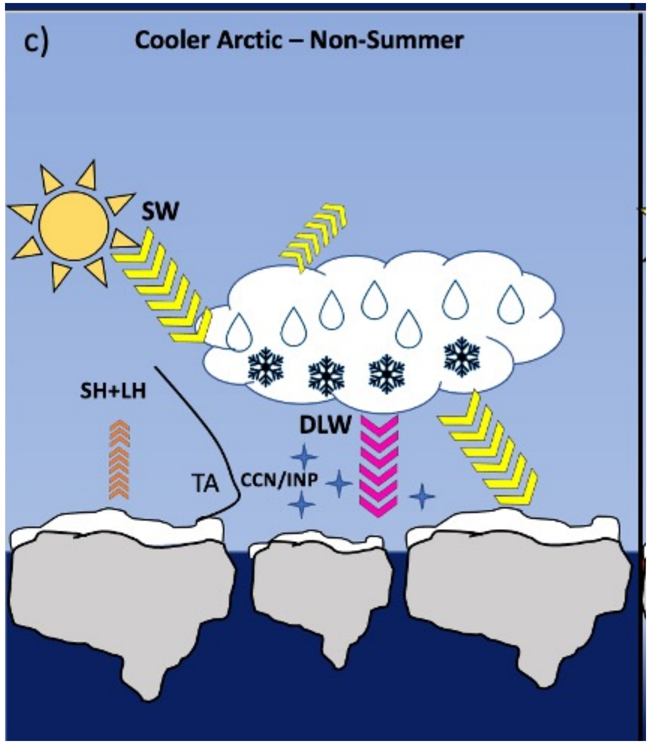
# An observationally-based determination of the Arctic sea ice-cloud feedback since 2000: Isolating the Arctic cloud response to sea ice loss





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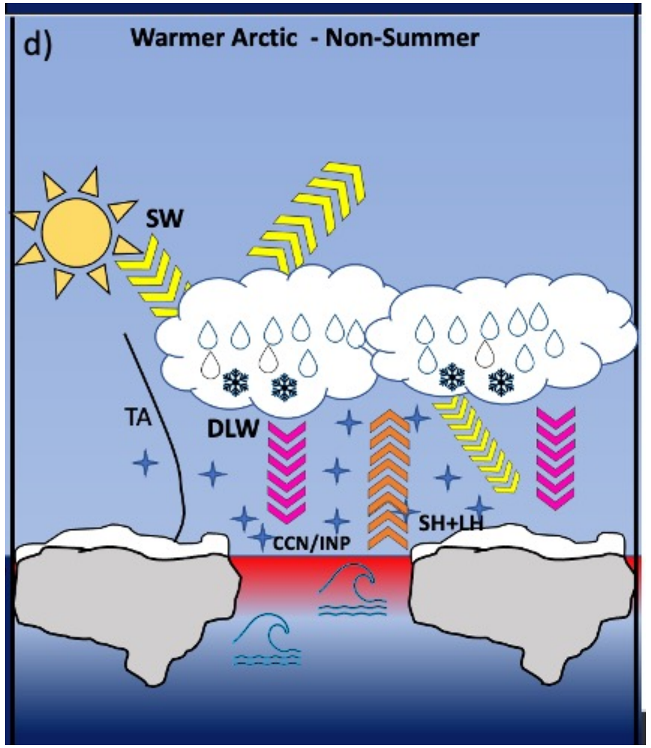
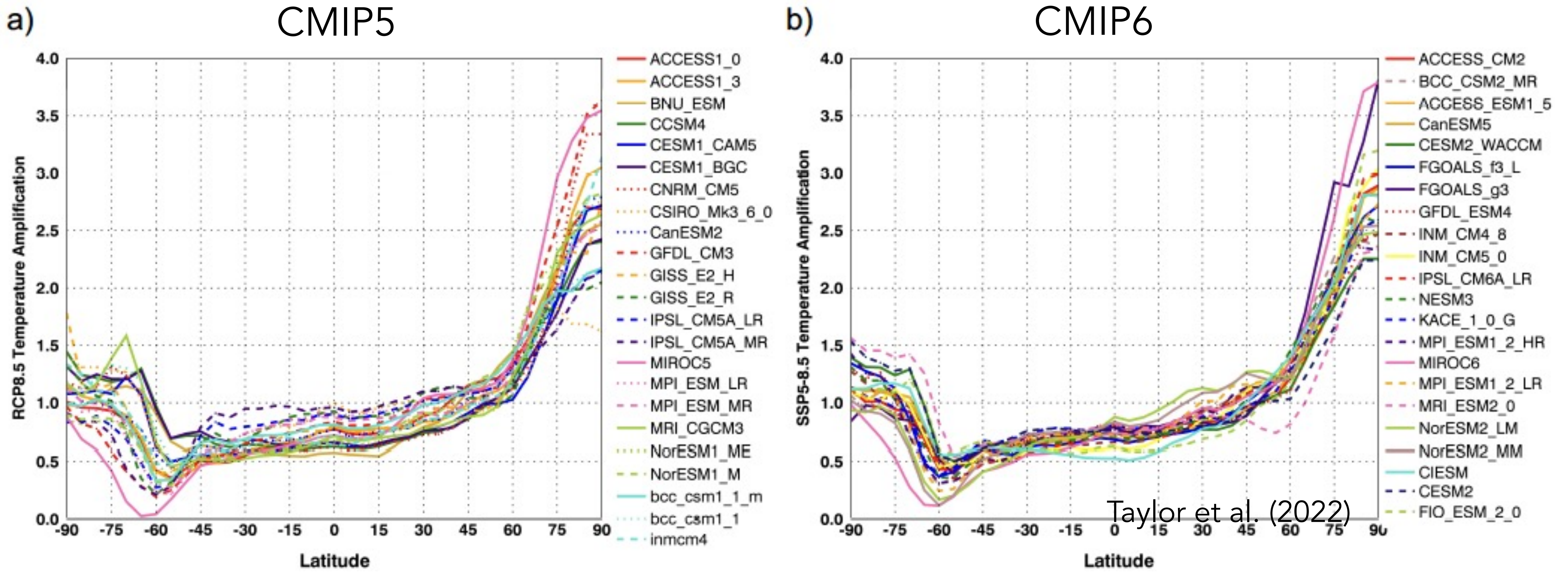


# Arctic climate projection uncertainty

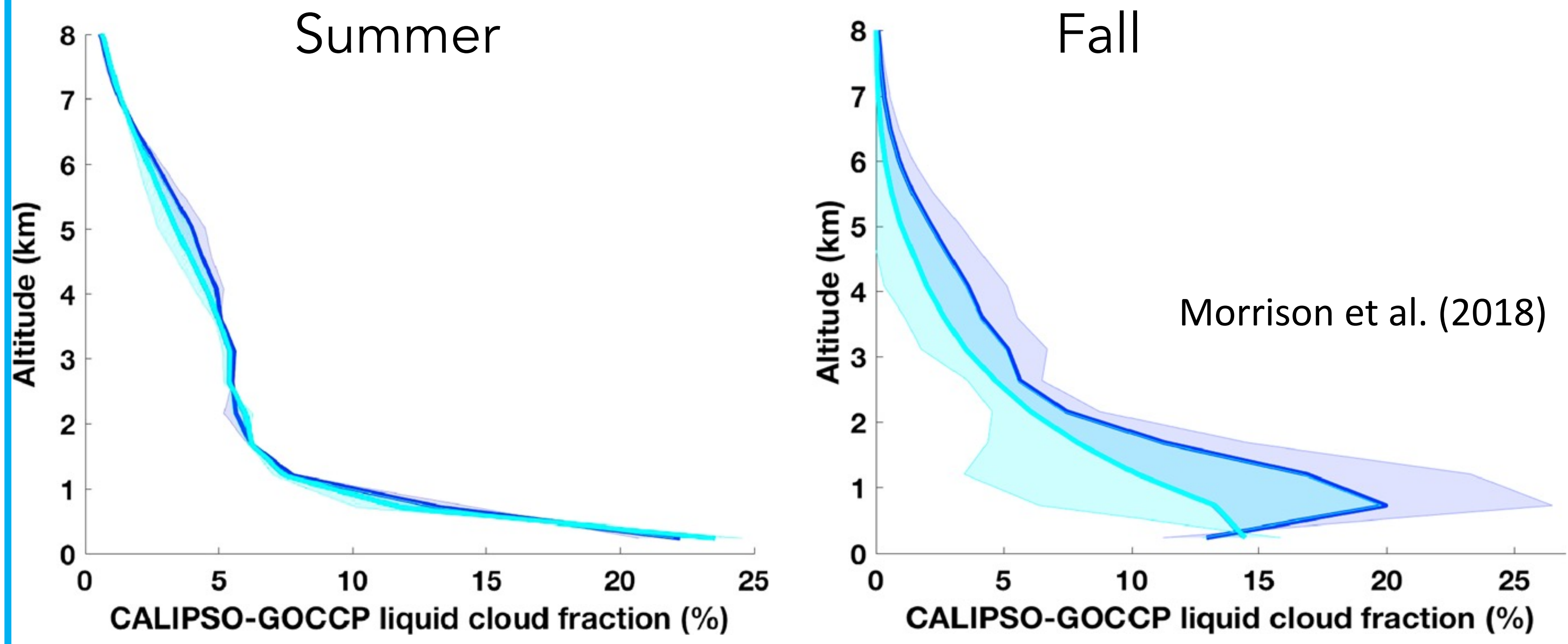



Climate projections differ more in the Arctic than anywhere else.

