Covariance between Arctic low clouds and sea ice in observations and climate models

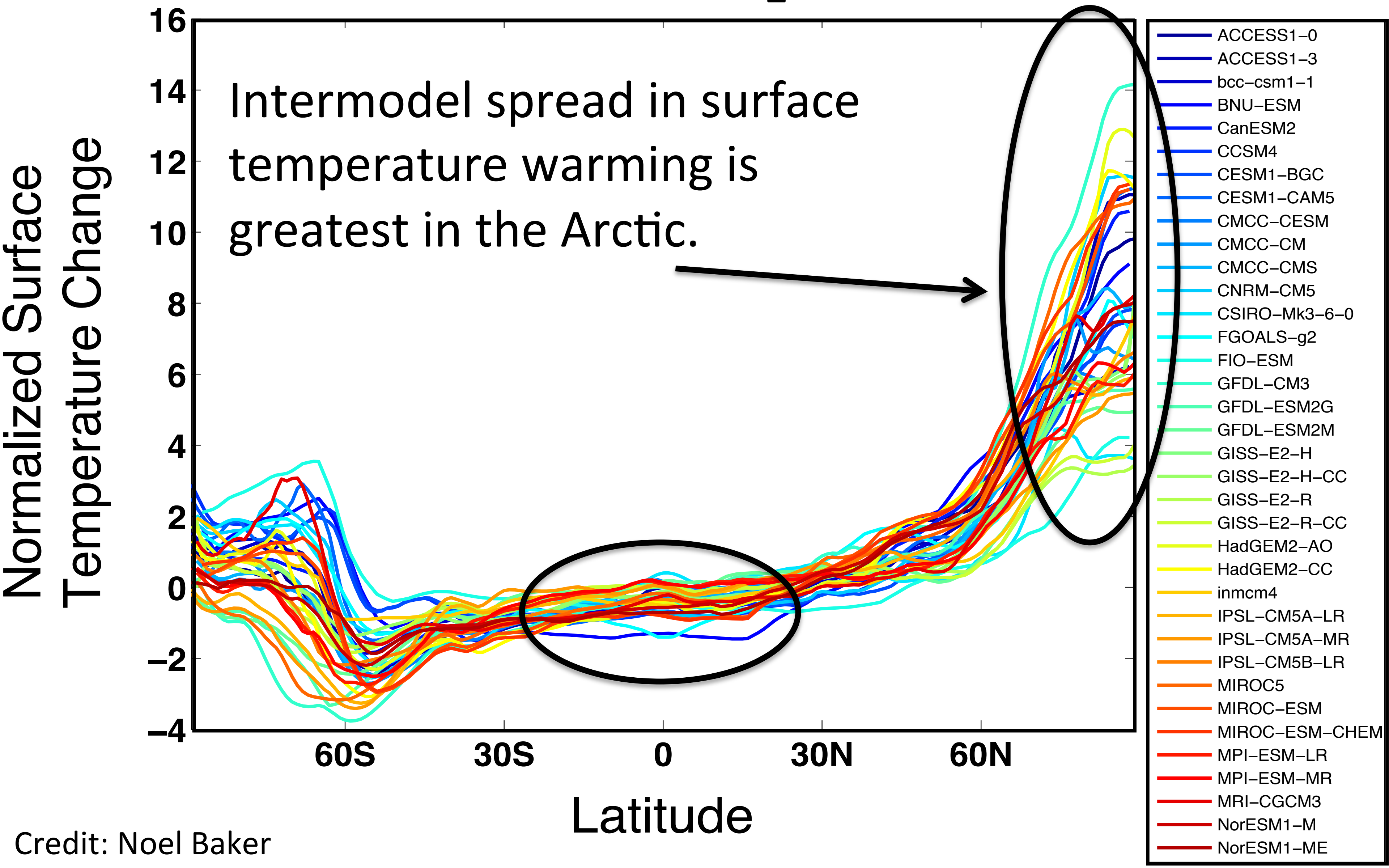
Patrick C. Taylor
NASA Langley Research Center
Climate Science Branch
9 June 2015
patrick.c.taylor@nasa.gov

Work supported by the NASA Interdisciplinary Studies in Earth Science Program

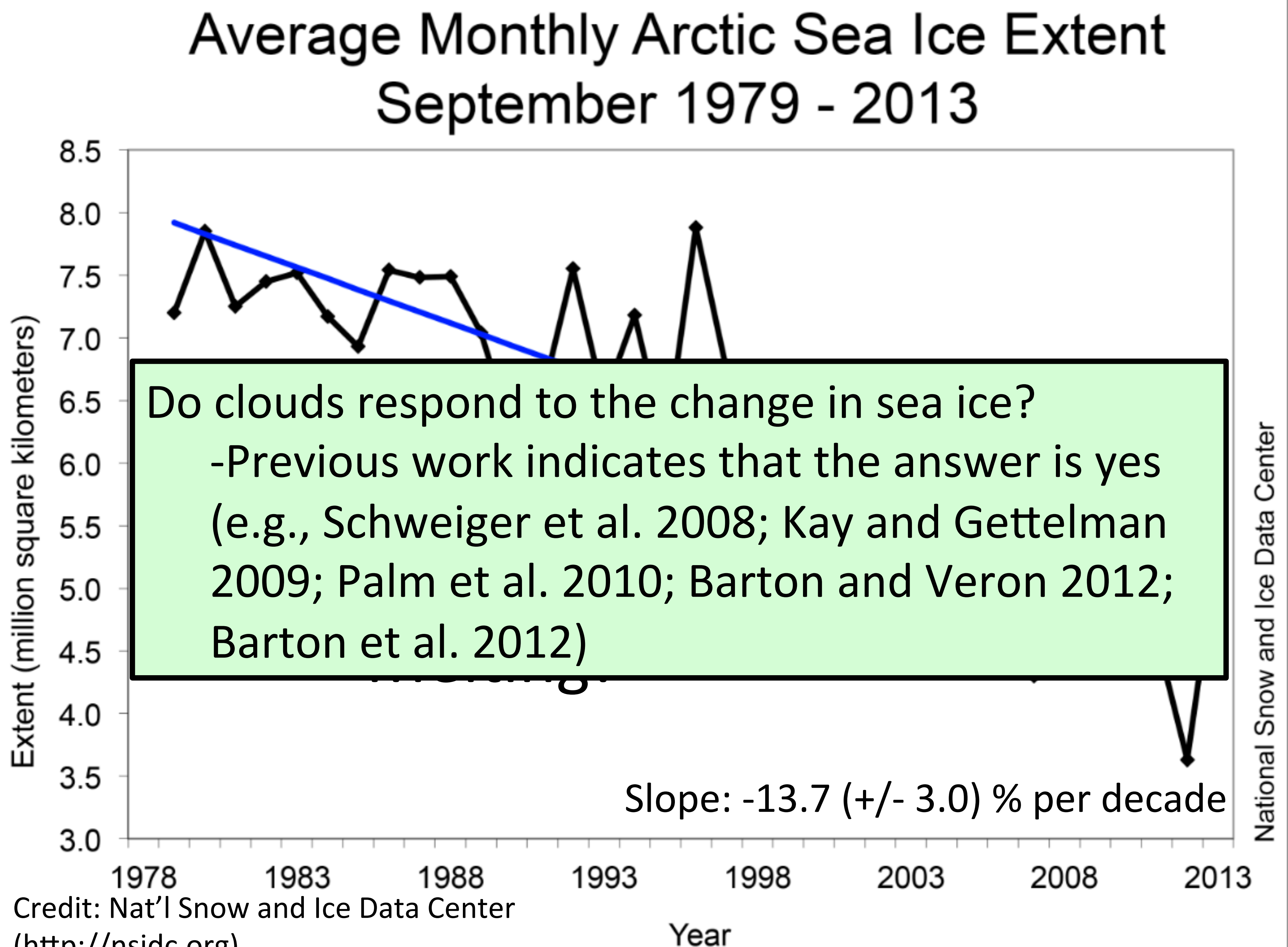
Picture Credit: NSIDC website

Acknowledgements: Robyn Boeke, Seiji Kato, Kuan-Man Xu, Noel Baker, and Ming Cai

Zonal mean Surface Temperature Response (1% per year CO_2 increase)



Credit: Noel Baker



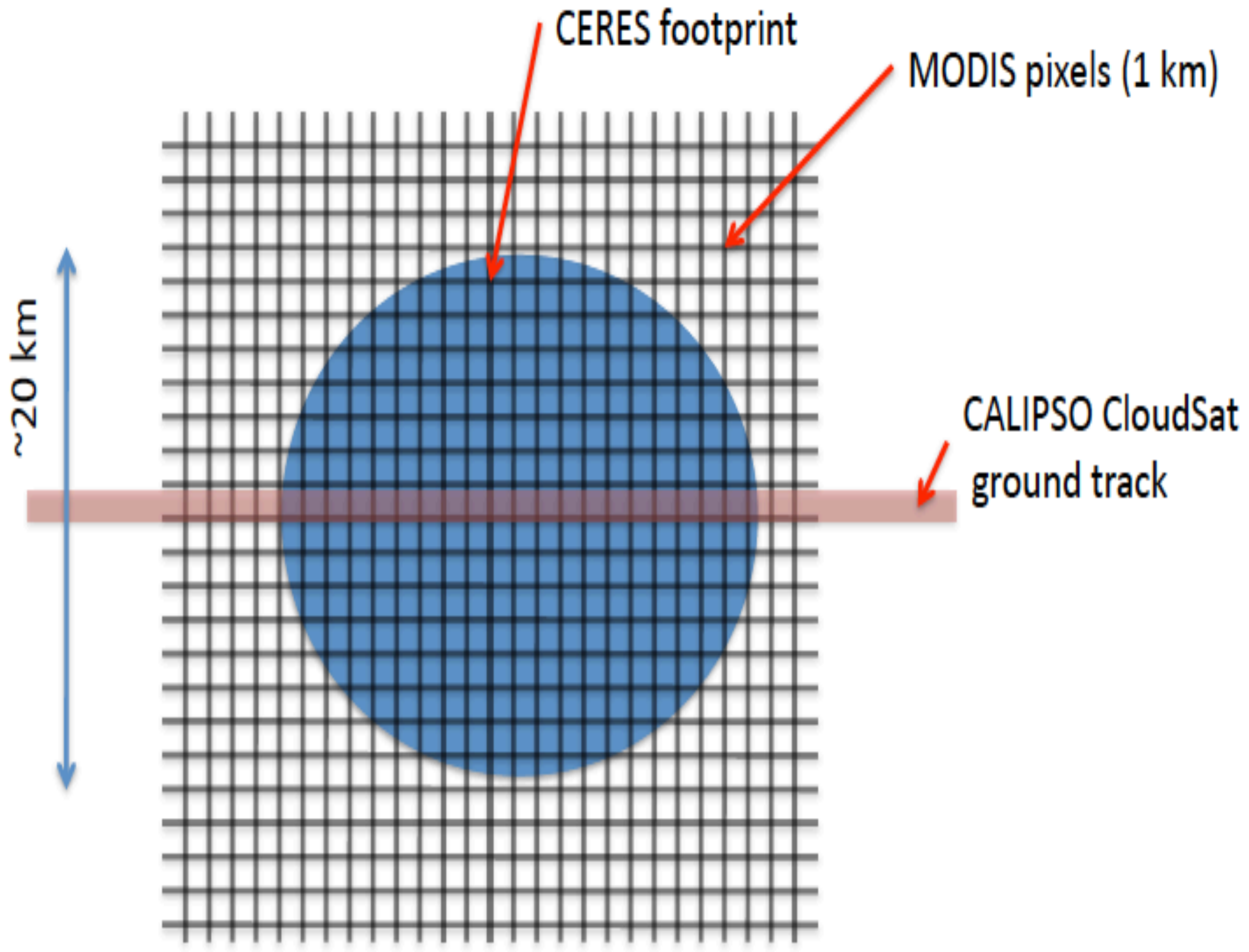
Do clouds respond to the change in sea ice?

