

Interactions between Arctic clouds, sea ice, and lower tropospheric stability

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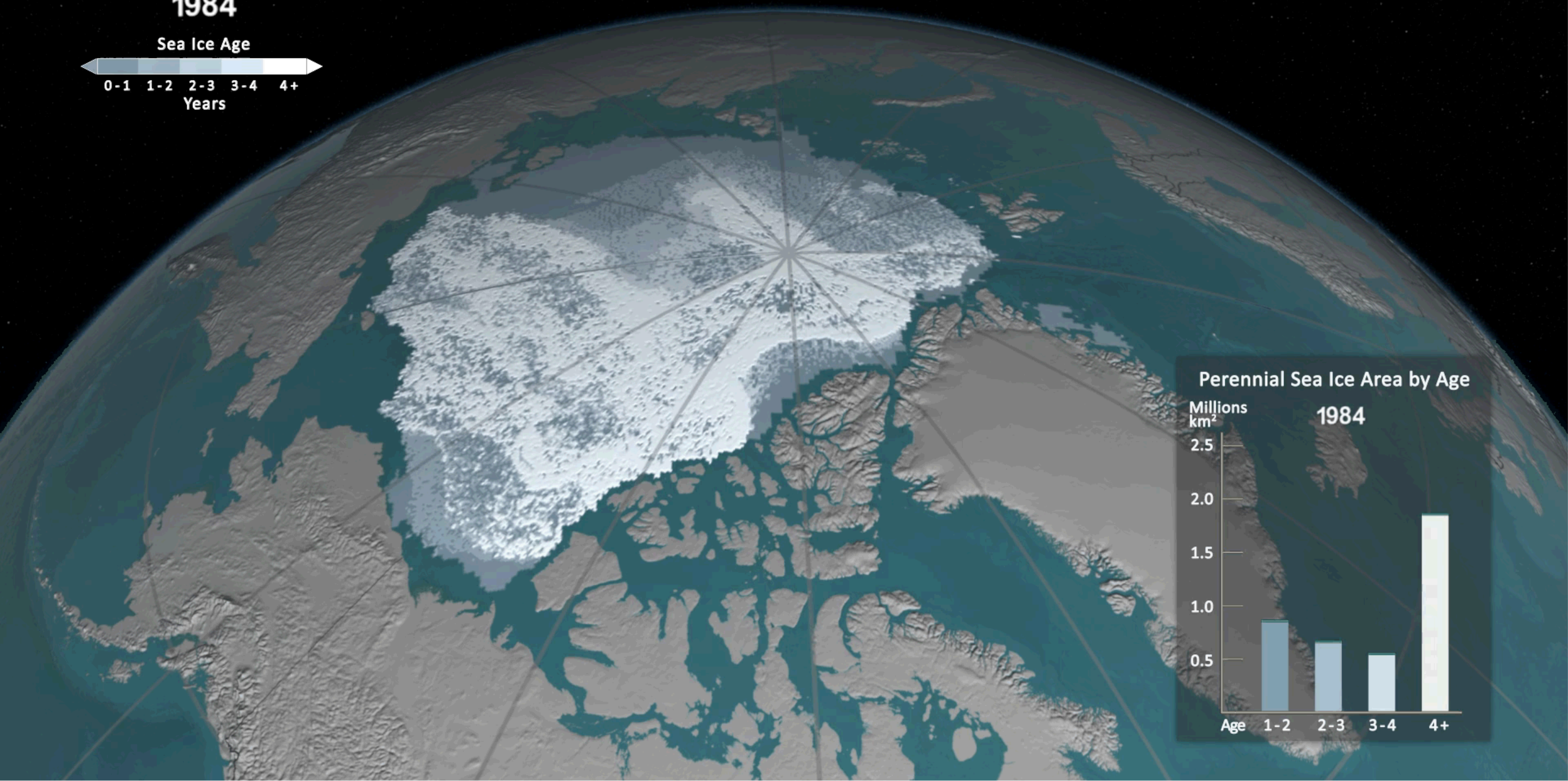
POLAR2018

June 20, 2018

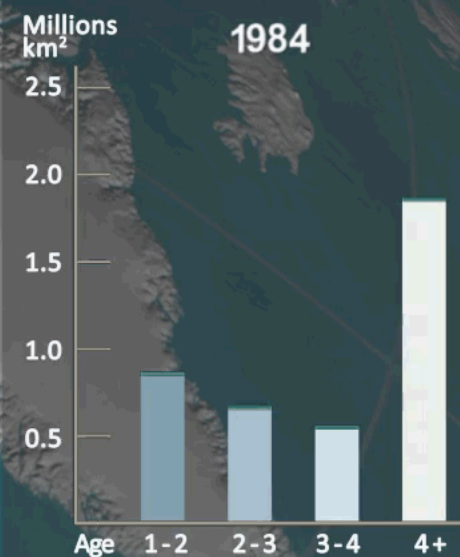
September

1984

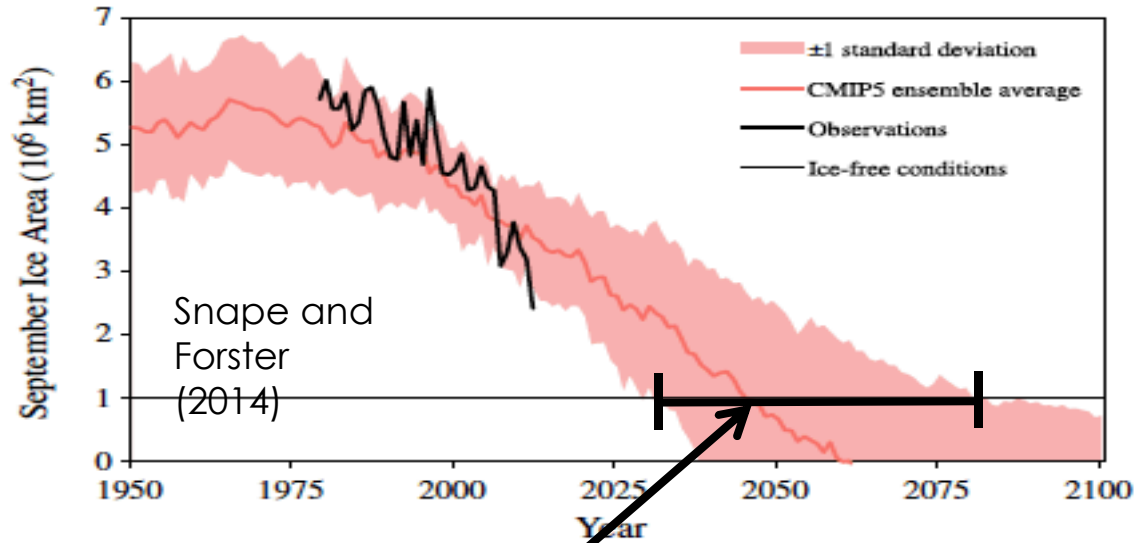
Sea Ice Age



Perennial Sea Ice Area by Age

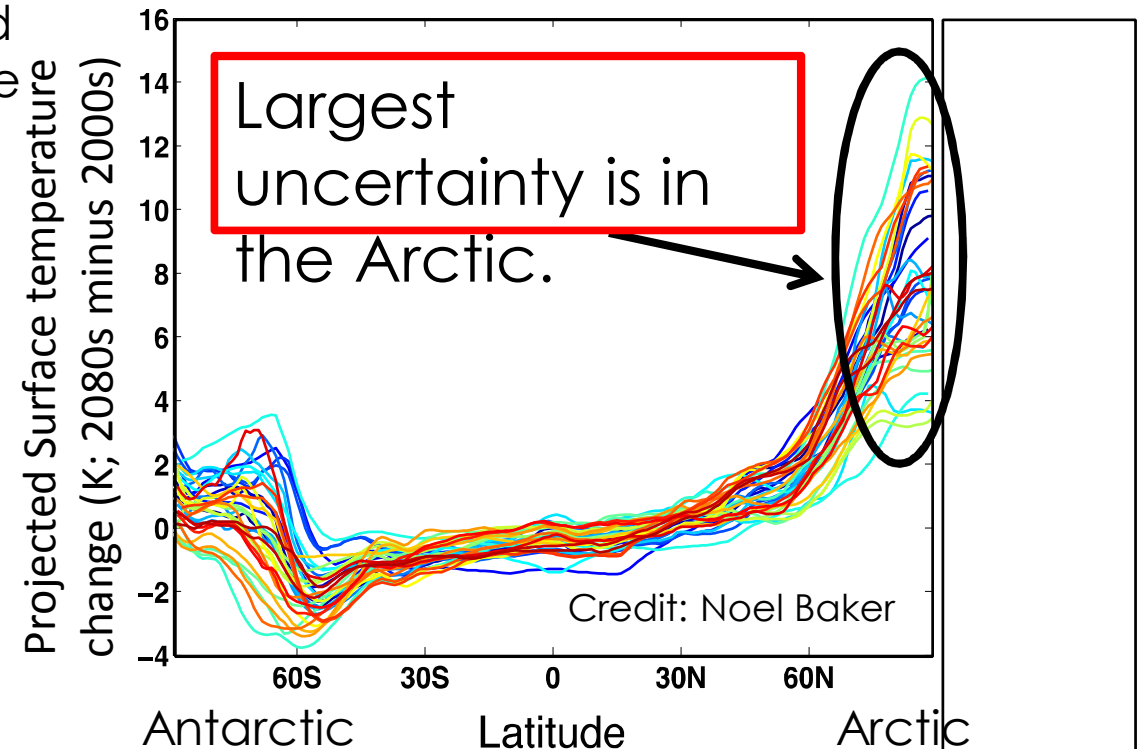


Oh, the uncertainty...

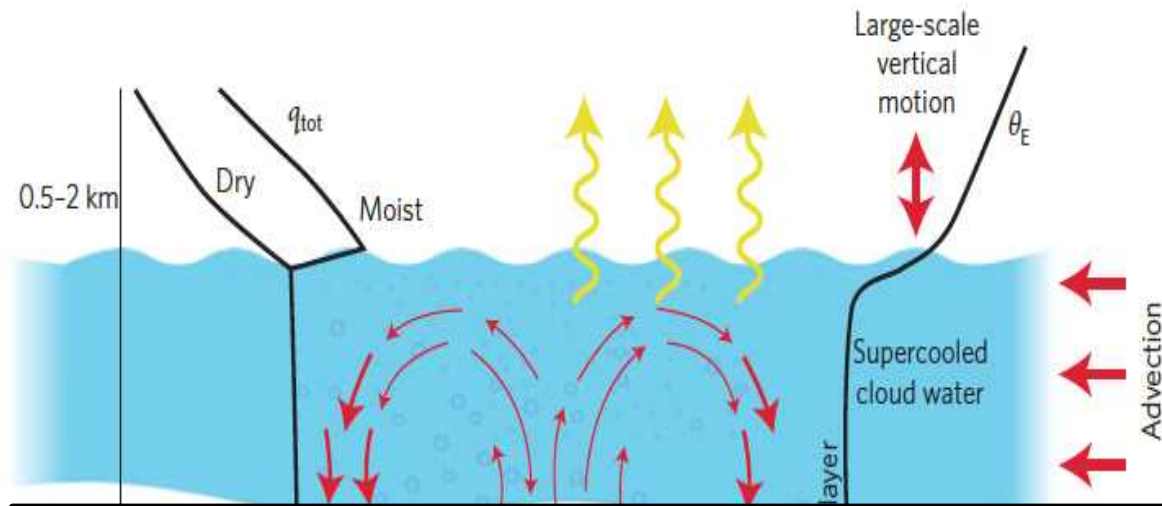


Projections of future Arctic sea ice decline and the timing of the first occurrence of a sea ice-free Arctic are very uncertain.

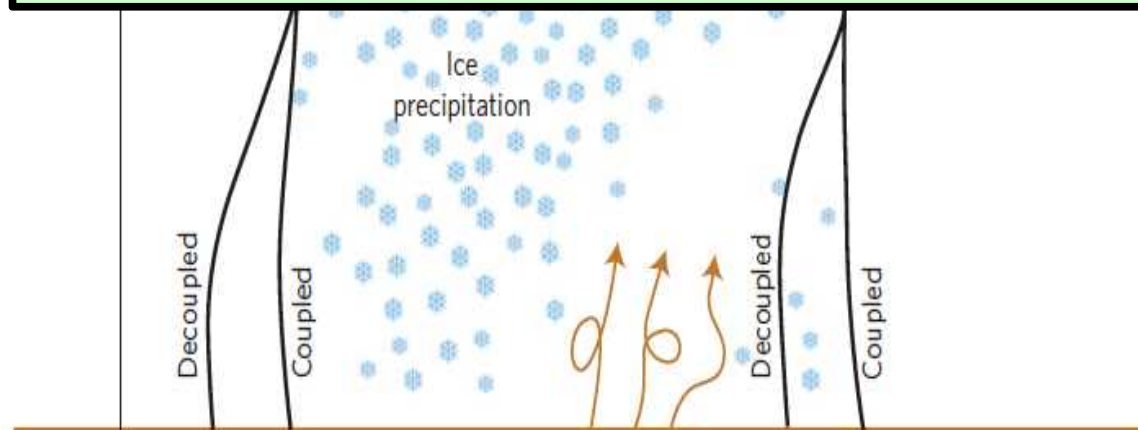
The large spread in climate model predictions of Arctic warming is attributed to model of sea ice melt and how it feeds back on the other components of the climate.



Arctic Low Cloud Processes



Do clouds respond to changes in sea ice?



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

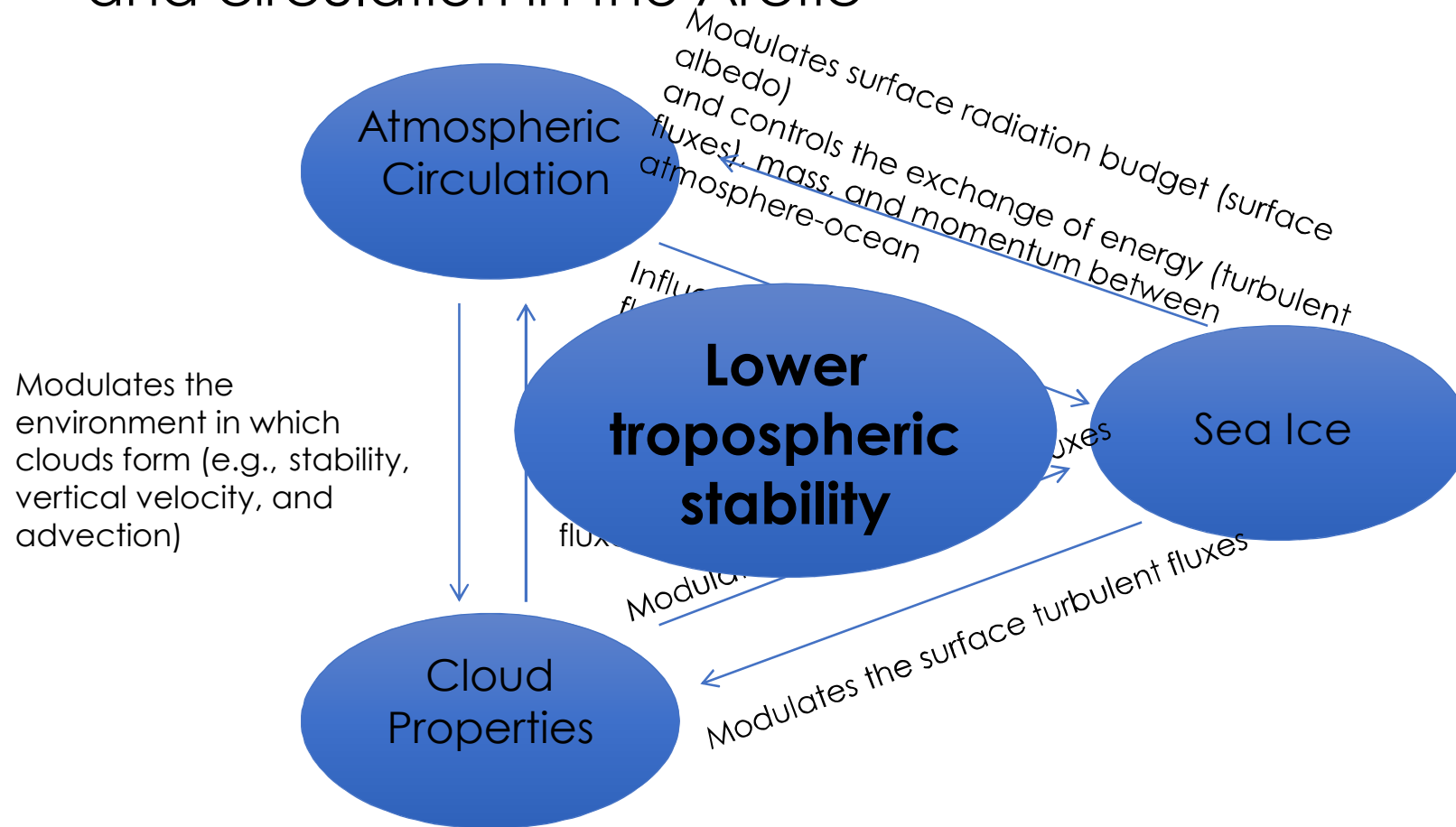
- Turbulence and q contributions can be weak or strong
- Sink of atmospheric moisture due to ice precipitation
- Surface type (ocean, ice, land) influences interaction with cloud

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)

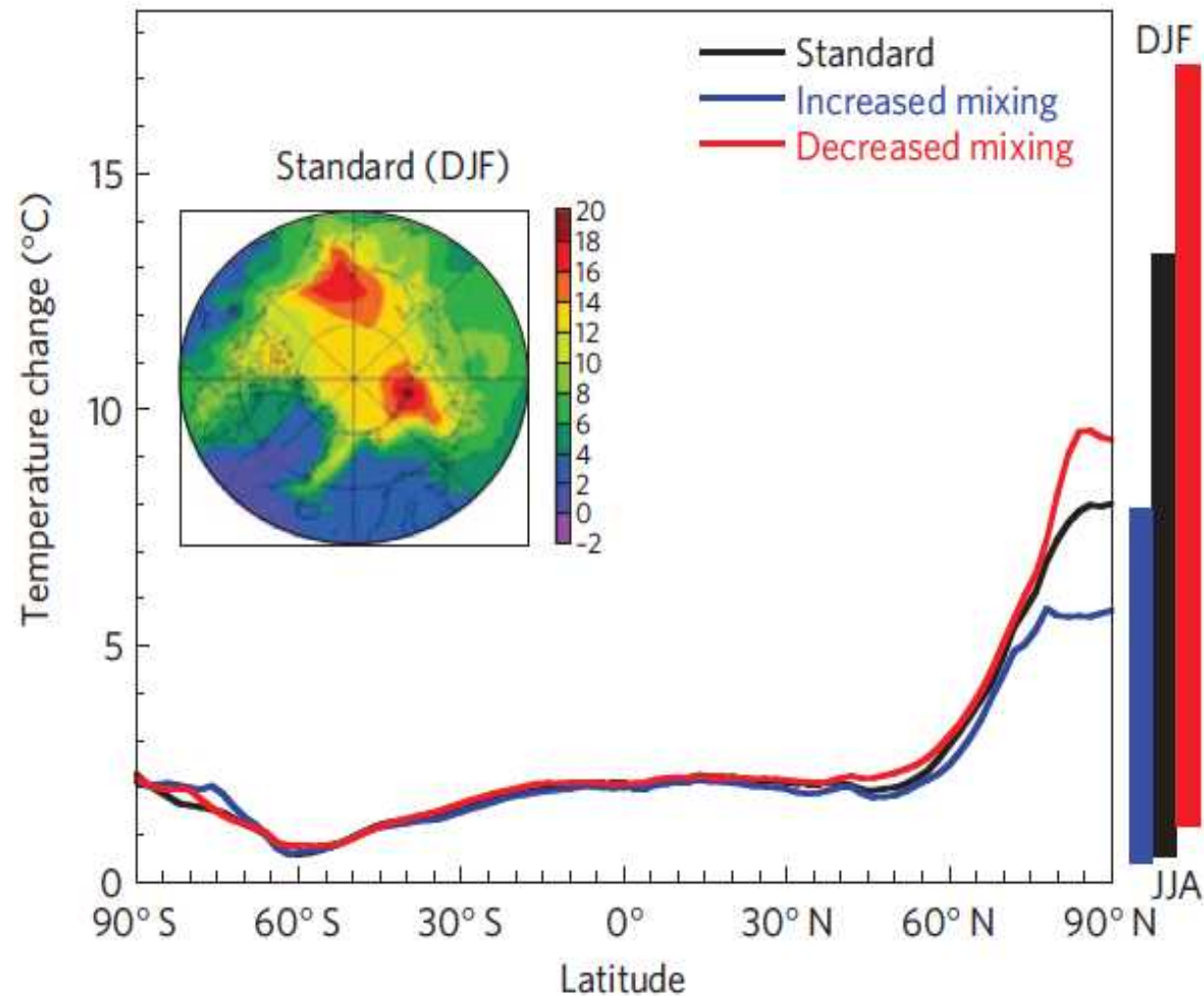
Another 3-legged stool?

