Simulating Sea Ice and Snow Linkages to the General Circulation

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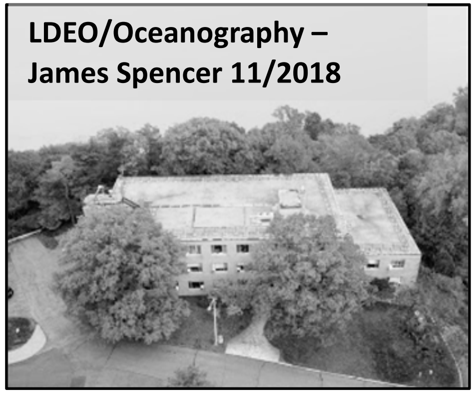
U of T, 3/2018

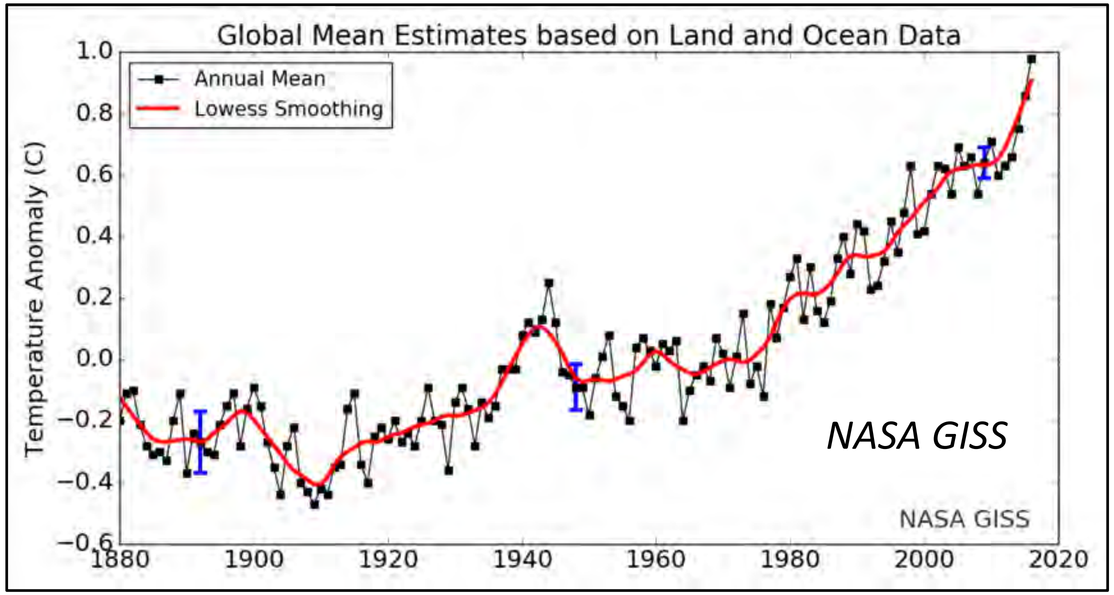

Munger Residence KITP, 5/2018

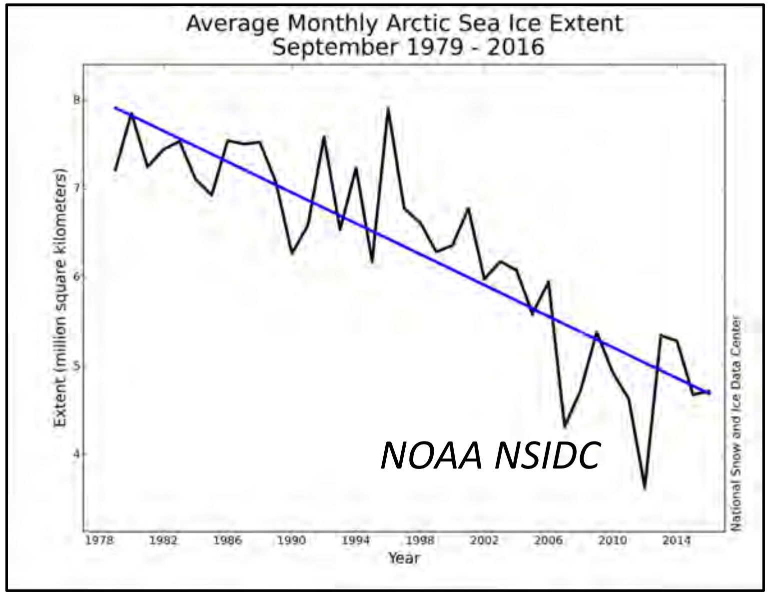

LDEO/Oceanography – James Spencer 11/2018

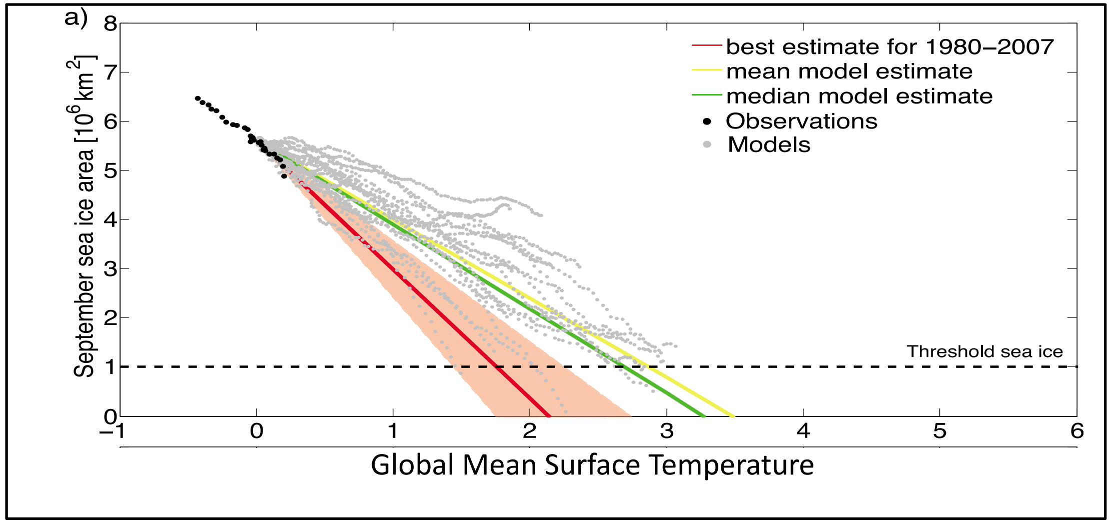

Mackenzie Delta flyover, 3/2018

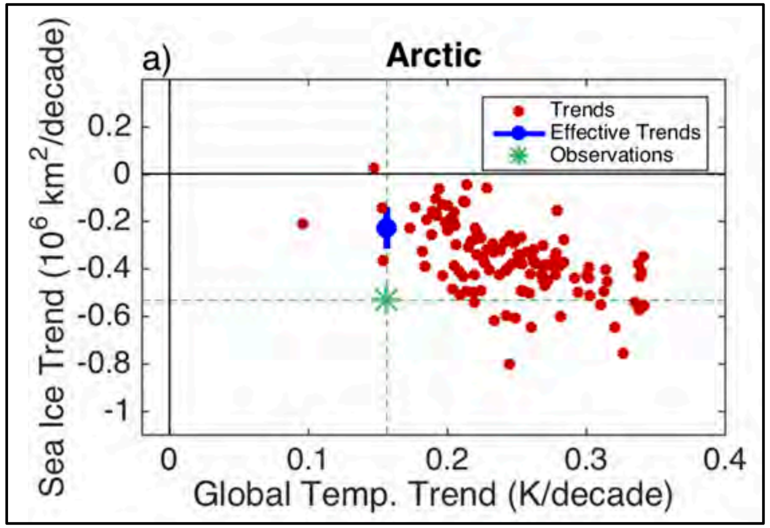
1. **Model temperature sensitivity to snow- and sea-ice loss is robust but biased low.**
2. **Isolated linkages to sea-ice loss are more robust than responses to tropical changes.**
3. **Short-term circulation linkages are challenging to attribute.**

Sea Ice Loss Is an Icon and Amplifier of Global Warming









Temperature sensitivity to sea ice loss under global warming is well characterized.

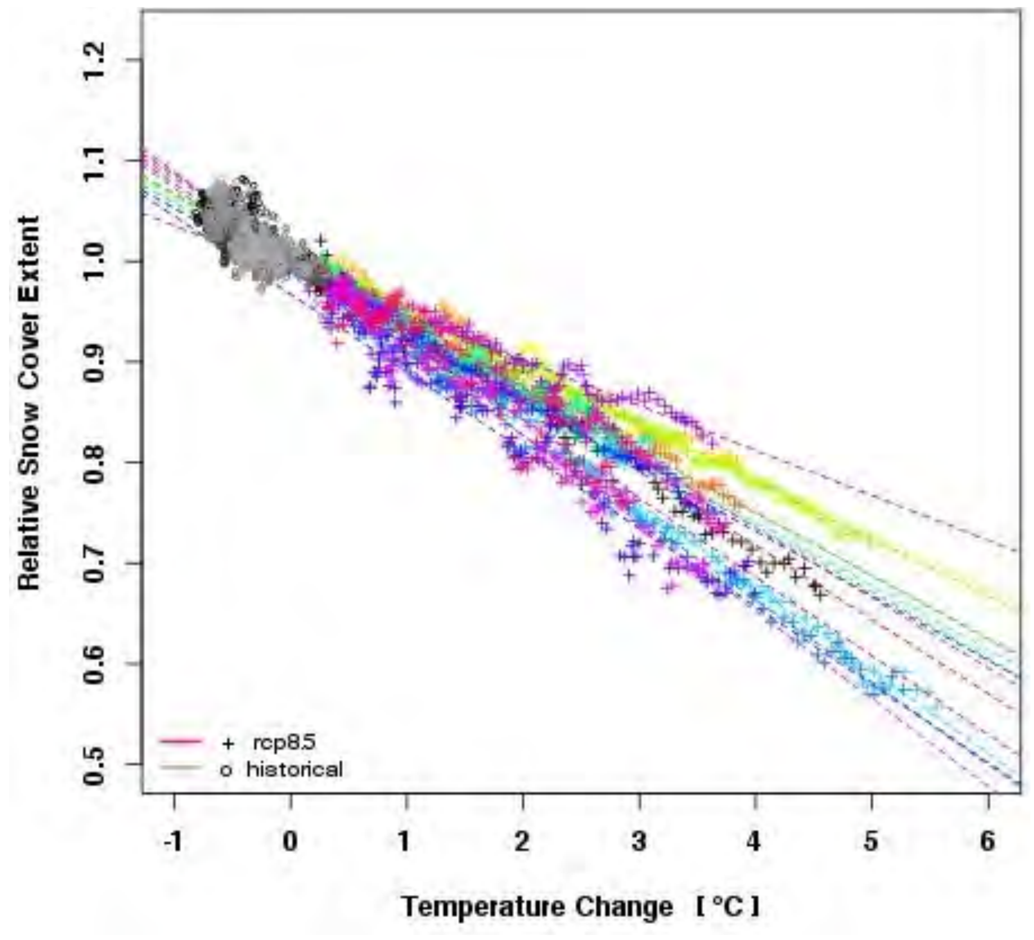
Model sea ice seems insensitive to temperature.

We should try to understand this connection and reconcile this inconsistency.

Mahlstein & Knutti 2012, Rosenblum and Eisenman 2017

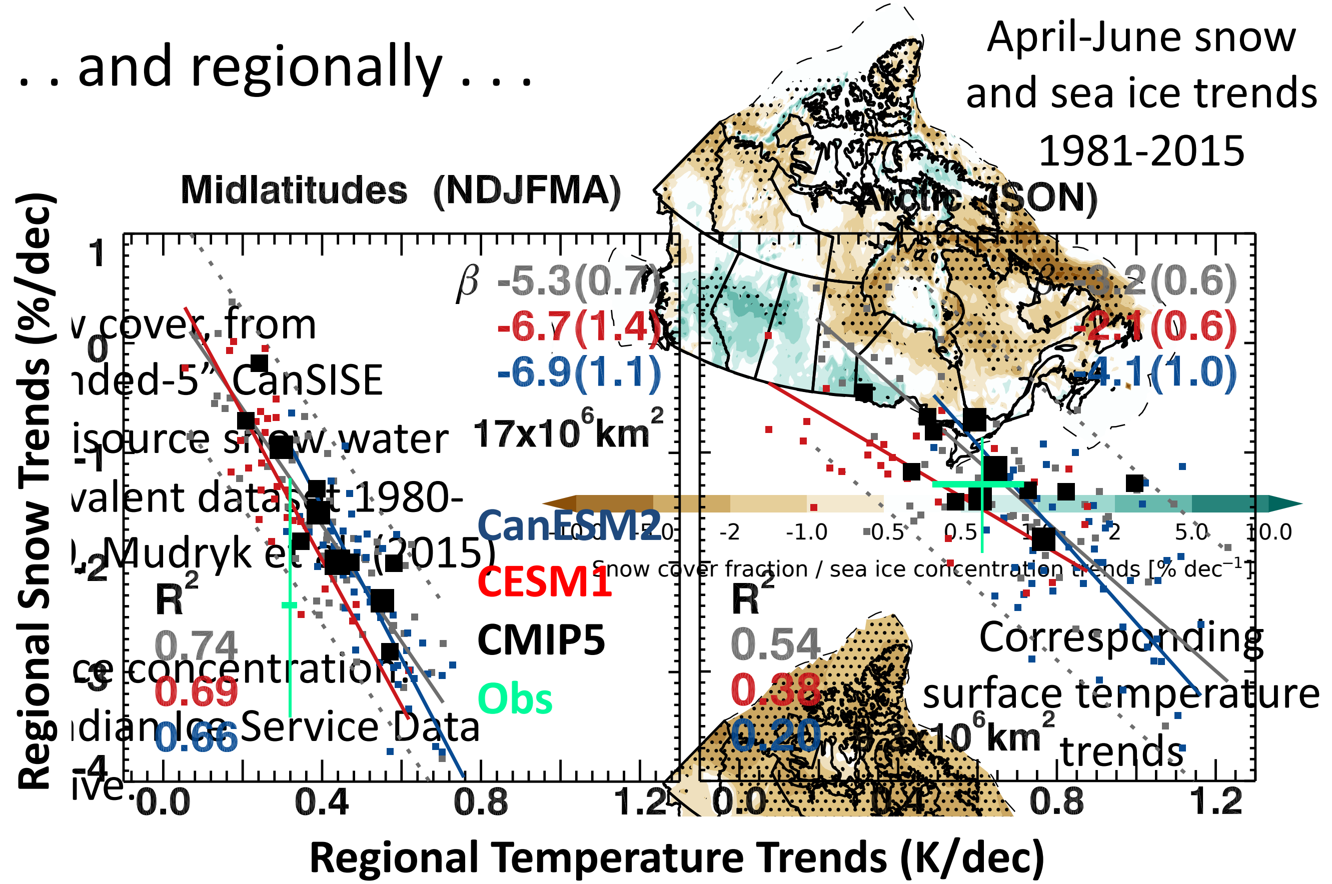
Snow Cover Is also Linked to Temperature . . .

