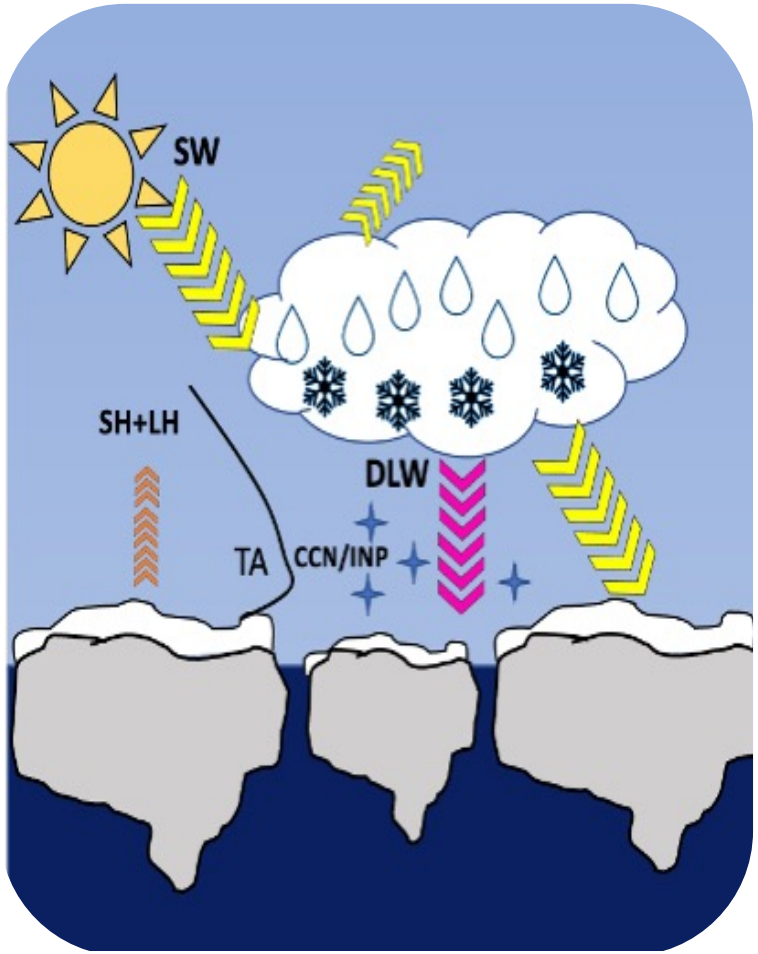
Clouds in the Arctic climate system: A force for change?

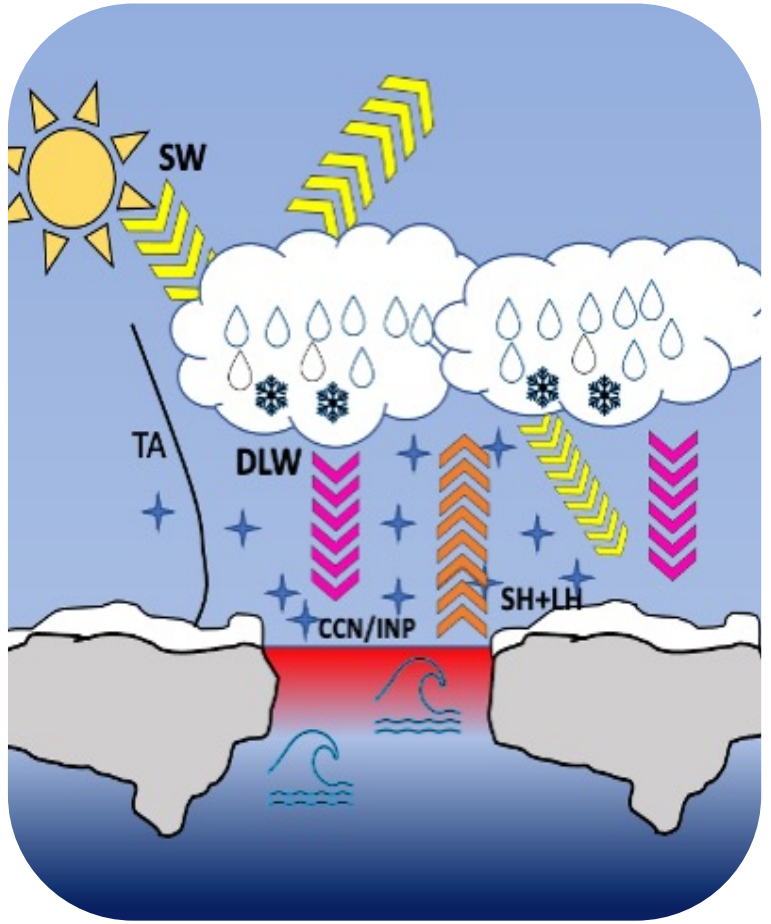


Patrick C. Taylor

NASA Langley Research Center

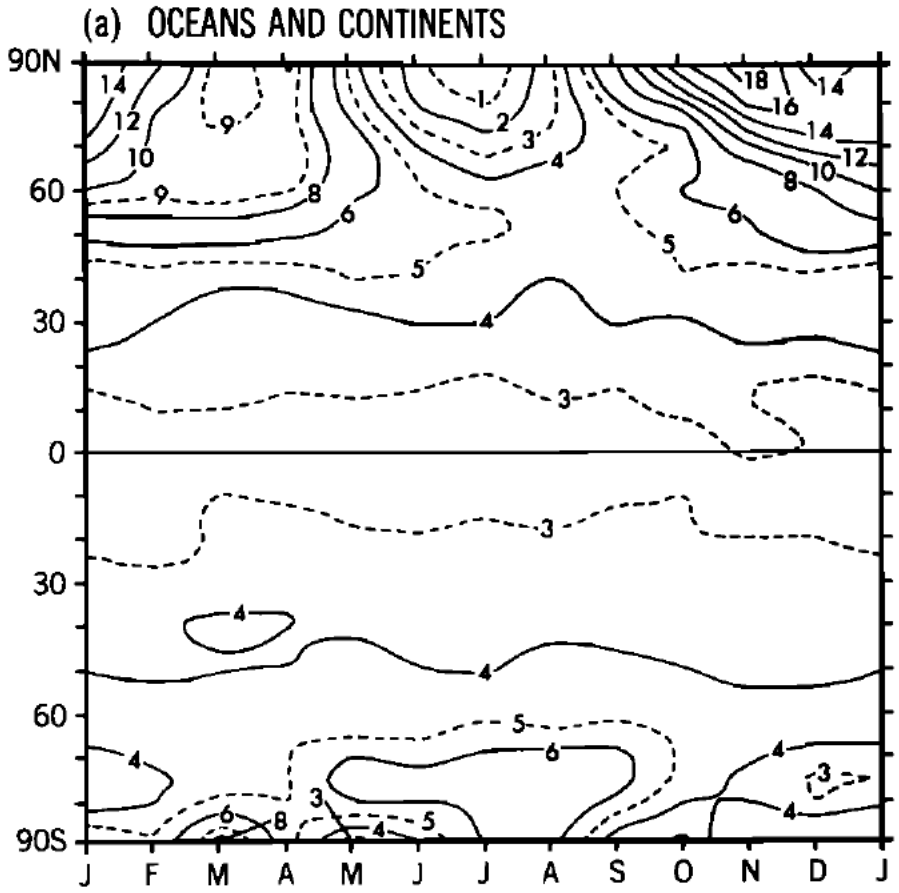
GMAO Seminar Series

October 10, 2023

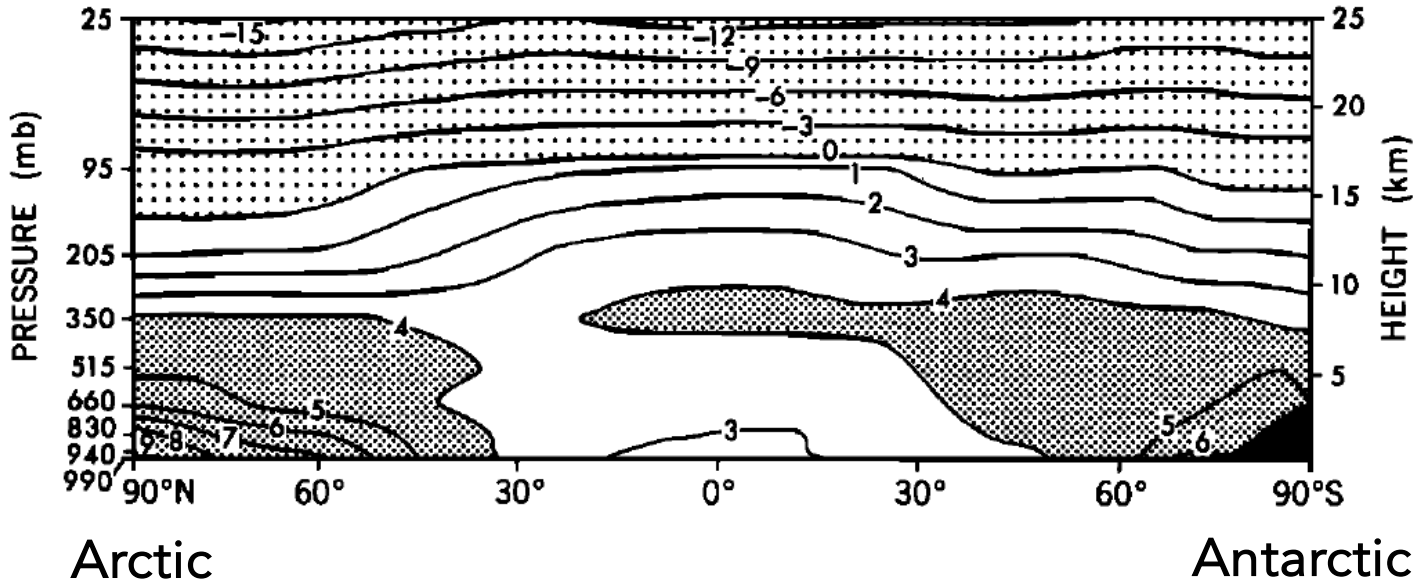


Figures: courtesy of Linette Boisvert

What is Arctic Amplification?

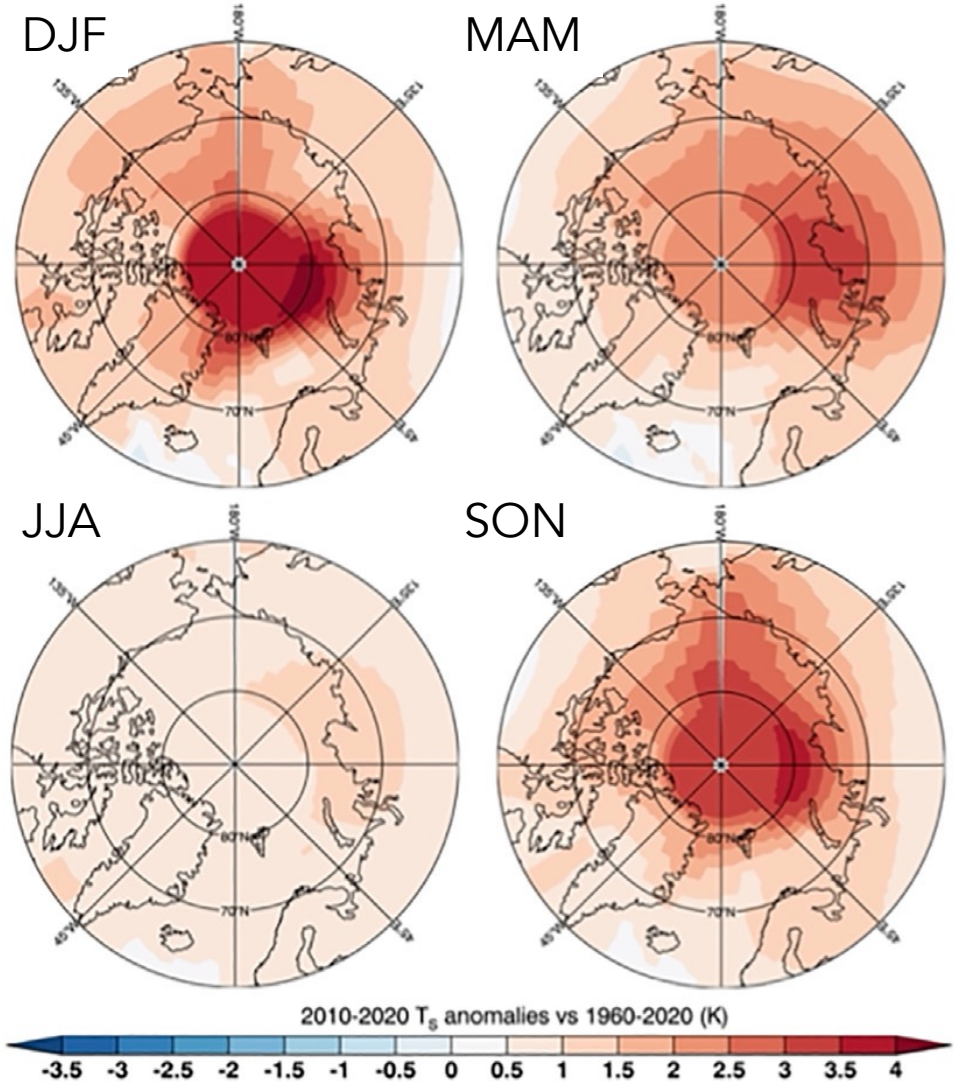


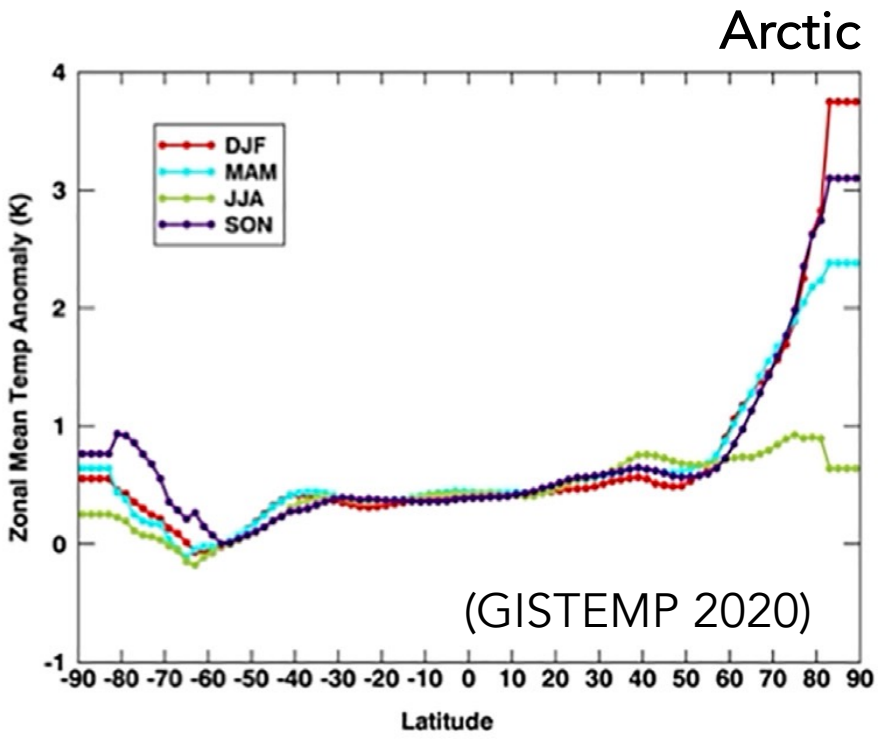
Arctic Amplification is the phenomenon where the Arctic is more sensitivity to a climate perturbation than the global average.



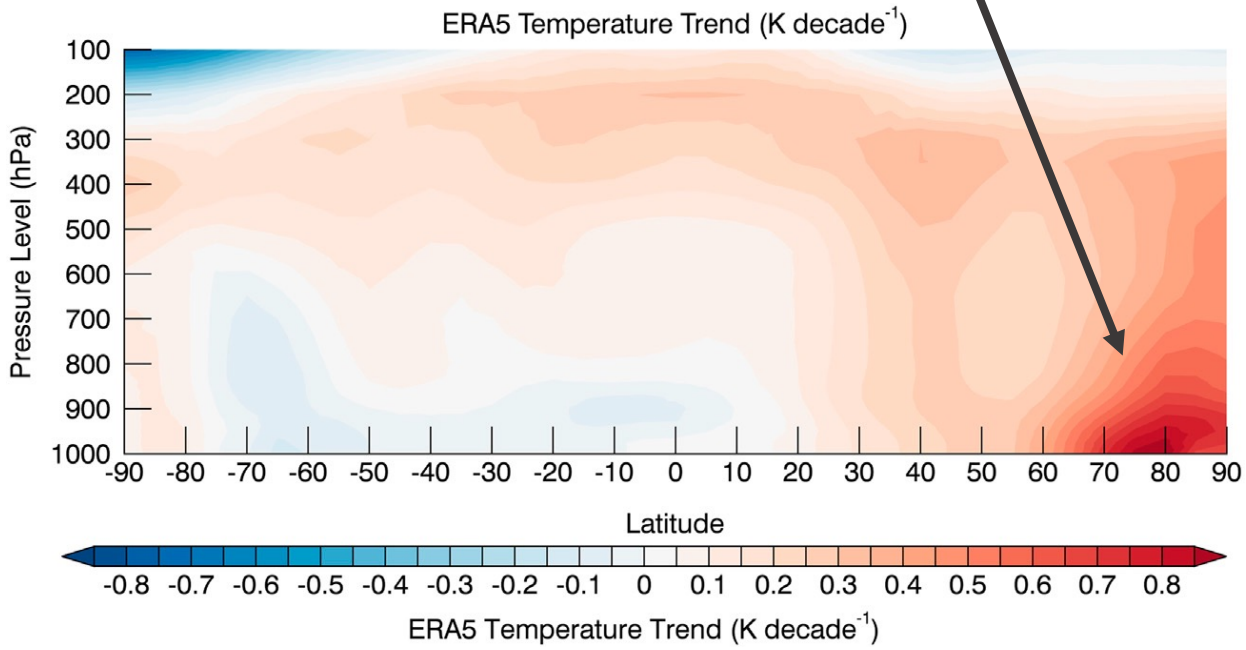
Manabe and Stouffer (1980)

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





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



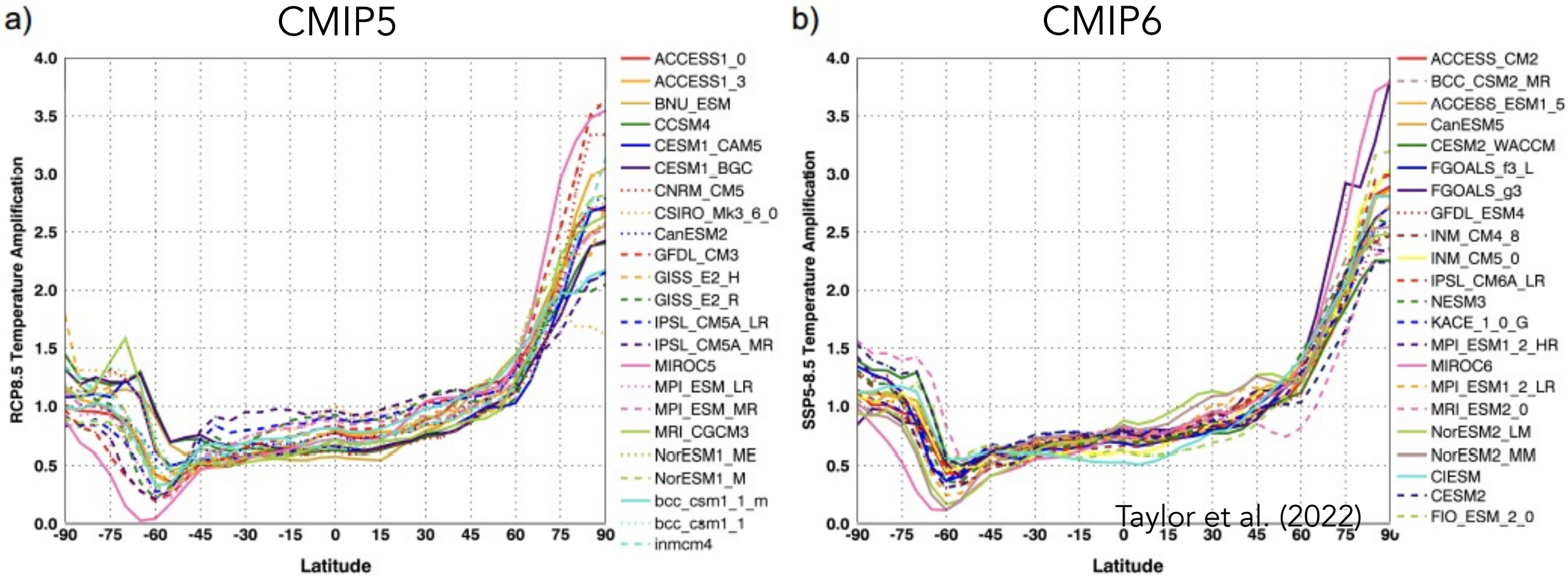
Observational of Arctic Amplification

Arctic Amplification…problem solved?





Arctic climate projection uncertainty



Taylor et al. (2022)

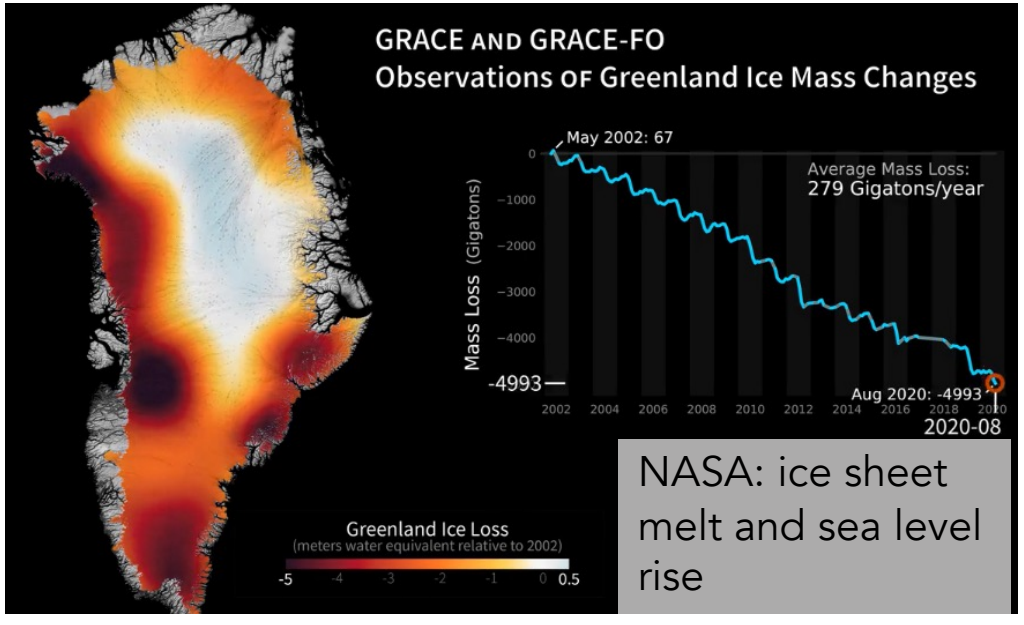
Climate projections differ more in the Arctic than anywhere else.