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 circulation.

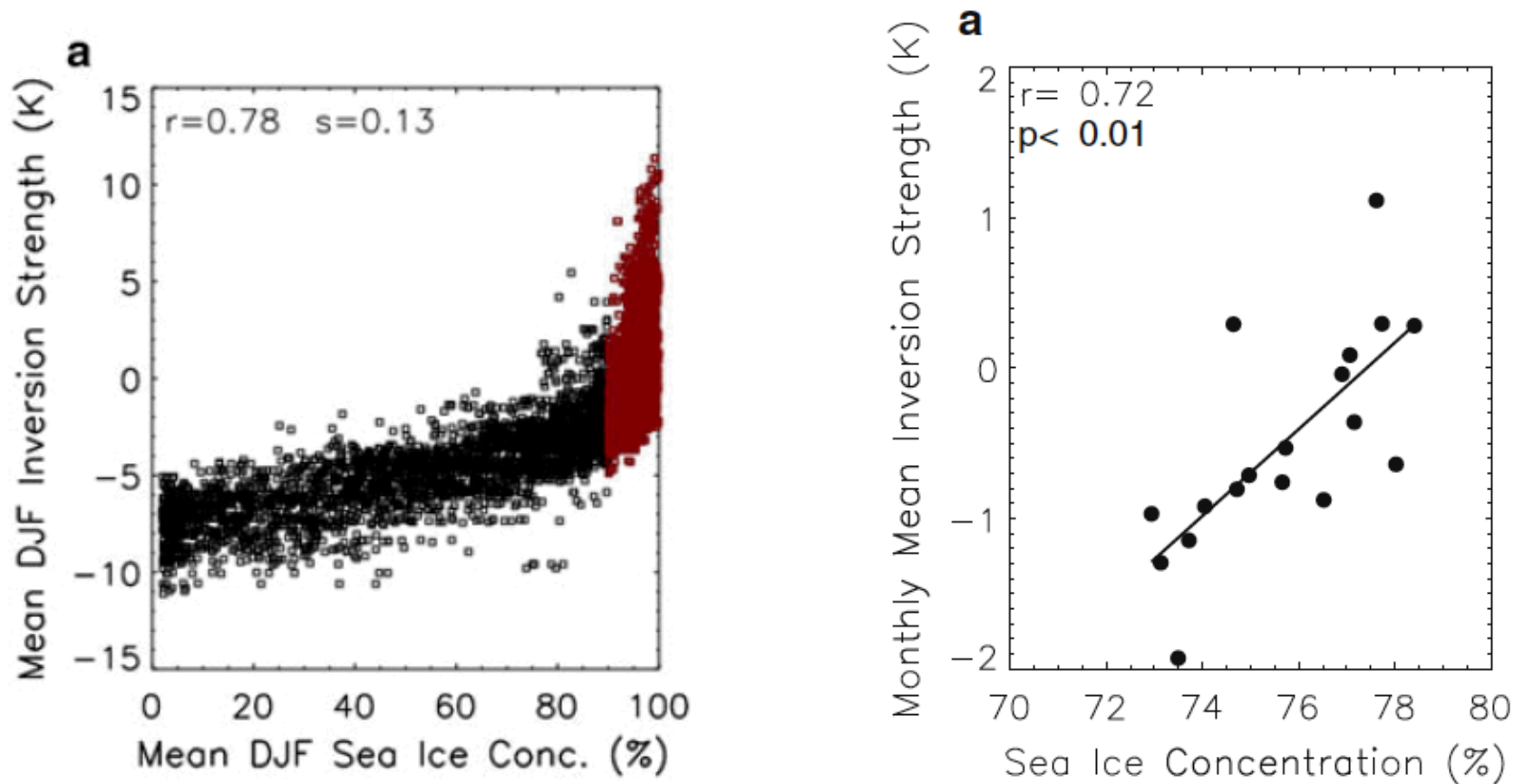
The impact of Lower Tropospheric Stability on Arctic Climate Change



Stronger lower tropospheric stability and weaker turbulent mixing yields stronger Arctic warming.

Relationship between Lower Tropospheric Stability and Arctic sea ice

(



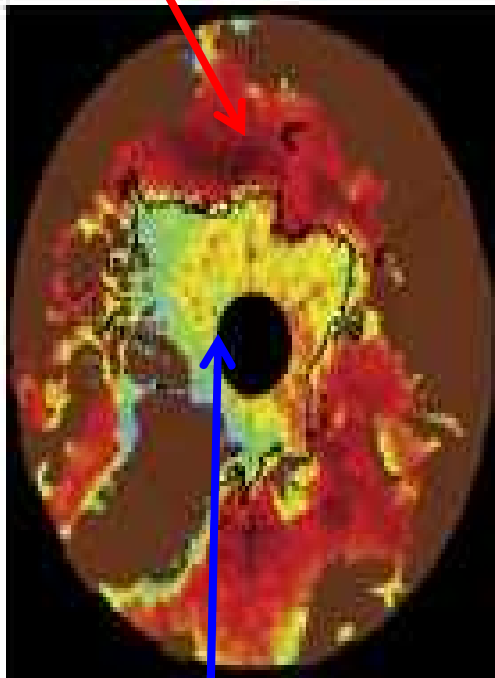
Lower tropospheric stability is strongly correlated in space and time the monthly average sea ice concentration (Pavelsky et al. 2011).

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

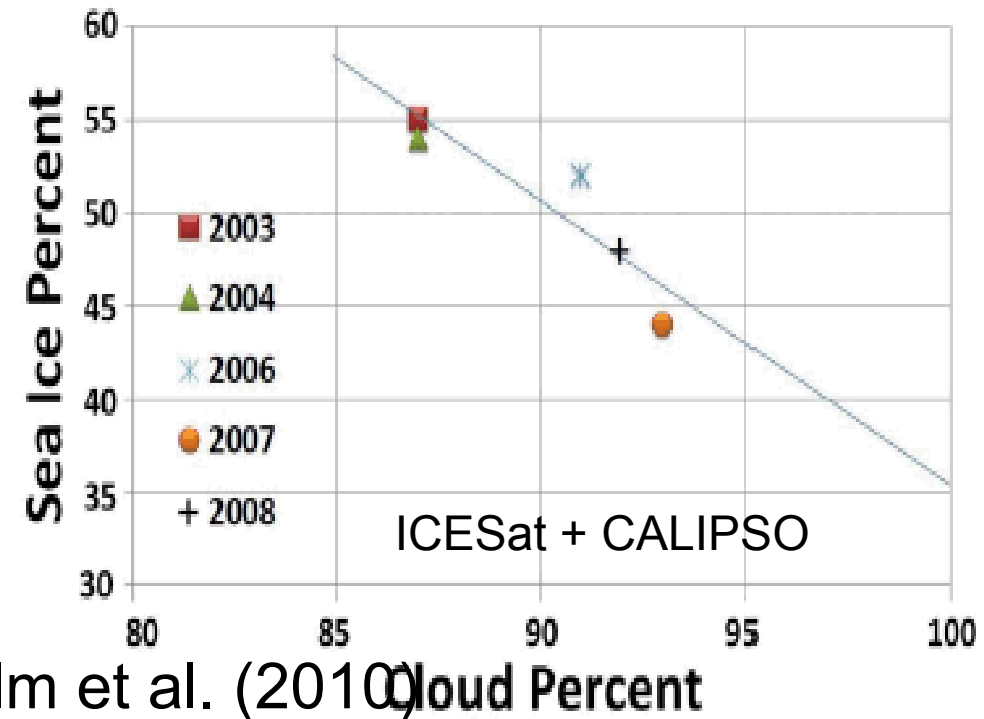
Kay and Gettelman (2009)



Sept. 2008

Sept. MODIS Total
Cloud Fraction

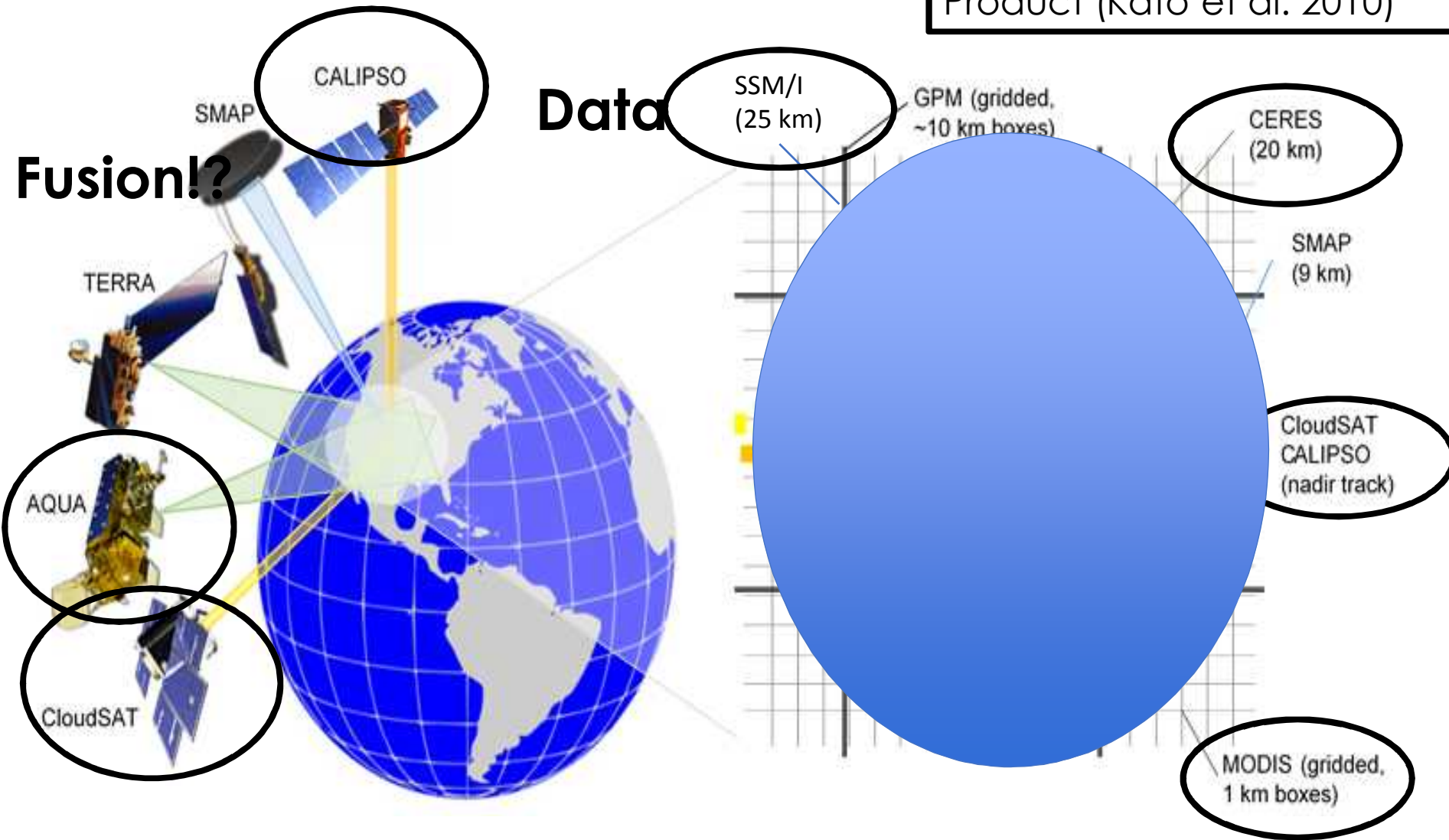
Smaller cloud fraction over sea ice



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

That's the power of...

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

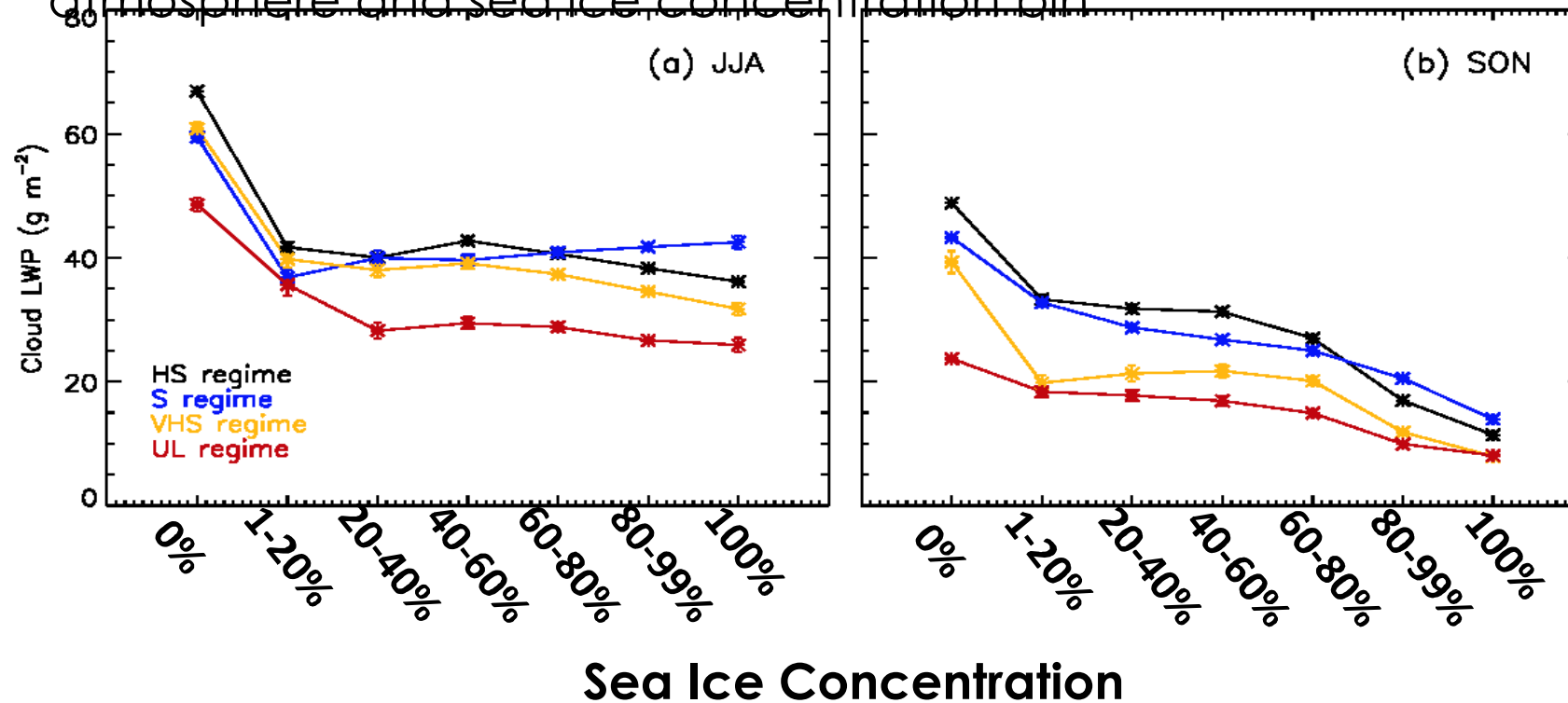


Data are available from the NASA Langley ASDC:

<http://eosweb.larc.nasa.gov/>

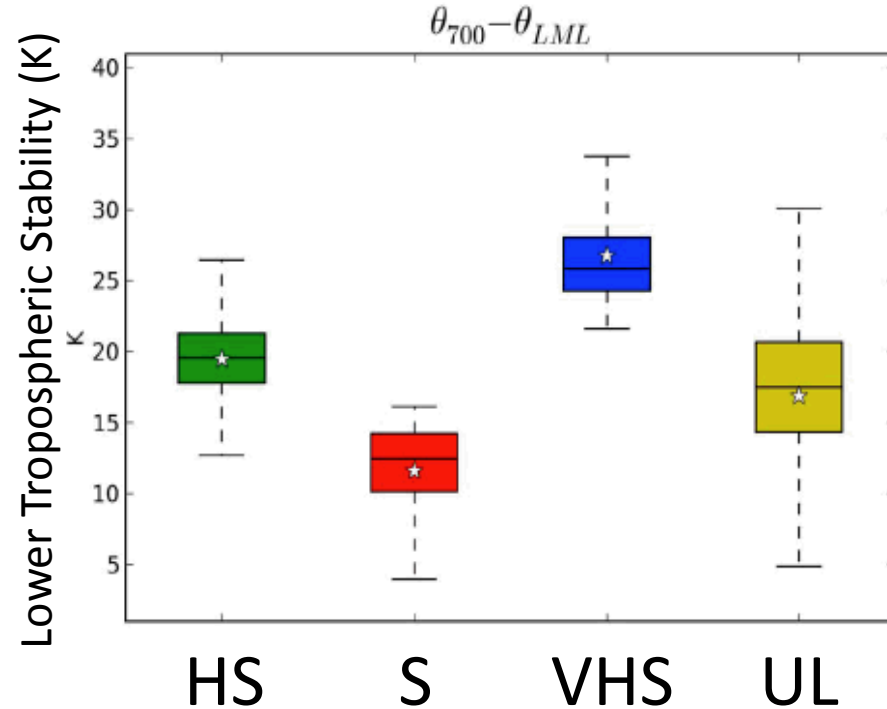
Compositing Methodology

- (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

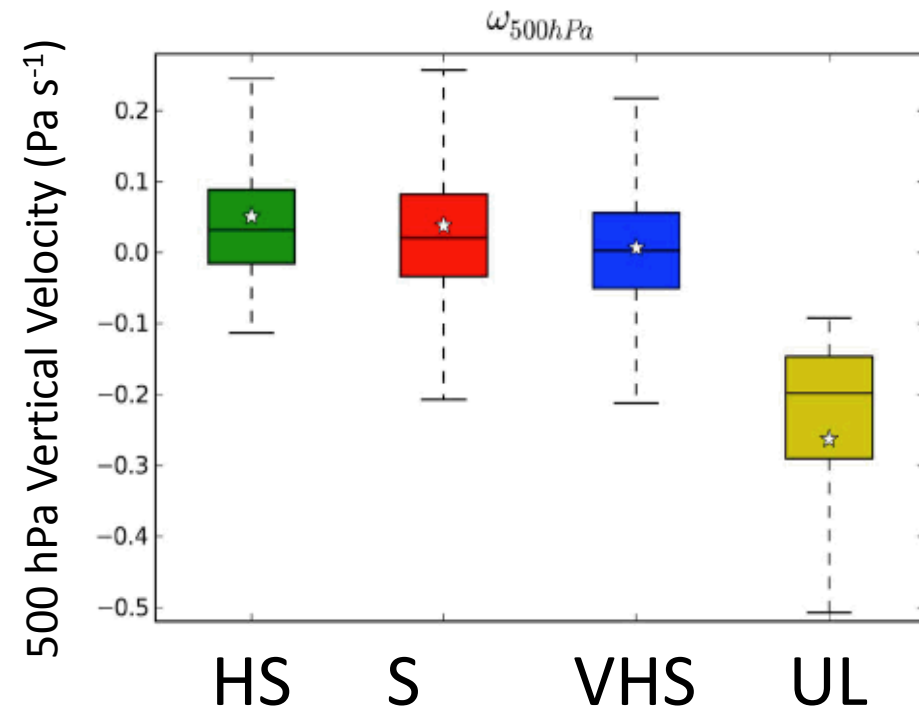


The goal of the methodology is to retain as much process level information as possible by using satellite footprint level data, not monthly mean averaged

Atmospheric Regimes (Barton et al. 2012)



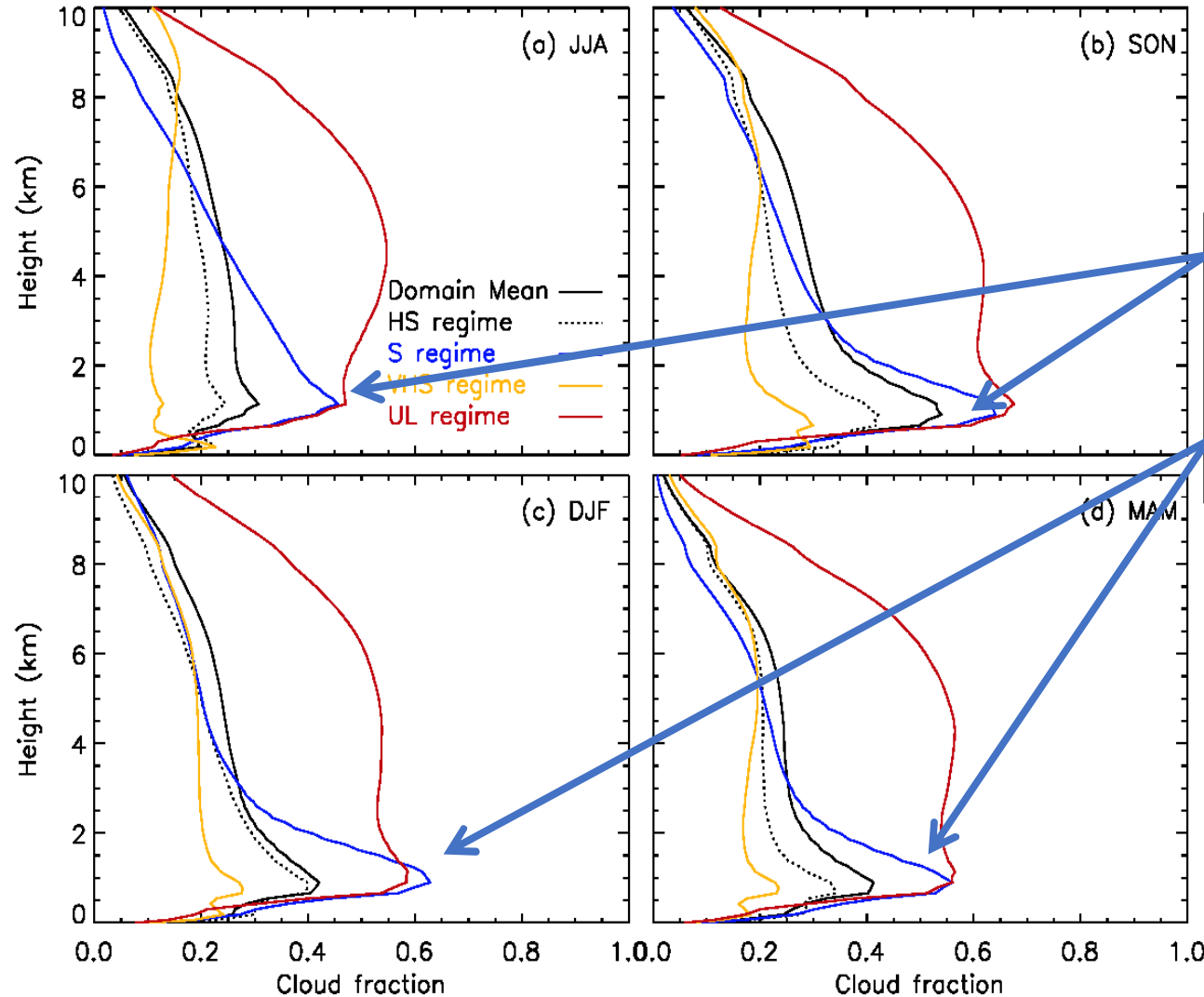
Atmospheric state regimes determined using K-means cluster analysis.