-Previous work indicates that the answer is yes (e.g., Schweiger et al. 2008; Kay and Gettelman 2009; Palm et al. 2010; Barton and Veron 2012; Barton et al. 2012)

Slope: -13.7 (+/- 3.0) % per decade

Credit: Nat'l Snow and Ice Data Center (http://nsidc.org)

CALIPSO-CloudSAT-CERES MODIS (C3M) Merged Data Product (Kato et al. 2010)

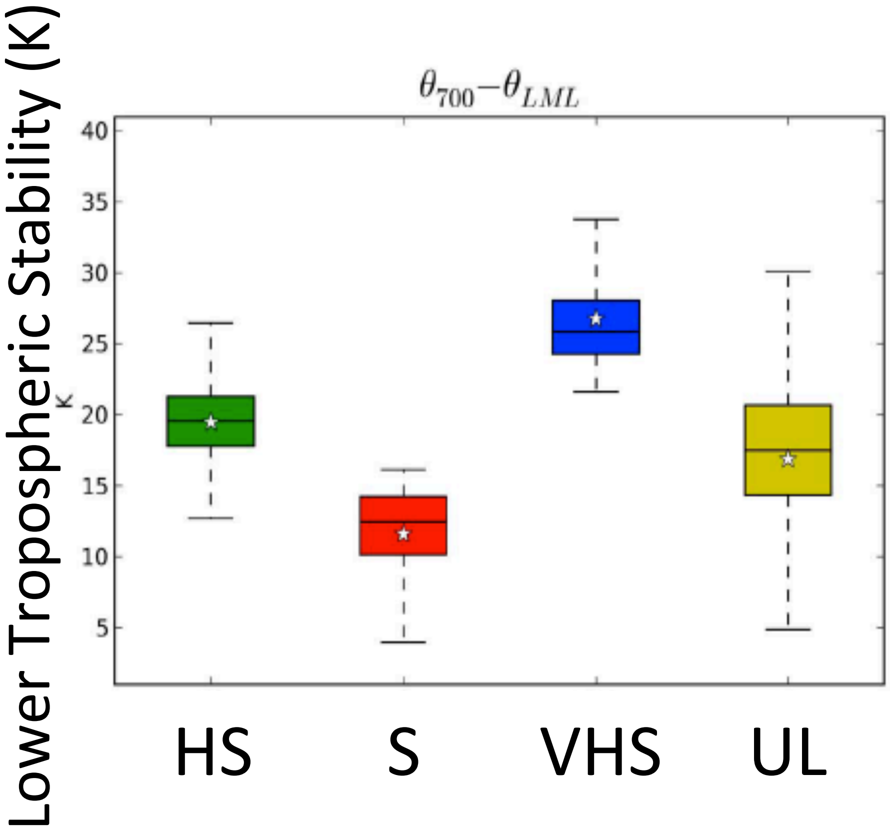


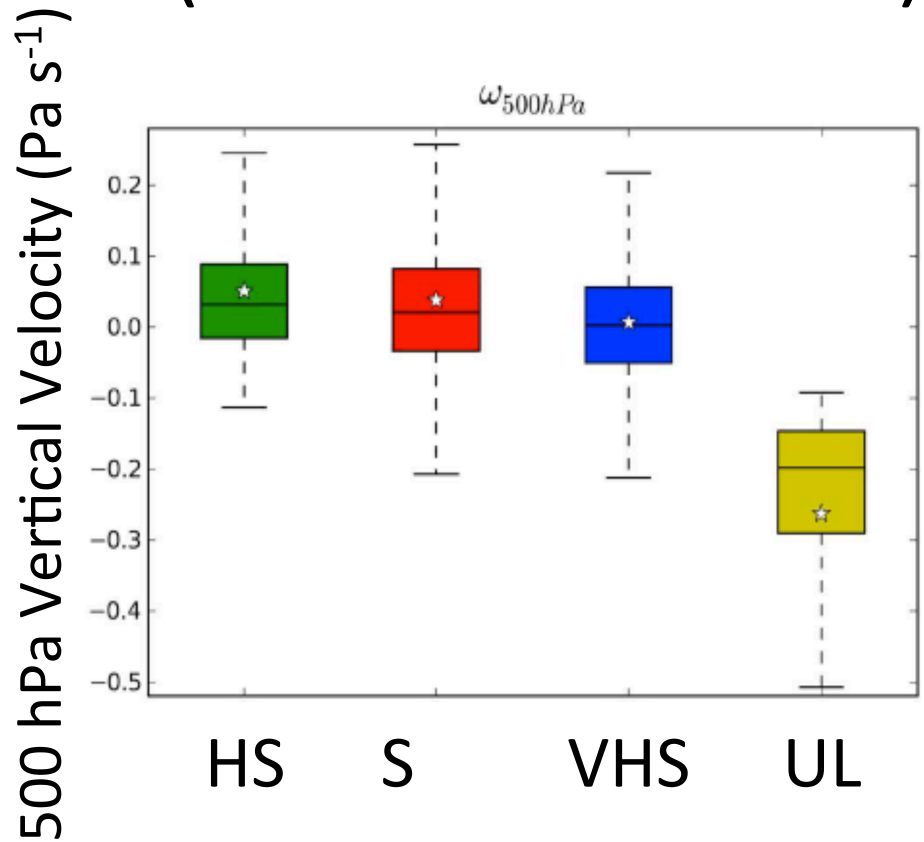
Data contains footprint averaged

1. Merged CALIPSO-CloudSAT vertical cloud property profiles (cloud fraction, LWC, IWC)
2. Computed vertical radiative flux profiles computed with CALIPSO and CloudSat derived cloud properties
3. Sea ice concentration (SSM/I)

Data are available from the NASA Langley ASDC: http://eosweb.larc.nasa.gov/

Atmospheric State Regimes (Barton et al. 2012)

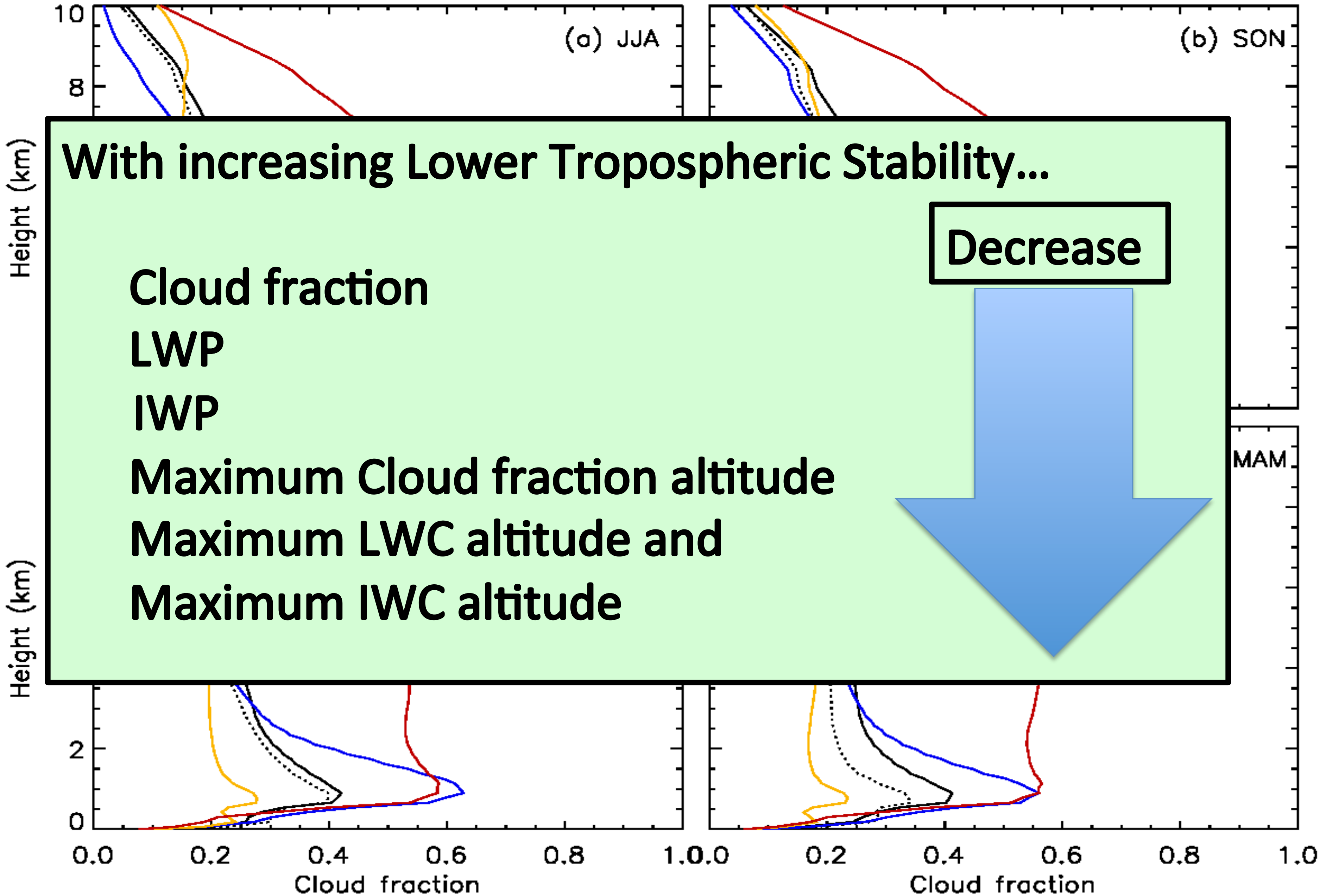




Atmospheric state regimes determined using K-means cluster analysis.

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}

Arctic Clouds and Meteorological State



With increasing Lower Tropospheric Stability…

Decrease

- **Cloud fraction**
- **LWP**
- **IWP**
- **Maximum Cloud fraction altitude**
- **Maximum LWC altitude and**
- **Maximum IWC altitude**

Compositing Method…

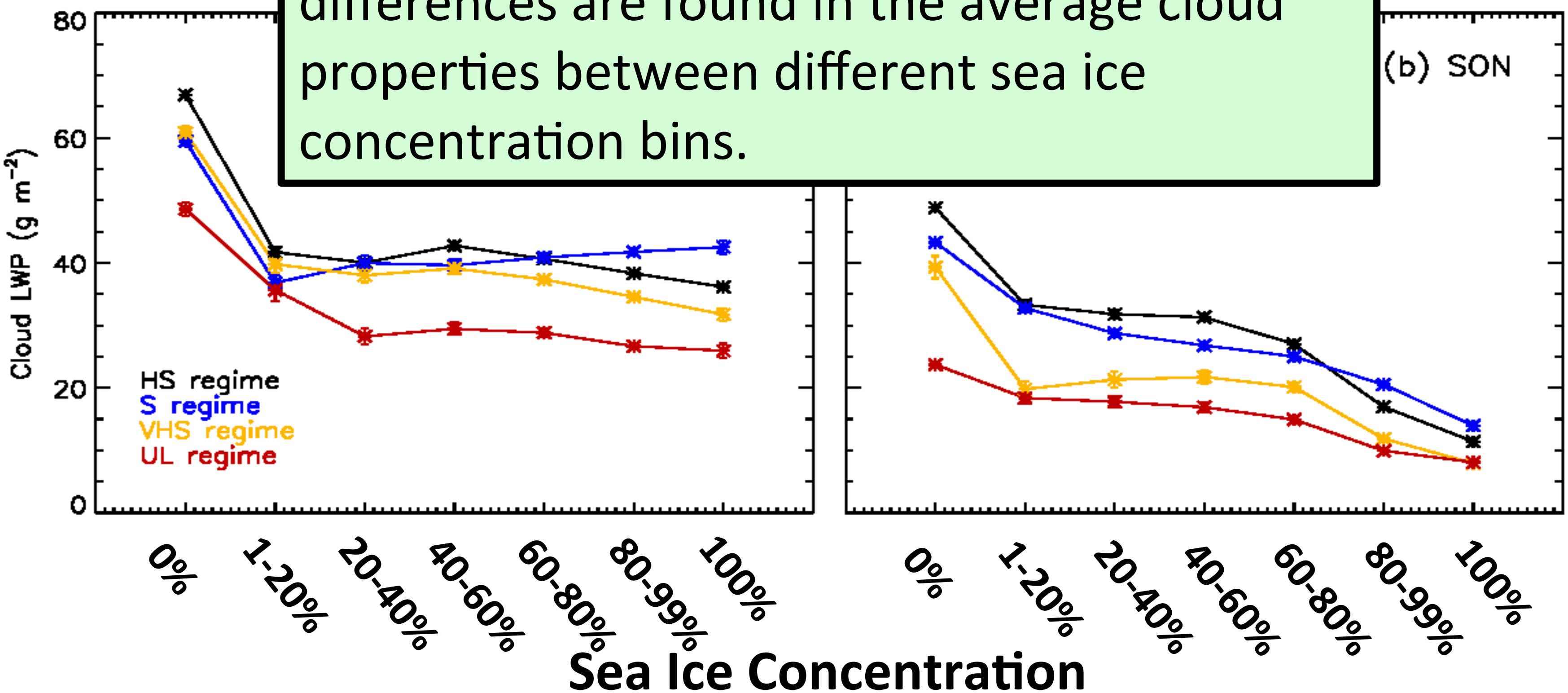
(1) Determine the Atmospheric Regime of each satellite footprint using MERRA

(2) Determine the instantaneous sea ice concentration from SSM/I retrieval

each

n bin

A covariance between clouds and sea ice is said to occur if statistically significant differences are found in the average cloud properties between different sea ice concentration bins.



