Extratropical atmospheric predictability from the Quasi-Biennial Oscillation and Madden Julian Oscillation in the S2S models

Chaim I. Garfinkel, Chen Schwartz, Daniela Domeisen,
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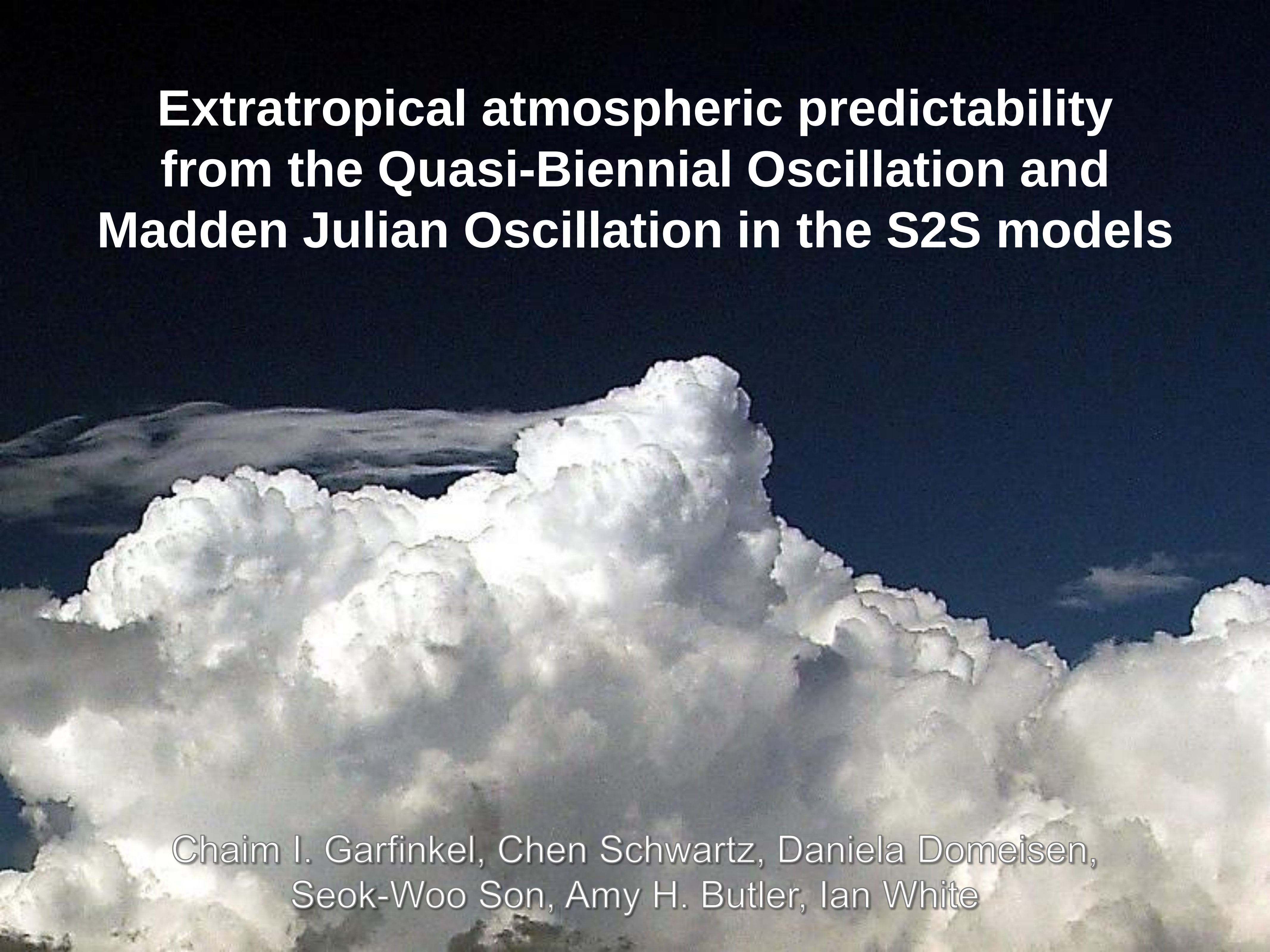

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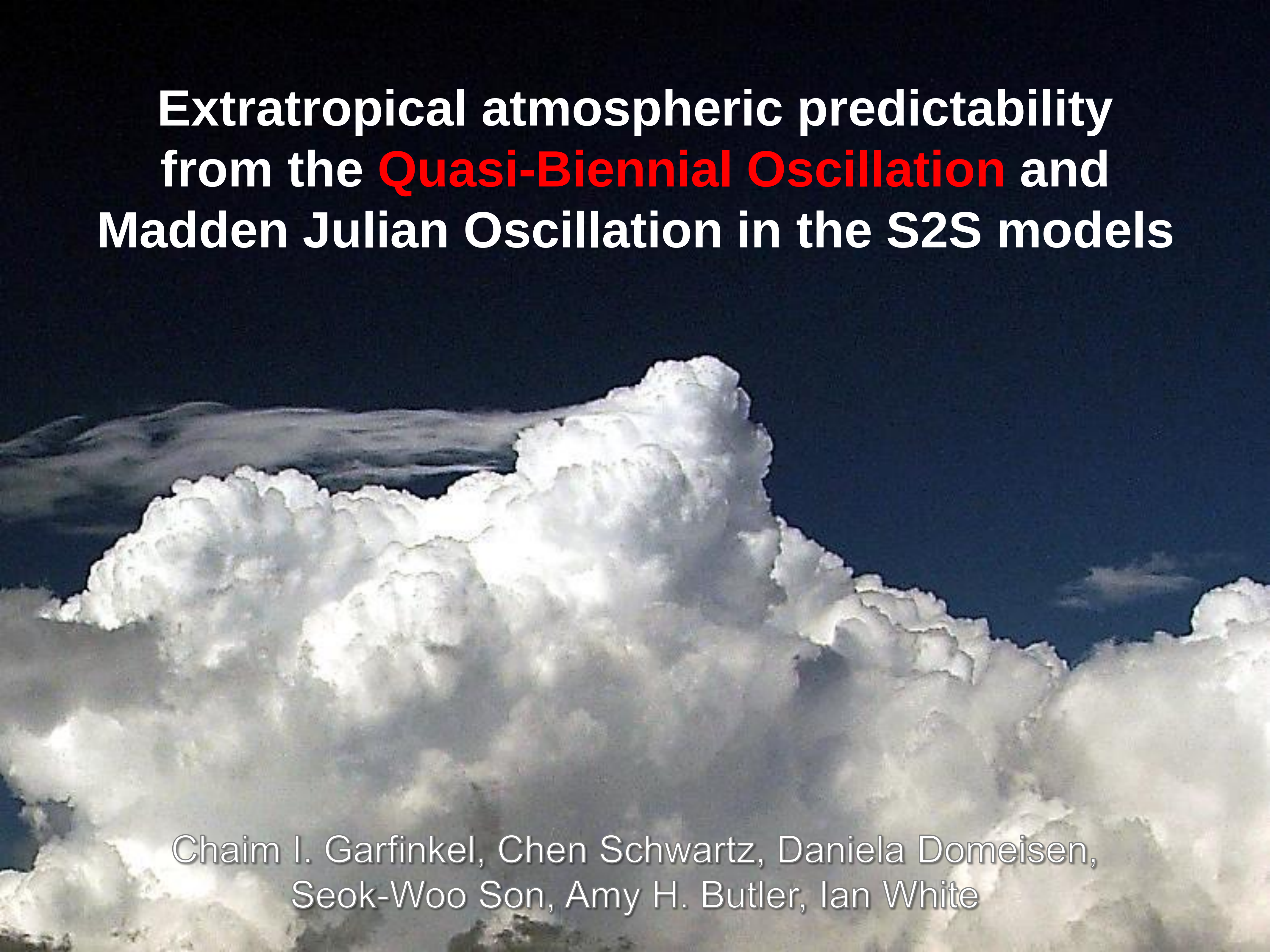

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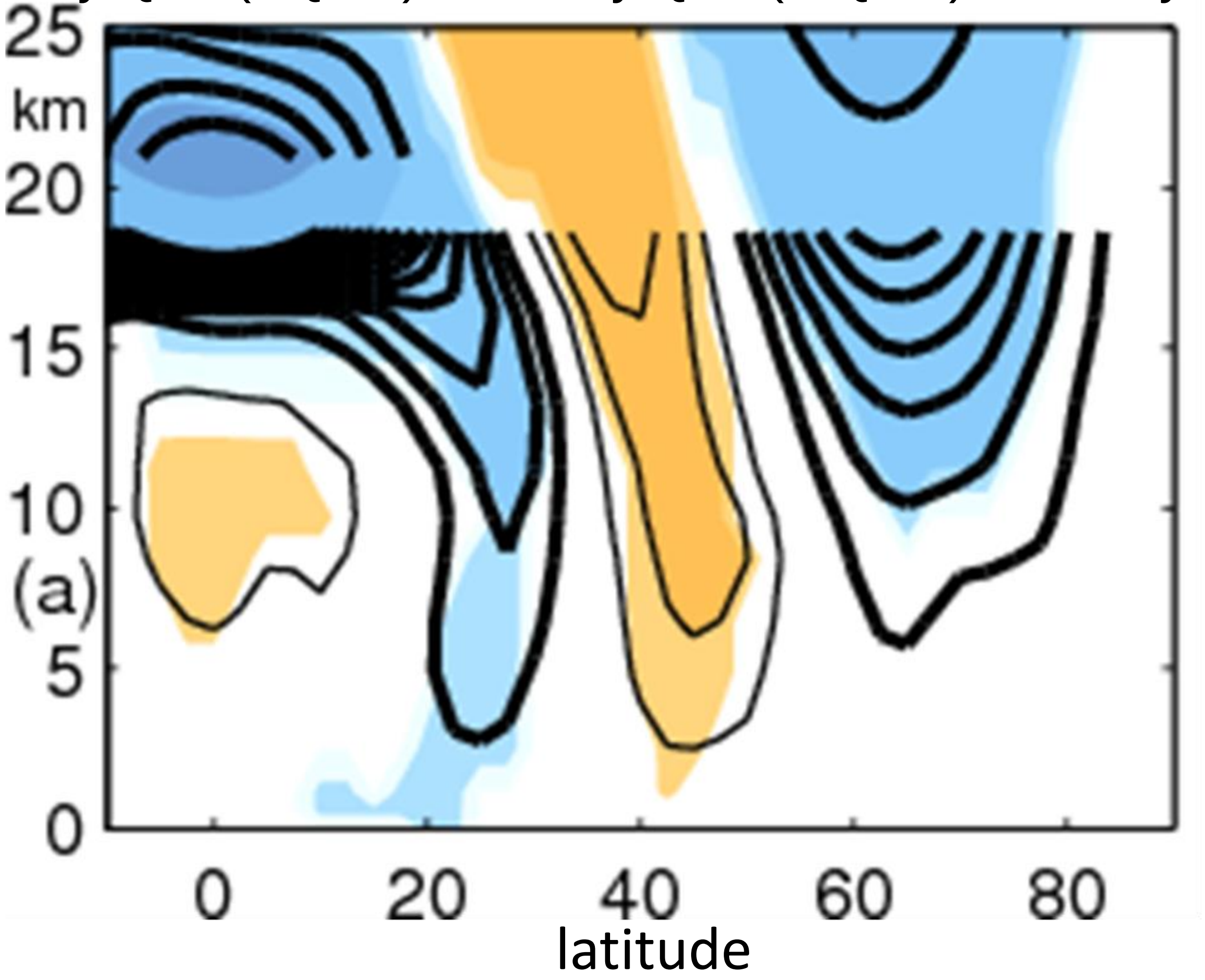
Easterly winds in the tropical lower stratosphere lead to a weaker vortex

