The influence of Arctic warming on the midlatitude jet-stream:

Can it? Has it? Will it?

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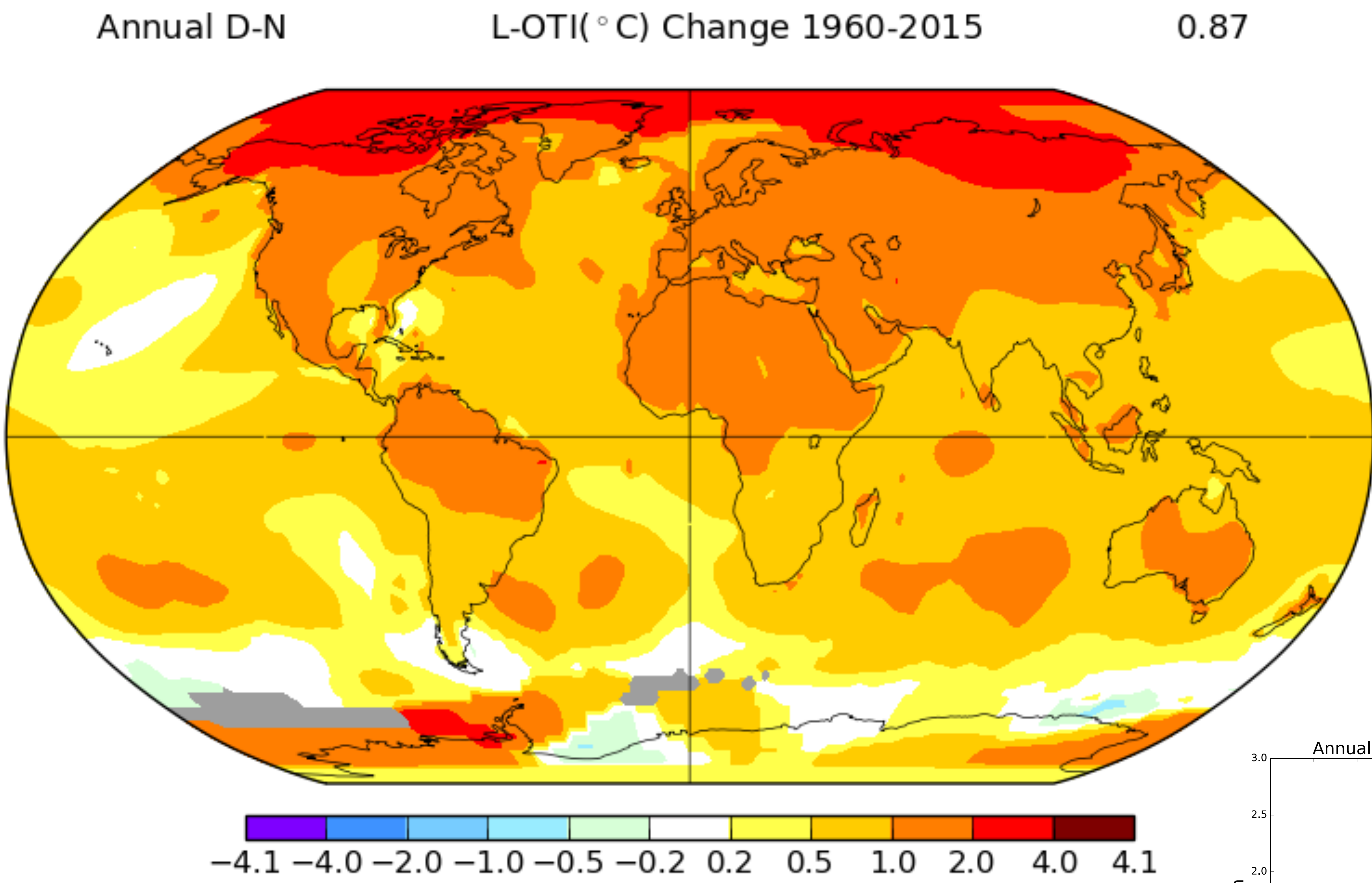
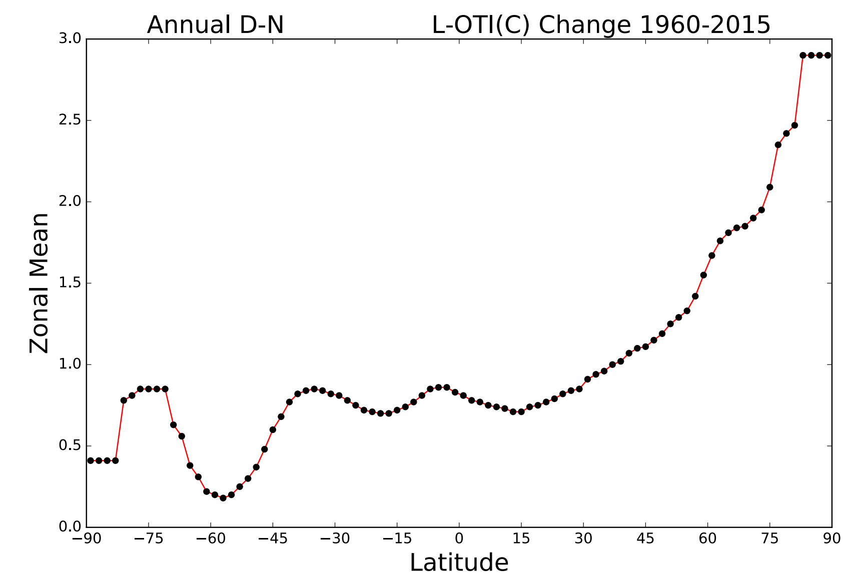
with much help and input from my collaborators:

Marie McGraw, CSU
James Screen, U. of Exeter
Lorenzo Polvani, Columbia U.
Etienne Dunn-Sigouin, Columbia U.
Giacomo Masato, U. of Reading
Tim Woollings, Oxford

The Arctic is warming and sea ice is melting





NASA GISS: GISTEMP

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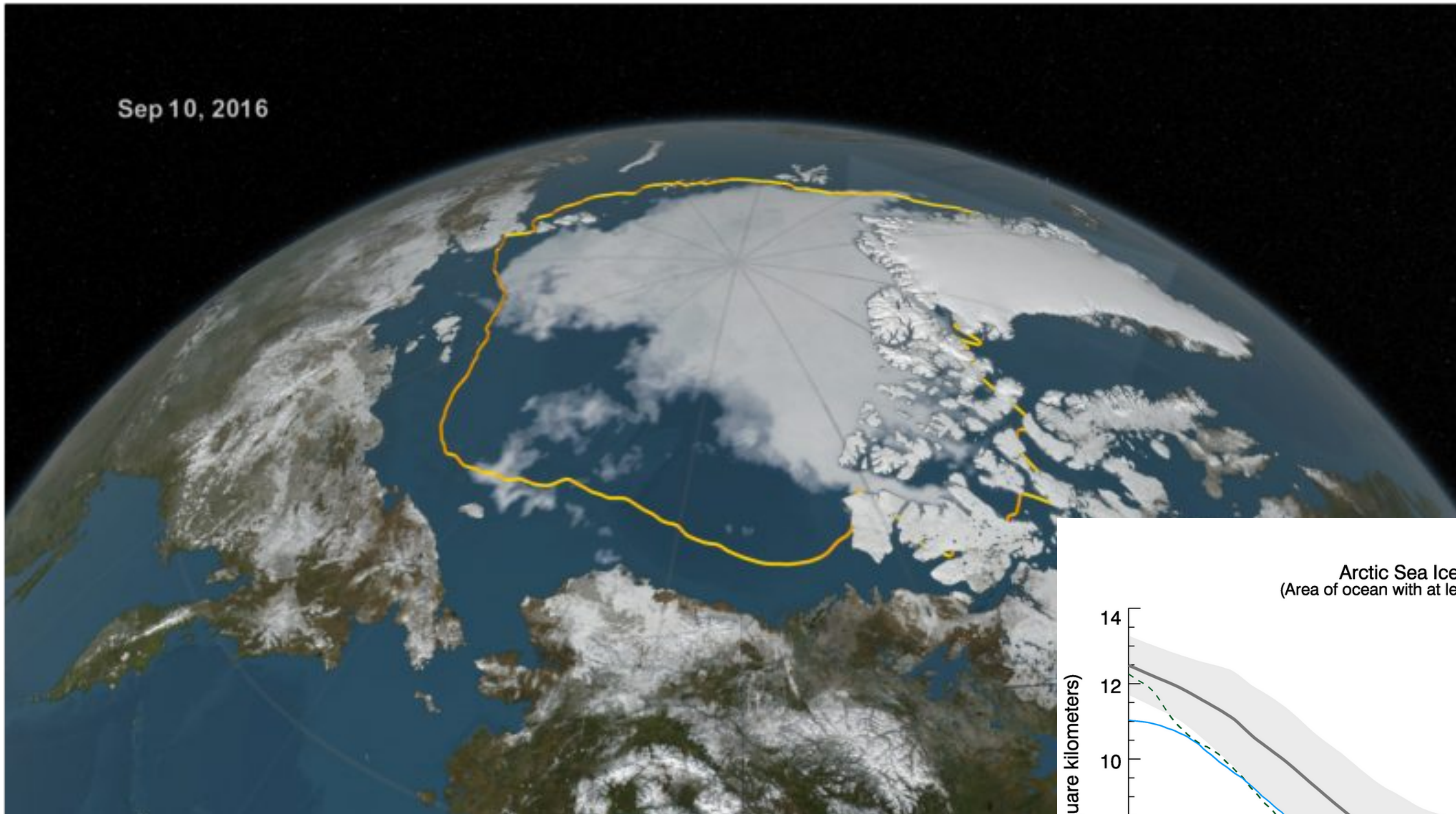
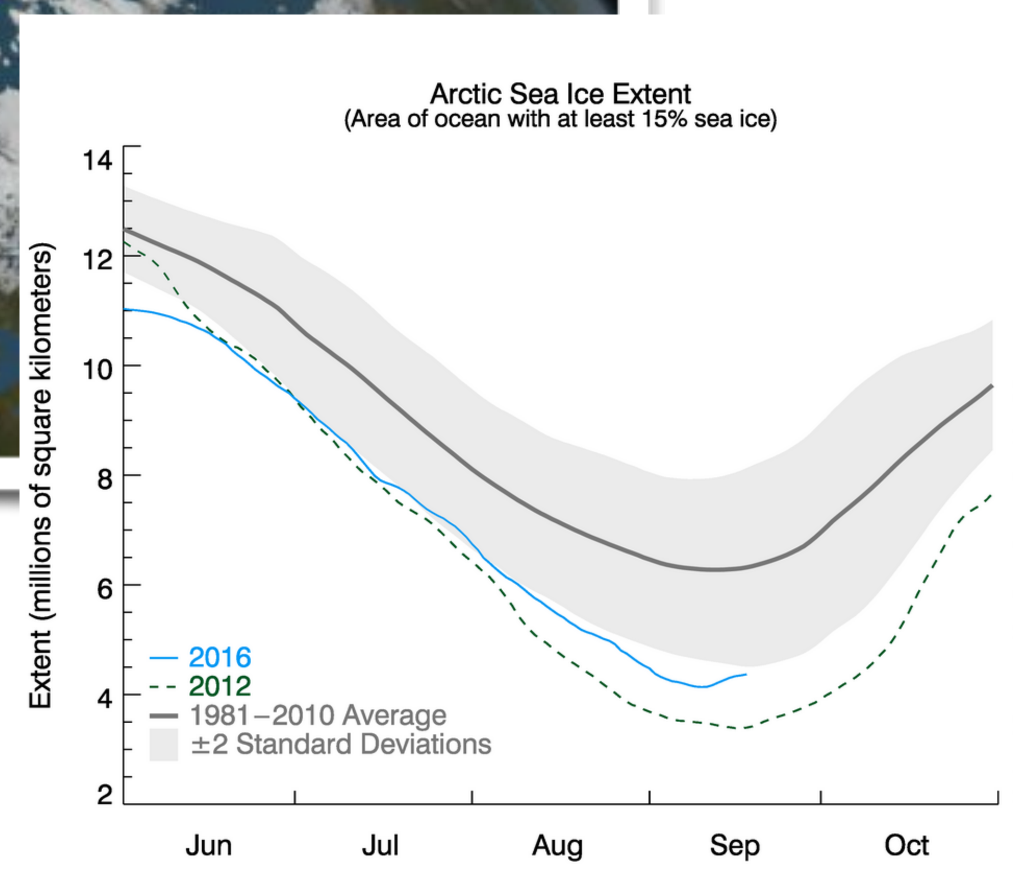
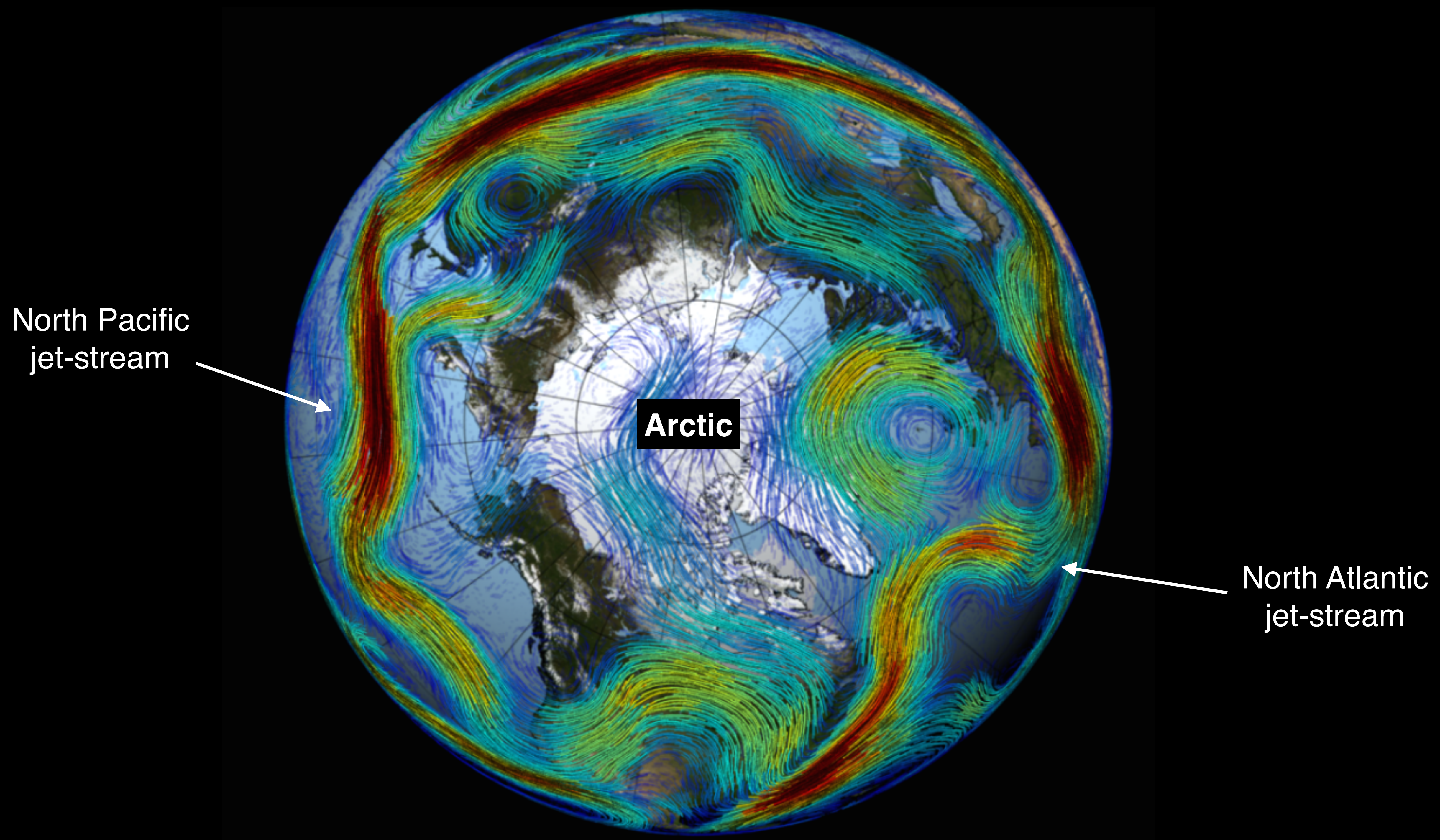


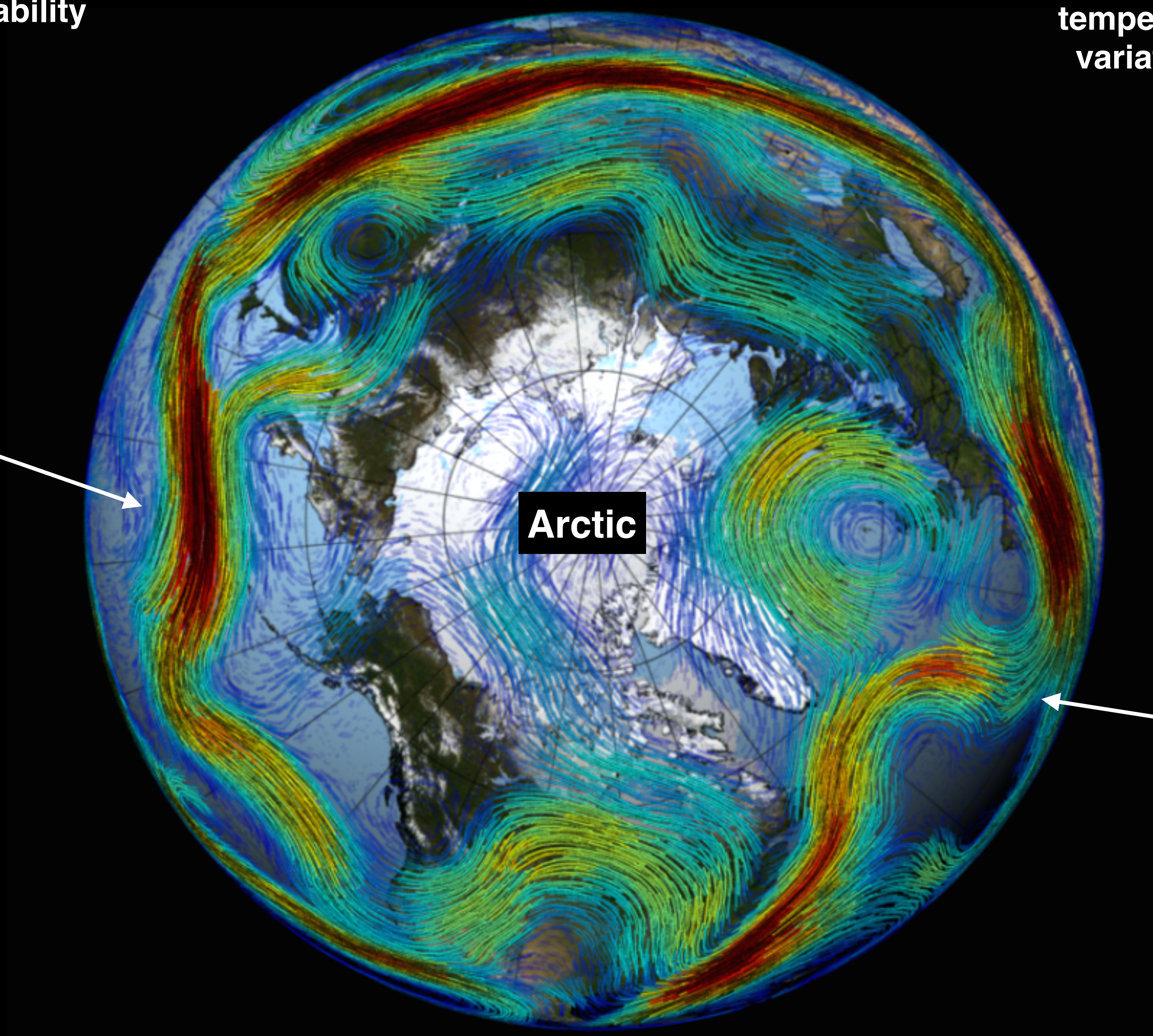


2016 is the second lowest sea ice minimum on record

NSIDC



NASA/Goddard Space Flight Center Scientific Visualization Studio



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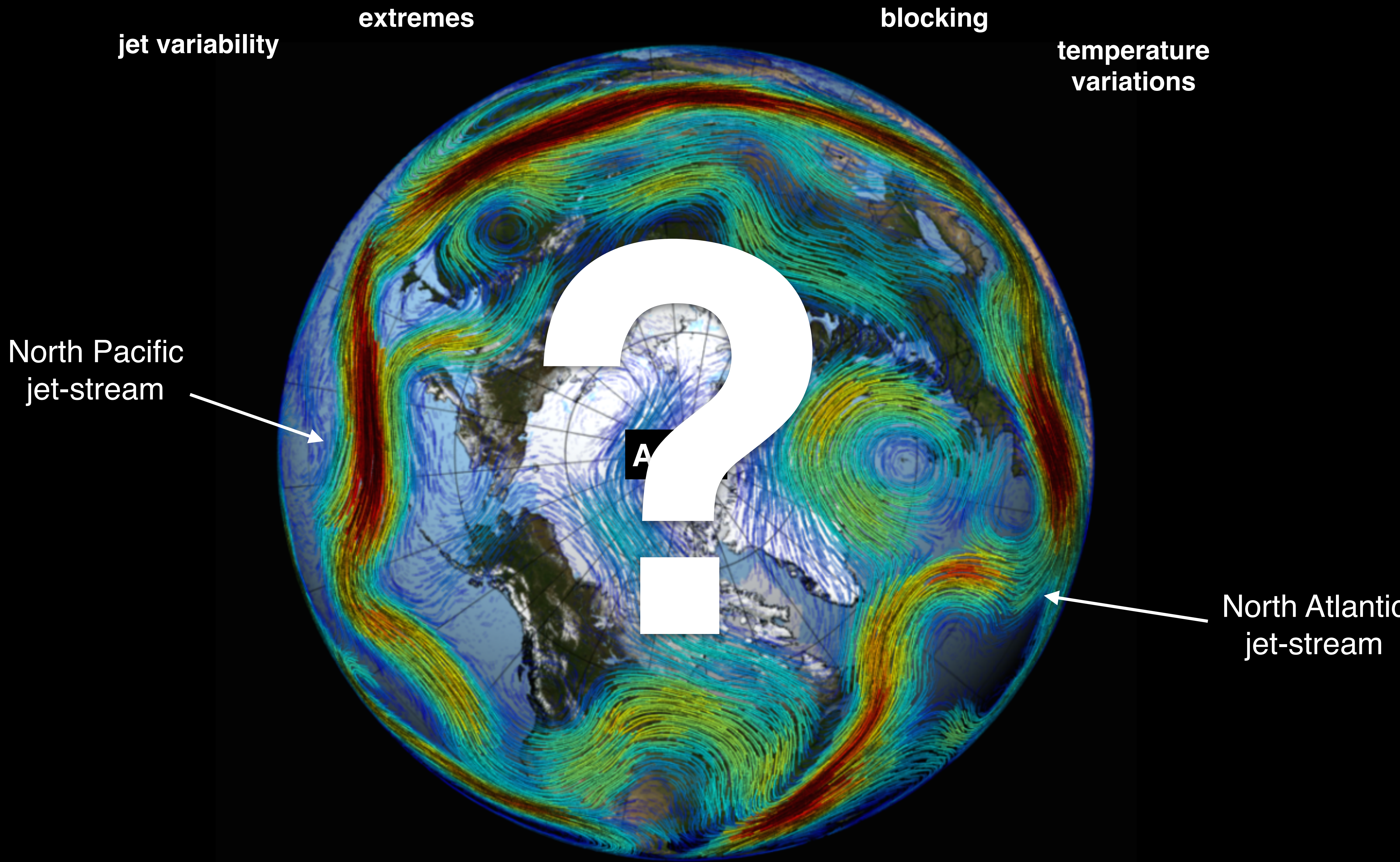

NASA/Goddard Space Flight Center Scientific Visualization Studio

3 distinct questions

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(1) **Can** Arctic warming influence the midlatitude jetstream?

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(2) **Has** Arctic warming significantly influenced the midlatitude jetstream?

3 distinct questions

(1) **Can** Arctic warming influence the midlatitude jetstream?

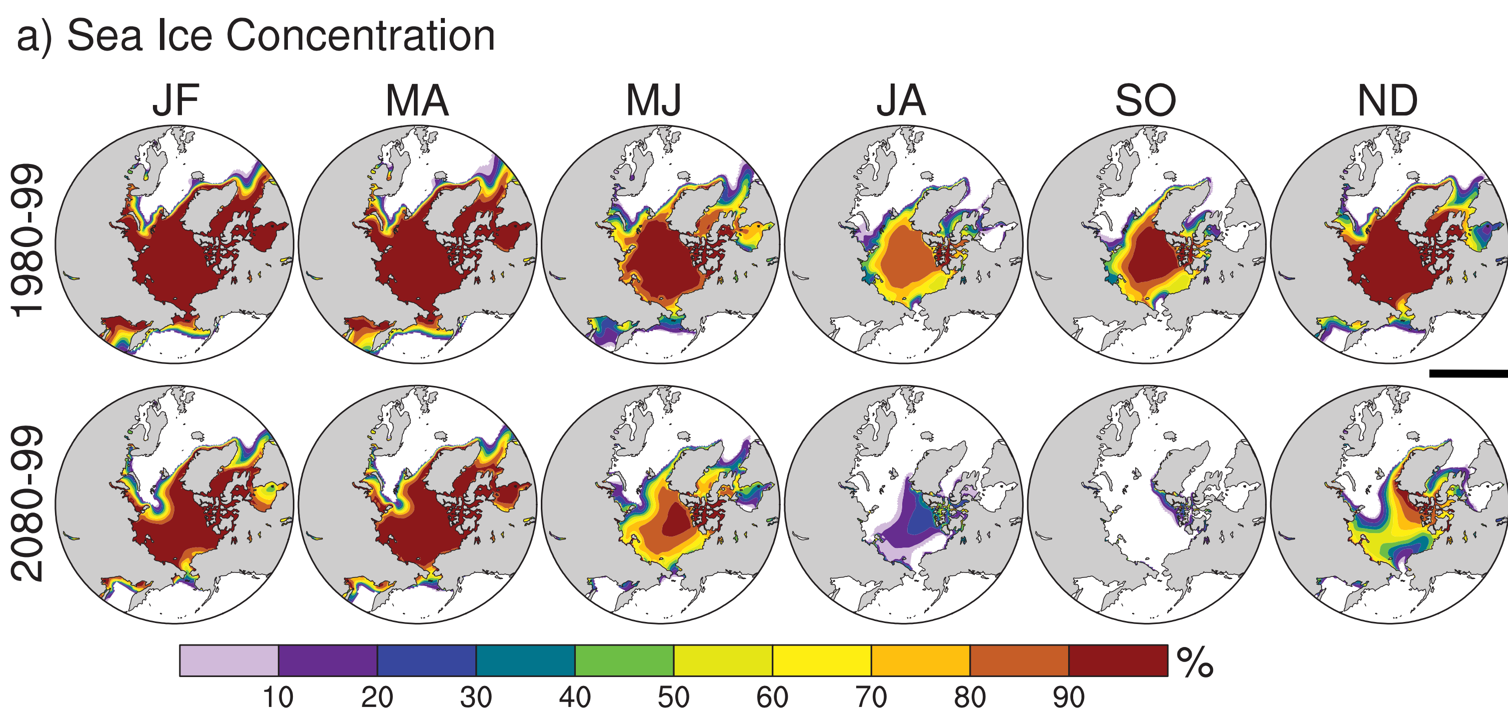
(2) **Has** Arctic warming significantly influenced the midlatitude jetstream?

(3) **Will** Arctic warming significantly influence the midlatitude jetstream?

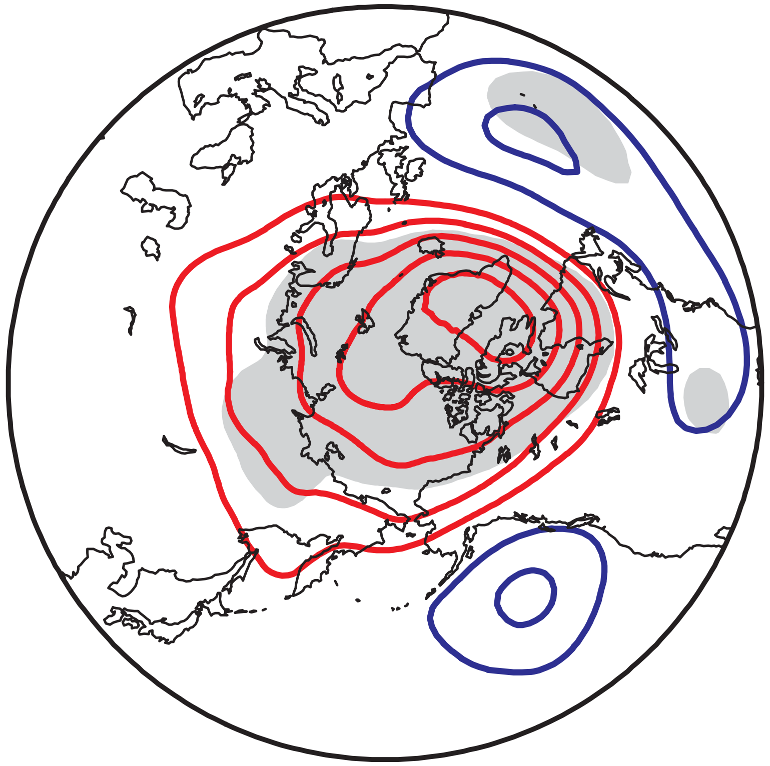
Can Arctic warming influence the midlatitude jetstream?

Model simulations & theory

Modeling evidence



500 hPa geopotential height response in Jan.-Feb.

