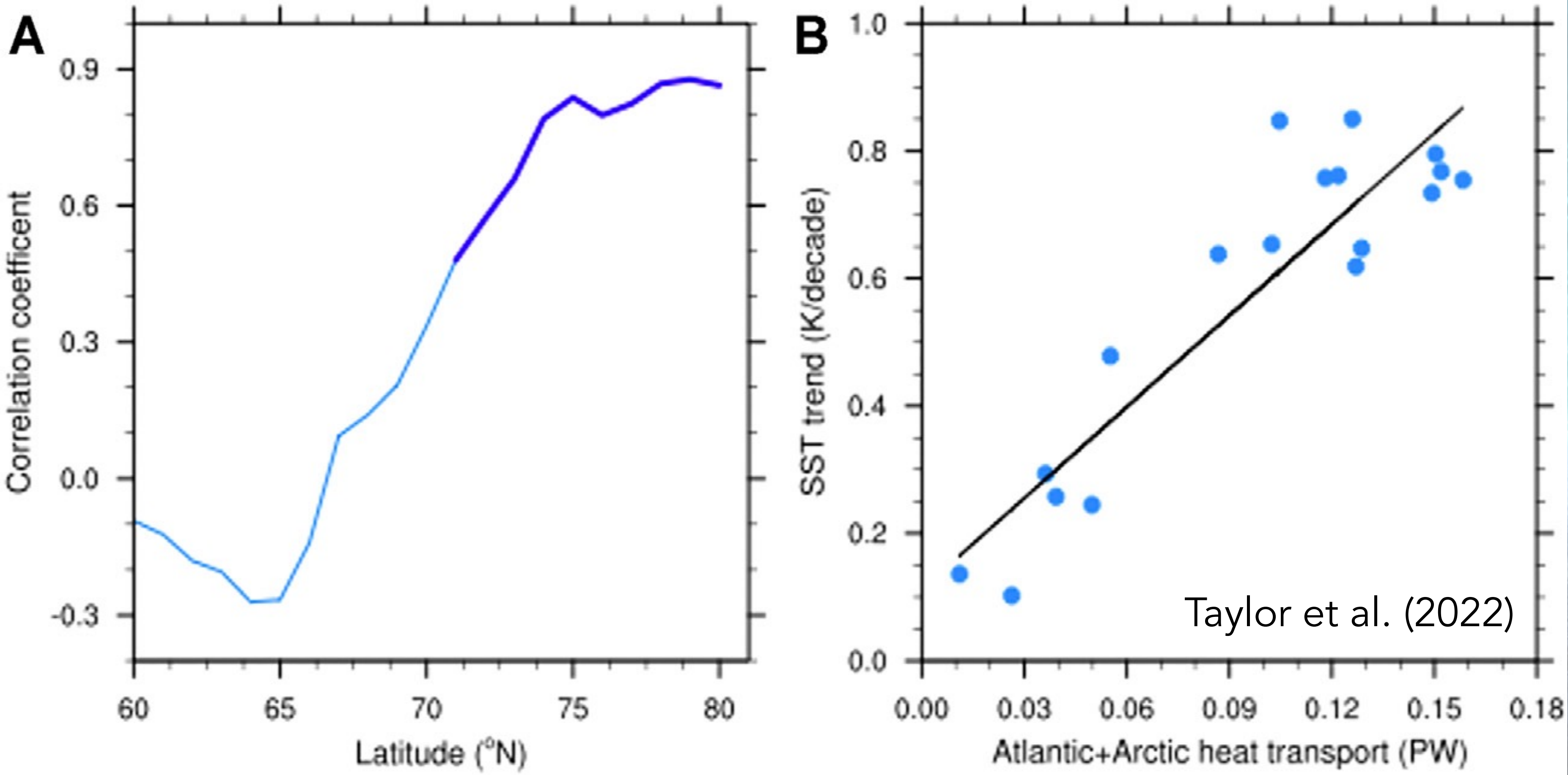


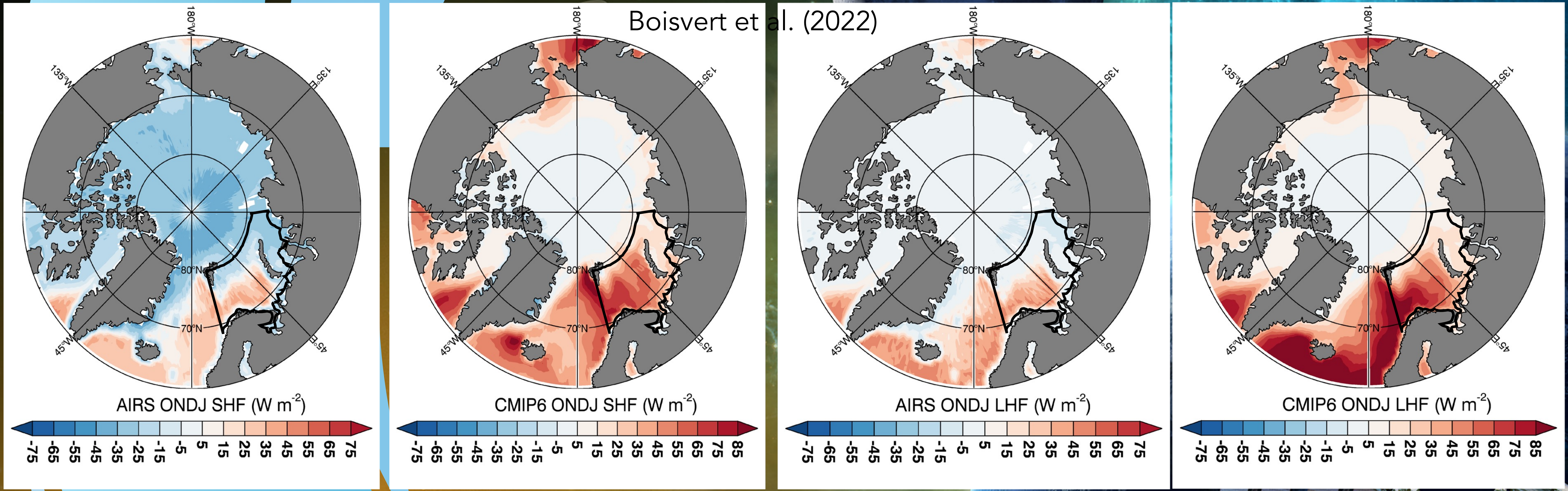
Ocean heat transport into the Arctic from the Atlantic correlates with projected Arctic warming, such that larger transport increases yields larger warming

Ocean heat transports may also play a key role in delaying sea ice freeze-up and enhancing surface turbulent fluxes in fall/winter.

Seasonal energy transfer: Surface turbulent flux uncertainty

Satellite observations => central Arctic is a heat sink to the Arctic atmosphere in winter
CMIP6 models => central Arctic is a heat source to the Arctic atmosphere in winter

AIRS *SHF* | CMIP6 *SHF* | AIRS *LHF* | CMIP6 *LHF*



Key uncertainties remain in the parameterization of surface turbulent fluxes in climate models.

Remote process and local feedback interactions:
Rectification of the synoptic scale onto the climate scale

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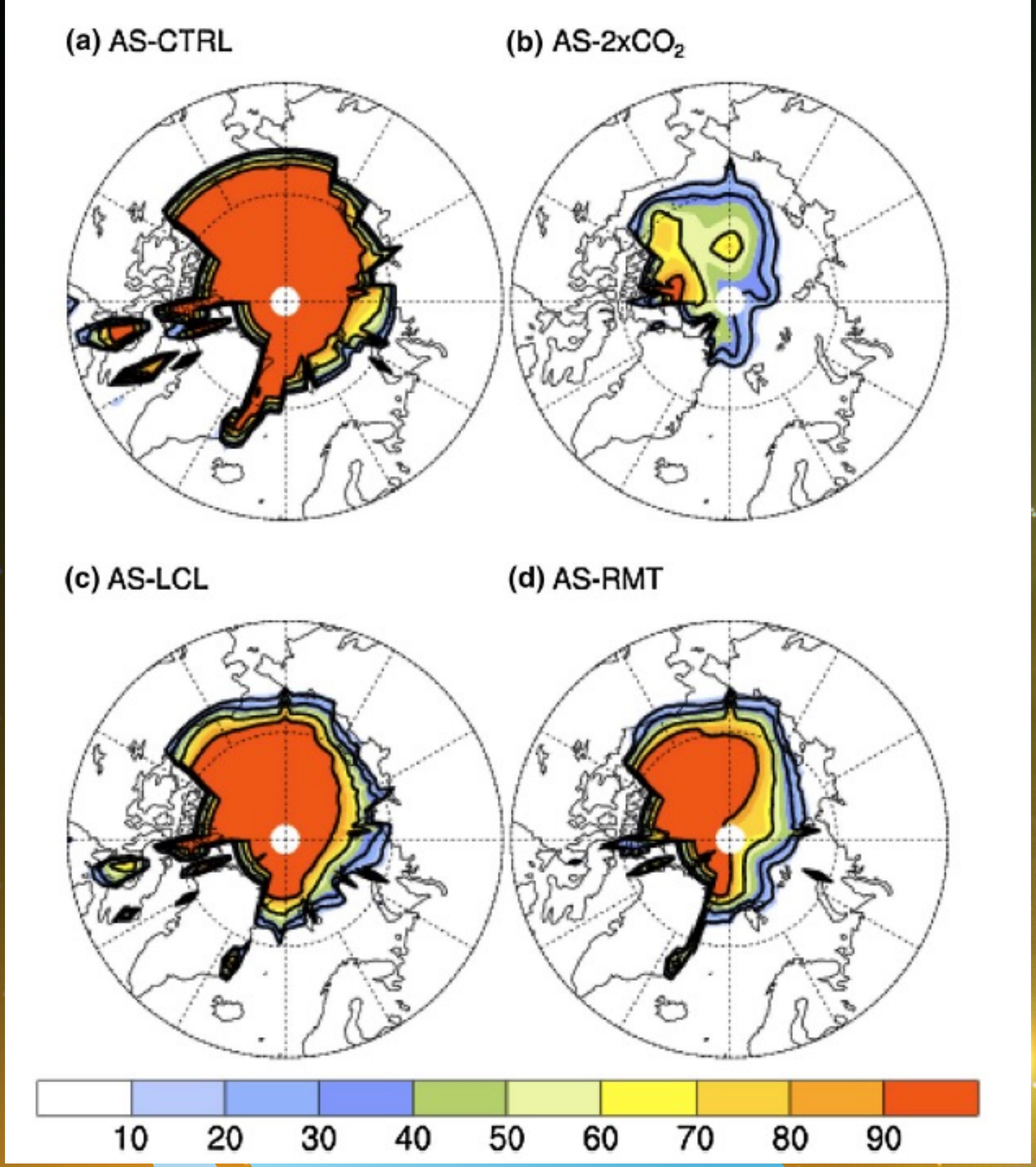

Sea ice concentration

Model simulations that account for **only local feedbacks** (AS-LCL) or **only remote processes** (AS-RMT) show less sea ice loss than when local and remote processes are both active (**AS-2xCO2**)

The amplification of remote warming by local feedbacks appears to be key to producing large Arctic Amplification.