Results: Low Cloud fraction vs. Sea ice Concentration

Cloud fracti
decreases
increasing

The magni
the cloud f
change wit
ice varies v
season and
atmospheric
regime.

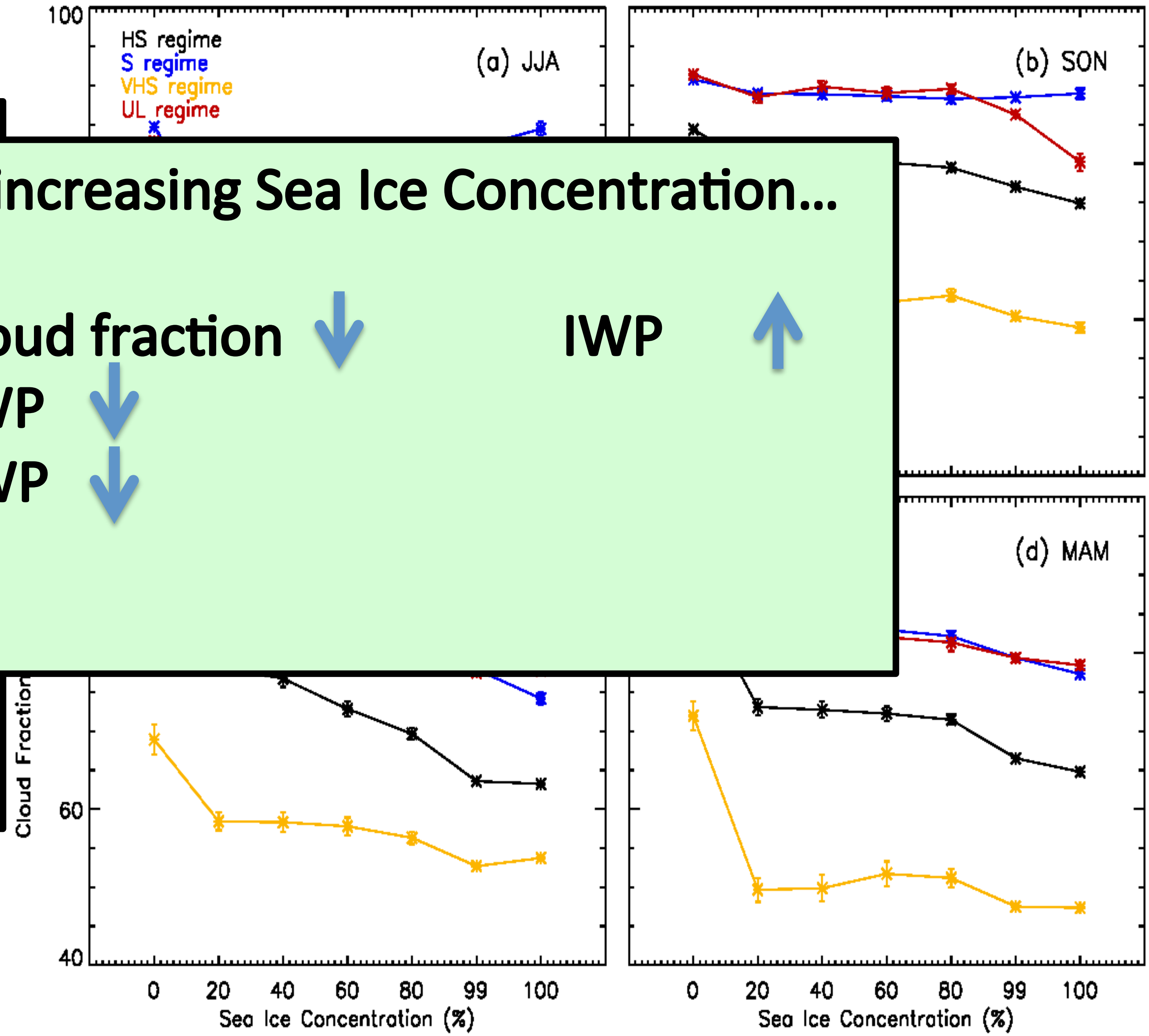
With increasing Sea Ice Concentration…

Cloud fraction ↓

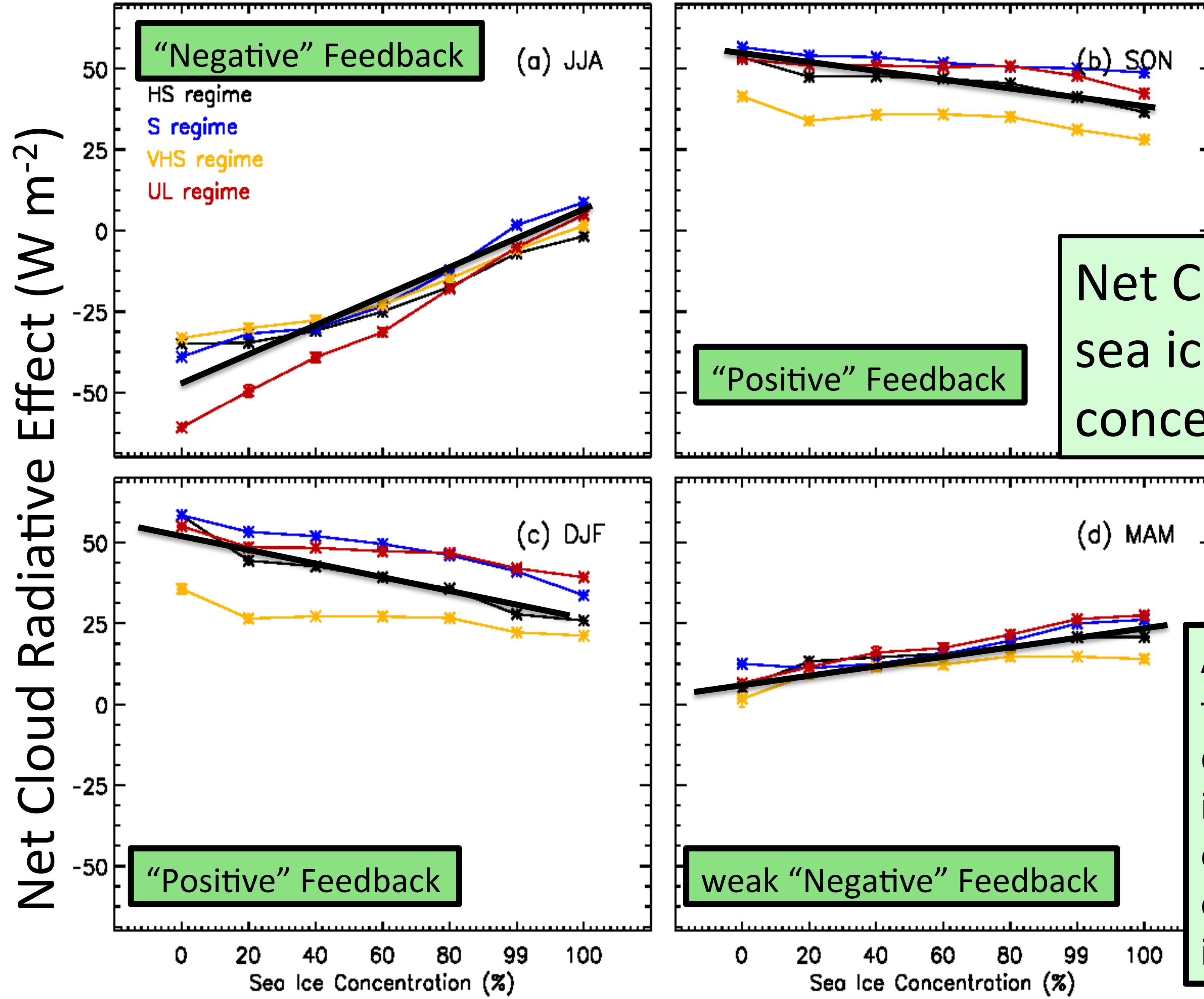
LWP ↓

TWP ↓

IWP ↑



$$\text{Net CRE} = (SW\downarrow - SW\downarrow_{clr\text{-}sky})\cdot(1 - \alpha) + (LW\downarrow - LW\downarrow_{clr\text{-}sky})$$



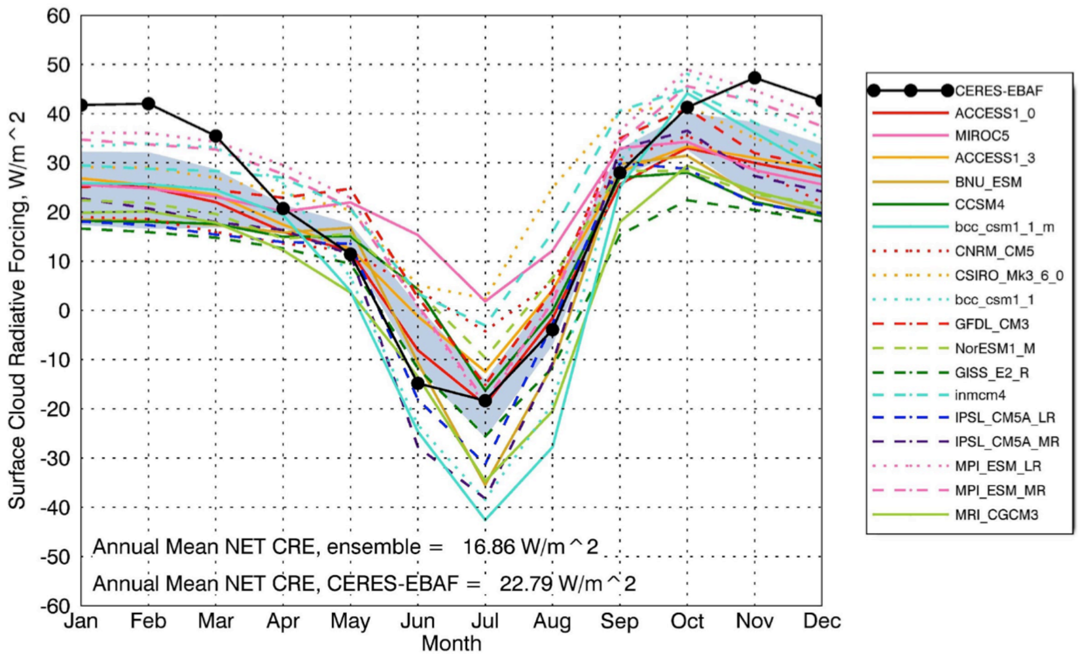
Net CRE vs. sea ice concentration

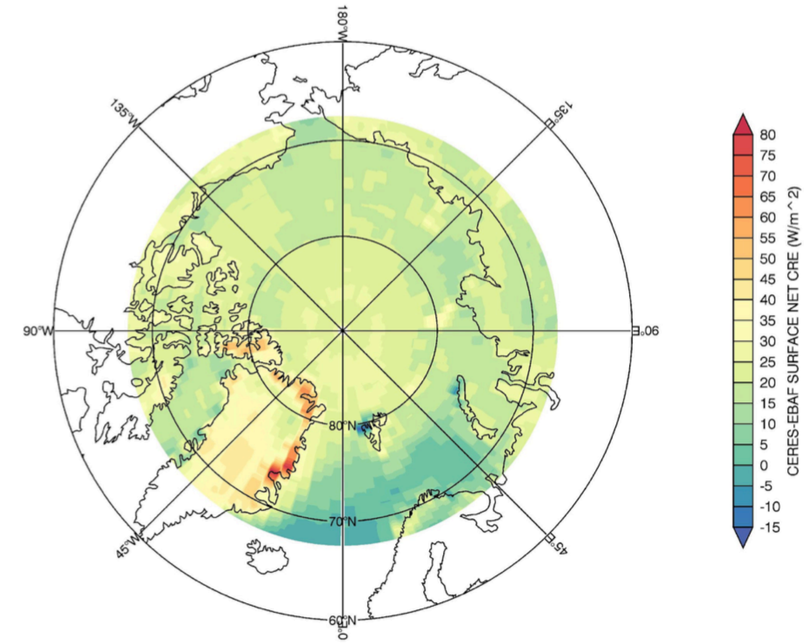
A cloud temperature decrease with increased SIC explains most of the change in LW CRE.