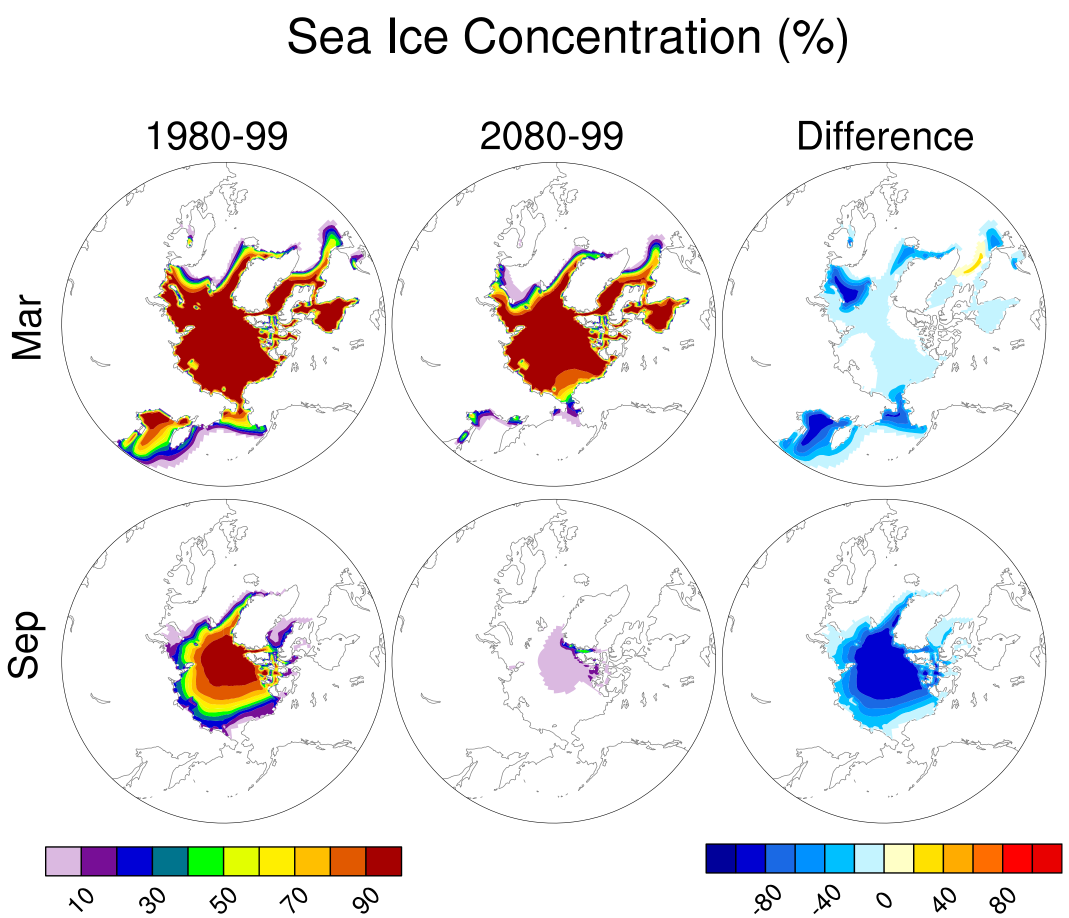


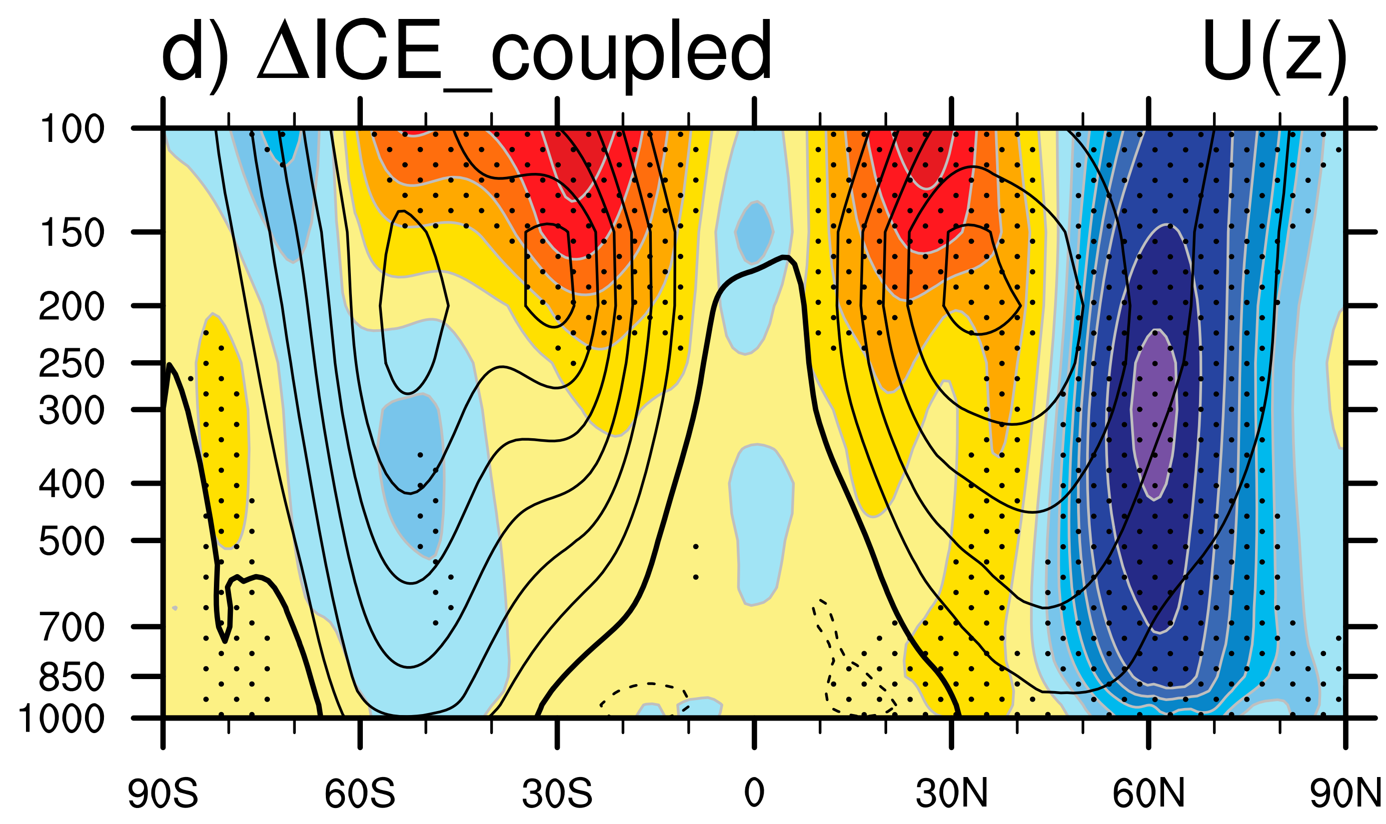
-NAO pattern
(equatorward jet shift)

dozens of atmosphere-only GCM studies have demonstrated that removing Arctic sea ice can influence the midlatitude circulation

atmosphere-only CAM3 simulations
Deser, Tomas, et al. (2010; JCLI)

Modeling evidence



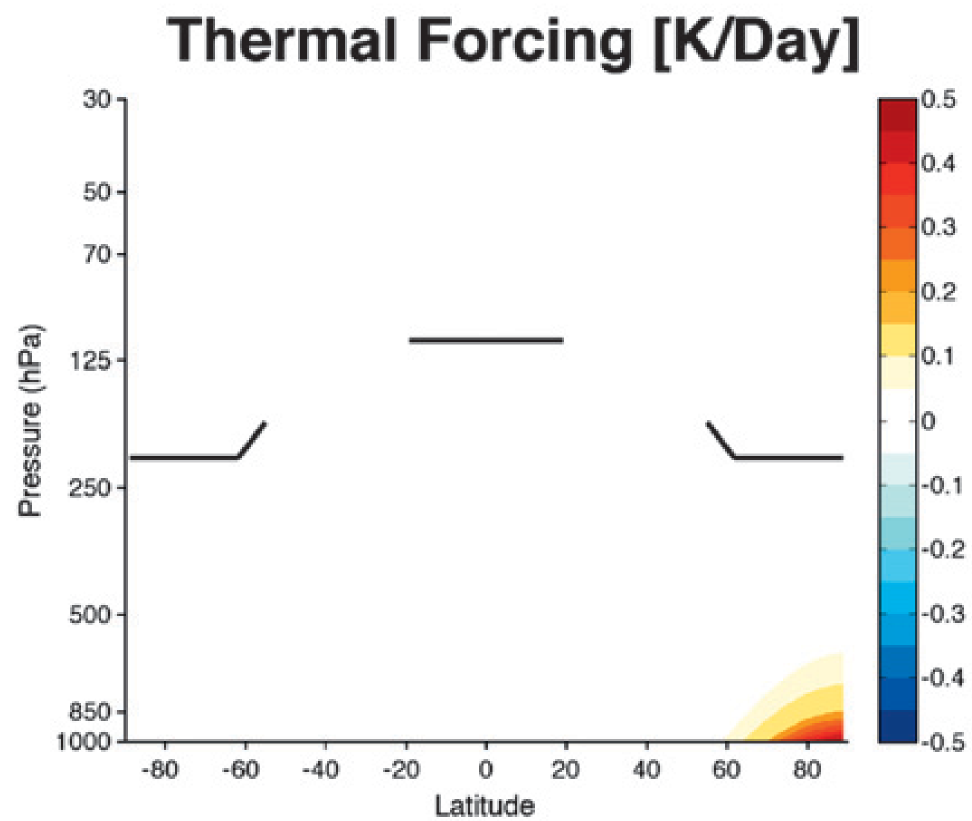


-NAO pattern
(equatorward jet shift)

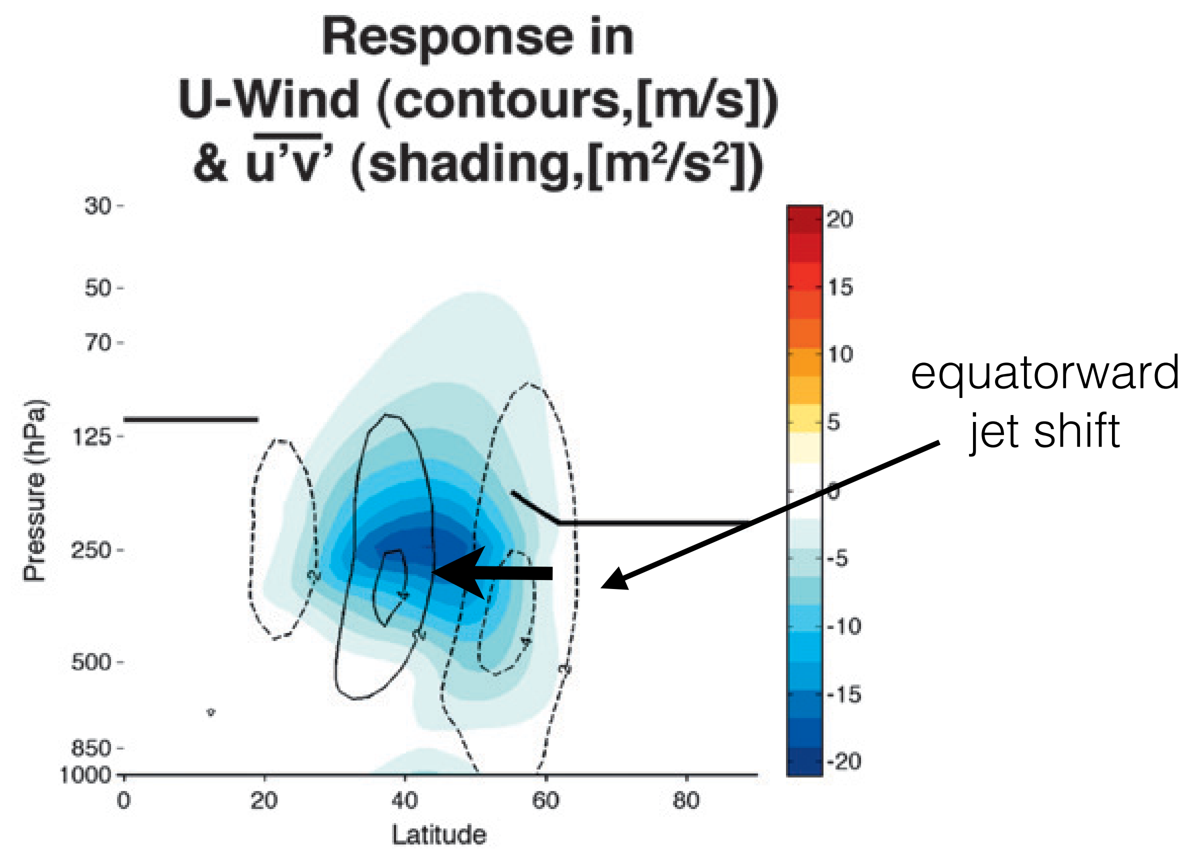
recent coupled GCM experiments also demonstrate a midlatitude response

coupled CCSM4 simulations
with additional long wave radiative fluxes in the ice model
Deser, Tomas, et al. (2015; JCLI)

Modeling evidence



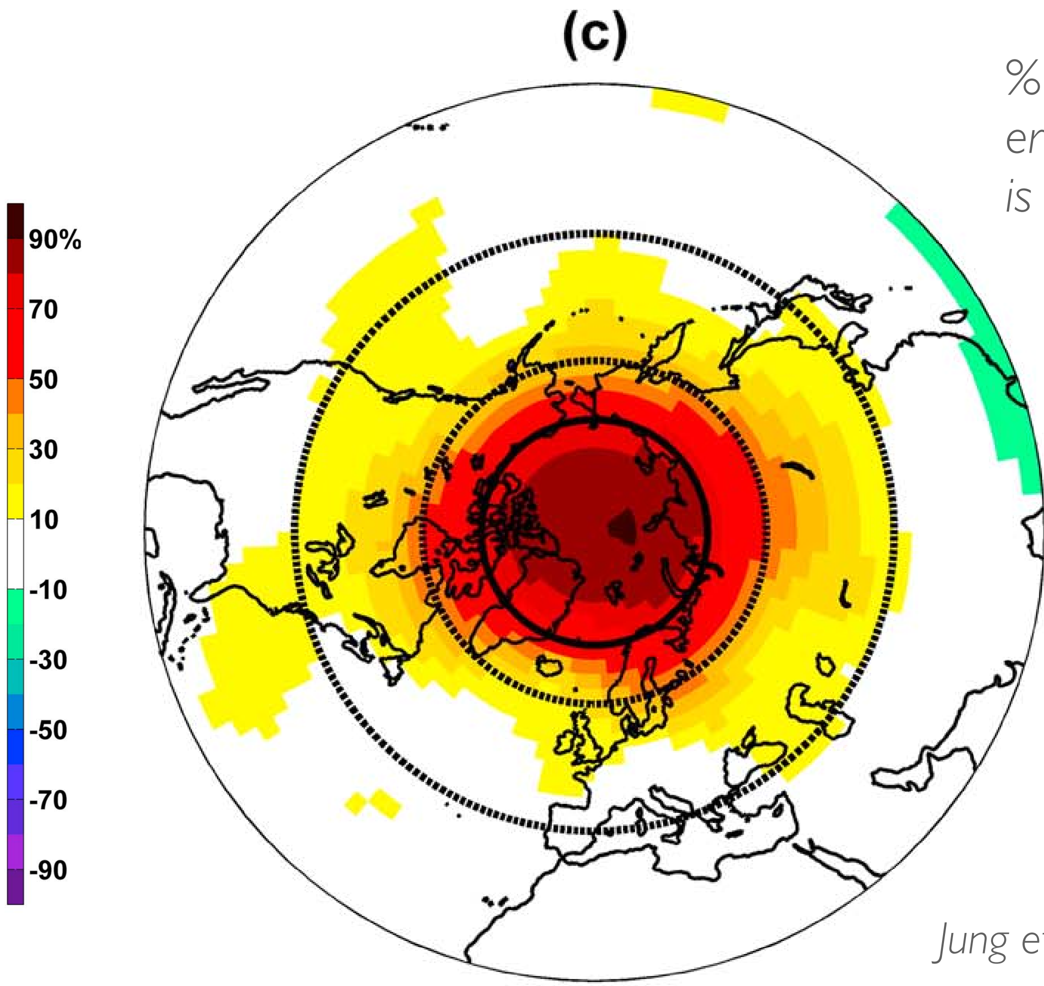
simulations of a dry, dynamical core with imposed polar surface heating under perpetual equinox conditions



Butler, Thompson et al. (2010)

idealized modeling studies with polar heating show an equatorward jet shift when polar cap is heated

Forecasting evidence



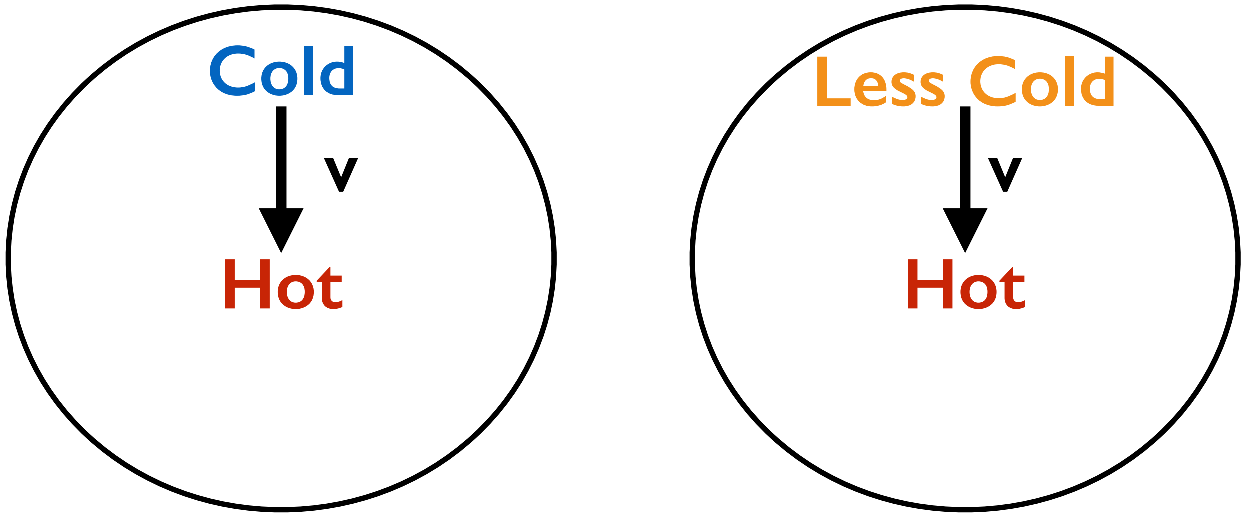
% reduction in RMS forecast error for days 11-30 when Arctic is relaxed toward reanalysis

Jung et al. (2014; GRL)

- Forecast experiments with ECMWF model shows that knowledge of the Arctic state can improve forecasts in mid- to high latitudes

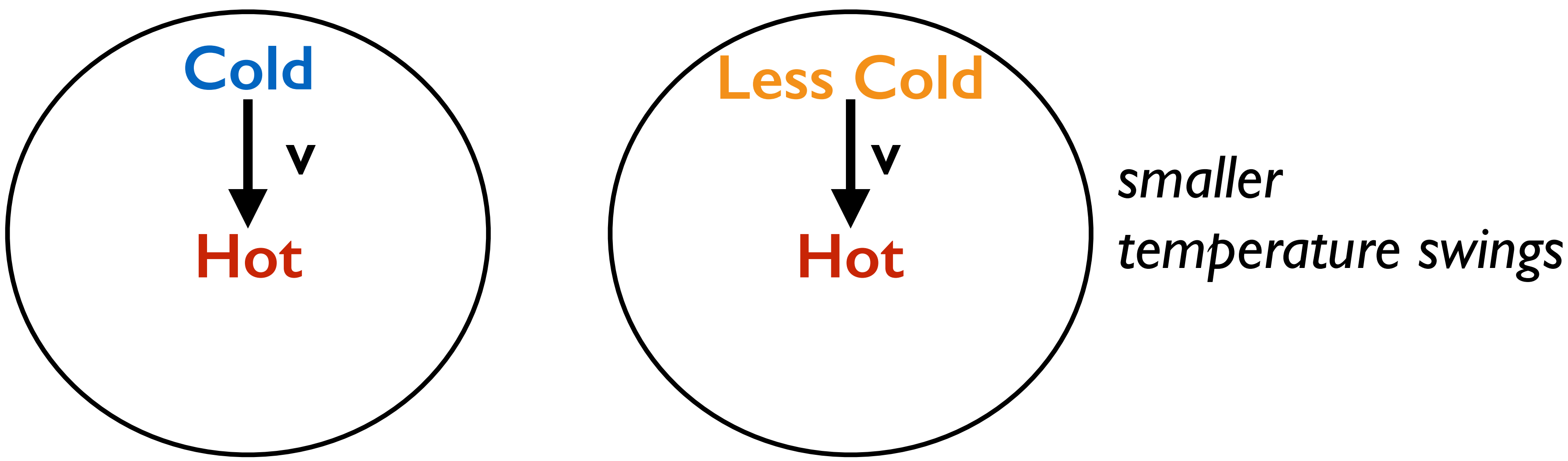
- Lowest improvement over the oceans where atmospheric variability is large

Midlatitude temperature variance



- temperature variance in midlatitudes *decreases* when sea ice decreases and the Arctic warms more than the surrounding areas
- theory suggests a decrease in variance when equator-to-pole temperature contrast decreases *(see also Schneider et al. (2014; JCLI) for more details and CMIP5 results)*

Midlatitude temperature variance



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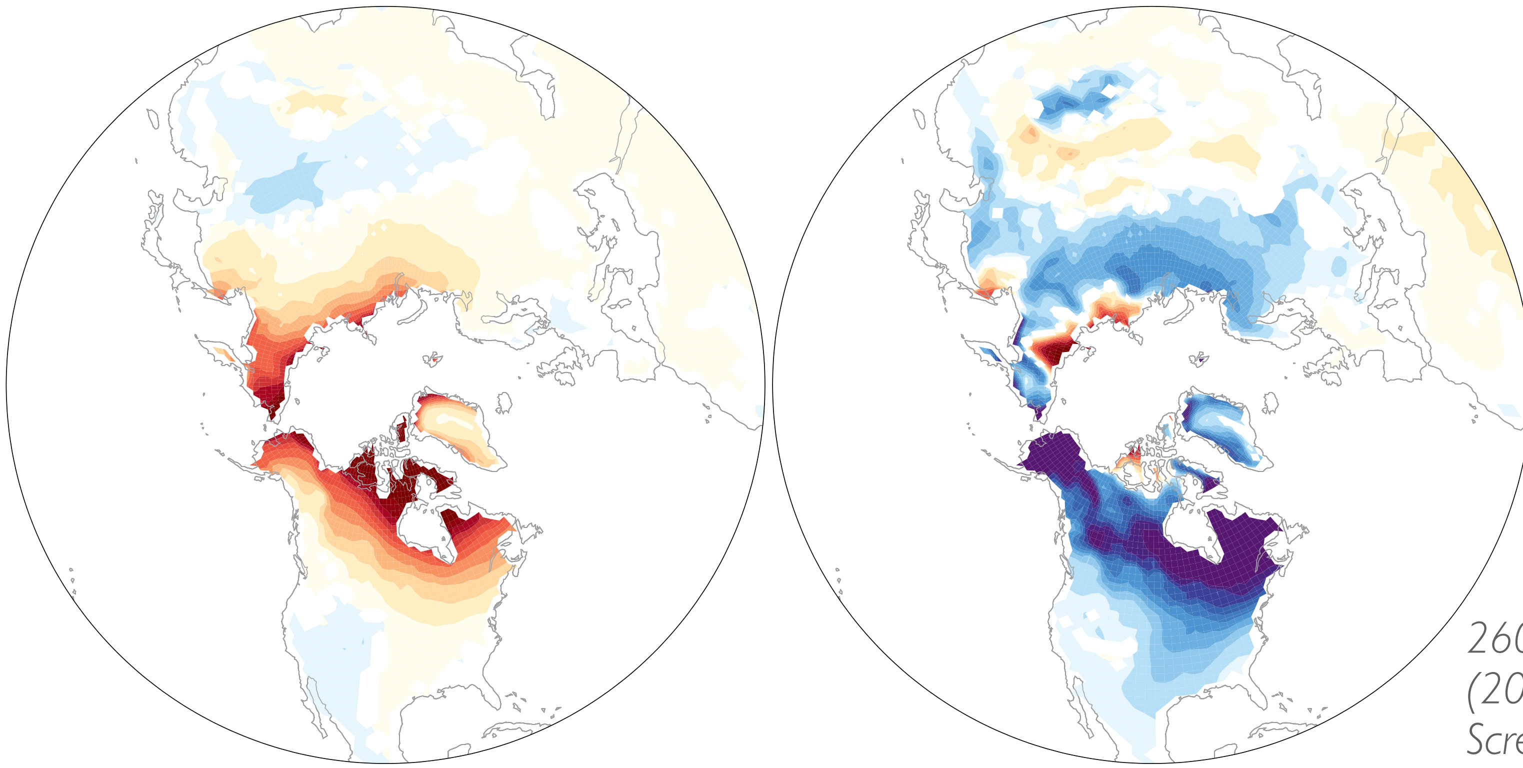
Midlatitude temperature variance

temperature response — variability response

a) HadGAM2 mean — b) HadGAM2 standard deviation



260 years of forced sea ice experiments
(2030-2049) - (1980-1999)
Screen et al. (2015; BAMS)

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- theory suggests a decrease in variance when equator-to-pole temperature contrast decreases *(see also Schneider et al. (2014; JCLI) for more details and CMIP5 results)*

Can it?

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- but…. **How?**

- equatorward jet shift
- more blocking, less blocking
- wavier jet-stream, less wavy jet-stream
- less temperature variance/more temperature variance

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- hemispheric temperature gradients
- local baroclinicity changes
- weekend stratospheric vortex

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many open research questions!

That the Arctic **can** influence the midlatitude circulation does not imply that it **has** in a significant way, nor does it imply that it **will** in the future.

Has Arctic warming significantly influenced the midlatitude jetstream?

Observational Evidence

Headlines

Arctic Warming is Altering Weather Patterns, Study Shows

Rapidly Warming Arctic Leading to Deadly Extreme Weather Events

Scientists Link Cold Spring to Dramatic Sea Ice Loss

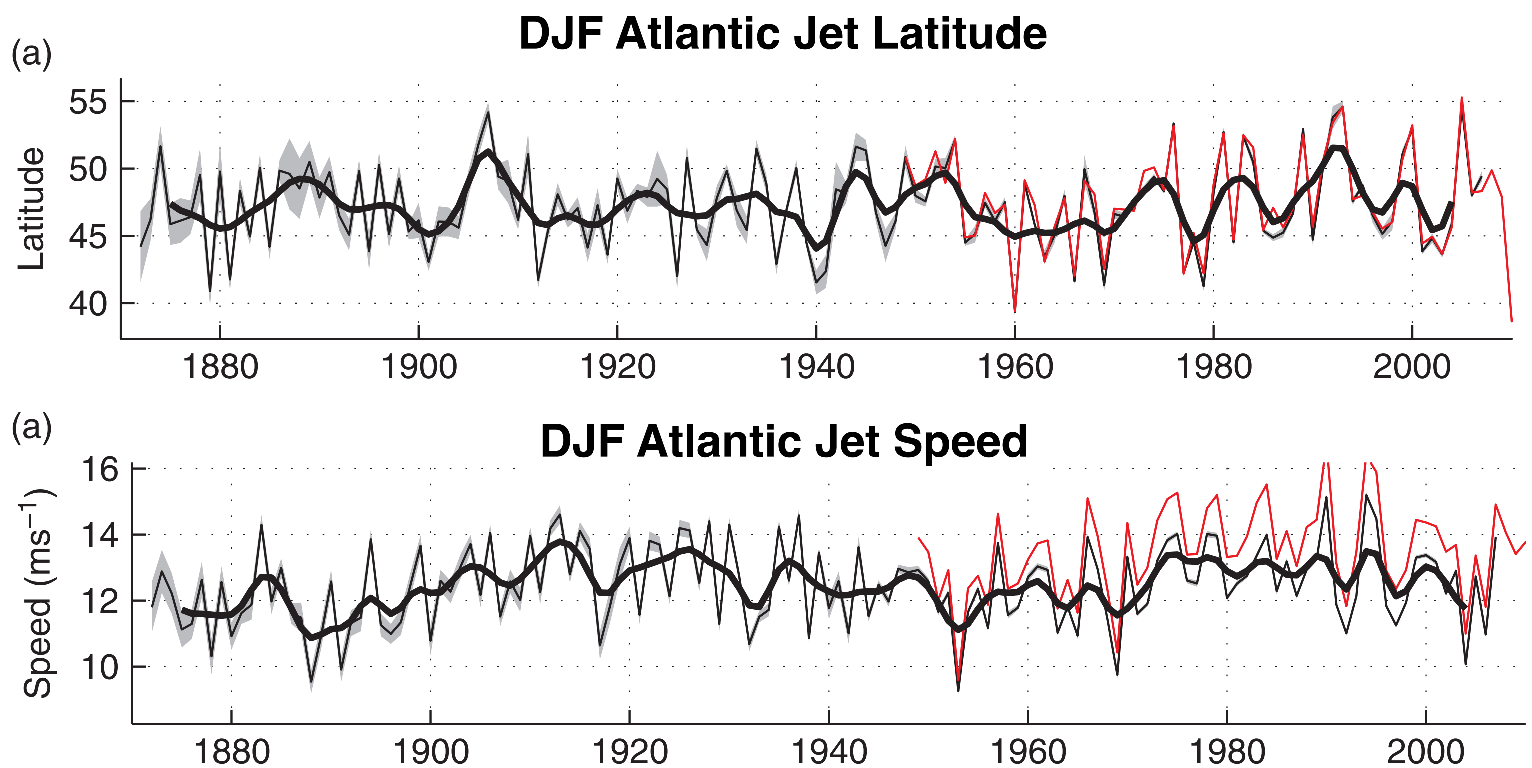
Winter 2013-2014: Sea Ice Loss Locks Jet Stream into Severe Winter Storm Pattern For Most of US

Superstorm Sandy

A Series of Unfortunate Events?

the past few years have seen a large increase in the number of studies and news articles discussing present-day influences of Arctic warming on midlatitude weather **… but is the evidence there?**

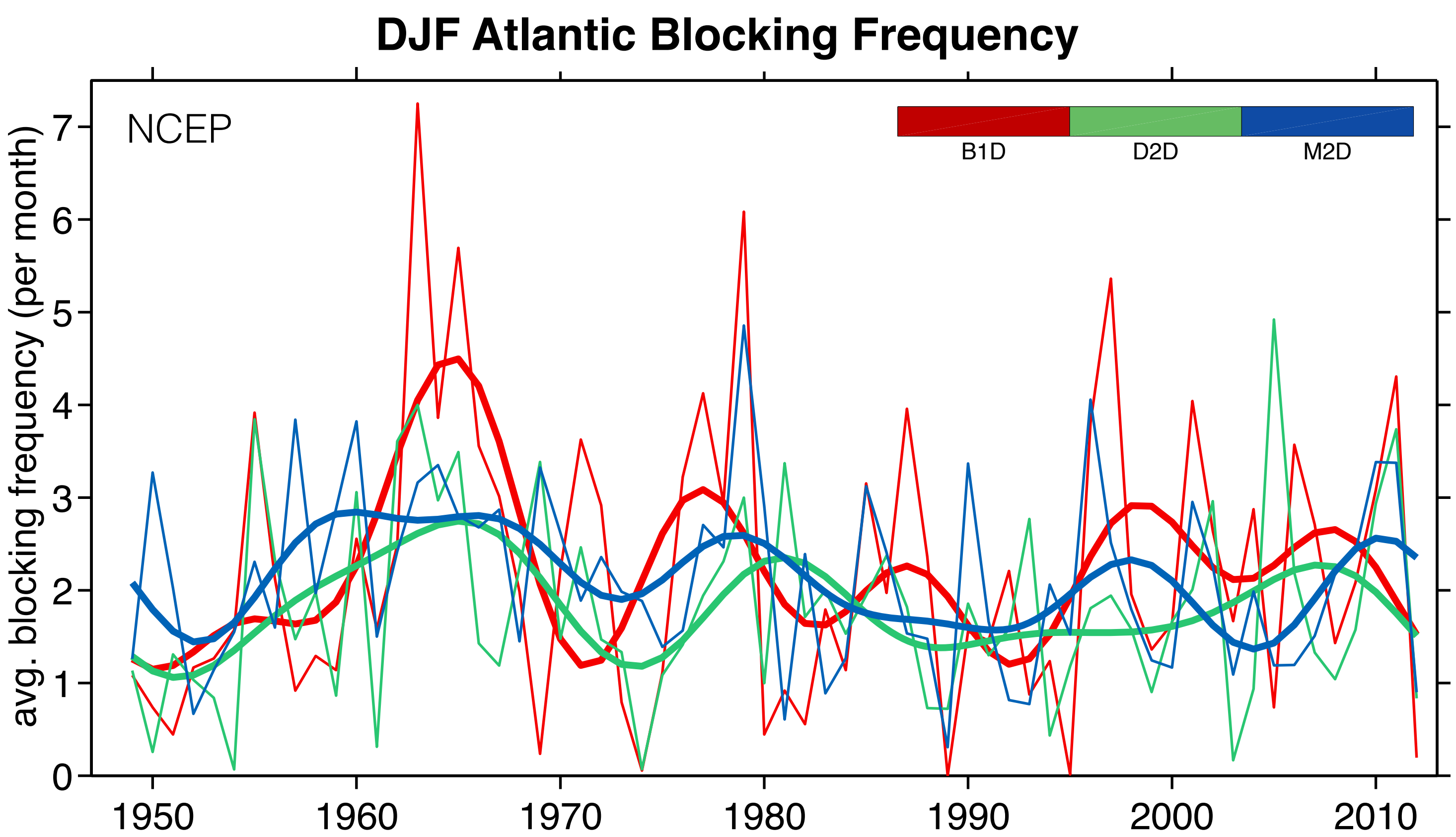
Internal atmospheric variability is large



20th Century Reanalysis jet latitude and speed
red line denote NCEP-NCAR Reanalysis
Woollings et al. (2014; QJRMS)

- Decadal variability of jet position and speed is large
- Behavior over the past decade does not appear exceptional compared to the long-term variability
- The midlatitude circulation response to past Arctic sea ice loss may be partially or wholly masked by atmospheric internal variability (Screen, Deser, et al. 2013; CDYN)

Internal atmospheric variability is large

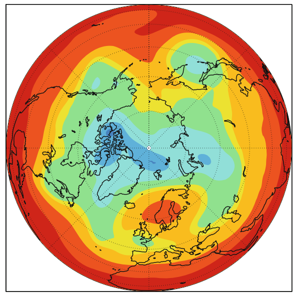


- 3 blocking identification methods
- 4 seasons
- 4 reanalyses
- 3 different time periods