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

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

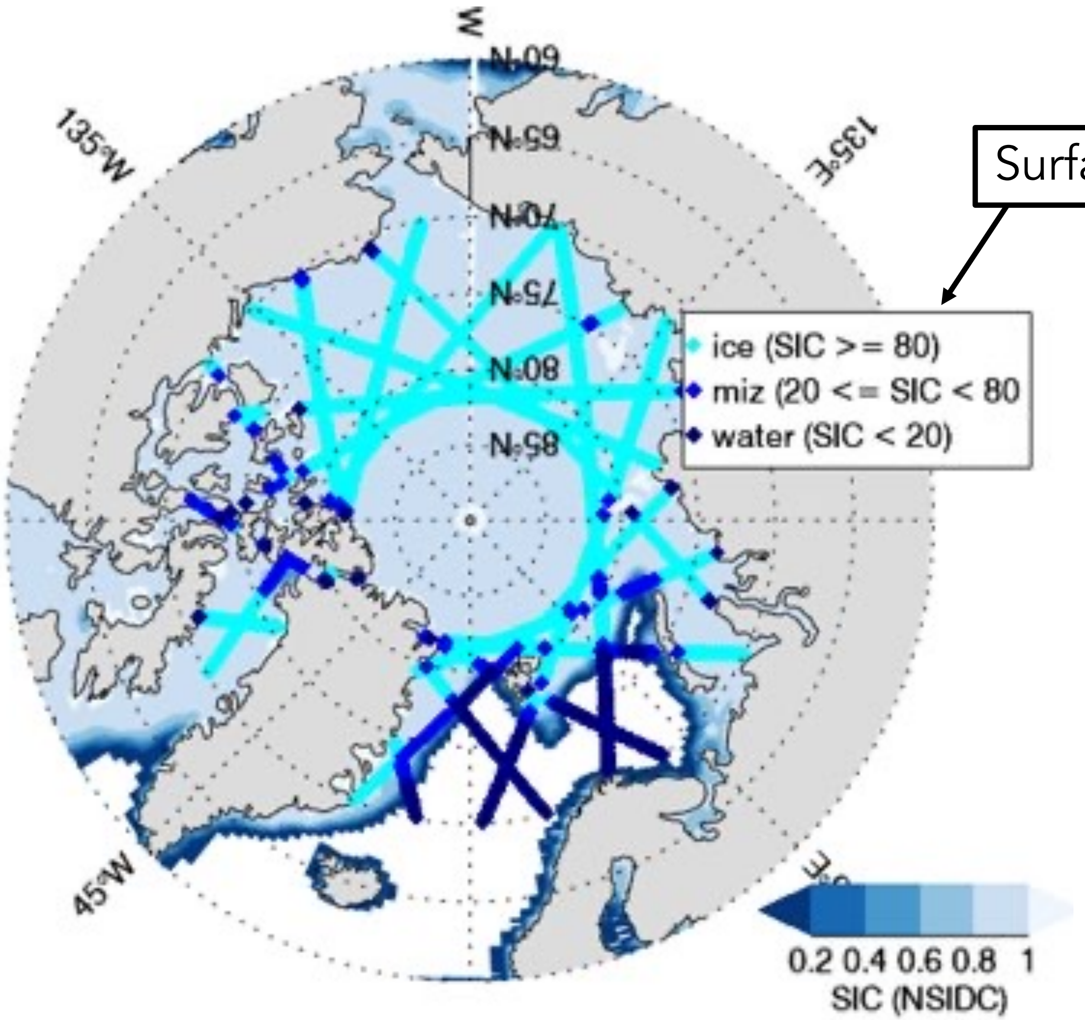
- No impact of surface type on summer clouds.
- Larger low cloud amount over ice-free ocean than sea ice.

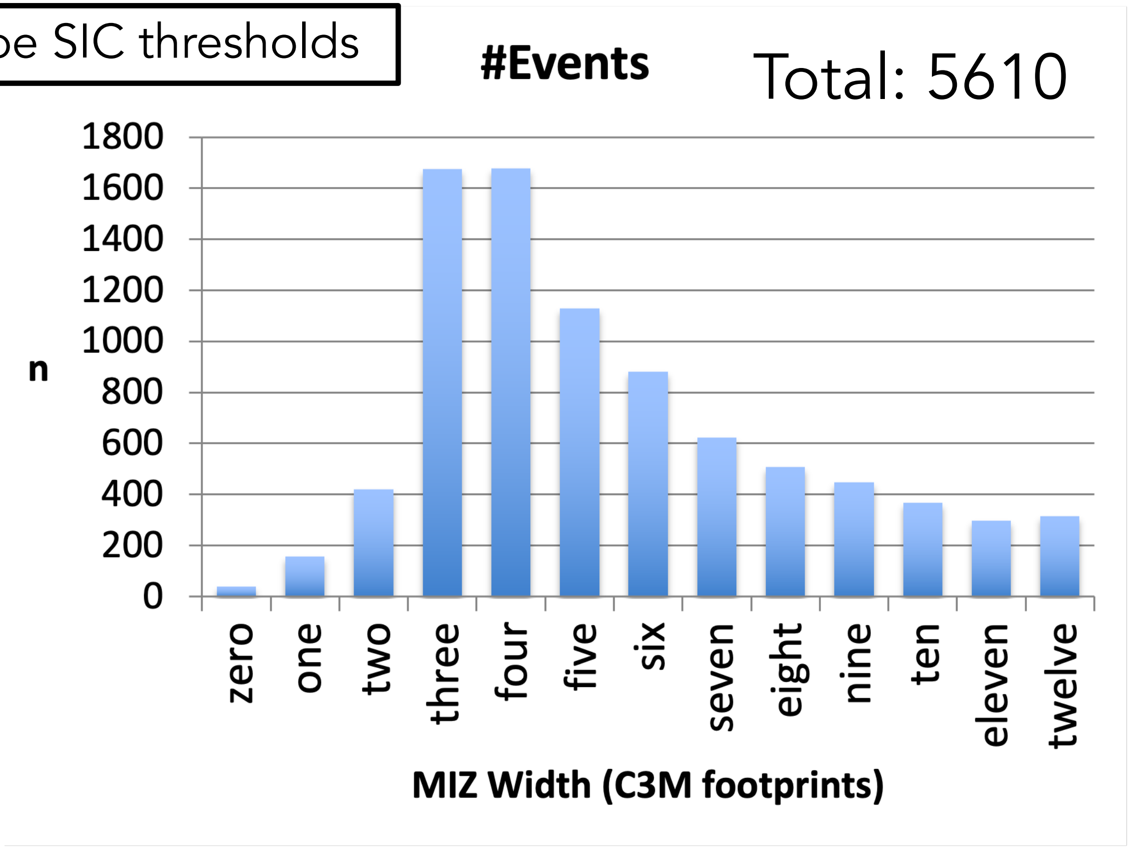



Morrison et al. (2018)

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)

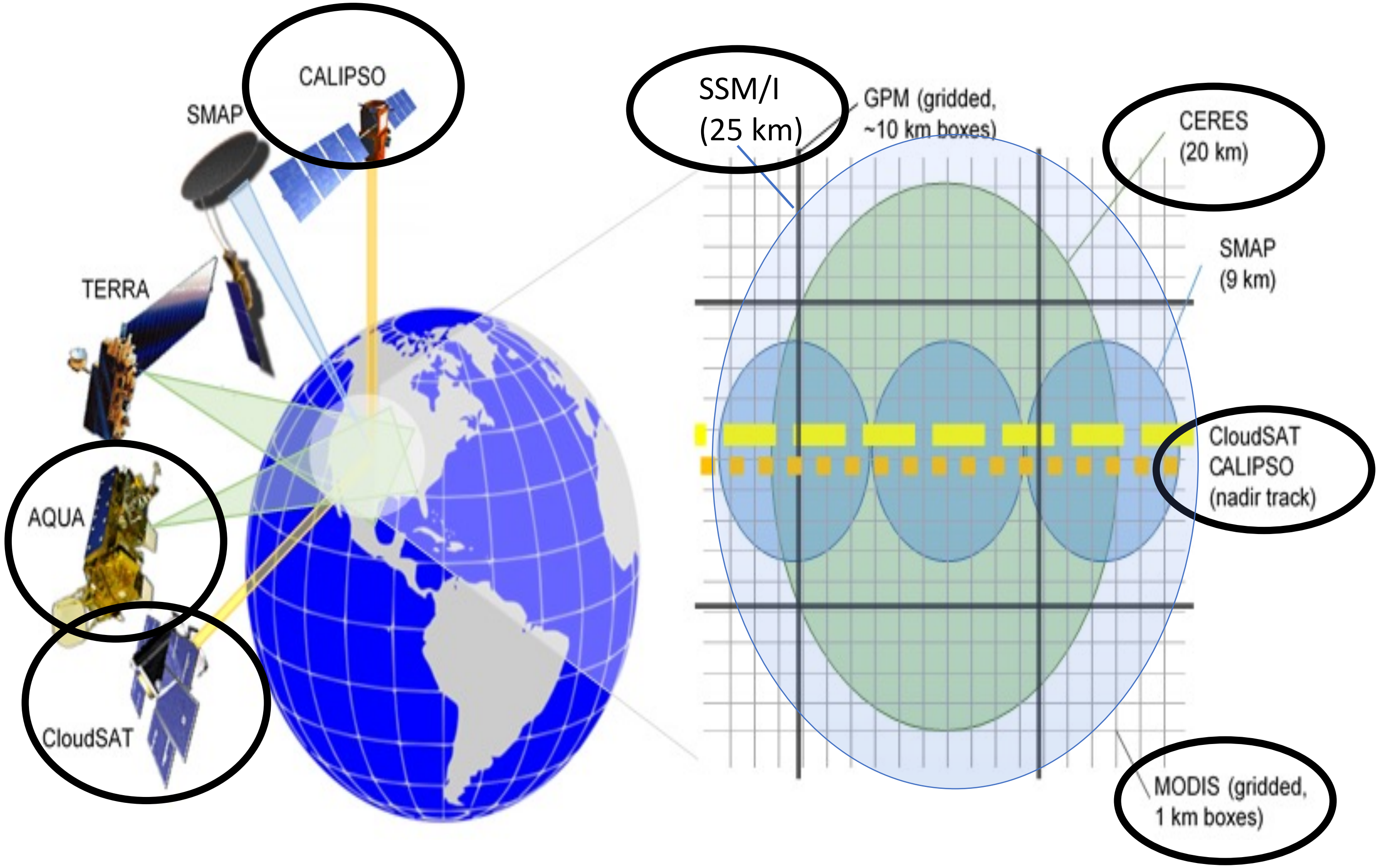
# Methodology: >5000 Marginal Ice Zone Crossing Events