Easterly QBO(EQBO)-Westerly QBO(WQBO), Reanalysis, NDJF



C.I.=0.5m/s in trop
5m/s in strat

After Holton and Tan (1980); Garfinkel et al 2011

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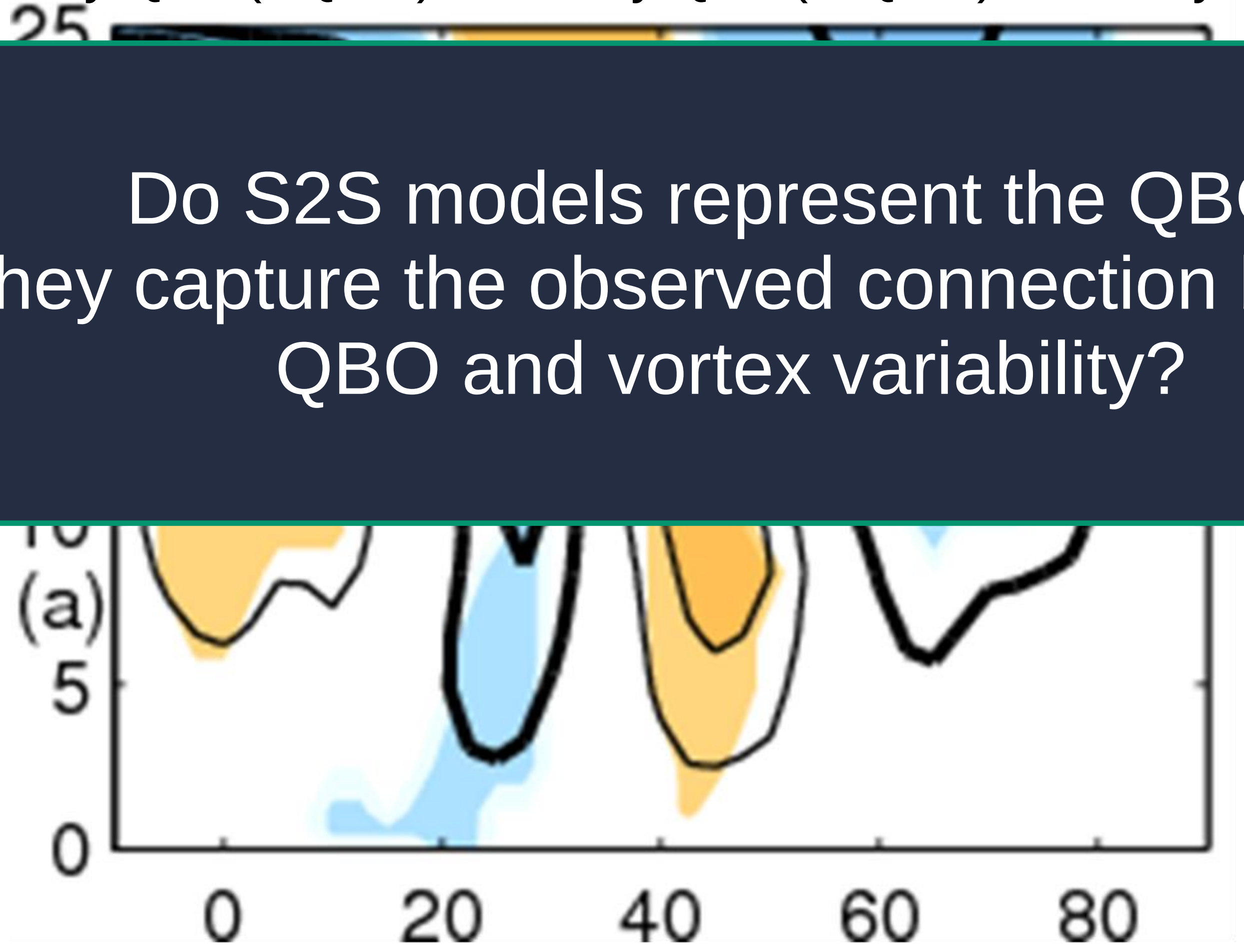

Do S2S models represent the QBO?
Can they capture the observed connection between the QBO and vortex variability?

latitude

After Holton and Tan (1980); Garfinkel et al 2011

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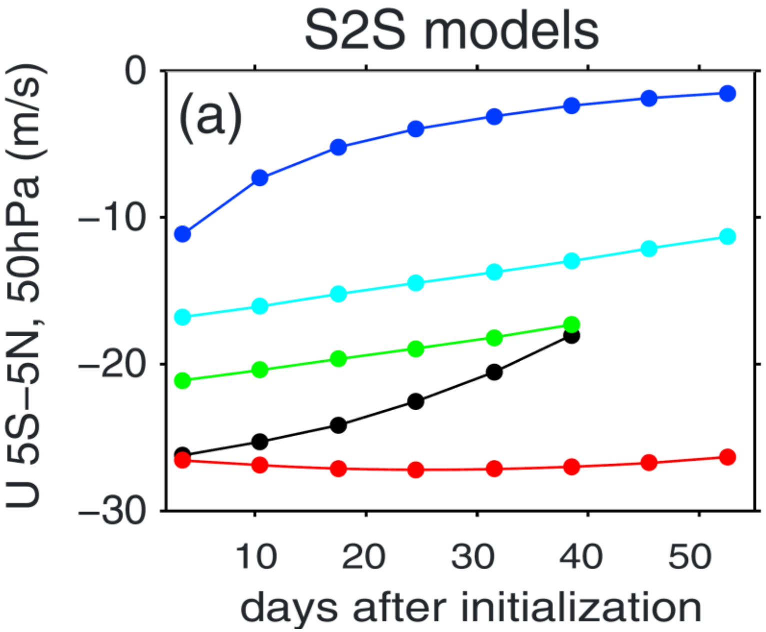
UKMO model represents QBO the best, ECMWF, UKMO, and CMA models worse

EQBO−WQBO



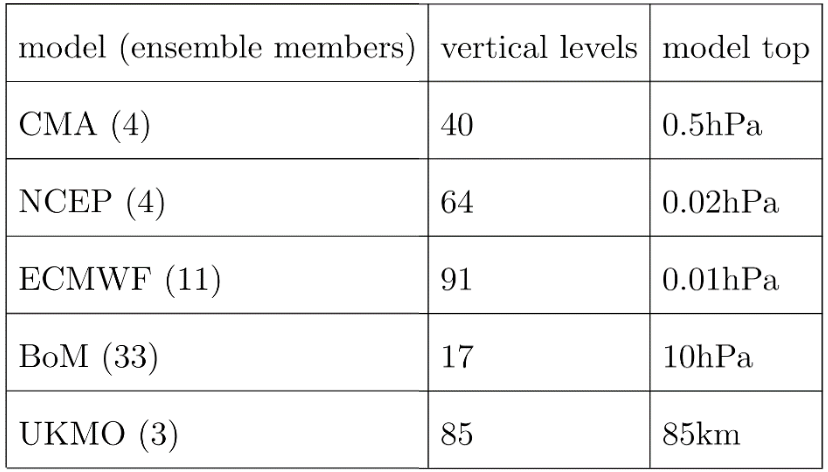
ECMWF (WQBO: 220; EQBO: 154)

NCEP (WQBO: 112; EQBO: 64)

UKMO (WQBO: 36; EQBO: 30)