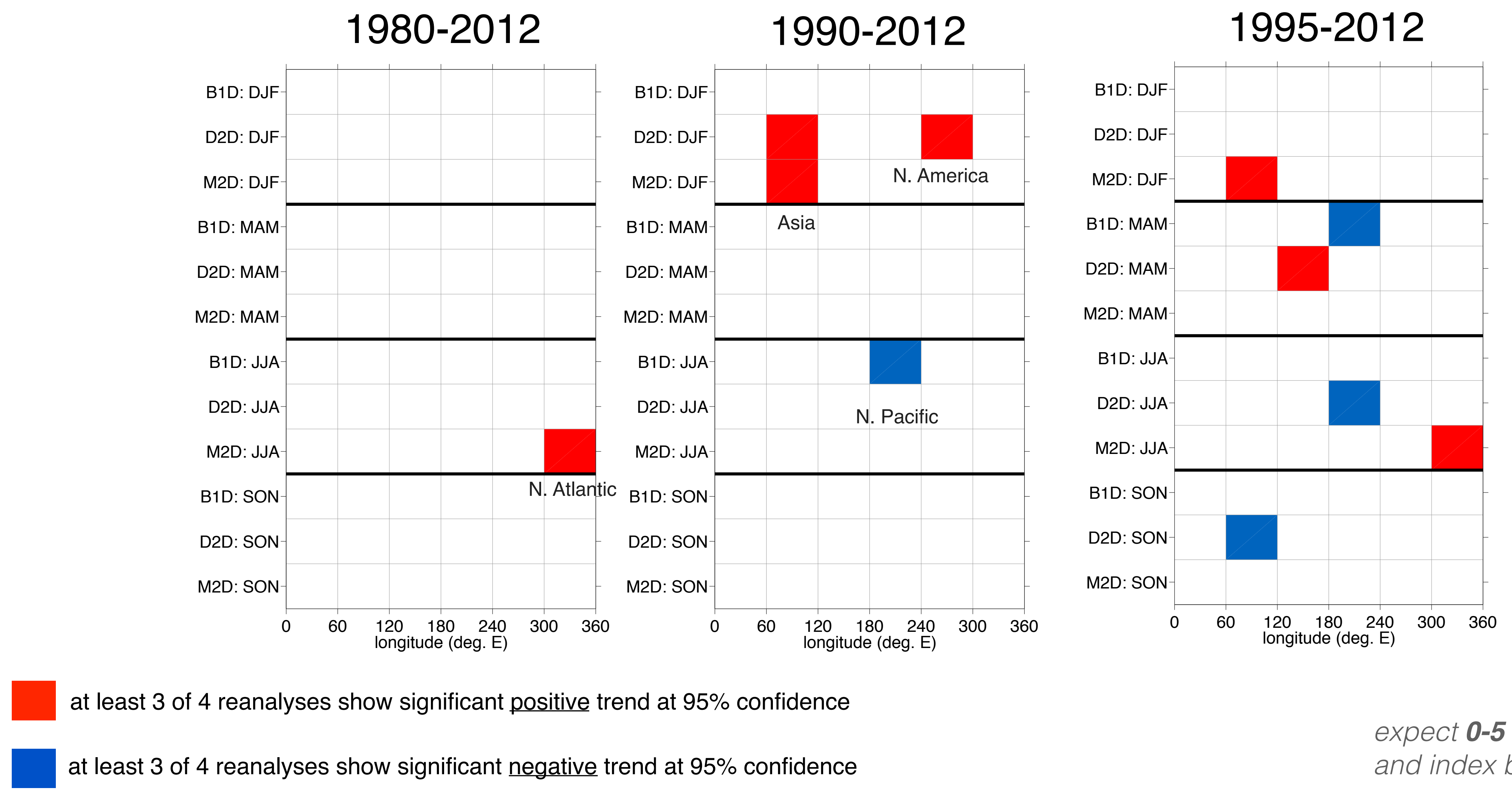
- Decadal variability of blocking frequency is very large, like jet-stream variability (the two are dynamically linked)
- Behavior over the past decade does not appear exceptional compared to the long-term variability

Barnes et al. (2014); GRL

Internal atmospheric variability is large



example blocking high
500 hPa Z anomaly

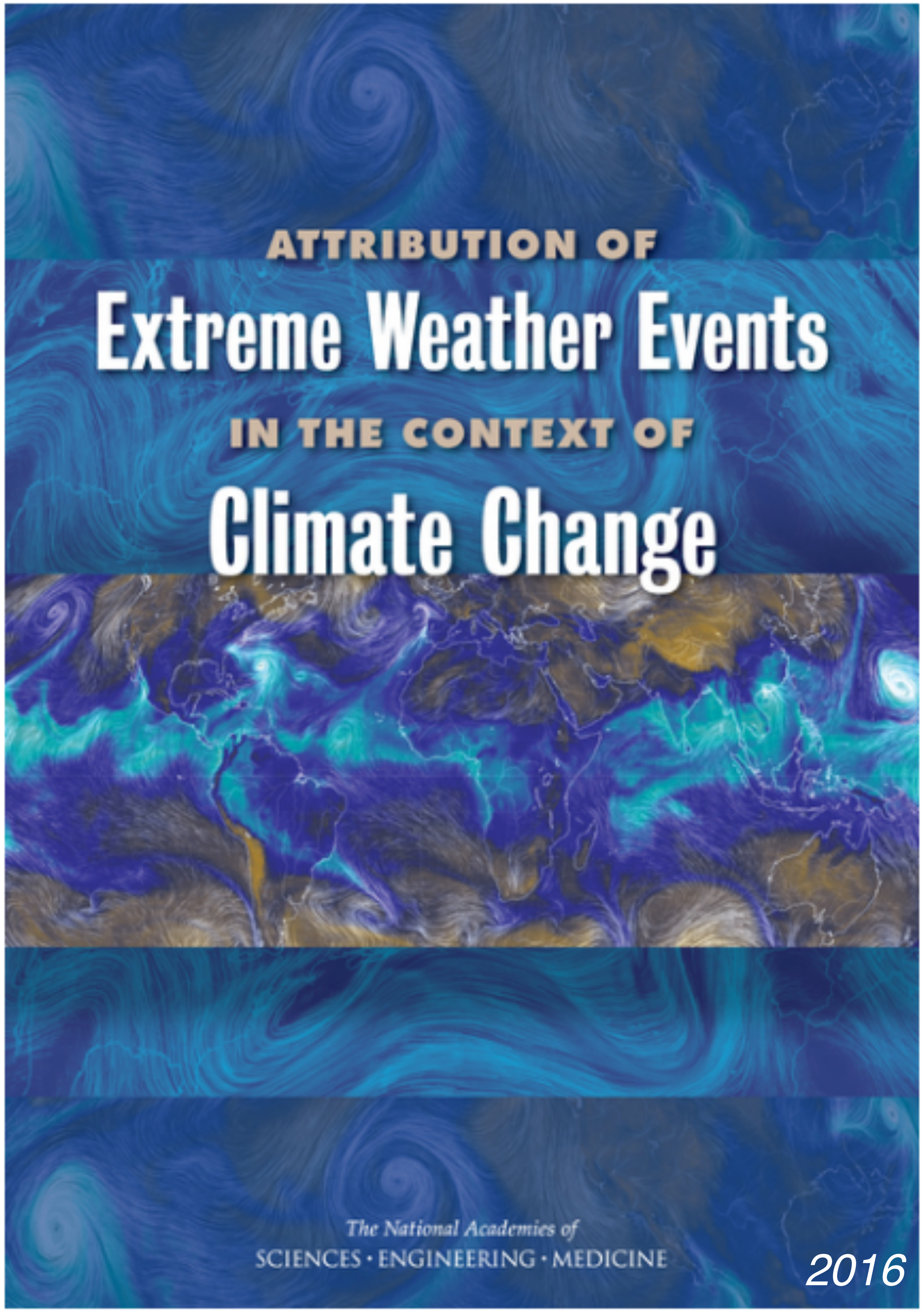


*expect **0-5** blocks per reanalysis and index by chance alone*

- Trends are very sensitive to the exact time period chosen
- Different results are obtained for different reanalyses and metrics
- No clear signal of increased blocking frequency emerges

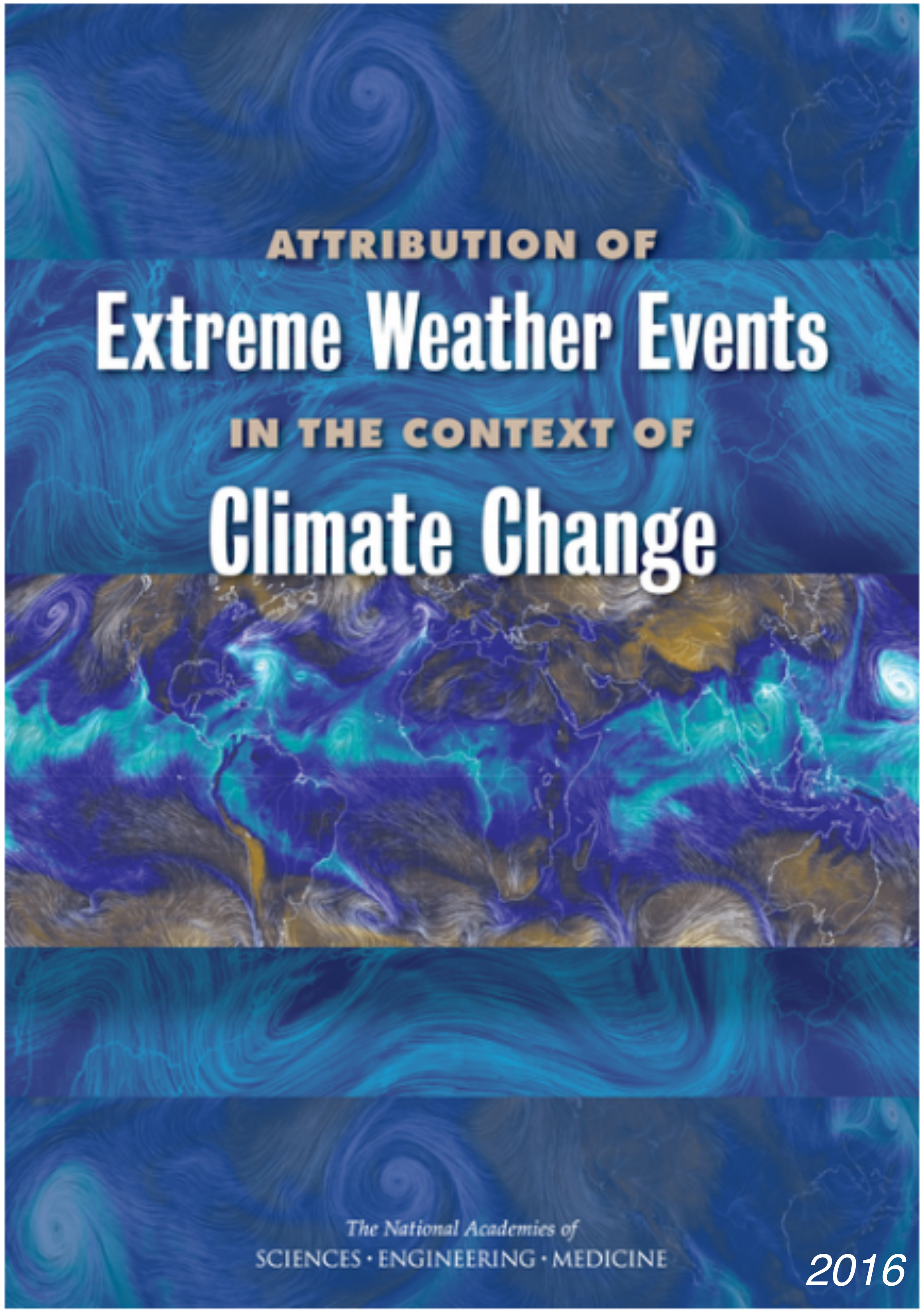
Barnes et al. (2014); GRL

Internal atmospheric variability is large



"Attribution of events to anthropogenic climate change may be complicated by low-frequency natural variability, which influences the frequencies of extreme events on decadal to multidecadal timescales."

Internal atmospheric variability is large

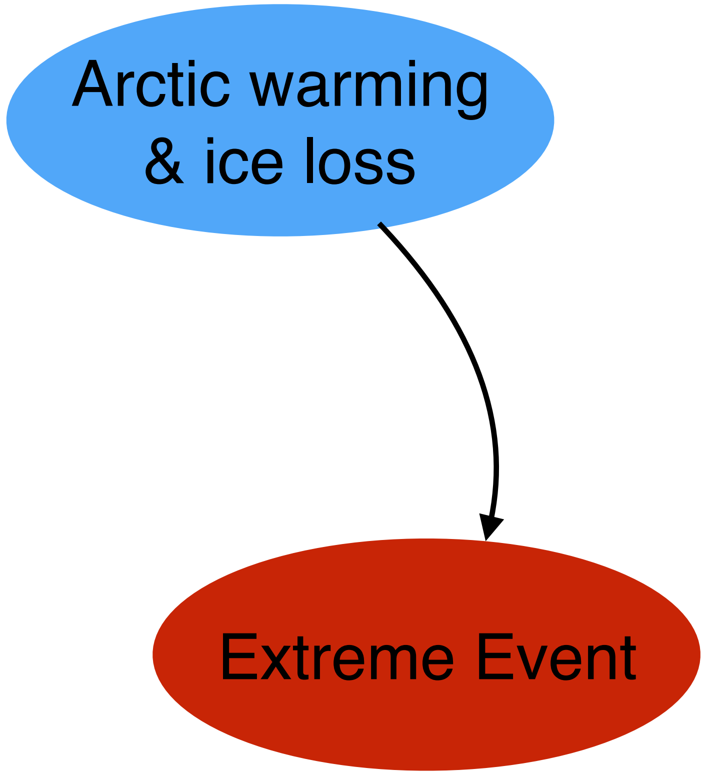


"…There is little or no confidence in the attribution of severe convective storms and extratropical cyclones."

Which way does causality point?

- It is well known that the midlatitude circulation is an important driver of Arctic climate.

- What if the mid-tropospheric Arctic warming is largely driven by processes outside of the Arctic? **Causality could go the other way.**



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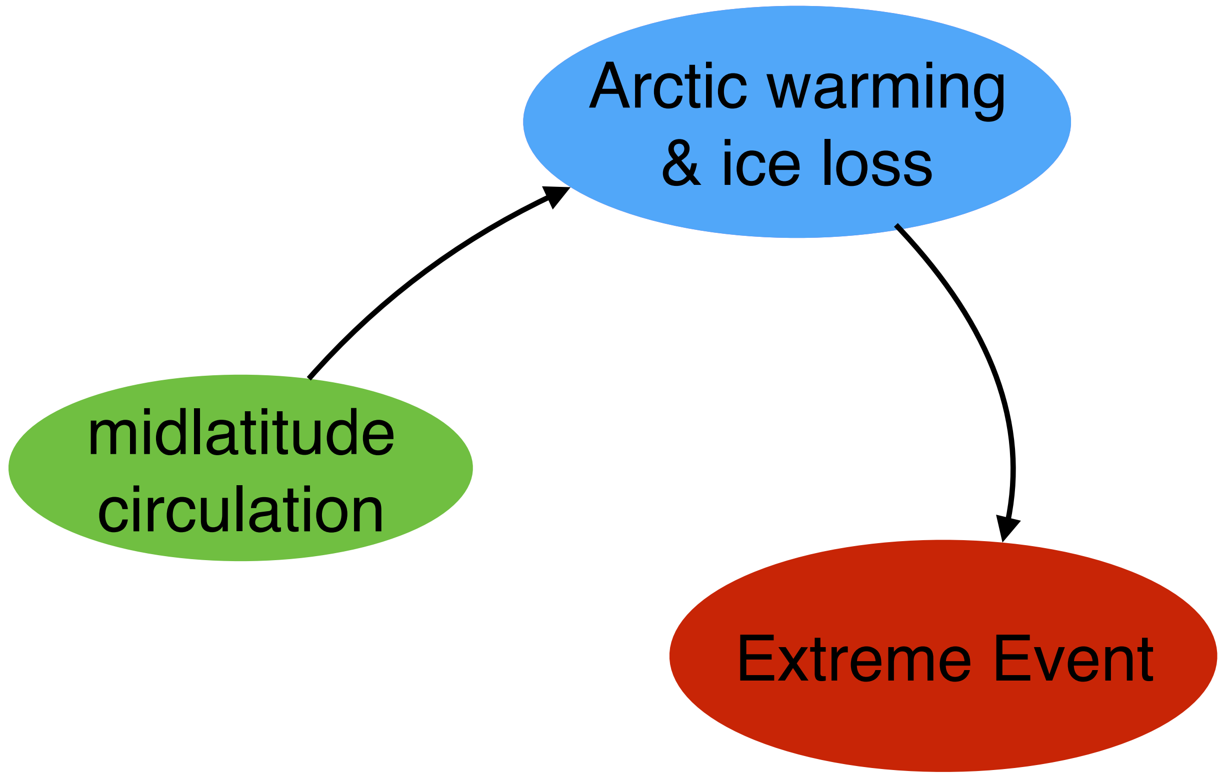

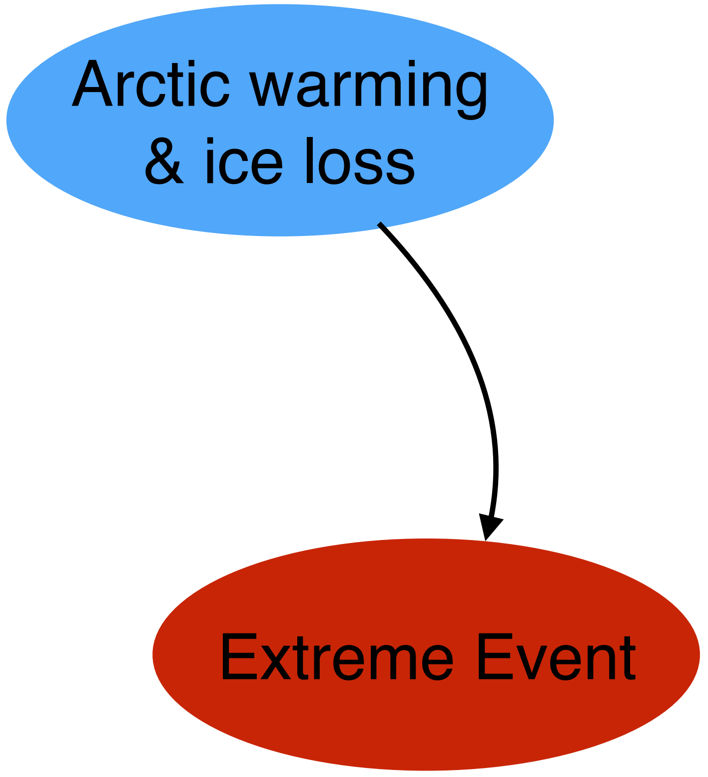

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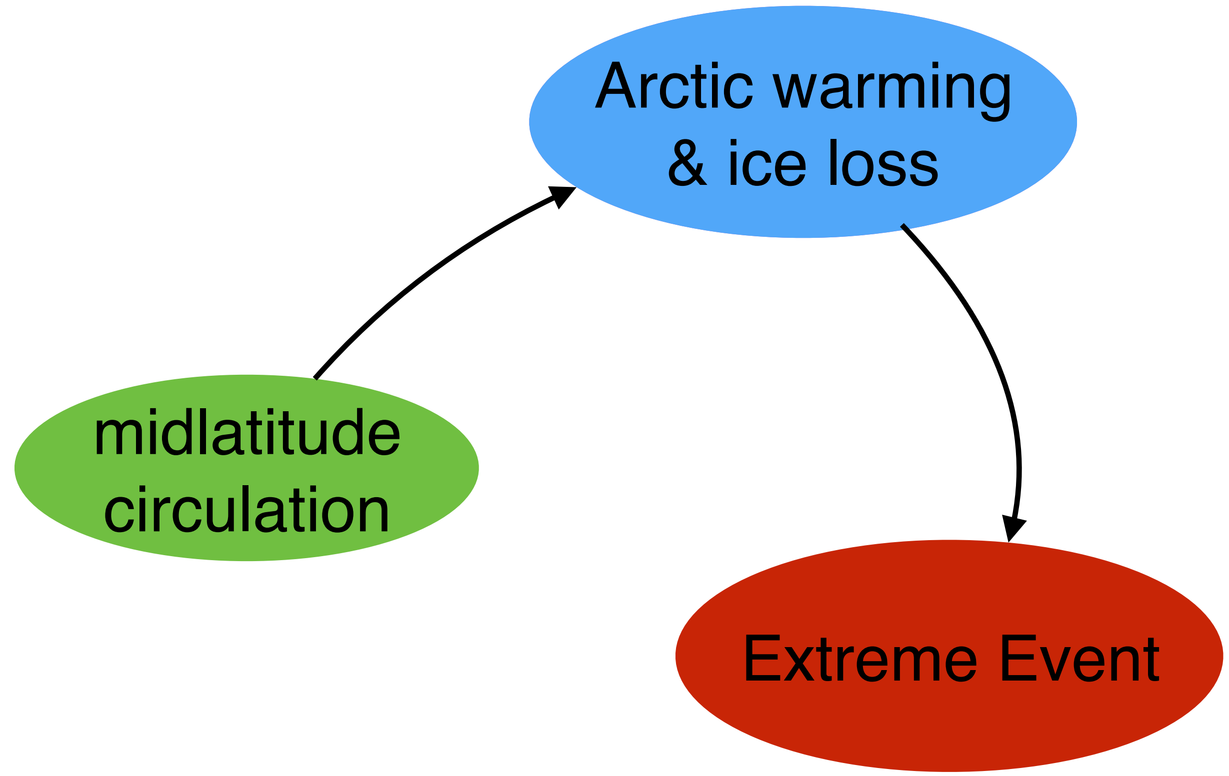

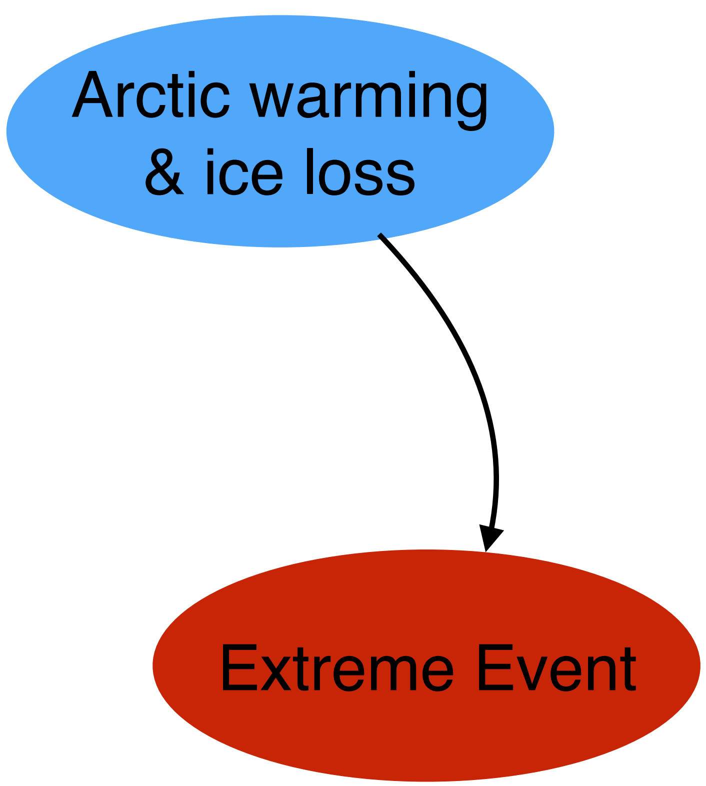

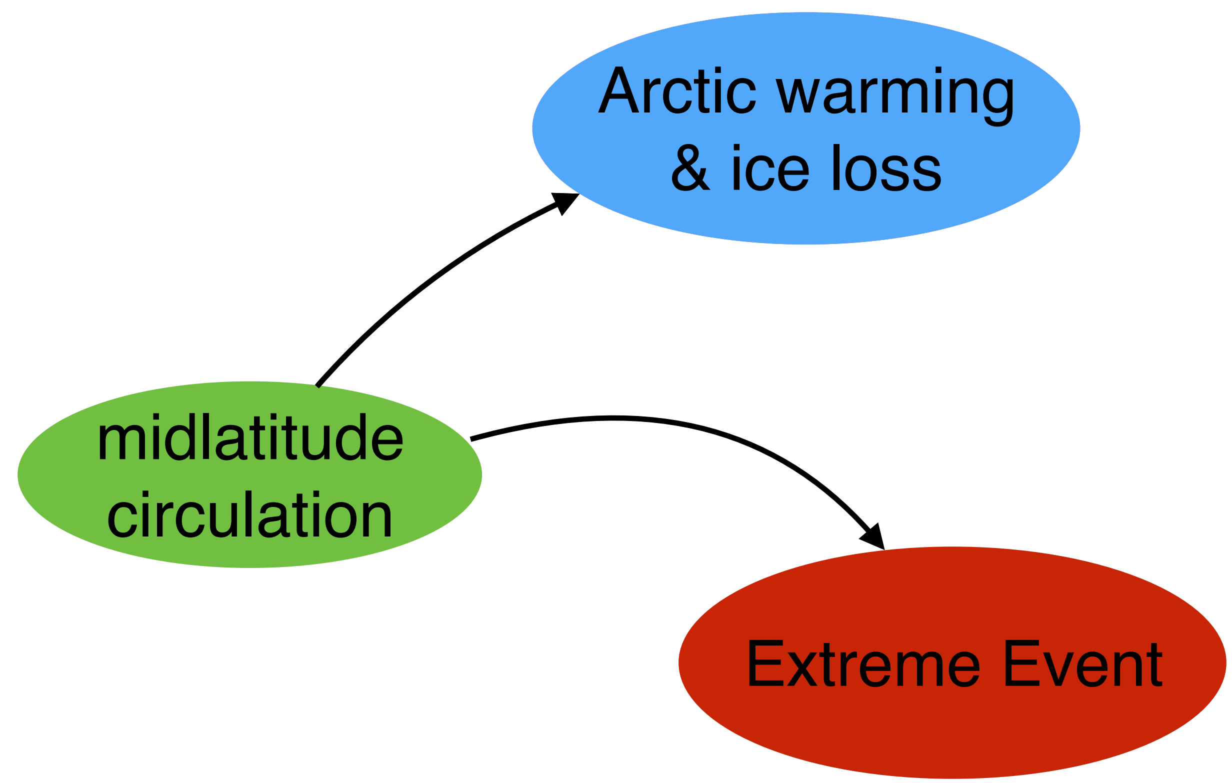

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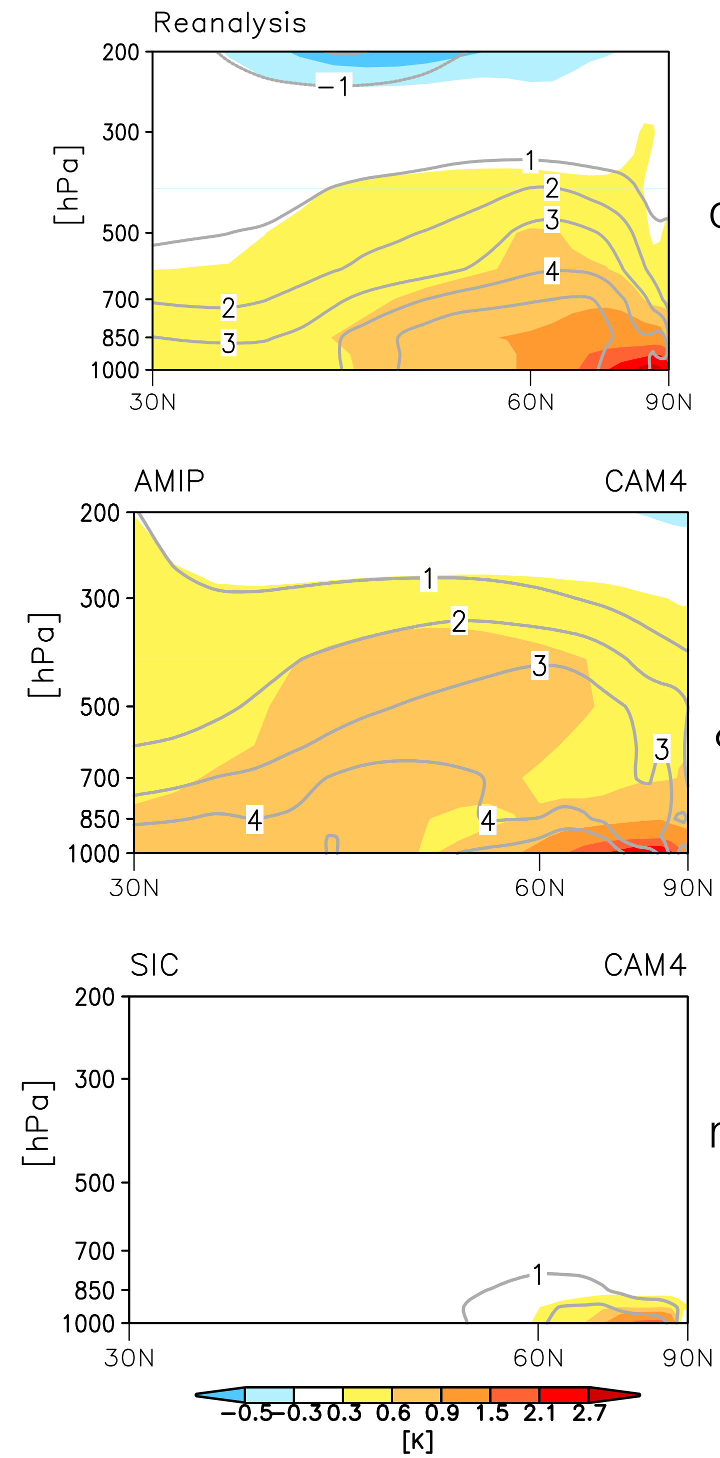
Change in Oct.-Dec. temperatures 2003-12 minus 1979-88



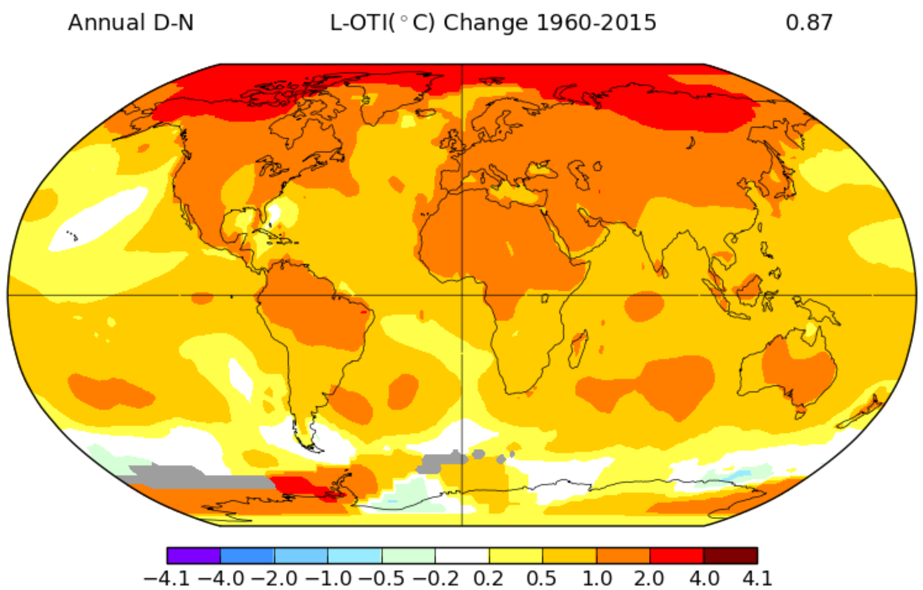
observations

model w/ observed SSTs & radiative forcing

model contribution of sea ice

CAM4 simulations
Perlwitz et al. (2015; JCLI)

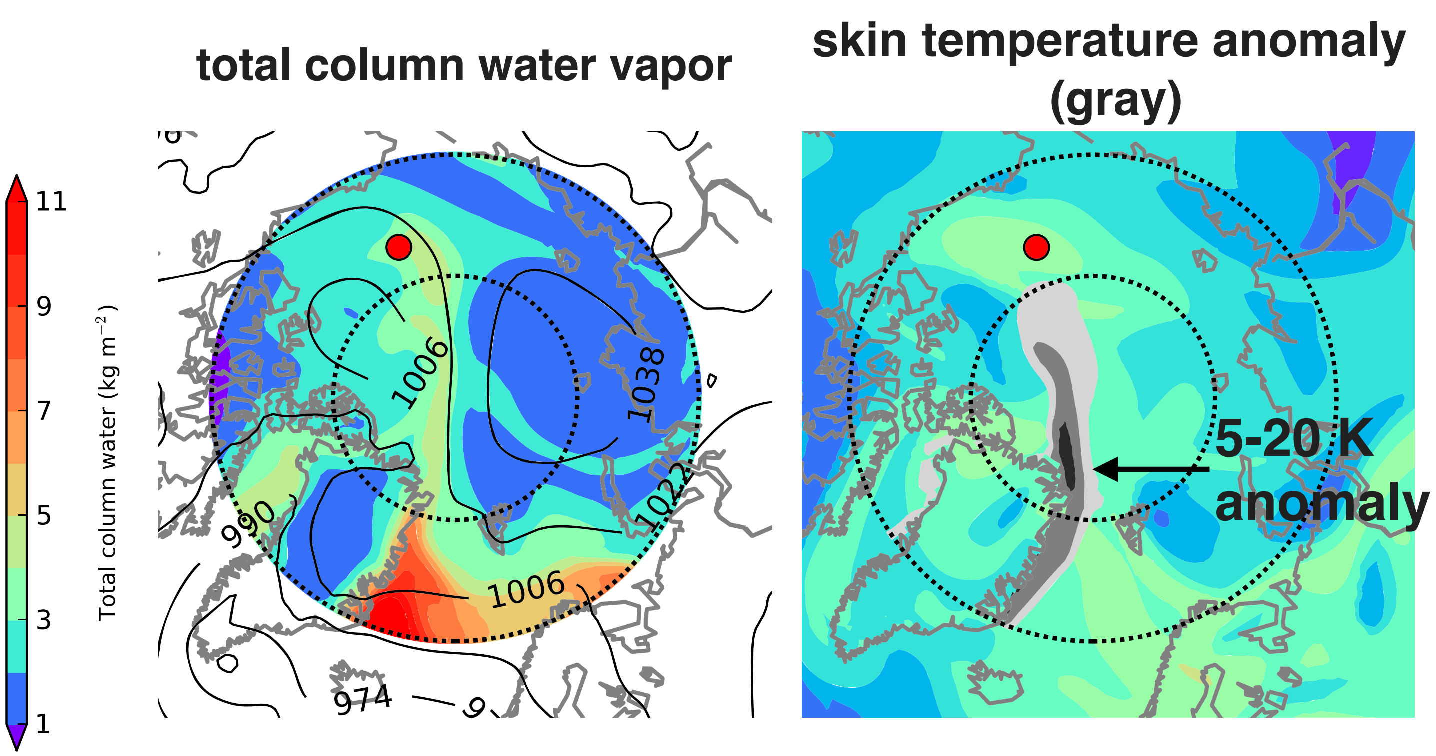
Which way does causality point?



