



Arctic Low Cloud-Sea Ice-Stability Interactions and the Arctic Surface Energy Budget

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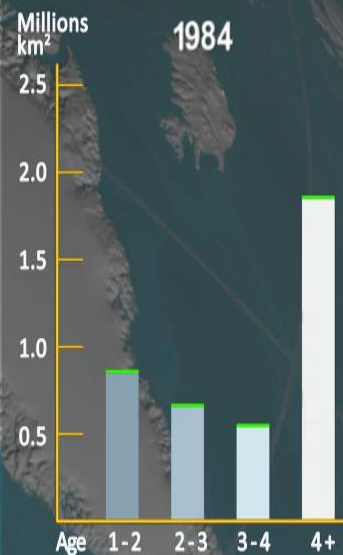
Acknowledgements: R. Boeke, B. Hegyi, S.
Kato, K.-M. Xu and M. Cai

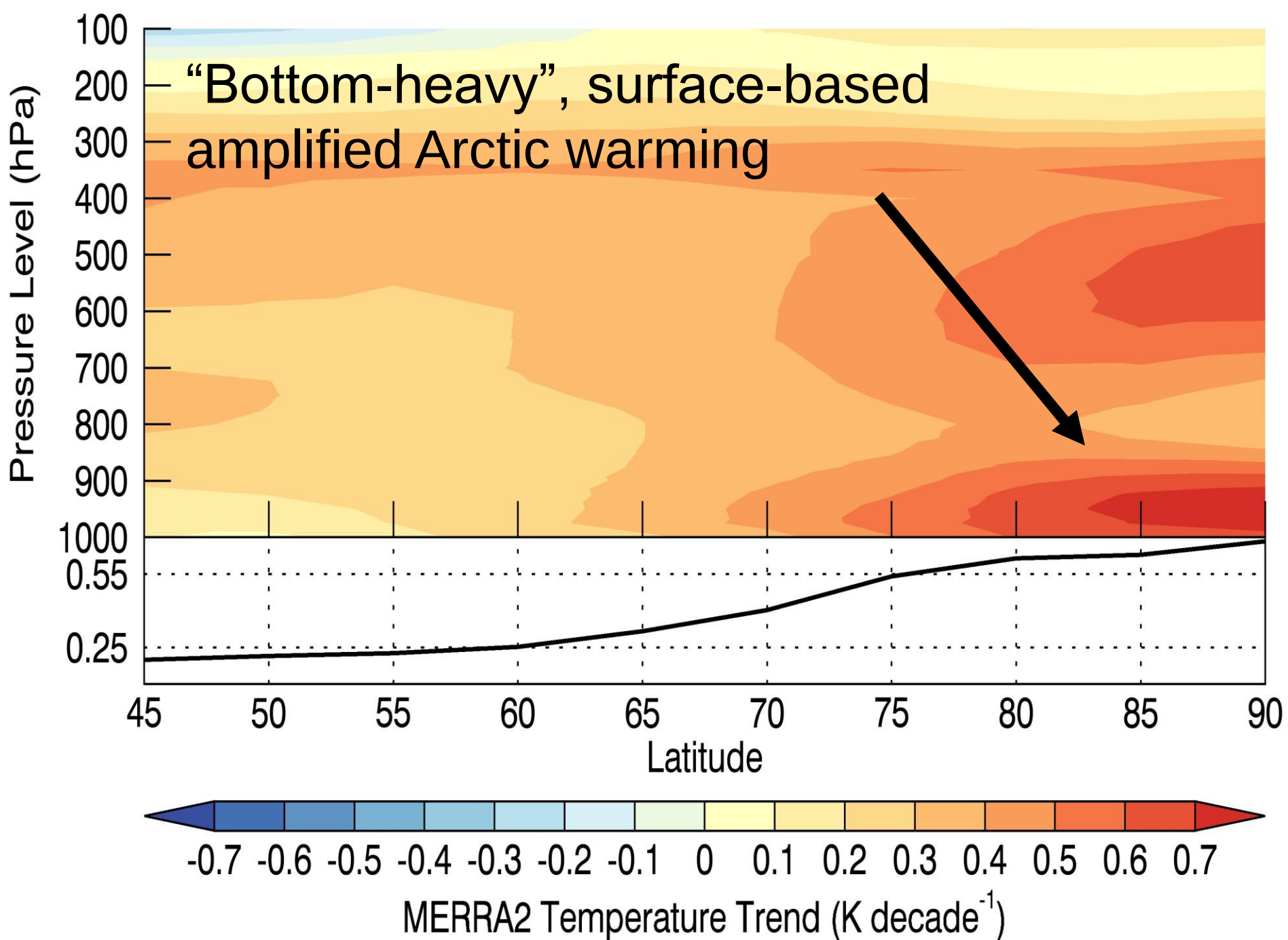
1984

Sea Ice Age

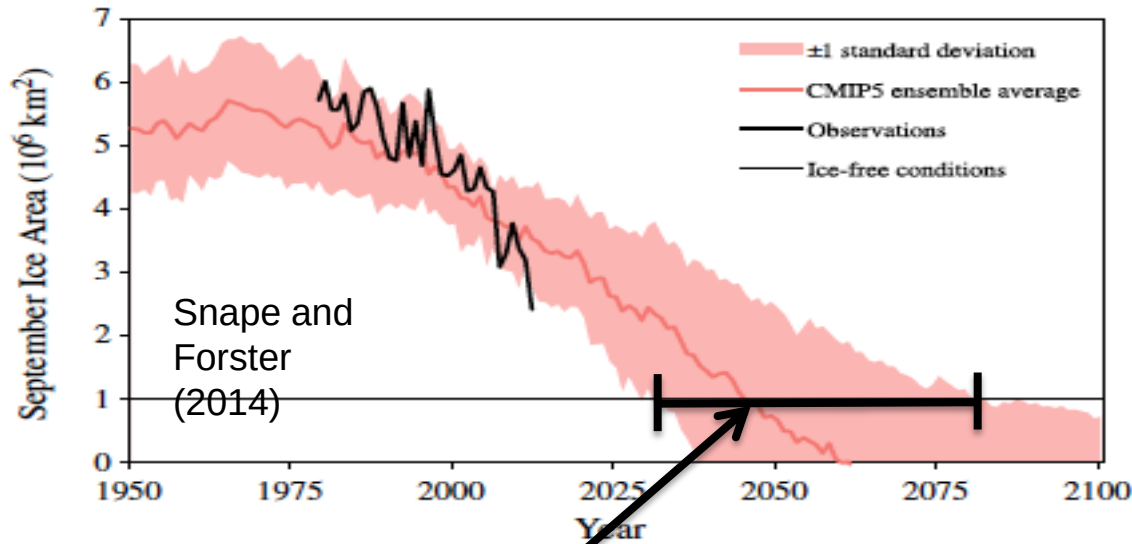
0-1 1-2 2-3 3-4 4+
Years

Perennial Sea Ice Area by Age





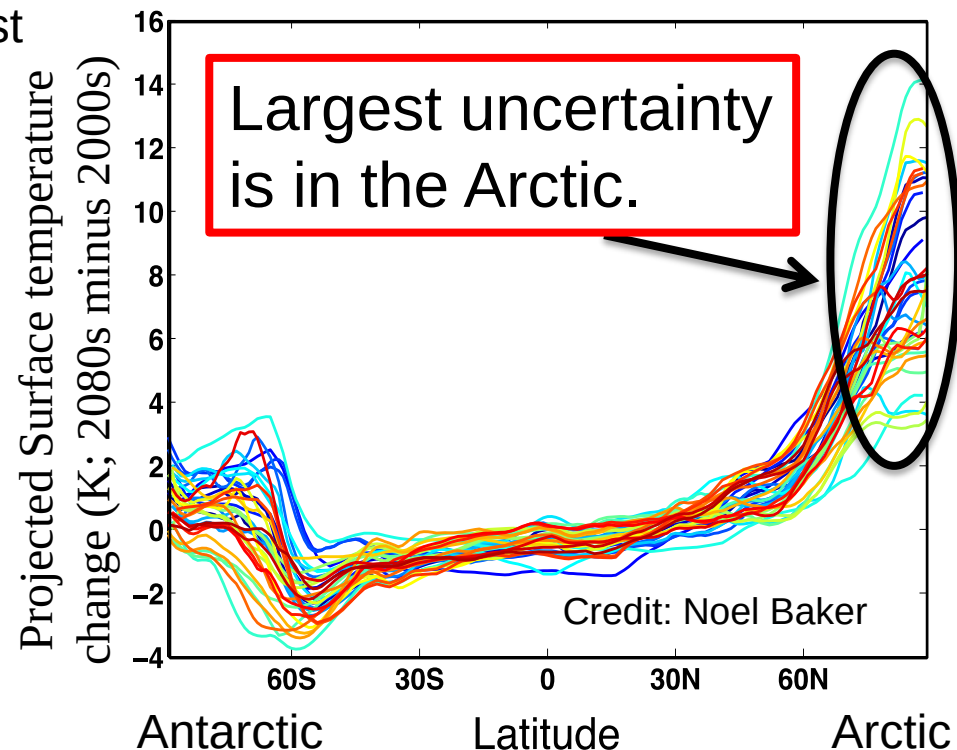
Oh, the uncertainty...



~50-year range in the projected first appearance of and ice-free Arctic

The large spread in climate model predictions of Arctic warming is attributed to model of sea ice melt and how it feeds back on the other components of the climate.

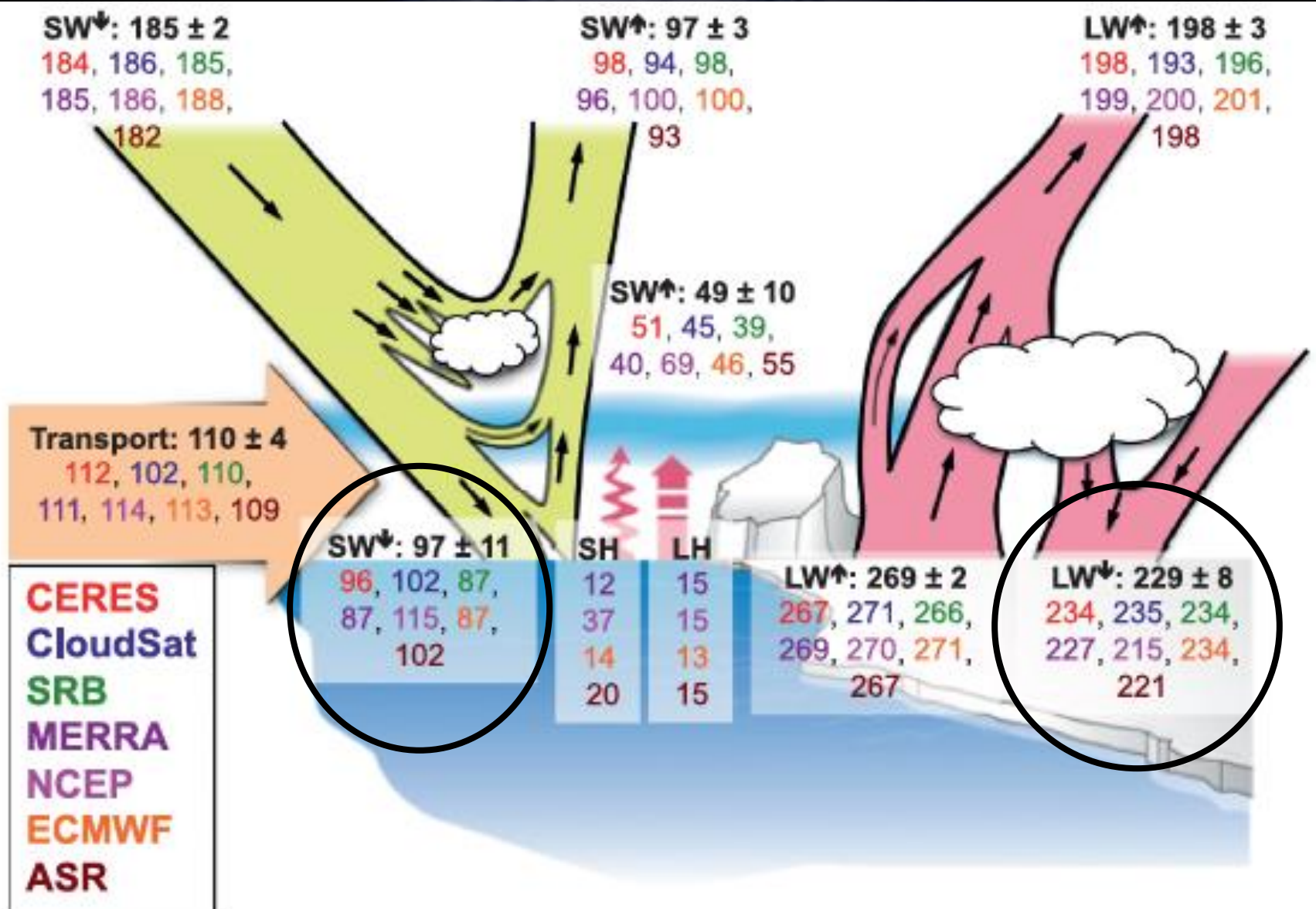
Projections of future Arctic sea ice decline and the timing of the first occurrence of a sea ice-free Arctic are very uncertain.