Climate model results: Seasonal Cycle

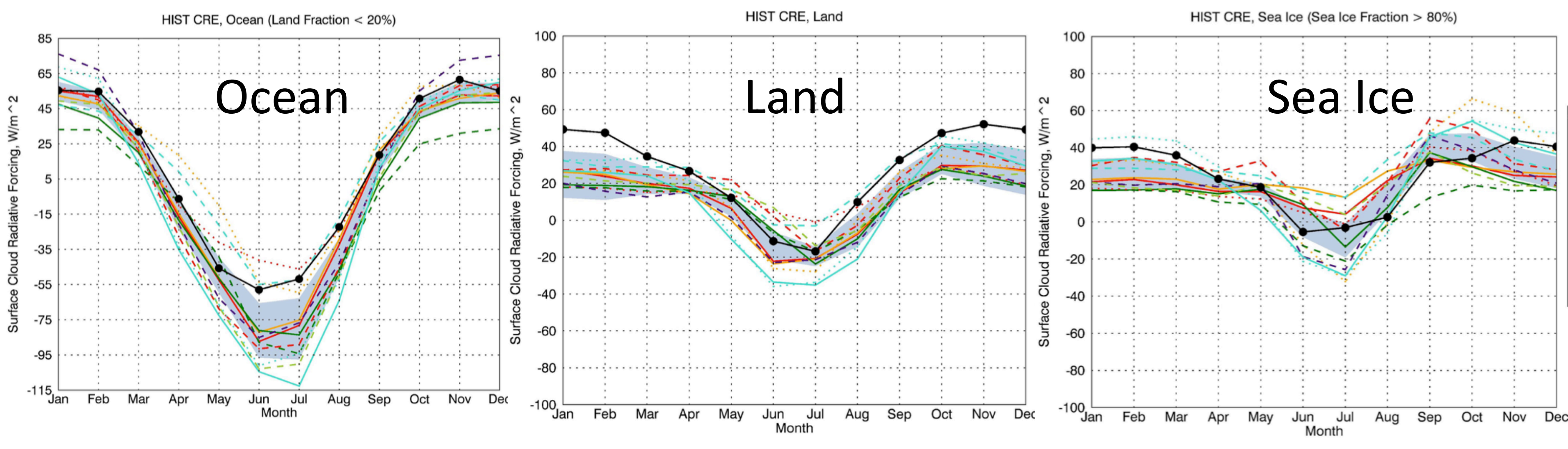
Historical Simulation vs. CERES EBAF Surface

Net Cloud Radiative Effect





Differences between model simulated and observed Net CRE vary with surface type.



What causes differences in LW CRE?

$$\text{LW CRE} = \text{LW}{\downarrow}_{all} - \text{LW}{\downarrow}_{clr} = N(F{\downarrow}_{cld,lw} - F{\downarrow}_{clr,lw})$$

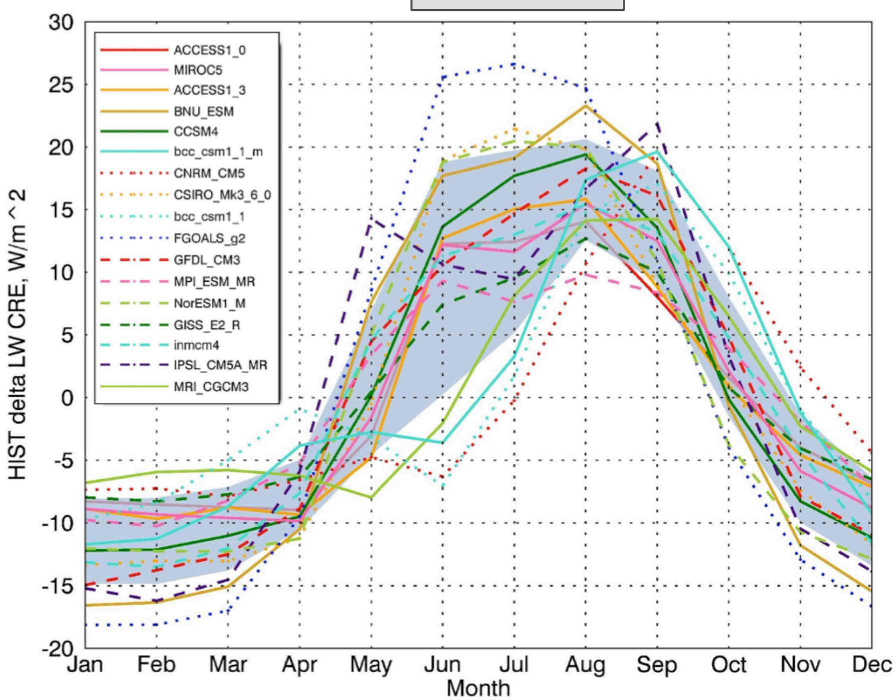
$$\delta\text{LW CRE} = \underbrace{\delta N(F{\downarrow}_{cld,lw} - F{\downarrow}_{clr,lw})}_{\text{Cloud Fraction Component}} + \underbrace{N\times\delta F{\downarrow}_{cld,lw}}_{\text{Cloud Property Component}} - \underbrace{N\times\delta F{\downarrow}_{clr,lw}}_{\text{Clr-Sky Component}}$$

Clr-Sky Component

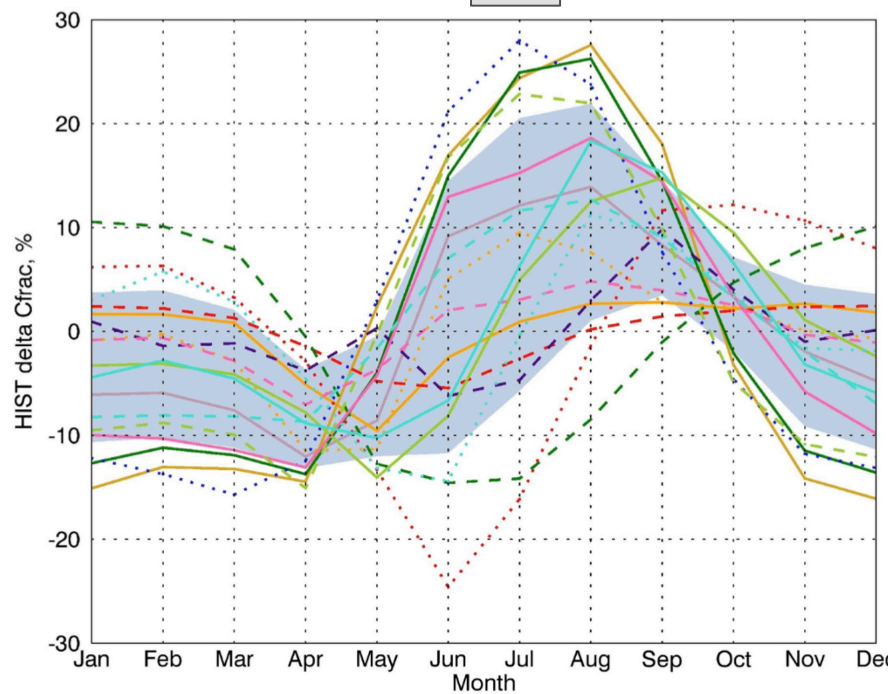
Cloud Property Component

Cloud Fraction Component

δLW CRE

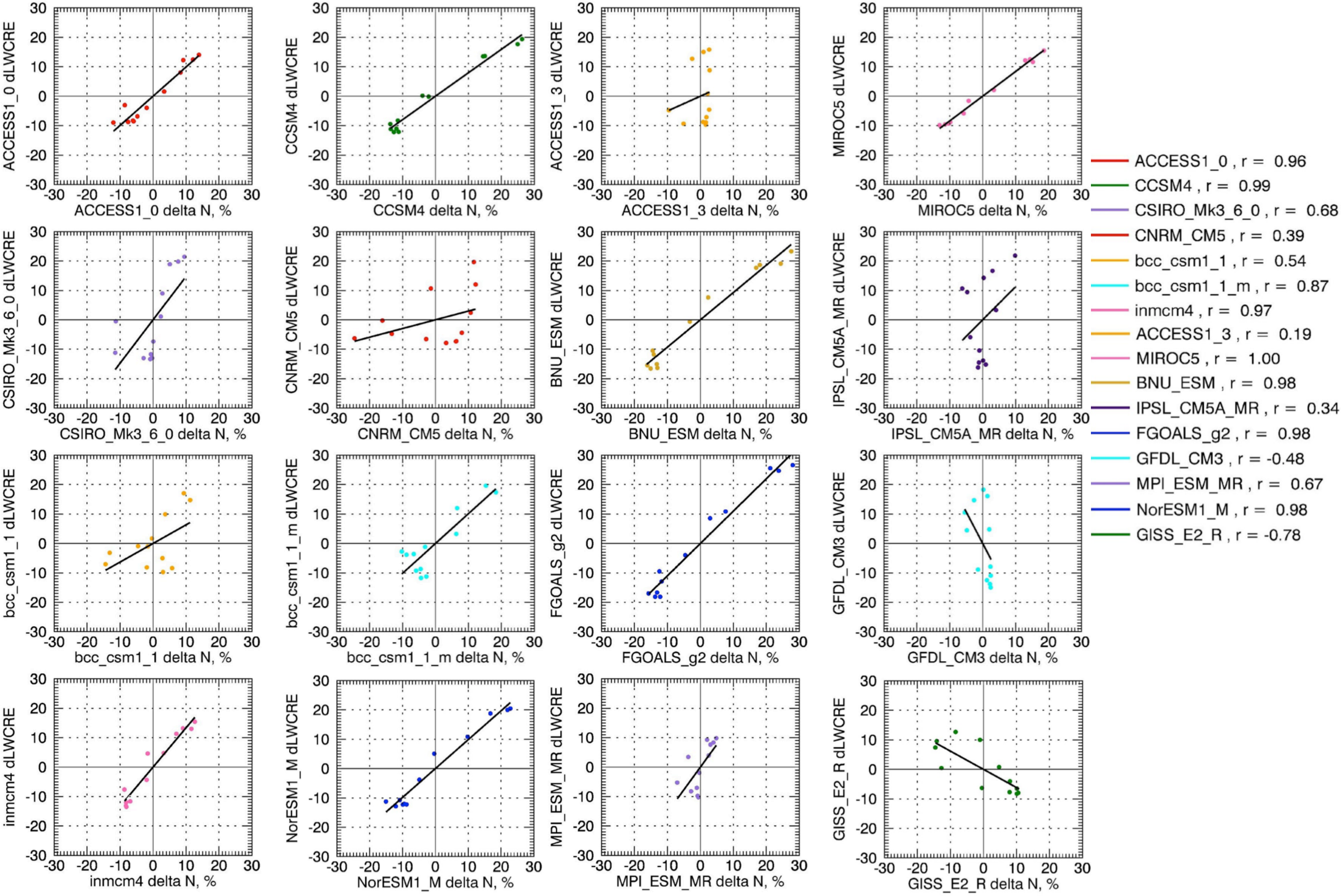


δN



(grey shaded region is the ensemble mean +/- one standard deviation)