Yoshimori et al. (2017)

Remote process and local feedback interactions:

Rectification of the synoptic scale onto the climate scale

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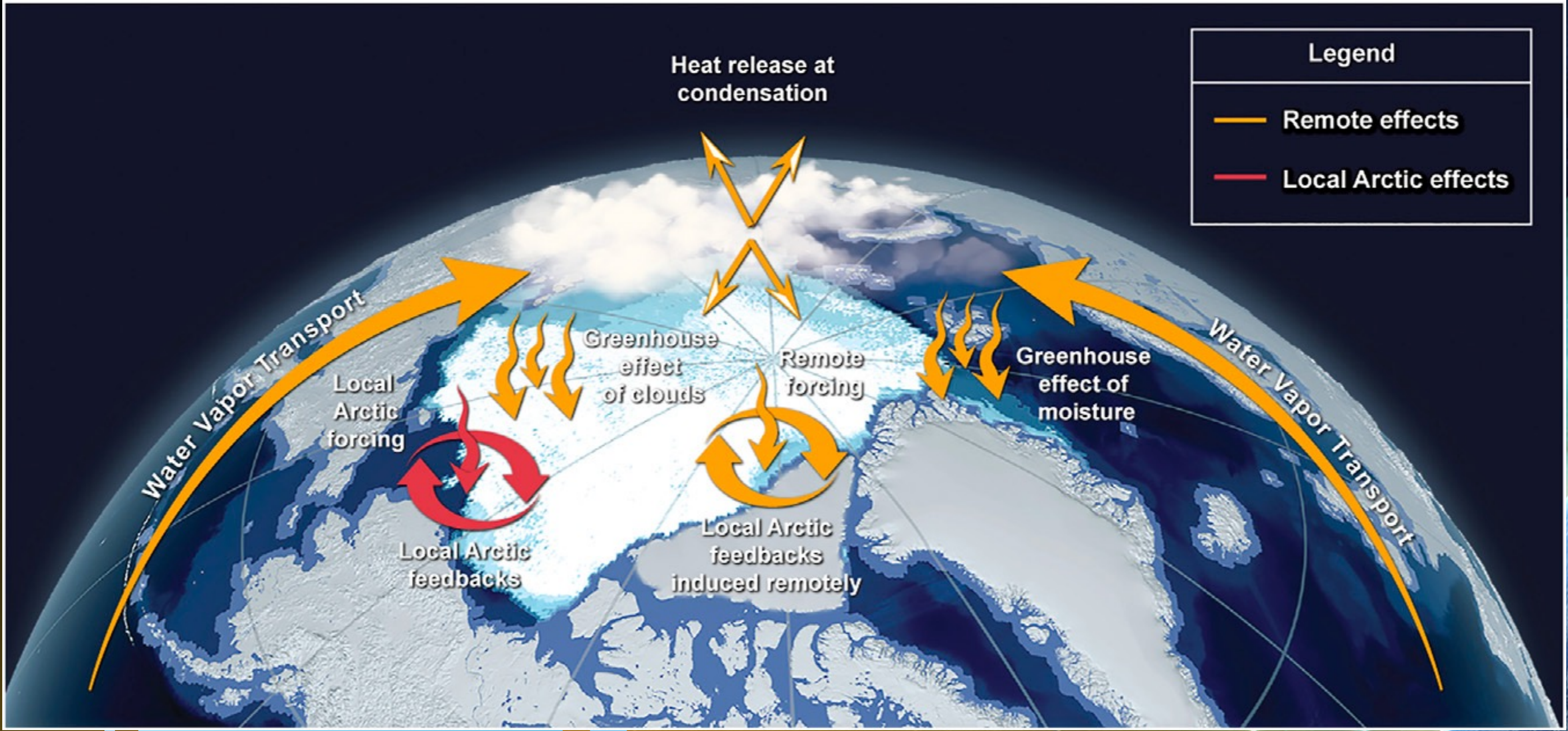
Key Concepts:

1. The Arctic shows a different sensitivity to changes in poleward moisture transport than to dry static energy transport.

2. The amount of surface warming and SEB perturbation to poleward heat transfer is sensitive to the vertical structure of the transfer.

Sensitivity or surface warming to moisture vs. dry static energy transport: "Water Vapor Triple Effect"



Taylor et al. (2022)

Water Vapor Triple Effect encapsulates the multiple influences of water vapor on the Arctic energy budget from condensation and greenhouse effects of moisture and clouds.

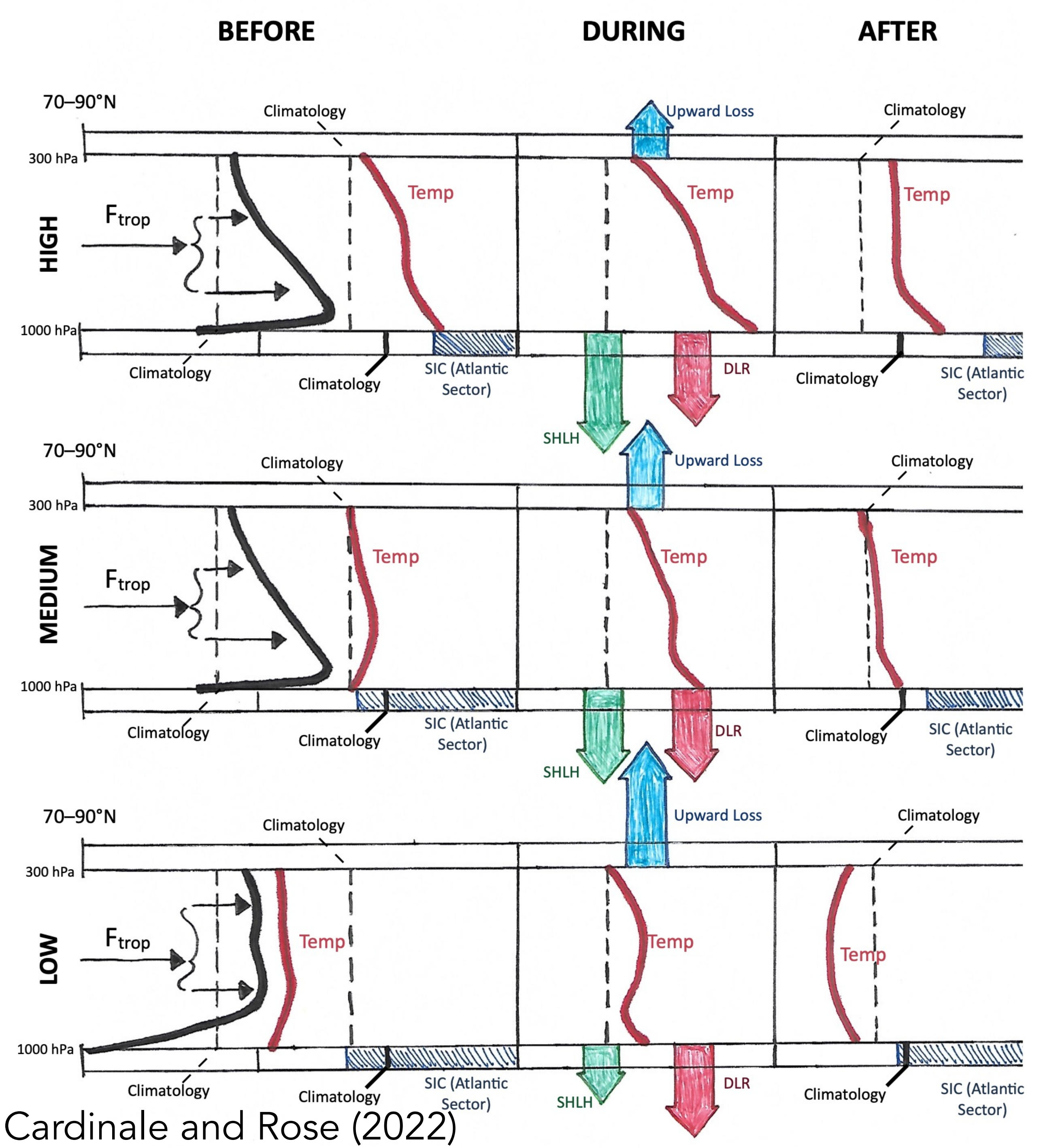
Moisture transport has an order of magnitude larger warming per unit of energy due to the Arctic LH transport than DSE (Graversen and Burtu 2016; Yoshimori et al. 2017)

The Arctic surface is more sensitive to a change in poleward moisture transport than a change in dry static energy transport.

Sensitivity of surface warming to synoptic scale heat transport vertical structure

Tropospheric heat transport events that are most efficient as warming the surface exhibit greater moist static energy transport in the lower troposphere and occur under lower sea ice cover.

The relationship between surface warming efficiency and sea ice suggests a potential positive feedback.