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

Influence of Meteorological State

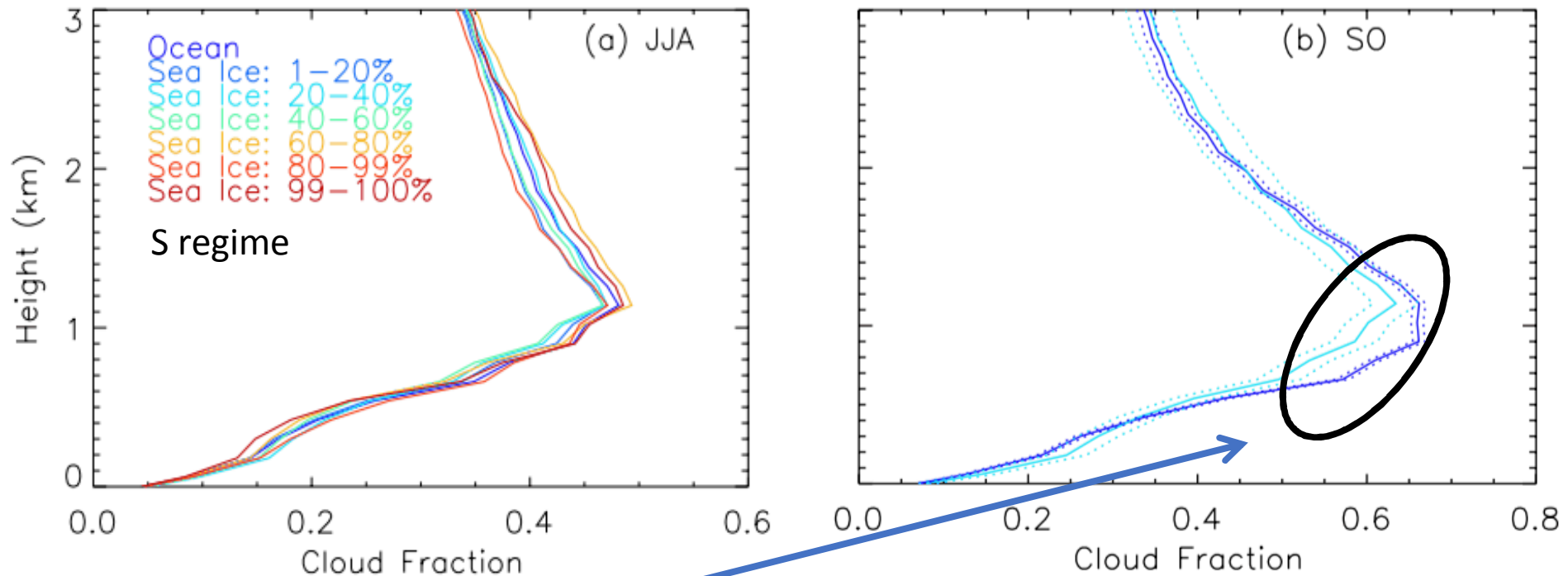


A decrease in the magnitude and height of the maximum cloud fraction is found as LTS increases.

Taylor et al. (JGR 2015)

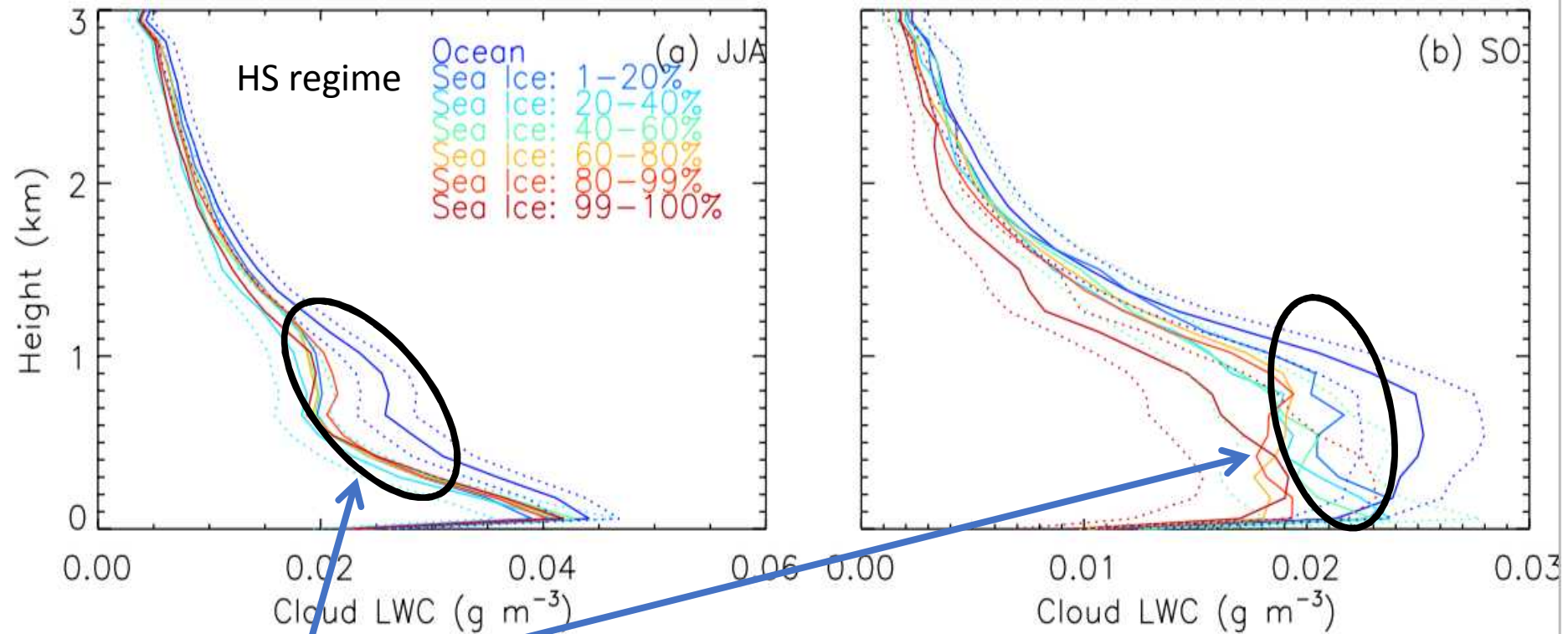
The results indicate that the characteristics of Arctic low clouds are primarily determined by the atmospheric conditions.

Results: Vertical Profile, CF



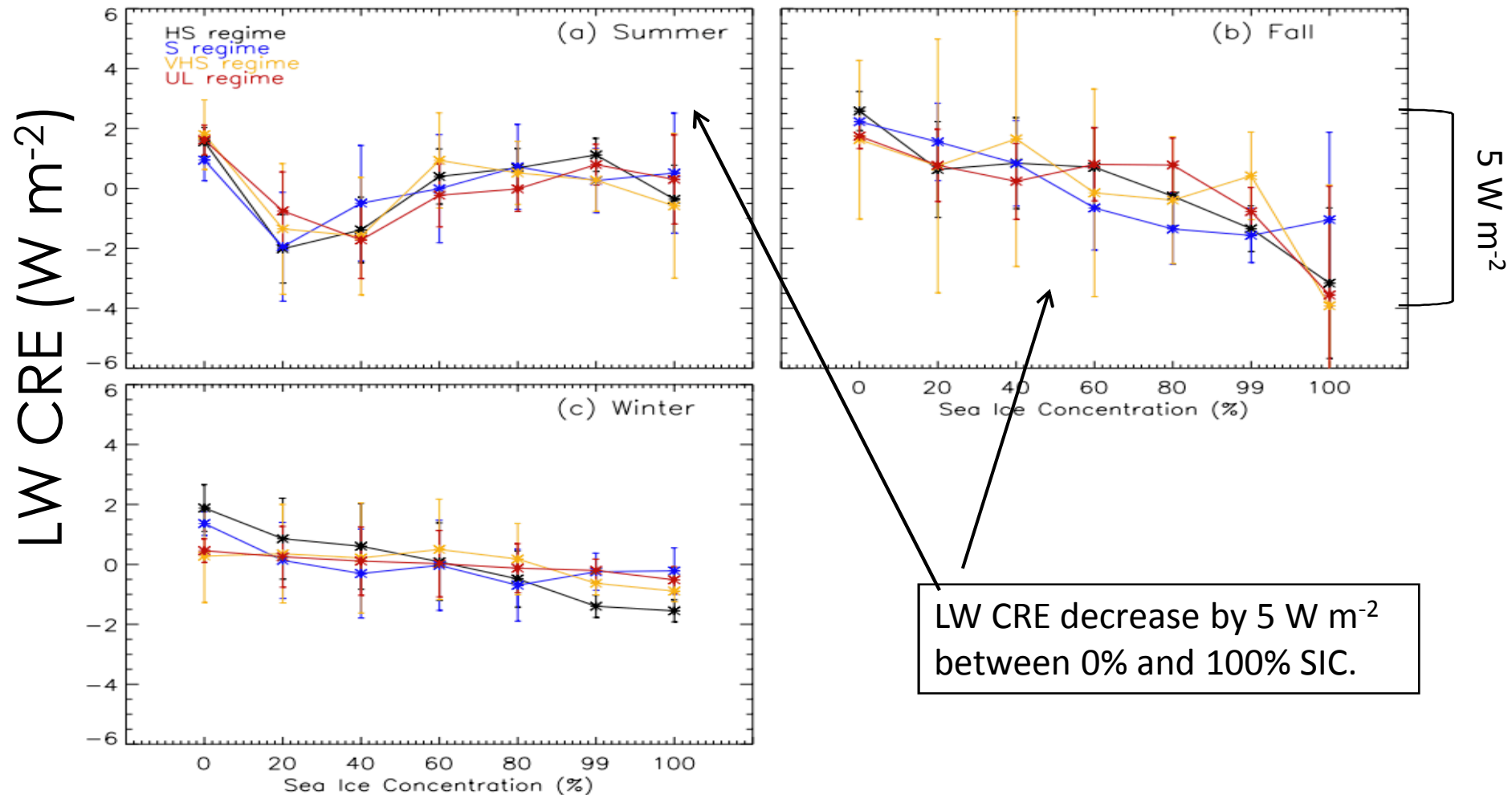
- General decrease in cloud fraction is found with increased sea ice concentration in in autumn, but no response in summer.
- Statistically significant differences at the 95% confidence interval are found at between 500 m and 1.2 km in autumn at 0% and 20-40% sea ice concentration.

Results: Vertical Profile, LWC



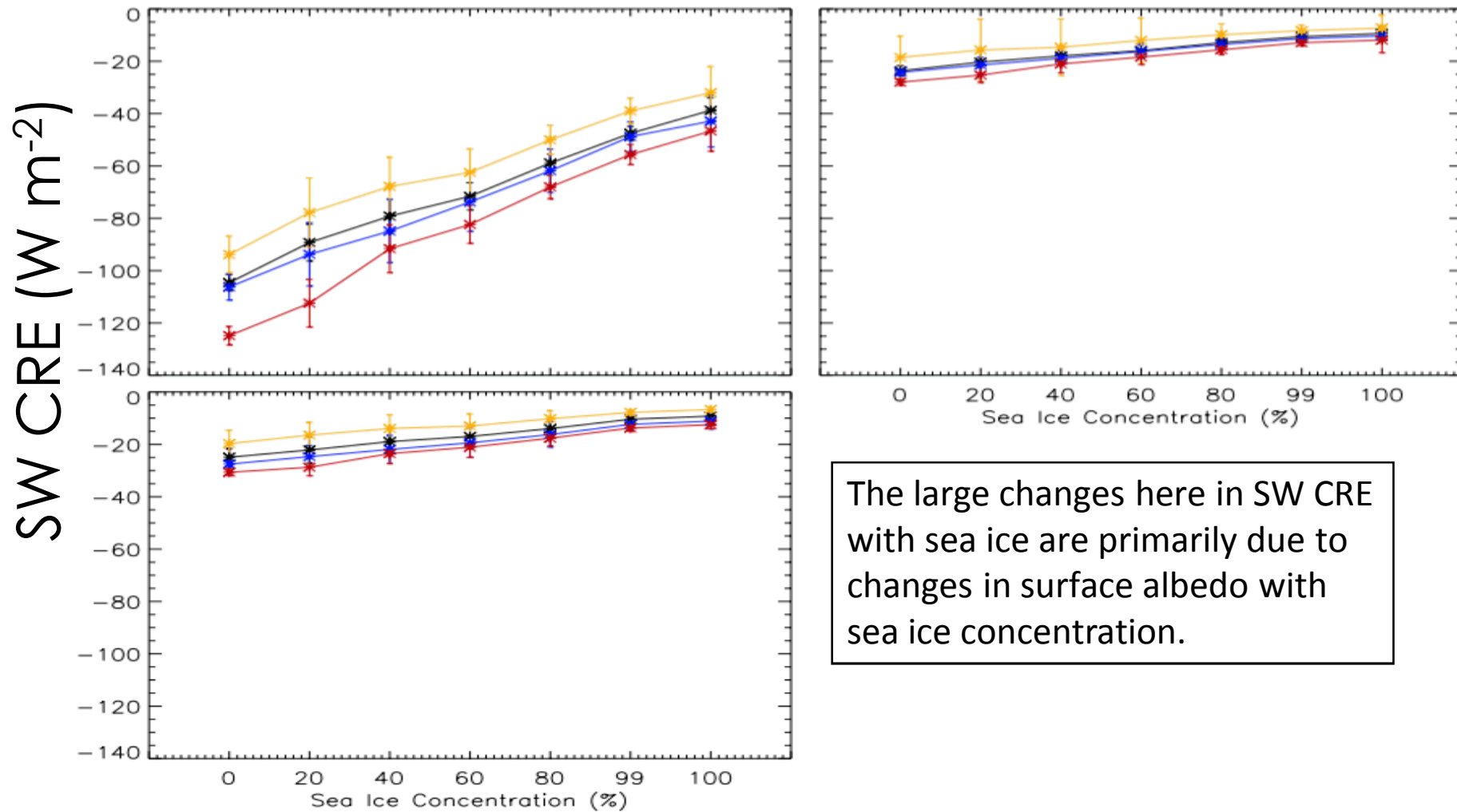
- General decrease in LWC is found with increased sea ice concentration in both summer and autumn.
- Statistically significant differences the LWC between 500 m and 1.2 km are found in summer and autumn at 0% and 20-40% sea ice concentration.

Results: Surface LW CRE



- General decrease in the LW CRE at the surface with increasing sea ice.
- Statistically significant differences at the 95% confidence interval are found in fall for the HS and S regimes.

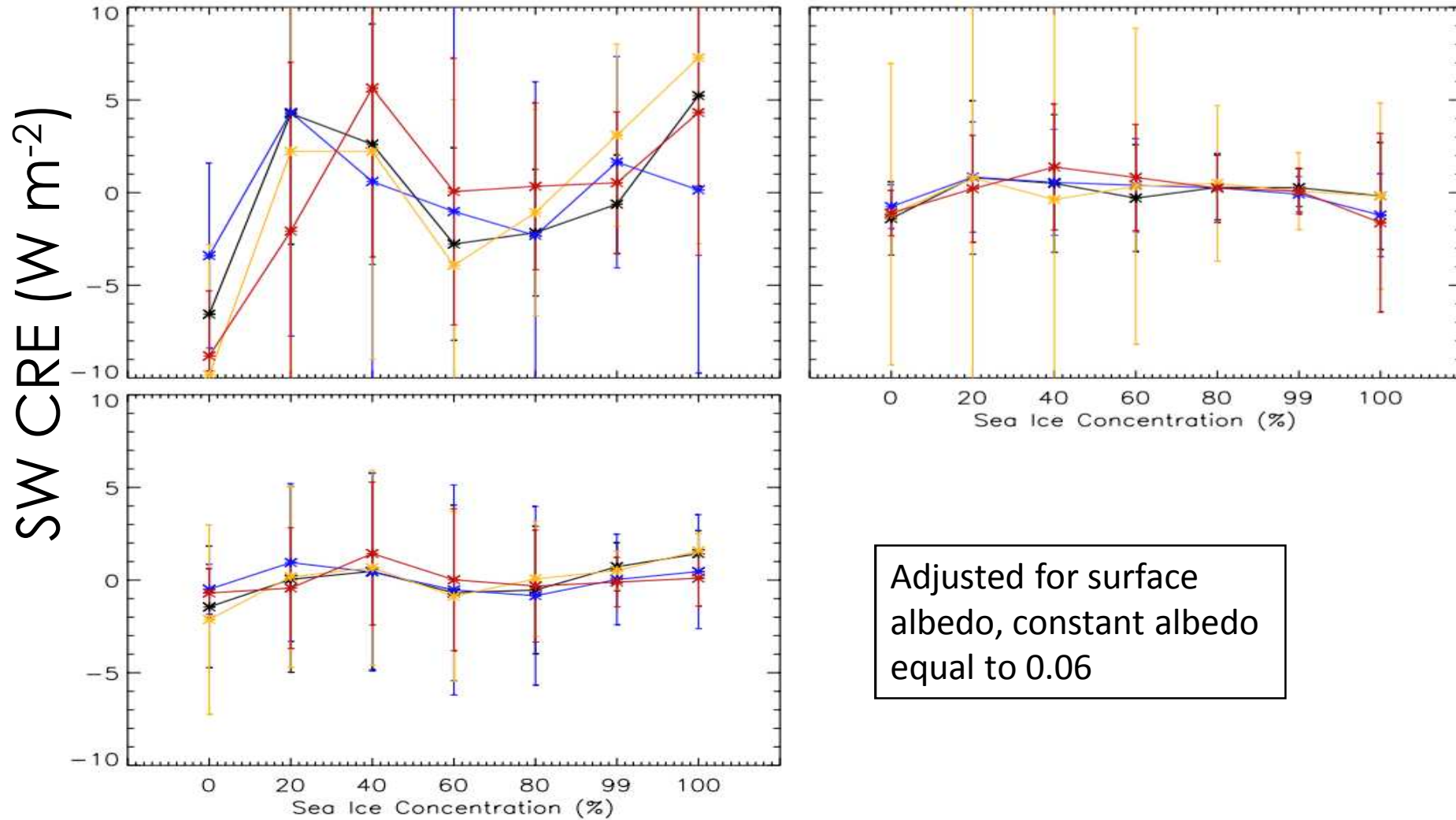
Results: Surface SW CRE



The large changes here in SW CRE with sea ice are primarily due to changes in surface albedo with sea ice concentration.

- Generally less negative SW CRE at the surface with increasing sea ice.
- Statistically significant differences at the 95% confidence interval are found in fall for the HS and S regimes.