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

# From our powers combined…




- CALIPSO-CloudSat-CERES-MODIS (C3M; Kato et al. 2010;2011)
  - July 2006-June 2010
  - Cloud Fraction
  - Cloud Liquid/Ice Water Content profiles
  - Radiative Fluxes
- MERRA-2 and ERA5
  - Thermodynamic Profiles
  - Winds
  - Surface Turbulent Fluxes

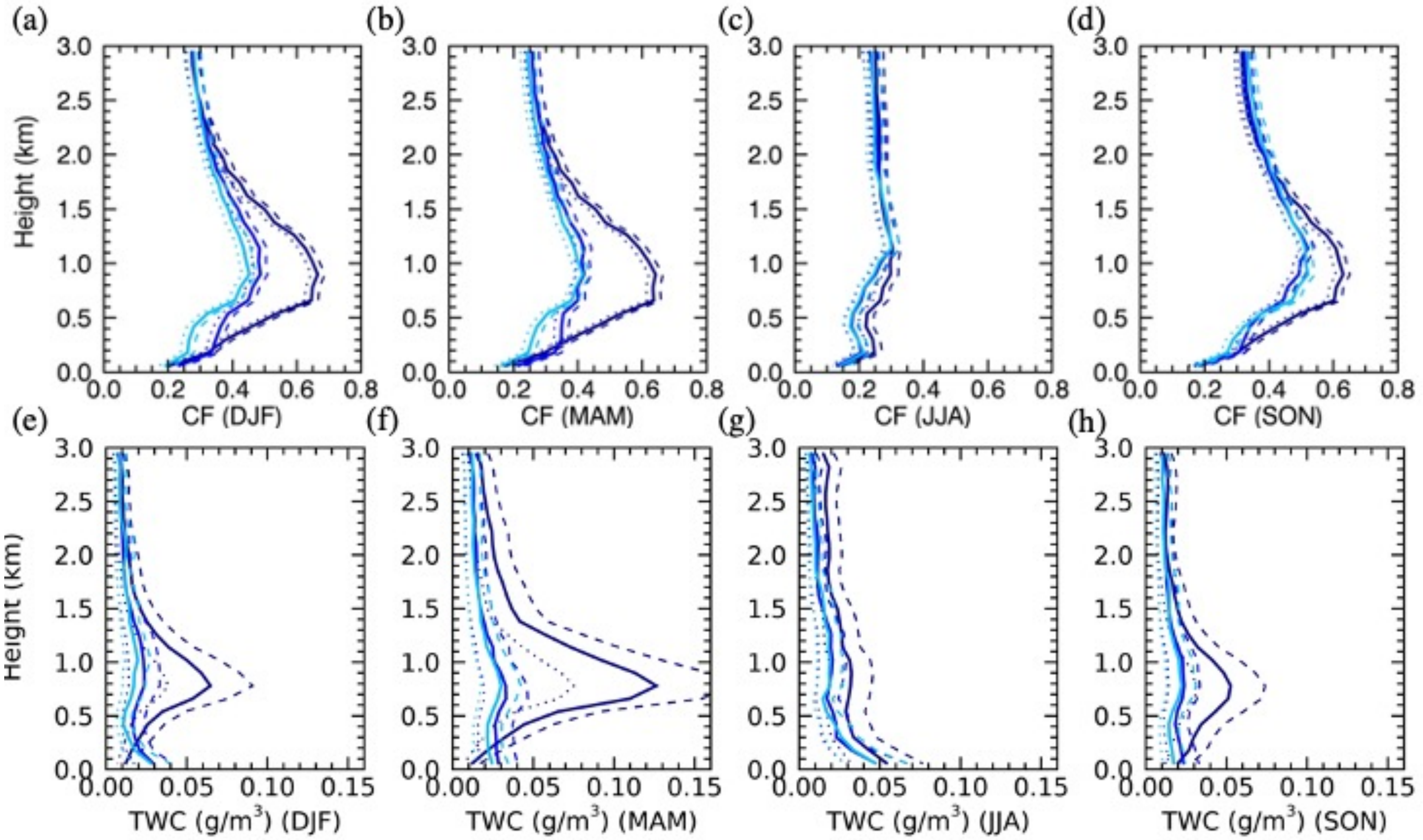
We leverage data fusion to advance cloud-sea ice interactions research.

# Results:

## Comparing cloud properties over ice-free and ice-covered ocean surfaces during MIZ crossing events

# 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: Methodology

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).

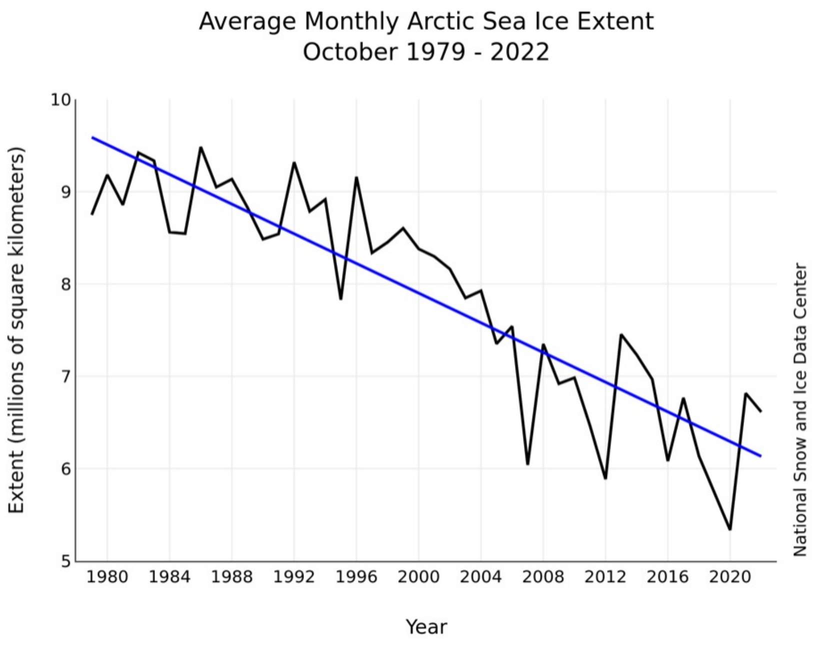
$$\delta CF_{Arctic}(z) = \delta SIC \left(\overline{CF_{ice-covered}}(z) - \overline{CF_{ice-free}}(z)\right) \quad (3)$$

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

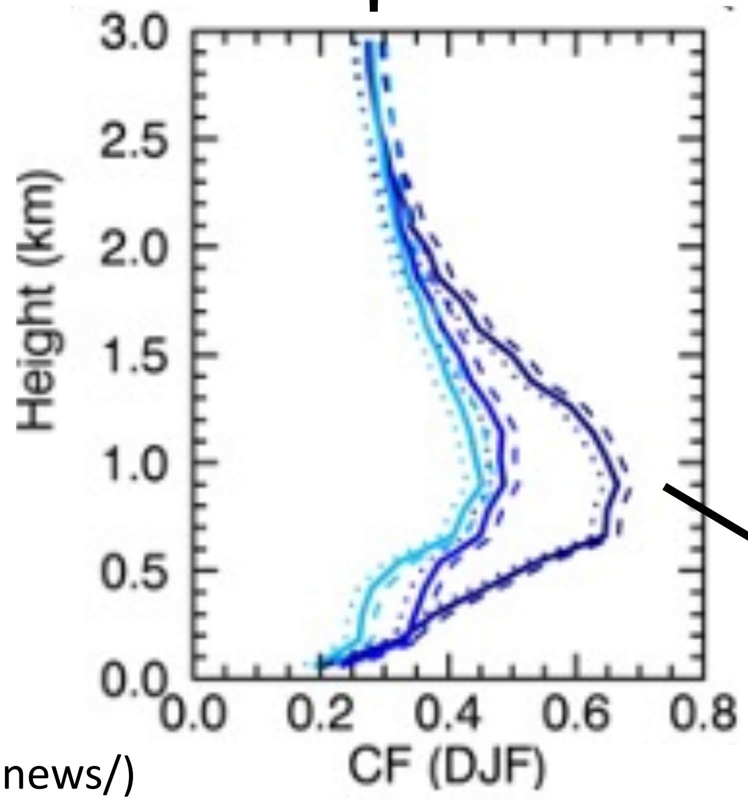
# Observational estimate of sea ice cloud feedback: Application