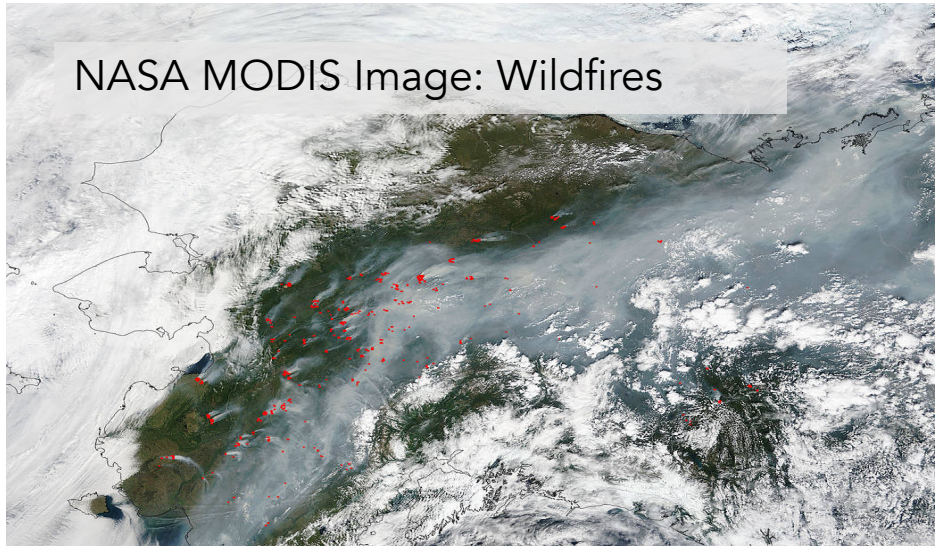
Why do we care…local to global impacts



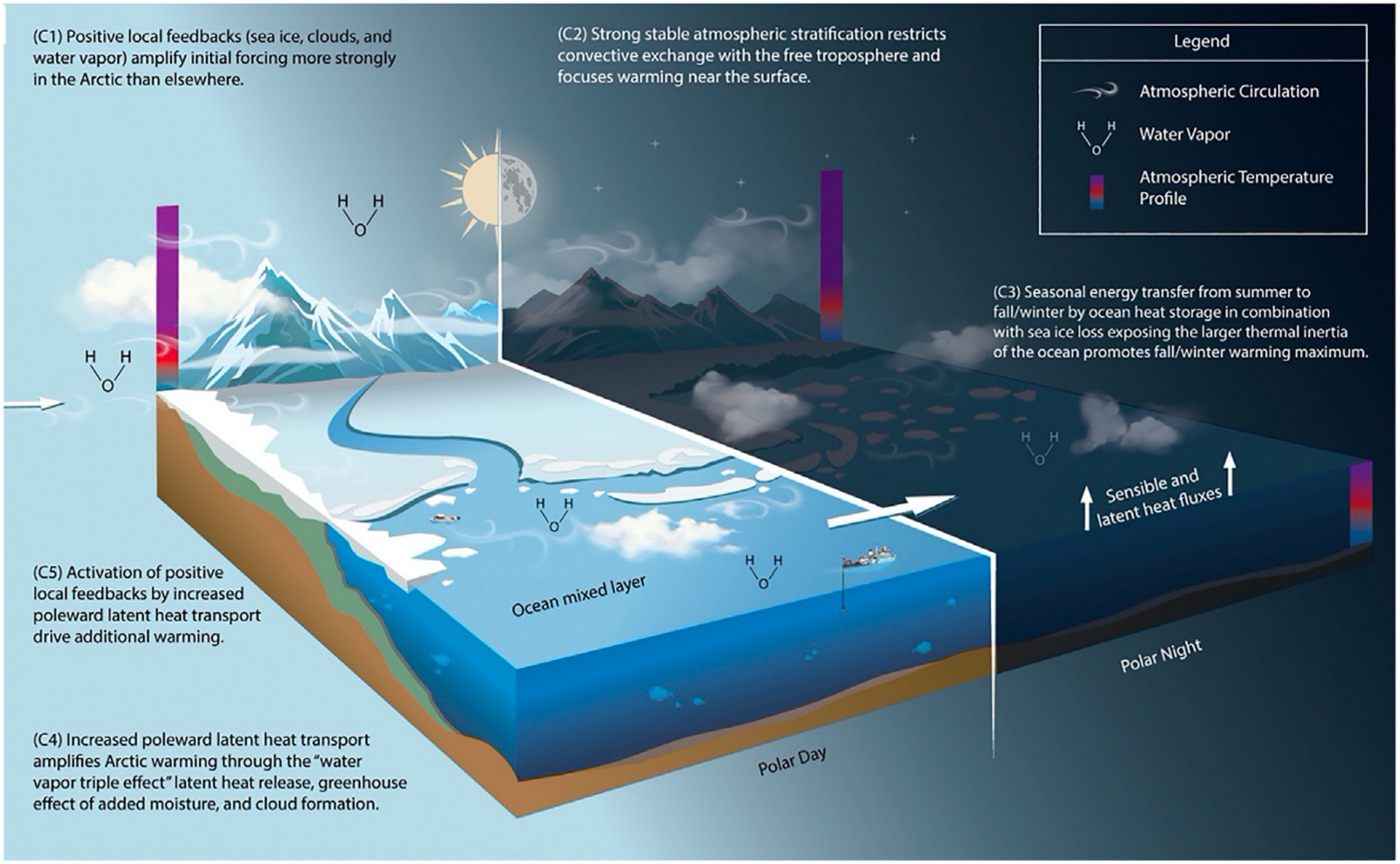








Conceptual model of Arctic Amplification

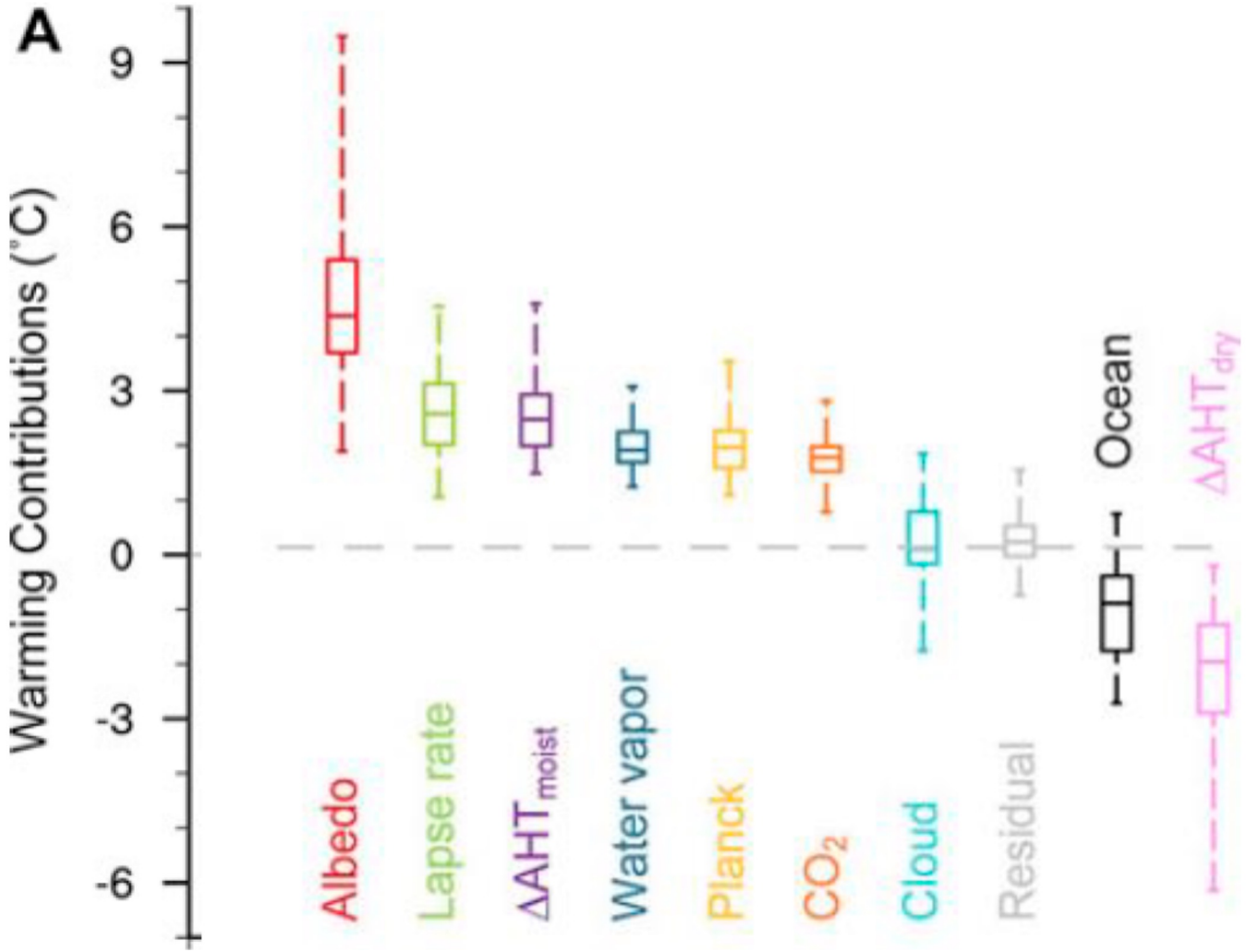


The conceptual model highlights the **need to account for local feedback and remote process interactions** within the context of the annual cycle to constrain the high-end of model projections.

Taylor et al. (2022)

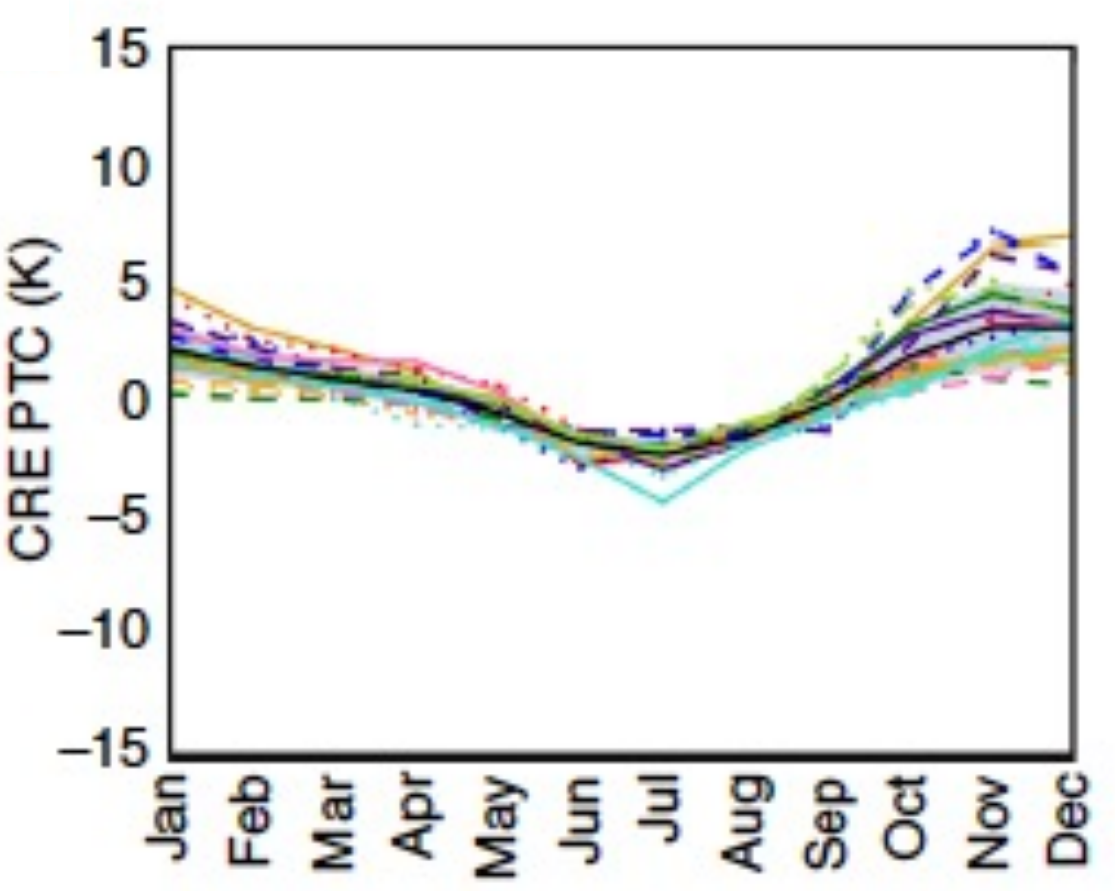
A ranking of feedbacks contributions to Arctic warming

Surface albedo feedback is still the largest factor contributing to the inter-model differences in Arctic warming.



Hahn et al. (2021)

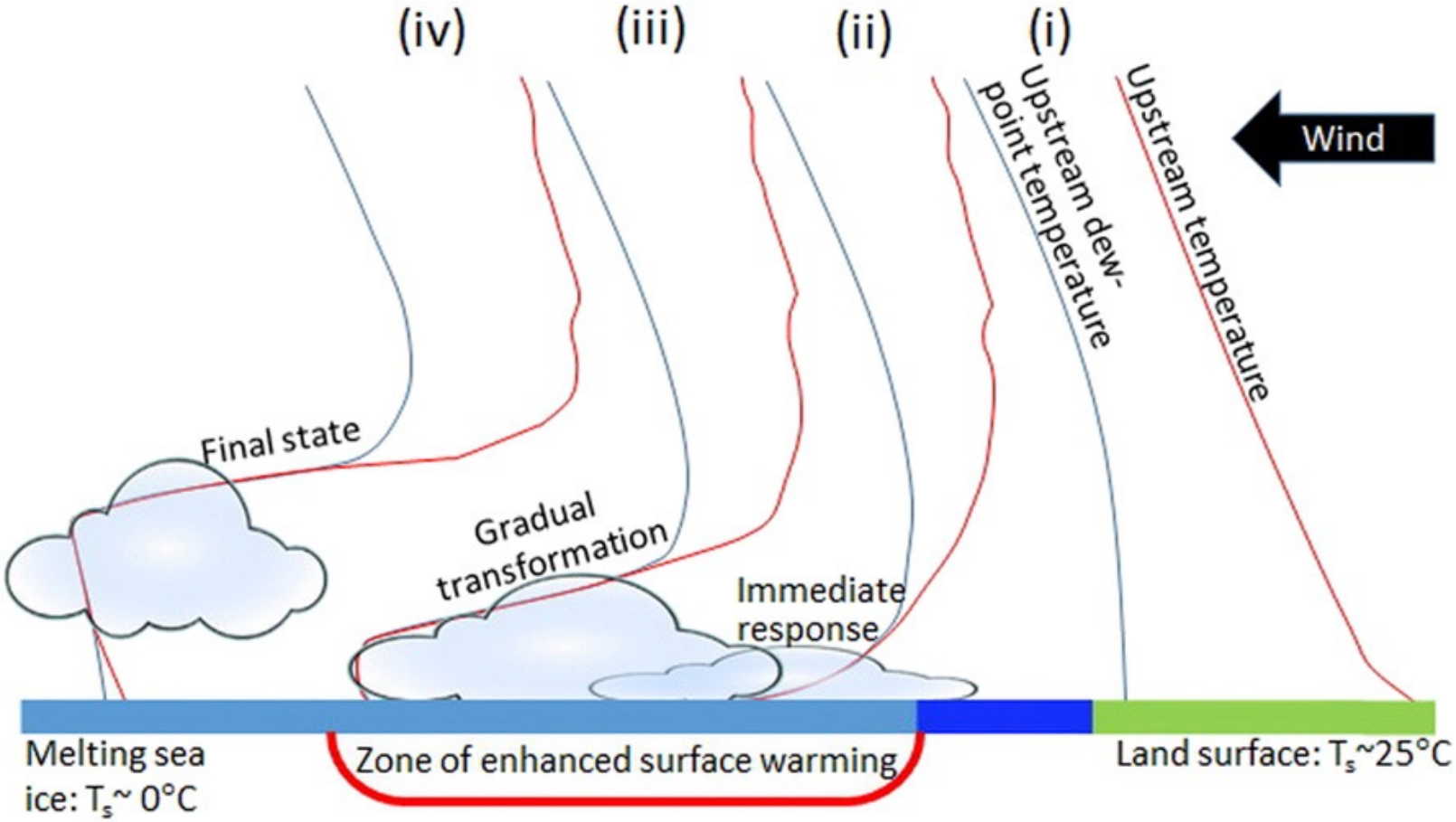
Cloud contributions to Arctic surface warming



- Arctic cloud feedbacks cool the surface in summer and warm the surface in fall and winter.
- Annual mean cloud feedback is a warming.
- The largest inter-model spread is found in fall.

Seasonal structure of the cloud contribution to the seasonal Arctic warming pattern is robust across CMIP5 models.

Airmass transformation in Arctic summer



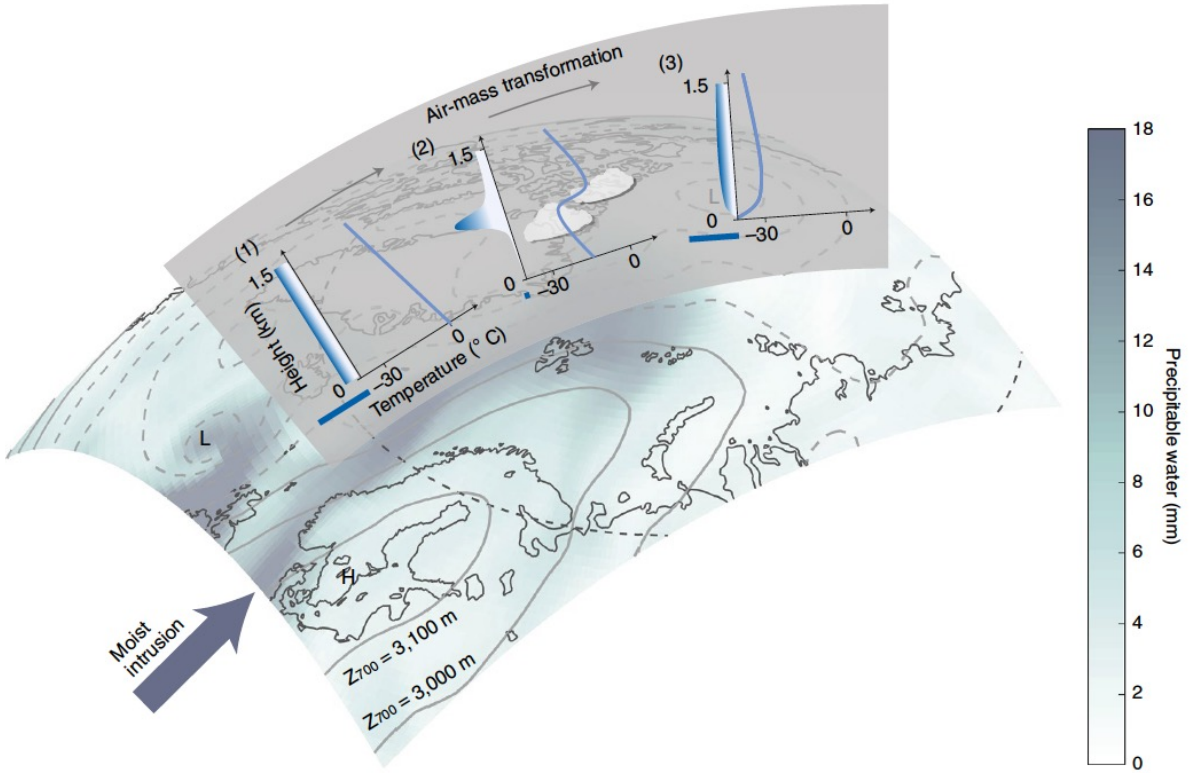
During summer, warm advection from the south leads to a persistent temperature inversion and a fog/low cloud layer the causes a zone of enhanced surface warming, promoted sea ice melt.

Tjernstrom et al. 2019

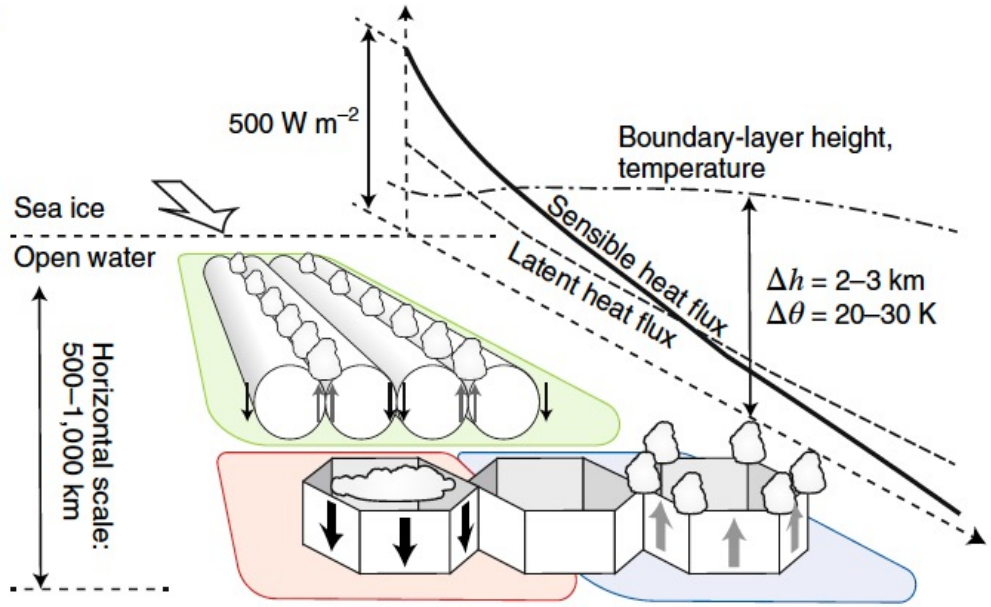
The representation of clouds are central to this process.