Cardinale and Rose (2022)

Increasing frequency of high efficiency synoptic scale heat transport events

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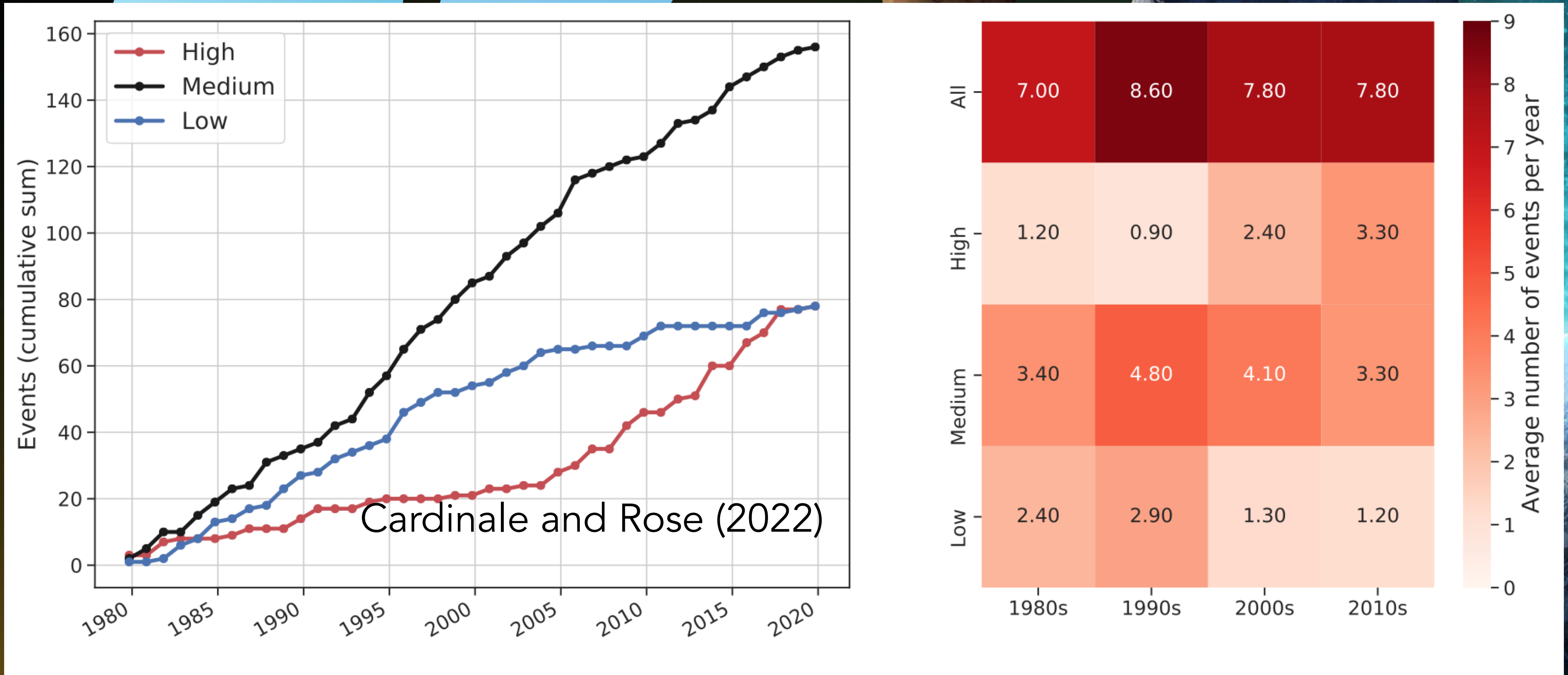
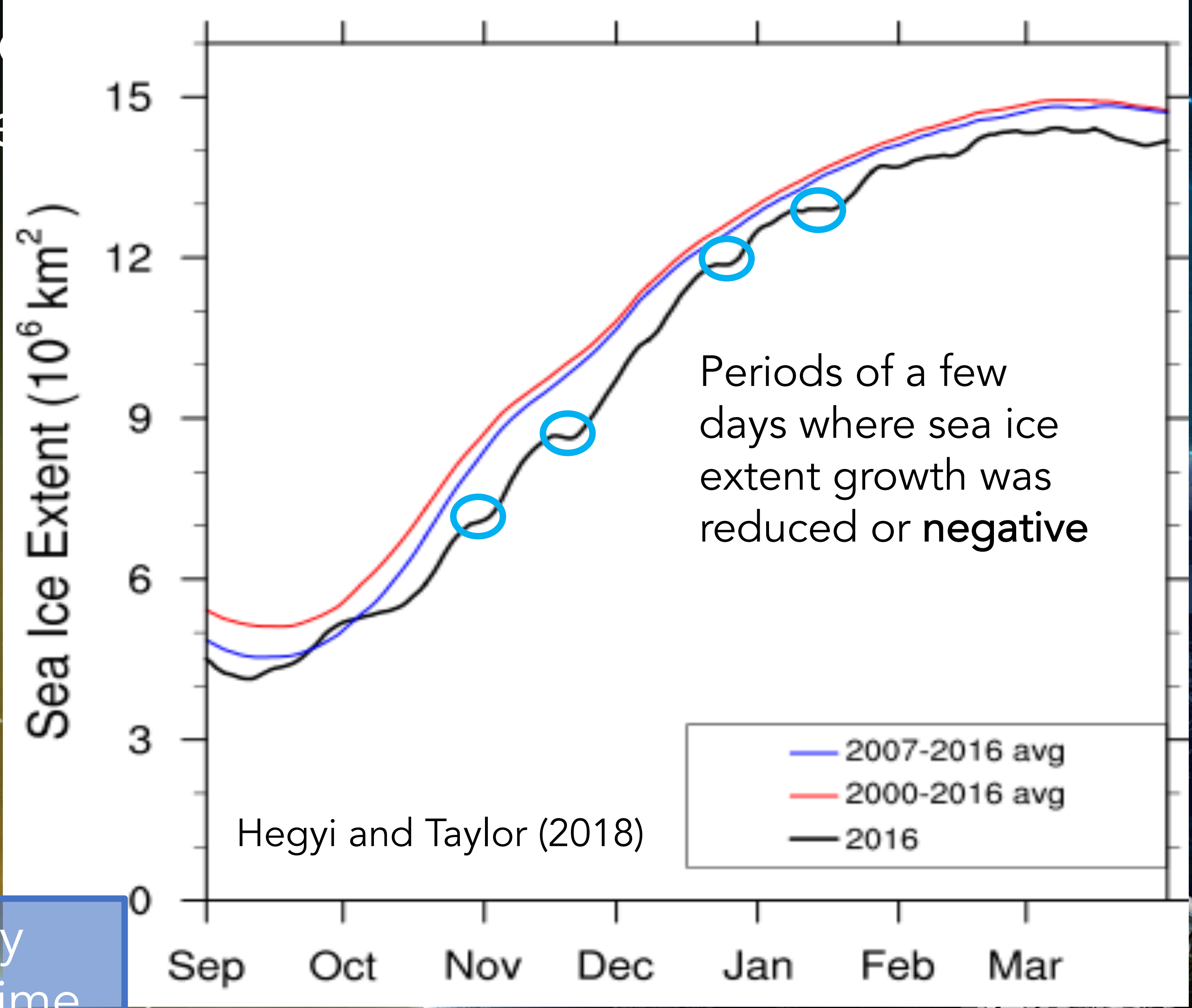


An increasing number of high efficiency heat transport events is found at the expense of low efficiency events.

This results provides additional evidence of a positive feedback between the surface heating efficiency of episodic heat transport and Arctic warming.

Synoptic to climate times sc
Sea ice as a memory source

The 2016-17 sea ice growth season exhibited several periods of reduced or negative sea ice extent growth between October-March and each event corresponded to a substantial moisture intrusion.



Sea ice provides a source of memory amplifying the influence of shorter time scales onto climate change time scales.

Community to do list:

- Field experimental program to resolve the seasonal evolution of the ocean mixed layer depth in the vicinity of the MIZ
- Arctic Ocean Mixed Layer Model Intercomparison Project (MIP): Comparing Arctic Ocean mixed layer properties, processes, and seasonal evolution
- Coordinated intercomparison of polar surface turbulent parameterizations across climate models against benchmark data set (e.g., SHEBA and MOSAiC) as in ICRCCM.
- Evaluation of synoptic scale Arctic heat transport events across climate models.
- Quantify the rectification of episodic heat and moisture transport events onto climate change time scales.
- Pay greater attention to ocean heat transport within the Arctic Amplification process.
- Develop a modeling protocol/diagnostic approach to quantify local feedback and remote process interactions.
- Establish a working group (e.g., WCRP) to rethink Polar climate feedback diagnostics: emphasis on resolving the polar lapse rate feedback processes.

Takeaways

- Our understanding of Arctic Amplification has evolved substantially over the last 100 years from a single-process phenomenon to a phenomenon known to be a coupled atmosphere-sea ice-ocean process.