NASA GISS surface temperature analysis

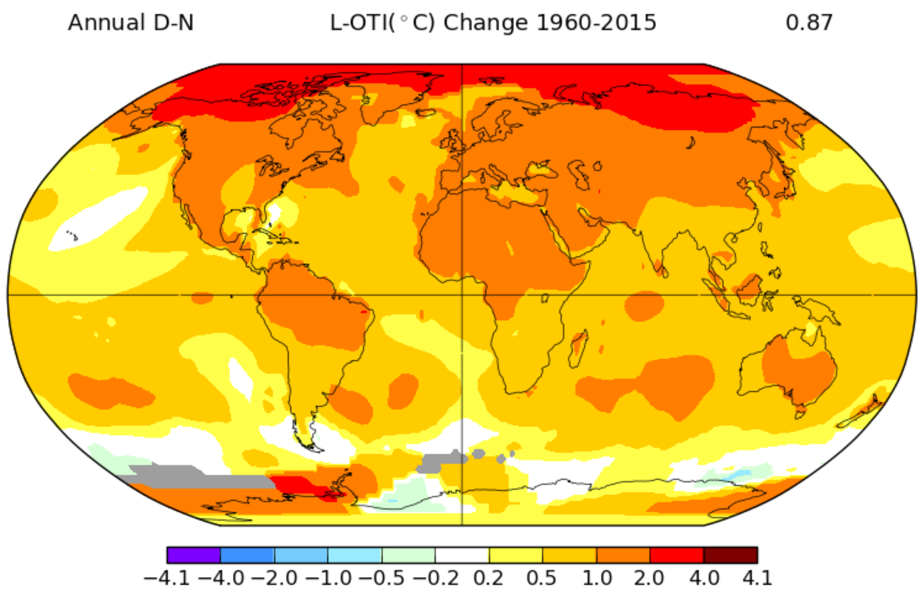
Intense, filamentary moisture intrusions into the Arctic can modulate the long-wave radiation reaching the surface

00:00 UTC 1 January 1998



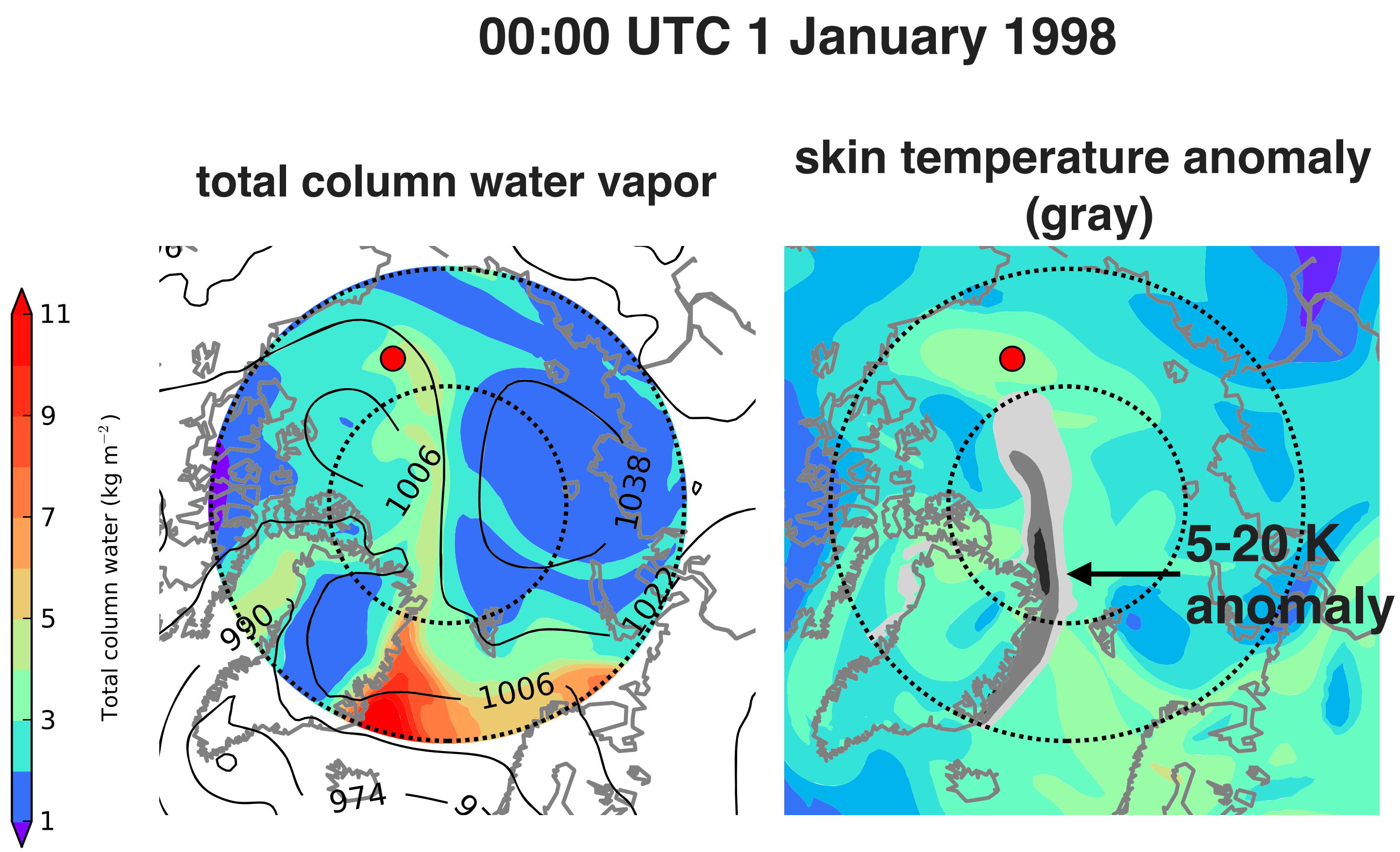
adapted from Figure 1 of Woods et al. (2013)
Woods & Caballero, 2016

Which way does causality point?



NASA GISS surface temperature analysis

30% of recent downward trends in Arctic sea ice can be explained by increased moisture intrusions into the Arctic (Woods & Caballero, 2016)



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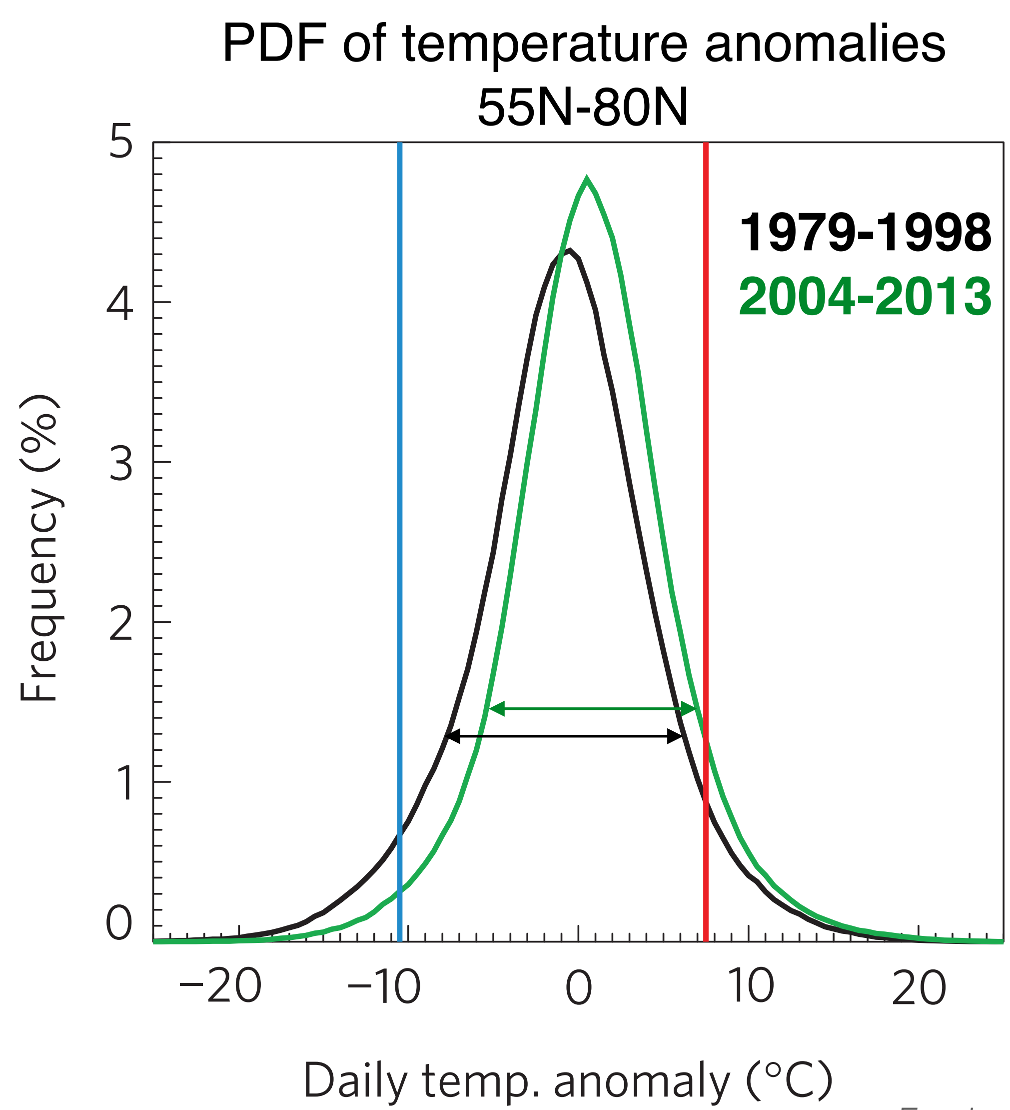
Woods & Caballero, 2016

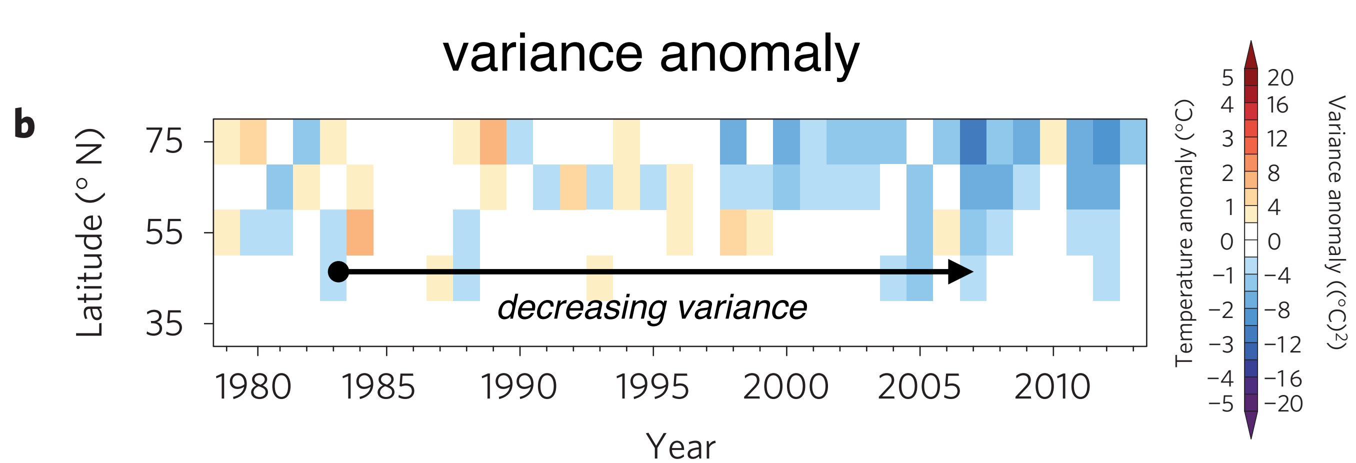
Temperature variance decreases

- temperature variance in midlatitudes has *decreased* in recent decades

- consistent with theory: a decrease in variance when equator-to-pole temperature contrast decreases (see also Schneider et al. (2014; JCLI))



Era-Interim, autumn
Latitudes 55N-80N
Screen (2014; NATCC)

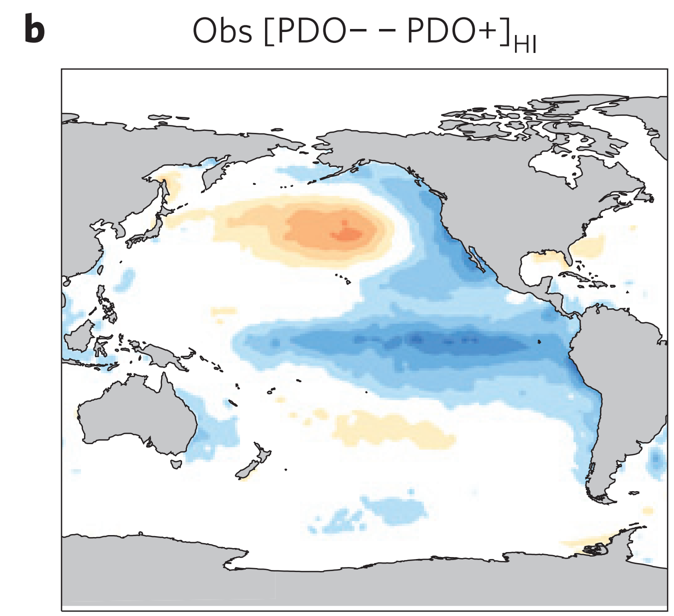


State dependence and non-linearities

nature climate change
LETTERS
PUBLISHED ONLINE: 2 MAY 2016 | DOI: 10.1038/NCLIMATE3011

Contribution of sea-ice loss to Arctic amplification is regulated by Pacific Ocean decadal variability

James A. Screen[1]* and Jennifer A. Francis[2]



Pacific Decadal Oscillation: dominant pattern of sea surface temperature variability that typically persists in one phase for 10+ years and impacts global weather.

State dependence and non-linearities

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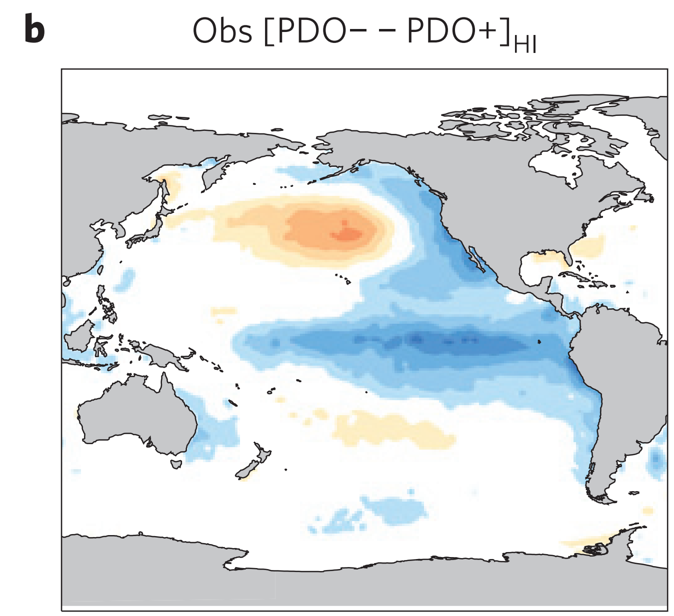
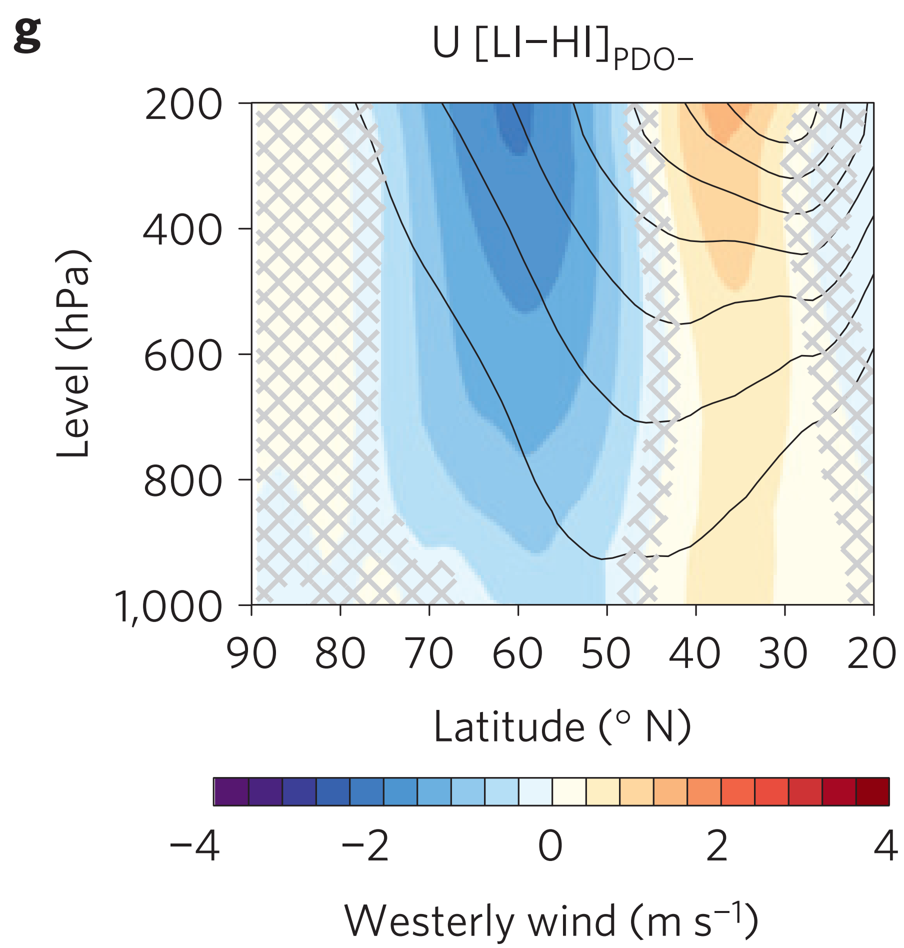
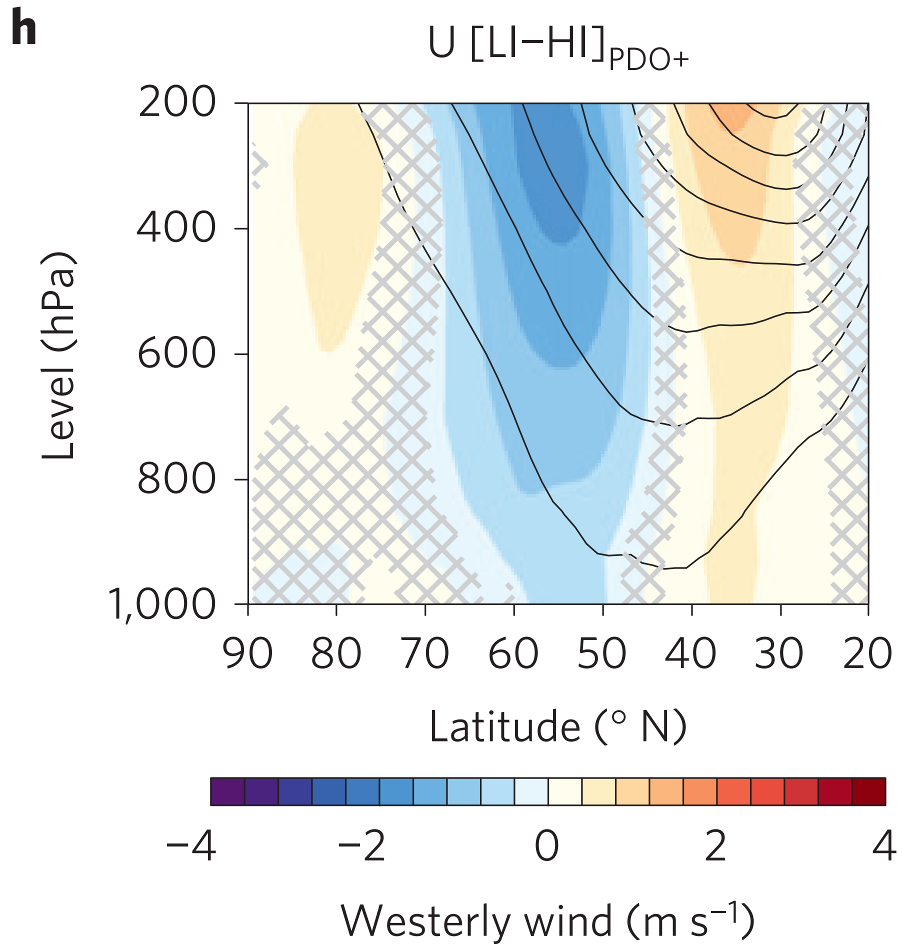
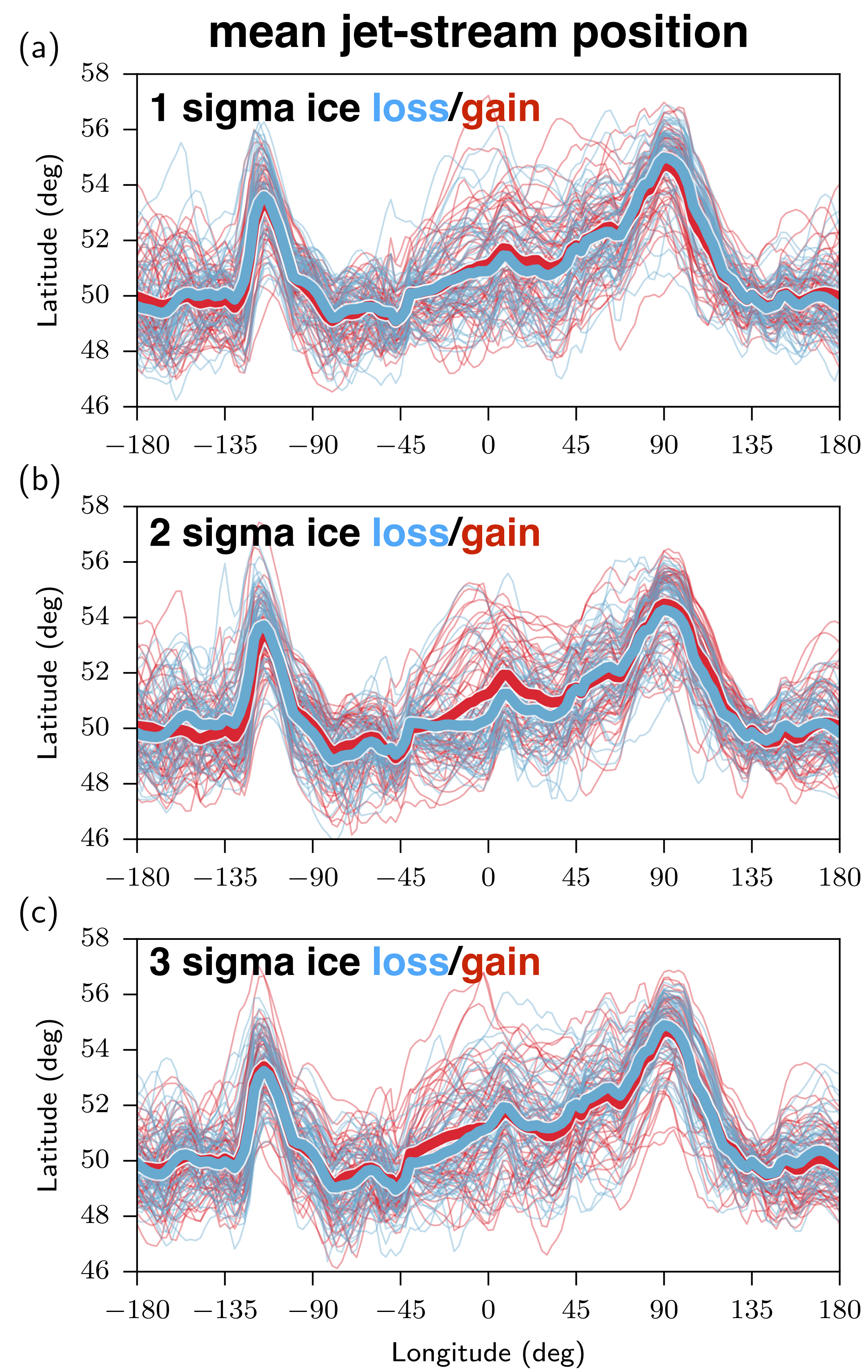






State dependence and non-linearities

- jet position response is small compared to internal variability
- no robust response of jet variability
- jet position response is non-linear: **a larger reduction in ice does not mean a larger jet-stream response**



CAM5 simulations: 55 years per simulation
Chen et al. (2016; JCLI)

Has it?

Unlikely that sea ice loss has significantly impacted the jet-stream.
The evidence suggests the effects of sea ice loss are small.

Has it?

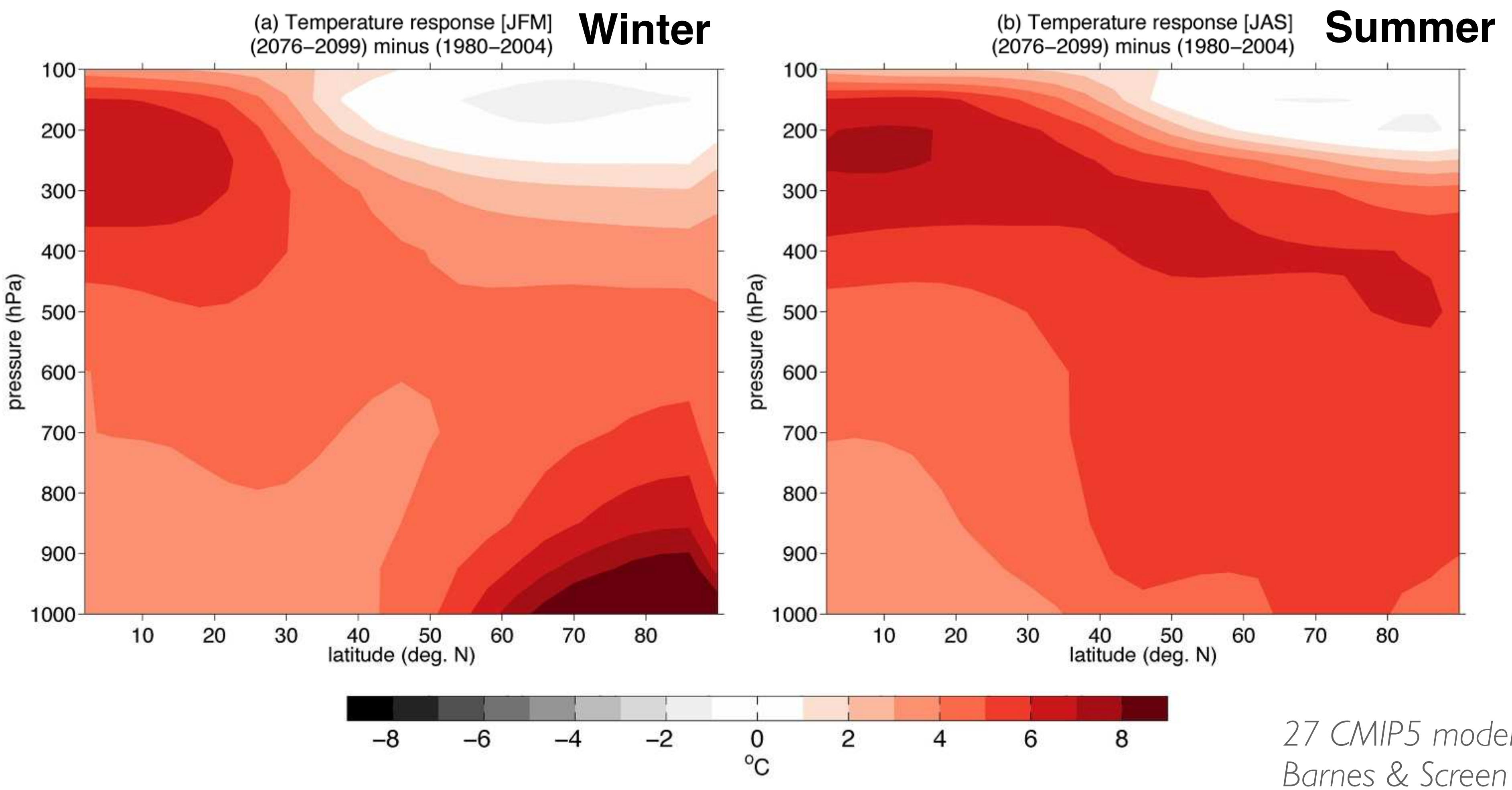
Unlikely that sea ice loss has significantly impacted the jet-stream. The evidence suggests the effects of sea ice loss are small.

1. **Internal atmospheric variability is large.** The data record is short.
2. **Which way does causality point?** This is practically impossible to determine from observations alone.
3. **Response exhibits climate state dependence and non-linearities** making mechanistic understanding and attribution even more difficult.
4. **Temperature variance decreases.**

Will Arctic warming significantly influence the midlatitude jetstream?