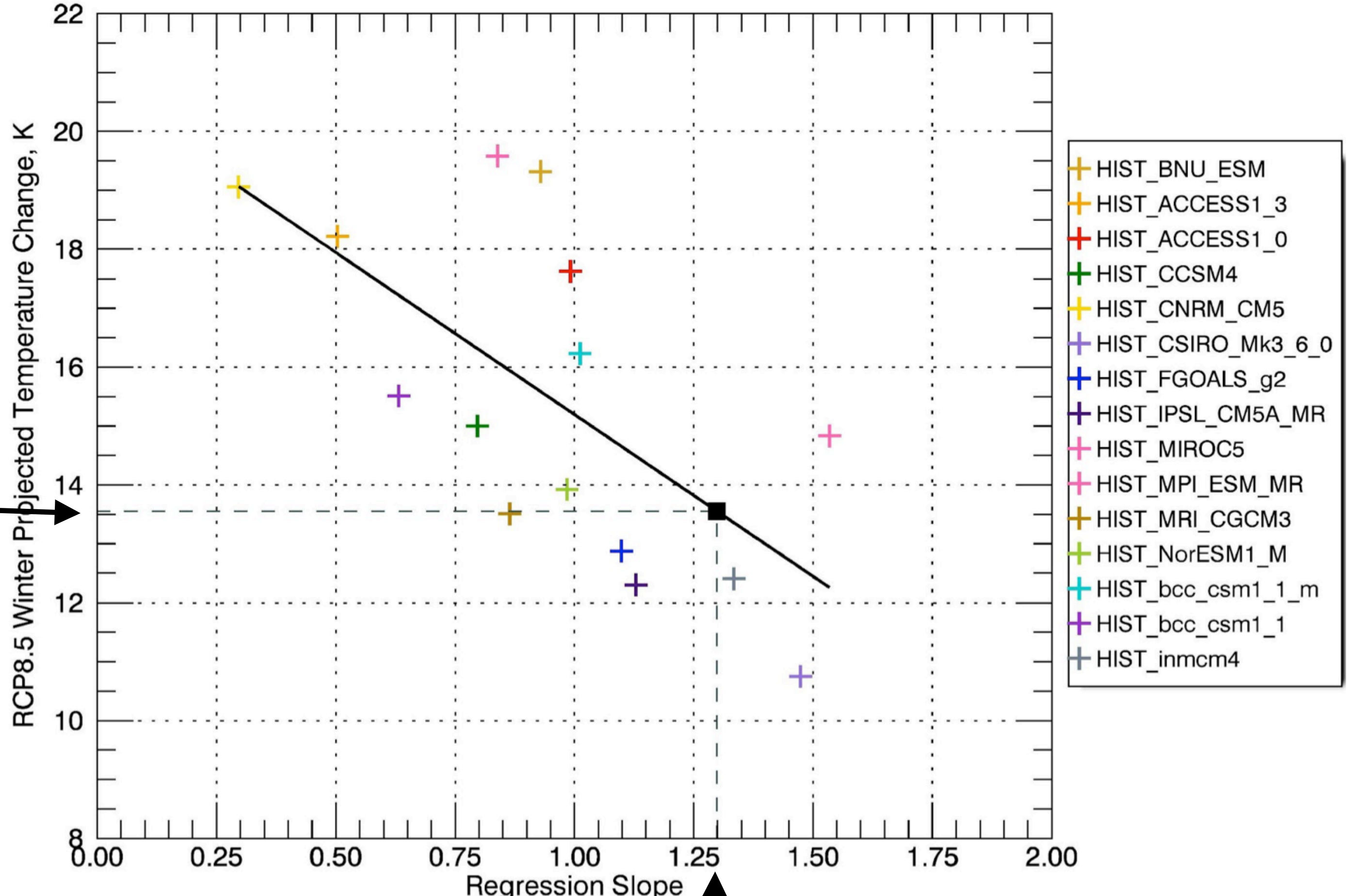
For some models, changes in LW CRE are closely coupled to changes in cloud fraction



The sensitivity of a model to changes in clouds is correlated to projected surface temperature change

The slope of the regression line from the δN vs δLW CRE is compared to projected ΔT_{surf} for CMIP5 models and C3M observations

Using the model line fit and the C3M regression slope, a predicted ΔT_{surf} for observations is ~13.6 K



C3M regression slope

Summary and Conclusion

-Arctic low cloud properties are sensitive to the atmospheric conditions: Cloud fraction, LWP, and IWP decrease with increased stability.

-A covariance between Arctic cloud properties and sea ice concentration are found in each regime and season: Cloud fraction, LWP, and TWP decrease with increased sea ice concentration.

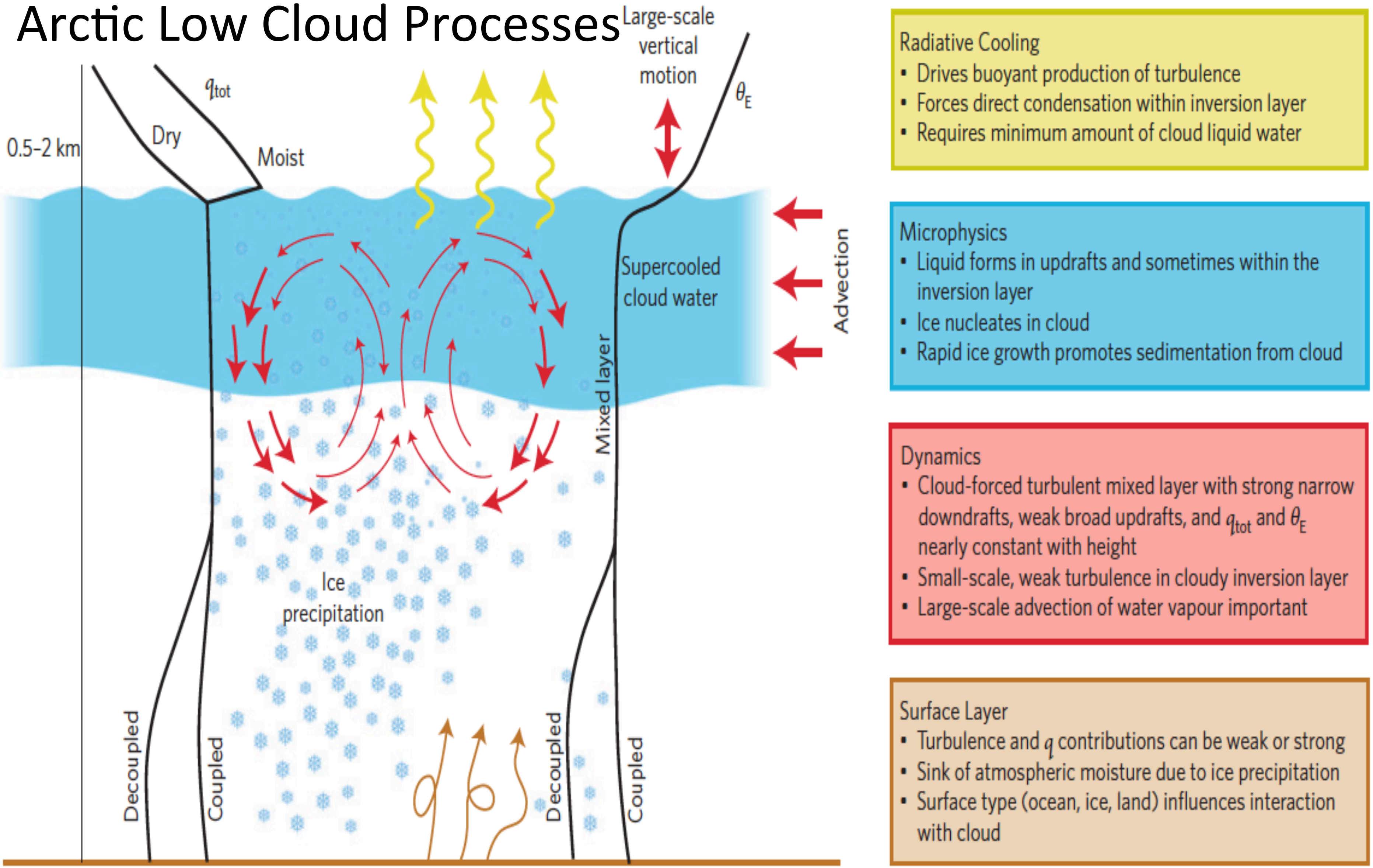
-Covariance between Arctic low cloud properties and sea ice concentration are also found to significantly influence the surface energy budget.

"Negative Feedback" in Summer (SW CRE dominates)

"Positive Feedback" in Fall and Winter (LW CRE dominates)


Questions?

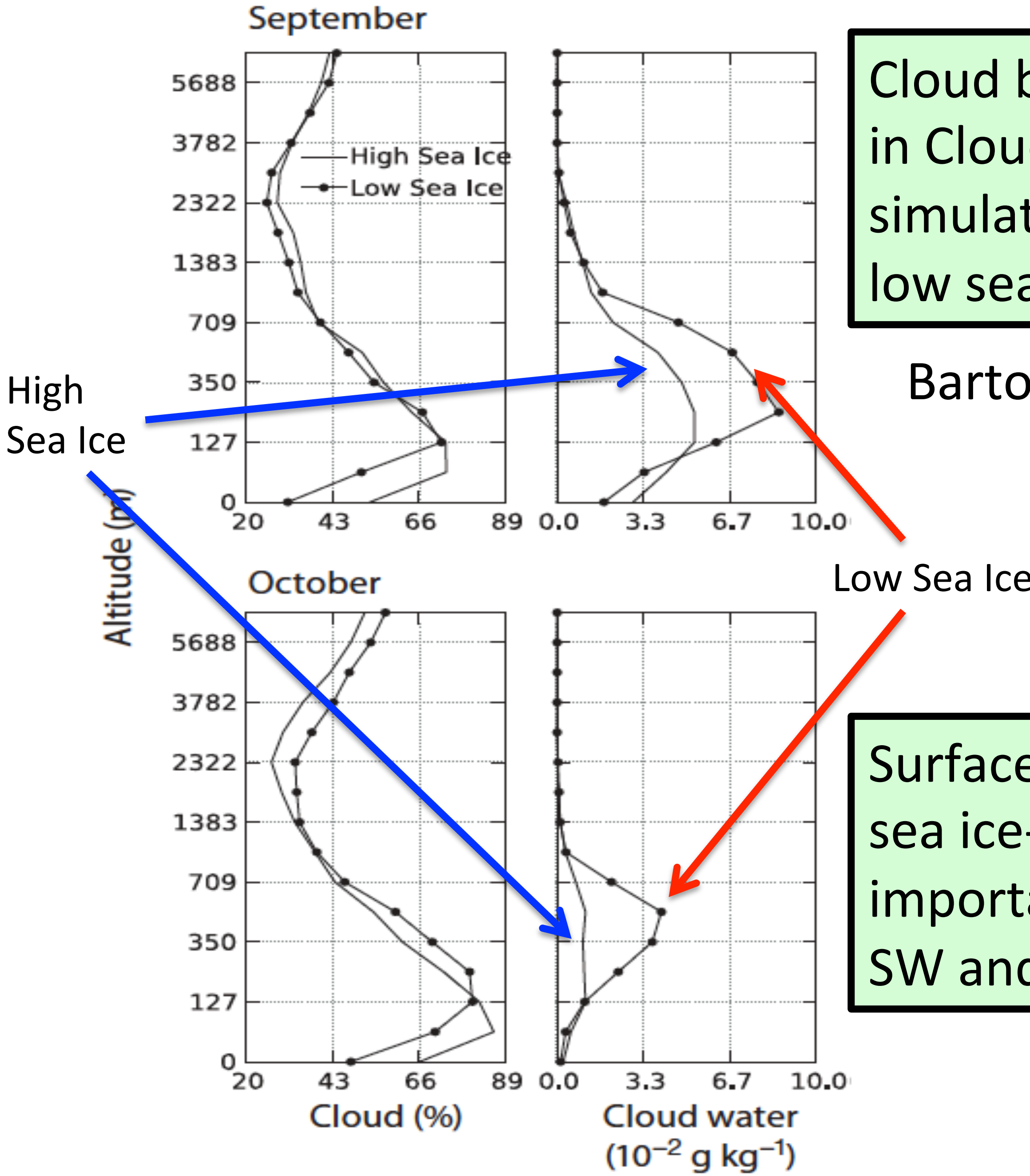
Arctic Low Cloud Processes



The influence of the surface type on the cloud properties implies an interaction between clouds and sea ice that may significantly influence Arctic climate change.

Morrison et al. (2012; Nature Geoscience)

Sea ice-Cloud Interaction: Some Modeling Evidence



Cloud base and LWC are higher in Cloud Resolving Model simulations with anomalously low sea ice.

Barton and Veron (2012)

Surface radiative forcing due to sea ice-cloud interactions is only important during Oct. because SW and LW CRF offset in Sept.

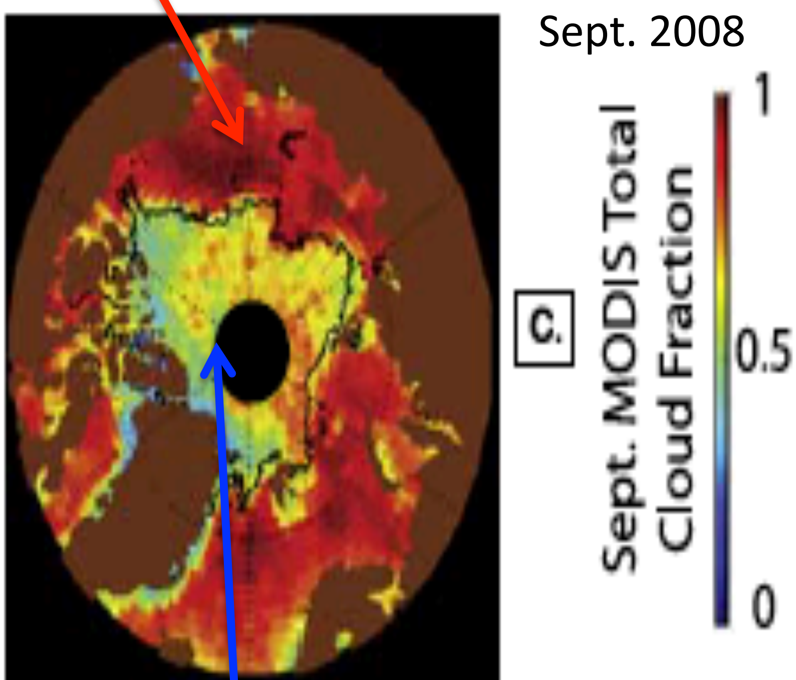
Sea ice-Cloud Interaction: Some Observational Evidence

Significant correlation between cloud fraction and the sea ice extent in AUTUMN: larger cloud fraction over open water and lower cloud fraction over ice.