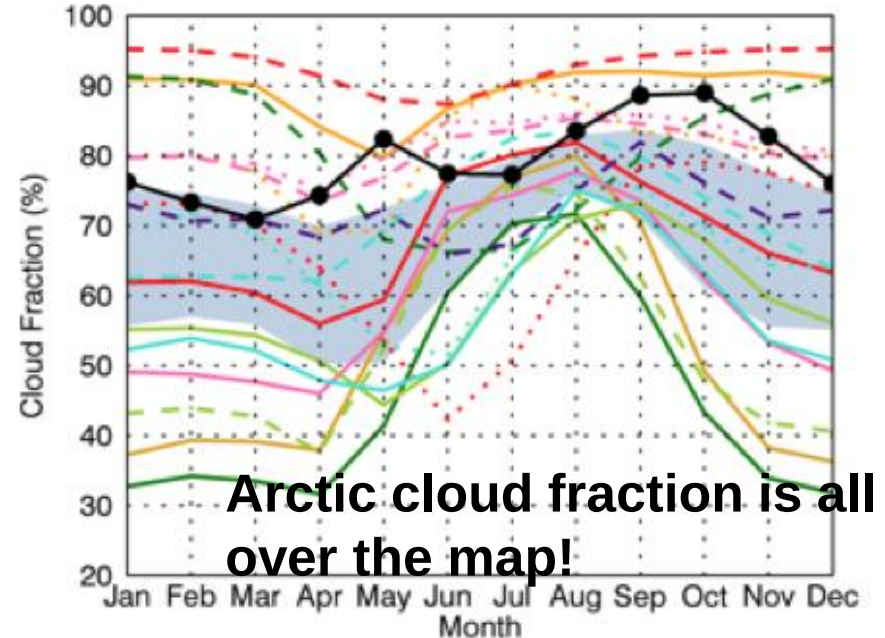
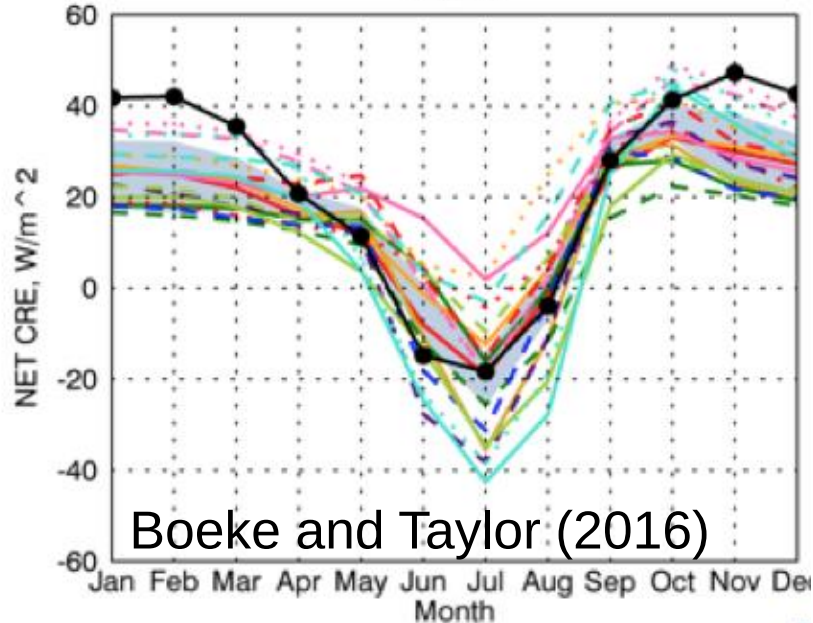
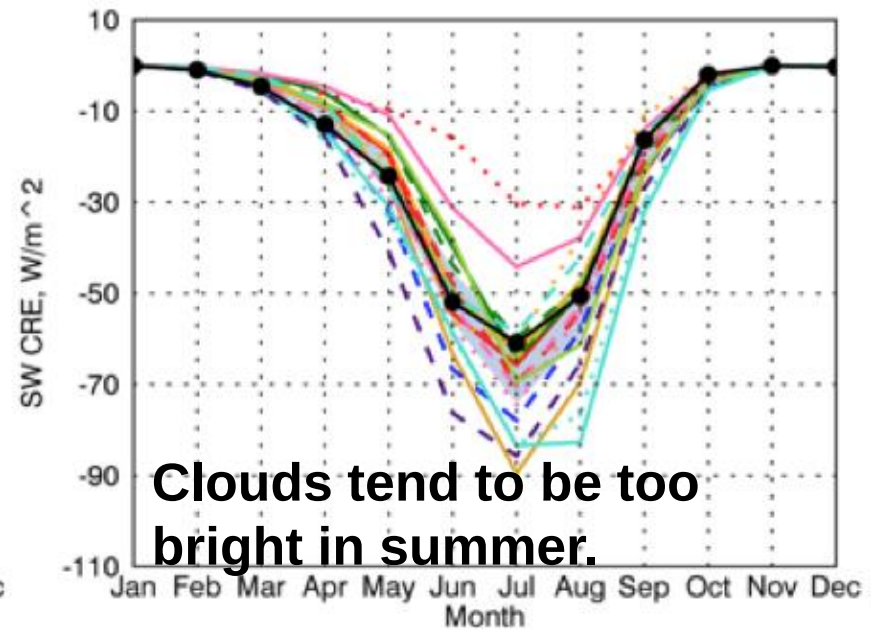
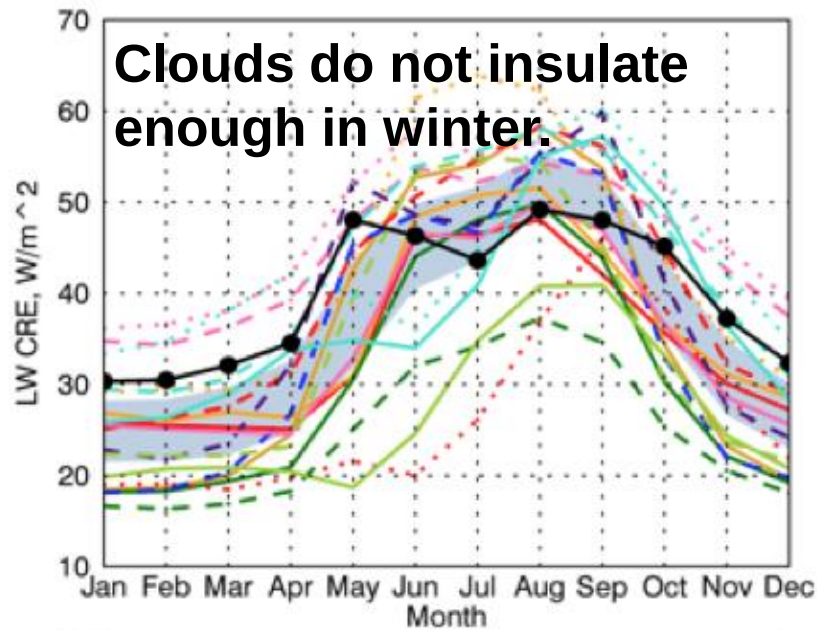
Arctic surface energy budget:

Current Status

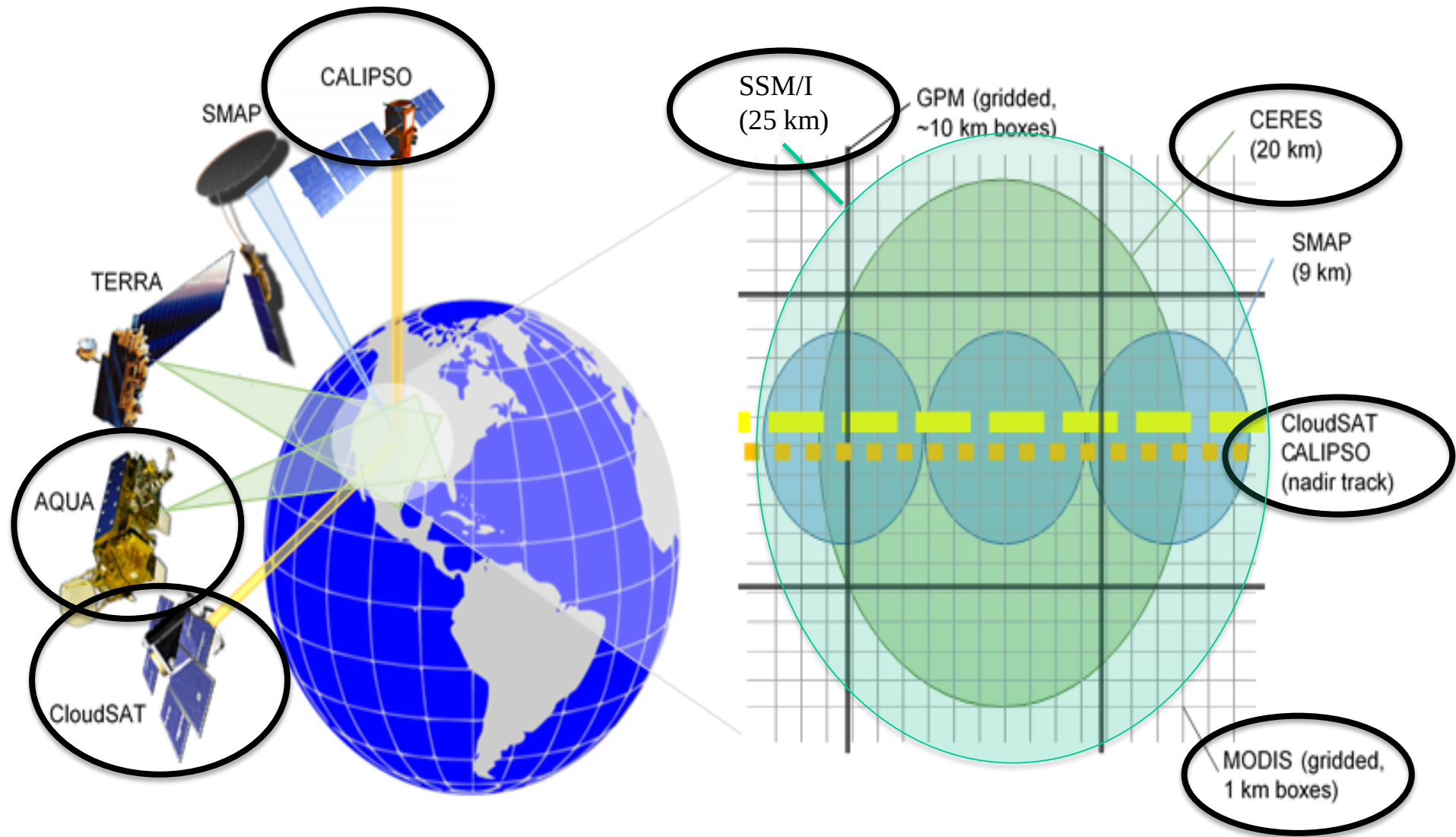
Christensen et al. (2016; BAMS)



CMIP5 vs. CERES Surface Cloud Radiative Effects

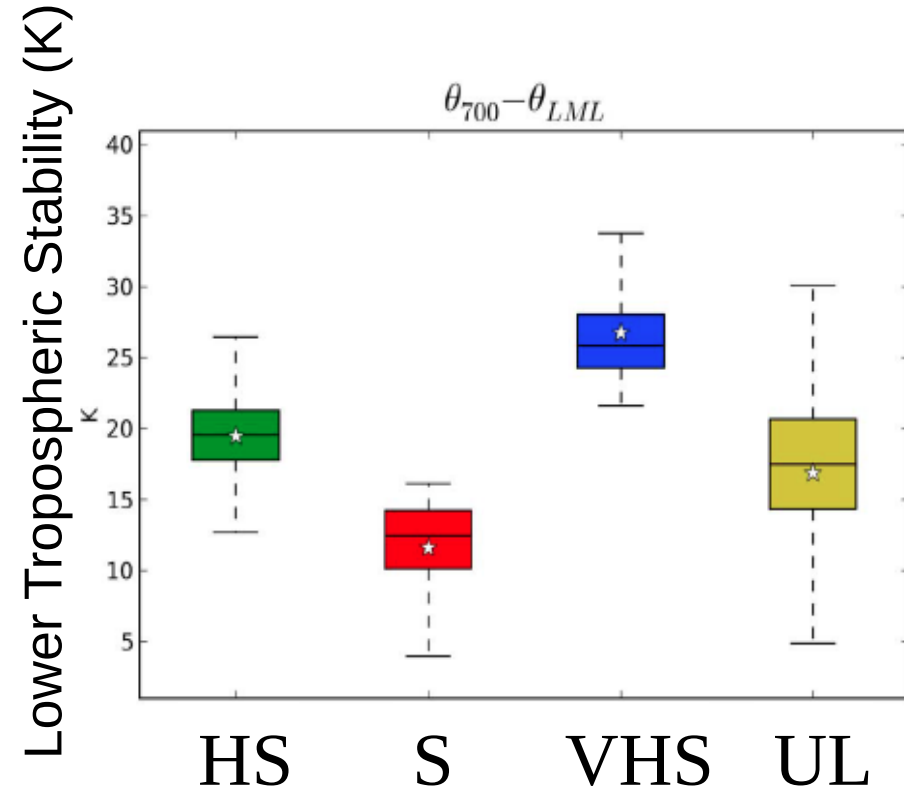


That's the power of...Data Fusion!?

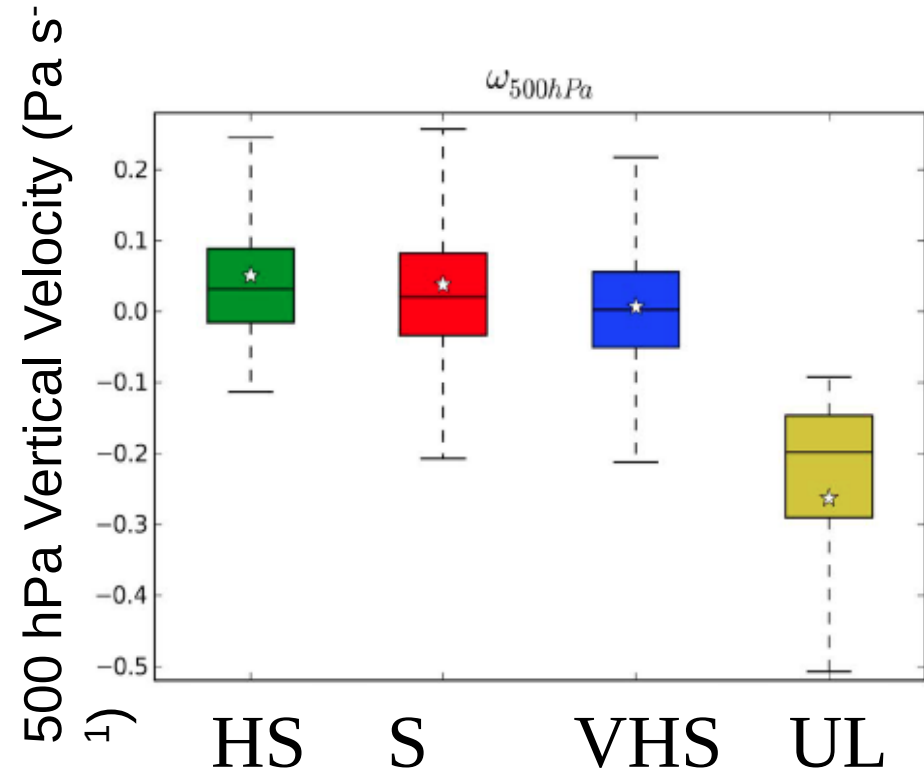


A new perspective is enabled by leveraging advances in data fusion made at NASA Langley Research Center—combining CALIPSO, CloudSAT, CERES, and MODIS.

Atmospheric Regimes (Barton et al. 2012)



Atmospheric state regimes determined using K-means cluster analysis.