. . . Globally . . .



Brutel-Vuilmet et al. 2013

. . . and regionally . . .



Models capture Arctic sensitivity, underestimate midlatitude sensitivity.

Are there links between the biases in feedbacks involving marginal sea ice and marginal snow?

Mudryk et al. 2018

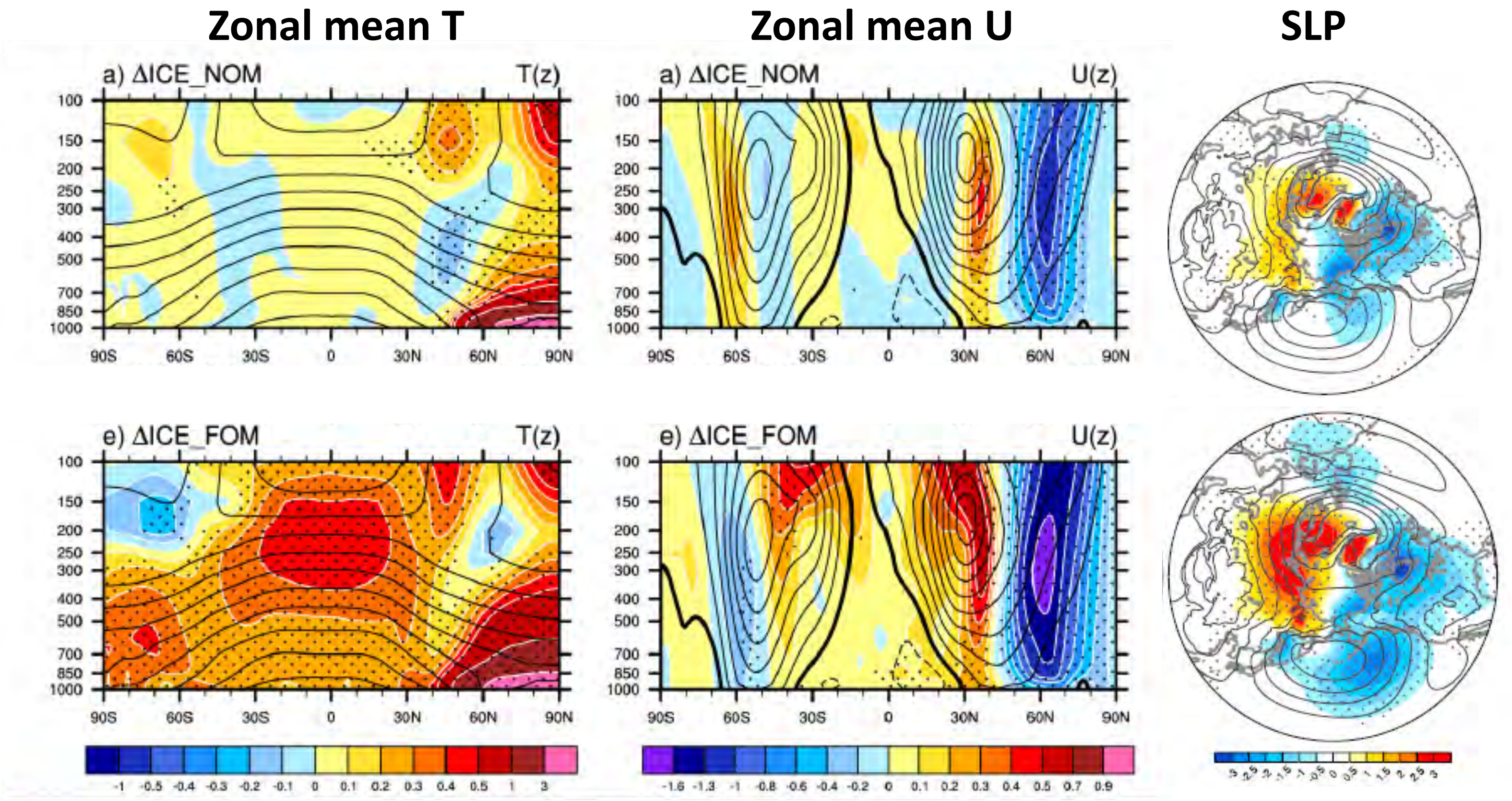
How Do Sea Ice and Snow Influence Regional Climate and the General Circulation?

- The thermal sensitivity of snow and sea ice is reasonably well characterized, and models capture aspects of it.
- What about the knock-on effects of snow and sea ice loss on, e.g., atmospheric circulation and the climate of remote regions?
- What observational constraints are there on these effects, and are additional observations needed?

Dynamical Coupling to the Ocean Changes the Story

Prescribed SST and sea ice, imposed sea ice loss. (CAM4)

Dynamical ocean and sea ice, induced sea ice loss (CCSM4)

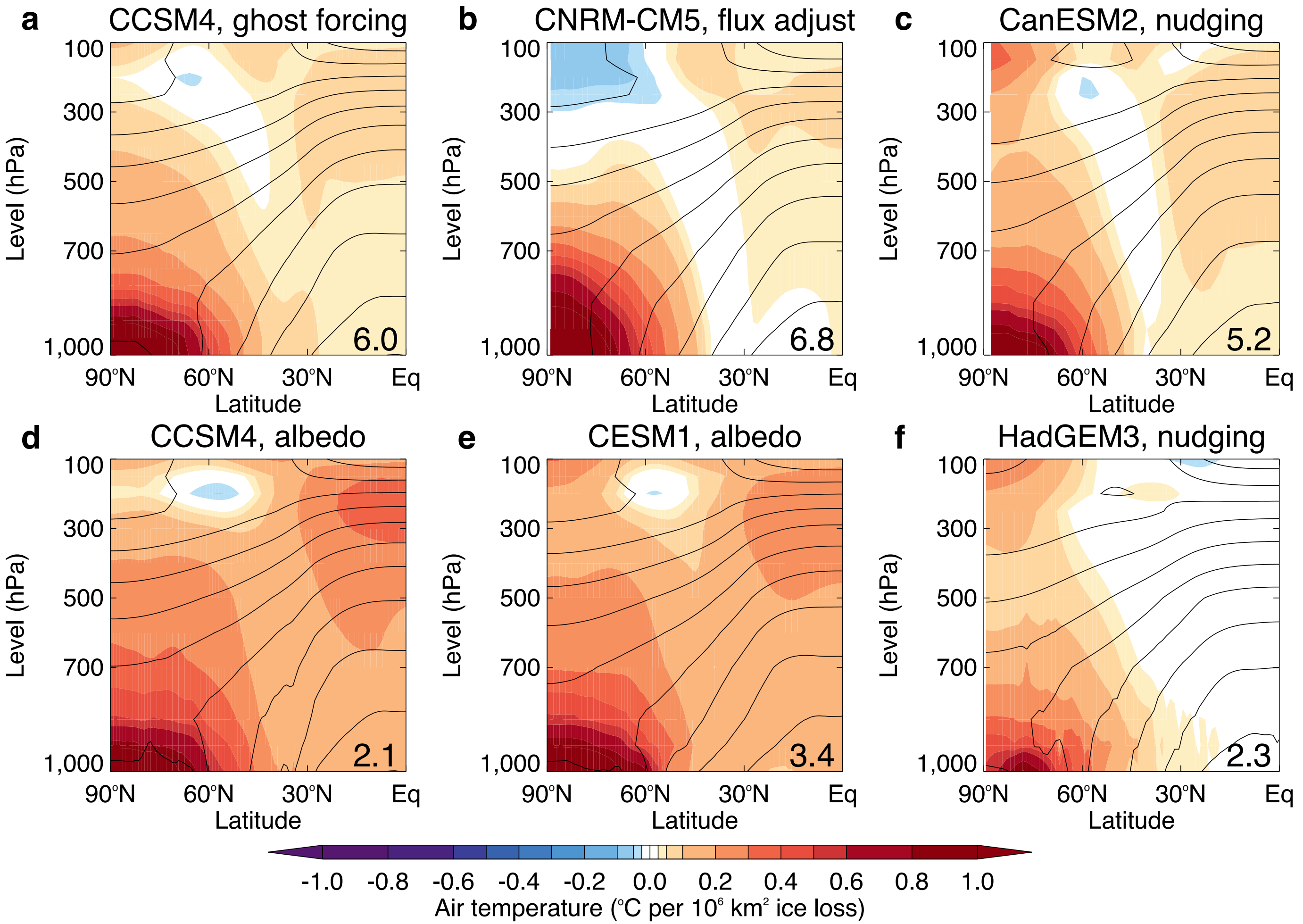


Chiang and Bitz 2005, Deser et al. 2015

- Sea ice loss with ocean-atmosphere coupling drives a ‘mini global warming’.
- Coupling increases the amplitude and extent of the response to Arctic sea-ice loss.

Sea ice loss responses in coupled models are quite robust . . .

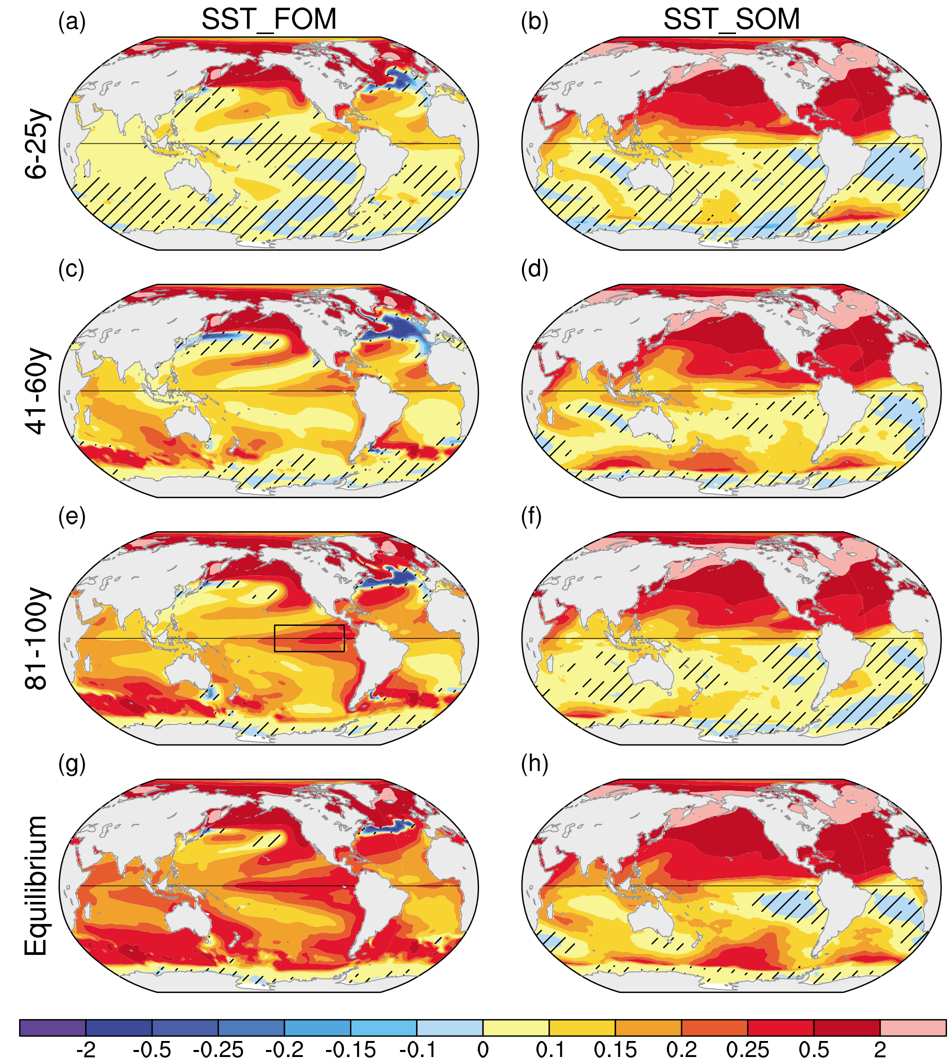
DJF T Response, per unit sea ice loss



Screen et al. 2018

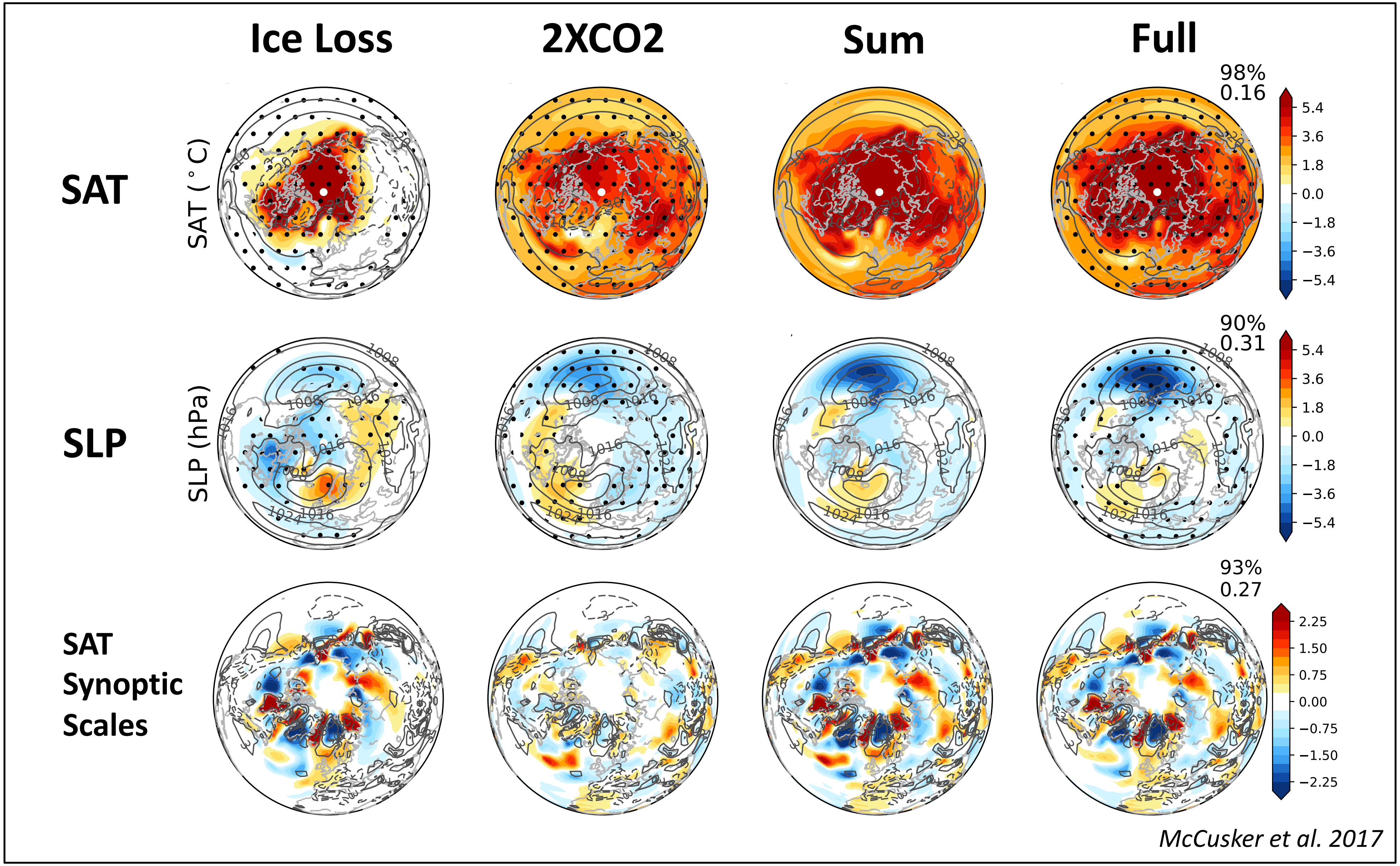
. . . and involve a rapid coupled ocean-atmosphere adjustment.