Future Projections

Arctic amplification under RCP8.5

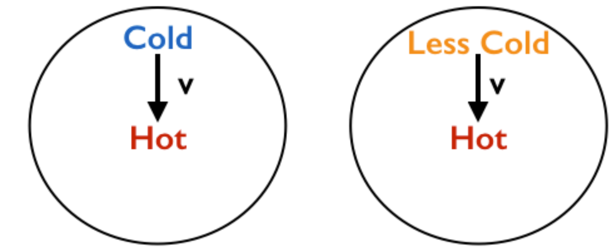


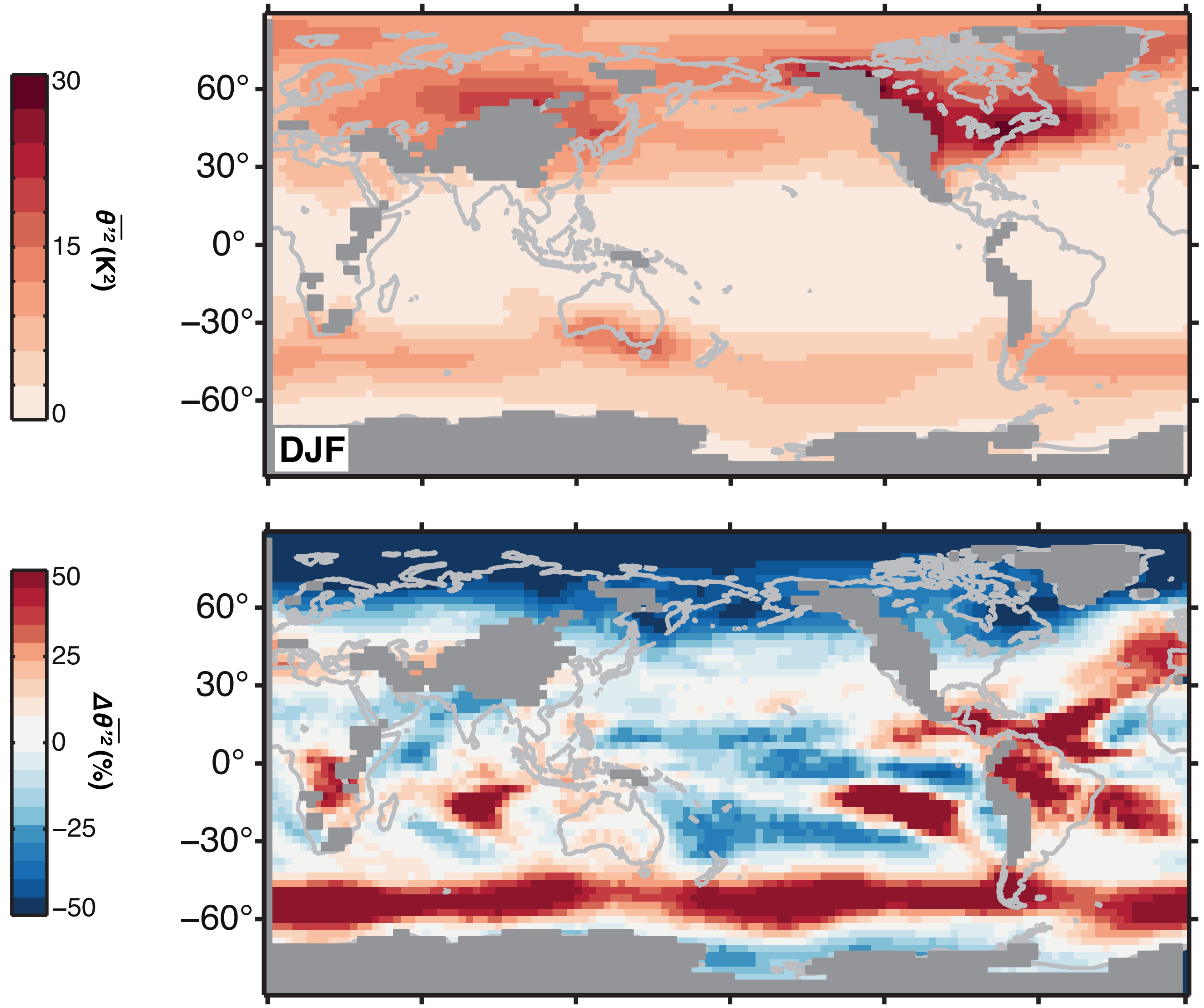
27 CMIP5 models
Barnes & Screen (2015)

- Under RCP8.5, Arctic expected to warm 1.5-2 times more than the global-average by 2100

- Arctic amplification is largest in winter

Temperature variance decreases





multi-model mean variance

multi-model mean variance response

RCP8.5 potential temperature differences
(2080-2099) - (1980-1999)
Schneider et al. (2014; JCLI), Fig. 6

- CMIP5 models show decreased temperature variance at high latitudes in the future due to decreased near-surface temperature gradient

Future Northern Hemisphere jet-streams

As the Arctic warms and the temperature gradient decreases some have argued that the midlatitudes will see …

MEAN FLOW

slower winds

weaker jet

equatorward jet

EDDIES/WAVES

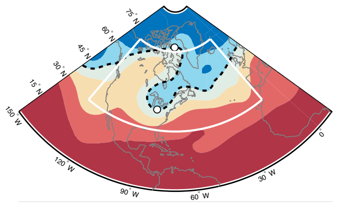
slower waves

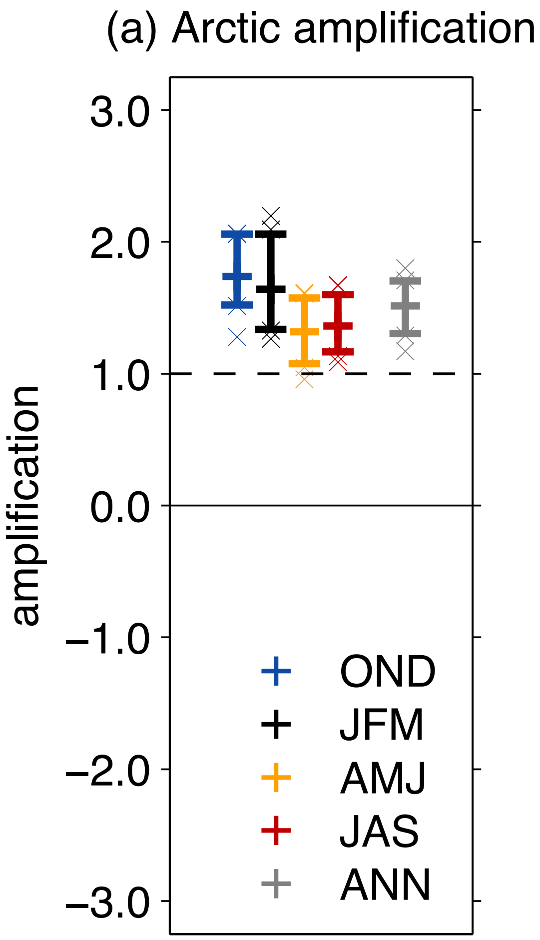
larger amplitudes

more blocking

posed by, for example
Francis & Vavrus (2012; 2015)
Liu et al. (2012)

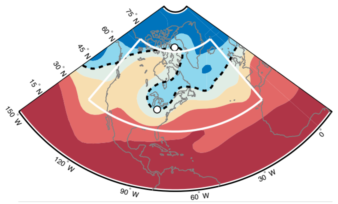
Future Northern Hemisphere jet-streams

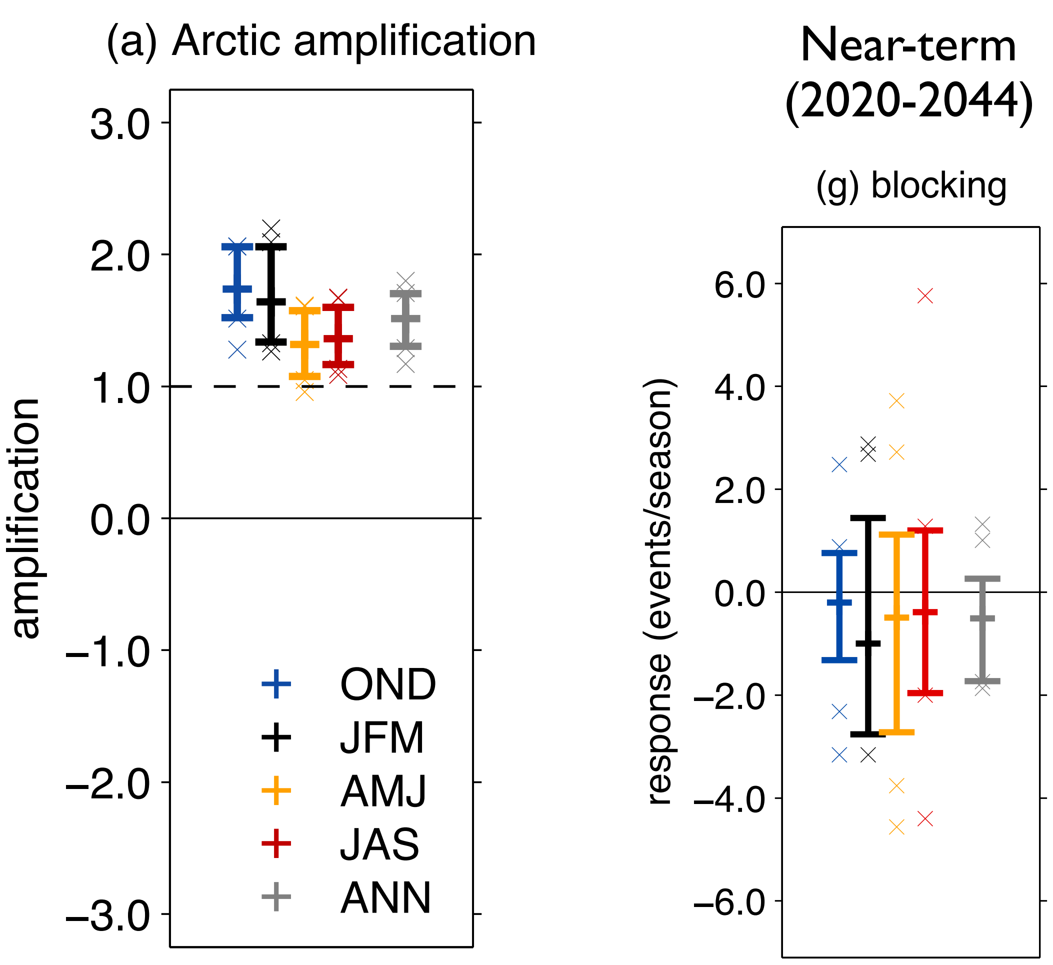




North America/North Atlantic results
27 CMIP5 GCMs
Barnes & Polvani (2015; JCLI)

Future Northern Hemisphere jet-streams





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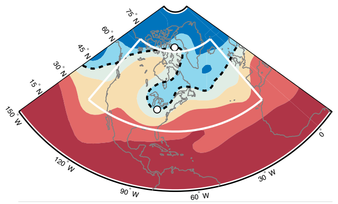
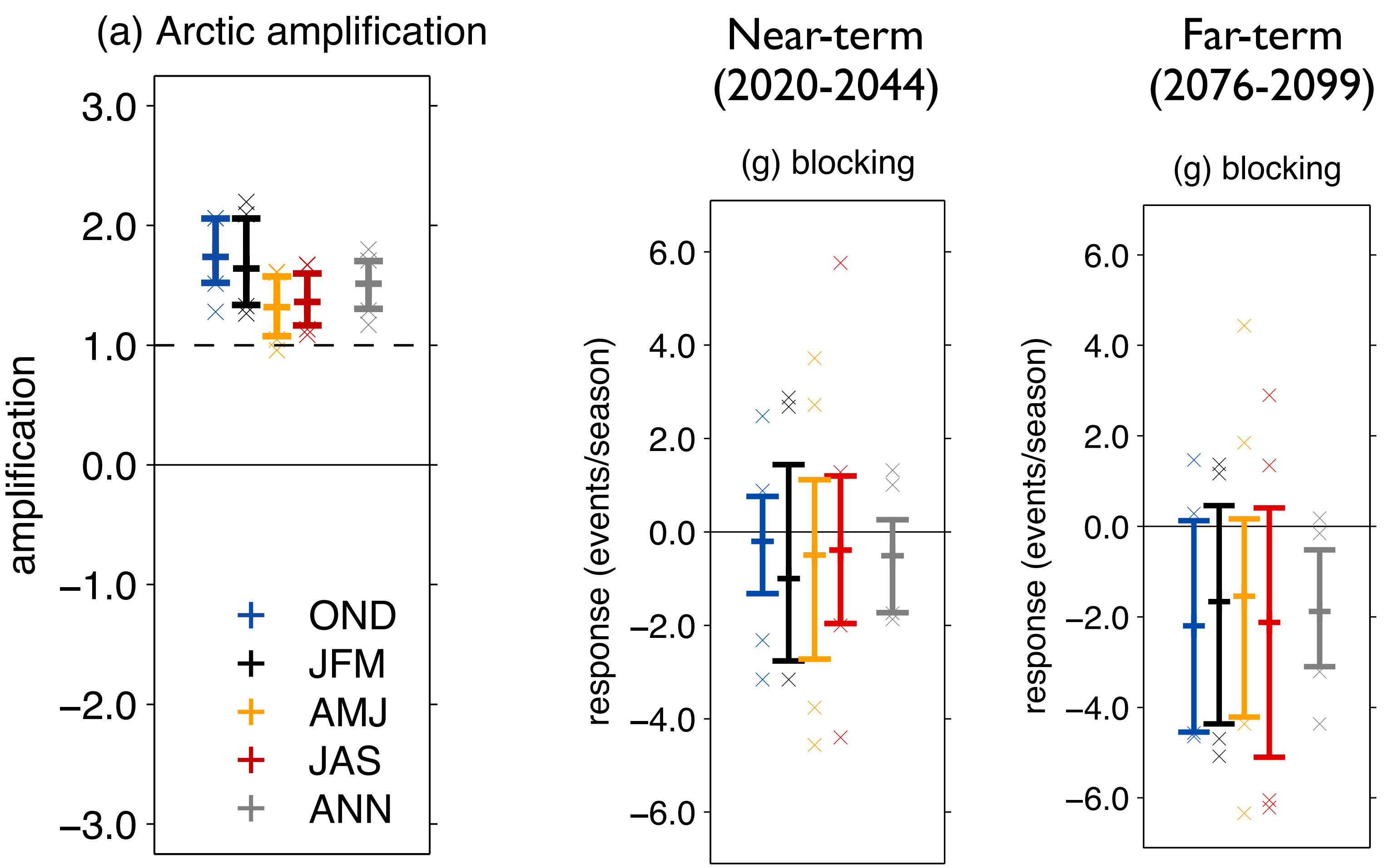
Future Northern Hemisphere jet-streams





North America/North Atlantic results
27 CMIP5 GCMs
Barnes & Polvani (2015; JCLI)

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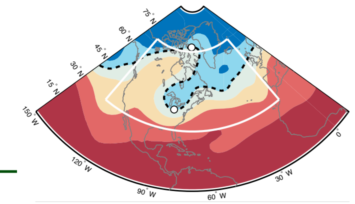

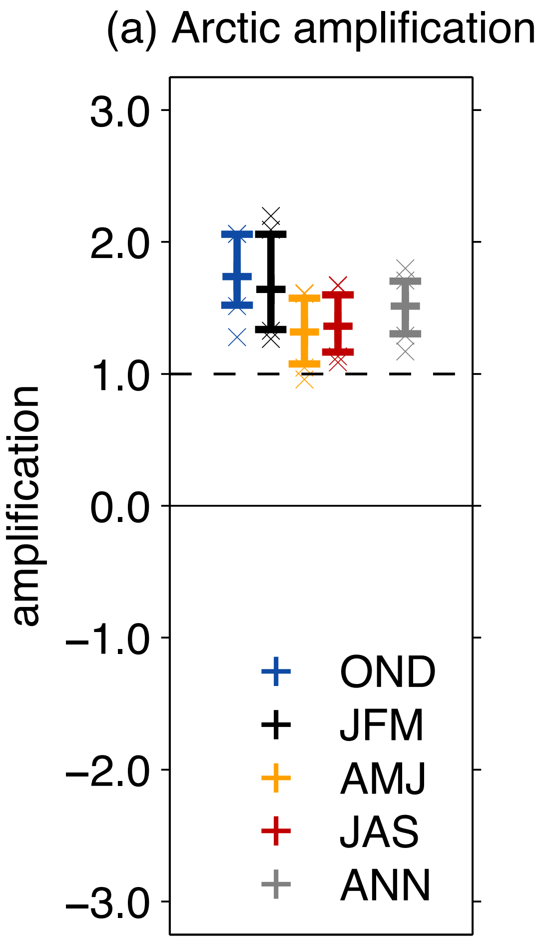

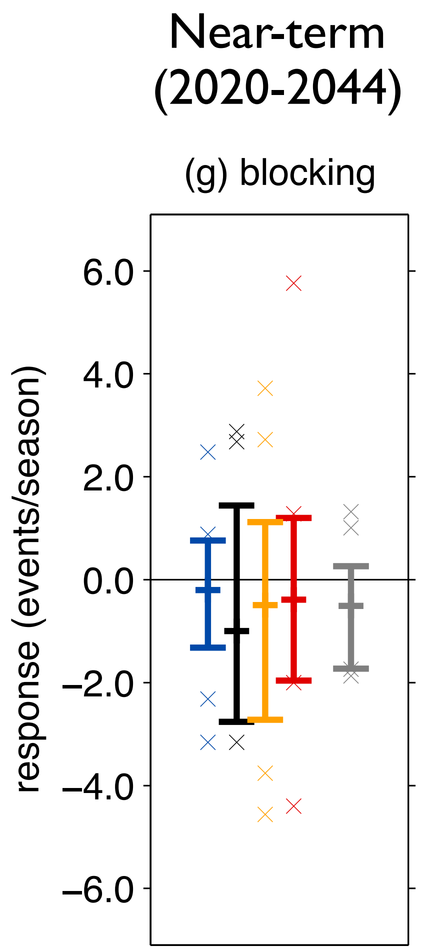

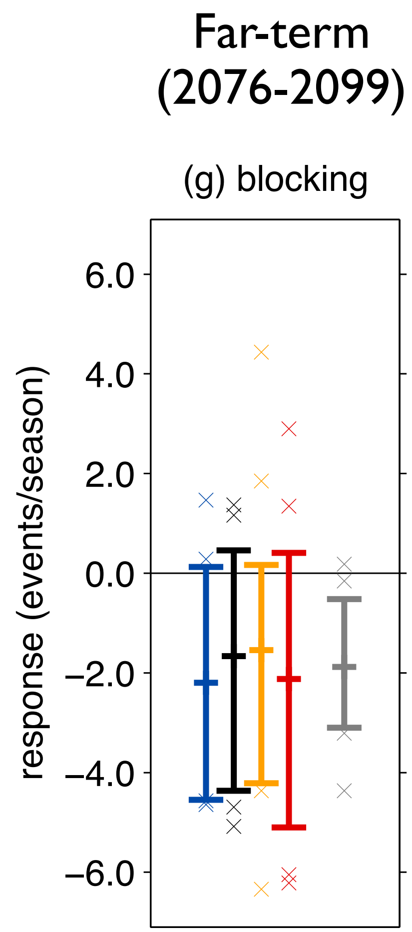

IN GENERAL:

No consensus in the circulation response or response is of the opposite sign to that hypothesized

North America/North Atlantic results
27 CMIP5 GCMs
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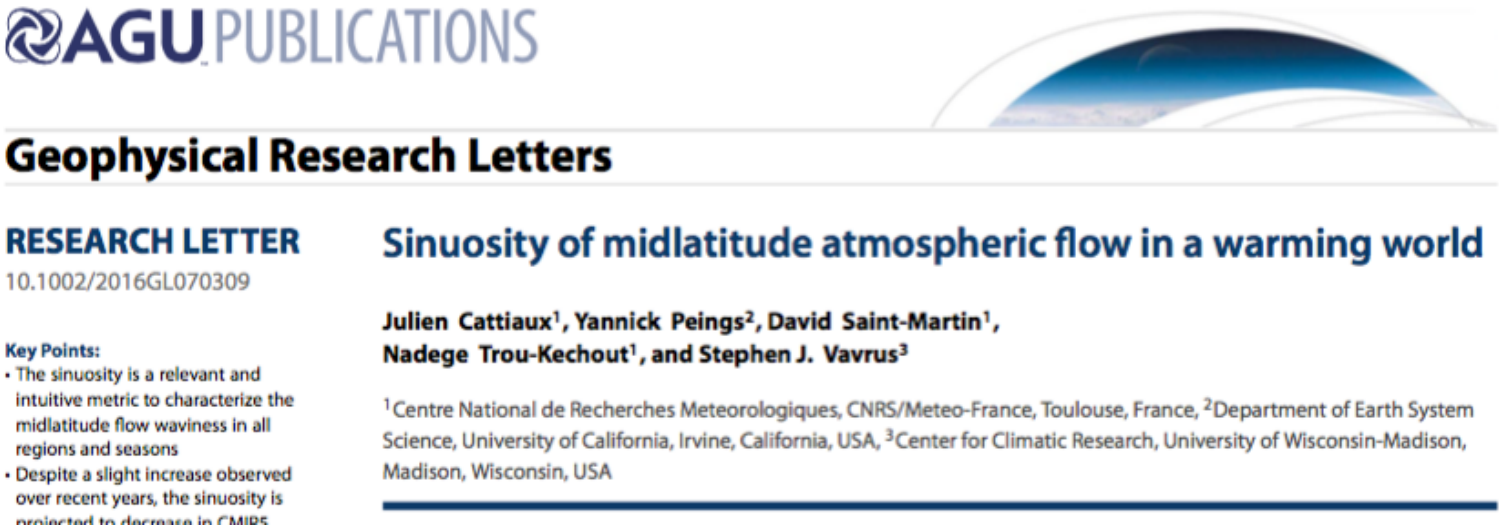
Future Northern Hemisphere jet-streams


AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL070309

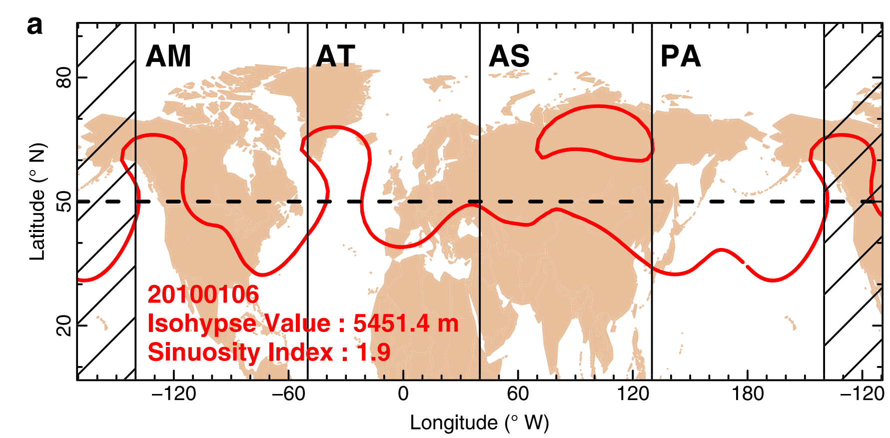
Key Points:

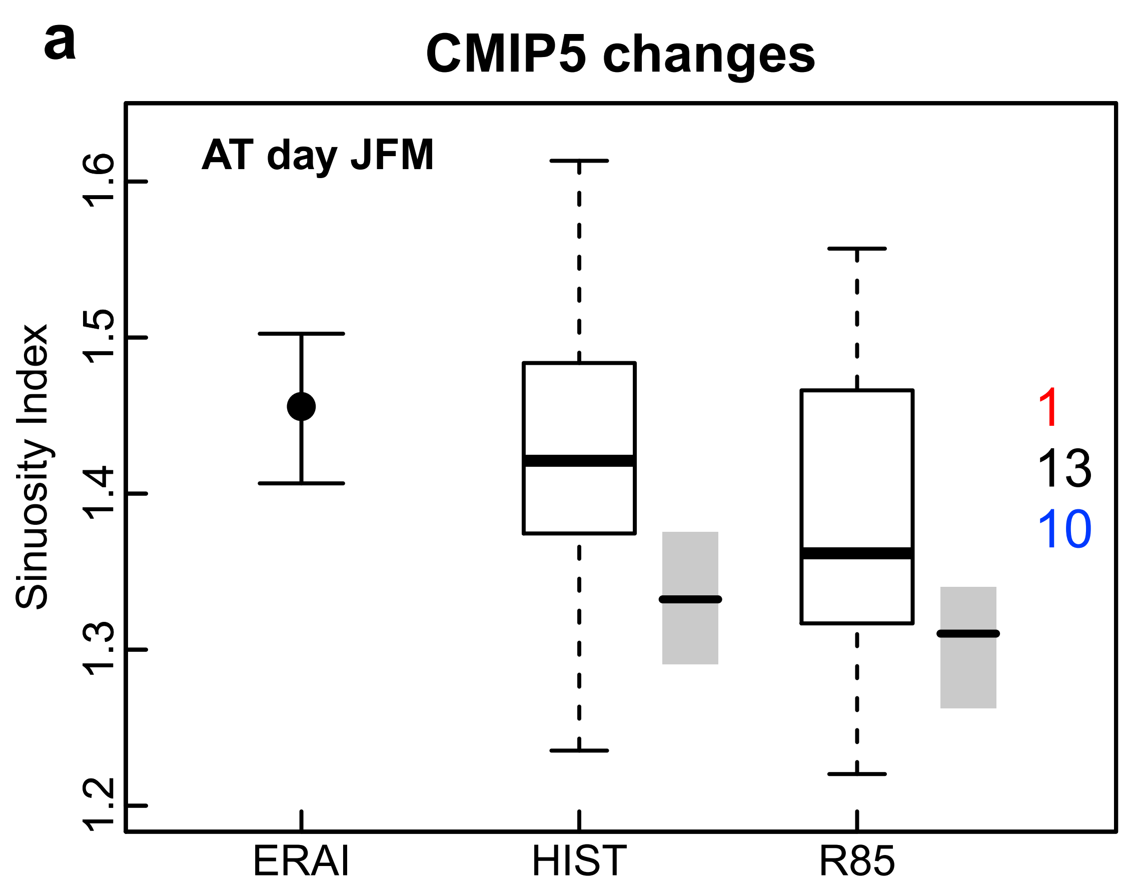
- The sinuosity is a relevant and intuitive metric to characterize the midlatitude flow waviness in all regions and seasons
- Despite a slight increase observed over recent years, the sinuosity is

Sinuosity of midlatitude atmospheric flow in a warming world

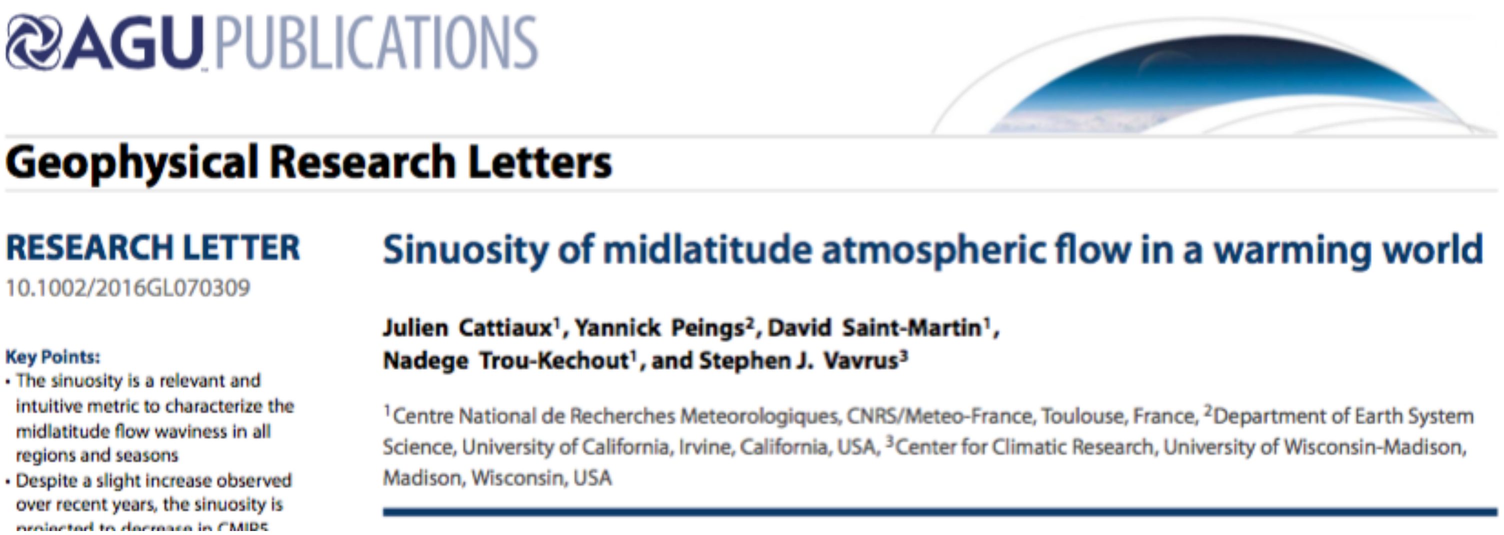
Julien Cattiaux[1], Yannick Peings[2], David Saint-Martin[1], Nadege Trou-Kechout[1], and Stephen J. Vavrus[3]

[1]Centre National de Recherches Meteorologiques, CNRS/Meteo-France, Toulouse, France, [2]Department of Earth System Science, University of California, Irvine, California, USA, [3]Center for Climatic Research, University of Wisconsin-Madison, Madison, Wisconsin, USA





Future Northern Hemisphere jet-streams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Key Points:
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Sinuosity of midlatitude atmospheric flow in a warming world

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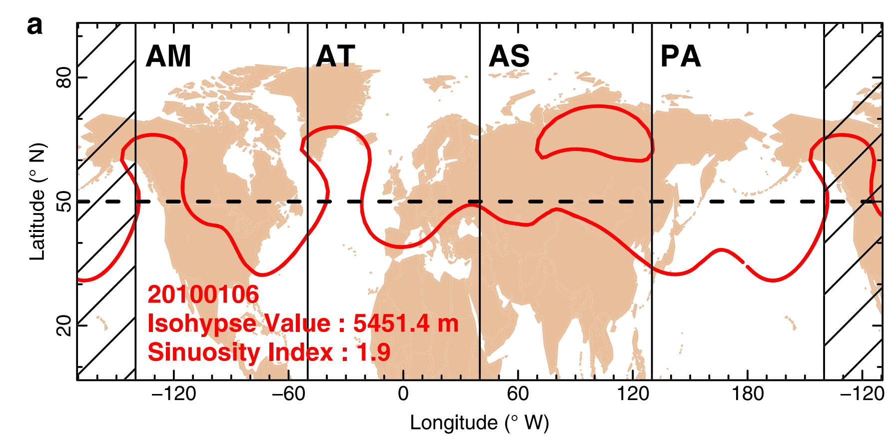
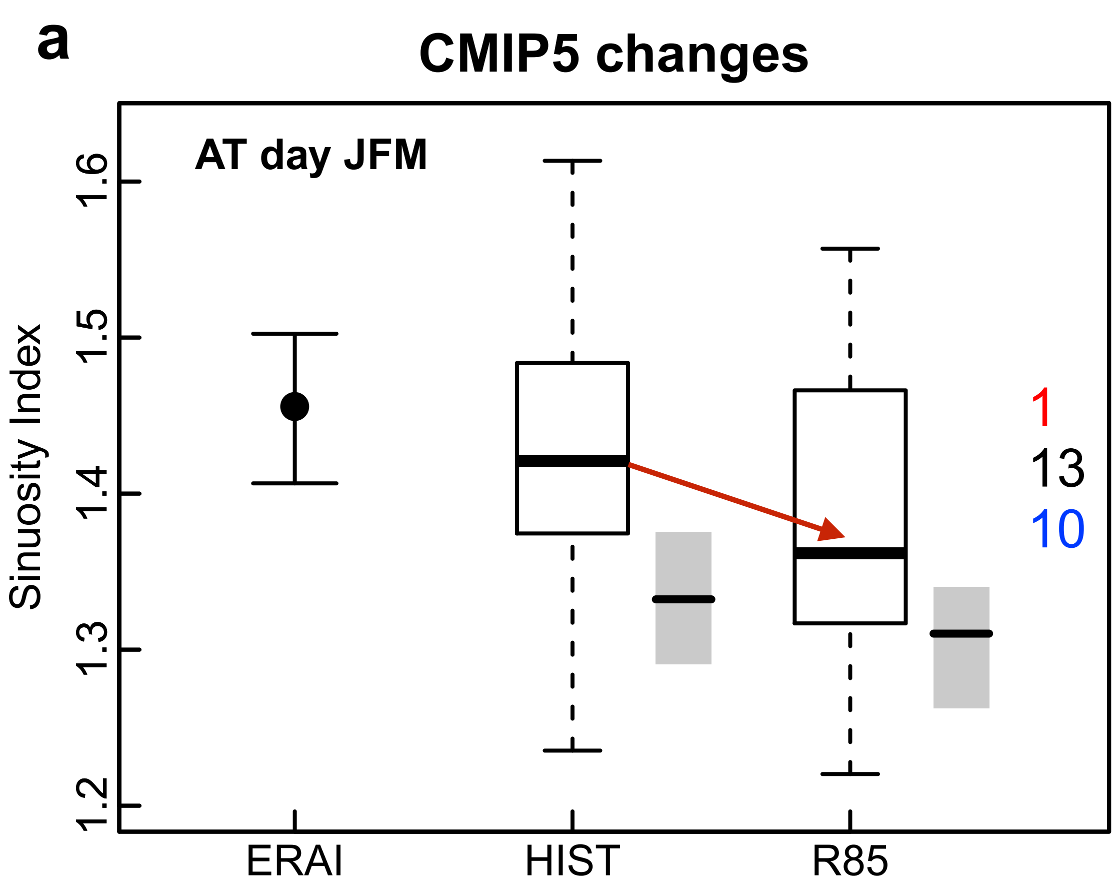
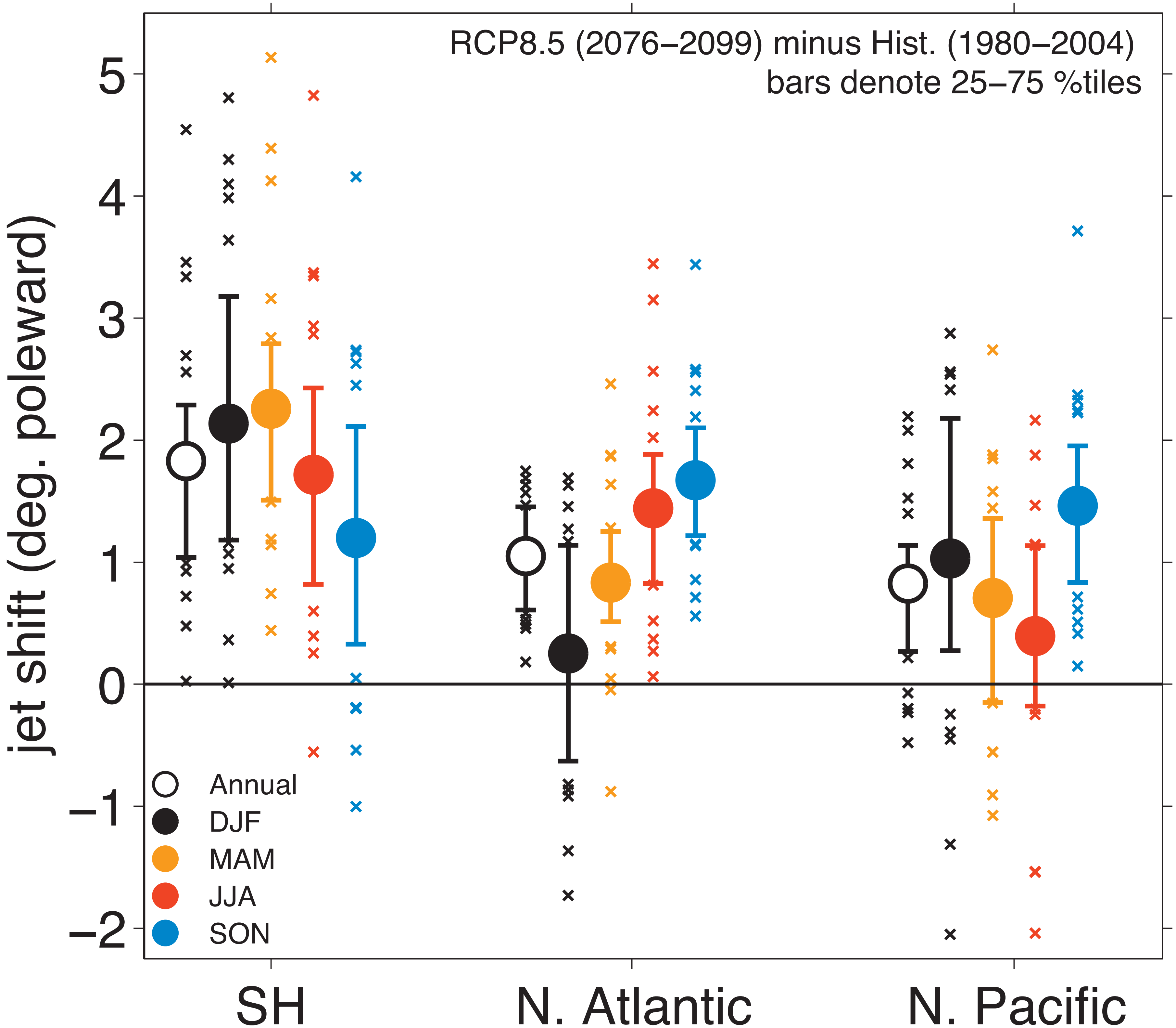




