funded in by NSF Climate and Large-Scale Dynamics

Quantifying the seasonal sensitivity of the Northern Hemisphere jet-streams to Arctic warming

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NCAR

along with graduate student collaborators
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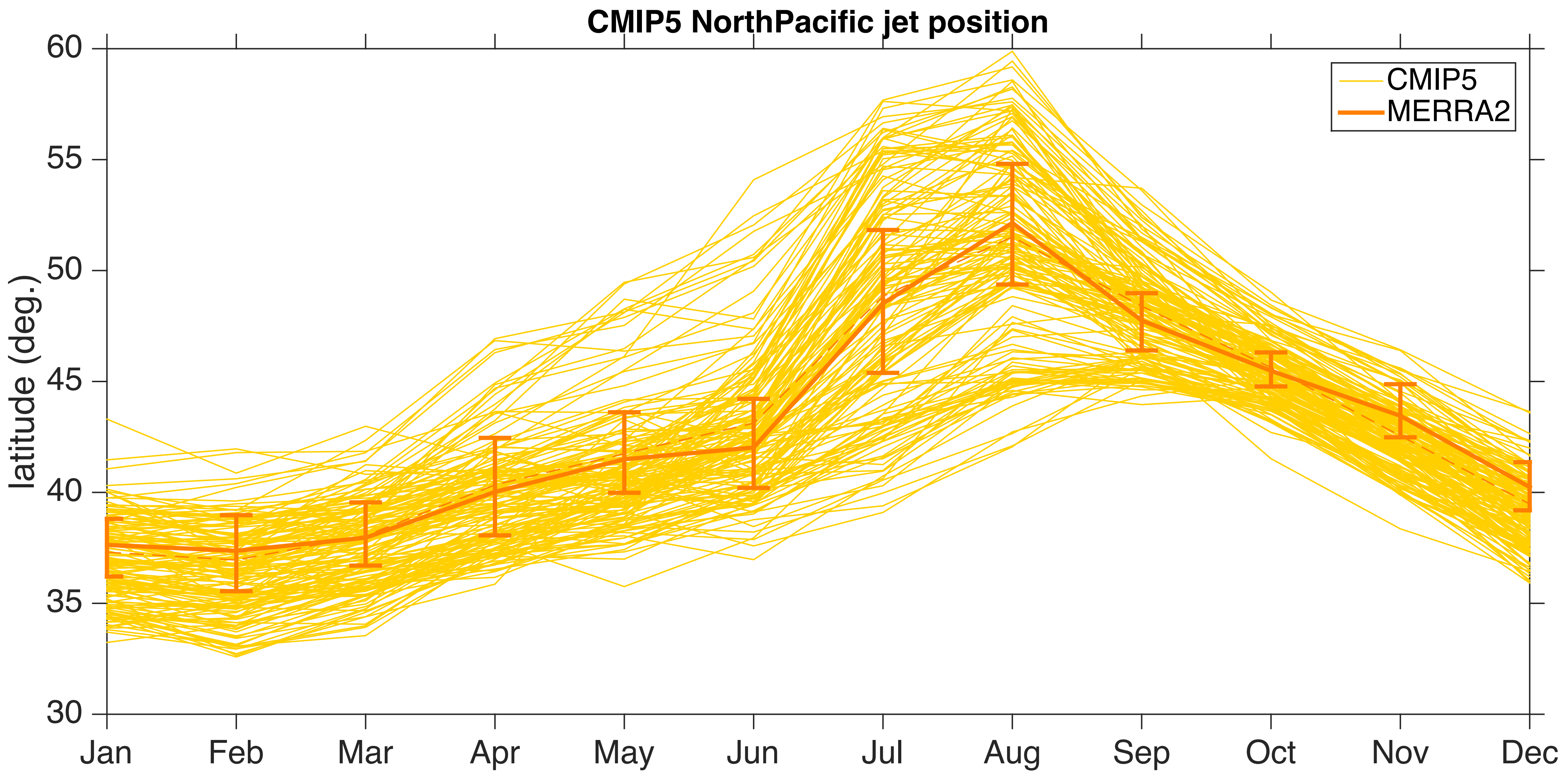
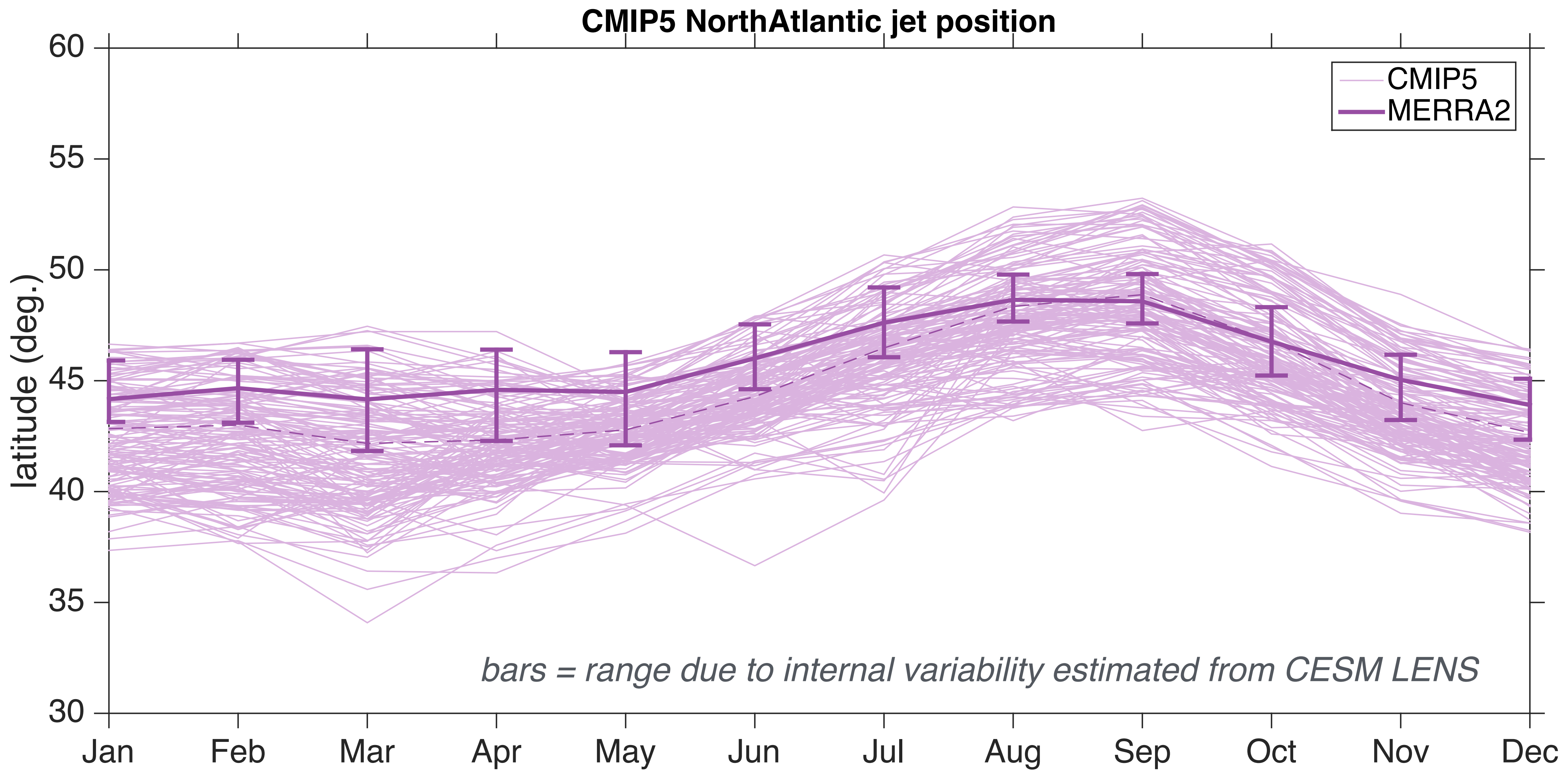
Bryn Ronalds, CSU

Seasonality of **the mean circulation**





jet-streams exhibit seasonality
in their latitude and variability

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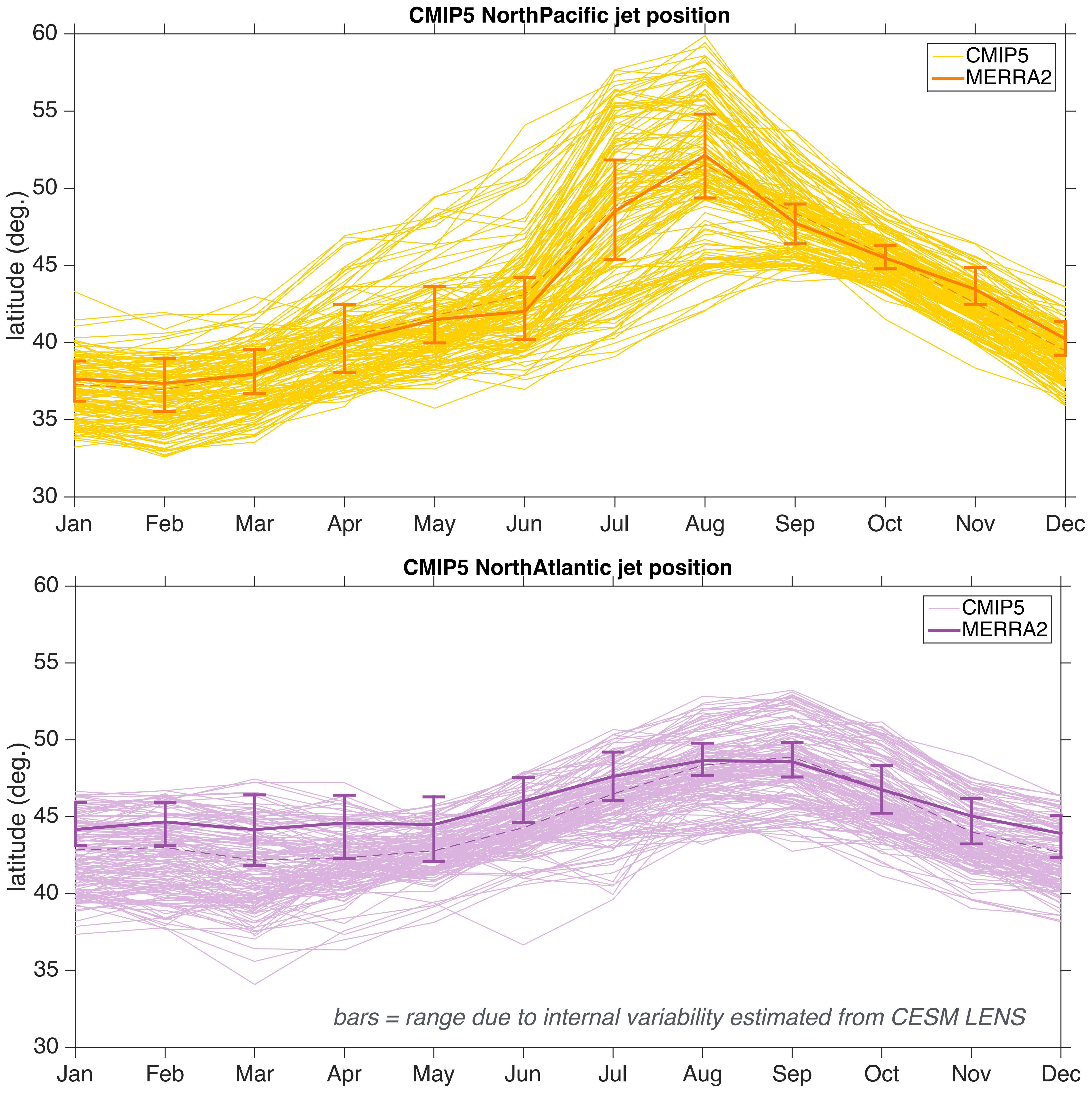
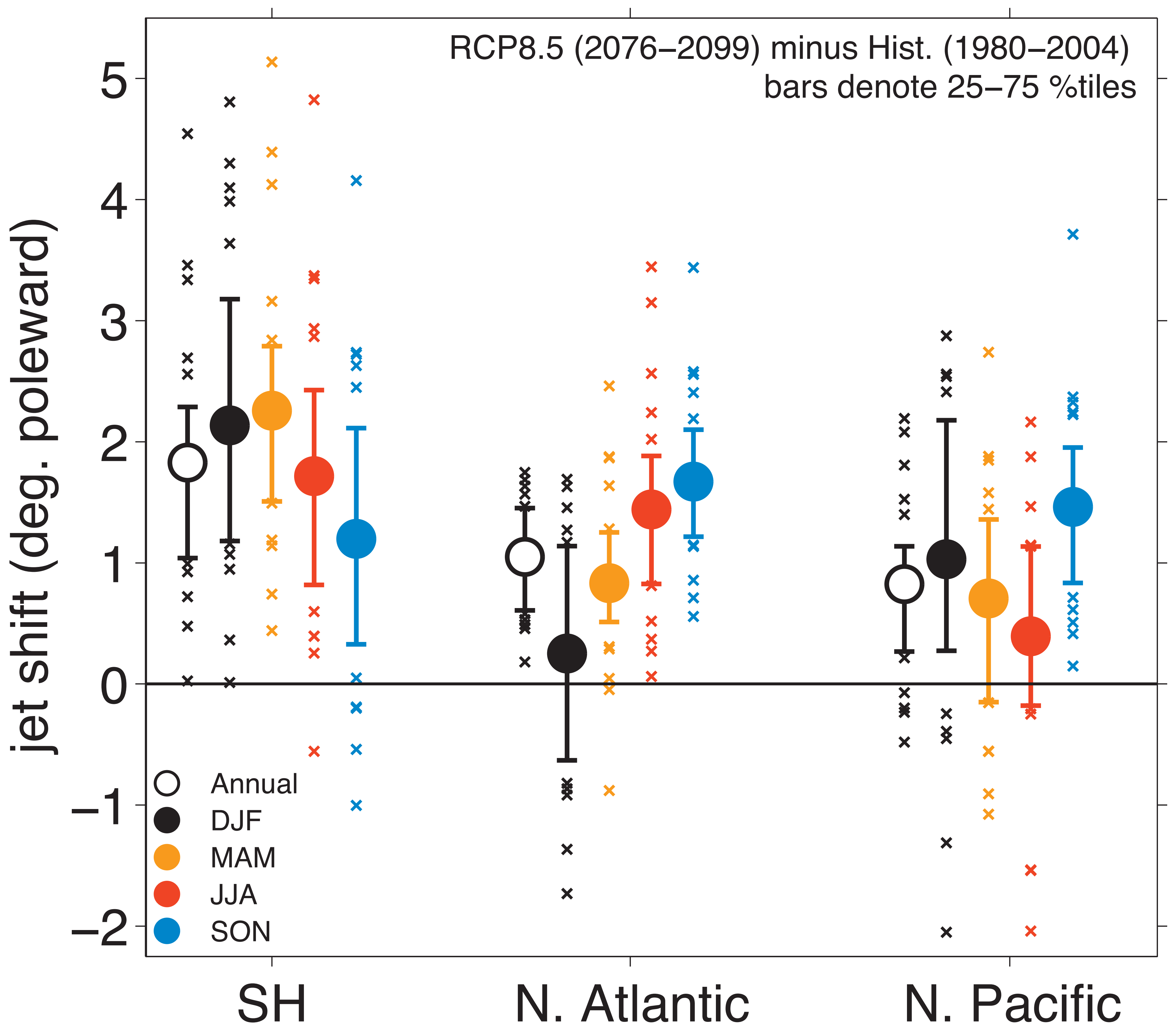


jet-streams exhibit seasonality in their latitude and variability

models exhibit seasonal biases in the mean jet position

Seasonality of **future jet shifts**



27 CMIP5 GCMs
Barnes & Polvani (2015; JCLI)

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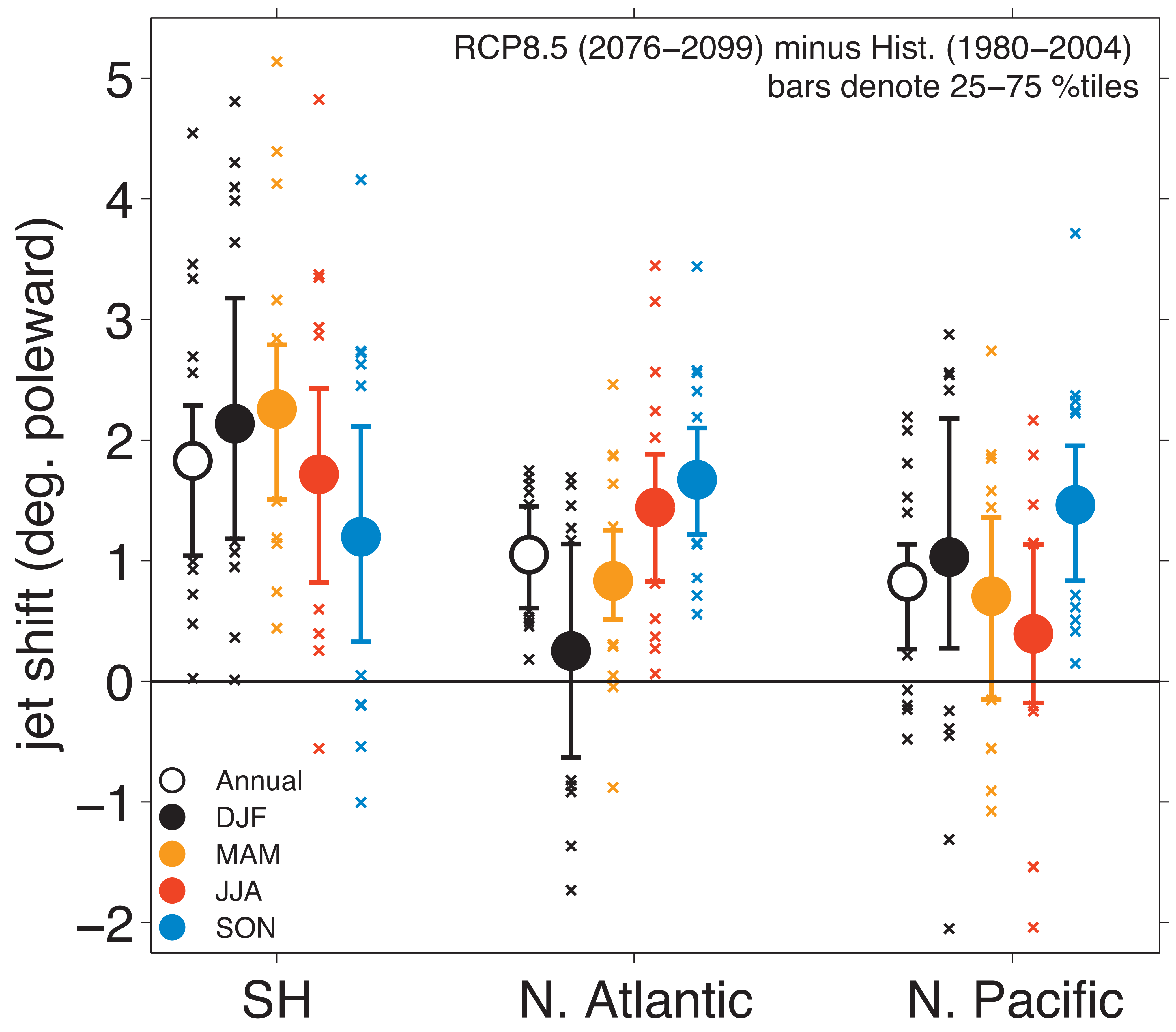

jet shift has a rich seasonality that could be due to a few factors

(1) **seasonality of forcing**
(e.g. sea ice loss)

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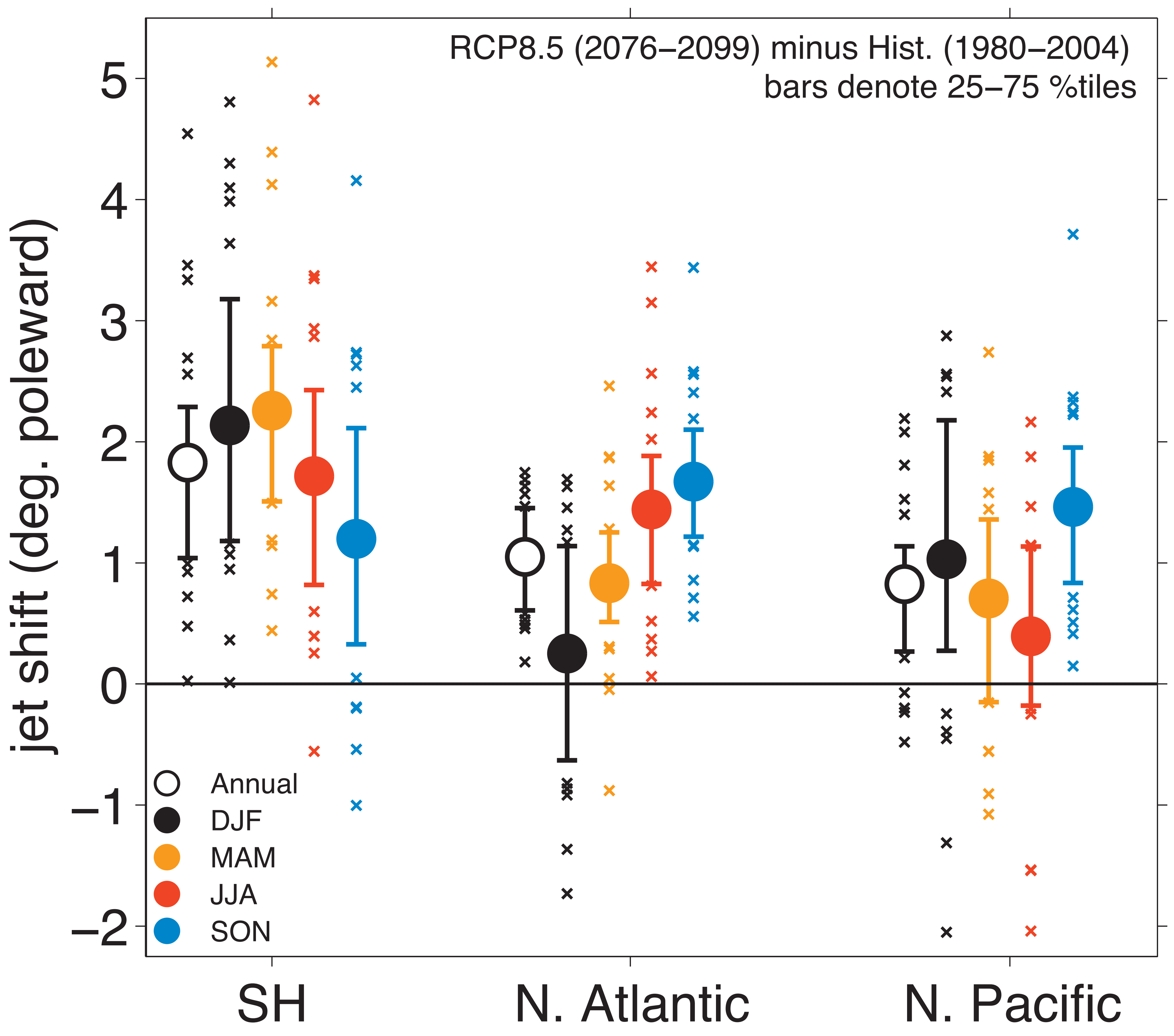

jet shift has a rich seasonality that could be due to a few factors

(1) **seasonality of forcing**
(e.g. sea ice loss)

(2) **seasonality of the circulation**
(e.g. even for constant forcing)

27 CMIP5 GCMs
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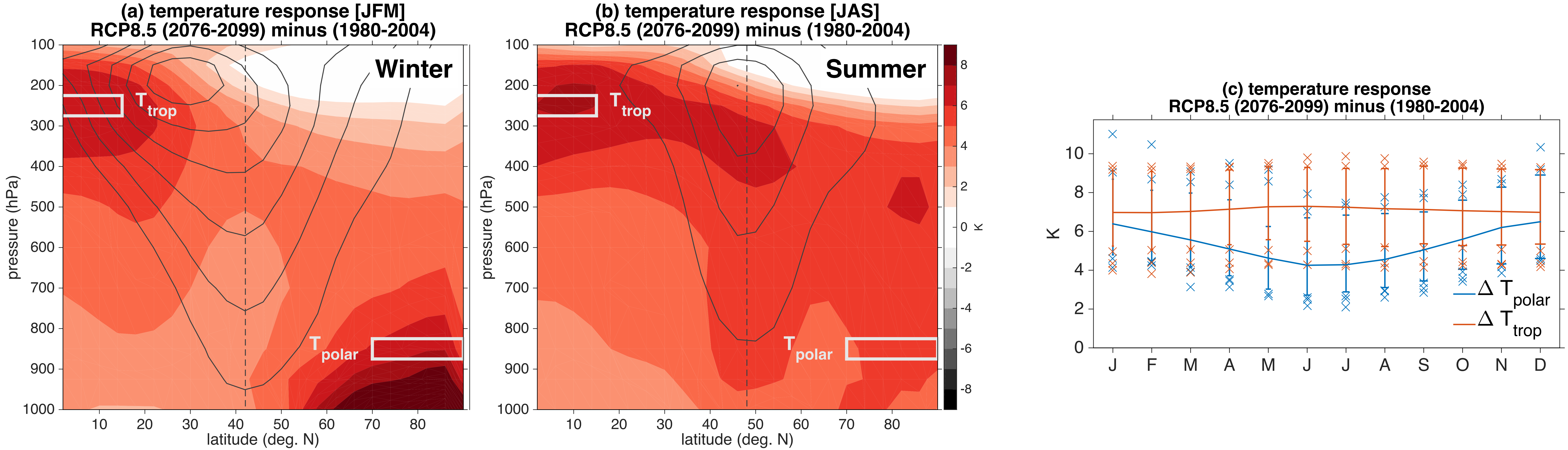
Seasonality of **future warming**



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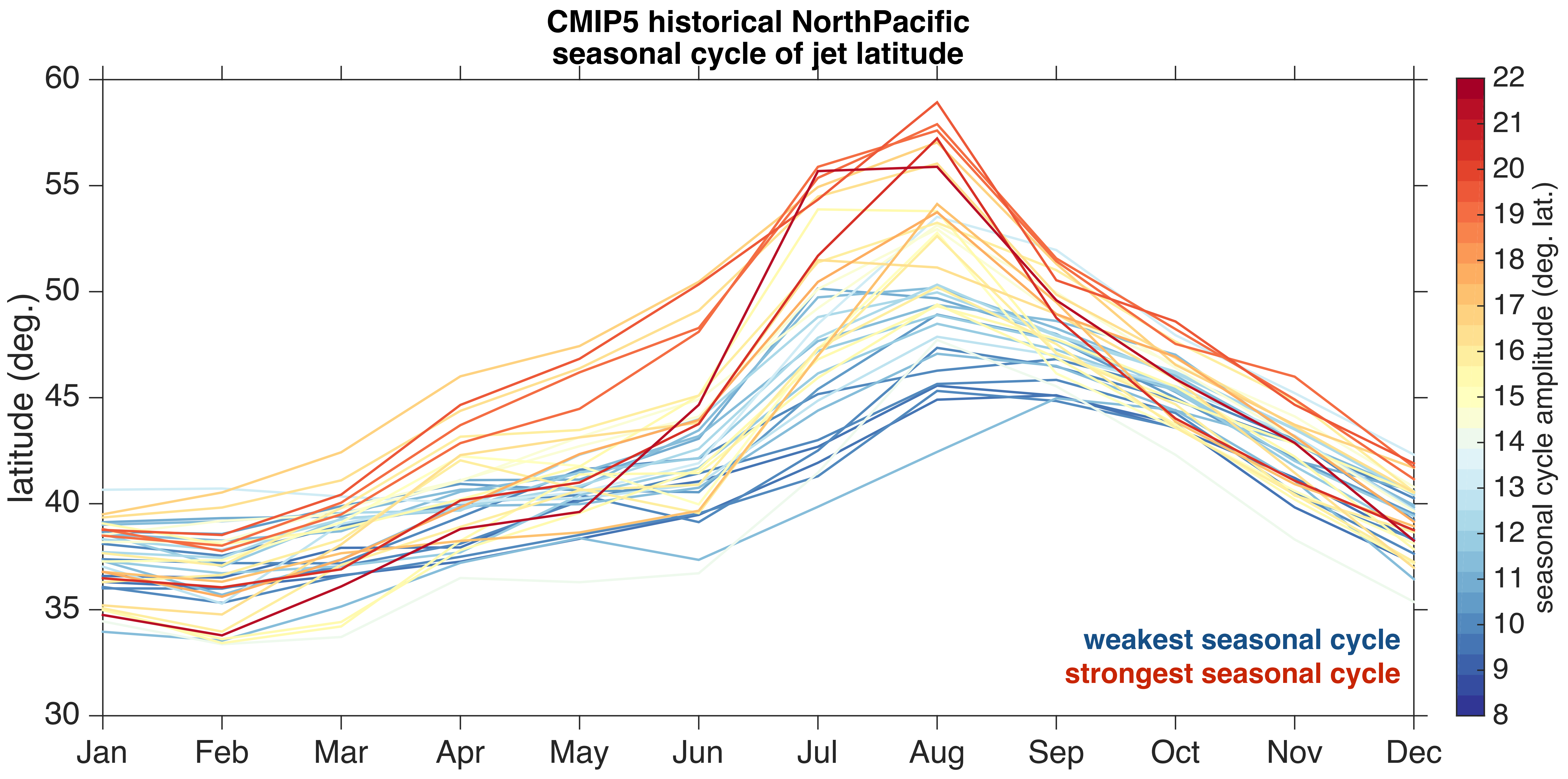

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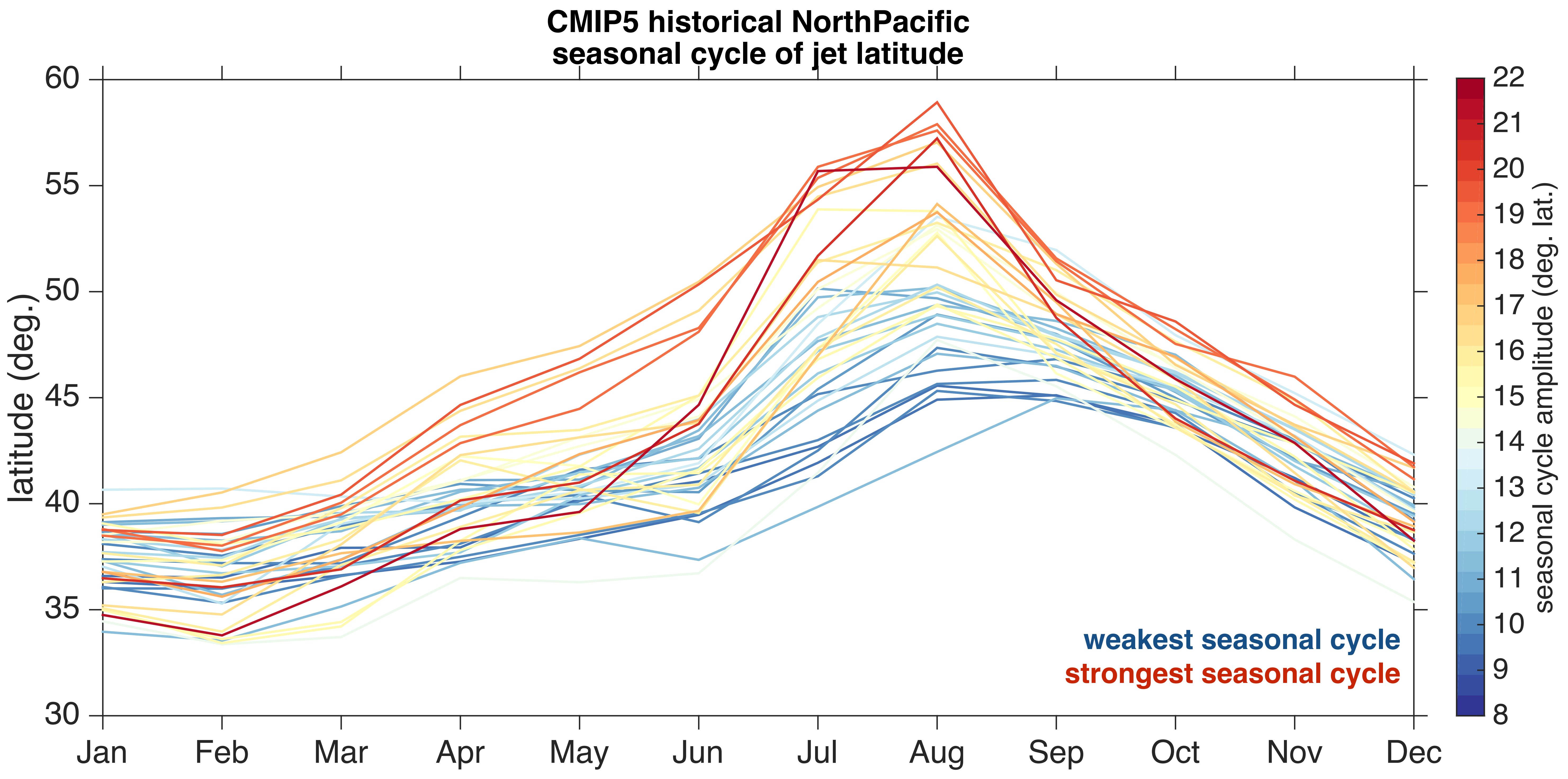

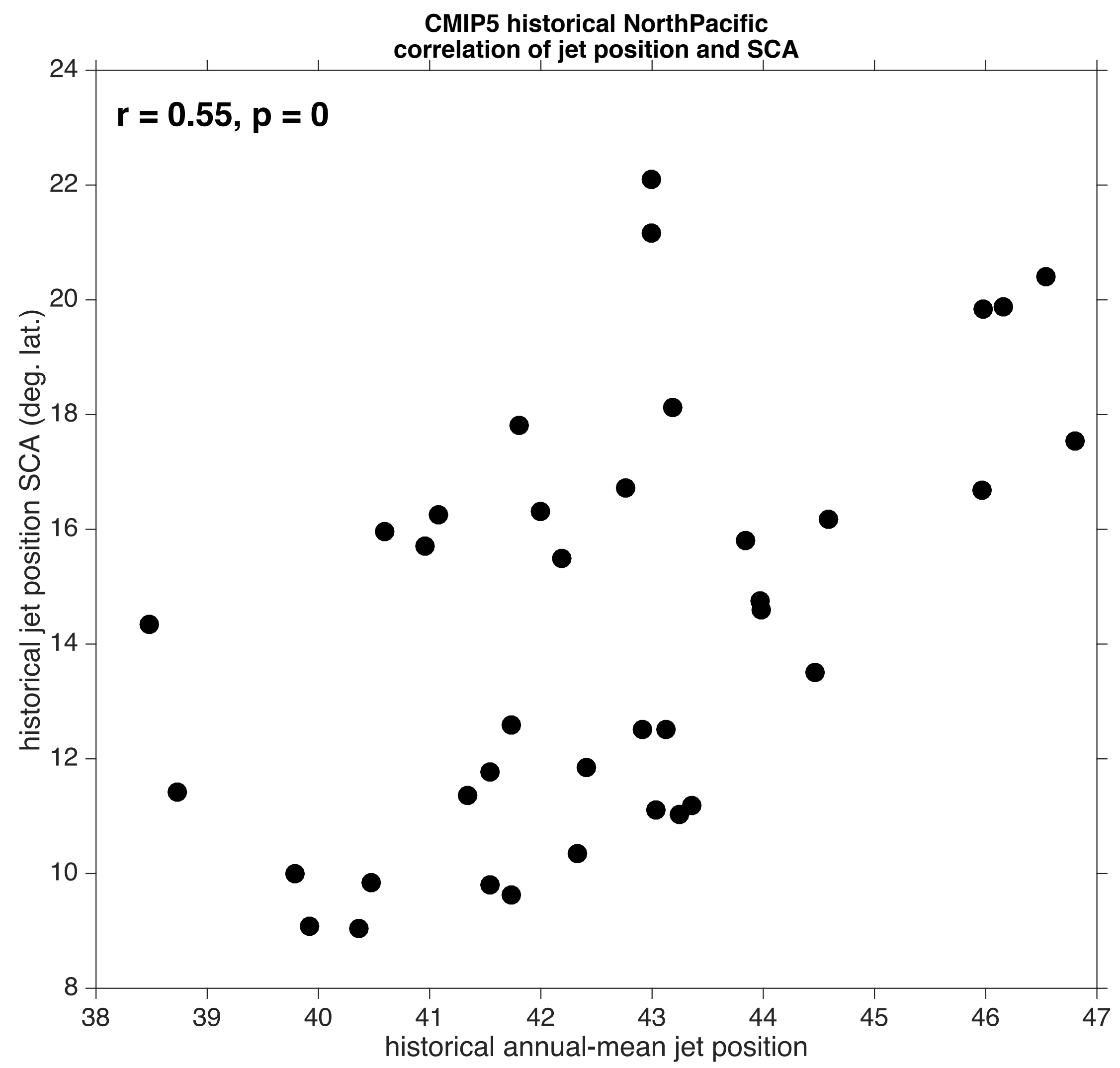

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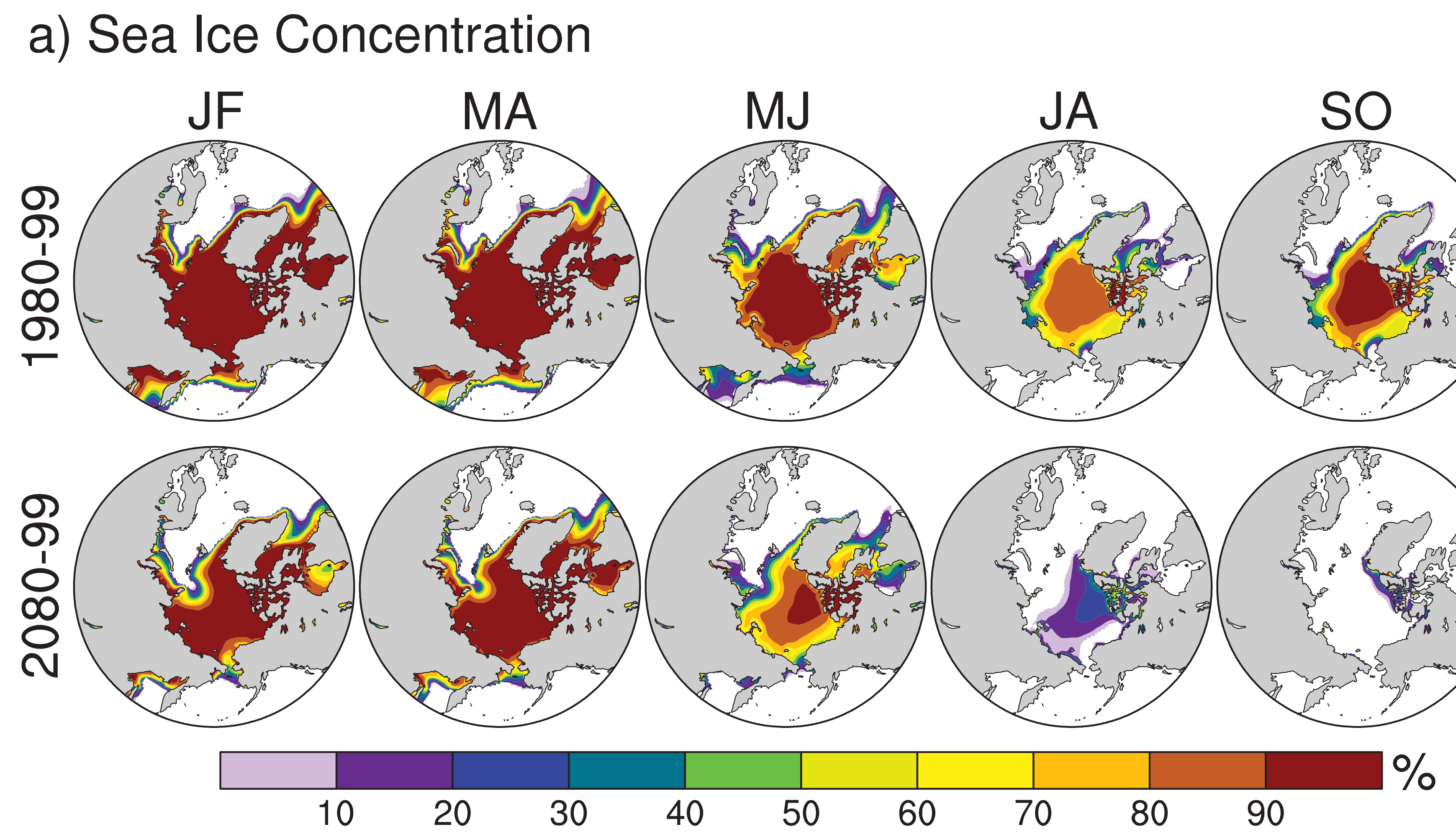
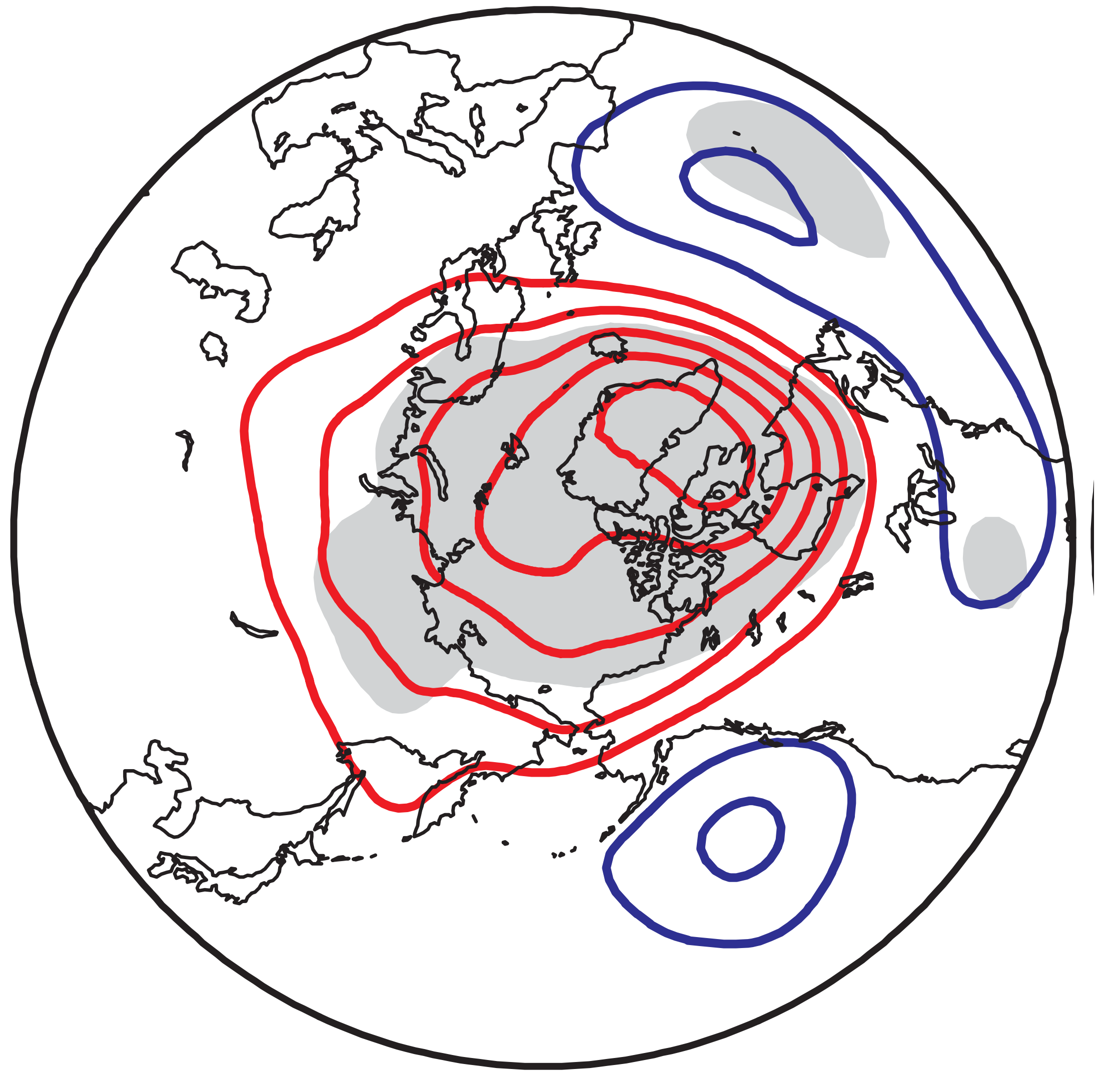
Jet response to sea ice loss



500 hPa geopotential height
response in Jan.-Feb.



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

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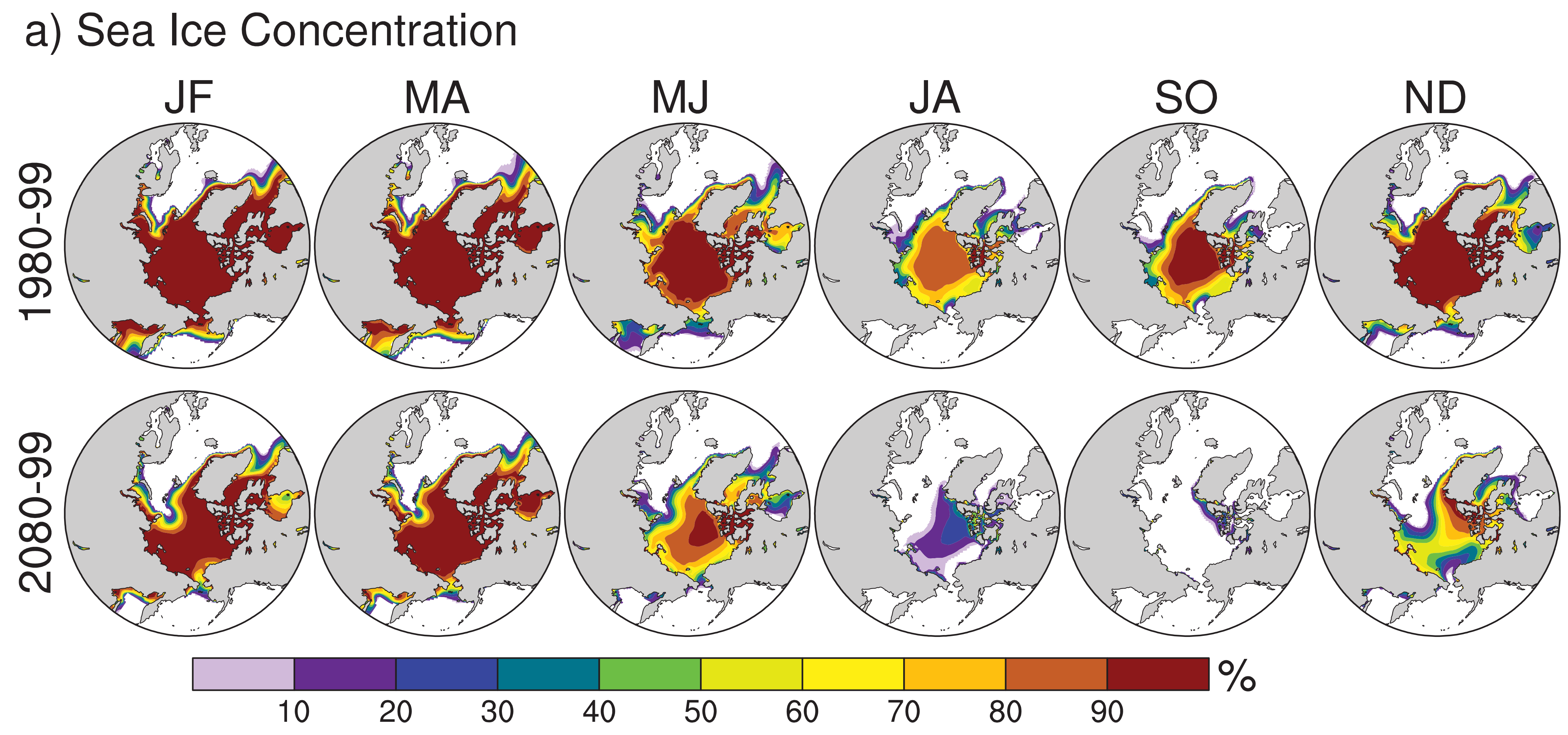

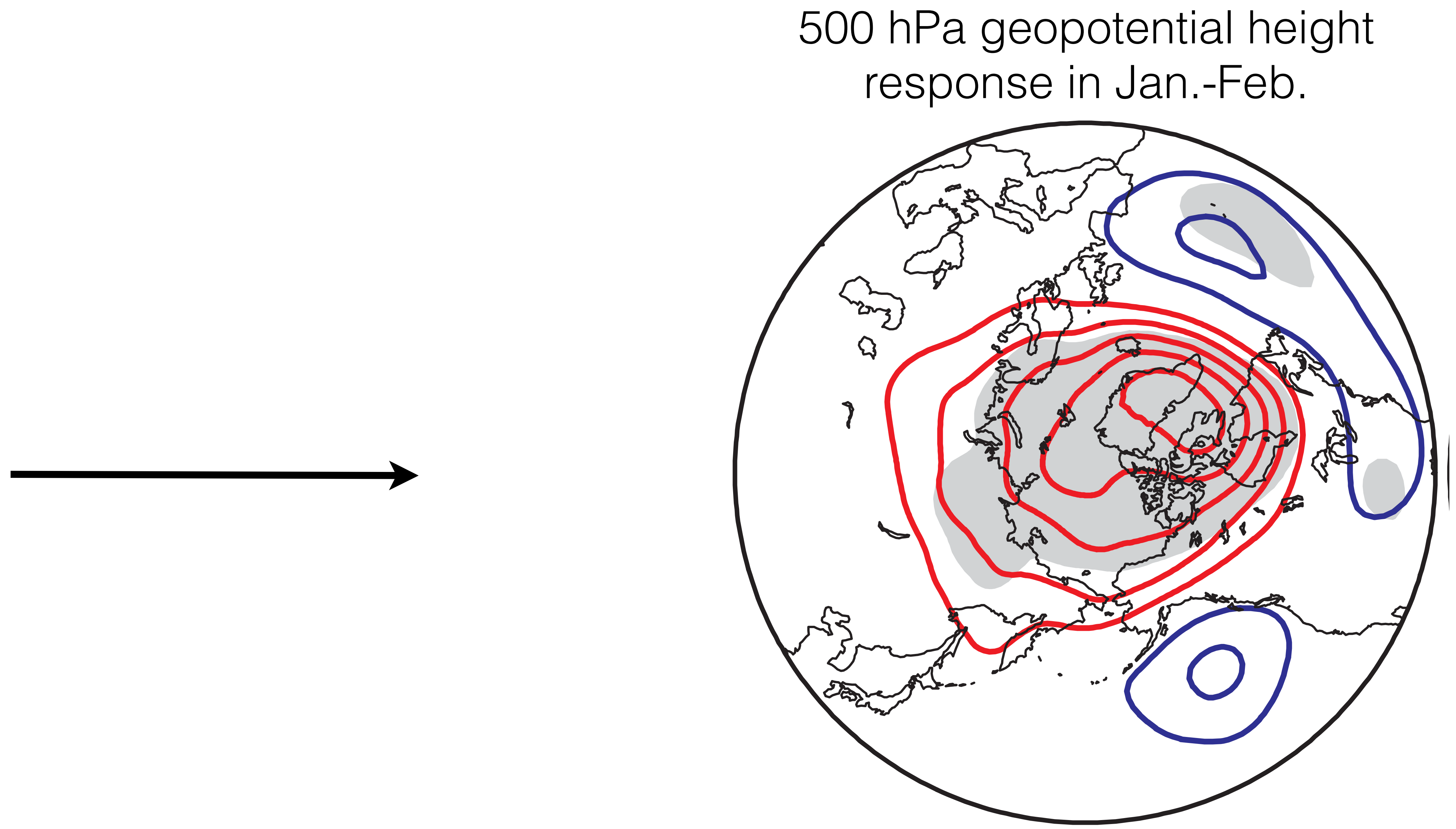

abstract of Deser et al. (2010):

"The loss of Arctic sea ice is greatest in summer and fall, yet the response of the net surface energy budget over the Arctic Ocean is largest in winter."

…

"[The circulation] response resembles the negative phase of the North Atlantic Oscillation in February only."

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

Ultimate Goal

- a lot of work has been done understanding the net response of the jet to GHG warming…**this is not our goal here.**
- instead, we wish to quantify the **seasonal sensitivity to a 1K warming in a particular region**

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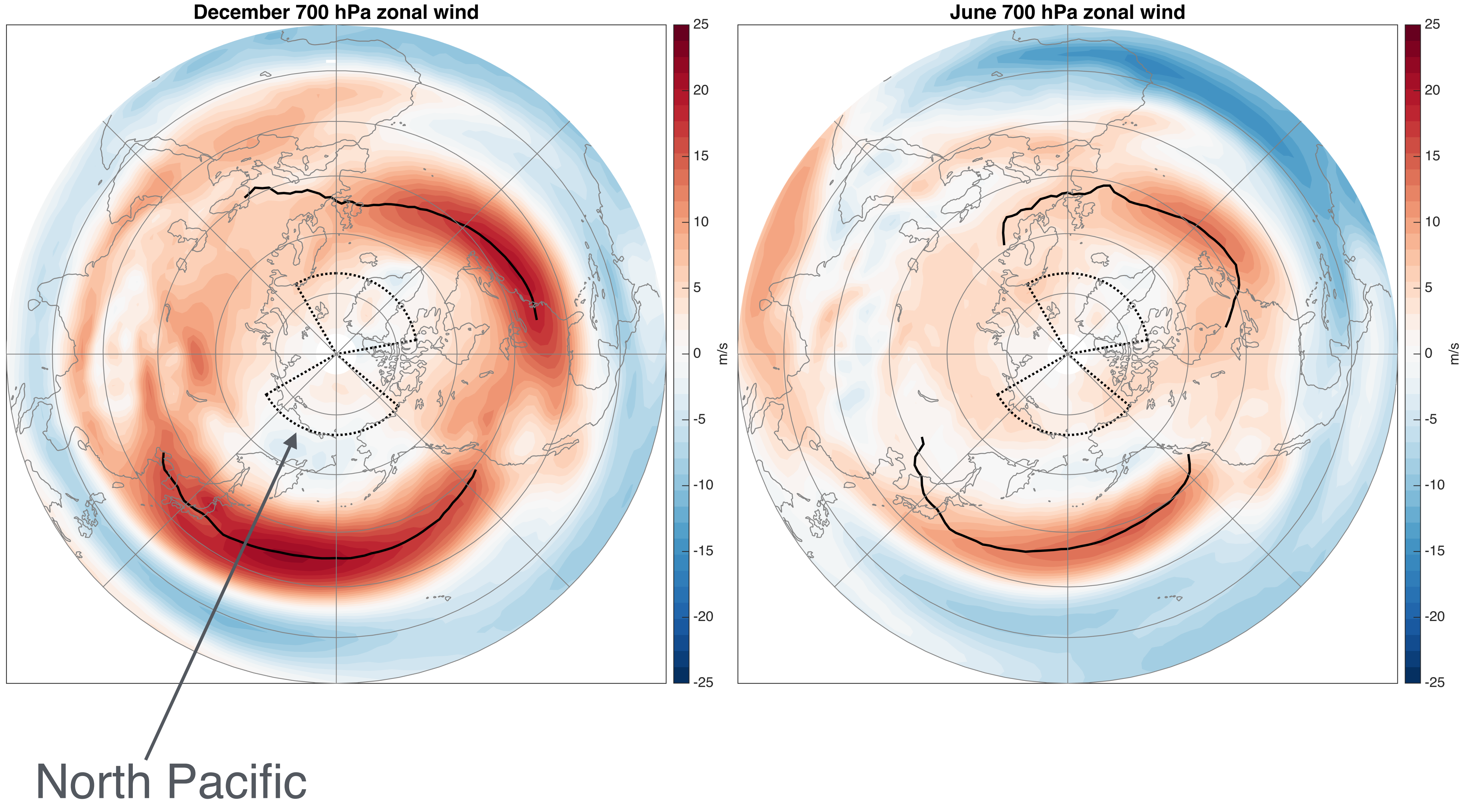
Data



- CMIP5 (historical + RCP8.5: *detrended*)
- daily data (averaged into 10-day chunks*)
- 700 hPa zonal wind
- 850 hPa air temperature

700 hPa zonal wind from the 20th Century Reanalysis (1851-2014)

*results are not sensitive to 10-days, e.g. could be 5-days

Approach

$$\mathcal{J}_t = rT_t + \epsilon$$

time
(within a particular month)

…tried this, but got worried about the direction of causality given the lag 0

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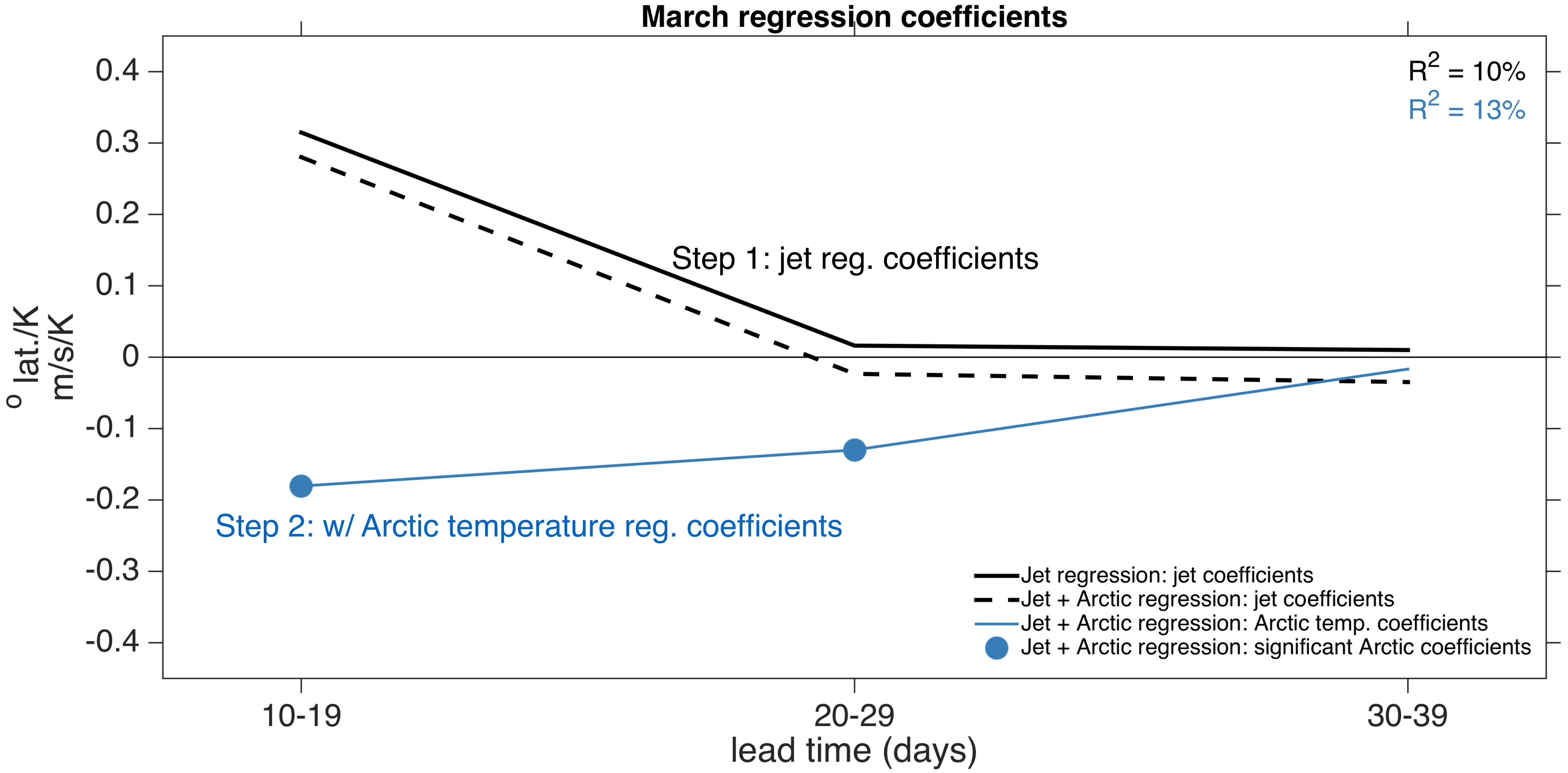
Granger-causality

Step 1 $$\mathcal{J}_t = a_0 + a_1\mathcal{J}_{t-1} + a_2\mathcal{J}_{t-2} + ... + a_k\mathcal{J}_{t-k} + \epsilon_t$$

Step 2 $$\mathcal{J}_t = c_0 + c_1\mathcal{J}_{t-1} + c_2\mathcal{J}_{t-2} + ... + c_k\mathcal{J}_{t-k} + b_1T_{t-1} + b_2T_{t-2} + ... + b_kT_{t-k} + \epsilon_t$$

- there exists at least one significant “b” according to a t-test
- all of the “b” terms collectively add power to the regression

Approach

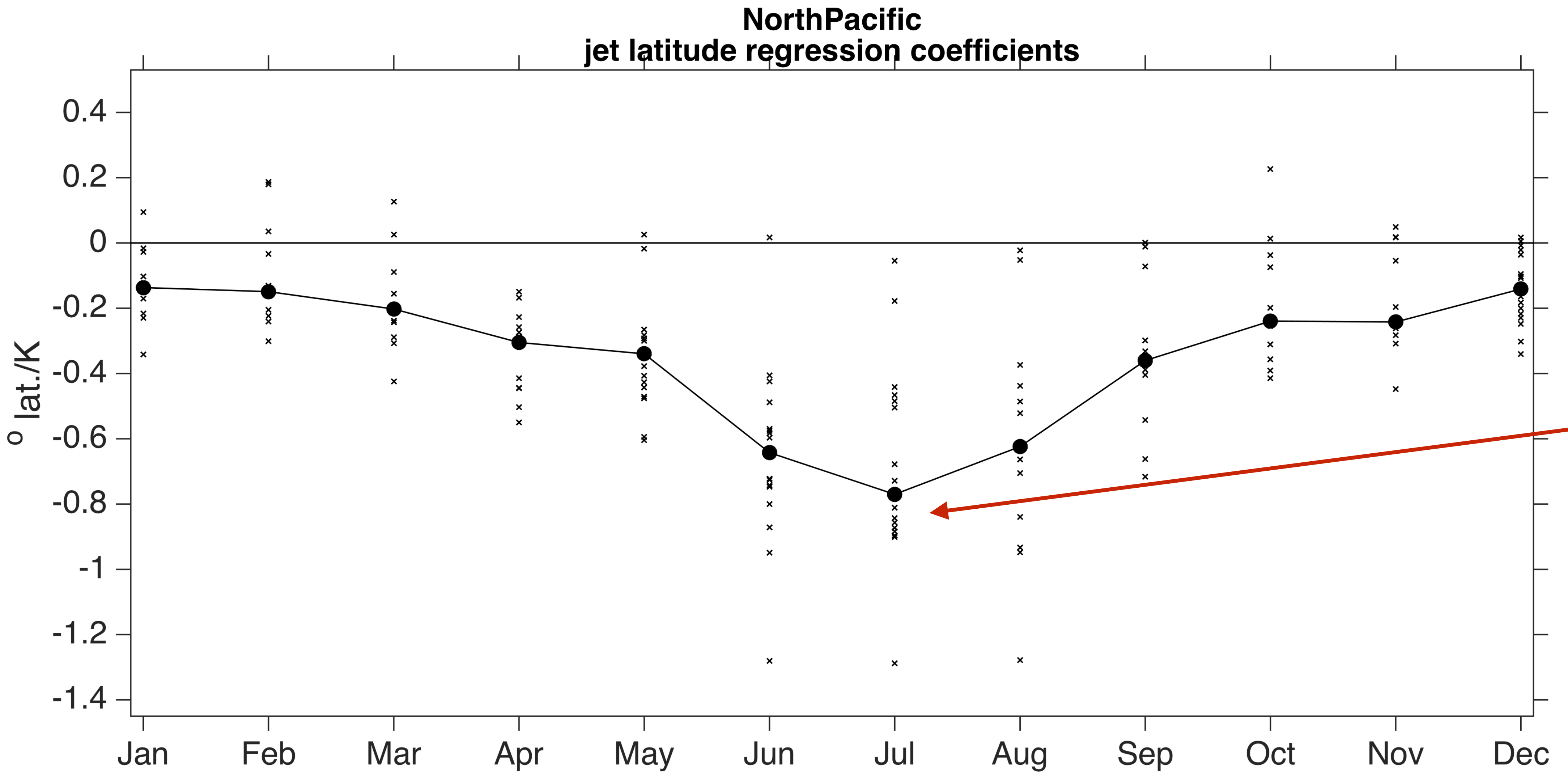


An example Granger causality calculation for North Pacific jet latitude in March from the CanESM2 model. For this example, we use the combined Historical + RCP8.5 time series.

- jet shifts equatorward when Arctic was warm 10-30 days earlier
- first two coefficients are significant

Barnes and Simpson (in prep)

Seasonal sensitivity: **jet position**



- jet shifts equatorward more in warm months

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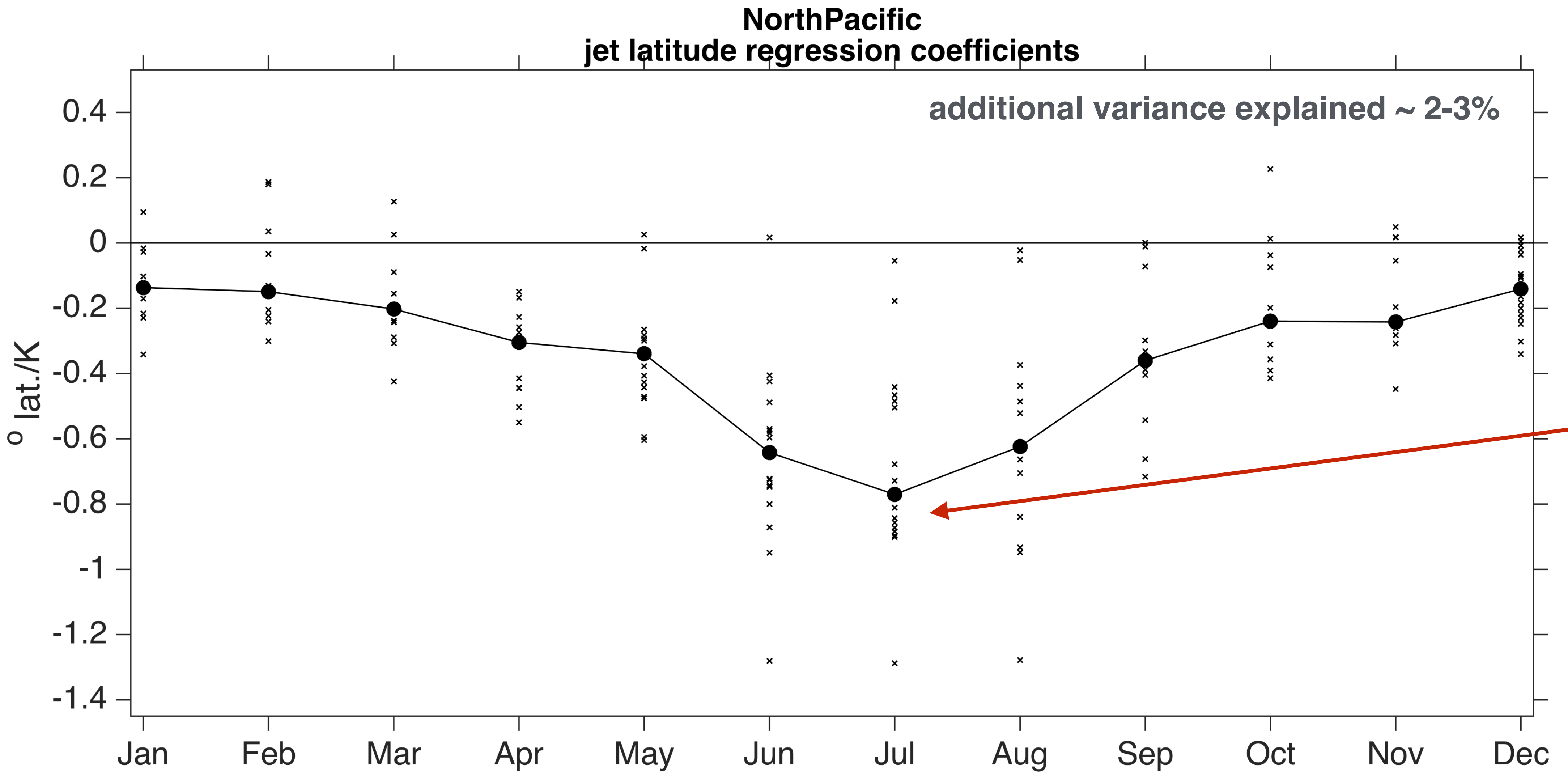

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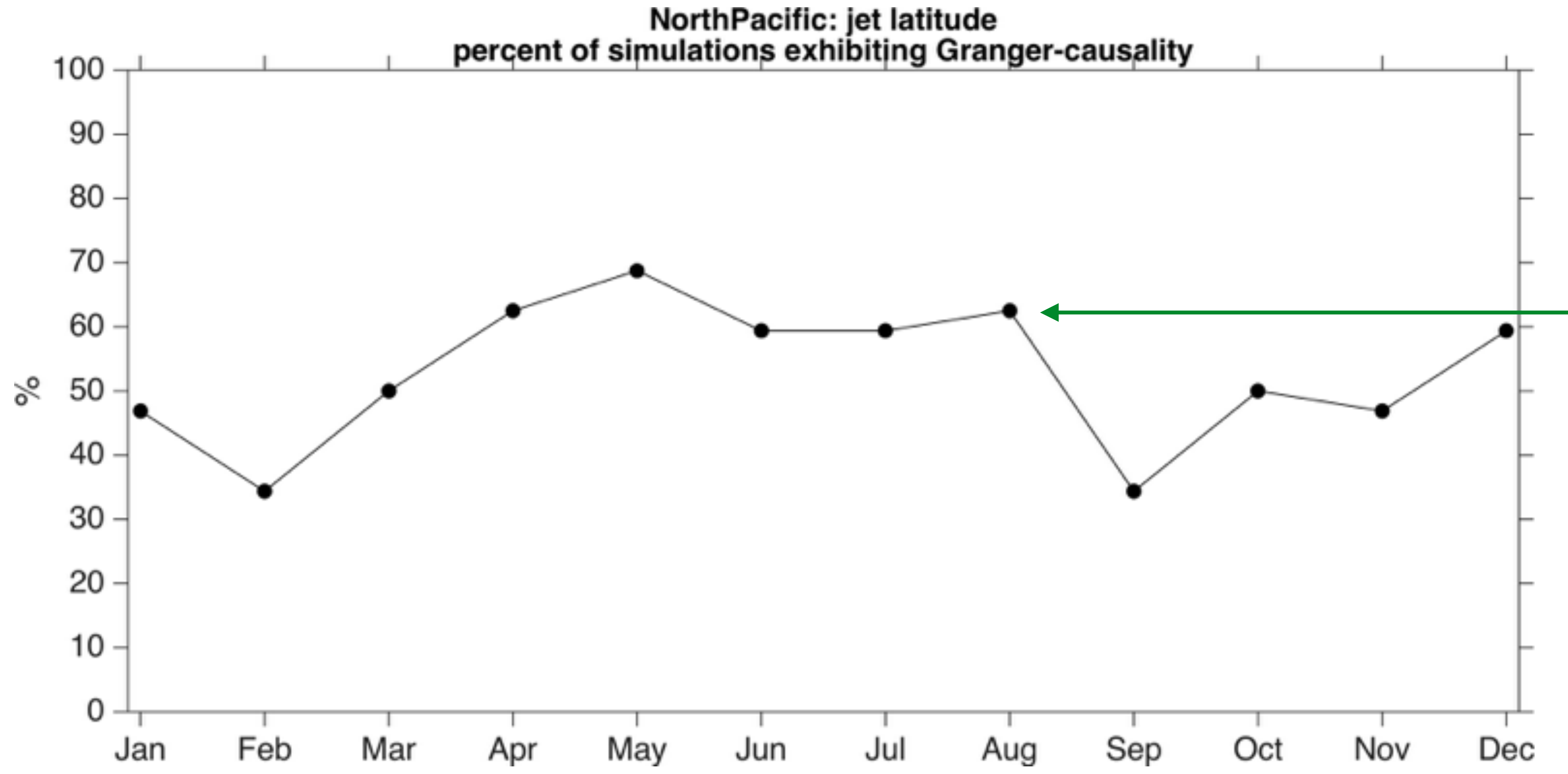
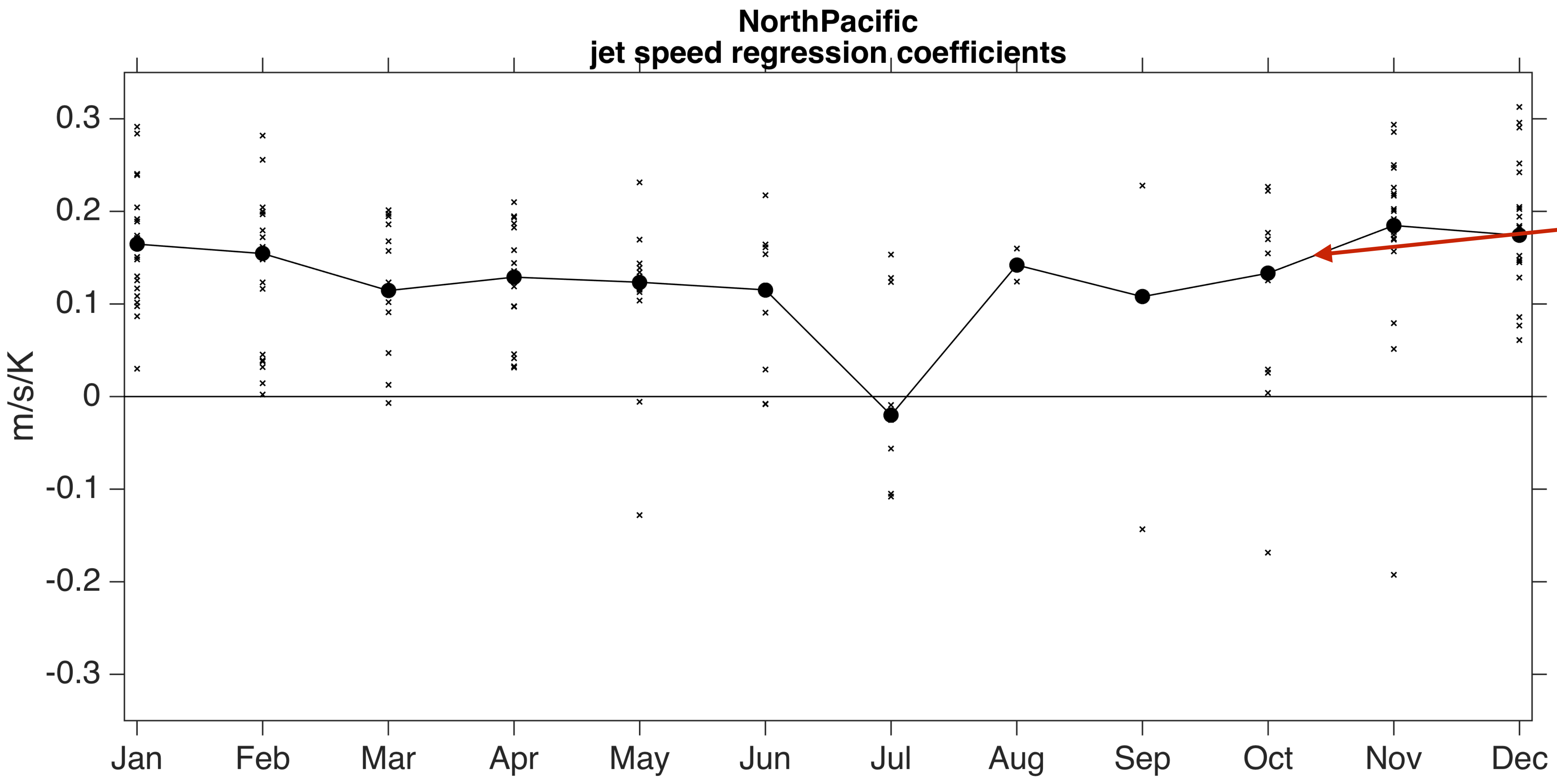