CCSM4 Sea Ice Loss, in Coupled and Slab Ocean



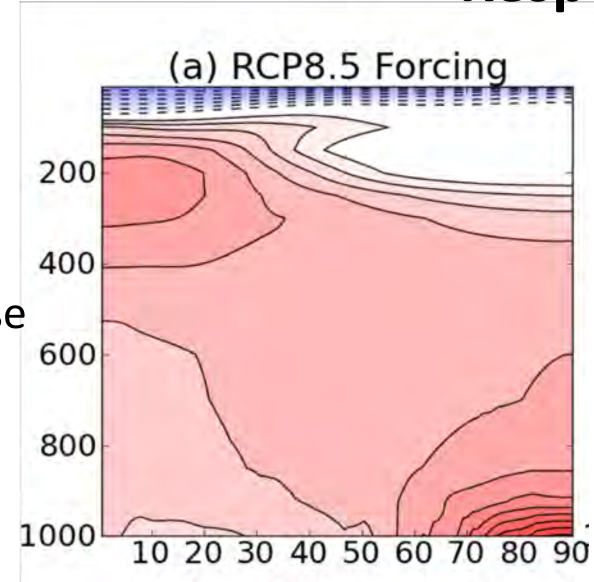
Wang et al. 2018

Sea Ice Loss and CO2 Responses Are Additive

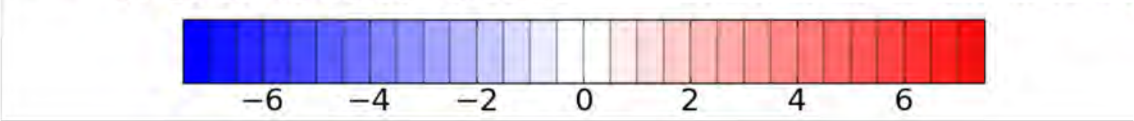


Zonal Mean ANN Temperature Response

Projected greenhouse warming (CESM)



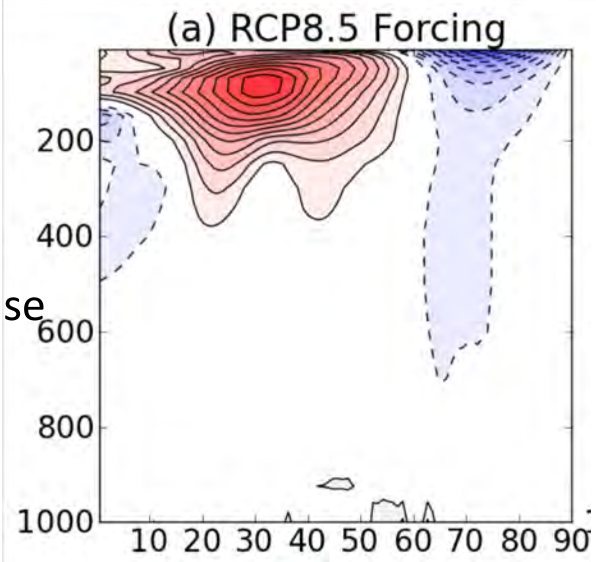
We use a simple pattern scaling technique to solve for the patterns proportional to sea ice loss and tropical warming.



Blackport and Kushner 2017

DJF Zonal-Mean Zonal Wind Response

Projected greenhouse warming (CESM)

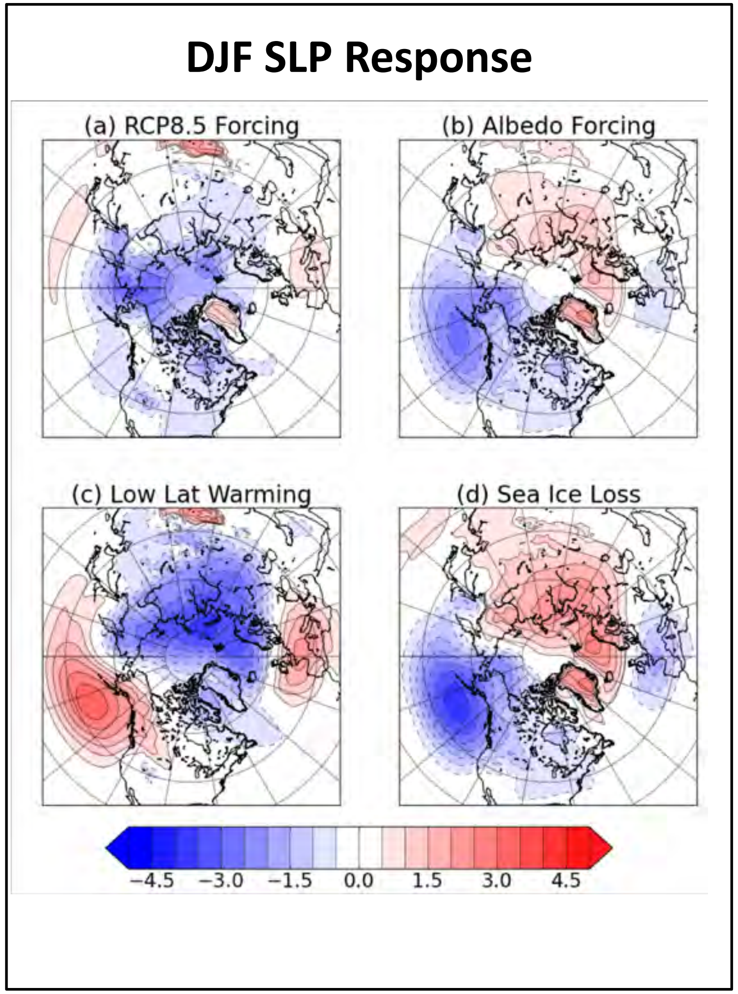


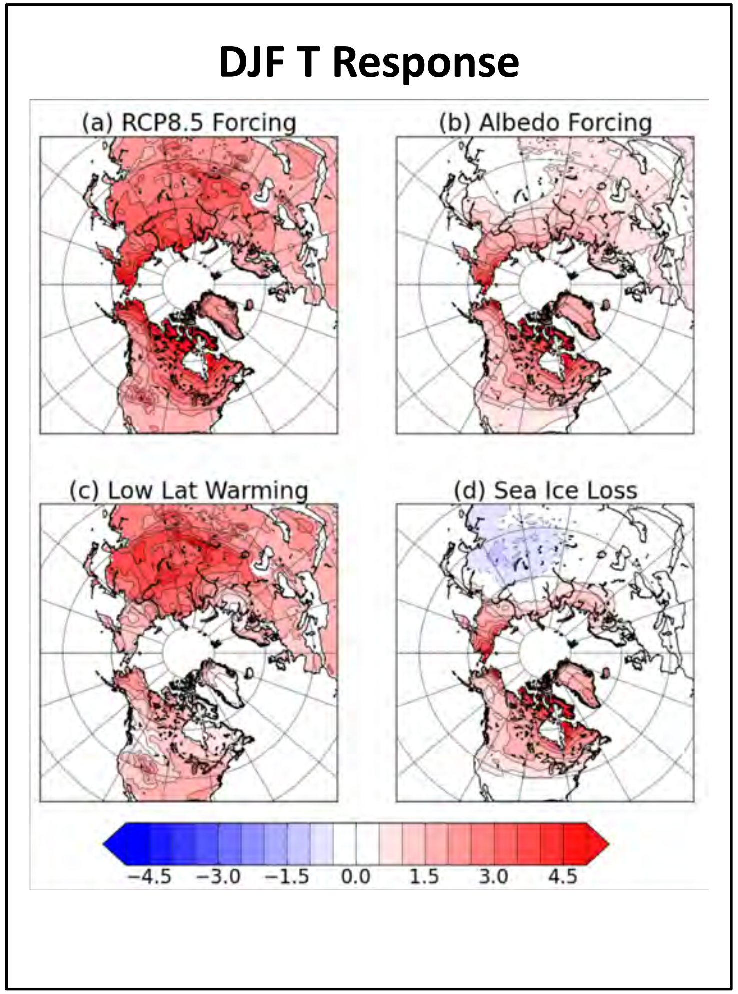
Blackport and Kushner 2017

A 'Regional' Tug of War

Coupled Model Experiments

Pattern Scaling Decomposition



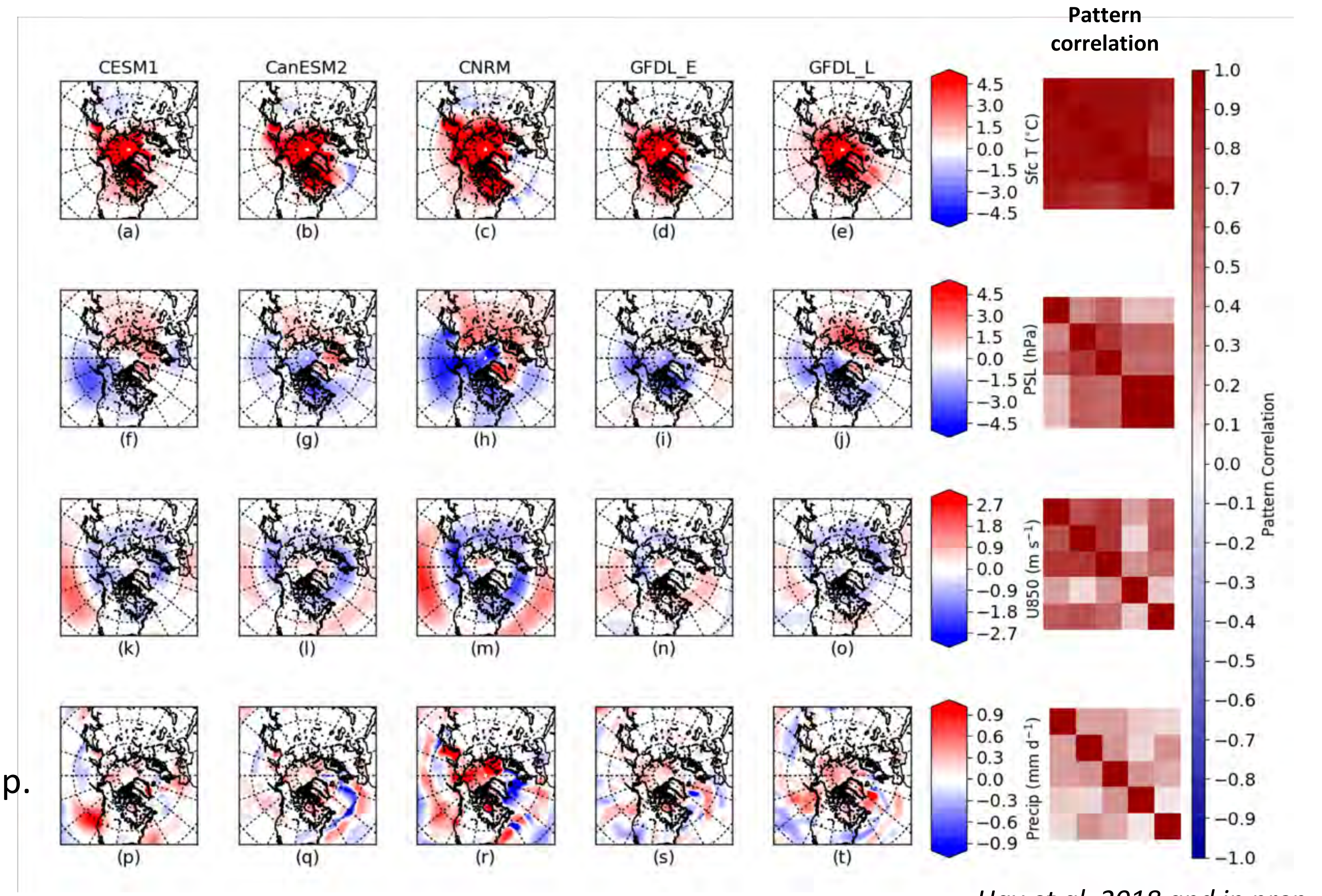


Sea ice loss in isolation strengthens the Siberian High and the Aleutian Low – but there is a tug of war with tropical warming impacts.

So sea ice loss feeds back negatively into regional forced circulation responses (Deser et al. 2004).