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

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




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

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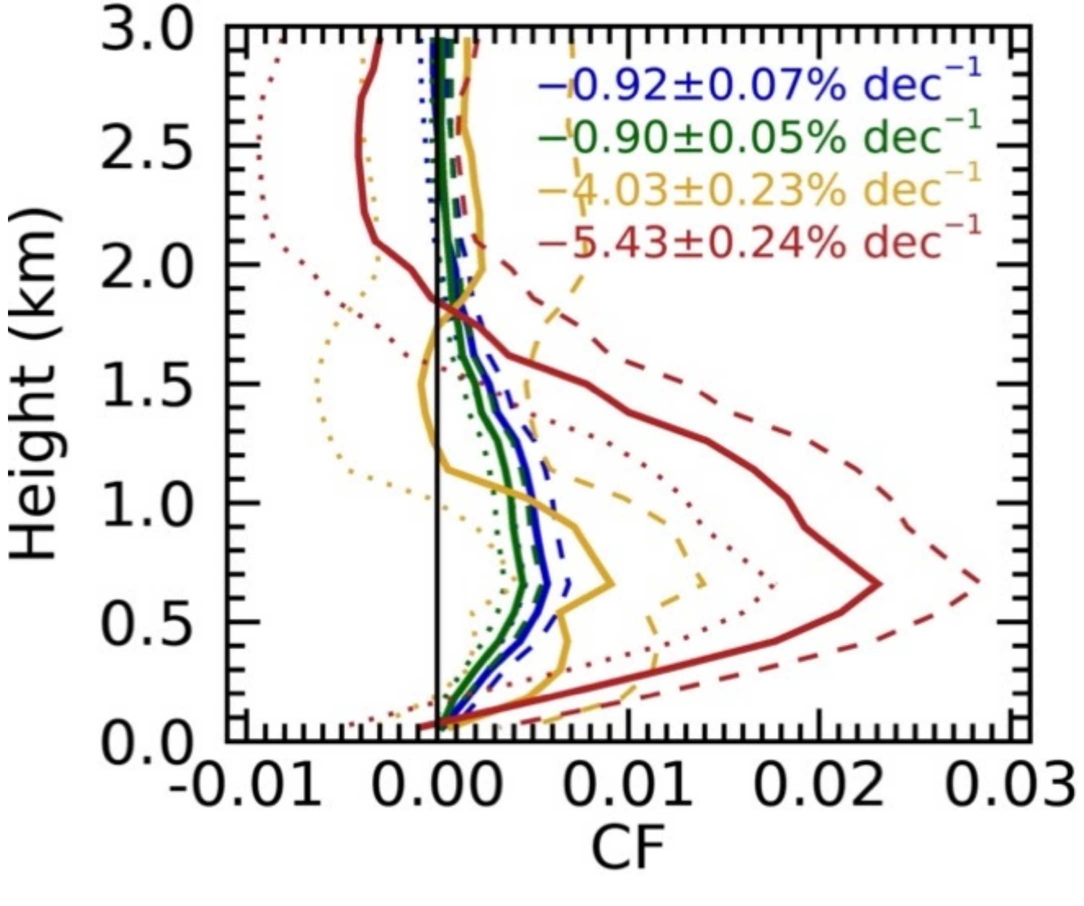
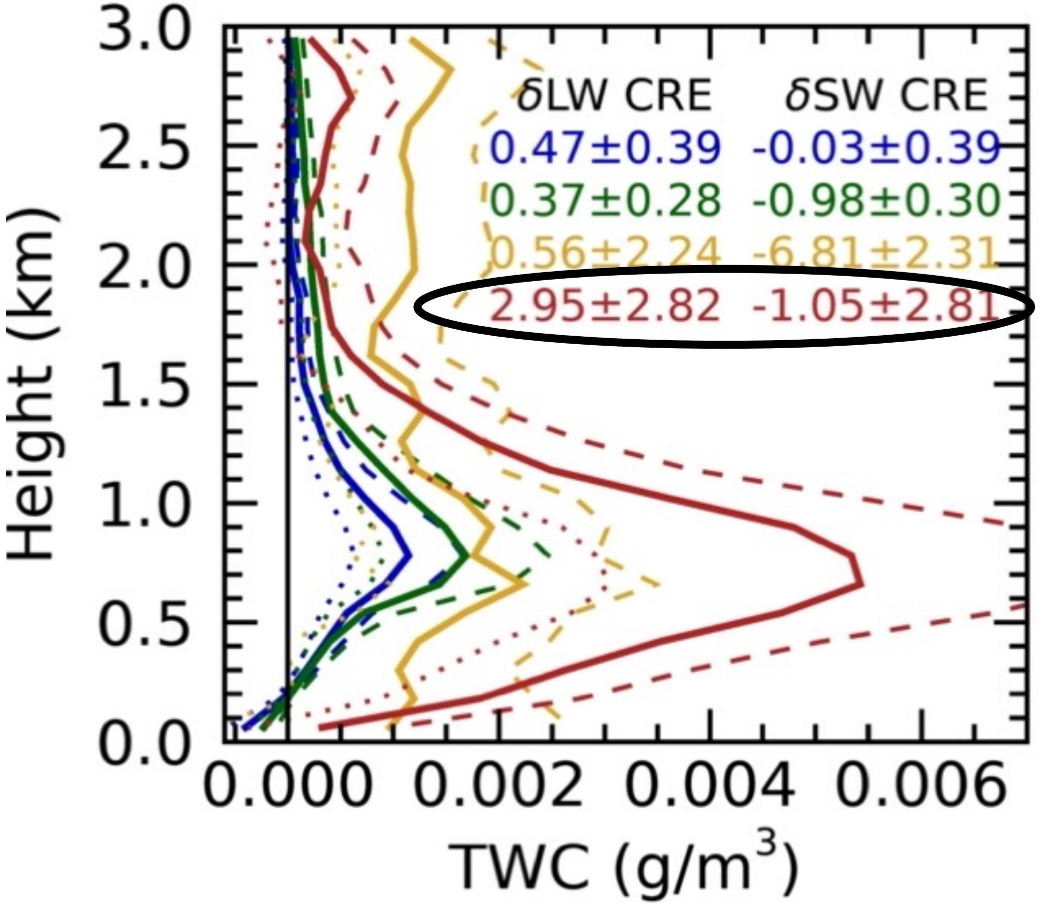
Observational estimate of the 20-yr cloud response to observed sea ice loss.

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

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



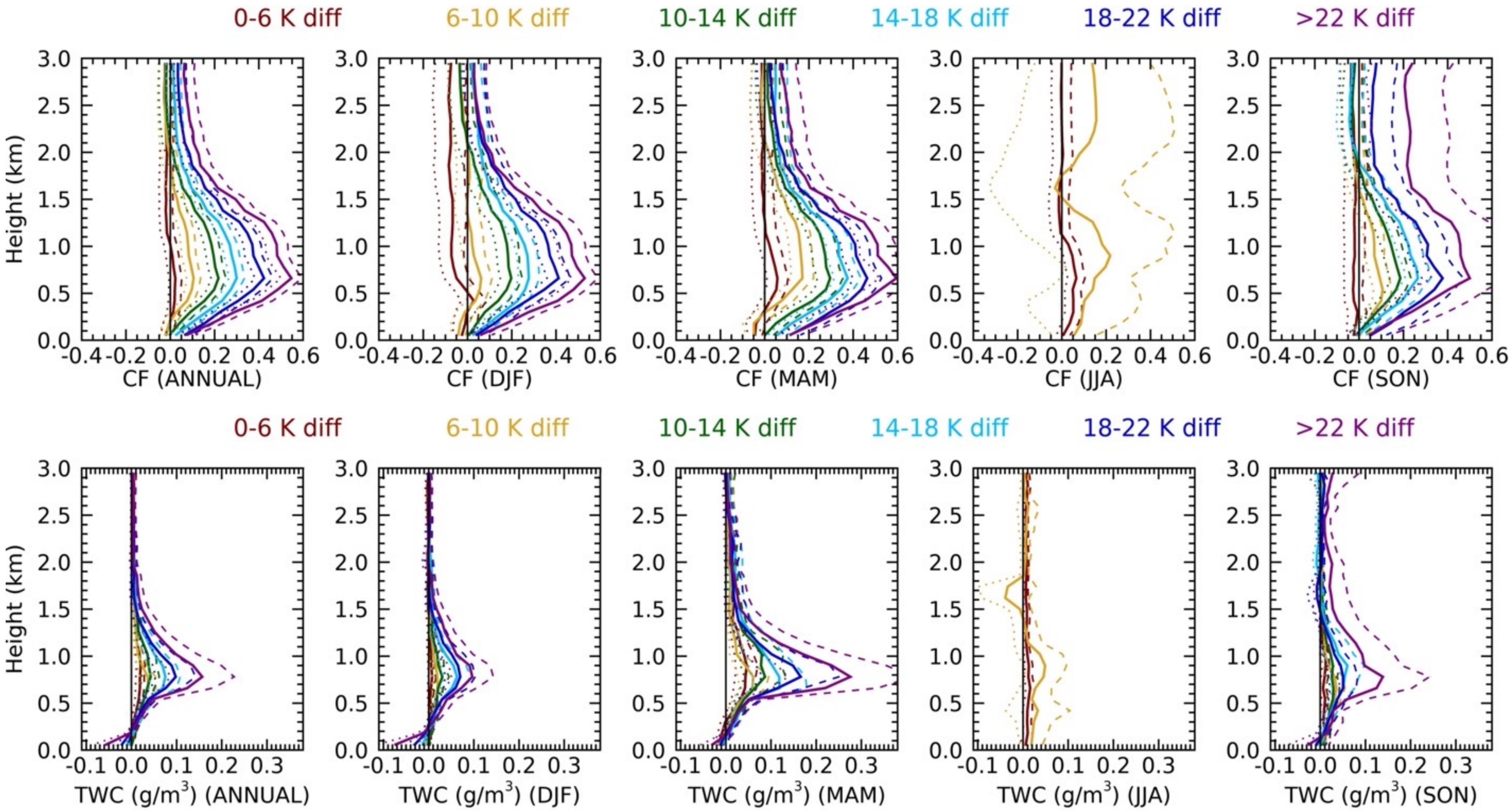




Estimated increase in surface LW CRE of ~3 $Wm^{-2}$ due to the sea ice-cloud feedback,

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.