decrease in jet-stream "waviness" in the future

Future Northern Hemisphere jet-streams



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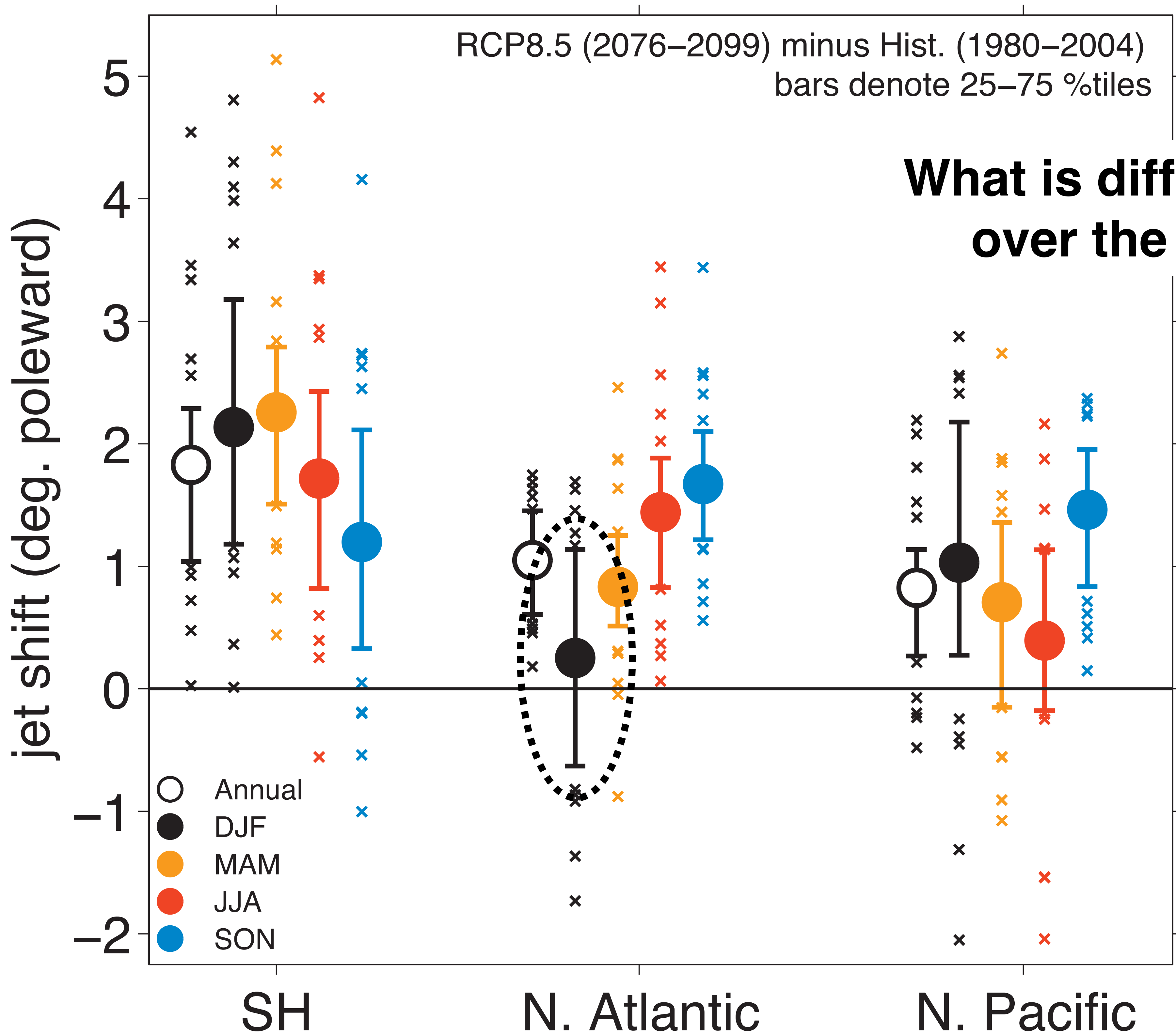
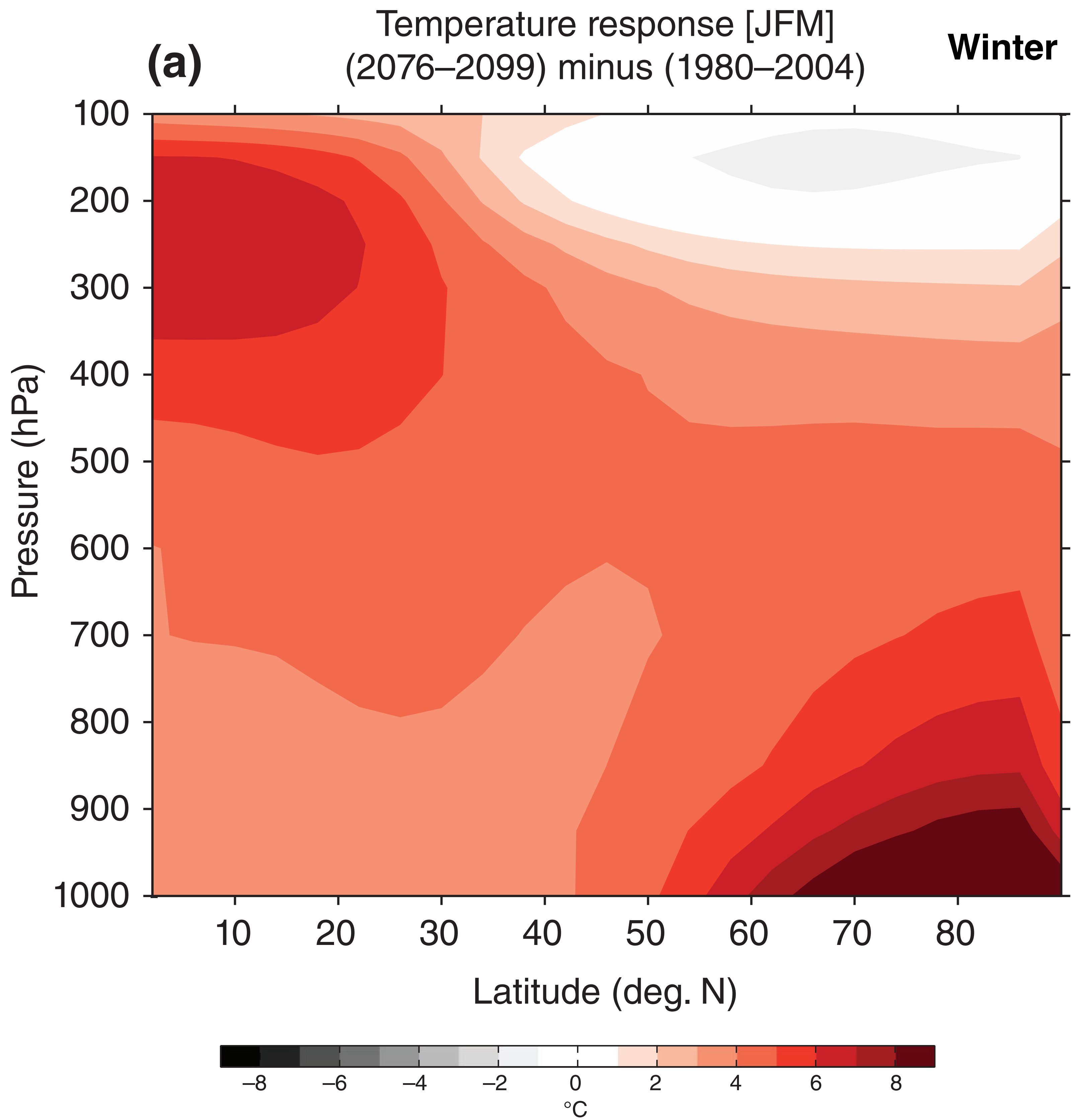


What is different about winter over the North Atlantic?

Elizabeth A. Barnes

Tug-of-war between tropics and pole

- Decrease in surface temperature gradient
- Increase in upper-level temperature gradient
- Who wins this tug-of-war?
  (see discussion” in Held (1993; BAMS))



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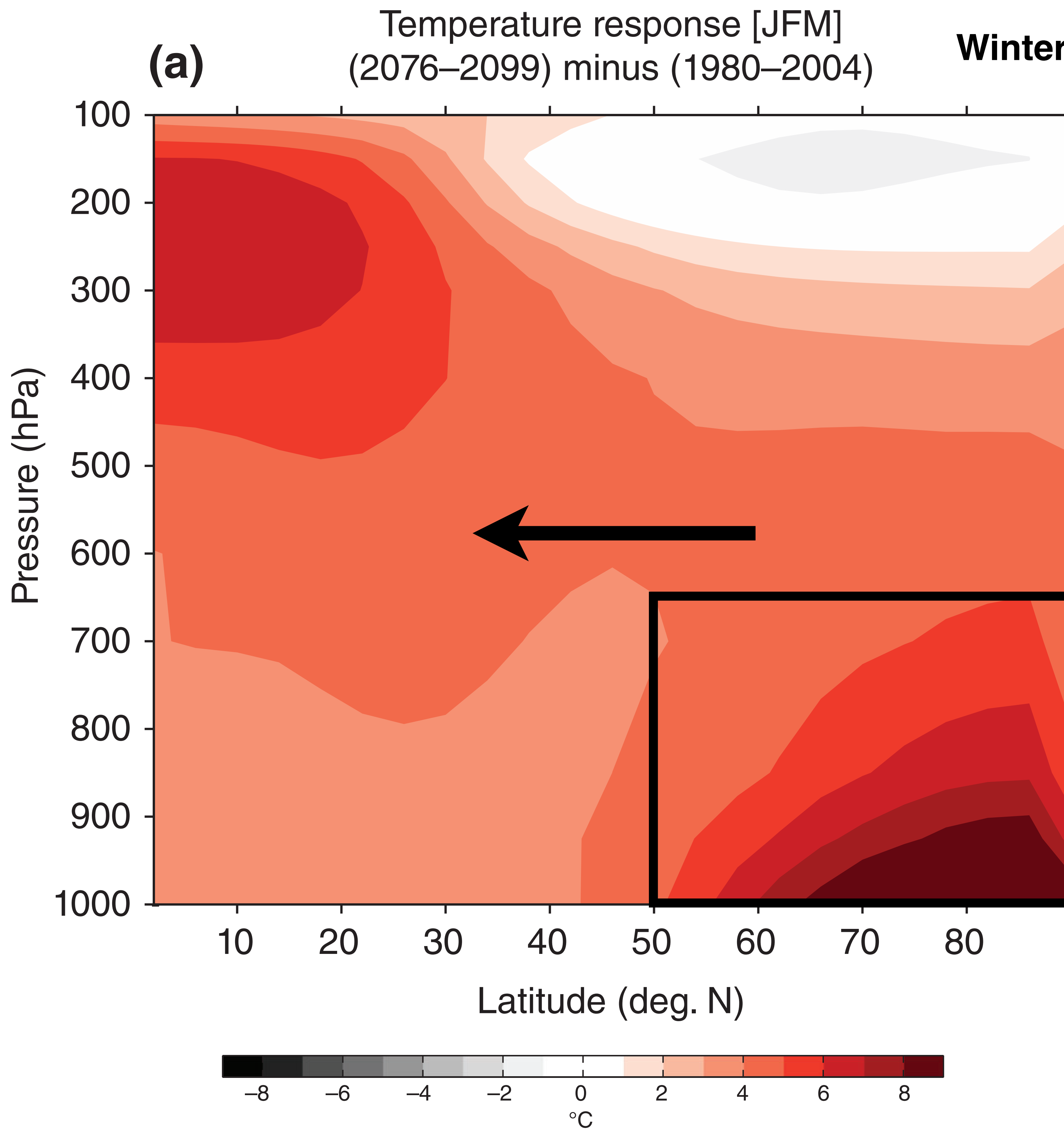

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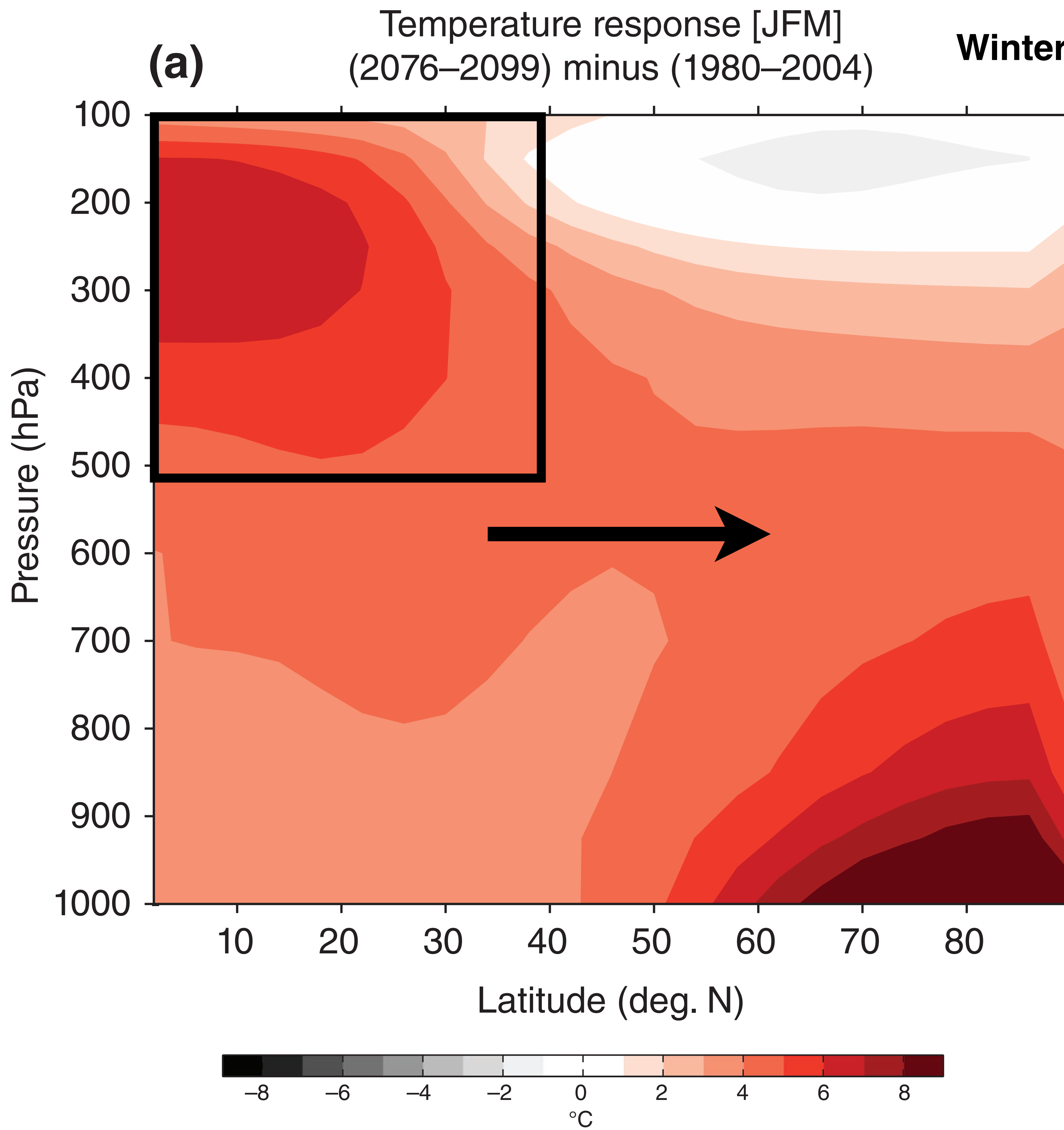

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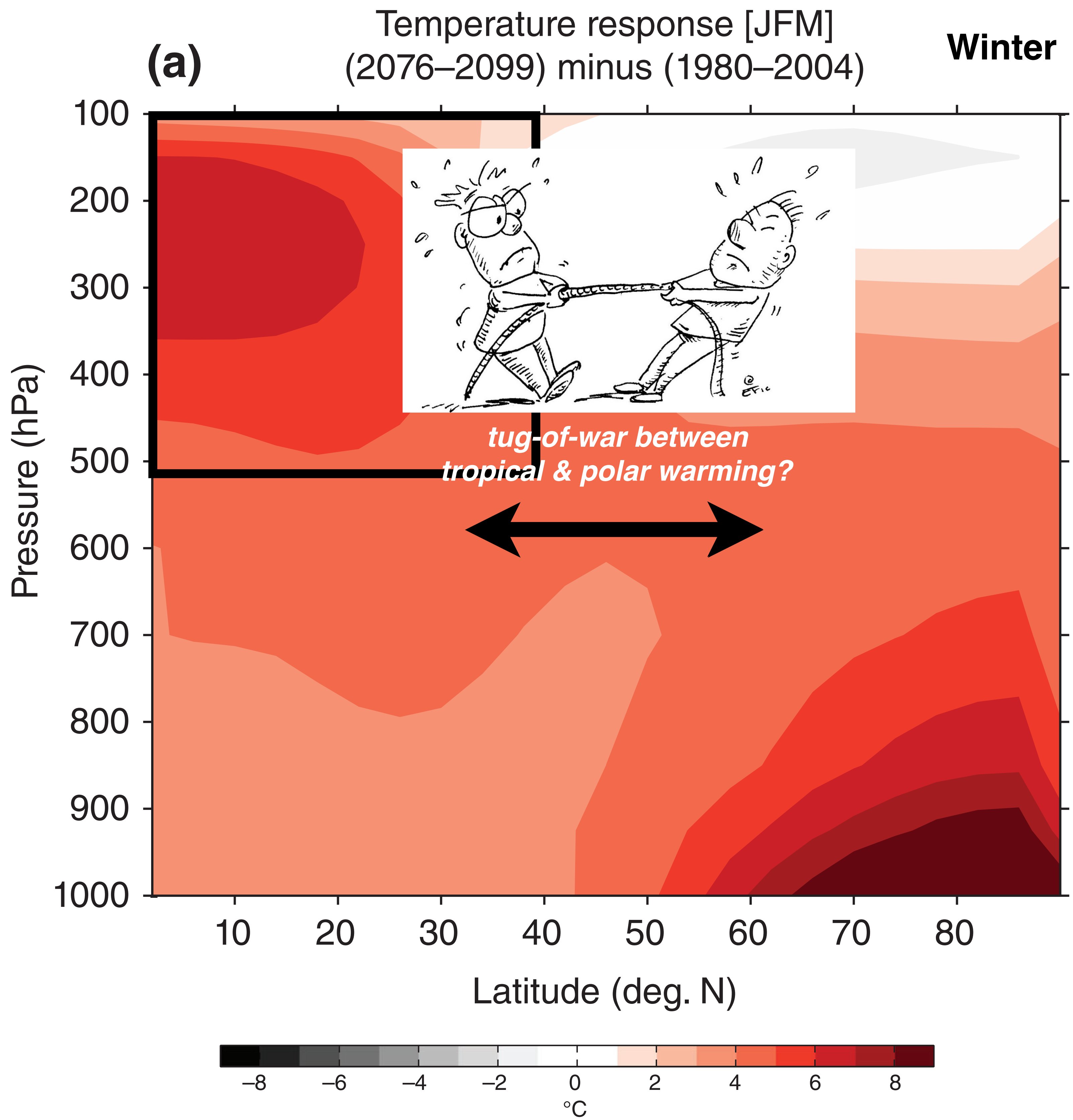

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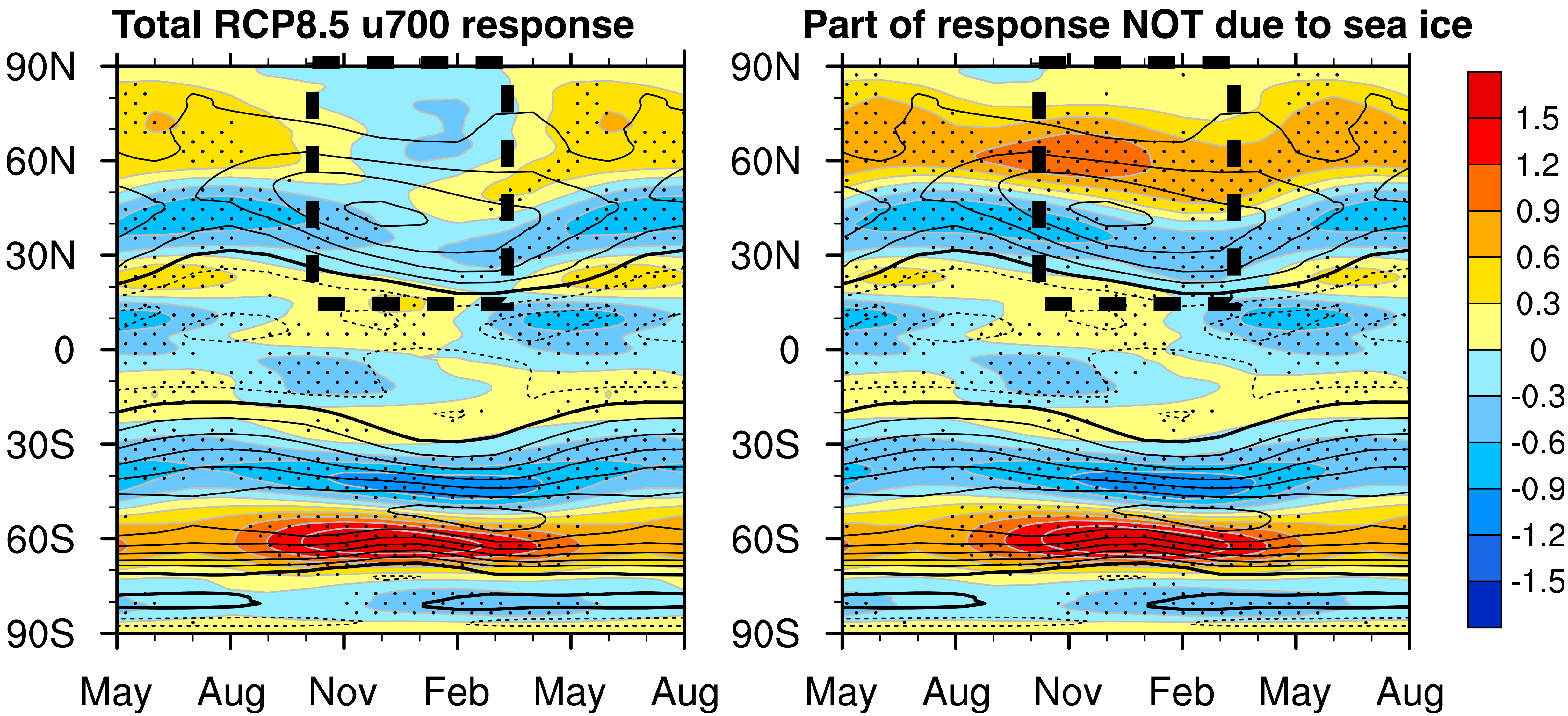

- In CCSM4, the sea ice loss effects appears to <u>cancel</u> the poleward shift of the jet
- In other CMIP5 models, the poleward shift "wins"

coupled CCSM4 simulations
with additional long wave radiative fluxes in the ice model
Deser, Tomas, et al. (2015; JCLI)

Will it?

Perhaps. But not in the way many papers suggest.

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Perhaps. But not in the way many papers suggest.

1. **Temperature variance decreases.**
2. **No consensus** in most jet-stream metrics (e.g. speed) in CMIP5 models, even though all exhibit Arctic amplification.
3. **Blocking decreases…maybe.**
4. **Jet-stream waviness decreases.**
5. **Evidence of a modulating effect** but Arctic warming will not determine the net jet-stream response.

Wrap-up

Conclusions

(1) **Can** Arctic warming influence the midlatitude jetstream?

(2) **Has** Arctic warming significantly influenced the midlatitude jetstream?

(3) **Will** Arctic warming significantly influence the midlatitude jetstream?

Conclusions

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Yes. There is substantial model evidence of an influence.

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Unlikely. The evidence-to-date does not support this conclusion - internal variability dominates. However, this doesn't exclude the possibility of a small effect.

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Yes. There is substantial model evidence of an influence.

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Unlikely. The evidence-to-date does not support this conclusion - internal variability dominates. However, this doesn't exclude the possibility of a small effect.

(3) **Will** Arctic warming significantly influence the midlatitude jetstream?

Perhaps…but not in the way some current hypotheses suggest. It may play a modulating role, rather than determining the sign of the response.

Conclusions

(1) **Can** Arctic warming influence the midlatitude jetstream?

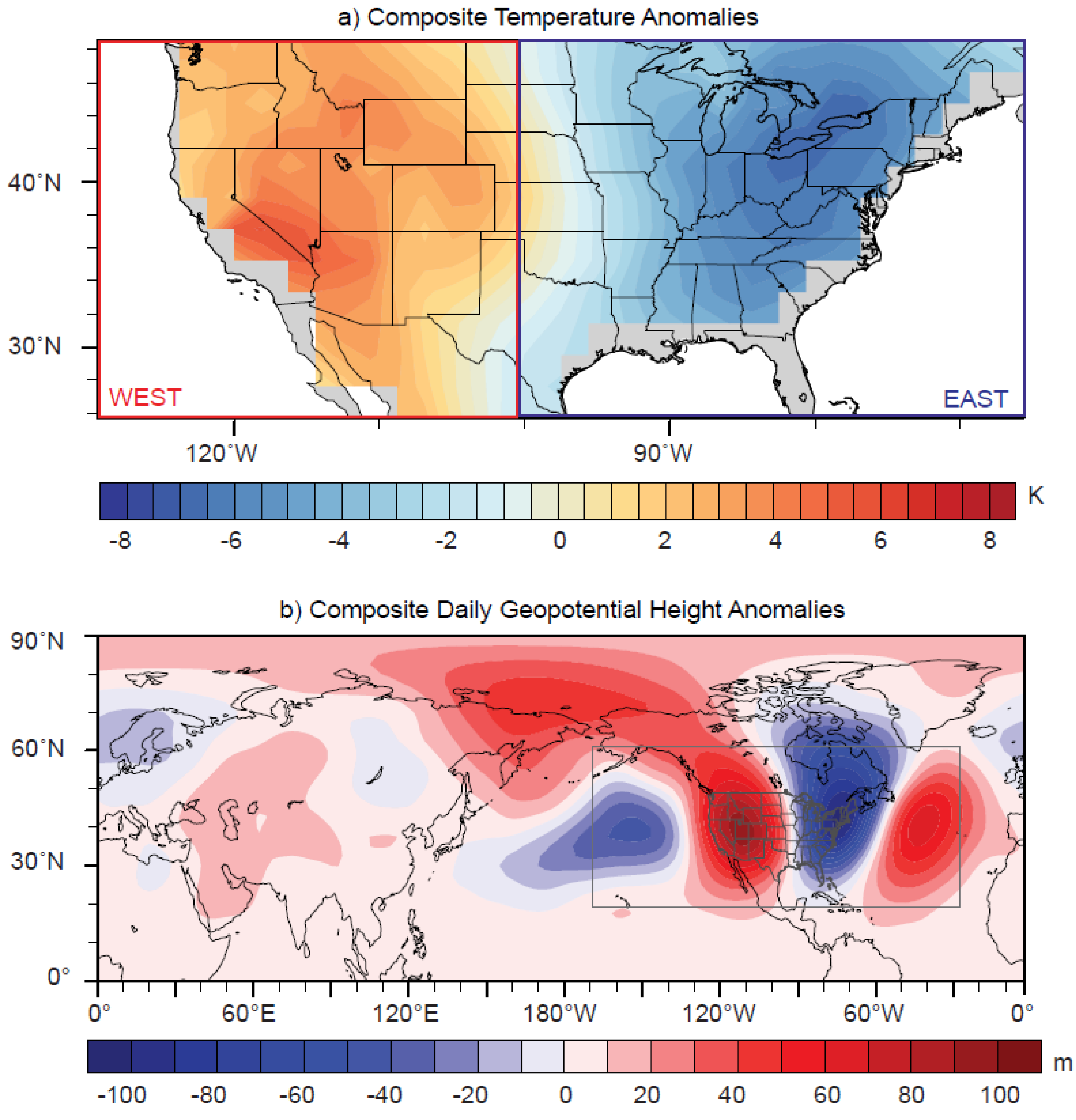
(2) **Has** Arctic warming significantly influenced the midlatitude jetstream?

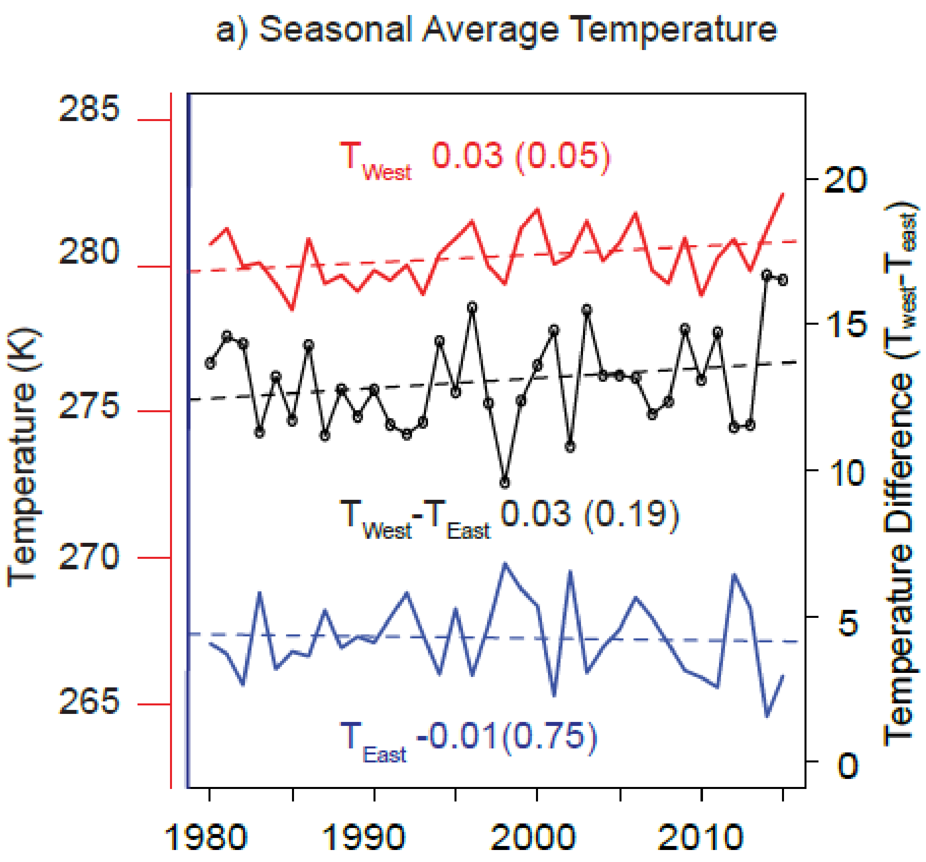
(3) **Will** Arctic warming significantly influence the midlatitude jetstream?