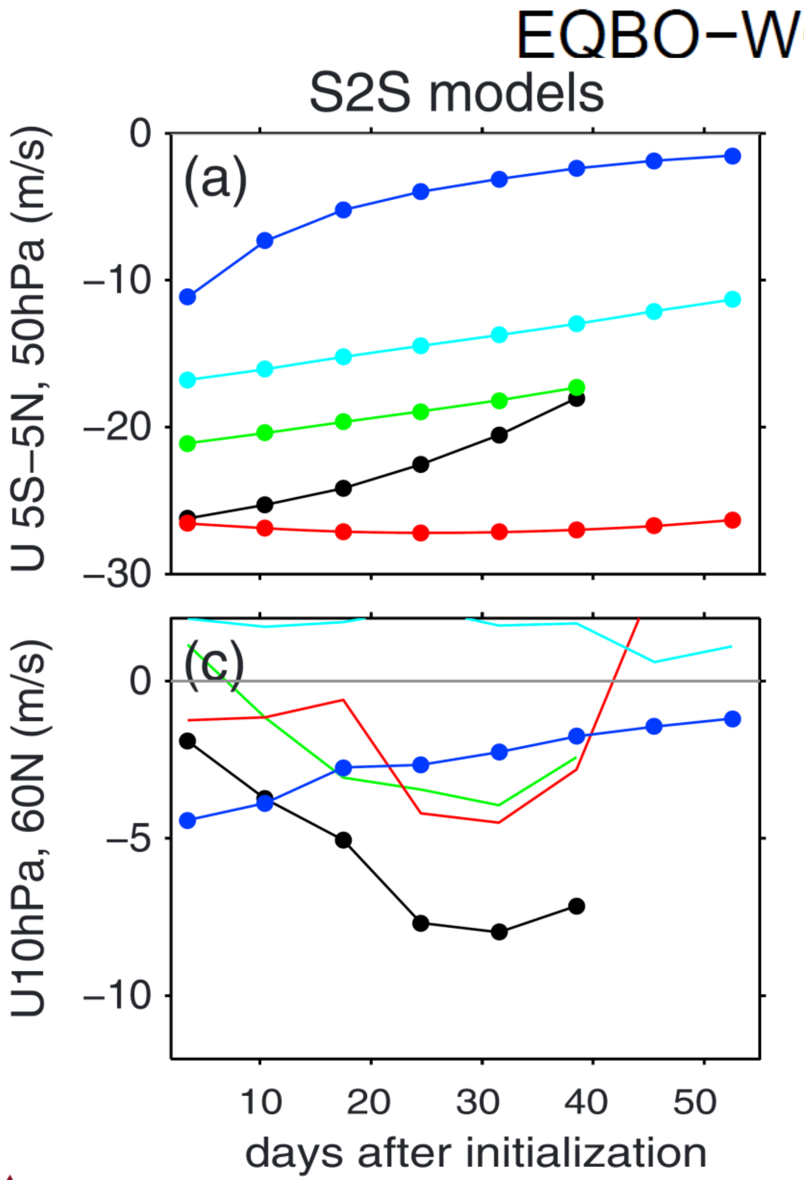
CMA (WQBO: 108; EQBO: 72)

BoM (WQBO: 528; EQBO: 1551)



model (ensemble members)	vertical levels	model top
CMA (4)	40	0.5hPa
NCEP (4)	64	0.02hPa
ECMWF (11)	91	0.01hPa
BoM (33)	17	10hPa
UKMO (3)	85	85km

ECMWF, UKMO, and NCEP models all capture the QBO→vortex effect



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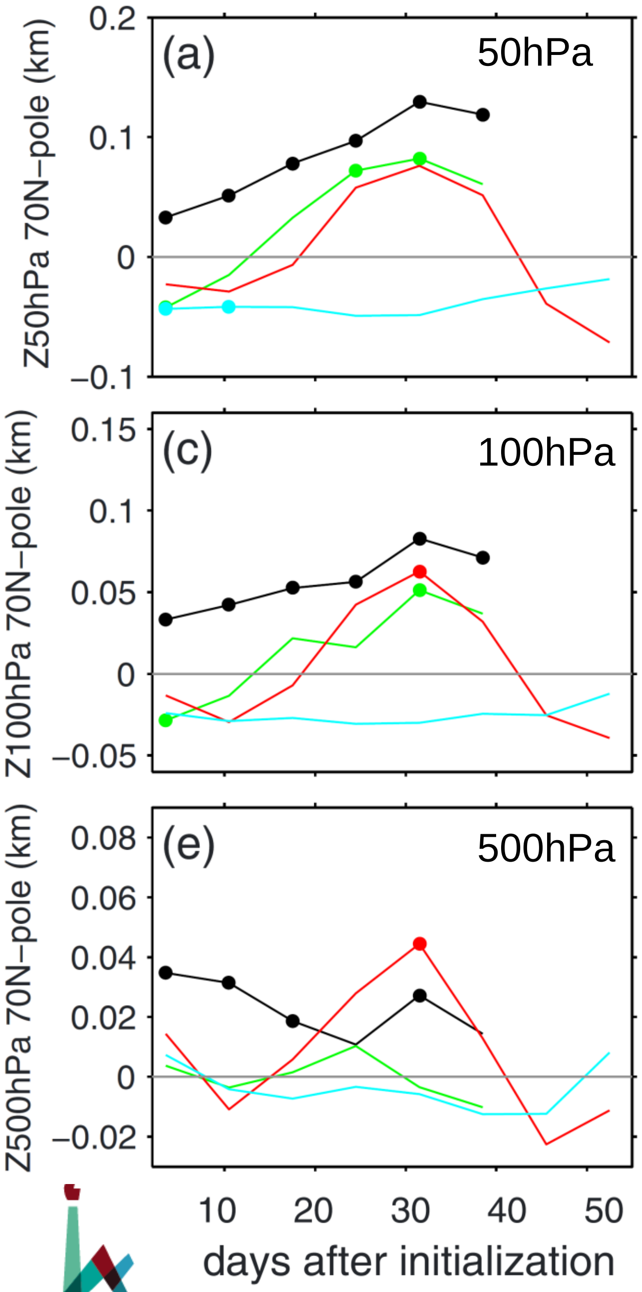
Does the QBO→vortex effect influence surface climate? Polar cap geopotential height



EQBO−WQBO

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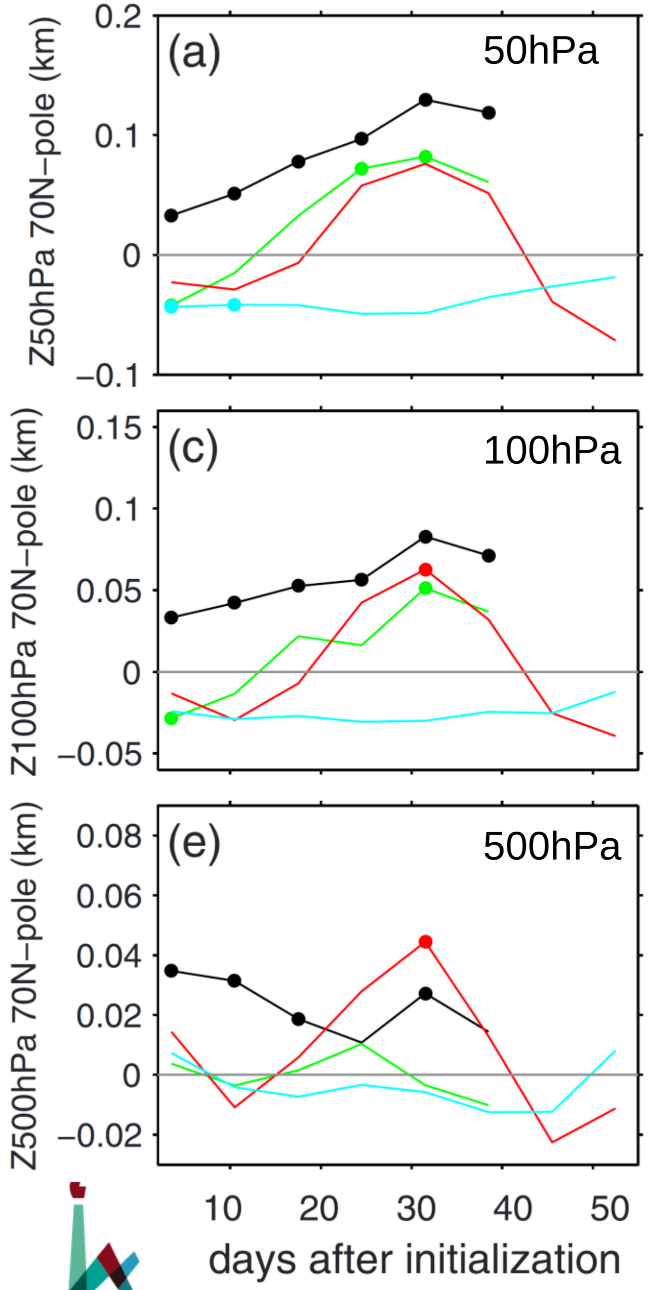
Does the QBO→vortex effect influence surface climate? perhaps…



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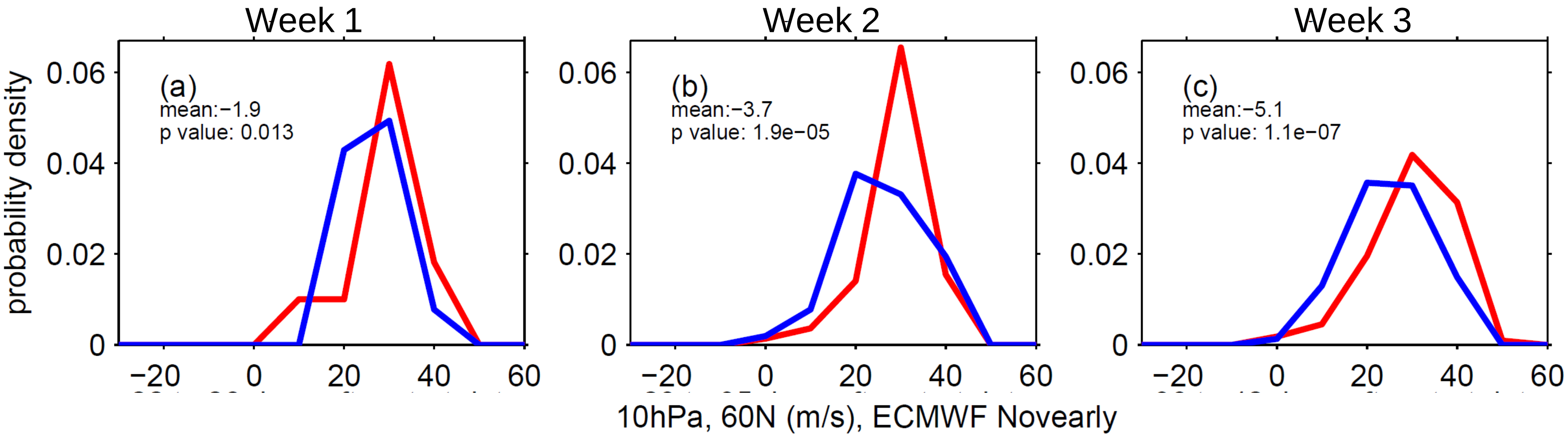
Useful for probabilistic forecasting of vortex zonal wind at 10hPa, 60N