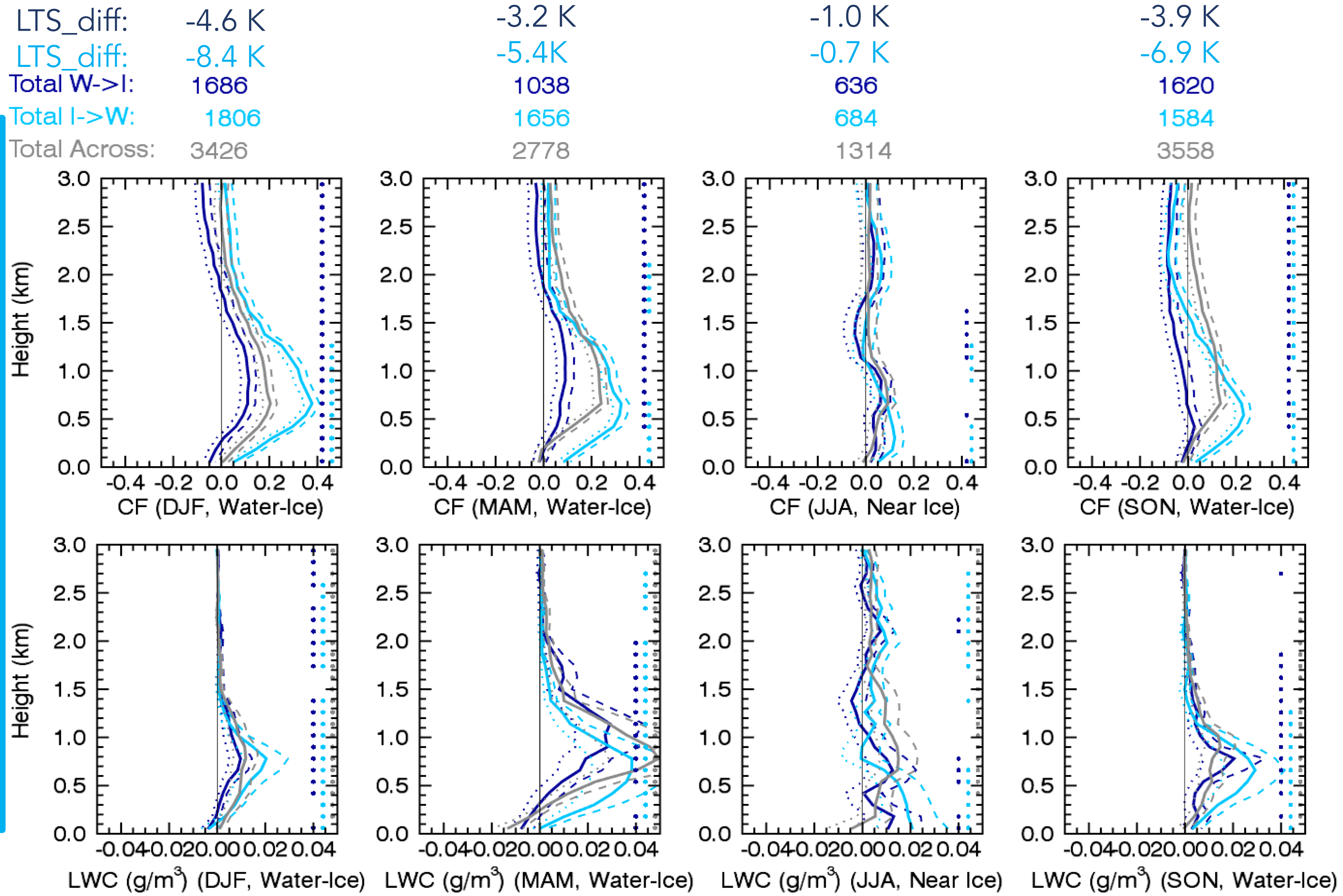
# Conclusions

- 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.
- **Takeaway: 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.**

# Stratifying by wind direction

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

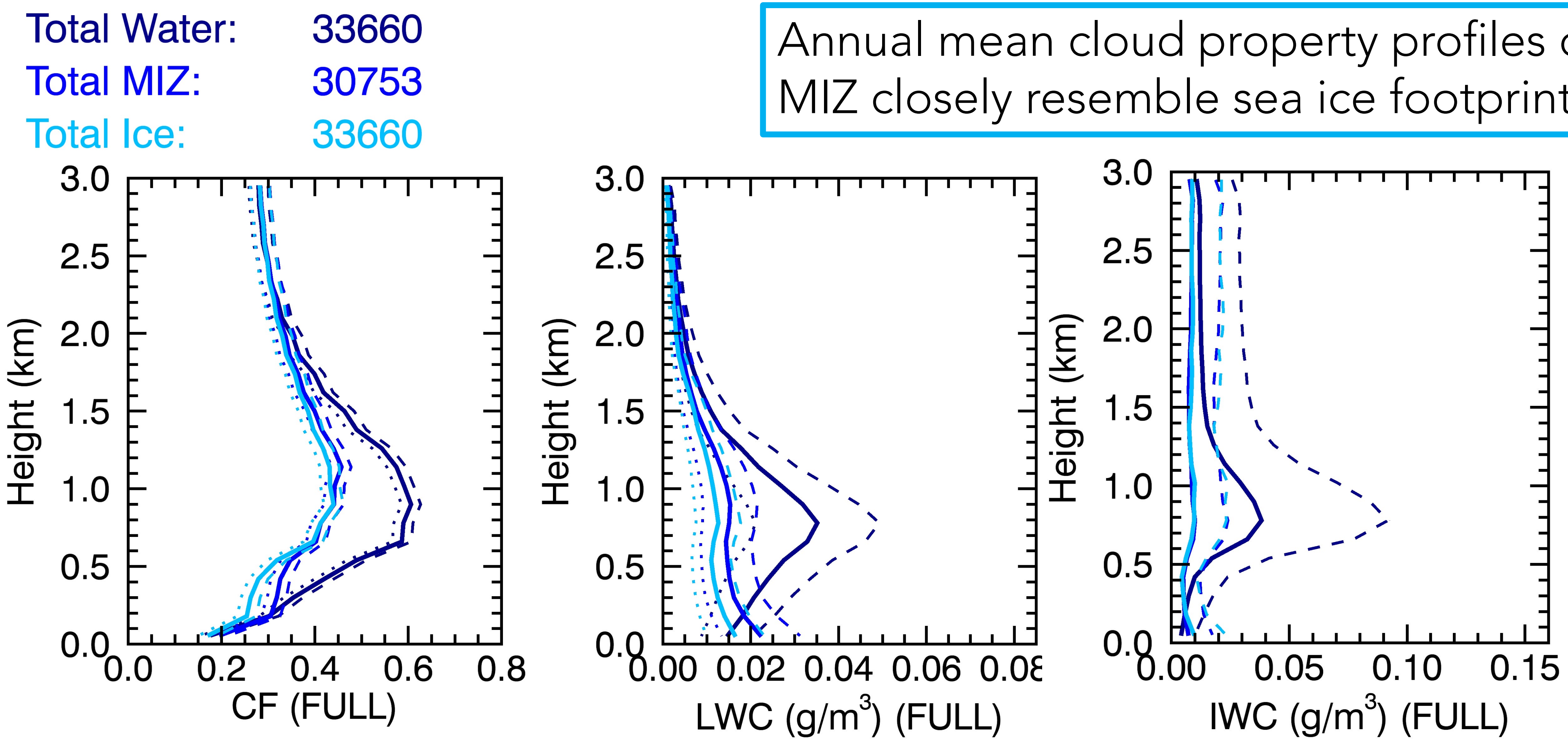
- Water-to-ice winds—weak surface turbulent fluxes
- Ice-to-Water winds—strong surface turbulent fluxes.




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

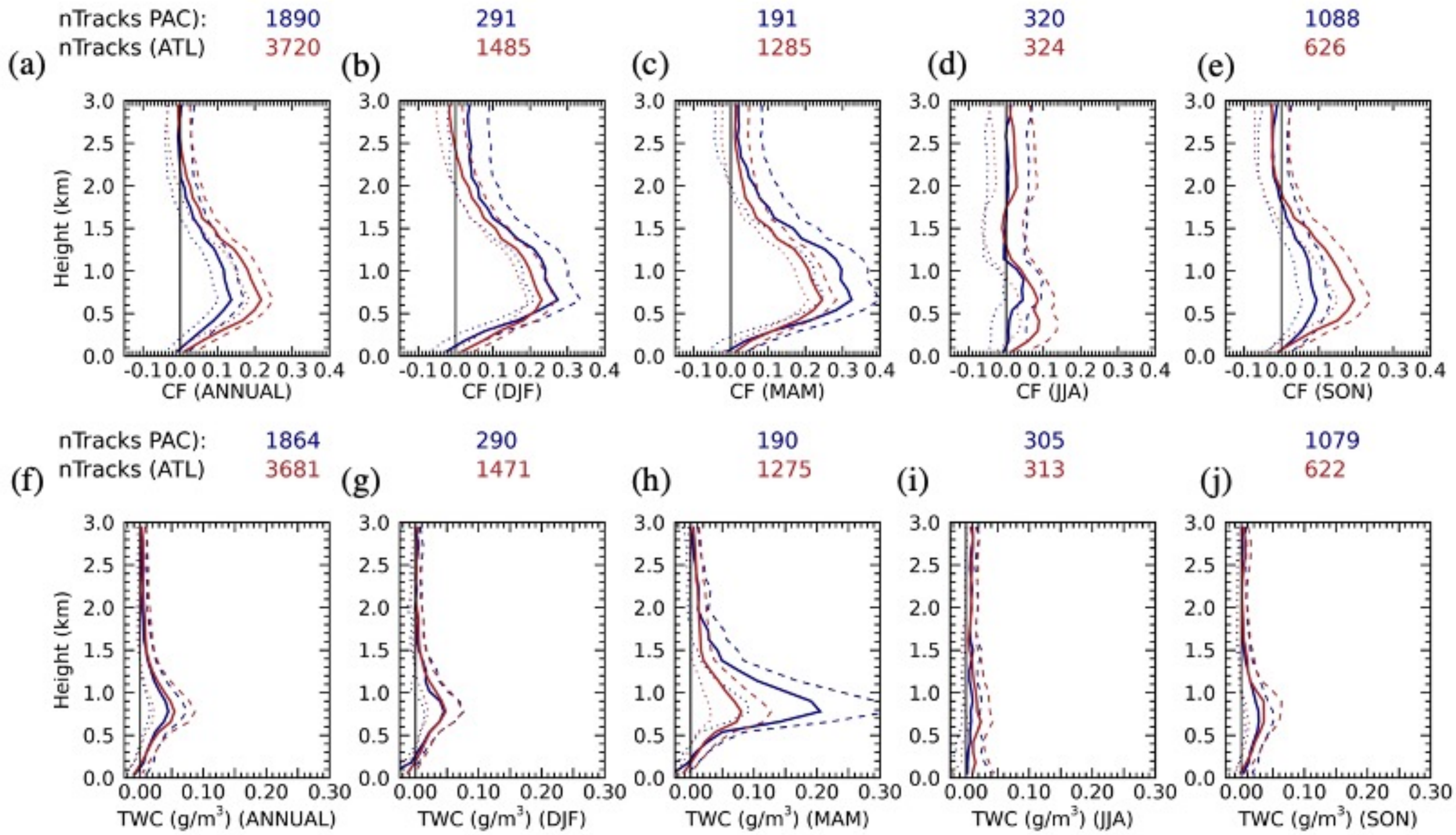
Annual mean cloud property profiles over the MIZ closely resemble sea ice footprints.