Blackport and Kushner 2017

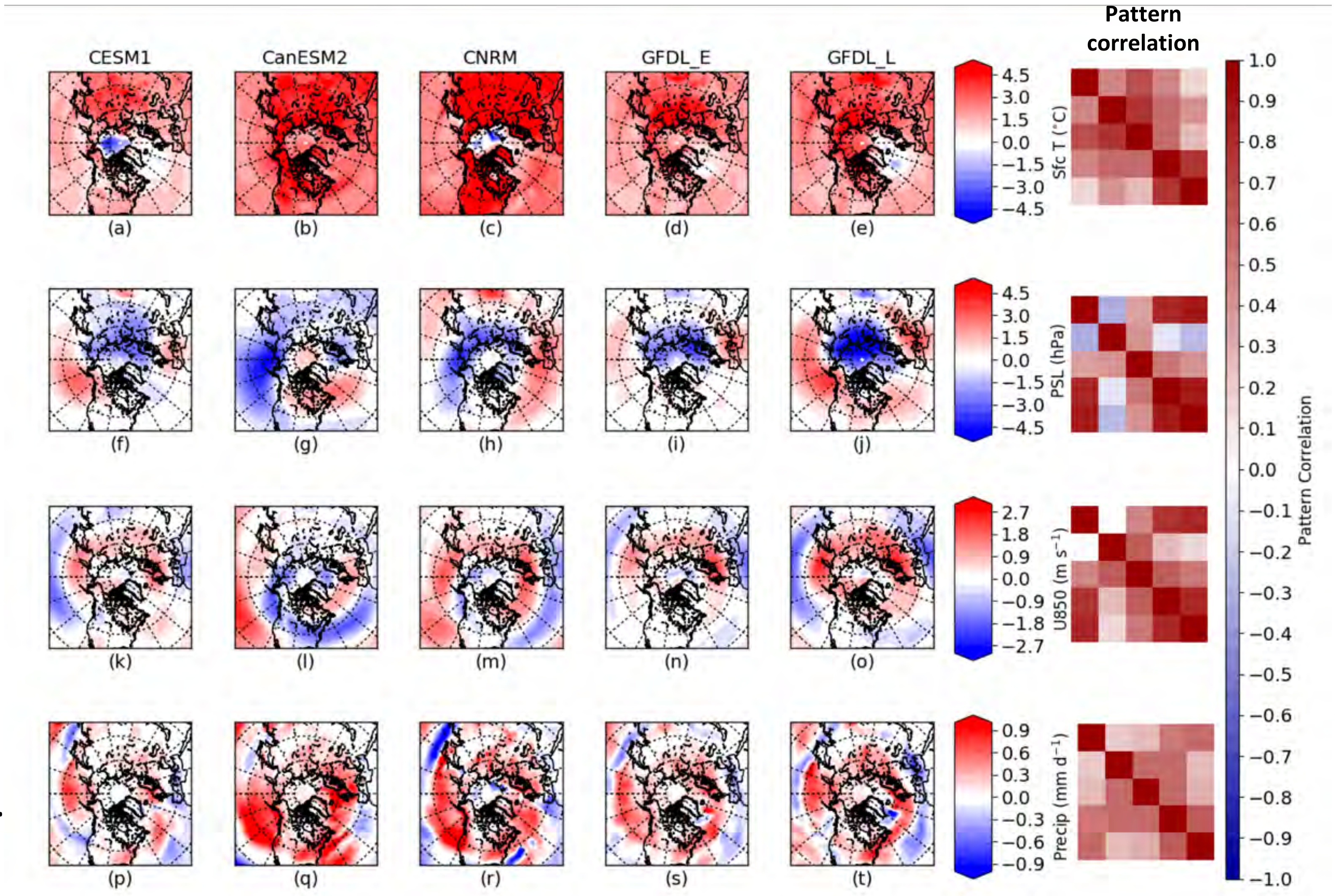
In different experiments, the isolated response pattern to Arctic sea ice loss . . .



Hay et al. 2018 and in prep.

. . . is fairly robust across models

The isolated response to low-latitude warming . . .



Hay et al. 2018 and in prep.

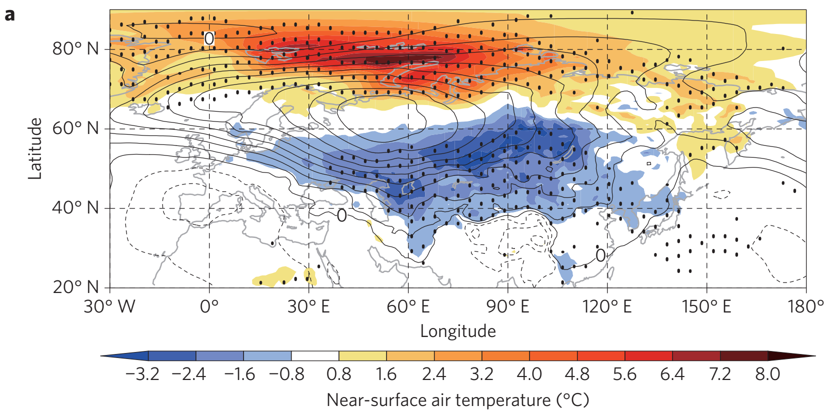
. . . isn't robust in circulation, but is robust in precipitation.

What Does this Mean for the Real World?

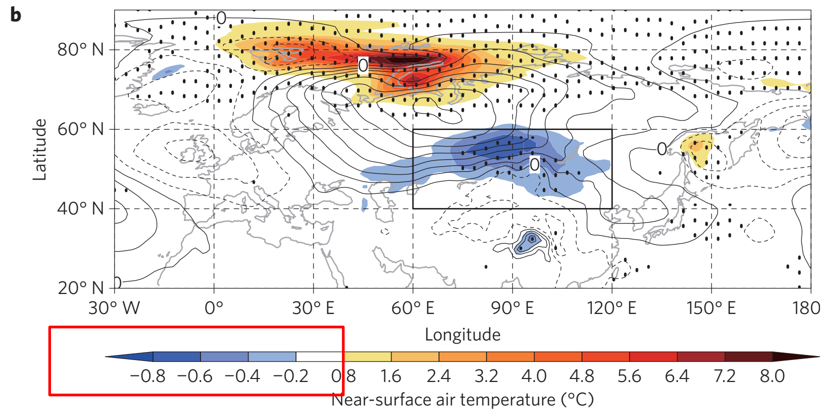
- With good sampling, we can pull out forced signals attributable to sea ice loss under projected climate change.
- But impacts of sea ice and snow variability on the circulation are more challenging to observe and attribute.

Cause and Effect Are Ambiguous in Sea Ice Experiments

Observed DJF T and SLP Anomalies, coherent with low Barents-Kara Sea Ice



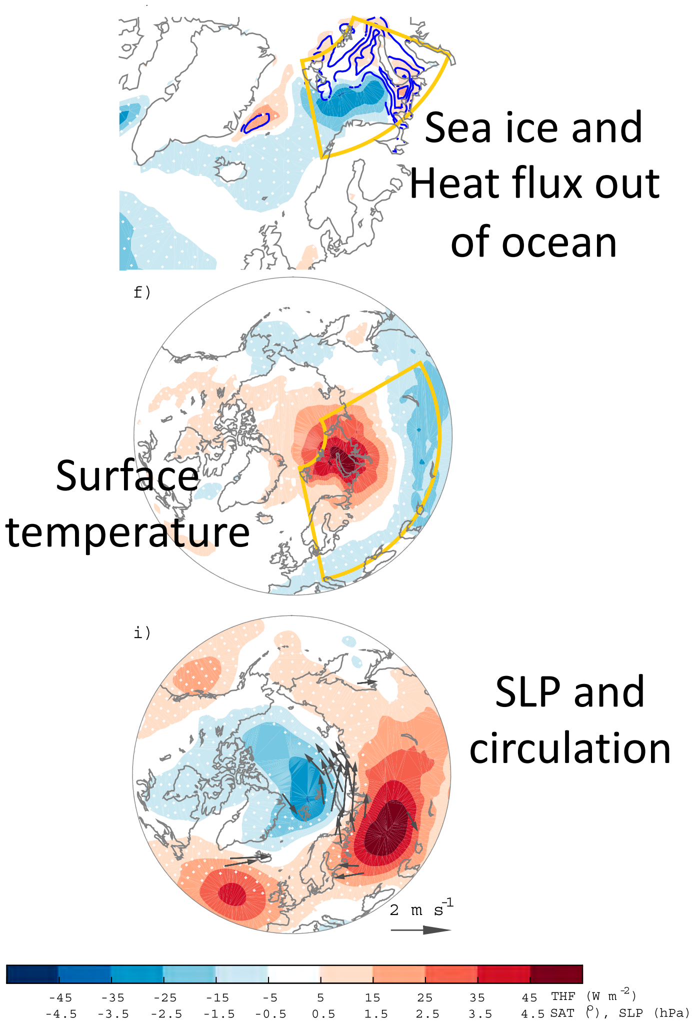
Anomalies in AGCM simulations



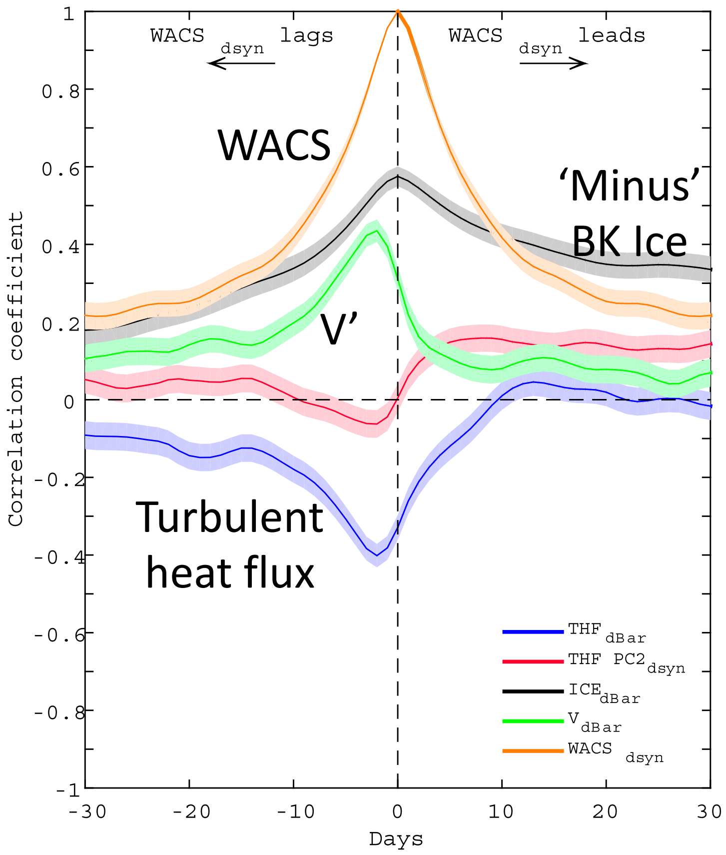
AGCMs produce weak winter cooling (they do better with good stratospheric representation)

Mori et al. 2014

Warm Arctic/Cold Siberia (WACS) Anomalies (February)



Daily lag correlation with WACS index

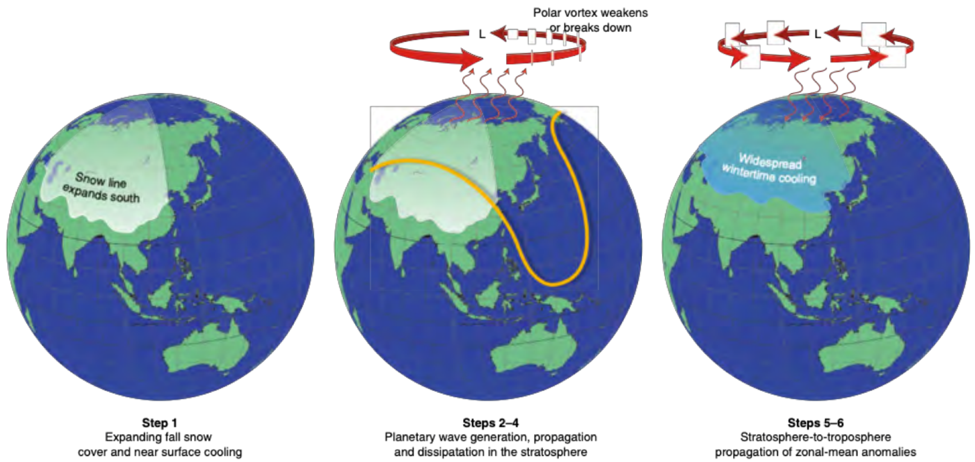


Atmosphere seems to drive ocean and sea ice during cold Eurasian winters

Sorokina et al. 2016

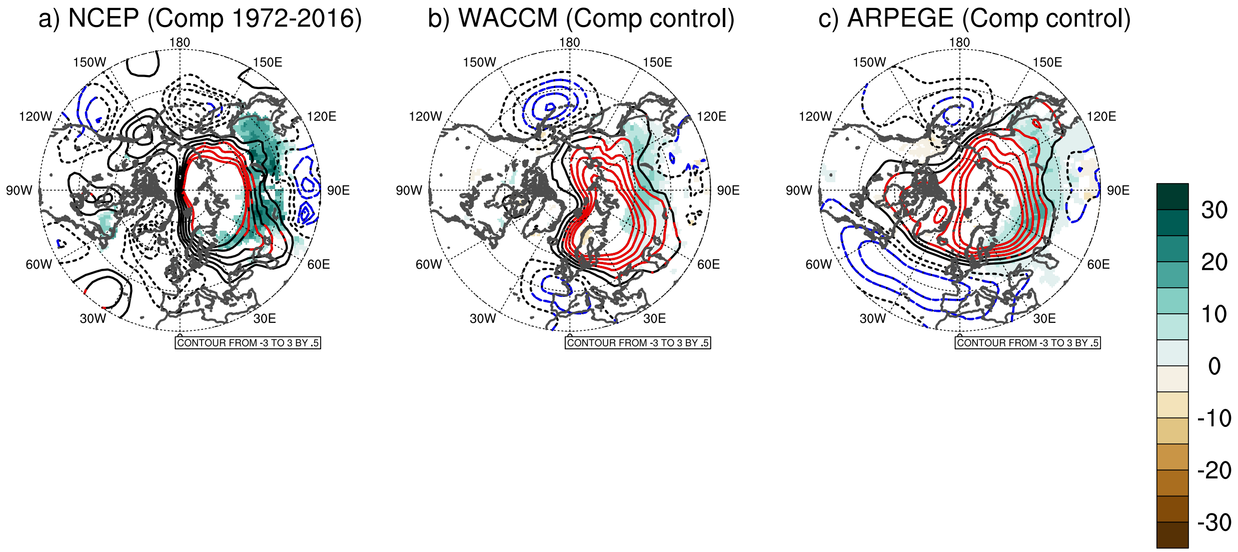
Can Snow Drive Circulation Anomalies?

Observations and models suggest that snow anomalies in fall over Eurasia are linked to wintertime anomalies in the Arctic Oscillation (Cohen & Entekhabi 1999; Cohen et al. 2007).



Henderson et al. 2018

Spontaneous snow-circulation relationships in reanalysis and models, suggests snow anomaly is forced by atmospheric circulation.



Key Points

1. The forced circulation response to sea ice loss includes long-range teleconnections featuring positive and negative feedbacks to the rest of global warming.
   – This likely applies to snow loss and other cryospheric changes as well (Bronselaer et al. 2018).
2. The response to sea ice loss is robust across models but coupled to the tropics.
   – These tropical responses are less robust and more model dependent.
3. Current model experiments are ambiguous in revealing mechanisms for sea ice and snow influence. Such influences require very good sampling.
   – Detecting teleconnected responses in observations is challenging and probably shouldn't be used for benchmarking models.

Recommendations for CLIMA

Models #1: Recognize two-way coupling. To get polar influence on global climate right, get remote influences on polar regions right.

- E.g. monitor how tropical moist-process improvements influence Arctic lapse rate.

Models #2: Go high(er) top. Polar circulation responses are likely influenced by the model stratosphere. Put resources into the stratosphere.