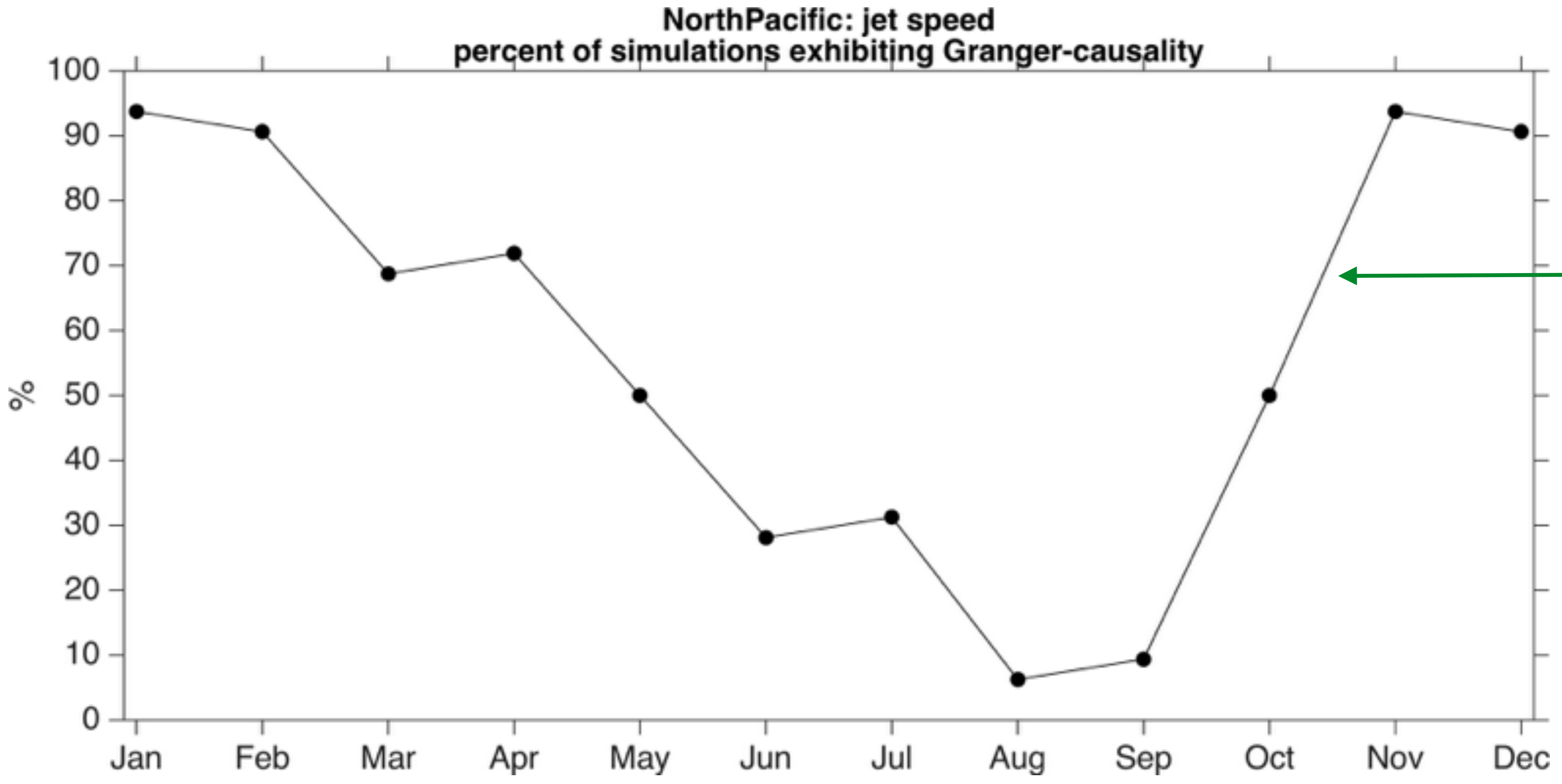
40-60% of simulations exhibit Granger-causality

Barnes and Simpson (in prep)

Seasonal sensitivity: **jet speed**



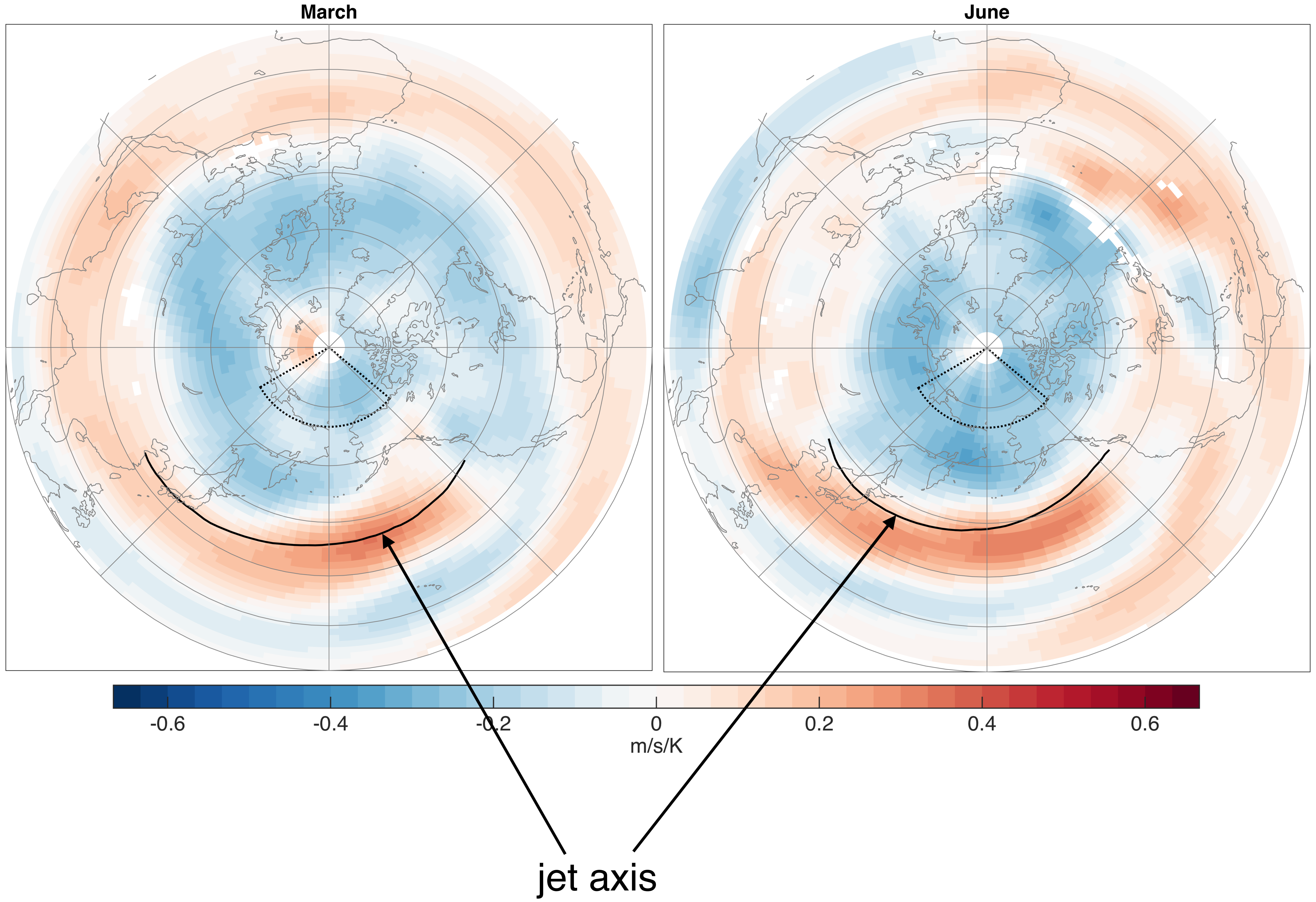
jet **strengthens** in most months



large seasonality in number of models exhibiting Granger-causality

Barnes and Simpson (in prep)

Explaining the seasonality



- jet shifts with the seasonal cycle
- wind anomalies remain relatively fixed in latitude

colors = CMIP5 model mean regression coefficients (via Granger-causality)

Barnes and Simpson (in prep)

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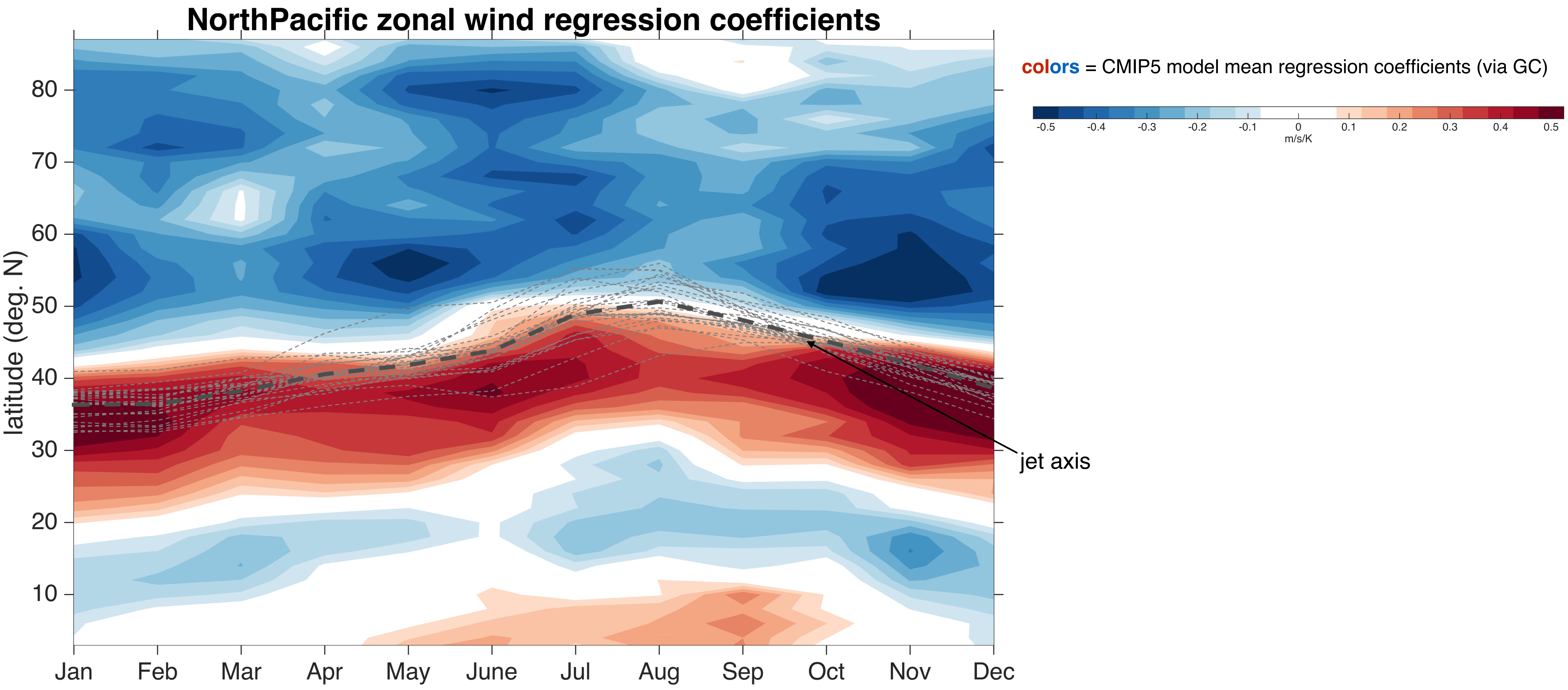

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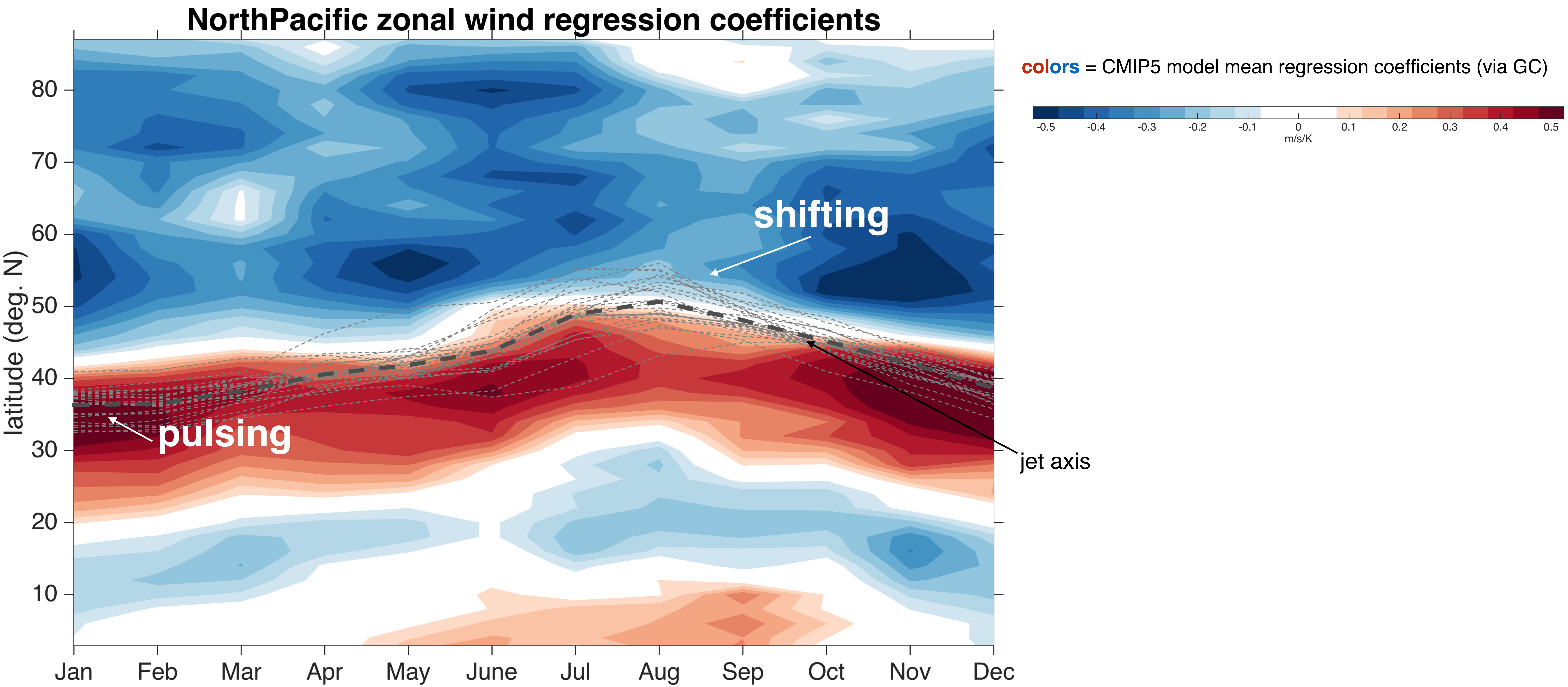
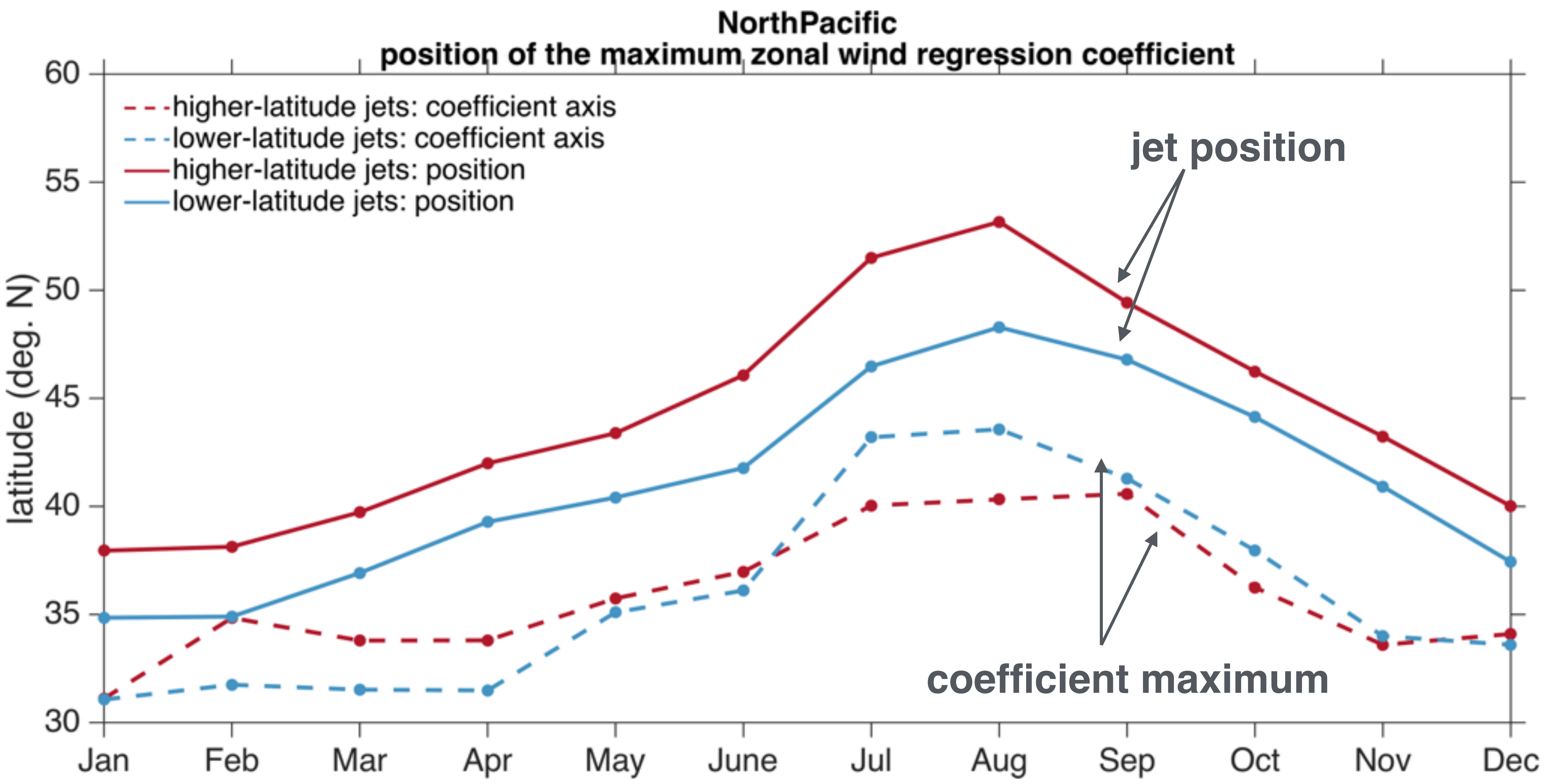


Barnes and Simpson (in prep)

Implications for models biases



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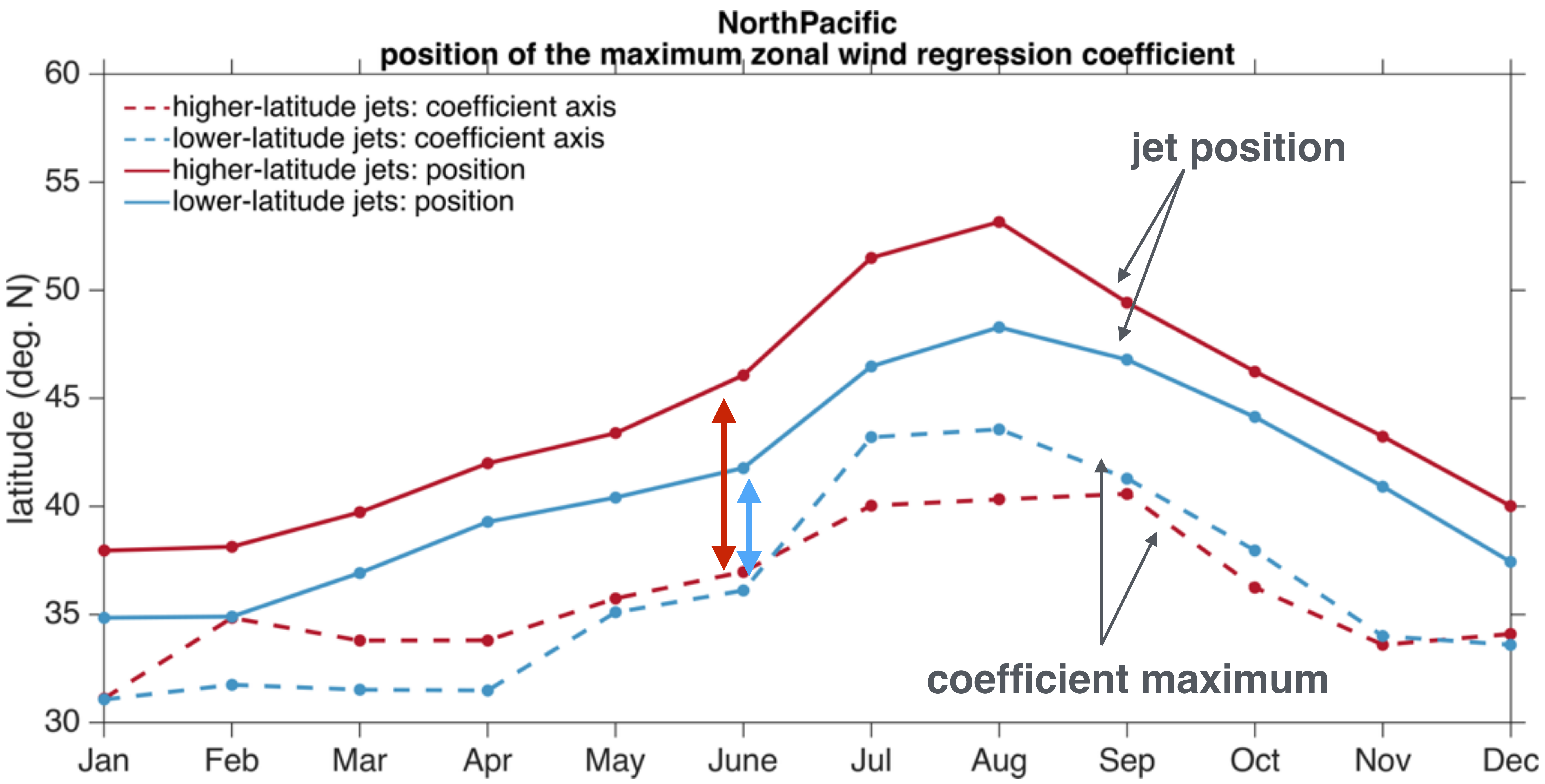

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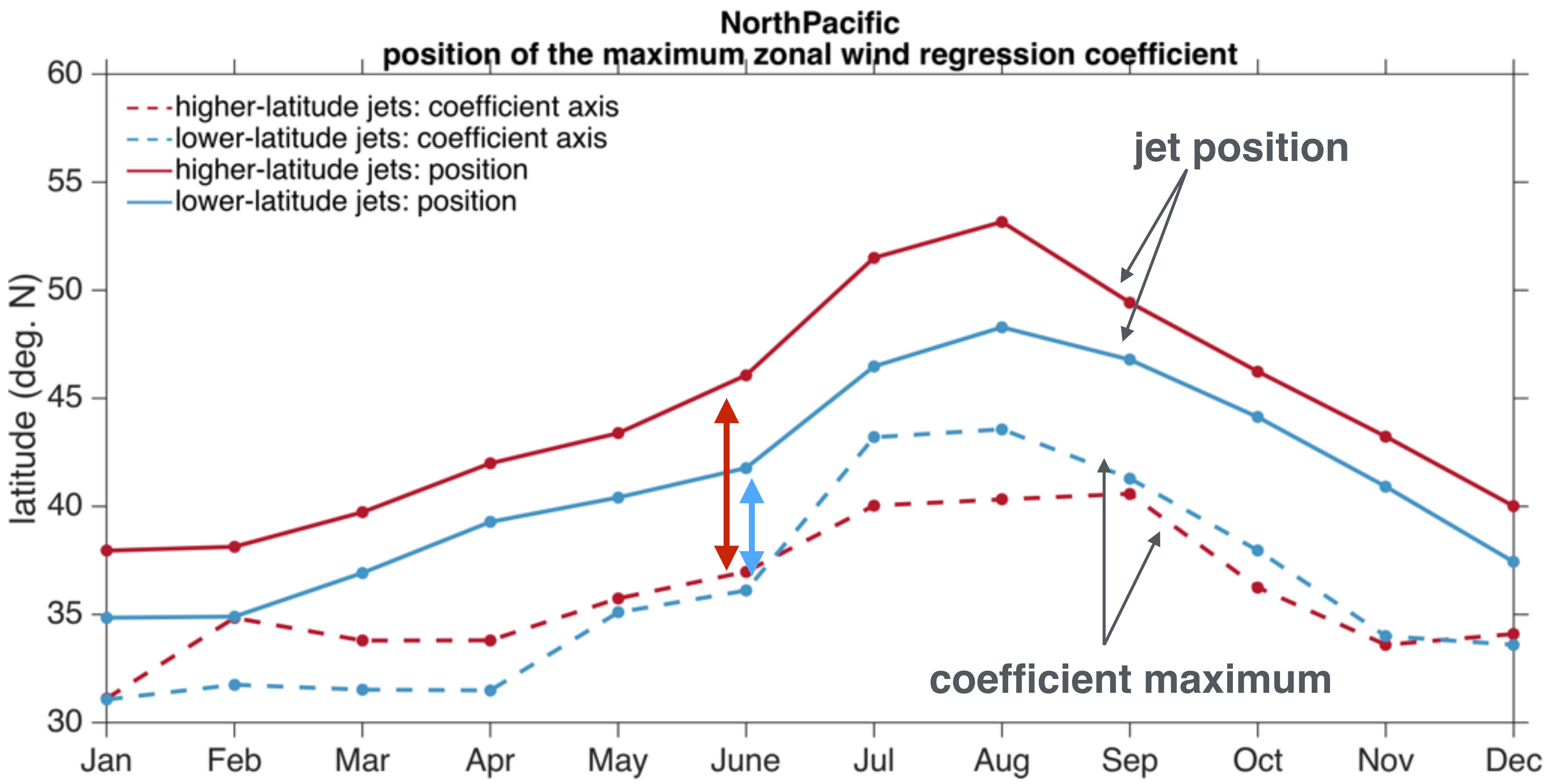

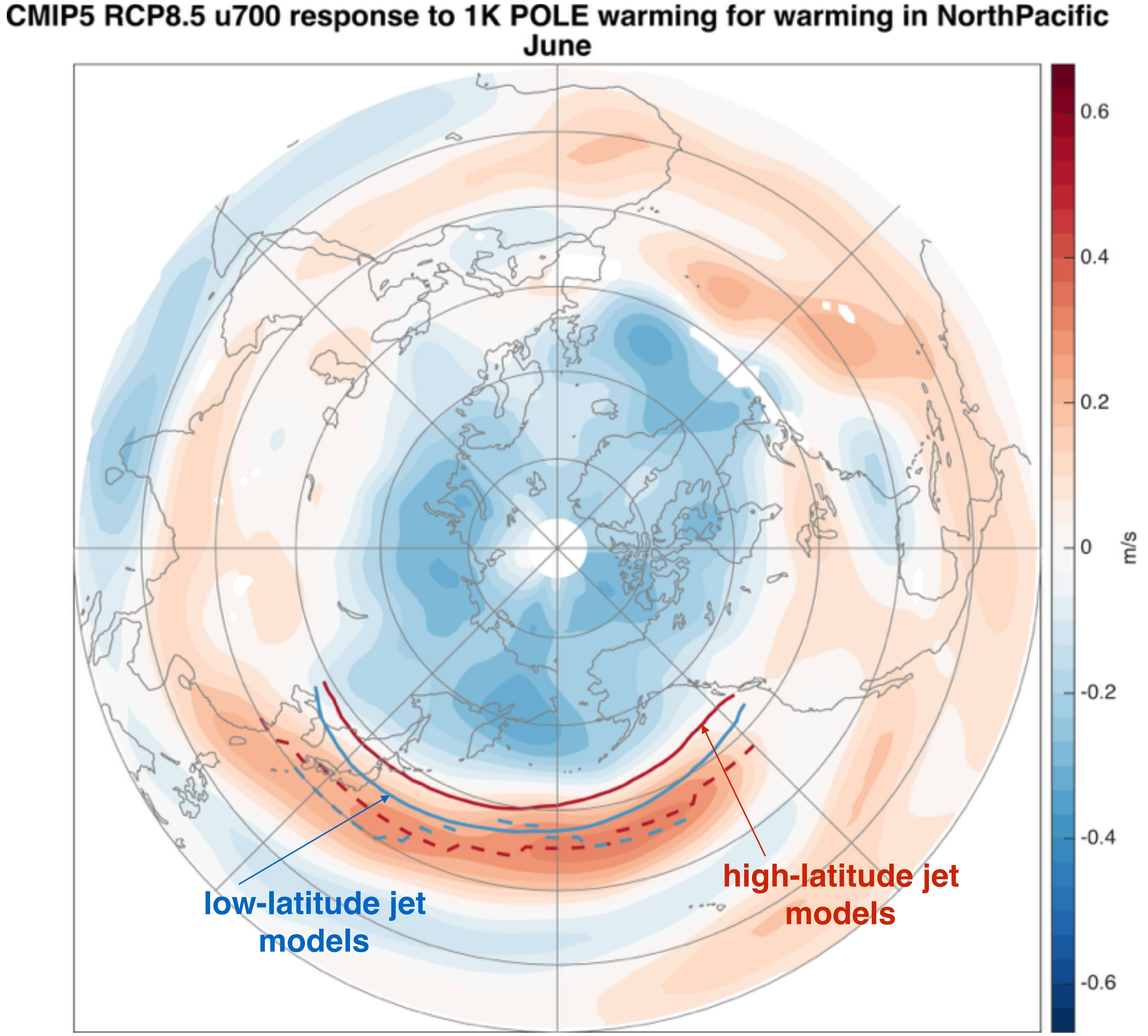

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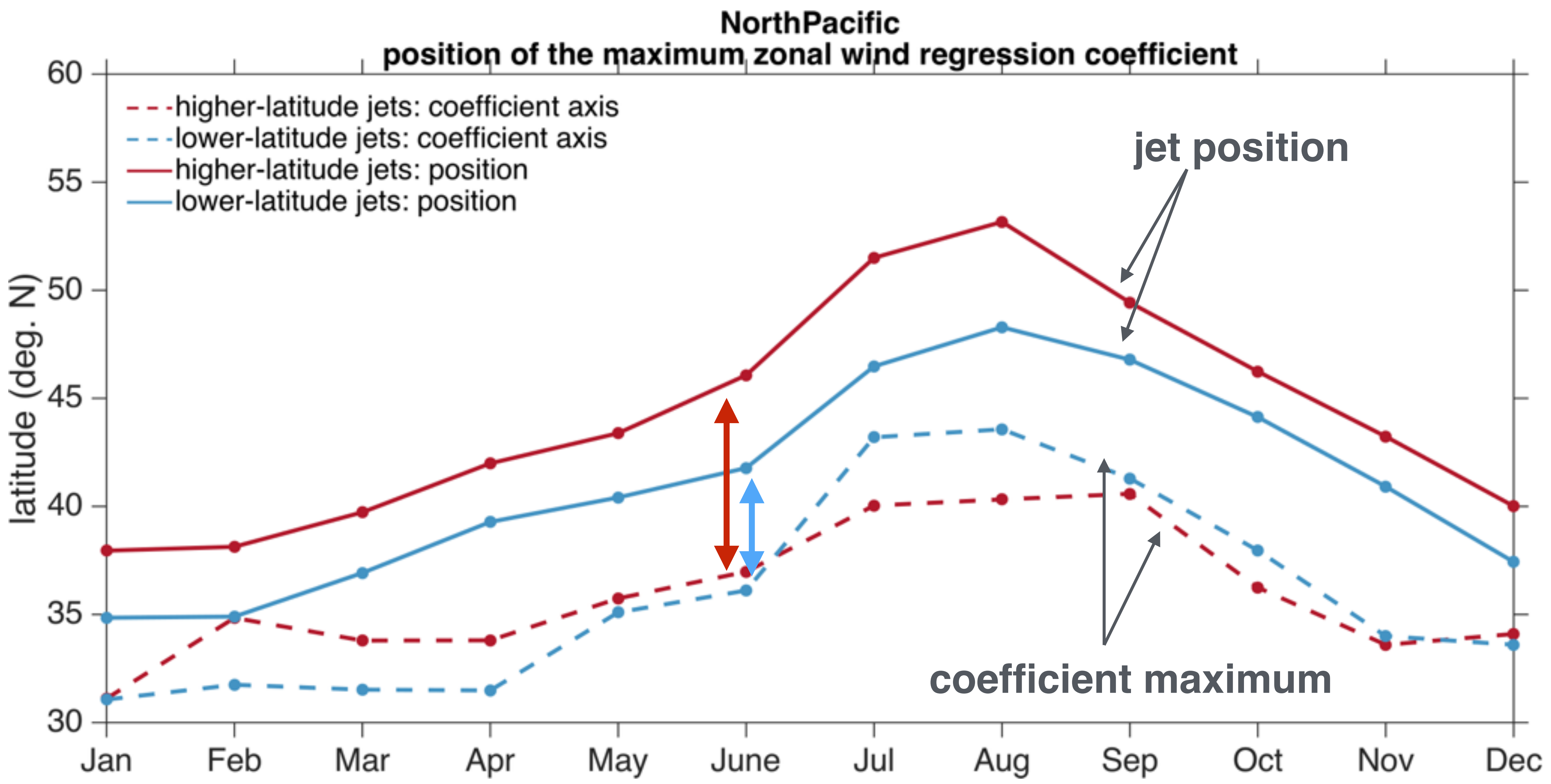

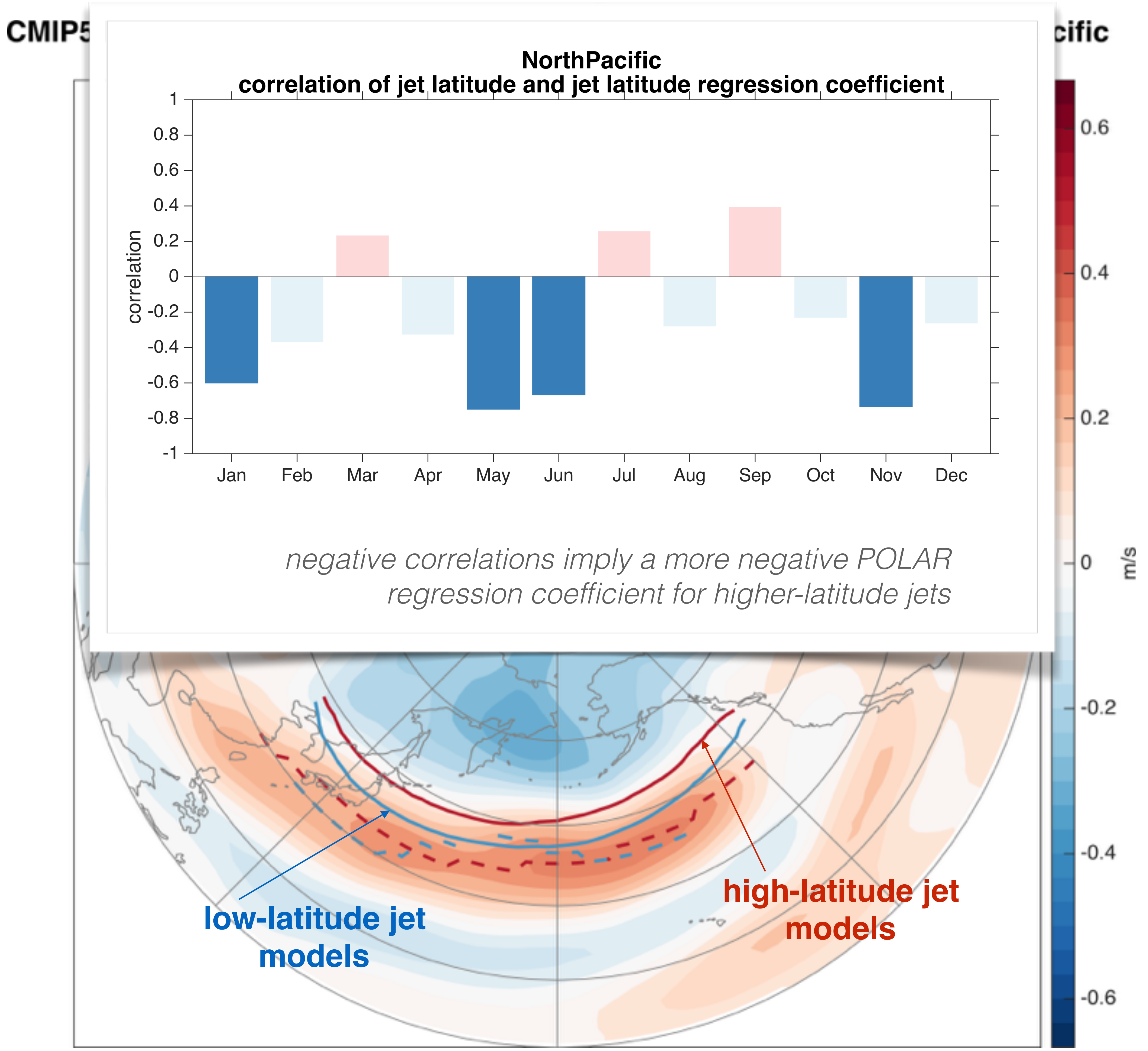

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Take-away points

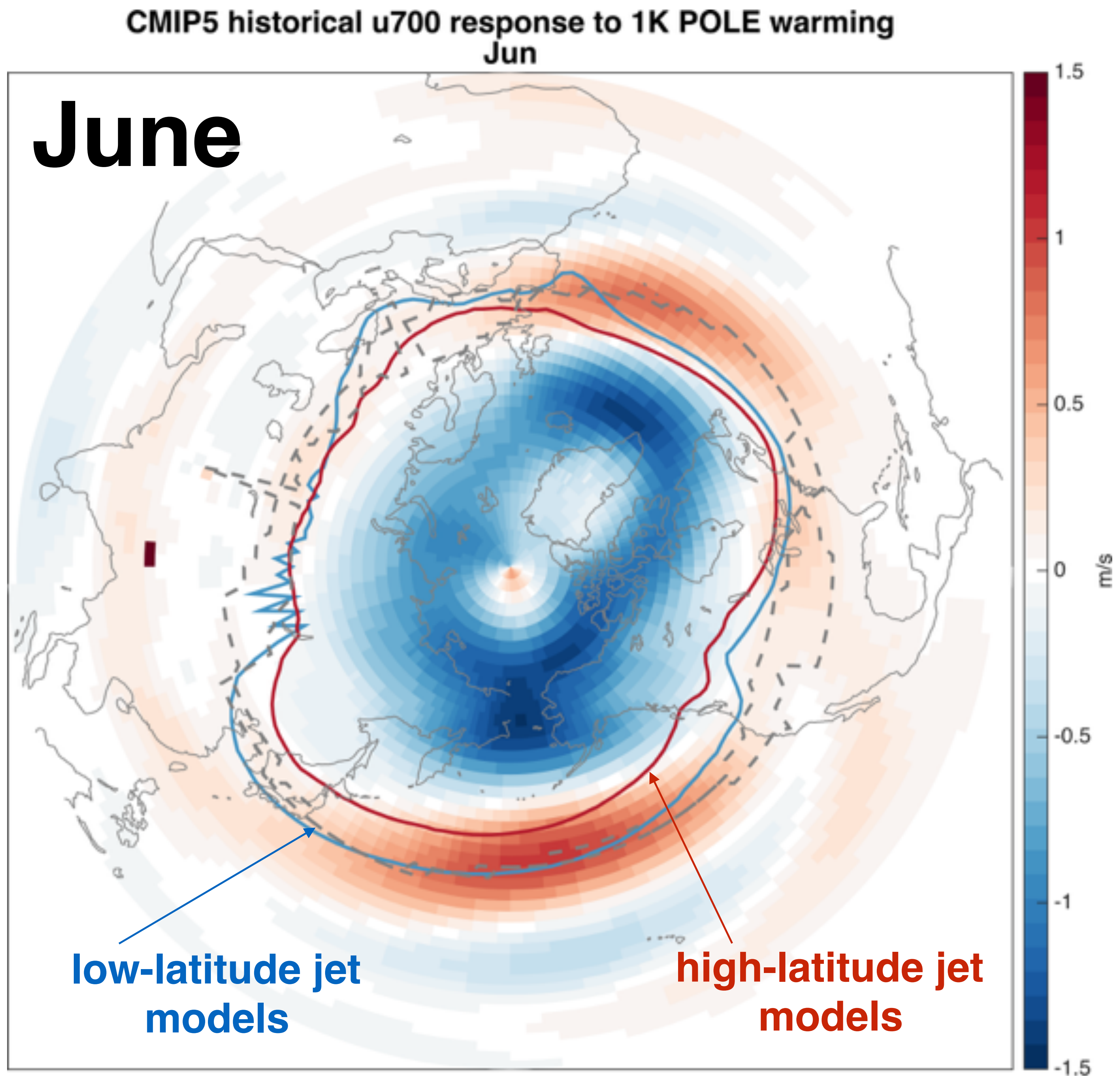
- Granger-causality approach shows that Arctic warming can influence the North Pacific jet latitude and speed

- The sensitivity of the jet-stream to ~weekly variations in Arctic temperatures varies as a function of season

    - e.g. the North Pacific jet latitude is most sensitive to Arctic warming in the summer months

- The seasonality of the jet position sensitivity to Arctic warming can be understood by the jet shifting in and out of the anomalies. This is shown to have implications for jet-stream biases in the CMIP5 models.

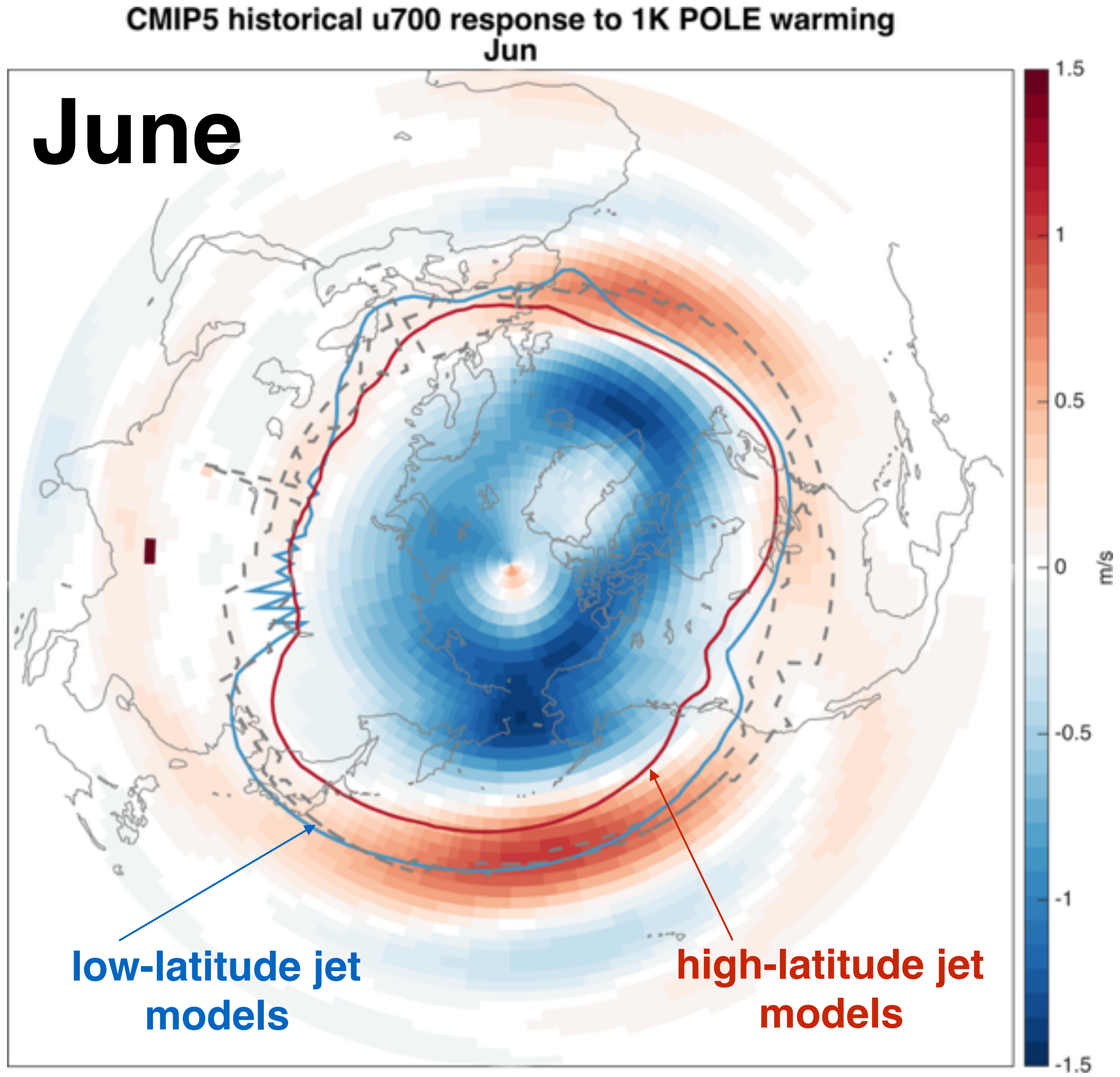
Implications for models biases (monthly, lag = 0 analysis)

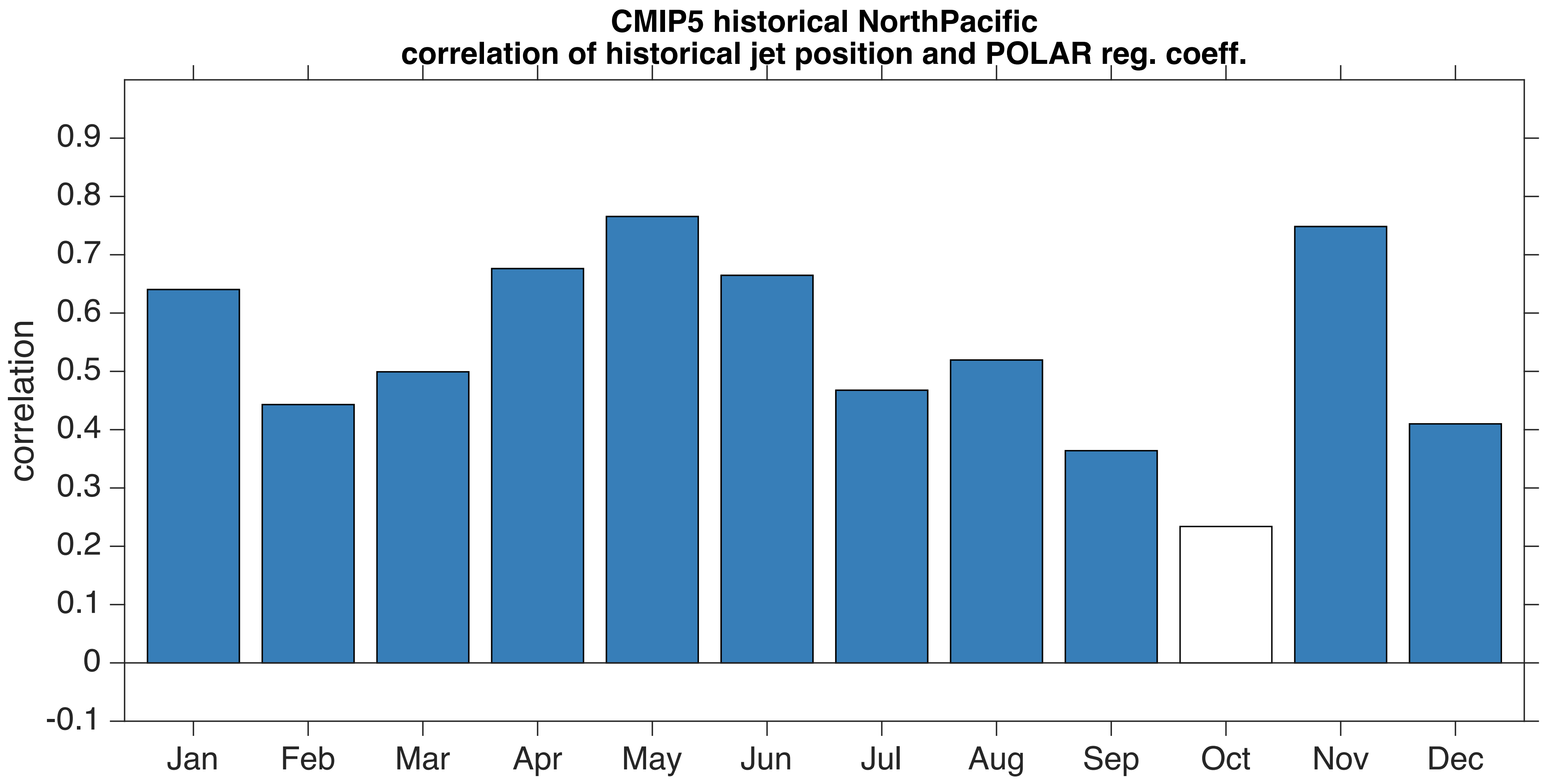


25% most equatorward CMIP5 jet-streams
25% most poleward CMIP5 jet-streams

latitude of maximum regression coefficient

Implications for models biases (monthly, lag = 0 analysis)





positive correlations imply a more negative POLAR regression coefficient for higher-latitude jets

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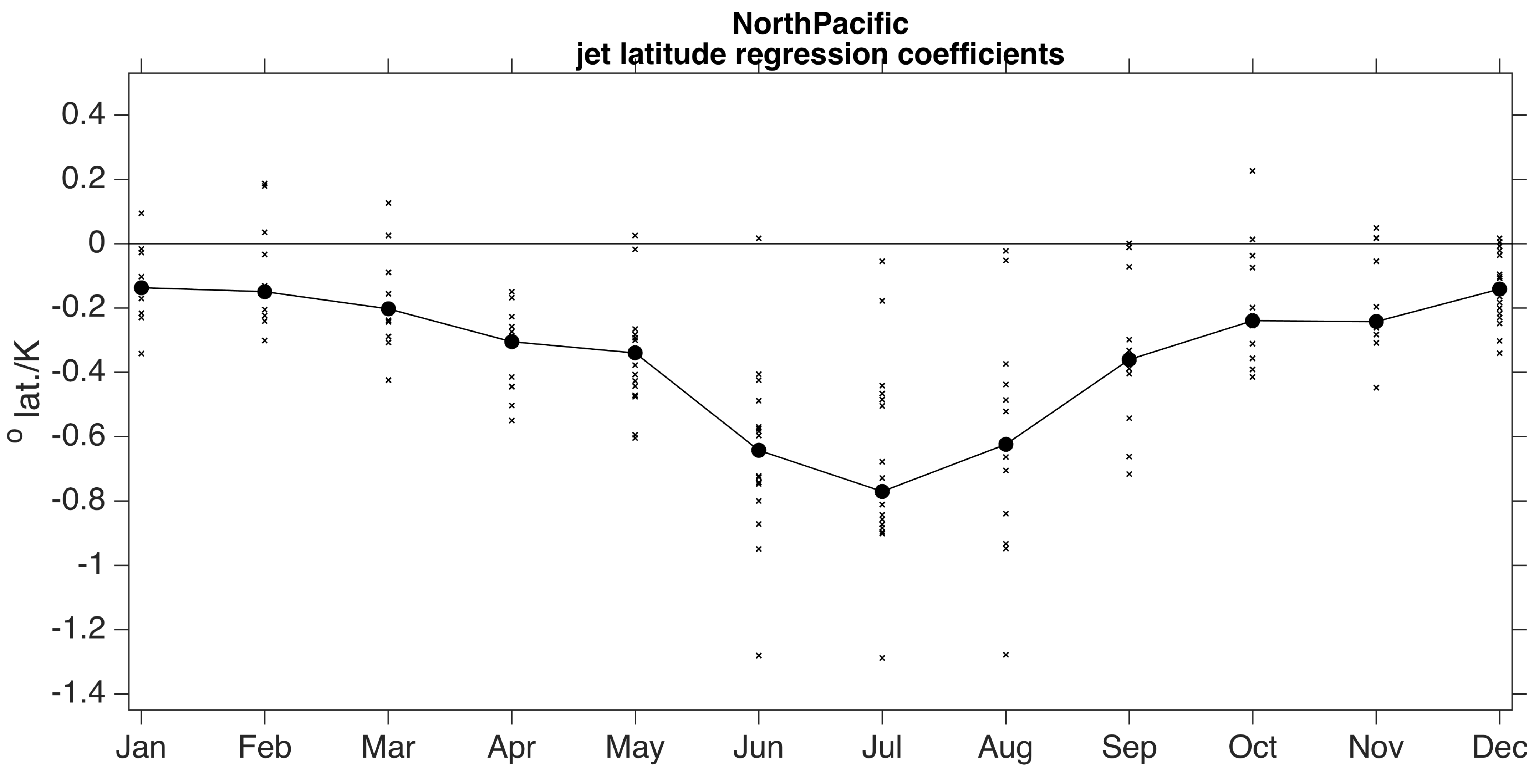
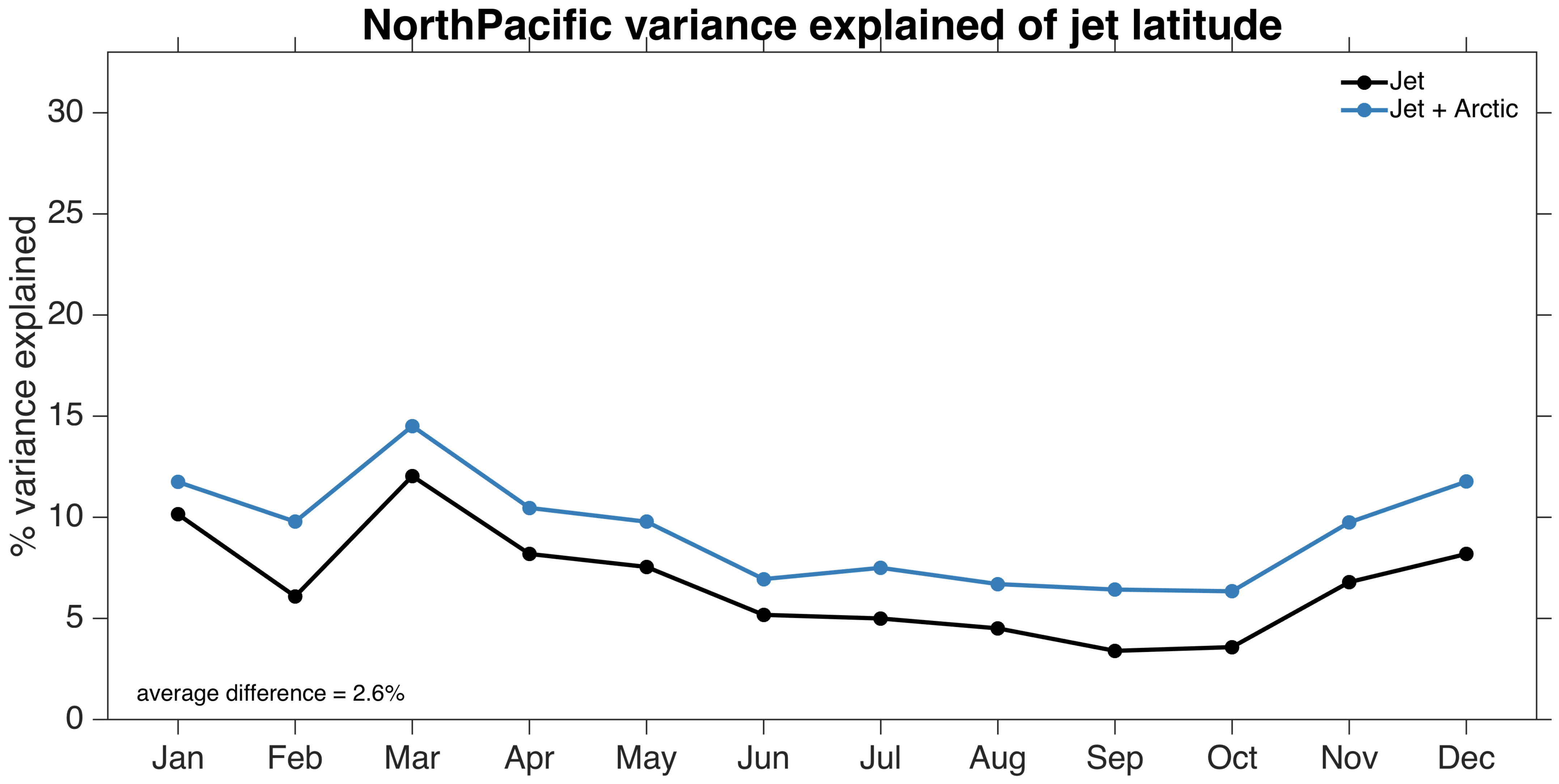
latitude of maximum regression coefficient

Seasonal sensitivity: jet position





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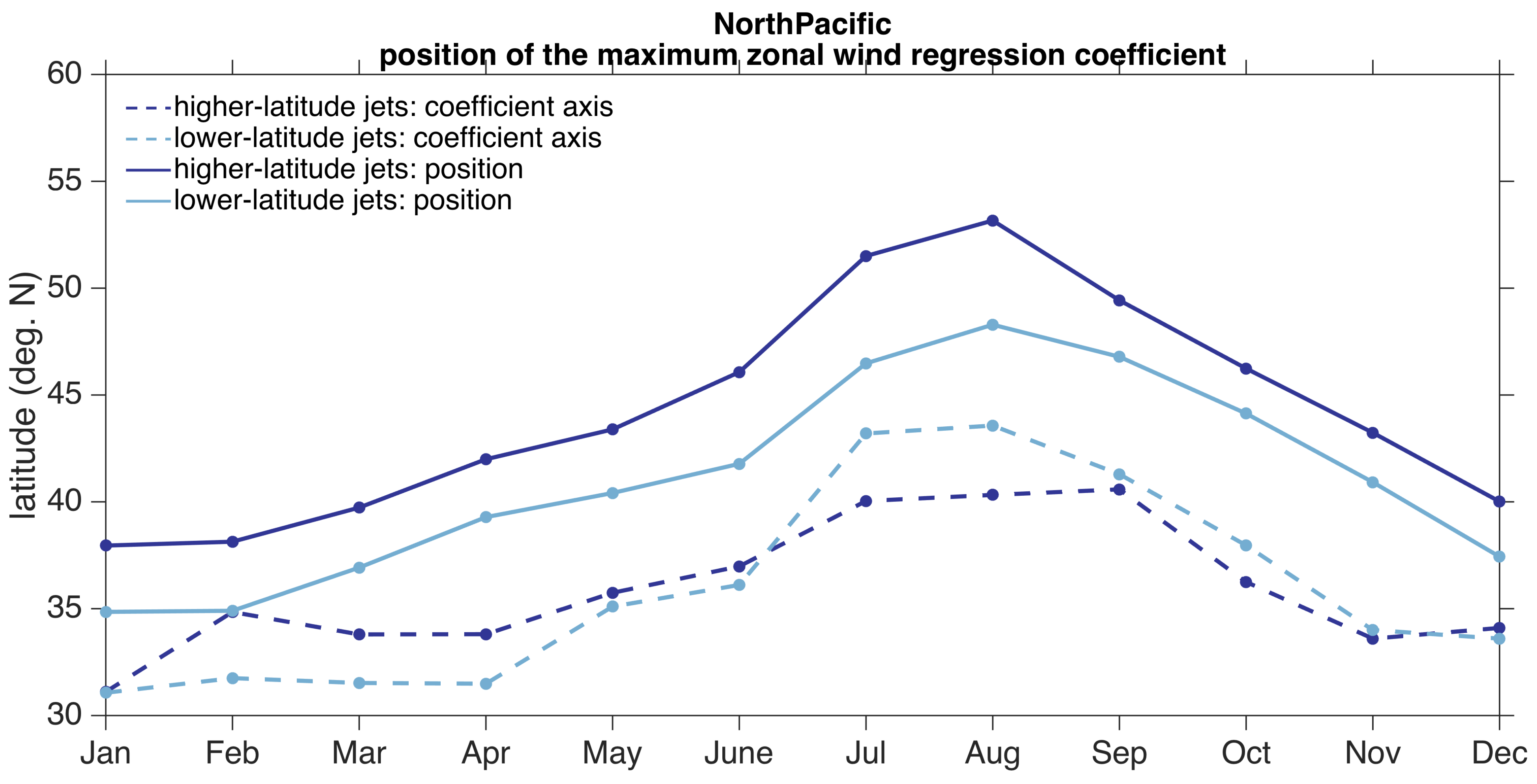

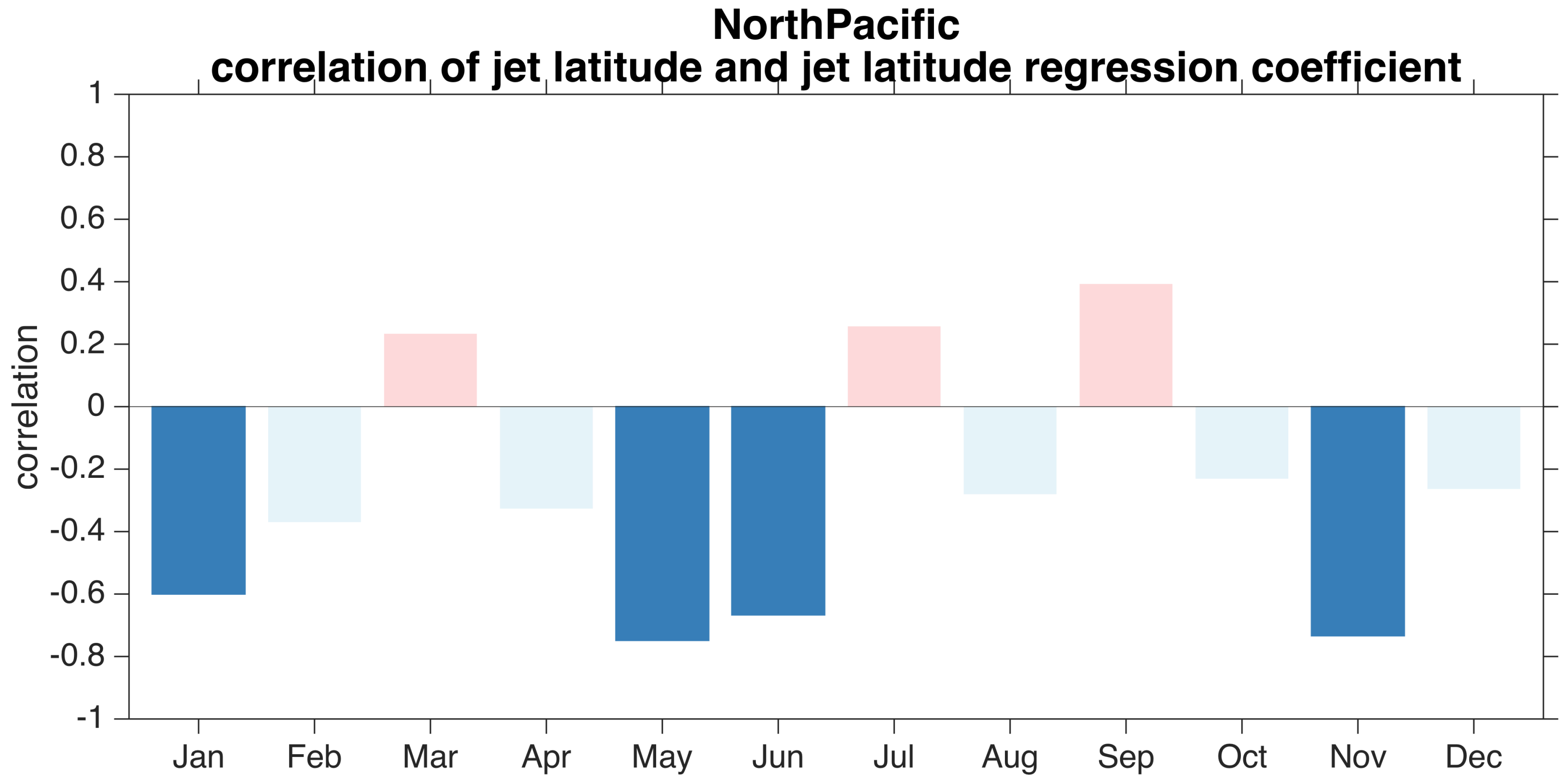

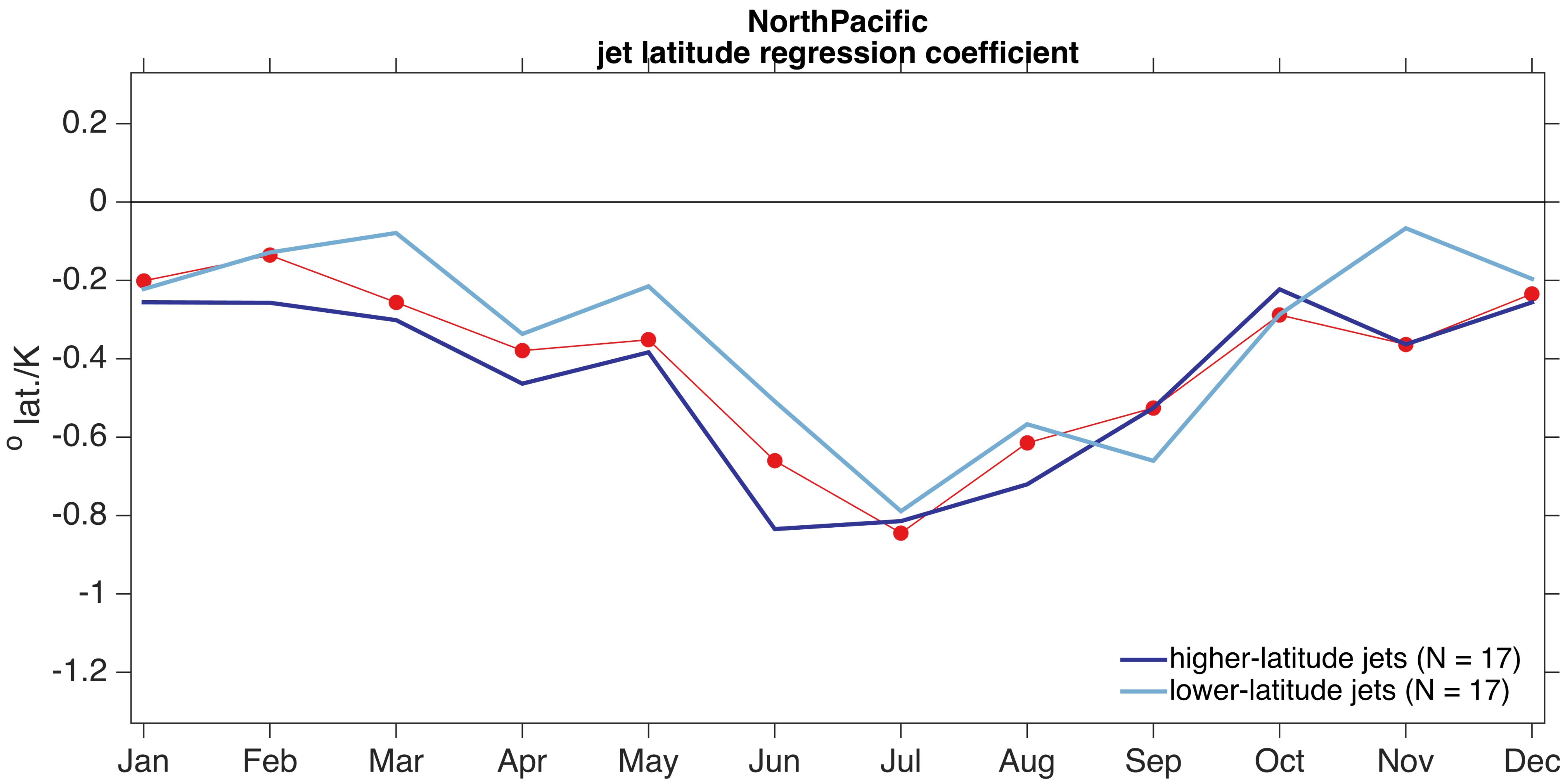

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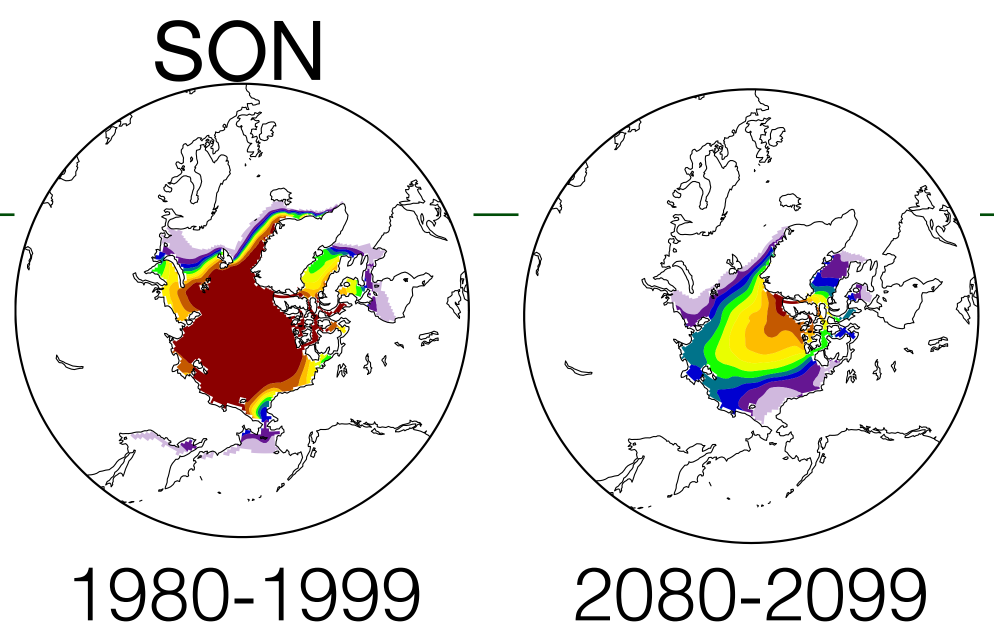
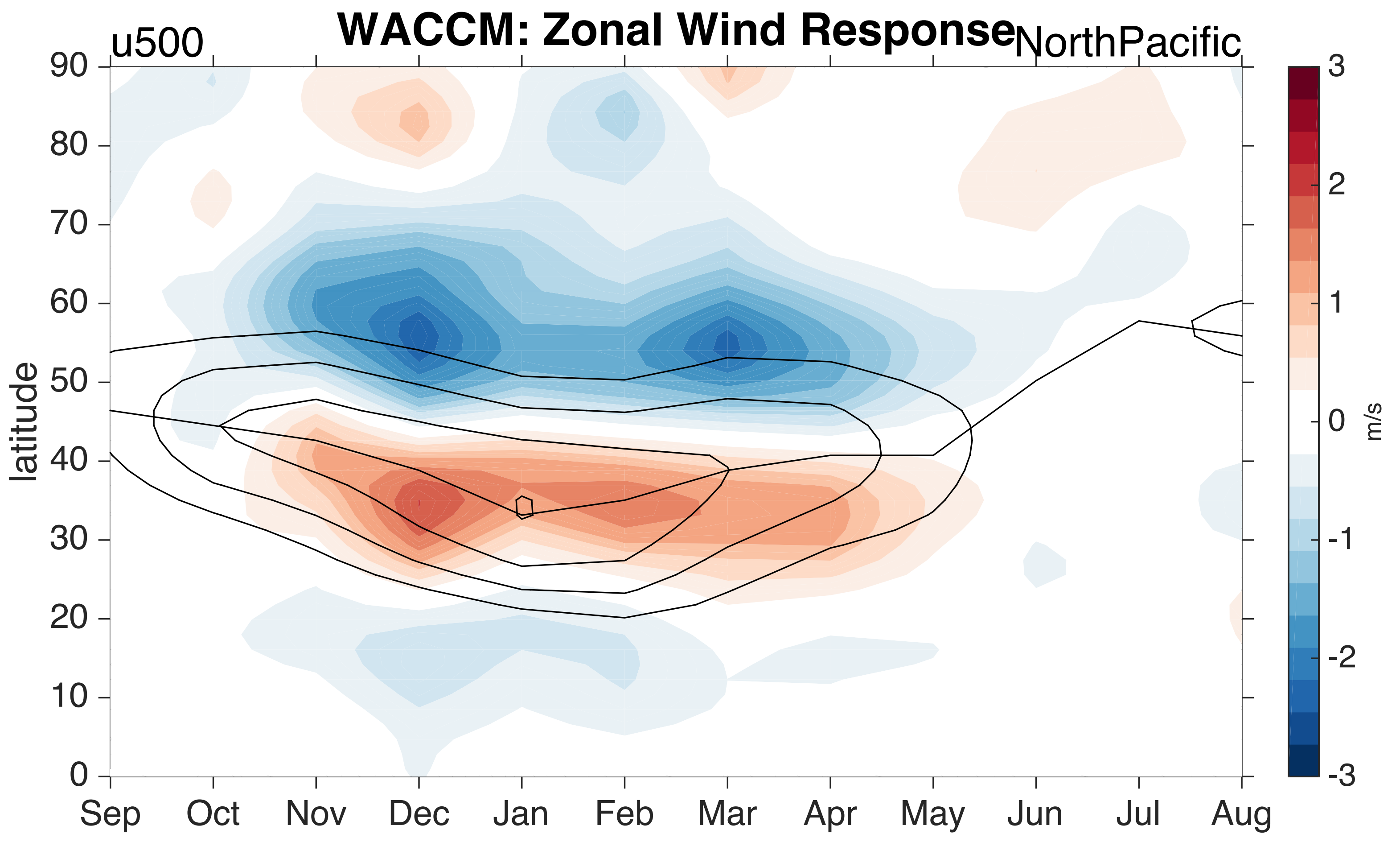
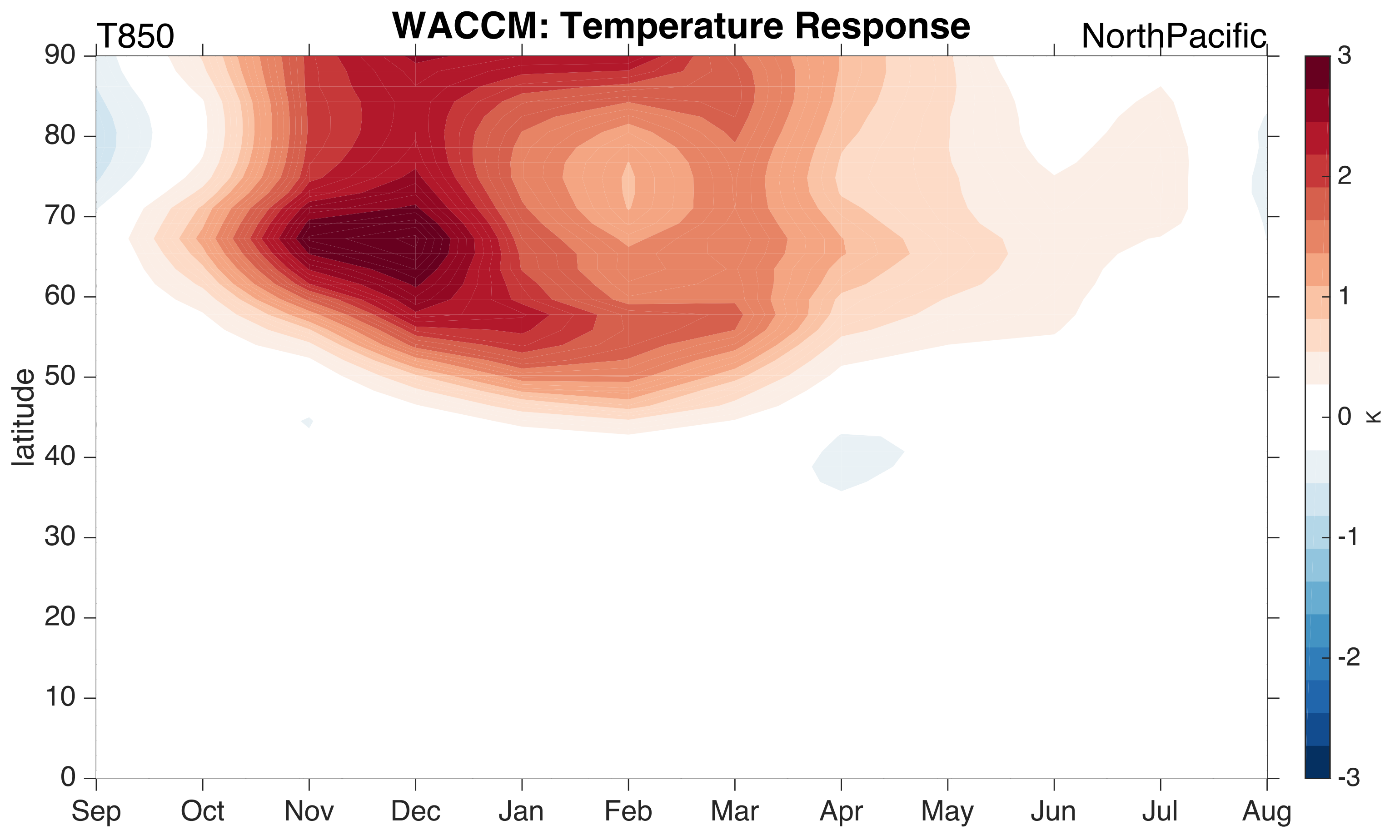
Jet response to sea ice loss