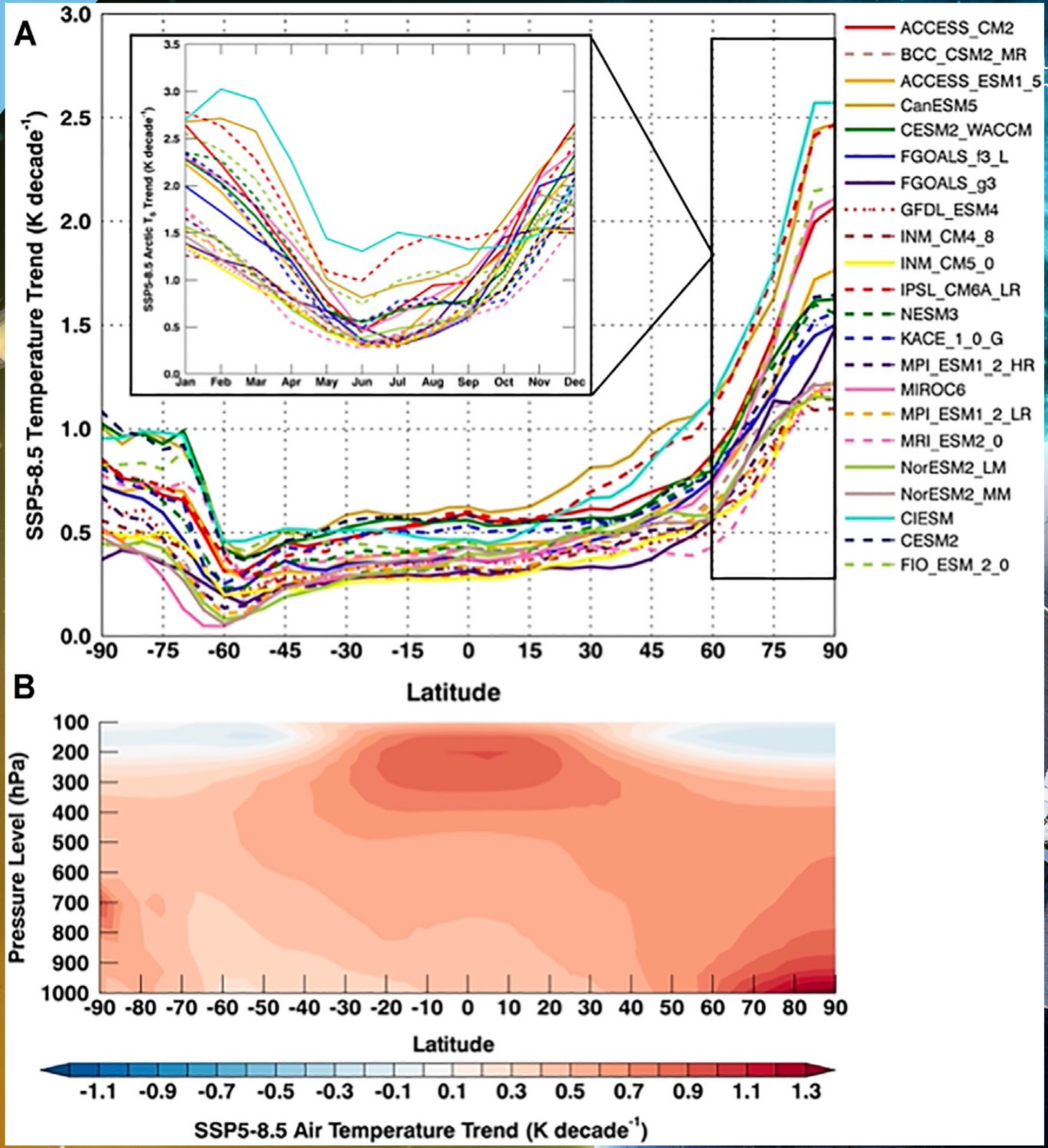
- One thing we know for sure is that the fate of this relatively small part of planet Earth has far outsized impacts on the society.

- Thus, we need to raise Arctic Amplification science to a higher place on the climate science priority list to ensure that the surprises that the climate system has in store for us don't have unmanageable consequences.

Surface type dependence: thermal inertia

- Changes in the distribution of surface types across the Arctic dictates feature of the spatial structure and seasonality of AA.
- The strong influence of surface type occurs due to the surface type dependent processes: albedo, surface turbulent fluxes, vertical and horizonal heat transport and heat capacity.
  - Regions with the largest declines in sea ice warming most rapidly.
  - Regional characteristics of warmig within a cliamte model are driven by surface type dependence feedback differences (Laine et al. 2016; Boeke and Tayor 2018).
- Sea ice retreat and sea ice covered surface type warming the most because:
  - Surface albedo feedback is strongest
  - Sea ice insulation feedbacks strongly enhance surface warming
  - Cloud feedbacks tends to be positive (strongly LTS changes increase clouds)
  - Large thermal inertia change and seasonal energy transfer drive Fall/Winter maximum warming
- Ice-free ocean regions Weaker and seasonally uniform warming
  - Large thermal inertia
  - Very small/no positive sea ice related feedbacks
  - Very small surface energy budget response
  - Unclear if the change in ocean heat transport influence ice-free and sea ice loss regions differently
- Land regions: similar structure to sea ice surface types with weaker magnitude
  - Surface albedo feedback slightly weaker than sea ice with a different seasonality (peaks in spring)
  - Surface turbulent fluxes differ with sea ice primarily cooling the surface
  - Summer warming minimum results from different SEB flux changes: increased STFs cooling surface.
- Understanding these surface type dependence response provides clues to the important processes, models

CMIP6 Projections of AA



CMIP5 vs. CMIP6: Reduced uncertainty in AA projections?

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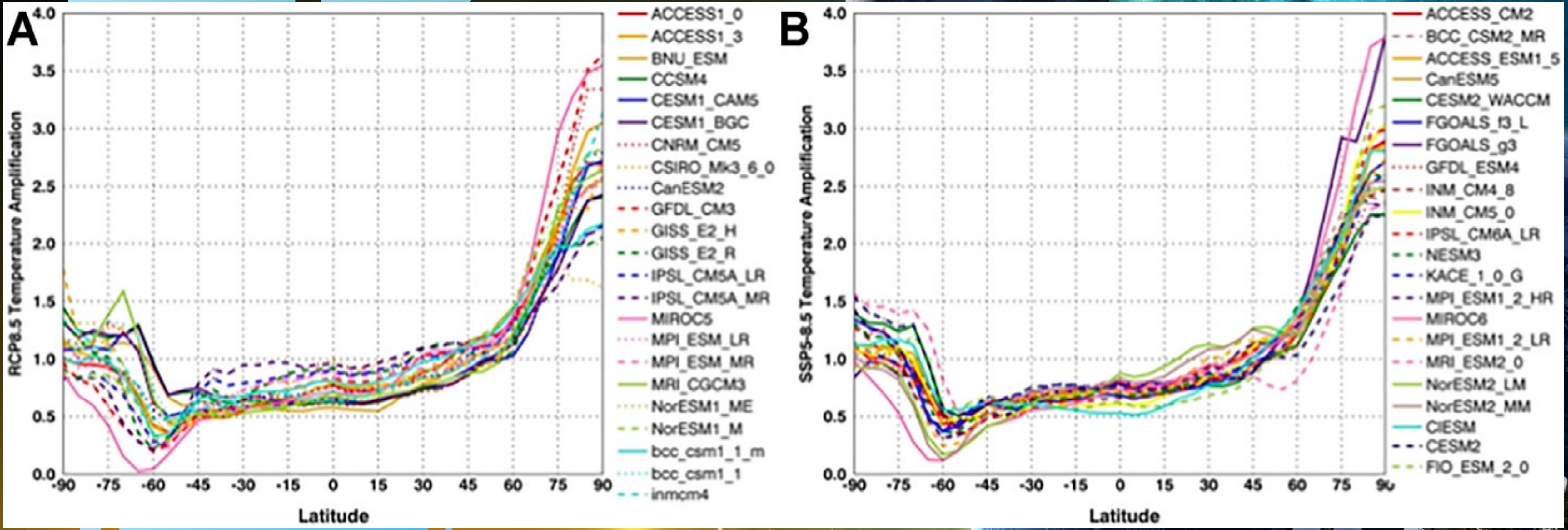
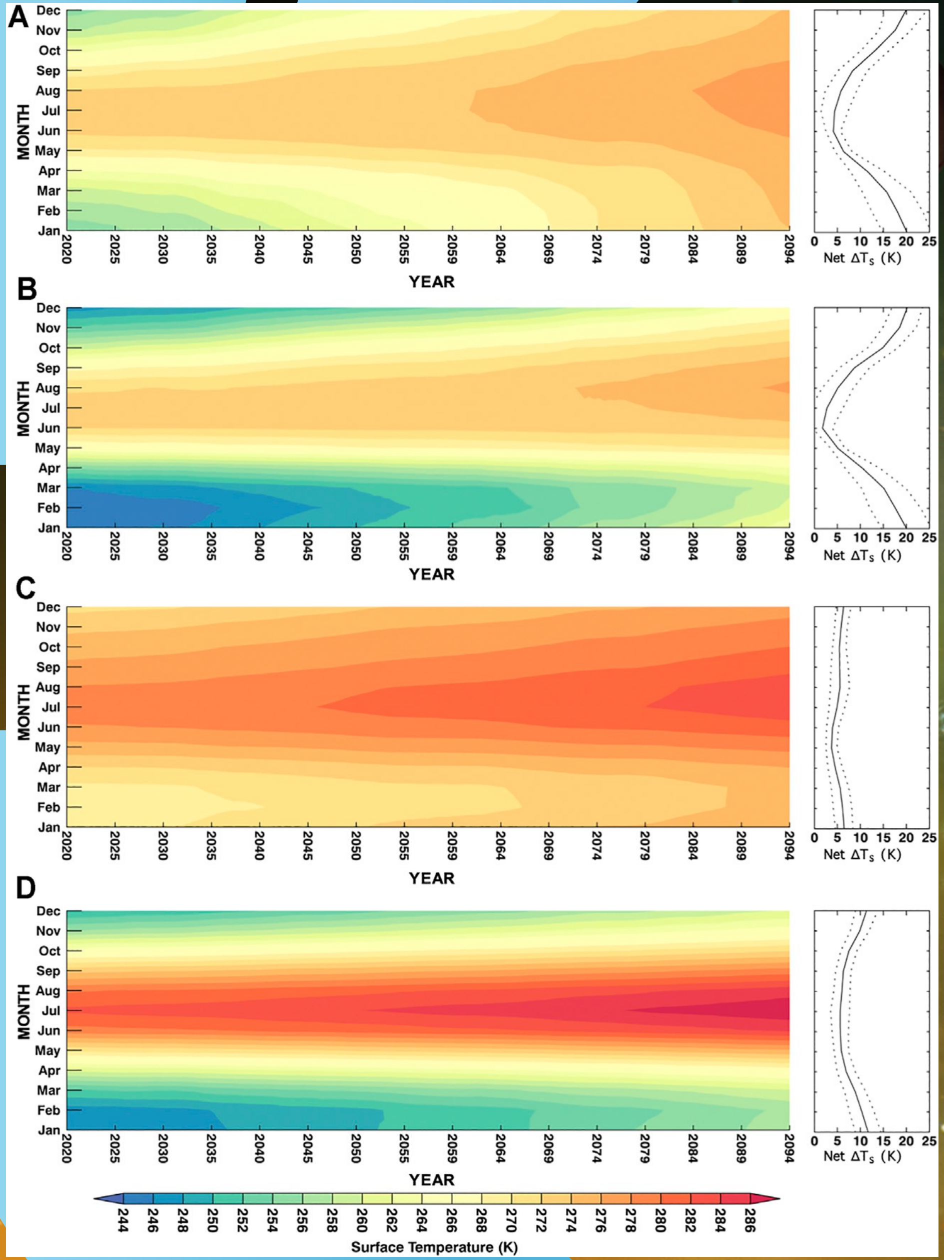
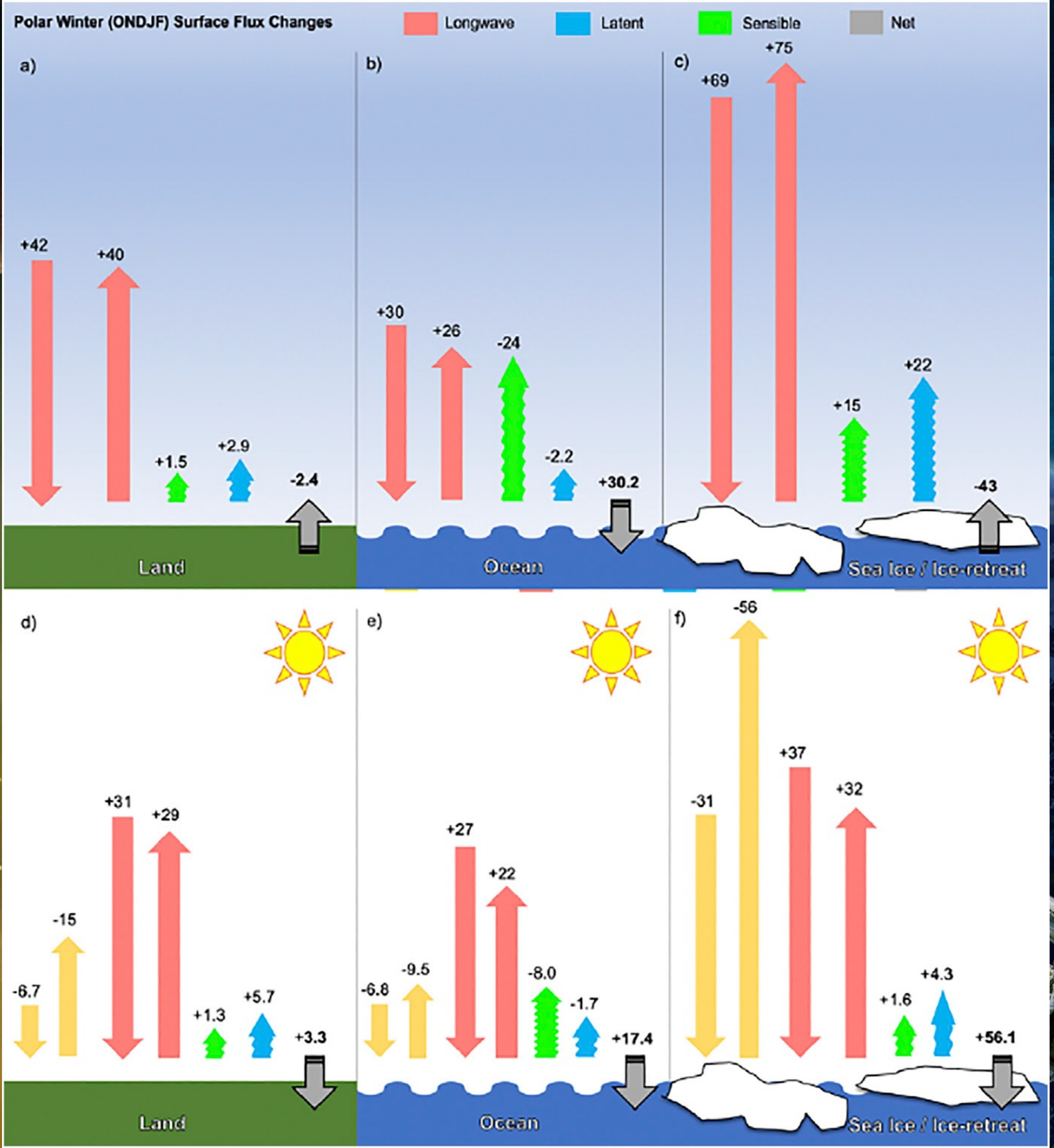