- E.g. DoE E3SM has devoted vertical resolution to both PBL and stratosphere (at a considerable computational cost).

Observations #1: Air-sea-ice fluxes. Better characterize real-world air-sea-ice fluxes of energy and momentum, and build these constraints into cost functions.

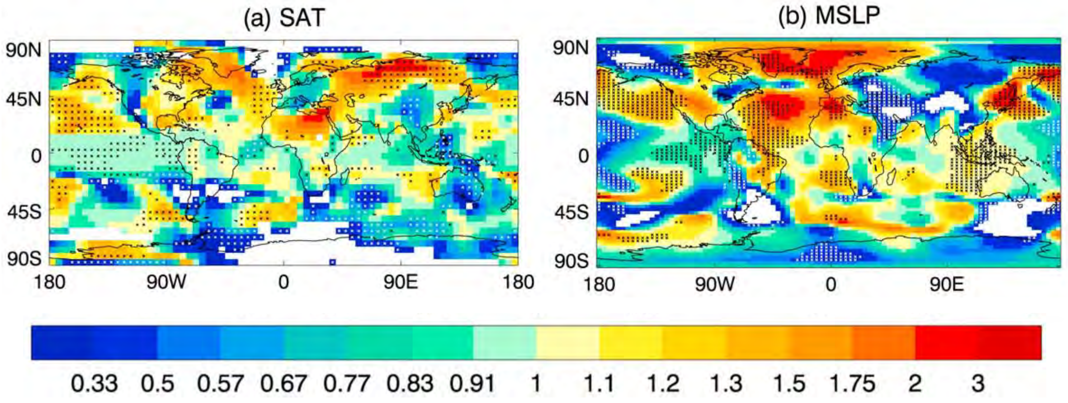
- Circulation impacts will be sensitive to this.

Observations #2: Don’t forget terrestrial snow cover! A huge influence on planetary energy balance, seasonal cycle, agriculture, water resources, and possibly circulation . . . and challenging to constrain observationally.

A Final Question: Are Models Responsive Enough to Snow and Sea Ice?

- Ensemble seasonal prediction in the North Atlantic sector is *better* than you might expect based on internal correlations: the “Signal-to-Noise Paradox”
- Is the model troposphere poorly constrained by ocean heat content, sea ice, snow, stratospheric conditions, etc.? Will improved models change this?

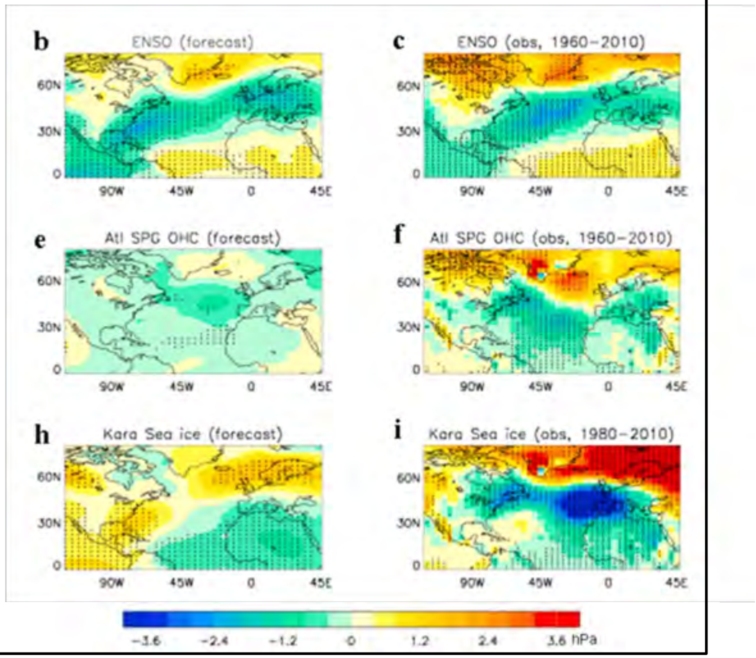
Ratio of predictable components



Models over confident

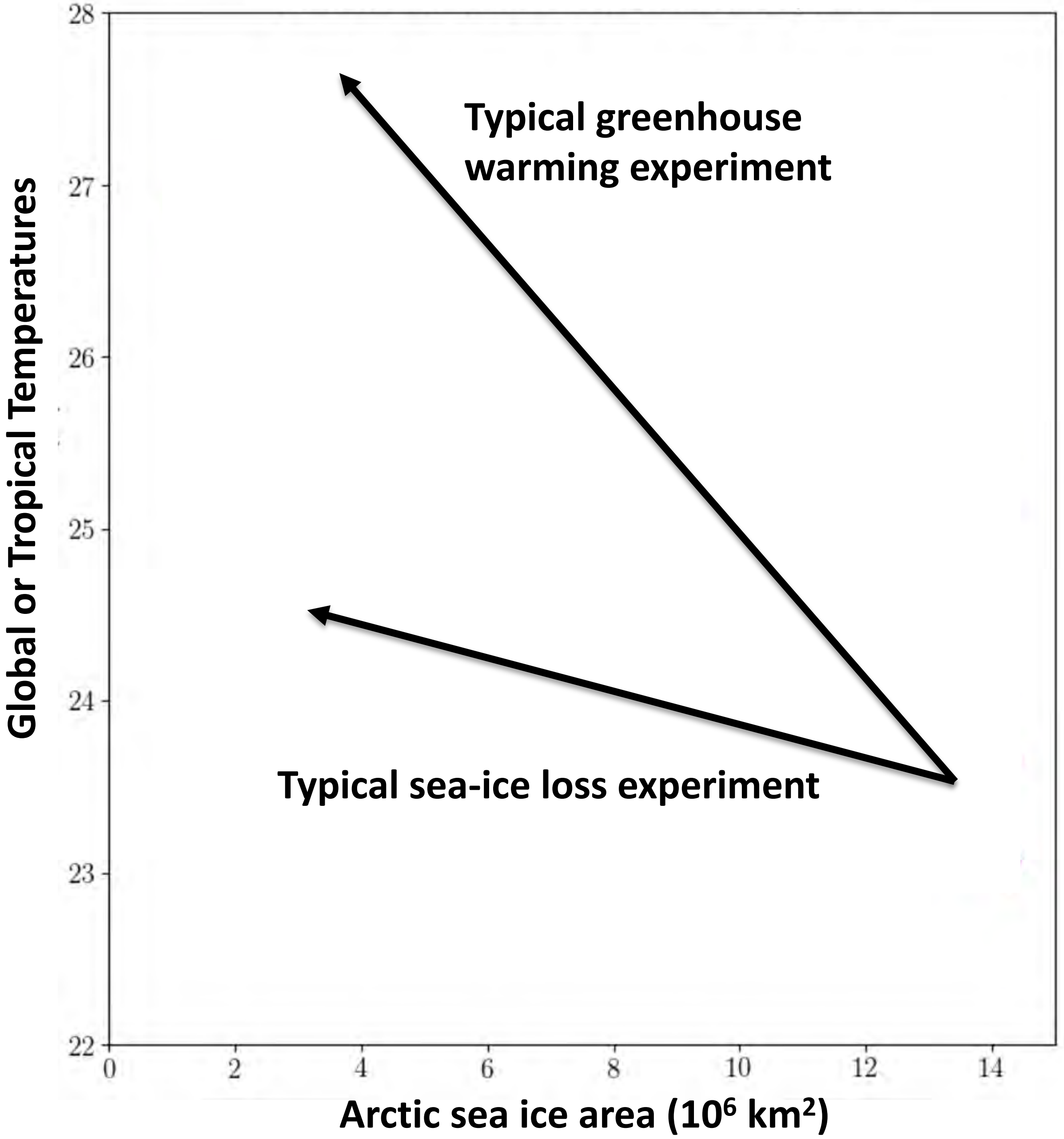
Models under confident

SLP composite anomalies for forecasts (left) and obs (right)



Eade et al. 2014, Scaife et al. 2014

Arctic and Tropical Change Are Coupled



To recap, in forced, well sampled, coupled ocean-atmosphere models:

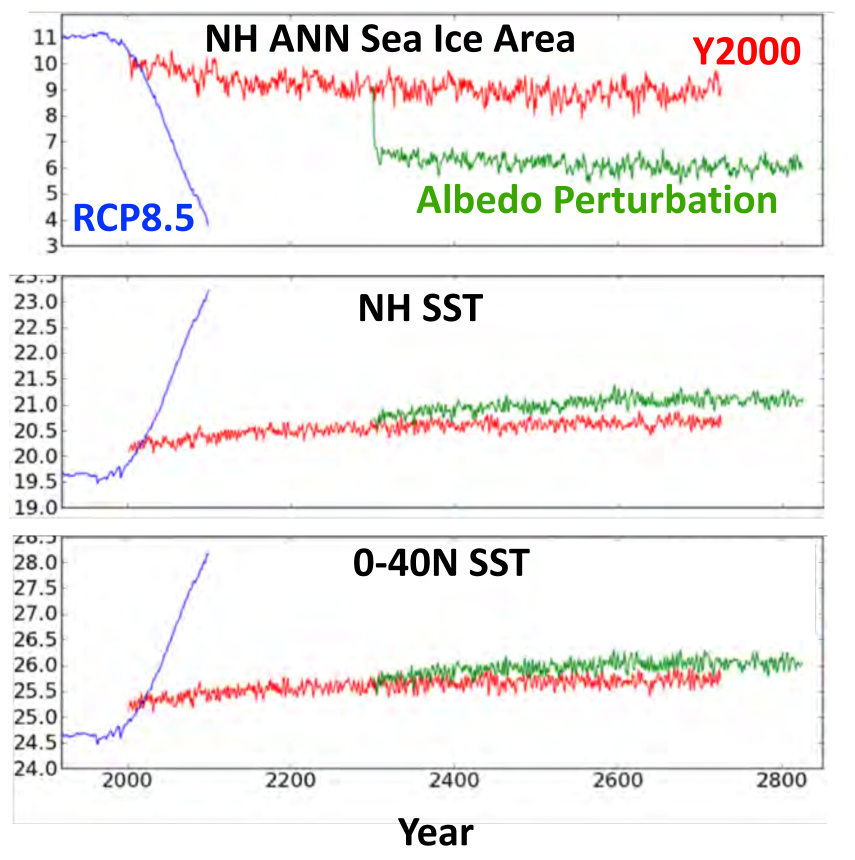
- Global warming drives sea-ice loss.
- Induced sea-ice loss drives 'mini' global warming.

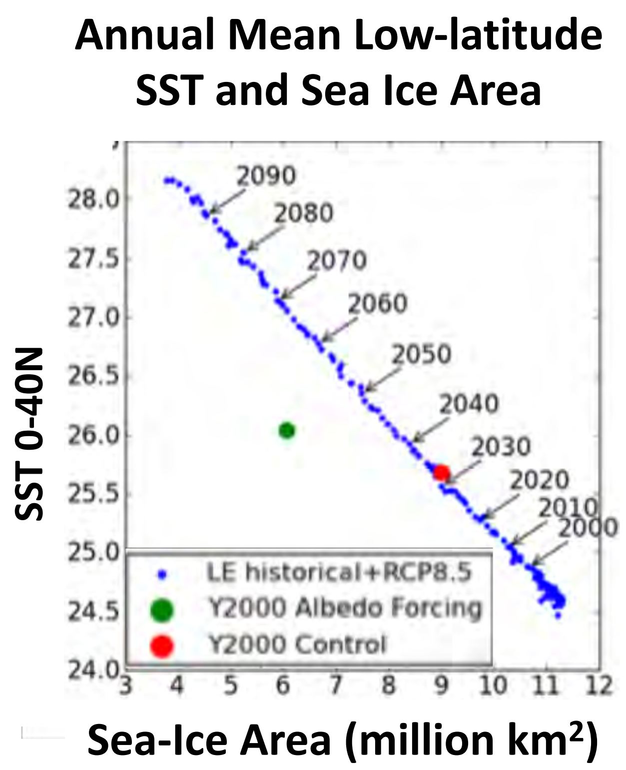
These effects are both at work in explaining Arctic tropospheric warming.

How does this impact other variables that are affected by changes in sea ice and ocean temperatures?

Russell Blackport: Albedo-Forcing Experiments with CESM1-CAM5

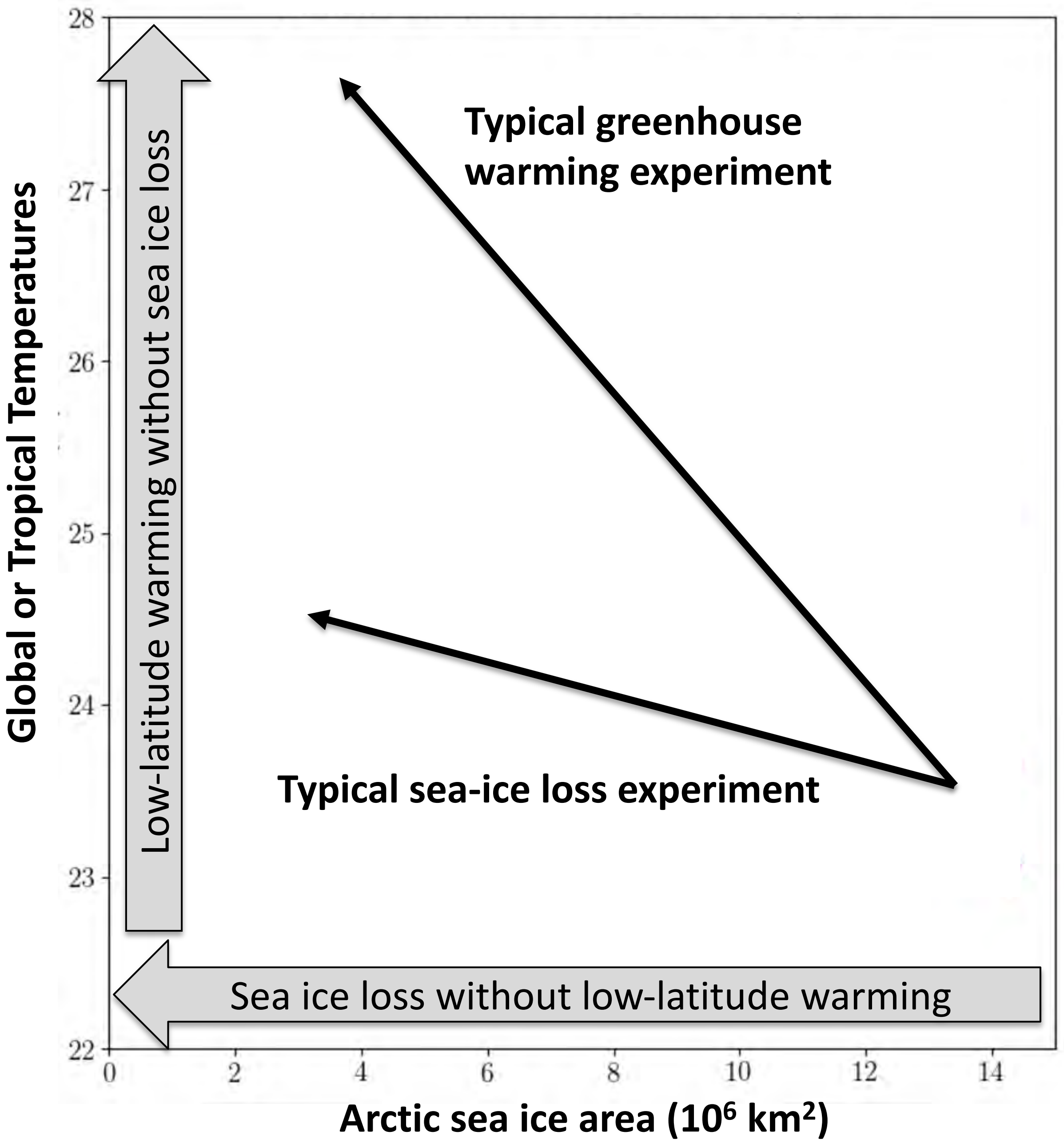
RCP8.5 Forced Experiment (CESM1)	Sea ice albedo forced experiment (CESM1)
• Large Ensemble 1920-2100 (30 members)	• Year 2000 Control (725 y) • Reduced sea ice albedo (525 y)
• A lot of sea ice loss year round.	• A lot of sea ice loss, more sea ice loss in summer.
• More low latitude warming.	• Less low latitude warming





Blackport and Kushner 2017

Can We Decouple Arctic and Tropical Change?