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

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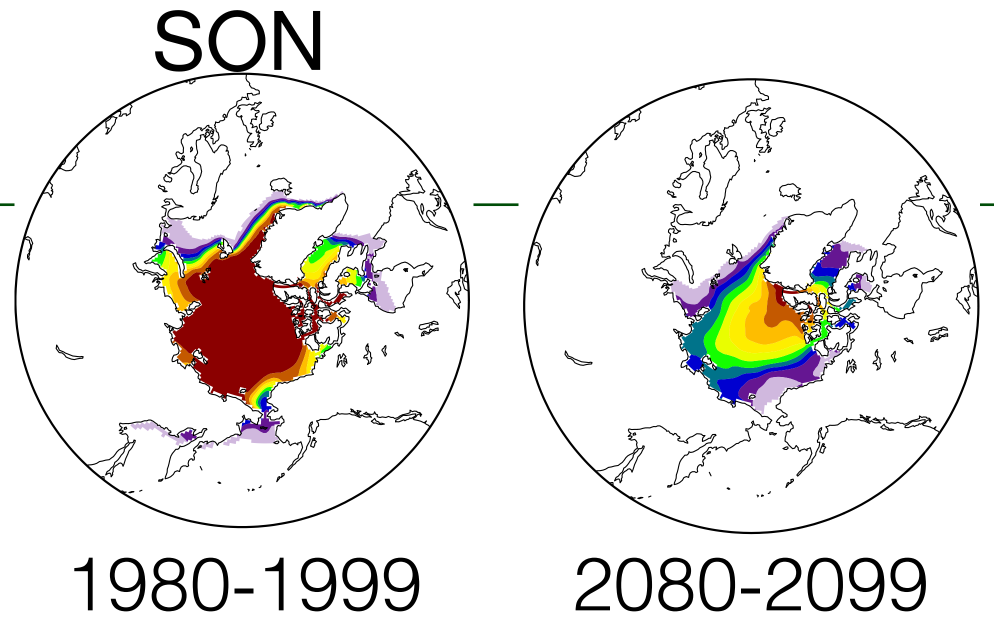

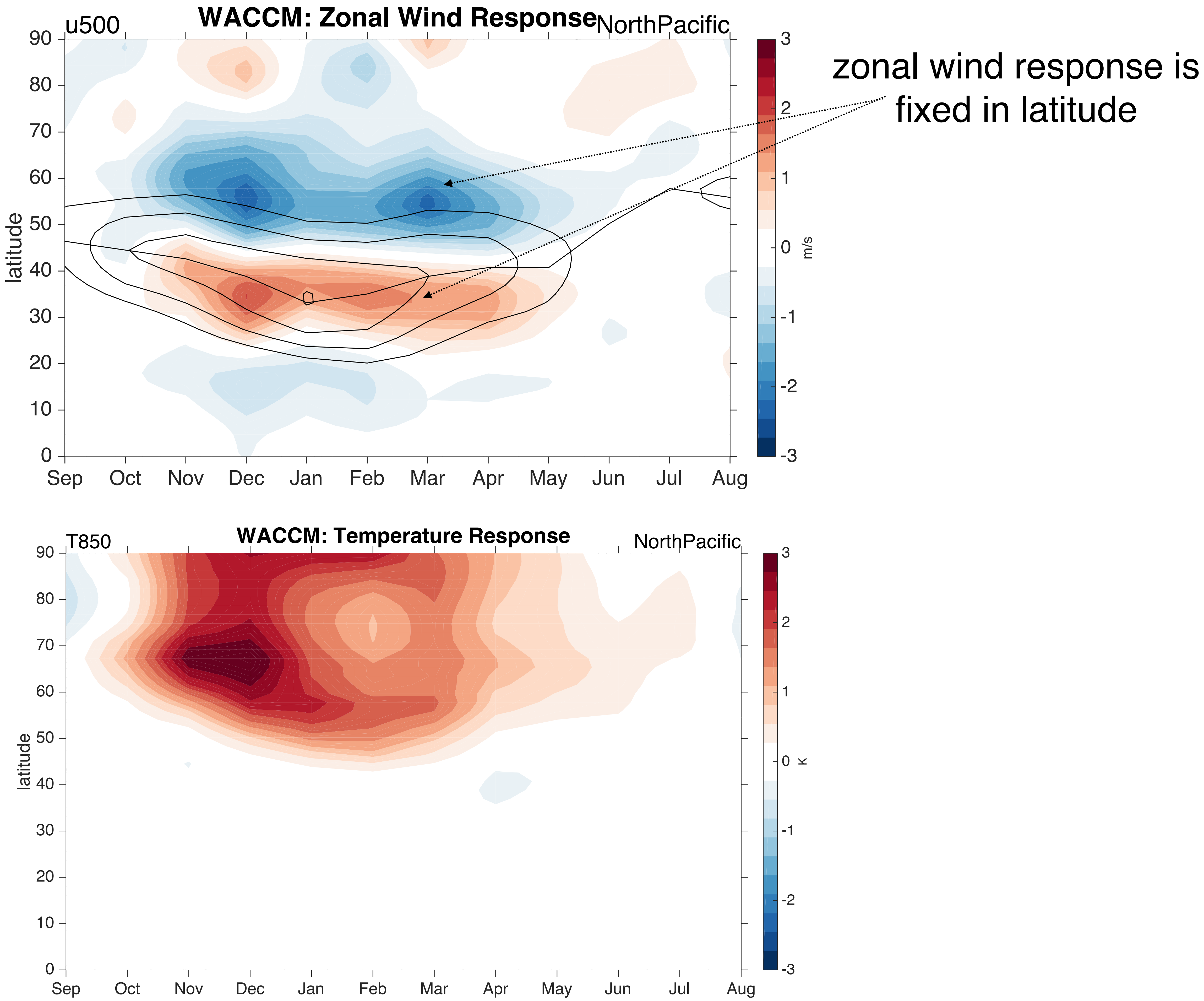

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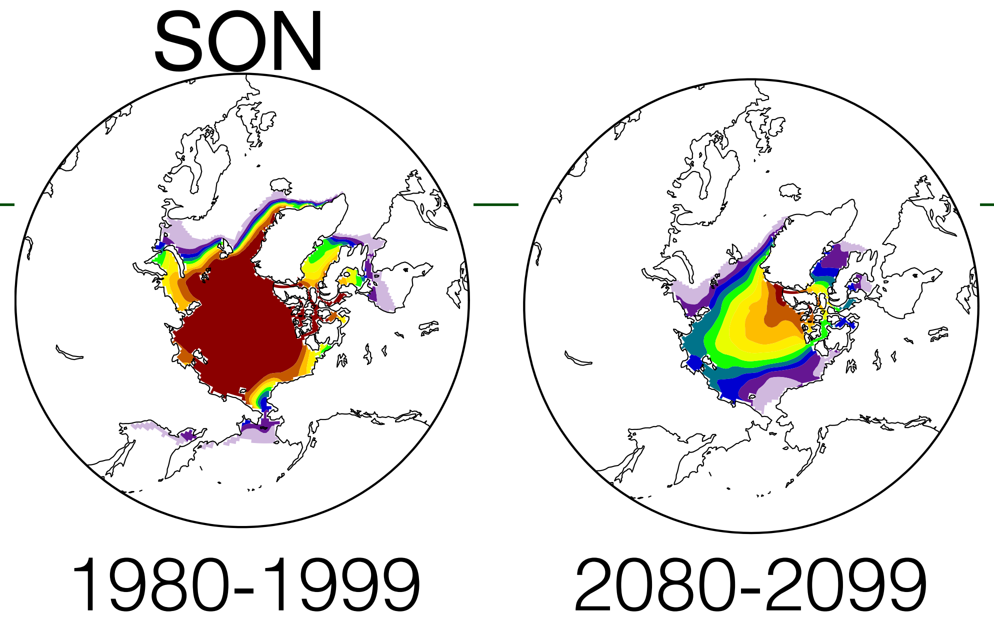

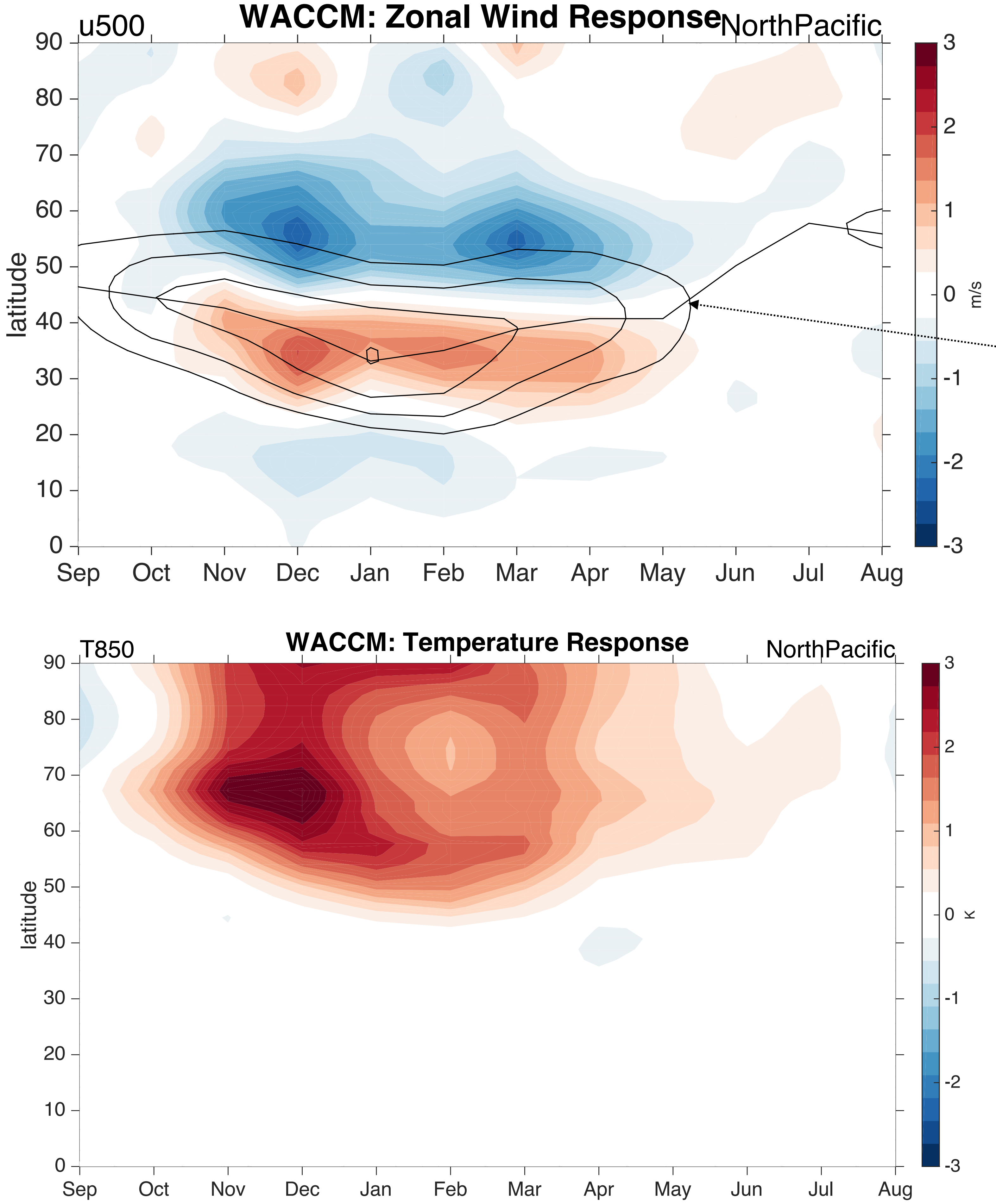

seasonality of jet shifts in-and-out of the sea-ice forced anomalies

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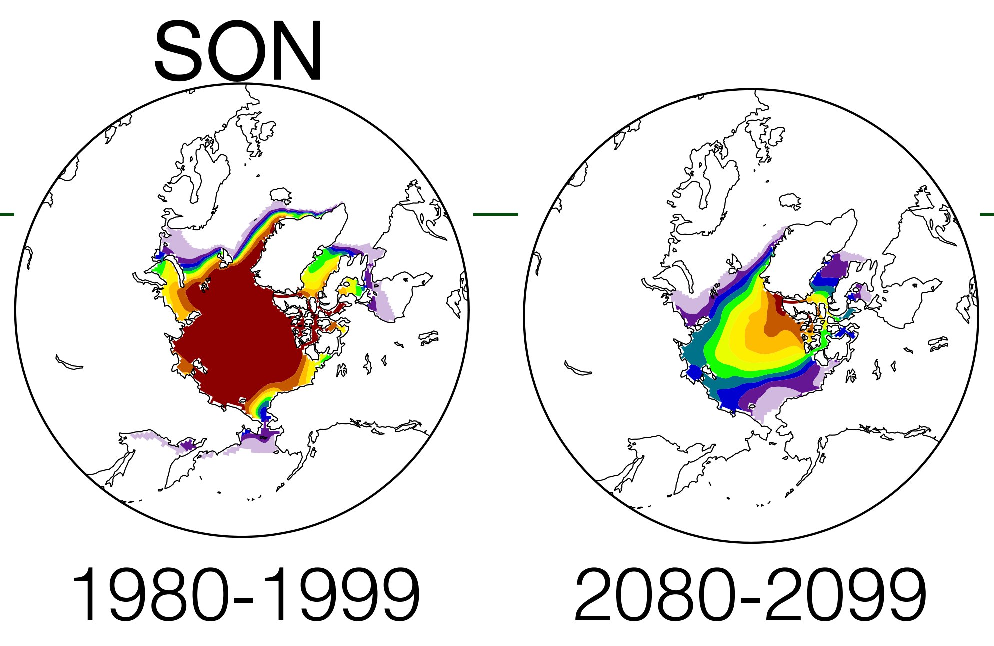

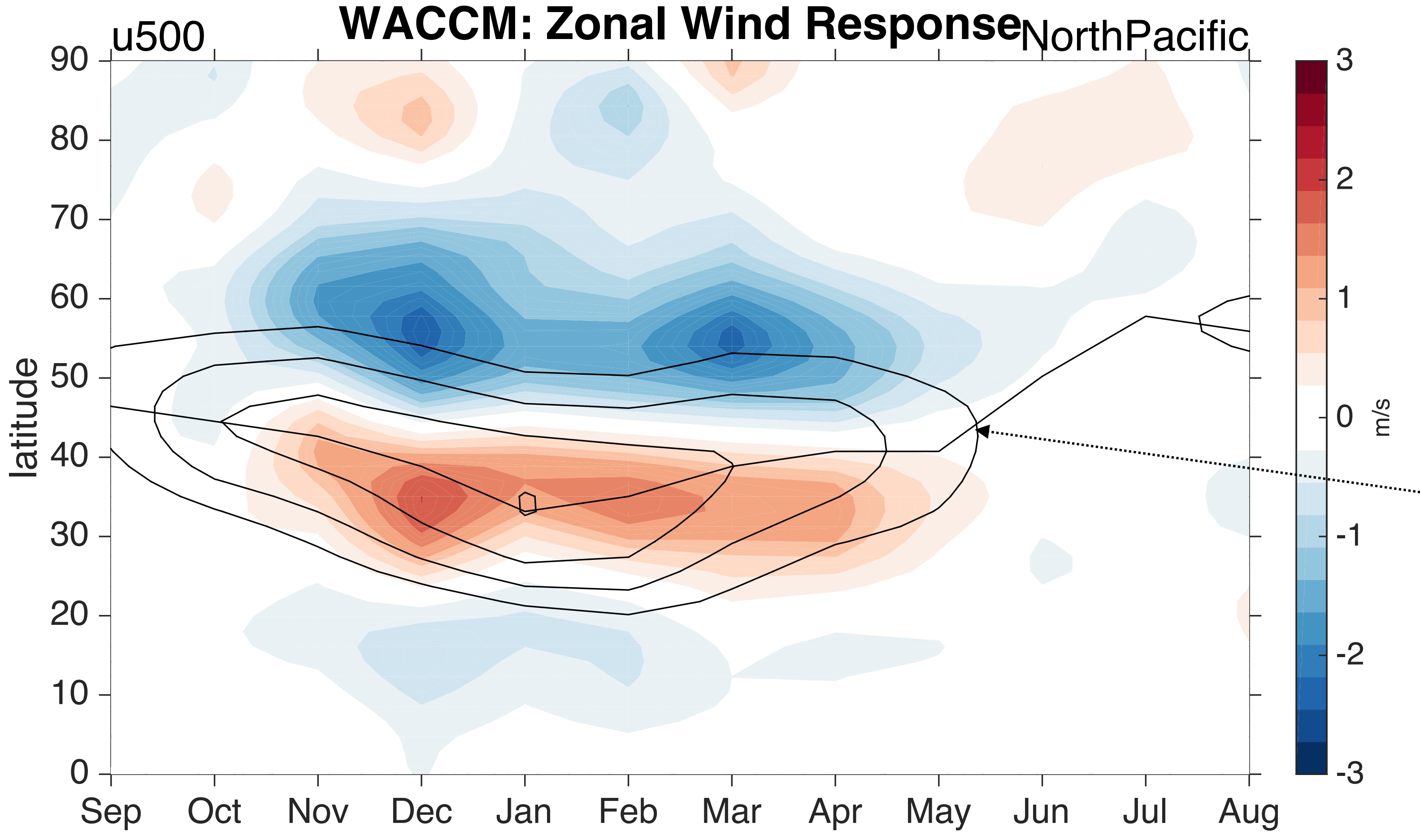

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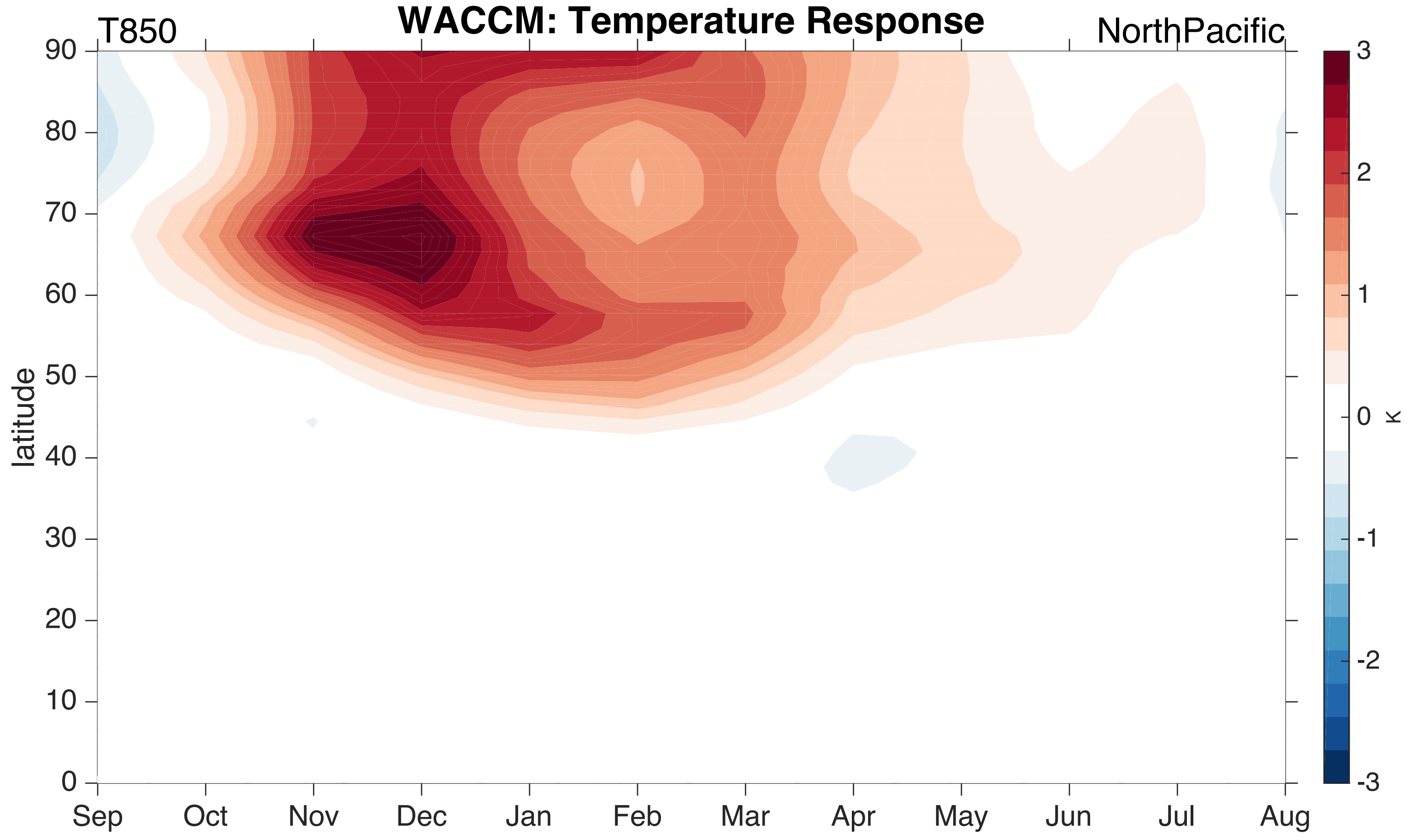

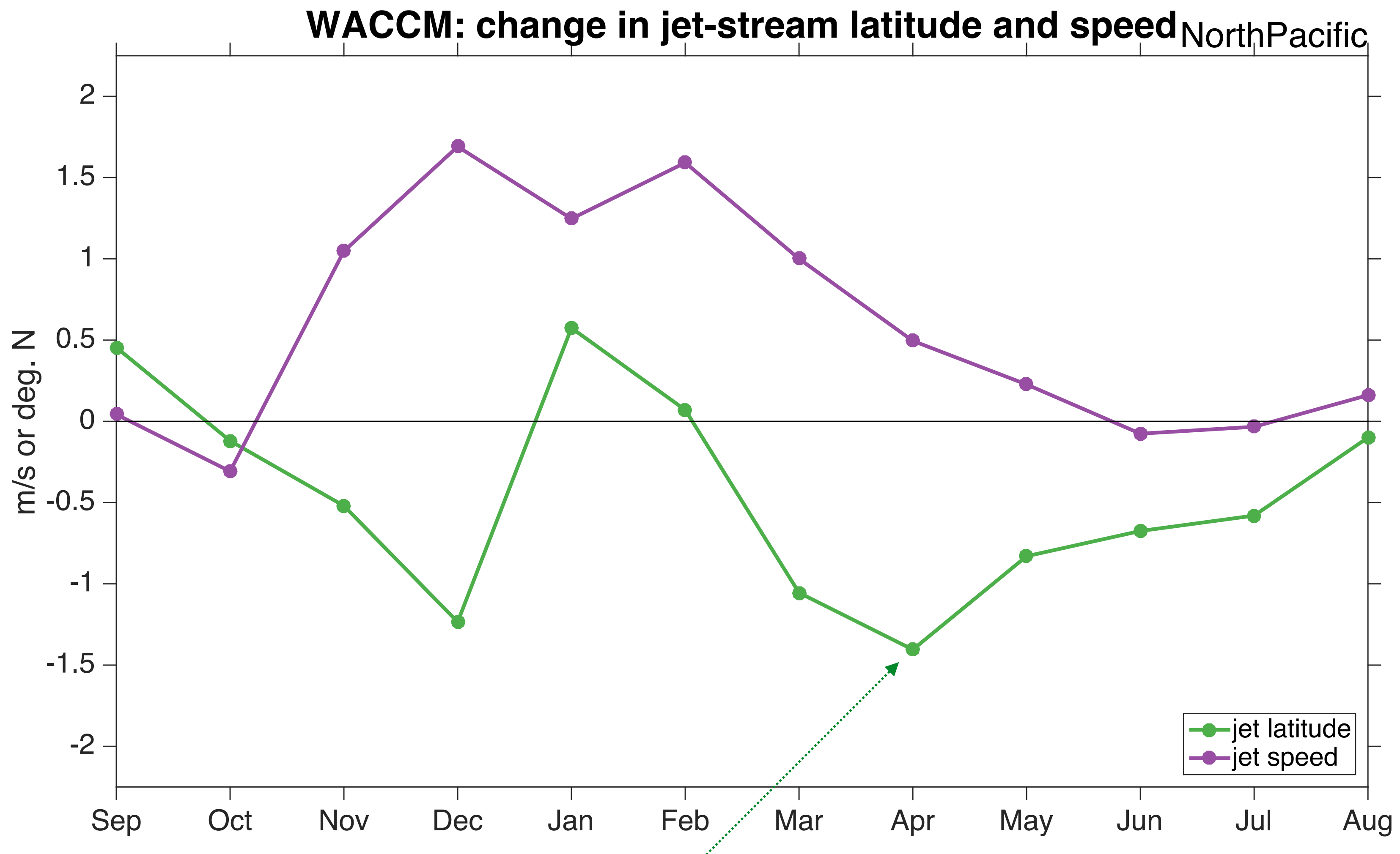

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jet shift largest in Mar.-Apr.

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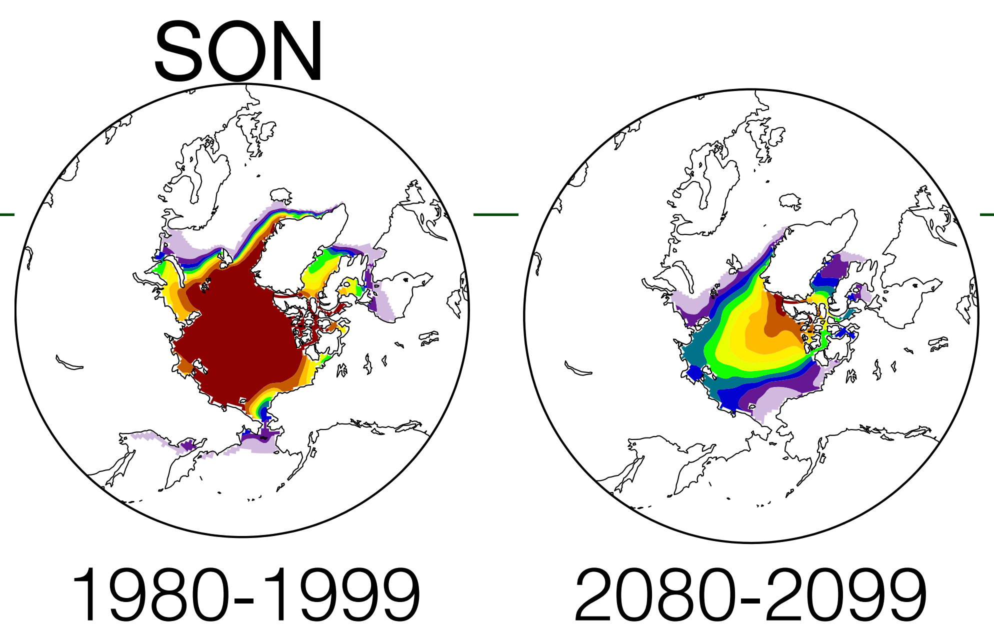

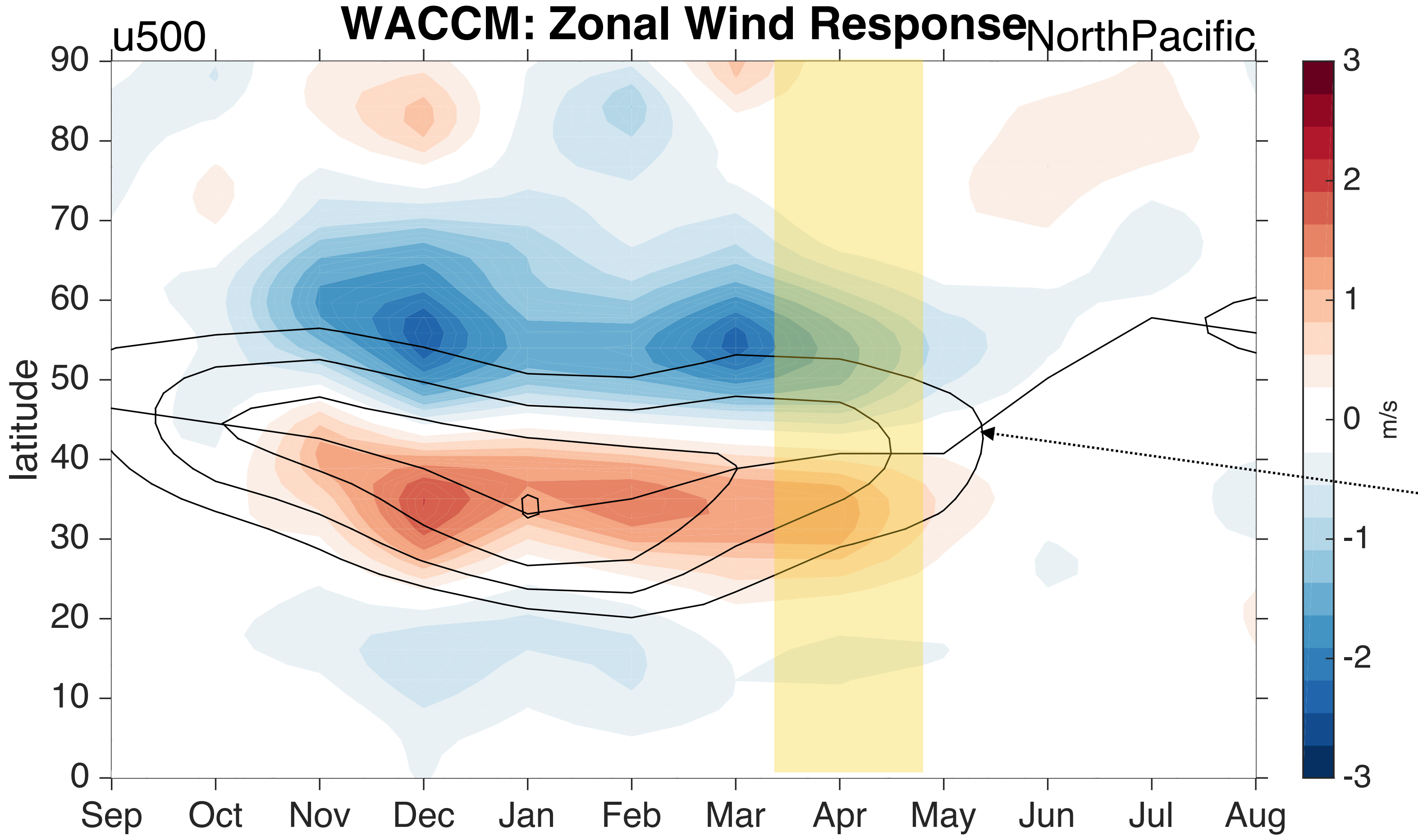

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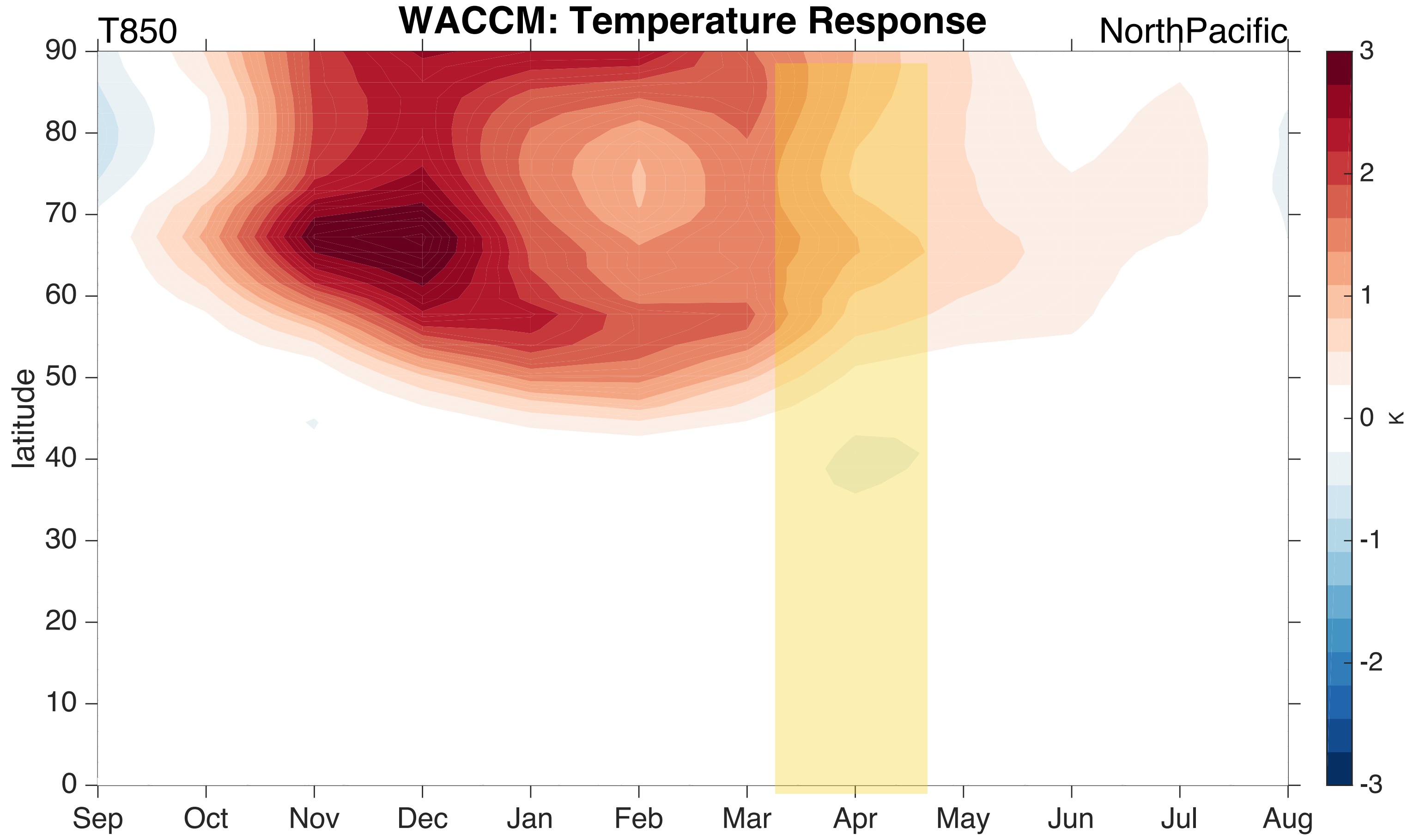

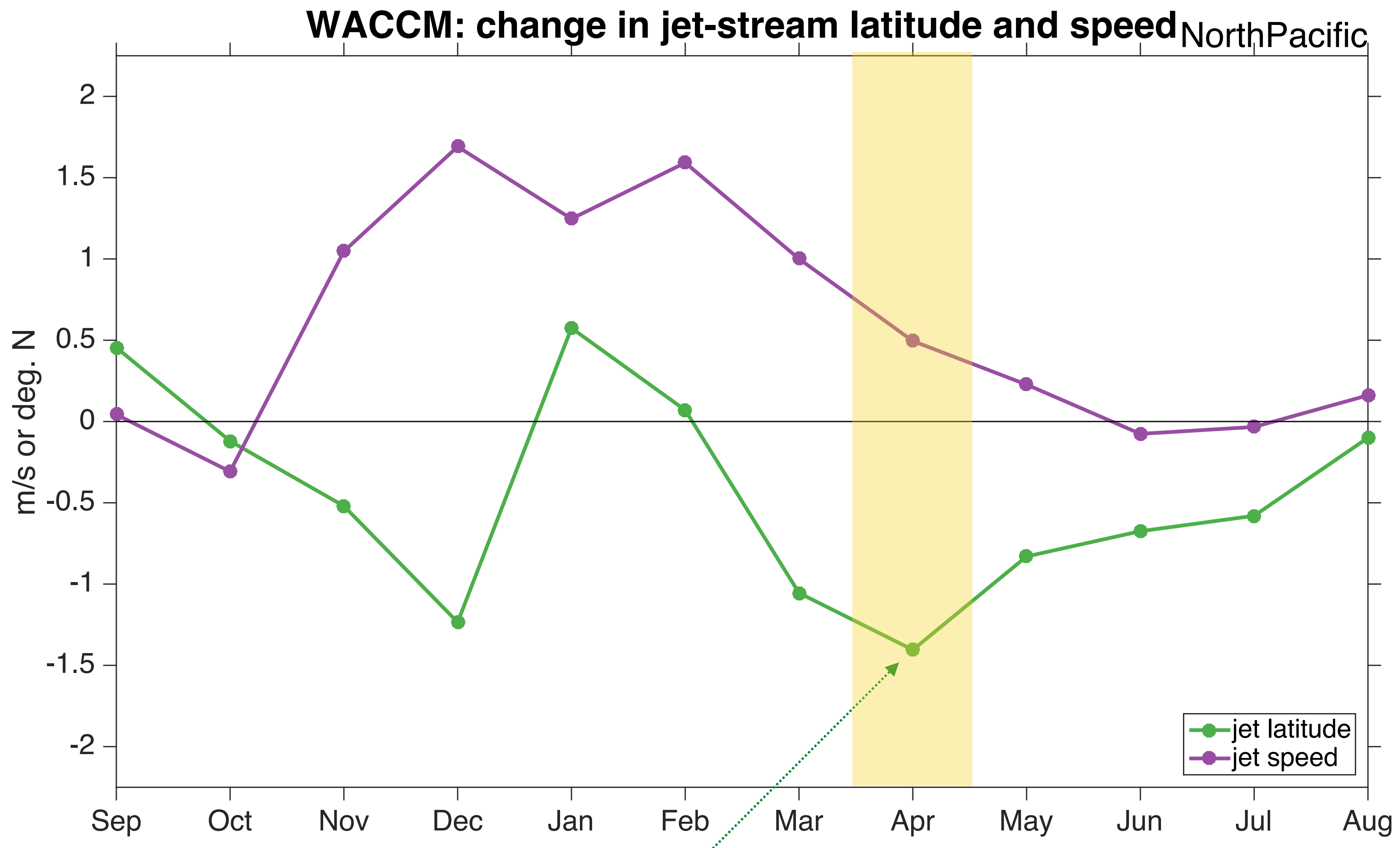

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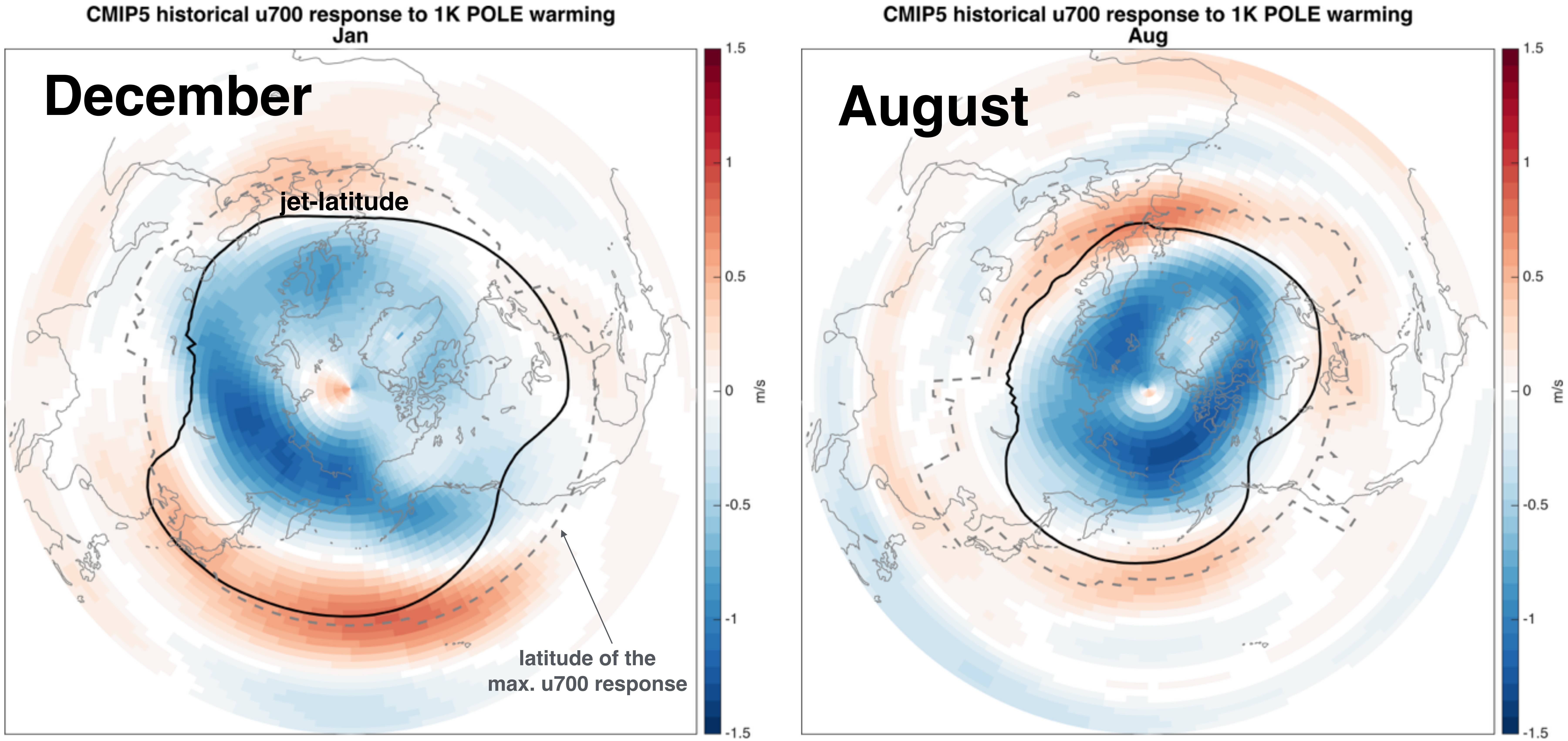
Summer vs. Winter: regression maps of u700



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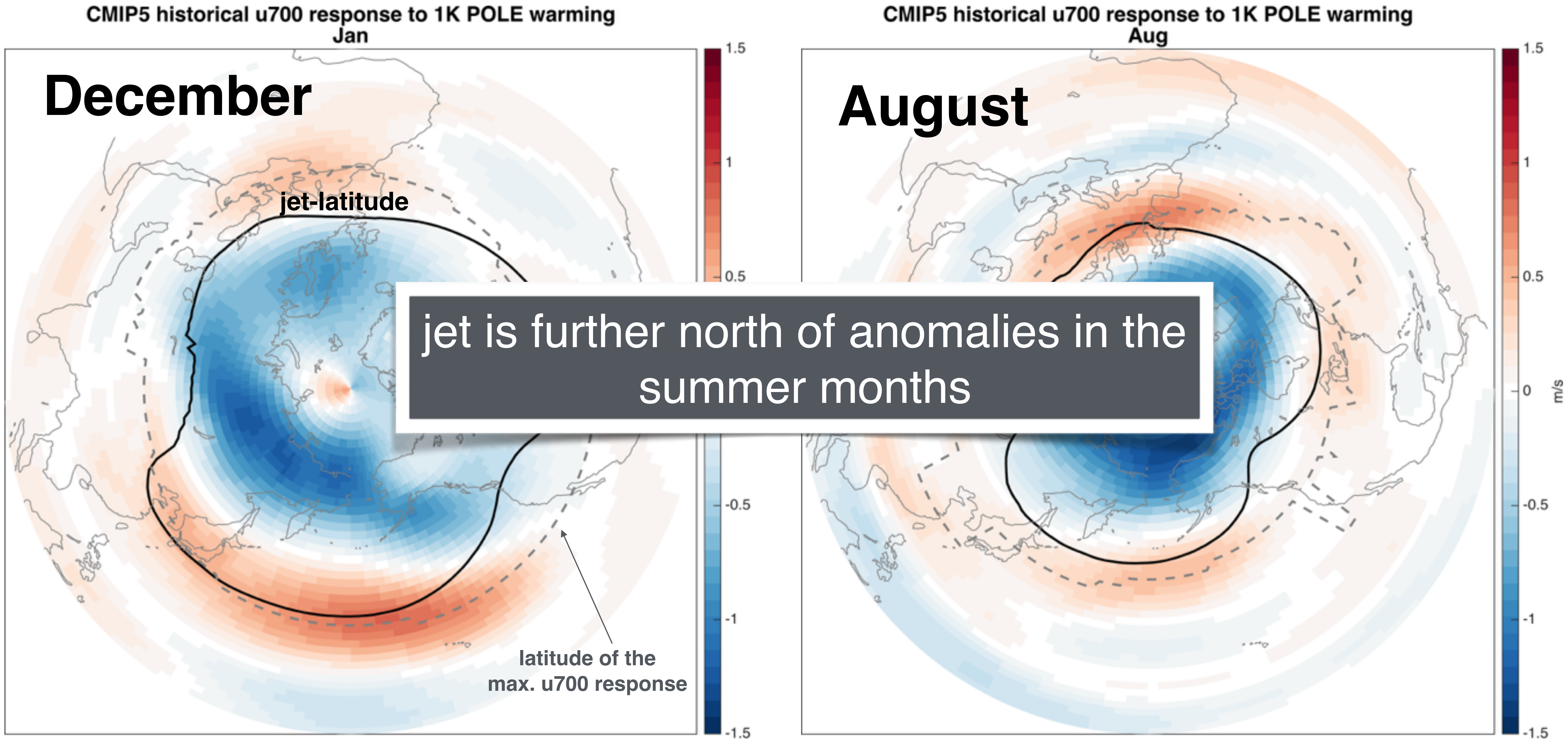
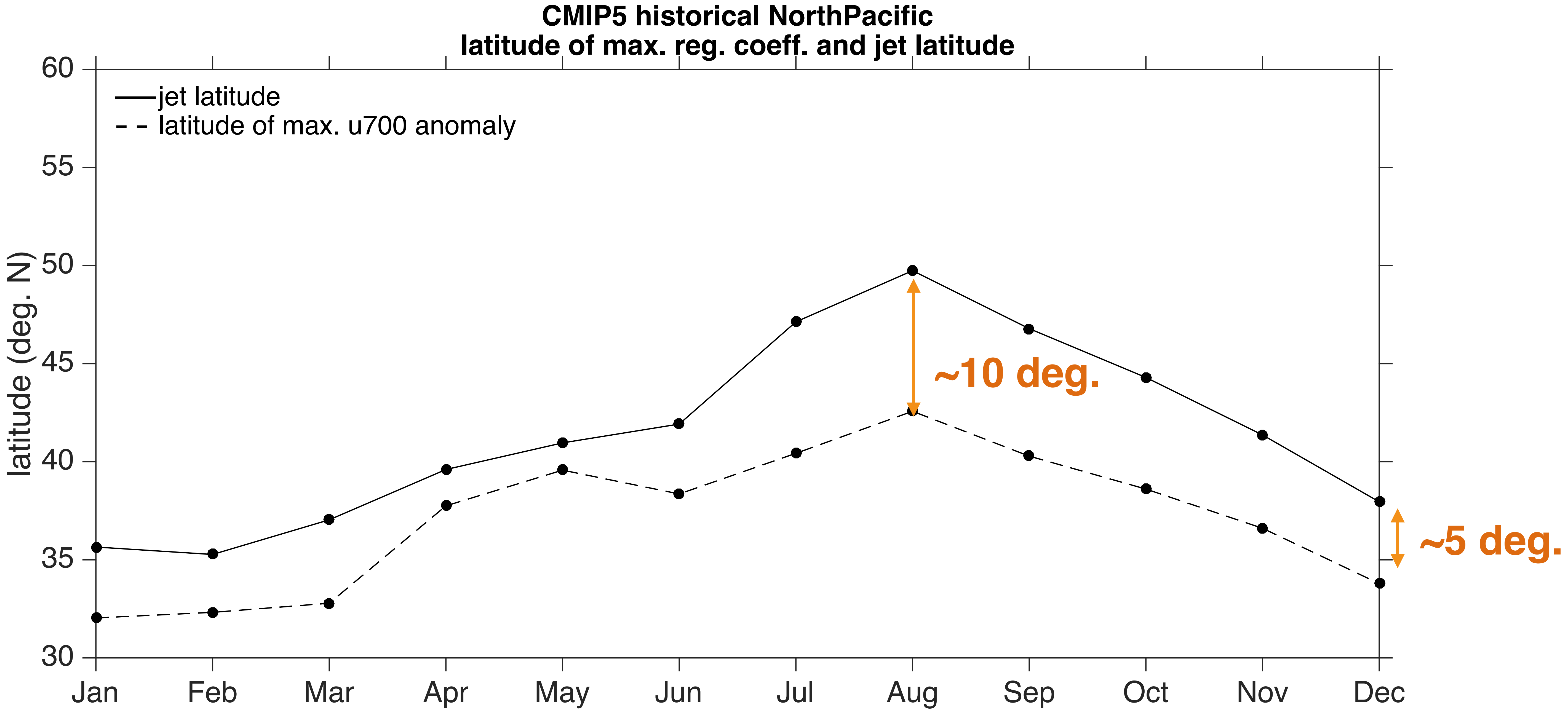


jet is further north of anomalies in the summer months

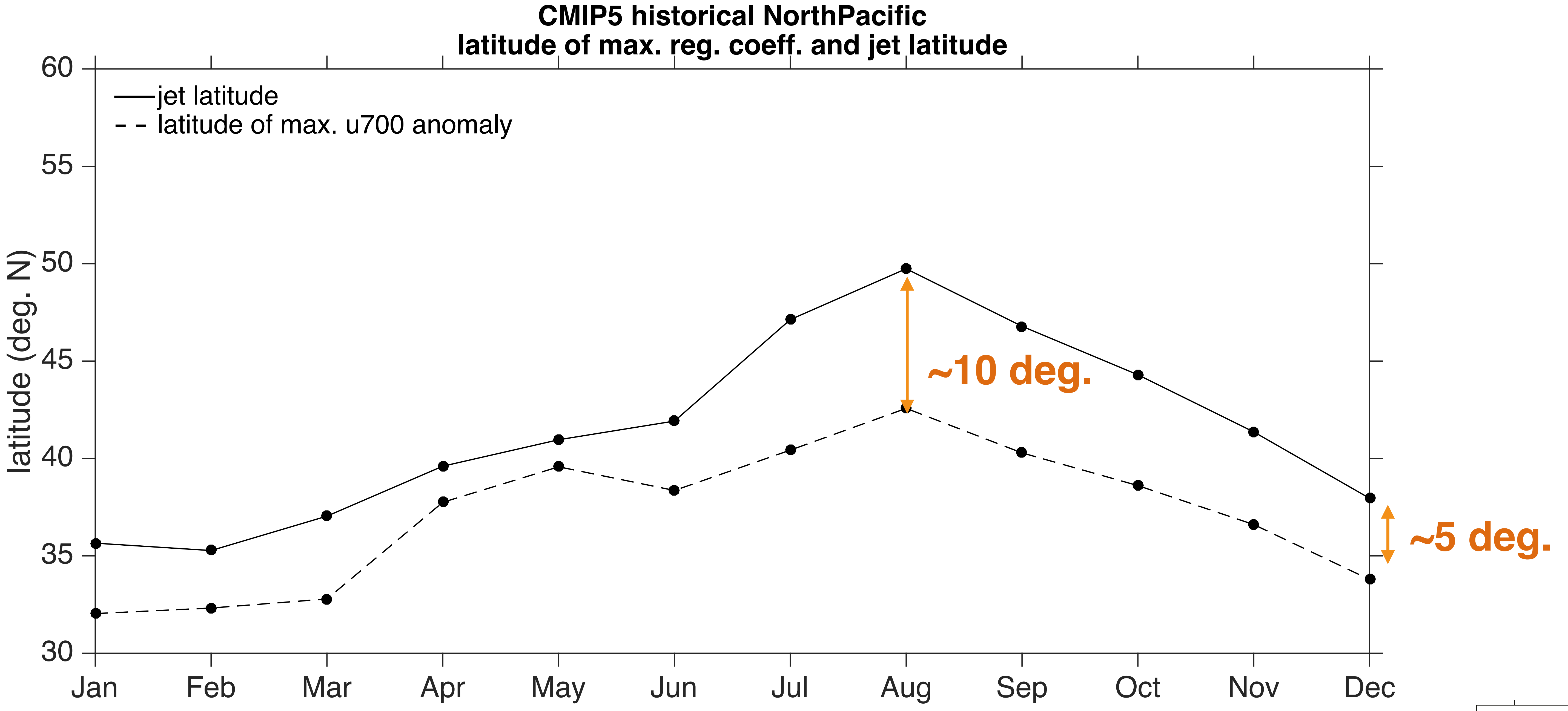
Relative location of the forcing matters for the jet shift



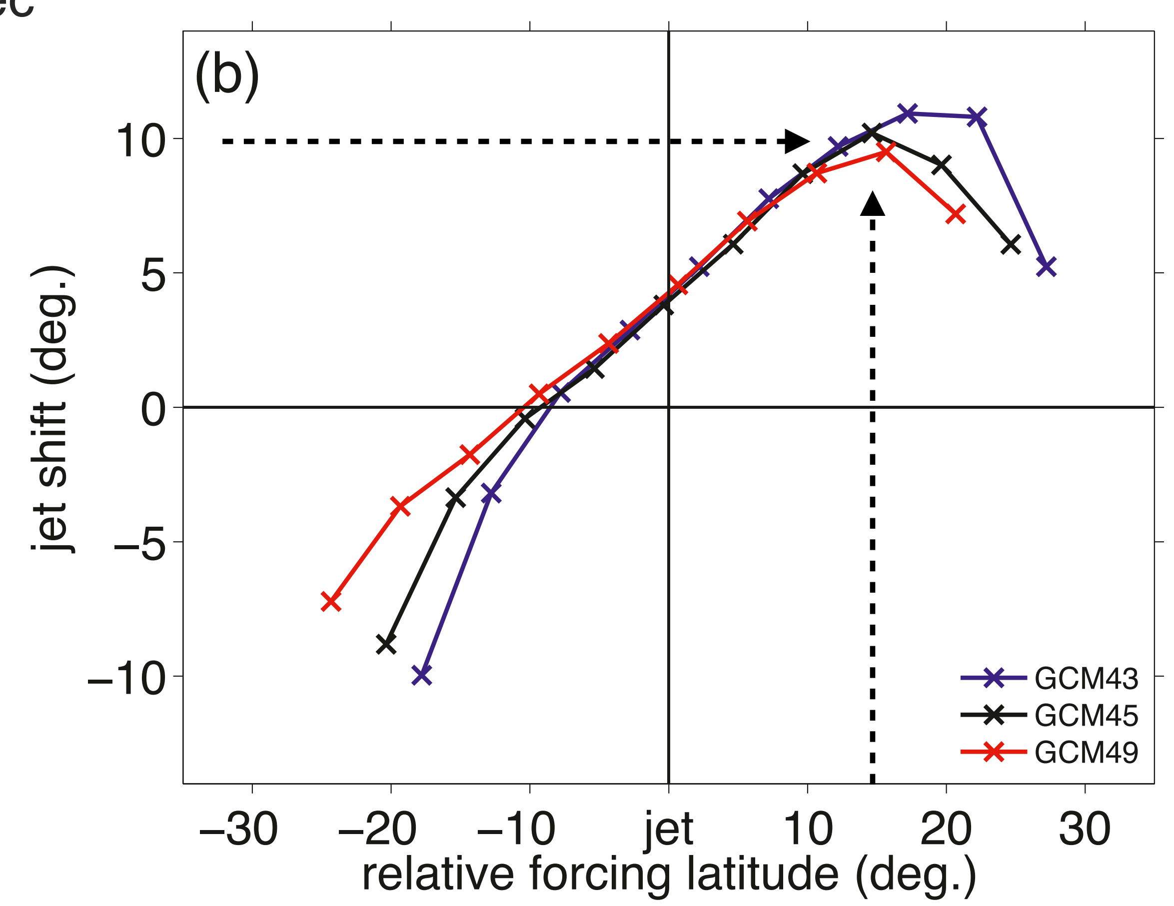
also explored in detail by Ring & Plumb (2007; JAS)

Barnes & Thompson (2014; JAS)

Relative location of the forcing matters for the jet shift



largest jet-shift when model is forced approximately 10-15 degrees off of its mean jet position

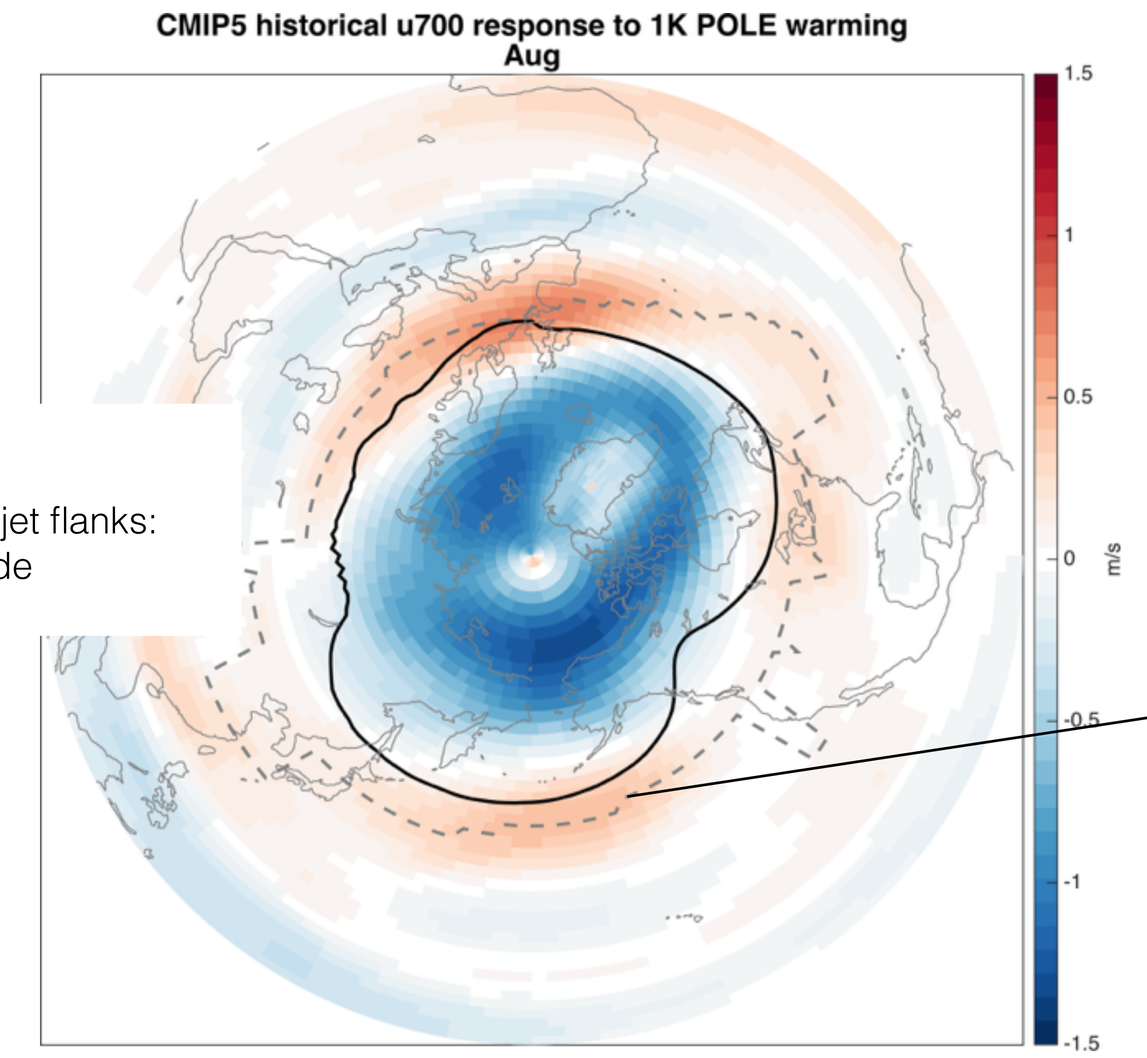


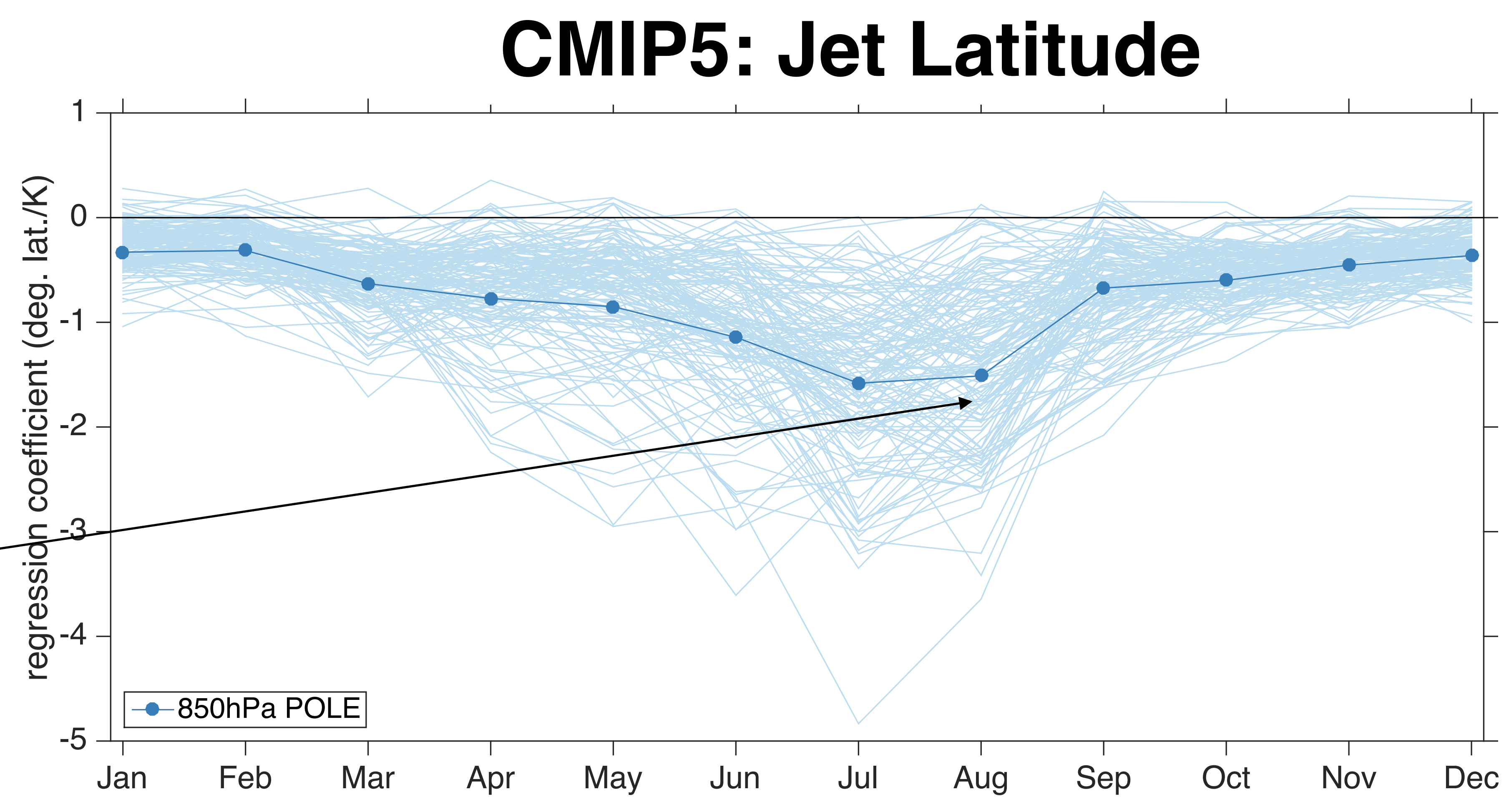
also explored in detail by Ring & Plumb (2007; JAS)

Barnes & Thompson (2014; JAS)

Summer vs. Winter: jet latitude vs. jet speed

AUGUST
anomalies project onto jet flanks:
impact jet latitude





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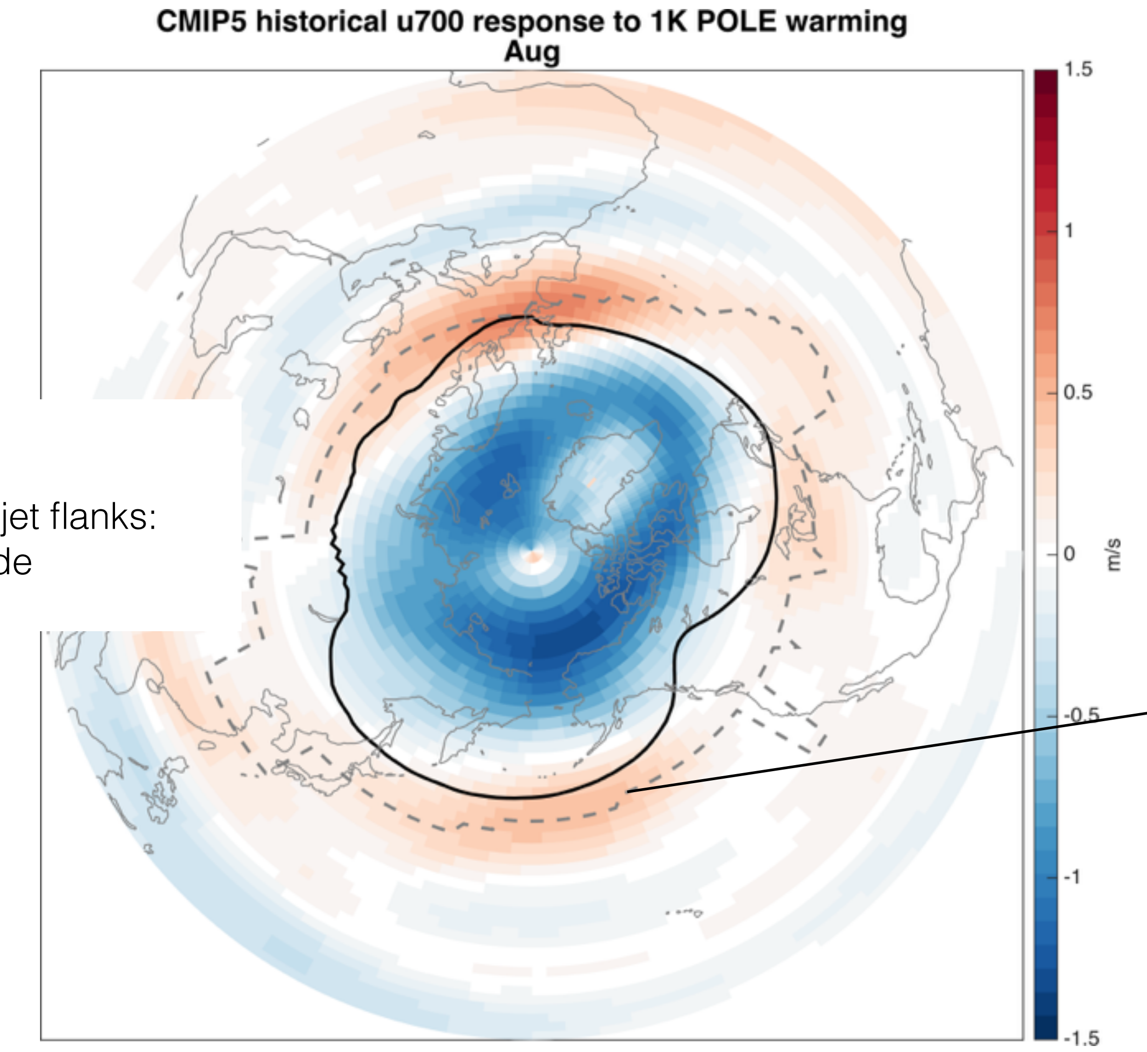
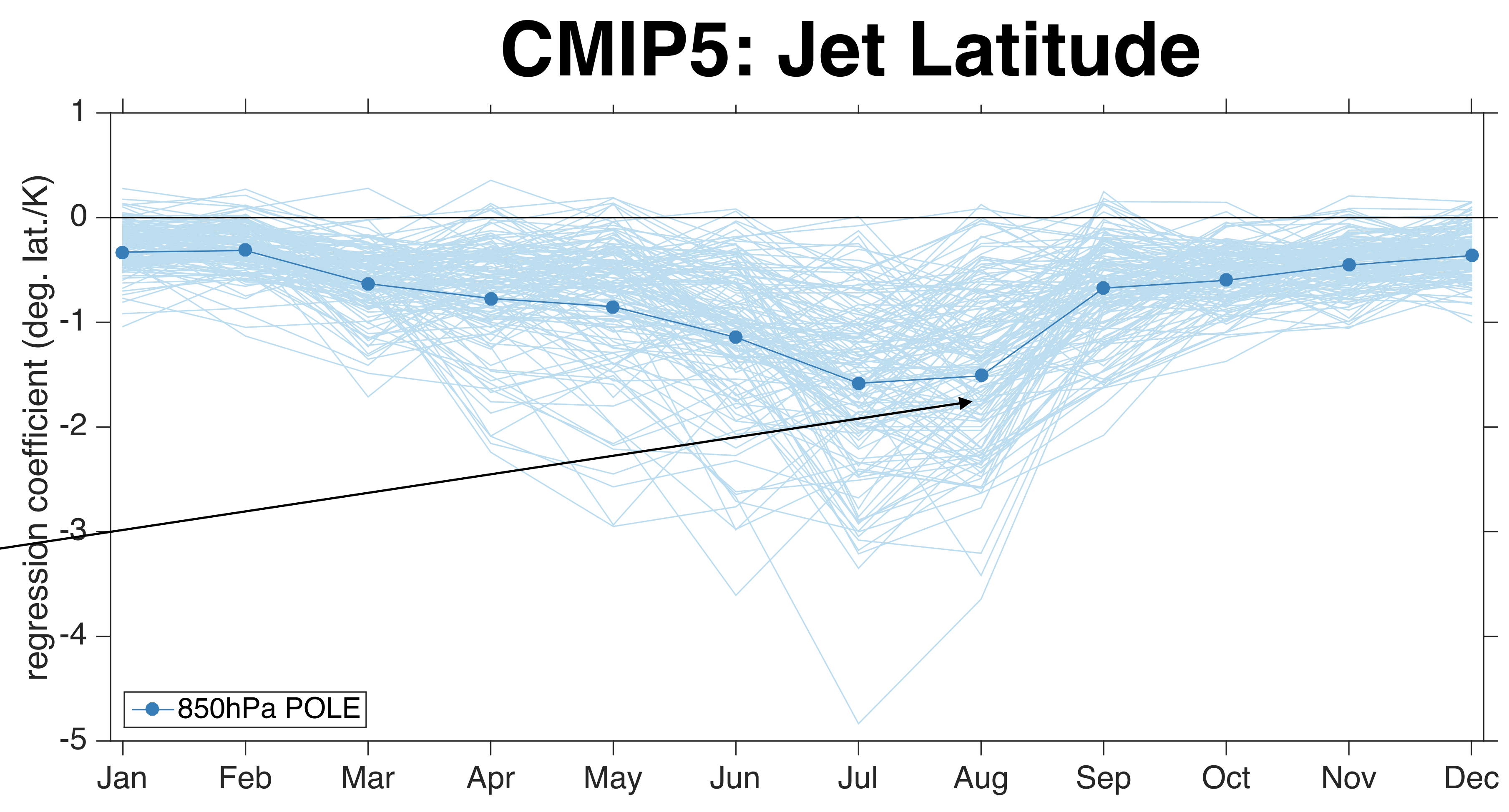
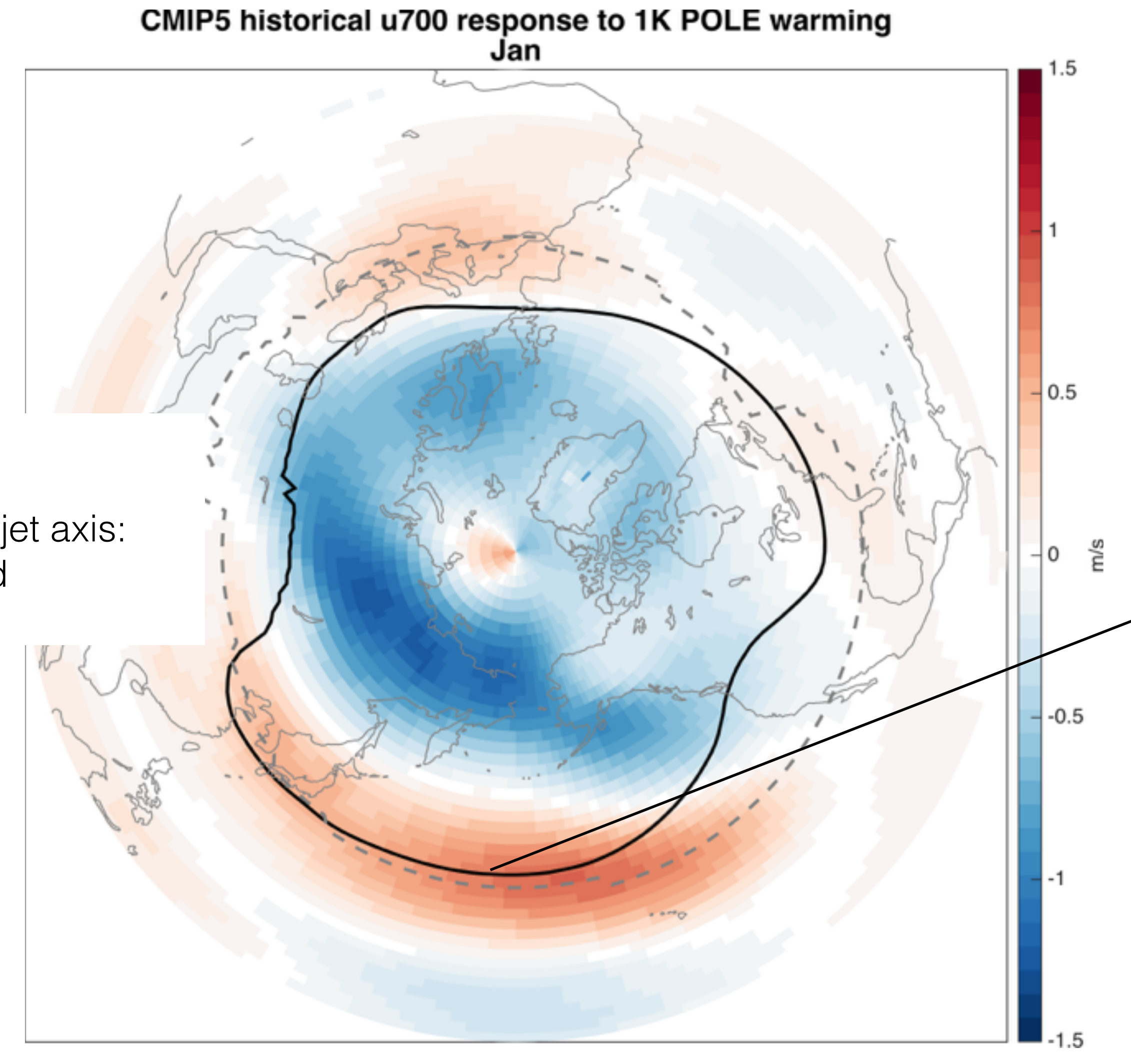
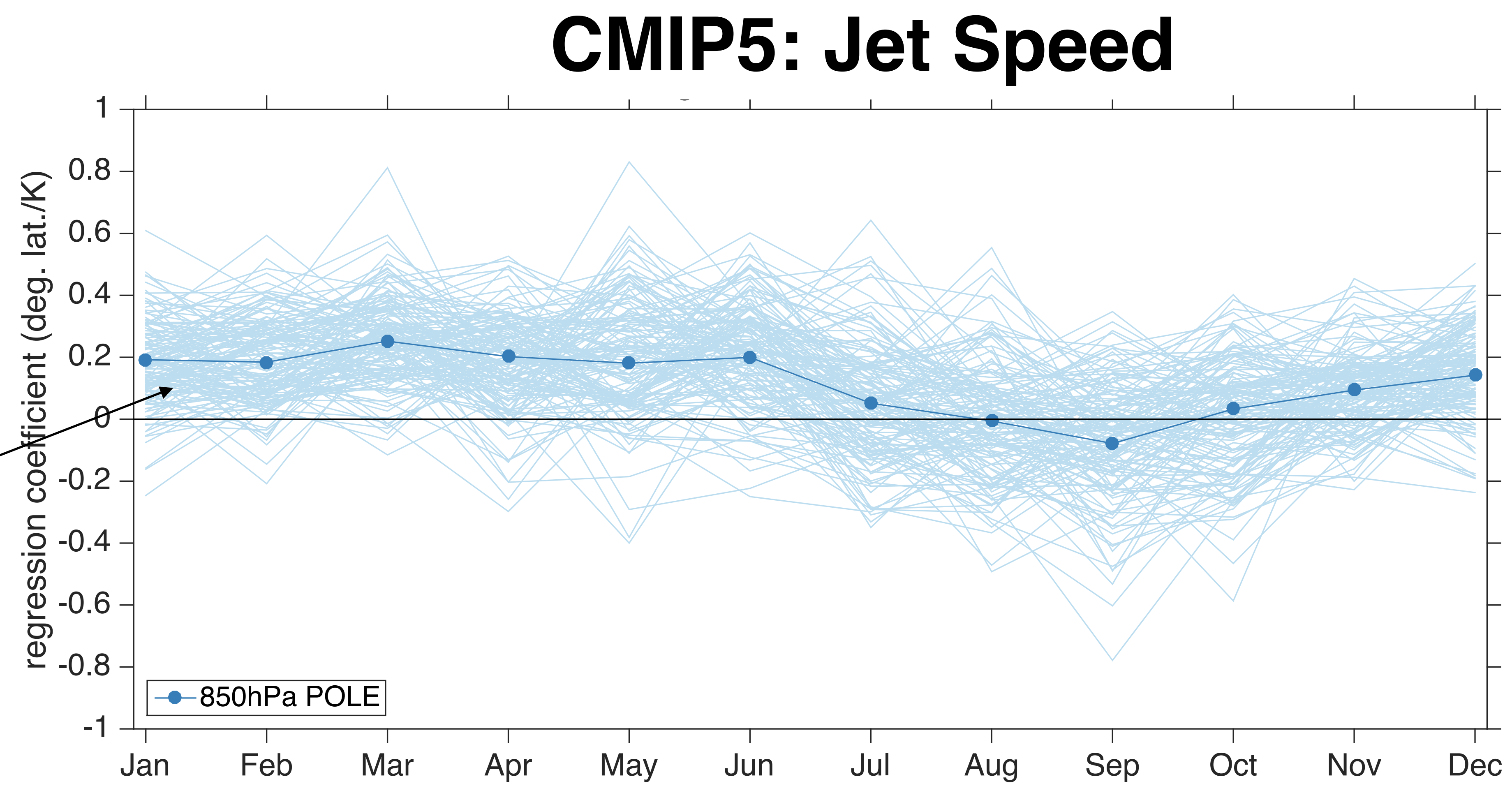