Airmass transformations in Arctic winter

Moisture Intrusion/Atmospheric River



Cold Air Outbreak

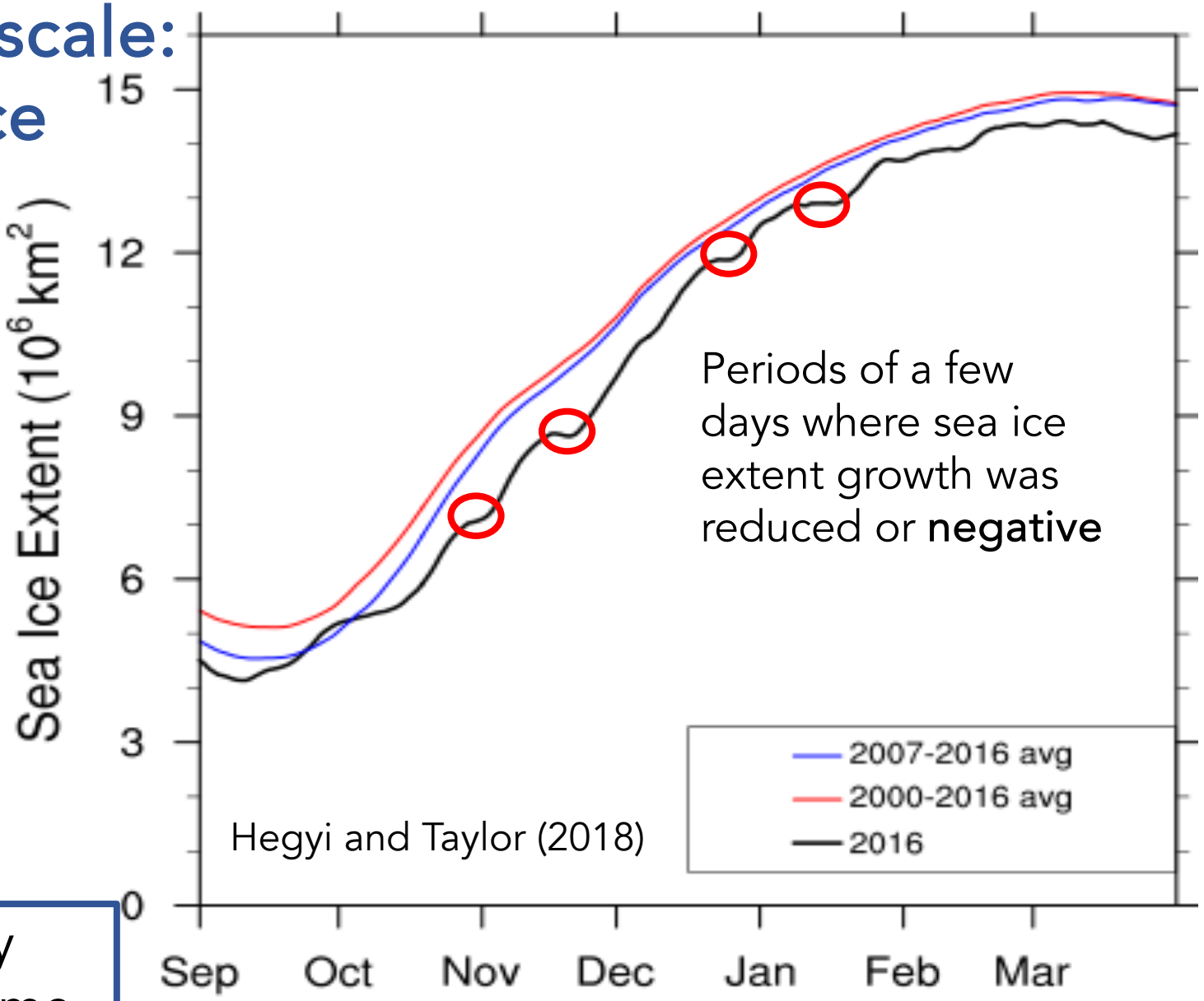


Pithan et al. 2018

Clouds play a central role in the surface energy budget and sea ice response to these events.

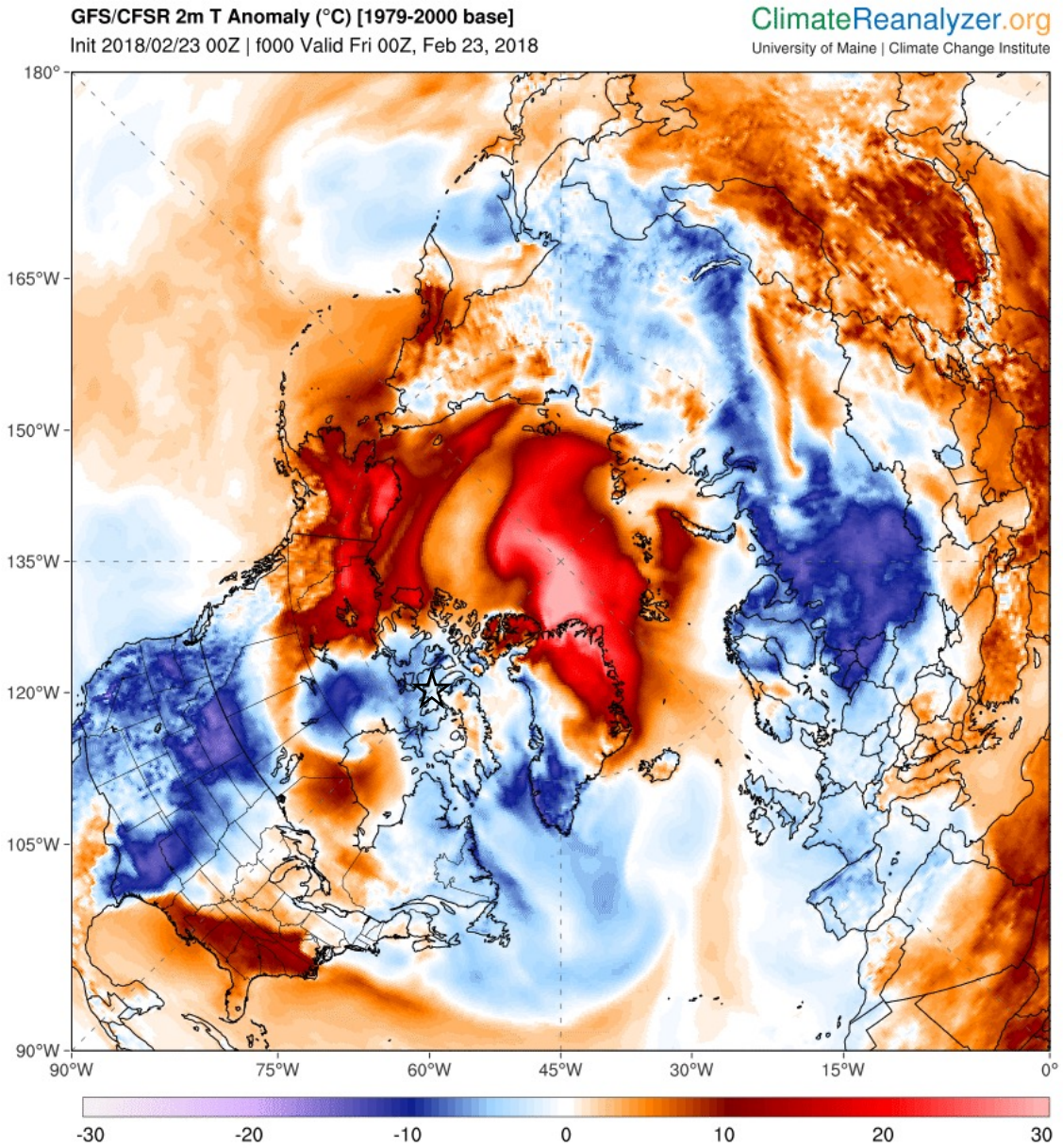
Synoptic to climate times scale: Sea ice as a memory source

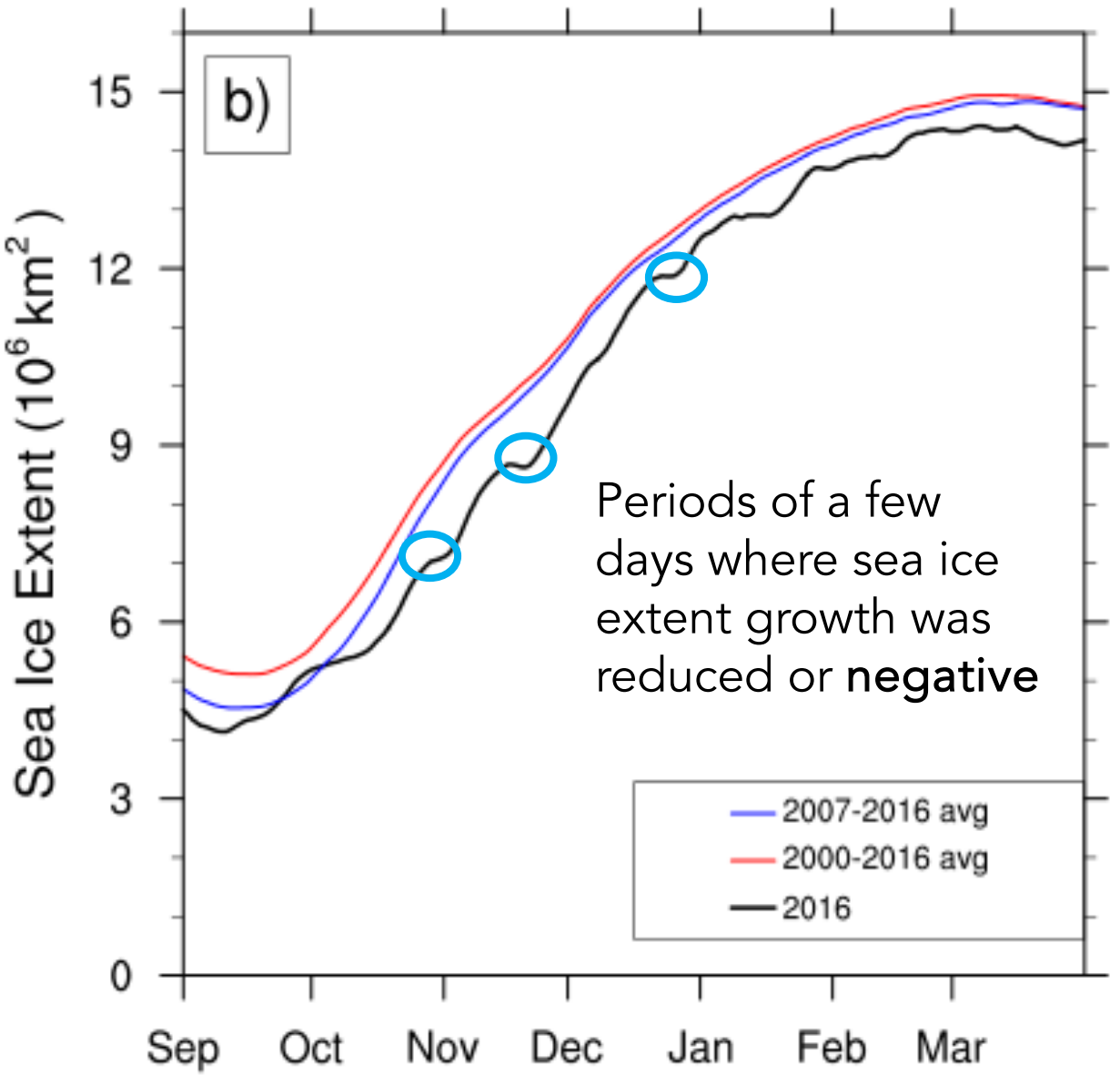
The 2016-17 sea ice growth season exhibited several periods of reduced or negative sea ice extent growth between October-March and each event corresponded to a substantial moisture intrusion.



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

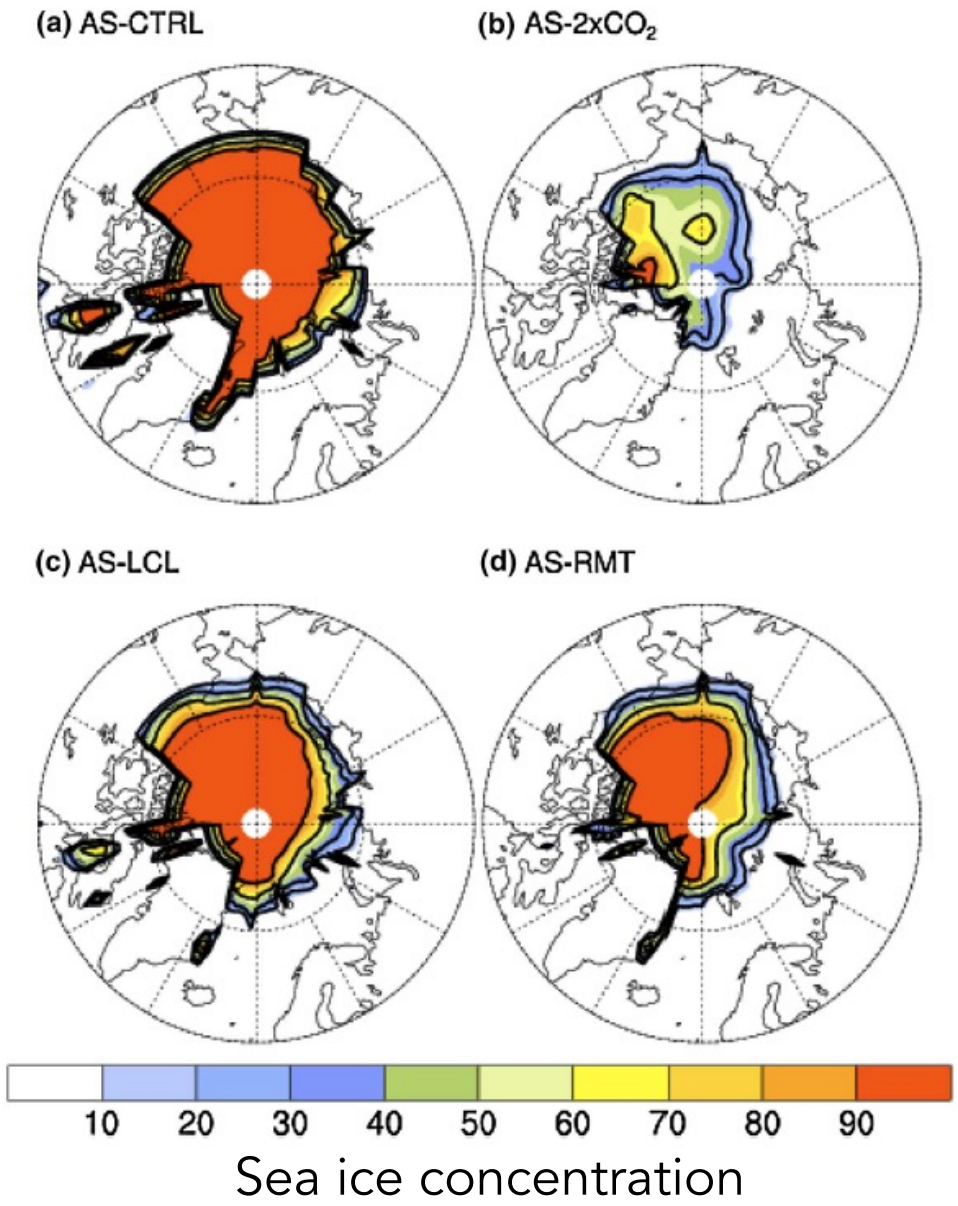
What do remote heat transport look like?





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

Remote process and local feedback interactions



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)

Controls on Arctic clouds

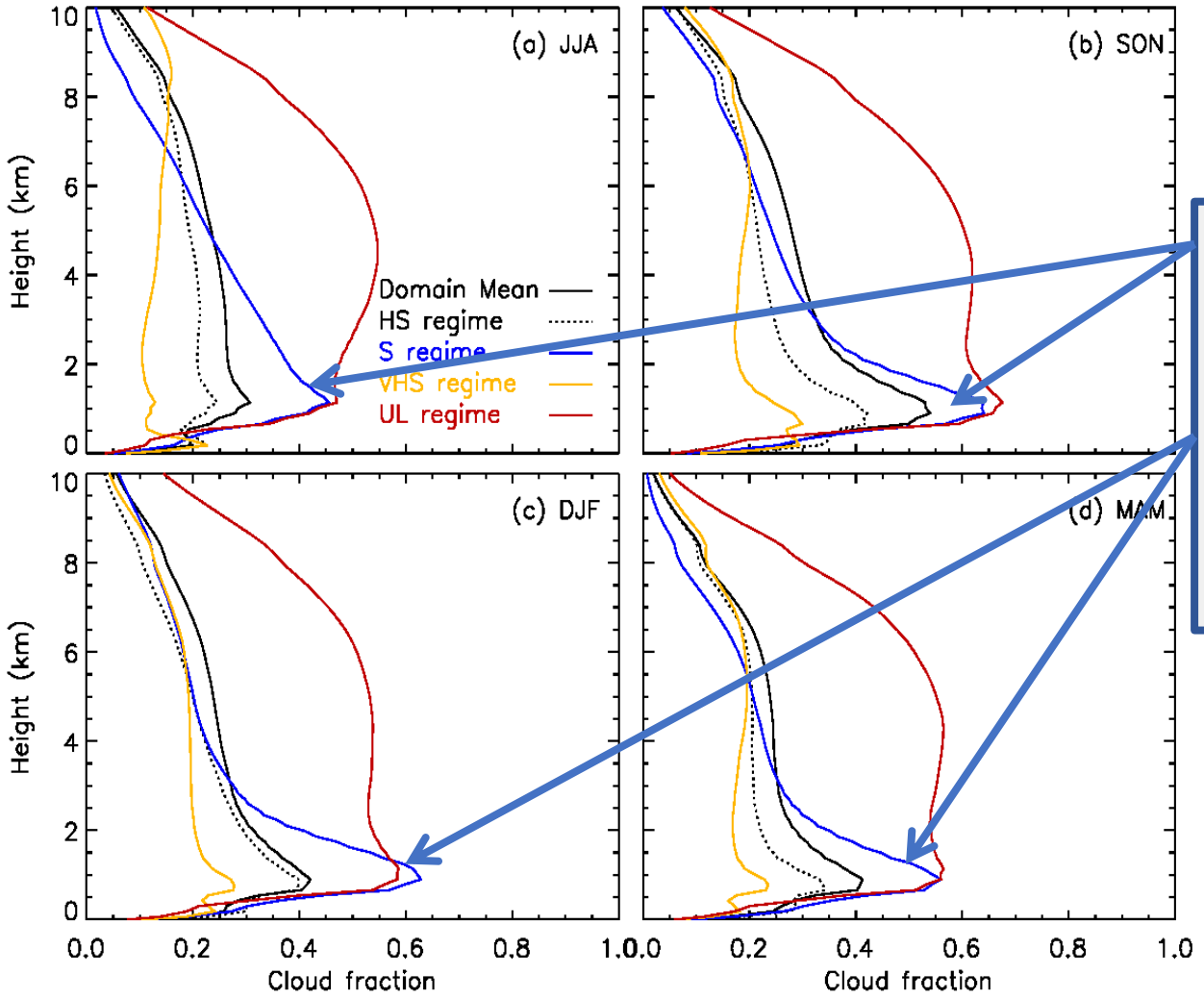
Meteorological controls on Arctic cloud properties

High Stability (HS):
16 K < LTS < 24 K

Stable (S):
LTS < 16 K

Very High Stability (VHS): LTS > 24 K

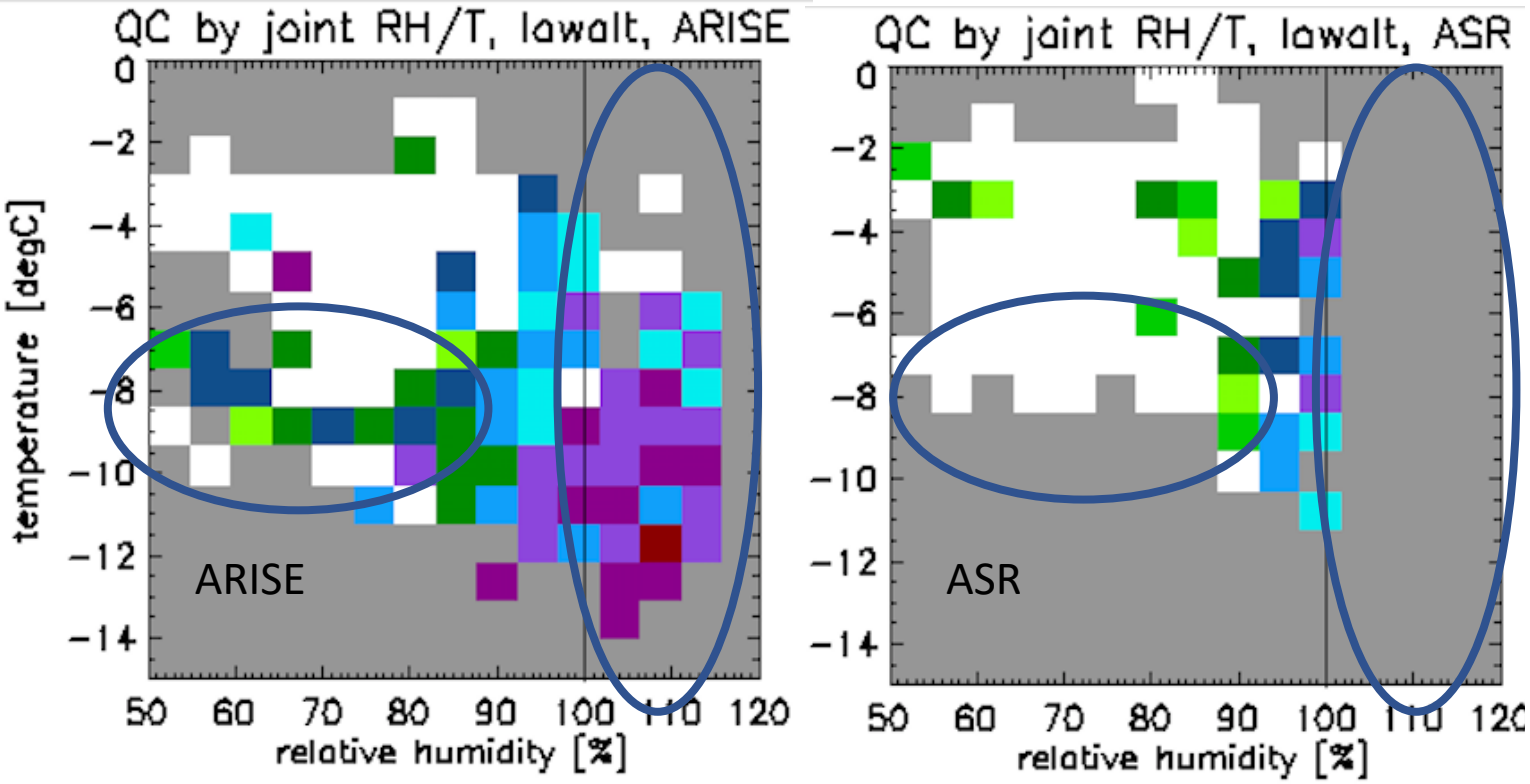
Uplift (UL): ω_{500} < -0.1 Pa s^{-1}



A decrease in the magnitude and height of the maximum cloud fraction is found as LTS increases.

Meteorology places a strong constraint on cloud properties.