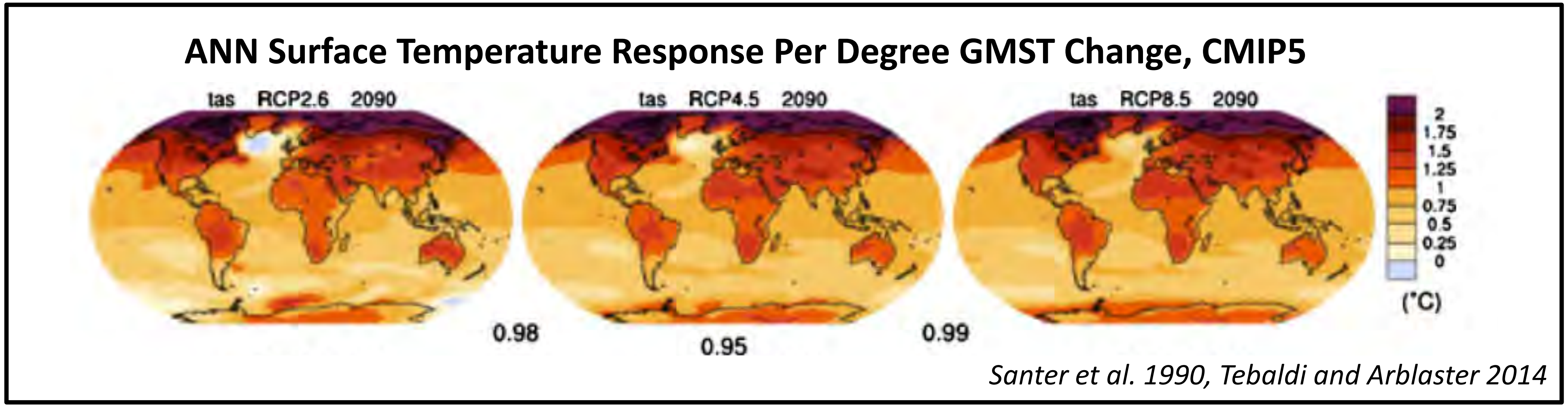
To disentangle the impacts of Arctic amplification and tropical warming, we developed a two-parameter pattern scaling technique (Blackport and Kushner 2017; Hay et al. 2018 and in prep.)

Conceptually, we look at sea ice and global or tropical temperatures as internal forcing (boundary forcing).

- Distinguish attribution to internal forcing from attribution to external forcing – C. Bonfils pers. comm.

What Is Pattern Scaling?

Classical pattern scaling assumes that the change in the long-term mean of a field Z, like surface temperature, precipitation, etc. scales with global mean surface temperature T_G



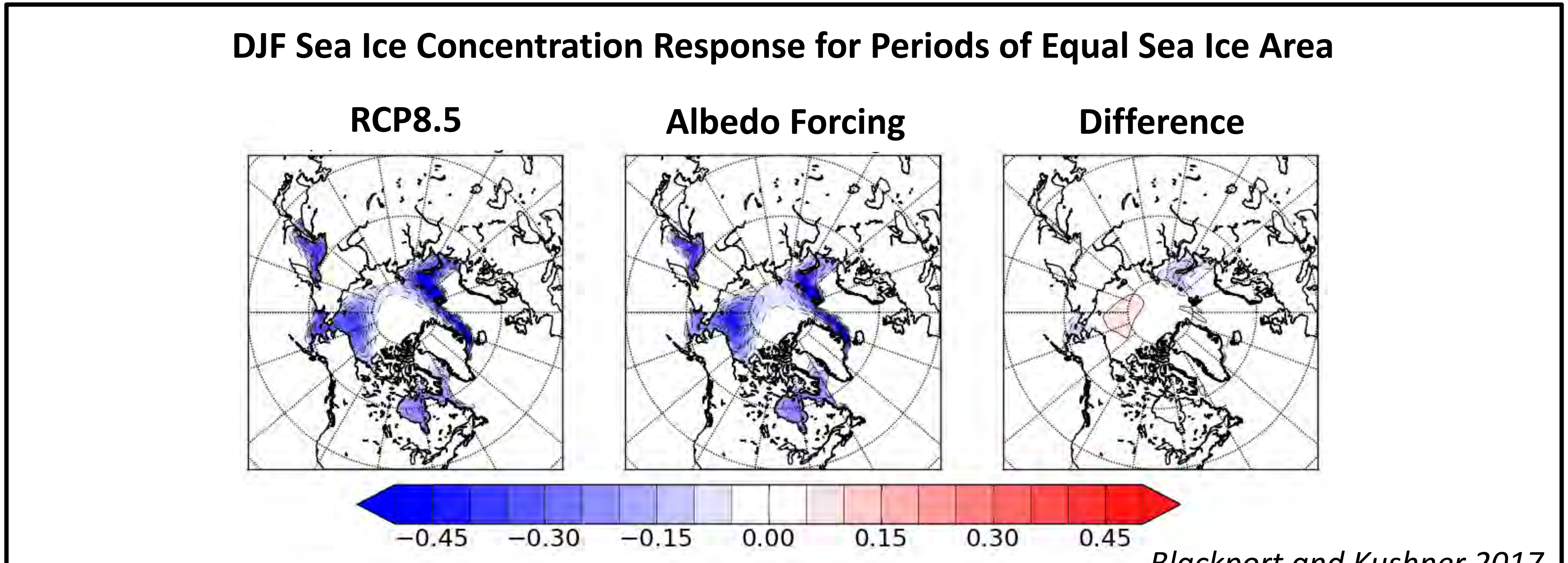
Santer et al. 1990, Tebaldi and Arblaster 2014

At each spatial point, assume the long-time statistics are controlled by GMT: $Z = Z(T_G)$, independently of what controls T_G. Then for a small change in T_G

The response pattern $\partial Z/\partial T_G$ is often independent of forcing scenario and other details.

$$\delta Z = Z(T_G + \delta T_G) - Z(T_G) \approx \frac{\partial Z}{\partial T_G}\delta T_G$$

How Can We Extend Pattern Scaling?



Blackport and Kushner 2017

The pattern of sea ice loss is similar for realistic anthropogenic forcing or 'fake' sea ice changes. Sea ice area is also a good scaling parameter, like temperature.

Let's explore the assumption that responses scale **separately** with 1) low latitude temperature and 2) sea ice area.

Let's Extend Pattern Scaling to More Internally Forced Variables

How does Z depend on sea ice area (I) and low-latitude temperature (T)?

$$Z = Z(T, I)$$

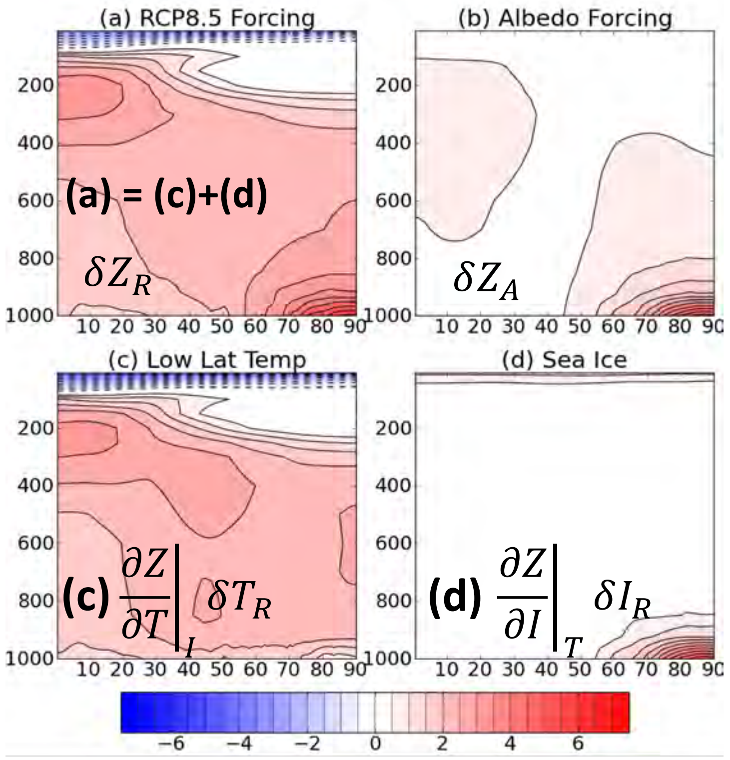
$$\delta Z = Z(T + \delta T, I + \delta I) - Z(T, I)$$

RCP8.5 forcing $$\delta Z_R \cong \left.\frac{\partial Z}{\partial T}\right|_I \delta T_R + \left.\frac{\partial Z}{\partial I}\right|_T \delta I_R$$

Albedo forcing $$\delta Z_A \cong \left.\frac{\partial Z}{\partial T}\right|_I \delta T_A + \left.\frac{\partial Z}{\partial I}\right|_T \delta I_A$$

$$\boxed{\begin{pmatrix} \left.\frac{\partial Z}{\partial T}\right|_I \\ \left.\frac{\partial Z}{\partial I}\right|_T \end{pmatrix} = \begin{pmatrix} \delta T_R & \delta I_R \\ \delta T_A & \delta I_A \end{pmatrix}^{-1} \begin{pmatrix} \delta Z_R \\ \delta Z_A \end{pmatrix}}$$

Zonal Mean ANN Temperature Response



Blackport and Kushner 2017

By this construction, Arctic tropospheric warming, even when caused by sea ice loss, arises in response to tropical and midlatitude changes.

Let's Extend Pattern Scaling to More Internally Forced Variables

How does Z depend on sea ice area (I) and low-latitude temperature (T)?

$$Z = Z(T, I)$$

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Albedo forcing $\delta Z_A \cong \left.\frac{\partial Z}{\partial T}\right|_I \delta T_A + \left.\frac{\partial Z}{\partial I}\right|_T \delta I_A$

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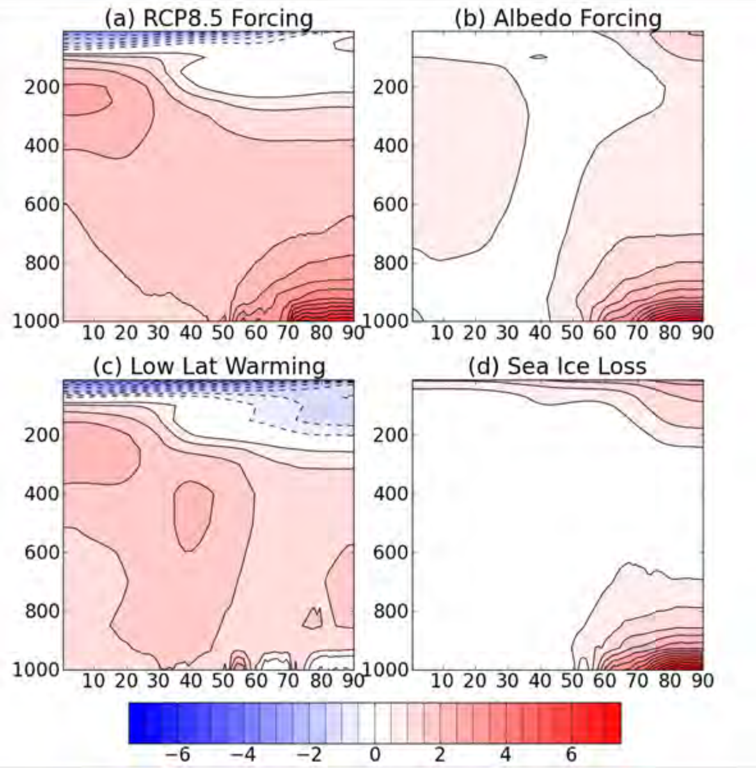
Zonal Mean DJF Temperature Response



Blackport and Kushner 2017

We can derive the sensitivities for other seasons, using seasonal output to calculate

$$\begin{pmatrix} \delta T_R & \delta I_R \\ \delta T_A & \delta I_A \end{pmatrix}$$

In boreal winter, sea ice loss and low latitude warming contribute to tropospheric warming.