High Stability (HS): $16 \text{ K} < \text{LTS} < 24 \text{ K}$

Stable (S): $\text{LTS} < 16 \text{ K}$

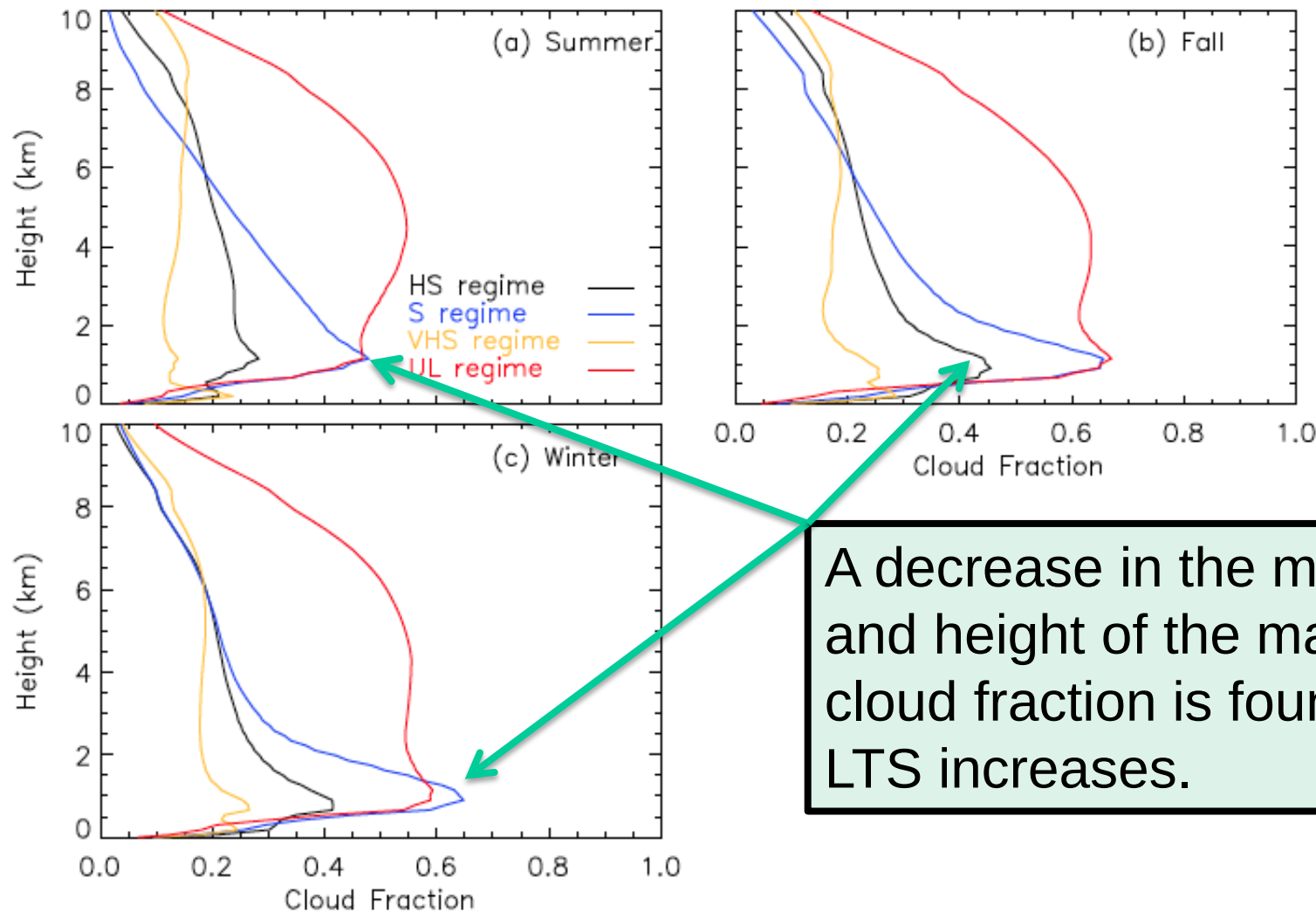
Very High Stability (VHS): $\text{LTS} > 24 \text{ K}$

Uplift (UL): $\omega_{500} < -0.1 \text{ Pa s}^{-1}$

K

8

How does meteorology influence Arctic clouds?



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

Takeaway Message: Meteorology places a strong constraint on cloud behavior.

Relationship between LTS-CRE by atmospheric regime

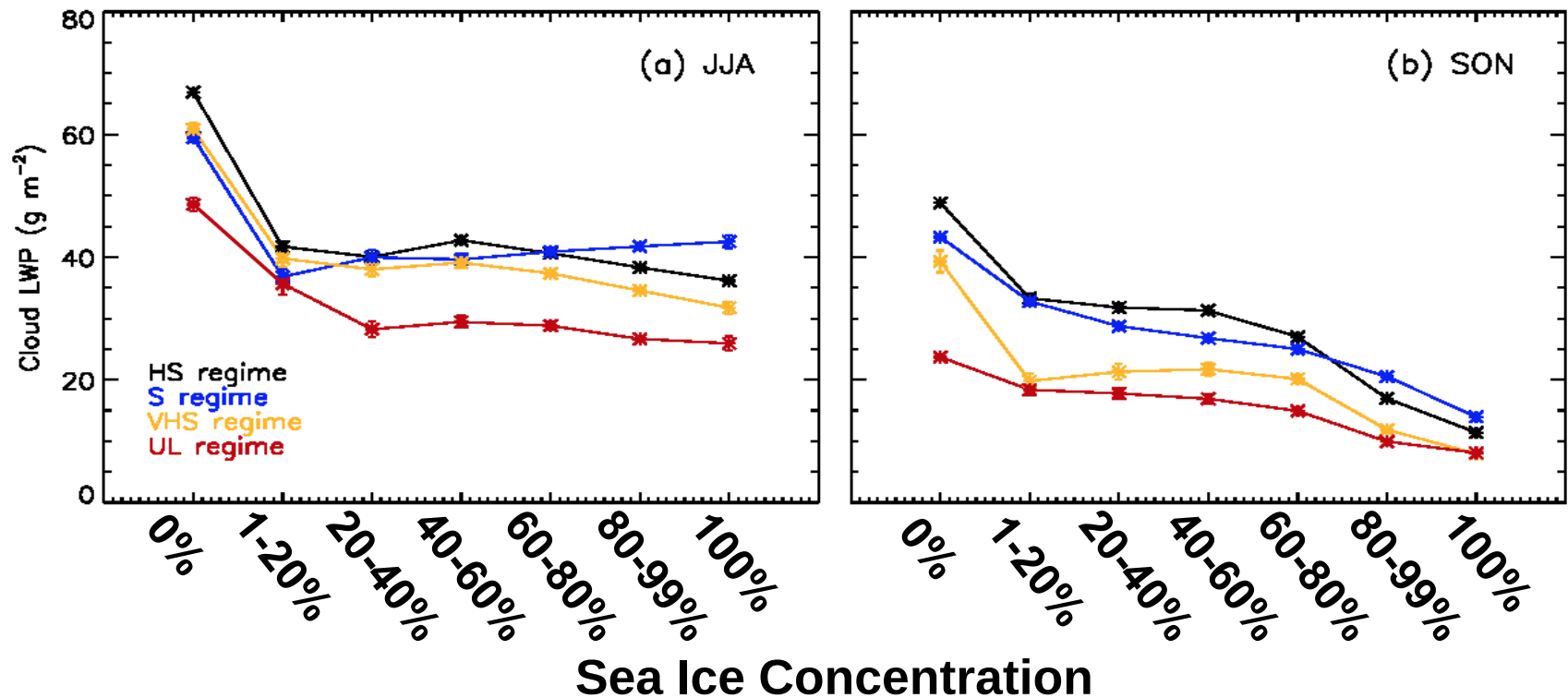
Units: W m^{-2}

Atmospheric Regime	Summer (JJA)		Fall (SO)		Winter (NDJFMAM)	
	LW CRE	SW CRE	LW CRE	SW CRE	LW CRE	SW CRE
VHS (LTS >24 K)	40.6	-57.5	37.9	-10.8	24.4	-8.1
HS (16<LTS<24 K)	50.1	-70.1	53.0	-16.6	37.9	-11.8
S (LTS<16 K)	55.7	-80.8	59.5	-20.2	53.6	-19.7
UL ($\omega_{500} < -8.6$ hPa day ⁻¹)	51.8	-85.1	56.6	-22.3	48.6	-18.6

Taylor (2017)

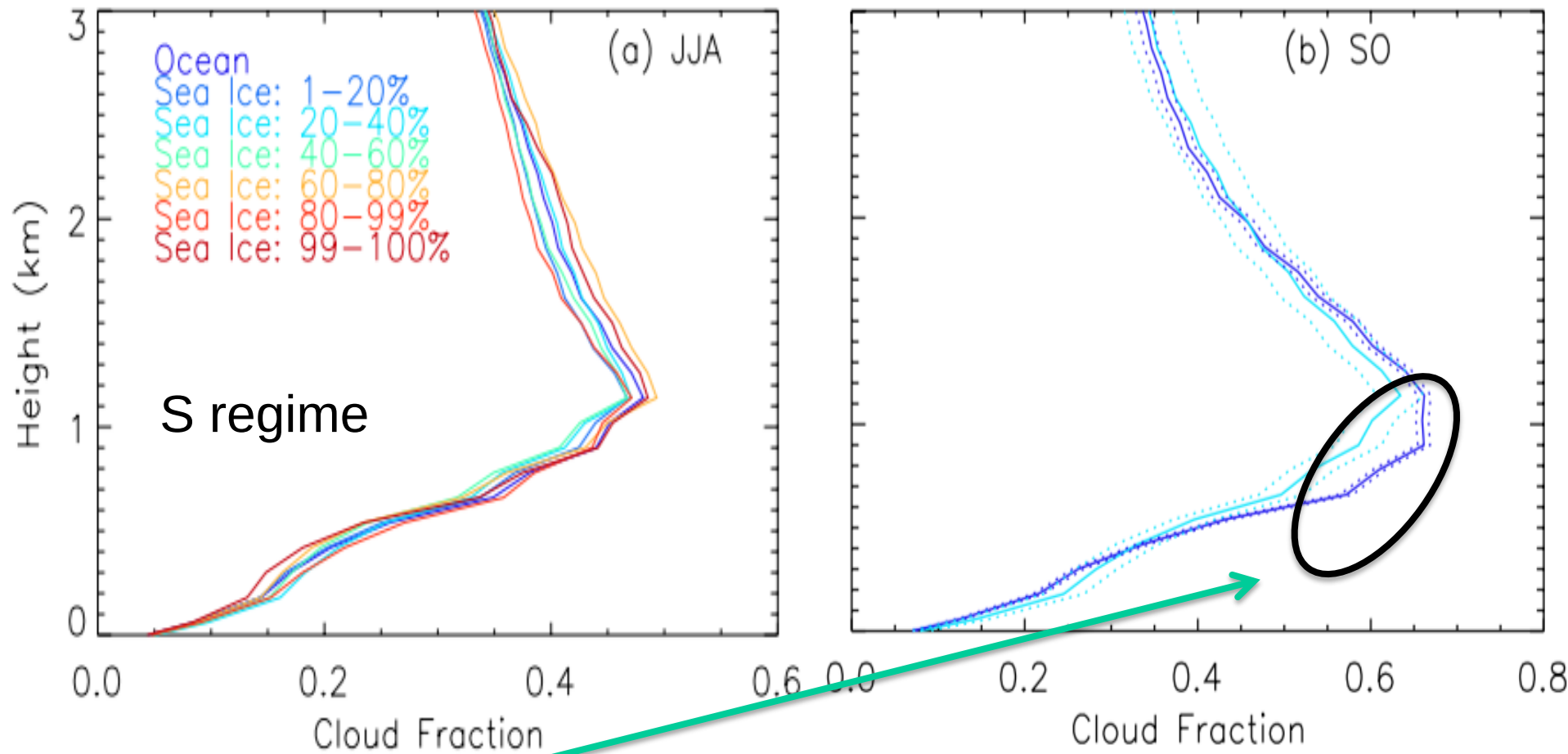
Compositing Methodology

- (1) Determine the Atmospheric Regime of each footprint using MERRA
- (2) Determine the instantaneous sea ice concentration from SSM/I retrieval
- (3) Average low cloud properties (cloud top < 3 km) within each atmosphere and sea ice concentration bin



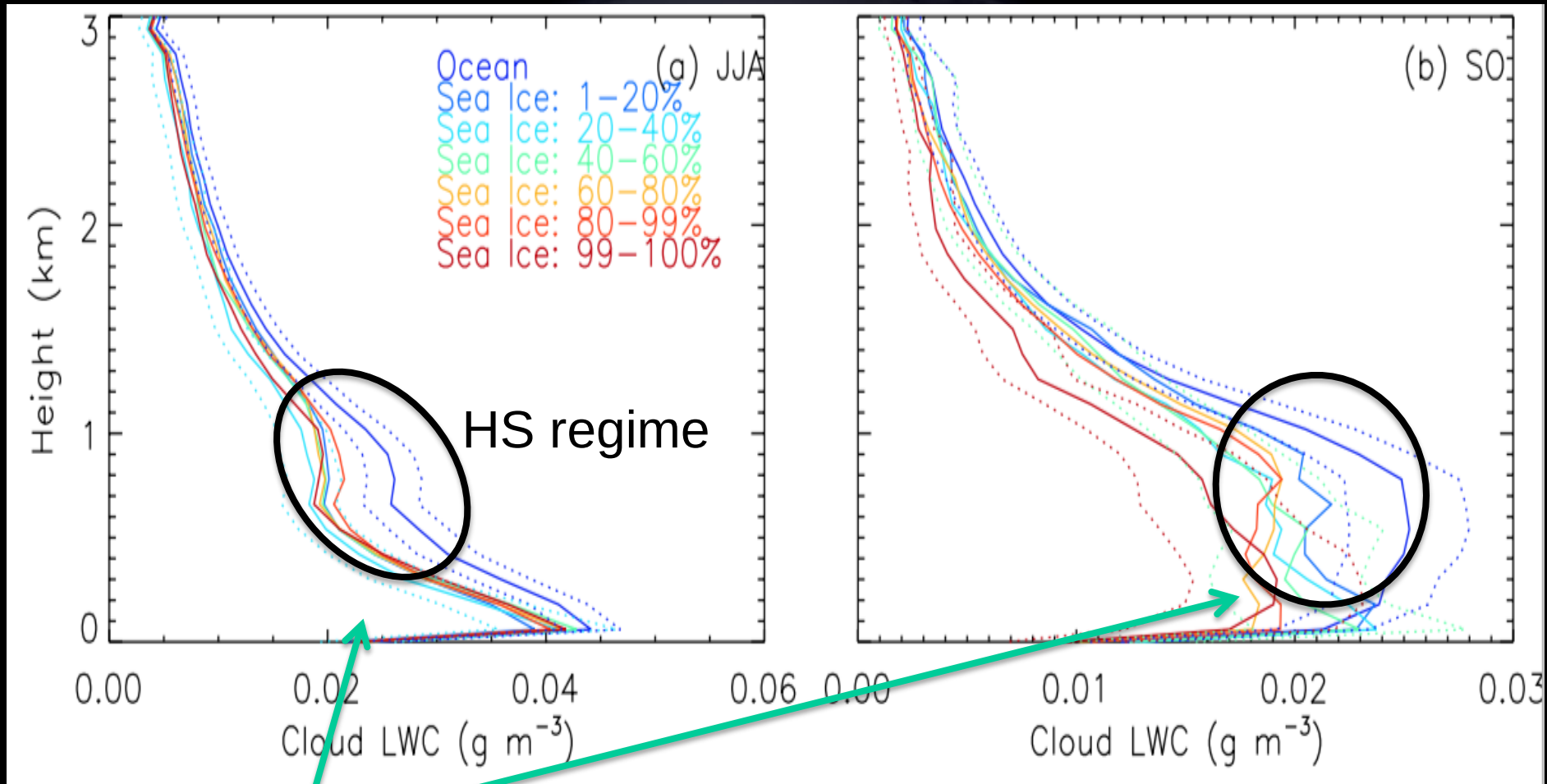
The goal of the methodology is to retain as much process level information as possible by using satellite footprint level data, not monthly mean gridded.

CF Vertical Profile vs. Sea ice



- General decrease in cloud fraction is found with increased sea ice concentration in autumn, but no response in summer.
- Statistically significant differences at the 95% confidence interval are found at between 500 m and 1.2 km in autumn at 0% and 20-40% sea ice concentration.

LWC Vertical Profile vs. Sea ice



- General decrease in LWC is found with increased sea ice concentration in both summer and autumn.
- Statistically significant differences the LWC between 500 m and 1.2 km are found in summer and autumn at 0% and 20-40% sea ice concentration.