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.

# Pacific vs. Atlantic Sectors

- Greater differences between water and sea ice cloud properties in the ATL vs. PAC in annual mean.
- Differences vary strongly by season as does the number of samples.

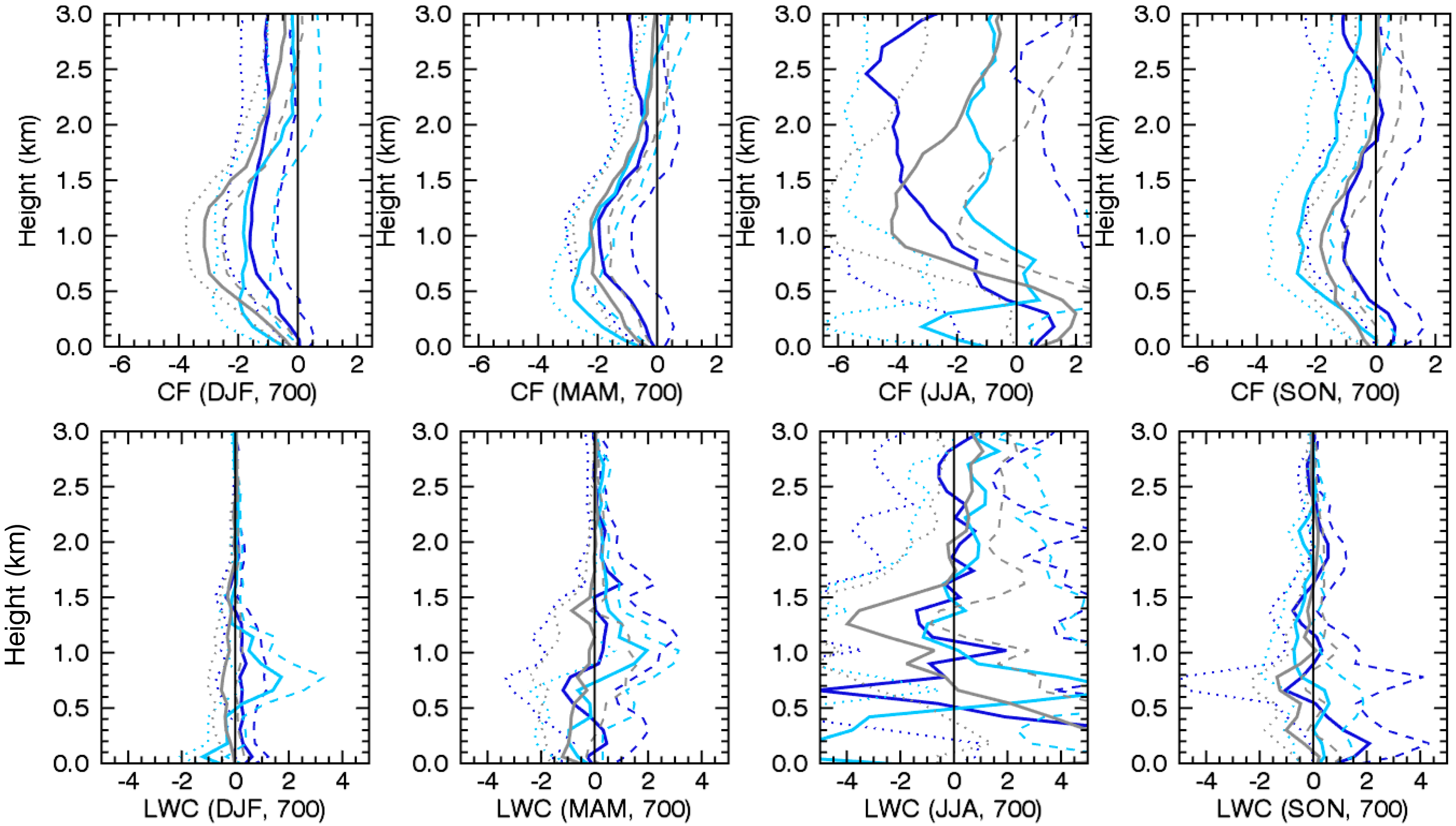



While the results point to some regional differences generally the differences between the Pacific and Atlantic sectors are statistically indistinguishable.

# Role of Lower tropospheric stability: stratifying by wind directions

Lower Tropospheric Stability (LTS) = ($\theta$_plev- $\theta$_sfc), $\theta$=> 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.



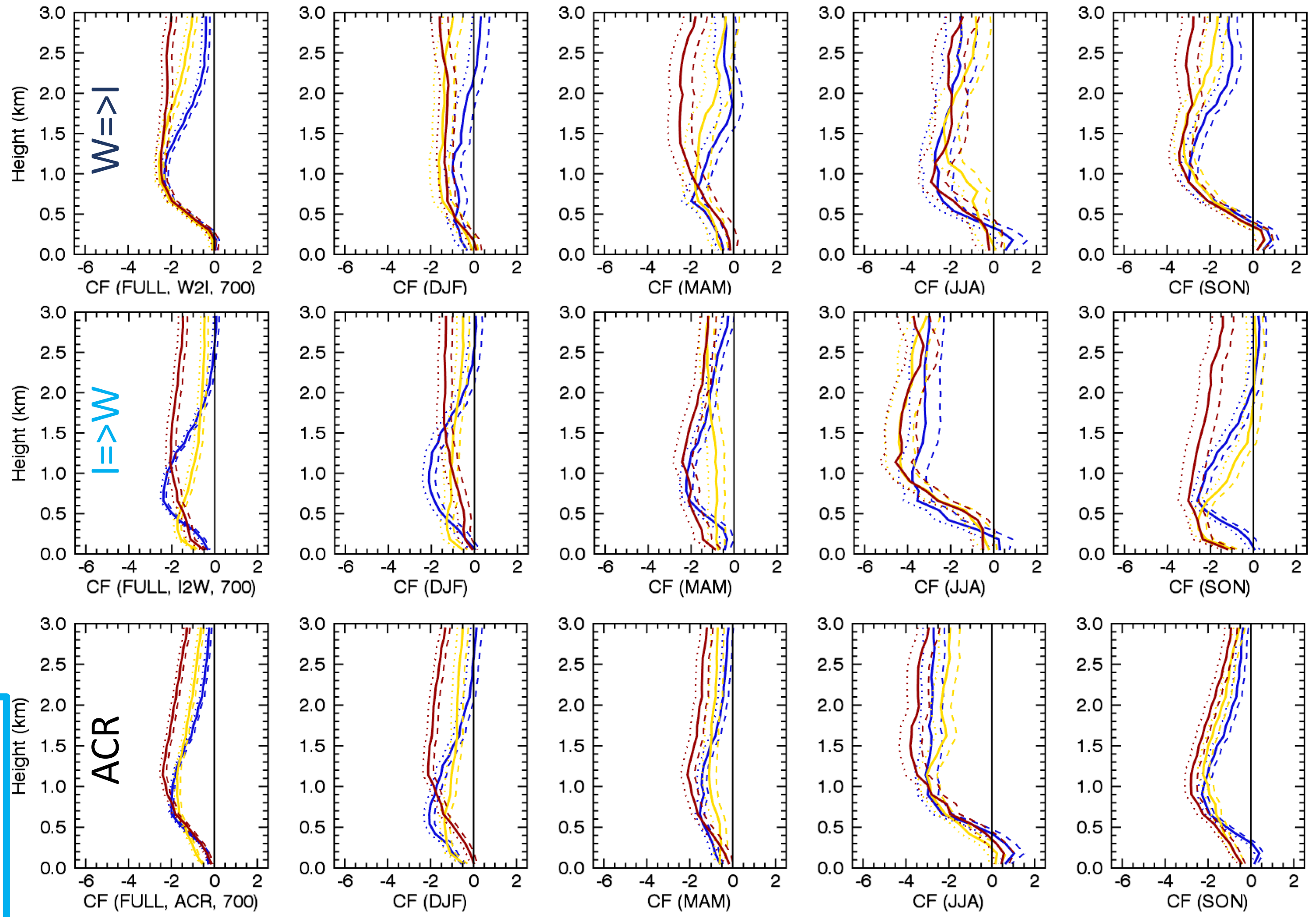

Lower tropospheric stability can be used as a diagnostic to capture the processes that drive the surface type dependent cloud property differences.