Surface type dependence response



Projected changes in the surface energy budget by surface type



Observed Characteristics of Arctic Amplification

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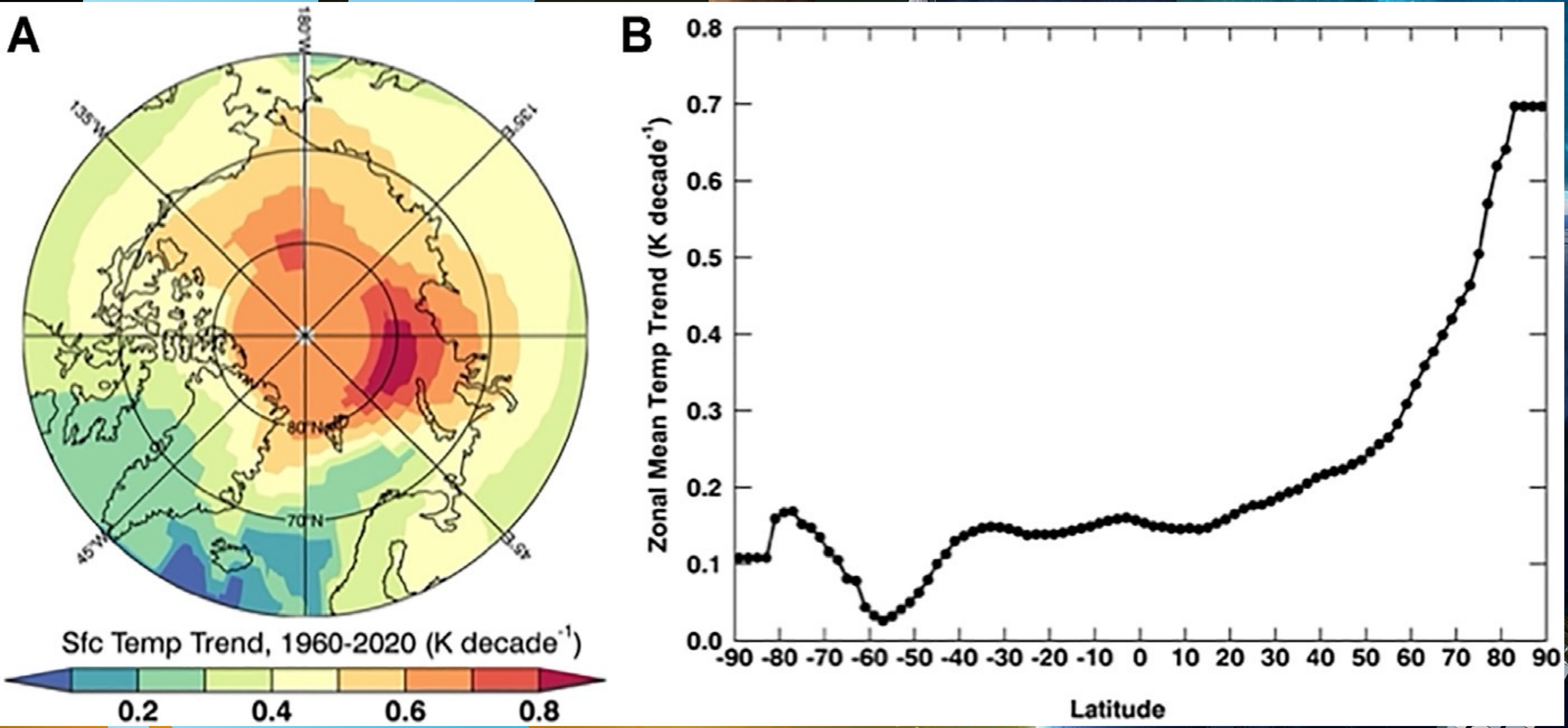

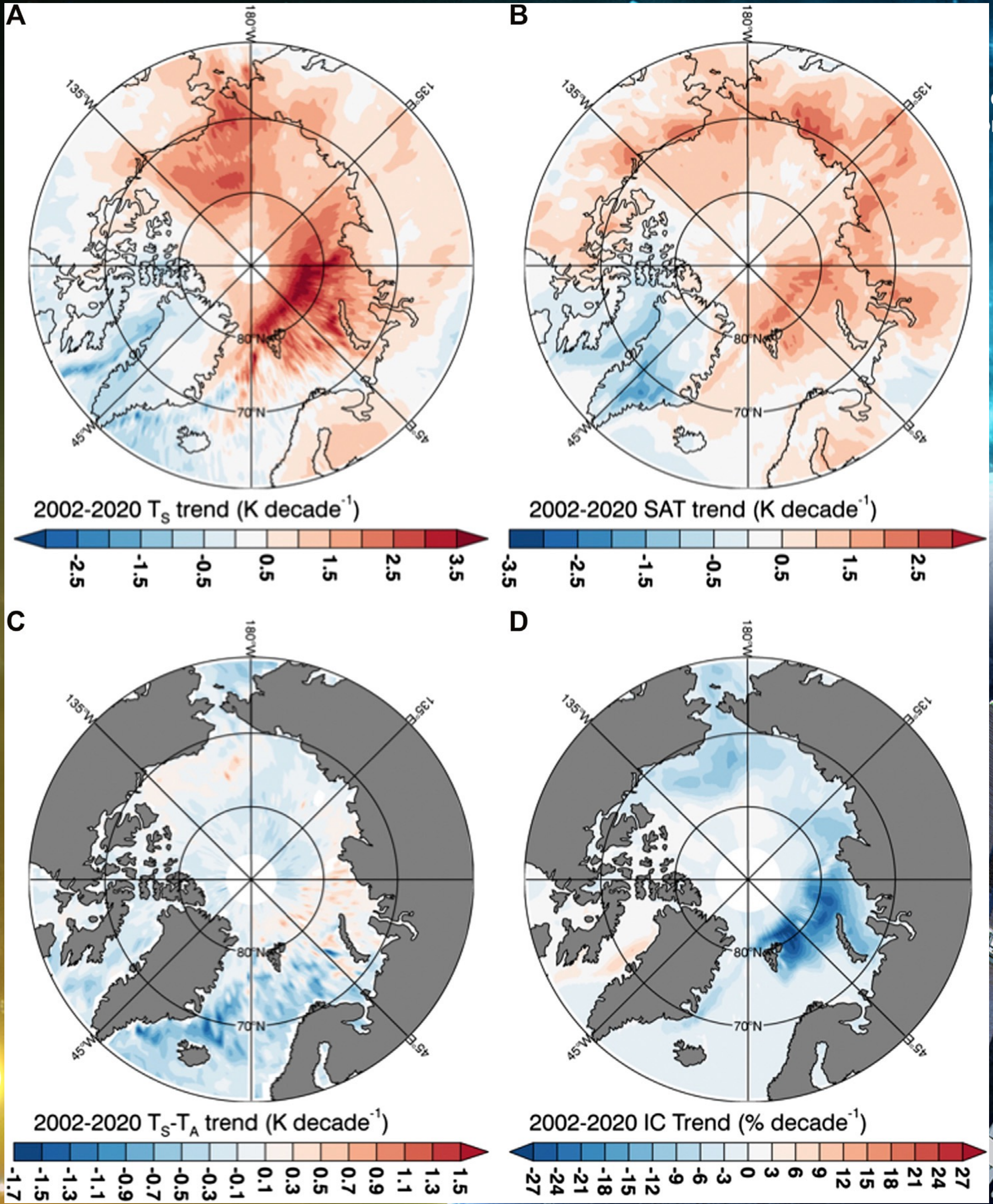
A
B
C
D
180°W
135°W
135°E
45°W
45°E
80°N
70°N
2002-2020 T_S trend (K decade^-1)
-2.5 -1.5 -0.5 0.5 1.5 2.5 3.5
2002-2020 SAT trend (K decade^-1)
-3.5 -2.5 -1.5 -0.5 0.5 1.5 2.5
2002-2020 T_S-T_A trend (K decade^-1)
-1.7 -1.5 -1.3 -1.1 -0.9 -0.7 -0.5 -0.3 -0.1 0.1 0.3 0.5 0.7 0.9 1.1 1.3 1.5
2002-2020 IC Trend (% decade^-1)
-27 -24 -21 -18 -15 -12 -9 -6 -3 0 3 6 9 12 15 18 21 24 27