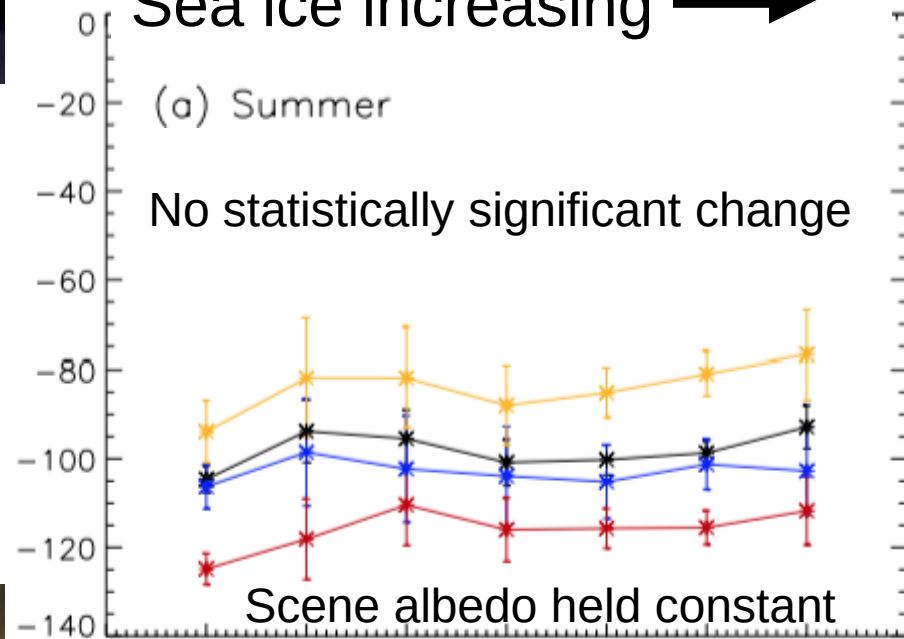
CRE vs.

SIG:

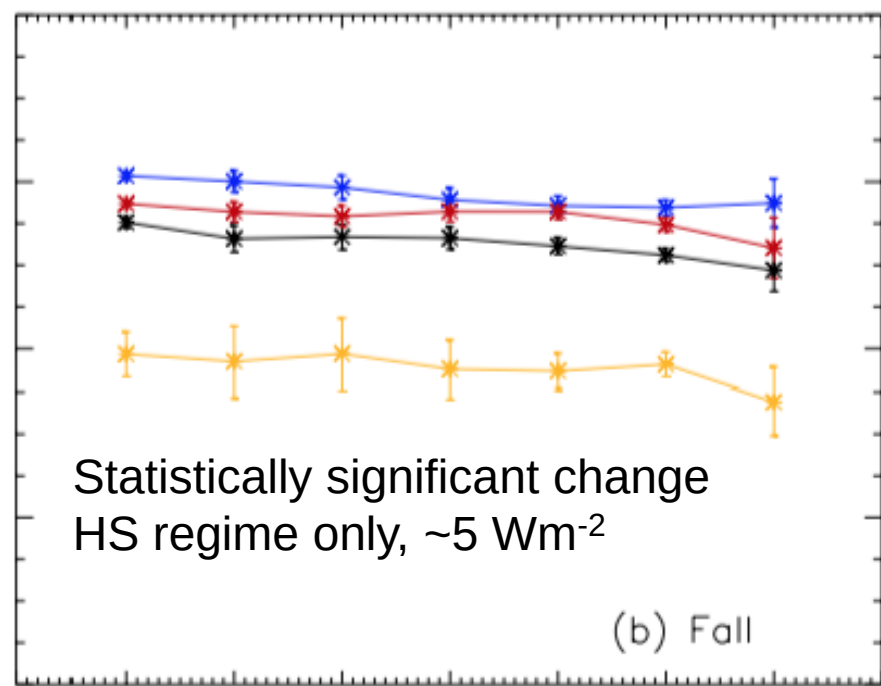
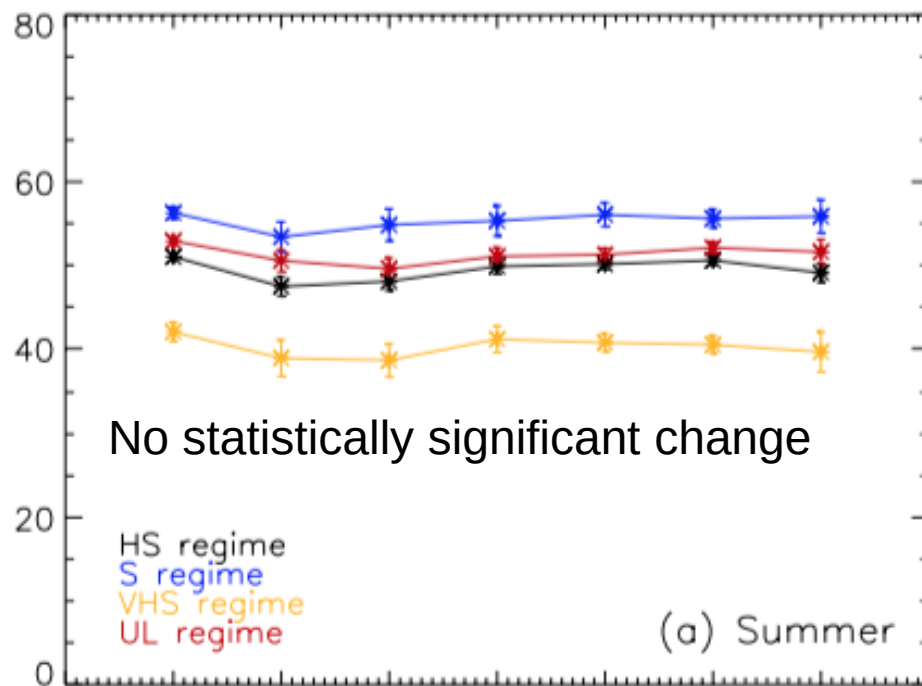
Large differences in LW and SW CRE in scene with different sea ice concentrations are found but few are statistically significant. Taylor (2017)

SW CRE (W m^{-2})

Sea ice increasing →



LW CRE (W m^{-2})



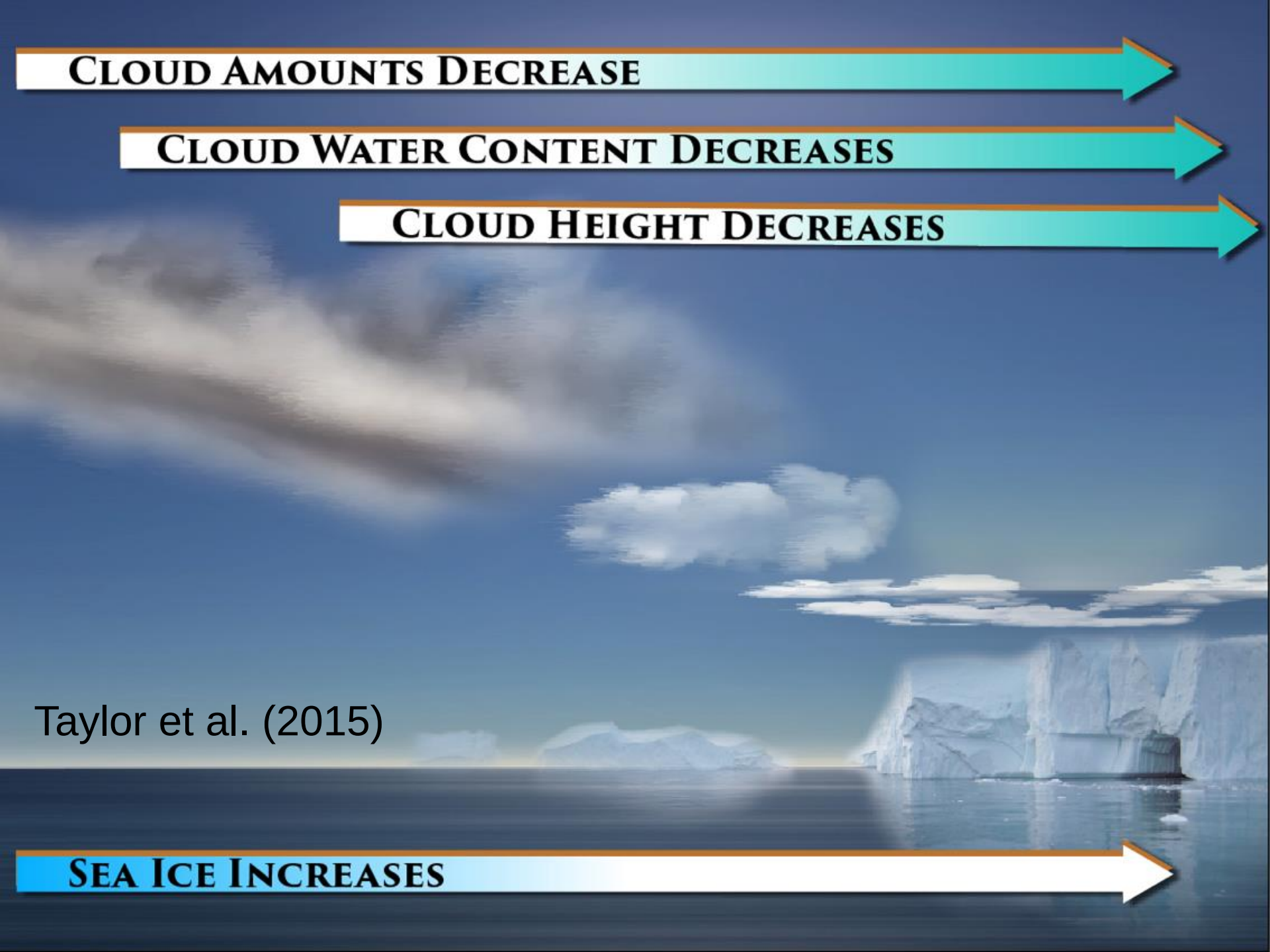
CLOUD AMOUNTS DECREASE

CLOUD WATER CONTENT DECREASES

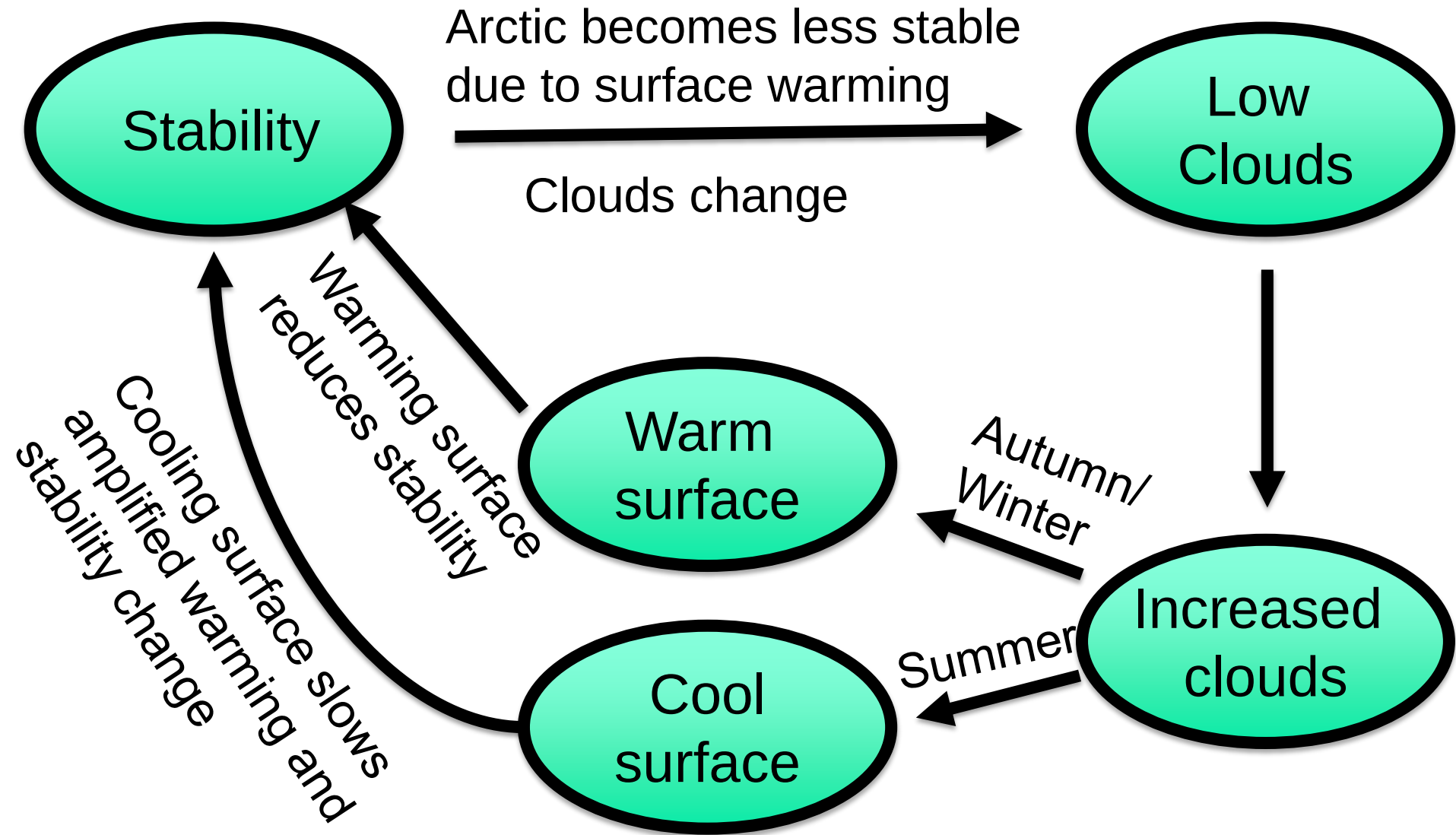
CLOUD HEIGHT DECREASES

Taylor et al. (2015)