WQBO; N=220
EQBO; N=154

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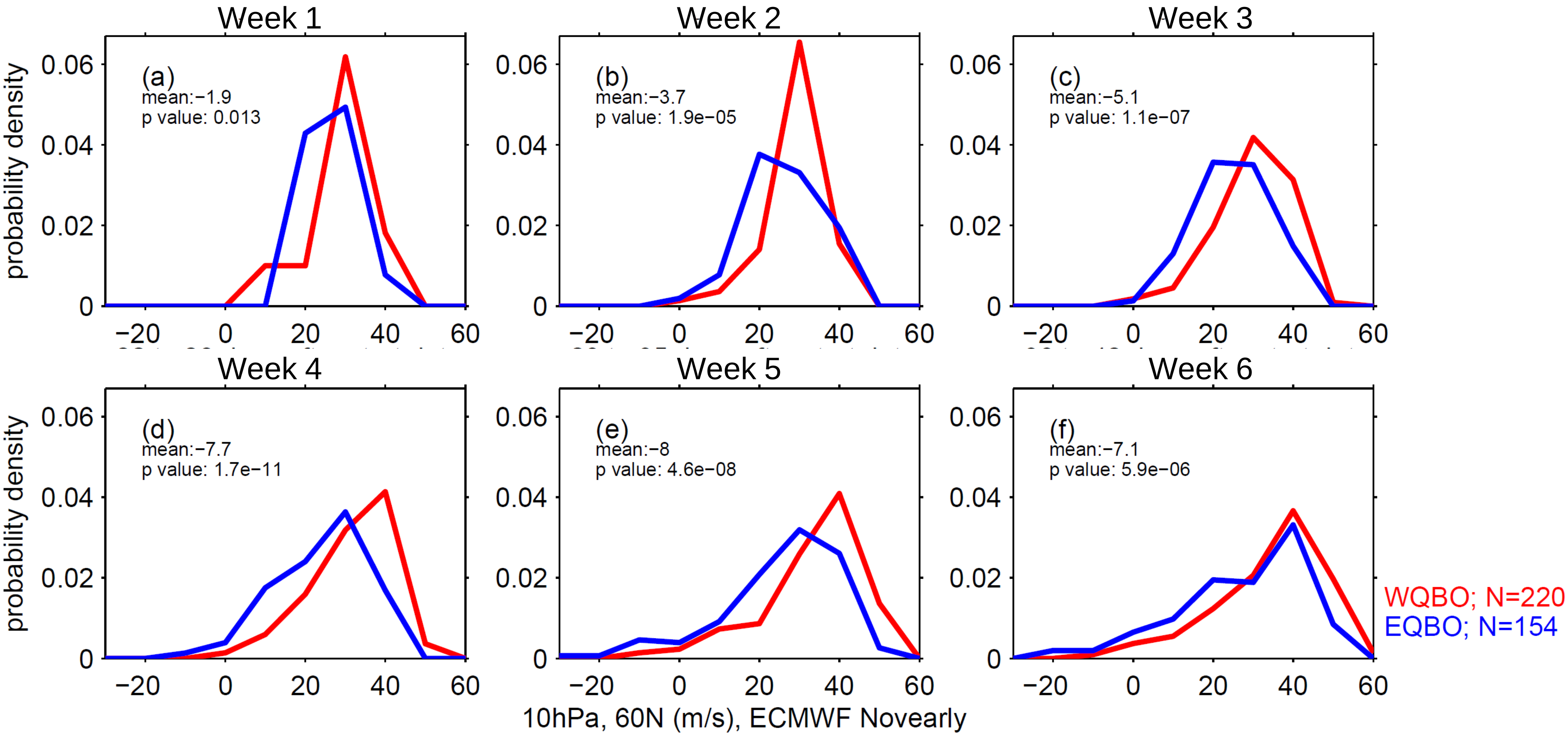

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Conclusions (part 1)

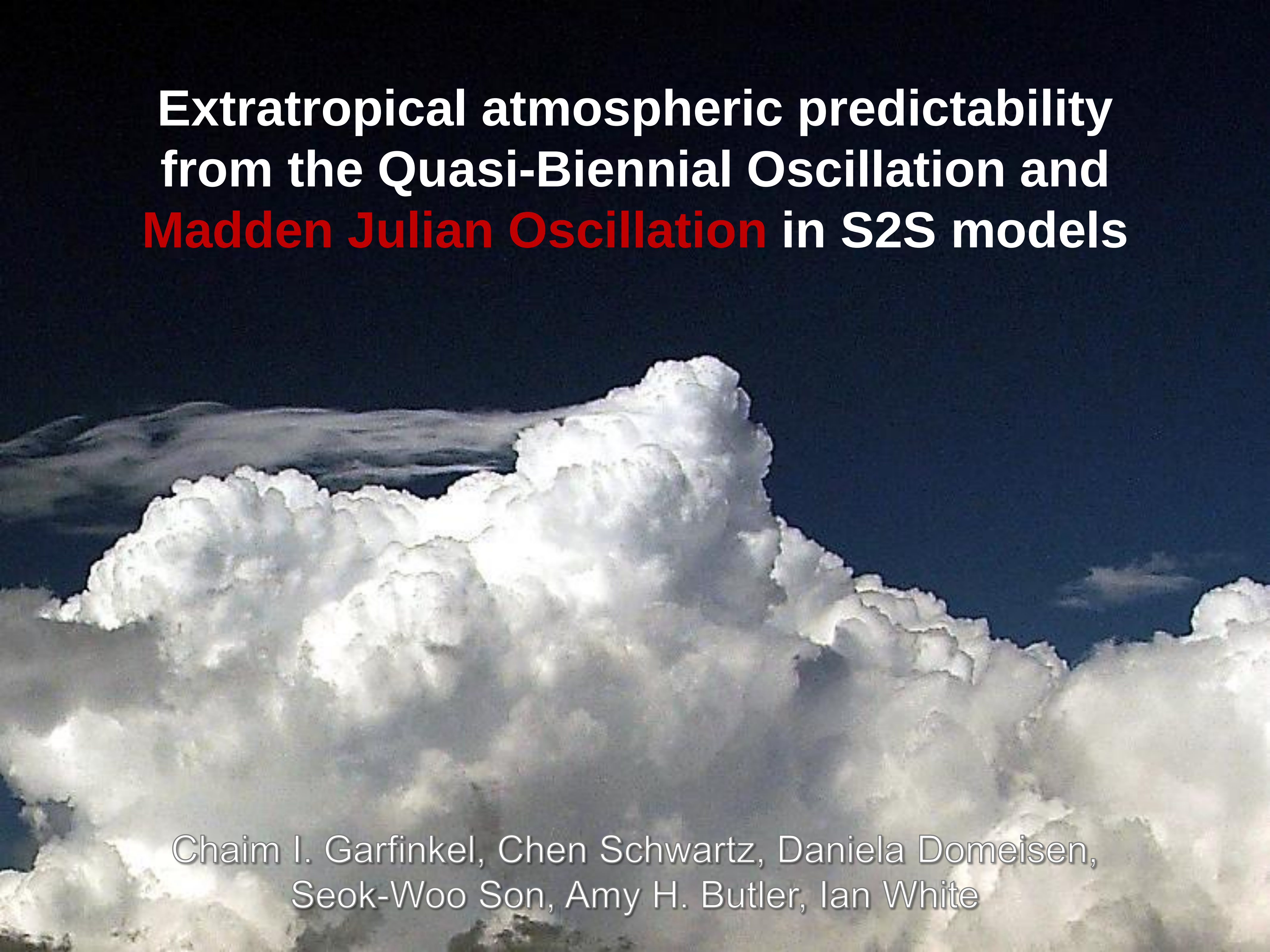
Easterly QBO regime leads to a weaker vortex as compared to westerly QBO regime.

- Models with good stratospheric resolution simulate effect qualitatively similar but weaker in magnitude to that observed.

- Hint of an effect in the troposphere.

- Any skill will be probabilistic, not deterministic

Garfinkel, C.I., Schwartz, C., Domeisen, D.I., Son, S.W., Butler, A.H. and White, I.P., 2018. Extratropical Atmospheric Predictability From the Quasi-Biennial Oscillation in Subseasonal Forecast Models. *Journal of Geophysical Research: Atmospheres*, *123*(15), pp.7855-7866.



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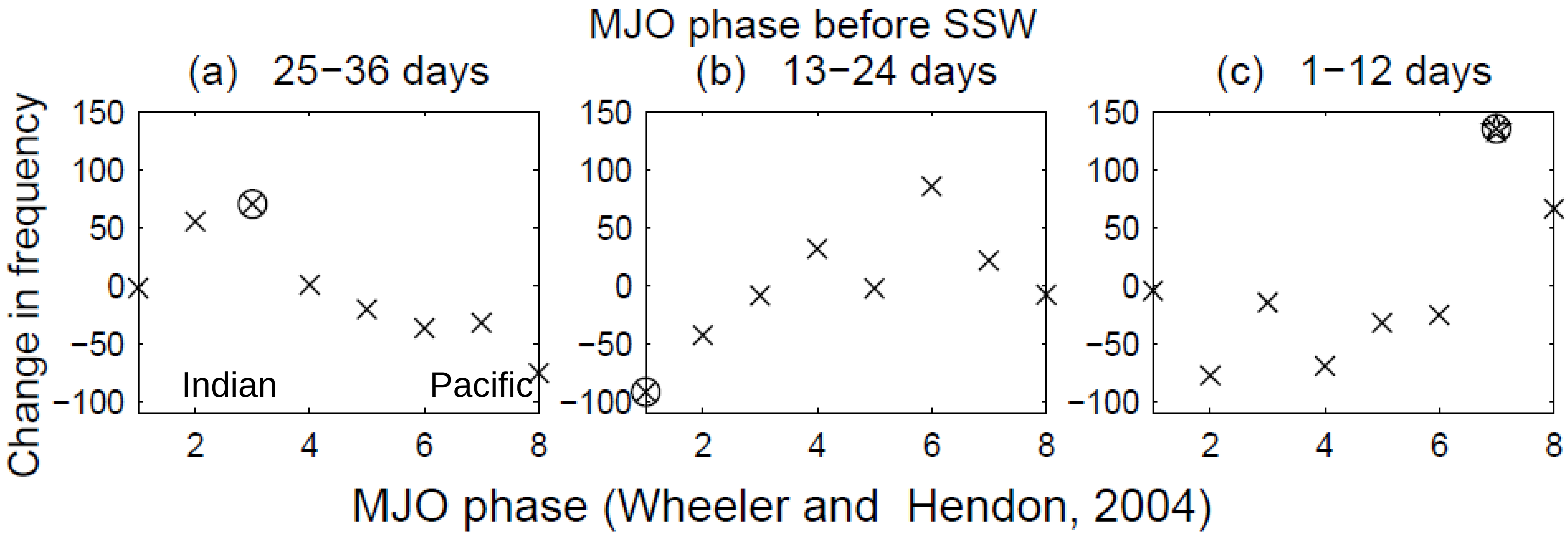
Significant connection between SSW and the MJO