The midlatitude circulation is **noisy** and **complex** - as we continue to investigate a possible link with Arctic sea ice loss we must keep in mind that **the Arctic does not and will not act in isolation**.

EXTRA SLIDES

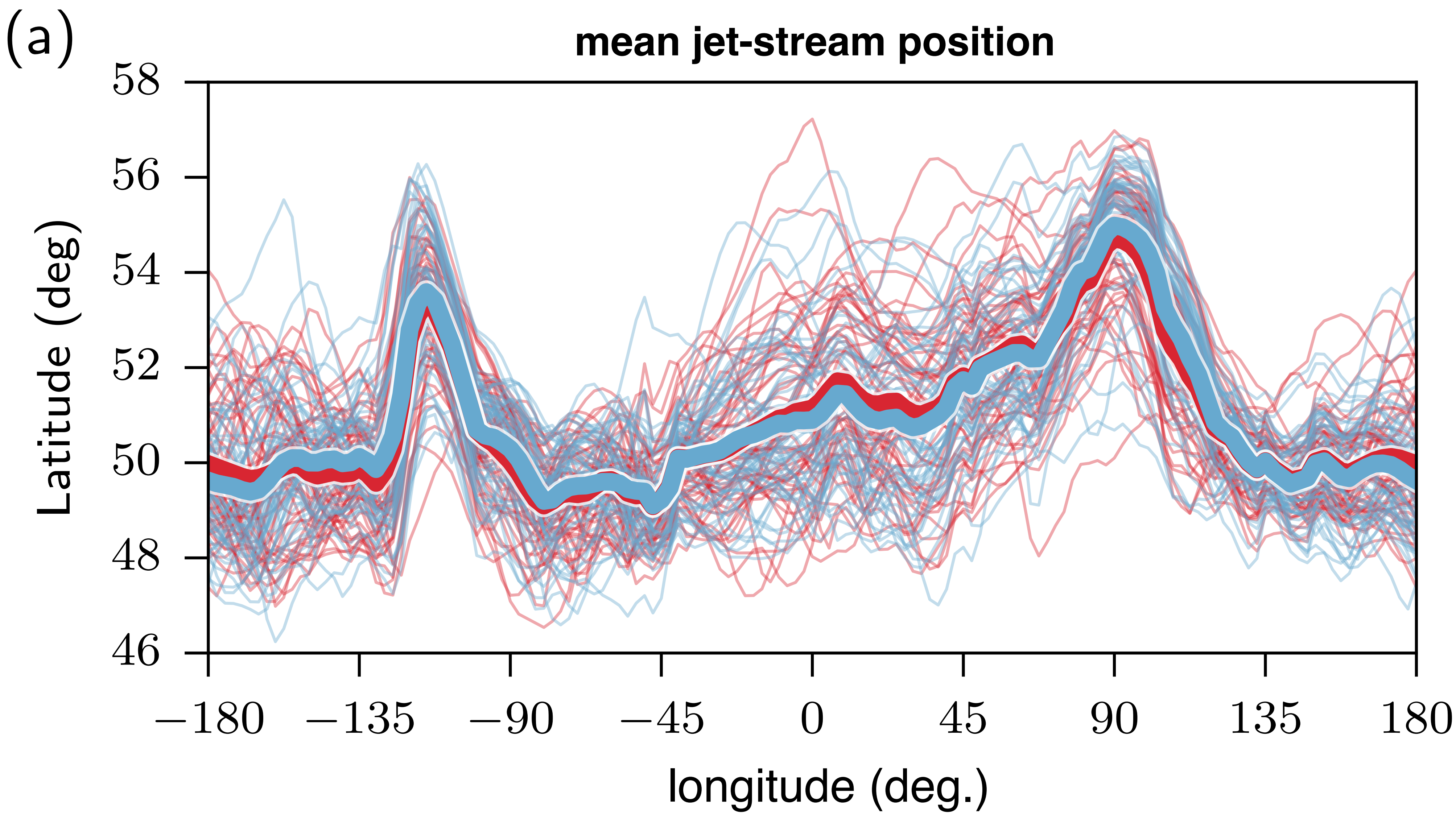
Changes in the North American winter dipole?





Singh et al. (2016; JGR)

Non-robust response and nonlinearities

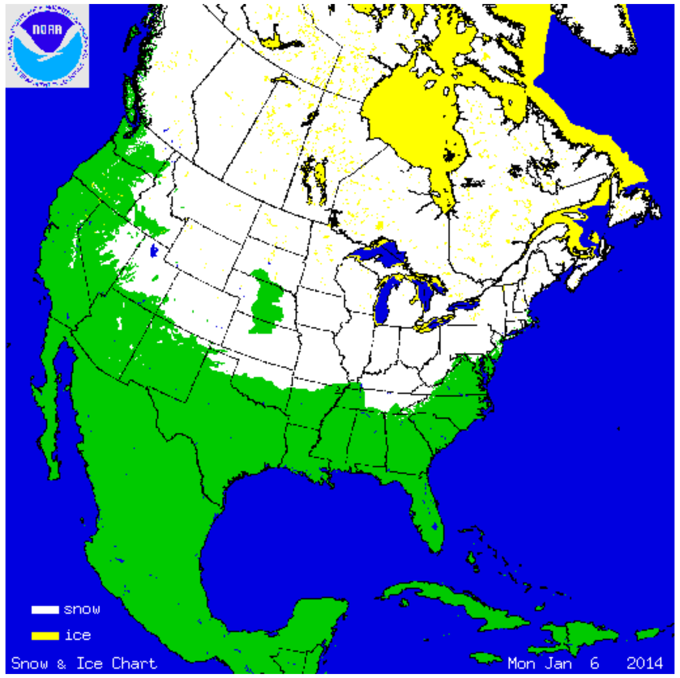


increased sea ice cover by 1 sigma
decreased sea ice cover by 1 sigma

CAM5 simulations: 55 years per simulation
Chen et al. (2016; JCLI)

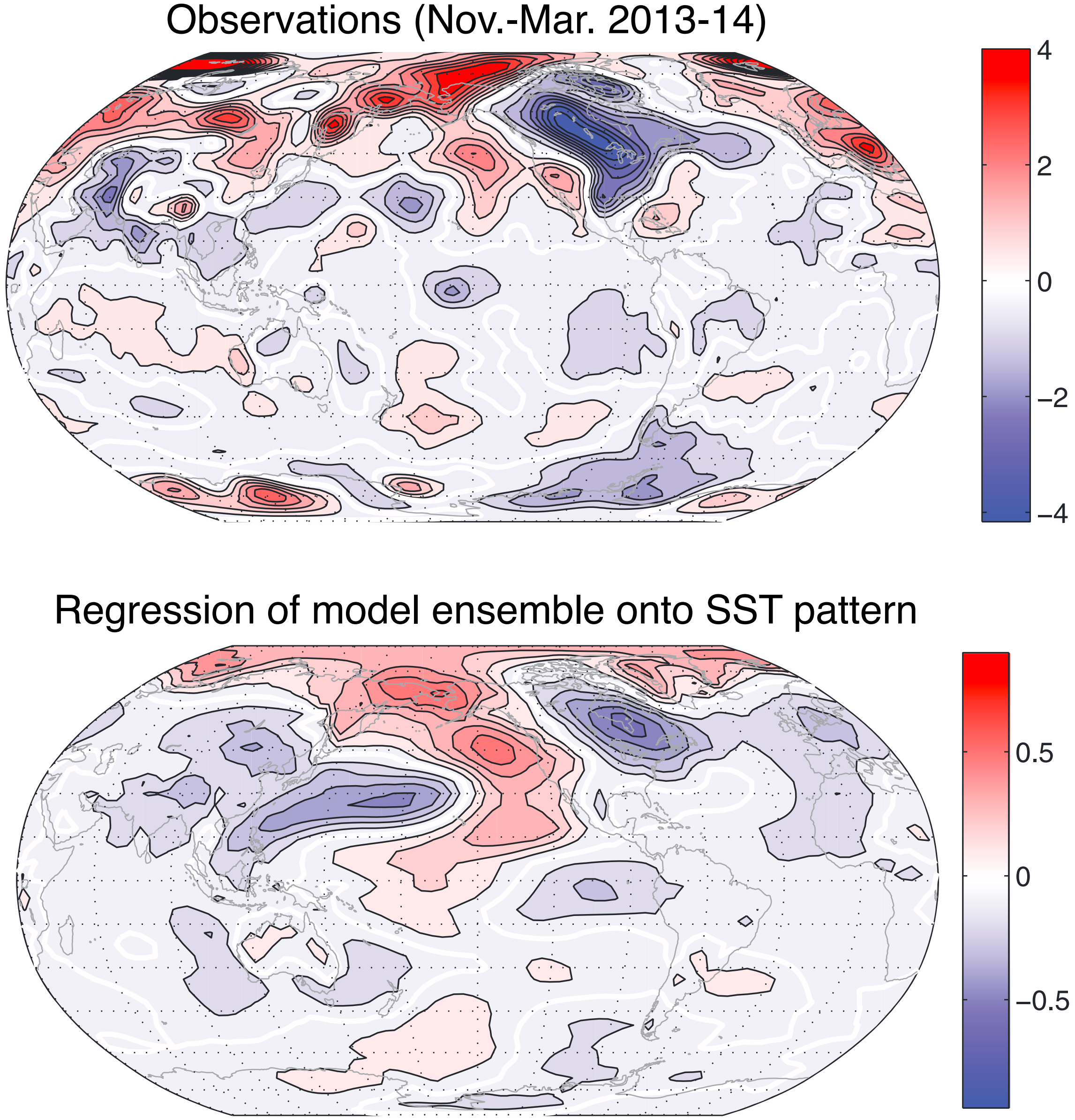
Which way does causality point?

Winter of 2013-14 was unusually cold…



Snow cover (white)
Jan. 6, 2014

Surface Air Temperature

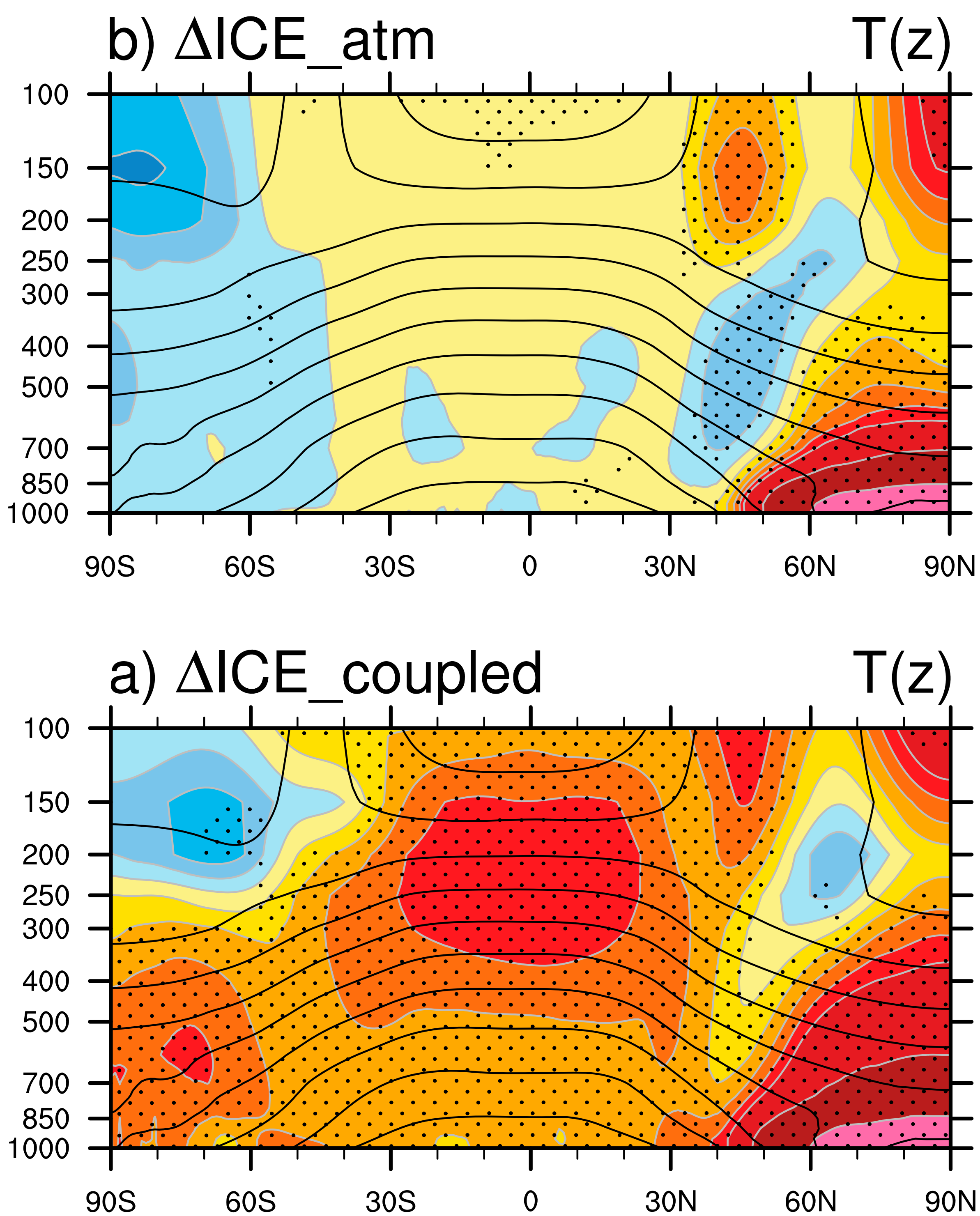


- Winter of 2013-14 was very cold over the US and Canada. It has been suggested that Arctic sea ice loss may have been responsible

- However, recent work suggests that the Pacific SST's may have been the proximate cause

Hartmann (2015; GRL)

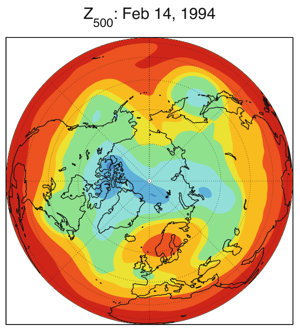
Coupled vs. AMIP simulations



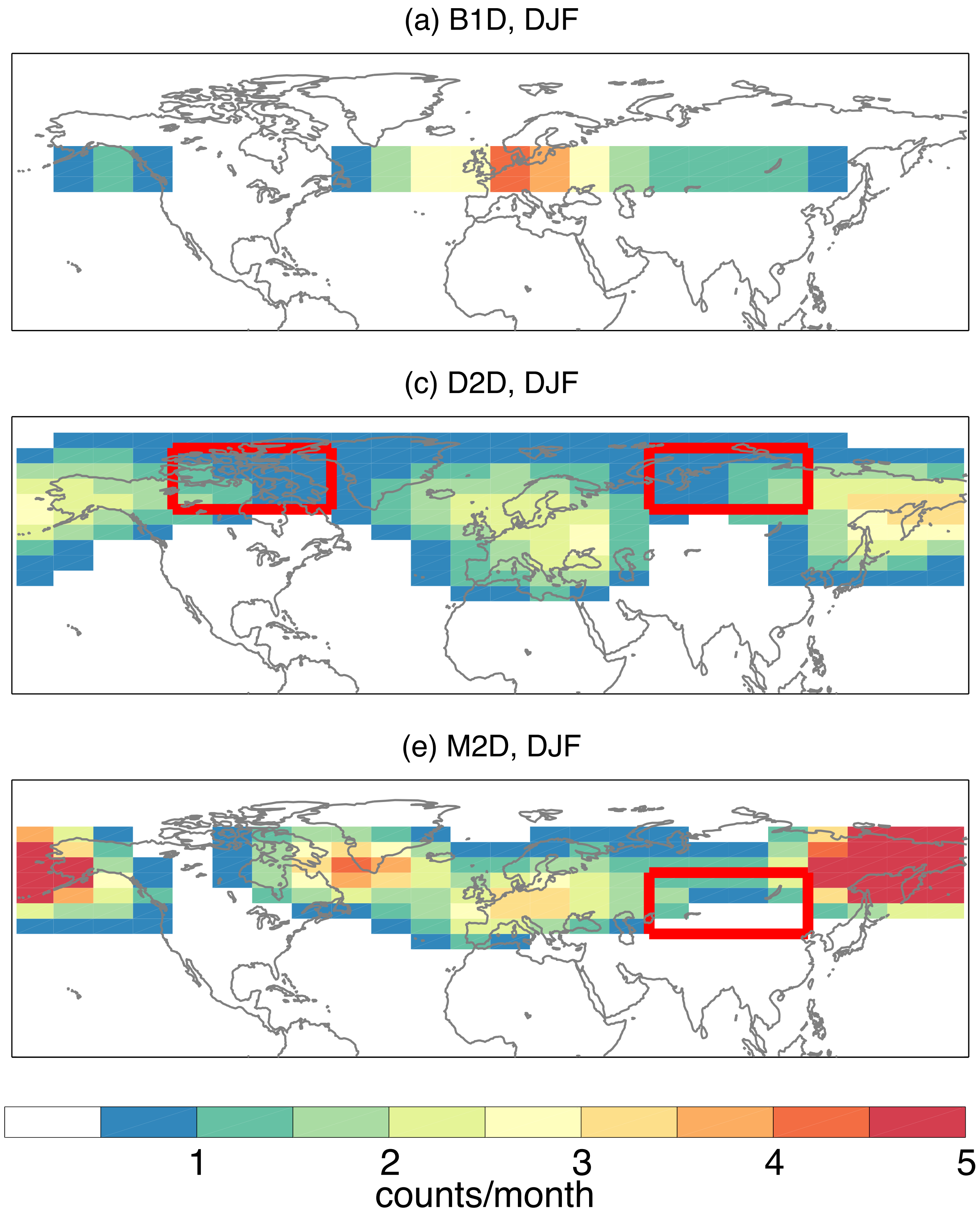
AMIP simulations may underestimate sea ice-induced warming

coupled CCSM4 simulations
with additional long wave radiative fluxes in the ice model
Deser, Tomas, et al. (2015; JCLI)

Internal atmospheric variability is large



example blocking high
500 hPa Z anomaly



- 3 blocking identification methods
- 4 seasons
- 4 reanalyses
- 3 different time periods

3 different blocking metric climatologies

B1D: Barnes et al . (2012)
D2D: Dunn-Sigouin et al. (2013)
M2D: Masato et al. (2013)

Barnes et al. (2014); GRL

Public belief

INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **34**: 1723–1728 (2014)
Published online 26 July 2013 in Wiley Online Library
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Royal Meteorological Society

Short Communication

Arctic warming and your weather: public belief in the connection

Lawrence C. Hamilton[a*] and Mary Lemcke-Stampone[b]
[a] *Department of Sociology, University of New Hampshire, Durham, NH 03824, USA*
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If the Arctic region becomes warmer in the future, do you think that will have **major effects**, **minor effects** or **no effects** on the weather where you live?

[1500 interviews of New Hampshire residents]

Hamilton and Lemcke-Stampone (2013; IJC)

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major effects:	**60%**
minor effects:	**29%**
no effects:	**5%**
don't know:	**6%**

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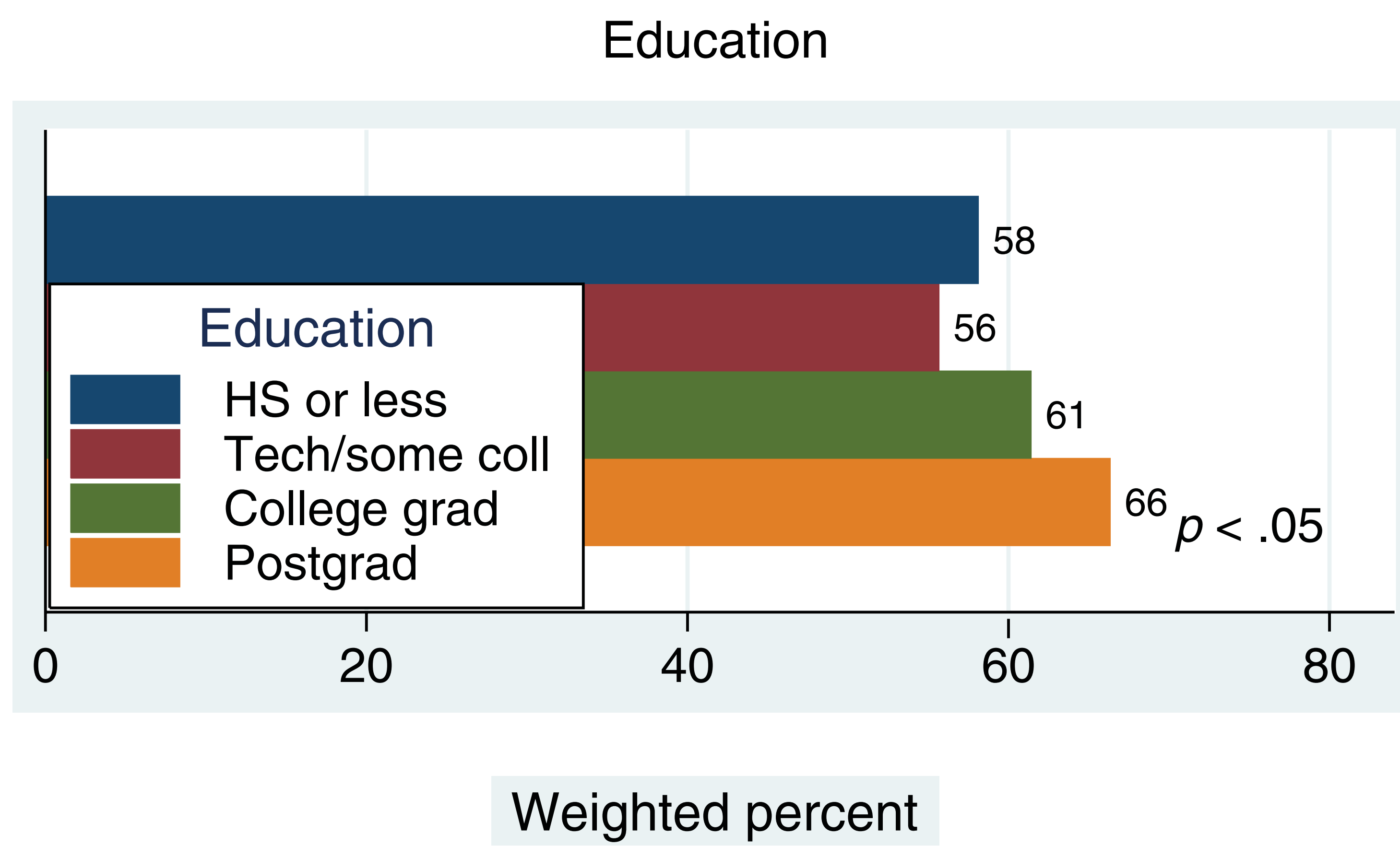

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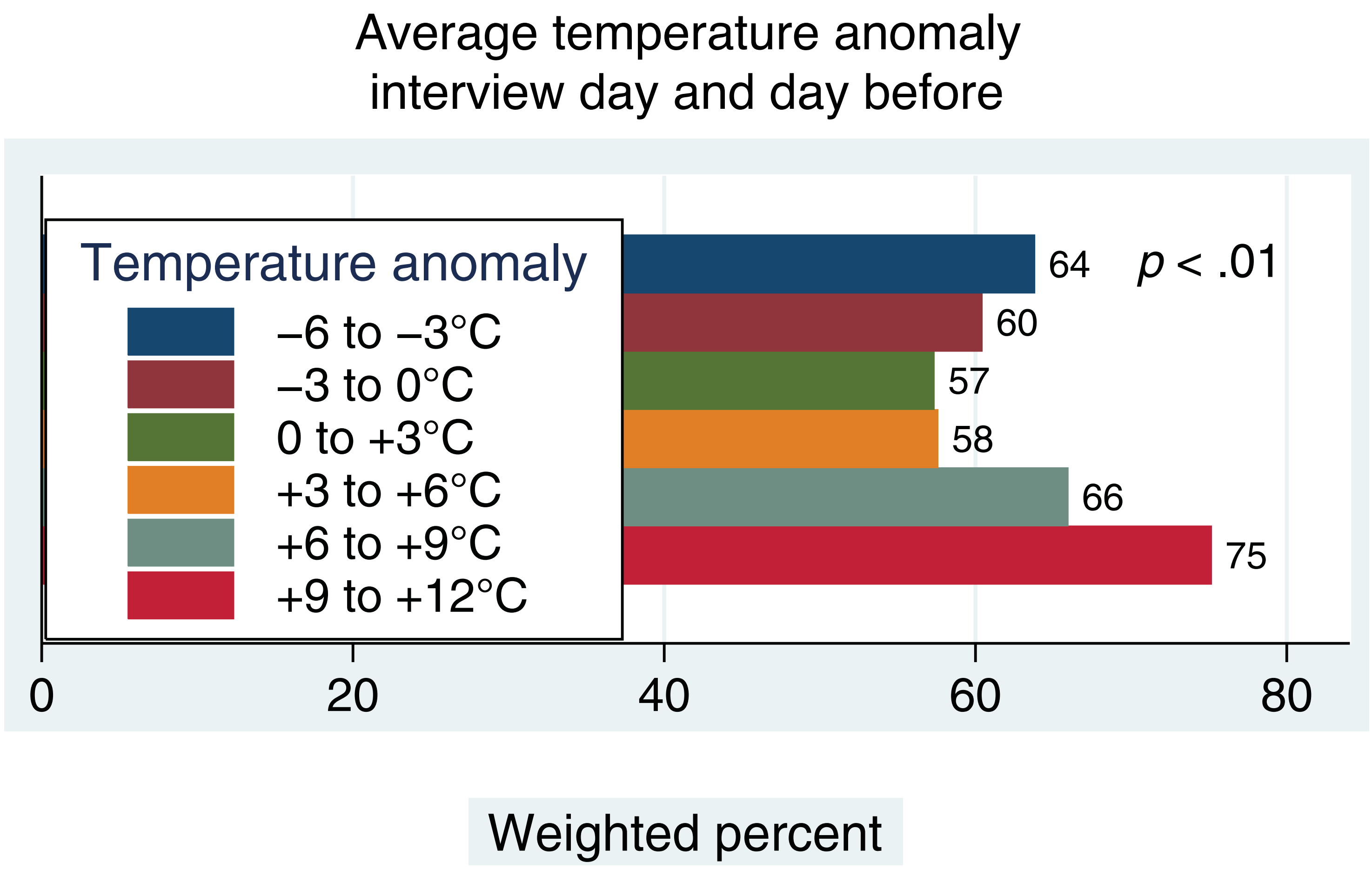
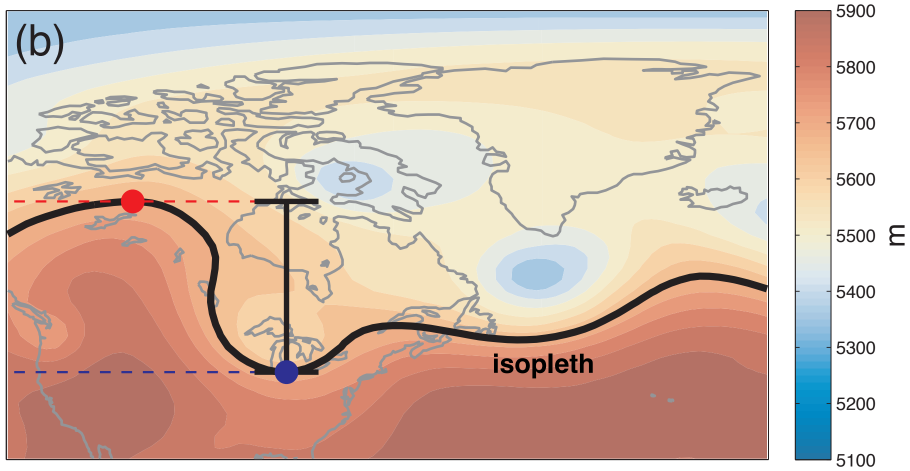
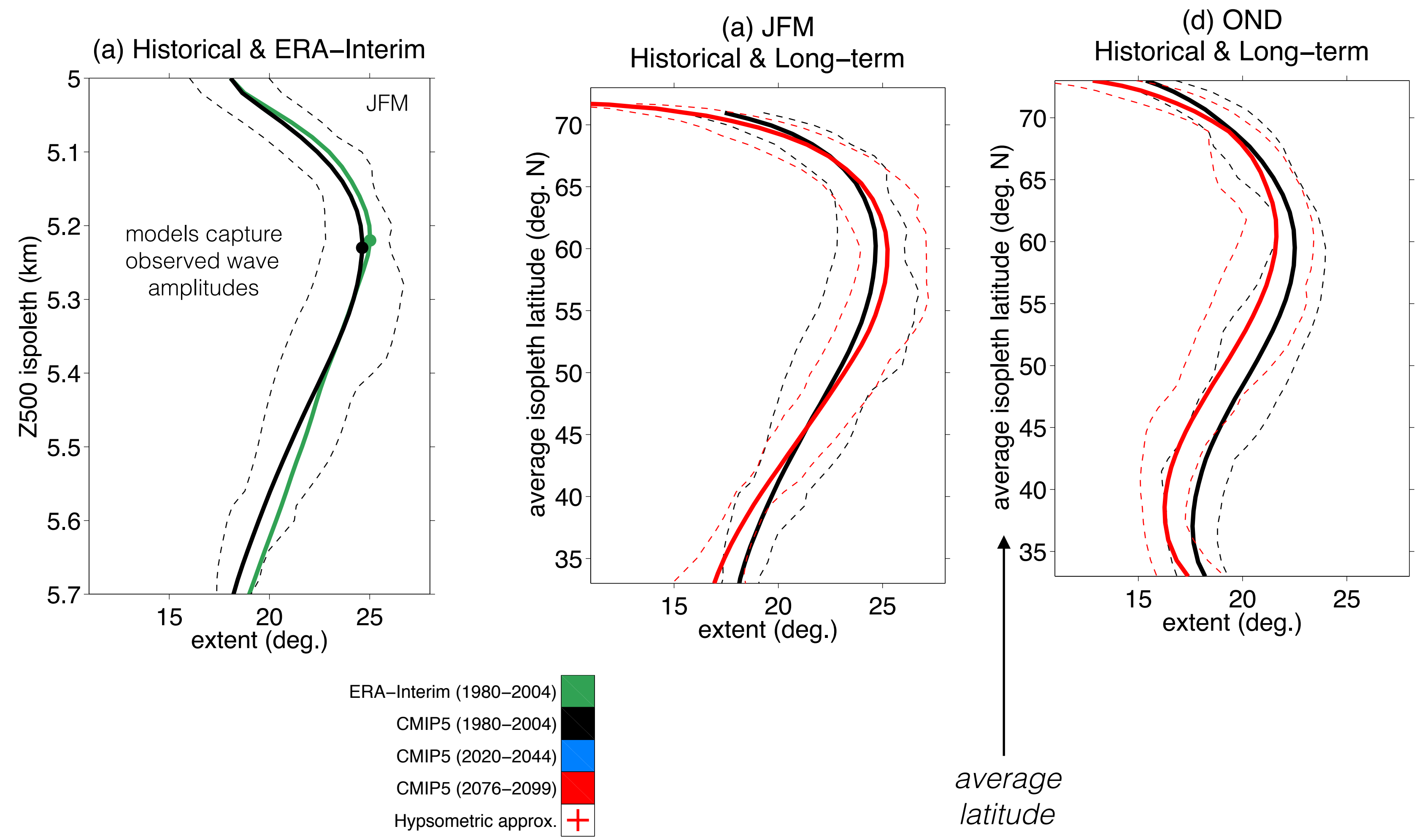


Hamilton and Lemcke-Stampone (2013; IJC)

Jet “waviness”



Barnes (2013)