SEA ICE INCREASES

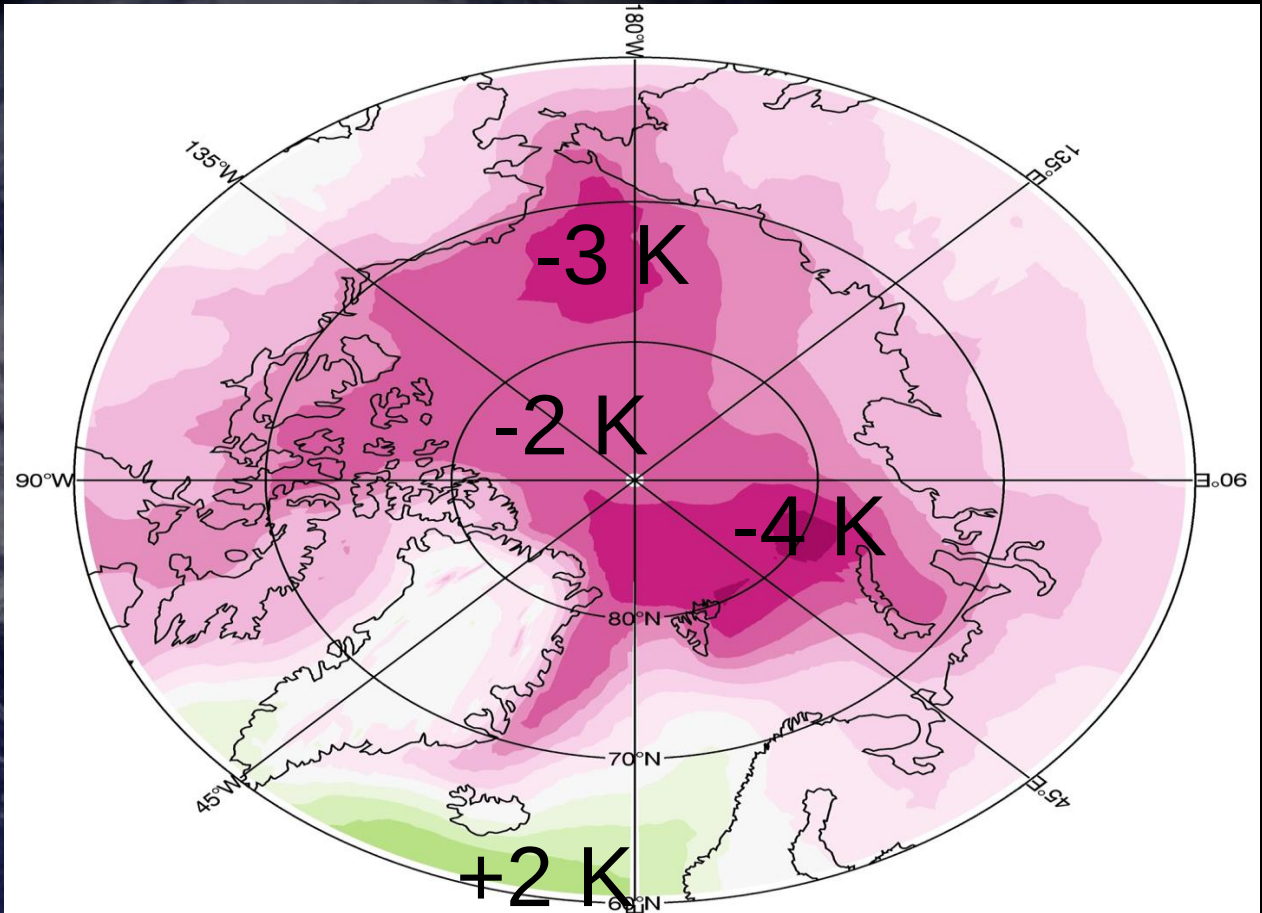


Stability-Cloud Response Pathway



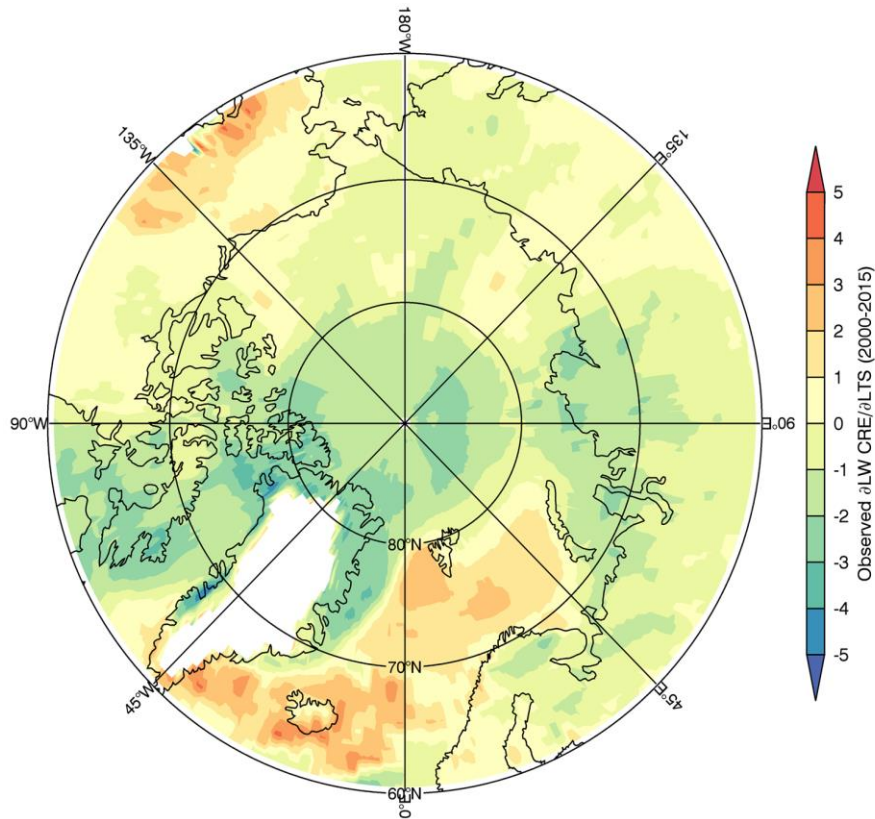
Overwhelmingly,
CMIP5 models
project
significant
decreases in
LTS over the
central Arctic

Ensemble Average transient change in LTS

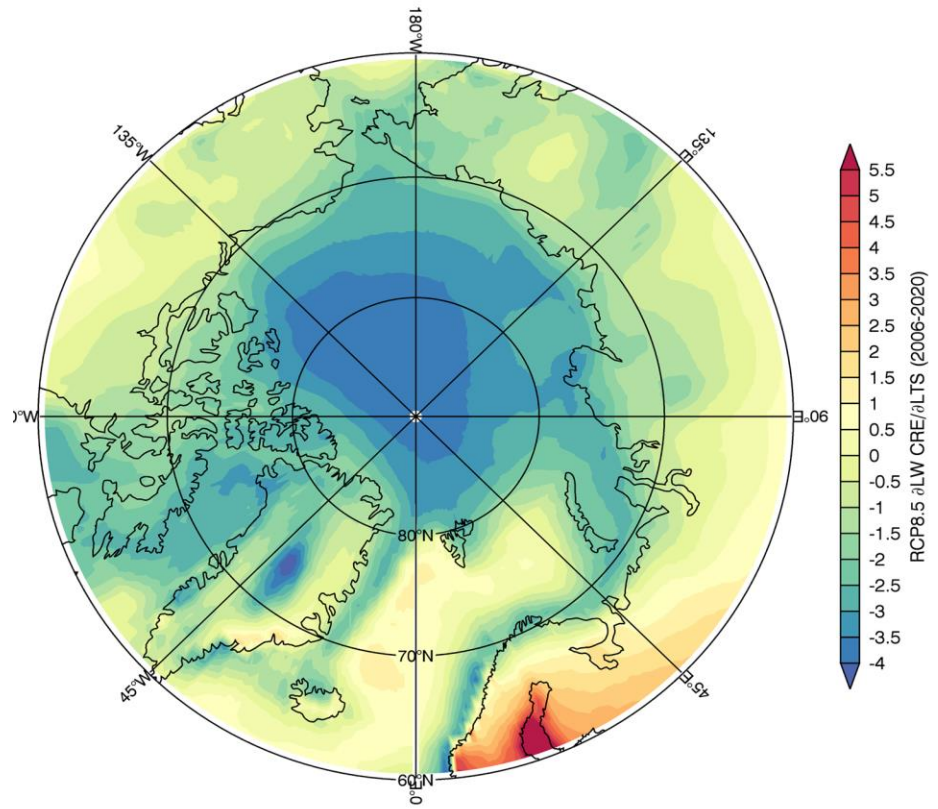


Inter-annual variability of LTS and LW CRE

Observed regression



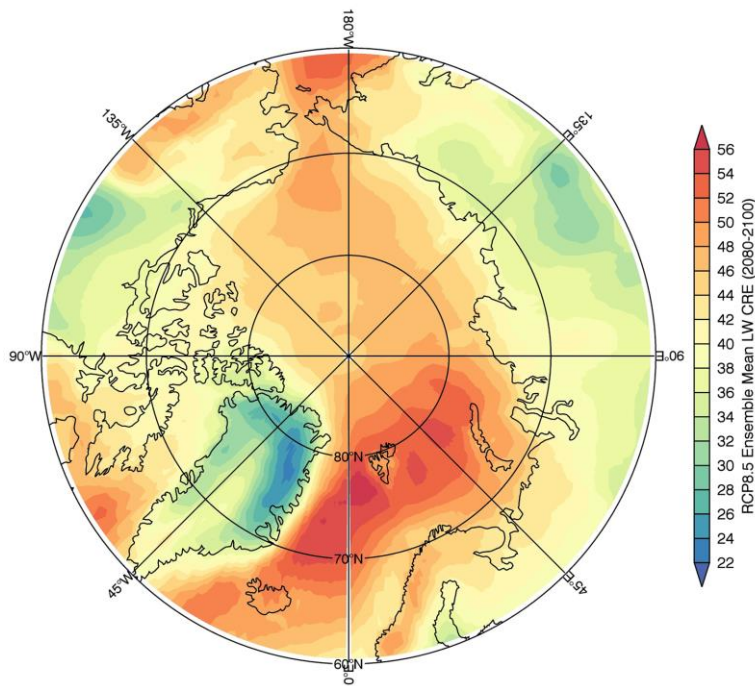
CMIP5 Ensemble Average



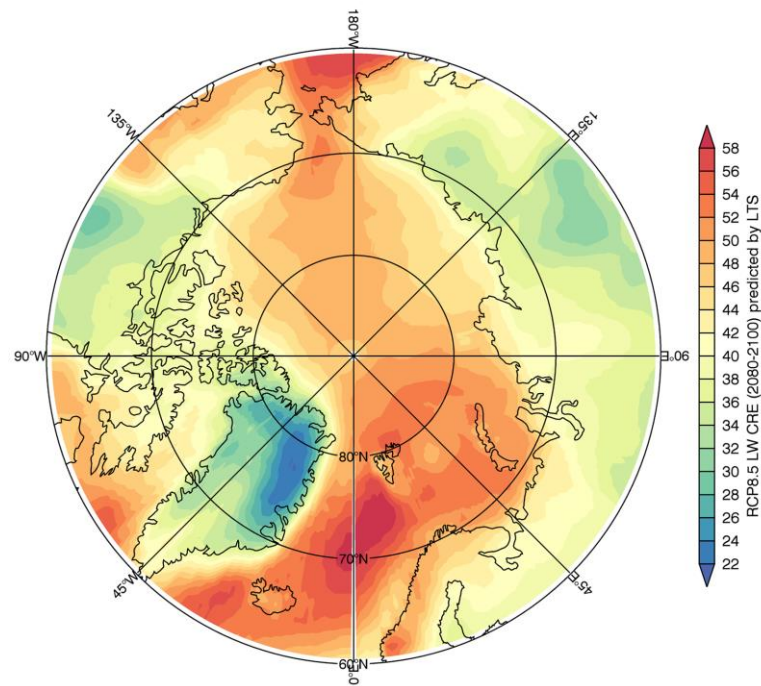
LW CRE-LTS regression slopes in climate models are more than 2 times larger than observations show over portions of the Arctic.

Can this regression be used to predict LW CRE?

Ensemble average:

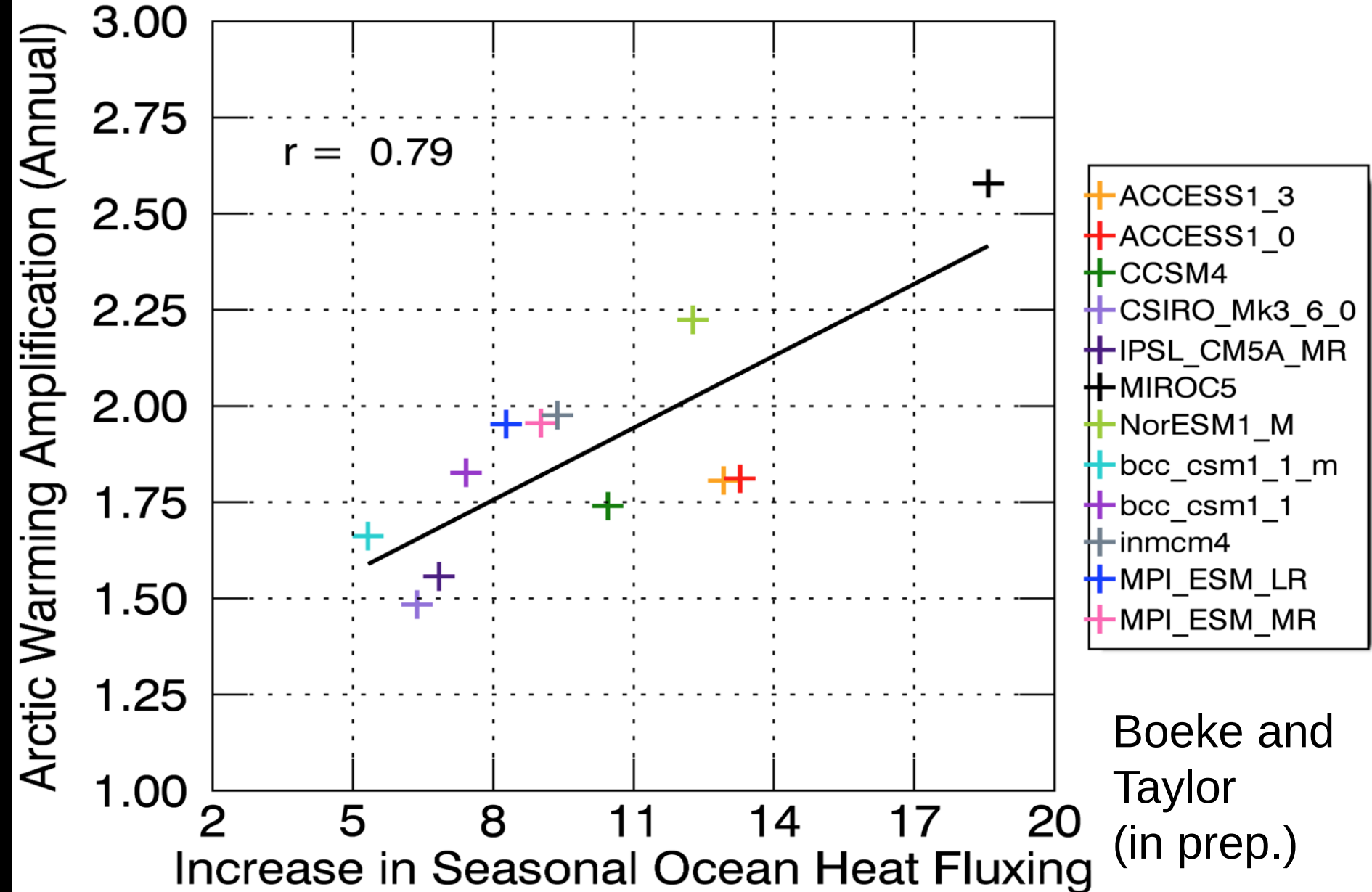


Regression result:



The patterns from the ensemble average and regression result agree well.

A big role for the ocean!



Takeaway messages:

- **Lower tropospheric stability, an excellent diagnostic** for Arctic low cloud properties and surface radiative effects.
- **Small change in atmospheric states can equal a large cloud feedback!** A small change in the frequency of occurrence of atmosphere states can yield a larger Arctic cloud feedback than any cloud response to sea ice.
- **Too strong LW CRE response to a reductions in Arctic stability.** Over the central Arctic, the LW CRE sensitivity to a change in LTS in climate models is much stronger (more than 2 times in places) than observations show.
- **Potentially significant amplifying sea ice-cloud feedback in fall.** Our results indicate that the cloud response to sea ice reduction in fall could delay the fall freeze-up and influence the variability in sea ice extent and volume, under certain meteorological conditions; It only takes 1 Wm^{-2} to make a big difference.