Observed Surface Energy Budget Changes

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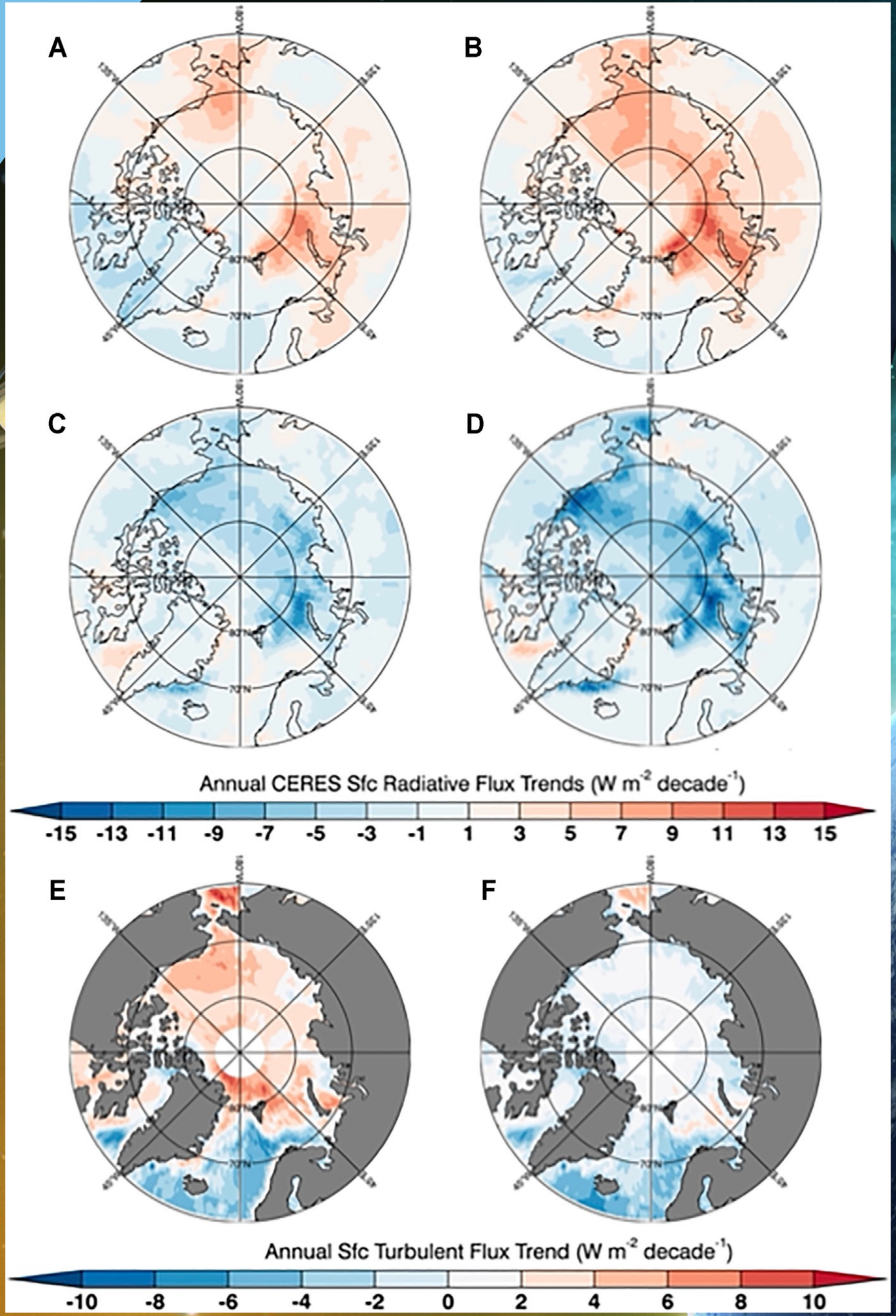
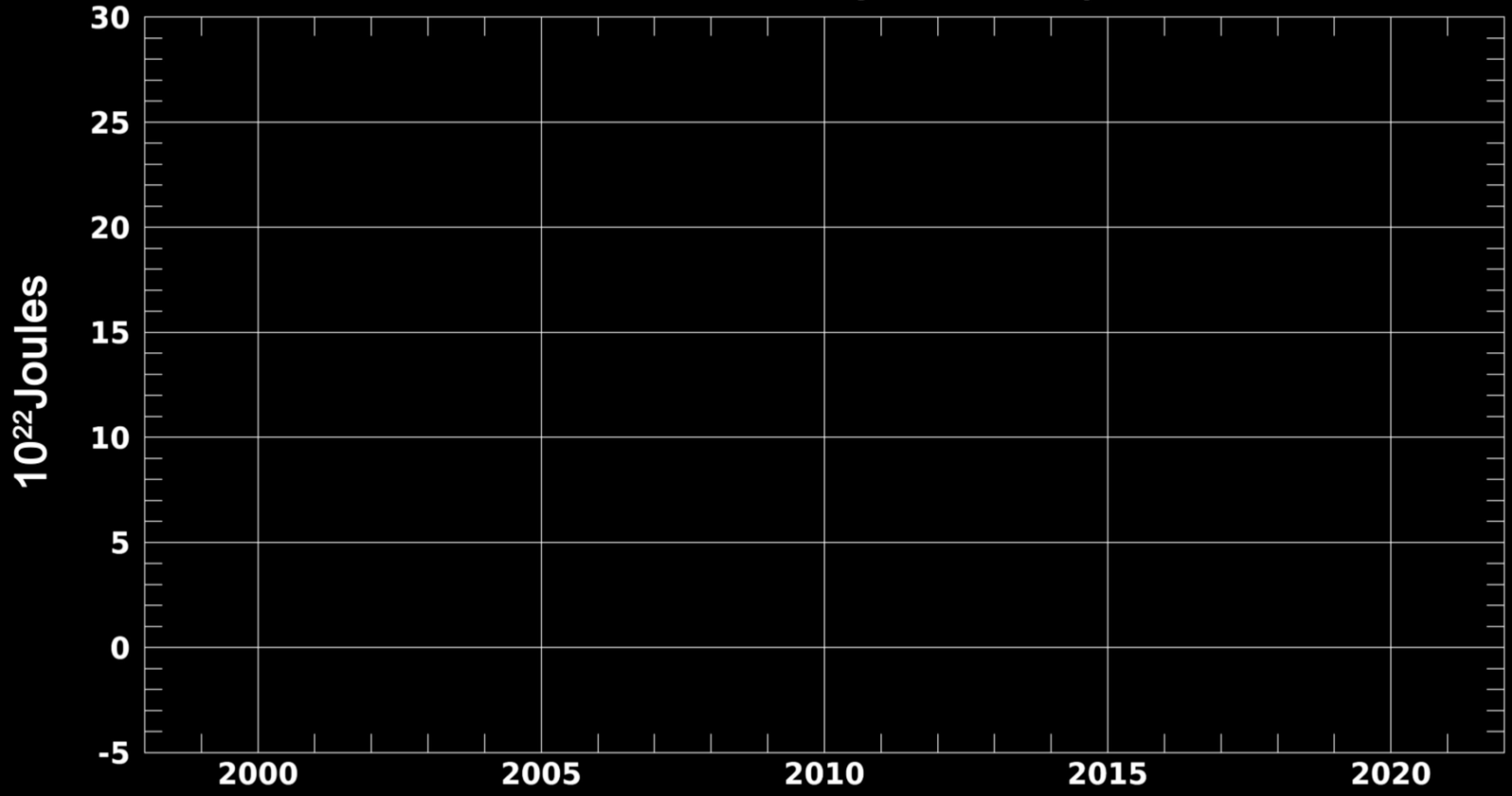