# CF-LTS relationship during stratifying by wind direction

WATER
MIZ
ICE

Lower Tropospheric Stability (LTS) = ($\vartheta$_plev- $\vartheta$_sfc), $\vartheta$=> potential temperature

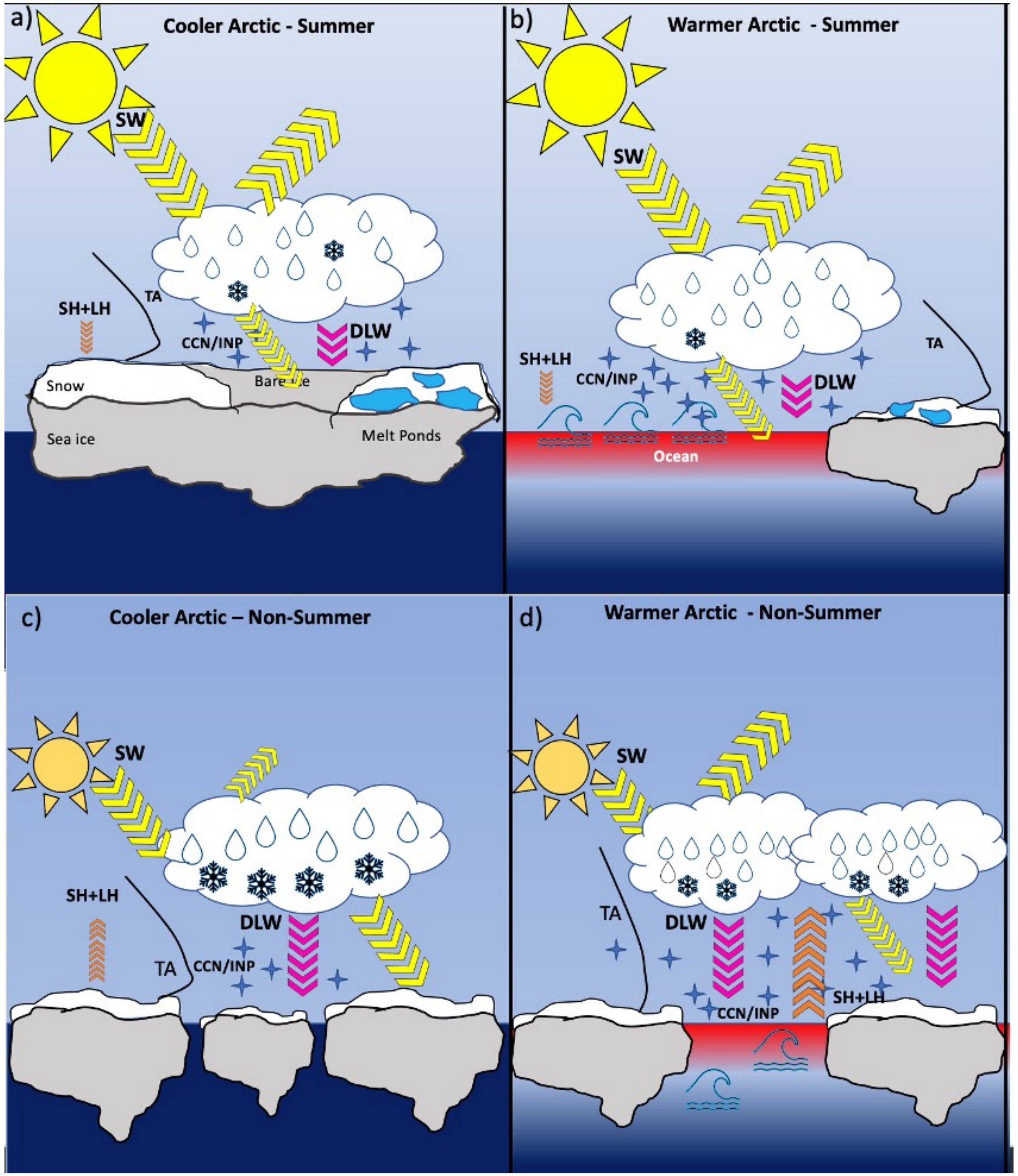
- Shown are regression relationships between CF and LTS for each wind direction and surface type.
- The regression relationships between CF and LTS are found to vary weakly with surface type and wind direction.




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

# Cloud processes and Arctic climate change: How much do they matter?

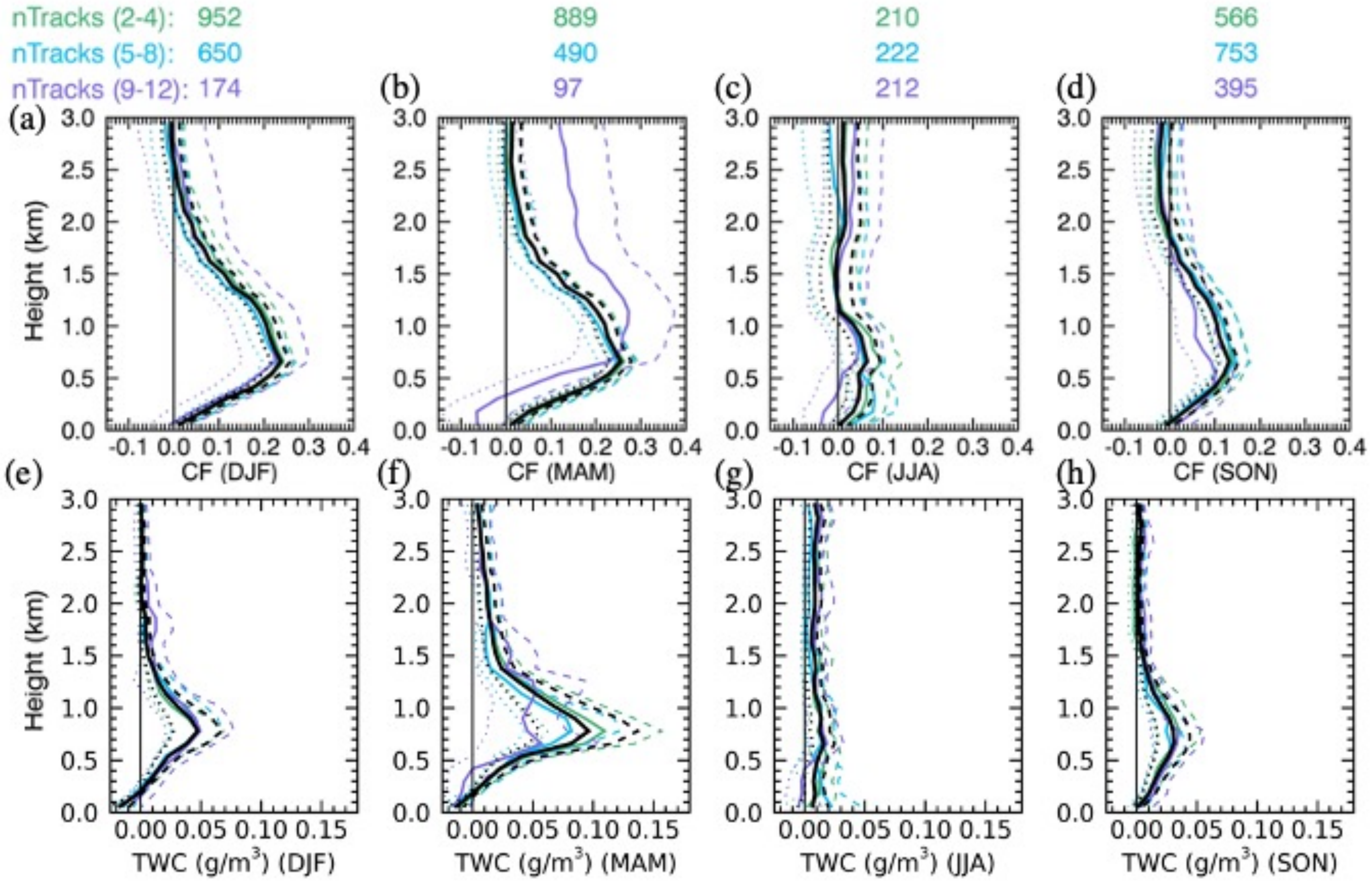
- There are many mechanisms through which clouds influence and are influences by the Arctic climate.
- Here we focus on the cloud-sea ice interaction mechanism of cloud feedback, where cloud properties are hypothesized to change in response to the transition from a sea ice to an ice-free ocean surface.




Taylor et al. (2022; Frontiers Earth Science)