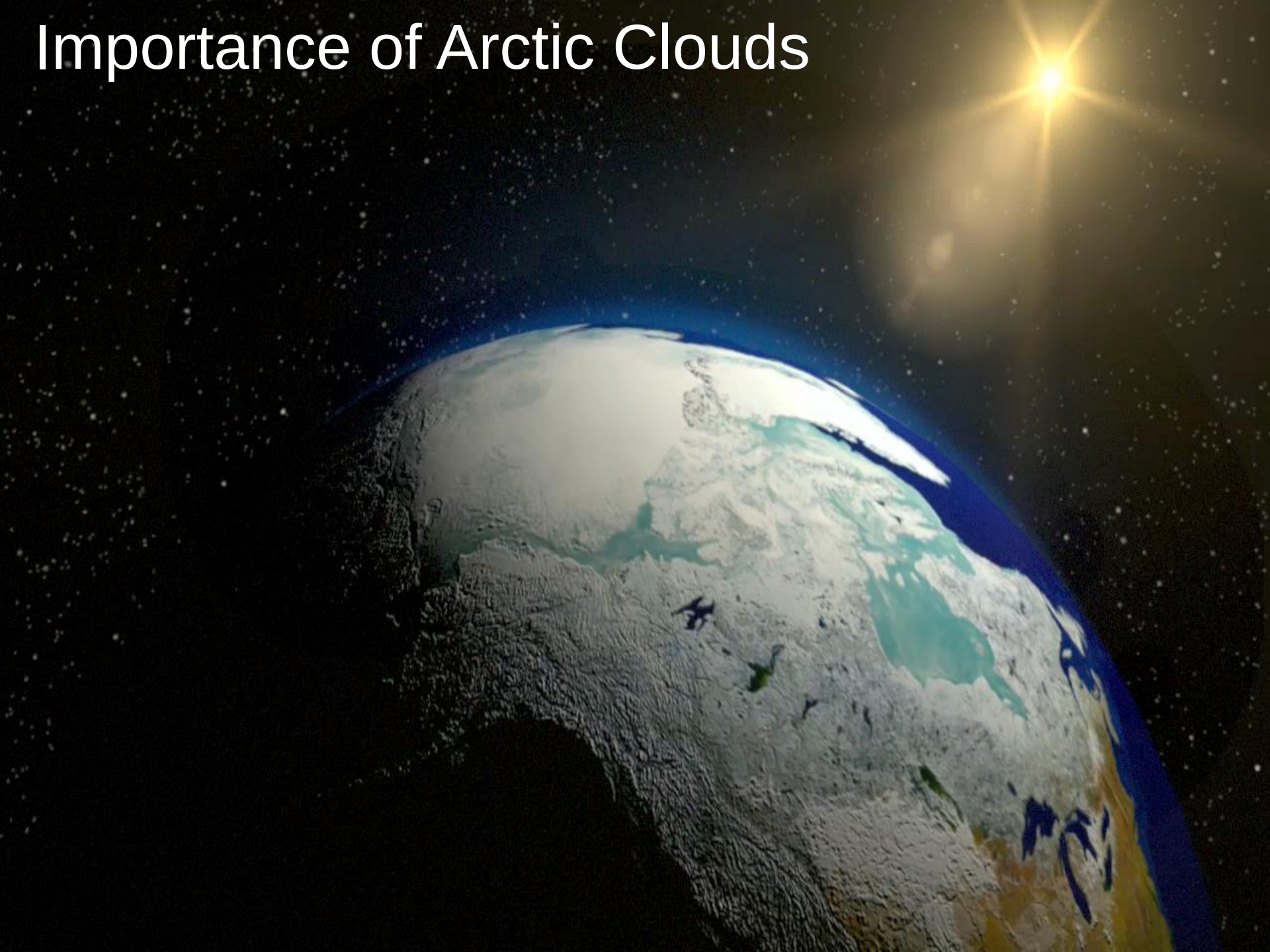
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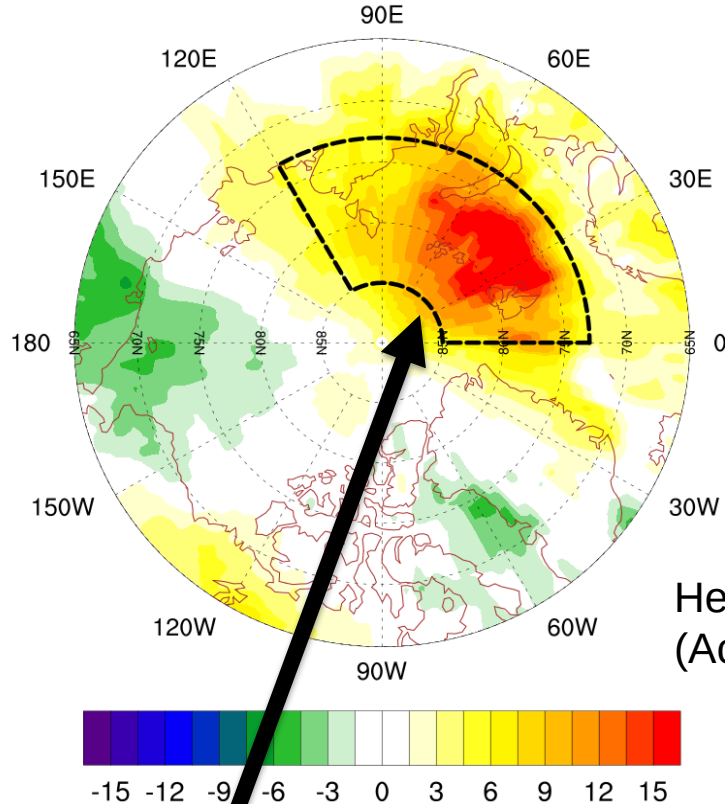


Importance of Arctic Clouds



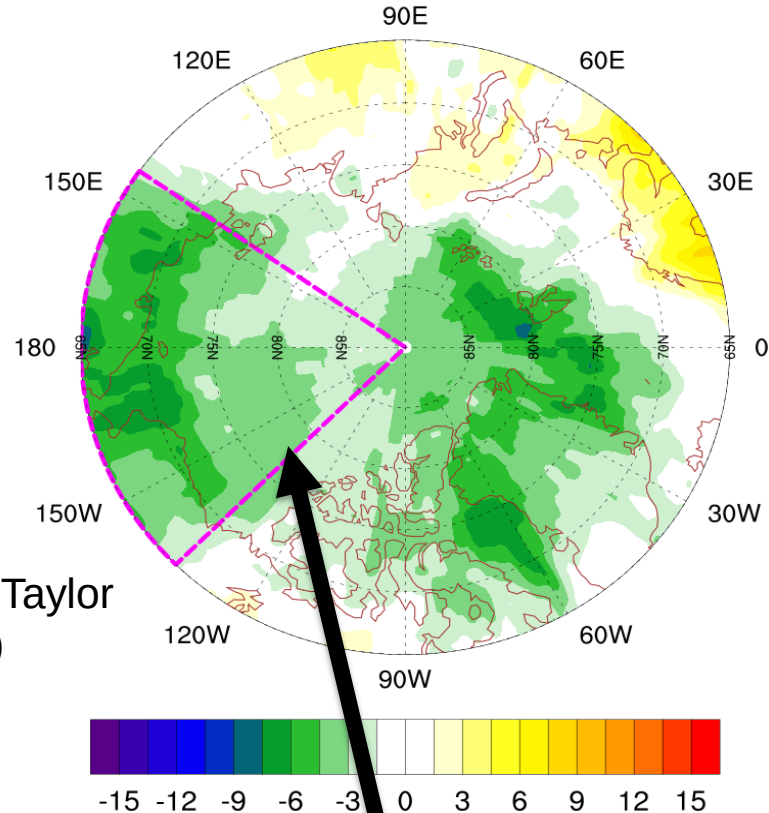
Any way the wind blows: Circulation and the Arctic Surface Energy Budget

NDJF Spatial Dist. of LWdownCLR Regression, AD



Positive AD: Significant positive clear-sky downwelling LW anomaly.

ON Spatial Dist. of LWdownCLR Regression, AO

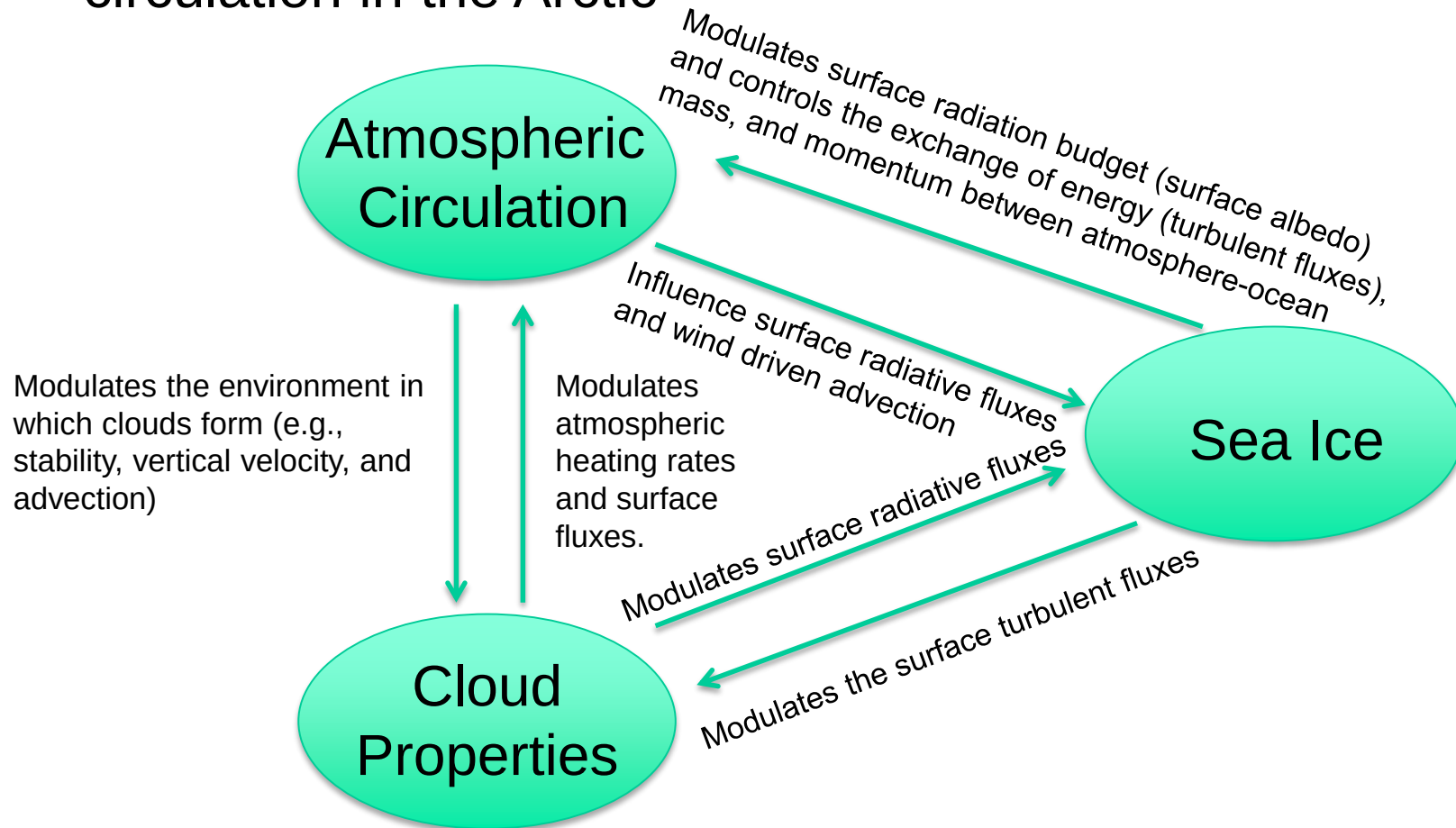


Positive AO: Significant negative clear-sky downwelling LW anomaly.

Hegyi and Taylor
(Accepted)

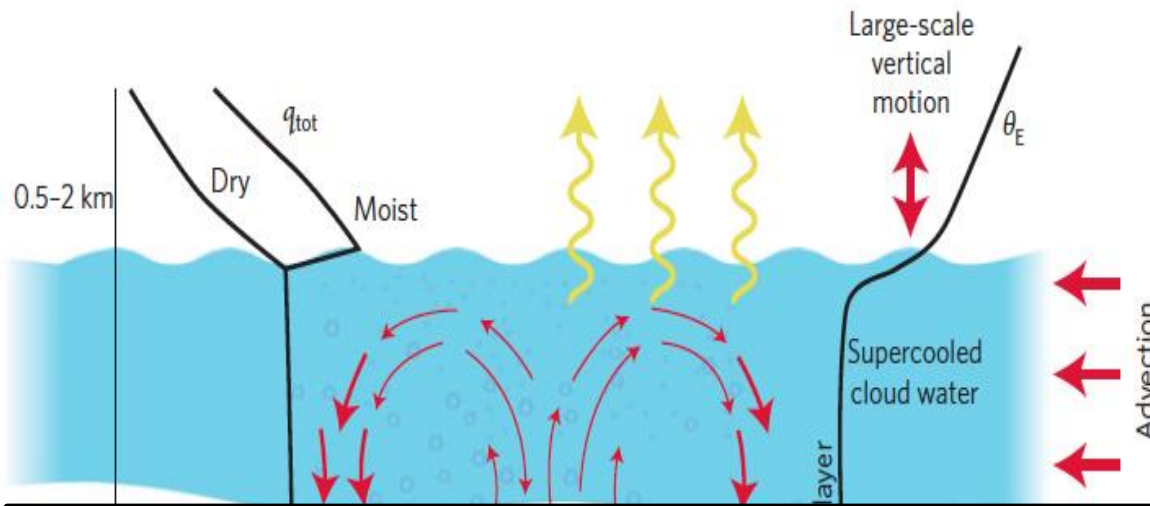
How do we reach the finish line?

Understanding the coupling between the cloud and circulation in the Arctic



In the Arctic, we cannot consider the interactions between clouds and the circulation without considering the sea ice state because sea ice influences both clouds and circulations.

Arctic Low Cloud Processes



Radiative Cooling

- Drives buoyant production of turbulence
- Forces direct condensation within inversion layer
- Requires minimum amount of cloud liquid water

Microphysics

- Liquid forms in updrafts and sometimes within the inversion layer
- Ice nucleates in cloud
- Rapid ice growth promotes sedimentation from cloud

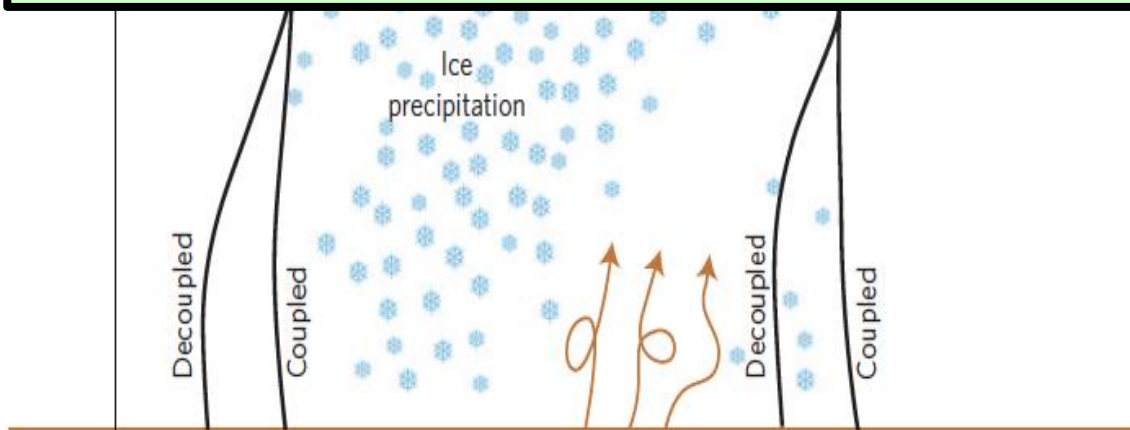
Dynamics

- Cloud-forced turbulent mixed layer with strong narrow downdrafts, weak broad updrafts, and q_{tot} and θ_E nearly constant with height
- Small-scale, weak turbulence in cloudy inversion layer
- Large-scale advection of water vapour important

Surface Layer

- Turbulence and q contributions can be weak or strong
- Sink of atmospheric moisture due to ice precipitation
- Surface type (ocean, ice, land) influences interaction with cloud