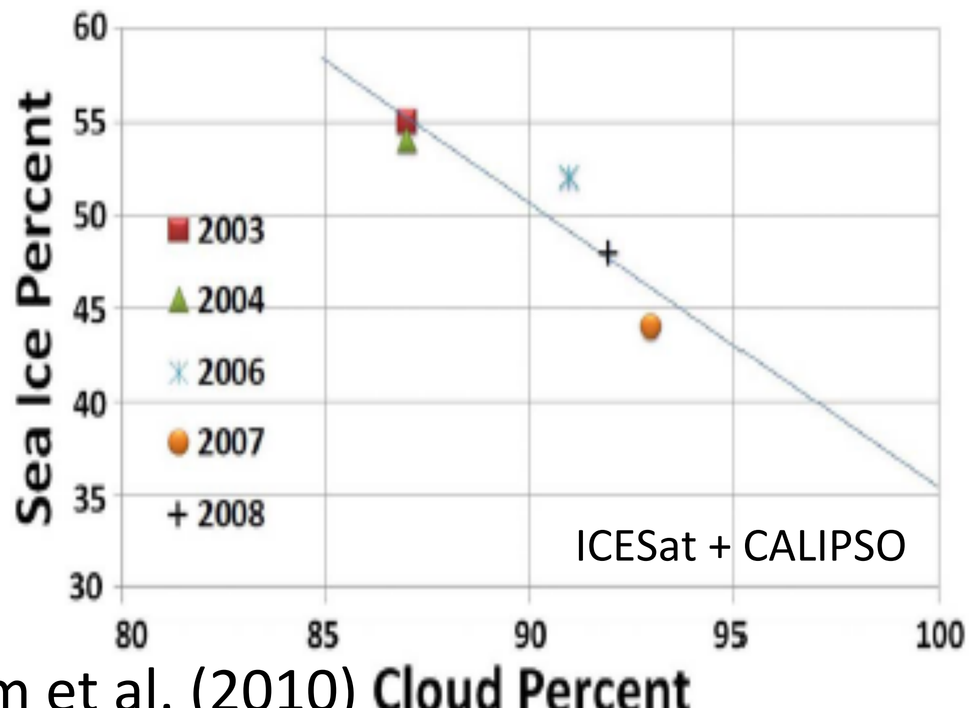
Larger cloud fraction over ocean

Kay and Gettelman (2009)

Sept. 2008



Lower cloud fraction over sea ice



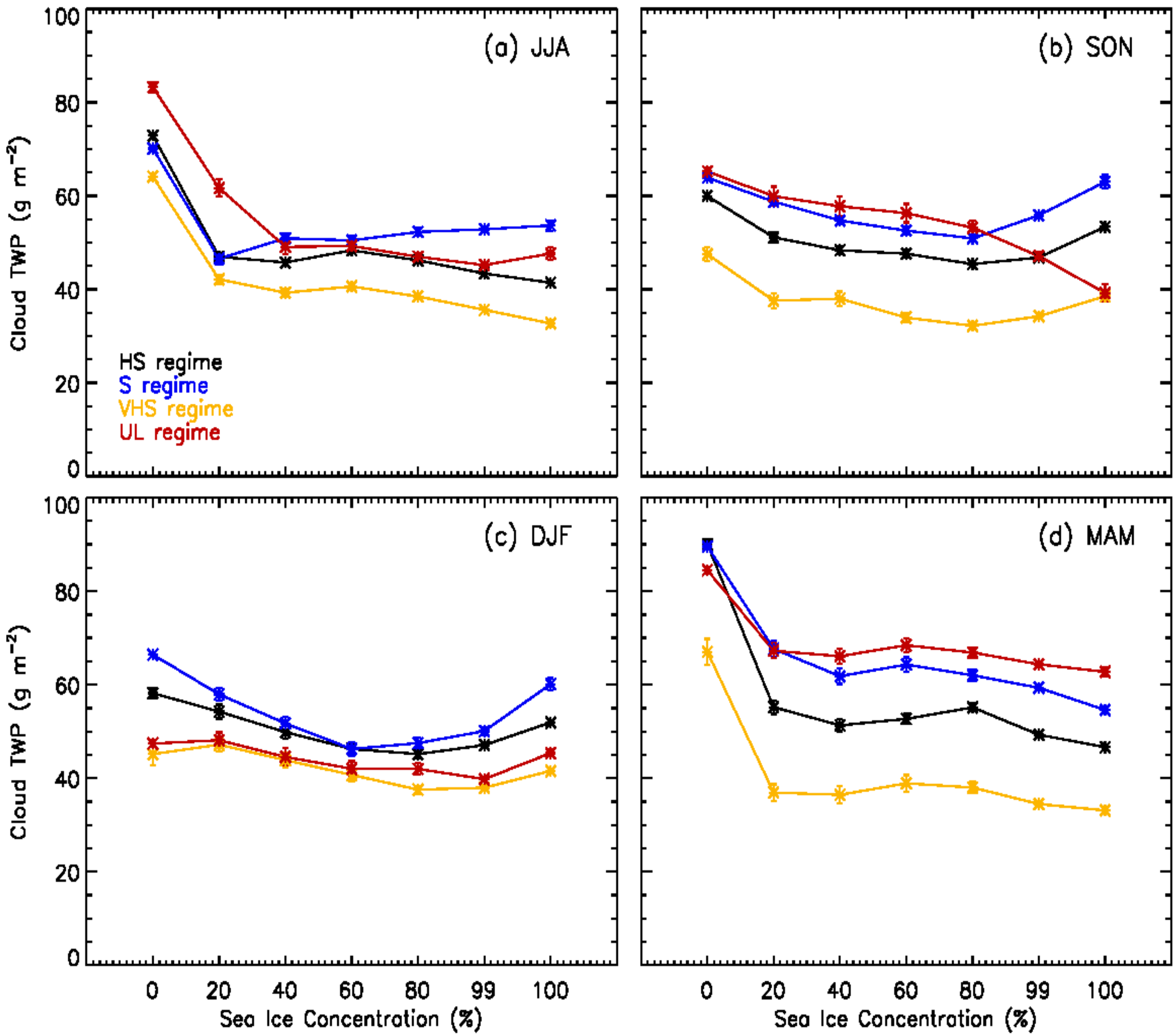
Palm et al. (2010)

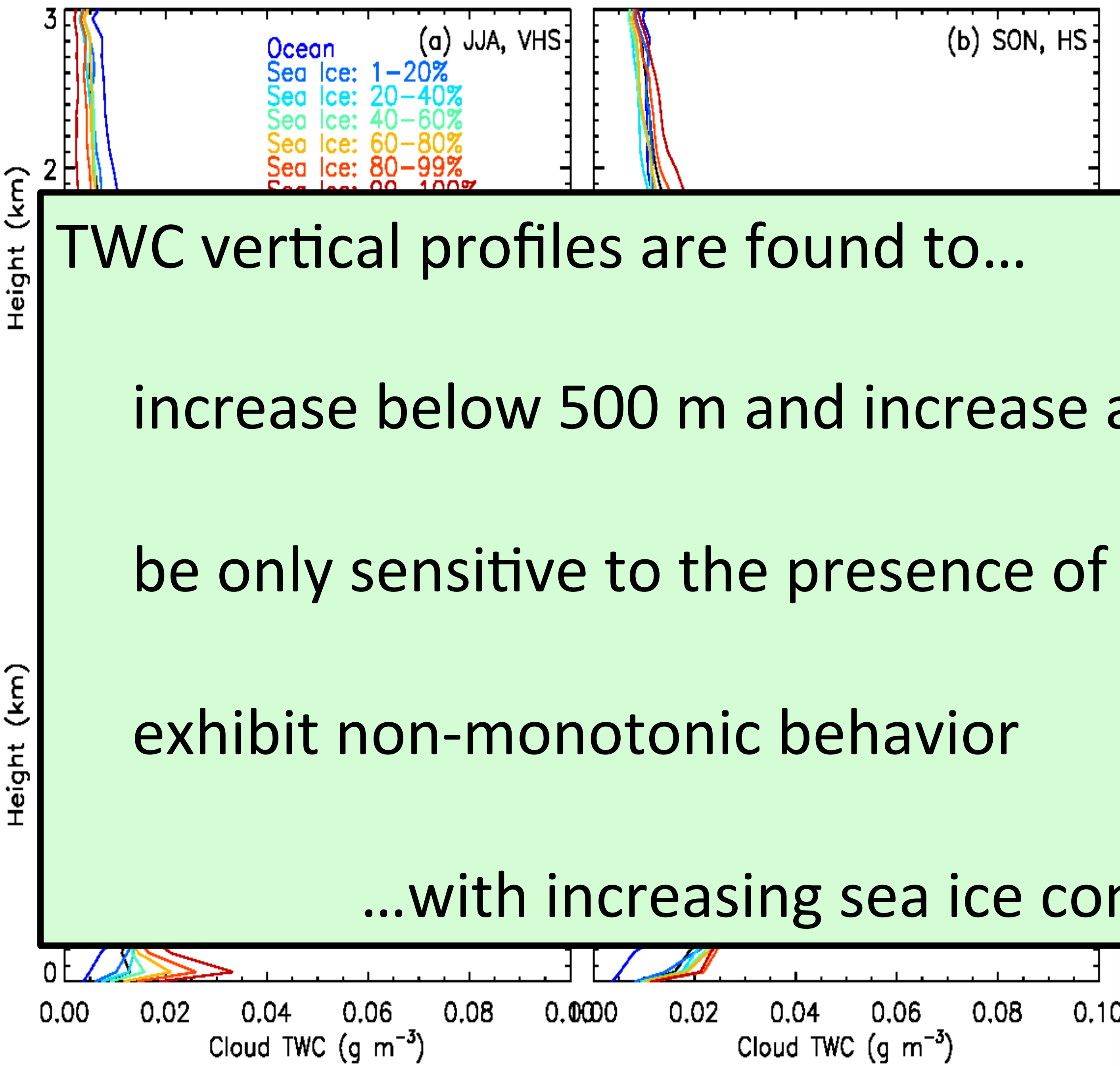
No relationship during summer because the atmosphere and surface tend to be decoupled.

Low Cloud TWP vs. Sea Ice Concentration

Cloud TWP decreases with increasing sea ice

The magnitude of the TWP change with sea ice varies with season and atmospheric regime.