Model cloud biases by regime

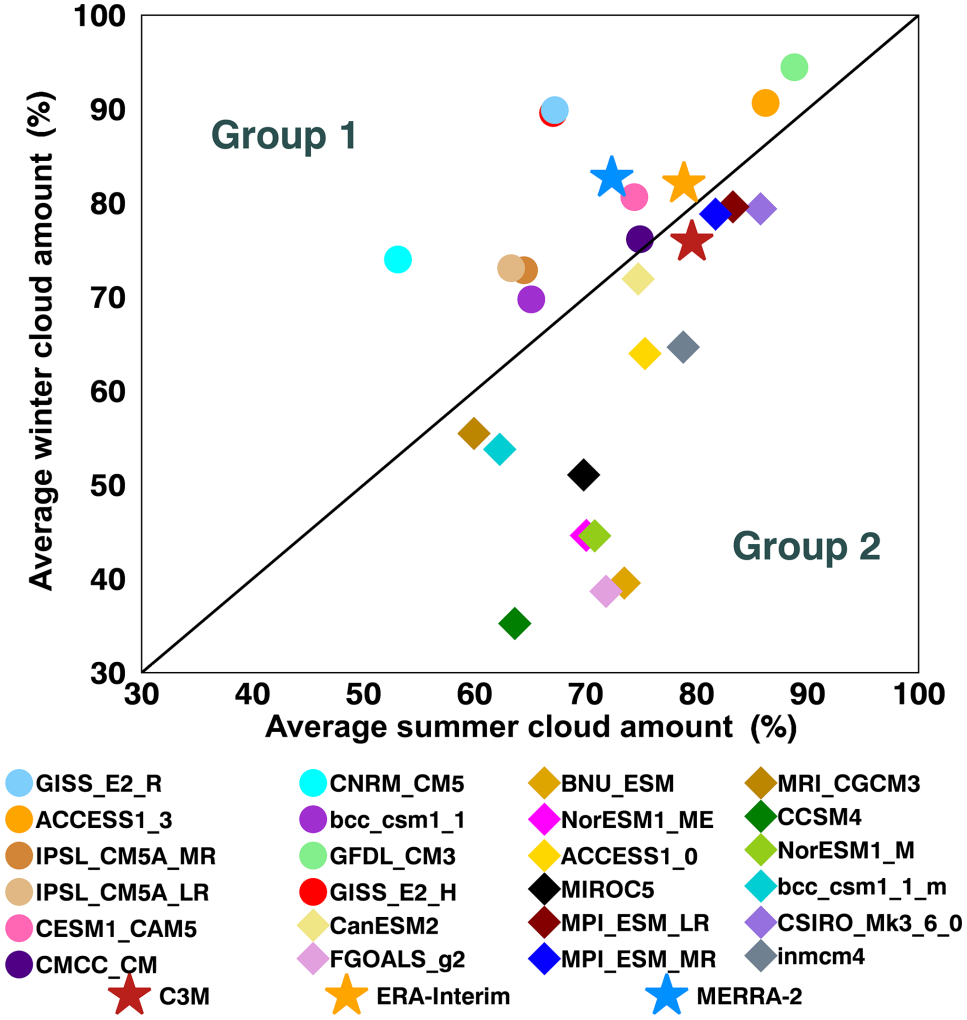


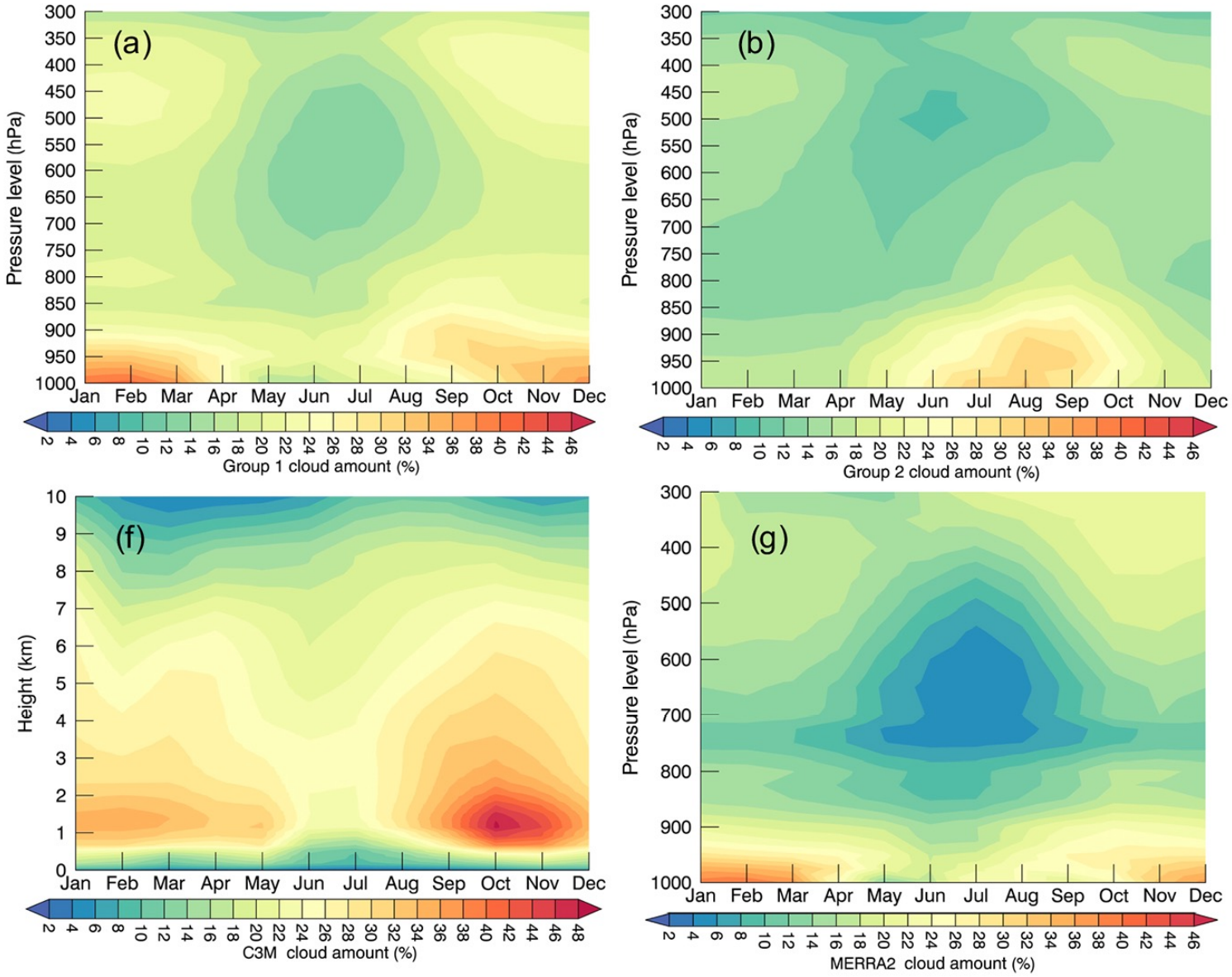
An important lesson: when comparing in situ airborne data and model output, do not restrict the comparison to flight-track-only model output. The results benefit from greater statistics.

The comparison with airborne in situ measurements reveals several shortcomings of the model cloud parameterizations:

- Produces less total and liquid cloud water.
- Is warmer and drier than observations.
- Produces cloud water over a narrower range of thermodynamic conditions.
- 2/3 of the differences are attributed to errors in the cloud-thermodynamic state relationships.

Model Biases: Seasonal cycle of Arctic cloud amount

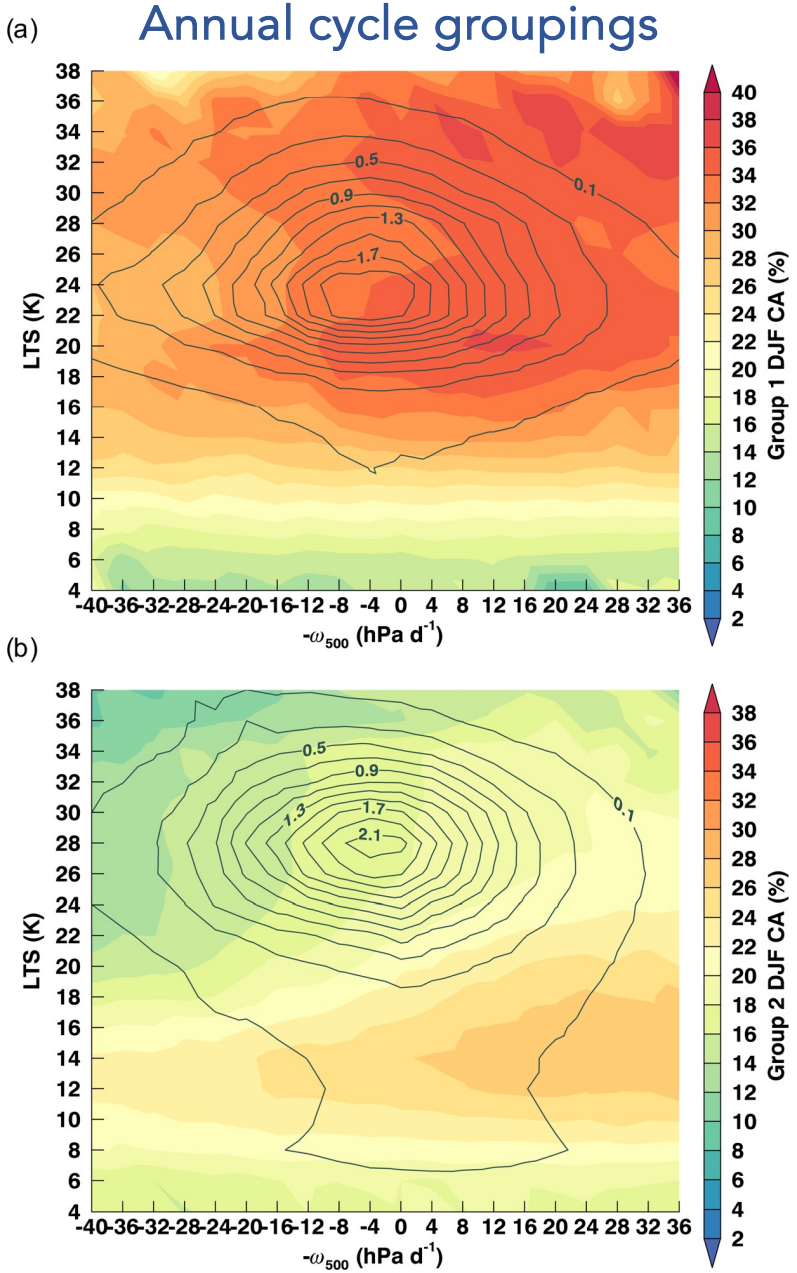




Stratified CMIP5 models into 2 groups: Group 1 winter cloud peak and Group 2 summer cloud peak.

Model Biases: Seasonal cycle of Arctic low cloud amount

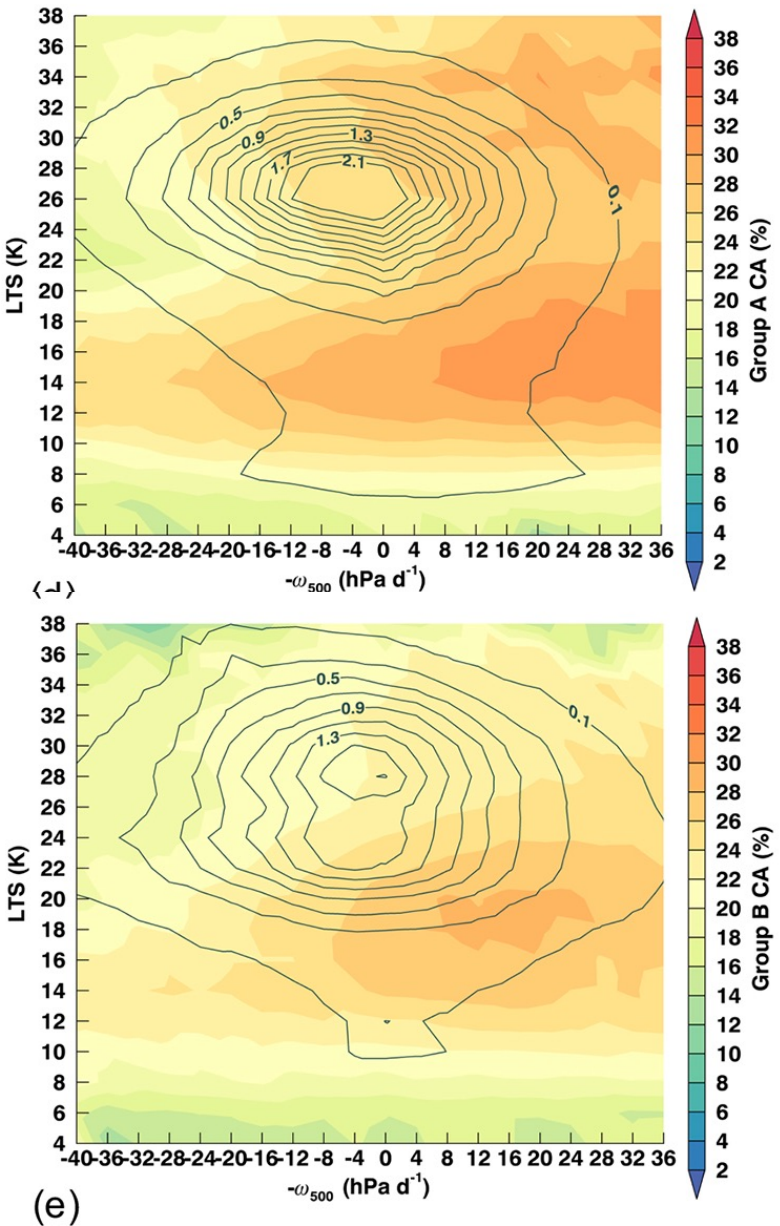
Annual cycle groupings



Results show:

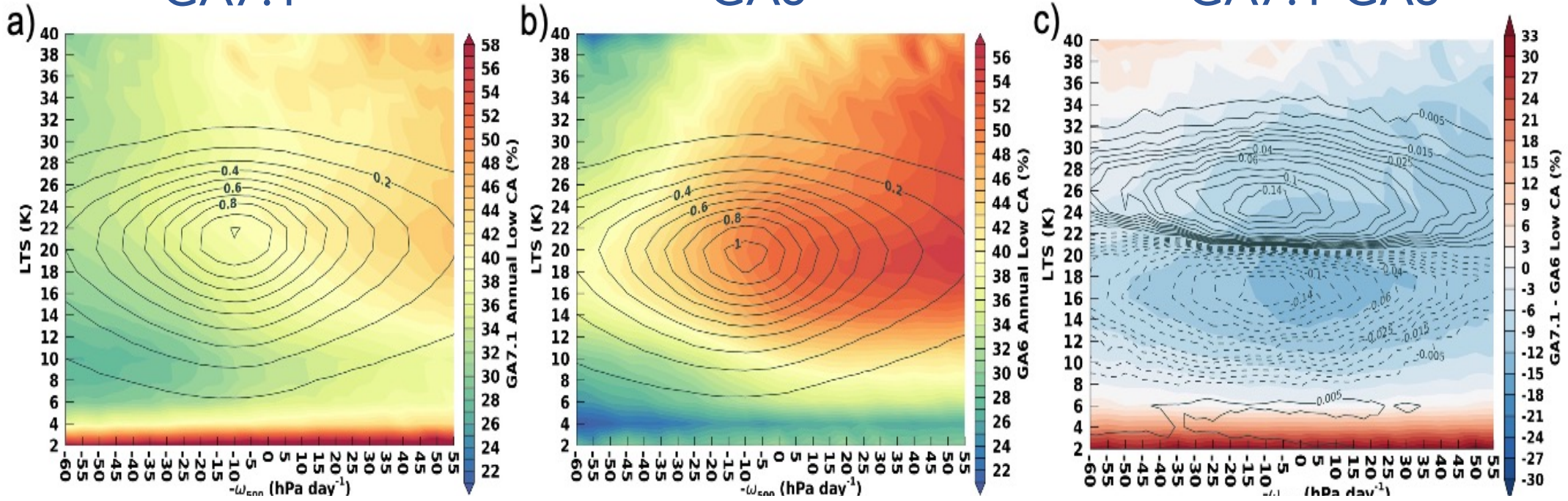
- Intergroup differences are a function of LTS
- Models with greater LCA in winter have great cloud ice, models with greater LCA in summer have less cloud ice
- Stratifying by cloud phase partitioning method=>models with a prognostic liquid and ice condensate scheme simulate greater winter clouds.
- Cloud phase partitioning matters to the annual cycle.

Phase partitioning groupings



Influence of parameterization changes on Arctic clouds

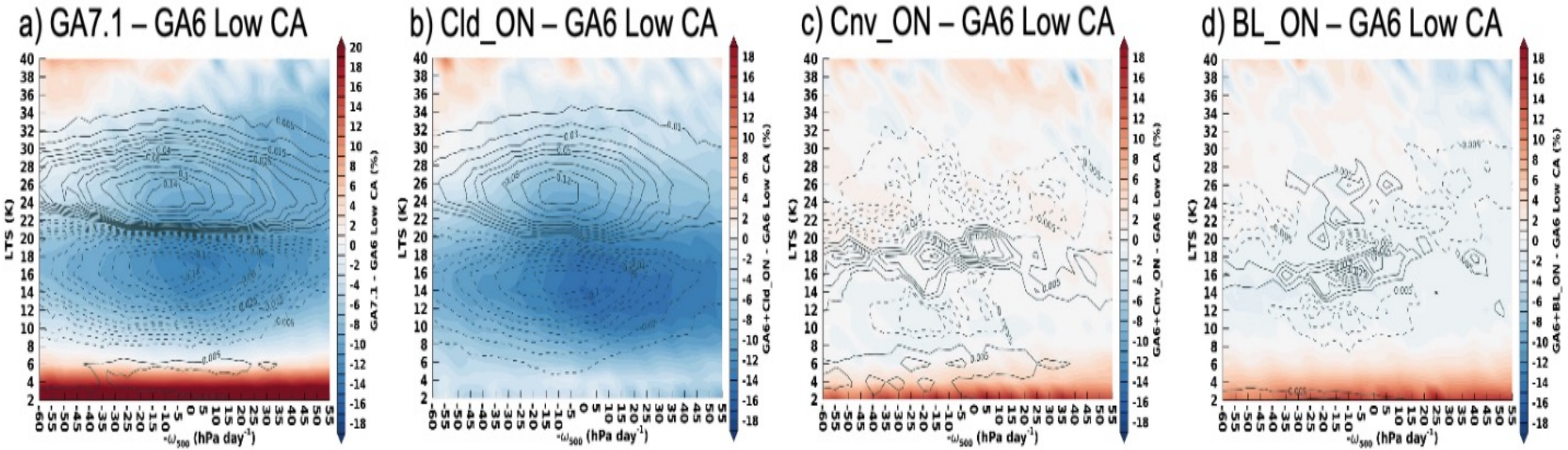
GA7.1 | GA6 | GA7.1-GA6



In this study we are asking:

- What parameterizations are most important to causing the cloud changes?
- How is the influence of parameterization changes distributed by meteorological regime?
- What can we learn about modeling or observing clouds?

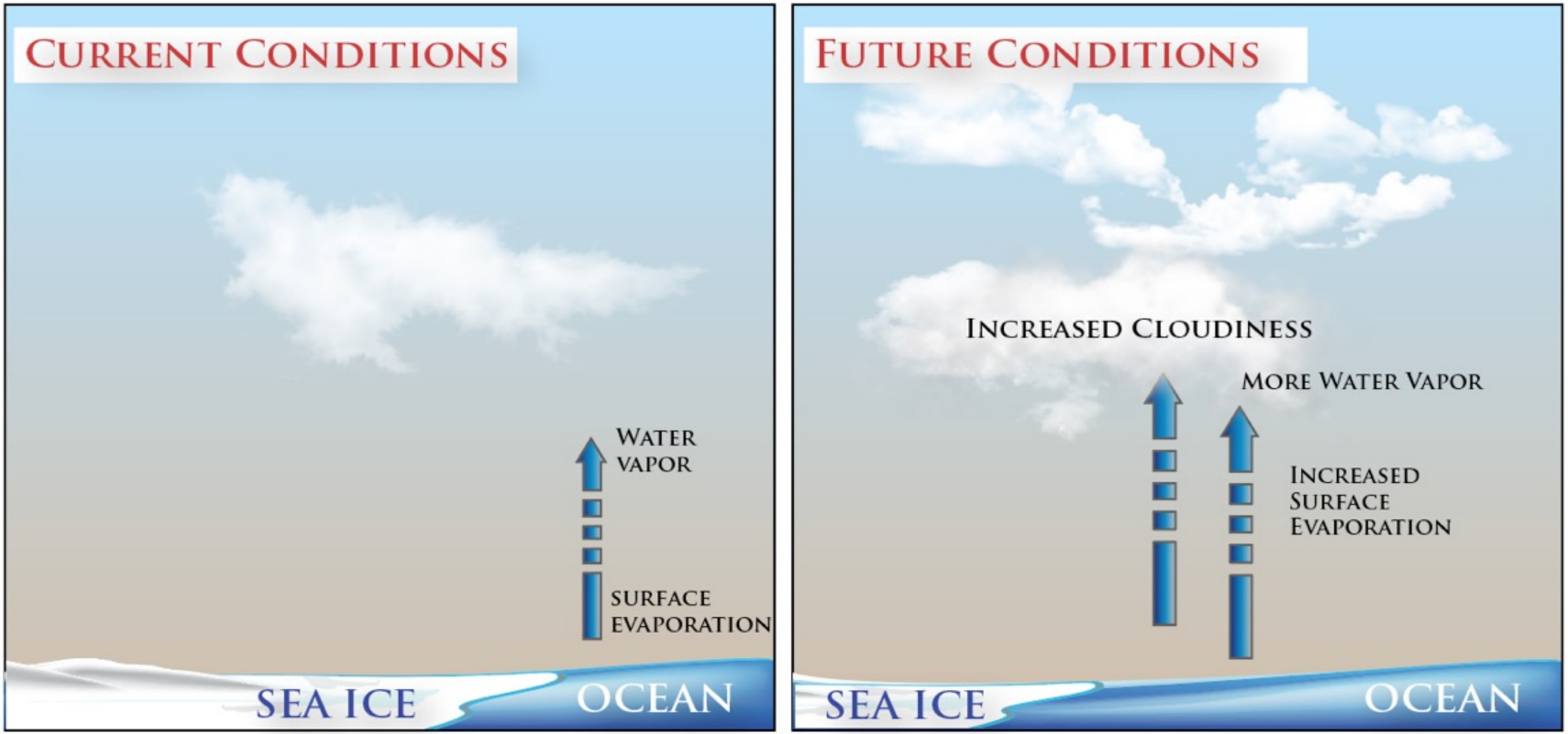
Influence of parameterization changes on Arctic clouds: On_experiments



- With "On_experiments," we determine the influence of parameterization packages changes on cloud properties within meteorological regimes.
- For cloud properties, most changes are caused by single parameterizations
- For CREs, multiple parameterization changes have effects, **including non-cloud schemes.**

Arctic low-cloud sea ice interactions

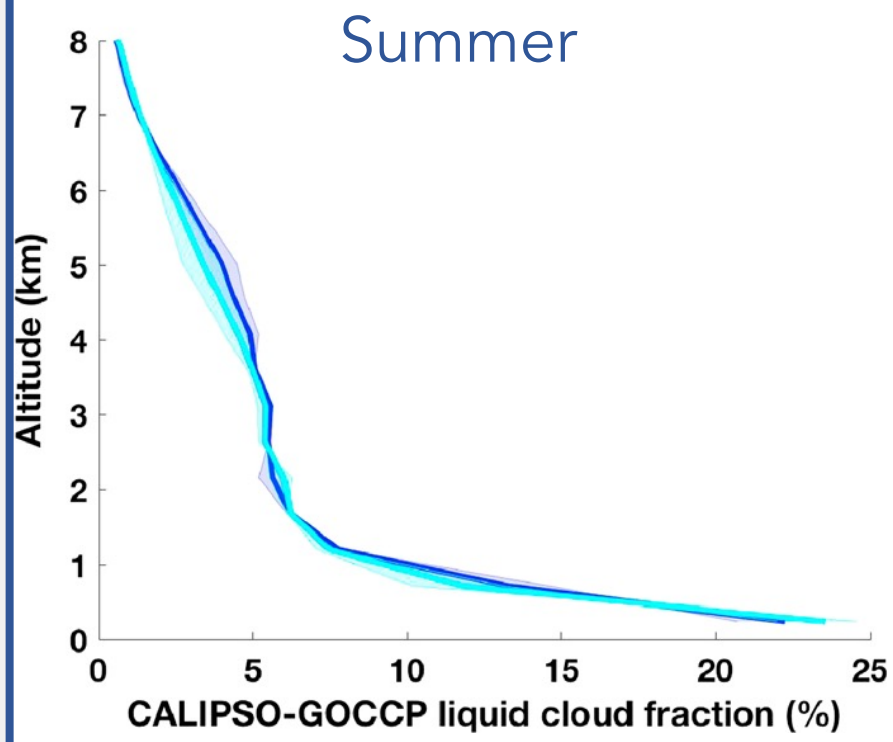
How Might Clouds Respond to Less Sea Ice In the Arctic?