Results: Surface SW CRE

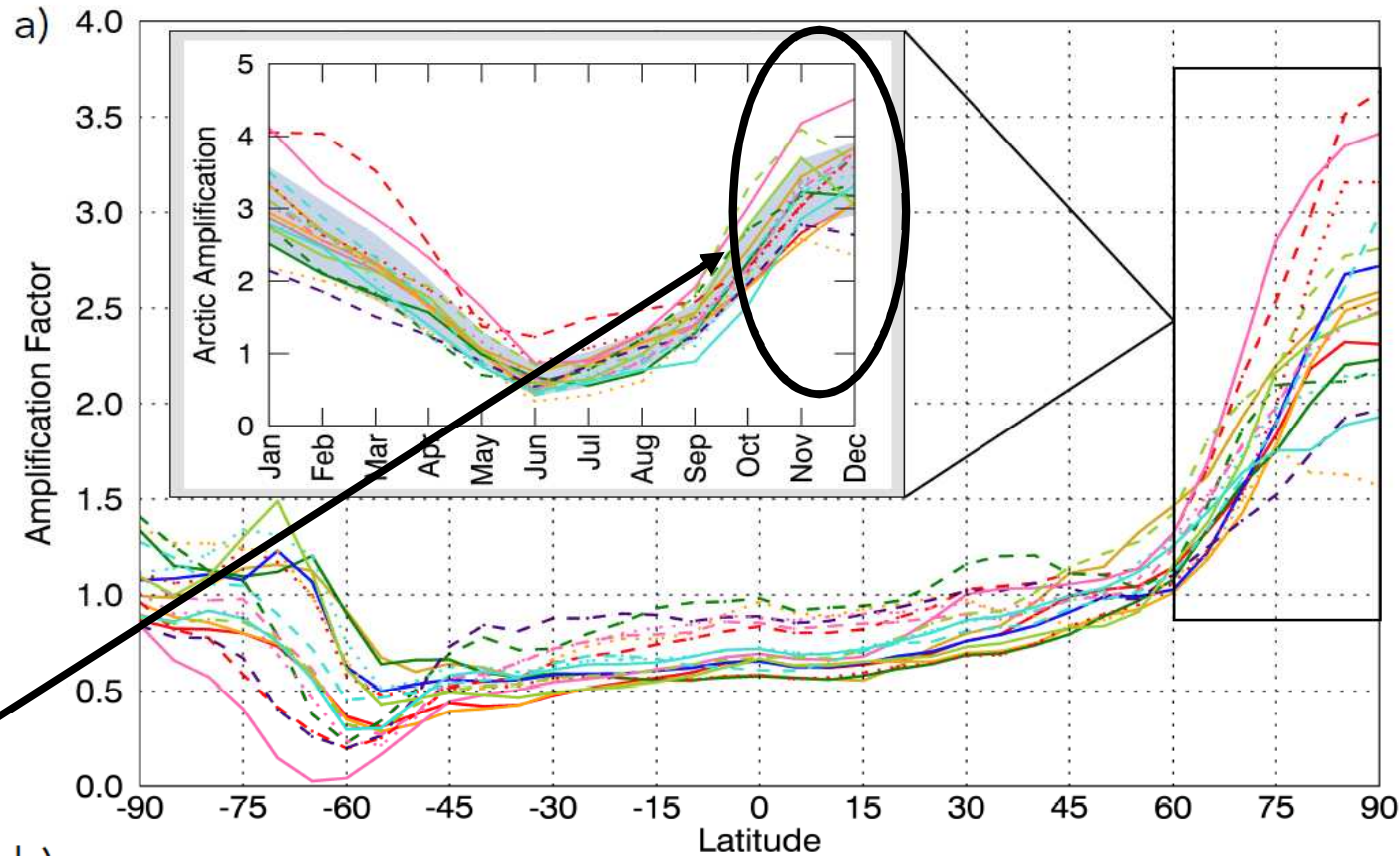


- Generally less negative SW CRE at the surface with increasing sea ice.
- No statistically significant differences around found at the 95% confidence interval.

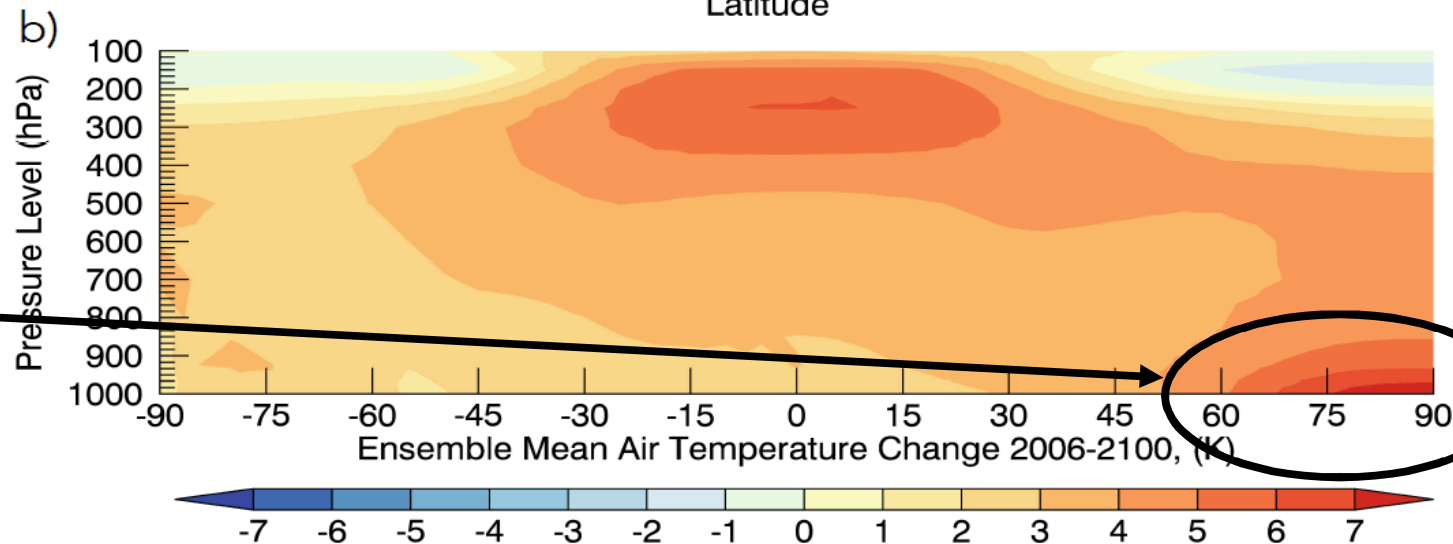
Nature of Arctic Amplification

Most warming in fall/winter

Bottom heavy warming profile

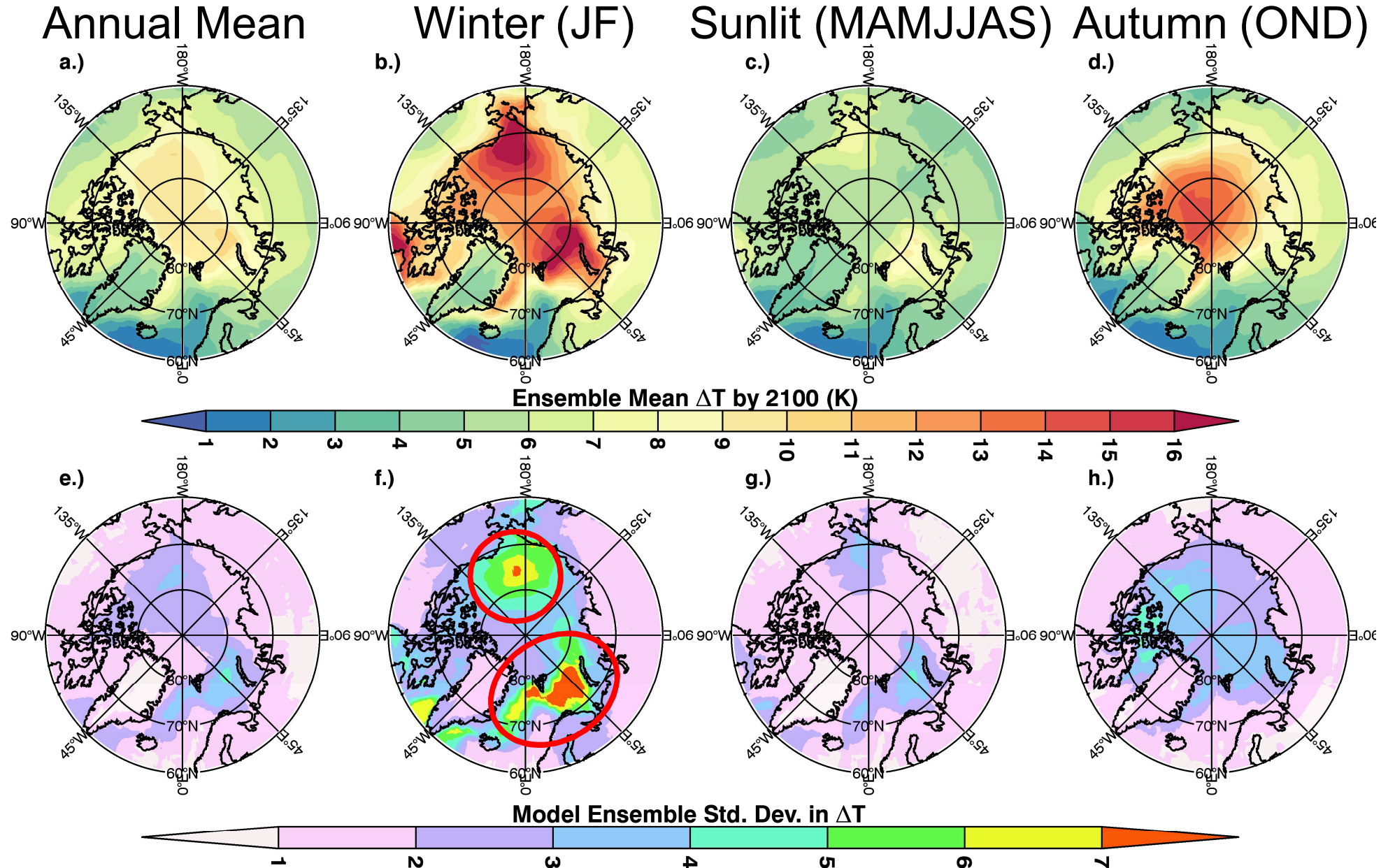


More model disagreement in the Arctic than any other region



Where and when do CMIP5 model differ on Arctic warming projections?

Largest differences between CMIP5 models occur in fall and winter in the Barents-Kara Seas and the Chukchi-Beaufort Seas regions.



Method: Surface energy budget decomposition

Lu and Cai (2009)

Surface energy budget Eq.:

$$Q = (1 - \alpha)S_{sw \text{ down}} + F_{lw \text{ down}} - \varepsilon\sigma T_s^4 - (S + L)$$

Rewriting using clear-sky fluxes and cloud radiative effects and solving for ΔT_s

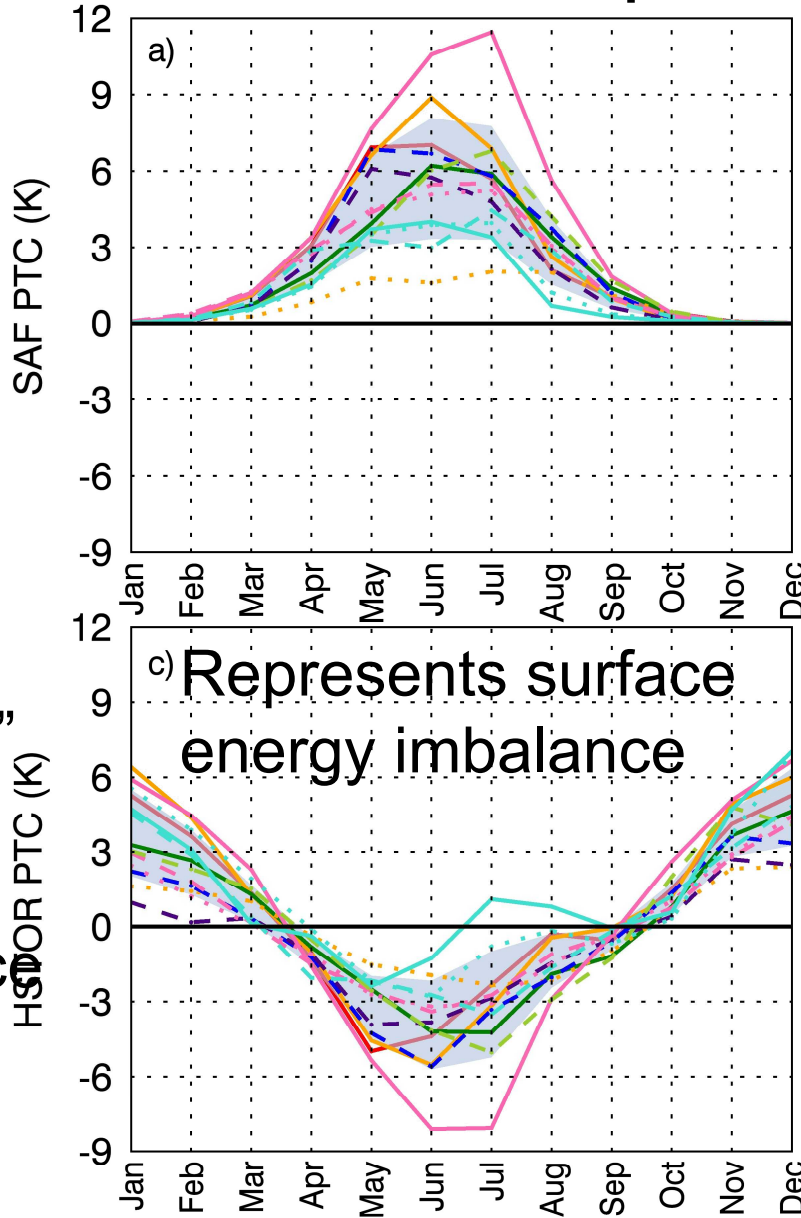
$\Delta T_s = (\text{the sum of})$

FEEDBACK	PTC (K)	ANNUAL MEAN (K)
<i>Surface Albedo Feedback (SAF)</i>	$\frac{-(\Delta\alpha)(\overline{S\downarrow} + \Delta S\downarrow)}{4\sigma T_s^3}$	1.82 ± 0.77
<i>Cloud Forcing (CRE)</i>	$\frac{(1 - \alpha)\Delta S\downarrow_{CLD} + \Delta F\downarrow_{CLD}}{4\sigma T_s^3}$	0.69 ± 0.88
<i>non-SAF shortwave clear-sky feedbacks</i>	$\frac{(1 - \alpha)\Delta S\downarrow_{CLR}}{4\sigma T_s^3}$	-0.43 ± 0.20
<i>Longwave clear-sky feedbacks (LWCS)</i>	$\frac{\Delta F\downarrow_{CLR}}{4\sigma T_s^3}$	7.27 ± 1.4
<i>Change in ocean heat storage (HSTOR)</i>	$\frac{-\Delta Q}{4\sigma T_s^3}$	-0.30 ± 1.2
<i>Change in latent and sensible heat fluxes (HFLUX)</i>	$\frac{-\Delta(S + L)}{4\sigma T_s^3}$	-1.67 ± 0.86

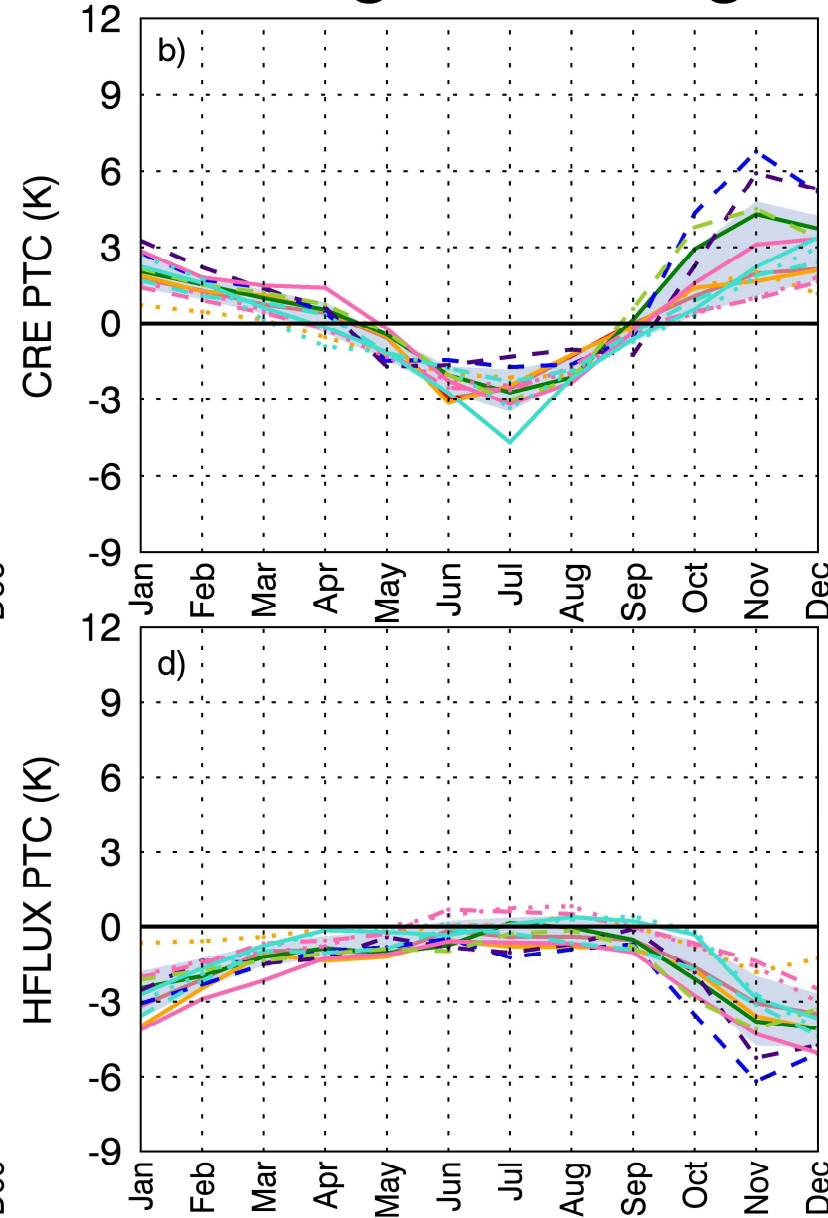
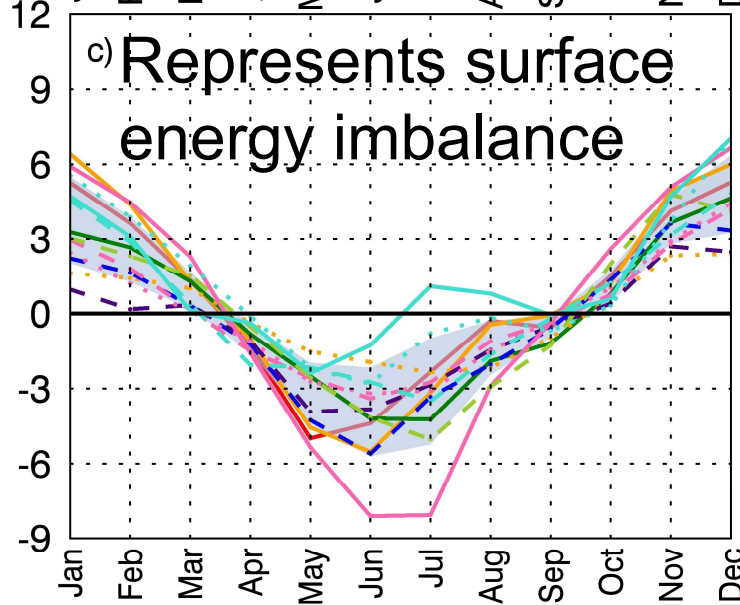
LW clear-sky feedbacks dominate the Arctic warming signal.

Contributions to surface temperature change--Strong seasonality

SAF strongly
warms surface
in summer.



HSTOR “**cools**”
surface in
summer and
“**warms**” surface
in summer.



Clouds **cool**
surface in
summer and
warm in
fall/winter.