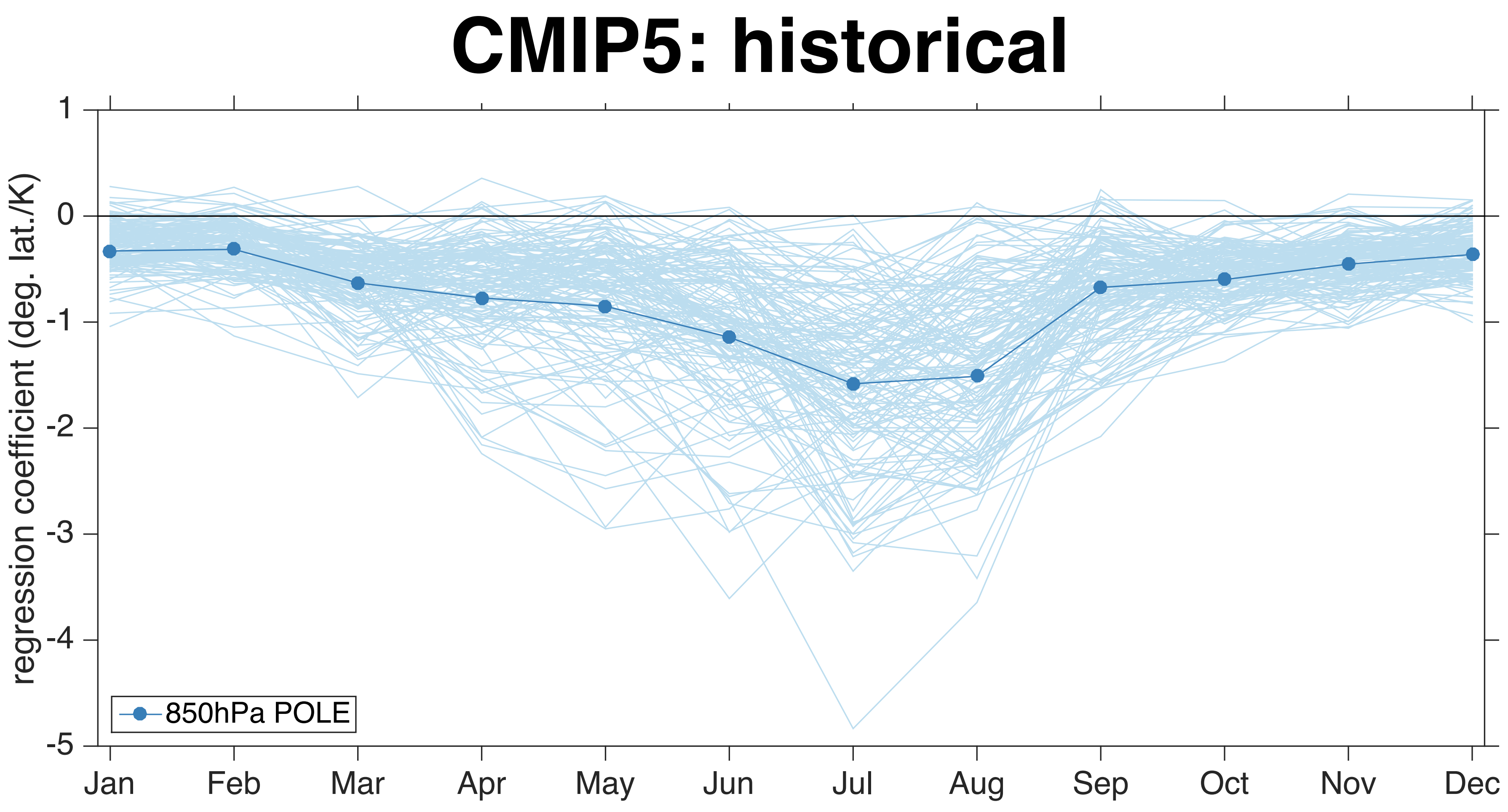


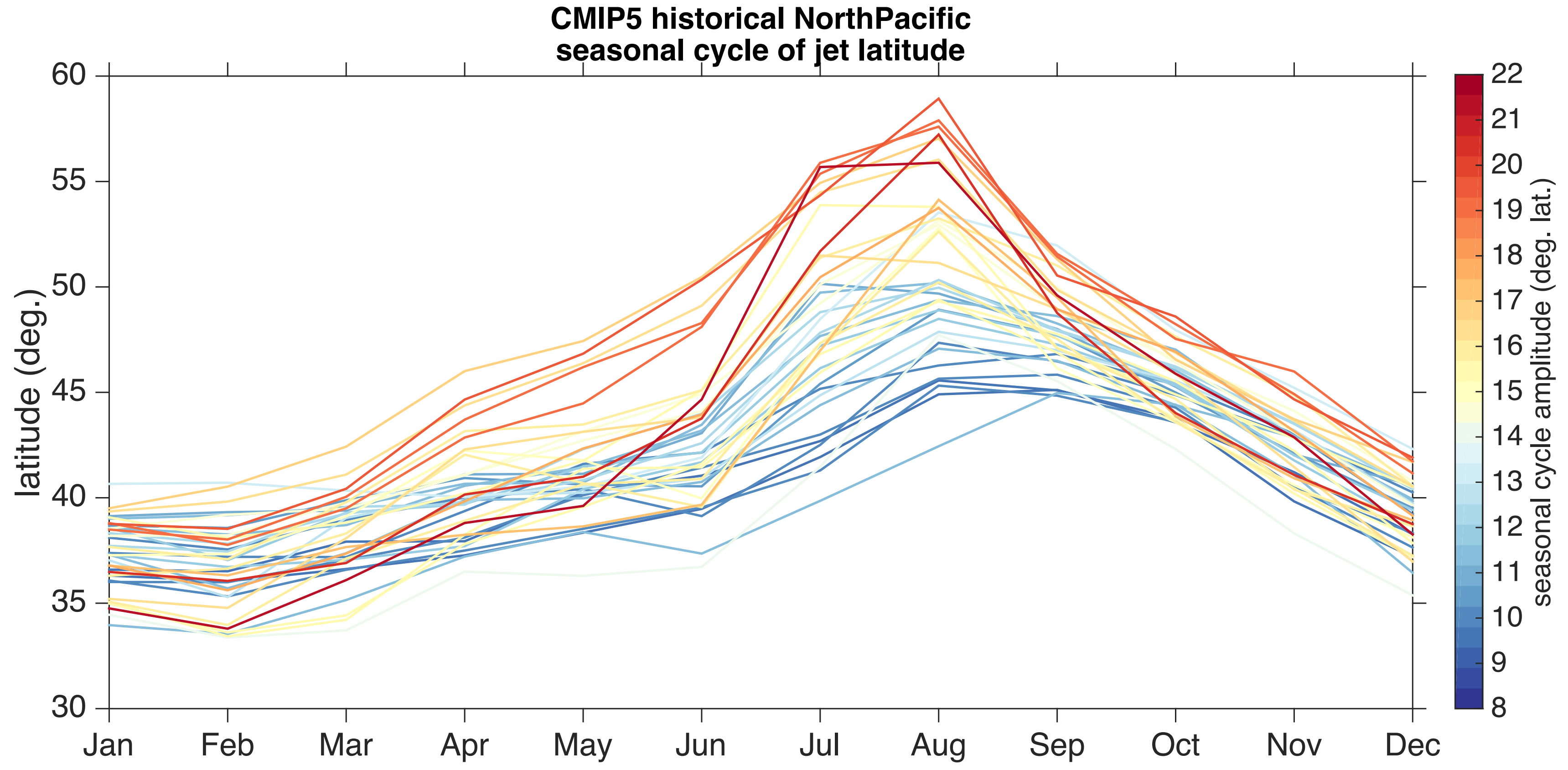
JANUARY
anomalies project onto jet axis:
impact jet speed





CMIP5 model biases in the seasonal cycle





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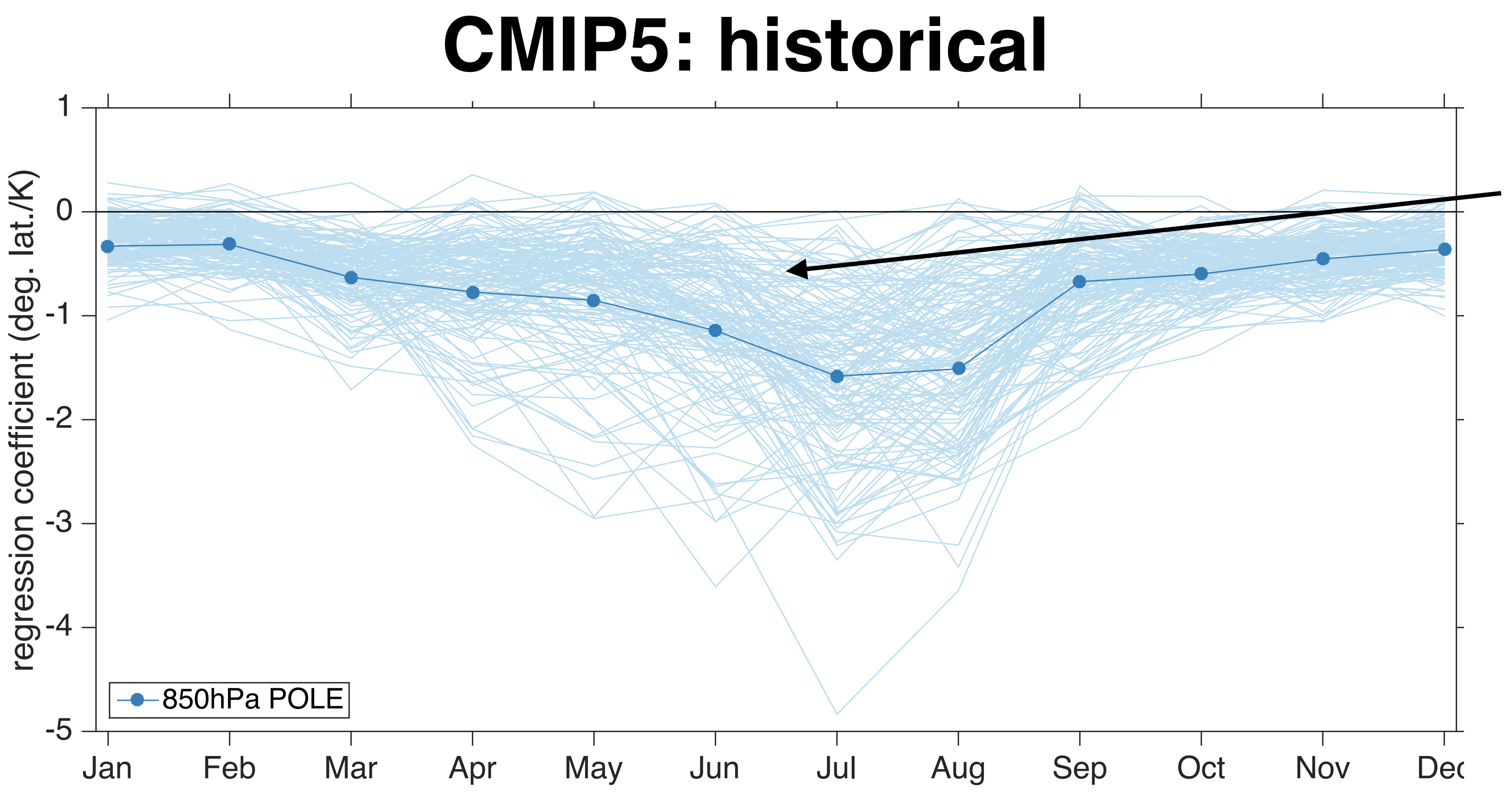

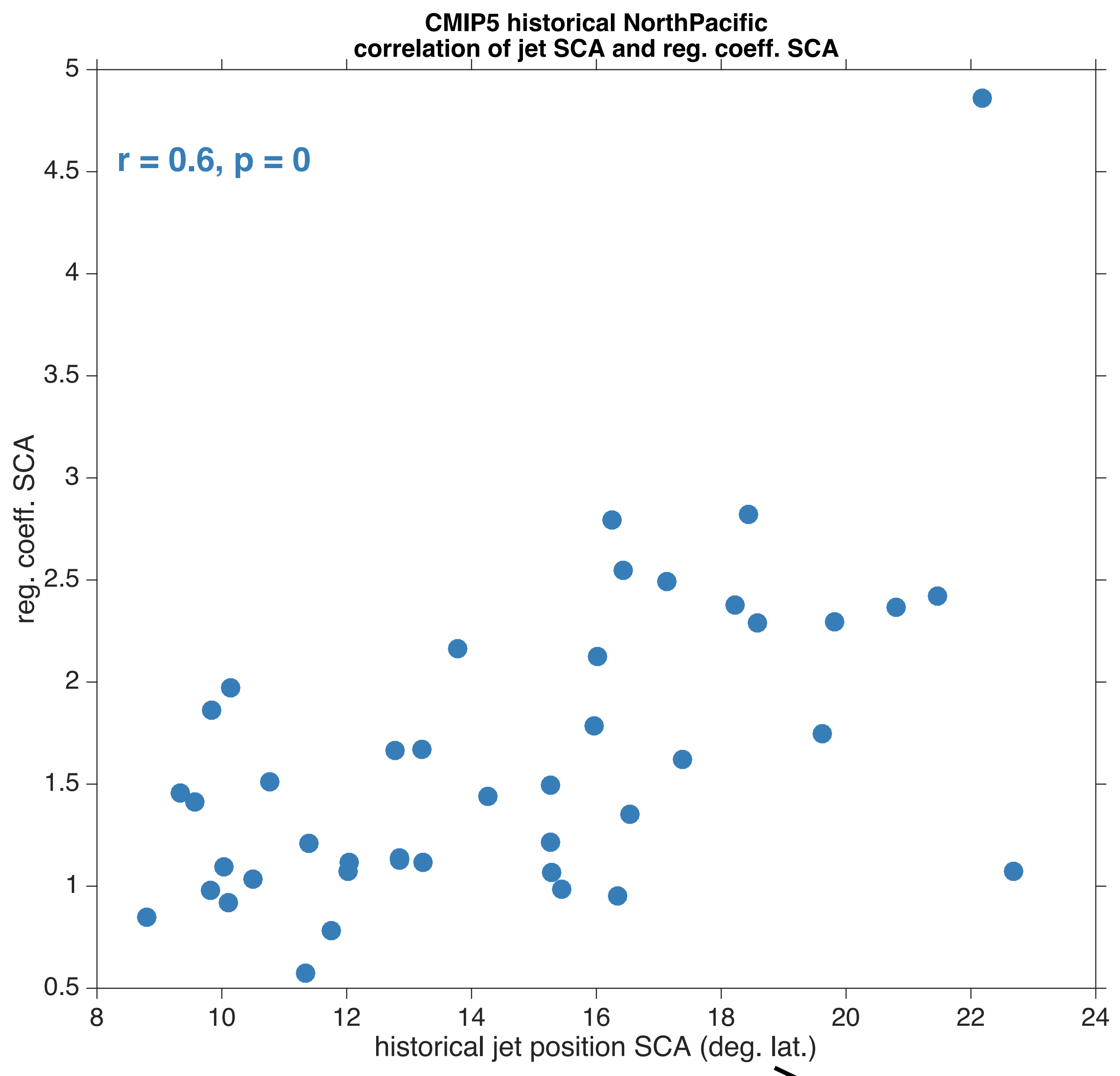

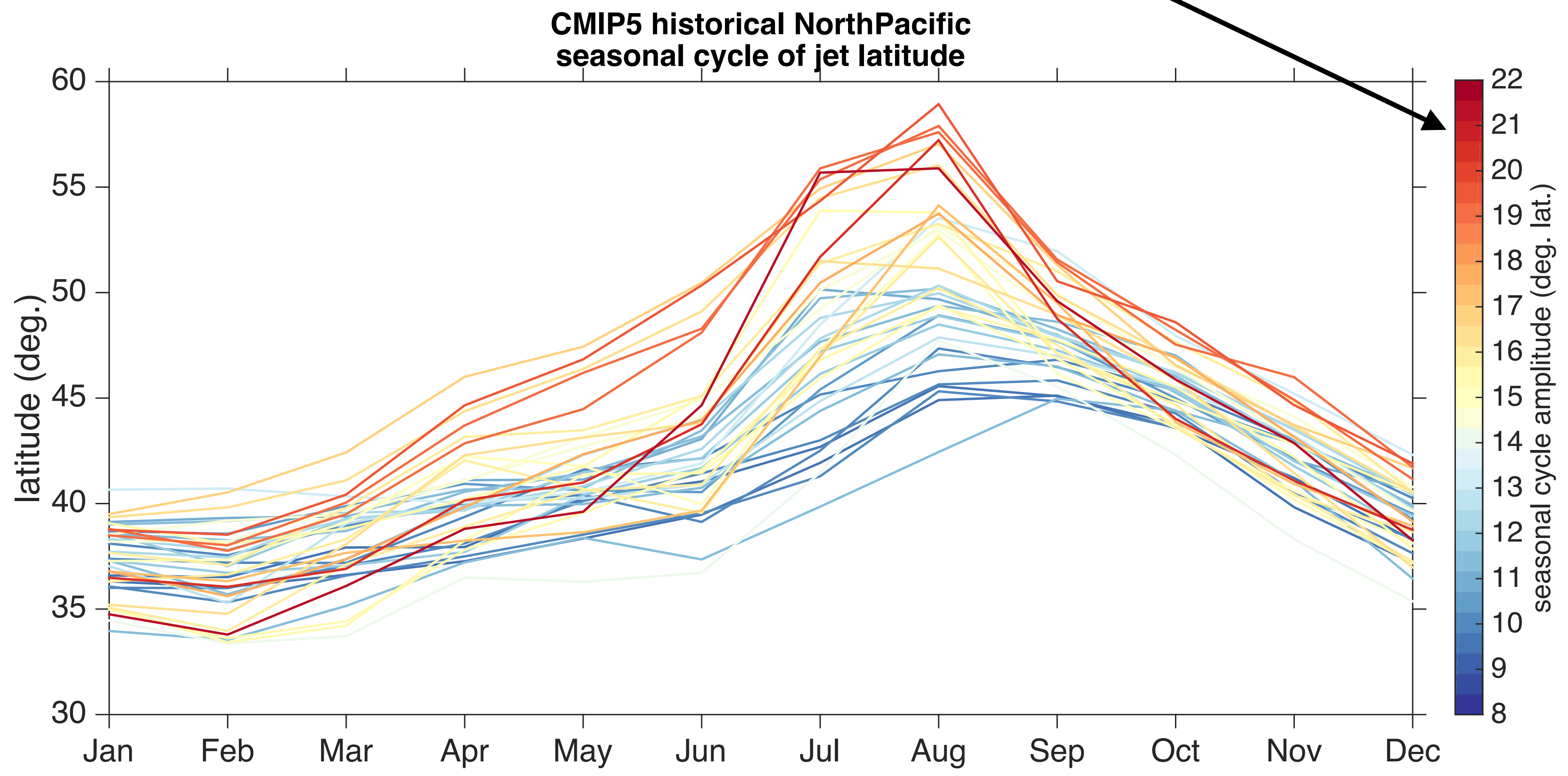

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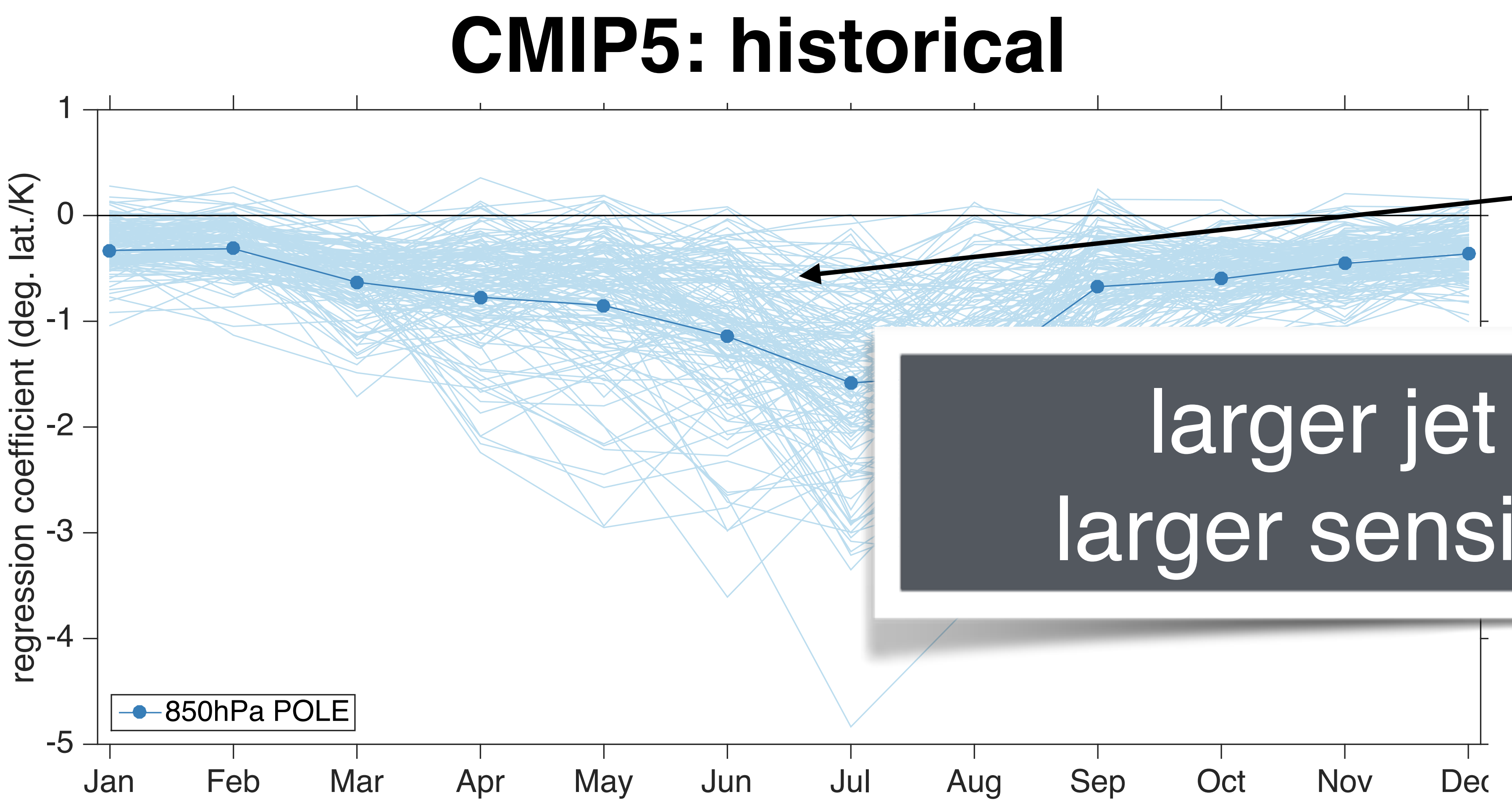
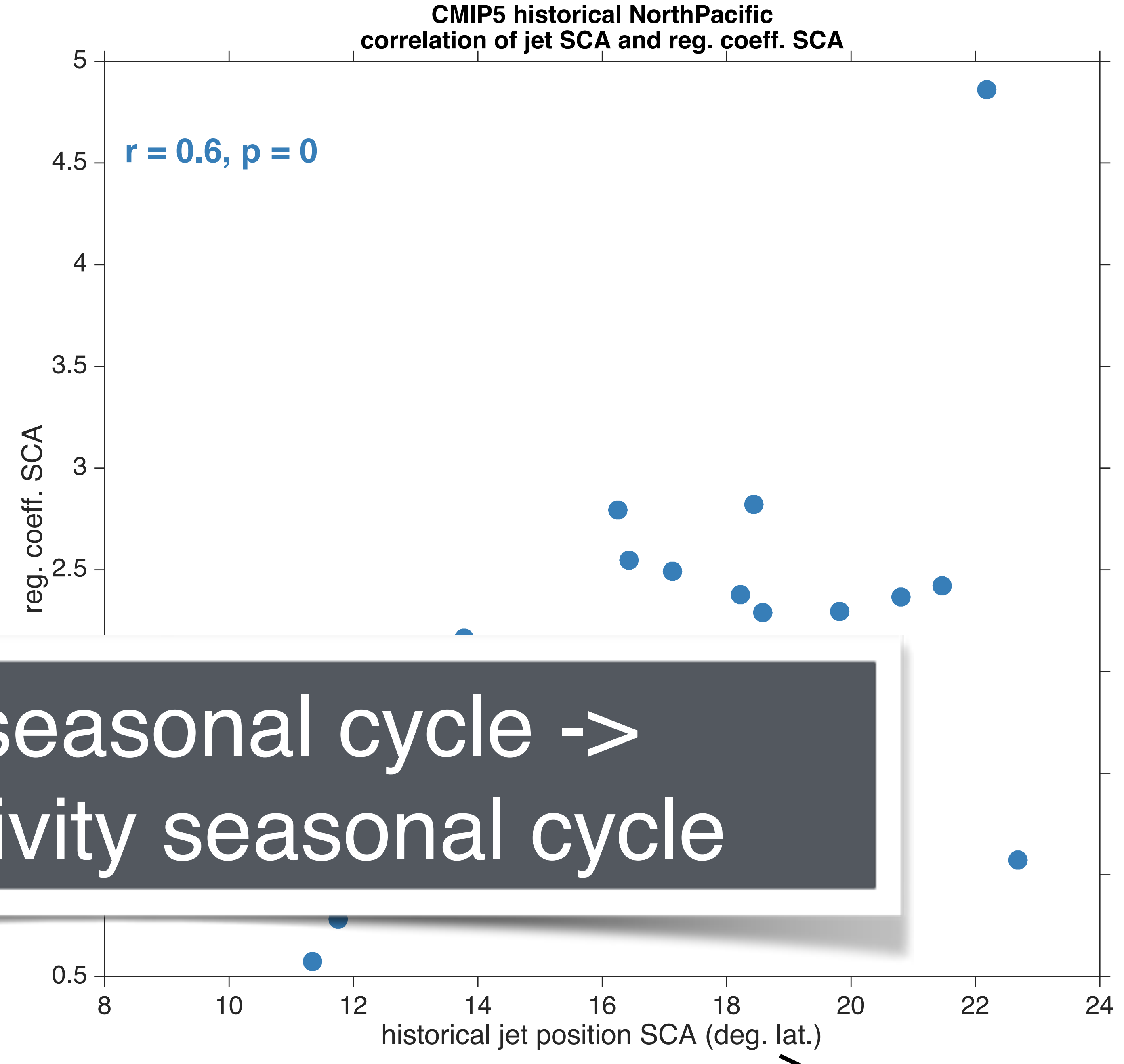
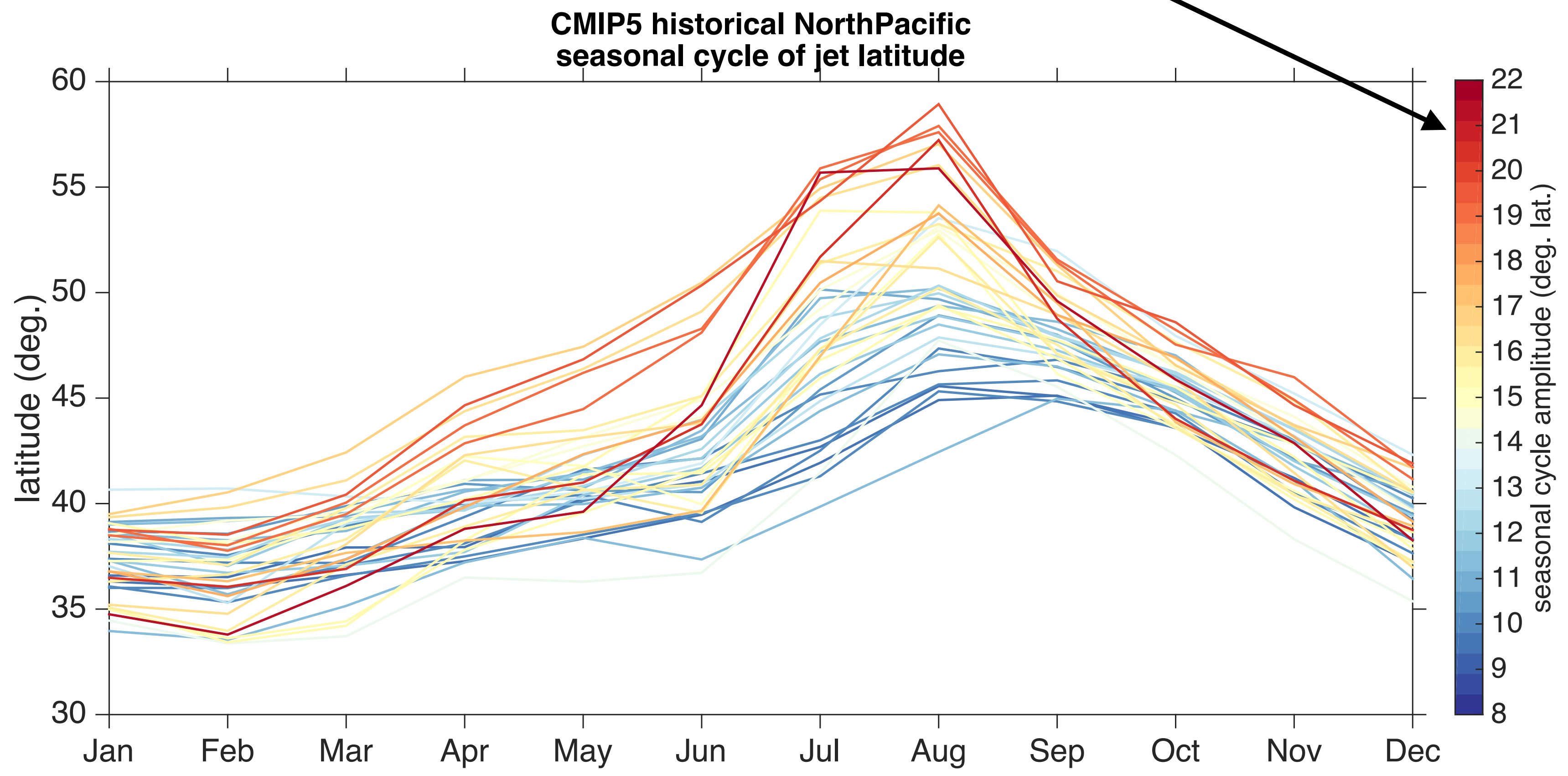
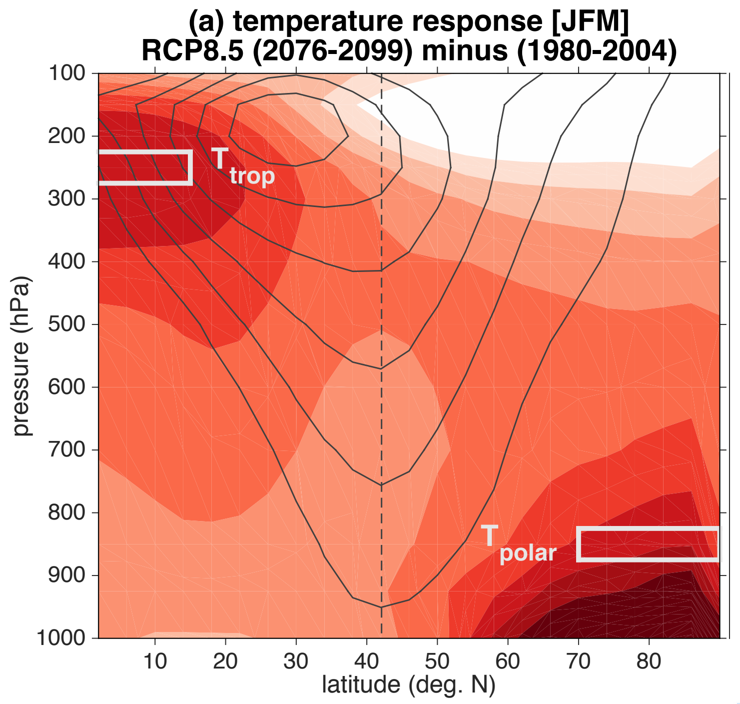




larger jet seasonal cycle ->
larger sensitivity seasonal cycle



Next…

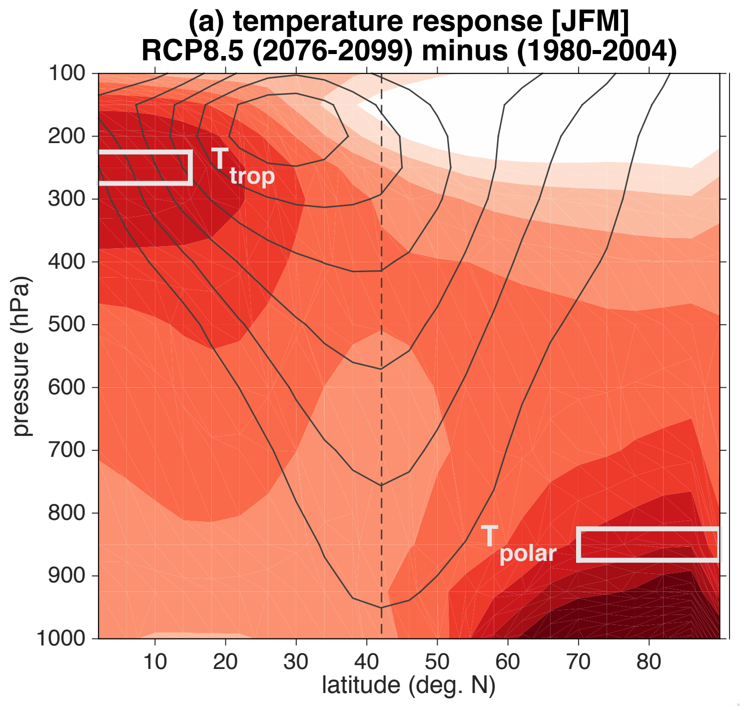


Can we find evidence of seasonal sensitivity of the jet-streams in comprehensive GCMs?

Data

- CESM1 Large Ensemble (LENS; 40 simulations)
- CMIP5 models (historical & RCP8.5)

Next…



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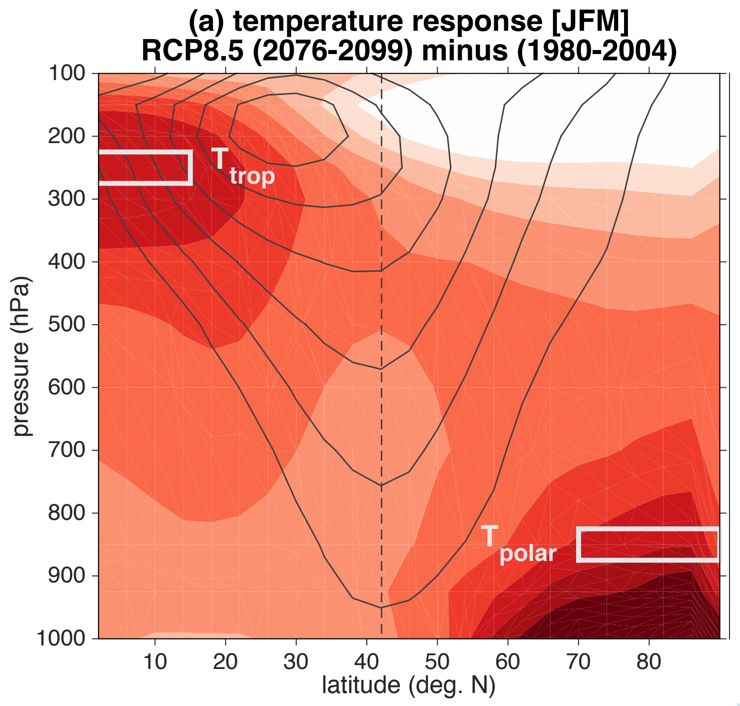
Spread across simulations

$$\Delta\theta_{jet} = r_{polar}\Delta T_{polar} + r_{trop}\Delta T_{trop}$$

Next…



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Time evolution within simulations

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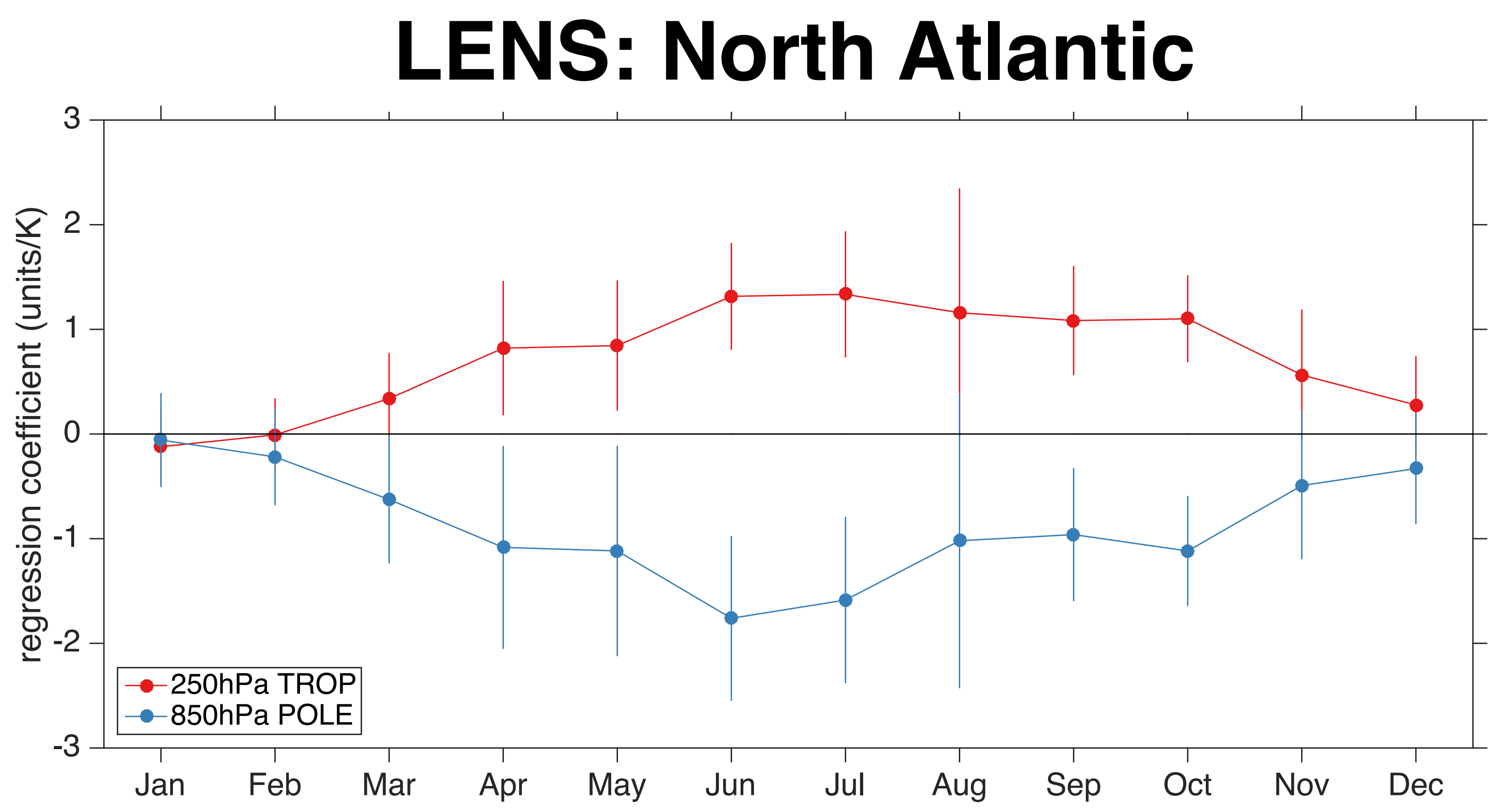
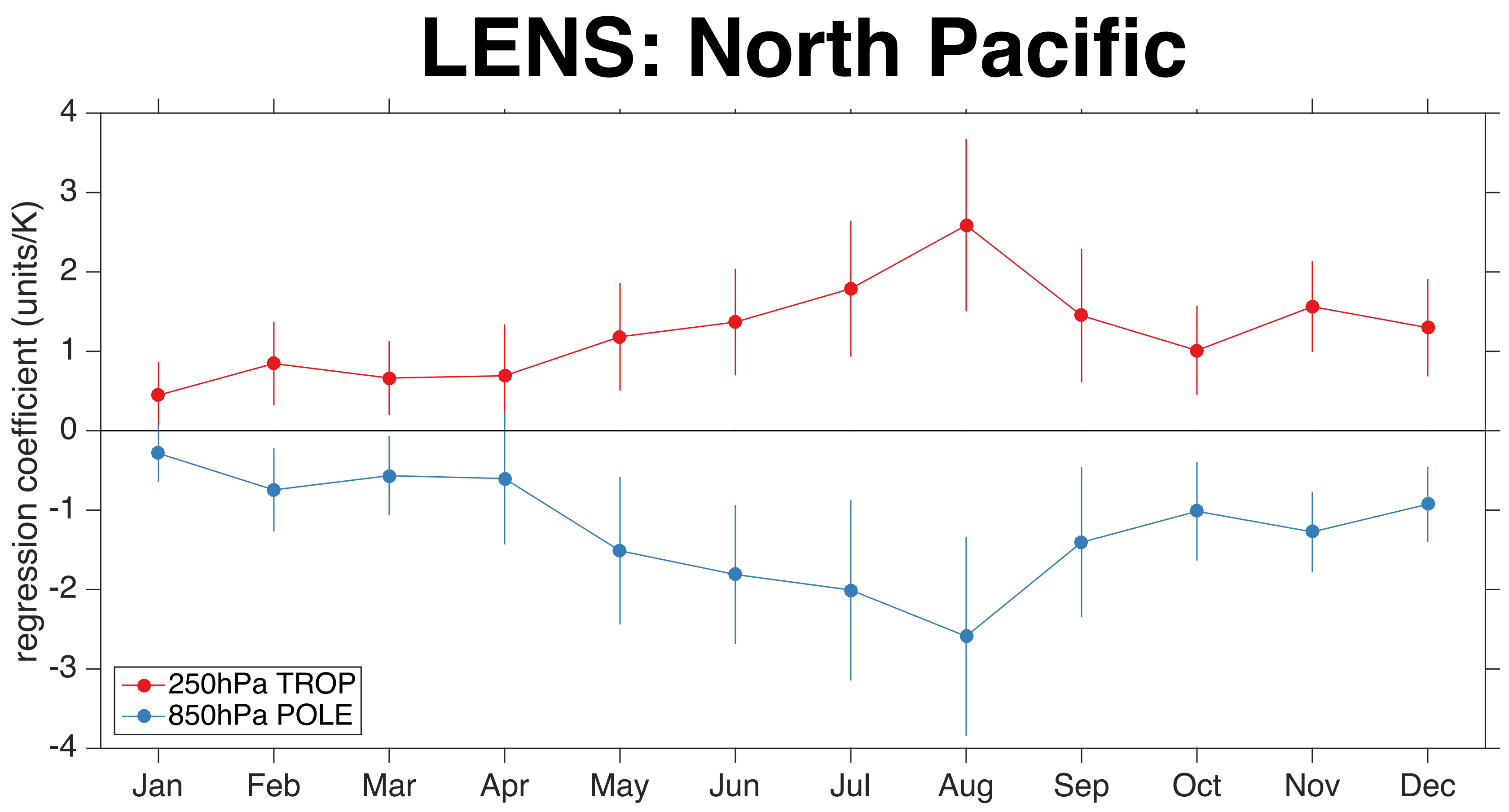
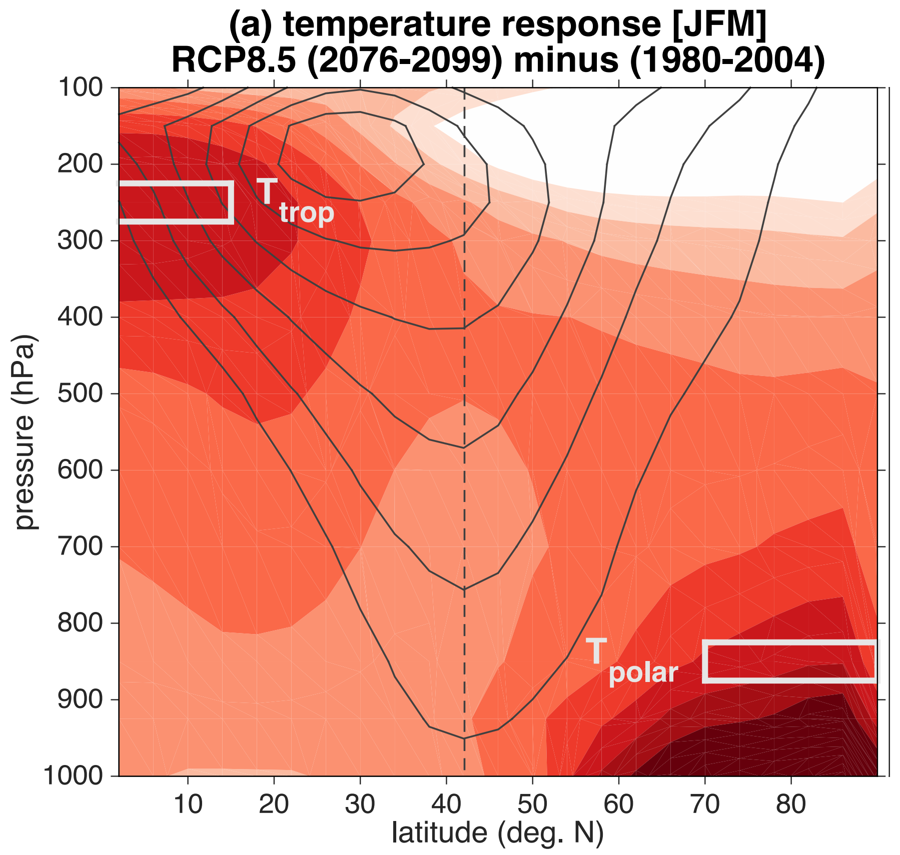
Model spread: seasonal sensitivity of jet position







Spread across LENS simulations

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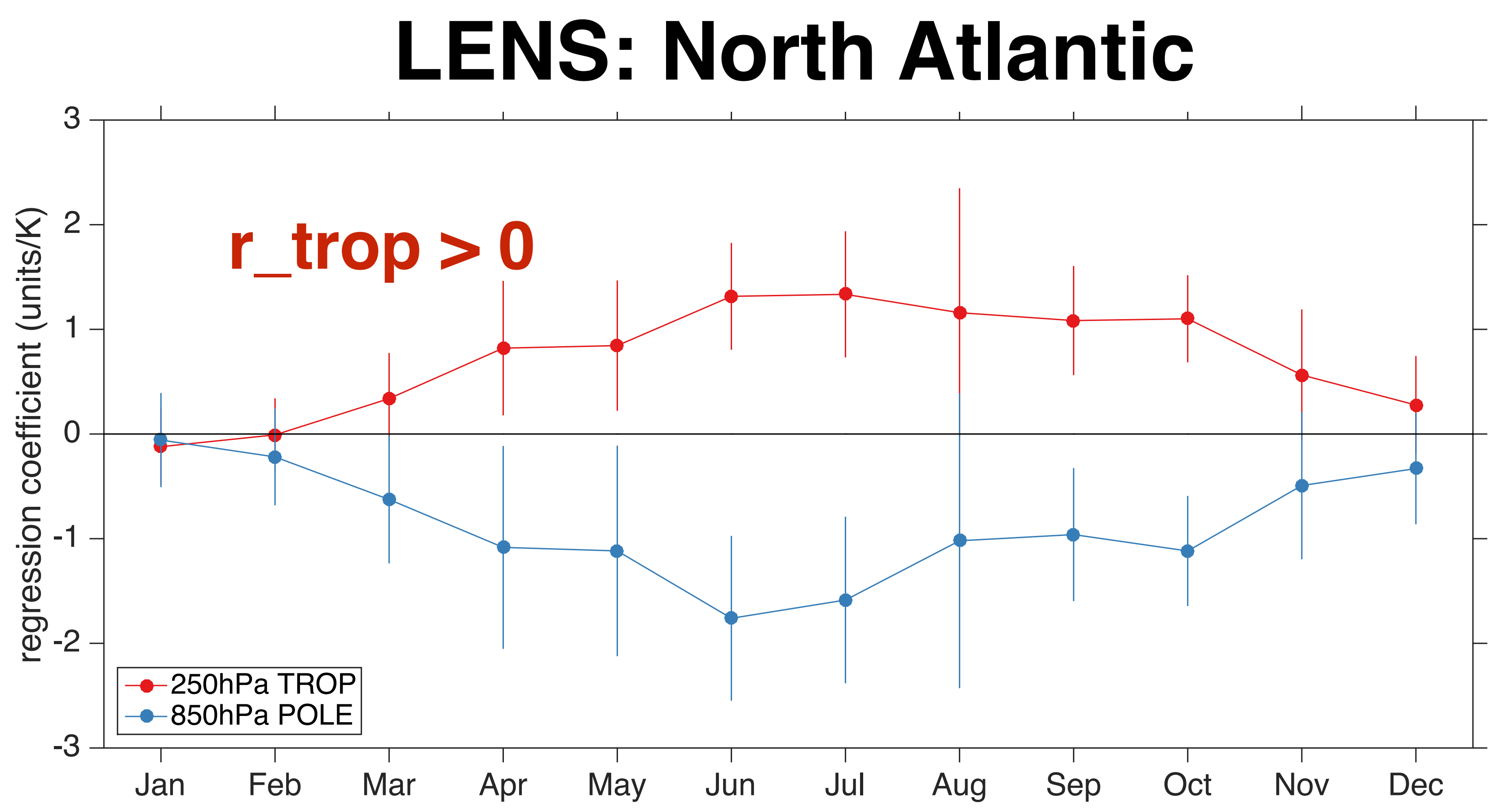
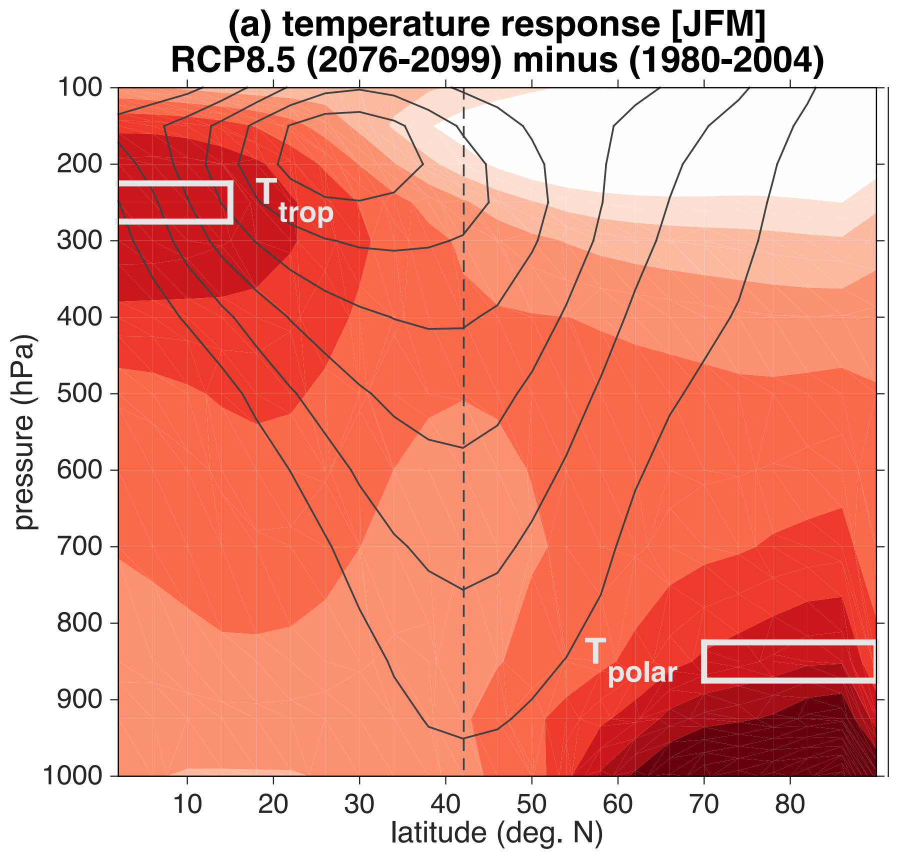
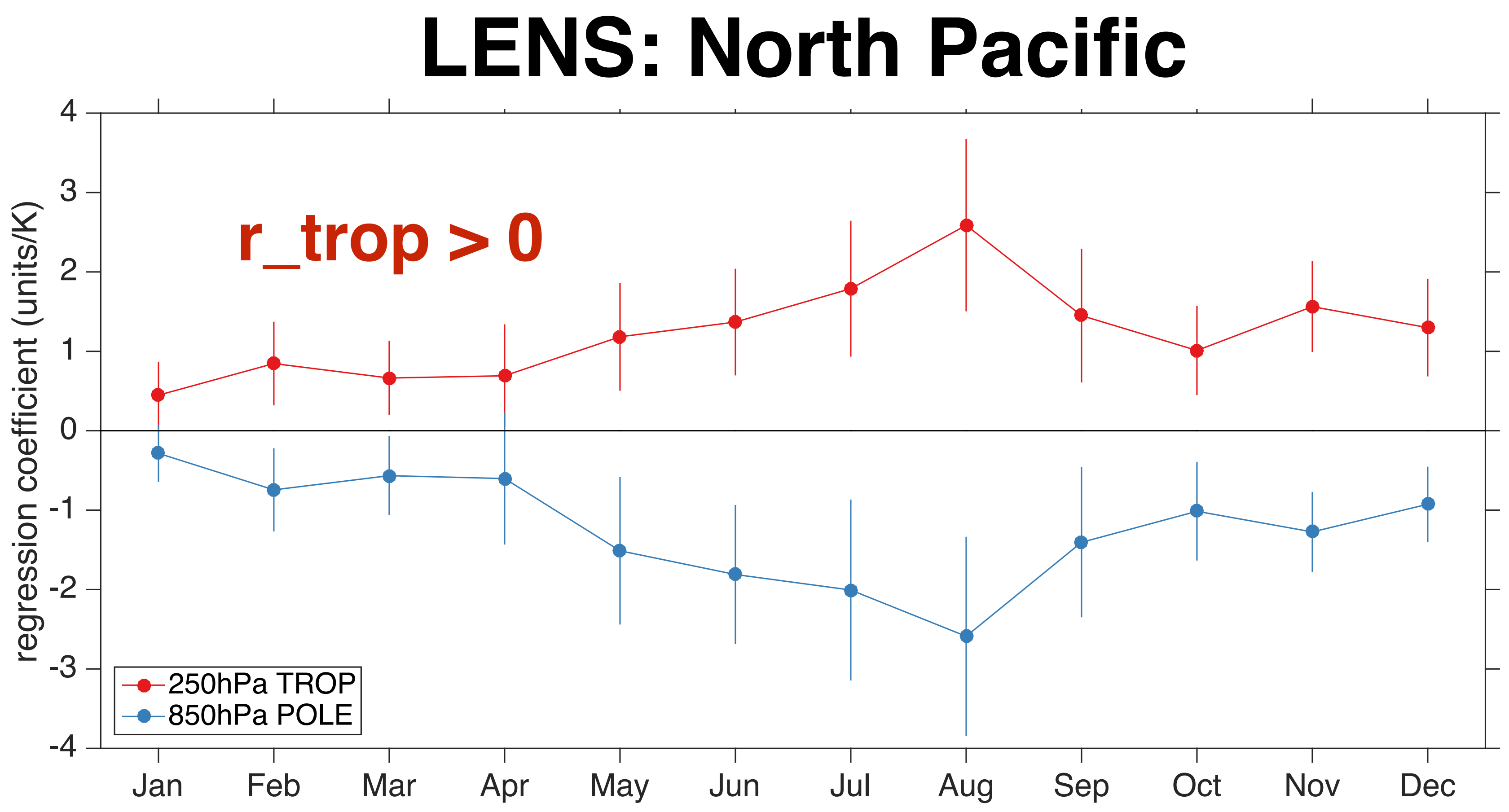
somewhat similar to Gerber & Son (2014) and Harvey et al. (2015; 2013)

Model spread: seasonal sensitivity of jet position







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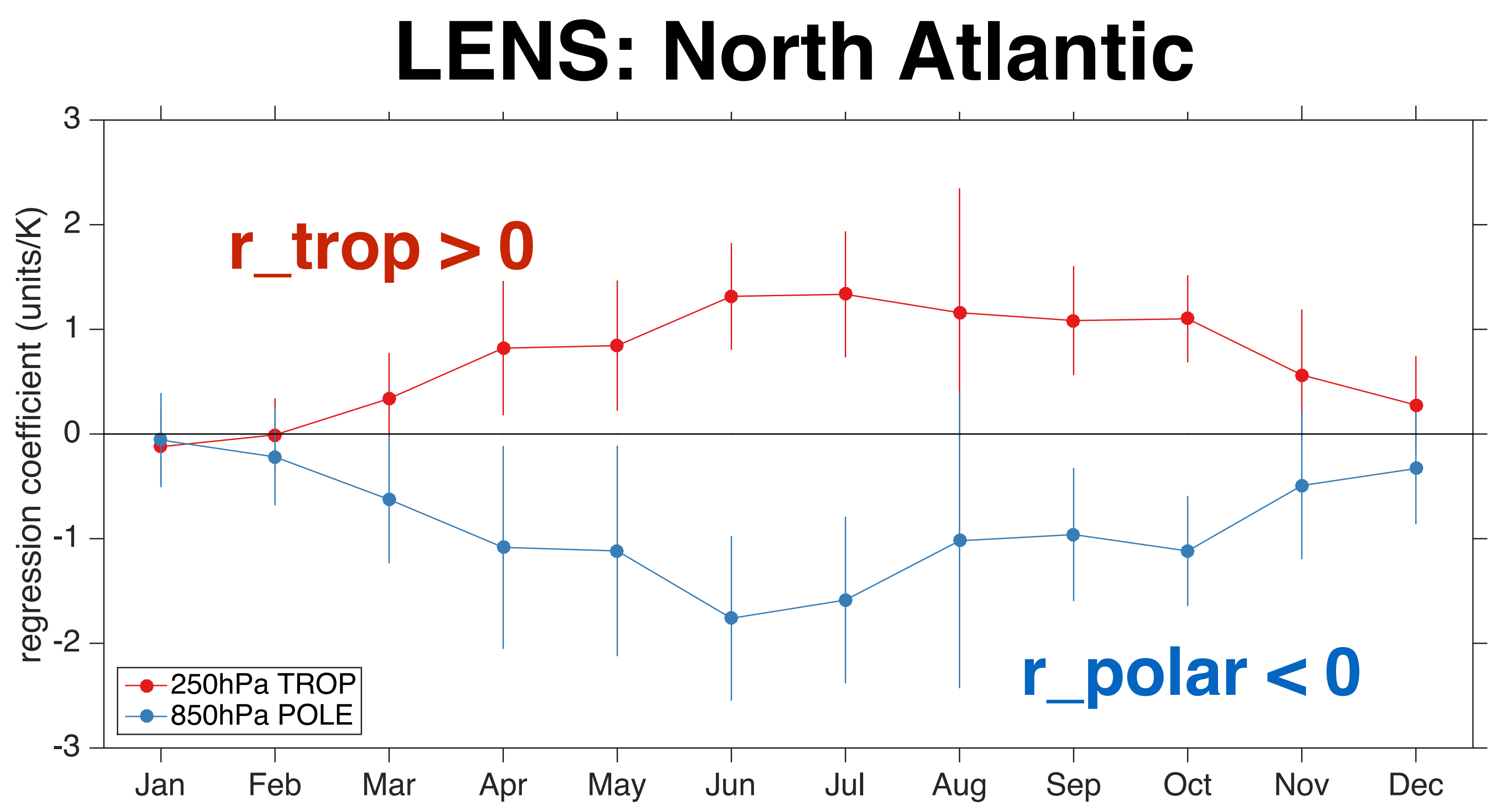

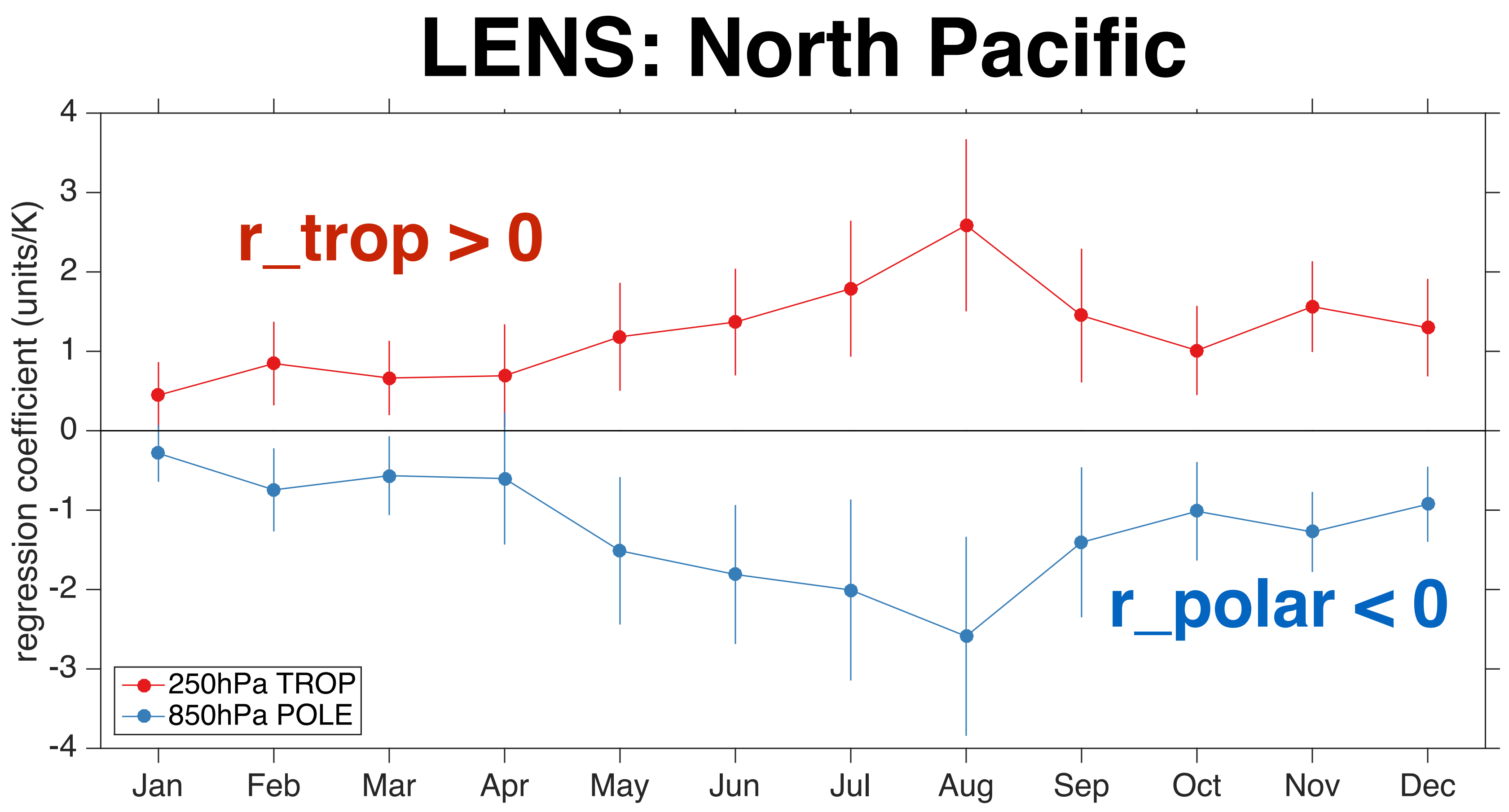

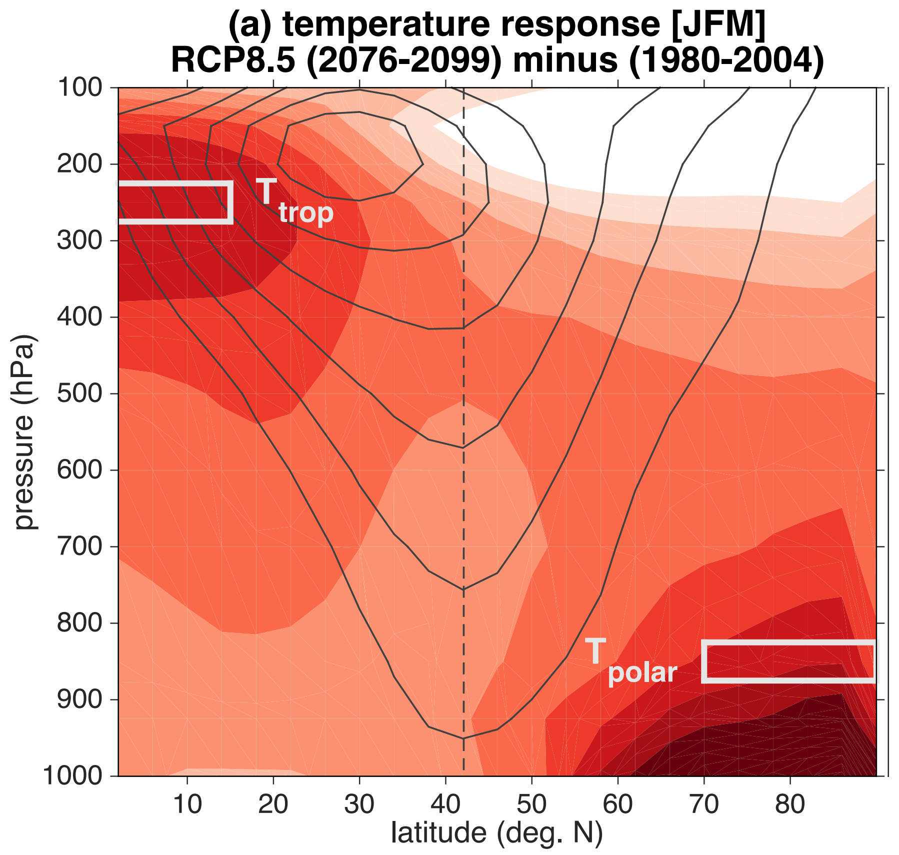

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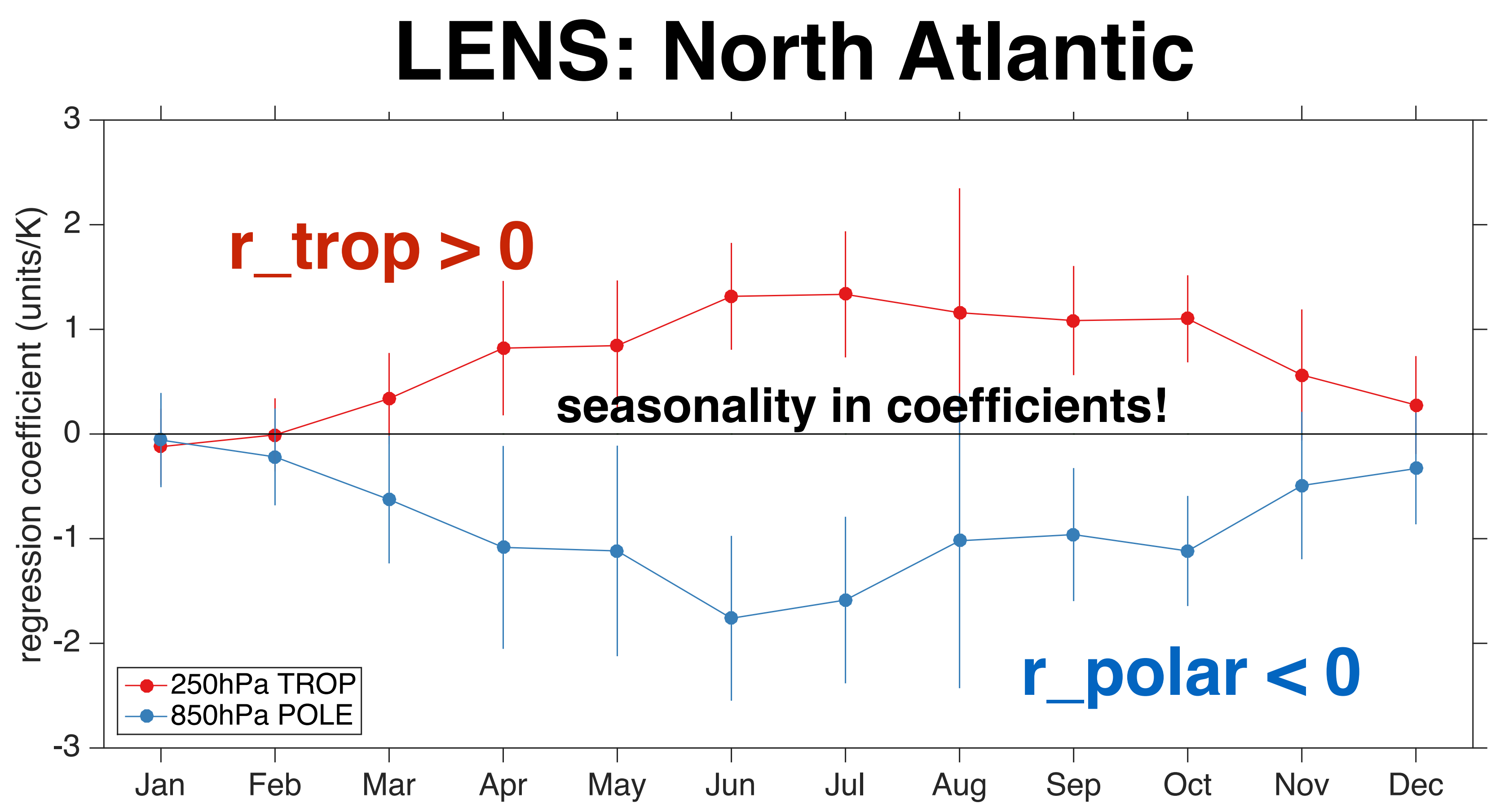