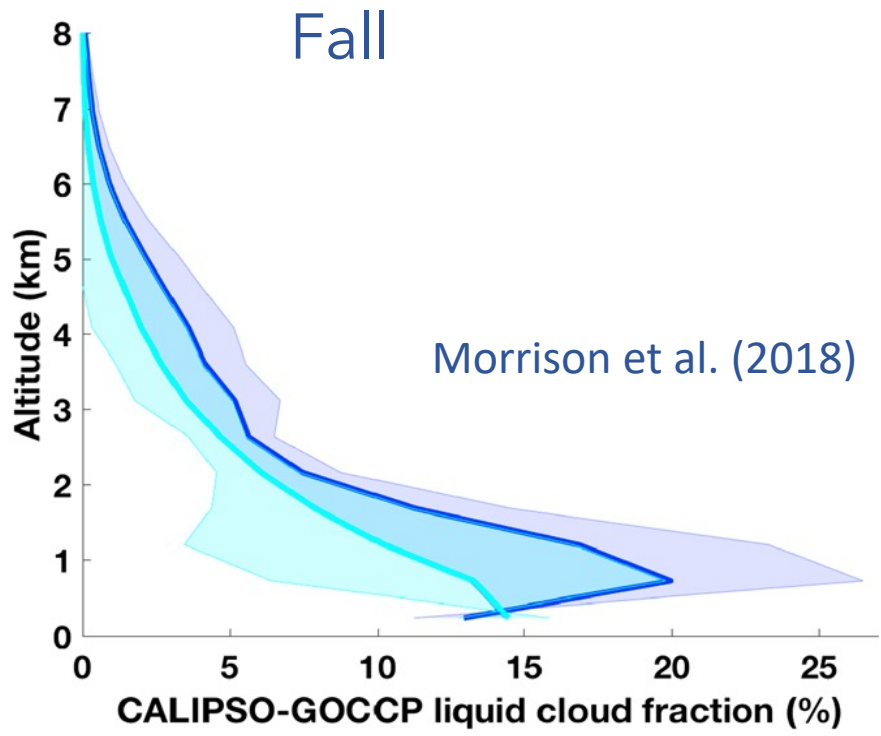


Is there consensus of how cloud feedbacks influence Arctic climate change projection uncertainty?

Morrison et al. (2018) illustrates the general consensus in the literature.

- No impact of surface type on summer clouds.
- Larger low cloud amount over ice-free ocean than sea ice.



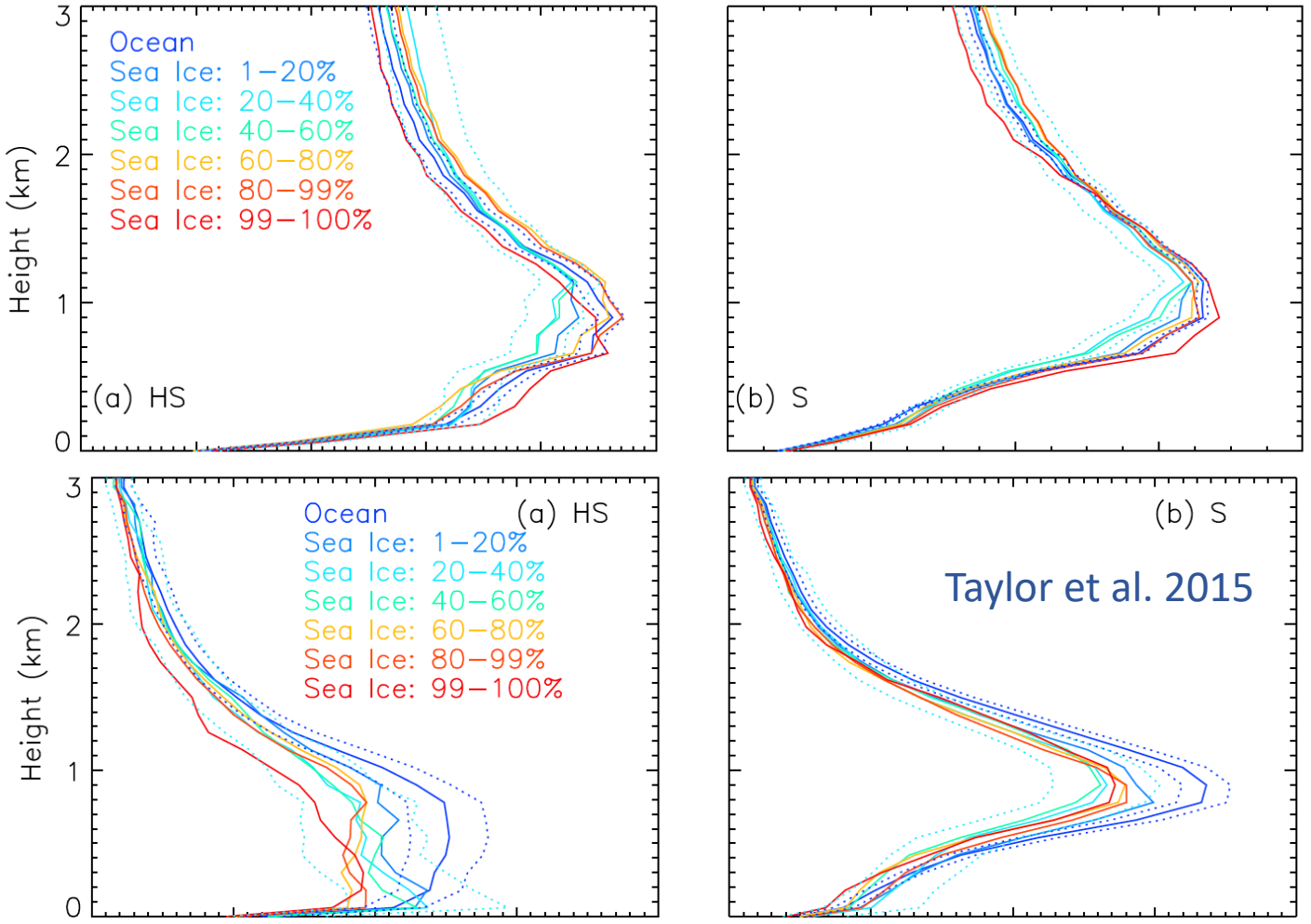


Morrison et al. (2018)

Other studies: Kay and Gettelman (2009) Barton et al. (2012), Taylor et al. (2015), Huang et al. (2017), Yu et al. (2019), Boeke and Taylor (2018)

Stratifying cloud properties by sea ice within meteorological regimes

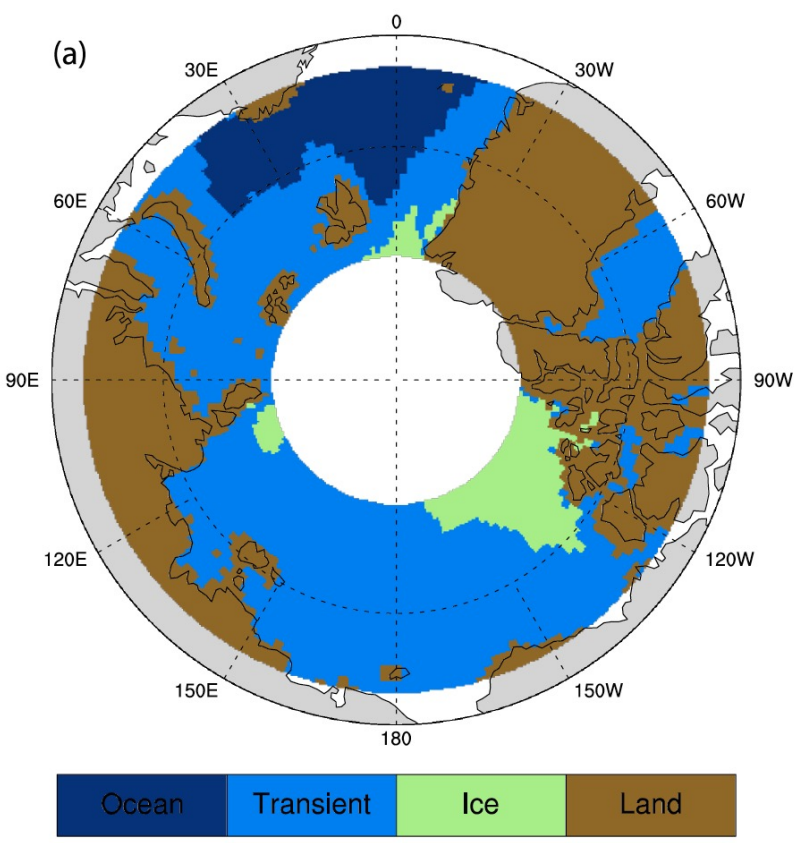
- With satellite footprint-level data CALIPSO/CloudSat (instead of monthly means)
- Cloud properties are stratified by
  - Meteorological regime using thresholds of lower tropospheric stability and mid-tropospheric vertical velocity, and
  - Sea ice concentration
- The largest-magnitude cloud-sea ice covariance occurs between 500m and 1.2 km when the lower tropospheric stability is between 16 and 24 K.



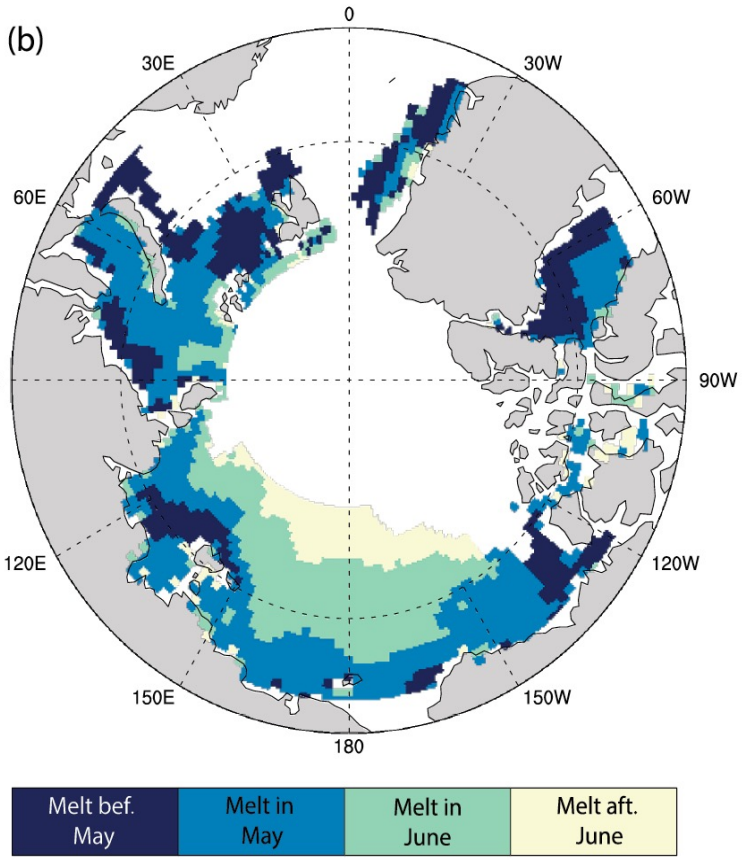
Largest cloud property differences are found in the high stability regime in fall and are accompanied by significant changes in boundary layer temperature structure.

Cloud LWP covariance to surface types and melt and freeze onset

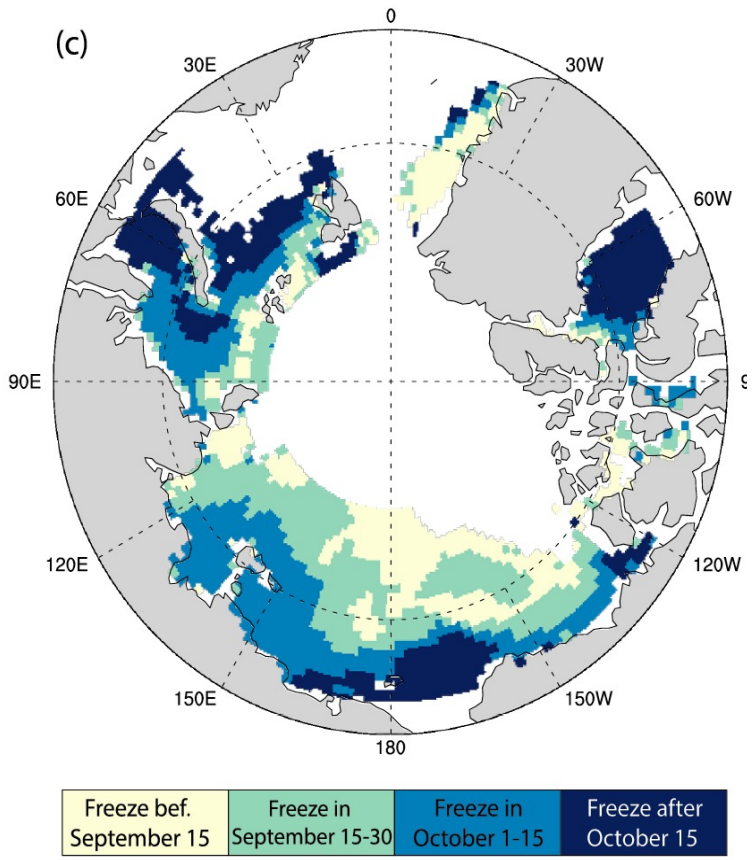
Sea ice types



Melt Onset Dates



Freeze Onset Dates

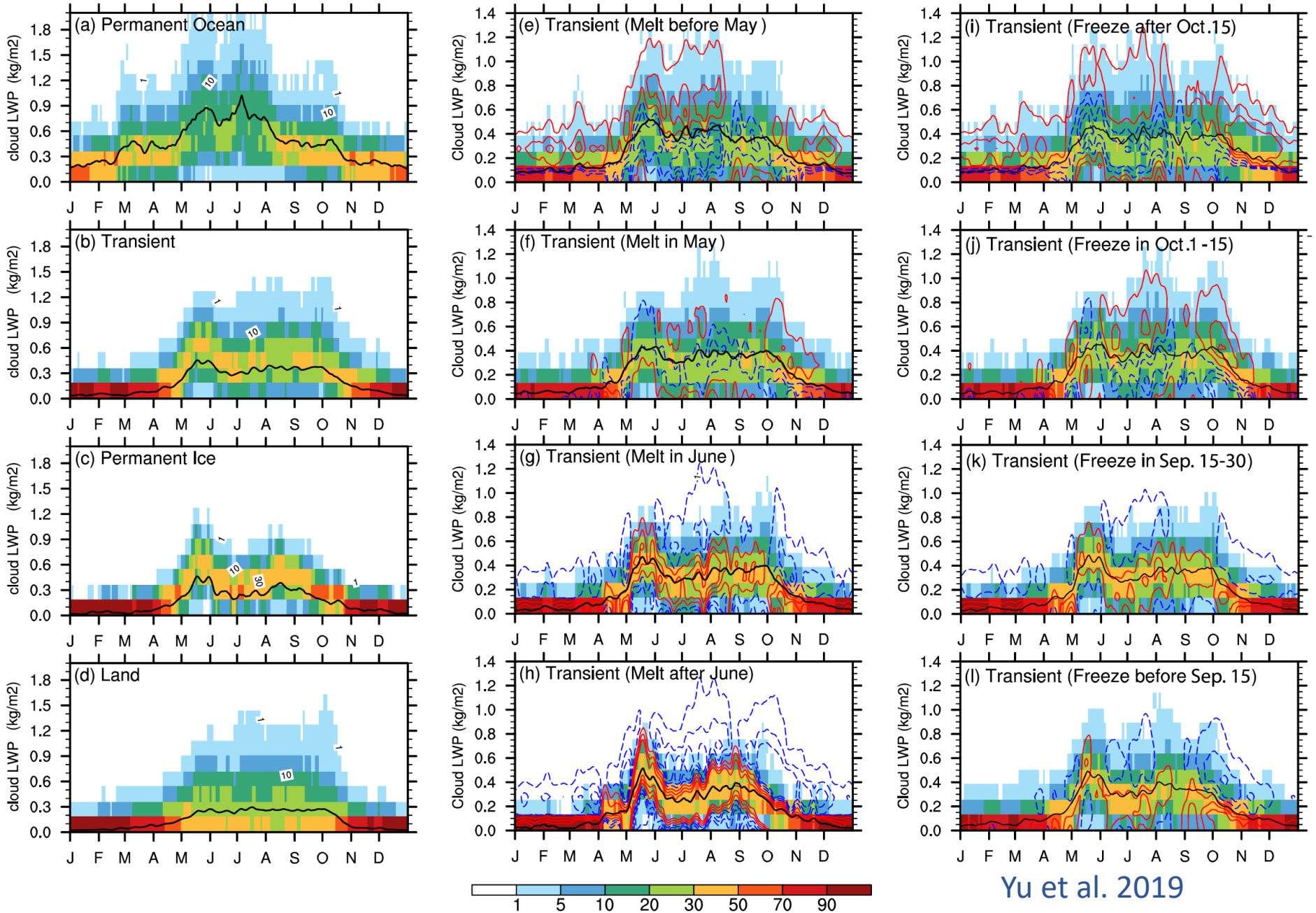


Yu et al. 2019

Stratification surface type and melt and freeze onset dates provides a means to isolate the surface influence relative to the meteorological influence.

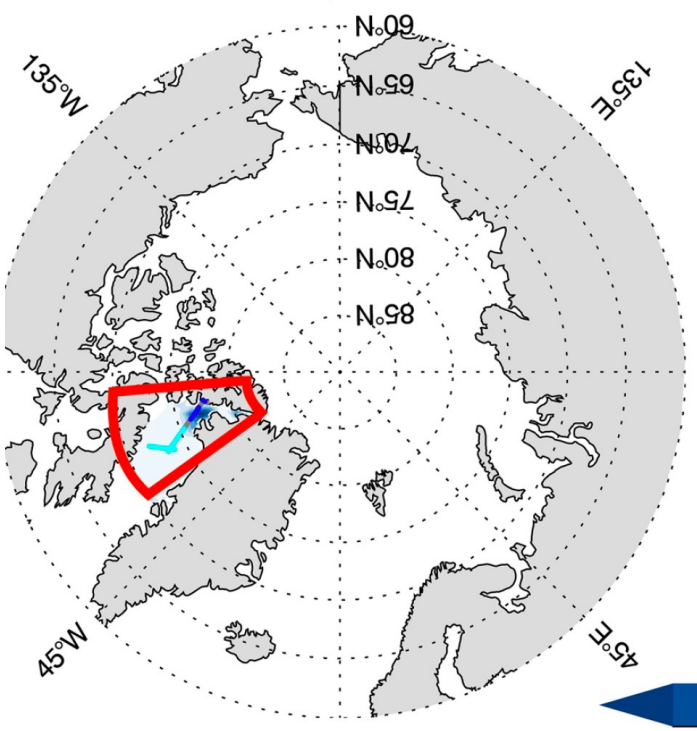
Cloud LWP covariance to sea ice types and melt and freeze onset

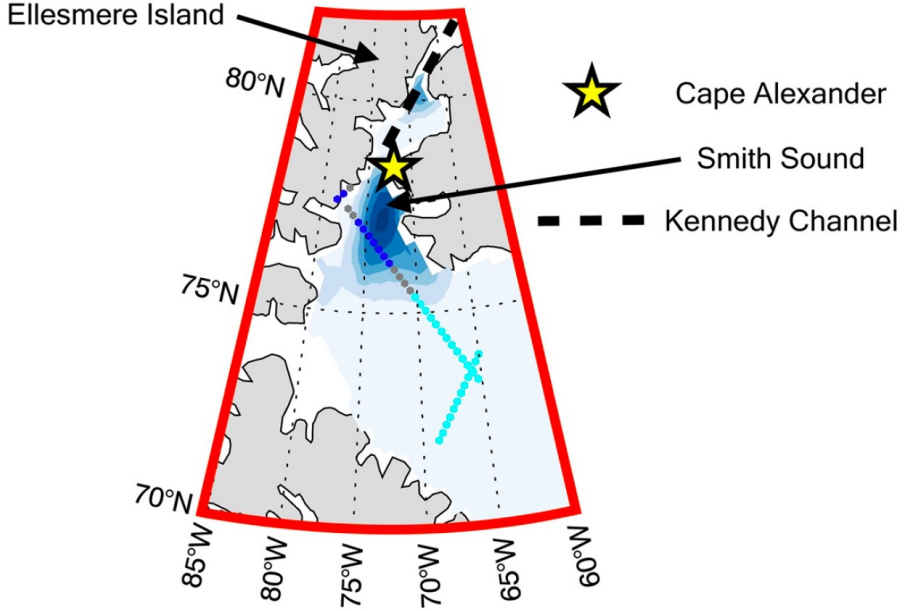
- We find significant variations in low-level cloud LWP by surface type.
- May LWP peak does not shift with melt onset date.
- Fall LWP peak follows the freeze onset date.