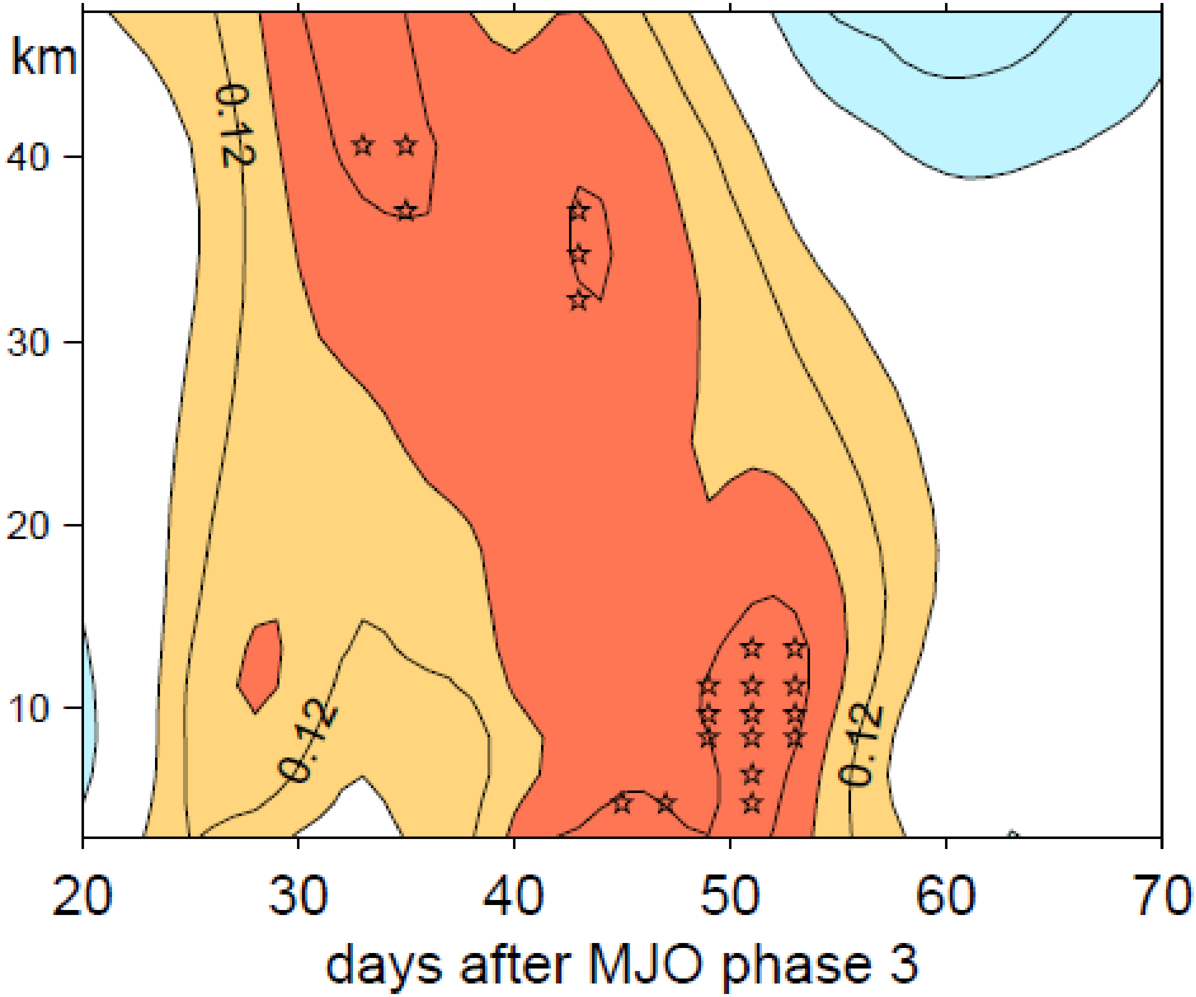
Garfinkel et al 2012, GRL

Potential for predictability of SSW by MJO phase exceeds one month.

12 of 23 SSW events since 1979 were preceded by a strong MJO phase 6/7 (Schwartz and Garfinkel 2017)

Downward propagation of MJO-induced vortex anomaly

normalized polar cap height anomalies



Contour interval: 0.06 standard deviations

Garfinkel et al 2012, GRL

MJO -> vortex -> tropospheric northern annular mode

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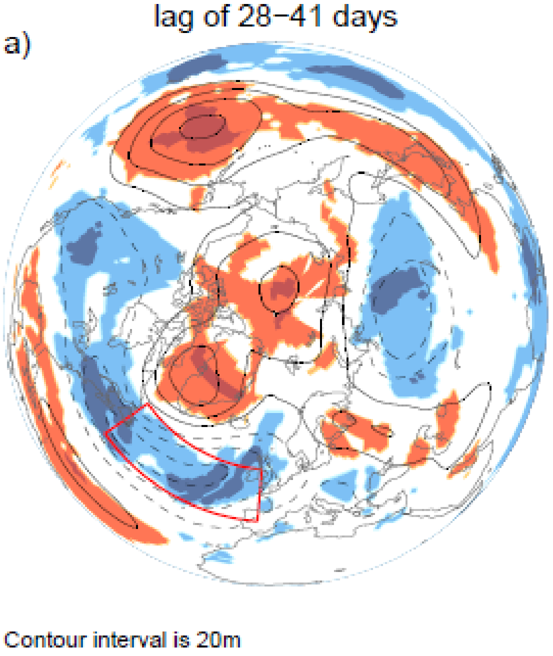
What are the extratropical impacts of the MJO?
Geopotential height at 500hPa

MJO w/SSW



MJO w/o SSW

Significant anomalies are only present for MJO phase 6/7 events followed by SSWs.

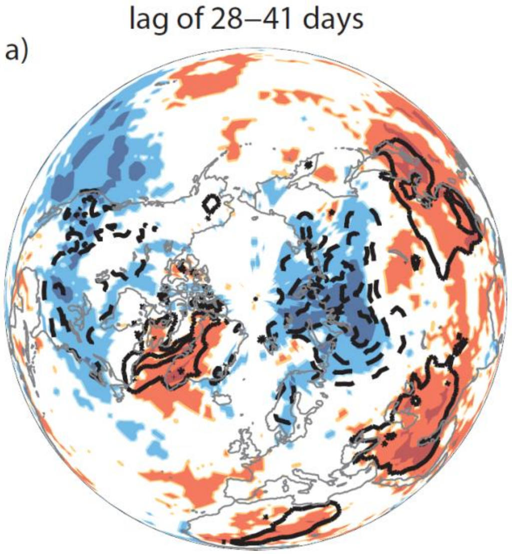
If MJO phase 6/7 event does not lead to a stratospheric anomaly, then the extratropical impacts are weak and short-lived.

Schwartz and Garfinkel 2017, JGR

Chaim I. Garfinkel

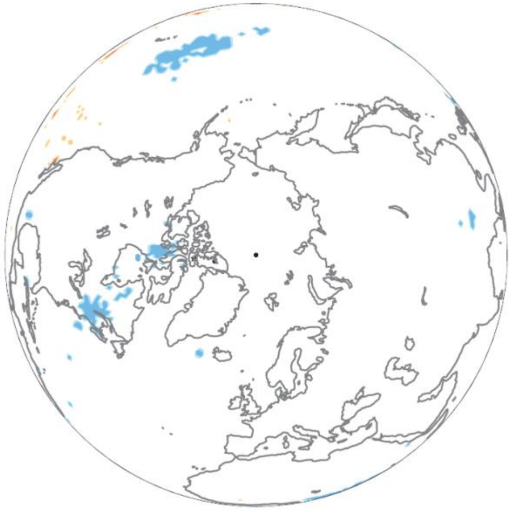
What are the extratropical impacts of the MJO?
2meter temperature

MJO w/SSW



Contour interval is 1°K

MJO w/o SSW



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What are the extratropical impacts of the MJO?

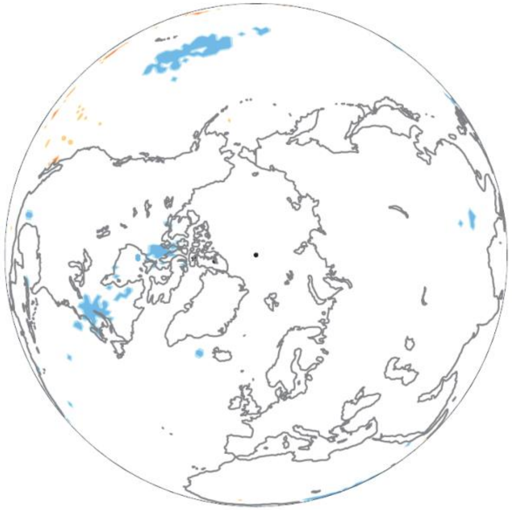
2meter temperature

Do S2S models capture this connection between the MJO and SSW?

Is stratospheric vortex variability more predictable if the MJO is strong?