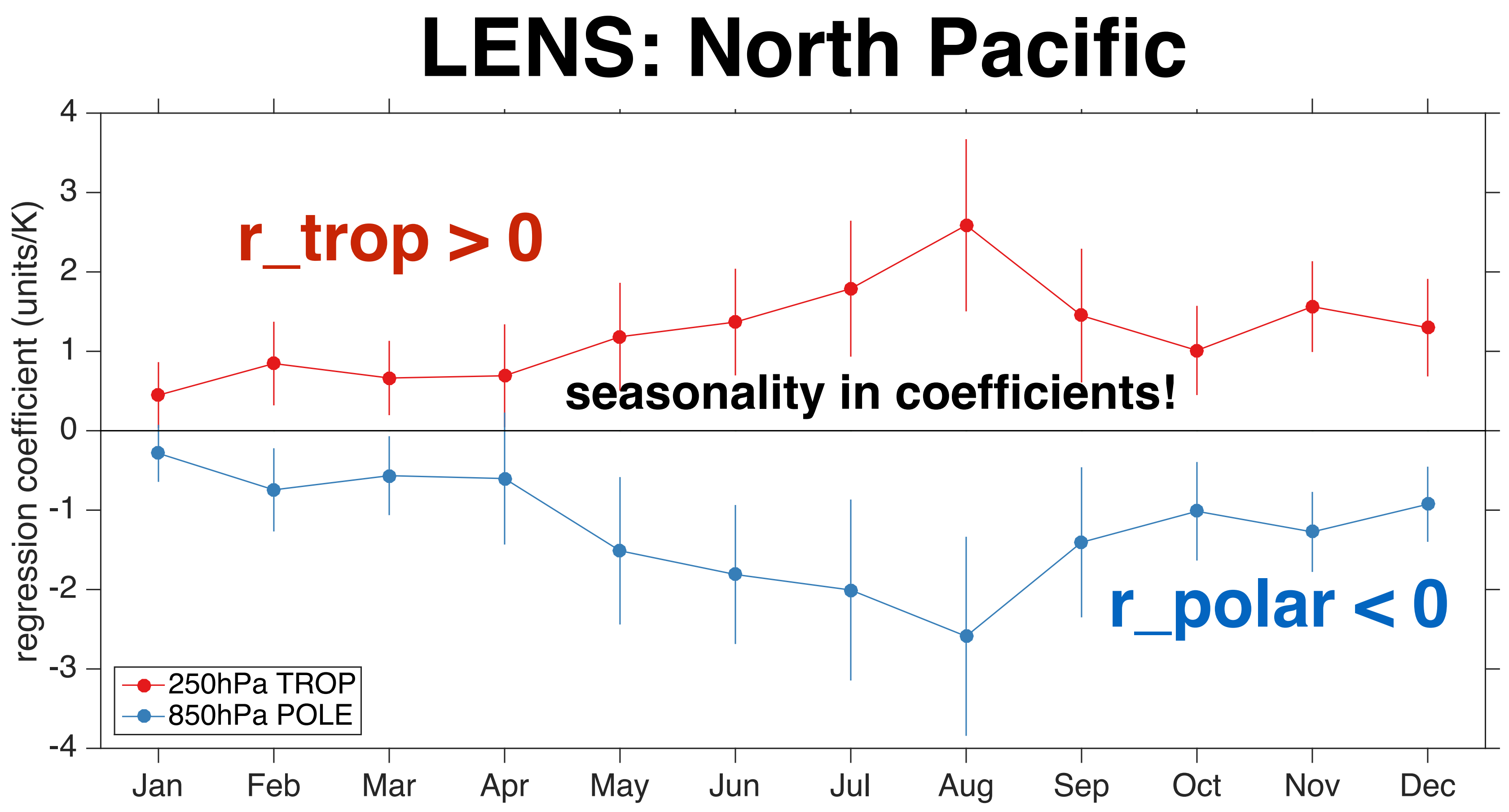

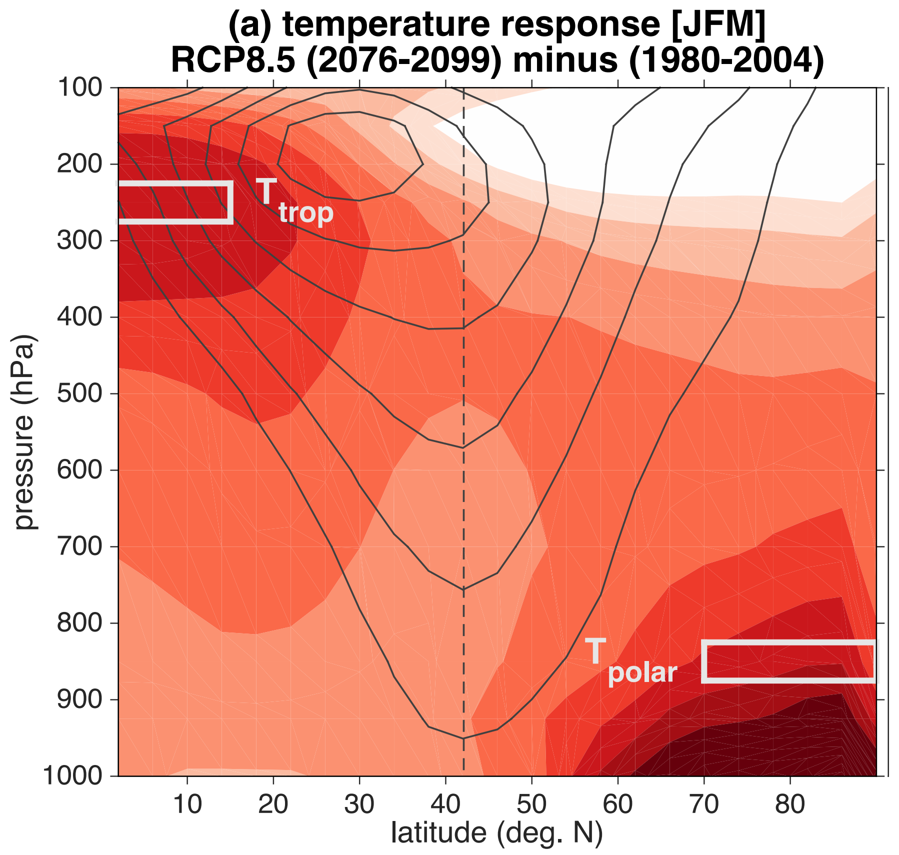

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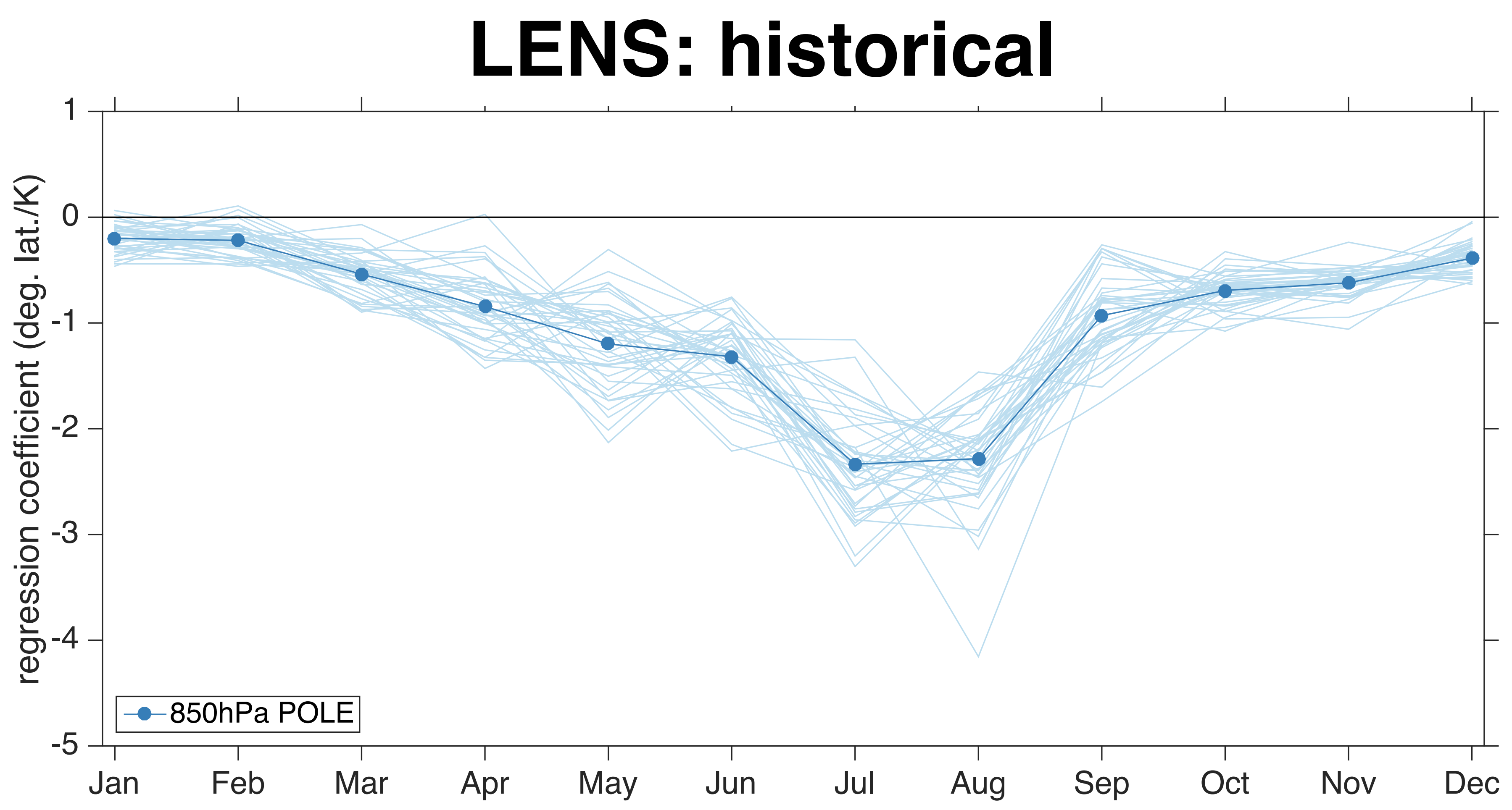
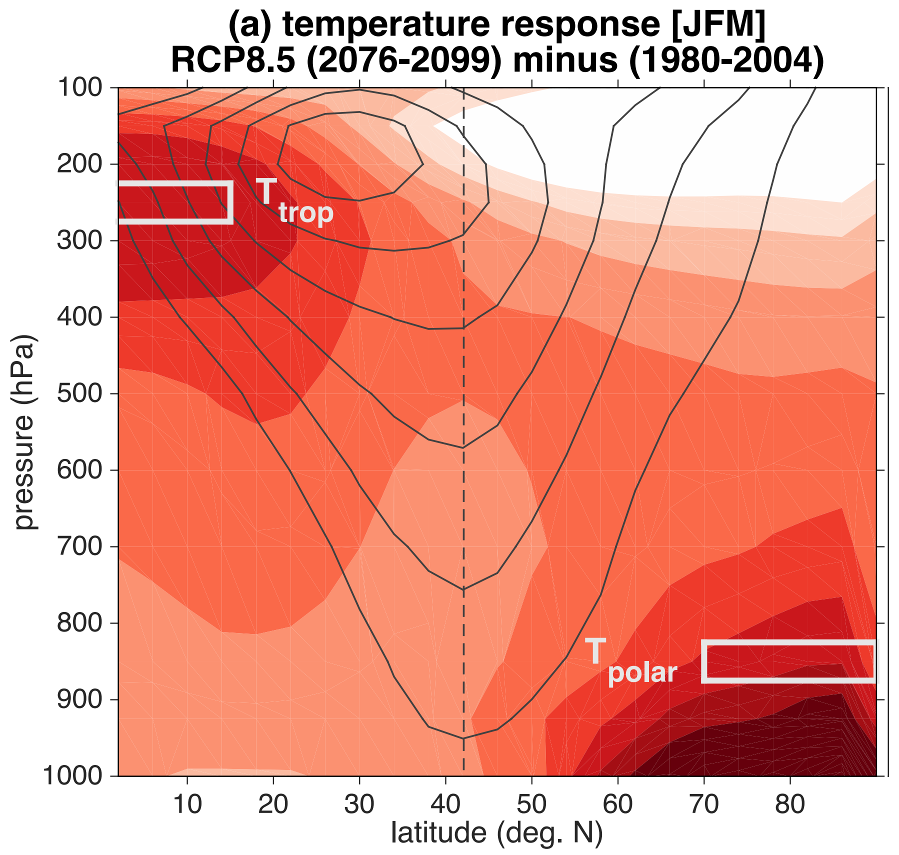
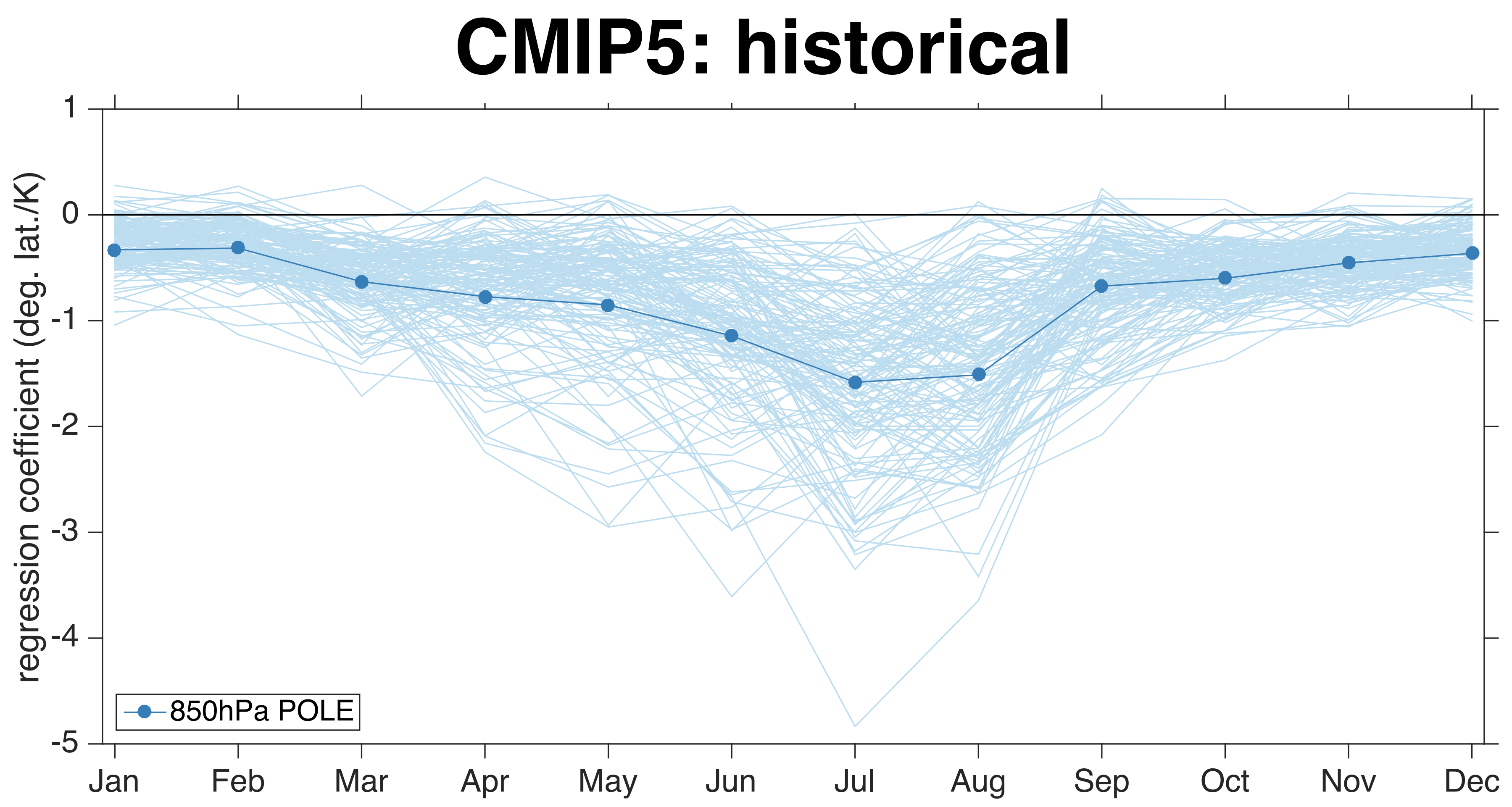
North Pacific: seasonal sensitivity of jet position







Time evolution within simulations

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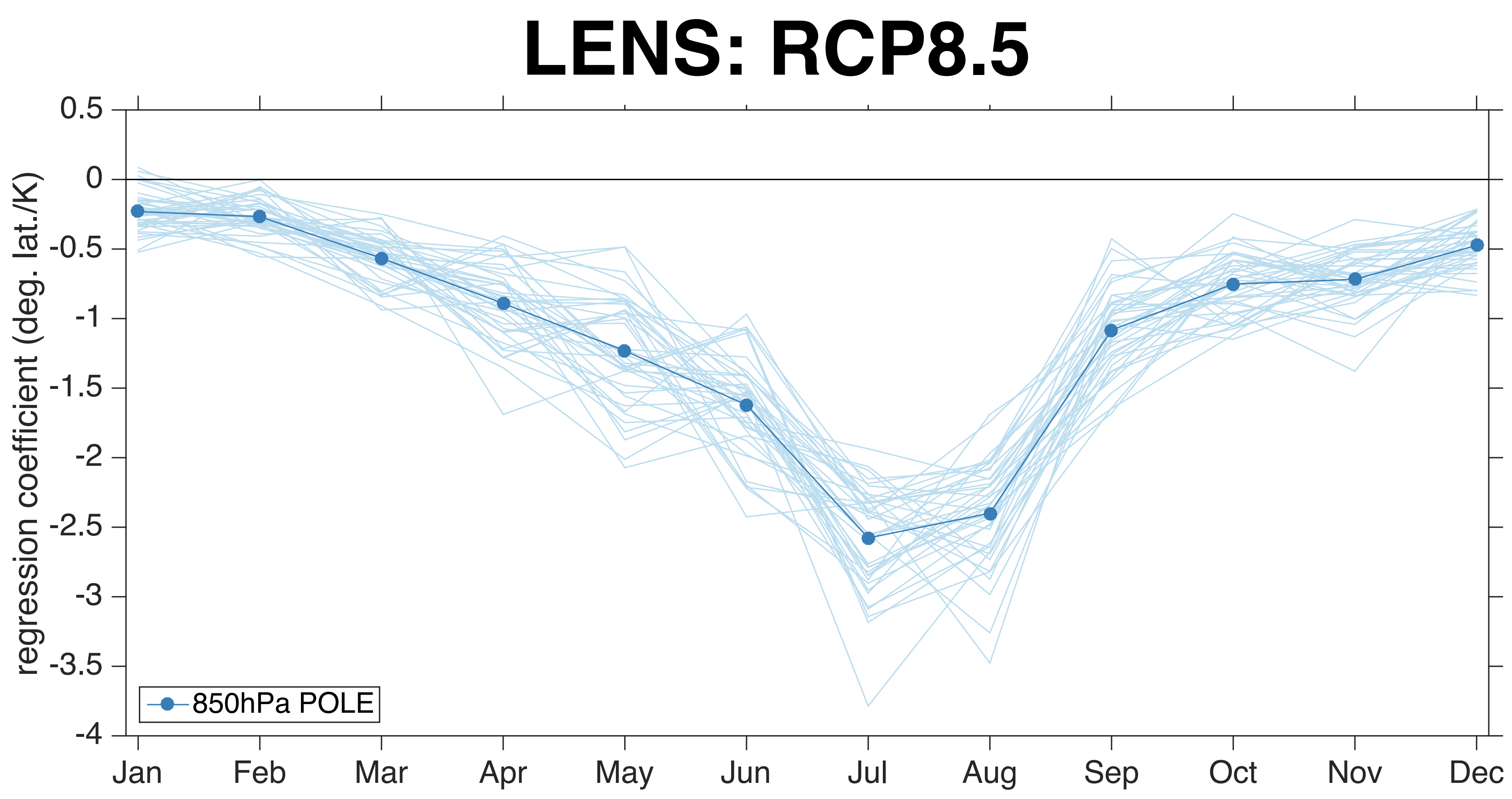

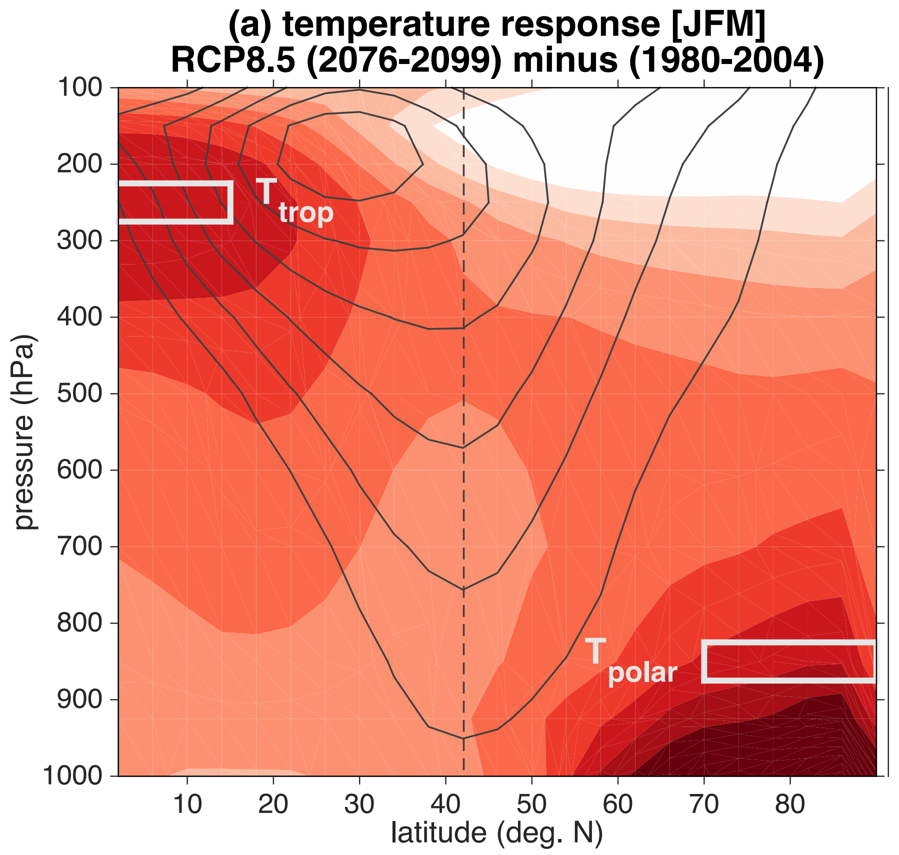

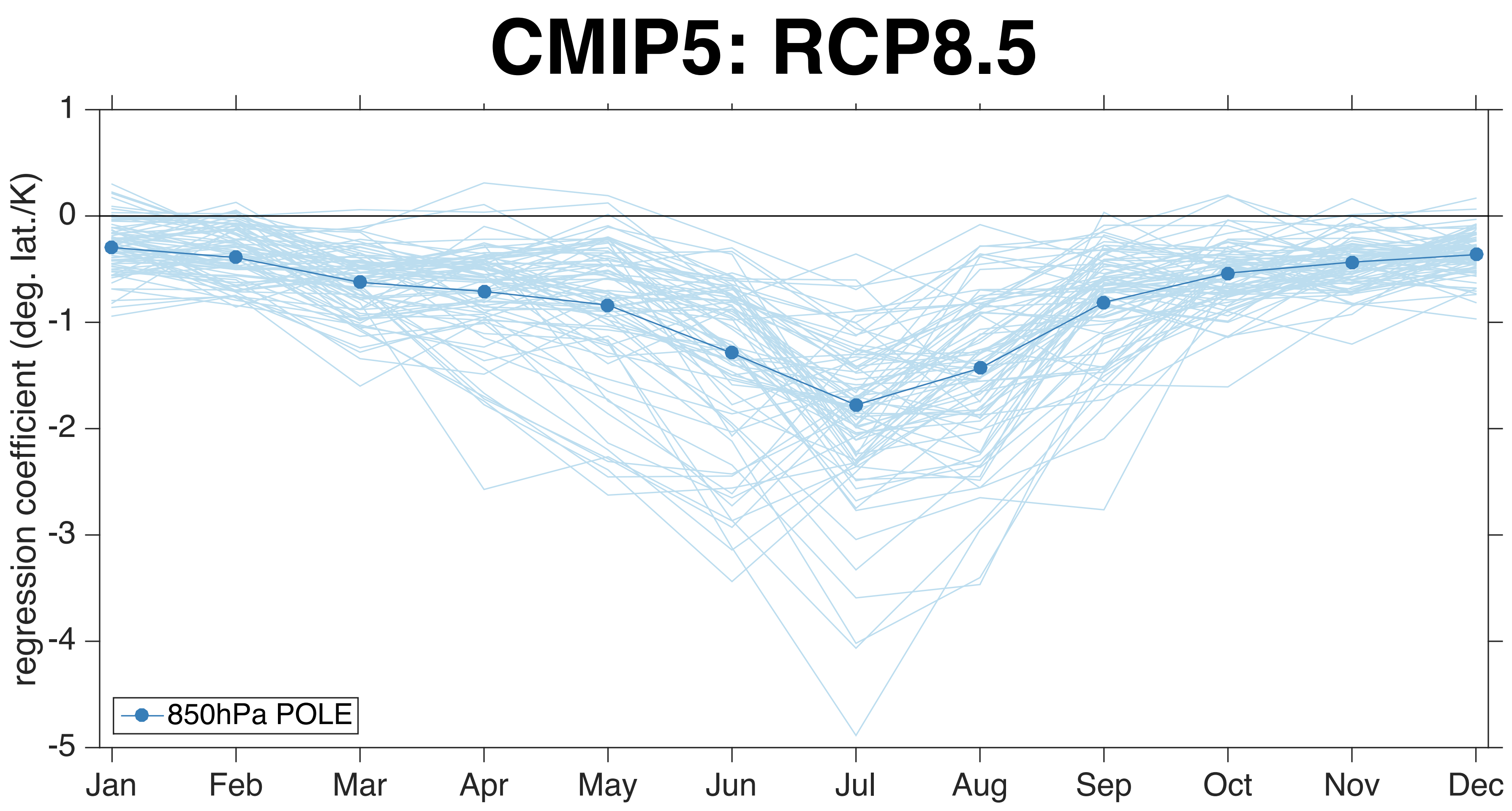

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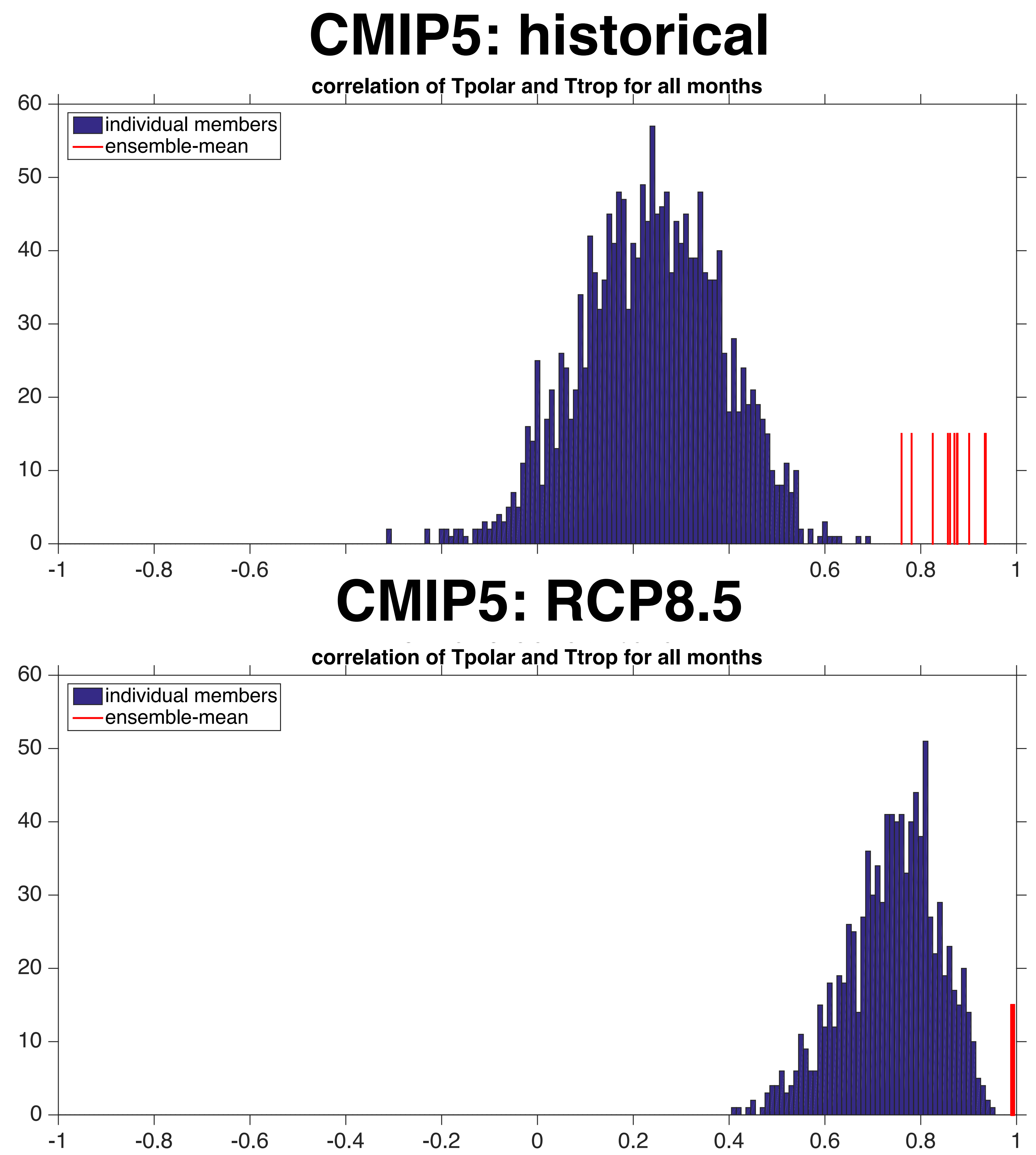
Aside: collinearity

Time evolution within simulations

$$\theta'_{jet} = r_{polar}T'_{polar} + r_{trop}T'_{trop}$$

- T_trop and T_polar are correlated in the future simulations, which can be a major problem for linear regression

- So far, similar results are obtained in different data sets, not detrended vs. detrended, LENS vs. CMIP5, and historical simulations



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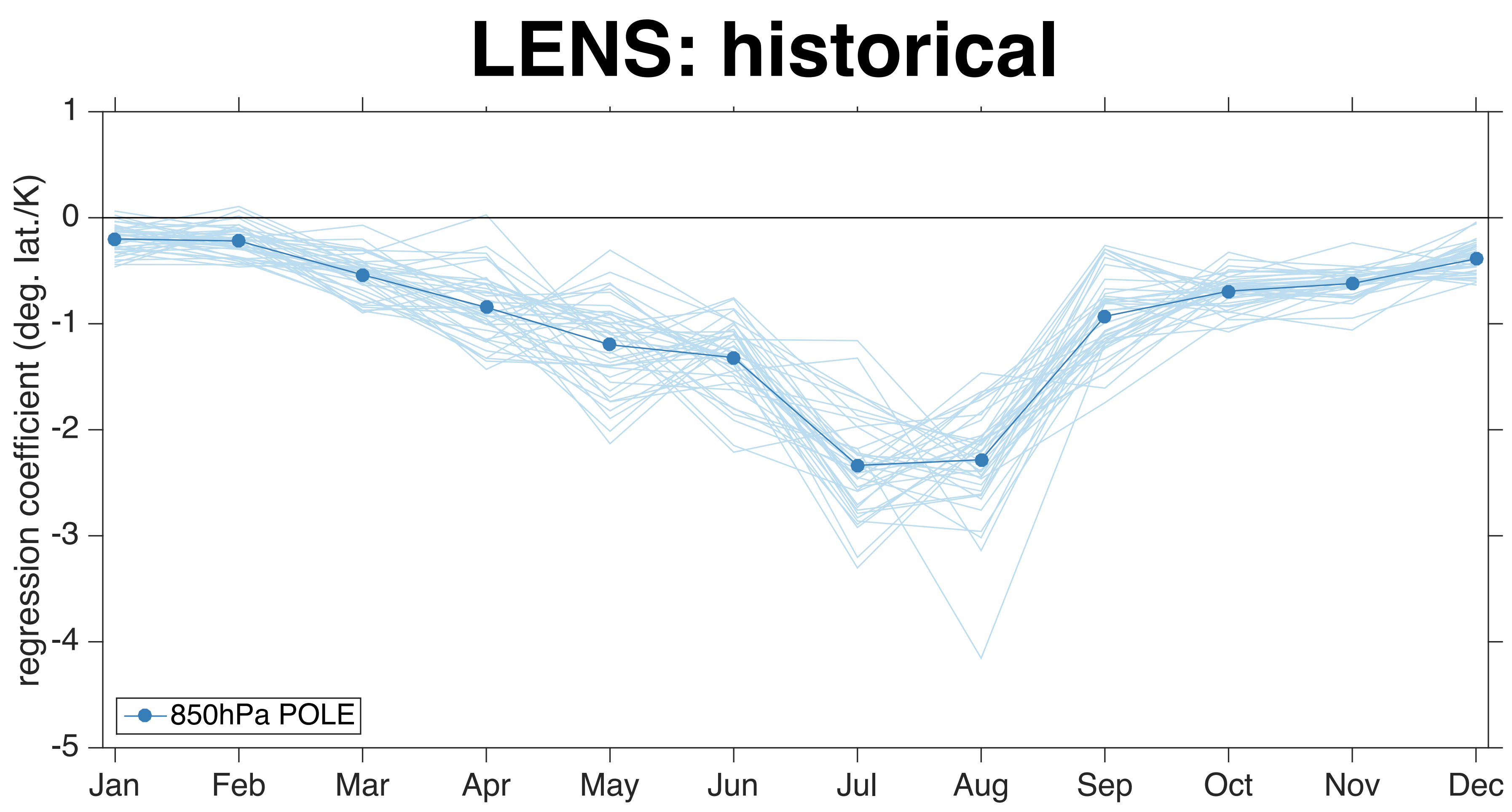

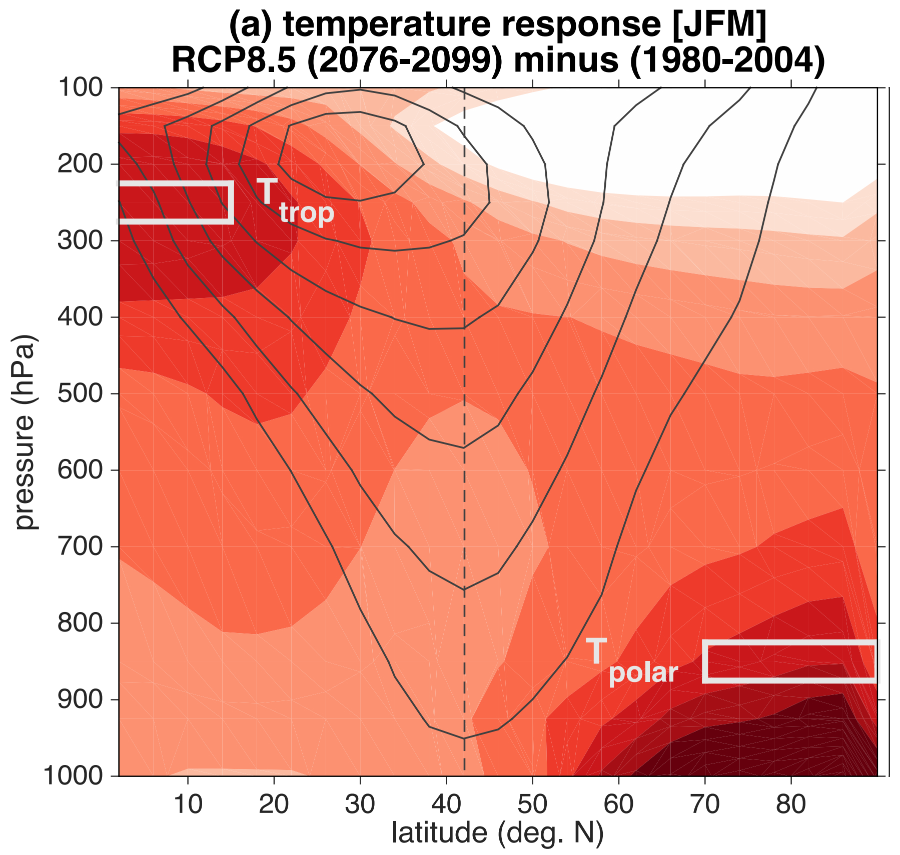

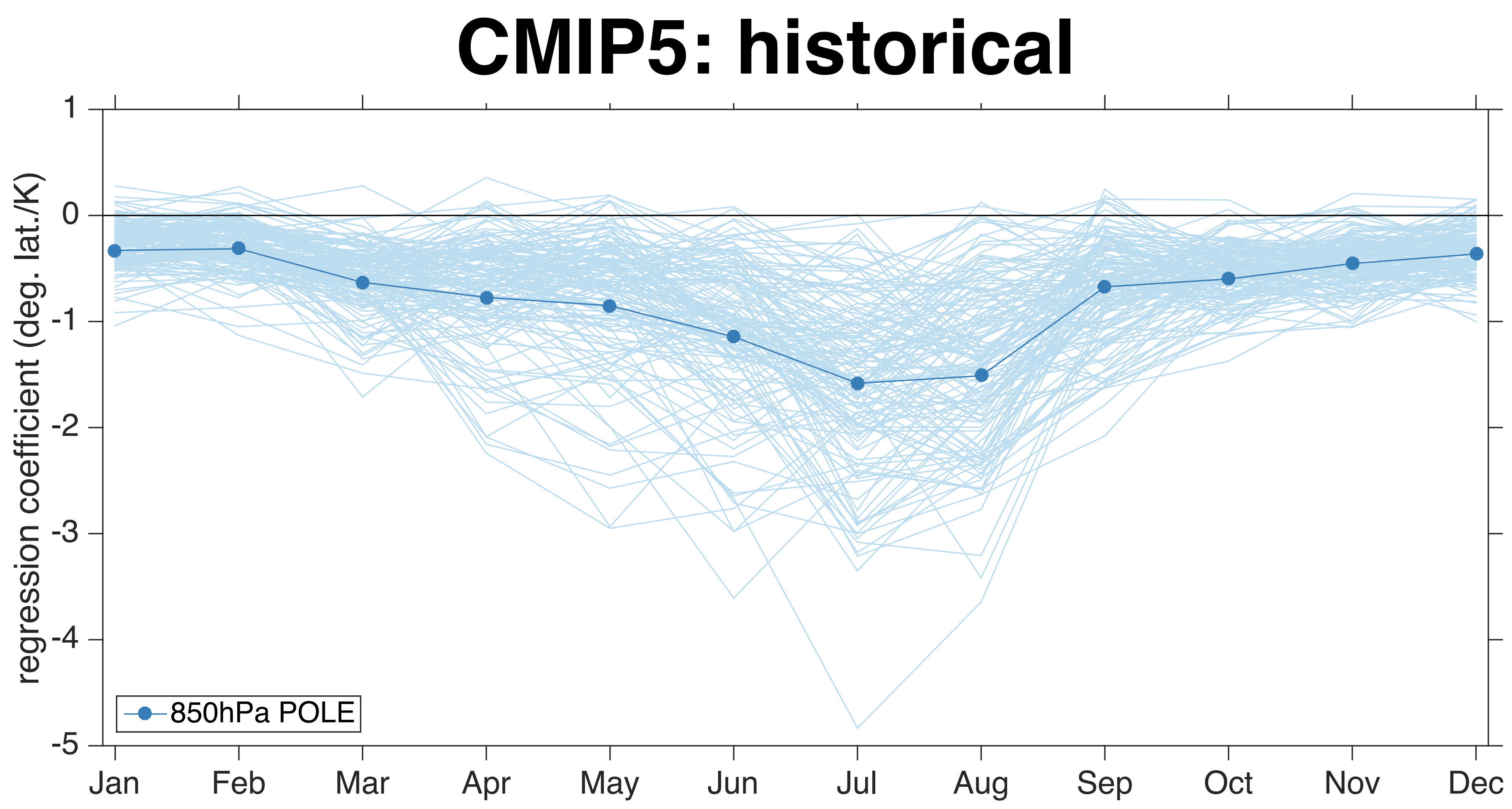

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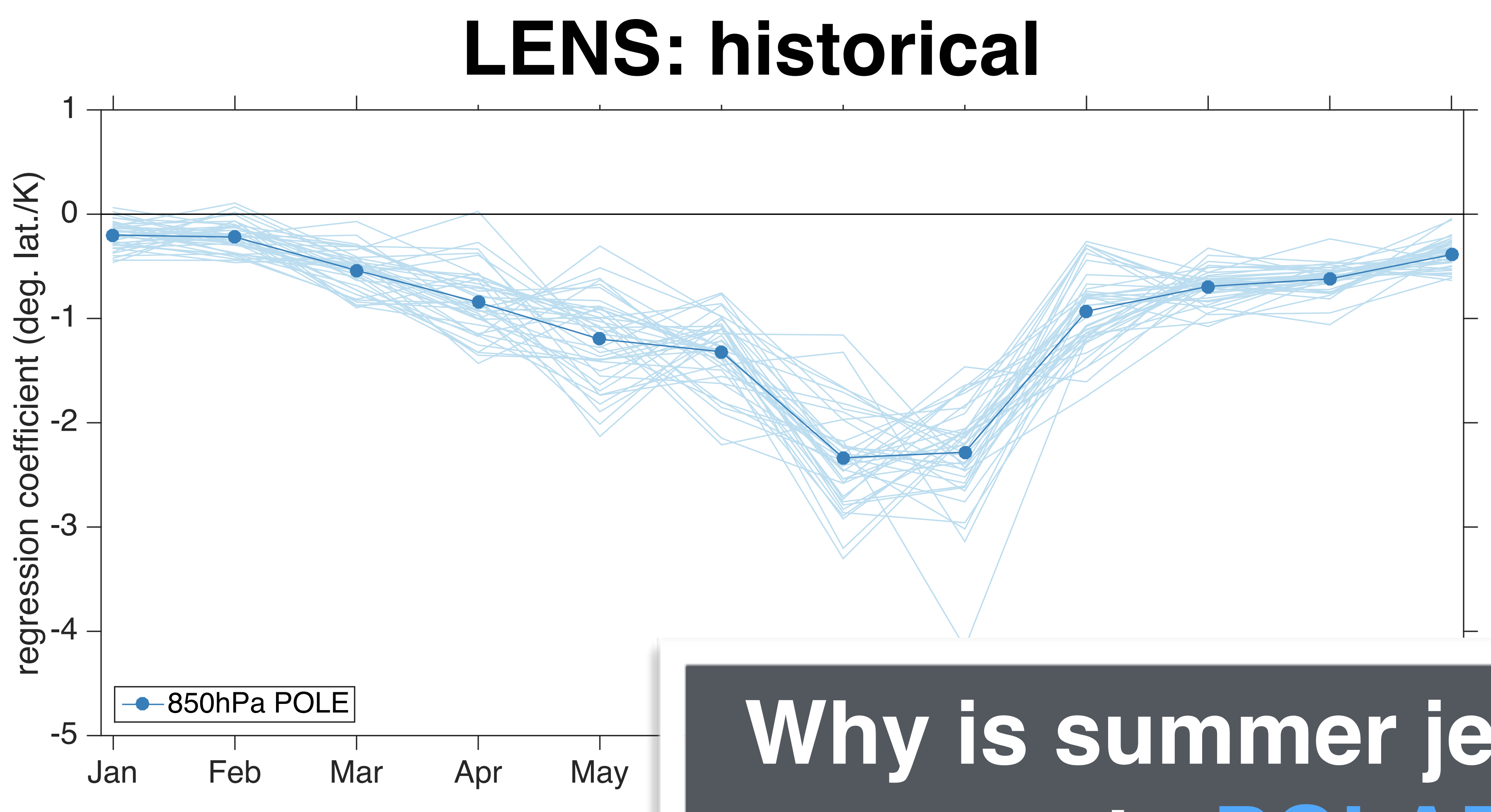
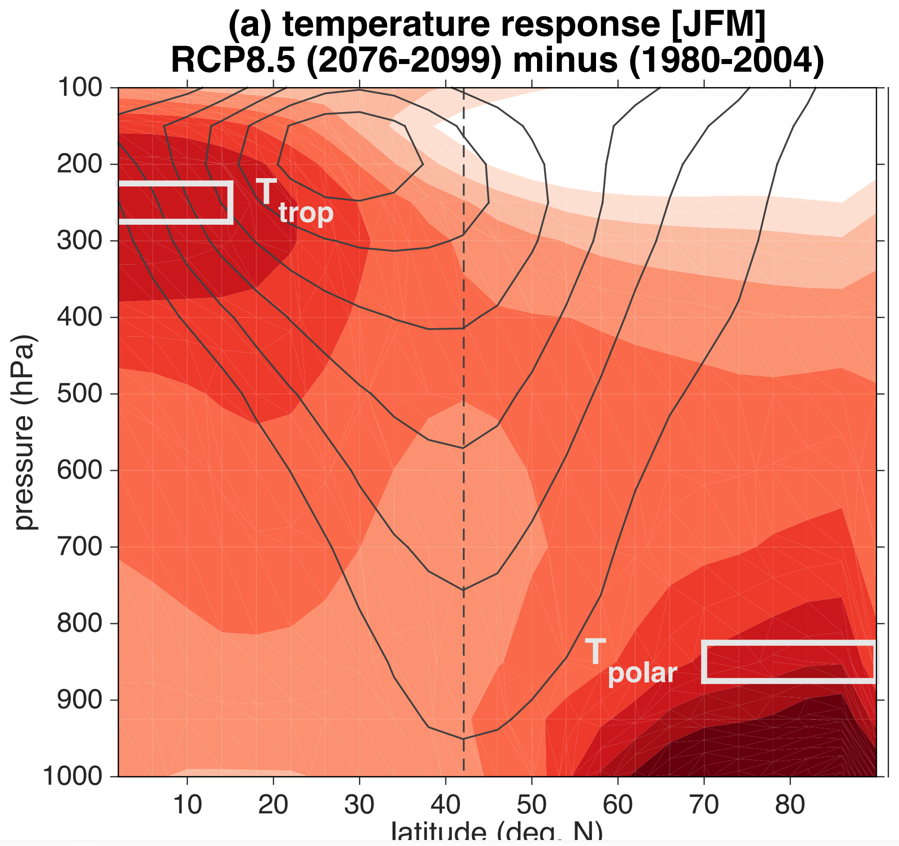
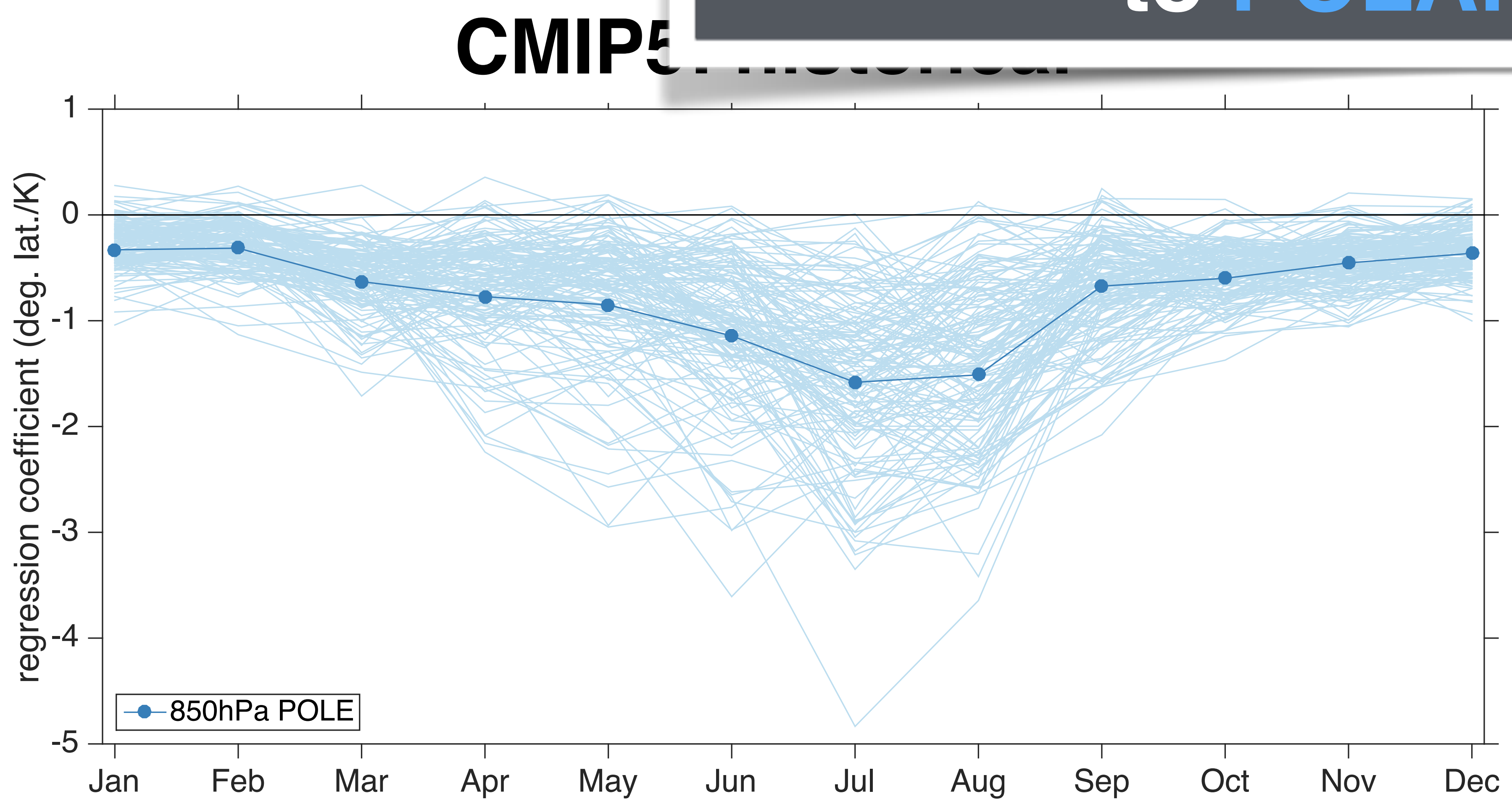




Why is summer jet the most sensitive to POLAR warming?



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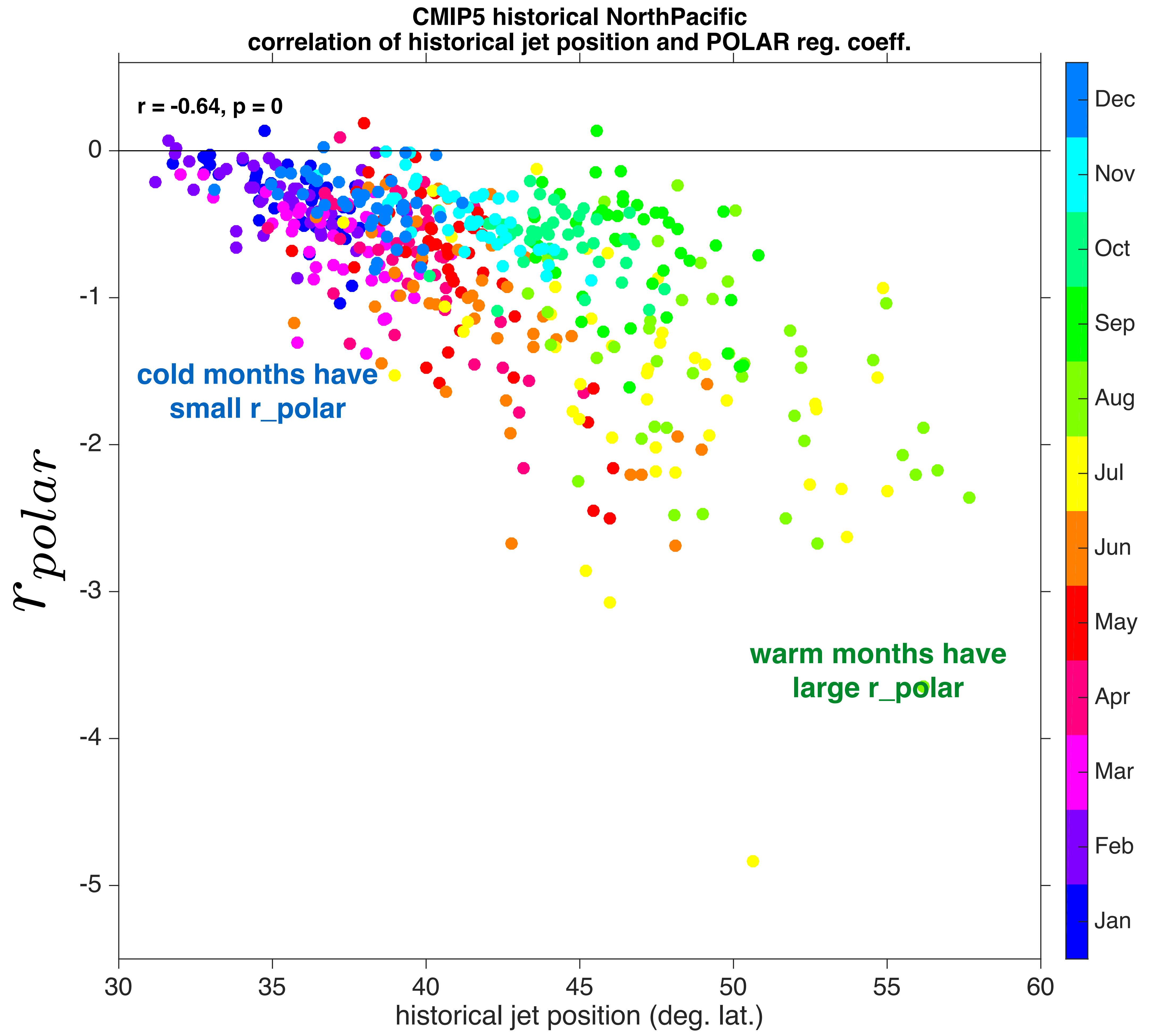
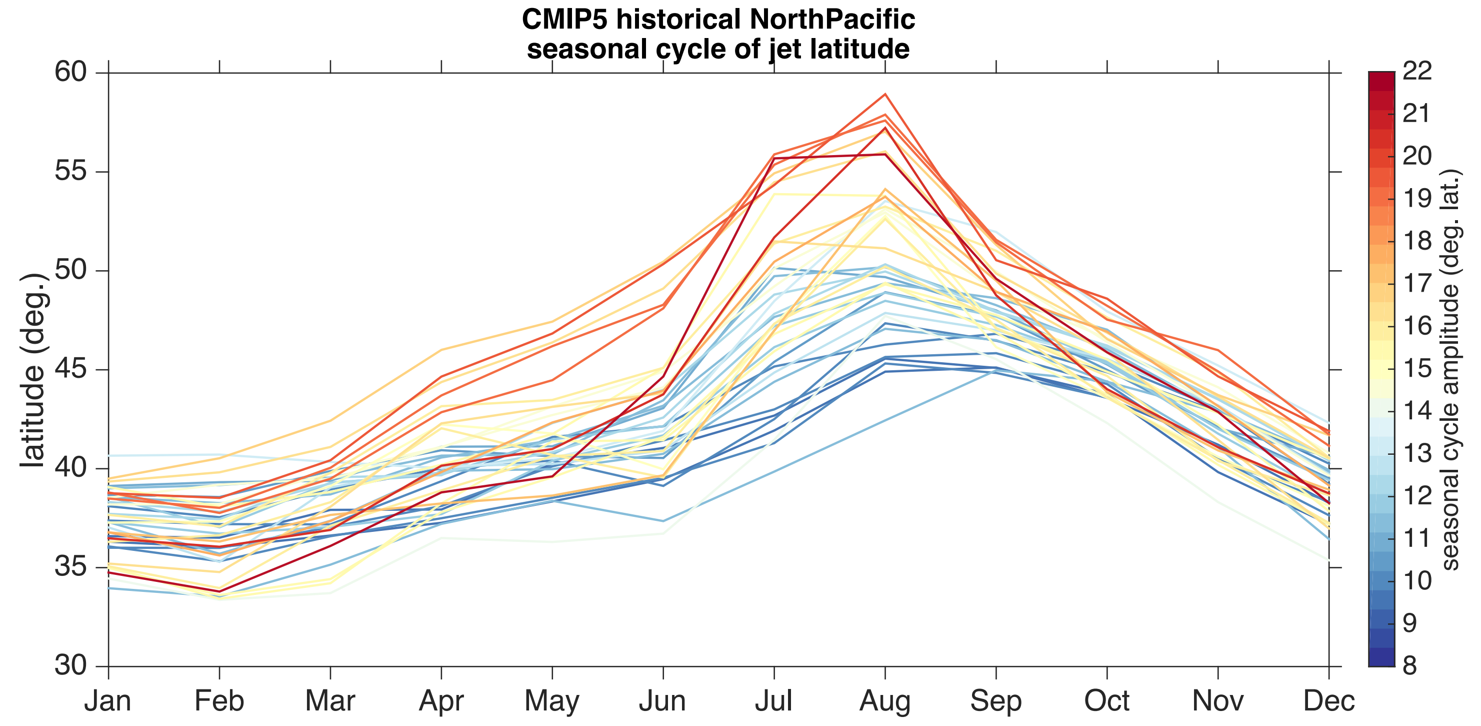
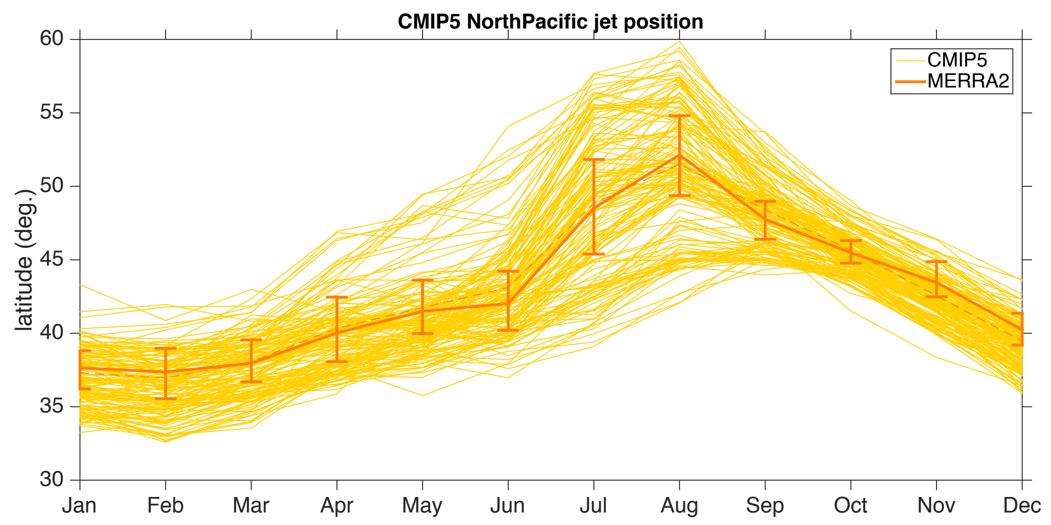
Seasonality of the jet shift w/ POLAR warming



The seasonal migration of the jet impacts the jet shift's seasonal sensitivity



Why might there be seasonal sensitivity?



hypotheses and framing based on multiple studies:
e.g. Garfinkel et al. 2013; Simpson et al. 2010; O'Rourke & Vallis 2013; Peng et al. 1995, 1997; Newman & Sardeshmukh 1998 …

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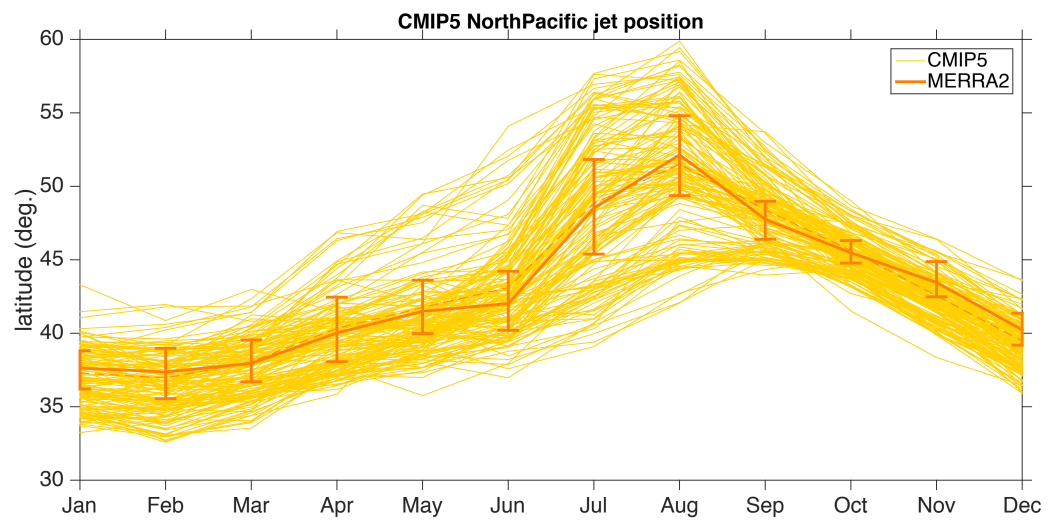

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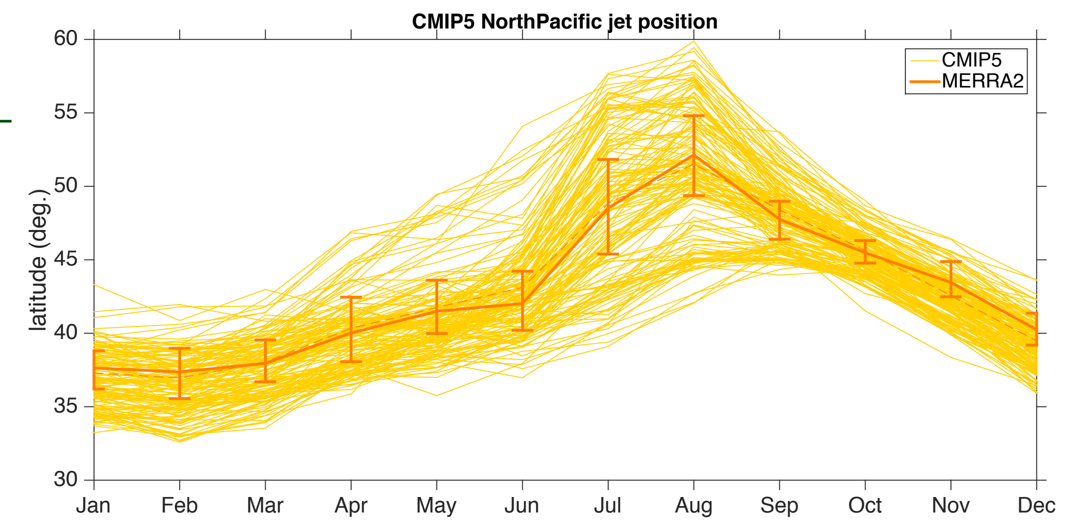

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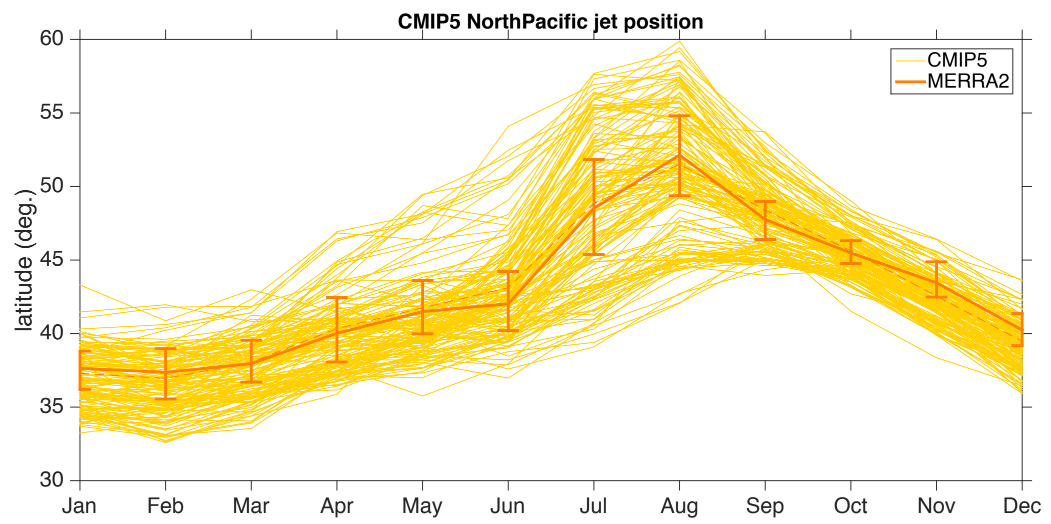

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Hypothesis 3: High-latitude jets are less responsive to external forcing. Since the climatological jet is furthest poleward in summer, the jet is most sensitive to both polar and tropical warming in winter.

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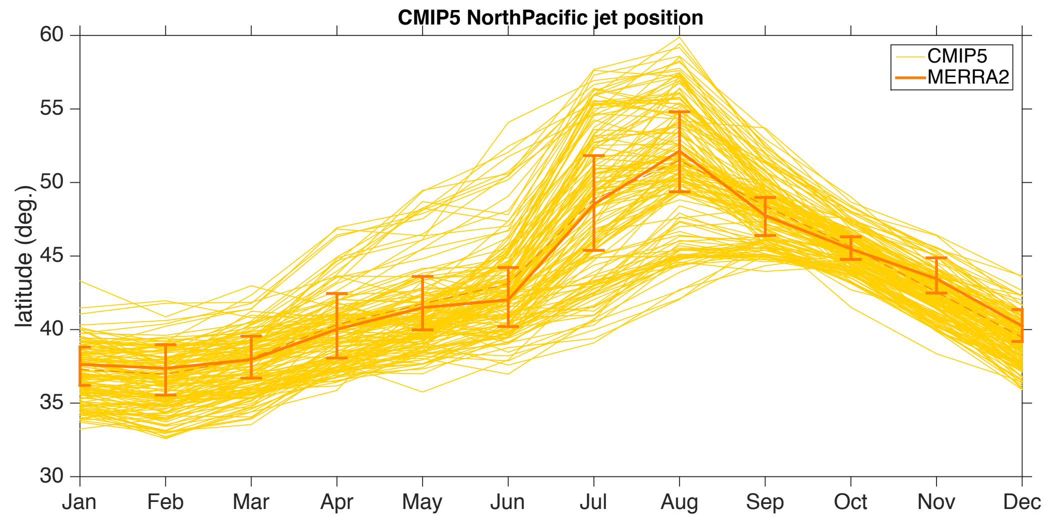

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Hypothesis 4: The shoulder seasons mark the transition between a high-latitude summer regime and low-latitude winter regime, and thus, the jet is most sensitive to forcing in spring and fall when the jet can move over a wider range of latitudes.

hypotheses and framing based on multiple studies:
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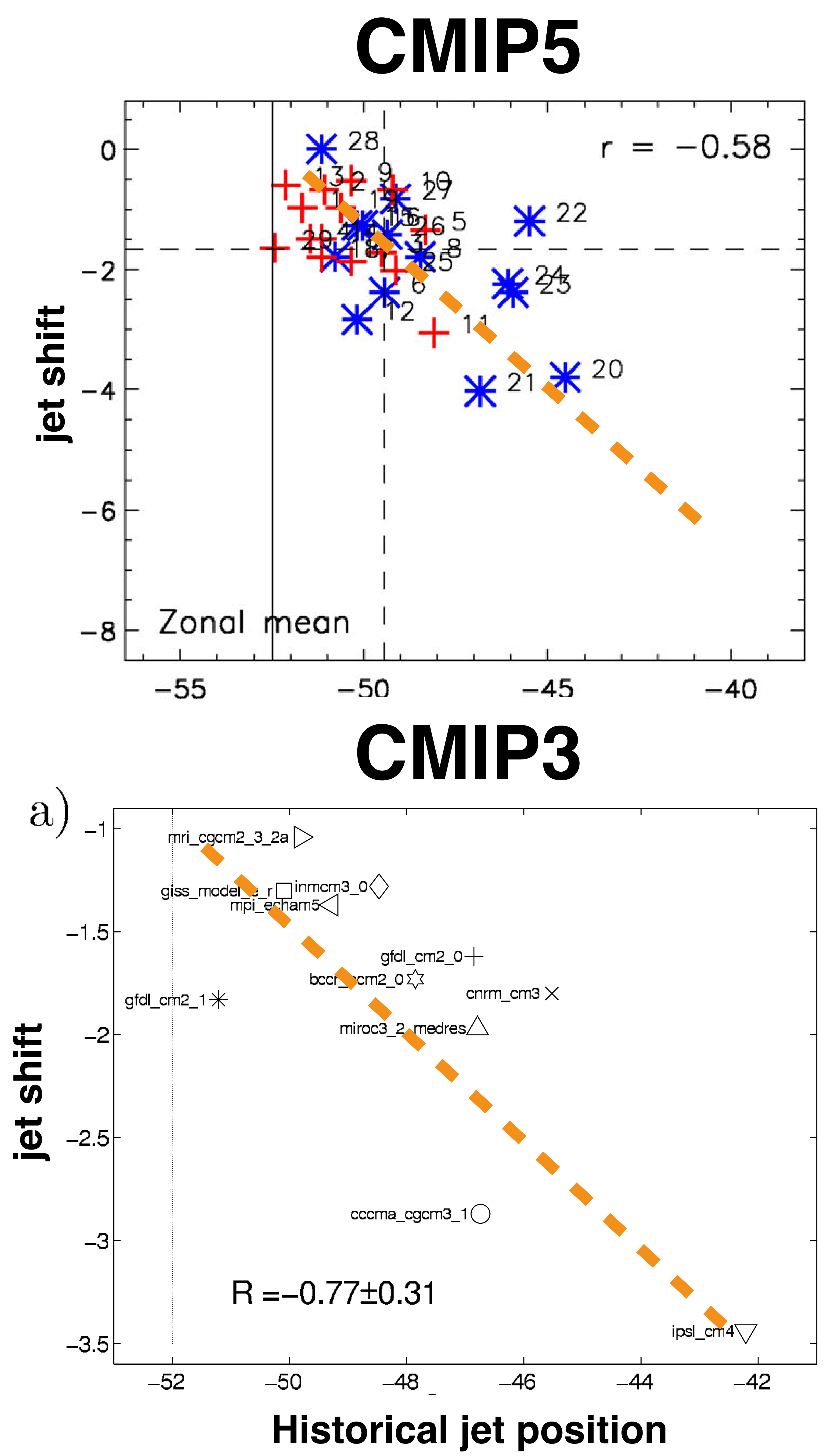
Historical jet position vs jet shift

Southern Hemisphere

- idealized and comprehensive GCM evidence that higher latitude jets shift less
- fluctuation-dissipation arguments have been invoked to explain why
- typically this relationship has been investigated for the annual mean or the winter season…



Bracegirdle et al. (2013); JGR
Kidston and Gerber (2010); GRL

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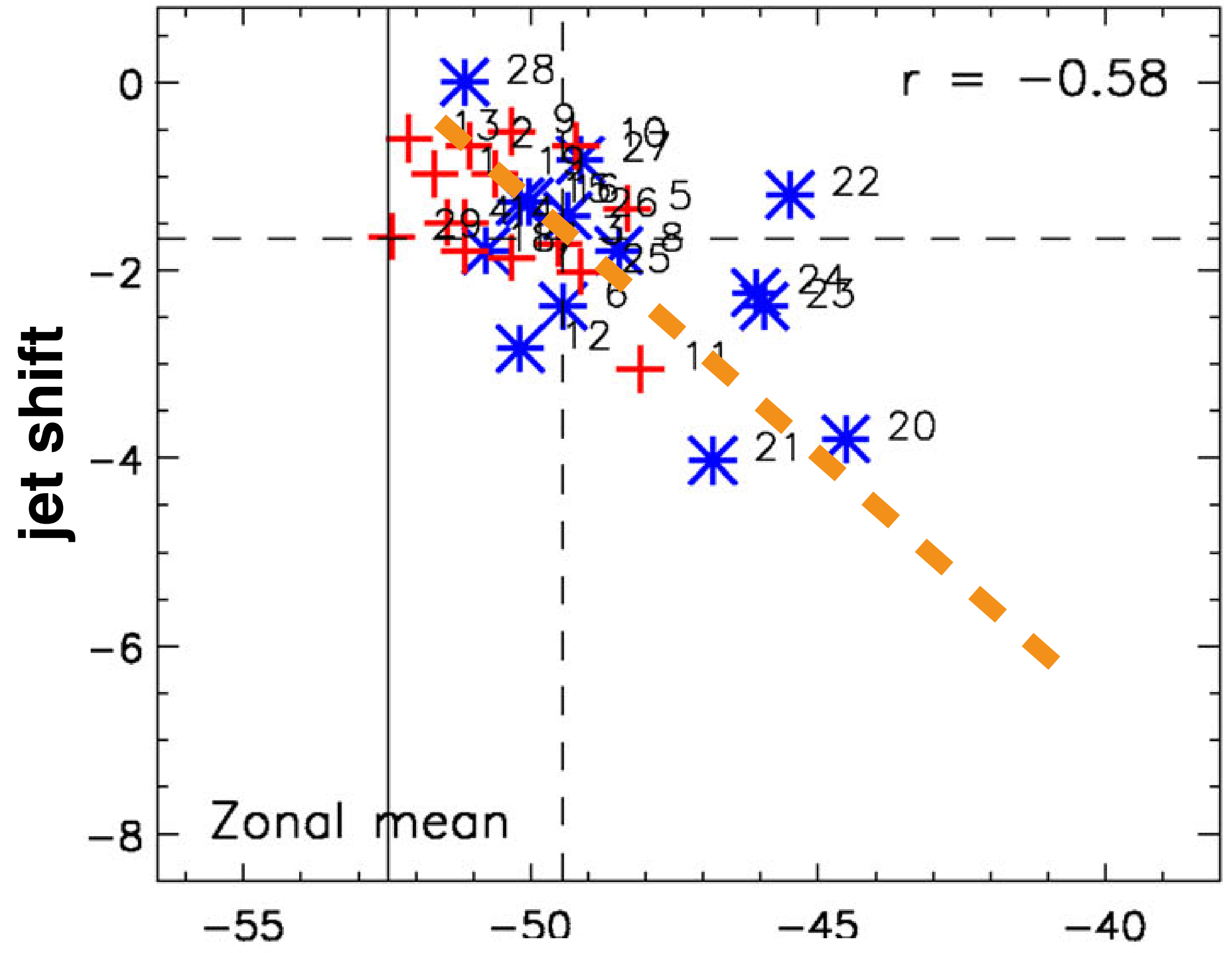
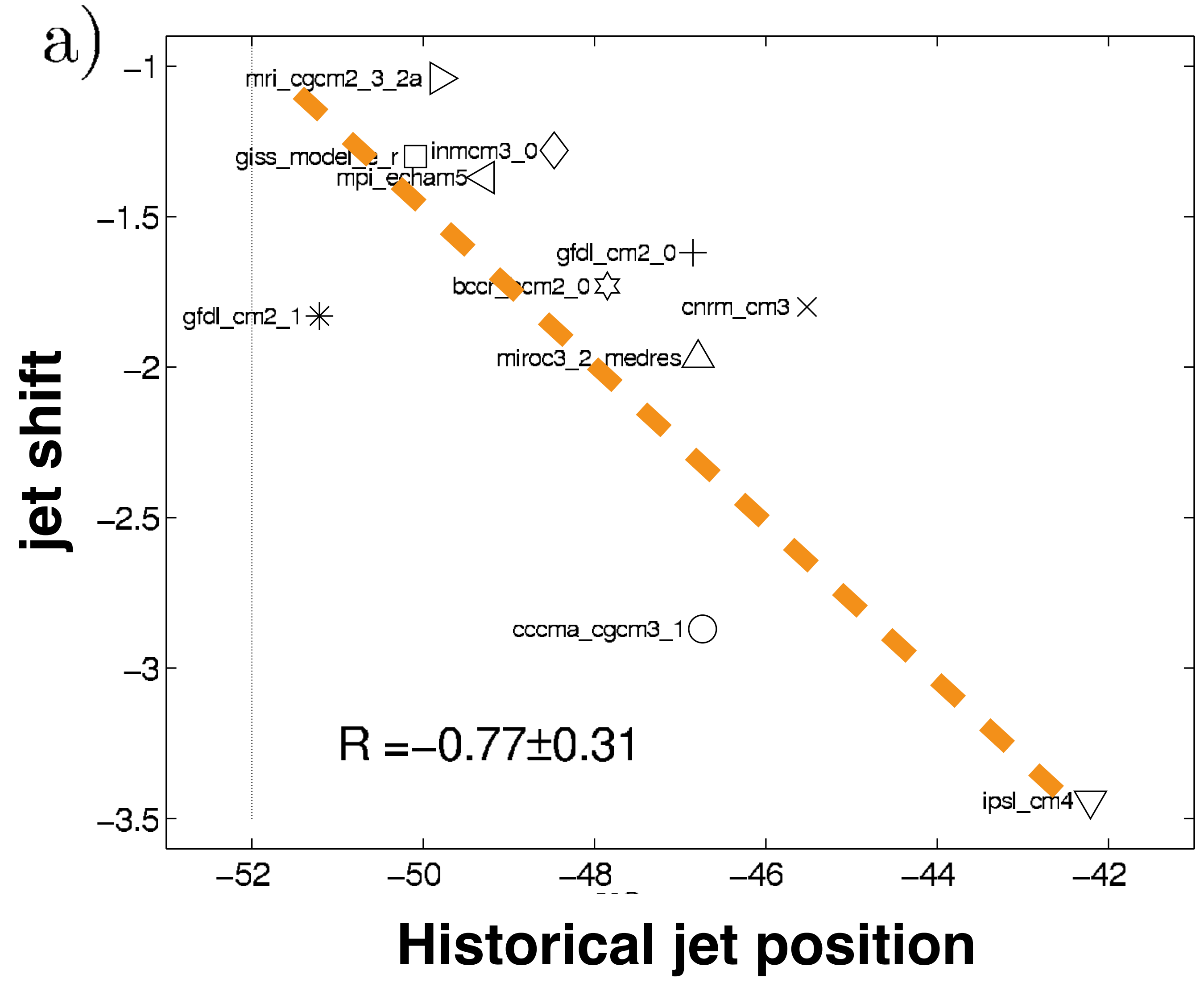
what about other seasons?