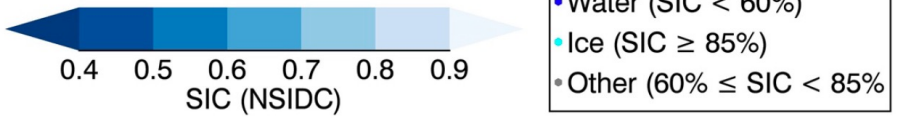


Yu et al. 2019

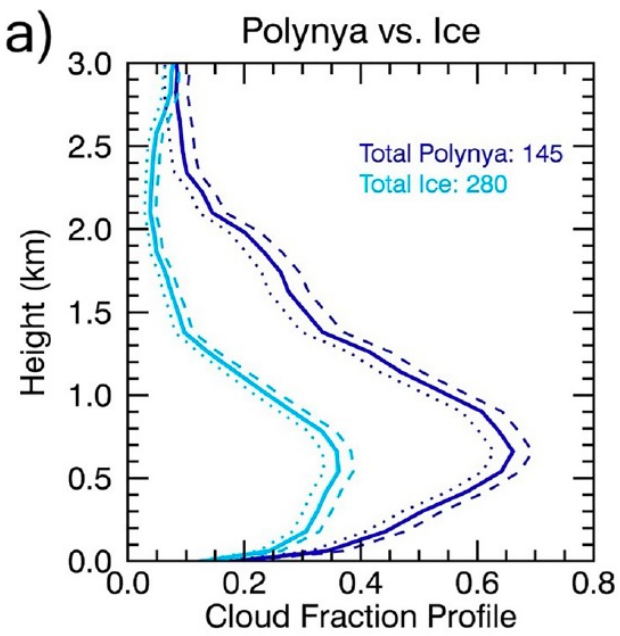
Low-cloud response to the North Water Polynya: a natural laboratory









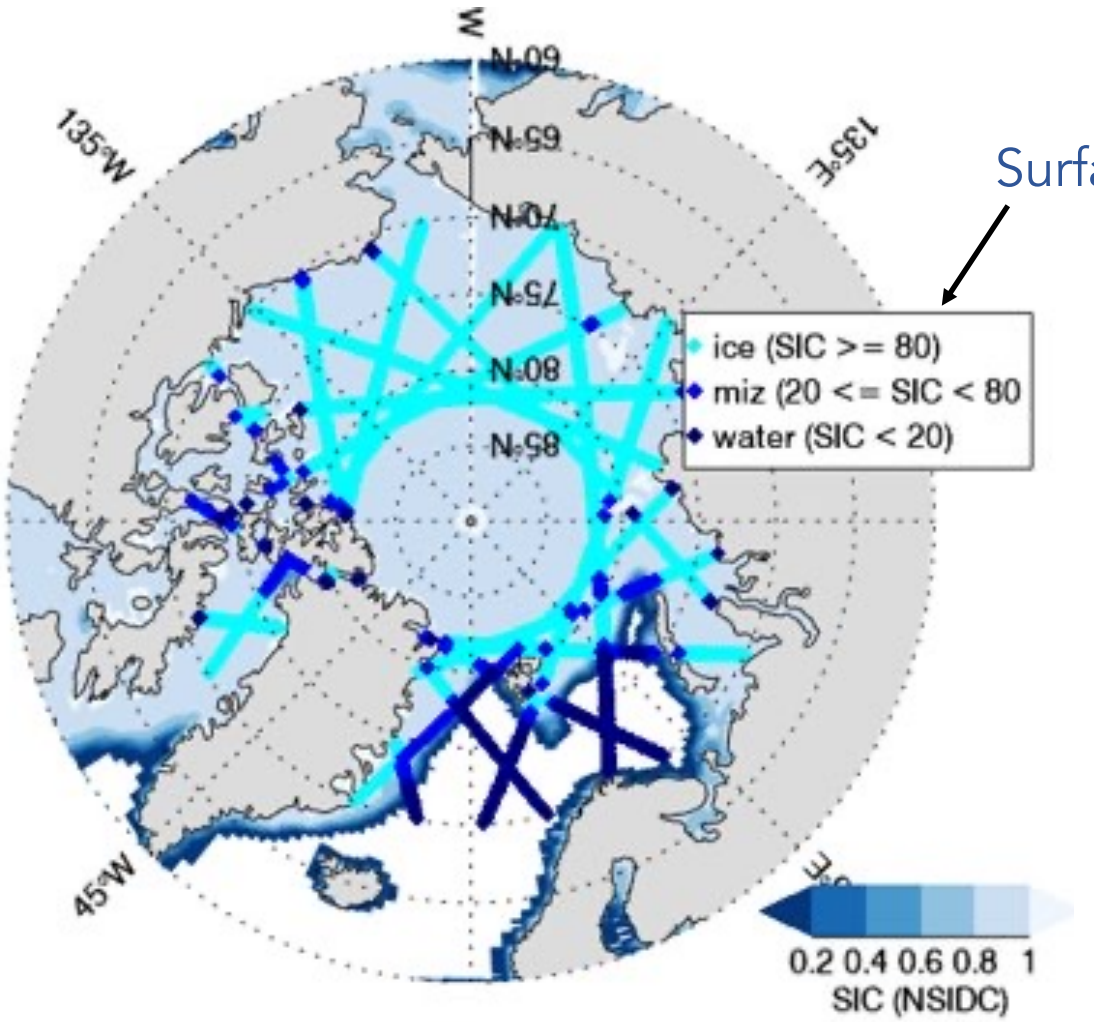


Our results show that over the polynya compared to nearby ice:

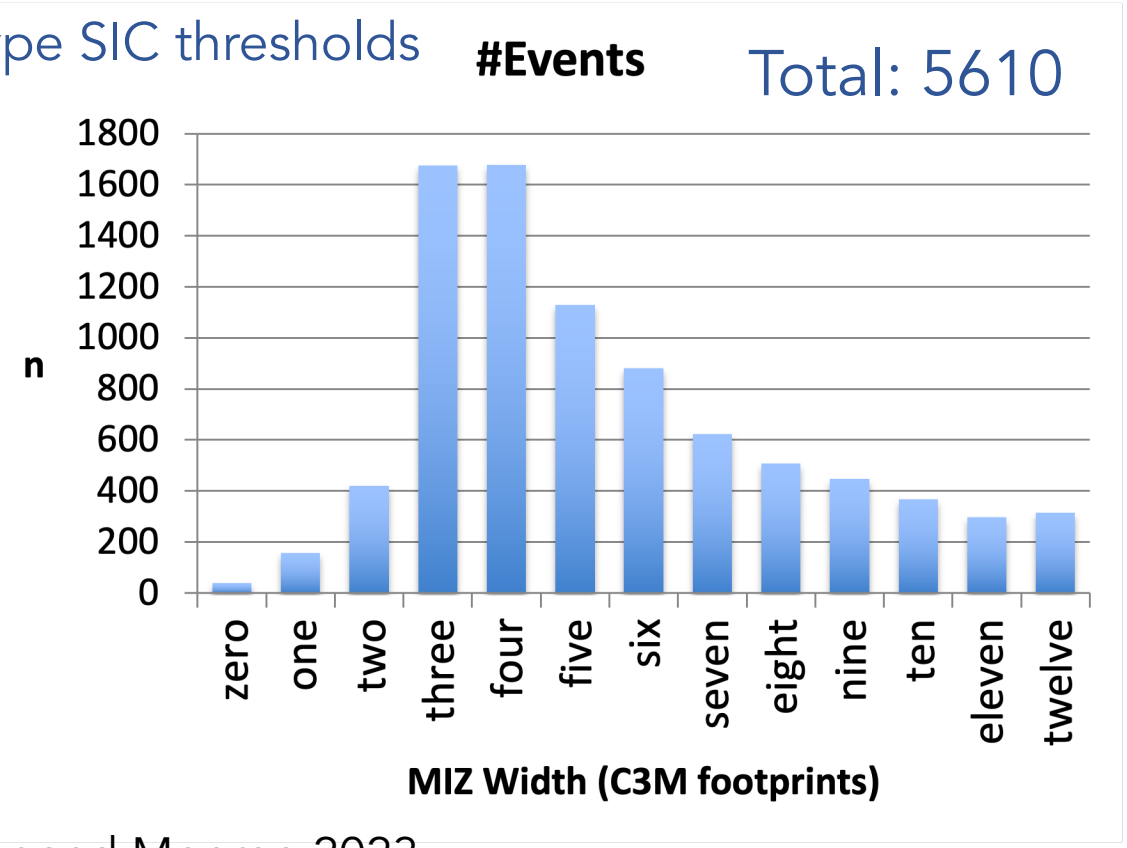
- Low-cloud cover is 10%–33% larger
- Cloud liquid water content is up to 400% larger; and,
- Surface cloud radiative effect is 18 W m−2 larger

Monroe et al 2021

Leveraging Marginal Ice Zone Crossing Events



Surface Type SIC thresholds

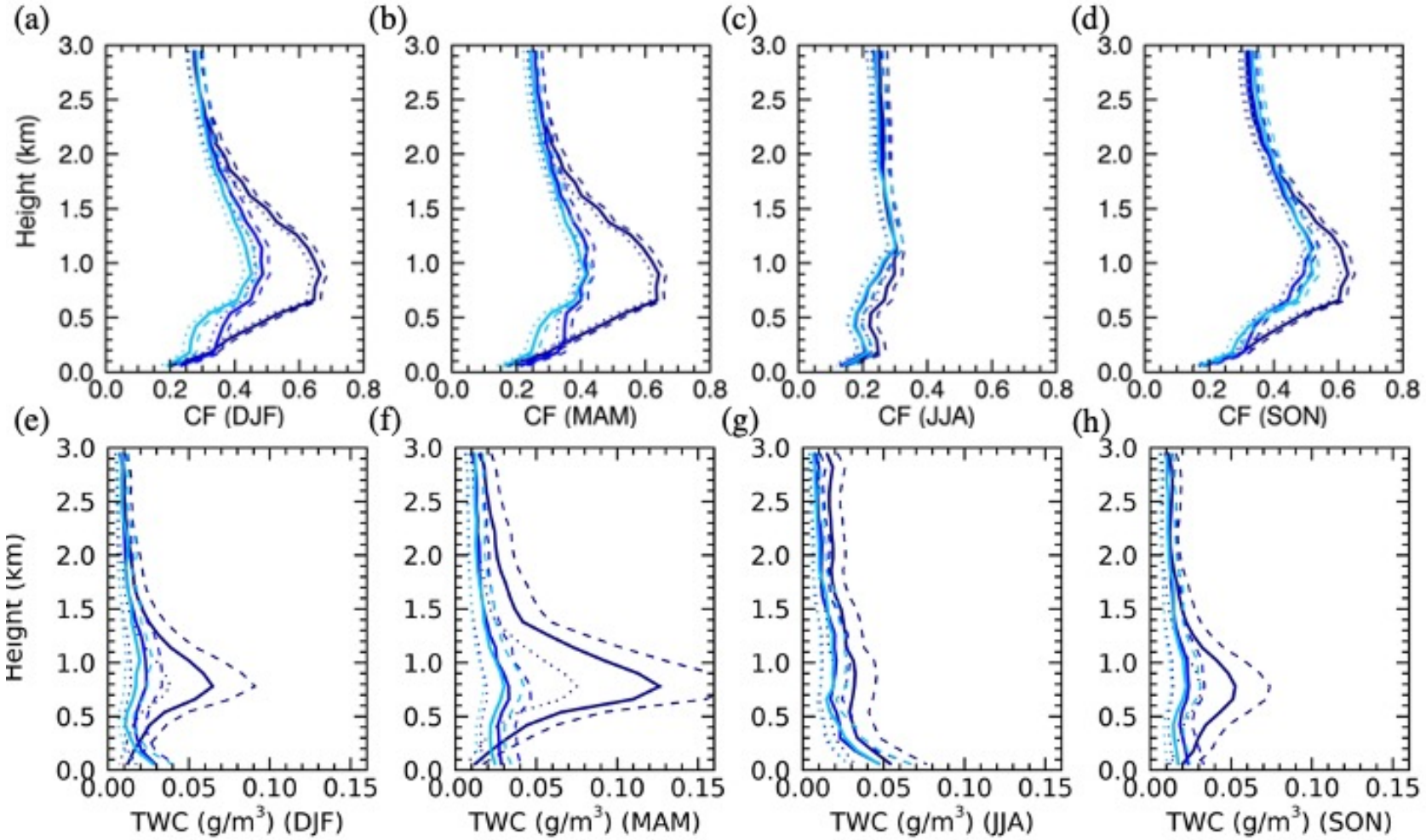


Taylor and Monroe 2023

An **event** is defined as when the there are at least 6 consecutive water and 6 consecutive sea ice footprints on either side of the Marginal Ice Zone (MIZ).

Seasonal Average Cloud Property Profiles

- Non-summer months exhibit statistically significant differences in Cloud Fraction and TWC.
- Summer months exhibit **no** statistically significant differences in Cloud Fraction or TWC.
- Largest cloud property differences in spring, not fall.



Our results are consistent with previous work suggesting that changing the surface type from ice-covered to ice-free ocean results in increased cloud fraction and TWC

Observational estimate of sea ice cloud feedback

First, express Arctic domain average cloud fraction (CF) as the sea ice concentration (SIC) weighted sum of the mean cloud fraction over sea ice covered and sea ice free footprints.

$$CF_{Arctic}(z) = CF_{ice-covered}(z) * SIC + CF_{ice-free}(z) * (1 - SIC) \quad (1)$$

Second, we differentiate (1) with respect to SIC and assuming the CF profiles to not change with time yields (2).

$$\frac{\partial CF_{Arctic}}{\partial SIC}(z) \approx \overline{CF_{ice-covered}}(z) - \overline{CF_{ice-free}}(z) \quad (2)$$

Third, we rearrange the terms to approximate the magnitude of the CF change due to a change in SIC to yielding (3).

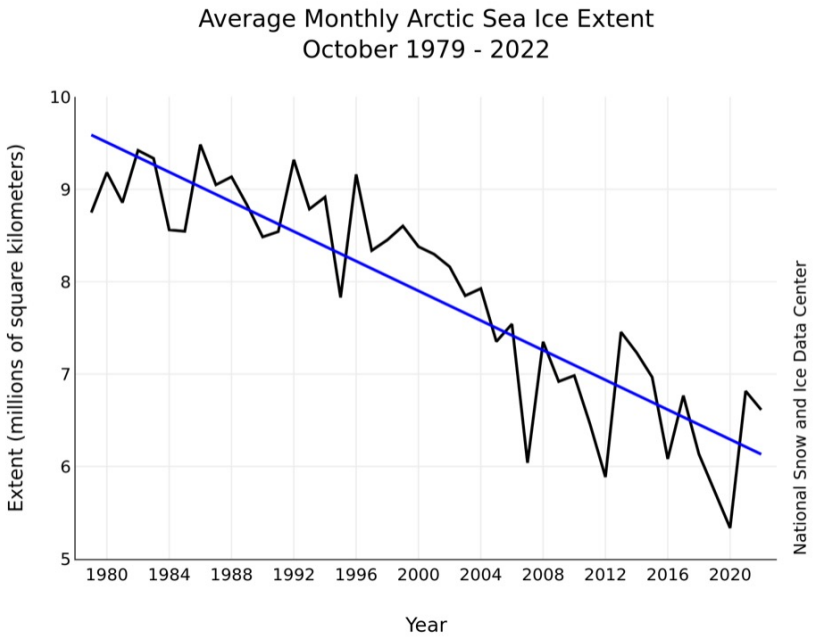
$$\delta CF_{Arctic}(z) = \delta SIC \left(\overline{CF_{ice-covered}}(z) - \overline{CF_{ice-free}}(z)\right) \quad (3)$$

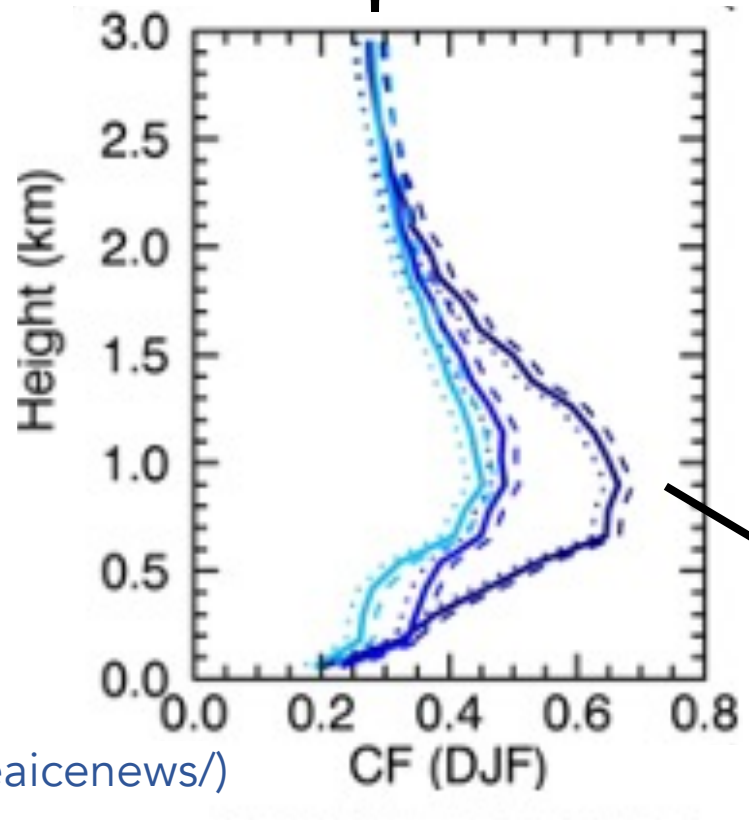
These equations provide a framework to estimate the observed cloud property response to the Arctic sea ice loss.

Observational estimate of sea ice cloud feedback

Taking equation (3) and applying it to our analysis results and observed sea ice loss…

$$\delta SIC \left(\overline{CF_{ice-covered}}(z) - \overline{CF_{ice-free}}(z) \right) = \delta CF_{Arctic}(z)$$





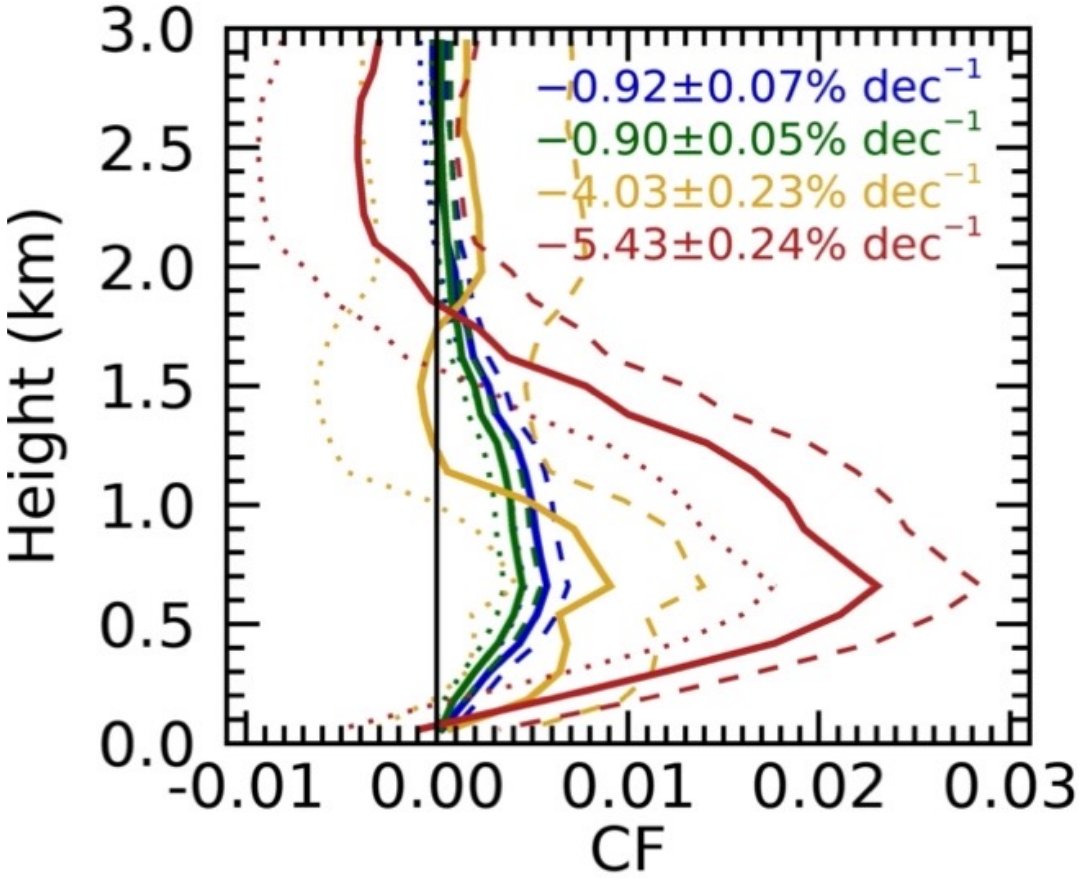
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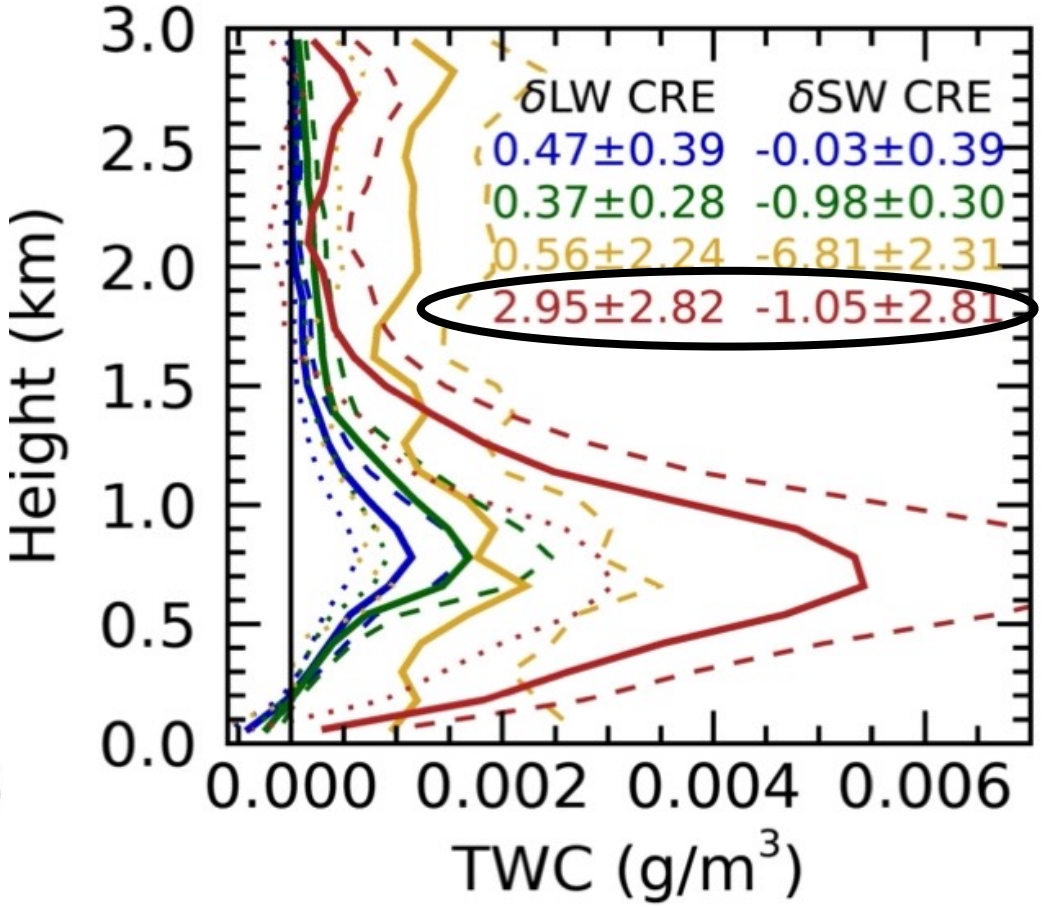
Observational estimate of the 20-yr cloud response to observed sea ice loss.