Let's Extend Pattern Scaling to More Internally Forced Variables

How does Z depend on sea ice area (I) and low-latitude temperature (T)?

$$Z = Z(T, I)$$

$$\delta Z = Z(T + \delta T, I + \delta I) - Z(T, I)$$

RCP8.5 forcing $$\delta Z_R \cong \left.\frac{\partial Z}{\partial T}\right|_I \delta T_R + \left.\frac{\partial Z}{\partial I}\right|_T \delta I_R$$

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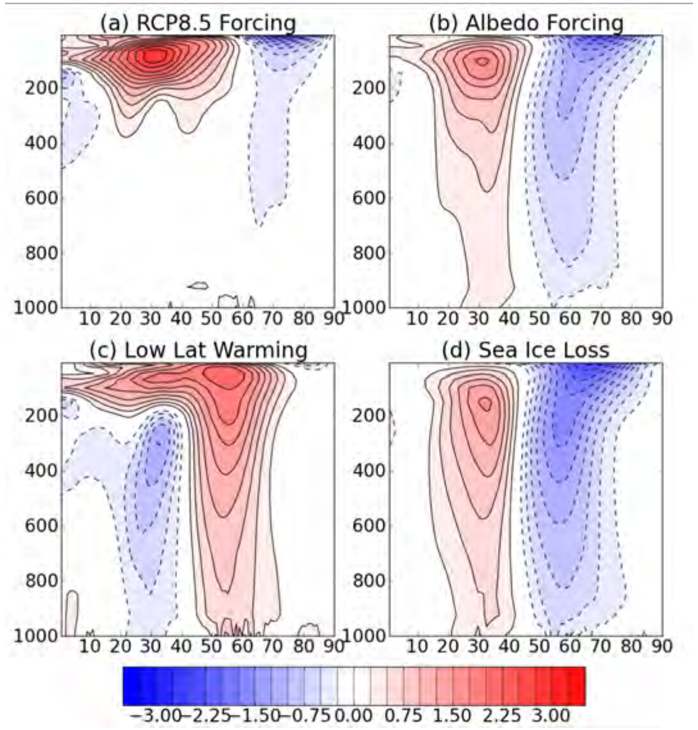
$$\boxed{\begin{pmatrix} \left.\frac{\partial Z}{\partial T}\right|_I \\ \left.\frac{\partial Z}{\partial I}\right|_T \end{pmatrix} = \begin{pmatrix} \delta T_R & \delta I_R \\ \delta T_A & \delta I_A \end{pmatrix}^{-1} \begin{pmatrix} \delta Z_R \\ \delta Z_A \end{pmatrix}}$$

Zonal Mean DJF Zonal Wind Response



Blackport and Kushner 2017

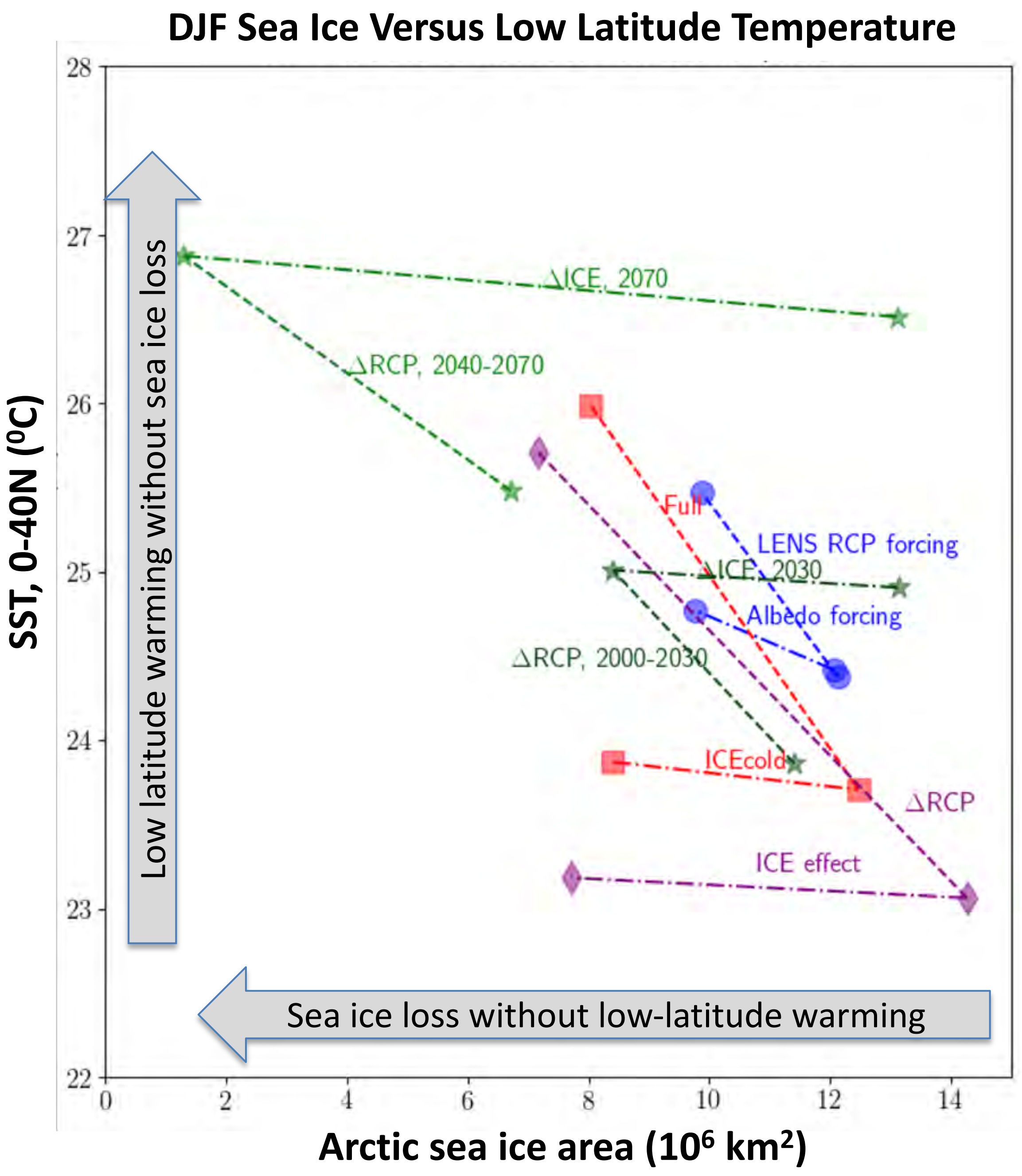
We can calculate these sensitivities for dynamical fields.

This construction highlights the 'tug of war' in the jet stream between tropical and Arctic warming impacts (Held, 1993; Harvey et al. 2014; Barnes & Polvani 2015).

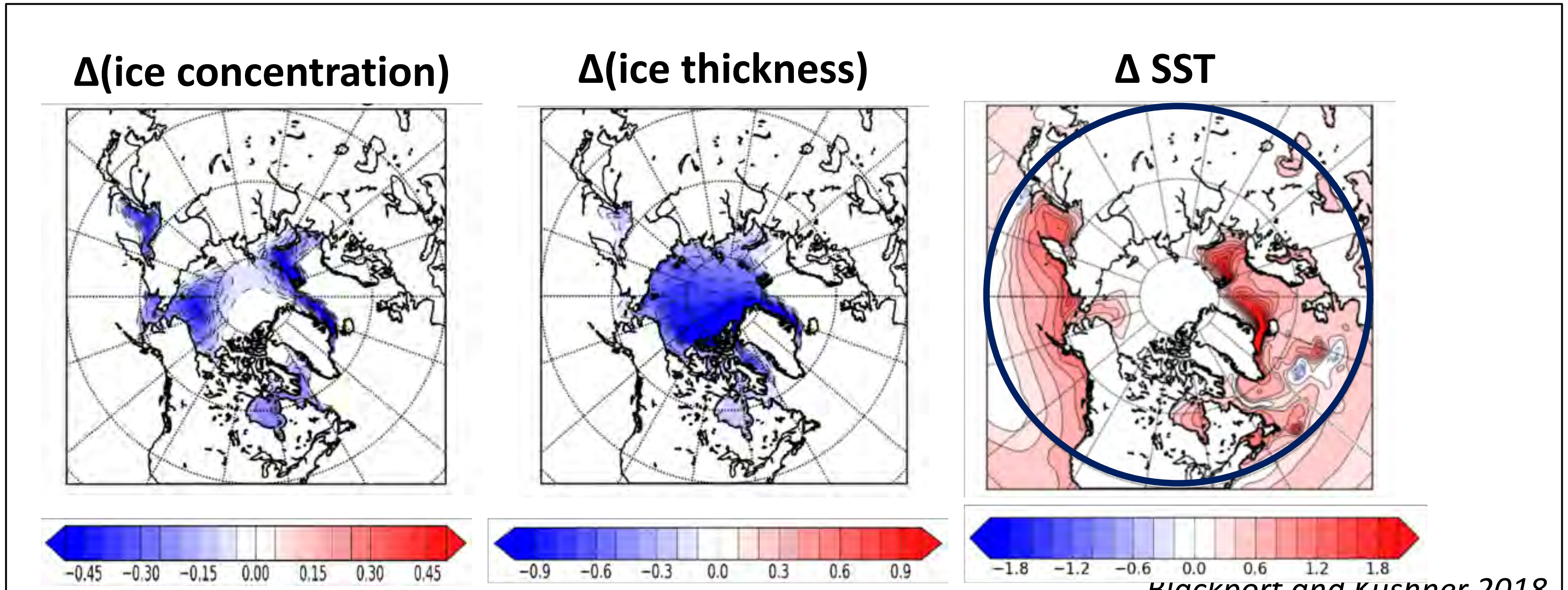
We estimate the circulation response to sea ice loss, controlling for low latitude warming.

We use *pattern scaling*, accounting for the two parameters of Arctic ice area and low latitude SSTs.

We are trying to understand the response to sea-ice loss without lower latitude warming, and vice versa.



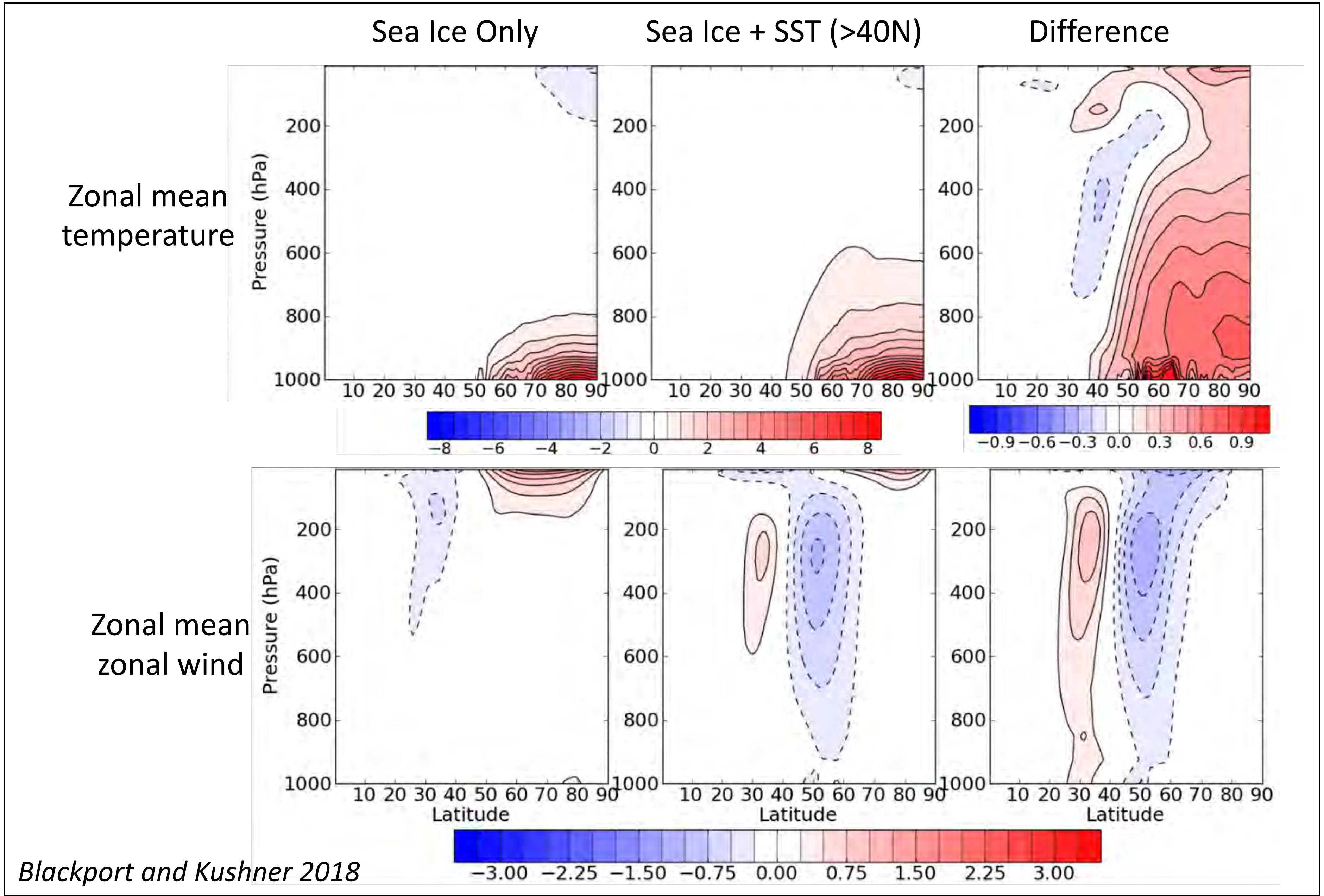
Why Does Polar Warming Amplify with Ocean Coupling?



Blackport and Kushner 2018

- Shown are the DJF ice-loss and SST warming patterns from Russell's sea ice loss simulations.
- We test the impact of midlatitude SST warming on the Arctic troposphere using AGCM CAM5.

Response to Sea Ice and SST Forcing, AGCM CAM5



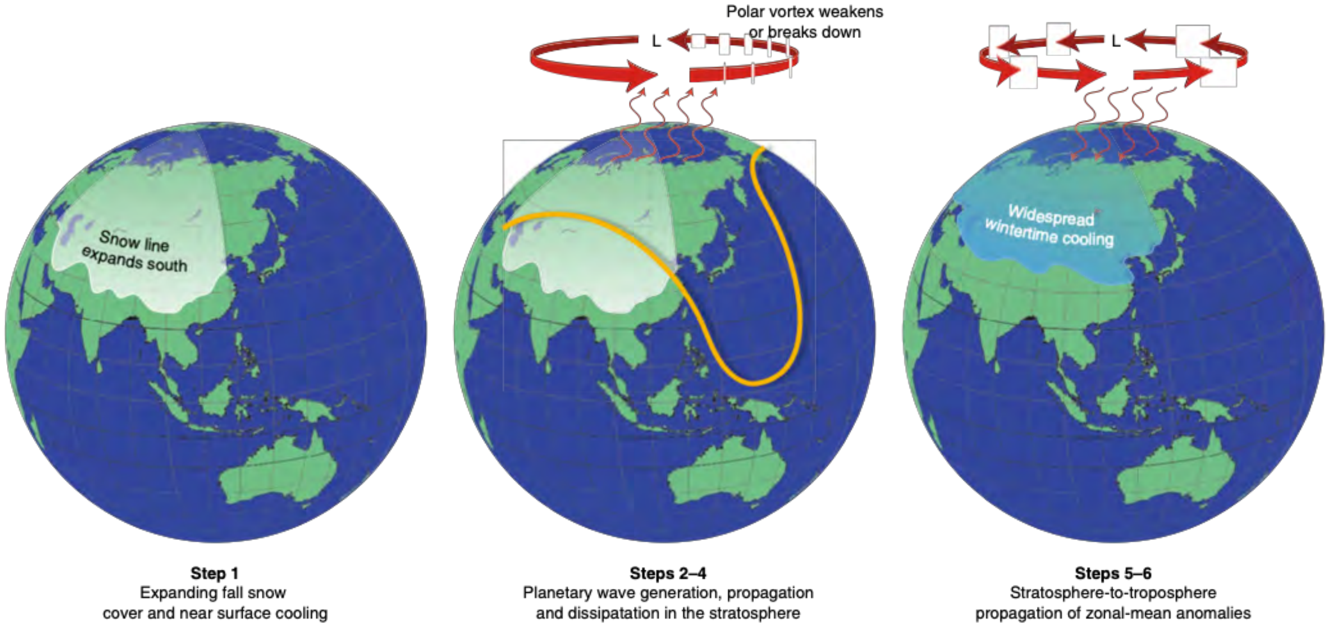
Blackport and Kushner 2018

Adjusted SSTs in midlatitudes heat the Arctic troposphere and shift winds equatorwards.