Bracegirdle et al. (2013); JGR
Kidston and Gerber (2010); GRL

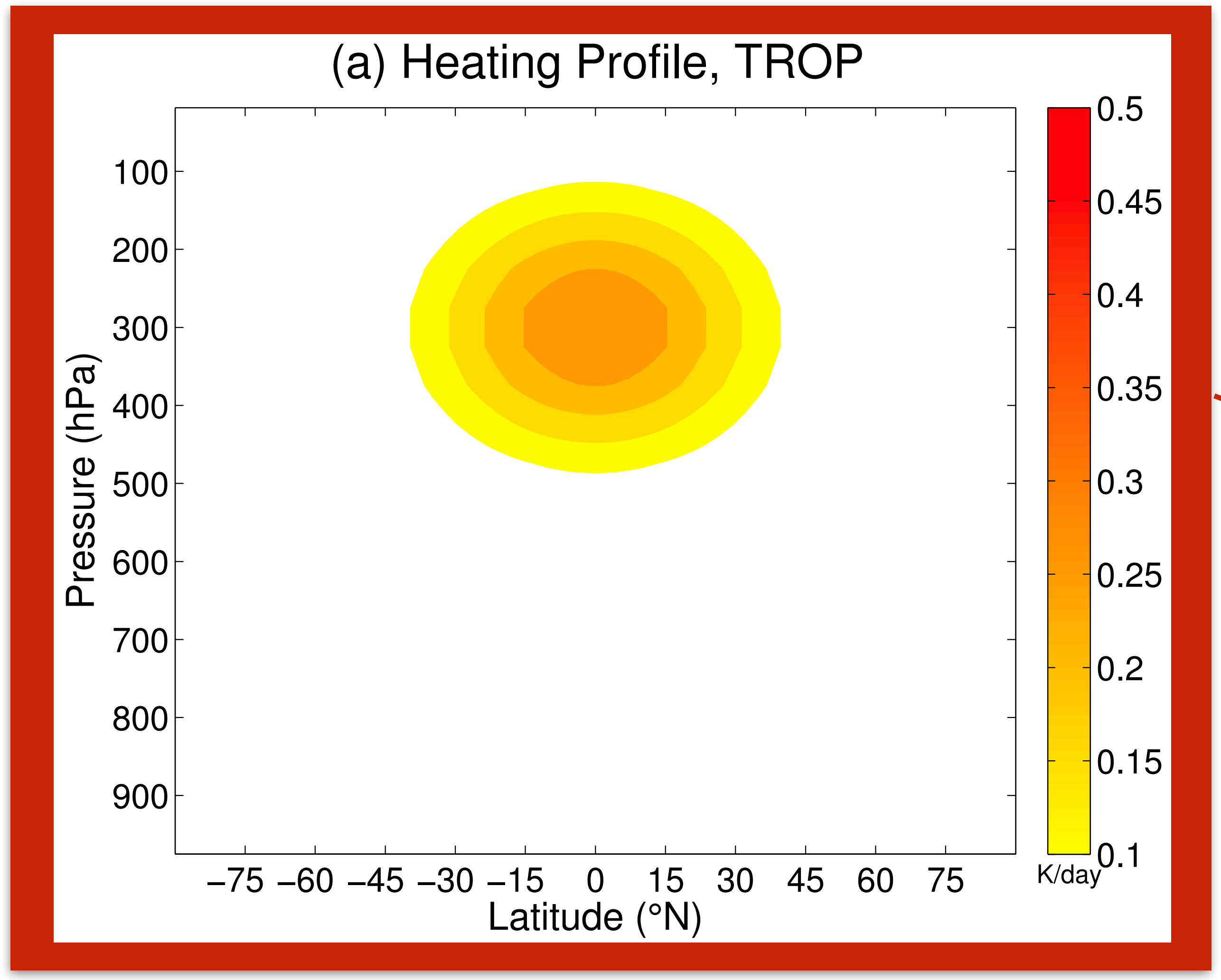
CMIP5

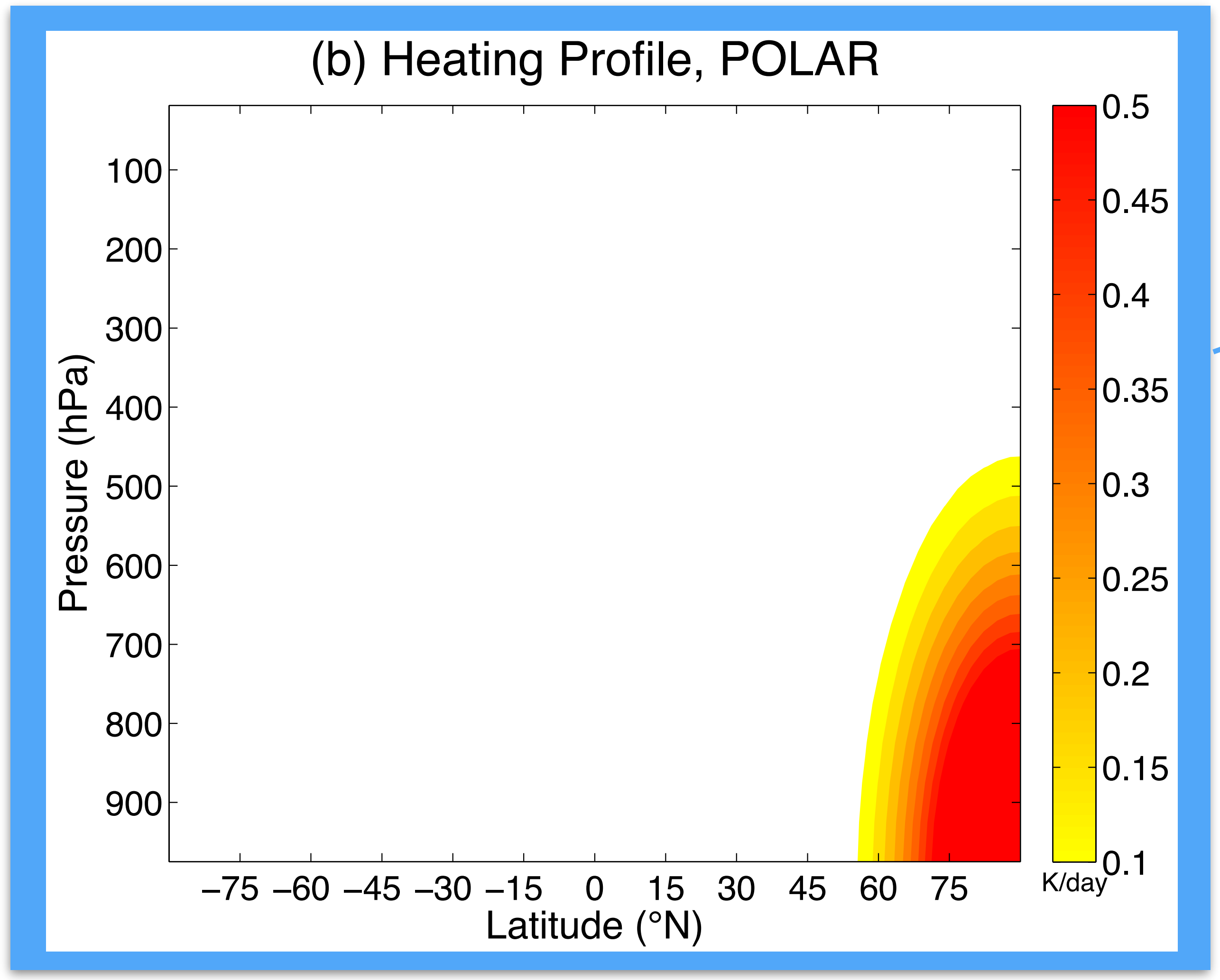


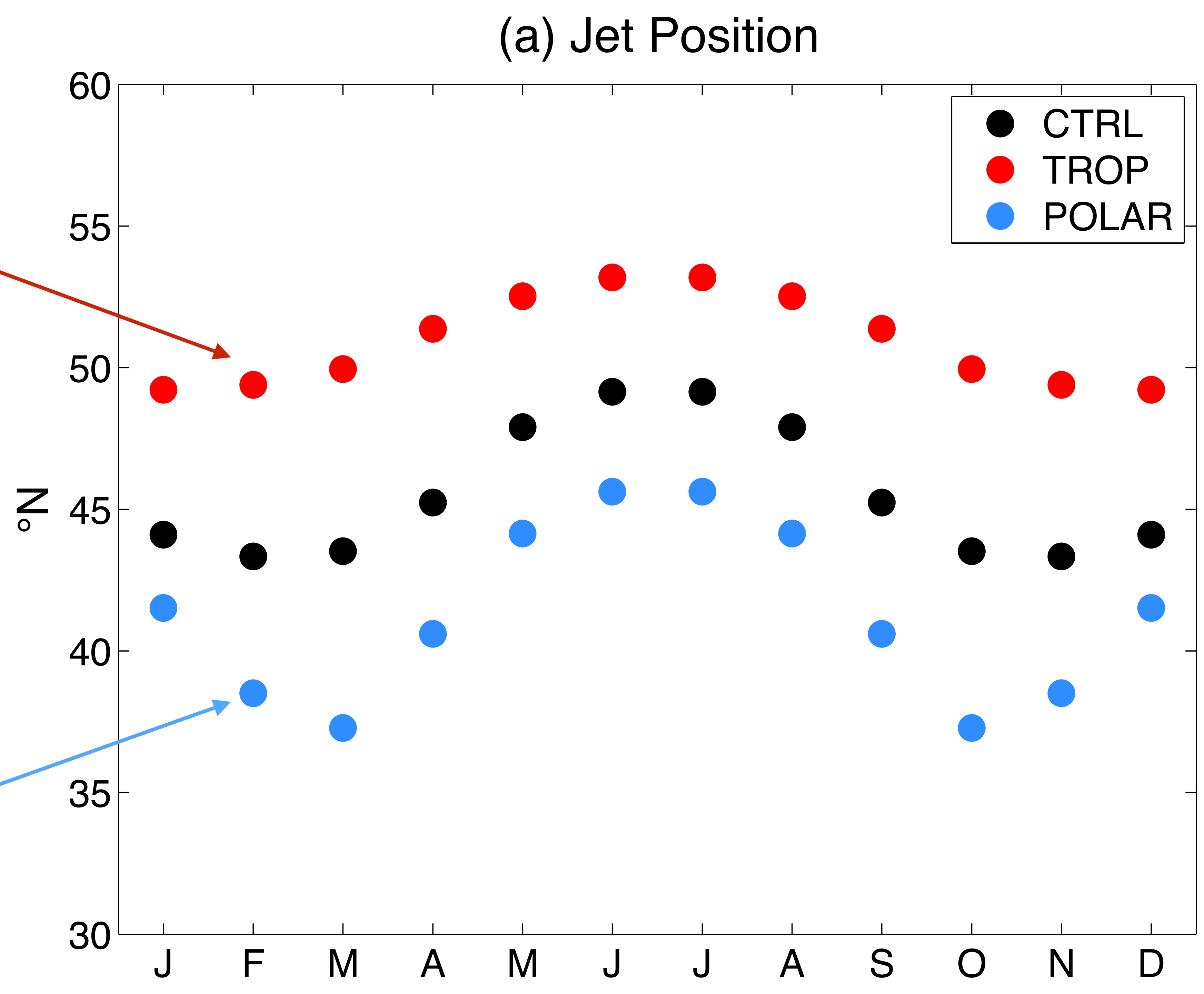
CMIP3



GFDL Dynamical Core simulations







McGraw & Barnes (2016); in press

- *forced by relaxing temperatures to an equilibrium profile based on Held & Suarez (1994)*
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- *zonally symmetric*
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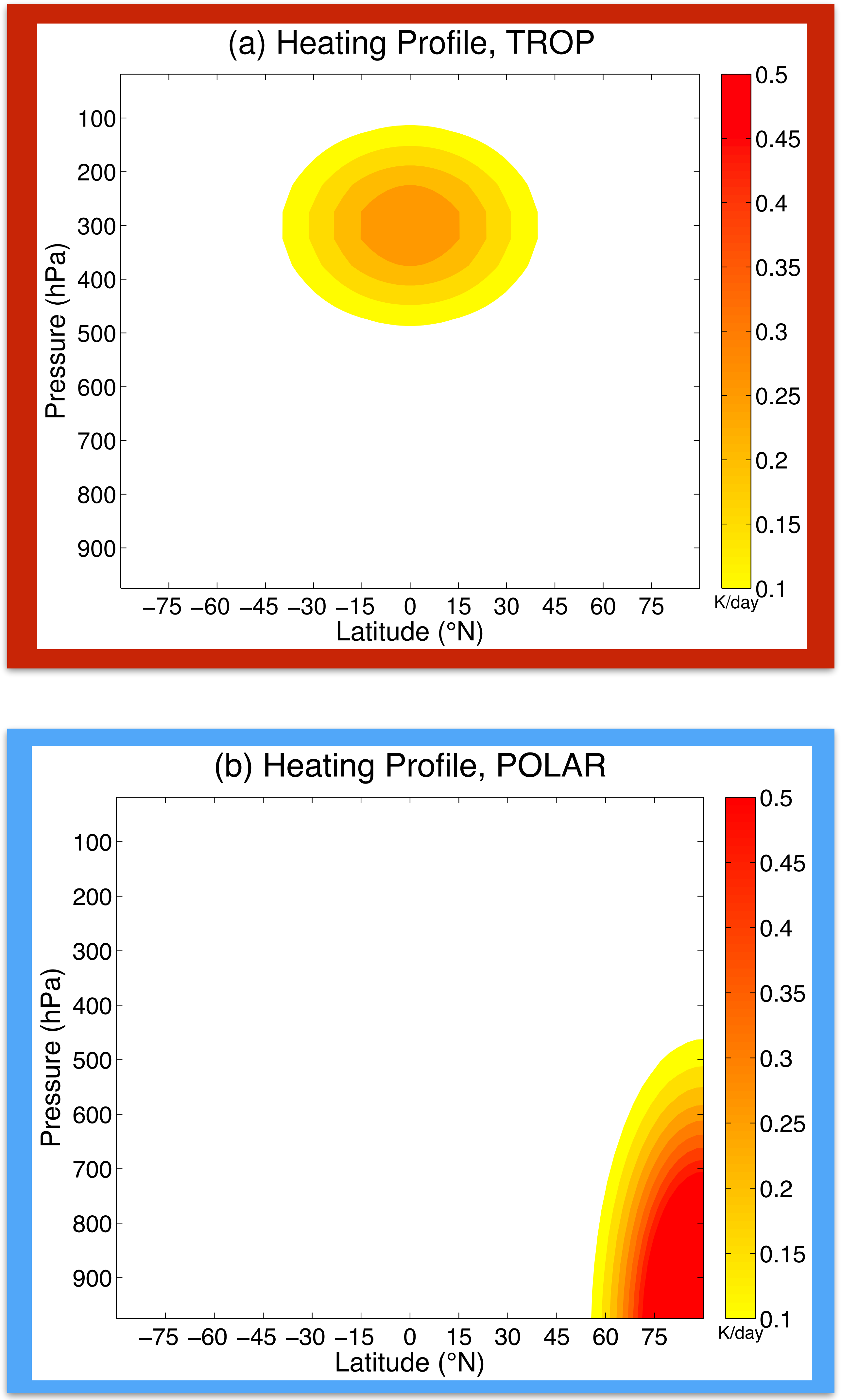
GFDL Dynamical Core simulations



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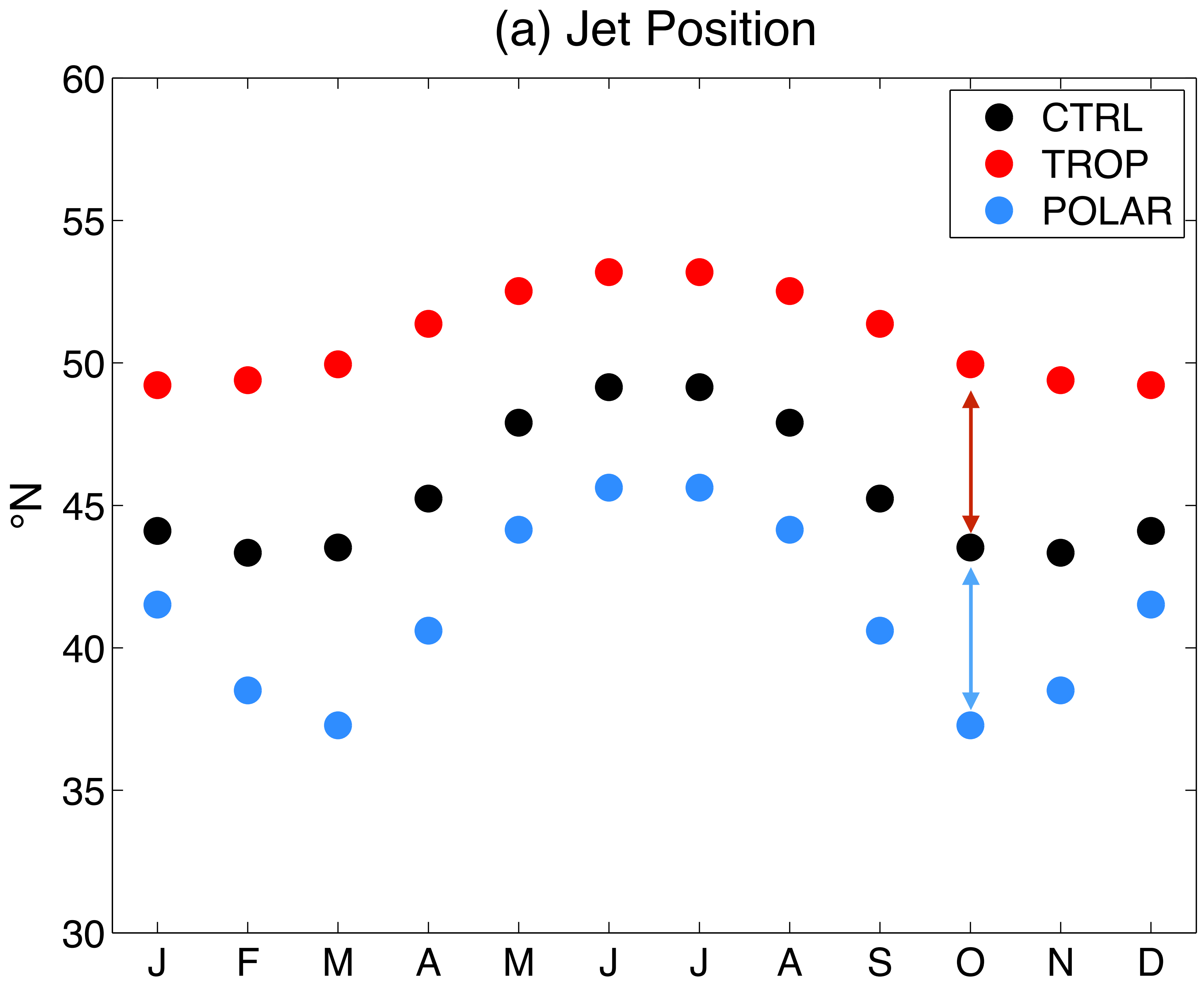

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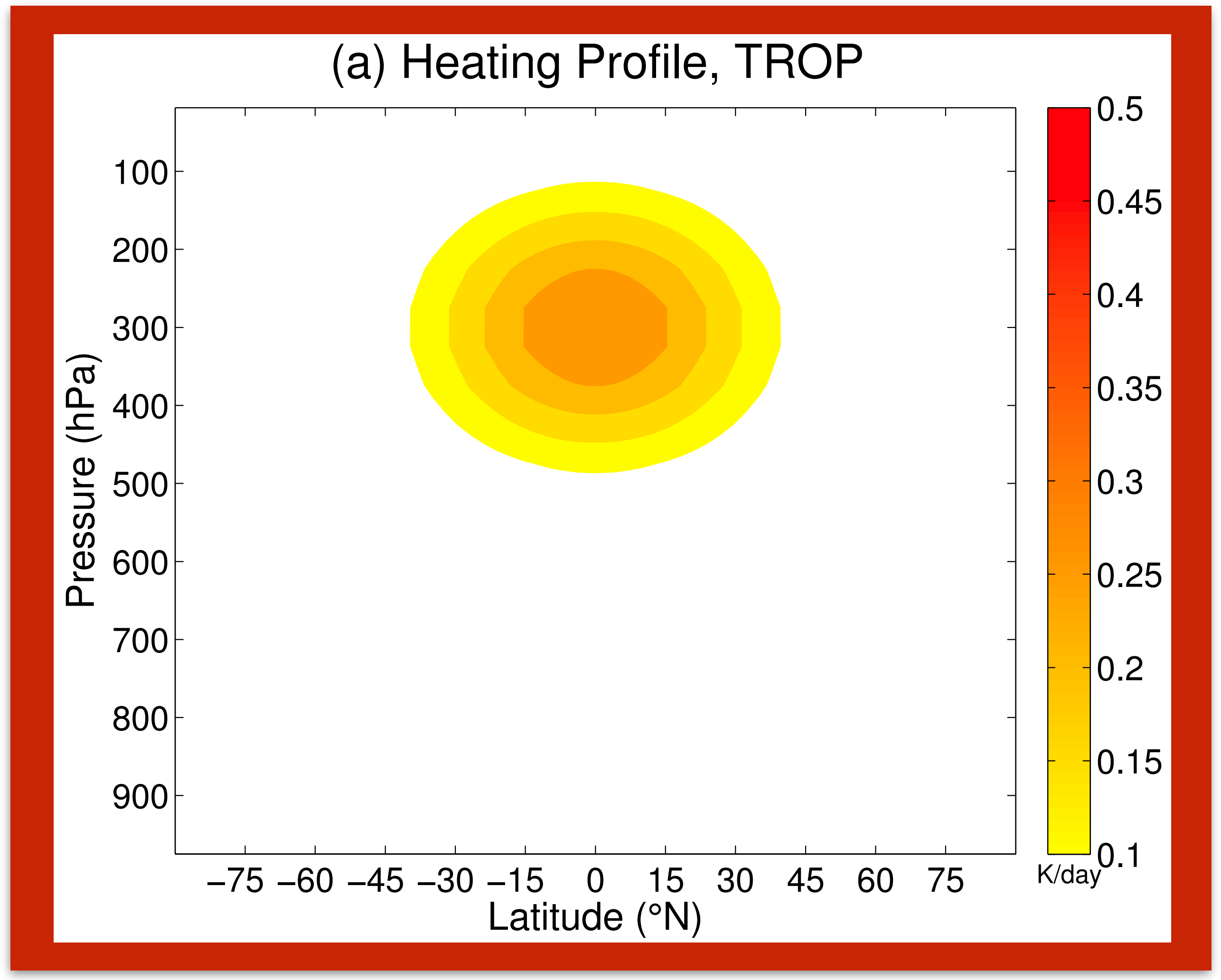

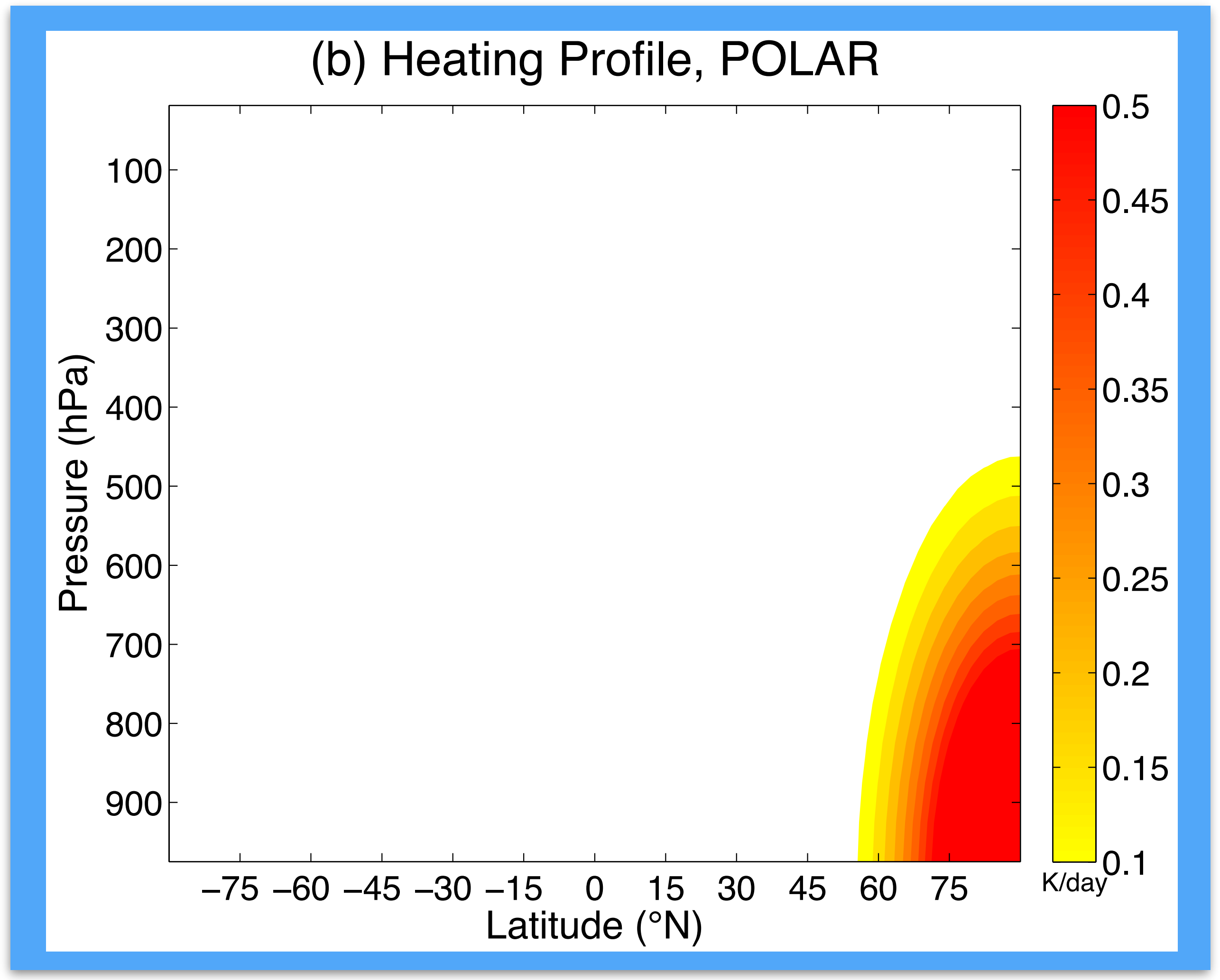

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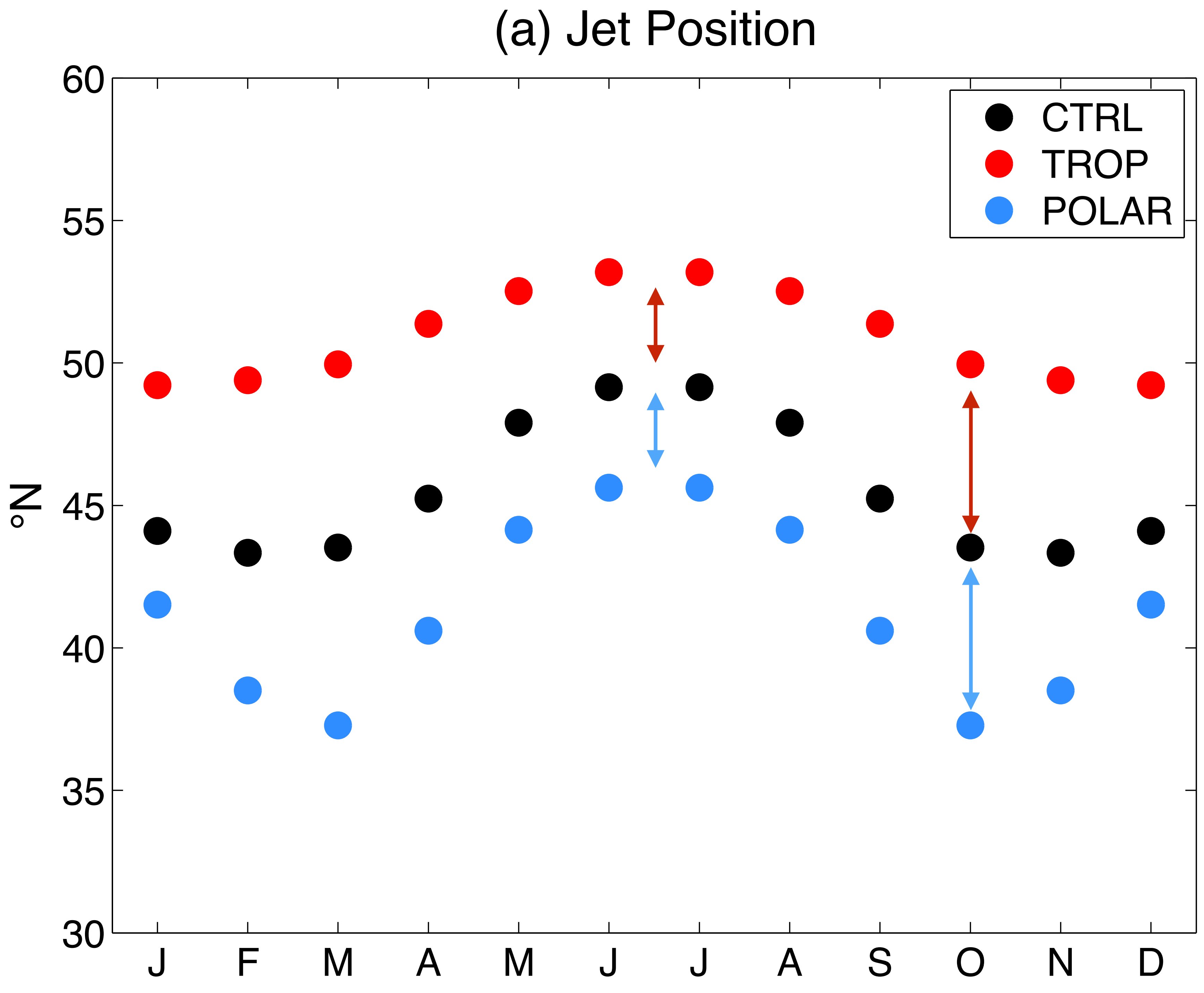

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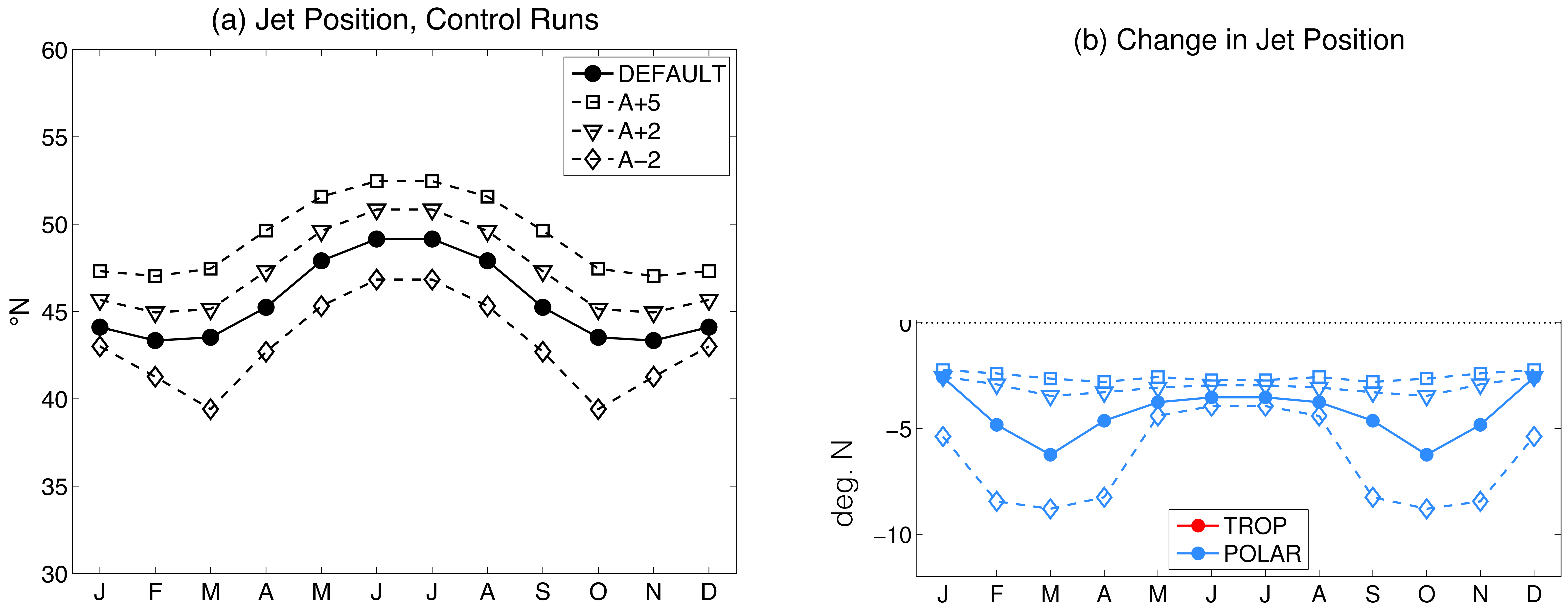

dependence on the basic state changes throughout the year:

- matters most in the shoulder seasons
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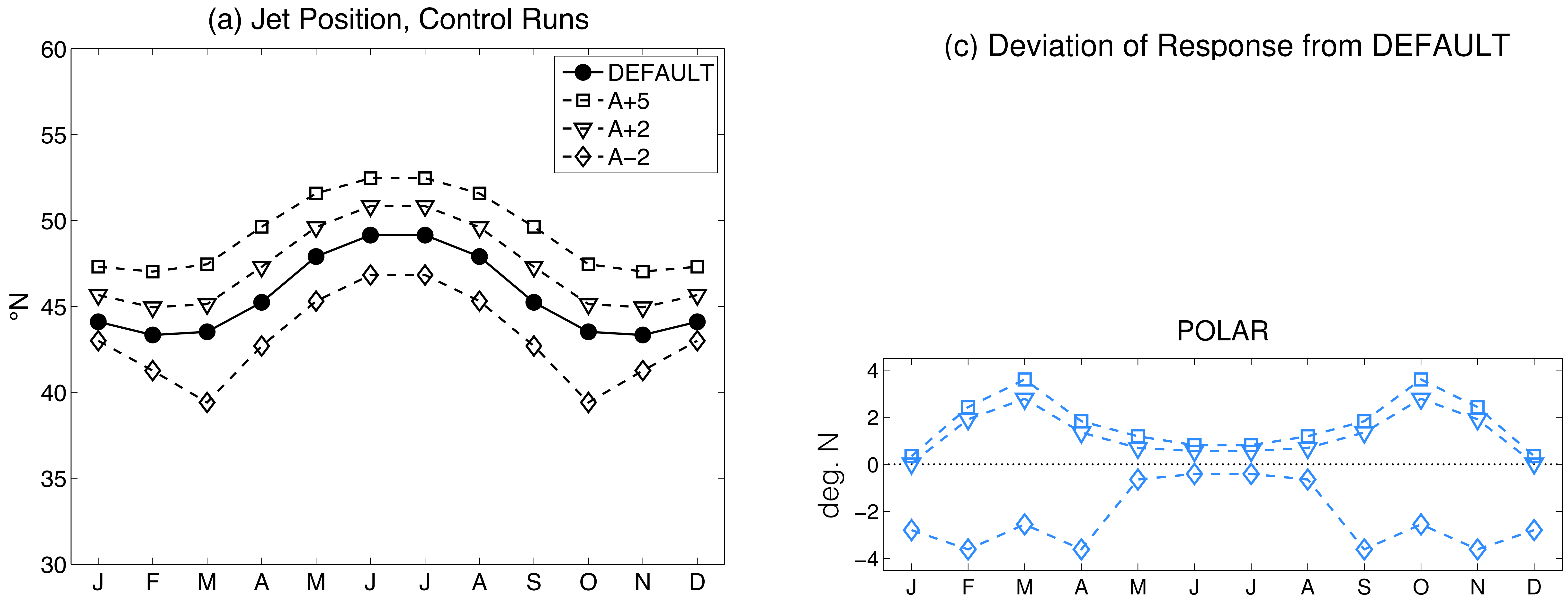

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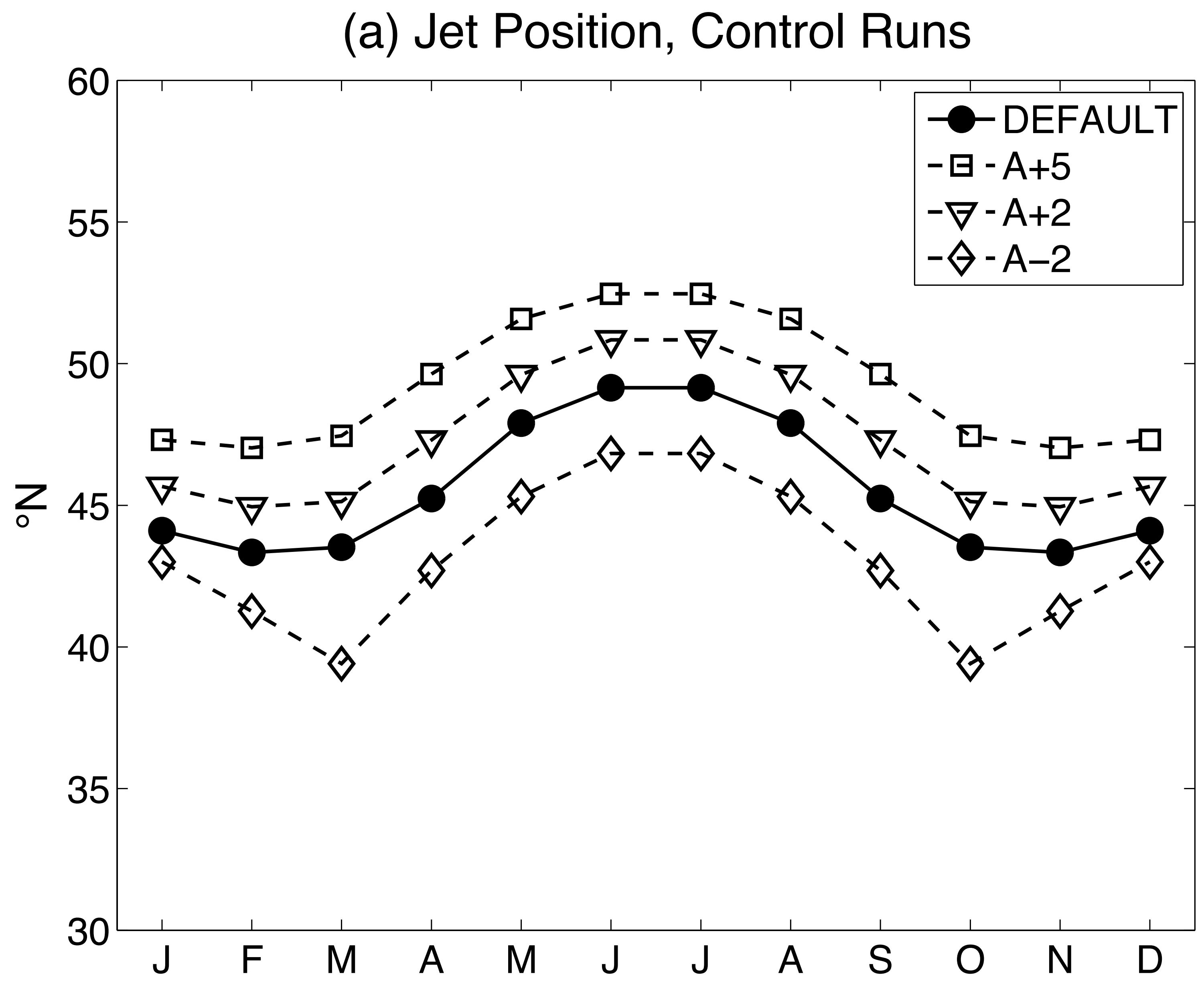

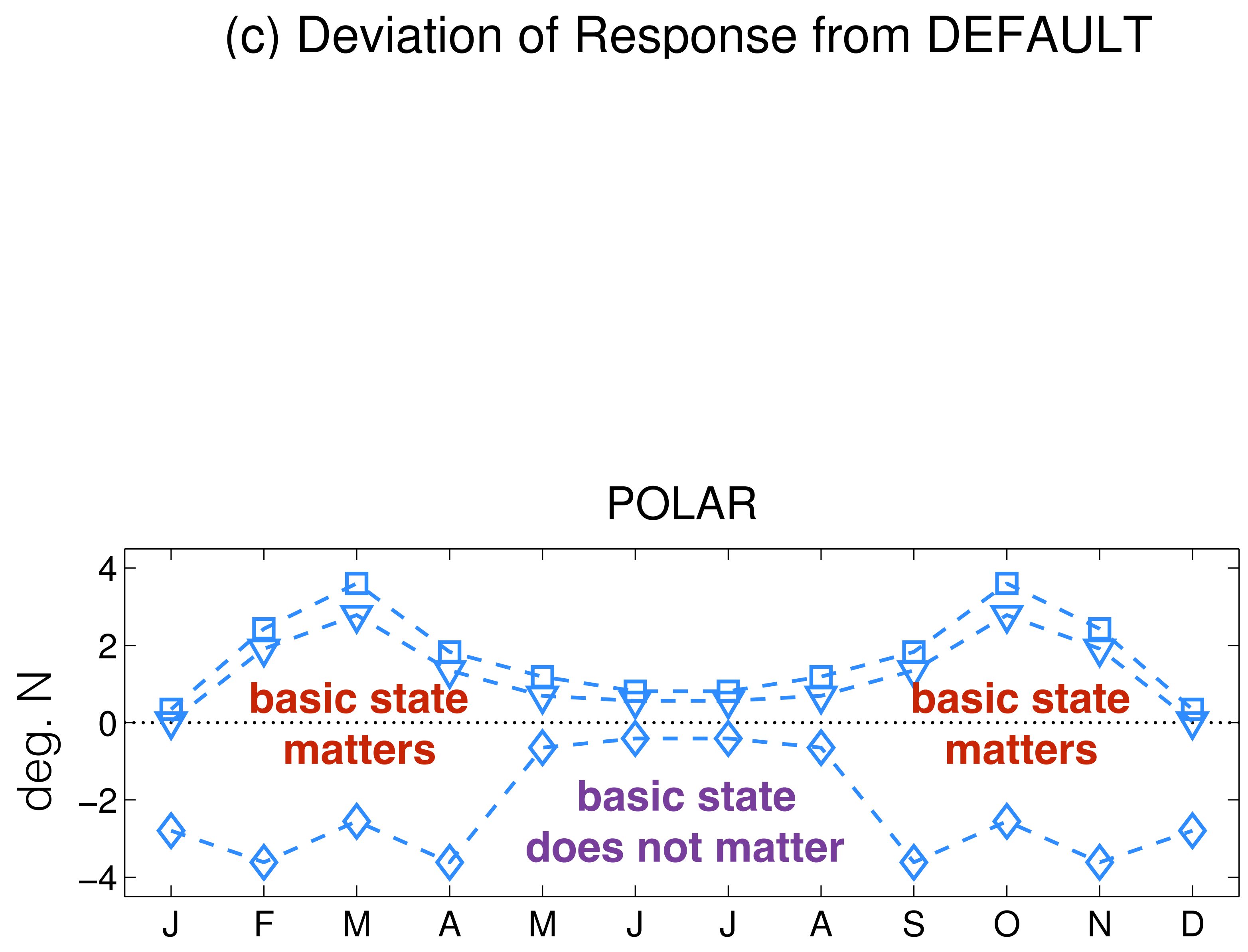

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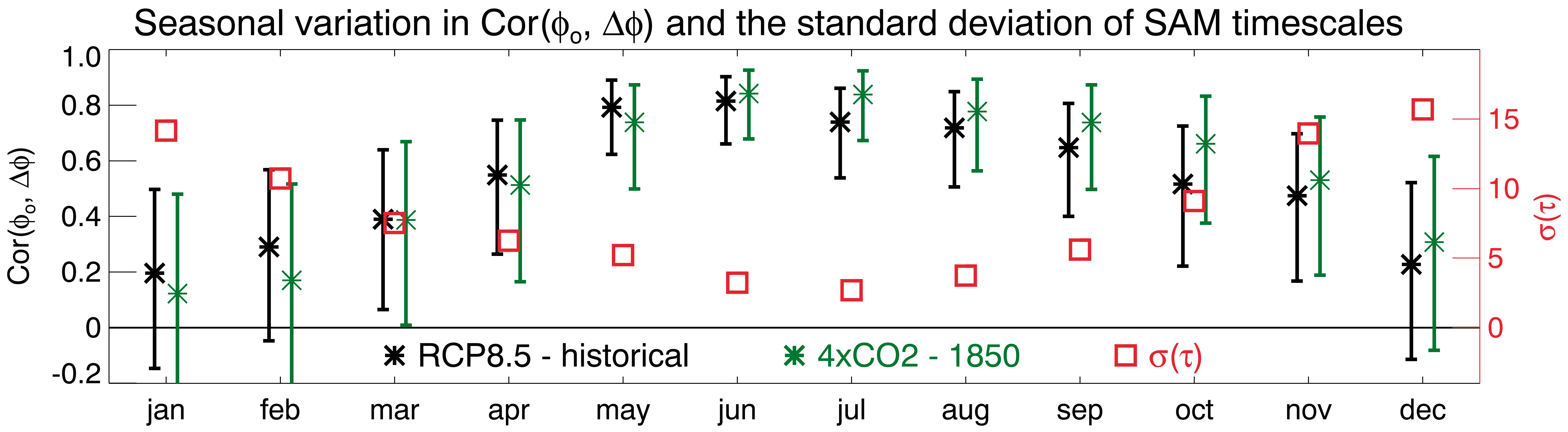
CMIP5 Historical jet position vs jet shift

Southern Hemisphere



Simpson & Polvani, (2016; GRL)

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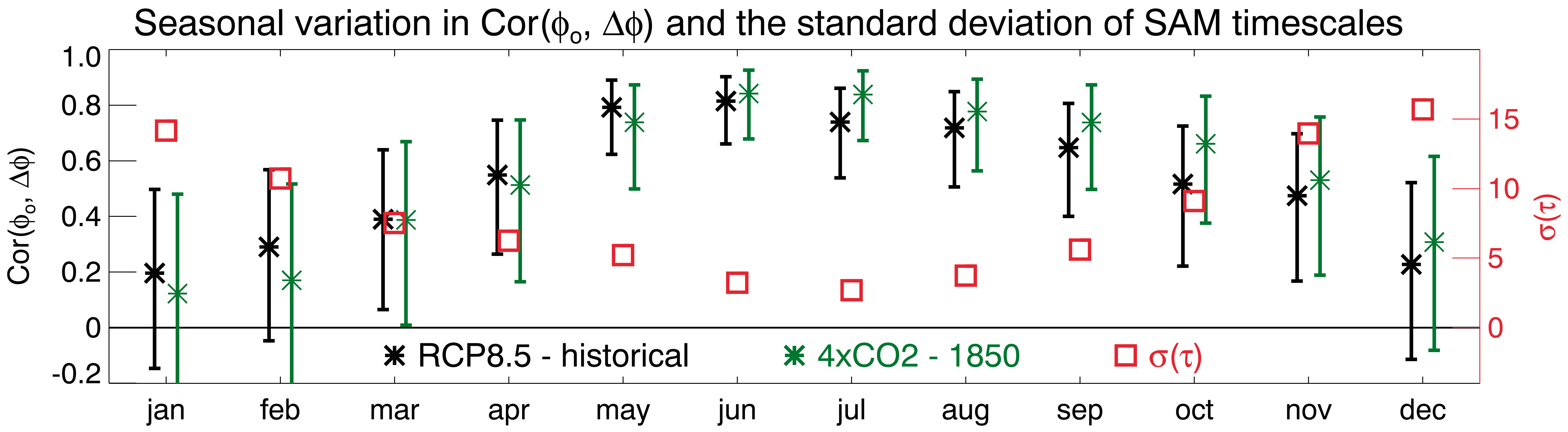
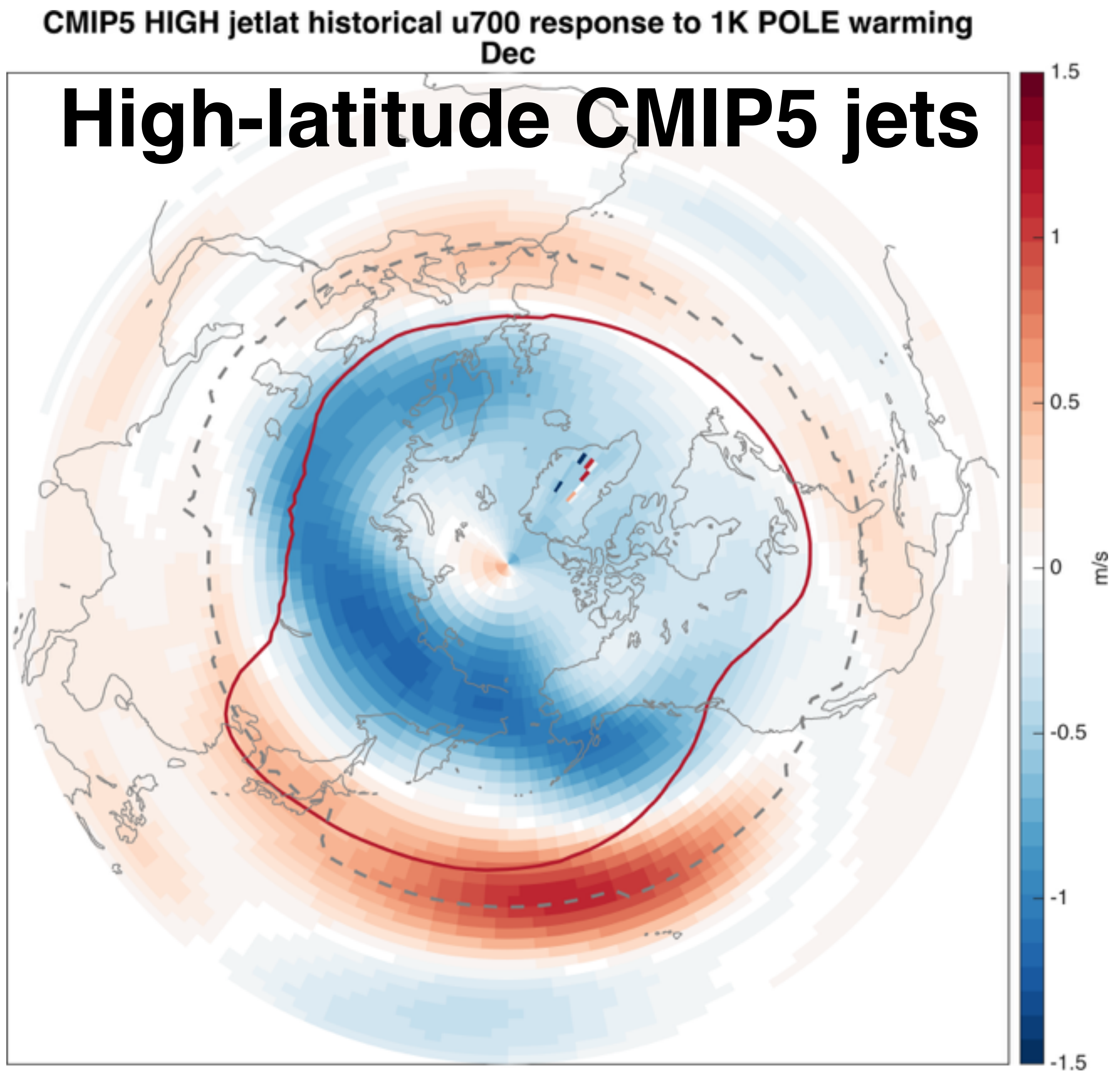
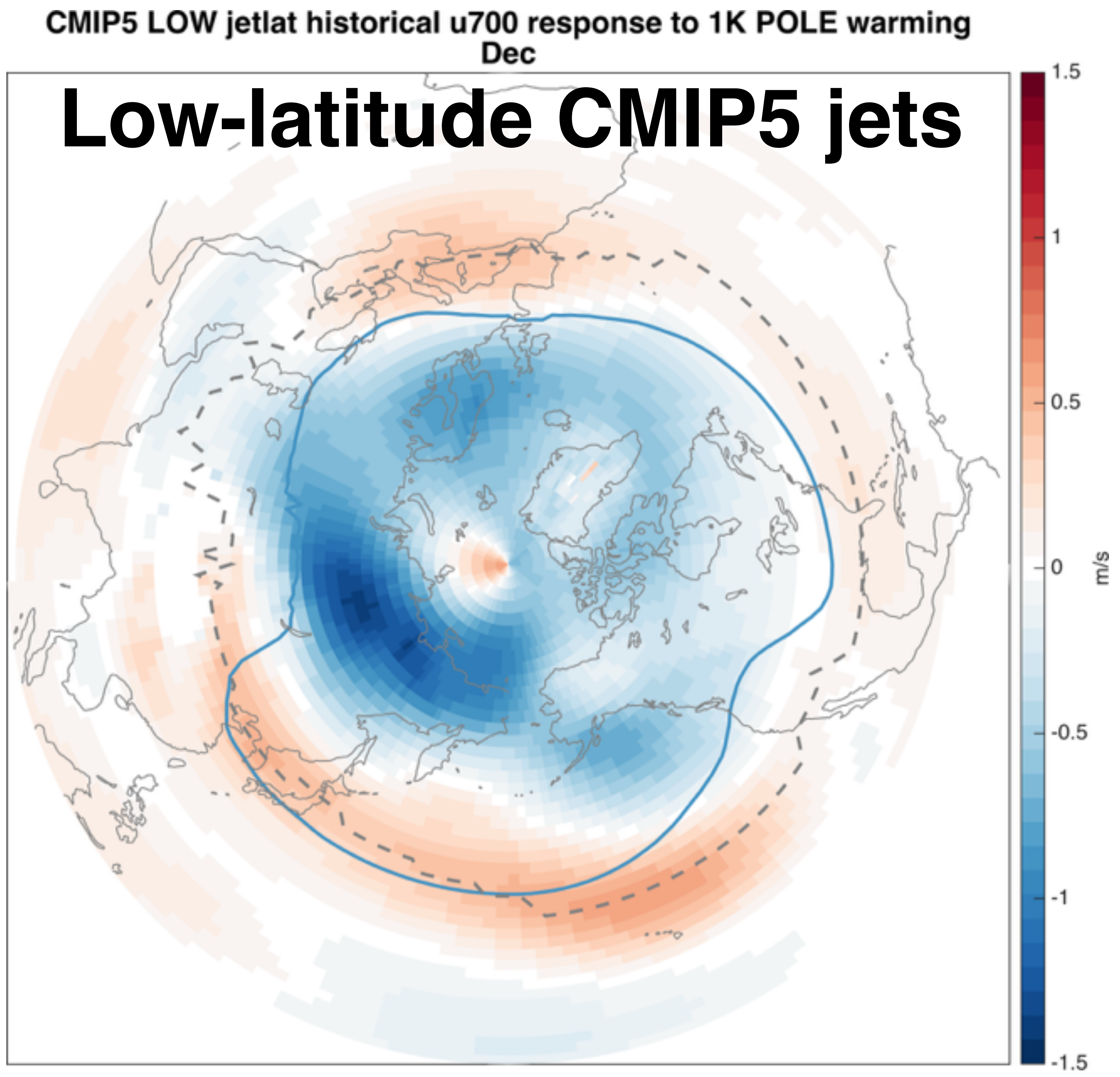


correlation between Southern Hemisphere jet position and jet shift largest in winter… when timescale is the *shortest*

Simpson & Polvani, (2016; GRL)

Regression maps: full wind field perspective



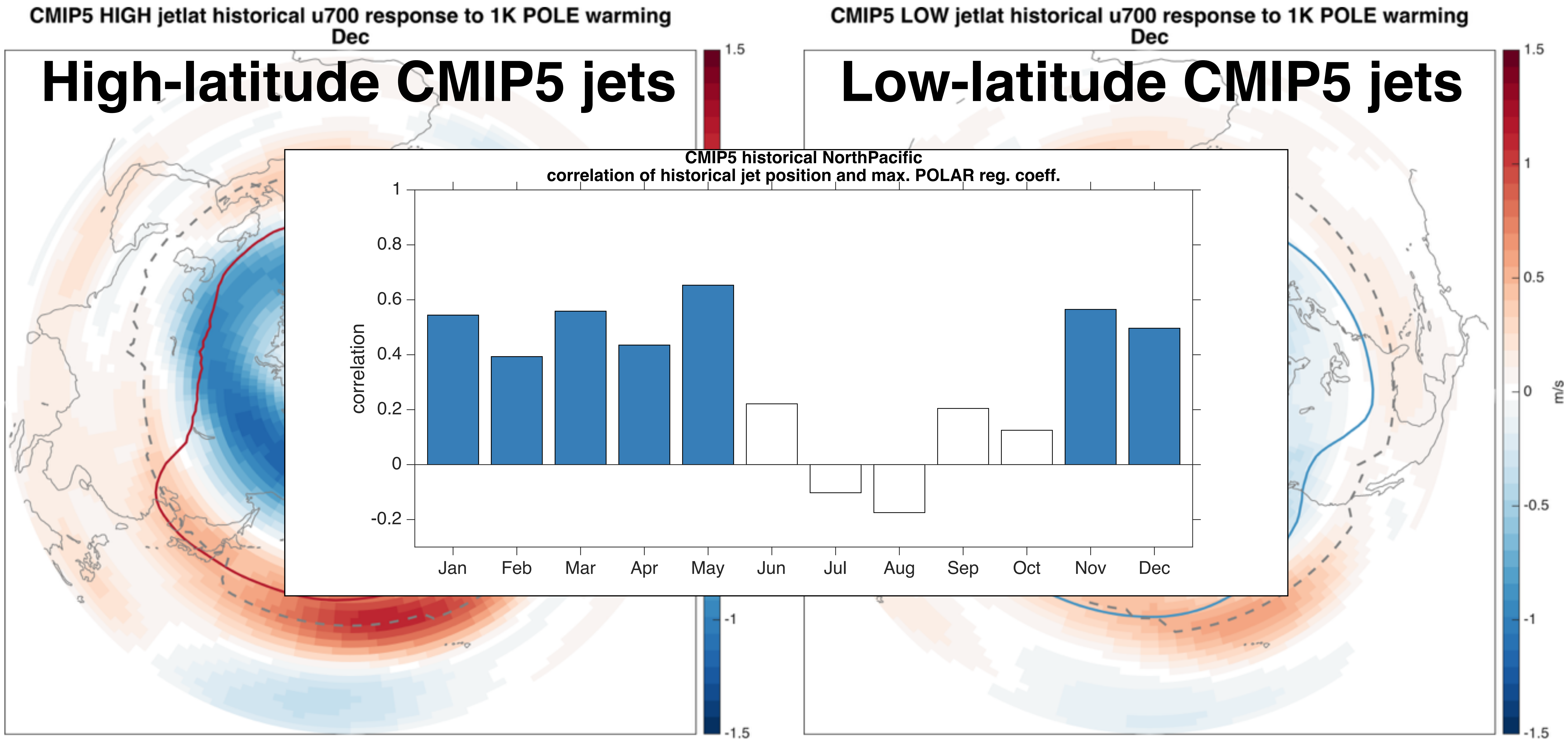


25% most equatorward CMIP5 jet-streams
25% most poleward CMIP5 jet-streams

latitude of maximum regression coefficient

We're still missing part of the story though…
eddy feedbacks are likely at play here.

Regression maps: full wind field perspective



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CMIP5: Improving climate change detection

Improving Climate Change Detection through Optimal Seasonal Averaging: The Case of the North Atlantic Jet and European Precipitation

GIUSEPPE ZAPPA, BRIAN J. HOSKINS, AND THEODORE G. SHEPHERD

Department of Meteorology, University of Reading, Reading, United Kingdom

(Manuscript received 4 December 2014, in final form 15 April 2015)

ABSTRACT

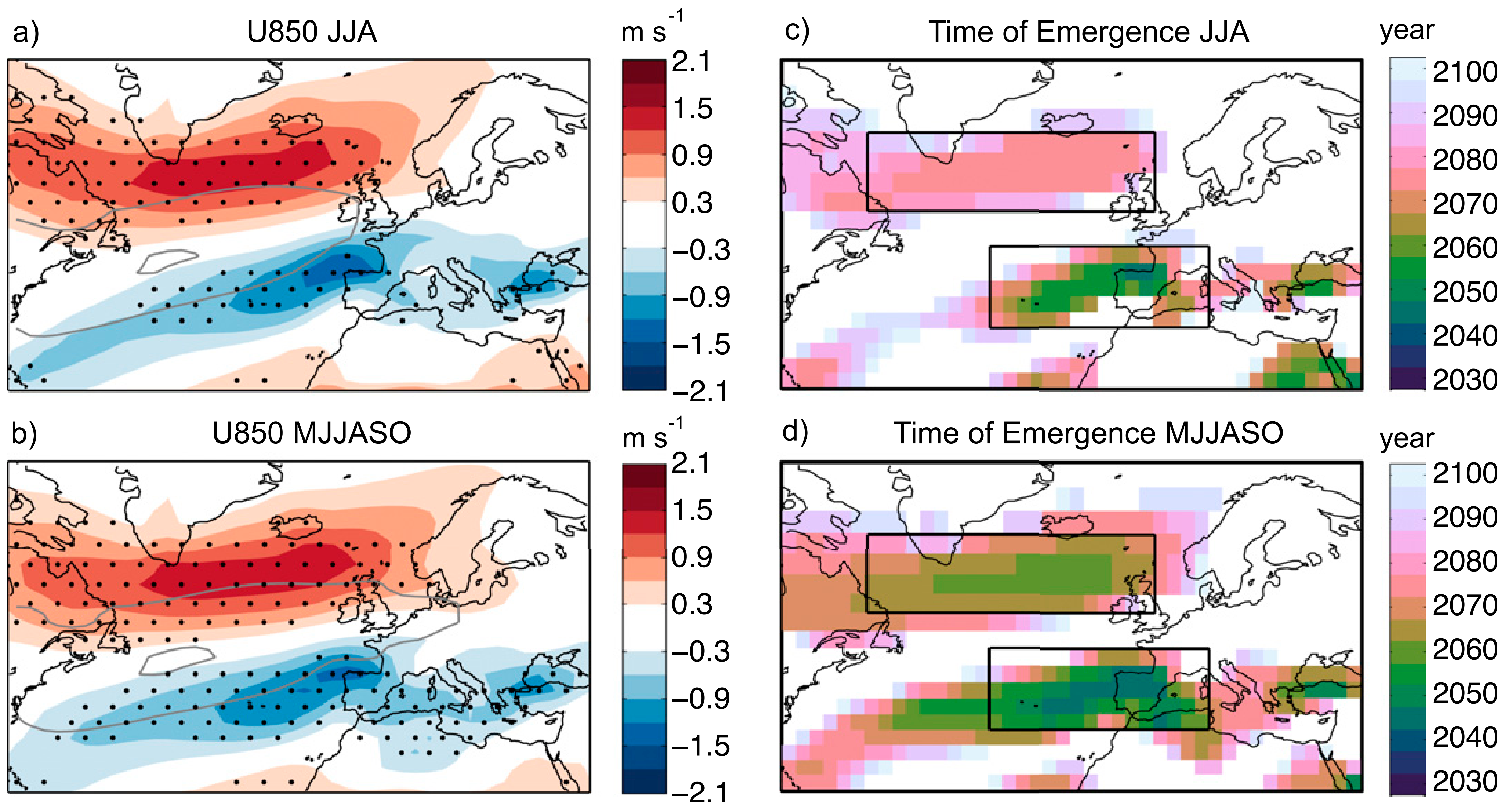
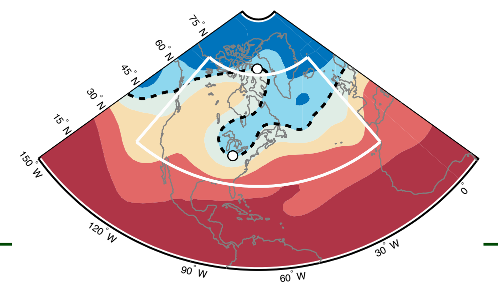
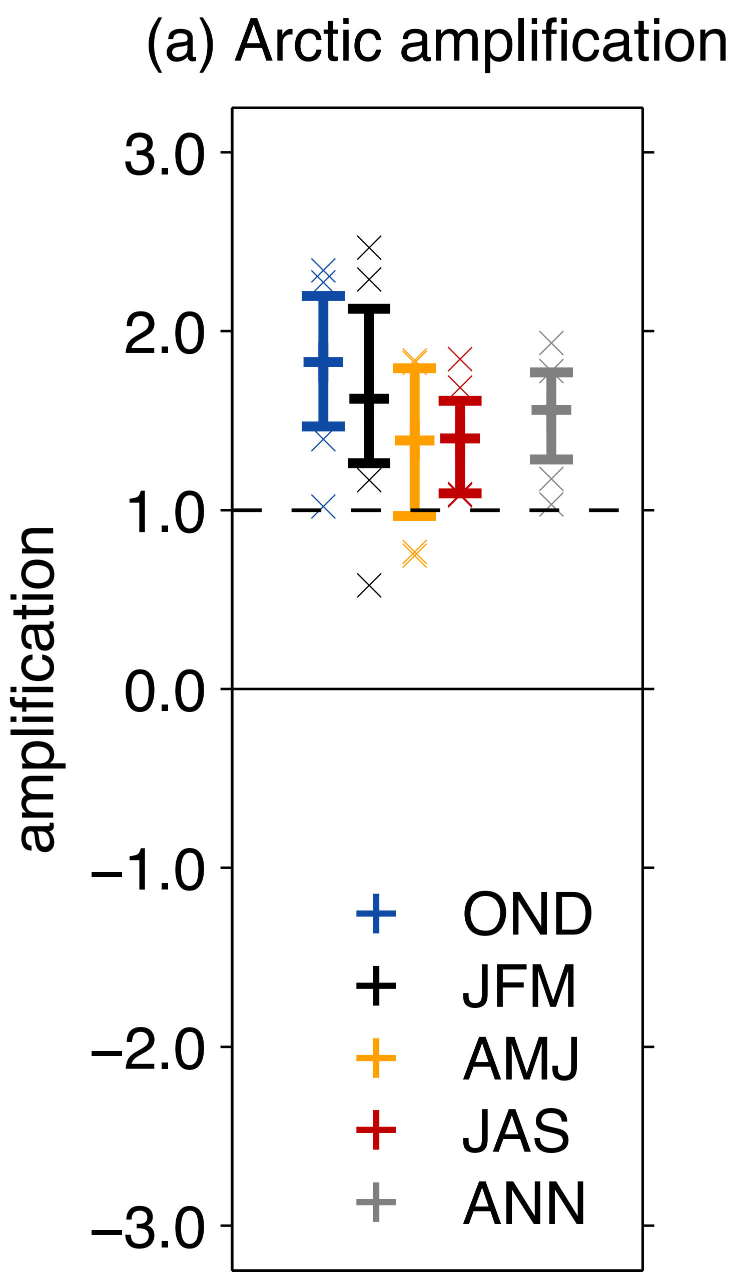


FIG. 2. Multimodel mean end-of-century U850 response separately computed for the (a) meteorological summer (JJA) and (b) extended summer (MJJASO) time averages. (c),(d) The time of emergence of the U850 response evaluated for the time periods in (a) and (b), respectively. In (a) and (b), stippling is applied where at least 90% of the models show a response of the same sign for the end-of-century climate change response, and the gray contours correspond to the 4 (outer) and 8 (inner) m s^{-1} isotachs of U850 in the historical period in the multimodel mean.