CERES Planetary Heat Uptake



Arctic Amplification: CMIP5 vs. CMIP6

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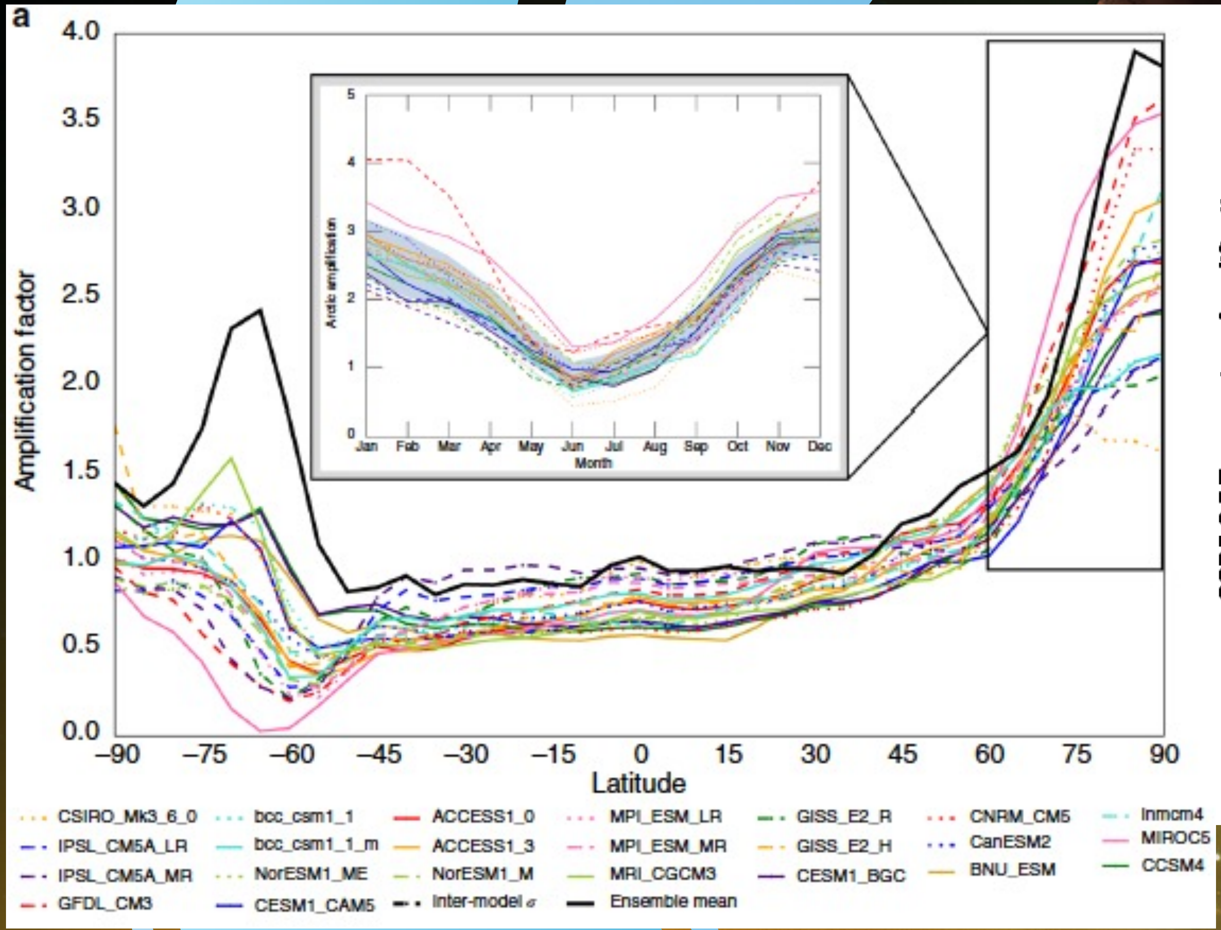
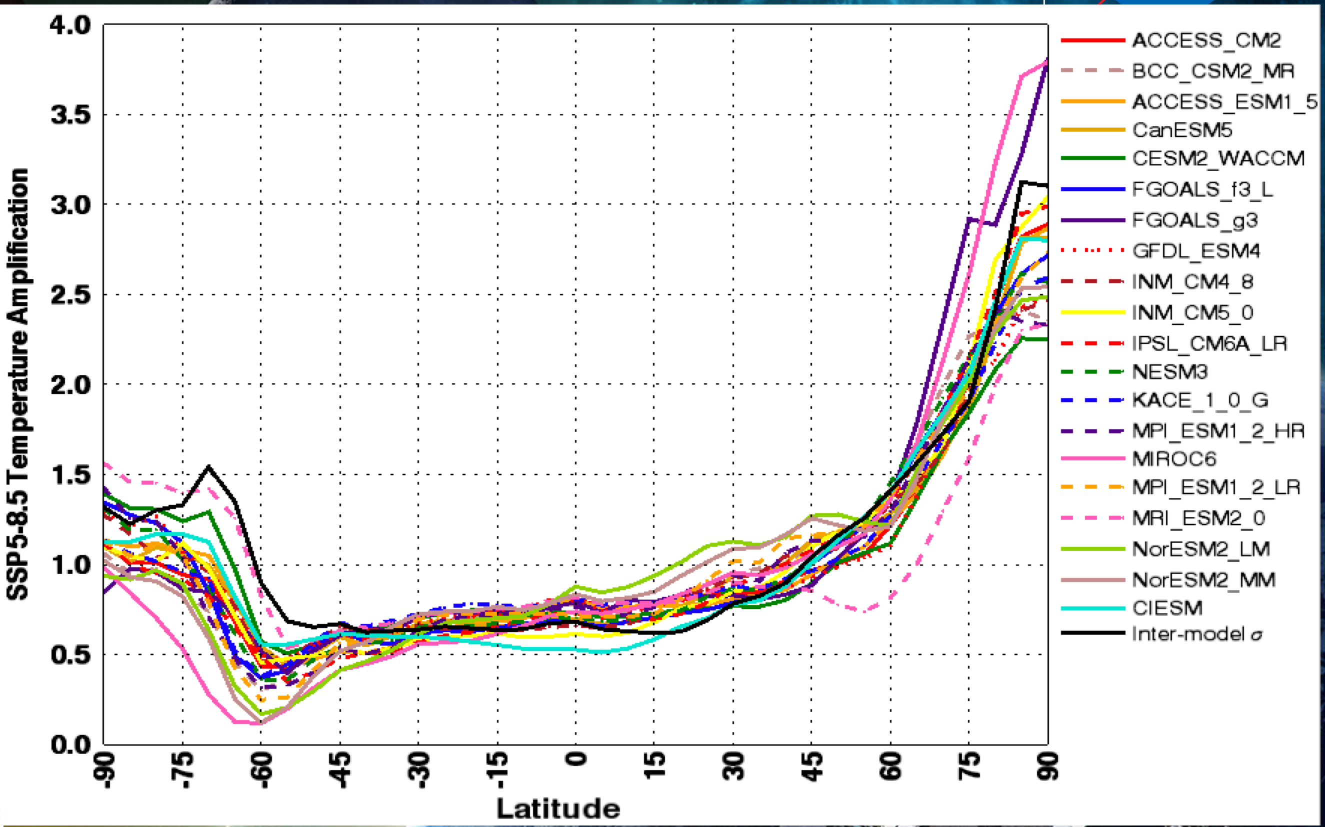
CMIP5



CMIP6



The inter-model spread in projected Arctic Amplification remains unchanged between CMIP5 and CMIP6.

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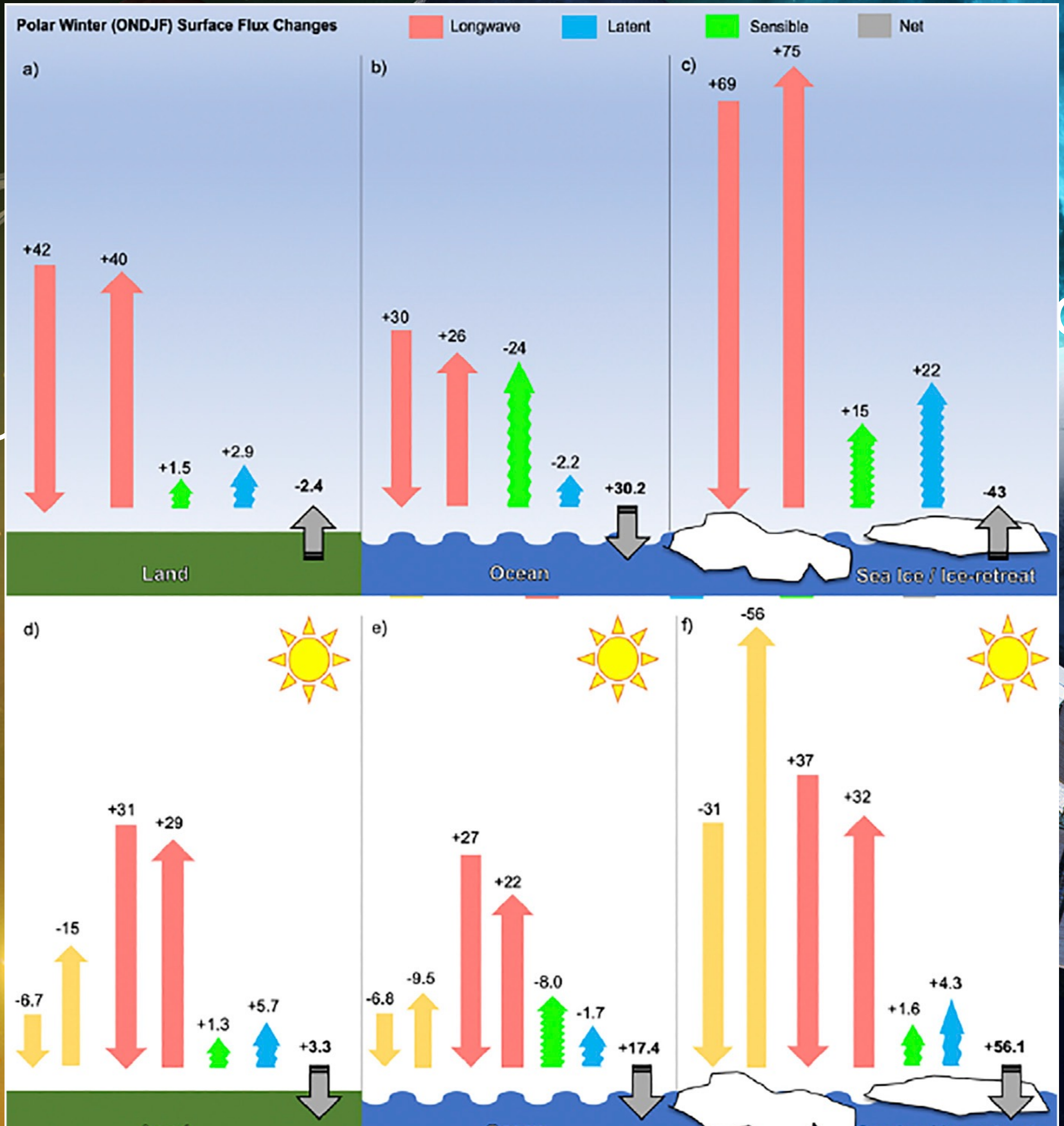
Why does the Arctic ... o
with the energy accu