From observed ice-free minus ice-covered cloud property differences across the MIZ

Credit: NSIDC (https://nsidc.org/arcticseaicenews/)

Observational estimate of sea ice-cloud feedback: CF and TWC



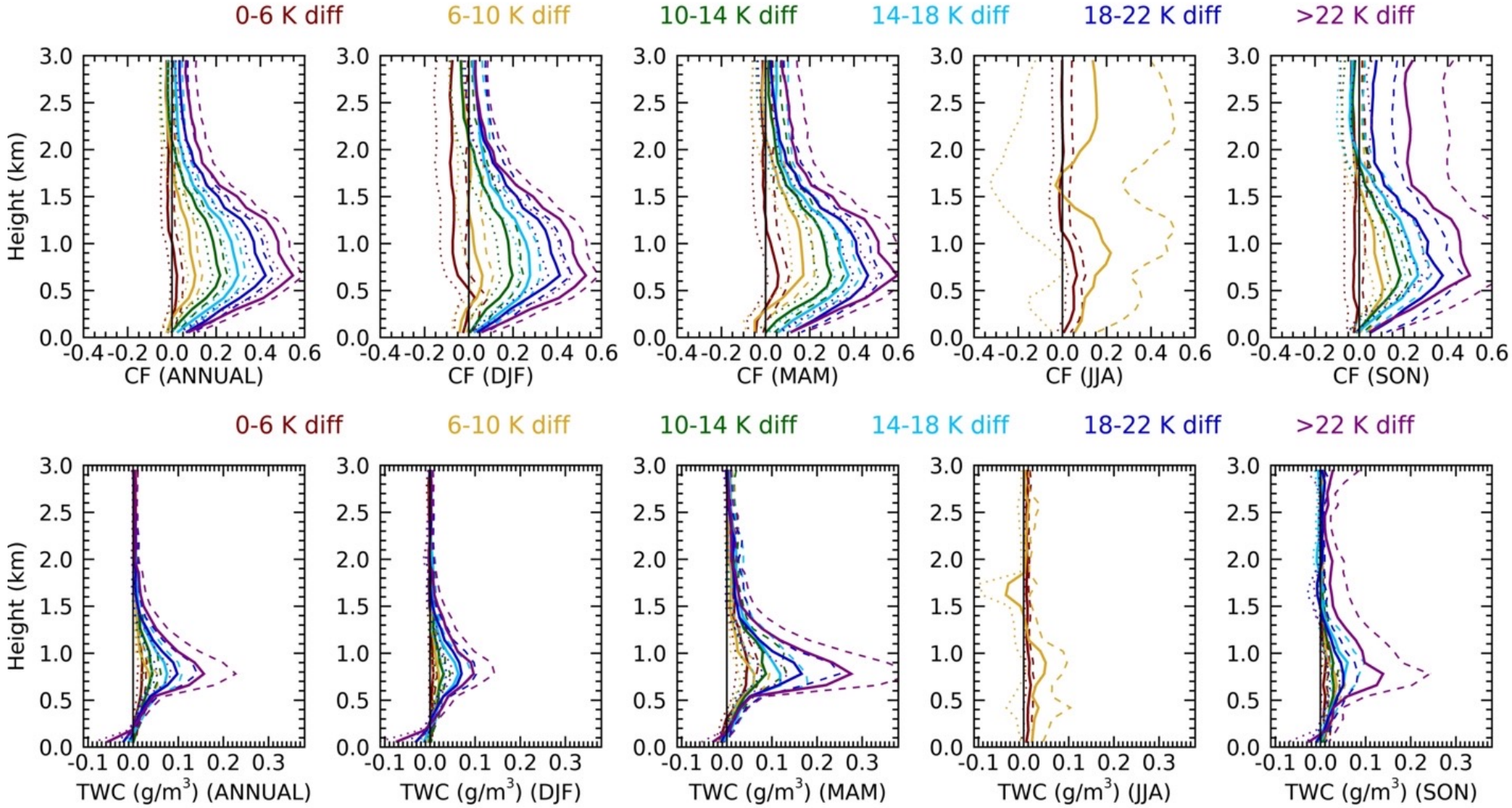


Estimated increase in surface LW CRE of ~3 Wm^{-2} due to the sea ice-cloud feedback,

The largest sea ice-cloud feedback in fall showing CF and TWC increases of ~0.02 and ~0.005 g m^{-3} due to observed sea ice loss over the last 20 years at the level of CF maximum.

Stratifying by surface temperature differences

Stratifying by surface temperature differences indicates that in all seasons a surface temperature difference is required to have a cloud property difference.

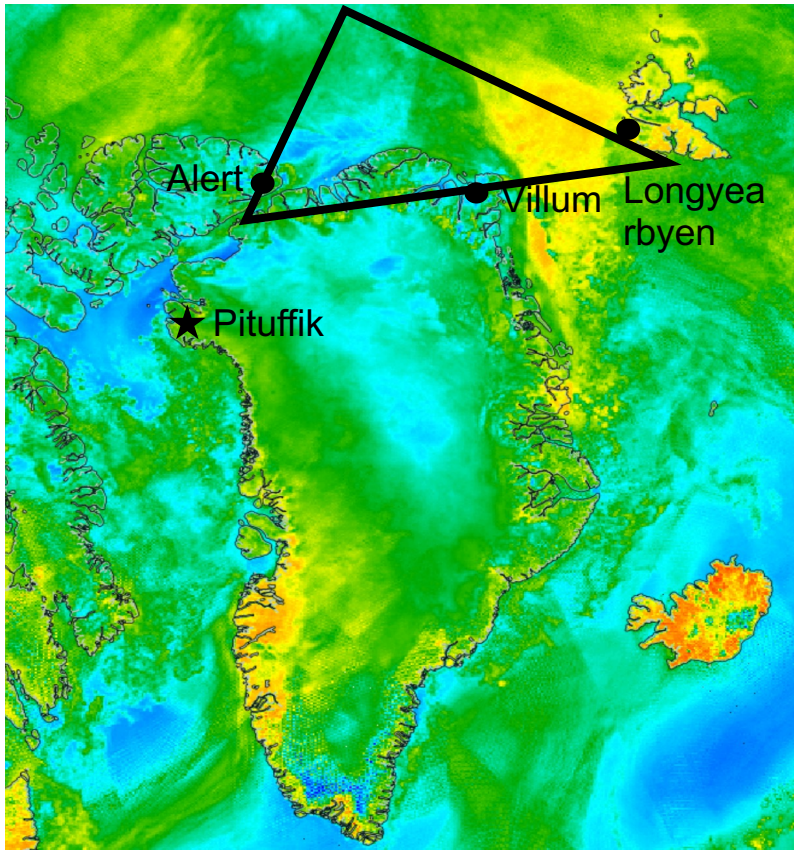


We propose an altered conceptual model where the cloud response to sea ice loss is controlled by the surface temperature differences between the surface types.

Conclusions: Cloud sea ice interactions

- Using MIZ crossing events, we isolate the influence of surface type on cloud properties from the influences in large-scale meteorology.
- Cloud property differences are strongly tied to differences in the thermodynamic profiles between the ice-free ocean and sea ice surface types.
  - The ice-free ocean surface is warmer, moisture, weaker lower tropospheric stability, and has more positive surface turbulent fluxes
  - This indicates that the feedbacks between the surface properties and the lower tropospheric thermodynamic profiles are critical to constraining the cloud response to sea ice loss.
- Our results suggest a sea ice-cloud feedback that is positive in Fall and Winter and negative in Spring.
- **<u>Takeaway:</u> The cloud response to observed sea ice loss is estimated to be +0.02 for CF and +0.005 gm^{-3} for TWC (~5%) in Fall corresponding to a ~3 W m^{-2} increase in the surface LW downwelling radiation.**

Project Overview



AMSR2 87 GHz Brightness temperature (June 11, 2023) showing the sea ice concentration contrast (from dark blue to green) in the primary sampling region.
Below are the primary platforms to be deployed.





- → Program / Project: Arctic Radiation-Cloud-aerosol-Surface Interaction Experiment (ARCSIX)
- → Program Mgrs: Hal Maring, Radiation Sciences and Thorsten Markus, Cyrospheric Sciences
- → Principal Investigators: Sebastian Schmidt (Univ. Colorado) and Patrick Taylor, LaRC
- → **Description:** The overarching goal is to **quantify the contributions of surface properties, clouds, aerosols, and precipitation to the Arctic summer surface radiation budget and sea ice melt** during the early melt season to advance understanding of rapid Arctic climate change and improve satellite retrievals.
- → Center Participants: LaRC, GSFC, JPL, AFRC
- → Partners: US academic researchers, NOAA, NCAR, NRL, NPS, SPEC
- → Deployment Dates: May-June and July-August 2024
- → Deployment Locations: Pituffik Space Base, Greenland
- → Budget: Managed by Hal Maring, HQ

Project Goals

ARCSIX is a mission concept motivated by a science community white paper with over 30 contributors. The ARCSIX instrument teams were competed in ROSES 2021 (NNH21ZDA001N-ARCSIX)

Project Goals

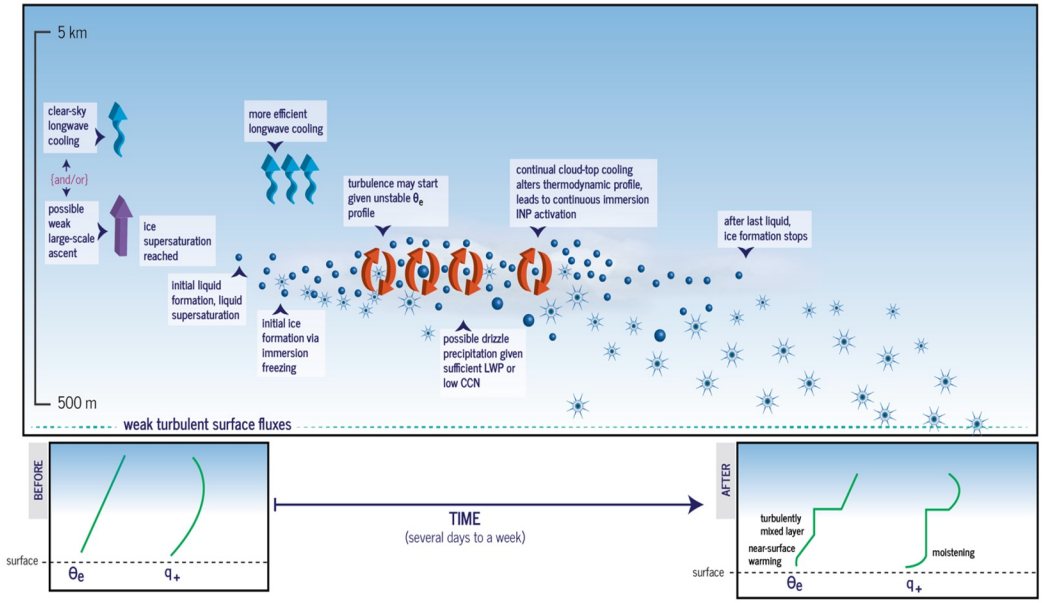
Provide an unprecedented data set of the clouds, aerosol, and surface properties in the region of multi-year sea ice North of Greenland to quantify the contributions to summer sea ice melt:

ARCSIX is driven by the need to:

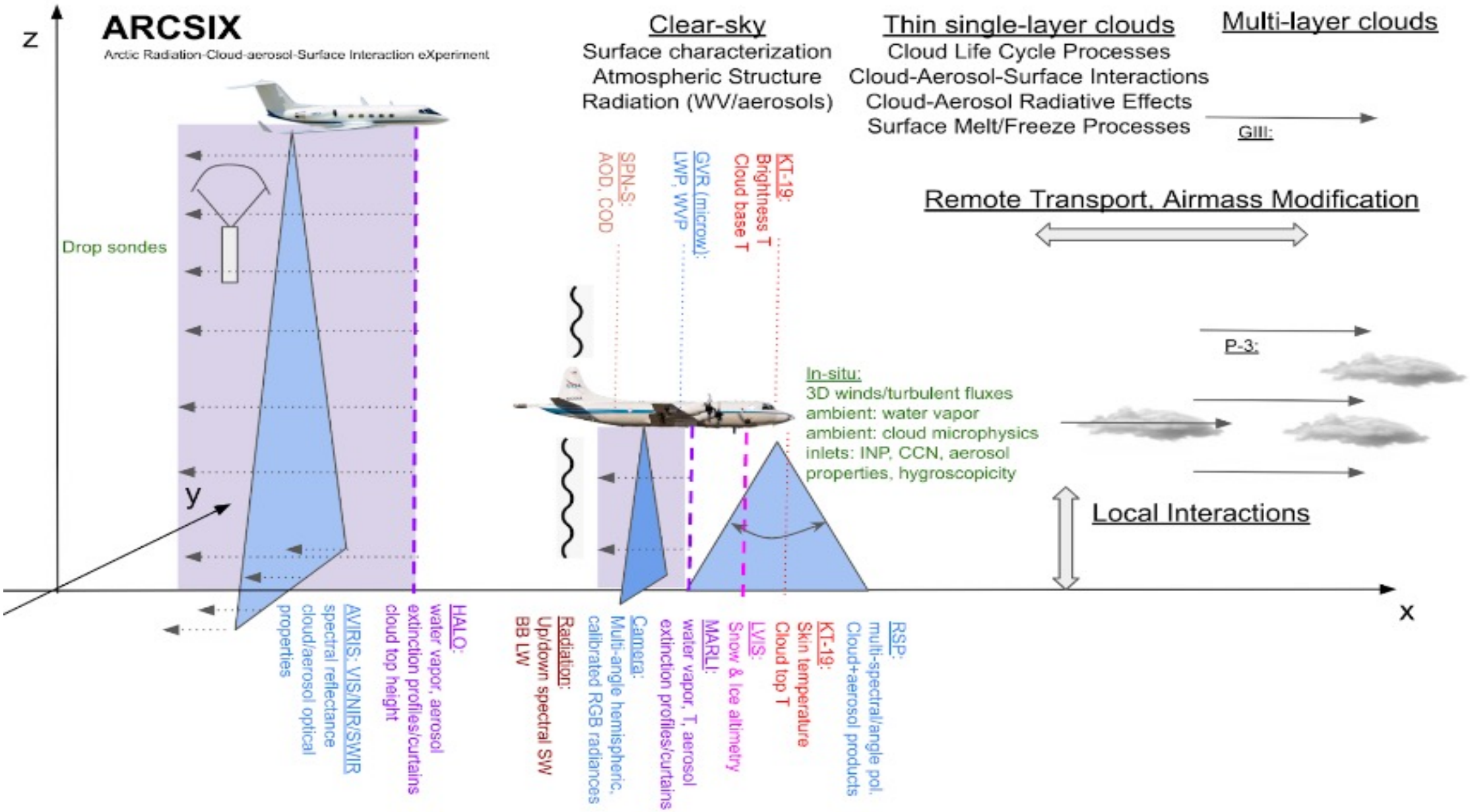
1) Understand how coupling between radiative processes and sea ice surface properties influence summer sea ice melt;

2) Understand processes controlling the predominant Arctic cloud regimes and their properties; and

3) Improve our ability to monitor Arctic cloud, radiation, and sea ice processes from space.



ARCSIX: An Arctic Airborne Experiment



Discussion points:

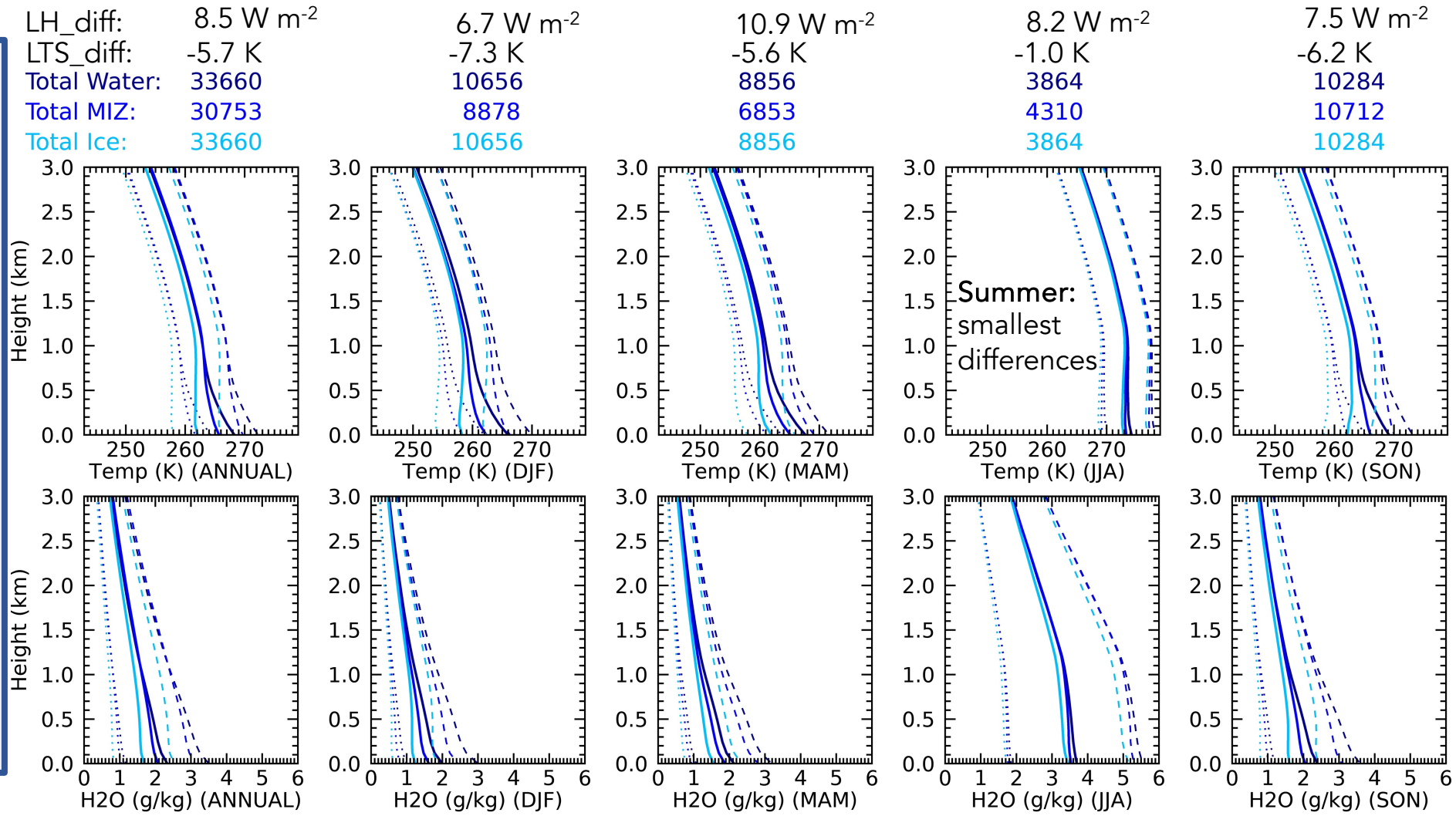
- Should be care about the model performance within infrequently occurring regimes?
- How do we best observe, quantify, and understand the role of clouds within the airmass transformation process? (It is very hard to accomplish Lagrangian observations)
- Others?

Questions?

Patrick.c.taylor@nasa.gov

Thermodynamic controls on surface type impact

- Ice-free footprints are warmer and moister than ice-covered footprints
- Largest differences near the surface and decay with altitude.
- Ice-free footprints have a weaker lower tropospheric stability.

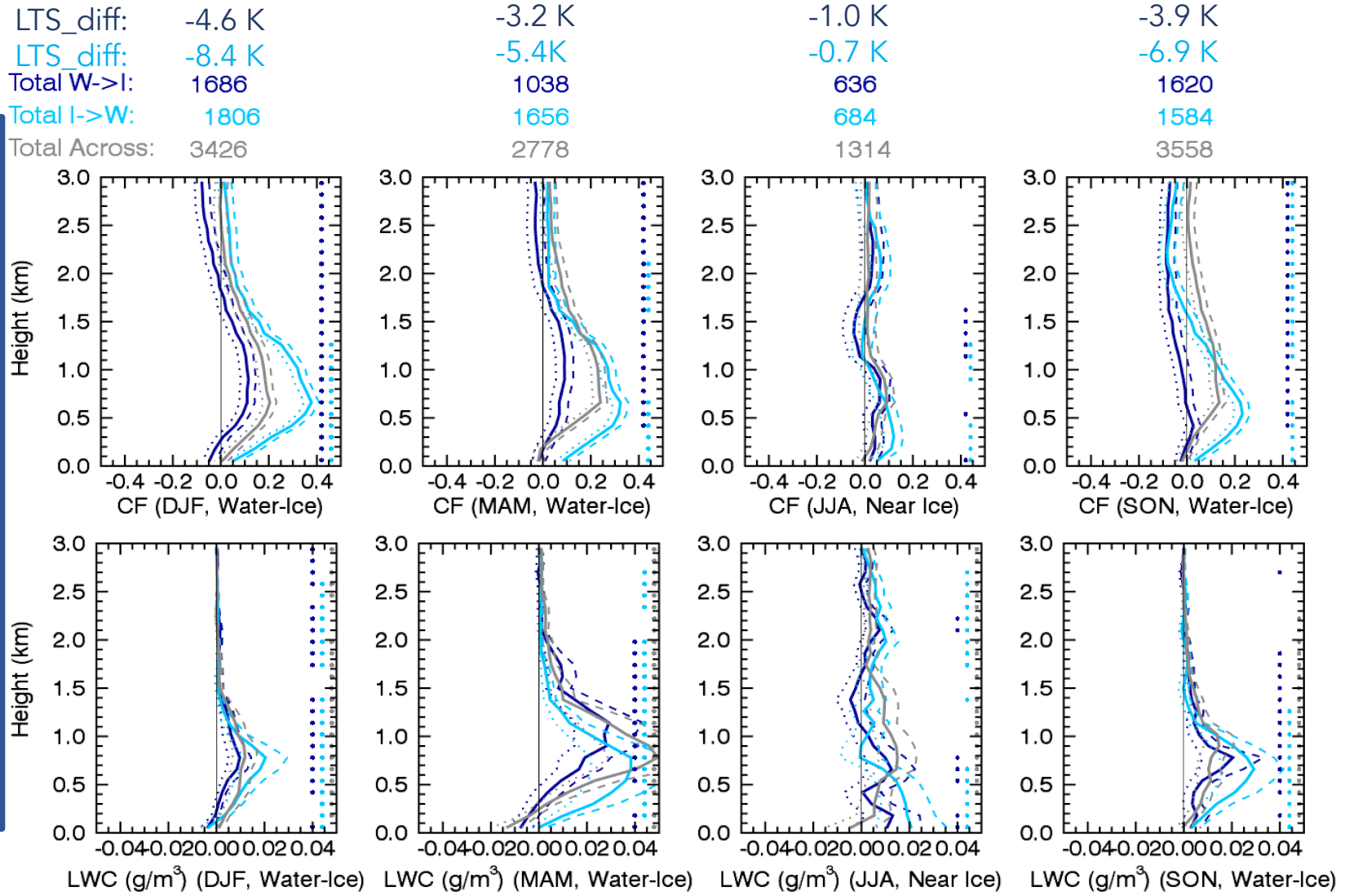


Surface type influences cloud properties through modulations of the lower tropospheric thermodynamic structure.

Stratifying by wind direction

Stratifying by wind direction allows for the assessment of the influence of surface turbulent fluxes perturbations.

- Water-to-ice winds—weak surface turbulent fluxes
- Ice-to-Water winds—strong surface turbulent fluxes.