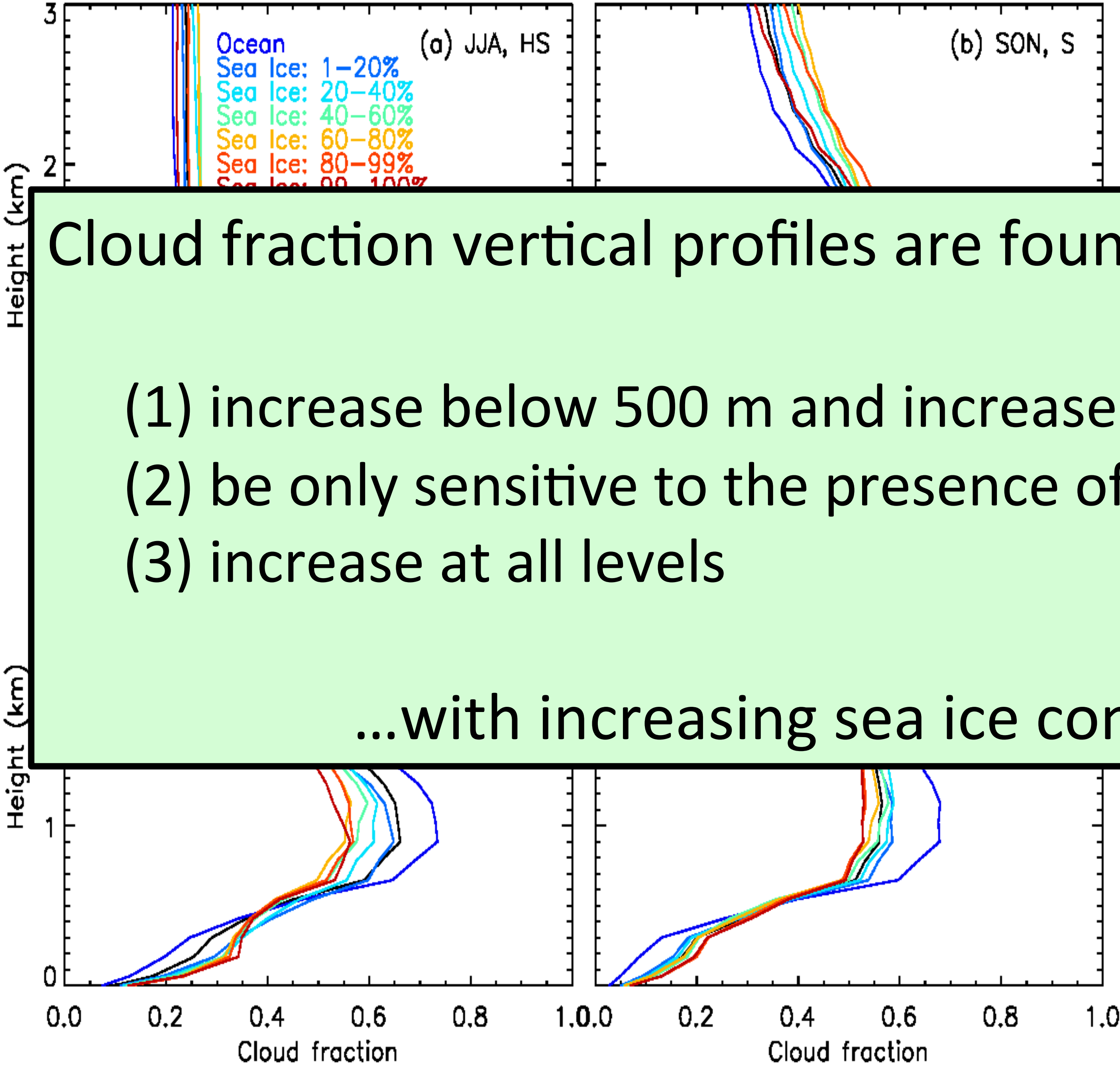
TWC vertical profiles are found to…

increase below 500 m and increase above 500m,

be only sensitive to the presence of sea ice, and

exhibit non-monotonic behavior

…with increasing sea ice concentration.



Cloud fraction vertical profiles are found to…

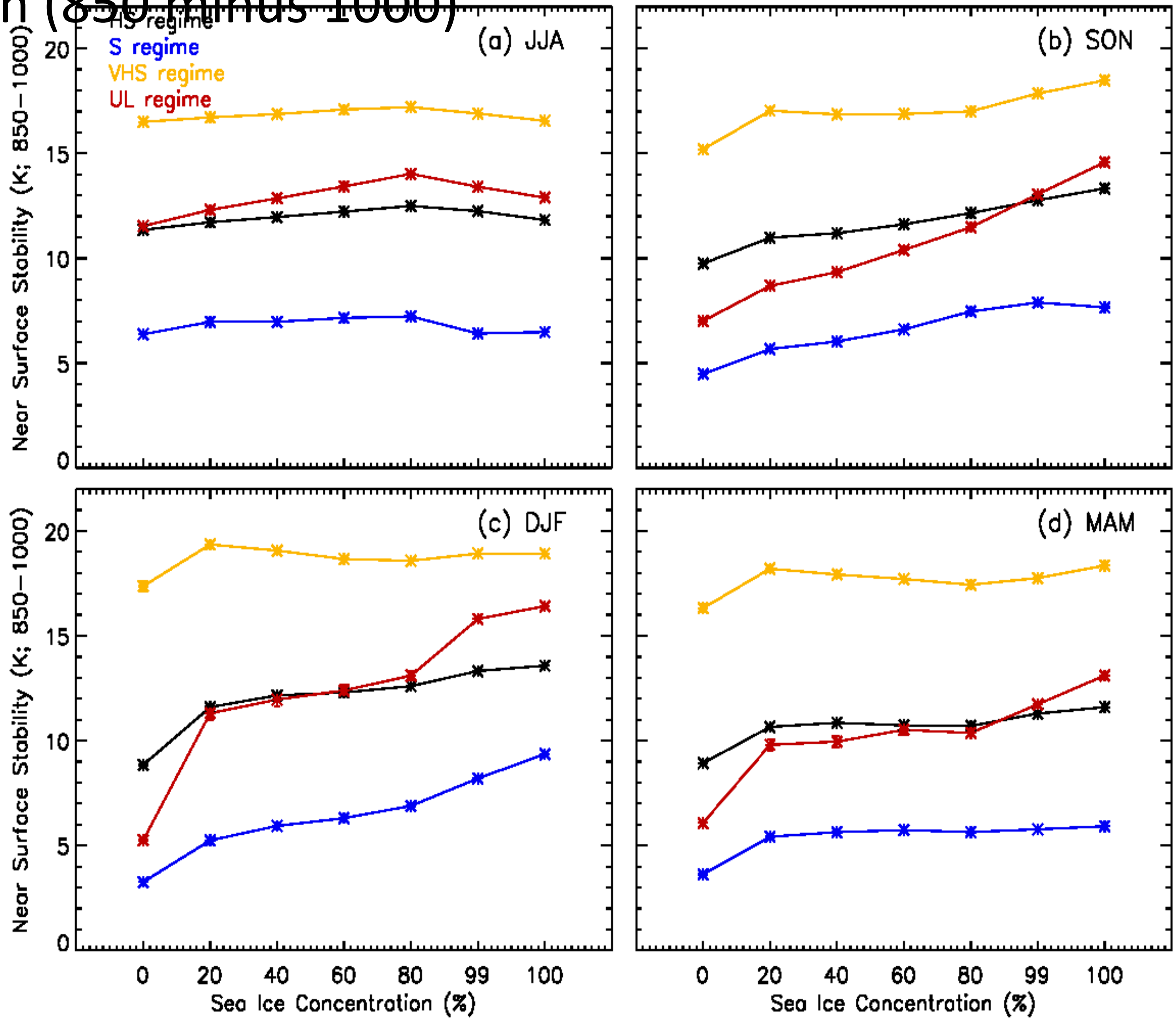
(1) increase below 500 m and increase above 500m,
(2) be only sensitive to the presence of sea ice,
(3) increase at all levels

…with increasing sea ice concentration.

Boundary Layer Temperature Structure and Sea Ice Concentration (850 minus 1000)

Higher LTS is associated with higher near surface stability.

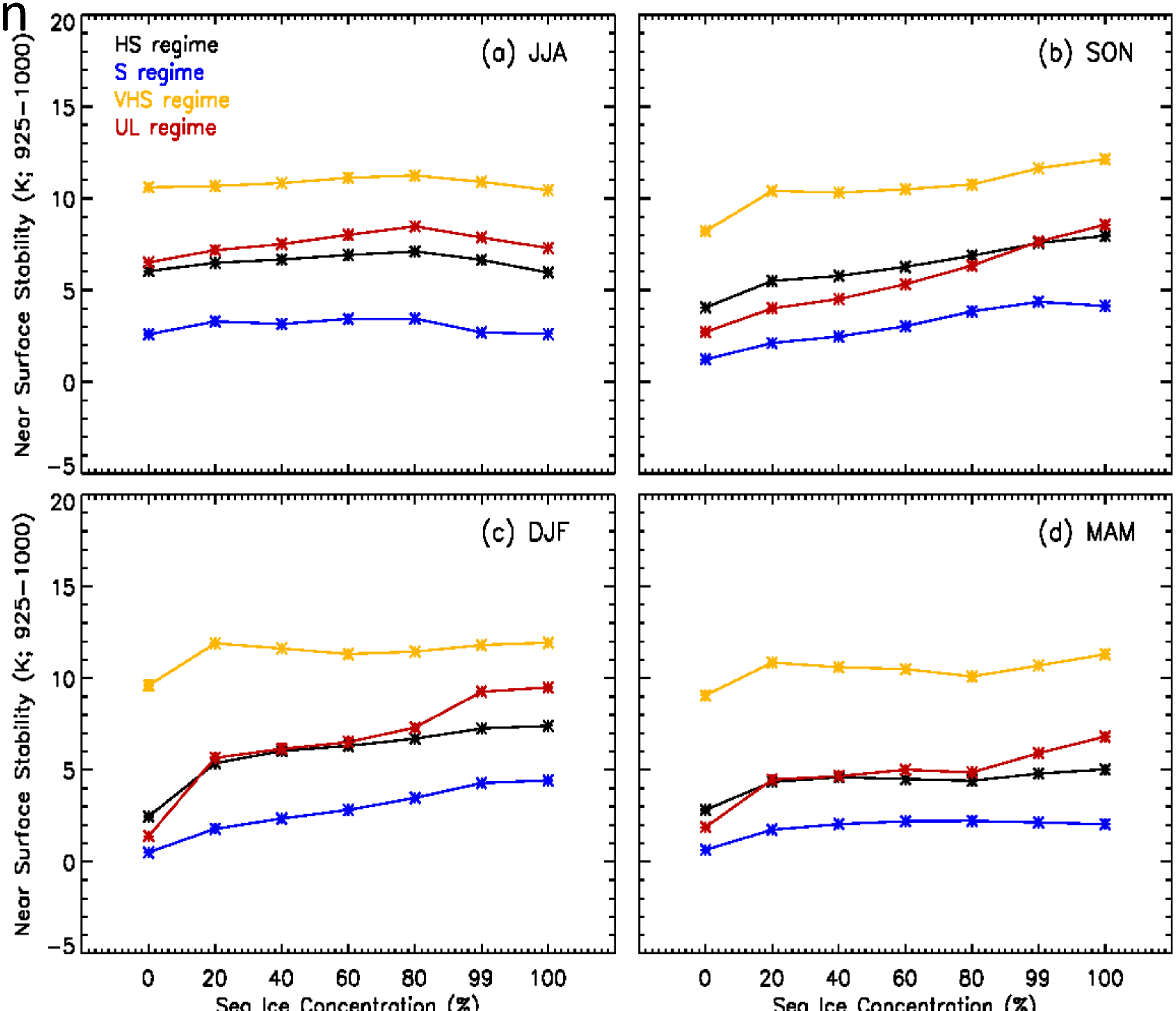
Near surface stability increase with increased sea ice



Boundary Layer Temperature Structure and Sea Ice Concentration

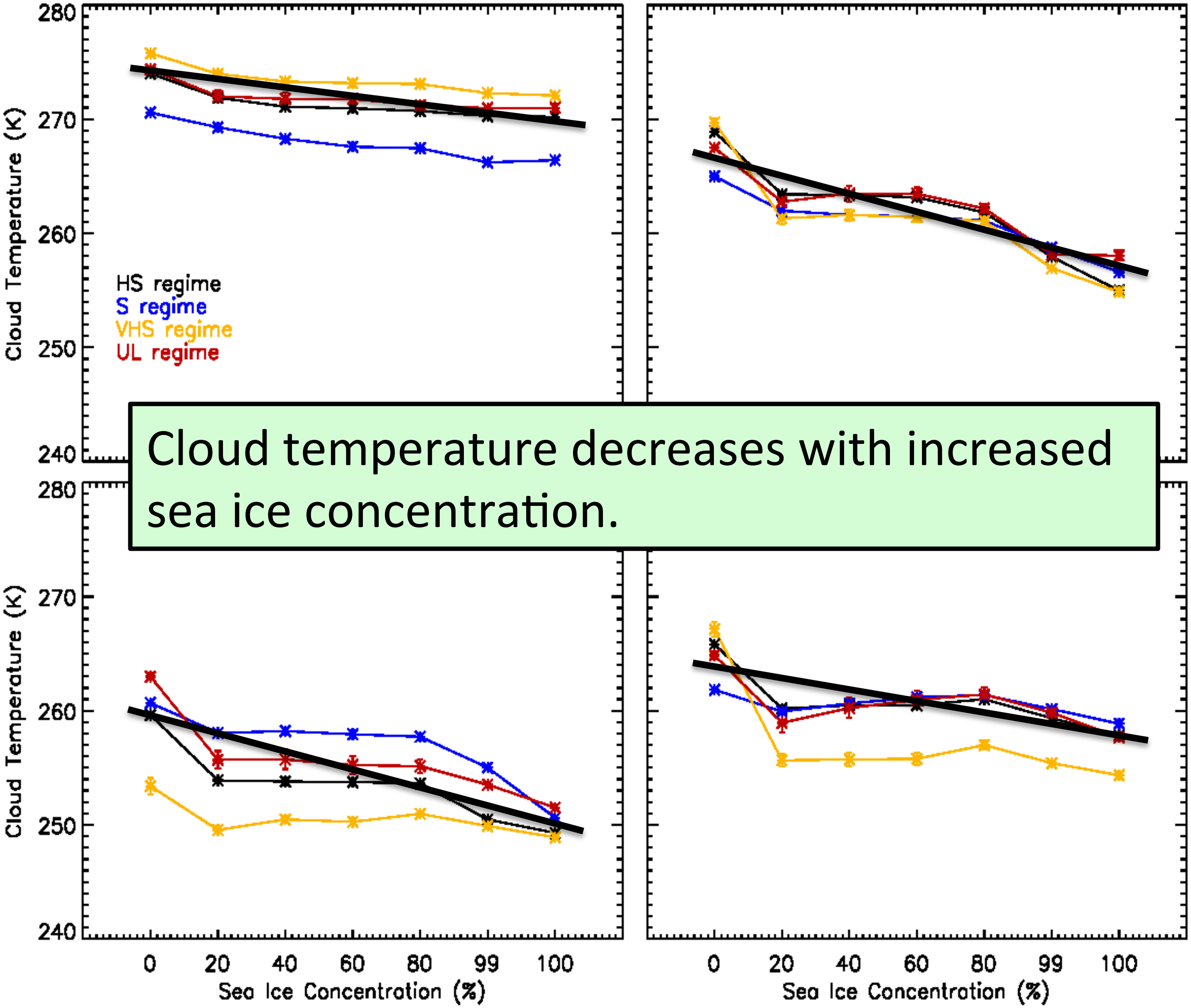
Higher LTS is associated with higher near surface stability.