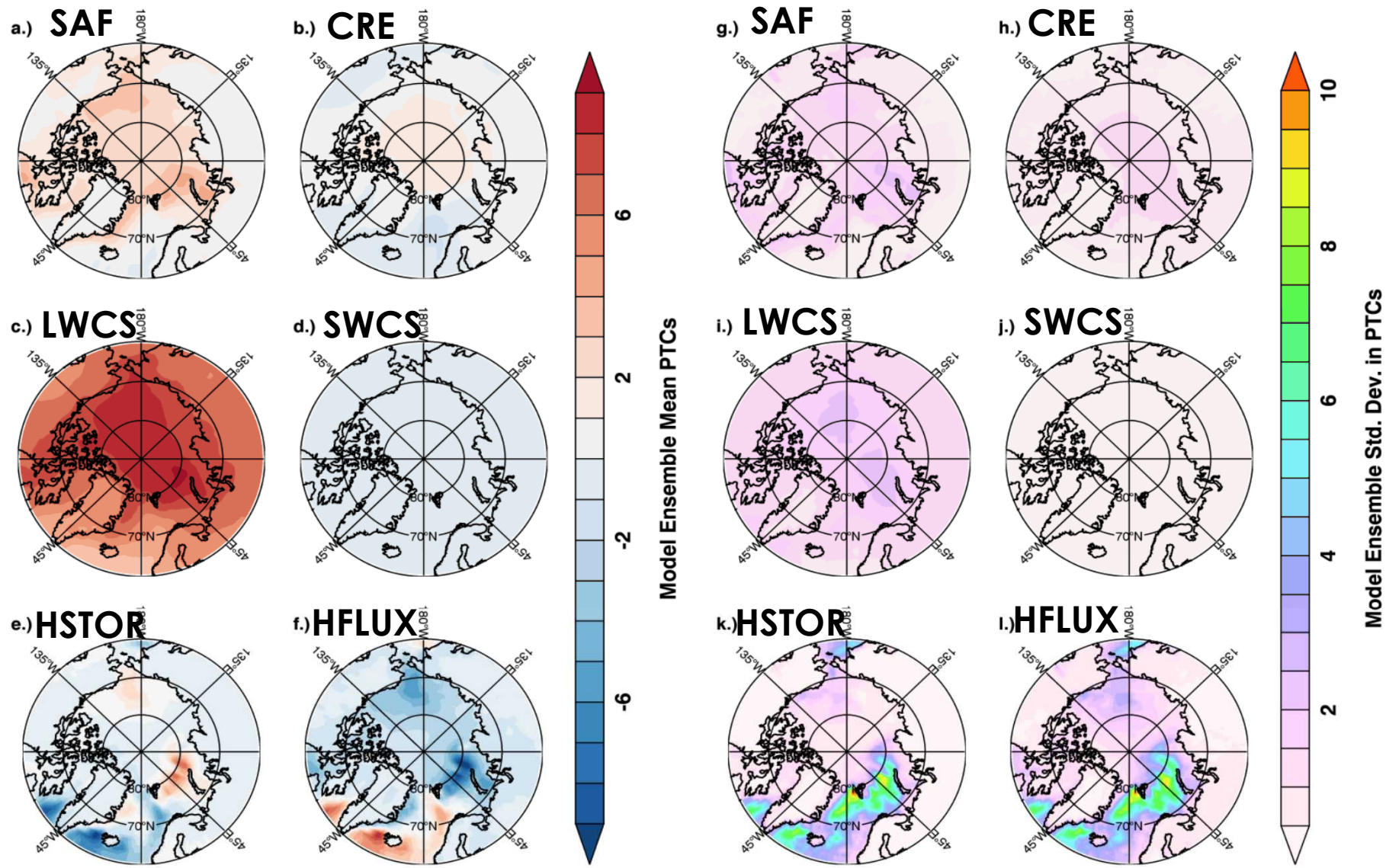
HFLUX show
no change in
summer and
cool surface in
fall/winter.

The seasonality of these contributions is amazingly consistent across models.

How are the model differences spatially distributed?

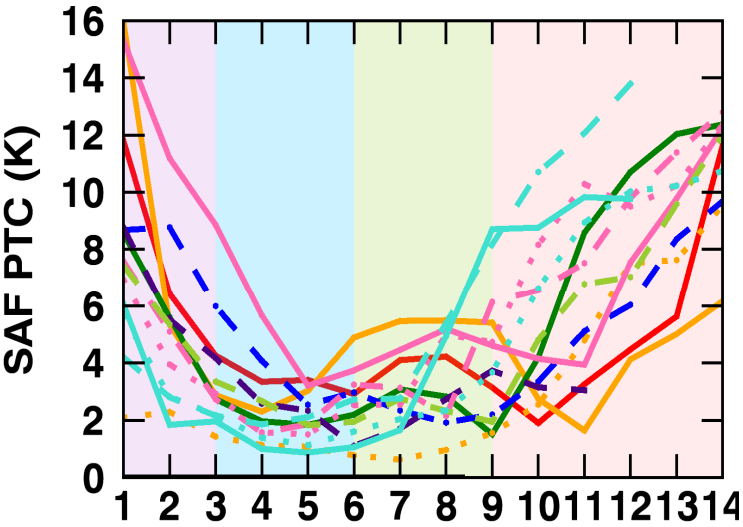
Radiative feedback spread=>spatially uniform

Surface non-radiative feedback spread=> regionally-focused



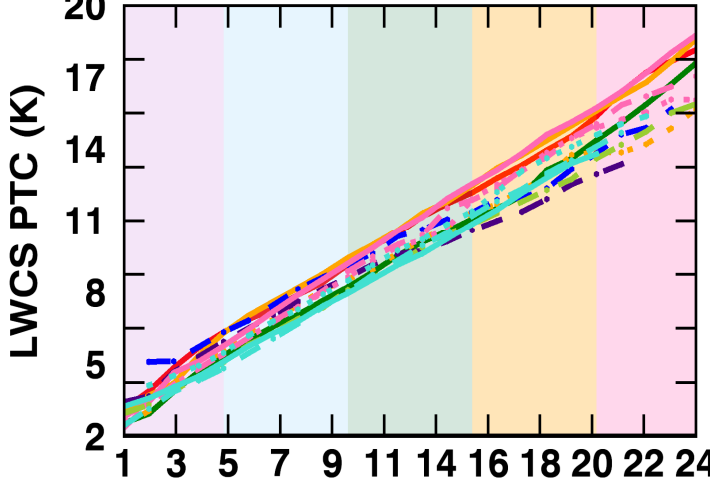
Regions that warm most have the largest feedback contributions...most of the time

Summer SAF

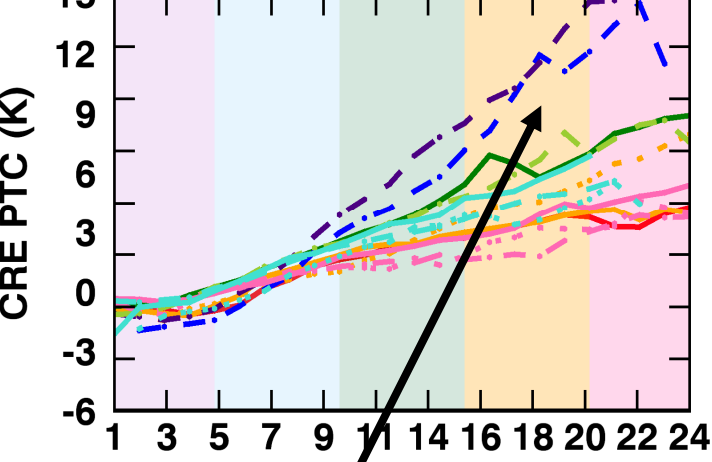


SAF exhibits a U-shape meaning that both regions of small and large warming exhibit a strong feedback.

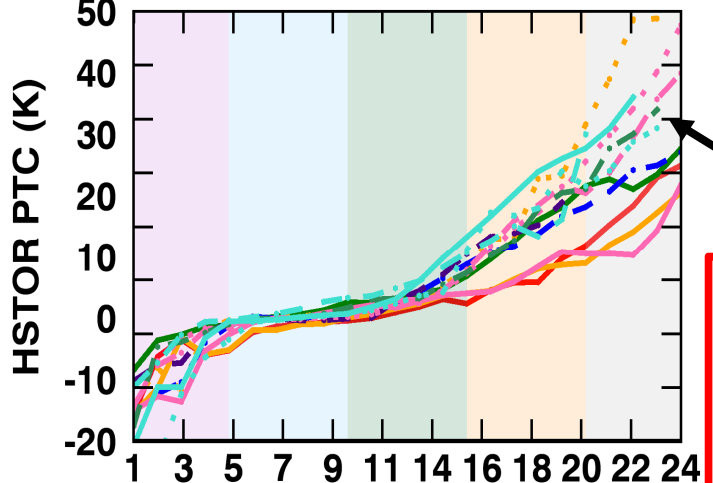
Autumn LWCS



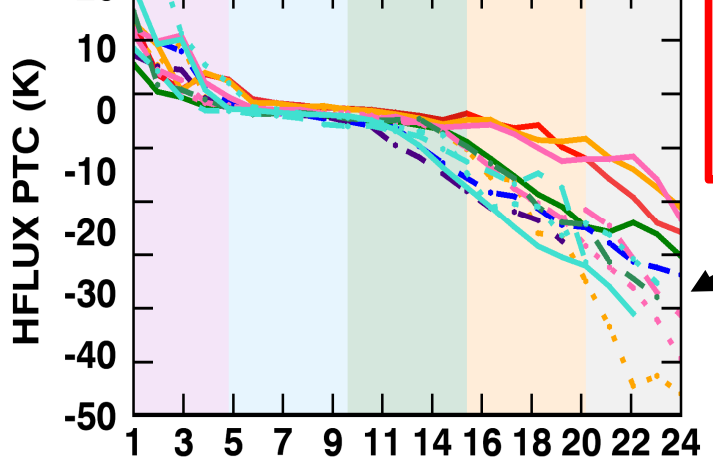
Autumn CRE



Winter HSTOR



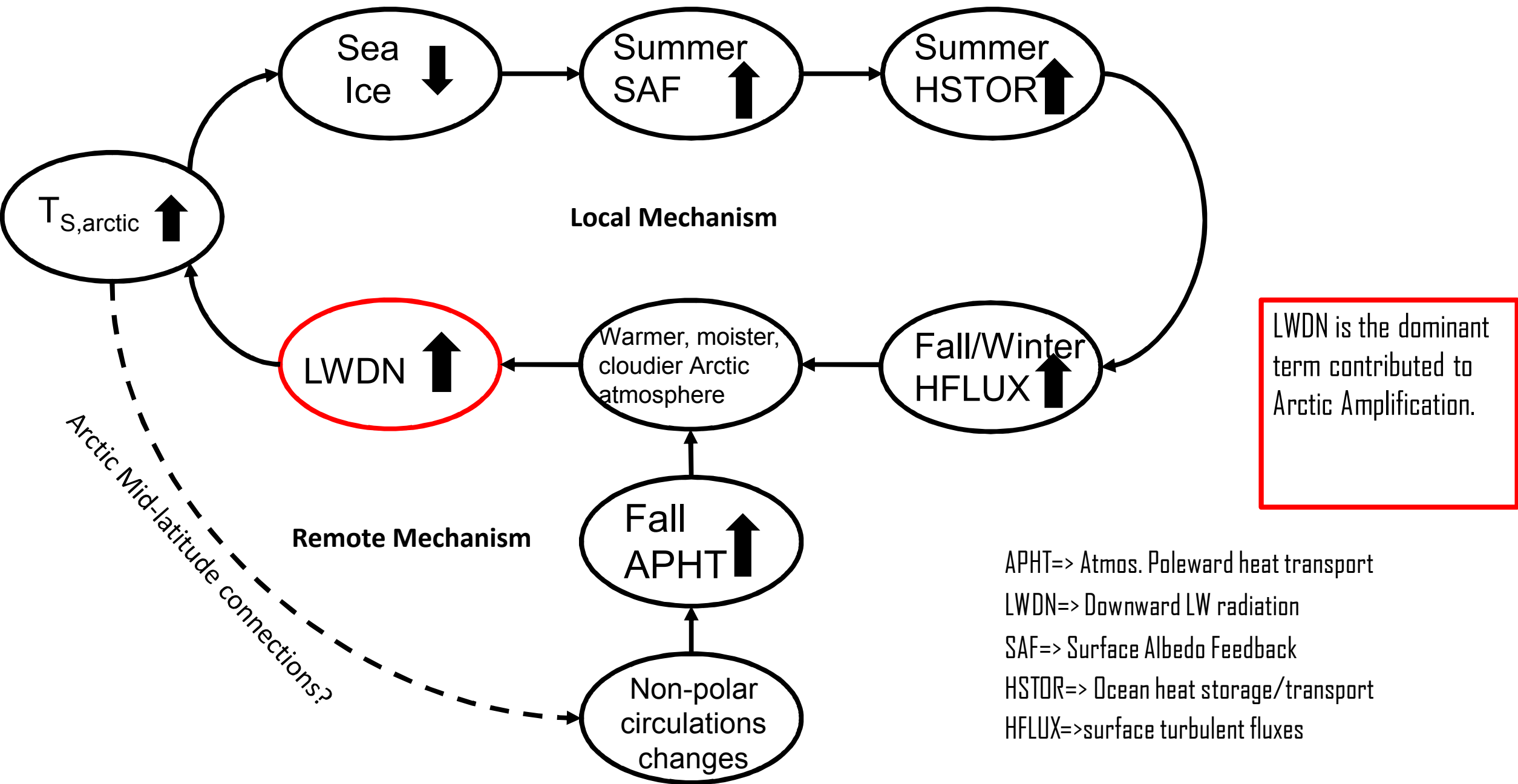
Winter HFLUX



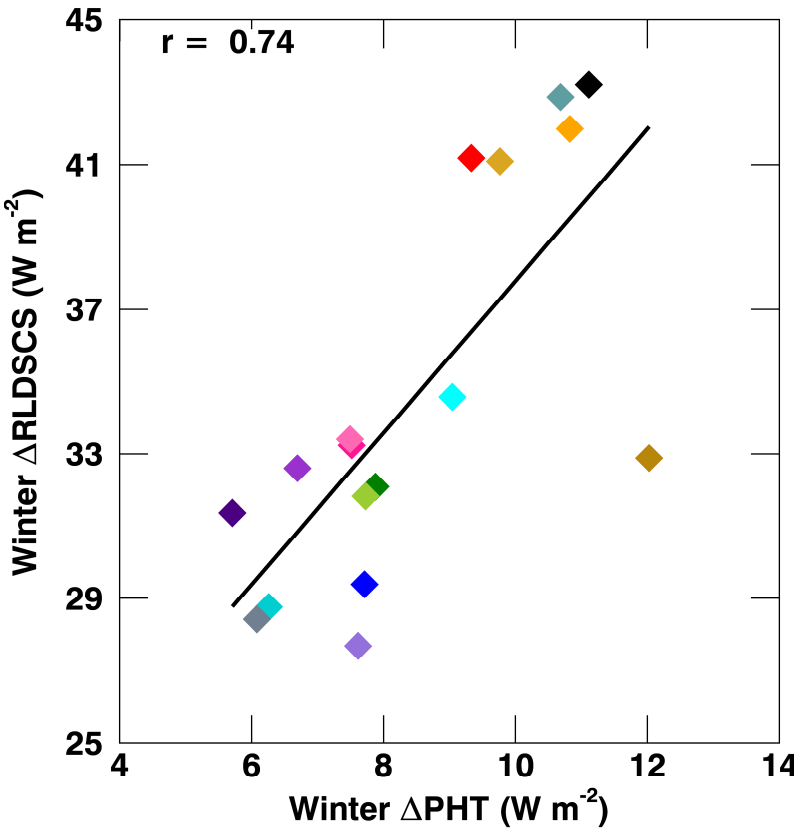
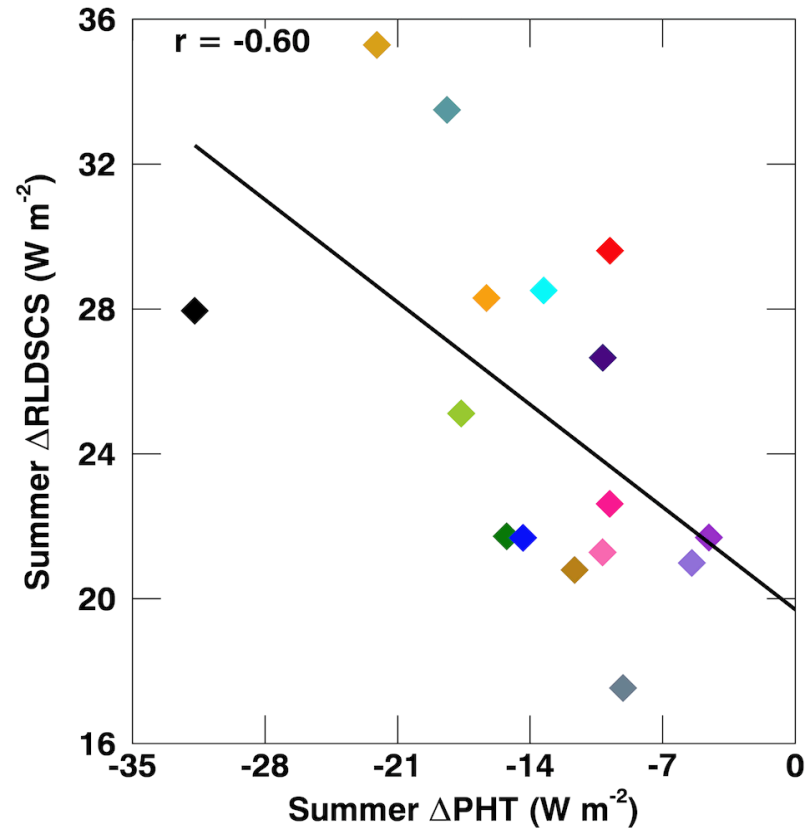
HSTOR and HFLUX show equal and opposite values.

Two models dominate the spread in cloud feedback

A complete picture of Arctic Amplification?

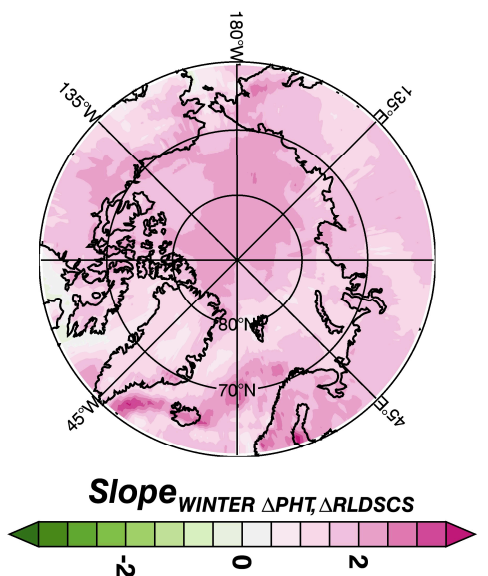
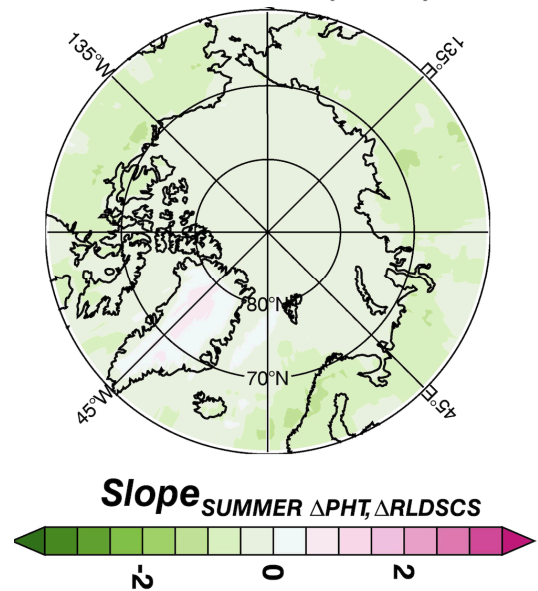


Atmospheric poleward heat transport induces a spatially uniform warming.