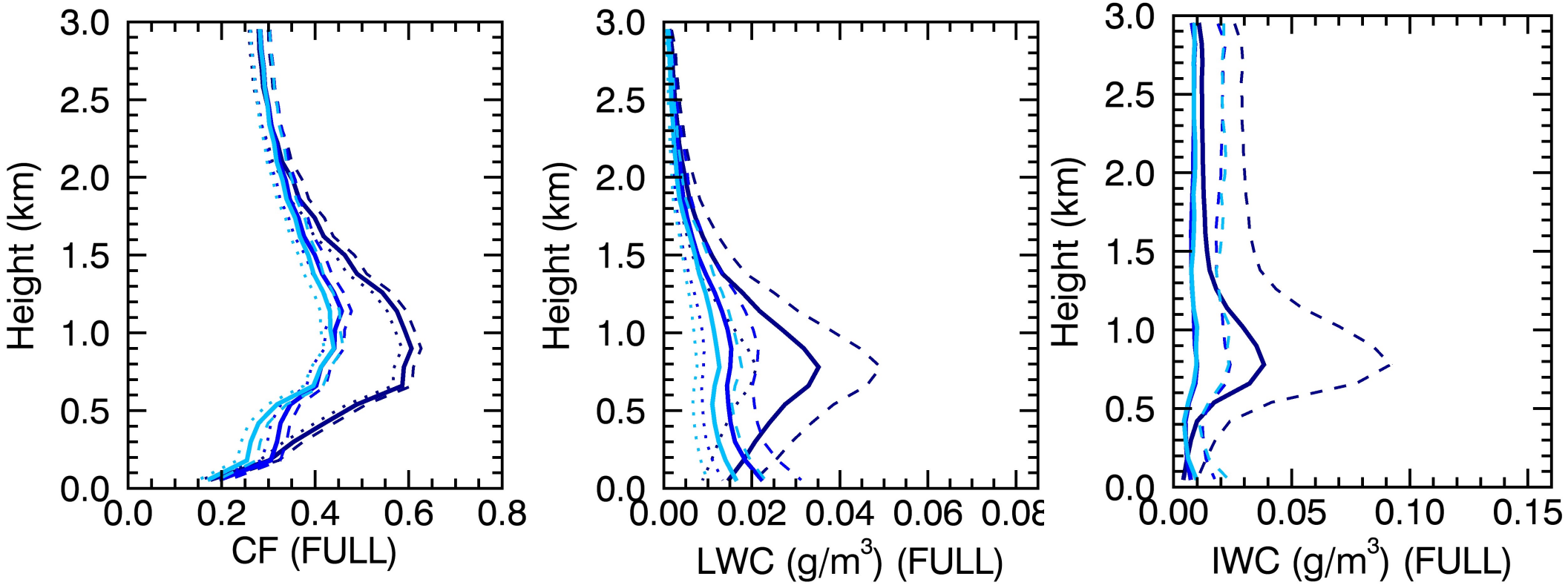


Surface turbulent flux differences influence the magnitude surface type cloud property differences in specific wind flow regimes and also correlate with LTS differences.

Annual Mean Cloud Property Profiles

Total Water: 33660
Total MIZ: 30753
Total Ice: 33660

Annual mean cloud property profiles over the MIZ closely resemble sea ice footprints.

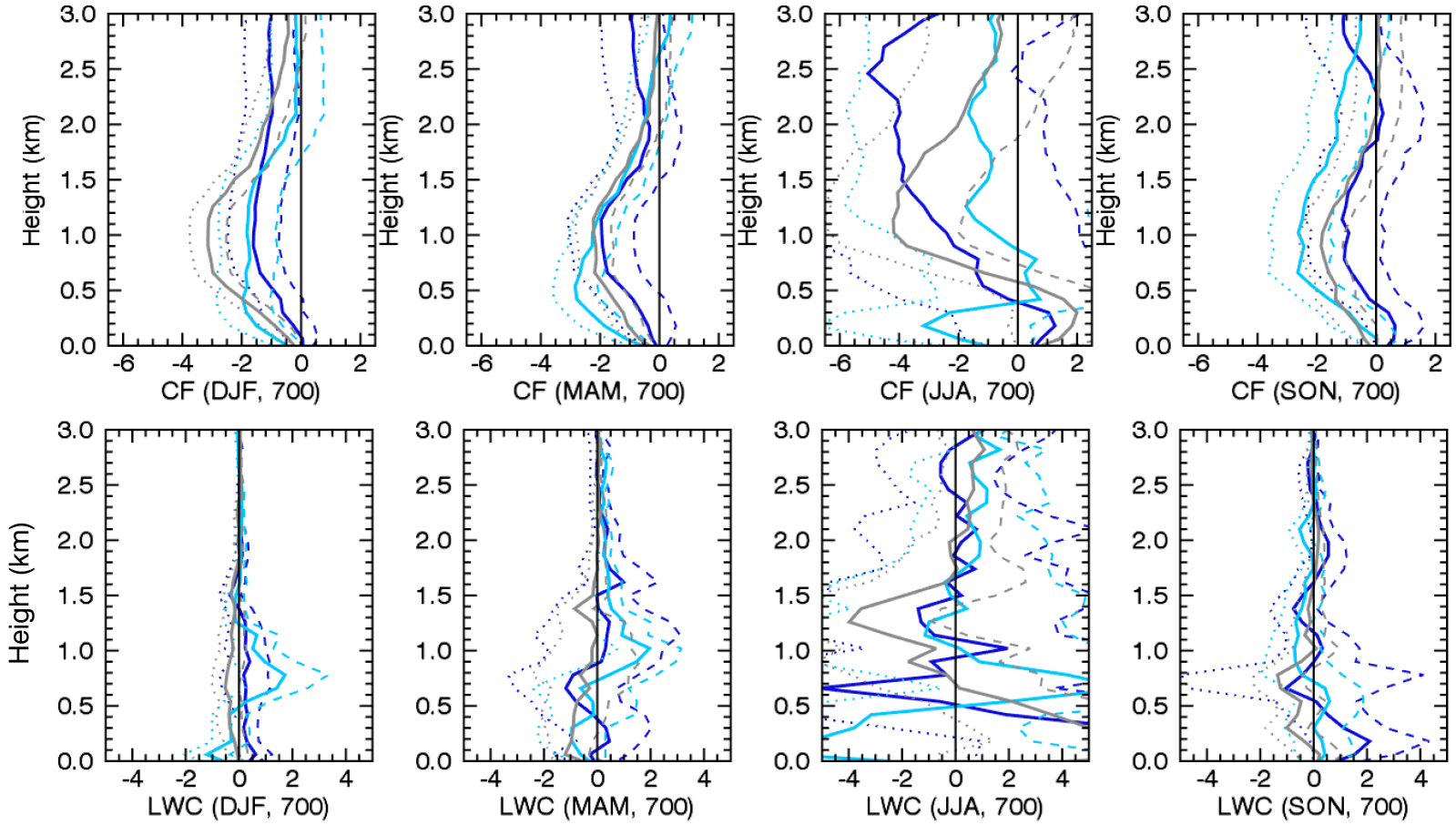


Water footprints exhibit statistically significantly larger cloud fraction and liquid water content than sea ice footprints between 300 m and 1.5 km in the annual mean.

Role of Lower tropospheric stability: stratifying by wind directions

Lower Tropospheric Stability (LTS) = (θ_plev- θ_sfc), θ=> potential temperature

- Shown are regression relationships between cloud property and LTS differences stratified by atmospheric wind regime.
- The contributions of water minus sea ice LTS differences to cloud property differences are statistically indistinguishable given available data.



Lower tropospheric stability can be used as a diagnostic to capture the processes that drive the surface type dependent cloud property differences.

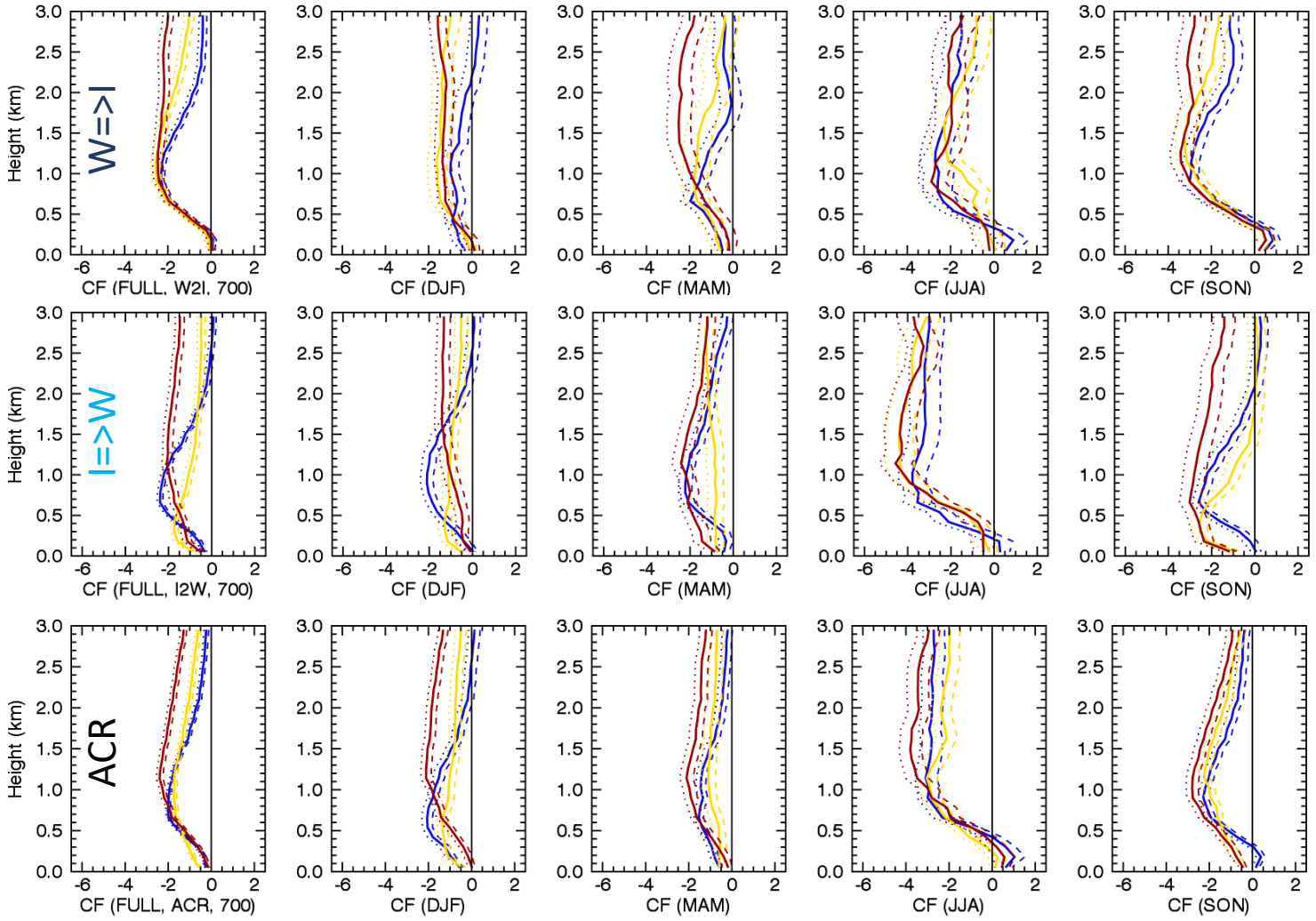
CF-LTS relationship during stratifying by wind direction

WATER
MIZ
ICE

Lower Tropospheric Stability (LTS) = (θ_plev- θ_sfc), θ=> potential temperature

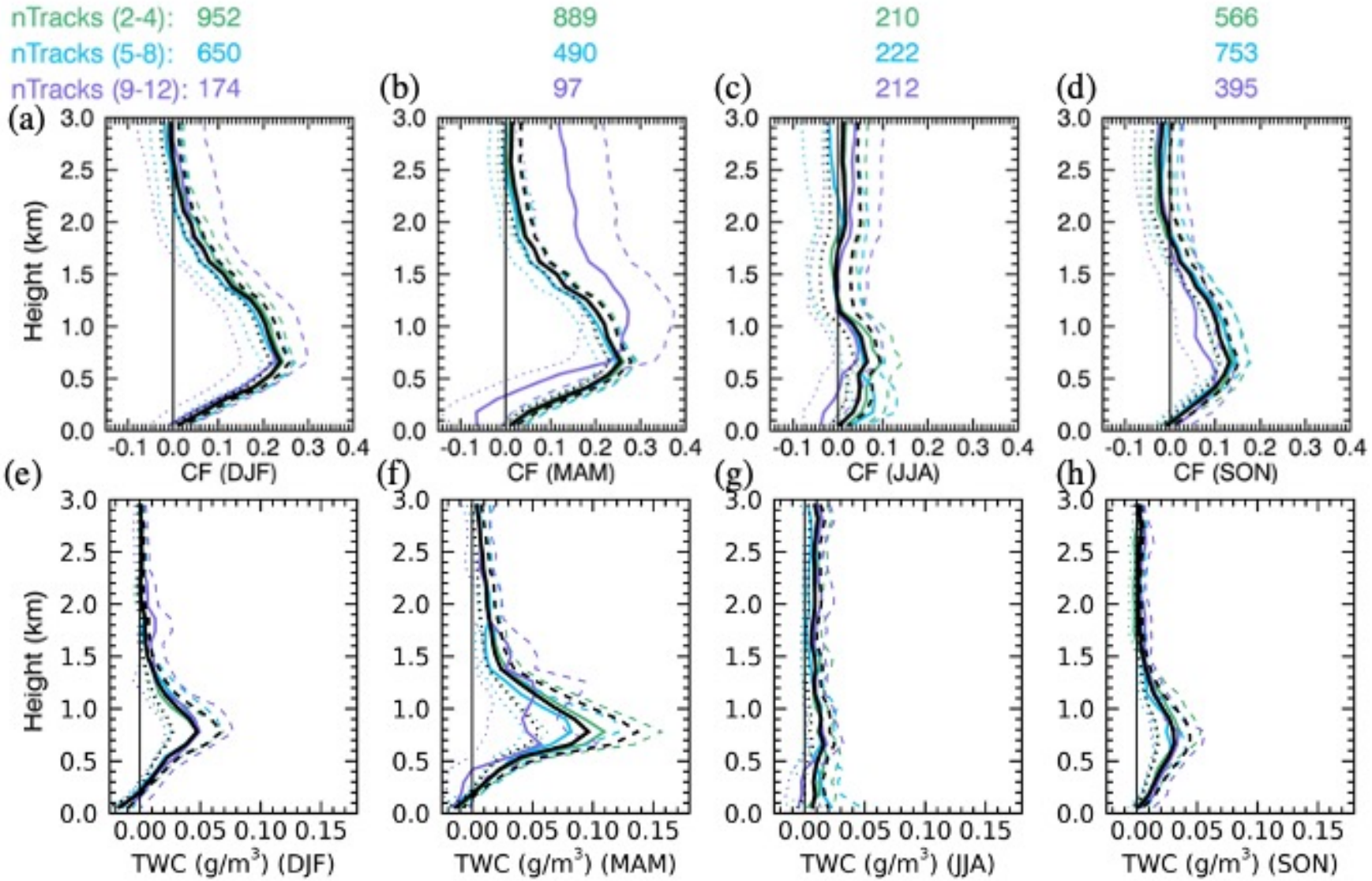
- Shown are regression relationships between CF and LTS for each wind direction and surface type.
- The regression relationships between CF and LTS are found to vary weakly with surface type and wind direction.

The relationships between CF and LTS are consistent across atmospheric wind direction regimes.



Sensitivity of cloud property differences to MIZ Width

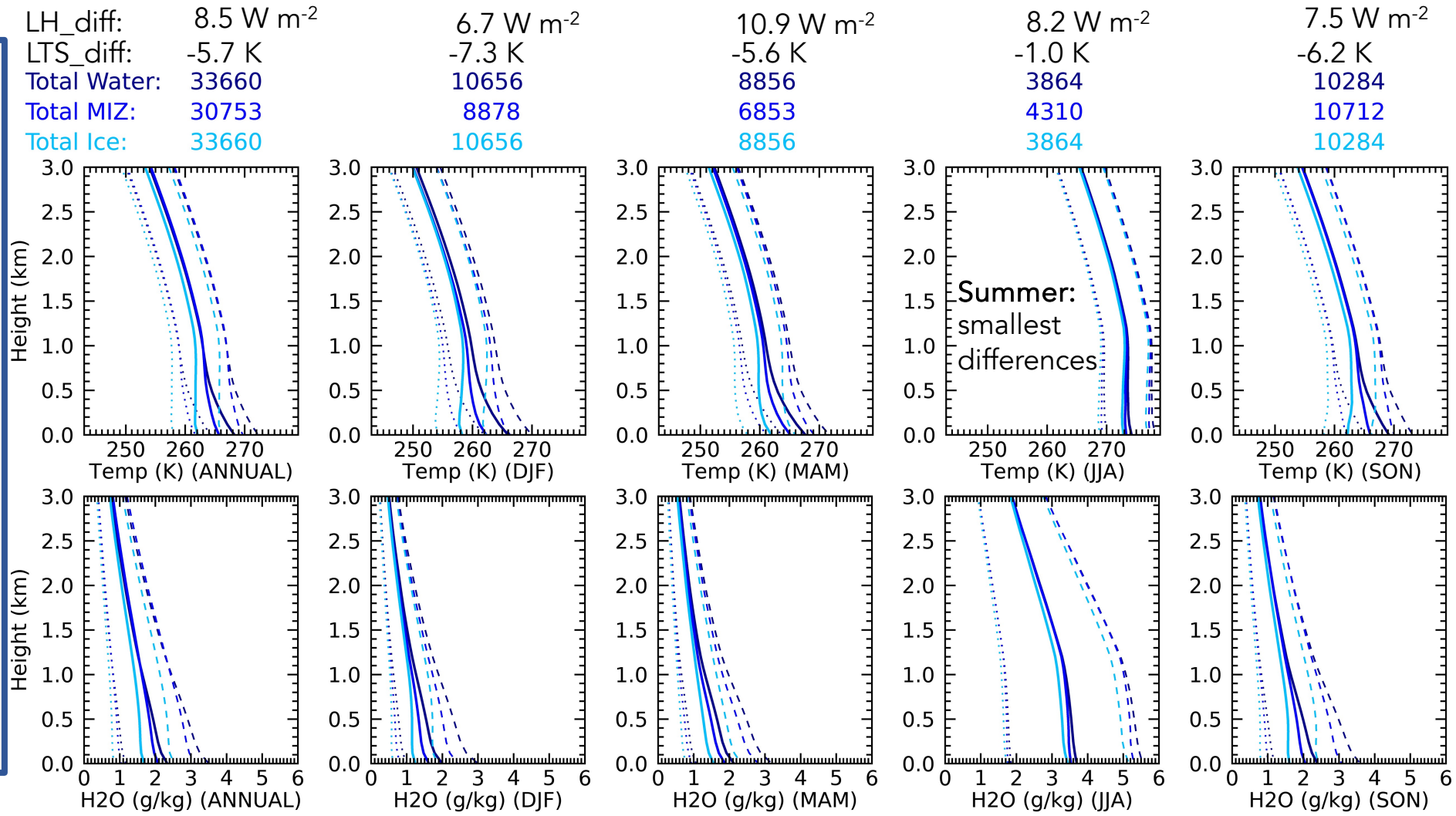
- Ice-free minus ice-covered cloud property profile differences are sorted into three MIZ width bins by the number of footprints.
  - Narrow (2-4)
  - Medium (5-8)
  - Wide (9-12)
- The cloud differences between the MIZ width bins are statistically indistinguishable.



Results insensitive to MIZ widths 2-12 footprints (40-240 km).

Thermodynamic controls on surface type impact

- Ice-free footprints are warmer and moister than ice-covered footprints
- Largest differences near the surface and decay with altitude.
- Ice-free footprints have a weaker lower tropospheric stability.

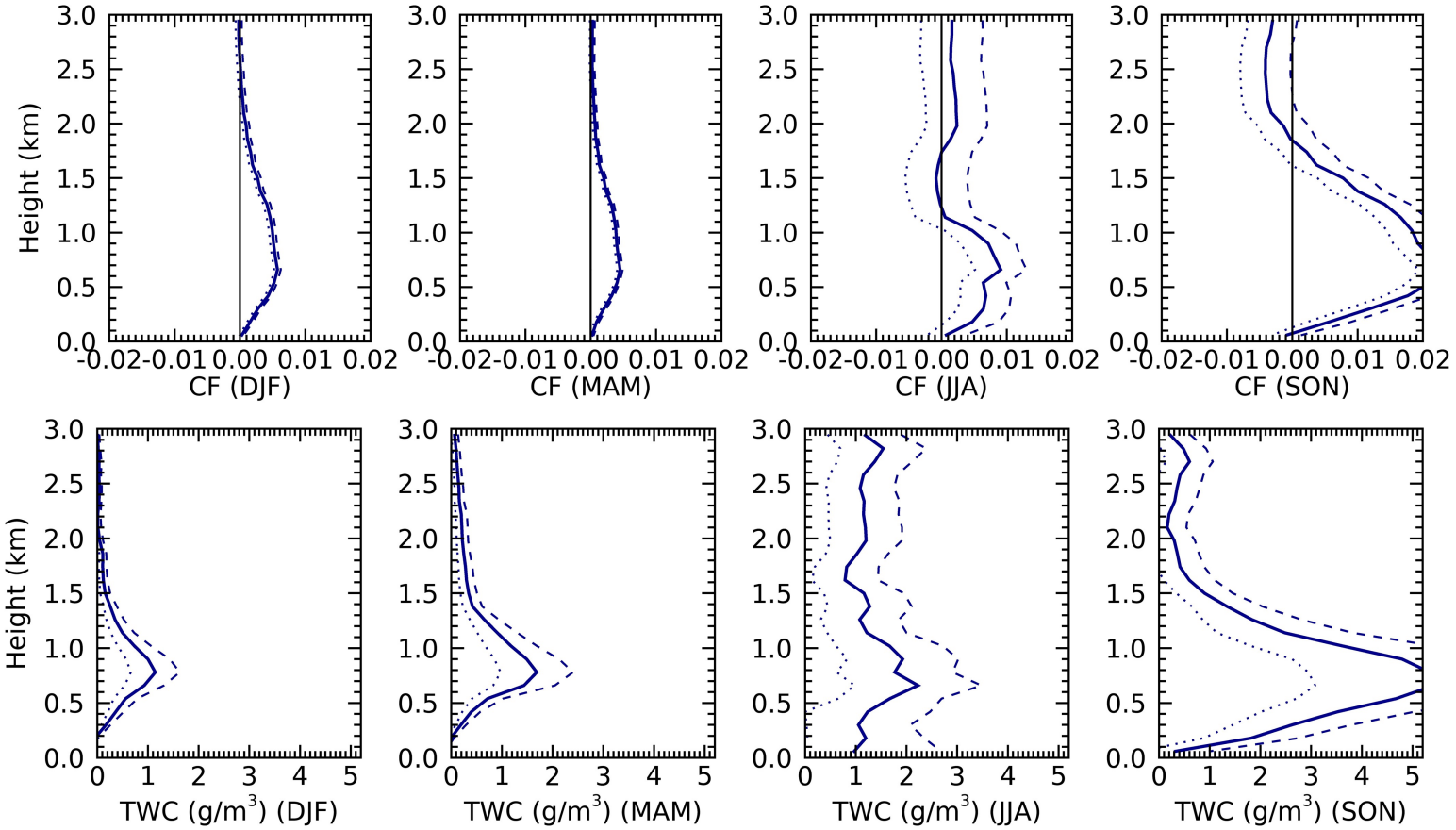


Surface type influences cloud properties through modulations of the lower tropospheric thermodynamic structure.

Observational constraint on sea ice cloud feedback

$$CF_{Arctic}(z) = CF_{ice-covered}(z) * SIC + CF_{ice-free}(z) * (1 - SIC)$$

$$\delta CF_{Arctic}(z) = \delta SIC \left(\overline{CF_{ice-covered}}(z) - \overline{CF_{ice-free}}(z) \right)$$



Observational estimates of 20-yr cloud response to observed sea ice loss using observed average ice-free minus ice-covered cloud differences

The results indicate that the largest sea ice-cloud feedback in fall showing a CF and TWC increase of ~0.02 and ~0.005 g m^{-3}, respectively, over 20 years at the level of CF maximum.