Causal influence in these experiments is, however, ambiguous (imposed midlatitude SST anomalies).

Can Snow Drive Circulation Anomalies?

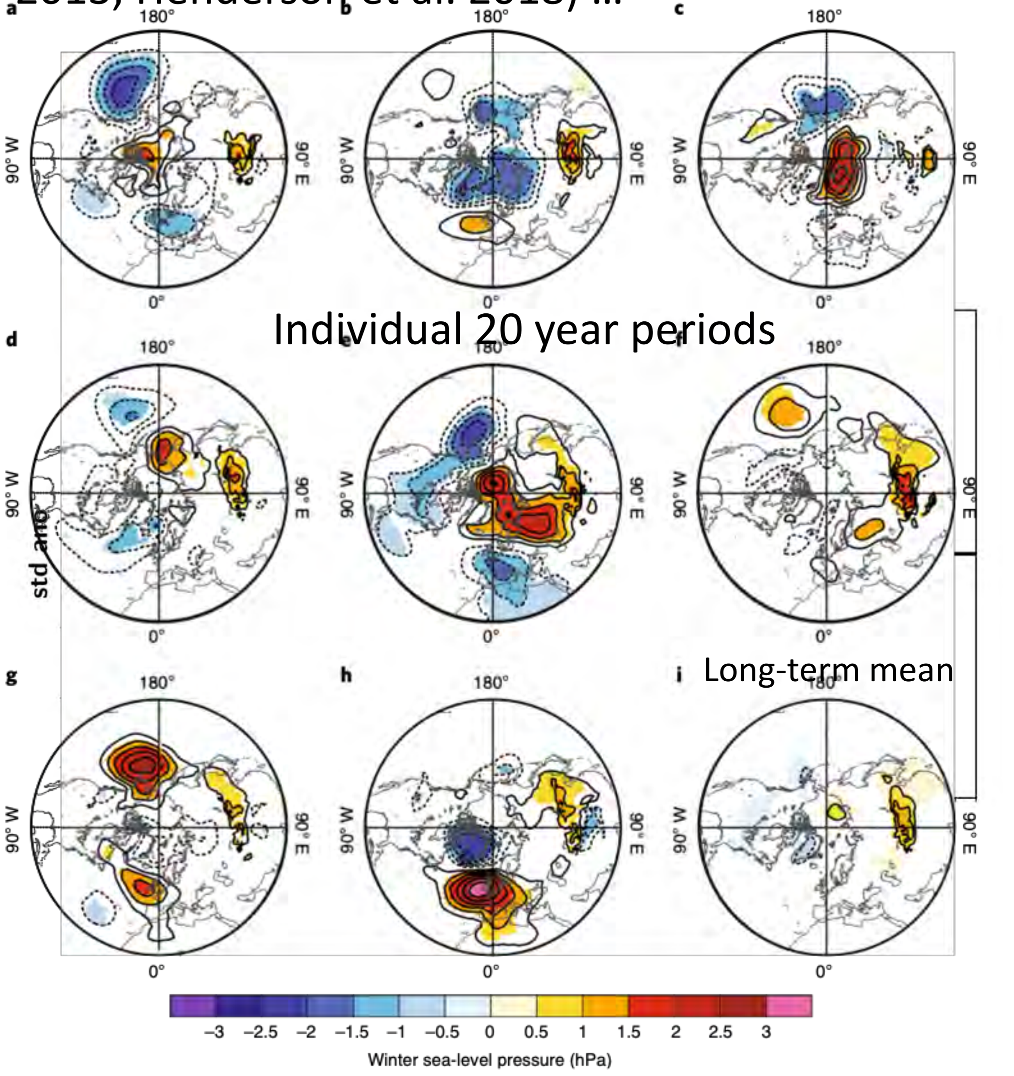
Observations and models suggest that snow anomalies in fall over Eurasia are linked to wintertime anomalies in the Arctic Oscillation (Cohen & Entekhabi 1999; Cohen et al. 2007).



Henderson et al. 2018

But the relationship is not stationary (Peings et al. 2013, Henderson et al. 2018) …

And statistical signal to noise is quite weak.



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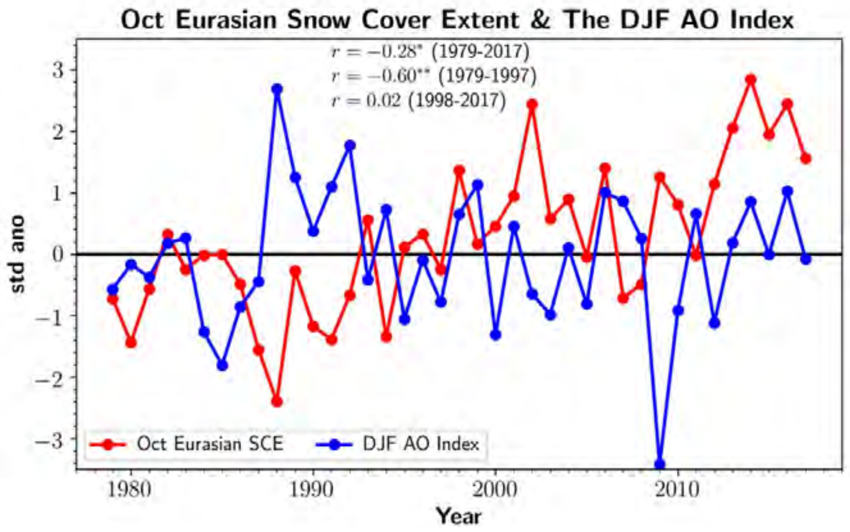
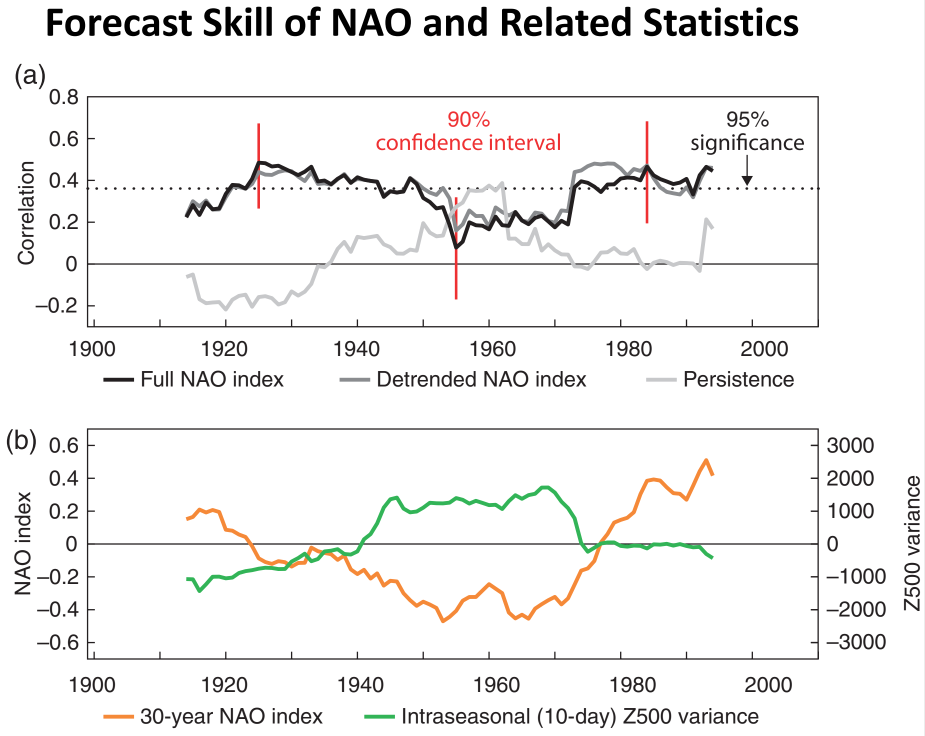
Are Observed Relationships Stationary?

- Empirical connections between snow/sea ice and circulation can be non-robust.
- There is evidence that seasonal and longer timescale NAO predictability is state dependent.

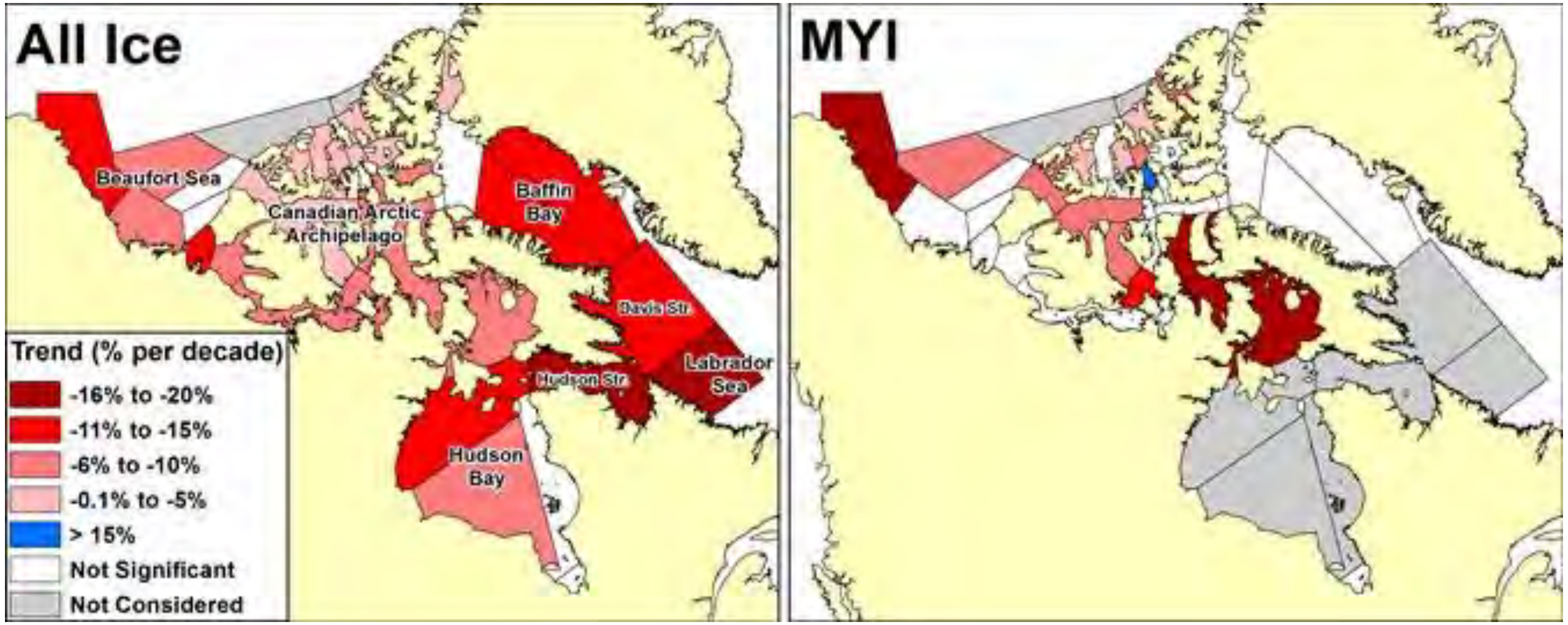


Henderson et al. 2018, Peings et al. 2013



Weisheimer et al. 2017

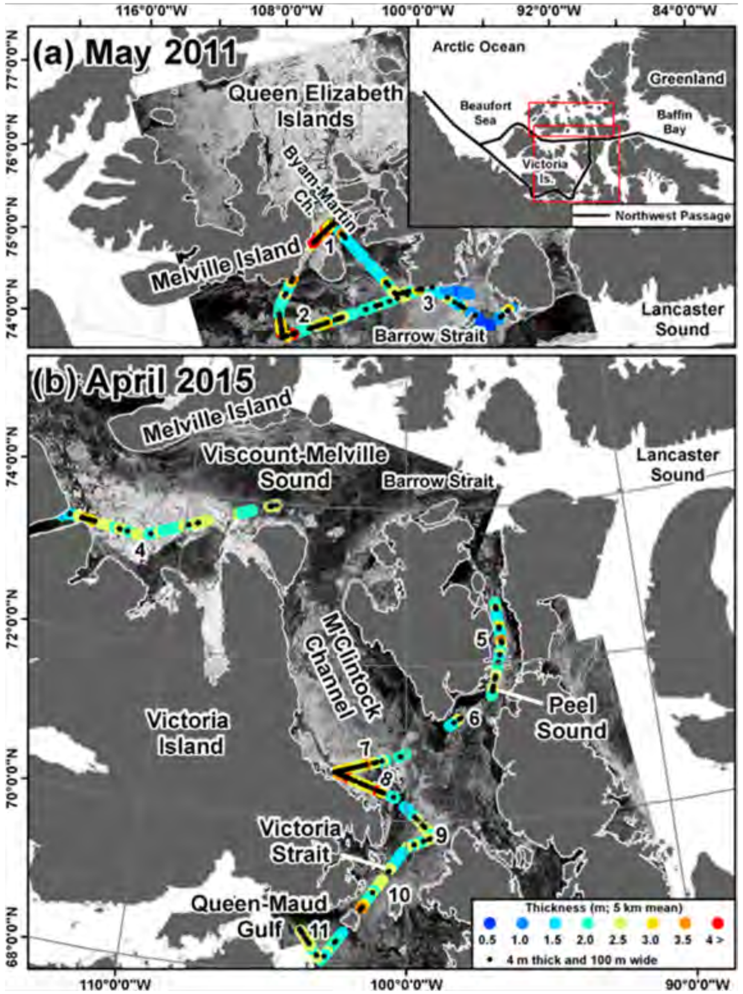
Recent changes in September Sea Ice from Ice Charts



1968-2016 (Updated from Tivy et al. 2011)

Mudryk et al. 2018, Slide from S. Howell

Ice thickness in the Northwest Passage



Haas and Howell, 2015, GRL

- First ever airborne electromagnetic induction (AEM) ice thickness surveys over the Northwest Passage carried out in April and May 2011 and 2015
- Even in today's climate ice is still very thick (3-4 m) and potentially hazardous
- Thick ice features more than 100 m wide and thicker than 4 m occurred frequently