Contour interval is 1°K

MJO w/o SSW



Schwartz and Garfinkel 2017, JGR

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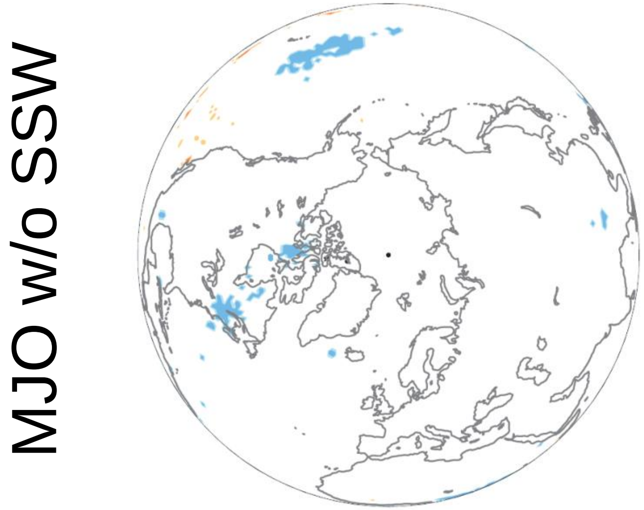
What are the extratropical impacts of the MJO?

2meter temperature

Do S2S models capture this connection between the MJO and SSW?
Is stratospheric vortex variability more predictable if the MJO is strong?

Short answer: yes, see Garfinkel and Schwartz 2017



Schwartz and Garfinkel 2017, JGR

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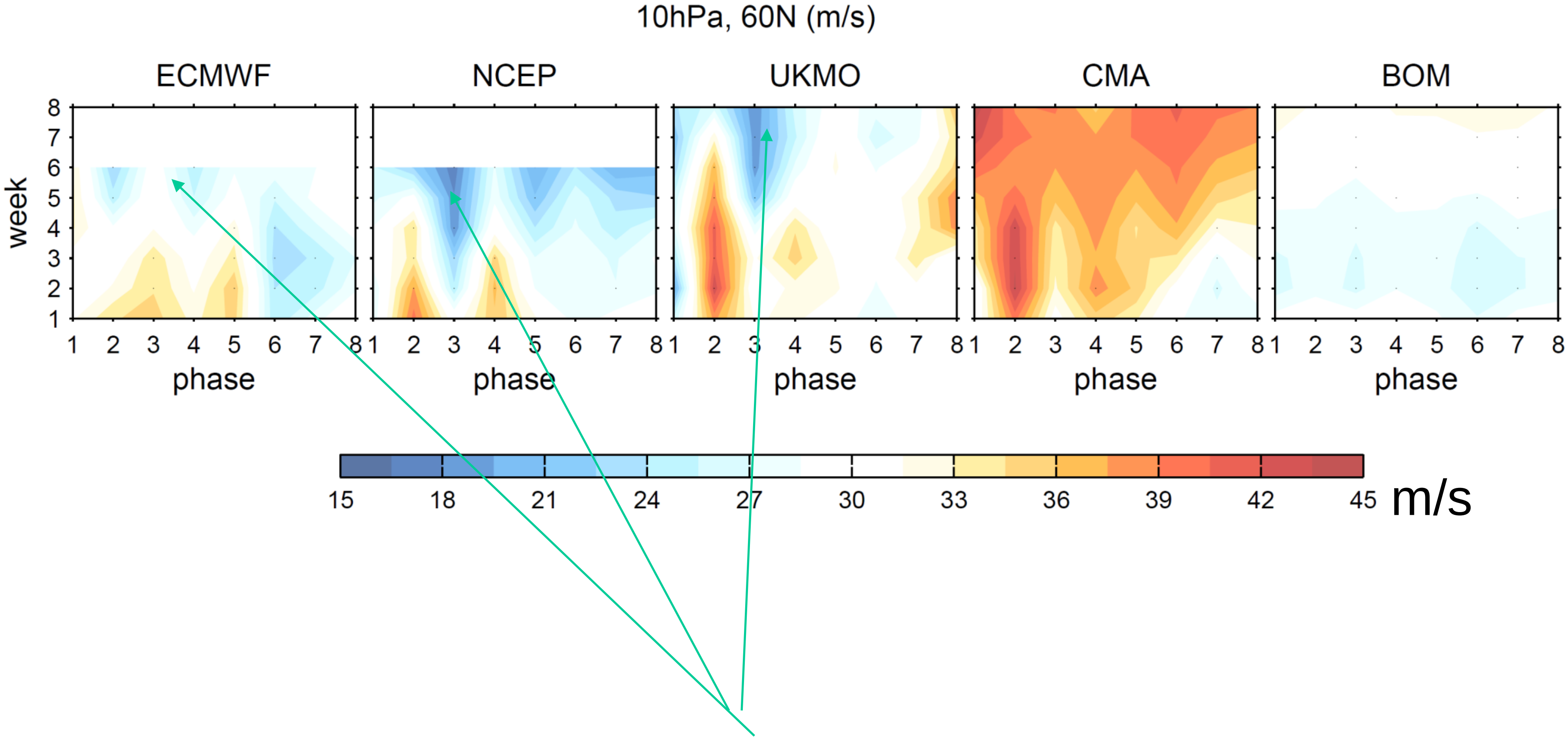
Response of zonal wind at 10hPa, 60N to the MJO



Relatively weak vortex at lags exceeding 5 weeks for phase 2/3 relative to 6/7 (as observed)

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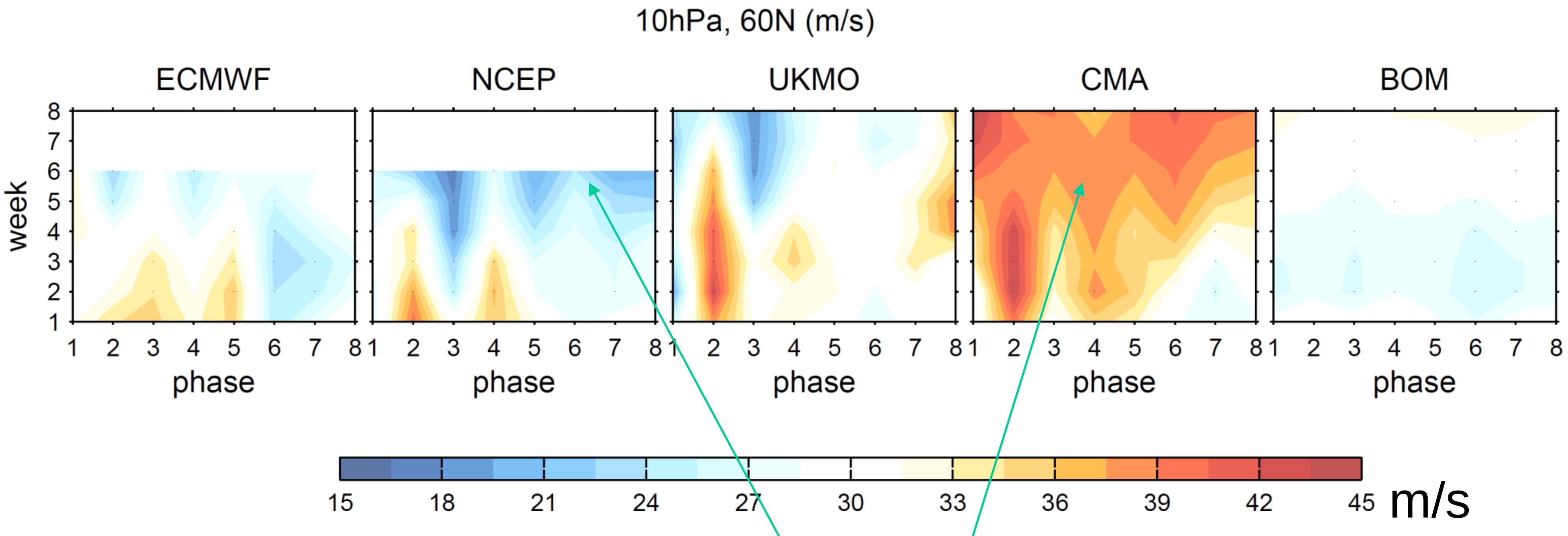
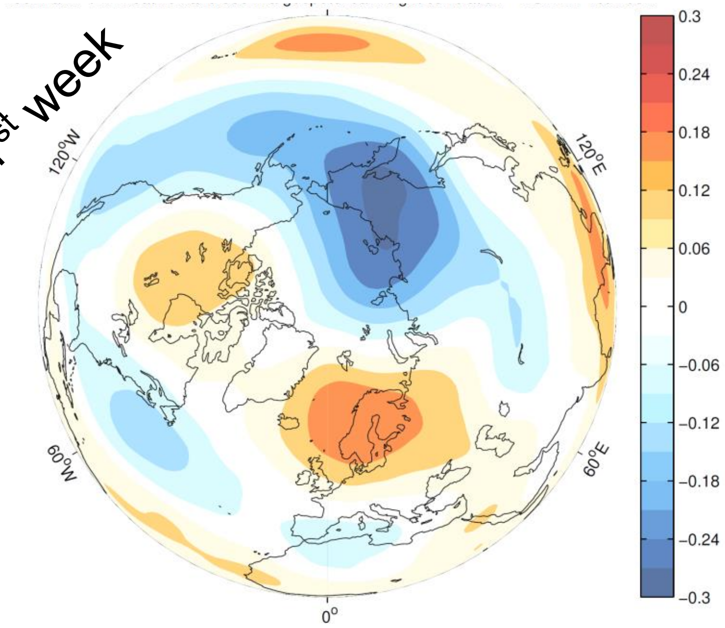
Subpolar stratospheric response to the MJO