Zappa et al. 2015; JCLI

Near-term projections over N. Atlantic/N. America (2020-2044) - (1980-2004)





27 CMIP5 GCMs
Barnes & Polvani (2015; JCLI)

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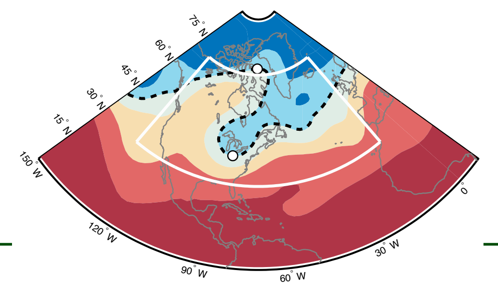

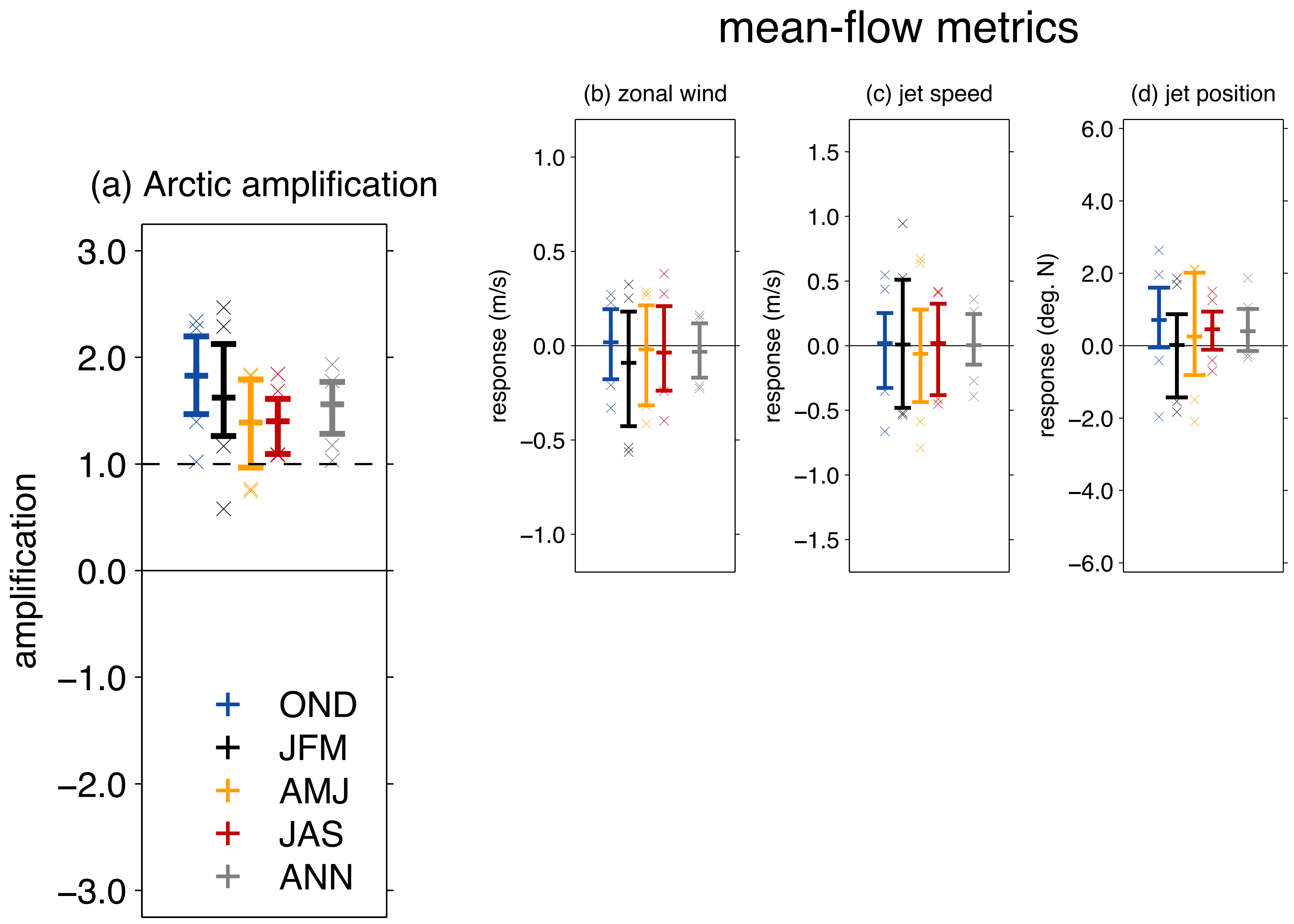

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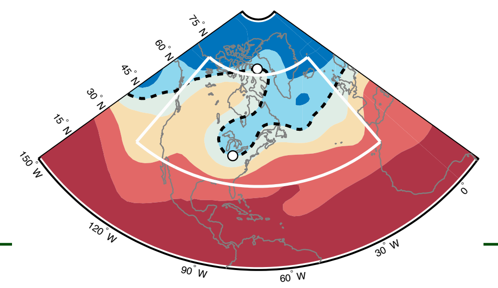

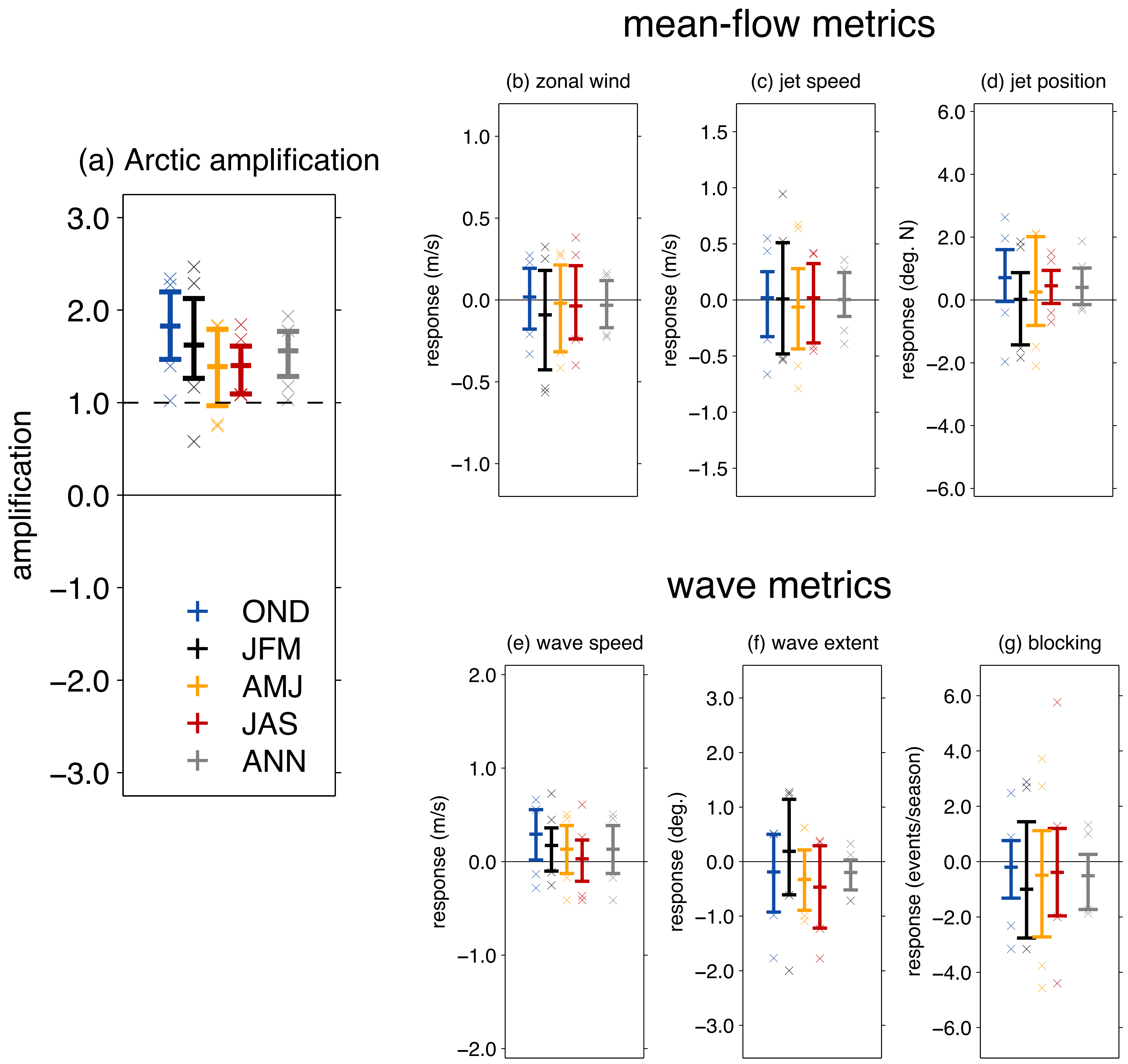

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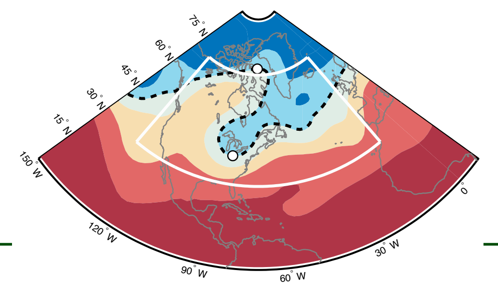

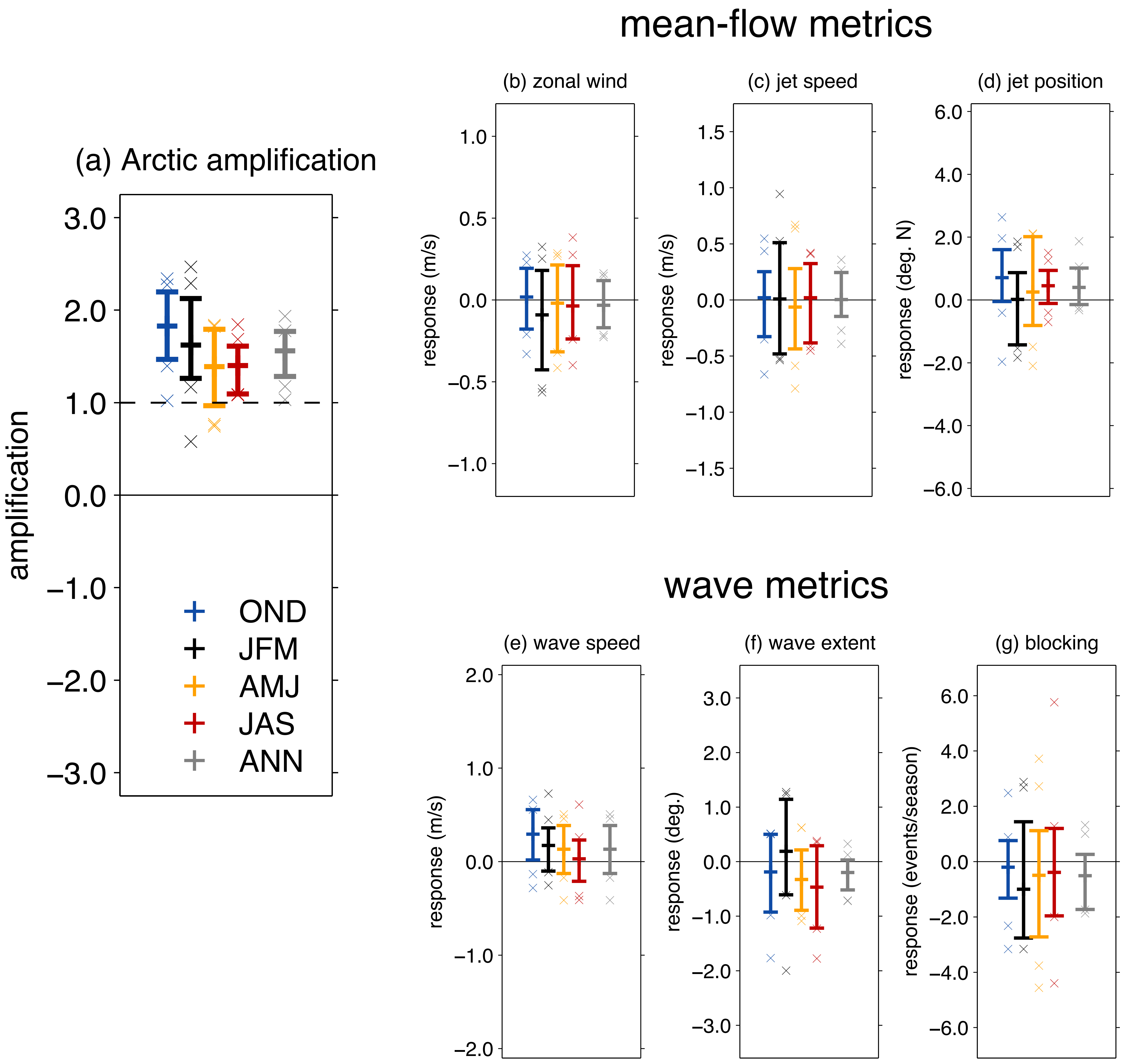

<u>No consensus</u> in the circulation response

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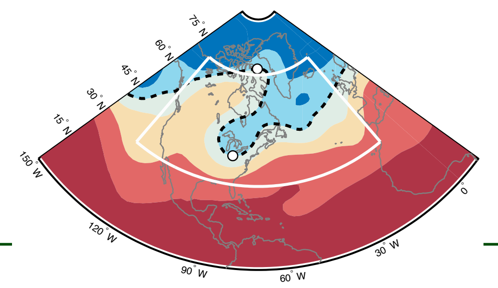

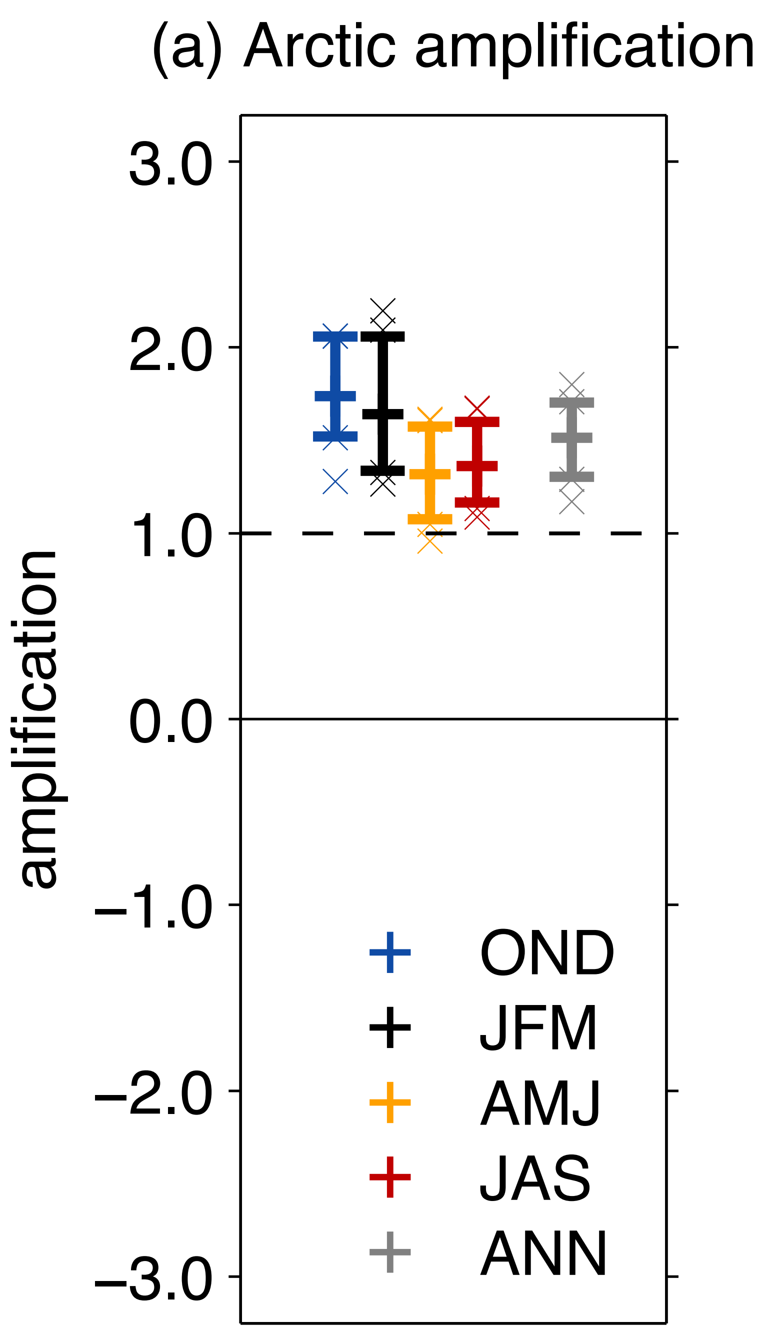

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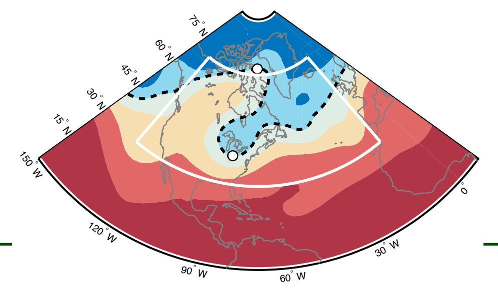

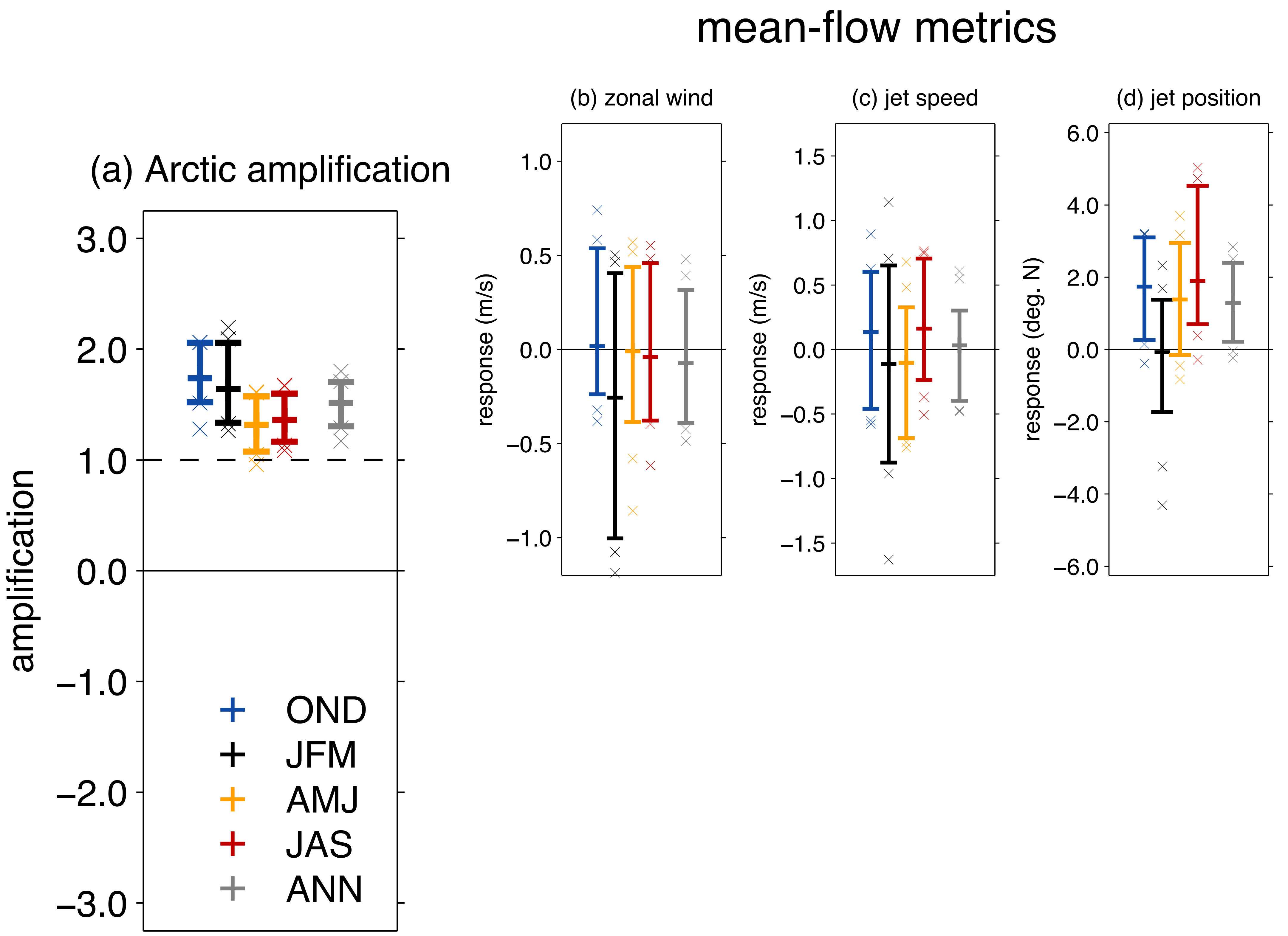

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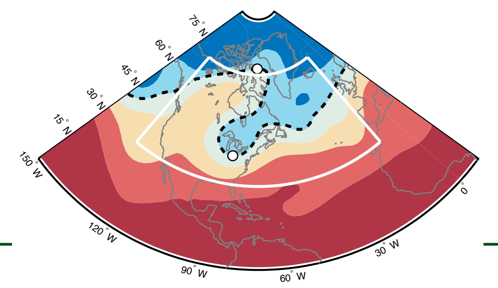

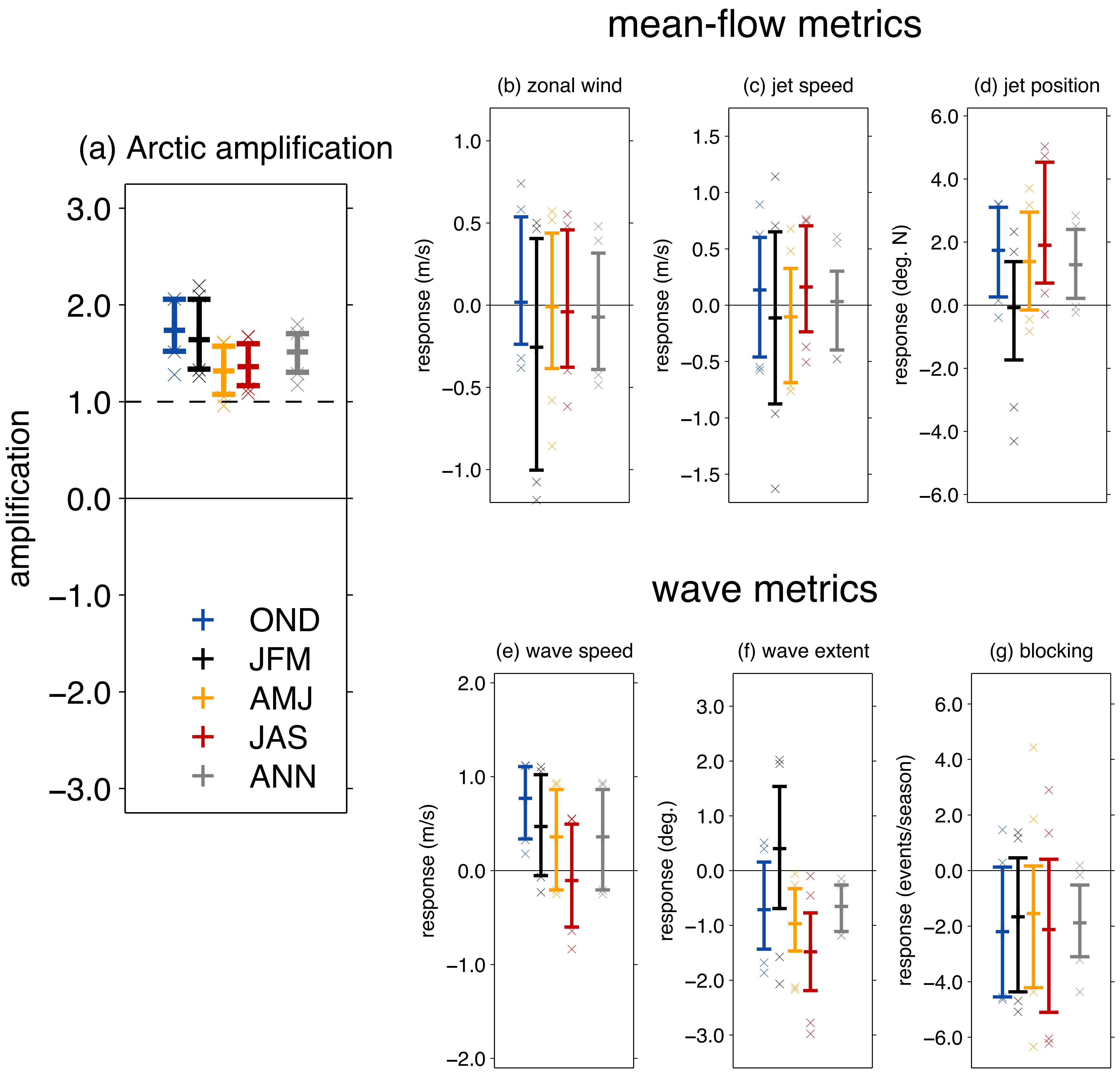

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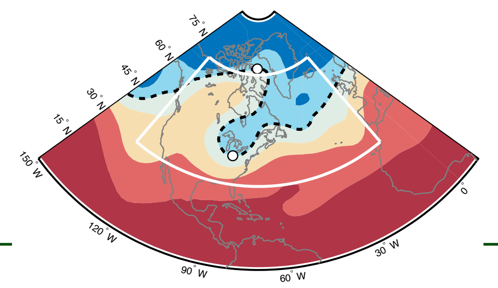

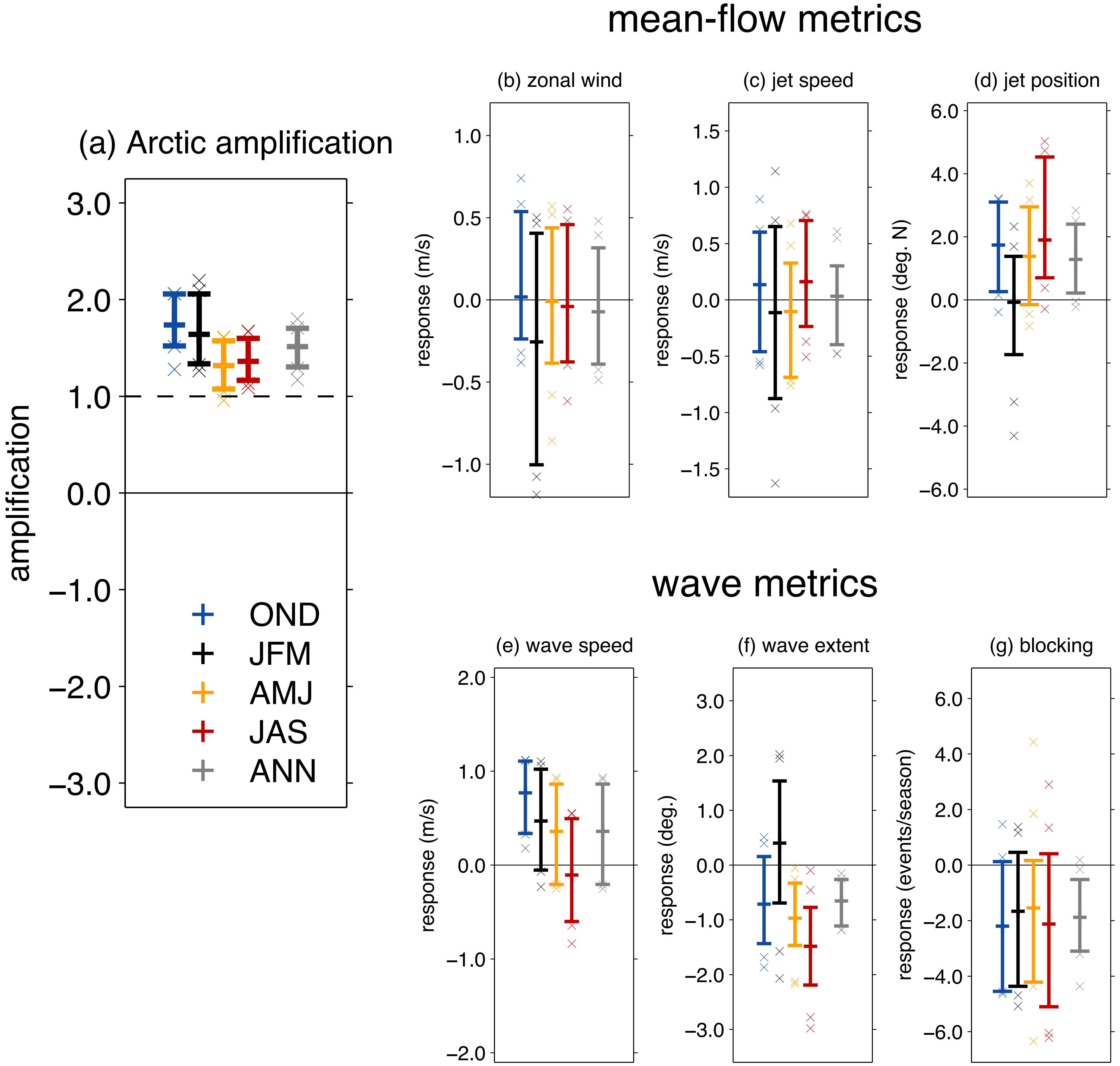

<u>No consensus</u> in the circulation response or response is of the <u>opposite sign</u> to that hypothesized

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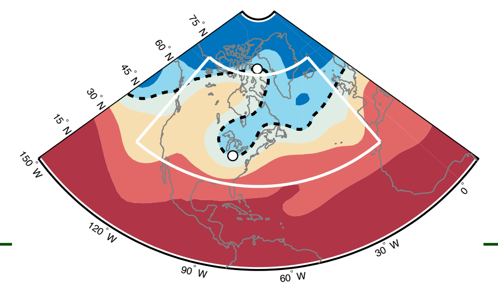
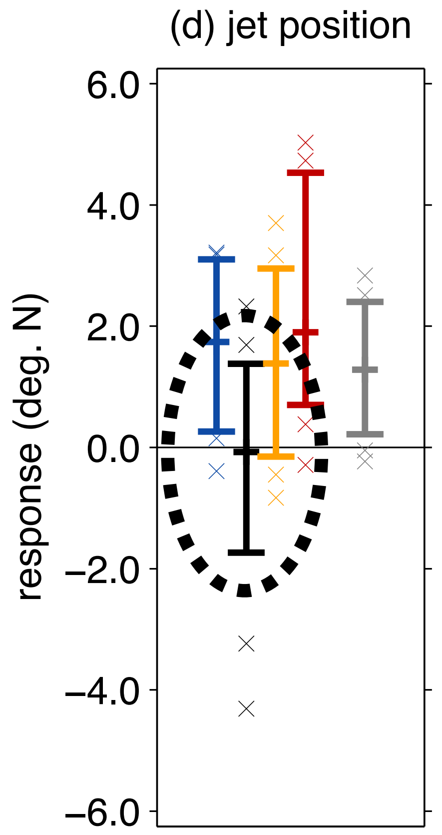


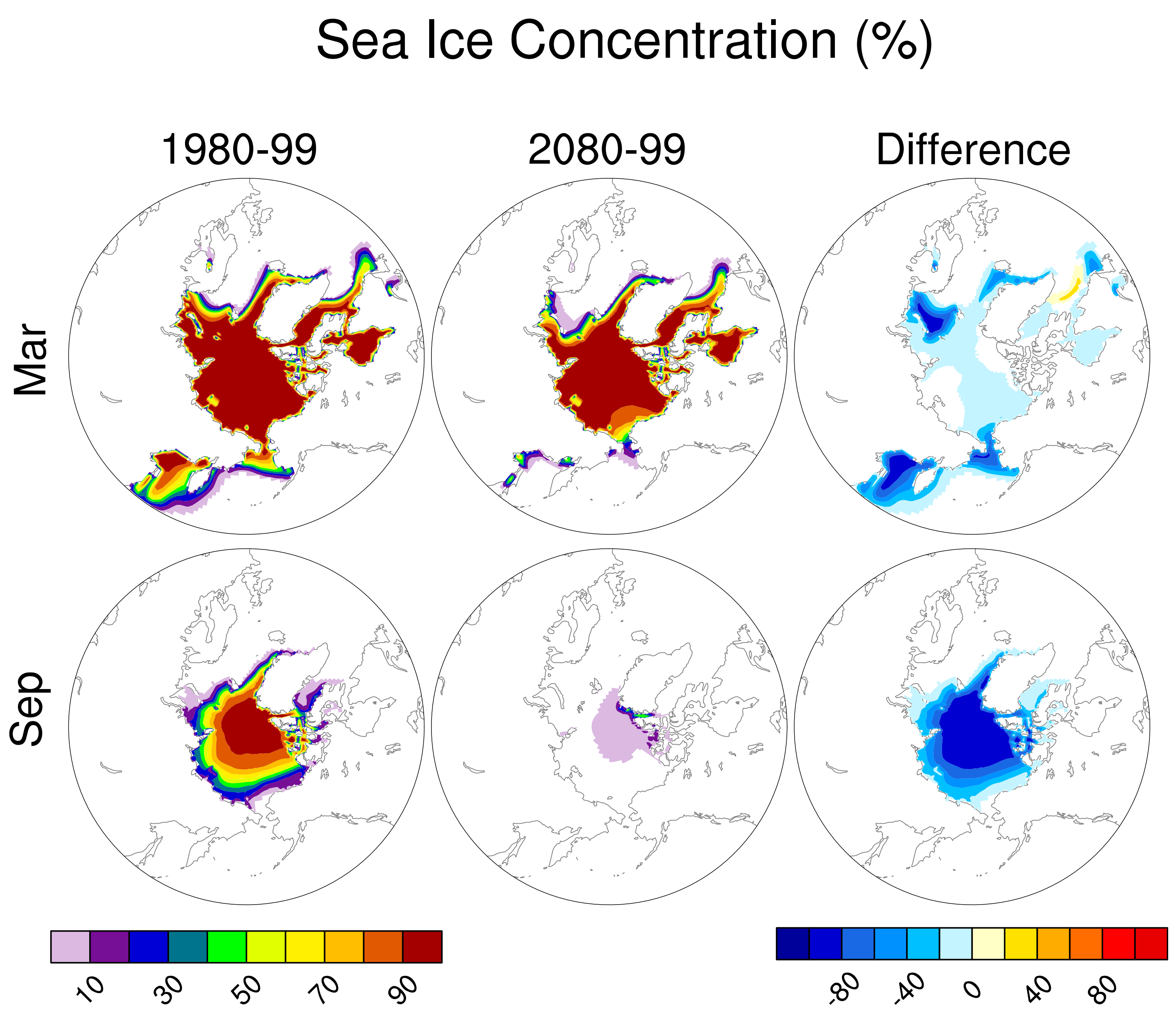
mean-flow metrics

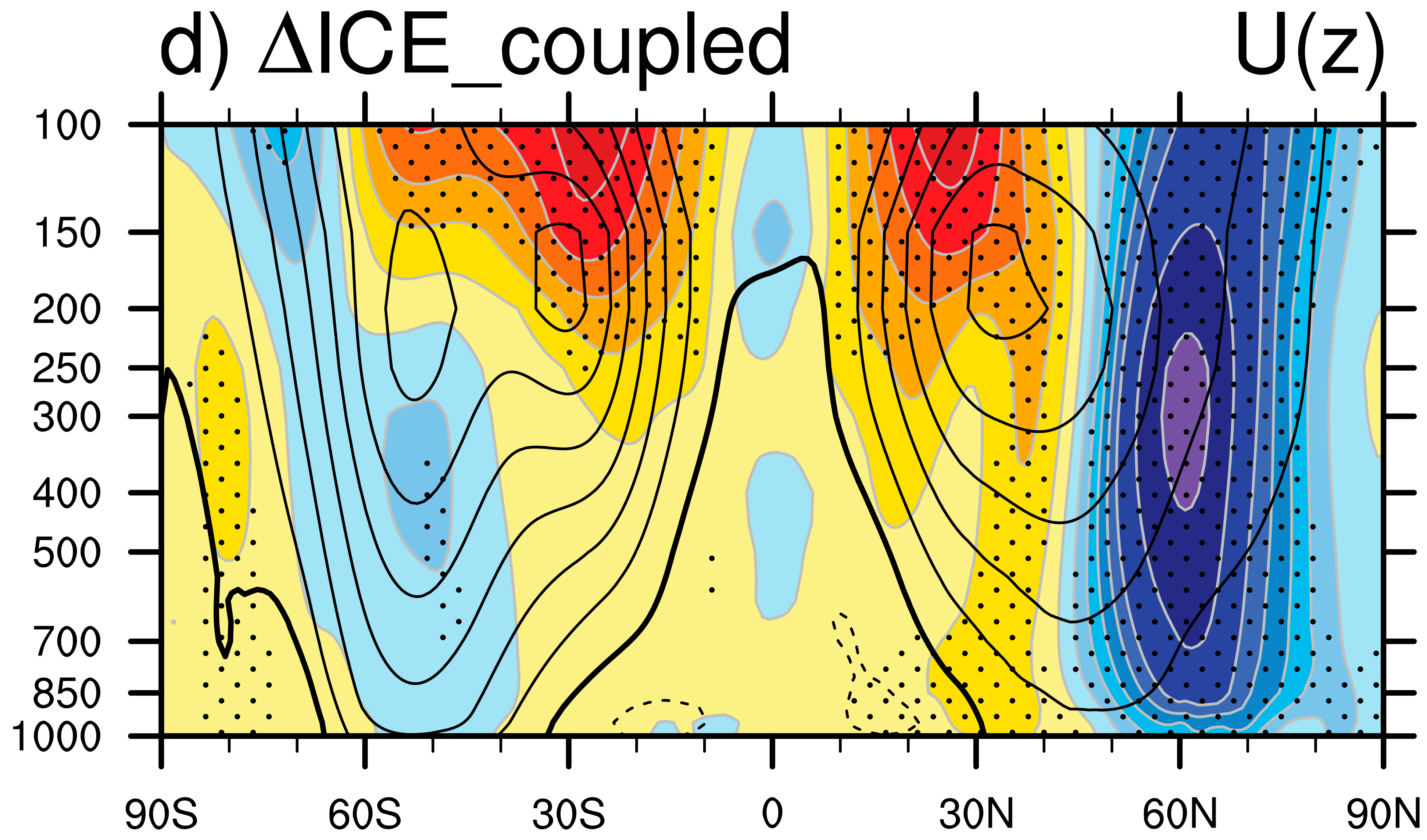


What is different about winter?

27 CMIP5 GCMs
Barnes & Polvani (2015; JCLI)

Can it? Modeling evidence



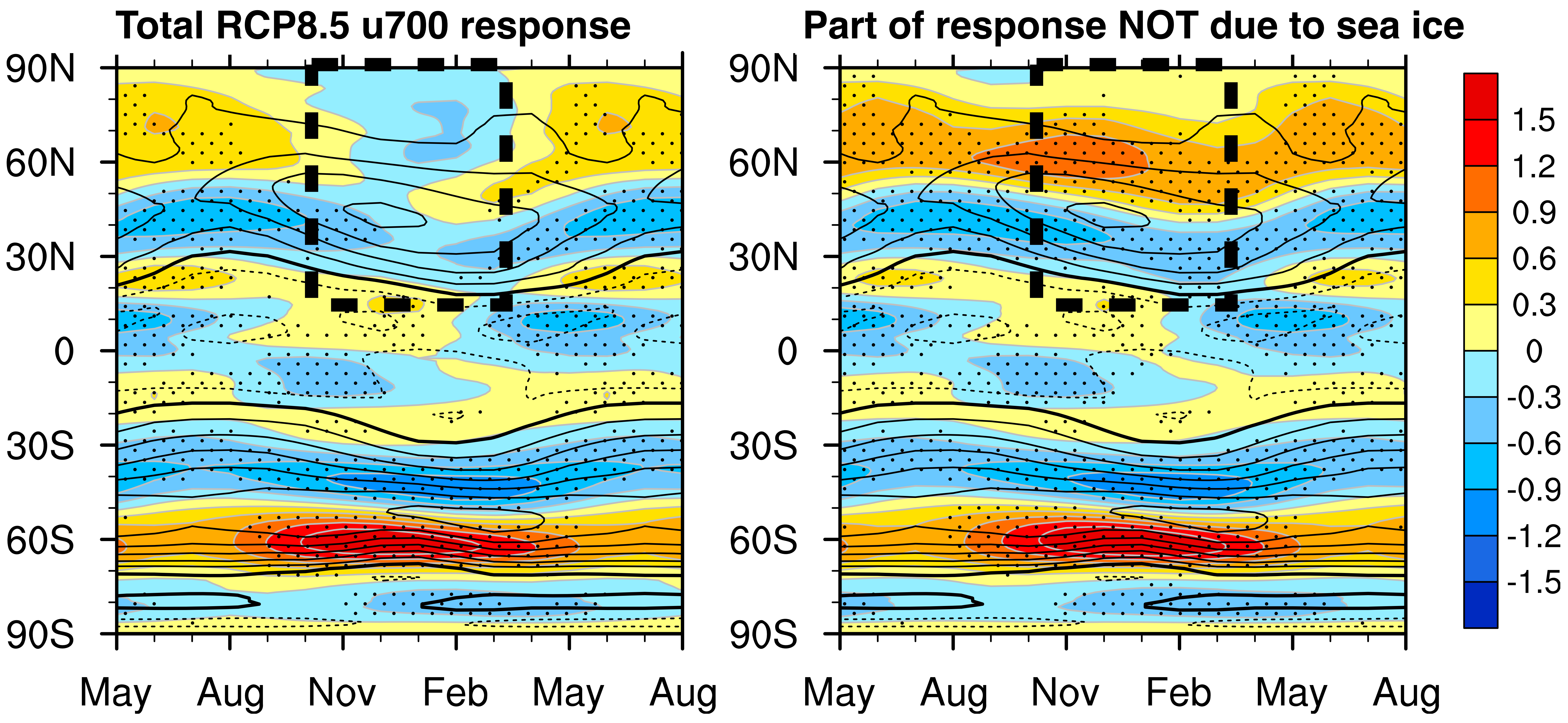


-NAO pattern
(equatorward jet shift)

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)

Tug-of-war



- In CCSM4, the sea ice loss effects appears to cancel the poleward shift of the jet

- In other CMIP5 models, the poleward shift "wins", and others the equatorward shift "wins"

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

Response to GHG independent of season in SH?

Delayed Southern Hemisphere Climate Change Induced by Stratospheric Ozone Recovery, as Projected by the CMIP5 Models

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Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York

NICHOLAS W. BARNES

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LORENZO M. POLVANI

Lamont-Doherty Earth Observatory, Columbia University, Palisades, and Department of Applied Physics and Applied Math, Columbia University, New York, New York

(Manuscript received 20 April 2013, in final form 5 August 2013)

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O3RCVR: (2040-2050) - (2000-2010)
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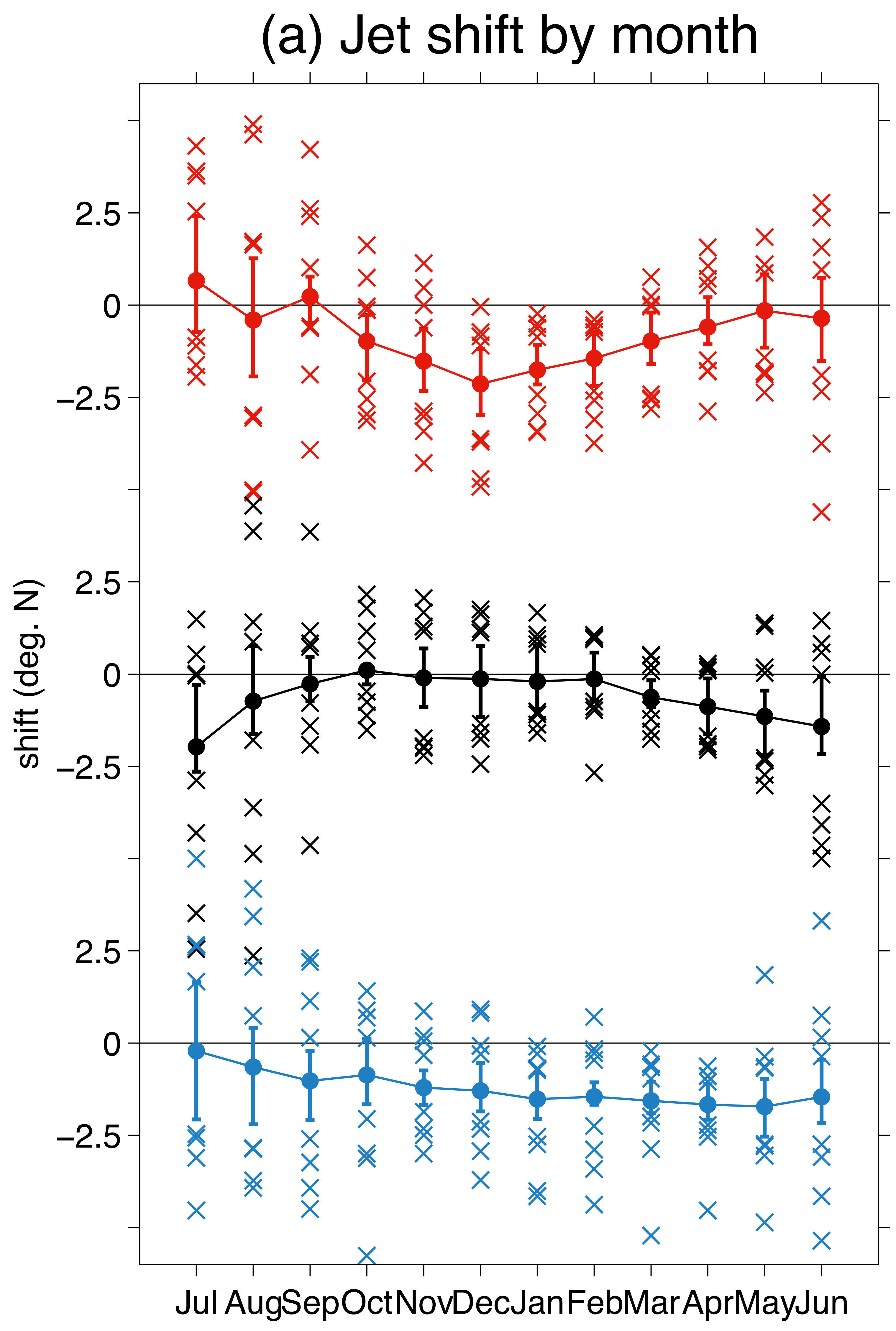

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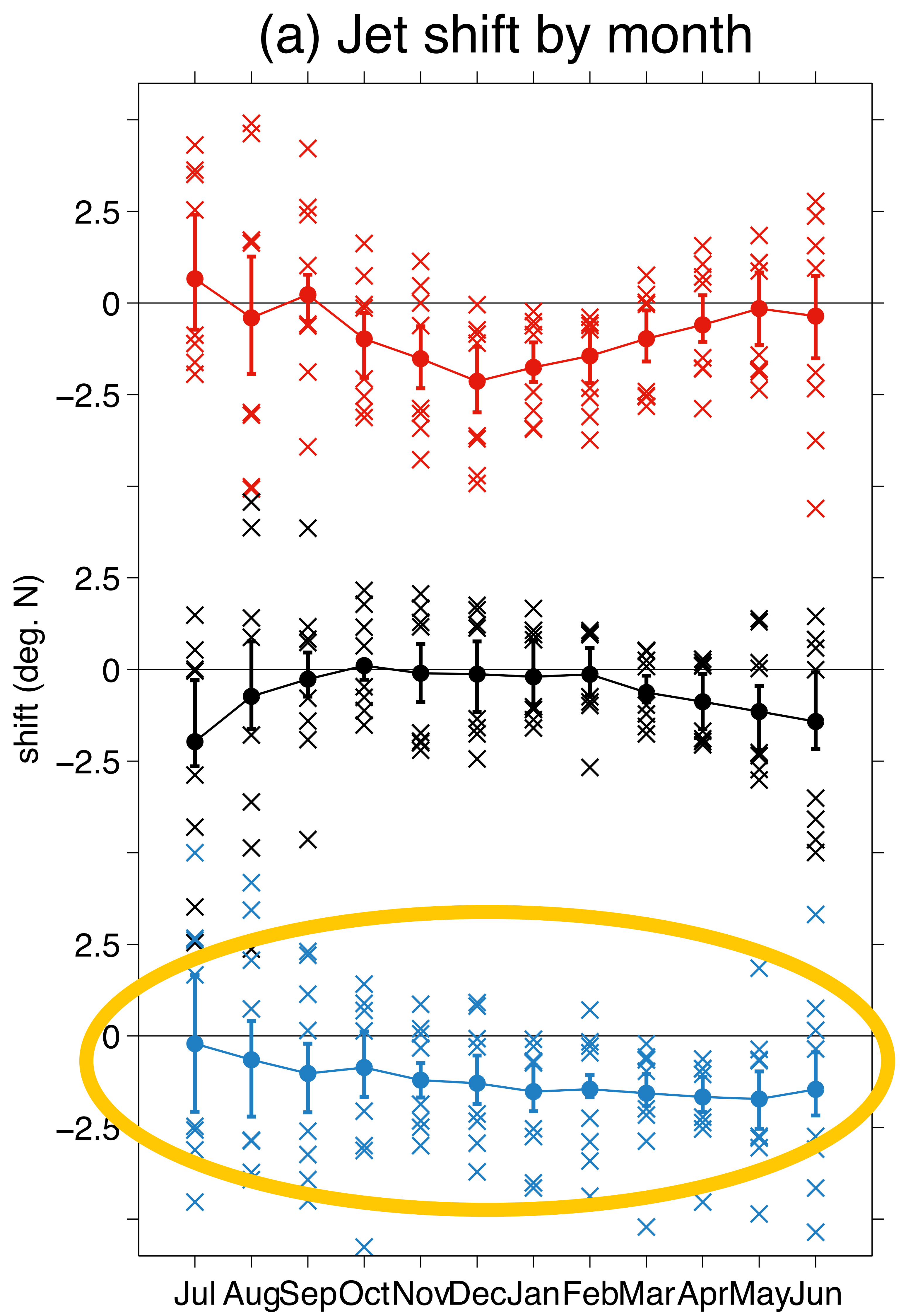
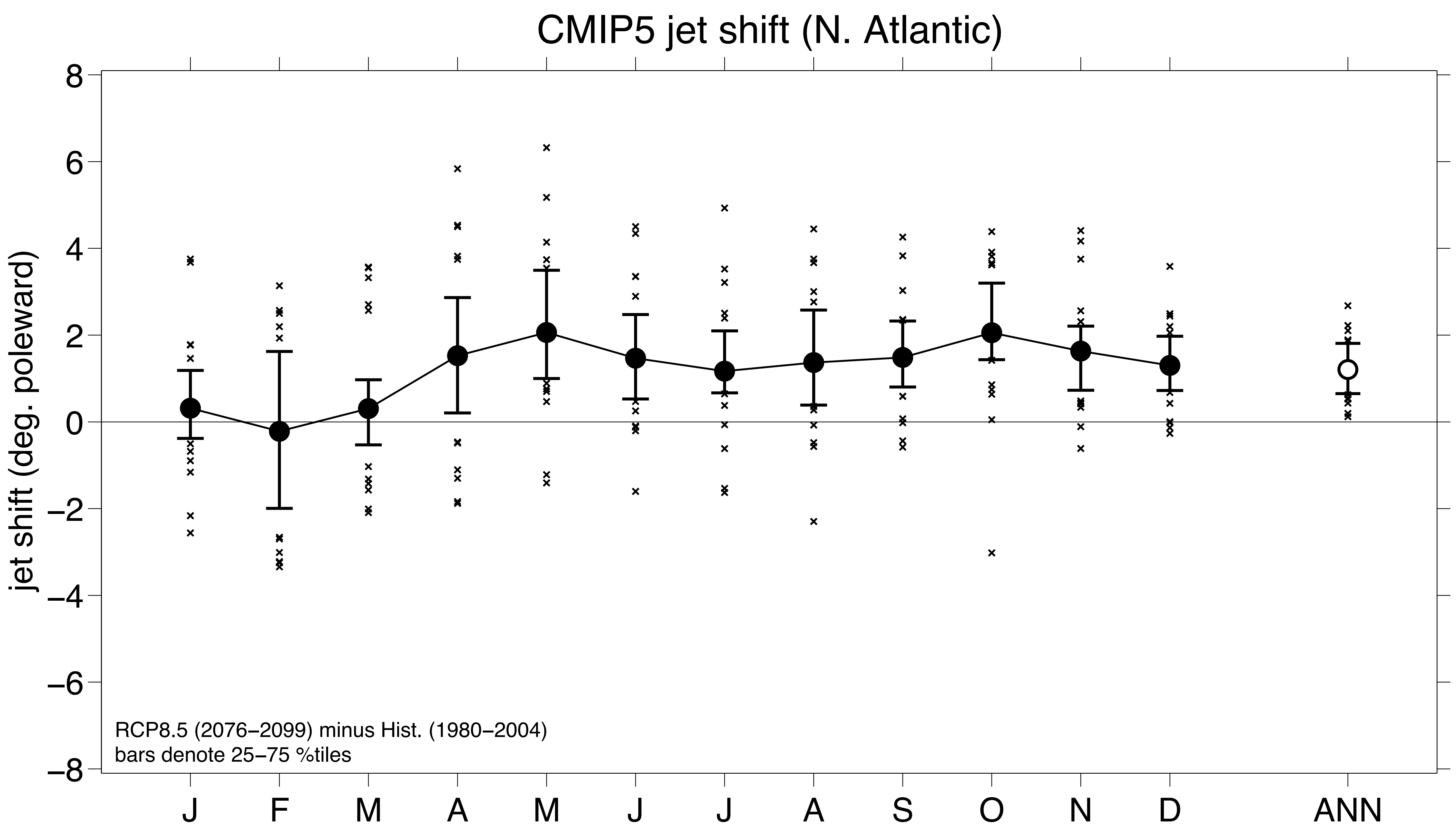


Shifts of the North Atlantic jet-stream by 2100



- jet-stream shifts poleward in most months of the year but not in winter
- interplay between high- and low latitude warming? *(see Held (1993; BAMS), Harvey, Shaffrey et al. (2013), Cattiaux & Cassou (2013))*

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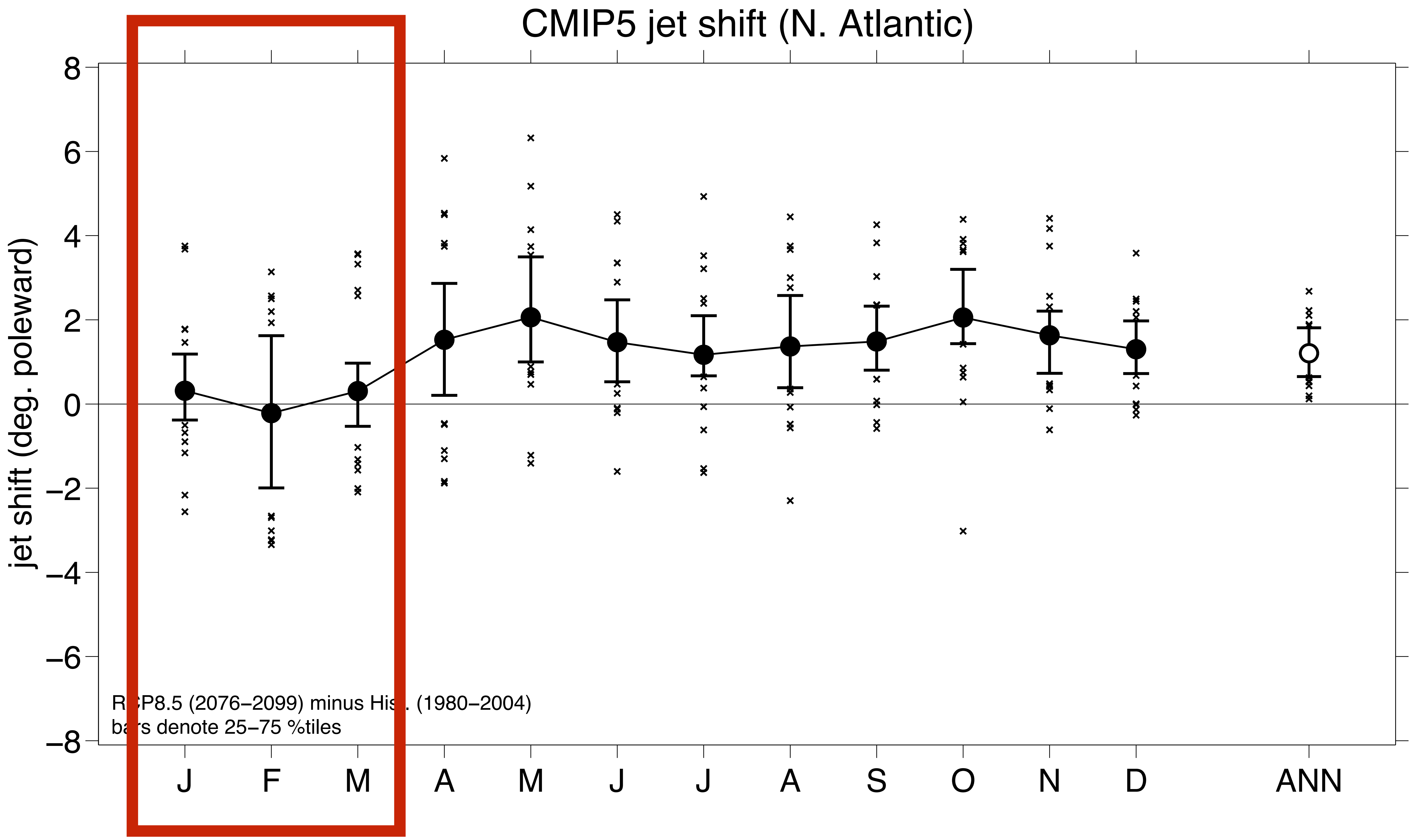

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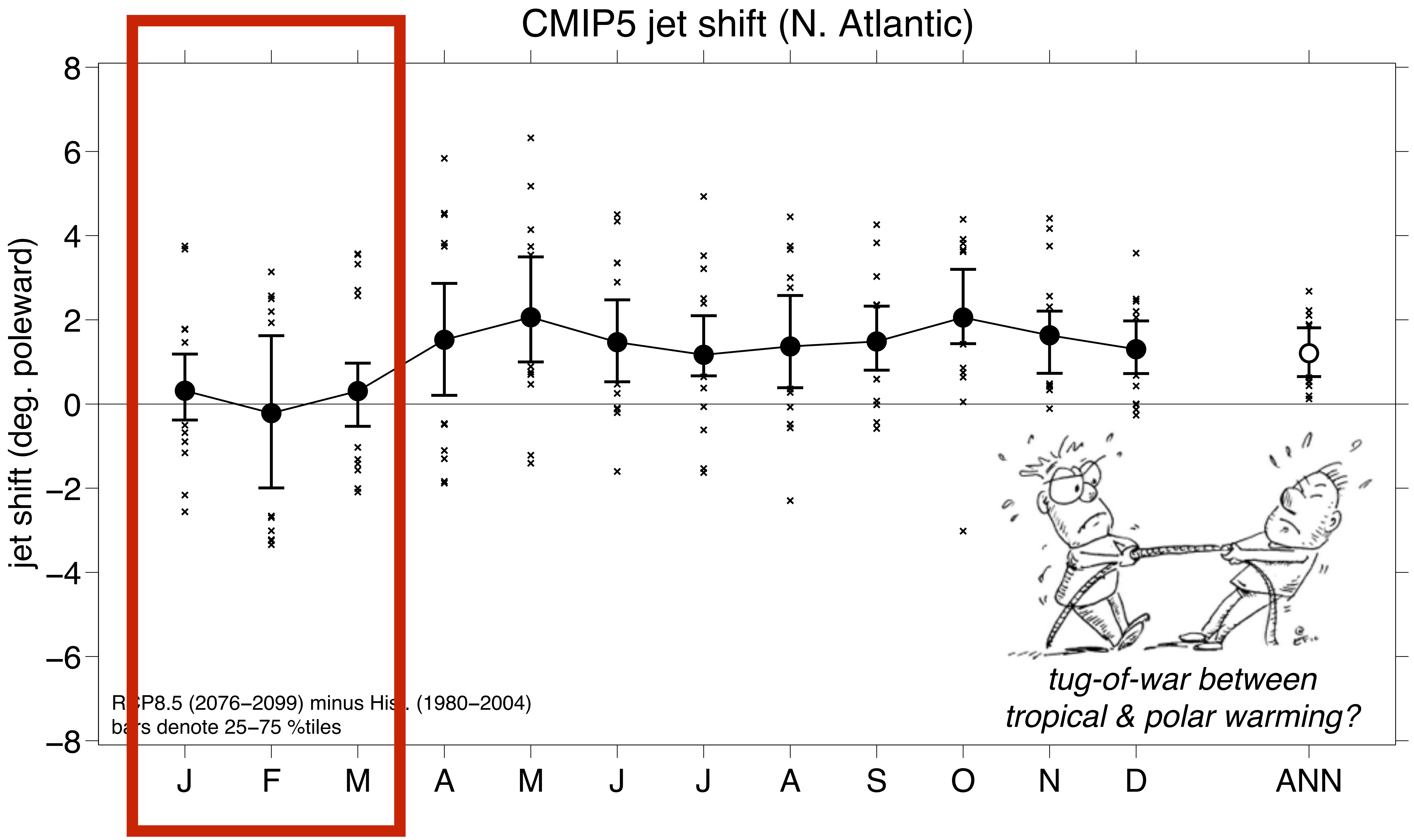

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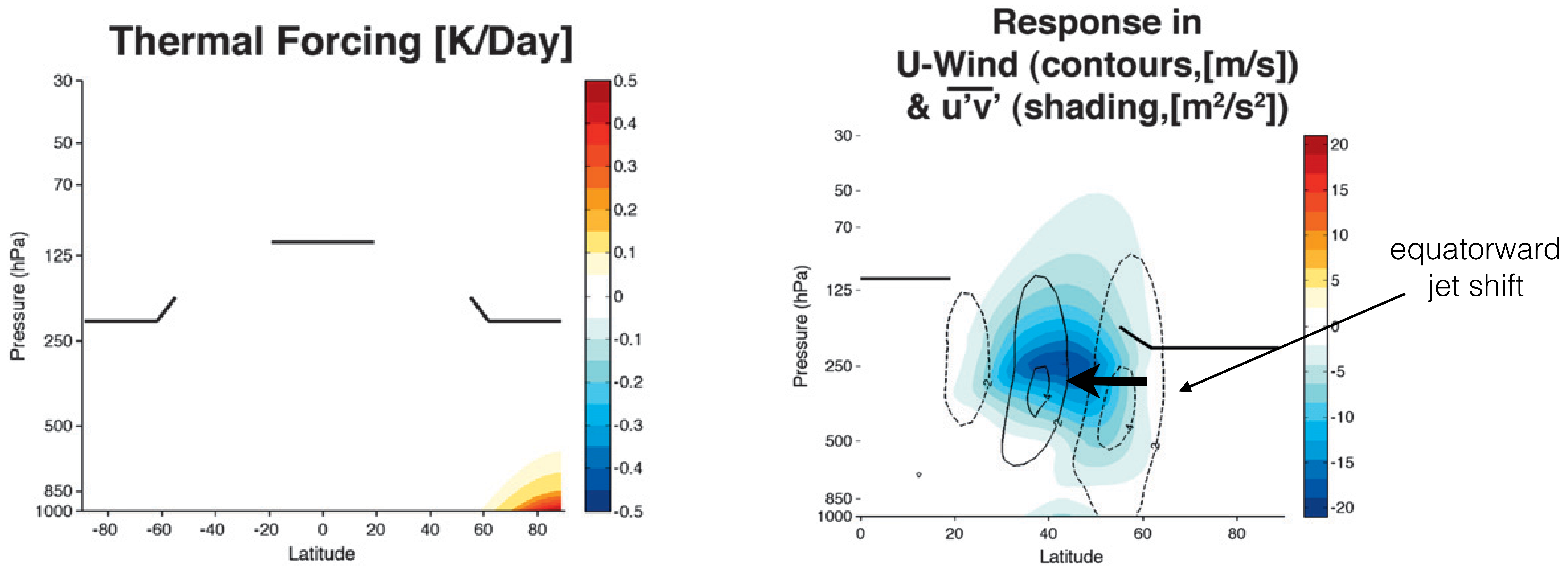
Modeling evidence



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

Title here

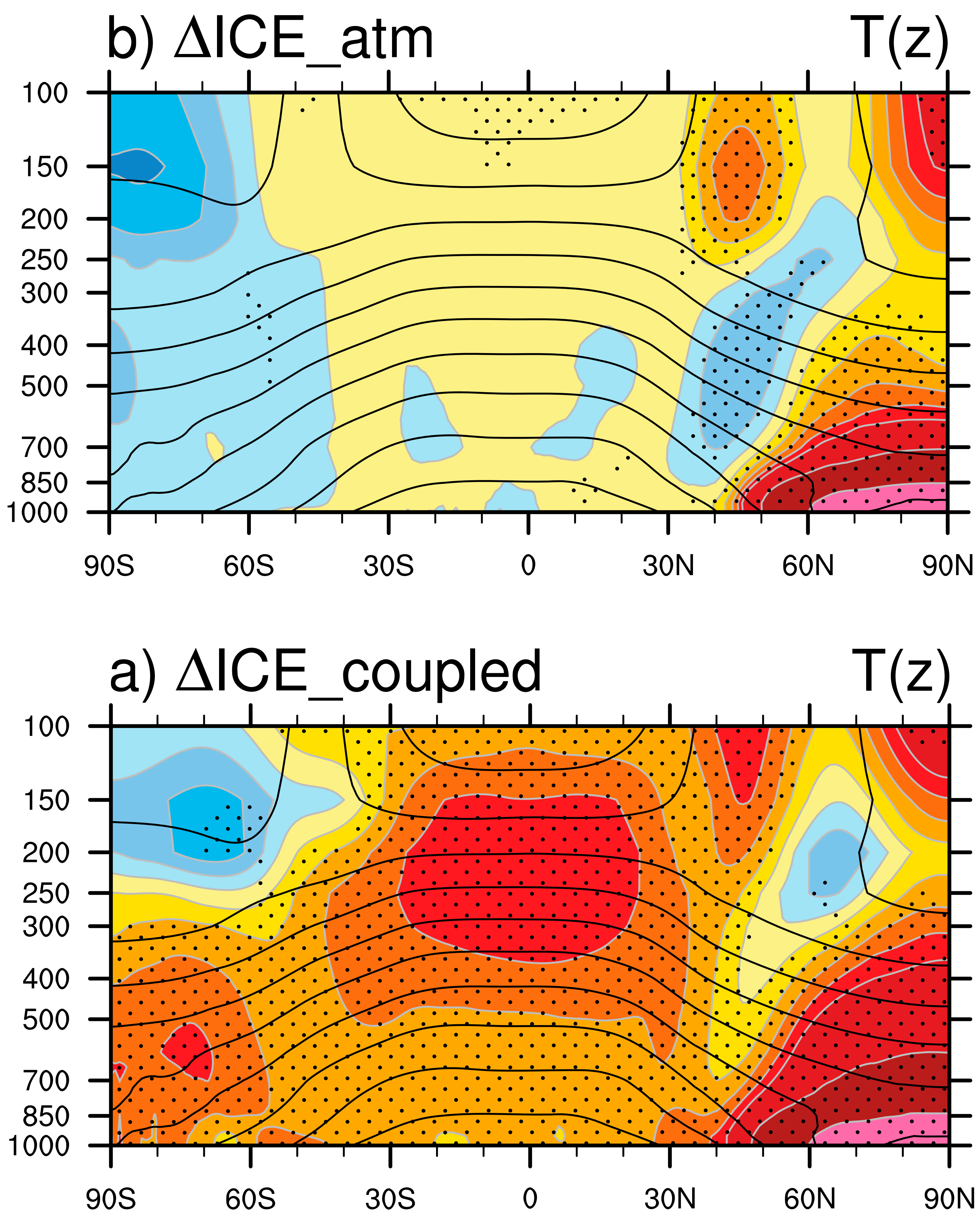
TABLE 1. Values of χ from equation 2 for every month.

Month	χ	Month	χ
JAN	+0.9659	JUL	-0.9659
FEB	+0.7071	AUG	-0.7071
MAR	+0.2588	SEPT	-0.2588
APR	-0.2588	OCT	+0.2588
MAY	-0.7071	NOV	+0.7071
JUN	-0.9659	DEC	+0.9659

$$T_{eq}^{trop}(p,\phi) = max\left[200\text{ K}, (T_0 - \delta T_{HS94})\left(\frac{p}{p_0}\right)^{\kappa}\right],$$

$$\delta T_{HS94} = (\Delta T)_y \sin\phi^2 + \varepsilon\chi\sin\phi + (\Delta T)_z \log\left(\frac{p}{p_0}\right)\cos\phi^2,$$

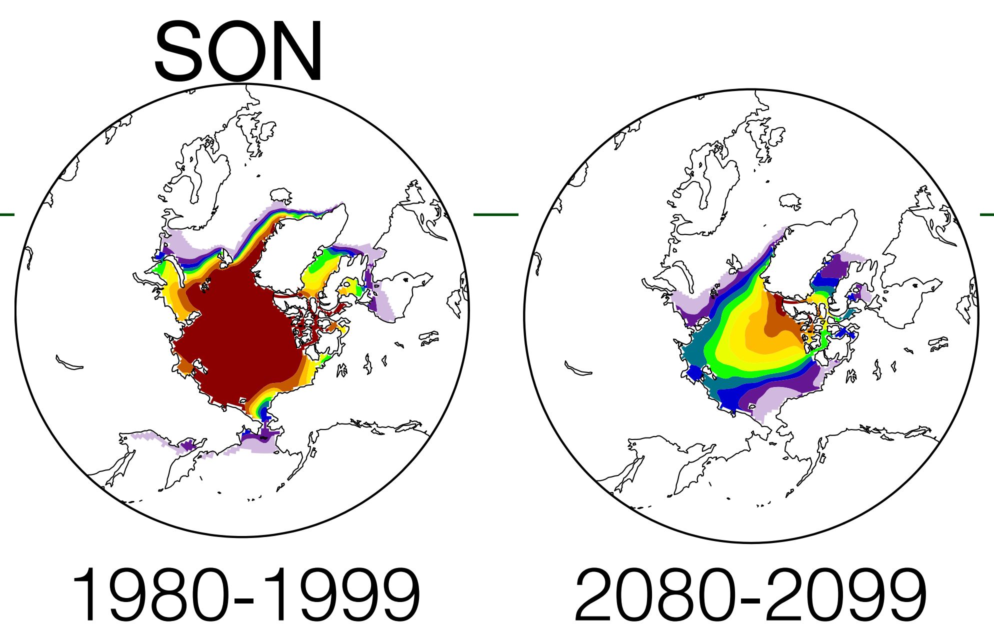
New results from Deser et al. (2015)



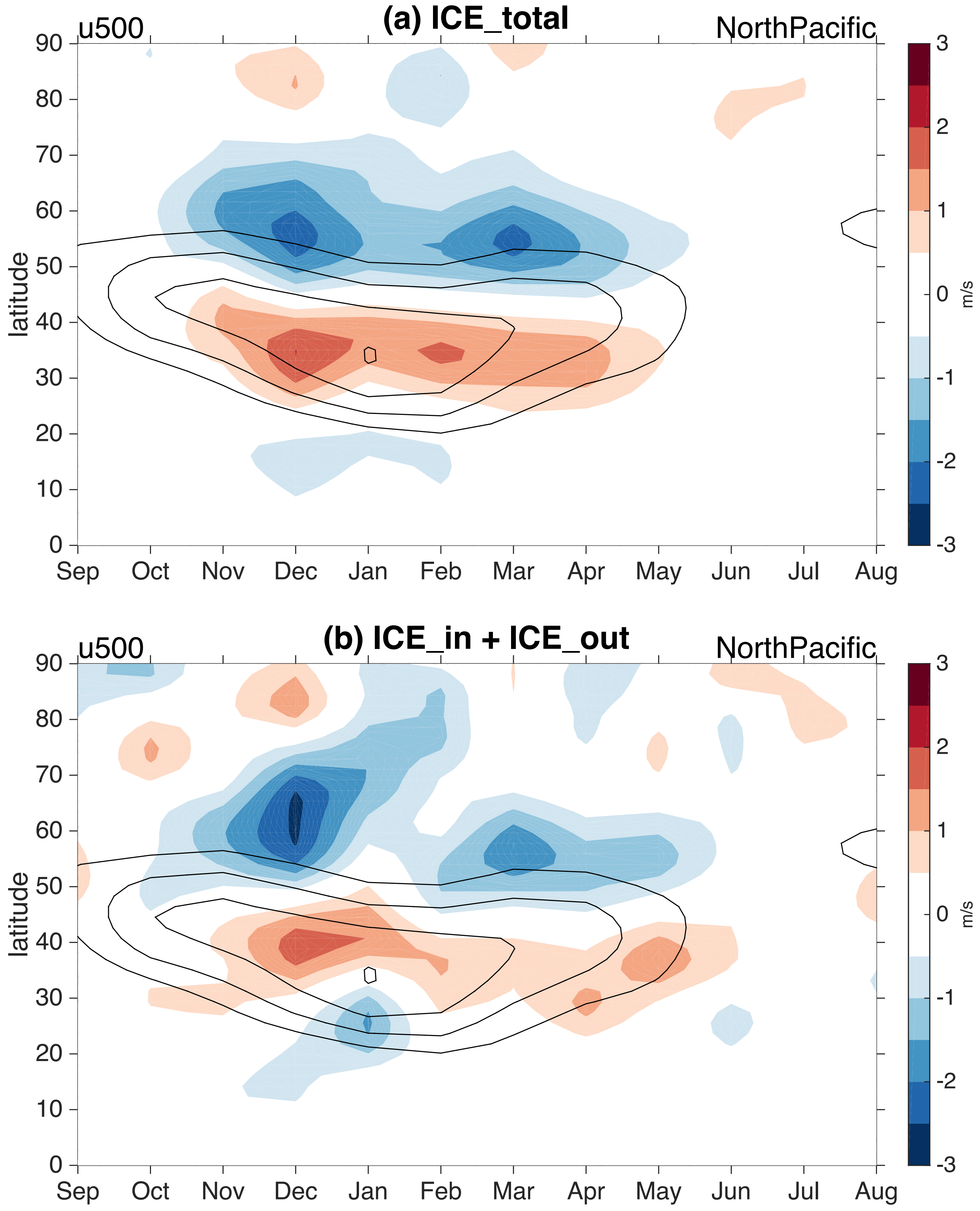
AMIP simulations may underestimate sea ice-induced warming compared to coupled simulations

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

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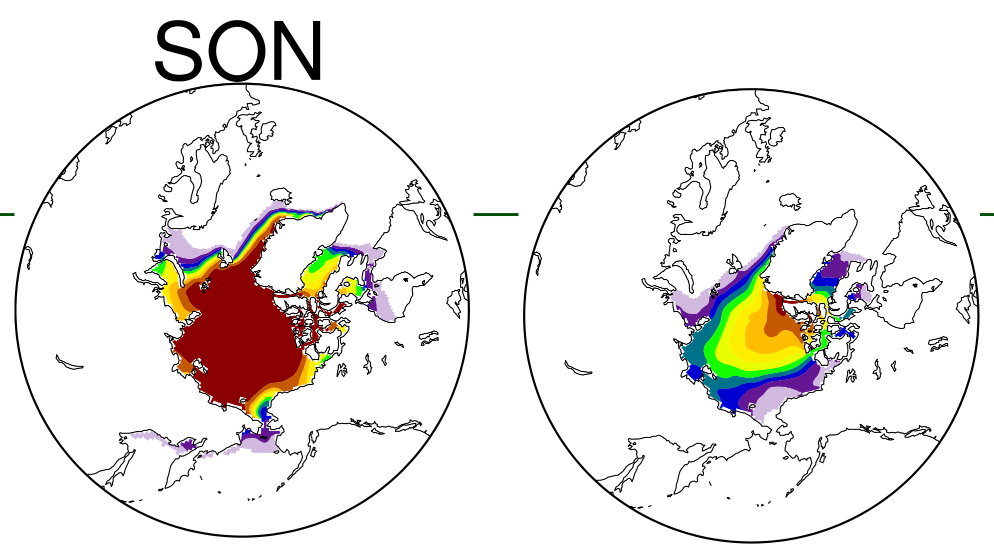

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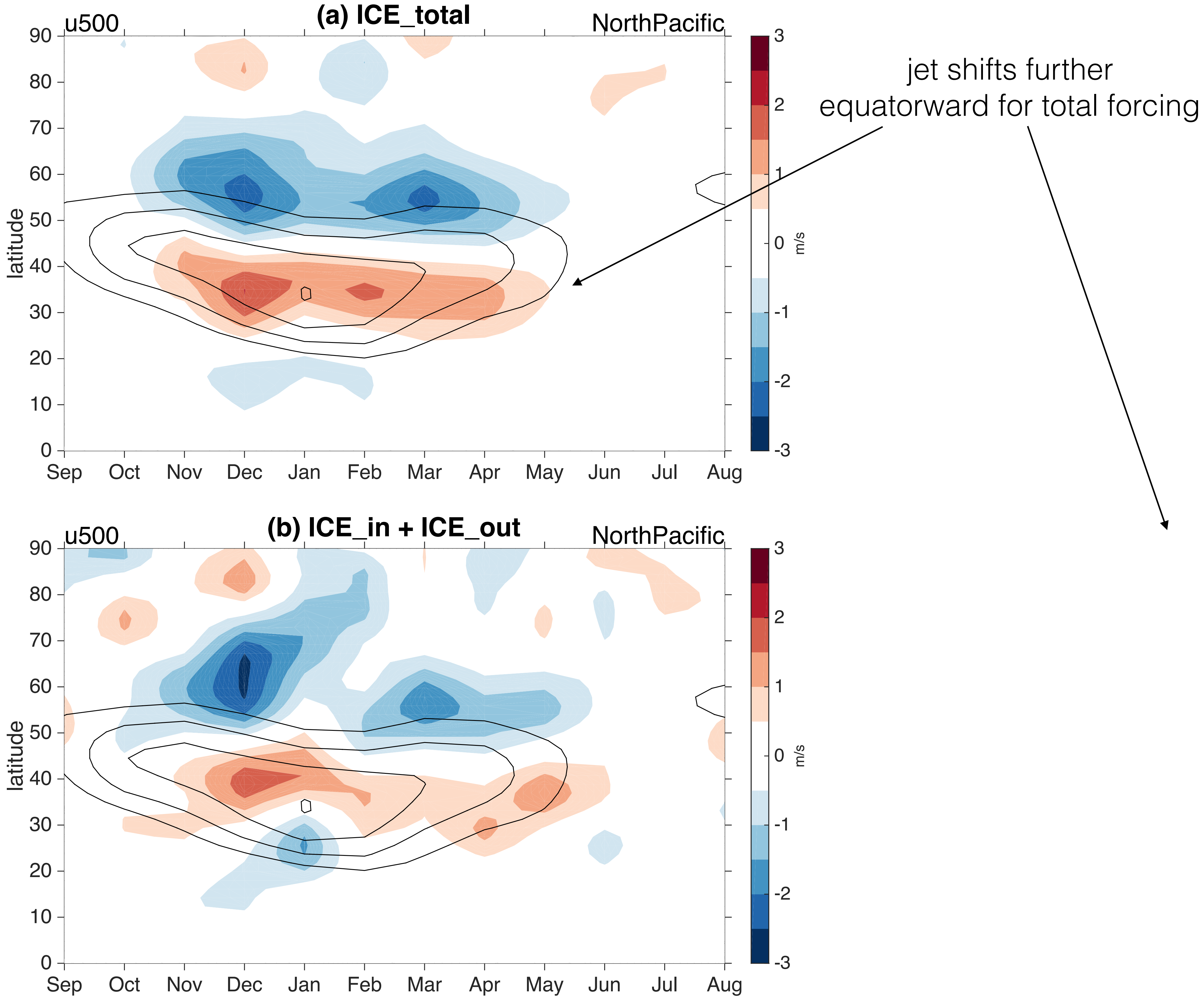

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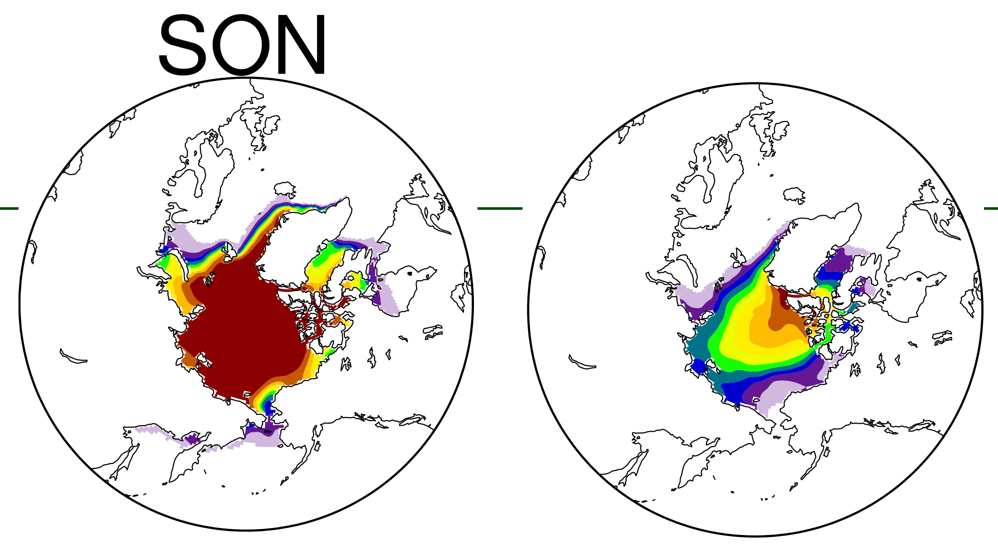

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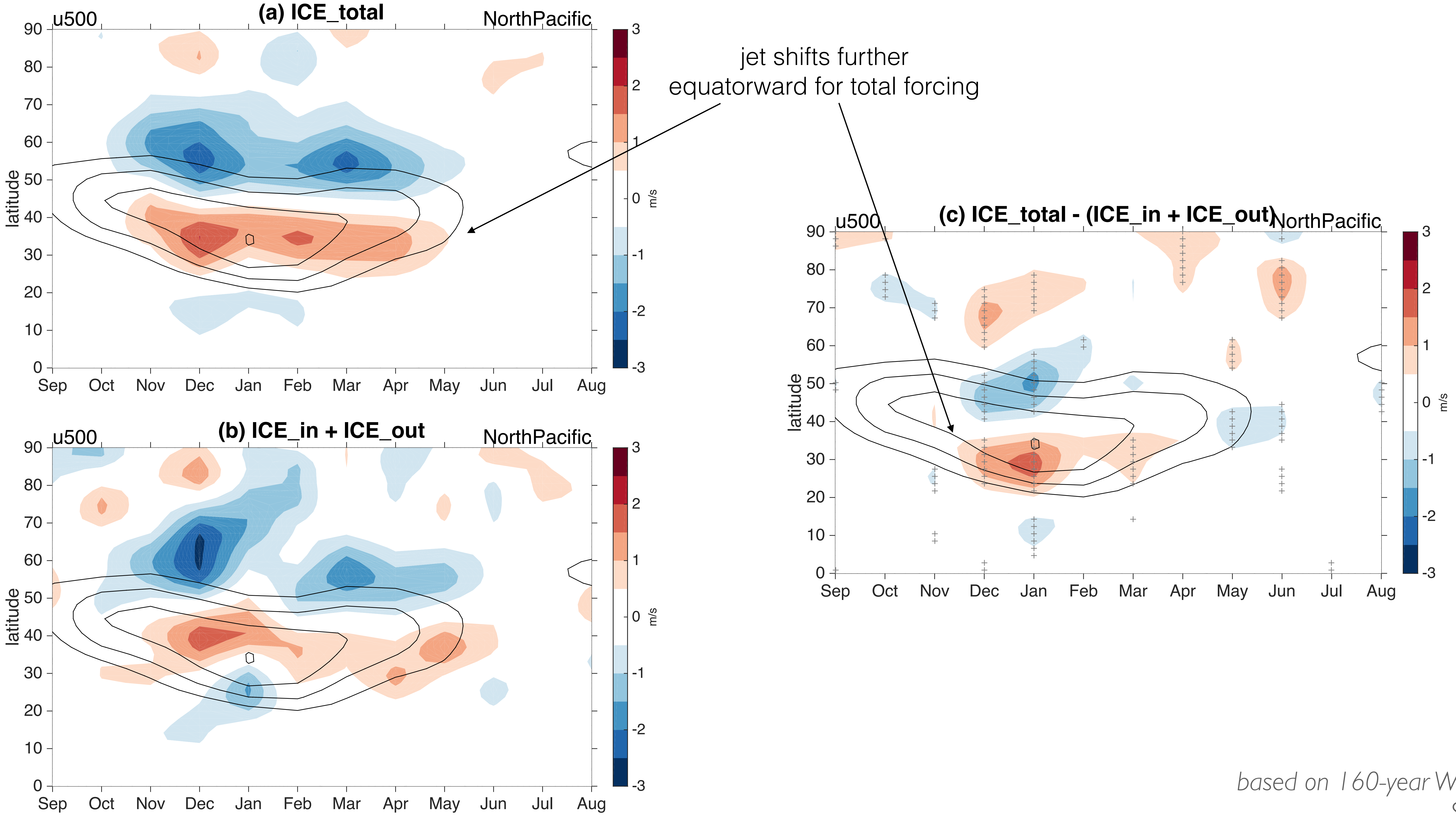

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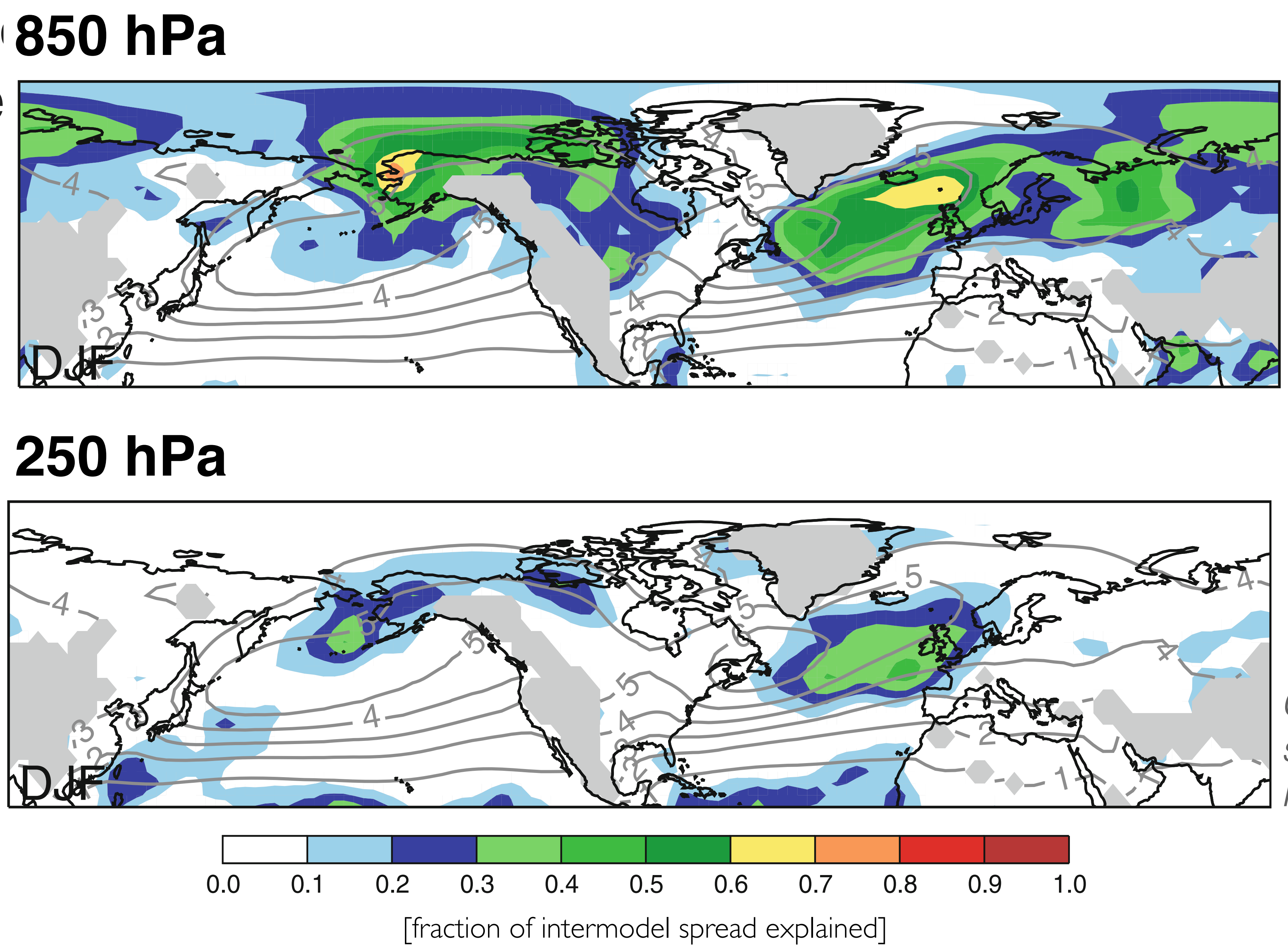
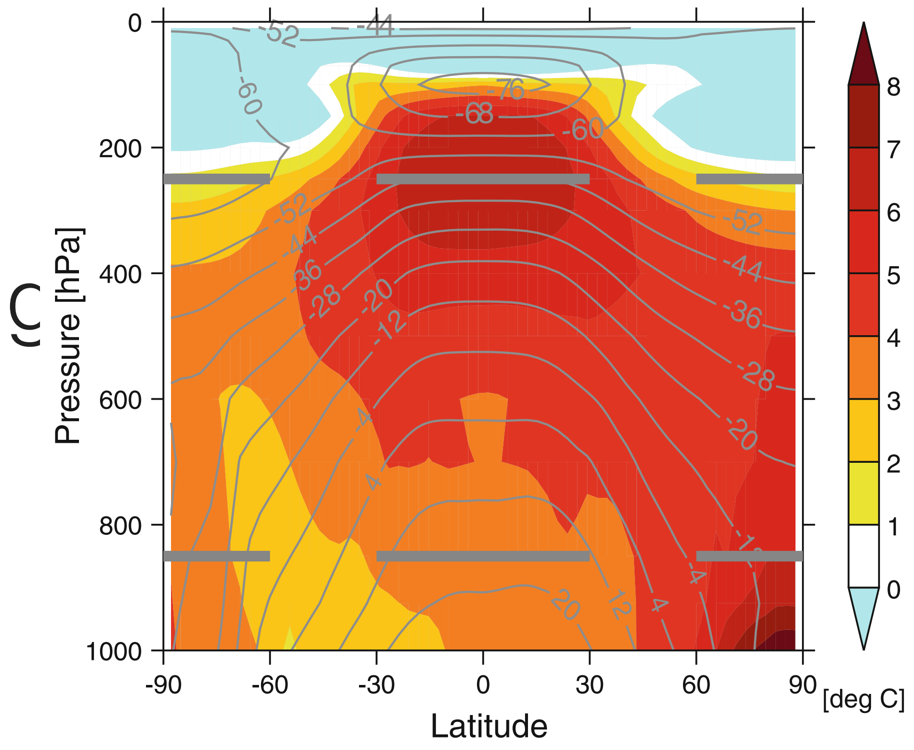
Will it modulate?