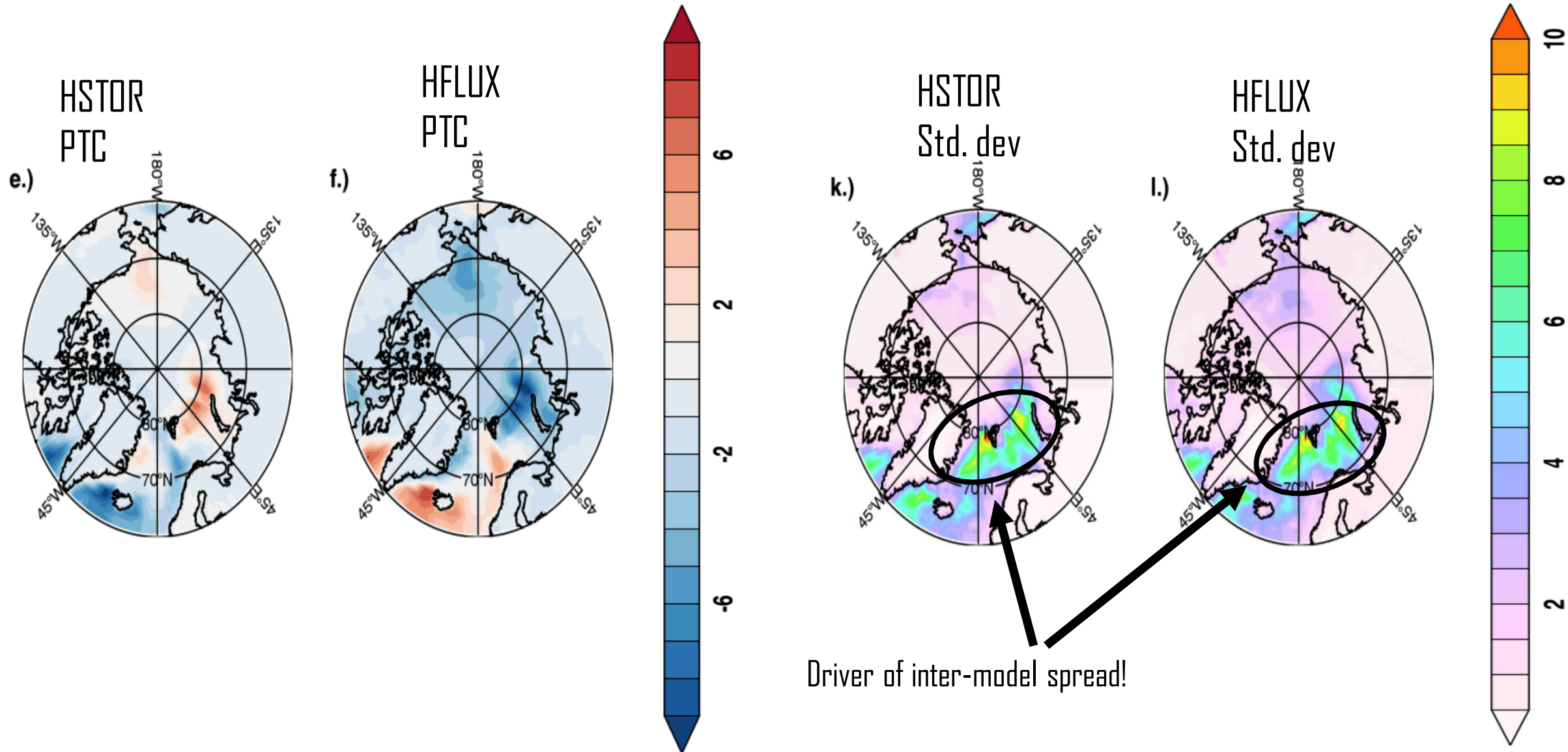


- ACCESS1_3
- CESM1_BGC
- IPSL_CM5A_LR
- ACCESS1_0
- CSIRO_Mk3_6_0
- IPSL_CM5A_MR
- BNU_ESM
- CanESM2
- bcc_csm1_1_m
- CCSM4
- NorESM1_M
- inmcm4

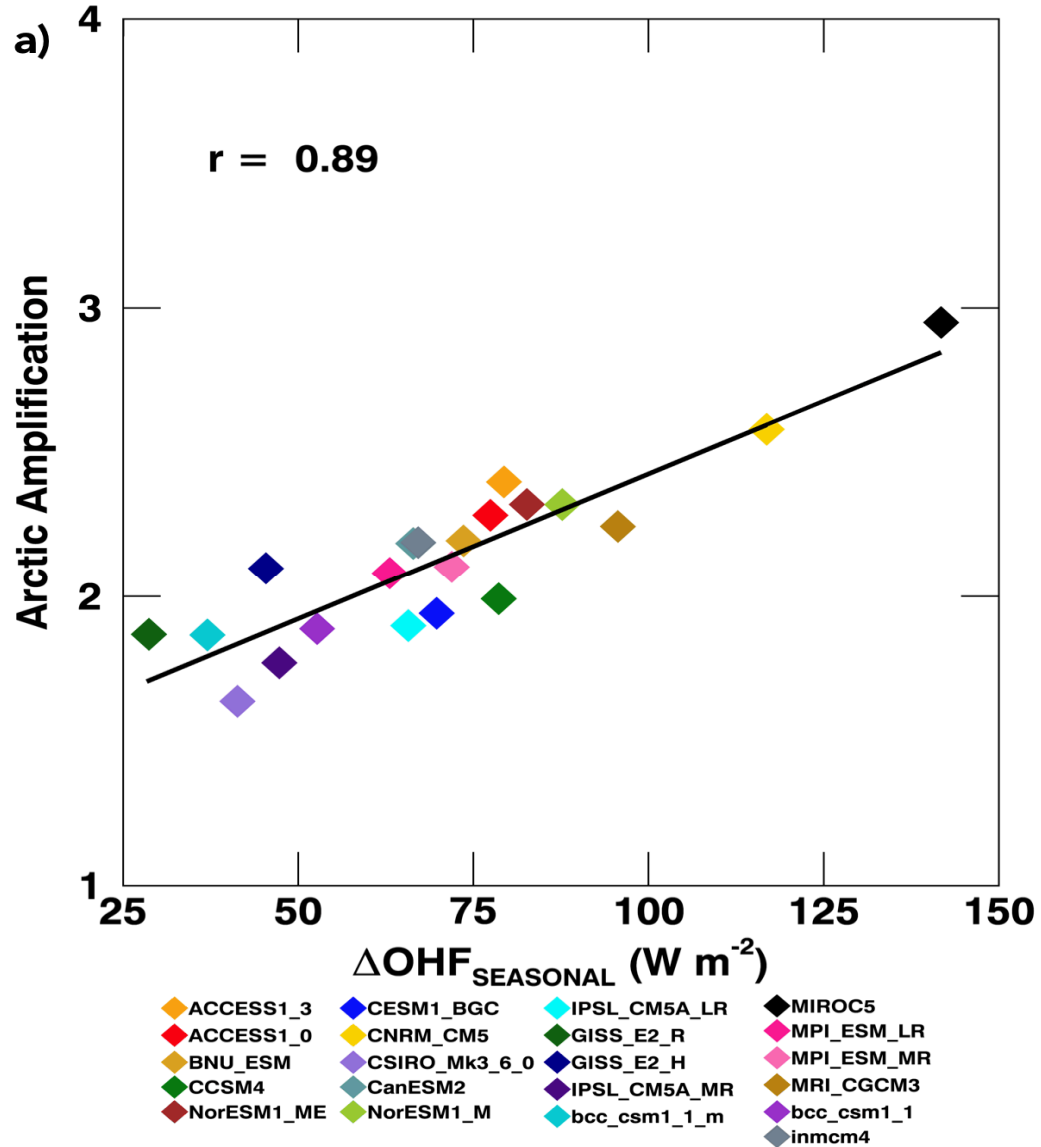
- MIROC5
- MPI_ESM_LR
- MPI_ESM_MR
- MRI_CGCM3
- bcc_csm1_1



Local mechanism sets the spatial structure of Arctic amplification.



A larger annual cycle ocean heat storage amplitude increase=>larger projected warming

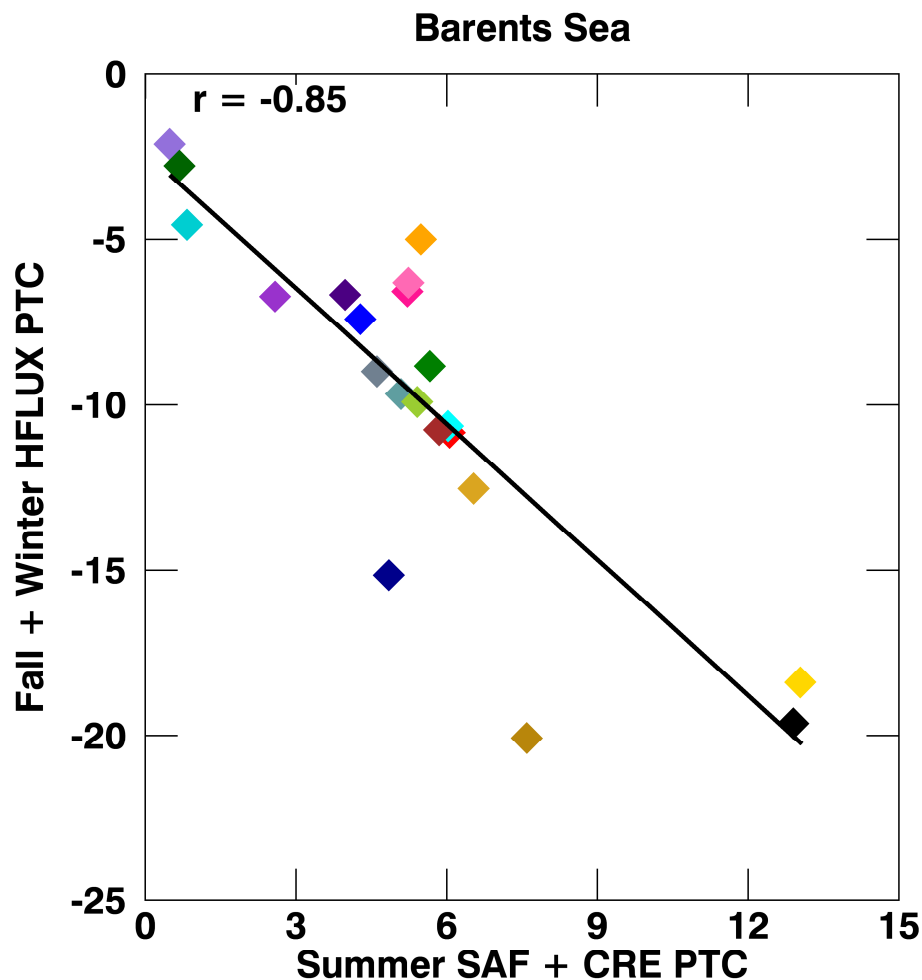


A strong positive correlation is found between the changes in the seasonal amplitude of ocean heat storage and projected Arctic Amplification.

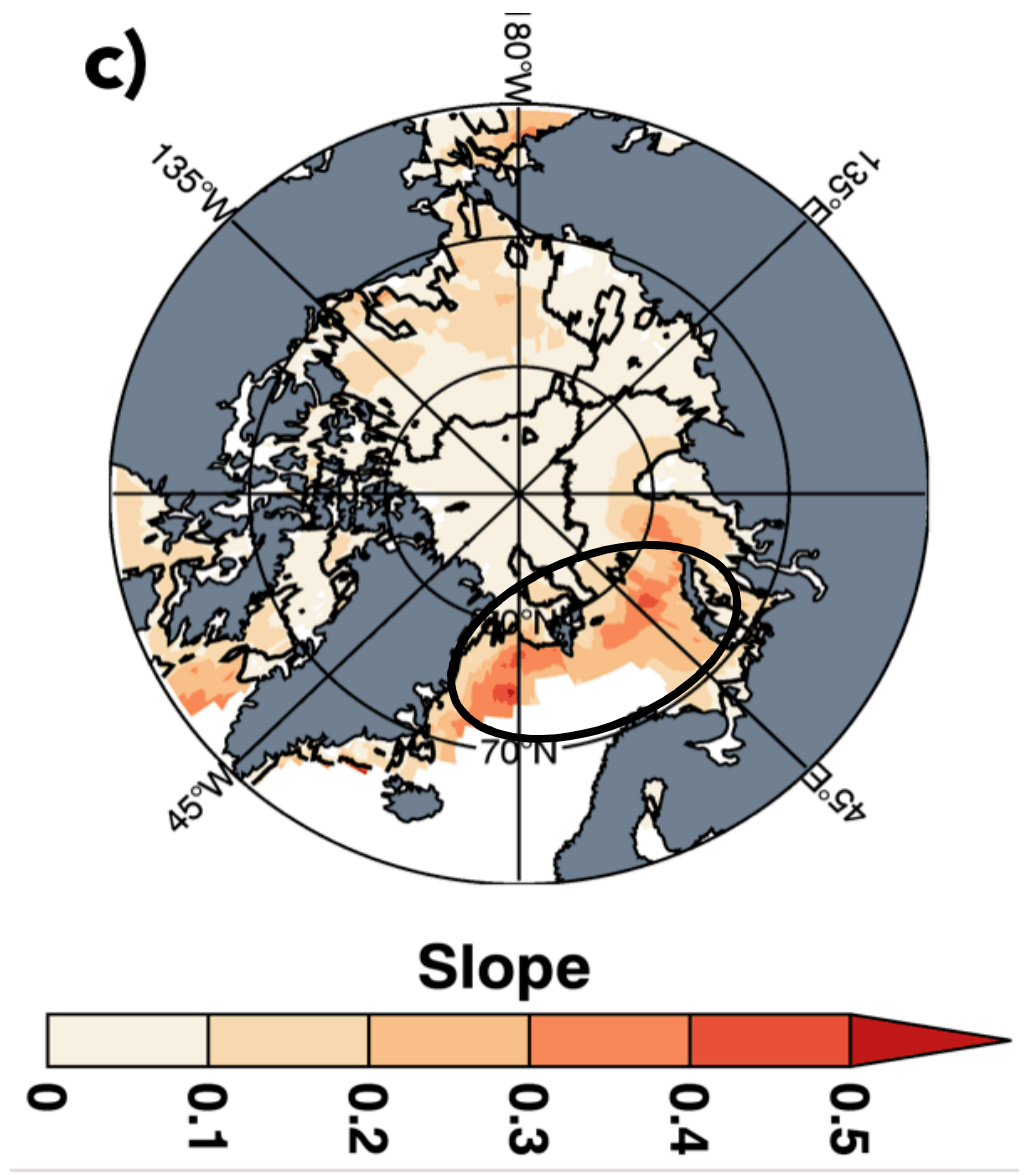
Thus, processes controlling the seasonality of ocean heat storage (upper ocean mixing, absorbed solar radiation, surface turbulent fluxes) may hold the key to unraveling inter-model differences in Arctic Amplification.

Summer=>ability to store energy (mixed layer depth, ASR)
Fall/winter=>ability to release energy (surface turbulent fluxes)

Models increase both SAF and fall/winter HFLUX



- | | | | |
|------------|---------------|--------------|------------|
| ACCESS1_3 | CESM1_BGC | IPSL_CM5A_LR | MIROC5 |
| ACCESS1_0 | CNRM_CM5 | GISS_E2_R | MPI_ESM_LR |
| BNU_ESM | CSIRO_Mk3_6_0 | GISS_E2_H | MPI_ESM_MR |
| CCSM4 | CanESM2 | IPSL_CM5A_MR | MRI_CGCM3 |
| NorESM1_ME | NorESM1_M | bcc_csm1_1_m | bcc_csm1_1 |
| | | inmcm4 | |



Surface turbulent flux changes in the Barents-Kara Seas region are show a statistically significant relationship with the model simulated SAF.

Takeaway messages:

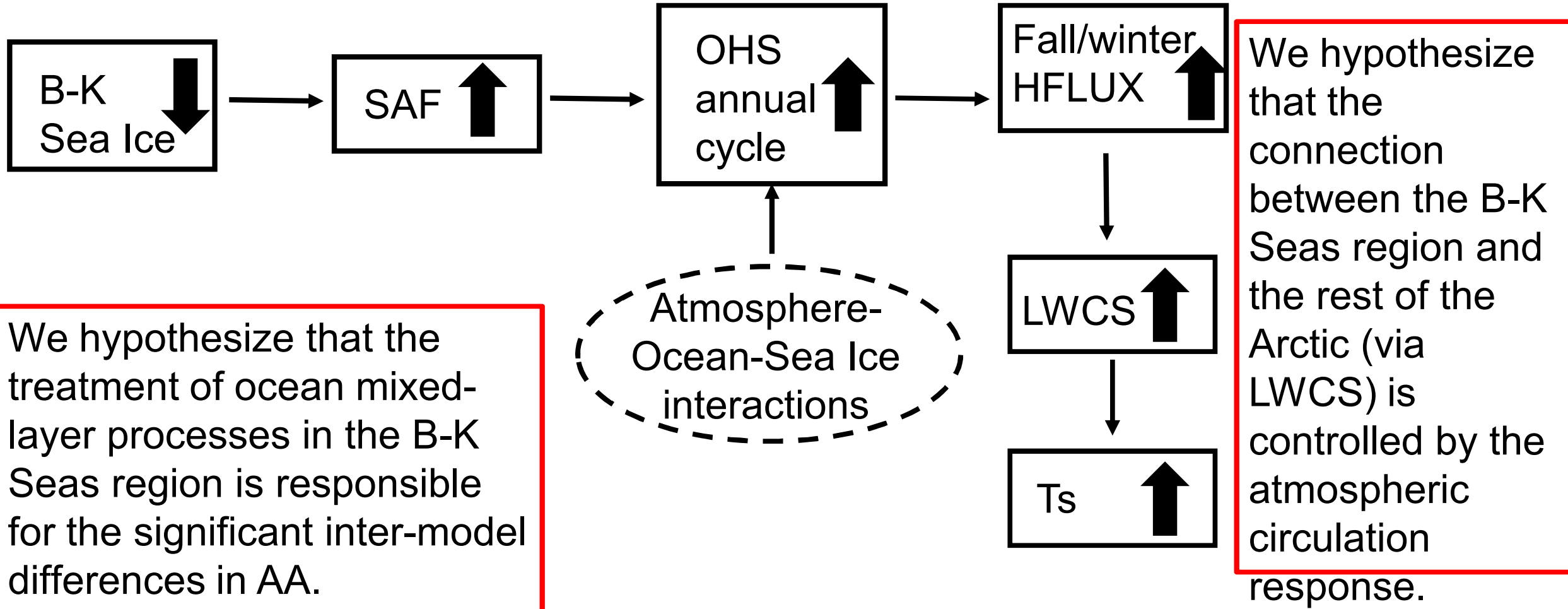
- 
- (1) Physical process of Arctic Amplification. **Barents-Kara Sea region as a pacemaker of warming.**
 - (2) Do clouds matter to Arctic Amplification and sea ice loss? **Yes.** However, the most important aspect may not be the direct impact, but rather indirect impacts by modulating other responses (e.g., the circulation response)
 - (3) What is the way forward? **System approaches and multi-disciplinary perspectives.**

Take away messages...

- Meteorological conditions are the primary driver of Arctic low cloud characteristics by at least an order of magnitude in most cases.
- Statistically significant covariance between cloud properties and sea ice are found in Autumn (agrees with previous work)
- A $\sim 5 \text{ Wm}^{-2}$ change in the LW CRE is found between open ocean and sea ice covered footprints. Indicating, a statistically significant influence of the cloud-sea ice interactions to the Arctic surface radiation budget in Autumn.

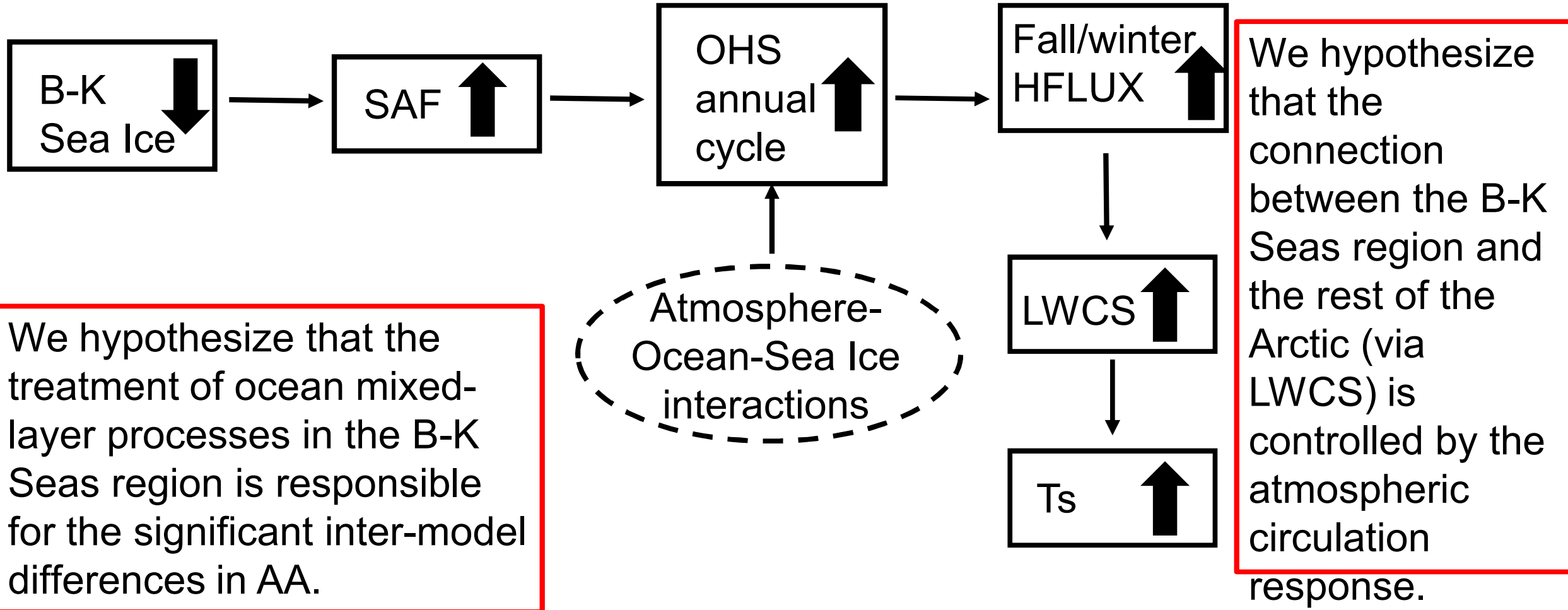
A picture of AA and the inter-model spread

LWCS sets the Arctic-wide magnitude of warming, and explains way all models produce AA. **Both models and spatial regions with the largest LWCS increases, warm more.**