Model drift

Overly weak upward coupling in S2S models

Correlation of 500hPa geopotential height with 100hPa wave1+2 heat flux

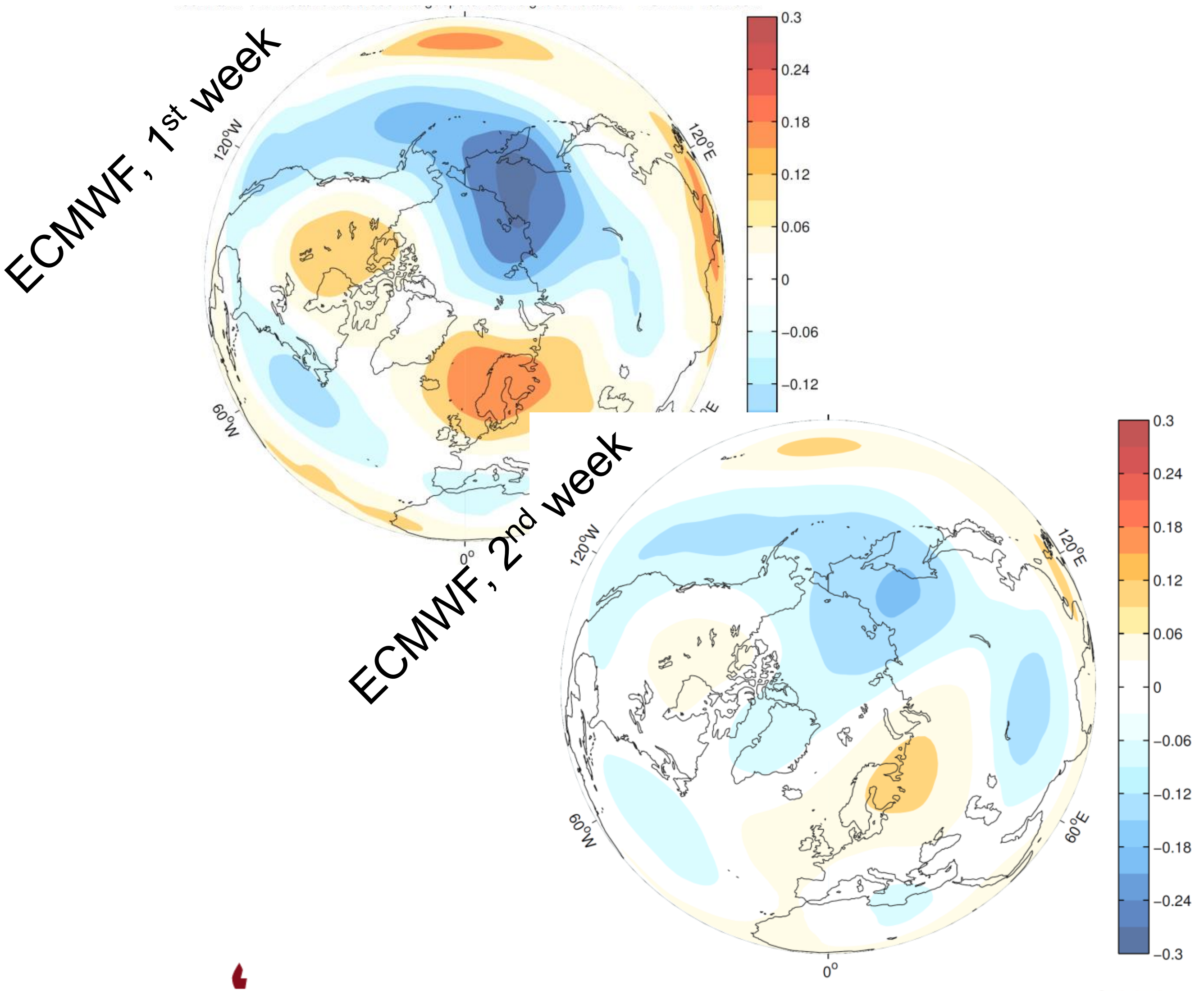


ECMWF, 1st week

Consistent with observed response: Garfinkel et al 2010, Woolings et al 2010; Cohen and Jones 2011

Overly weak upward coupling in S2S models

Correlation of 500hPa geopotential height with 100hPa wave1+2 heat flux



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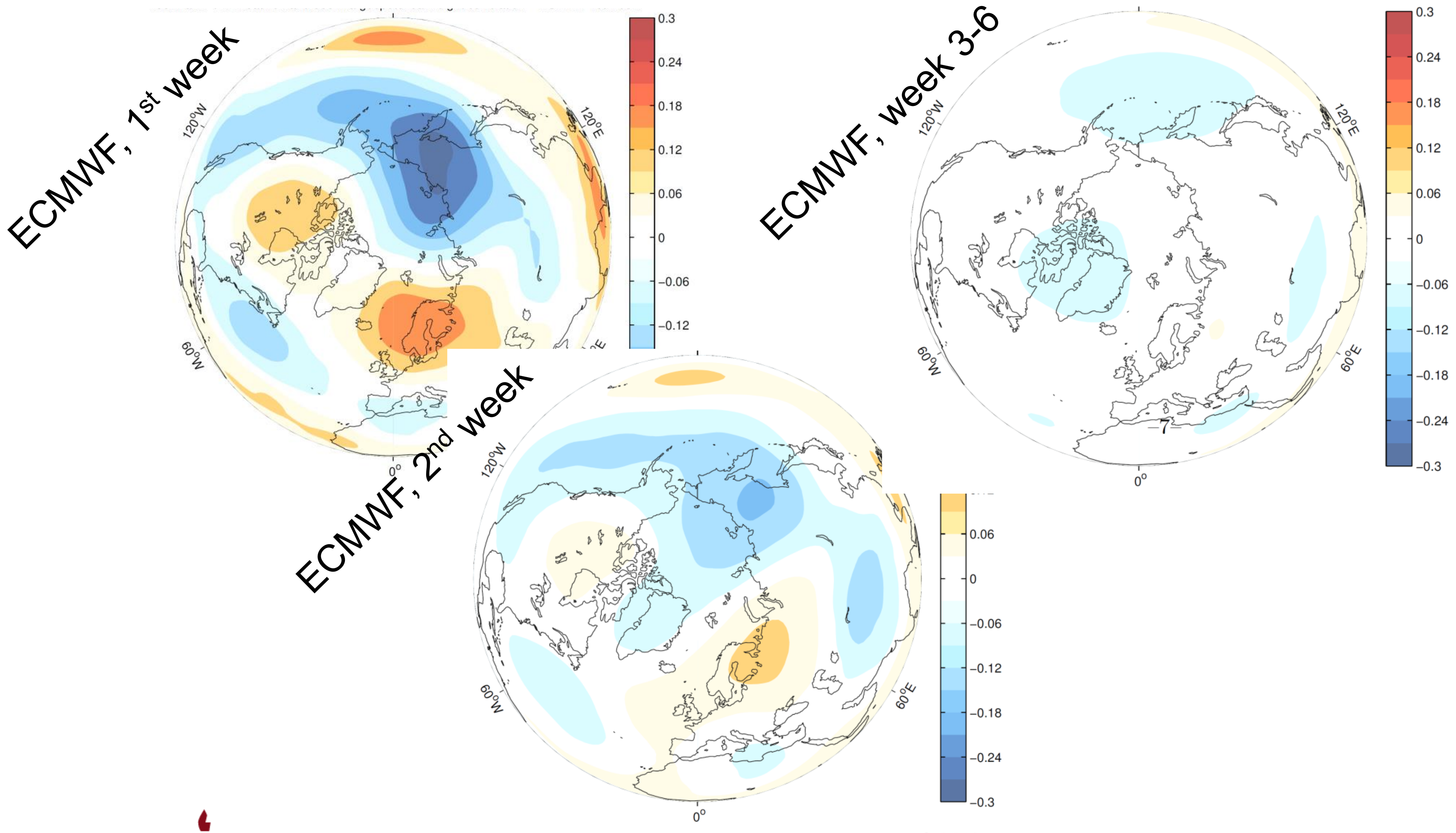

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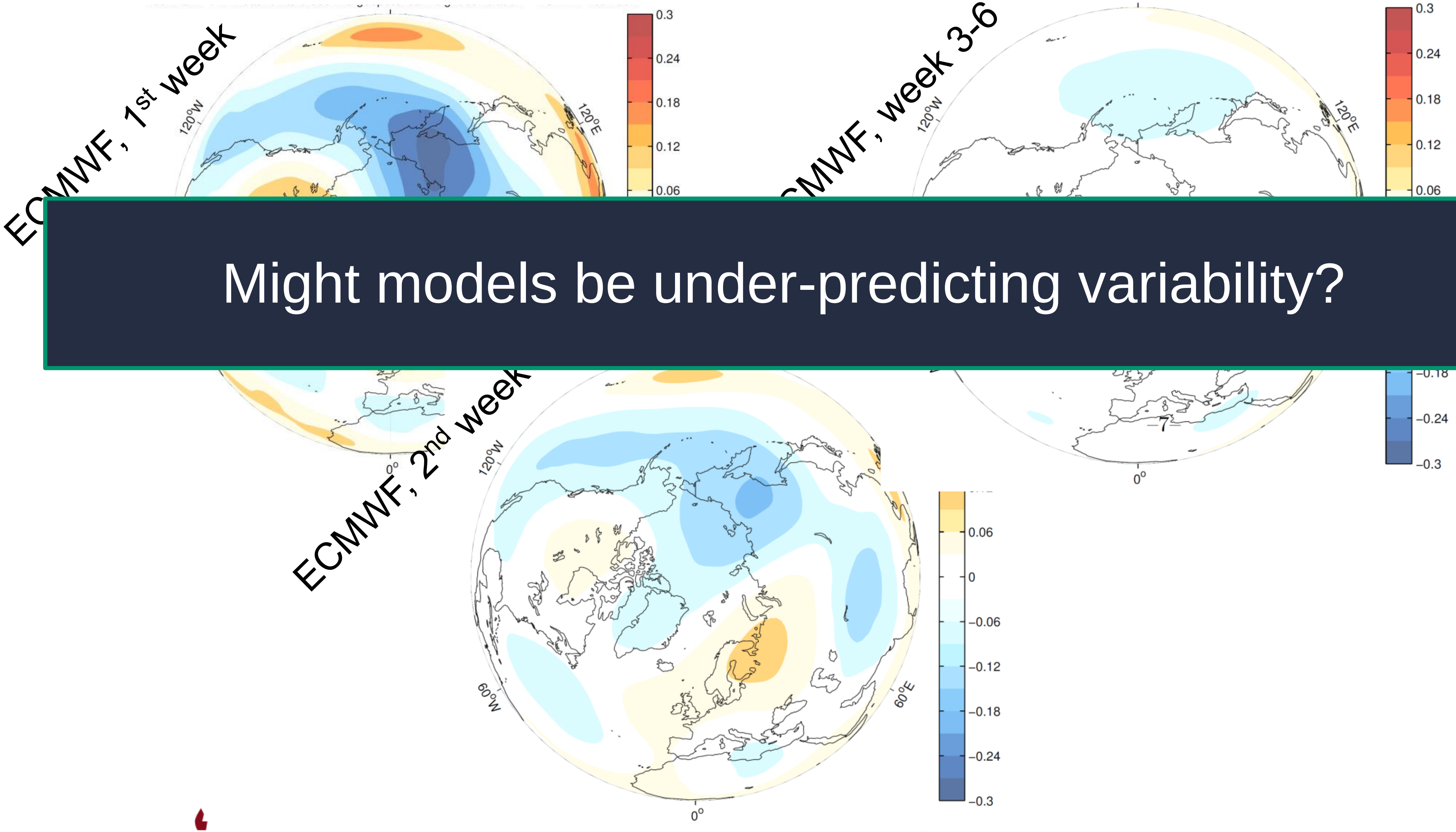

Might models be under-predicting variability?