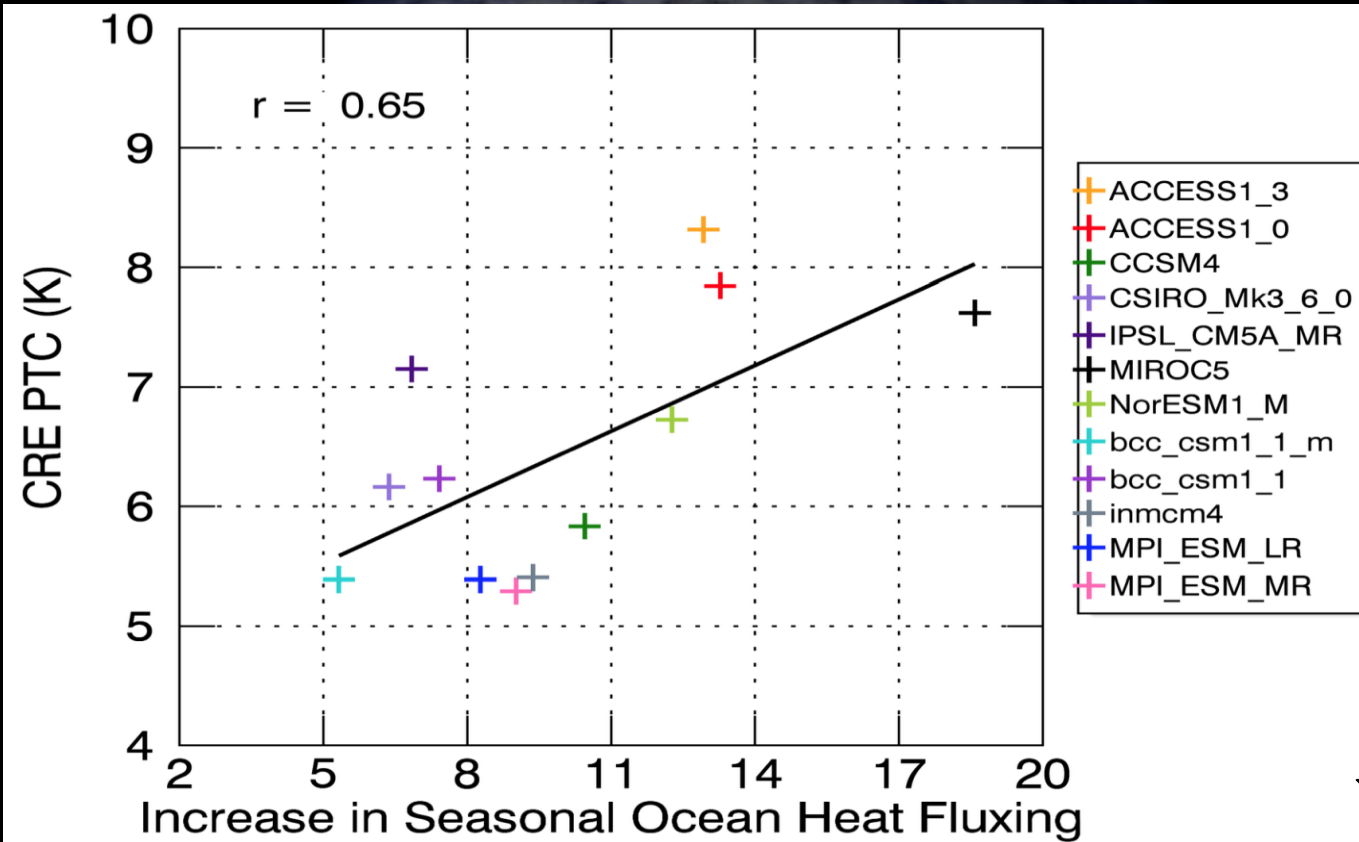
Do clouds respond to changes in sea ice?



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.

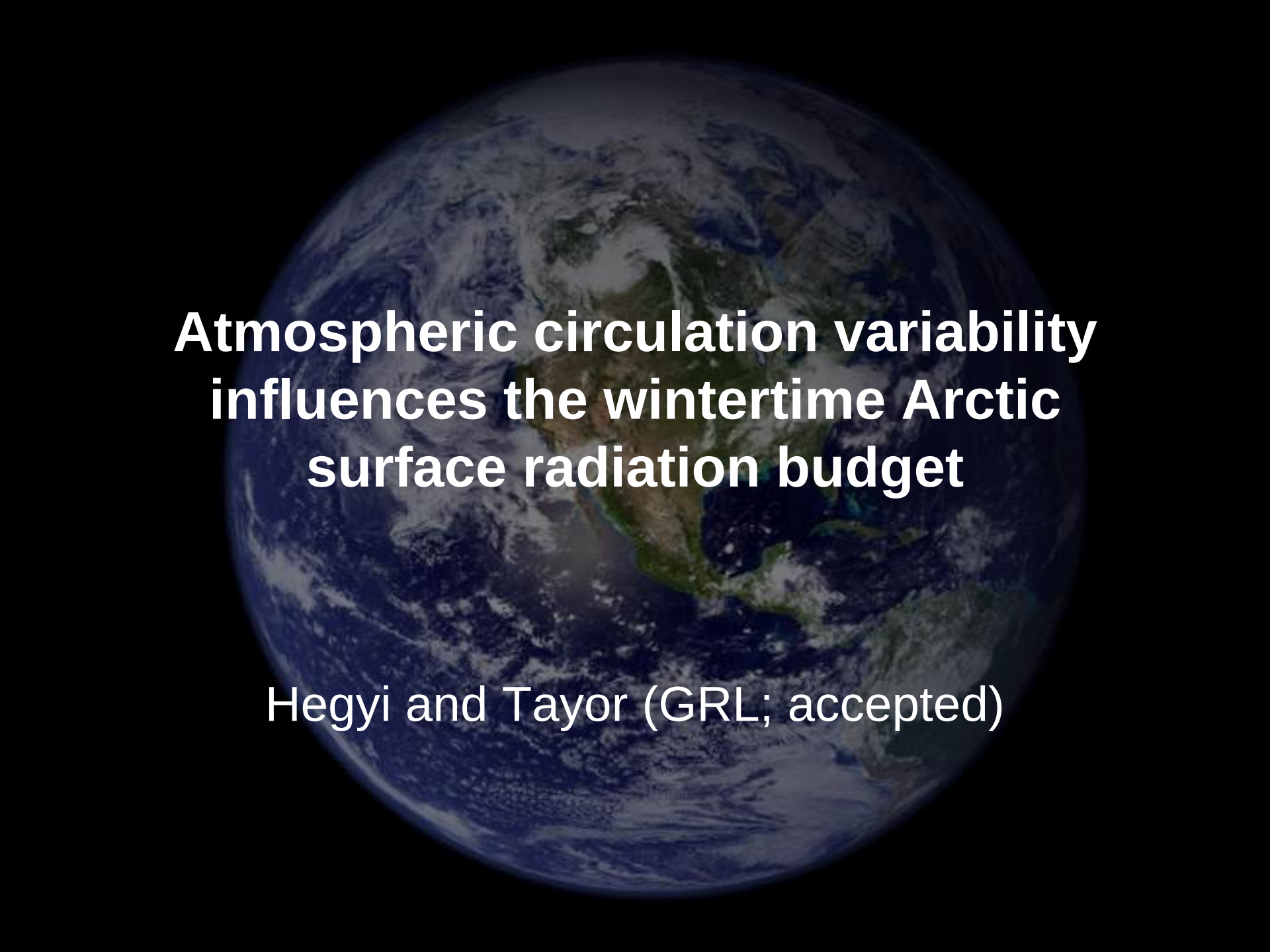
Morrison et al.
(2012; Nature
Geoscience)

Larger CRE results in more summer storage



Increases in clouds strengthen the CRE PTC

Increases in storage facilitates cloud formation and IR feedbacks

A satellite image of Earth, centered on the Arctic region. The image shows the Arctic Ocean, surrounded by landmasses including North America, Europe, and Asia. The image is dark, with the Earth's surface appearing in shades of blue, green, and brown against a black background.

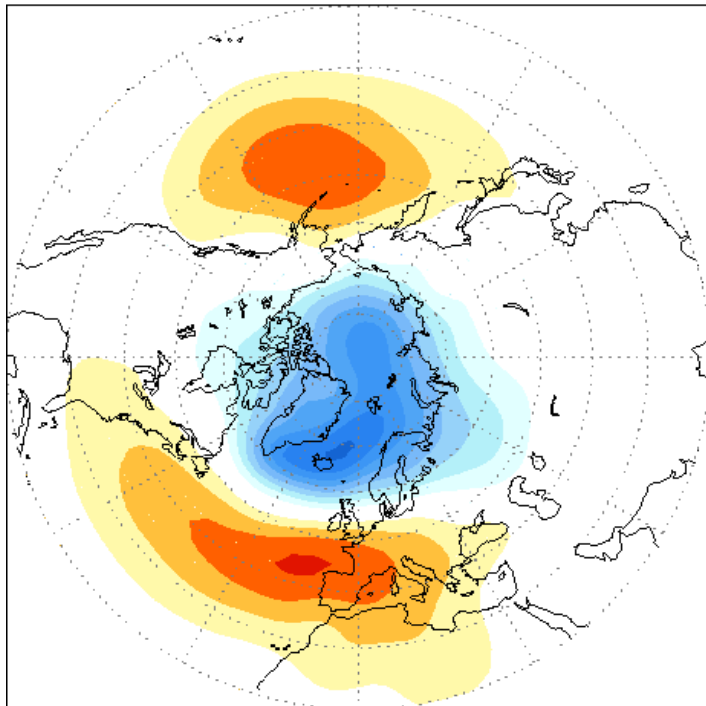
Atmospheric circulation variability influences the wintertime Arctic surface radiation budget

Hegyi and Taylor (GRL; accepted)

Defining the Arctic circulation

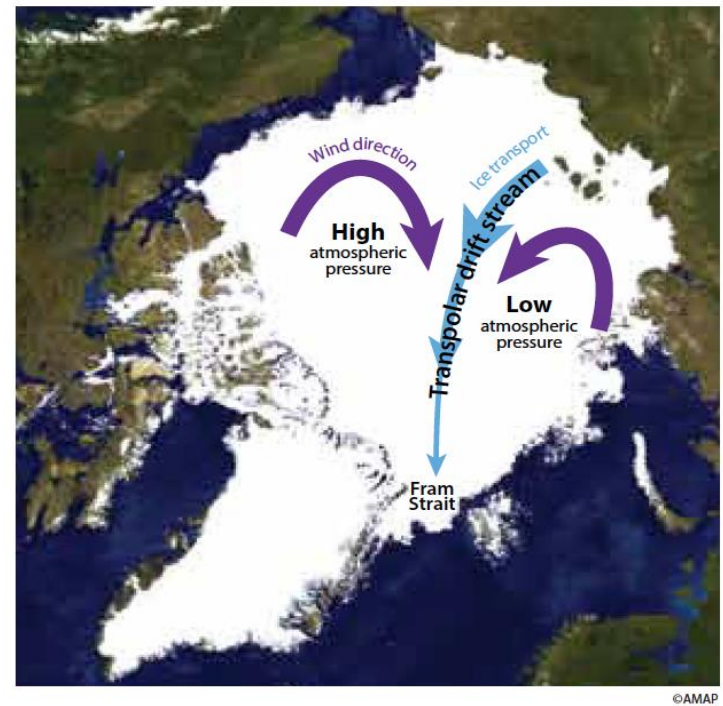
AO: Leading EOF of the 1000 hPa height pattern from 20-90N.

Leading EOF (19%) shown as regression map of 1000mb height (m)



Zonally symmetric

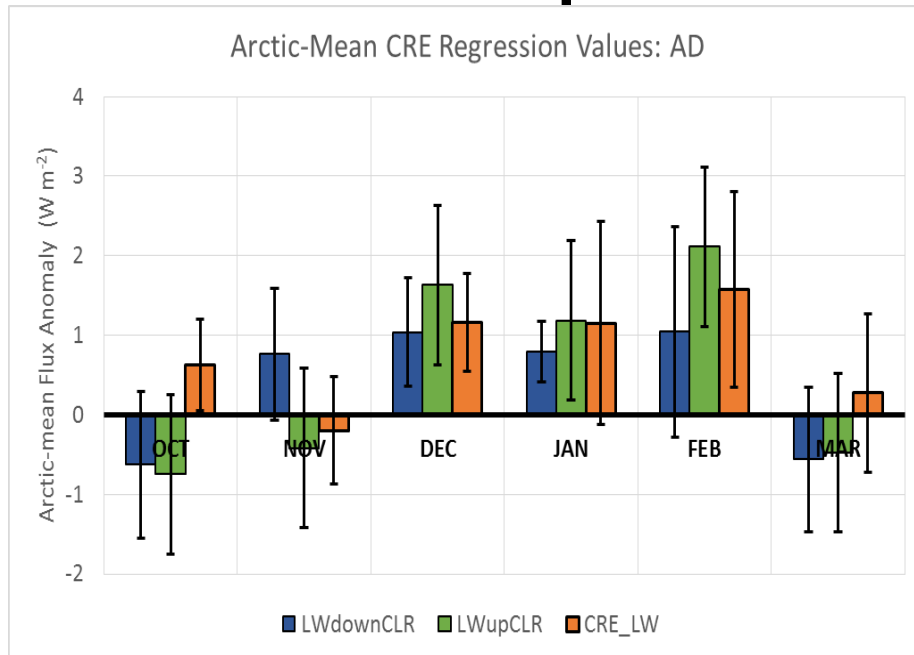
AD: Leading EOF of the 1000 hPa height pattern from 70-90N.