- In the N. Atlantic, 850hPa gradient explains over 50% of variance
- Northern Hemisph… Pa and 250hPa chang… l storm track responses in winte…

Variance explained of storm track response by N. Atlantic temperature gradients



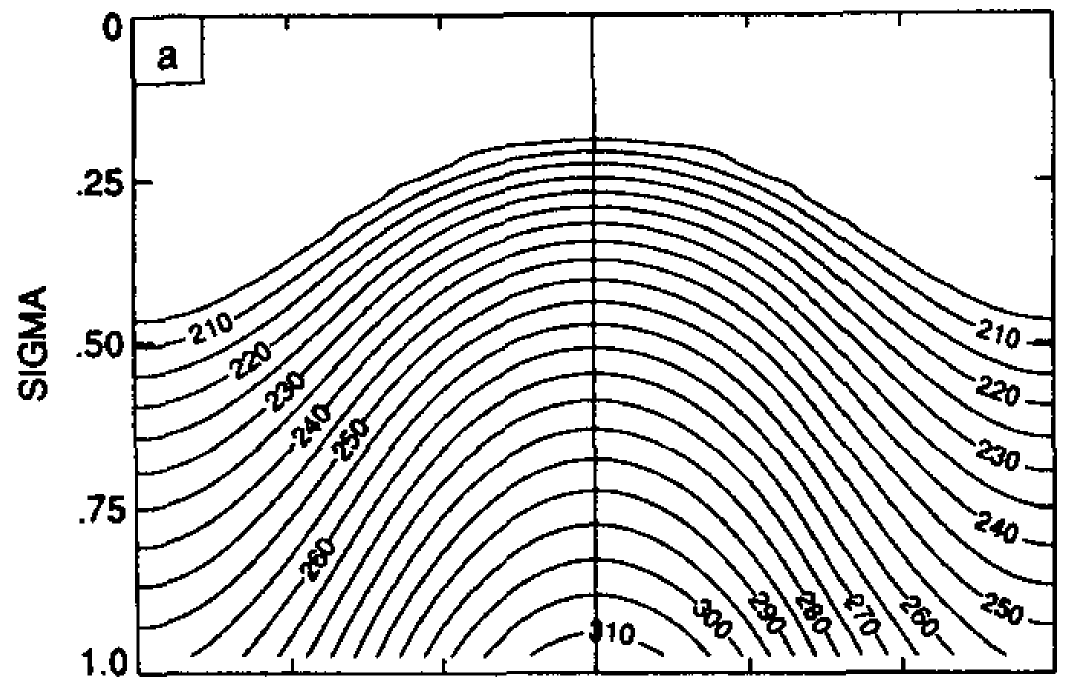
CMIP5 model analysis
storm track = variance of 2-6 dy. SLP
Harvey, Shaffrey et al. (2013)



temperature response under RCP8.5
(1976-2005) - (2070-2099)

GFDL Dynamical Core simulations

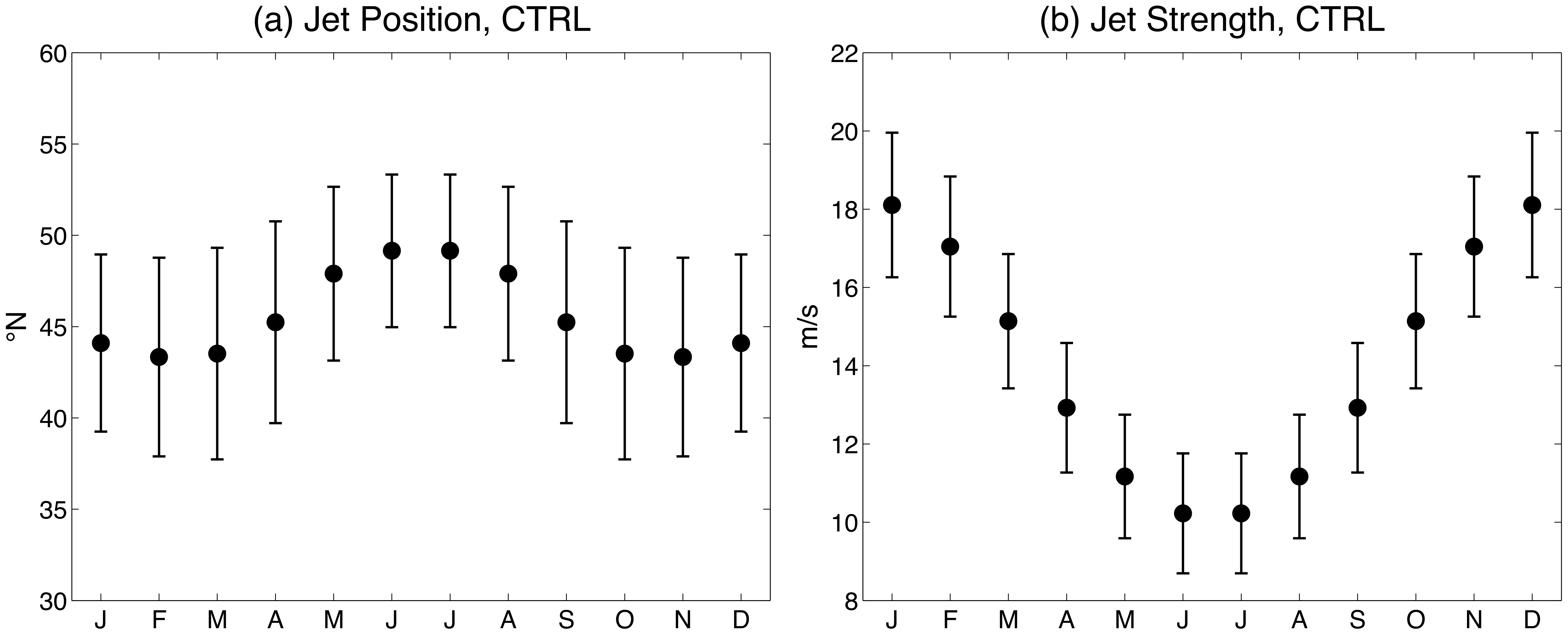
equilibrium
temperature profile



- driven by Newtonian relaxation to an equilibrium temperature profile
- simulation 360-day seasonal cycle by varying the equilibrium temperature profile (as in Polvani & Kushner, 2002)
- no well-resolved stratosphere
- zonally-symmetric
- each month is run under perpetual conditions (e.g. perpetual January, perpetual February…)

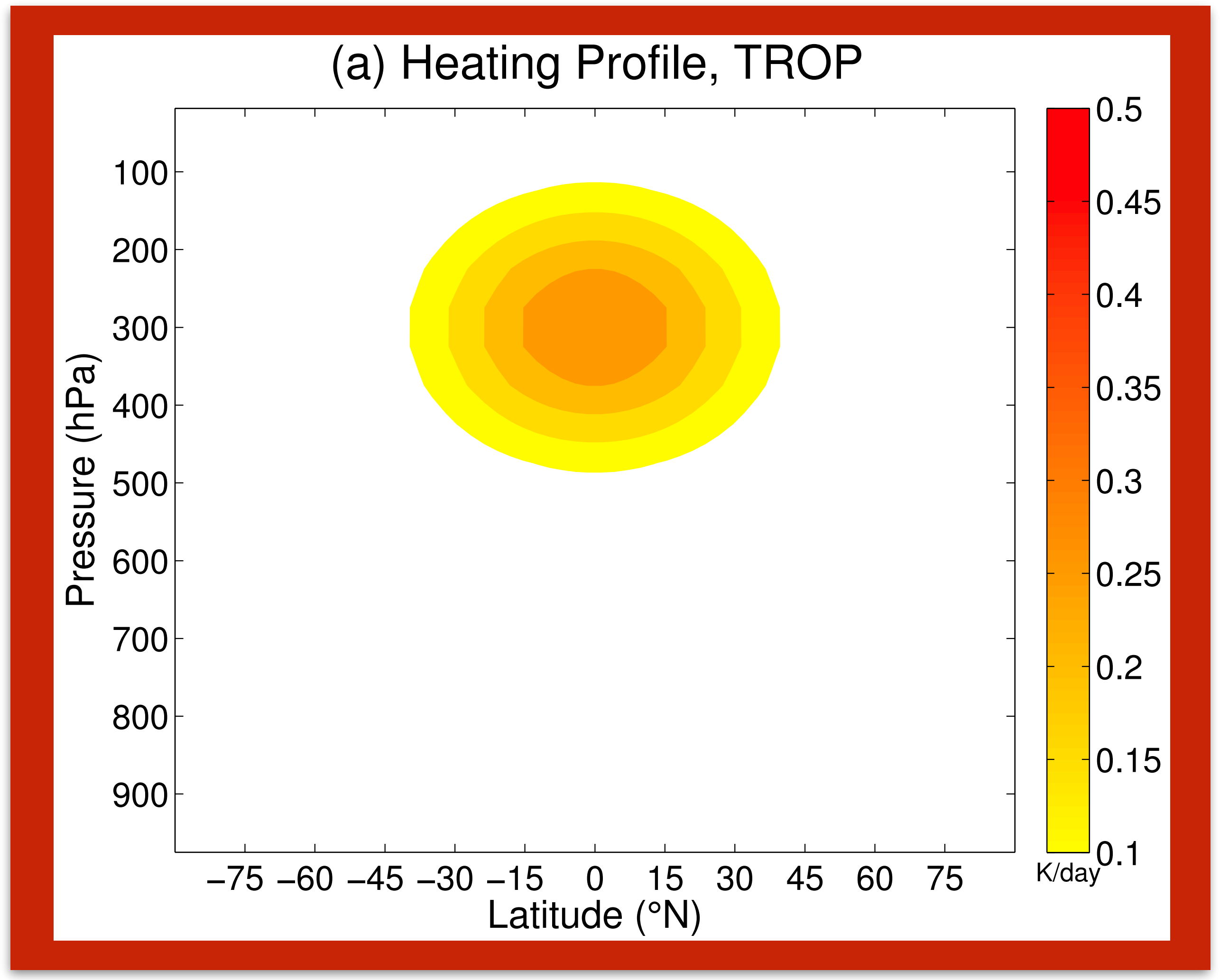
Held & Suarez (1994)
Polvani and Kushner (2002)

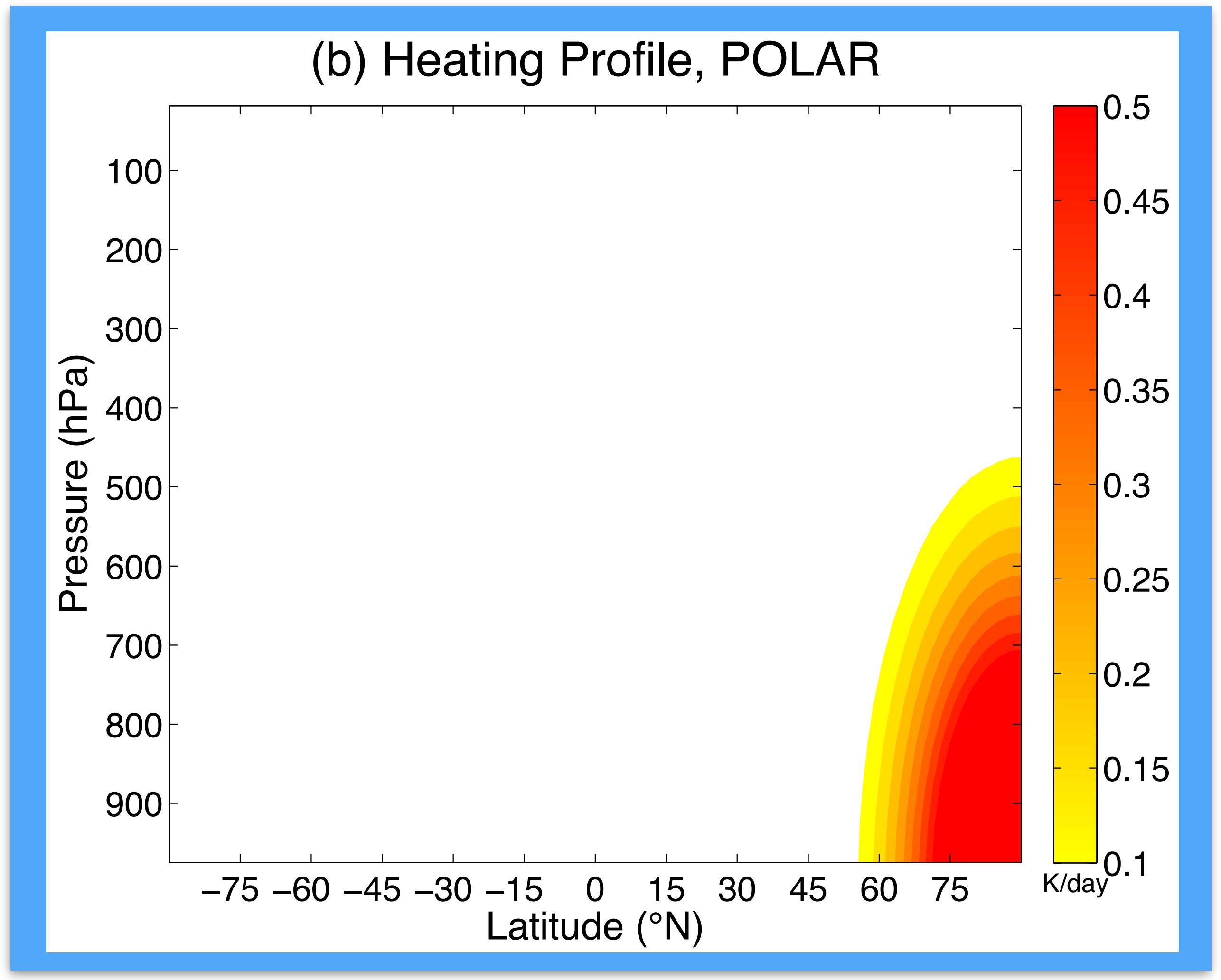
Control simulations

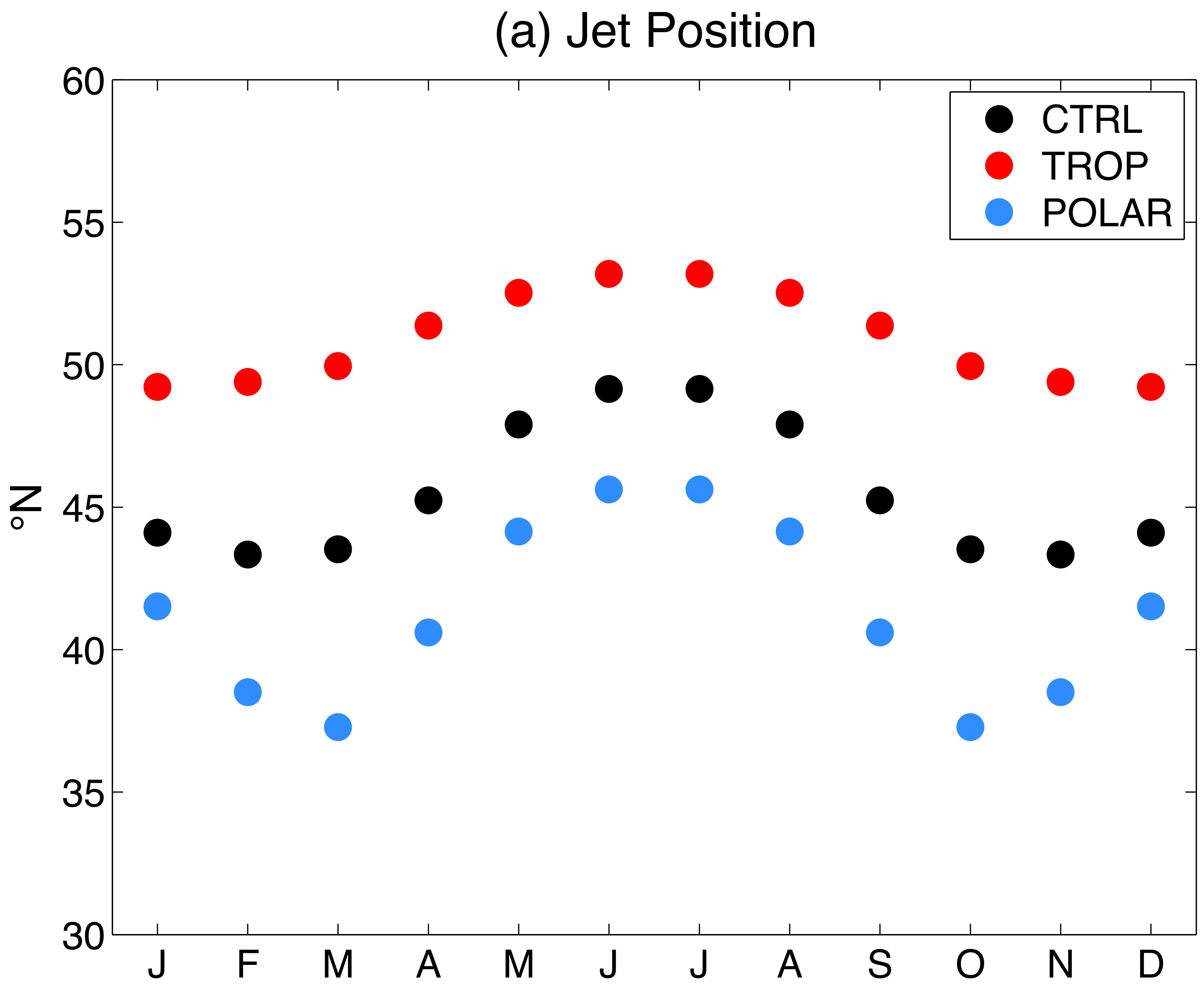


McGraw & Barnes (2016); in review

Title here







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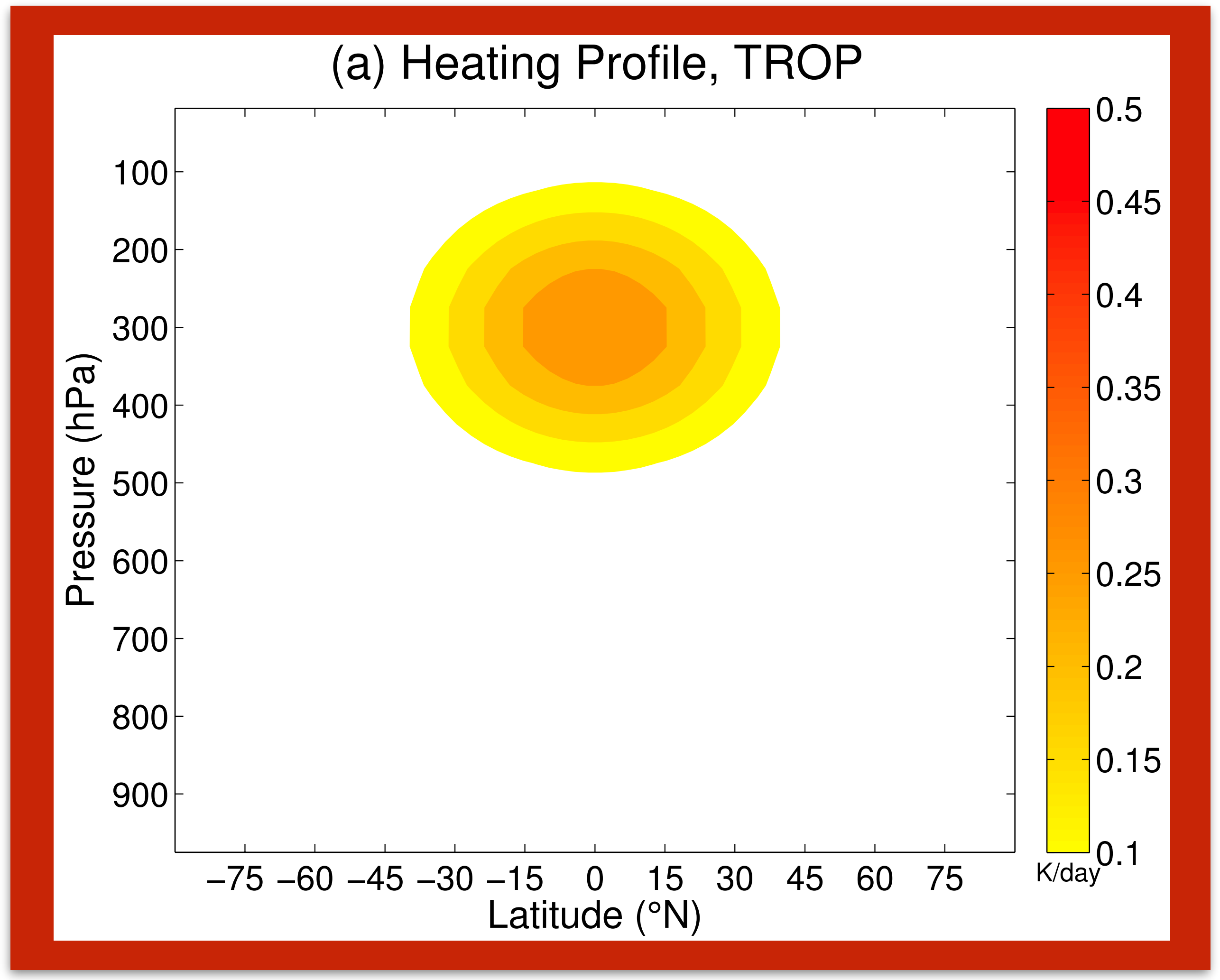

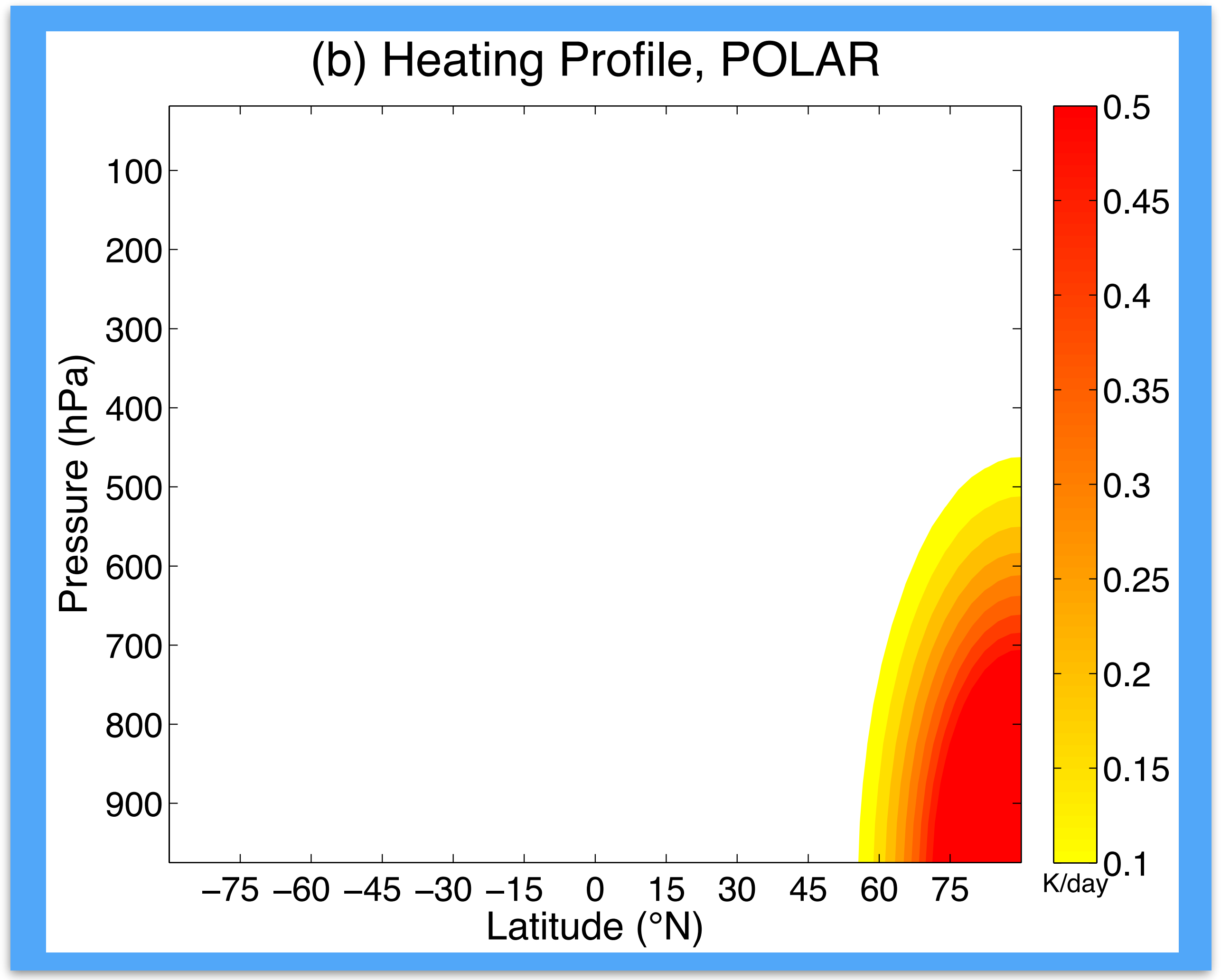

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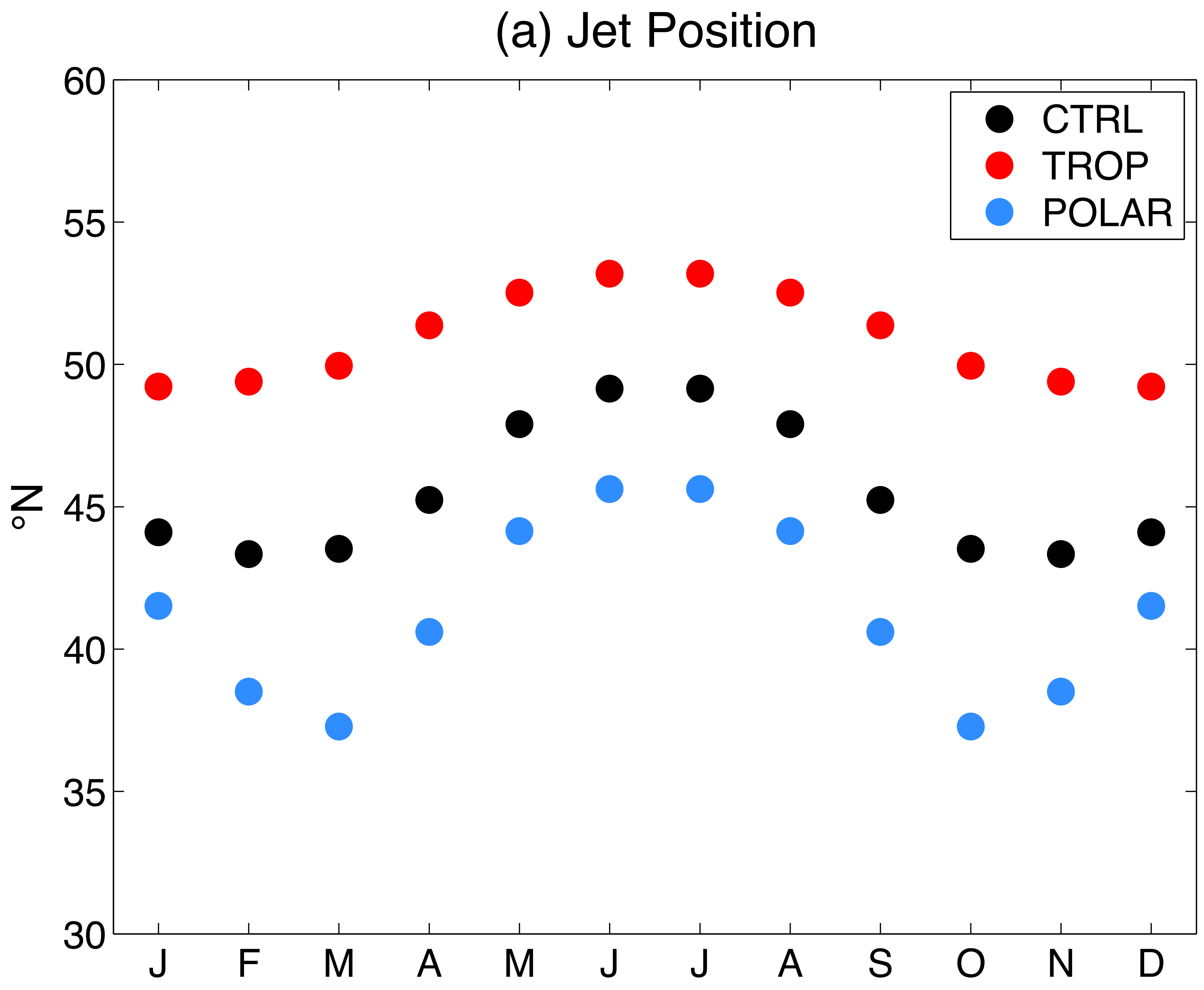
Dry core: Jet-stream response



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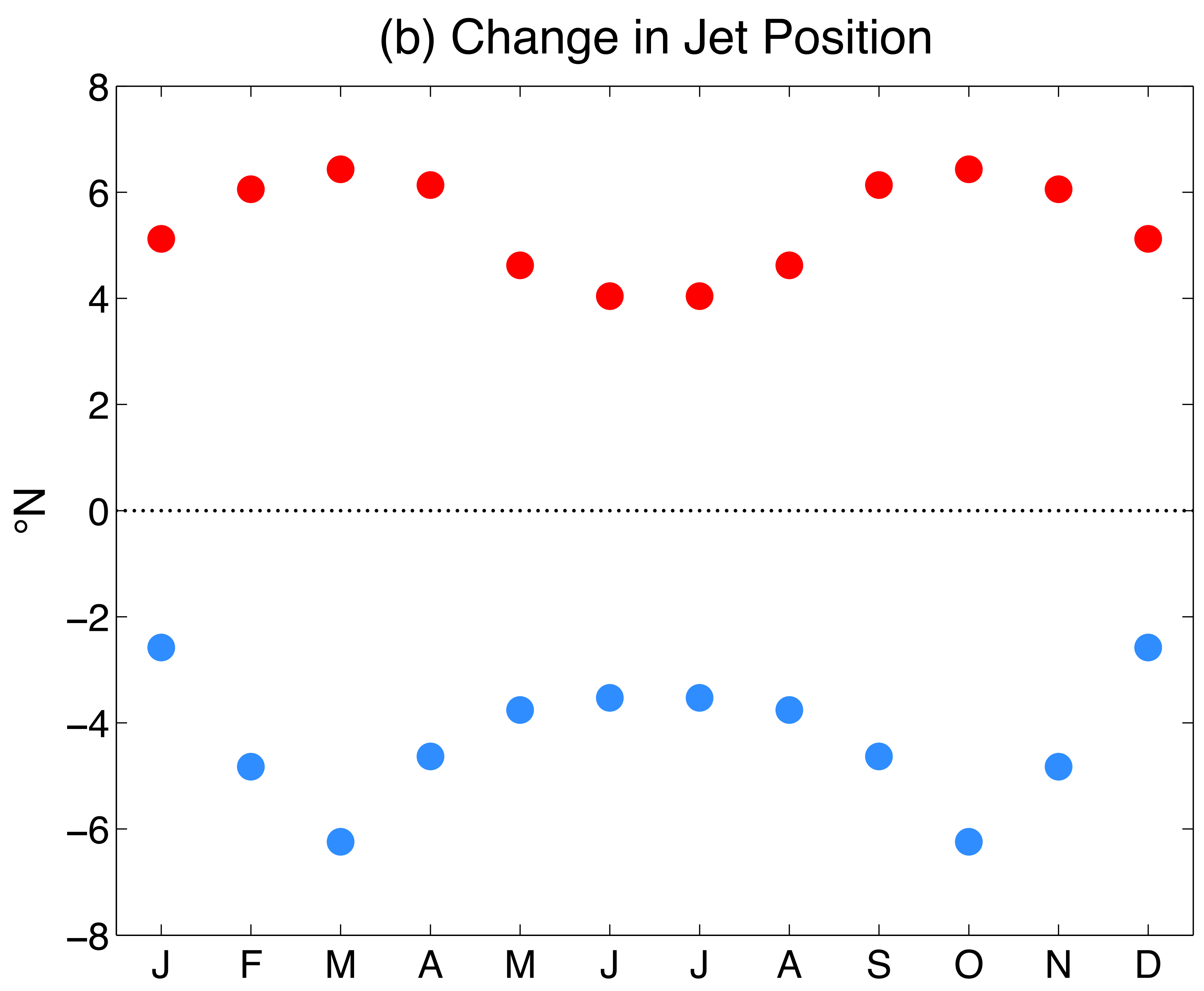

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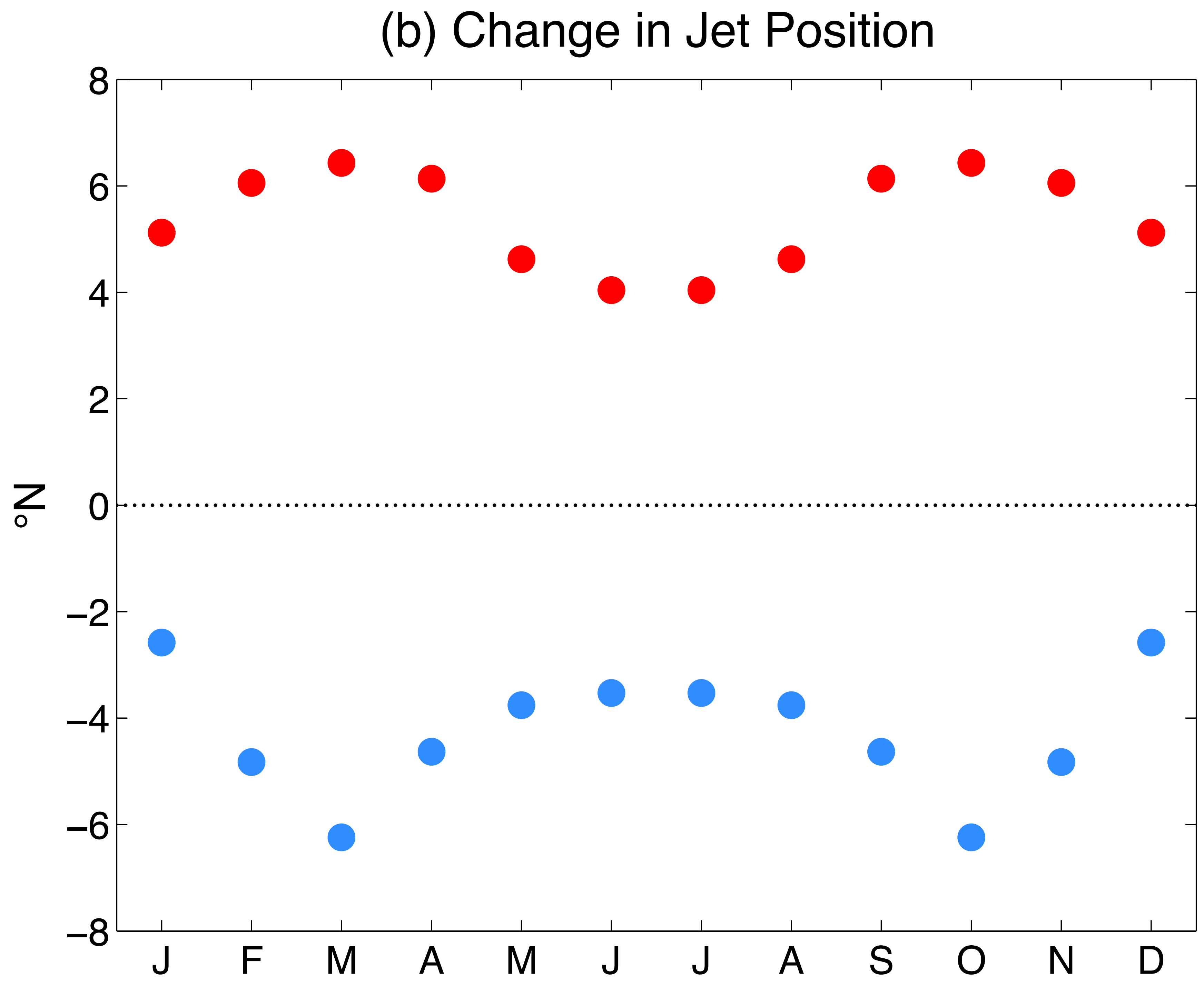
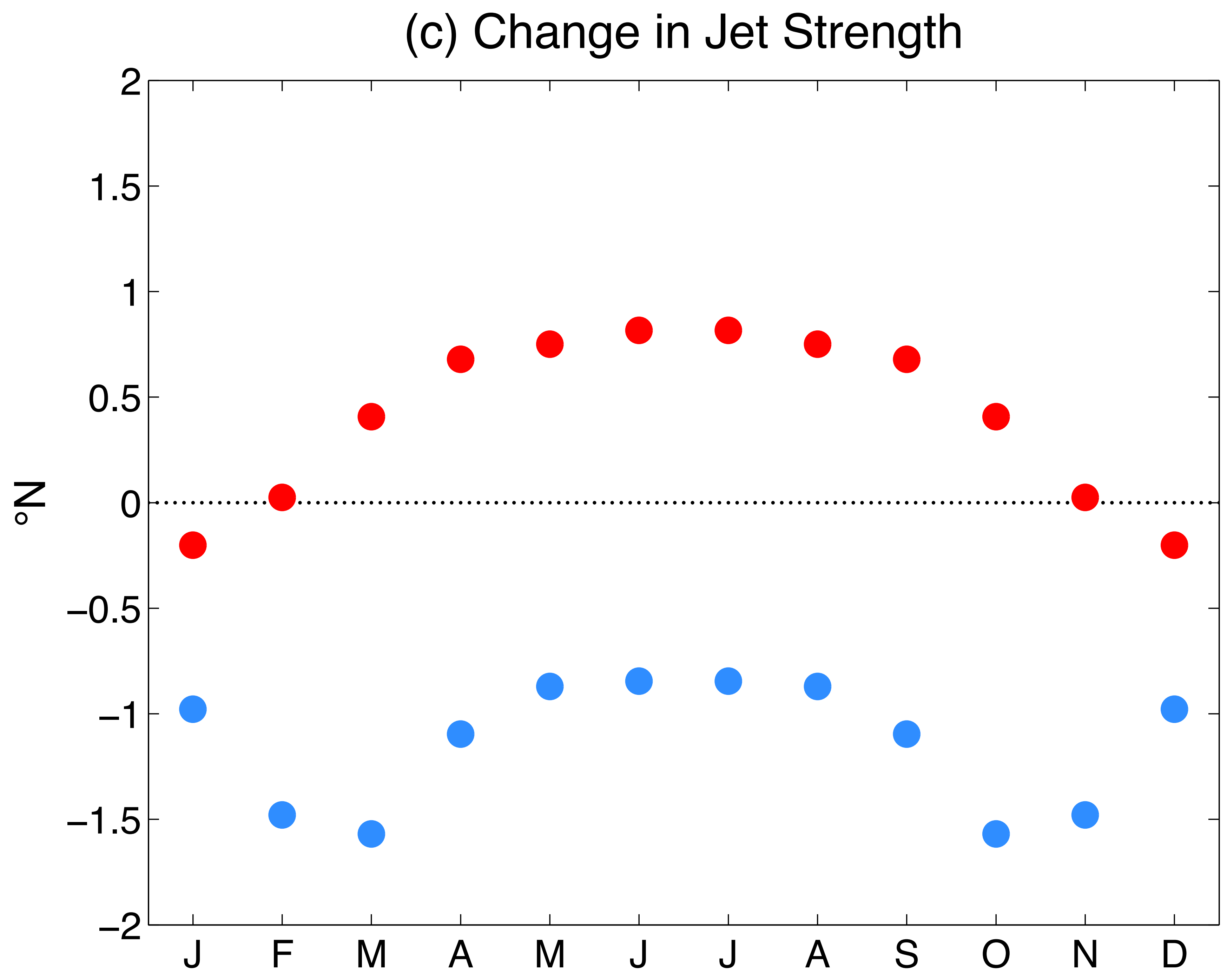
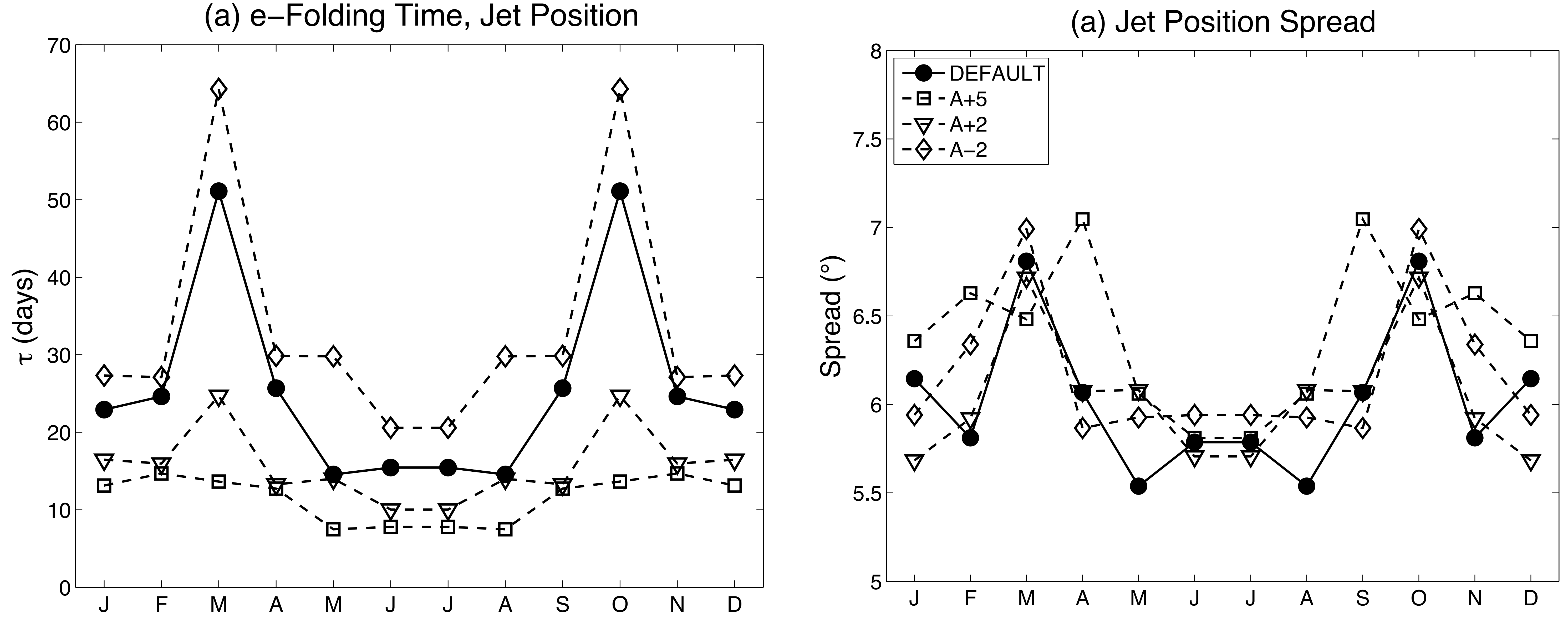




McGraw & Barnes (2016); in review

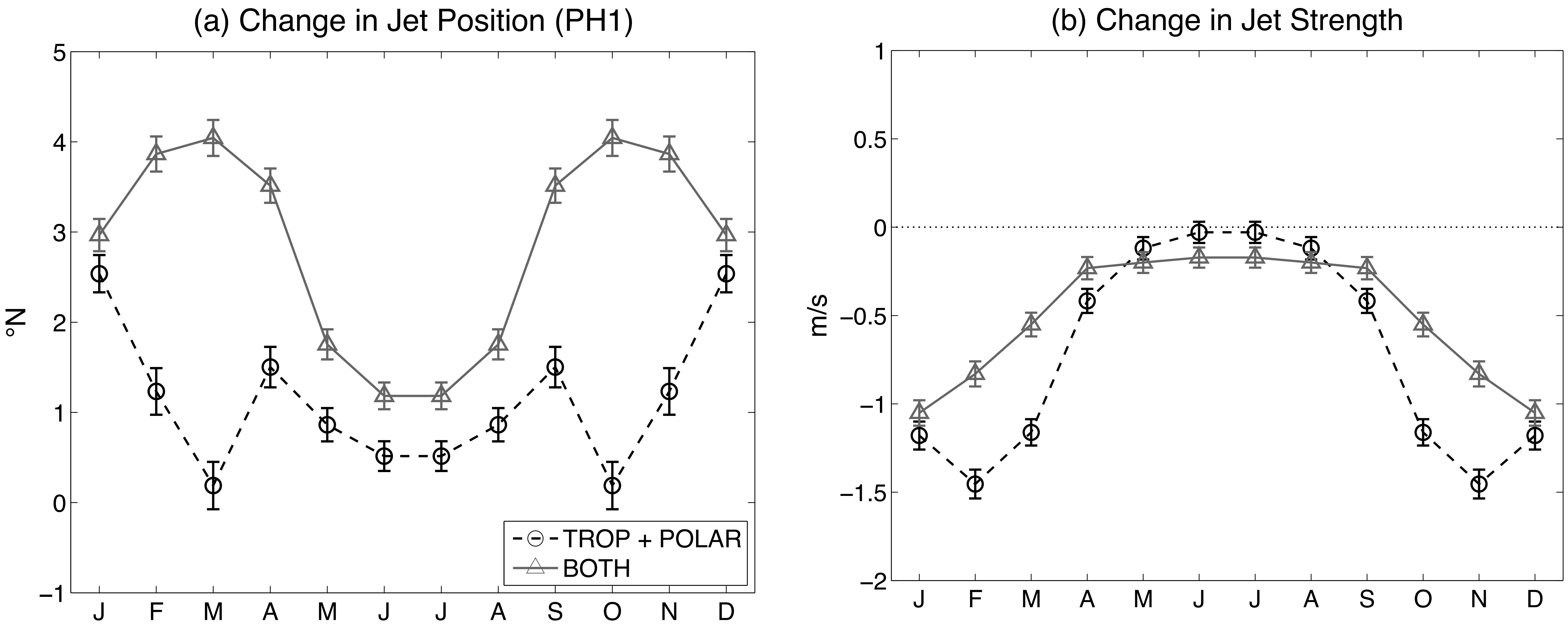
Dry core: Fluctuation-dissipation?

- shoulder seasons have the largest internal variability
- these seasons also exhibited the largest response



McGraw & Barnes (2016); in review

Dry core: Nonlinearity of response



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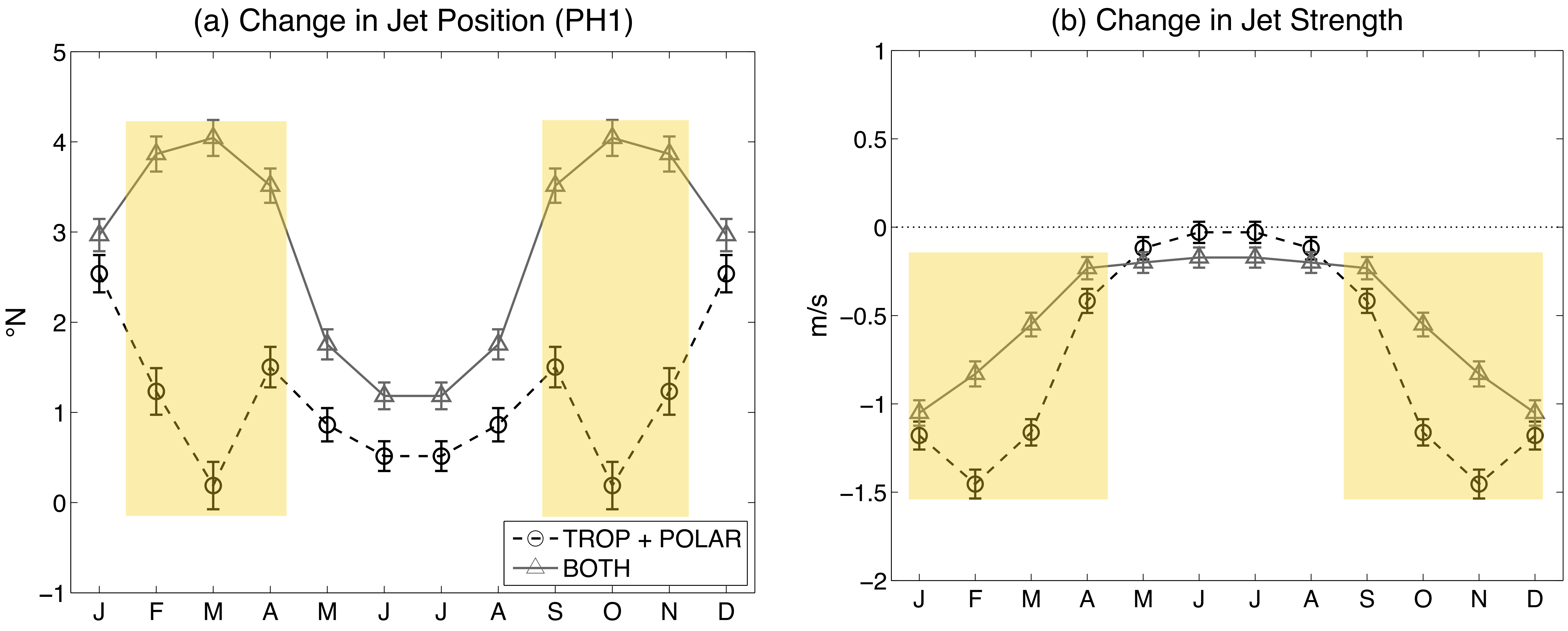

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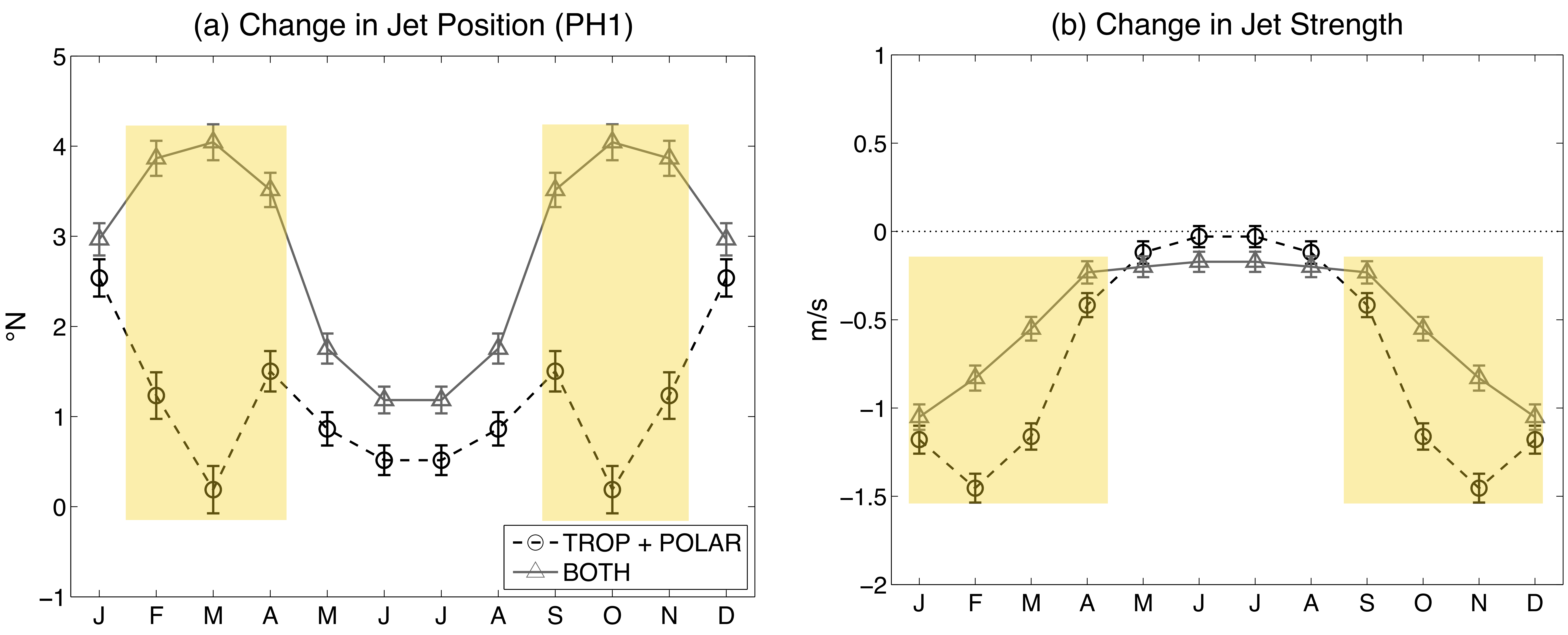
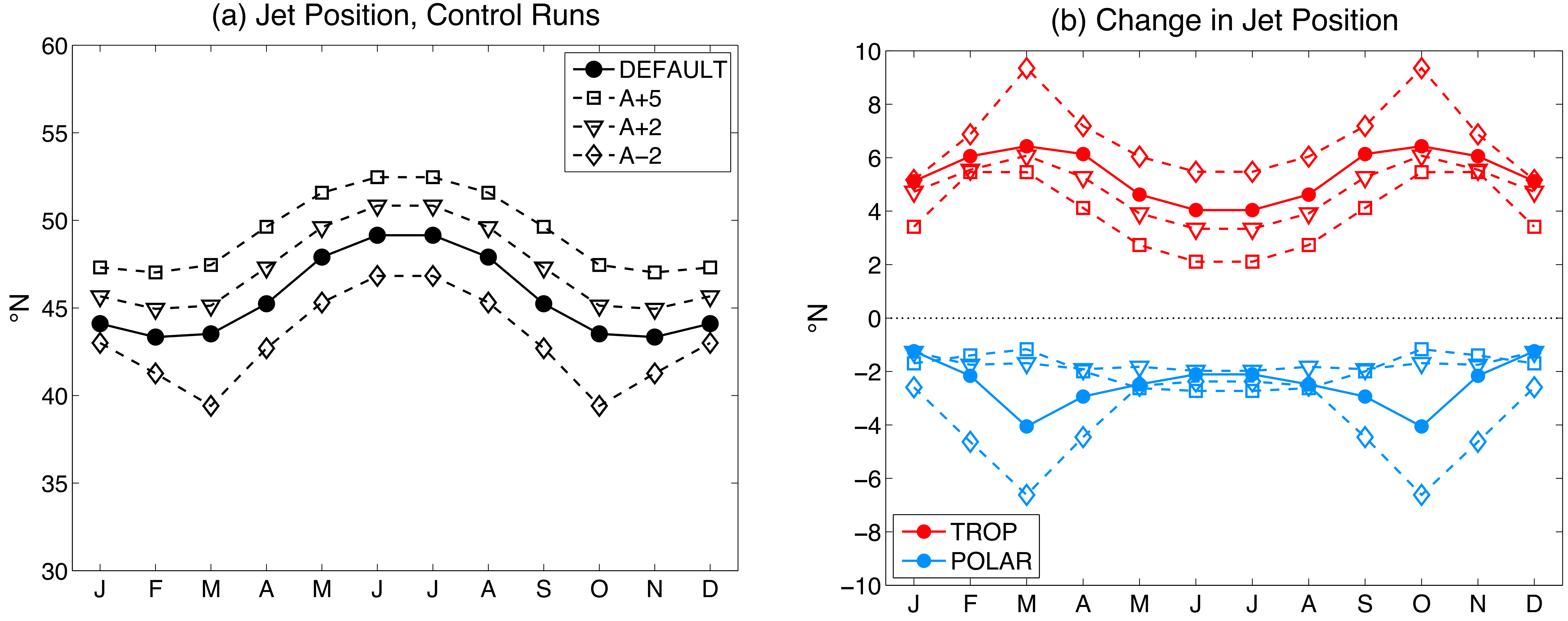


Nonlinearity present in shoulder seasons:
POLAR matters less when both forcings are simulated at the same time

McGraw & Barnes (2016); in review

Dry core: initial jet position important in all seasons?



dependence on the basic state changes throughout the year:

- matters most in the shoulder seasons
- for POLAR warming, Dec/Jan & Jun/Jul are independent of basic state

POLAR heating weaker and elevated off of the surface for these simulations
McGraw & Barnes (2016); in review

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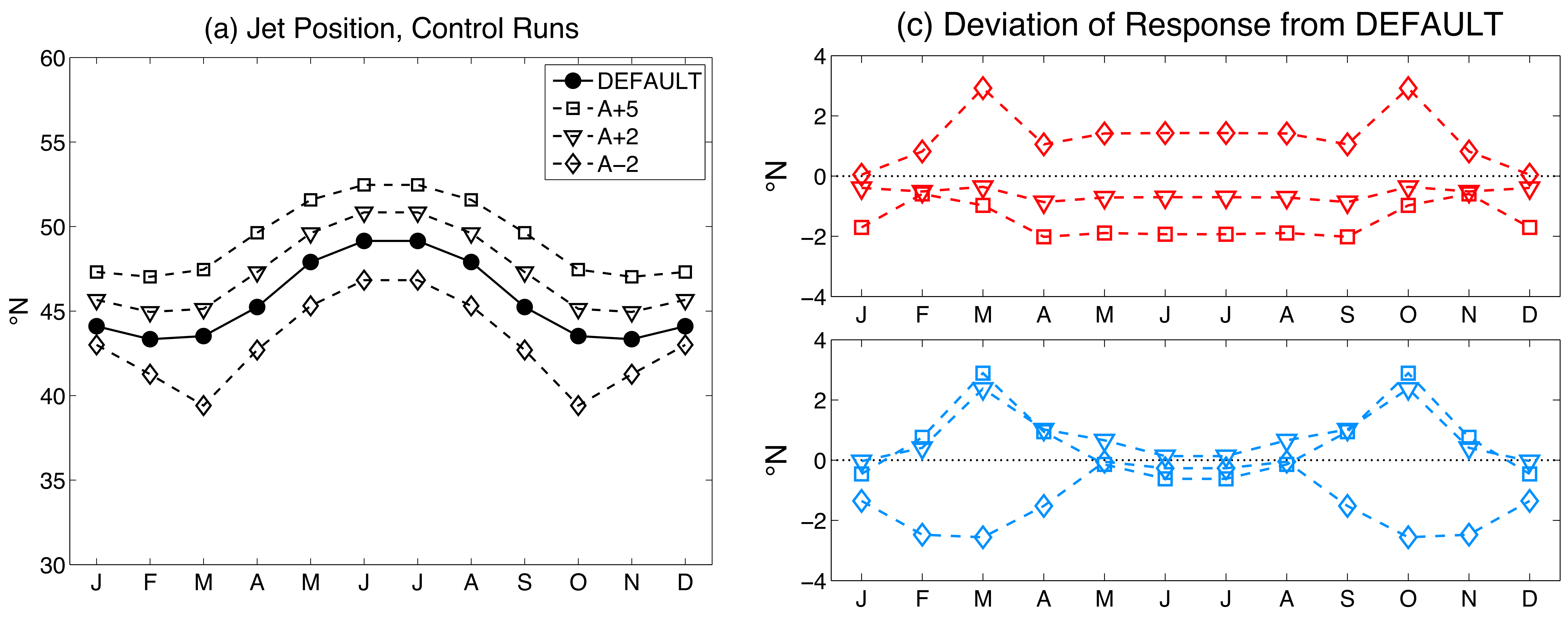

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Seasonality of SH response to GHG

- forced GCM with increased GHGs
- found largest SH response in the zonal winds in summer/fall

Southern Hemisphere Atmospheric Circulation Response to Global Warming

Paul J. Kushner, Isaac M. Held, and Thomas L. Delworth
NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

(Manuscript received 24 February 2000, in final form 1 August 2000)

ABSTRACT

The response of the Southern Hemisphere (SH), extratropical, atmospheric general circulation to transient, anthropogenic, greenhouse warming is investigated in a coupled climate model. The extratropical circulation response consists of a SH summer half-year poleward shift of the westerly jet and a year-round positive wind anomaly in the stratosphere and the tropical upper troposphere. Along with the poleward shift of the jet, there is a poleward shift of several related fields, including the belt of eddy momentum-flux convergence and the mean meridional overturning in the atmosphere and in the ocean. The tropospheric wind response projects strongly onto the model's ''Southern Annular Mode'' (also known as the ''Antarctic oscillation''), which is the leading pattern of variability of the extratropical zonal winds.

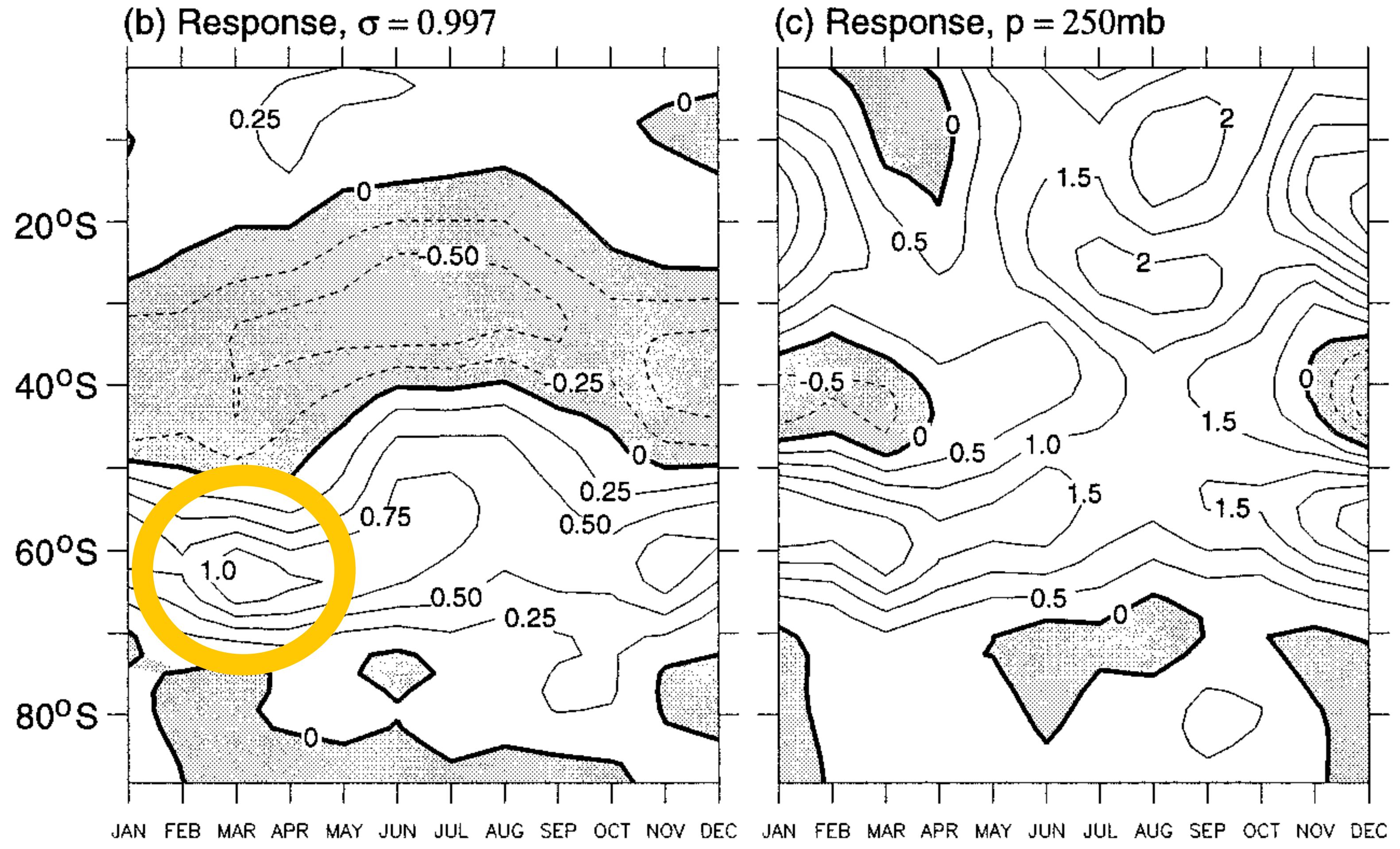

Fig. 4. The seasonal cycle of the climatological surface zonal-mean zonal wind for (a) the 800-yr time mean of the control integration, and (b) the ensemble mean response, years 2065–89. (c), (d) As in (a) and (b), but at 250 mb. Shading and dashed contours indicate negative values. Contour interval: (a) 2 m s^{-1}; (b) 0.25 m s^{-1}; (c) 5 m s^{-1}; (d): 0.5 m s^{-1}.

Kushner et al. (2001), JCLI

Seasonality of SH response to GHG

- forced GCM with increased GHGs
- found largest SH response in the zonal winds in summer/fall

We will investigate the seasonal sensitivity of the circulation under constant forcing

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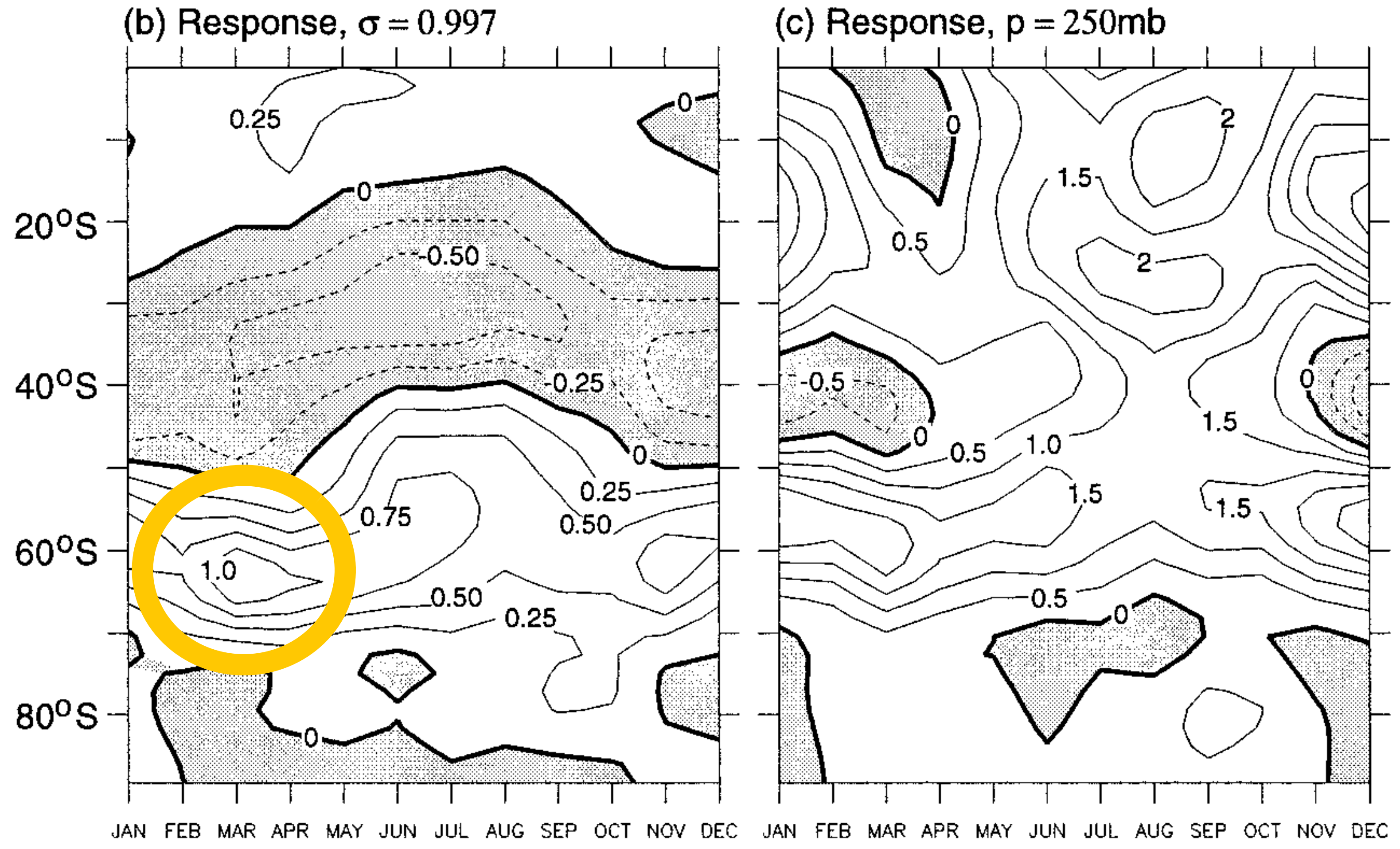

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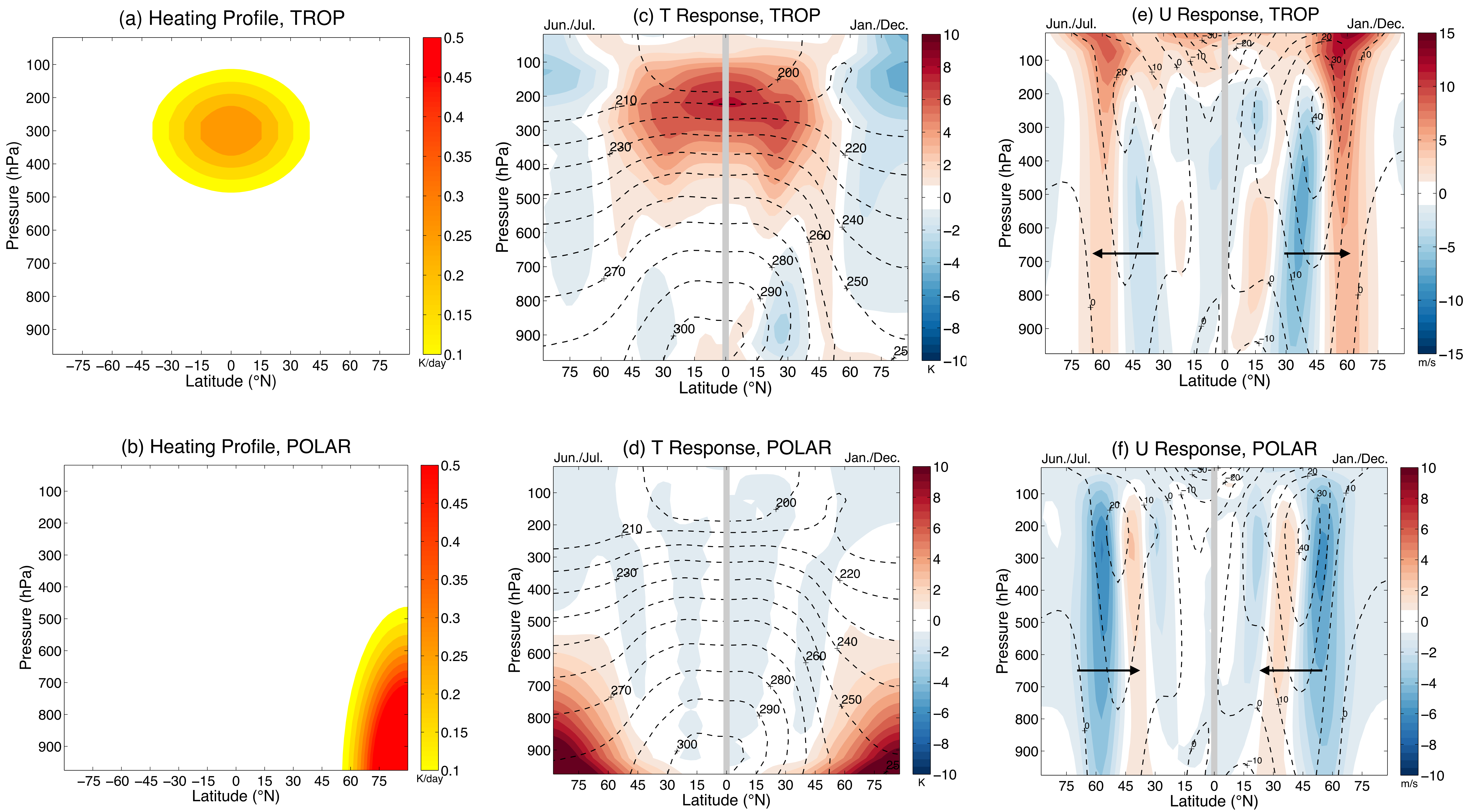
Kushner et al. (2001), JCLI

TROP heating



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