Describe fundamentally how these an



Leading uncertainties in Arctic Amplification Science

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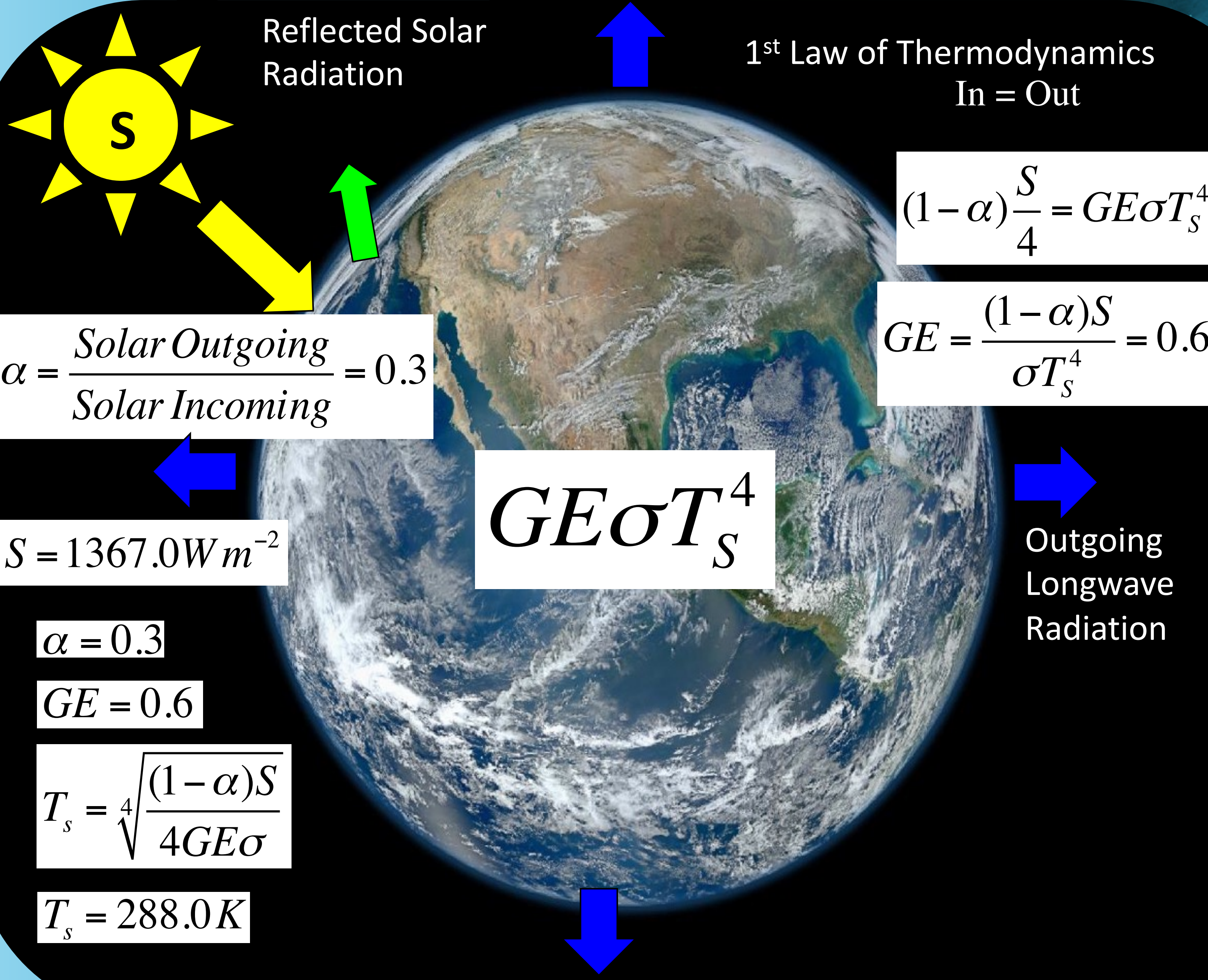

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1st Law of Thermodynamics

In = Out

$$(1-\alpha)\frac{S}{4} = GE\sigma T_S^4$$

$$GE = \frac{(1-\alpha)S}{\sigma T_S^4} = 0.6$$

$$\alpha = \frac{Solar\ Outgoing}{Solar\ Incoming} = 0.3$$

$$GE\sigma T_S^4$$

$$S = 1367.0\,W m^{-2}$$

$$\alpha = 0.3$$

$$GE = 0.6$$

$$T_s = \sqrt[4]{\frac{(1-\alpha)S}{4GE\sigma}}$$

$$T_s = 288.0\,K$$

Evolution towards Multi-model Intercomparison Projects (MIPs)

- Emergence of Model Intercomparison Projects (MIPs)
  - The principal utility of MIPs is to understand how and why models differ.
  - The first coordinated climate model intercomparison occurred in the late 1980s, finding a 3-fold difference in global climate sensitivity (Cess et al. 1989;1990)
  - Cess et al. (1991) reported a substantial snow-albedo feedback differences stemming from both

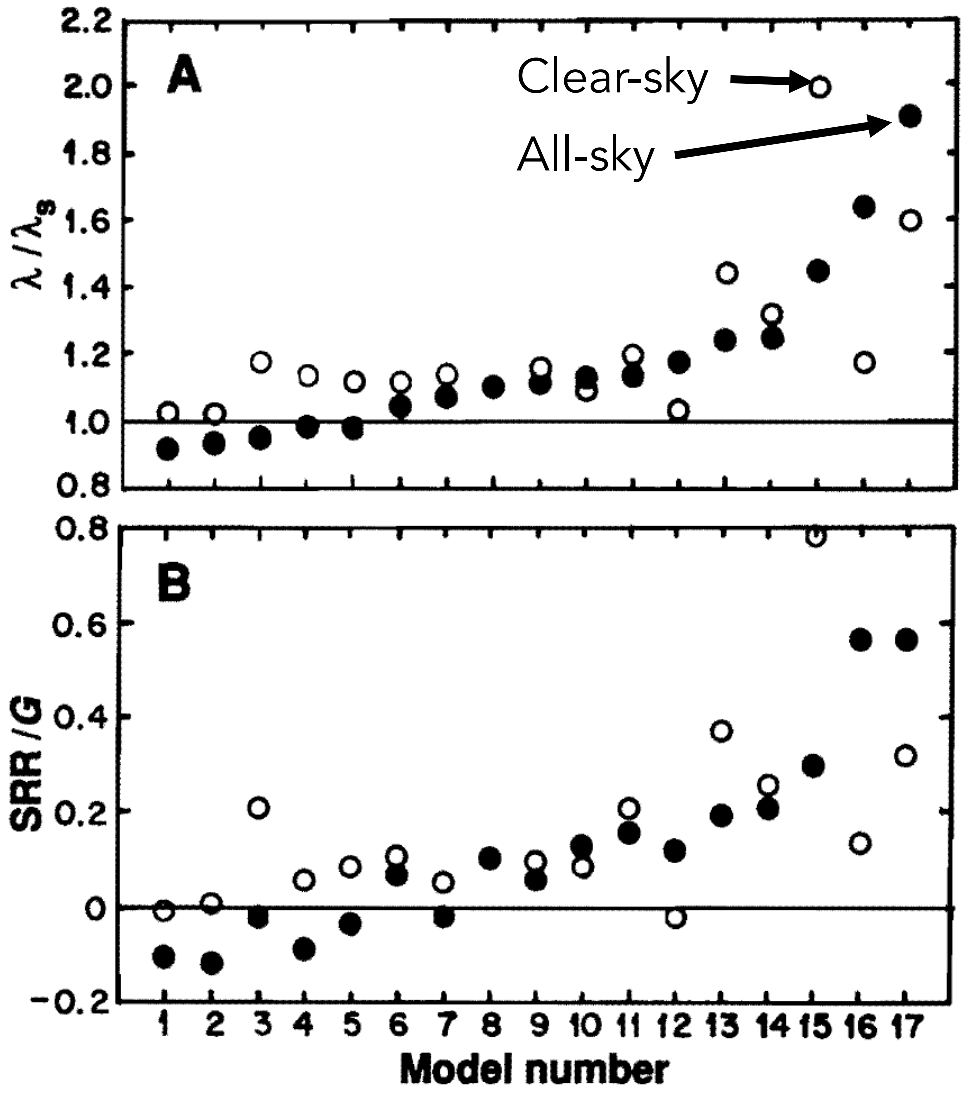

Fig. 1. (**A**) The snow feedback parameter λ/λ_s for the 17 GCMs and for both global (●) (entire Earth) and clear (○) designations. For model 8 the global and clear values are the same. (**B**) Values of SRR/G for the 17 GCMs and for both global and clear designations.

Towards Multi-model comparisons: Model diagnostics

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- The purpose of model diagnostics is to identify and quantify the processes causes of model differences.
- These model diagnostics focused on quantifying the contributions of TOA radiative feedbacks to model differences, since these could be relatively easily be diagnosed from TOA flux model output.
- Early diagnostics focused on surface albedo feedback:
  - Multiple studies found substantial differences in the magnitude of the surface albedo feedback.
  - While this conclusion was valid, Ingram et al. (1989) illustrate that a substantial portion of these differences were due to methodological differences in the feedback diagnostic methods.
- These feedback diagnostic methods paved the way for broader model intercomparisons and enabled a consistent understanding of why projections differences.