Near surface stability increase with increased sea ice



CRE vs. Sea ice Concentration

Cloud Temperature vs. Sea Ice Concentration



Cloud temperature decreases with increased sea ice concentration.

A systematic decrease in cloud temperature with increased SIC explains most of the change in LW CRE with SIC.

Use the concept of cloud radiative forcing to evaluate the influence of clouds on shortwave and longwave fluxes at the surface.

$$CRE = (SW{\downarrow} - SW{\downarrow}_{clr\text{-}sky})\cdot(1 - \alpha) + (LW{\downarrow} - LW{\downarrow}_{clr\text{-}sky})$$

"Cloud Radiative Effect"

where
- $SW{\downarrow}$, $LW{\downarrow}$ are all-sky fluxes
- $SW{\downarrow}_{clr\text{-}sky}$, $LW{\downarrow}_{clr\text{-}sky}$ are clear-sky fluxes
- α is the albedo calculated using clr-sky sw fluxes, $SW{\uparrow}_{clr\text{-}sky}/SW{\downarrow}_{clr\text{-}sky}$

Terms in the equation represent cloud influence on solar and infrared radiation

$(SW{\downarrow} - SW{\downarrow}_{clr\text{-}sky})\cdot(1 - \alpha)$ ⇒

Shortwave cloud radiative forcing (SW CRE)

Usually negative because downwelling solar flux decreases with the presence of clouds

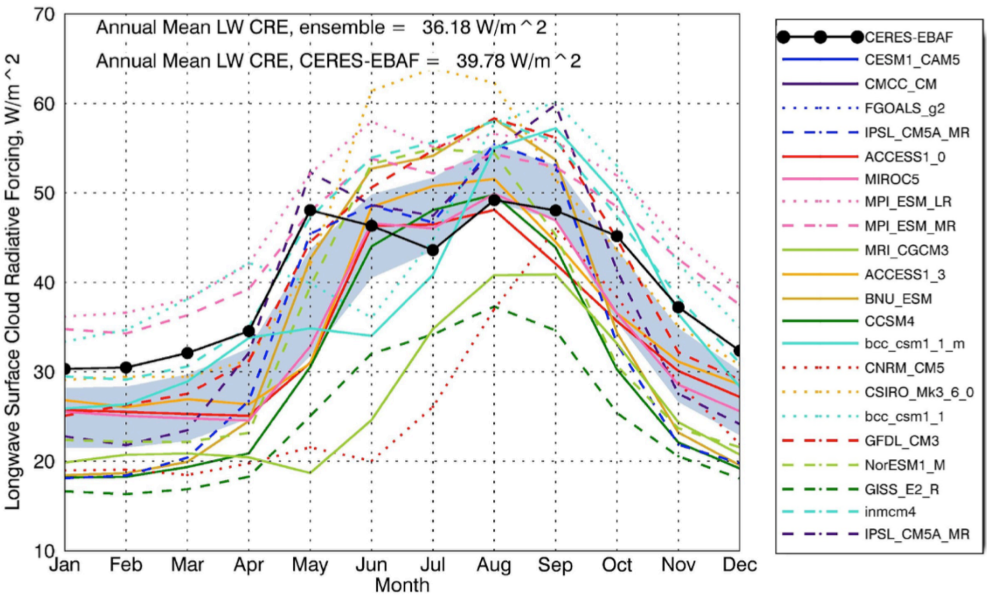
Magnitude of SW CRE is smaller over a white surface than over ocean

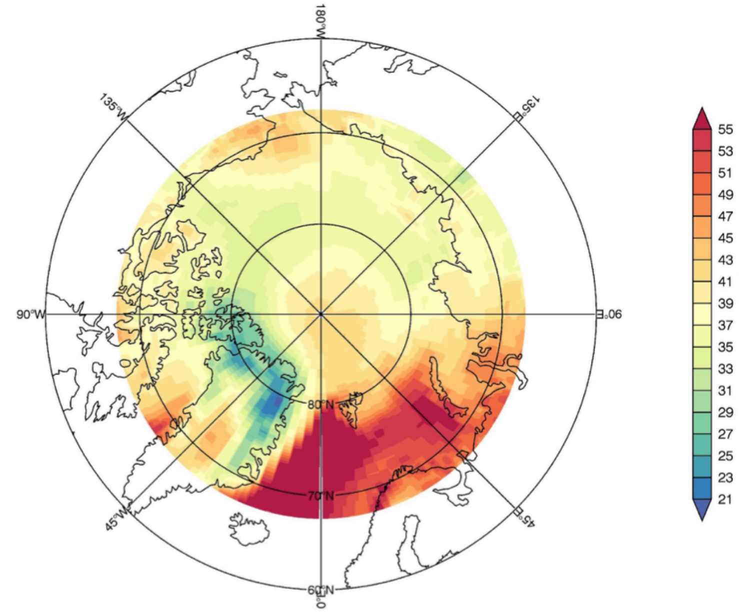
$(LW{\downarrow} - LW{\downarrow}_{clr\text{-}sky})$ ⇒

Longwave cloud radiative forcing (LW CRE)

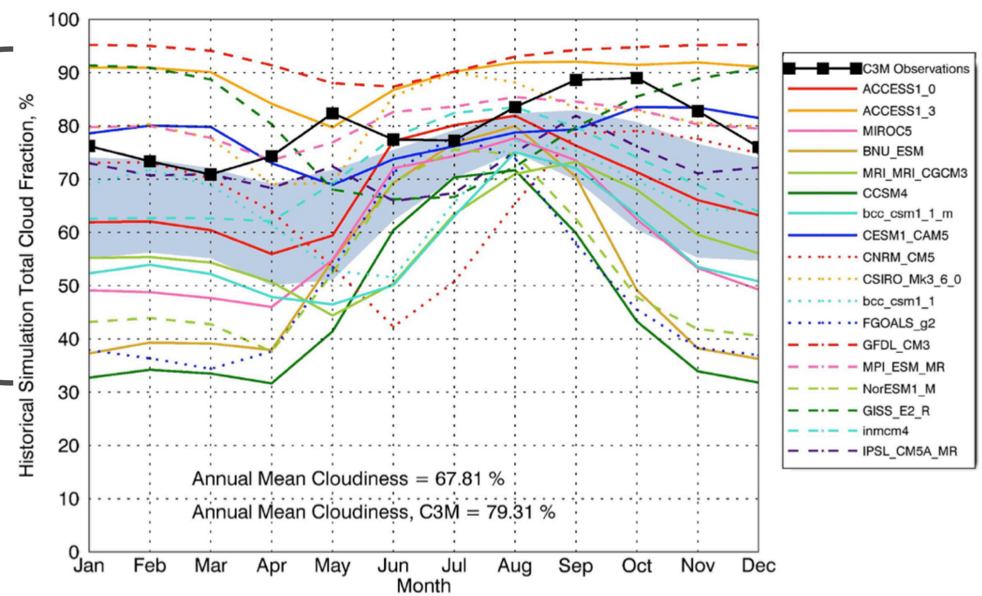
Usually positive because downwelling longwave radiation increases with the presence of clouds

Longwave Cloud Radiative Effect

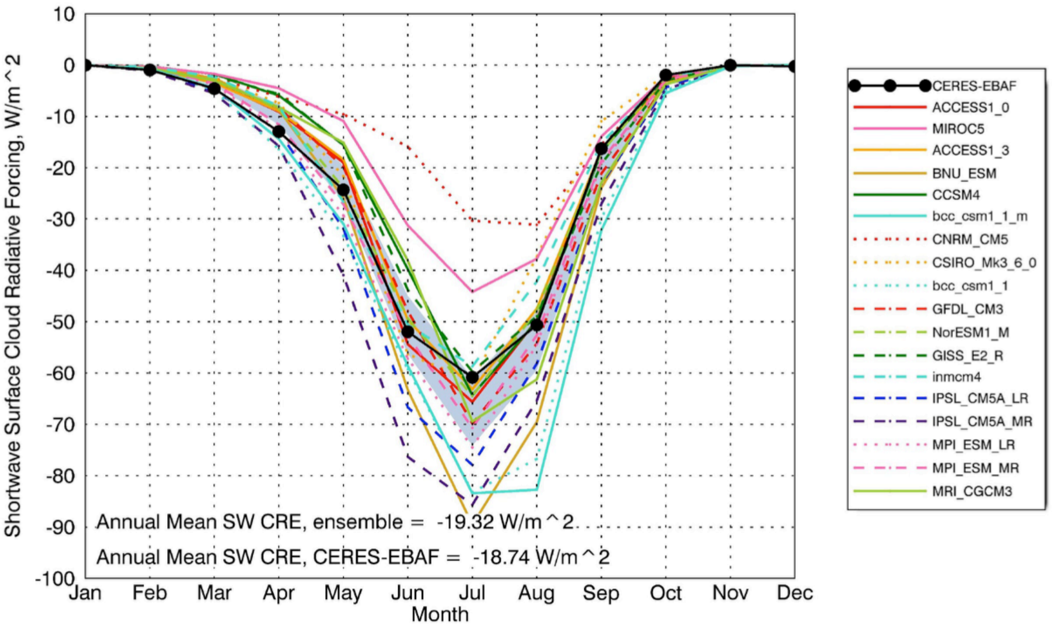


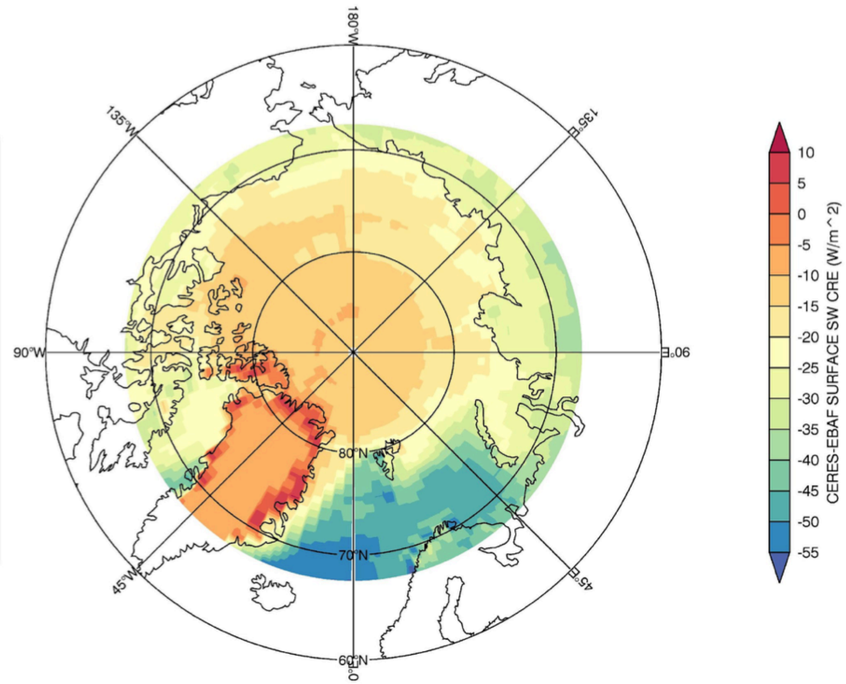


The large discrepancy in wintertime cloudiness is due to the representation of low clouds (Karlsson 2011)



Shortwave Cloud Radiative Effect





Generally, models with higher surface albedo have a weaker SW CRE and vice versa