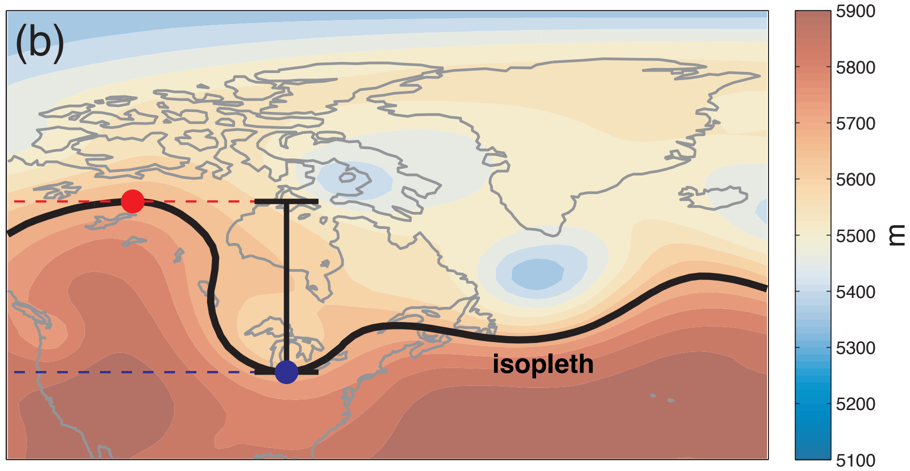


- Has been suggested that wave amplitude increases with Arctic amplification
  (Francis & Vavrus (2012; GRL))

- However, models show *decreases* or no clear change over North America and the North Atlantic

Barnes & Polvani (2015; JCLI)

Wave amplitudes in the future



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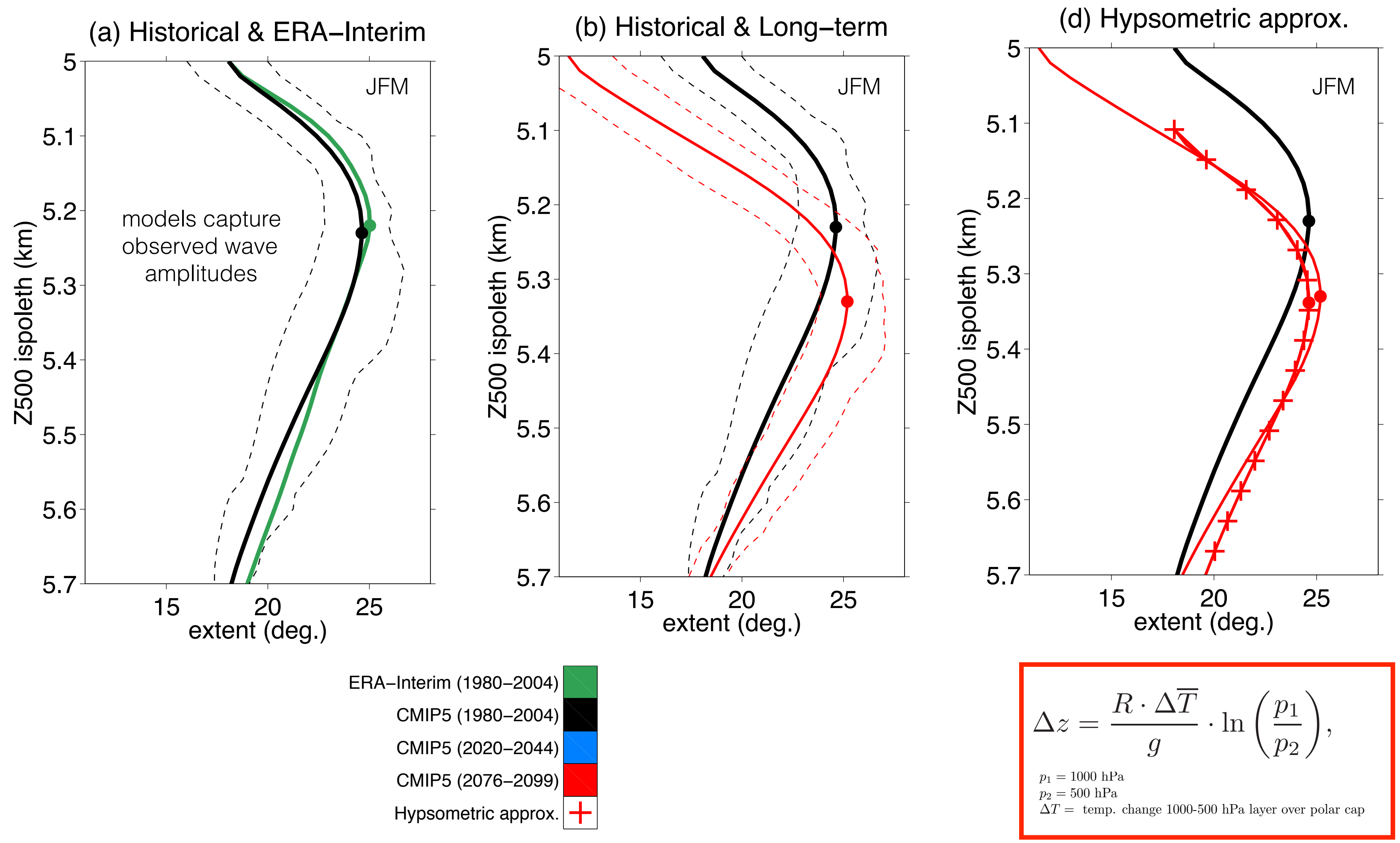


$$\Delta z = \frac{R \cdot \Delta \overline{T}}{g} \cdot \ln\left(\frac{p_1}{p_2}\right),$$

$p_1 = 1000$ hPa
$p_2 = 500$ hPa
$\Delta T =$ temp. change 1000-500 hPa layer over polar cap

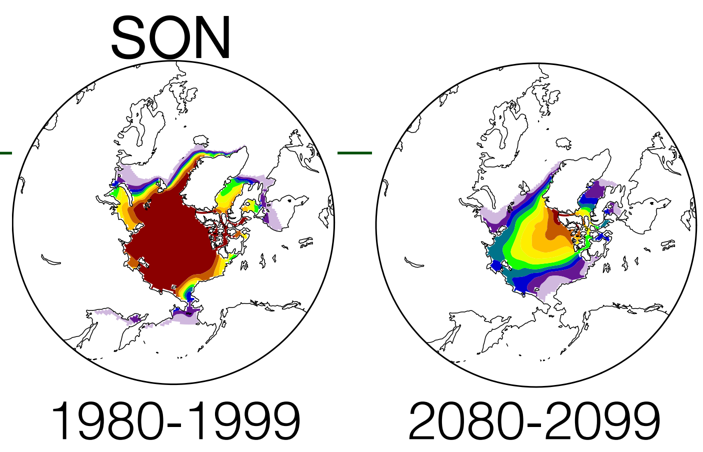
- Has been suggested that wave amplitude increases with Arctic amplification
  (Francis & Vavrus (2012; GRL))

- Let's look further into the CMIP5 wave amplitude response

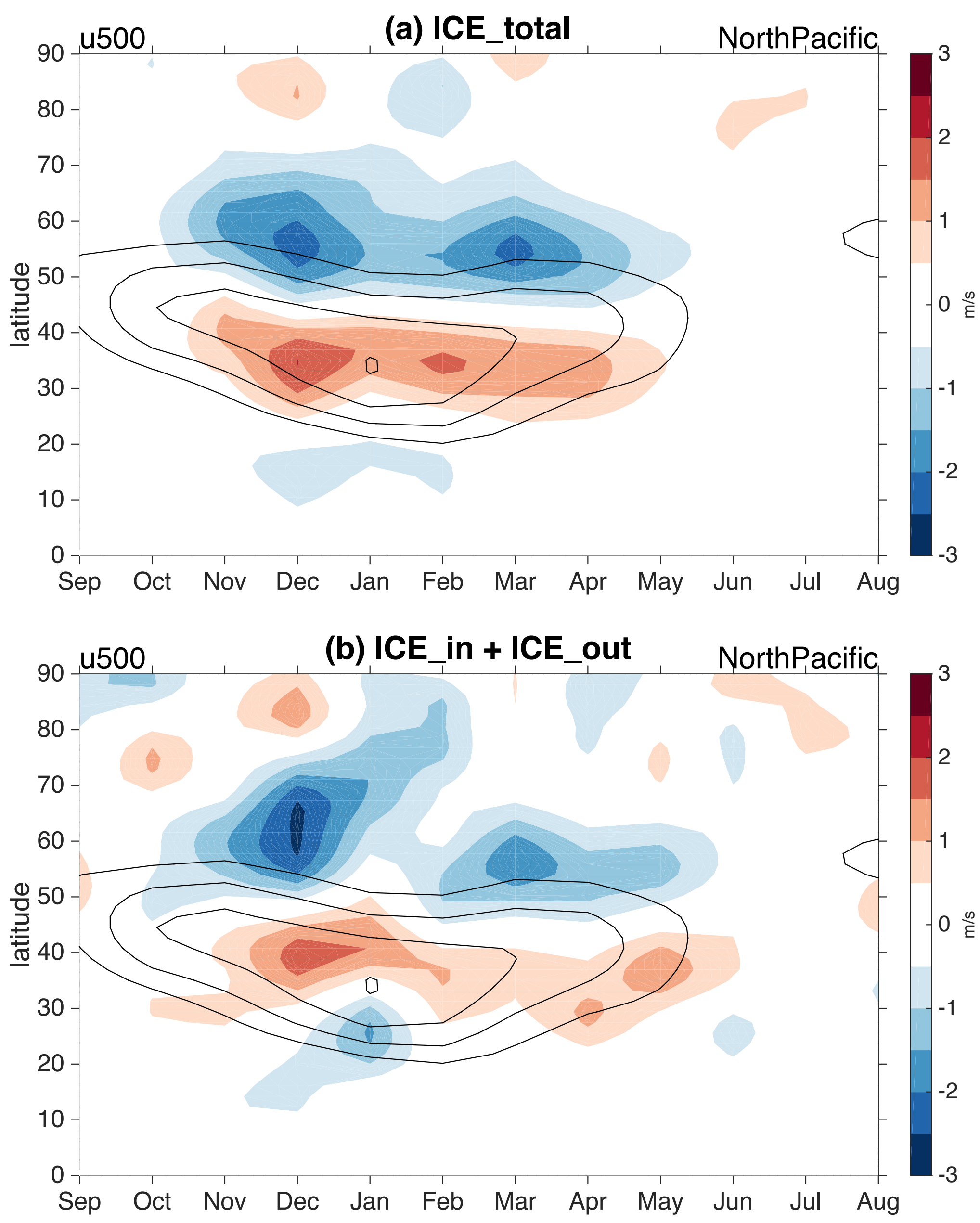
- other seasons show decreases everywhere

Barnes & Polvani (2015; JCLI)

Nonlinear response

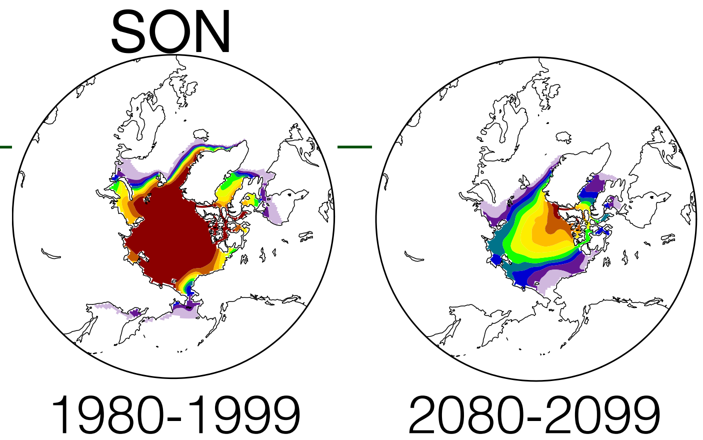


North Pacific jet response to sea ice loss **inside** and **outside** of the Arctic circle.



based on 160-year WACCM simulations of Sun et al. (2015; JCLI)

Nonlinear response



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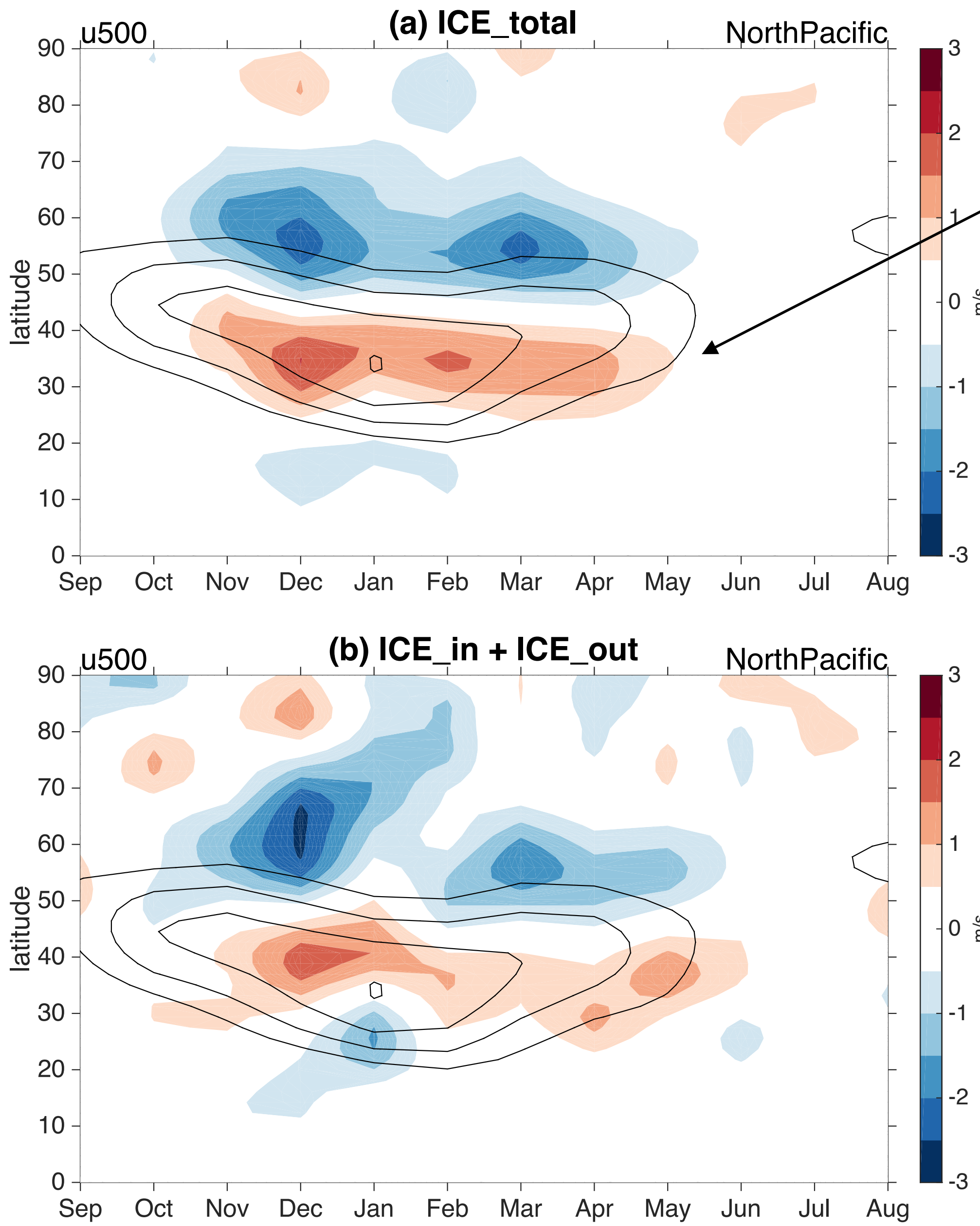
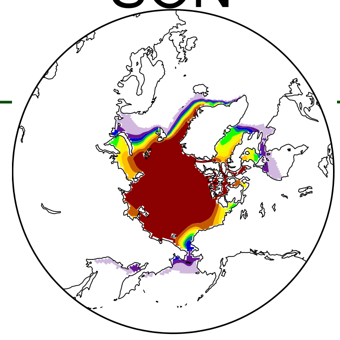


jet shifts further equatorward for total forcing

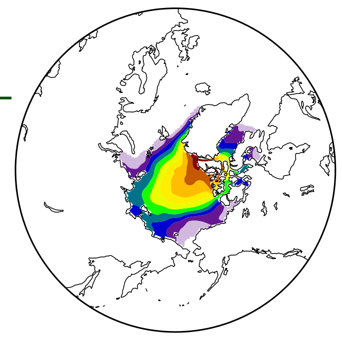
based on 160-year WACCM simulations of Sun et al. (2015; JCLI)

Nonlinear response

SON



1980-1999



2080-2099

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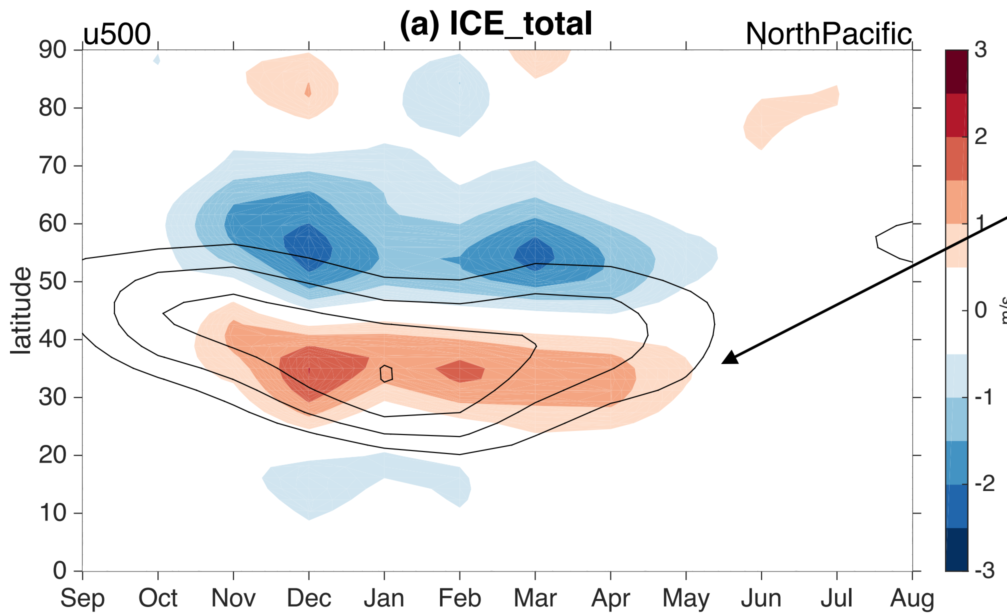

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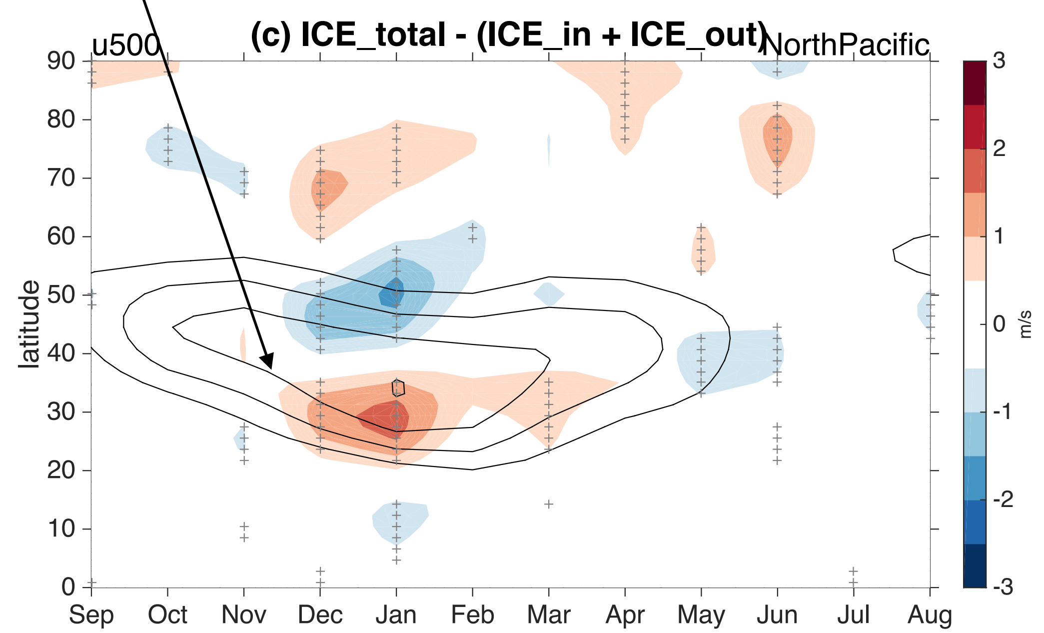

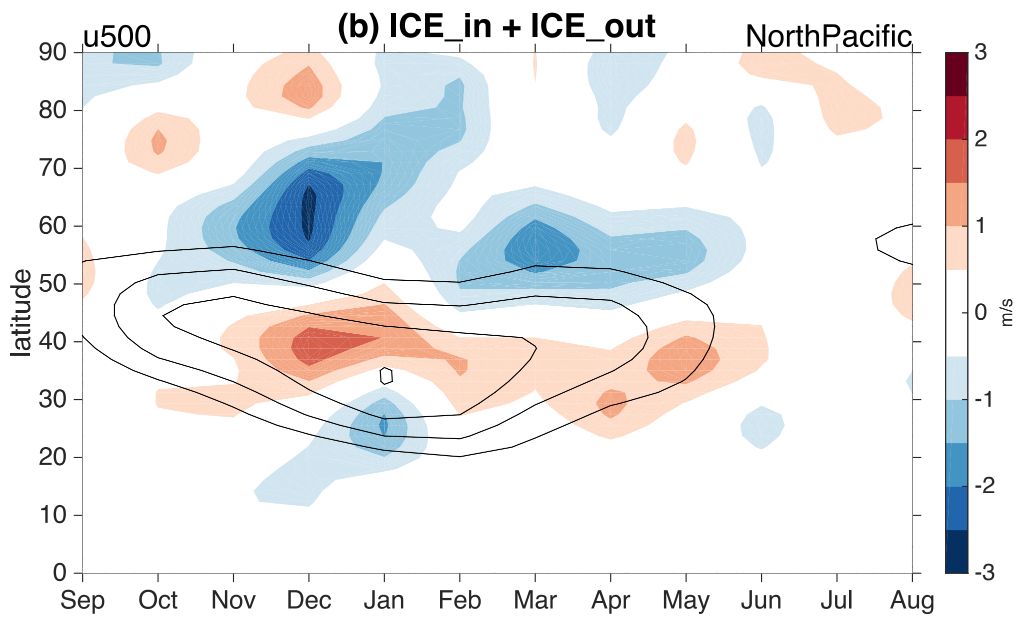

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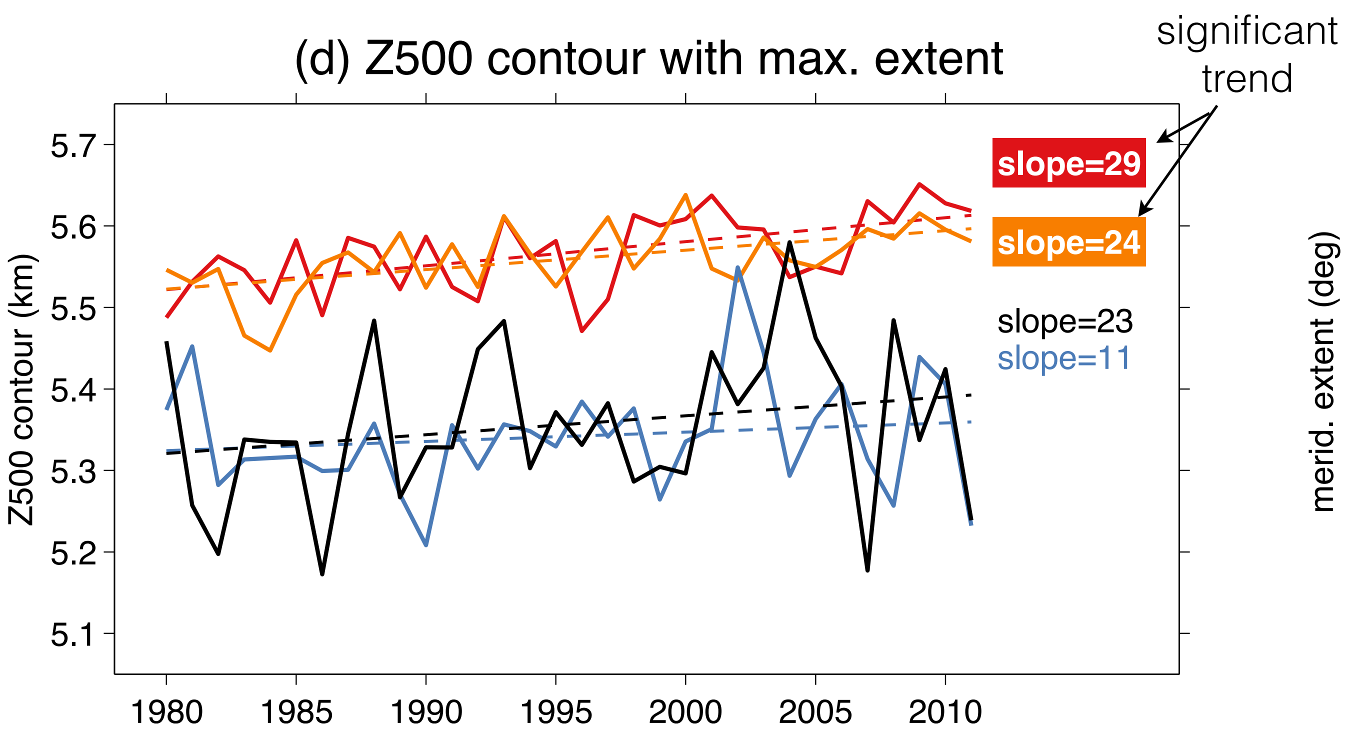
Arctic amplification and Rossby-wave scales

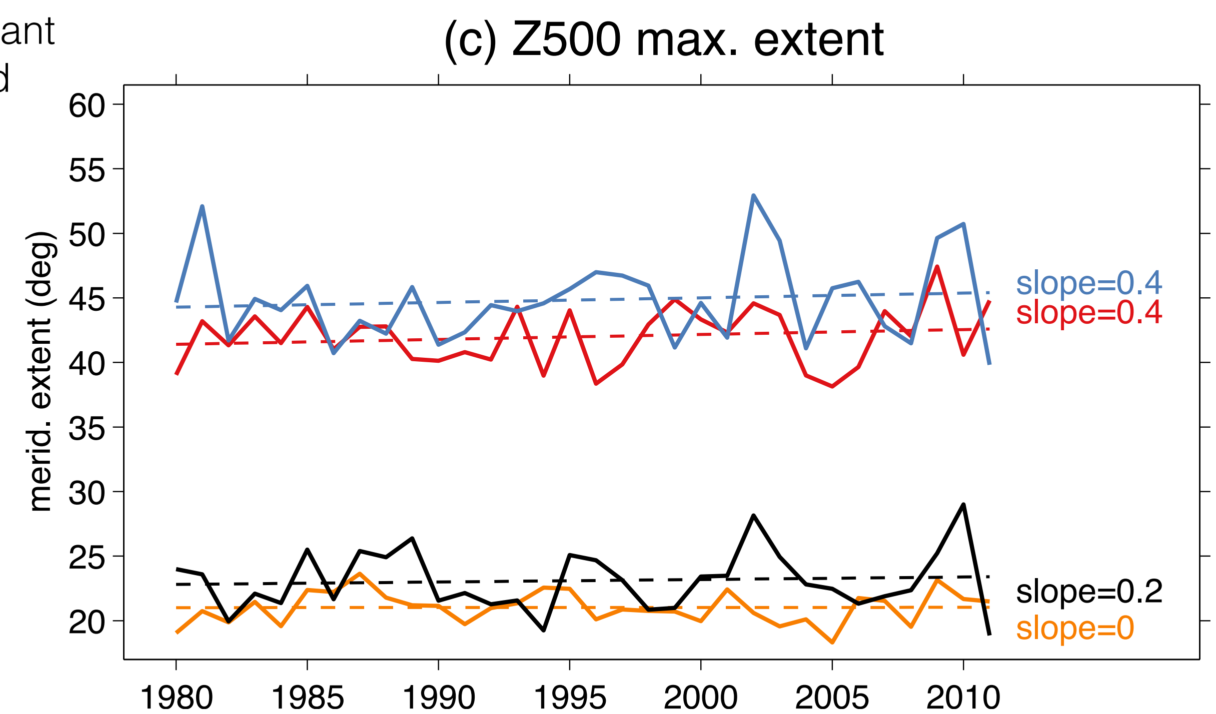
Barnes (2013) suggest that trends in wave extents may not be robust if

1. daily wave extents are analyzed instead of seasonal maxima and minima

2. a larger range of isopleths are analyzed: *namely, a poleward shift of the isopleths with Arctic amplification may appear as a change in wave extent when a narrower range is used instead*



significant trends in the ISOPLETH that is "waviest"



no significant trends in the AMOUNT of "wavyness"

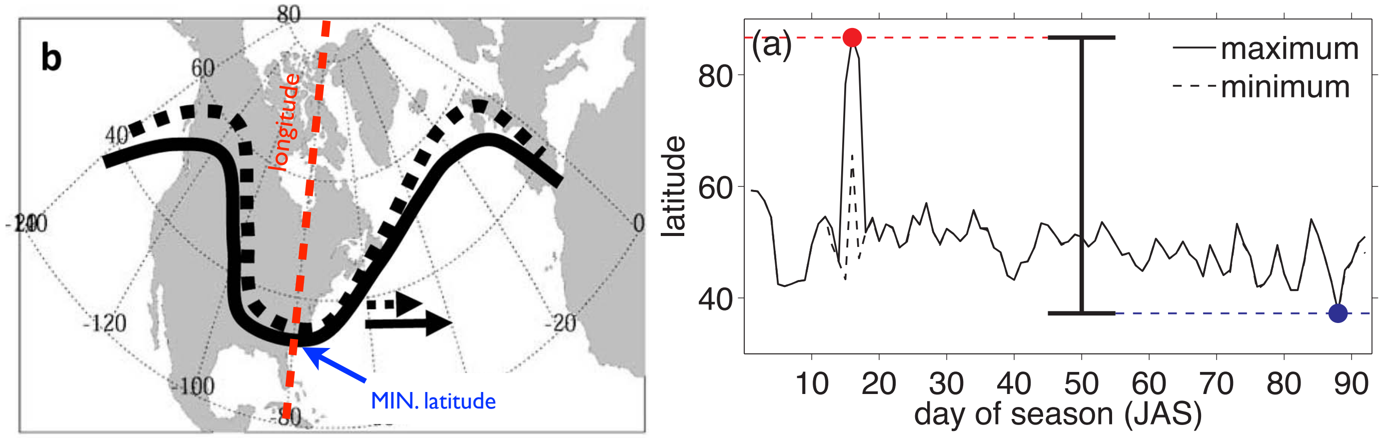
SeaMaxMin* (JAS)
DayMaxMin (JAS)
SeaMaxMin* (OND)
DayMaxMin* (OND)

Barnes (2013)

Wave amplitudes in the future

SeaMaxMin

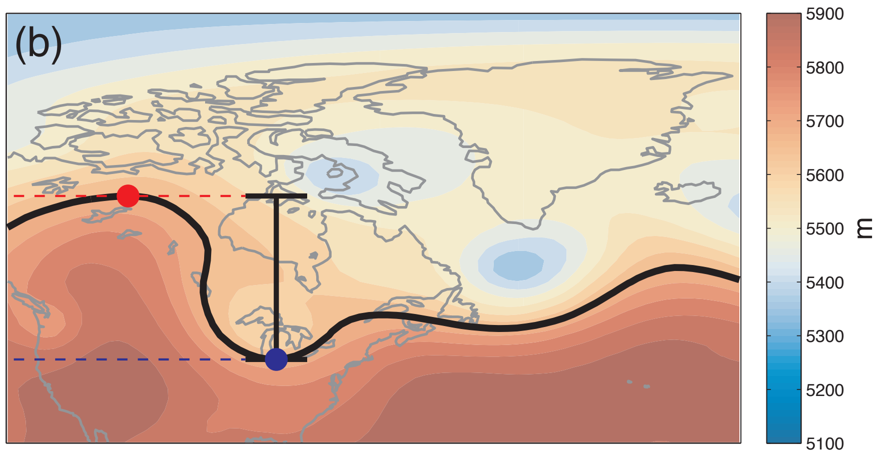
following Francis & Vavrus (2012)



Francis & Vavrus, (2012)

Barnes (2013)

DayMaxMin



Barnes (2013)

- DayMaxMin = a simple wave extent metric
- calculate wave extents using both metrics for 3 isopleths, then average over the domain and the season when applicable
- <u>IMPORTANT:</u> *both* metrics appear to have problems

Barnes (2013)