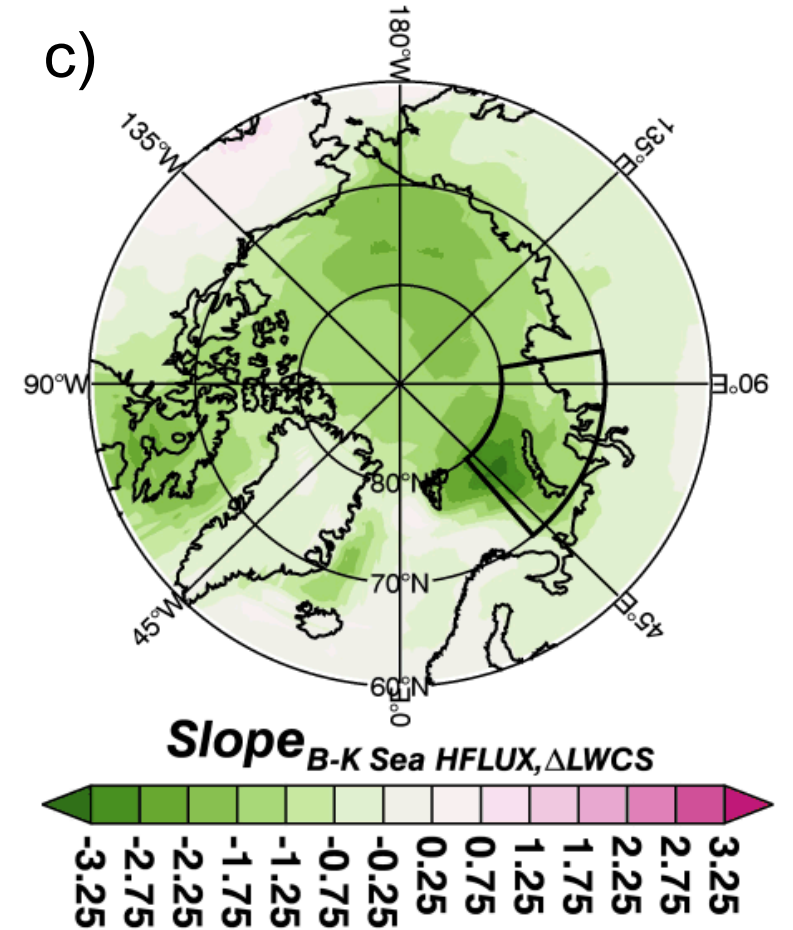
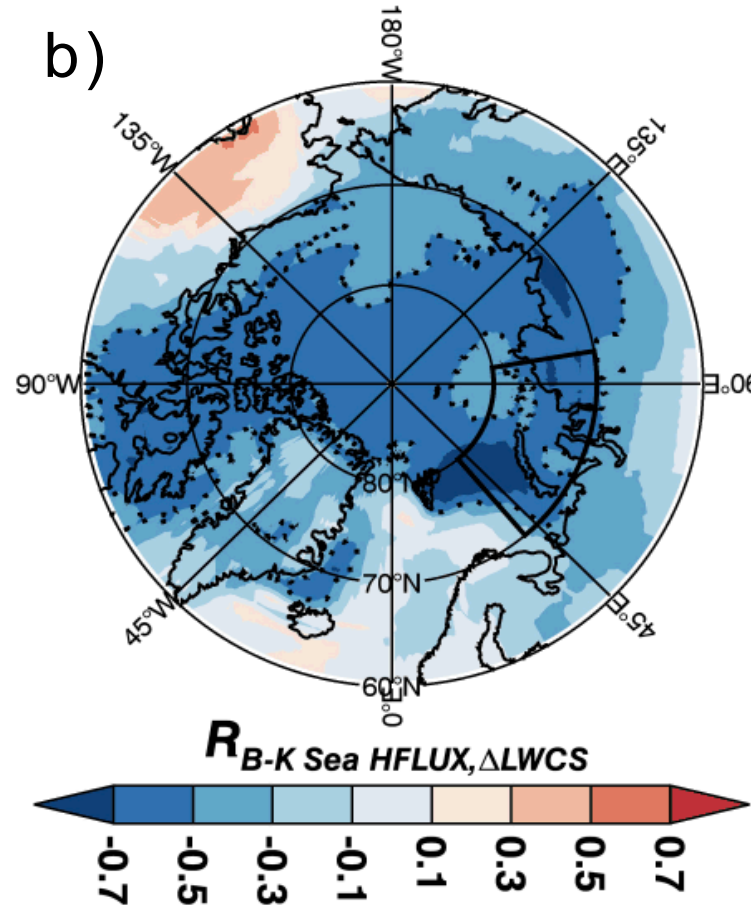
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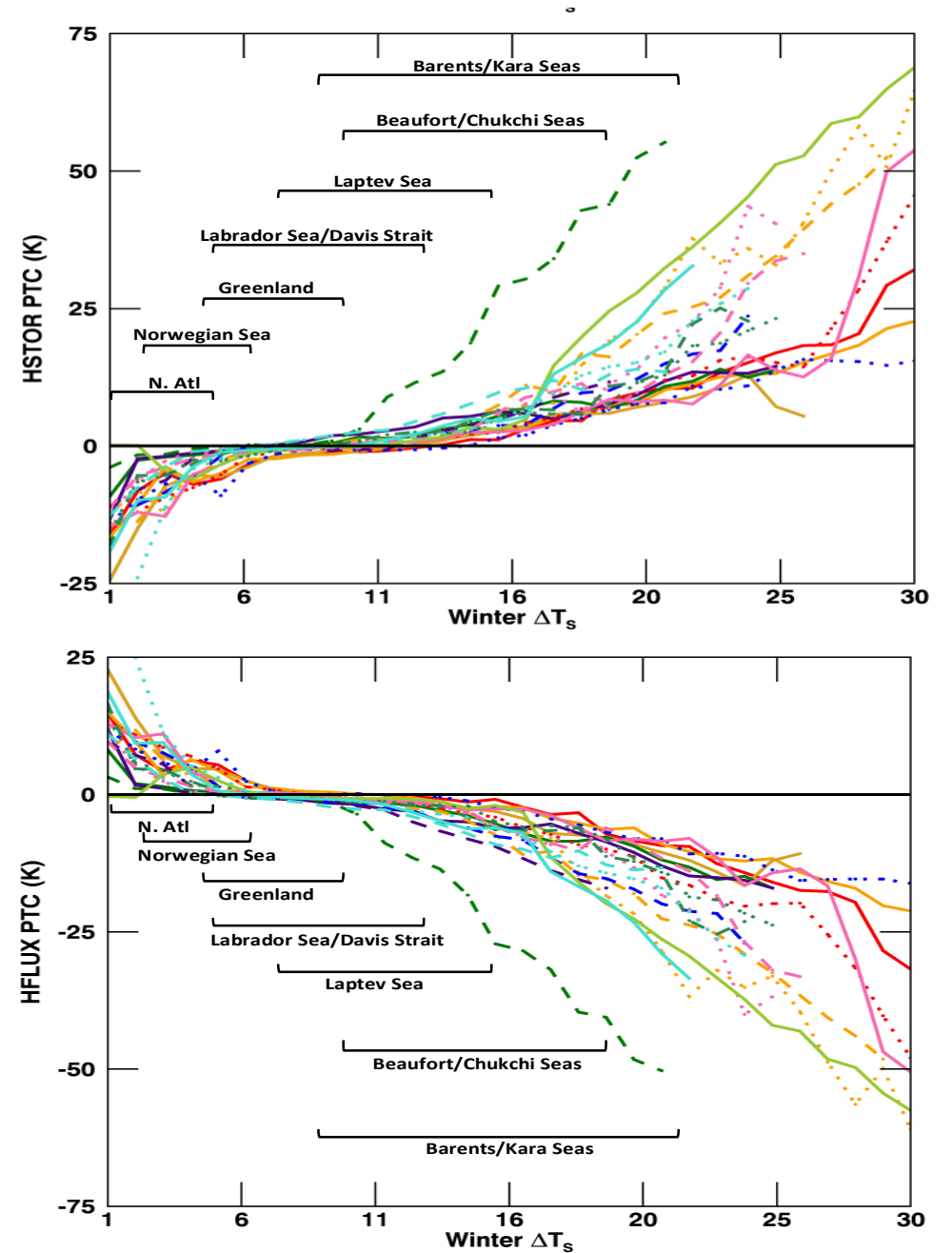
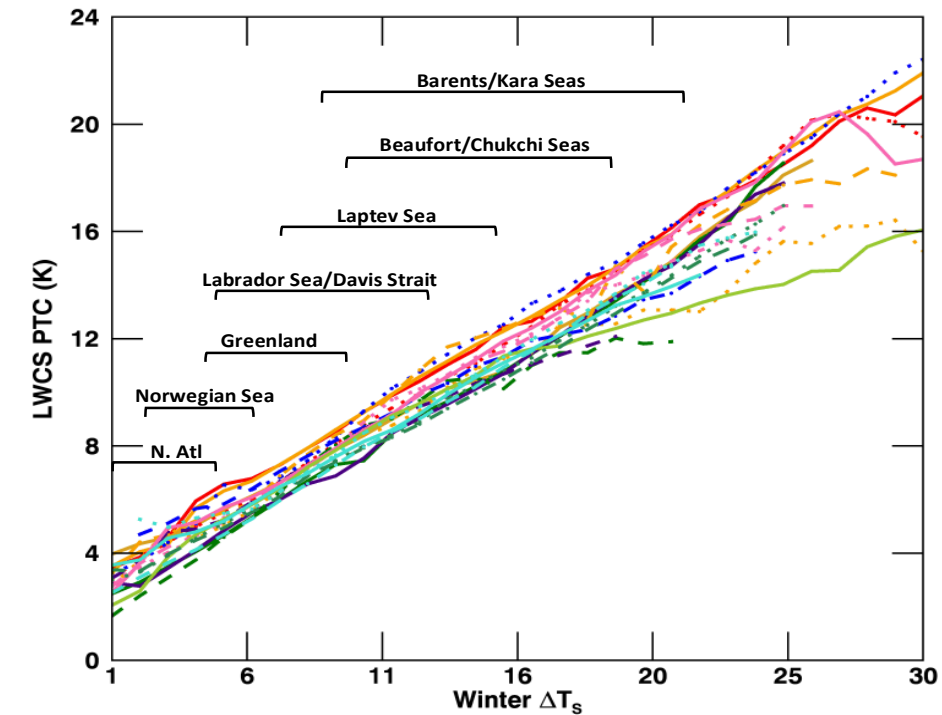


Increased B-K Sea region surface turbulent fluxes have an Arctic-wide impact

Surface turbulent flux changes in the Barents-Kara Seas region show an Arctic-wide impact on LWCS, magnitude of which is strongest locally.

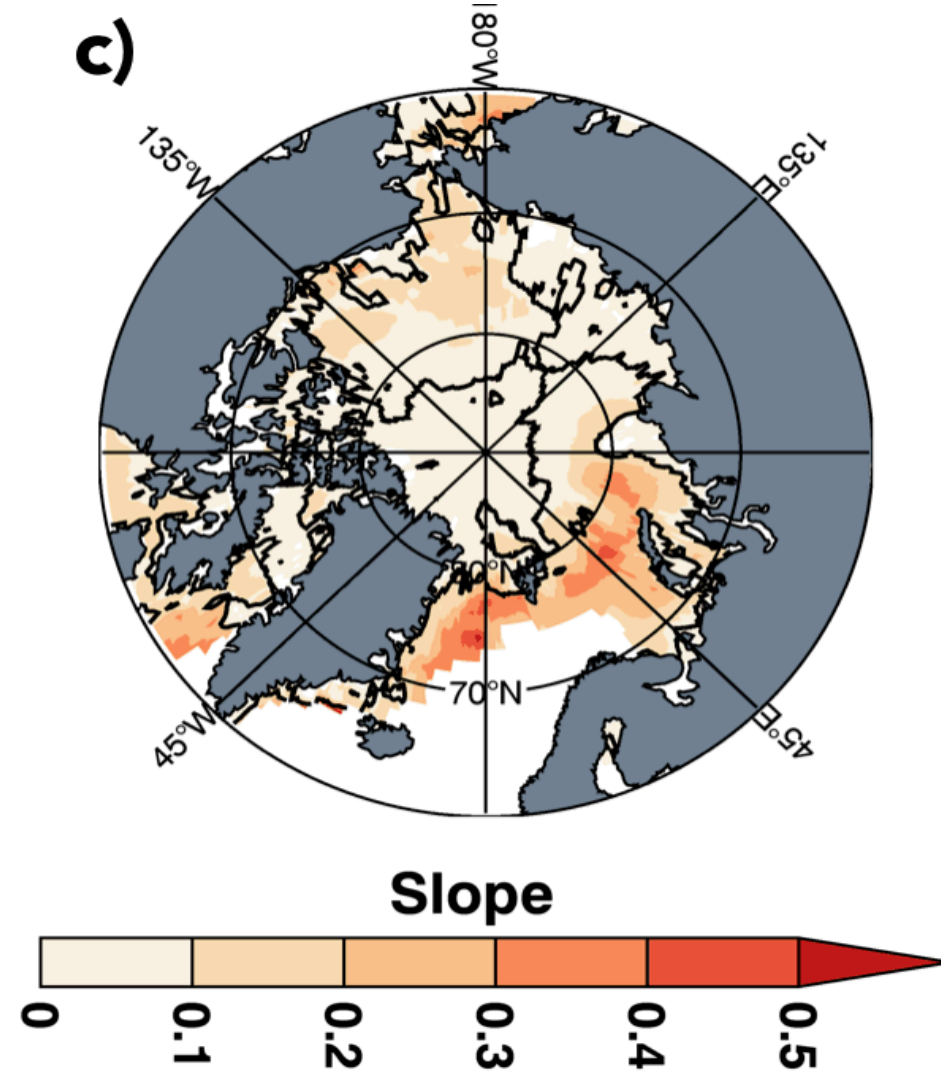


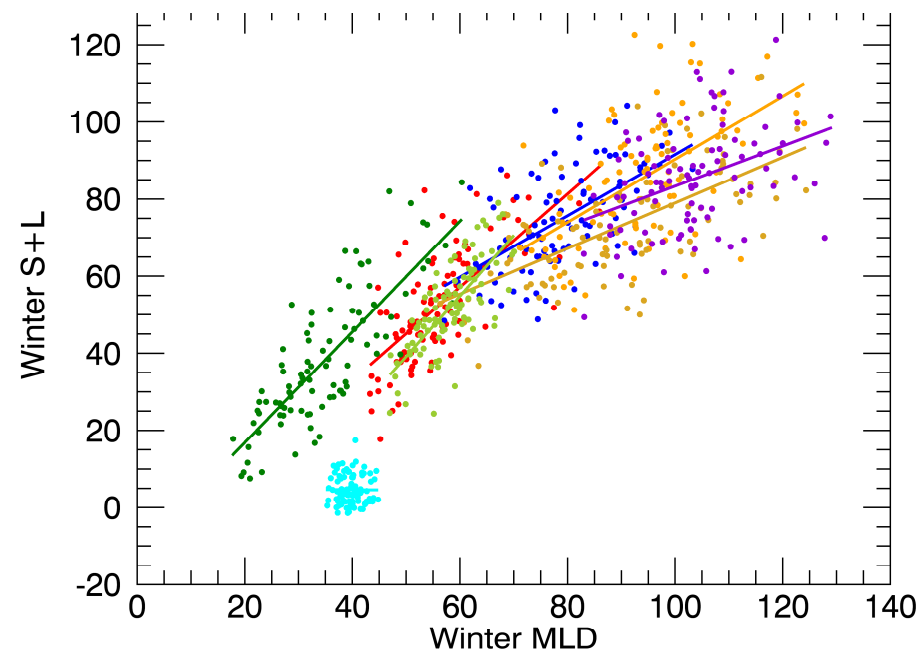
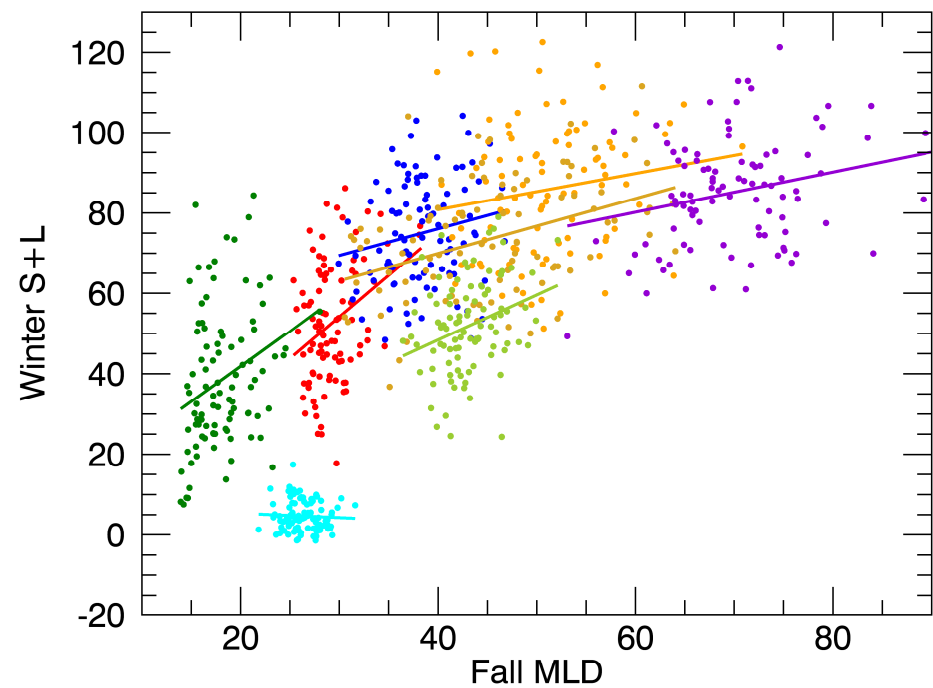
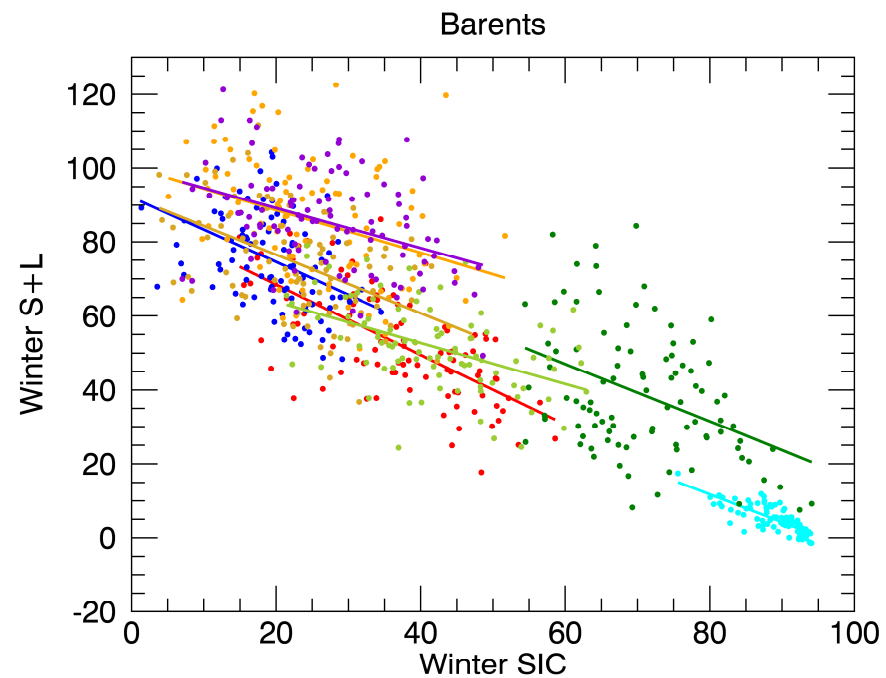
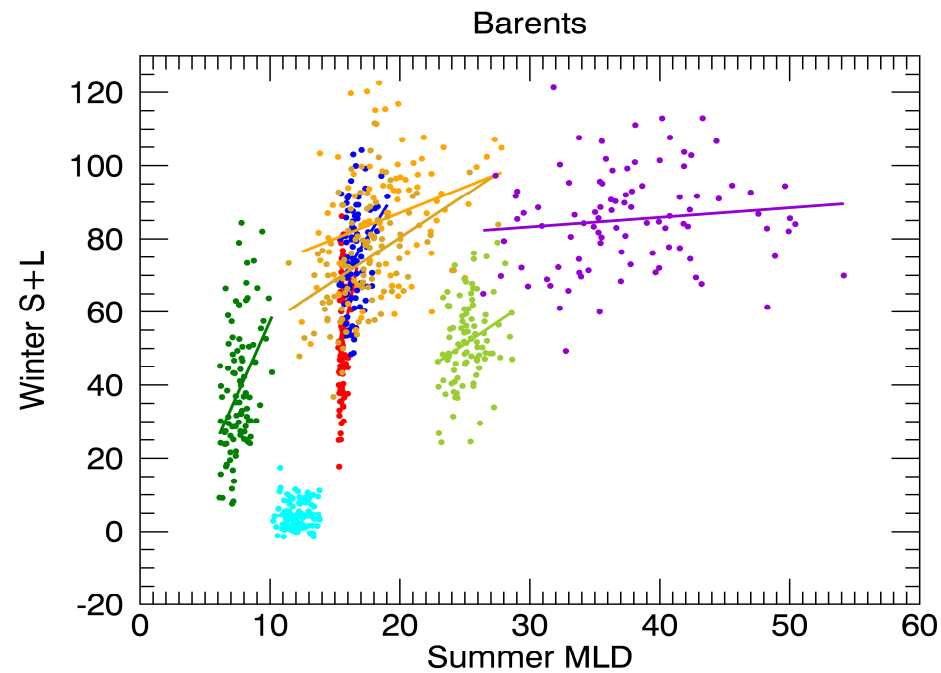
Regions that warm most have
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contributions...most of the time