# 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.



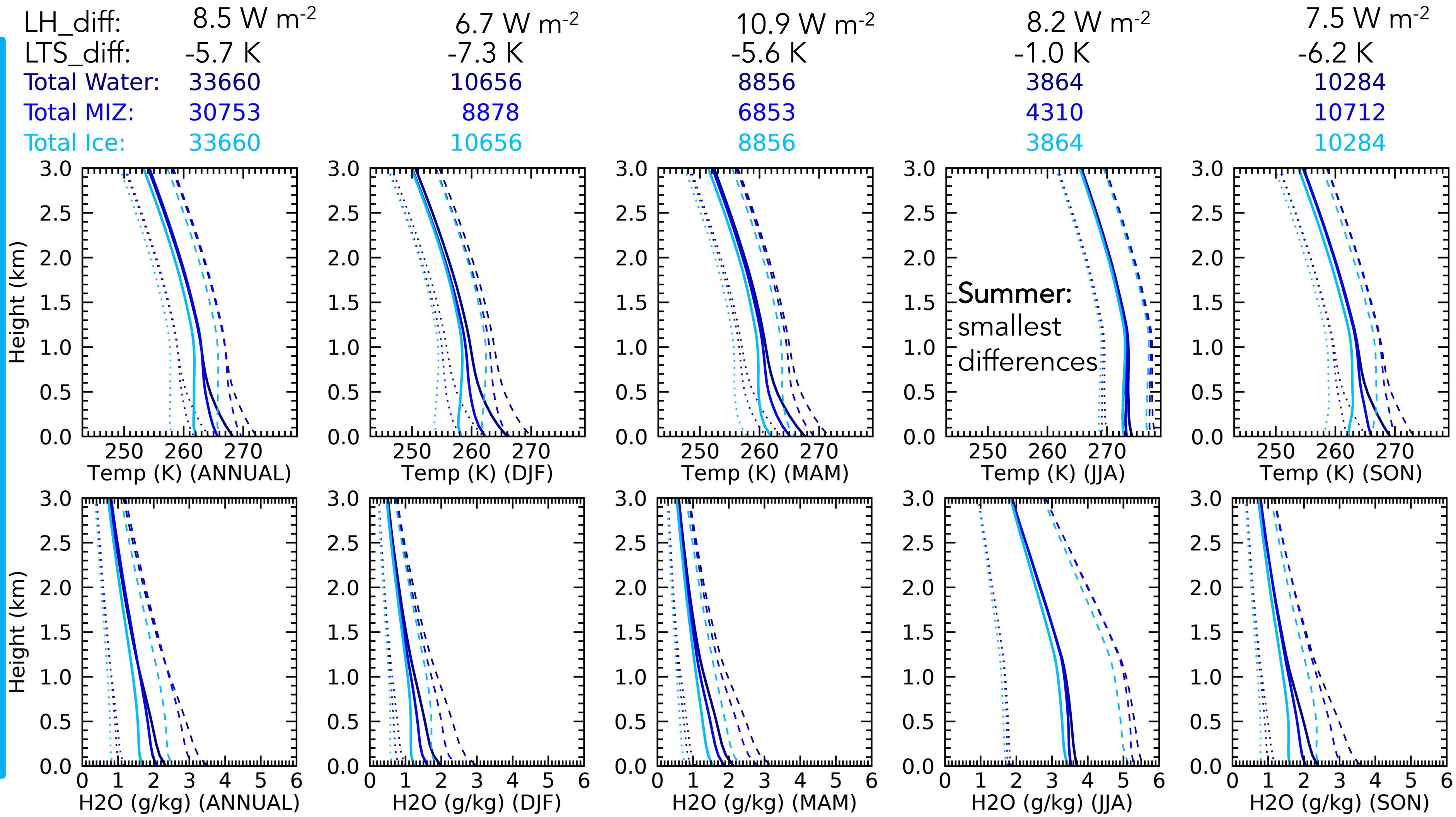

Results insensitive to MIZ widths 2-12 footprints (40-240 km).

# Interpretation:

What controls the magnitude of the ice-free minus ice-covered surface cloud property differences?

# 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.

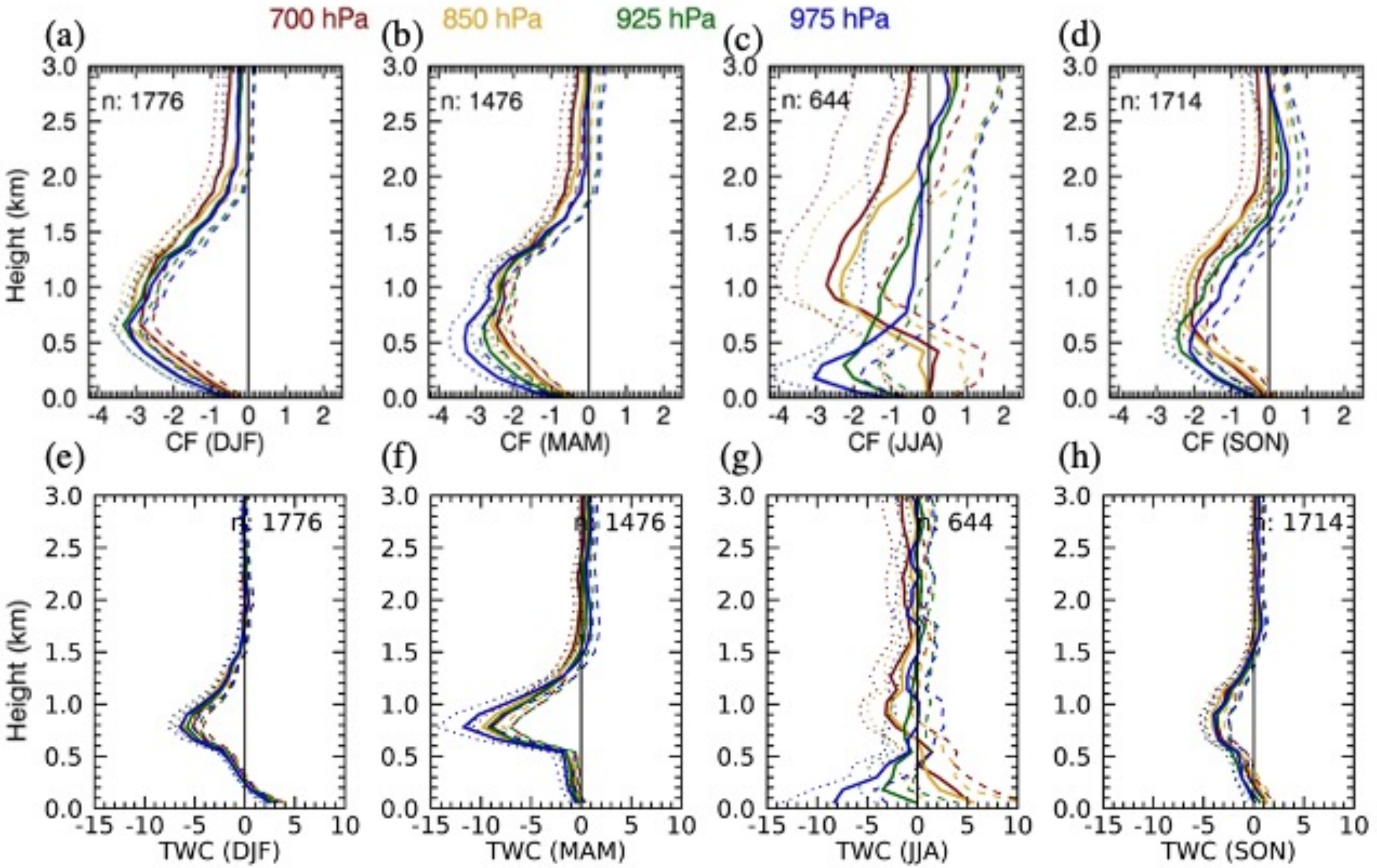



Surface type influences cloud properties through modulations of the lower tropospheric thermodynamic structure.

# Surface type cloud differences metric

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

- Shown are regression relationships between cloud property and LTS differences.
- Surface-type differences in the **cloud fraction and TWC vertical profiles** are largely explained by the differences in LTS in non-summer months.

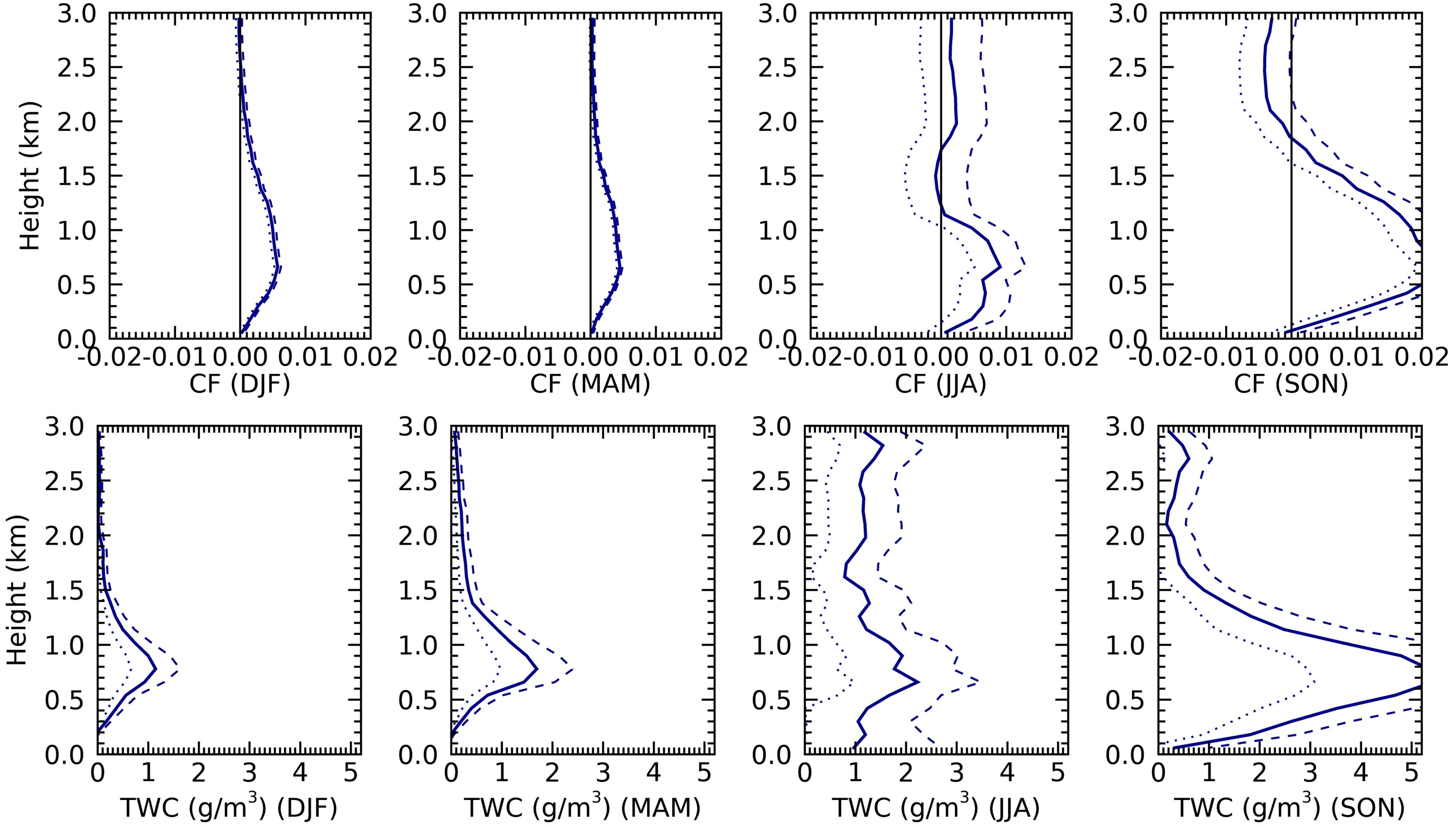



Differences in LTS significantly contribute to the variability in ocean minus ice Cloud Fraction differences and are not as important for LWC

# 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.