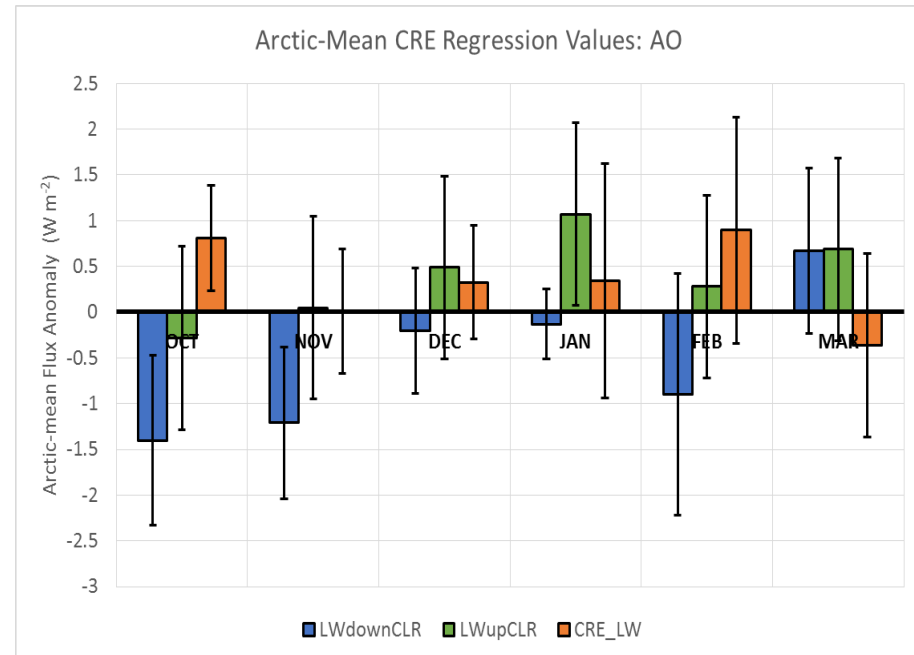
Zonally asymmetric

Any way the wind blows: Circulation and the Arctic Surface Energy Budget

Arctic Dipole

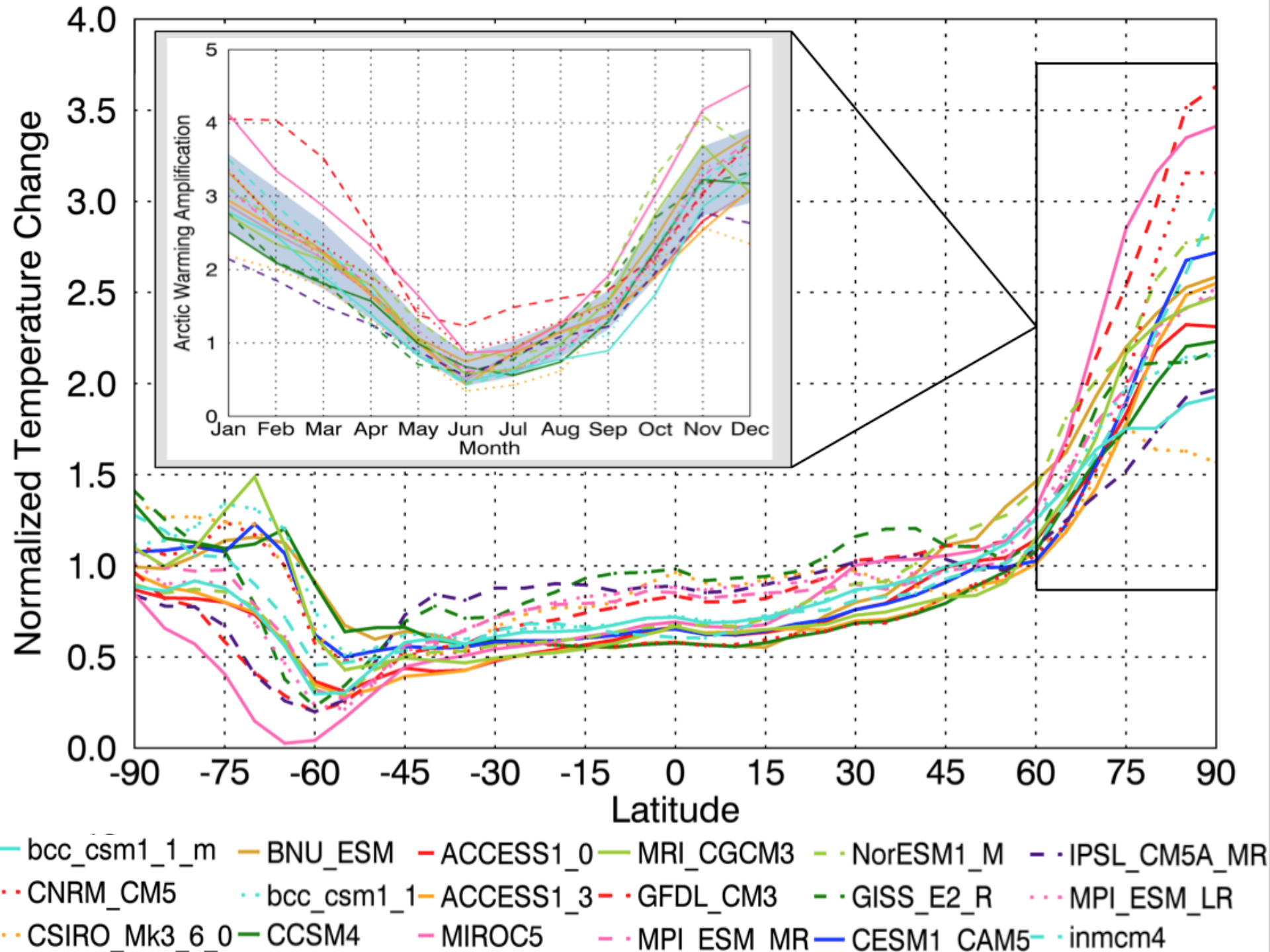


Arctic Oscillation



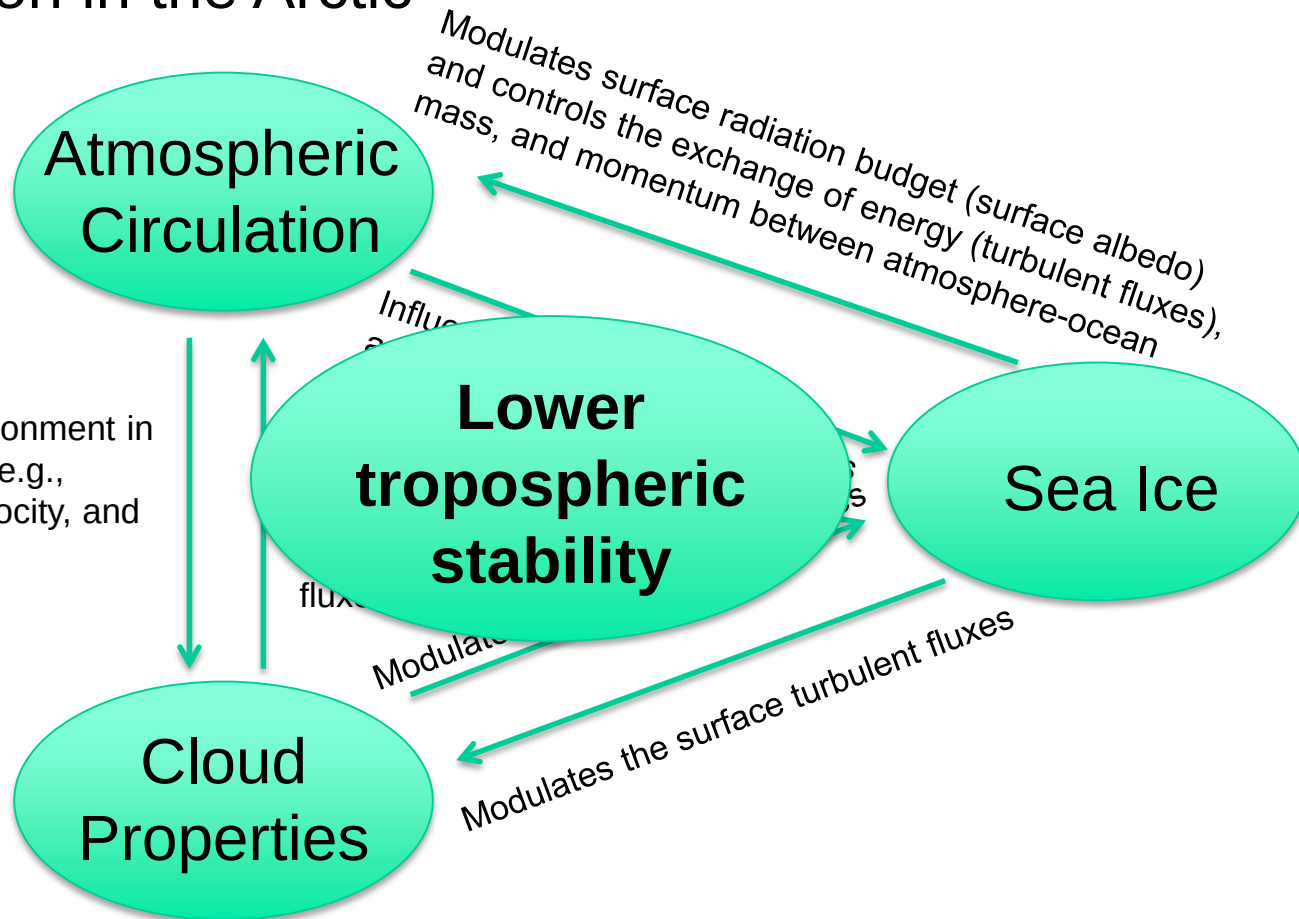
Robust, domain averaged associations between the Arctic circulation and the surface radiation budget.

Hegyi and Taylor
(GRL; accepted)



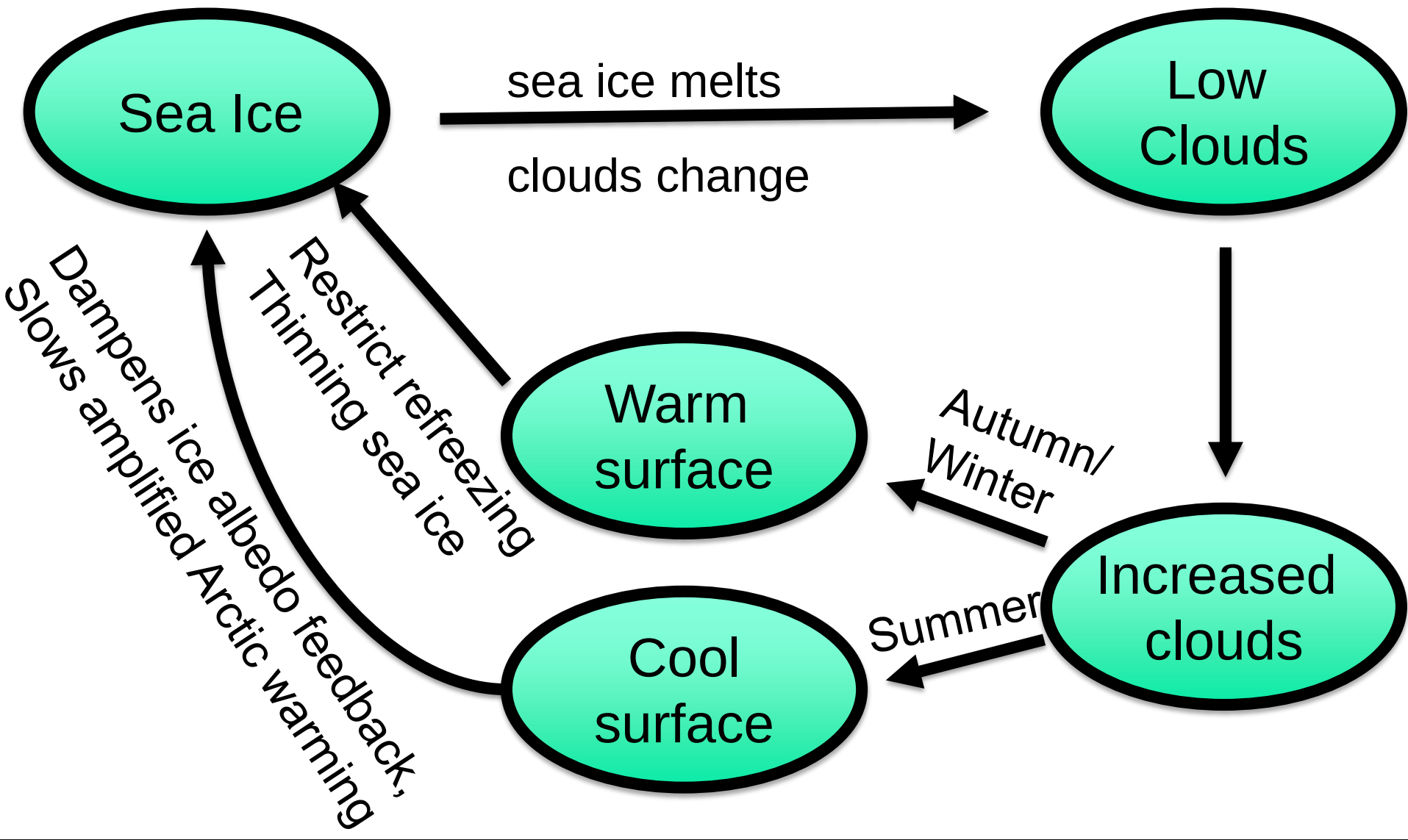
Another 3-legged stool?

Understanding the coupling between the cloud and circulation in the Arctic

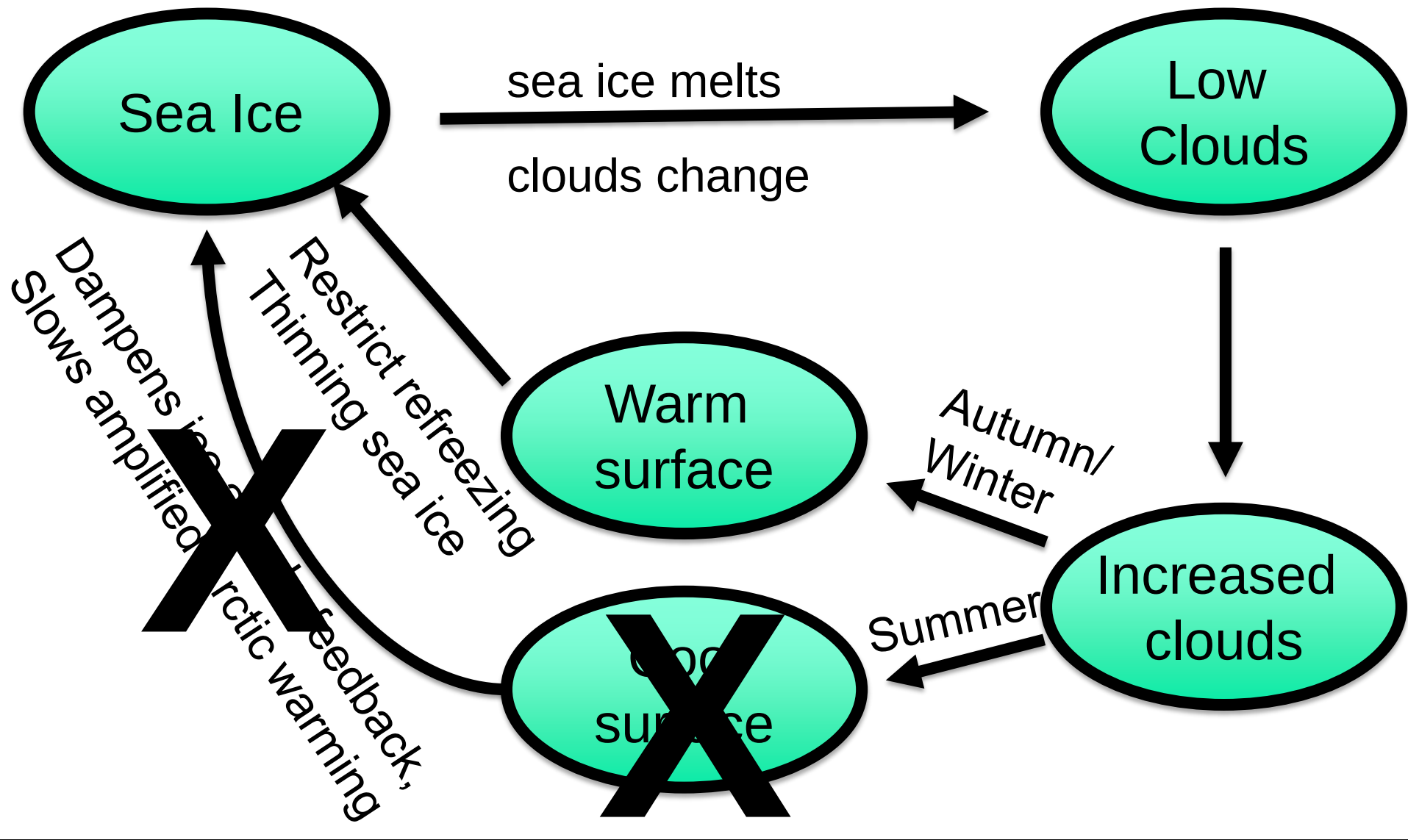


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Example pathways: Sea Ice-Clouds



Example pathways: Sea Ice-Clouds



Example pathways: Sea Ice-Circulation