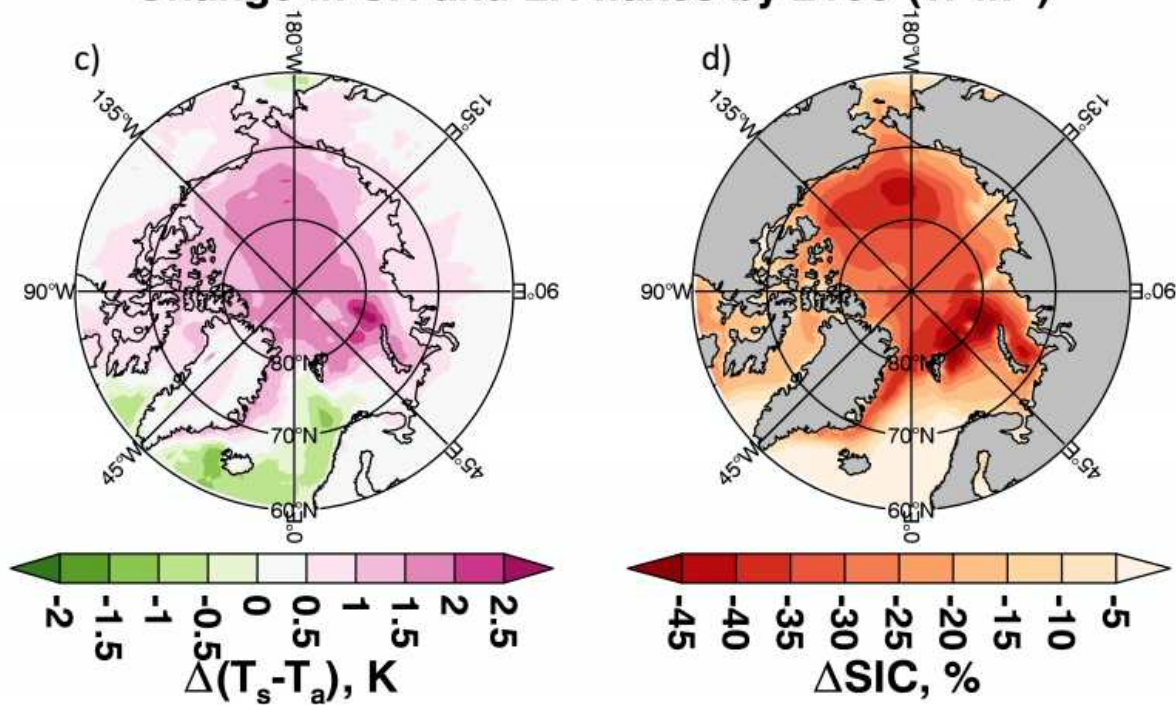
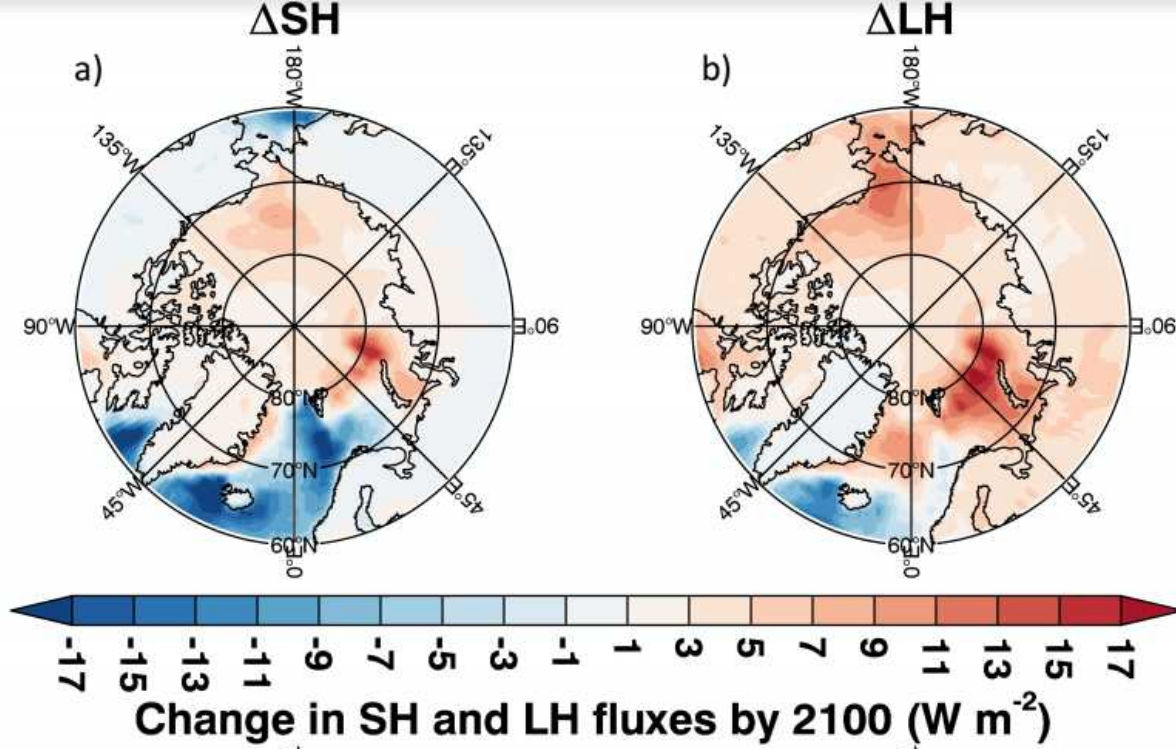


Increased B-K Sea region surface turbulent fluxes have an Arctic-wide impact

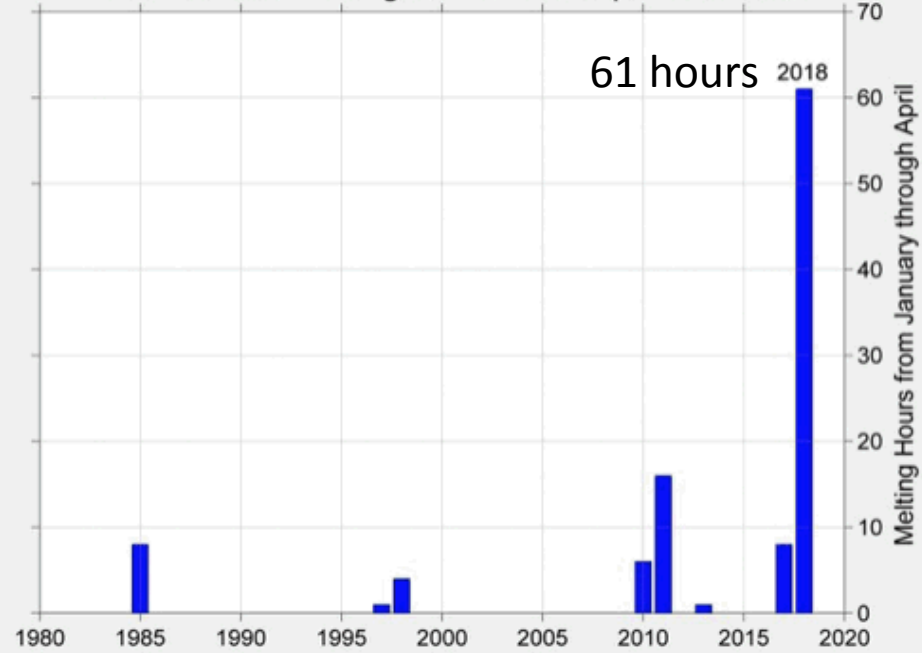
Surface turbulent flux changes in the Barents-Kara Seas region are show a statistically significant relationship with the model simulated SAF.







Hours above Freezing at Morris Jesup, Greenland



 **Robert Rohde**
@rarohde

Replying to @rarohde

In 2018, there have already been 61 hours above freezing at Cape Morris Jesup, Greenland.

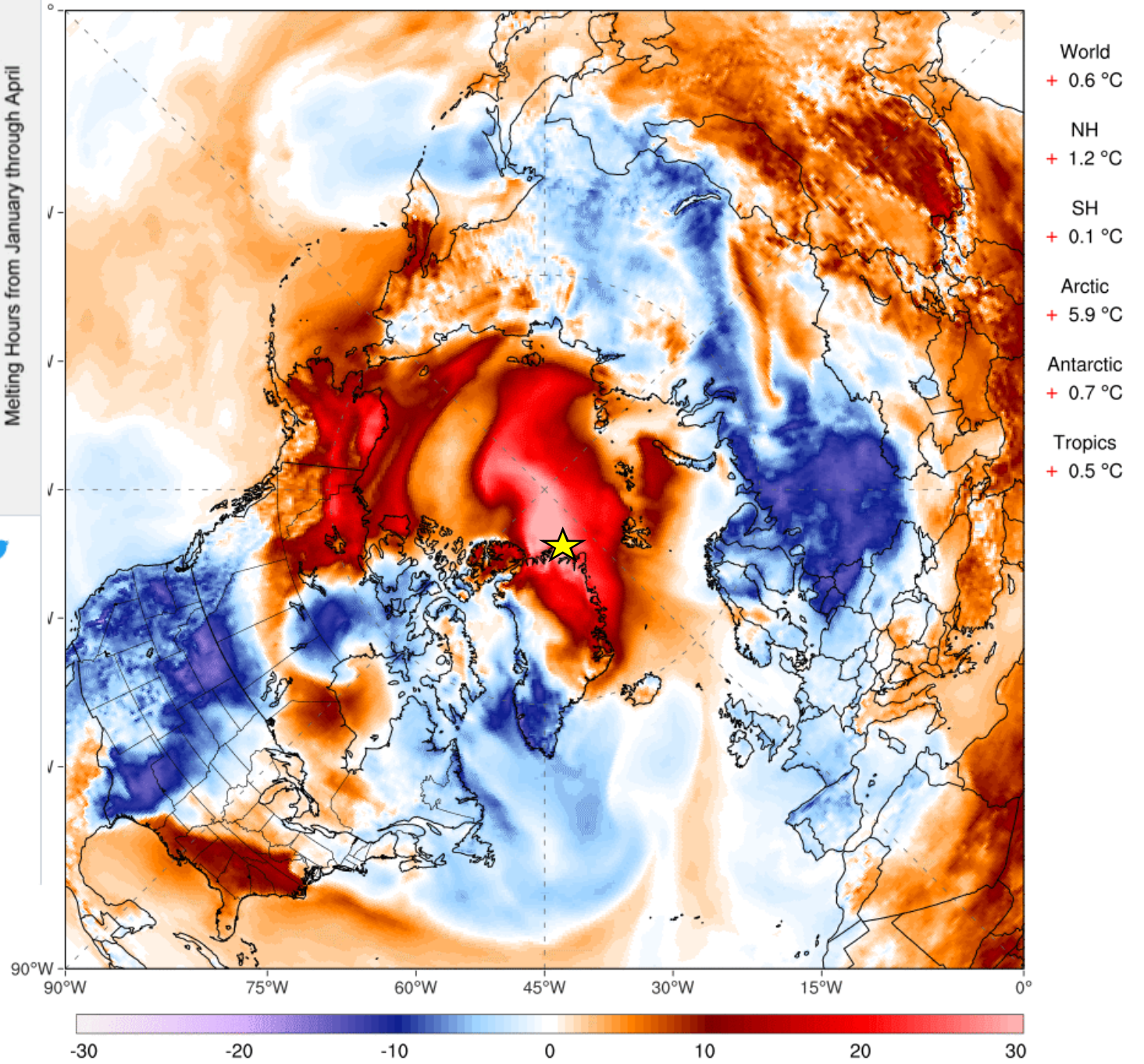
The previous record was 16 hours before the end of April in 2011.

8:02 PM - Feb 25, 2018

♡ 157 💬 180 people are talking about this

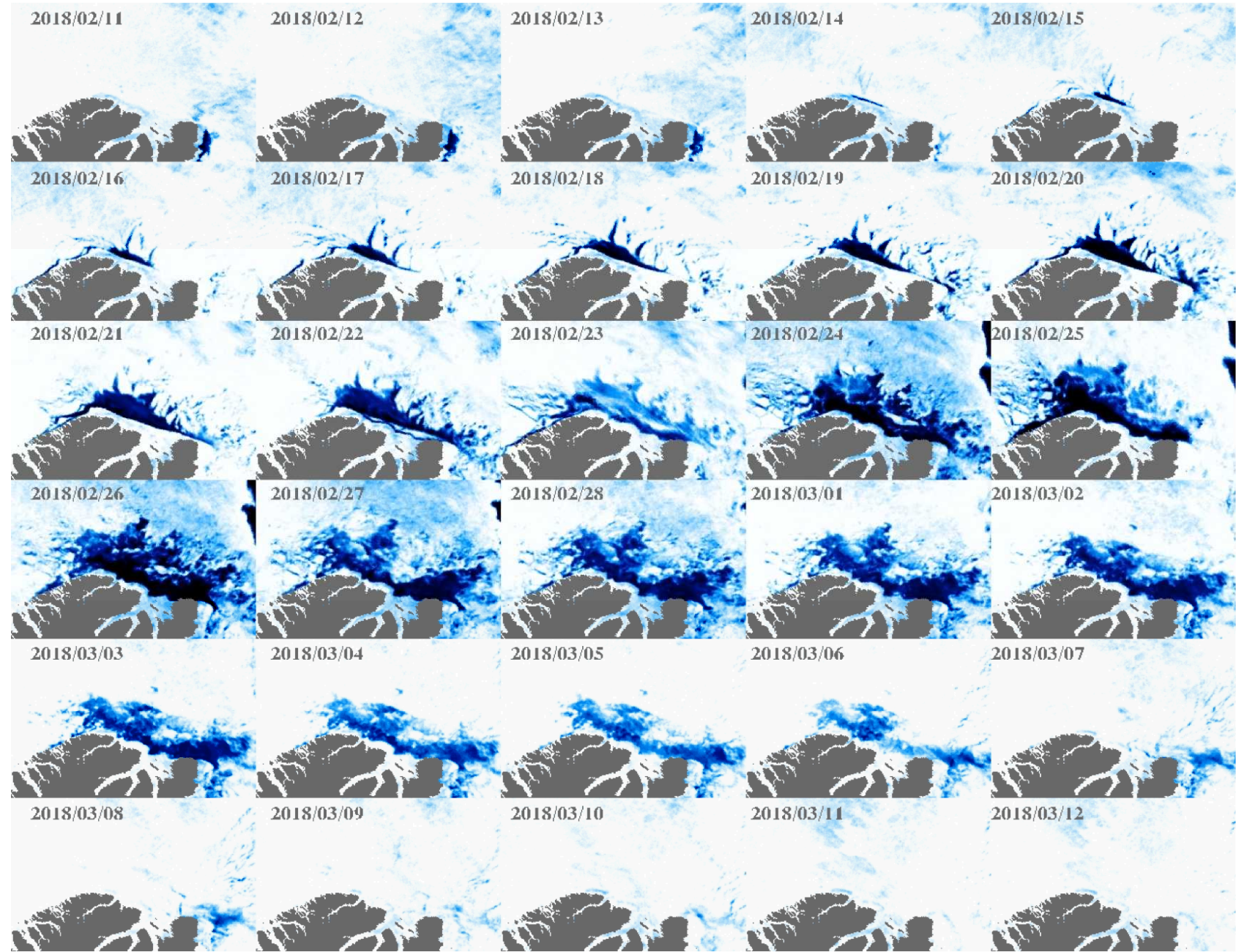
GFS/CFSR 2m T Anomaly (°C) [1979-2000 base]
Init 2018/02/23 00Z | f000 Valid Fri 00Z, Feb 23, 2018

ClimateReanalyzer.org
University of Maine | Climate Change Institute



Sequence Images of Polynya Opening North of Greenland Feb 11, 2018 to March 12, 2018

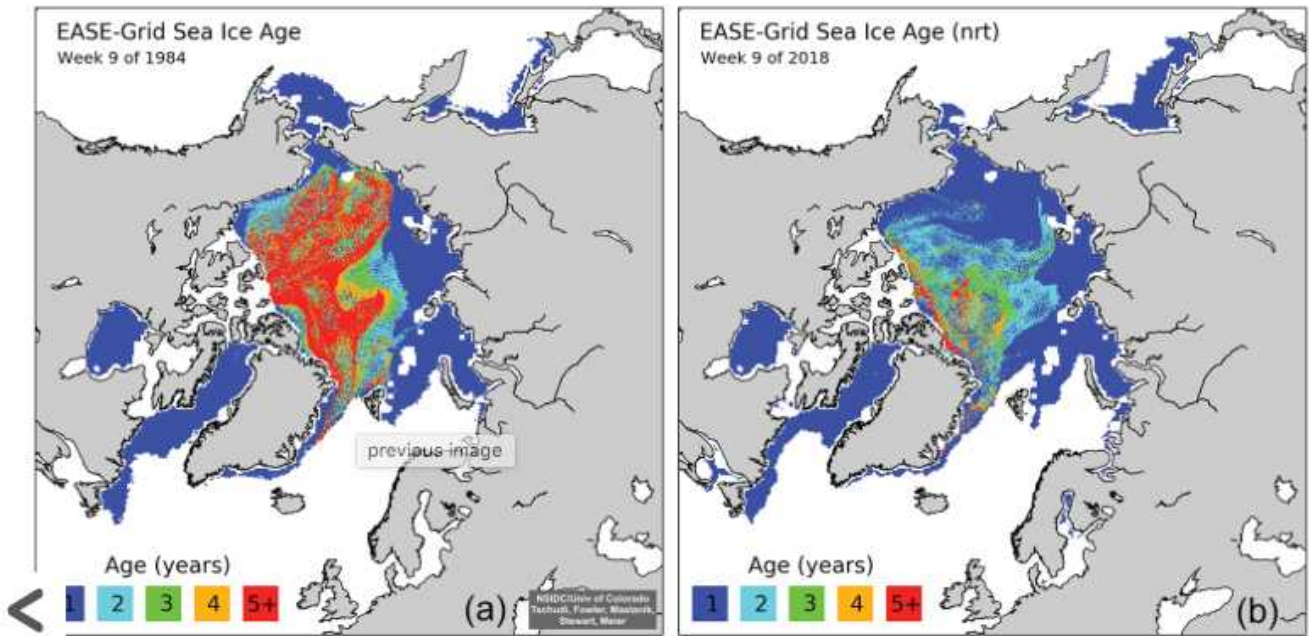
Associated rare polynya:
Lasting more than 3 week.



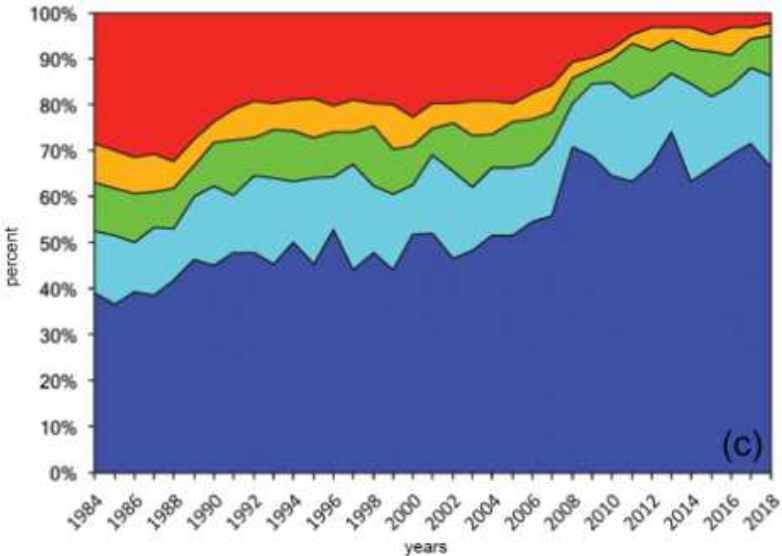
Transformation from multi-year to first-year sea ice.

Arctic sea ice cover continues to decline.

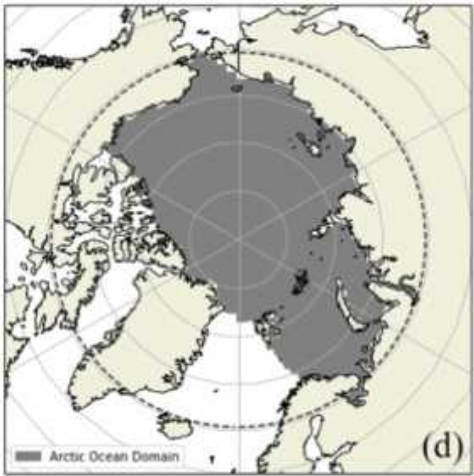
Ice Age Distribution During Week Nine in 1984 and 2018



Percent of Sea Ice Extent During Week Nine for Different Age Classes



Arctic Ocean Domain



Source: NSIDC

Images by M. Tschudi, S. Stewart, University of Colorado Boulder, and W. Meier, J. Stroeve, NSIDC