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Take home messages

Operational subseasonal forecasts already have some probabilistic skill in forecasting stratospheric vortex and surface conditions at ~1 month leads using the state of the MJO and QBO.   But…..

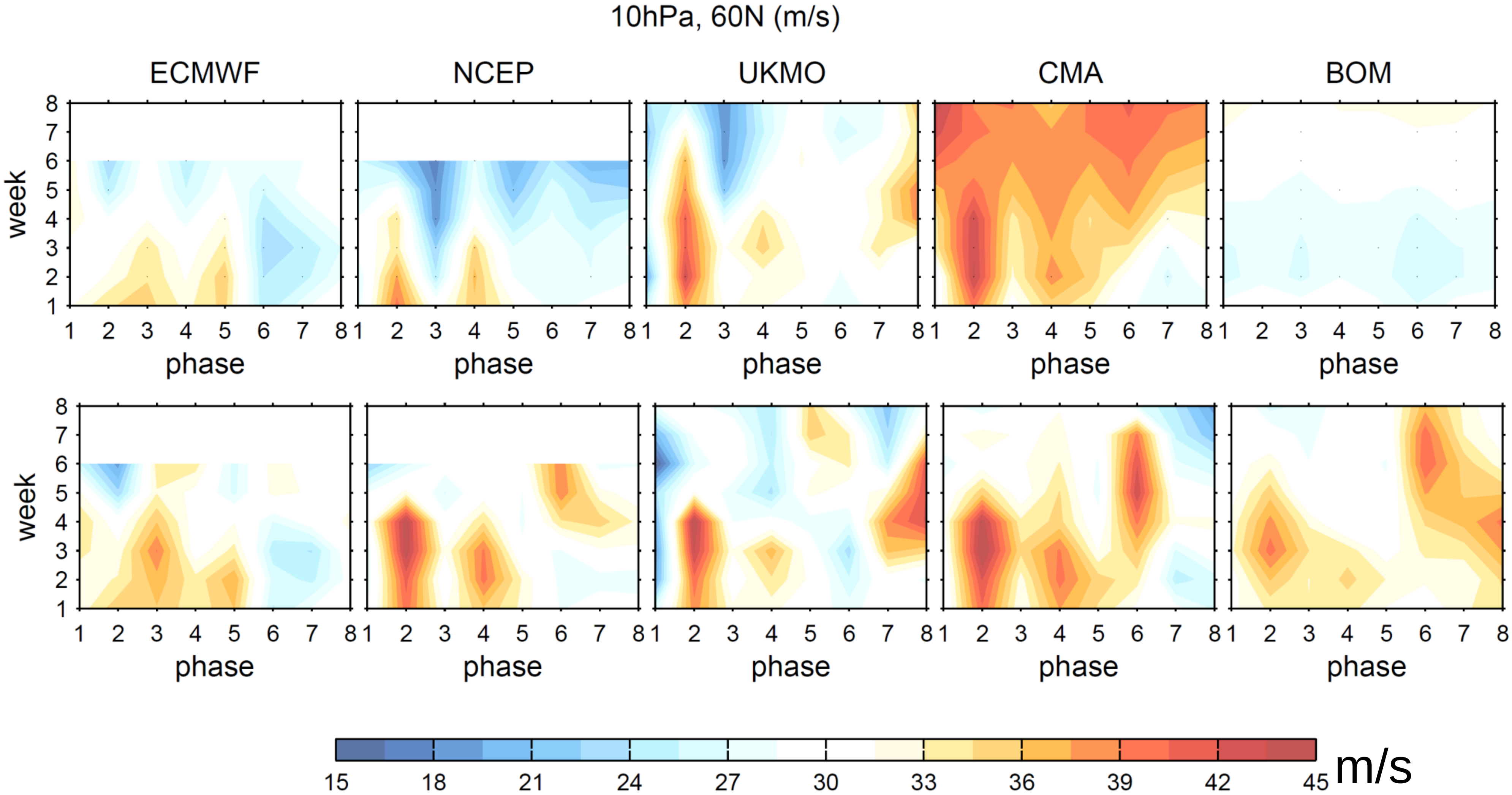
There are biases – QBO decays in time, upward coupling is too weak in the models, and low-top models systematically perform worse than high-top models (model drift and overly weak variability)

Also, data archive only includes four stratospheric levels. More data would be helpful (see SNAP request)!!

Garfinkel, C.I. and Schwartz, C., 2017. MJO-Related Tropical Convection Anomalies Lead to More Accurate Stratospheric Vortex Variability in Subseasonal Forecast Models. *Geophysical research letters*, *44*(19).

Garfinkel, C.I., Schwartz, C., Domeisen, D.I., Son, S.W., Butler, A.H. and White, I.P., 2018. Extratropical Atmospheric Predictability From the Quasi-Biennial Oscillation in Subseasonal Forecast Models. *Journal of Geophysical Research: Atmospheres*, *123*(15), pp.7855-7866.

Subpolar stratospheric response to the MJO



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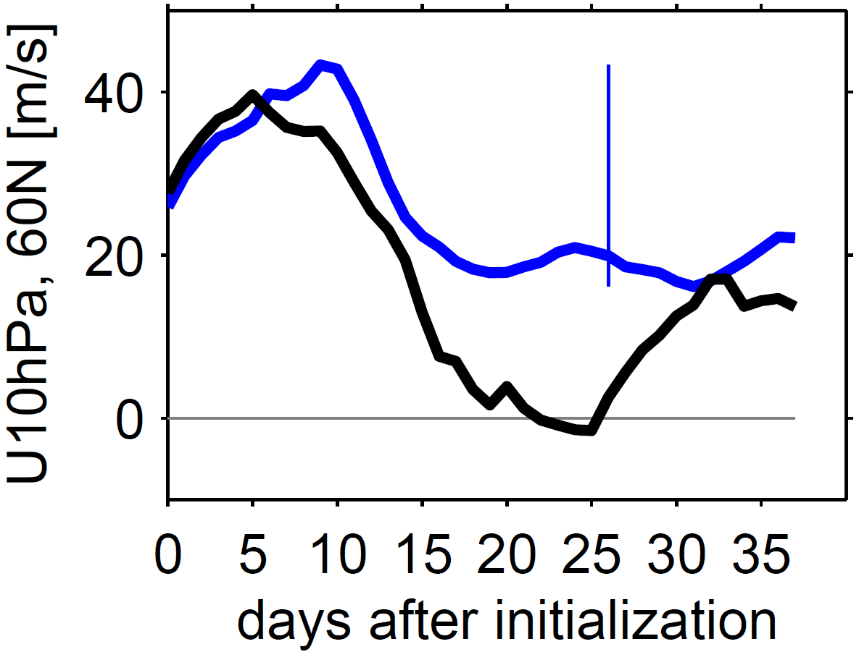
Case study: SSW on Jan 2, 2002

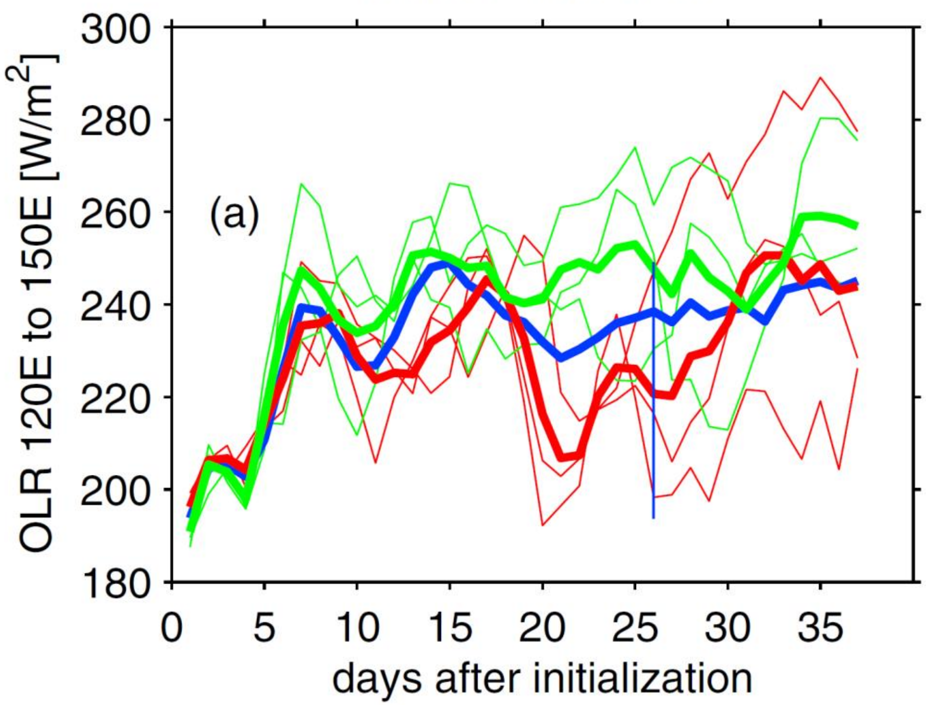


MERRA
S2S (ECMWF), ens. mean

SSW on Jan 2, 2002 was preceded by long-lived phase 6 and 7 MJO event

Ensemble mean of forecasts initialized 26 days prior (ECMWF) shows a weakening of the vortex but no SSW.

Case study: SSW on Jan 2, 2002



MERRA

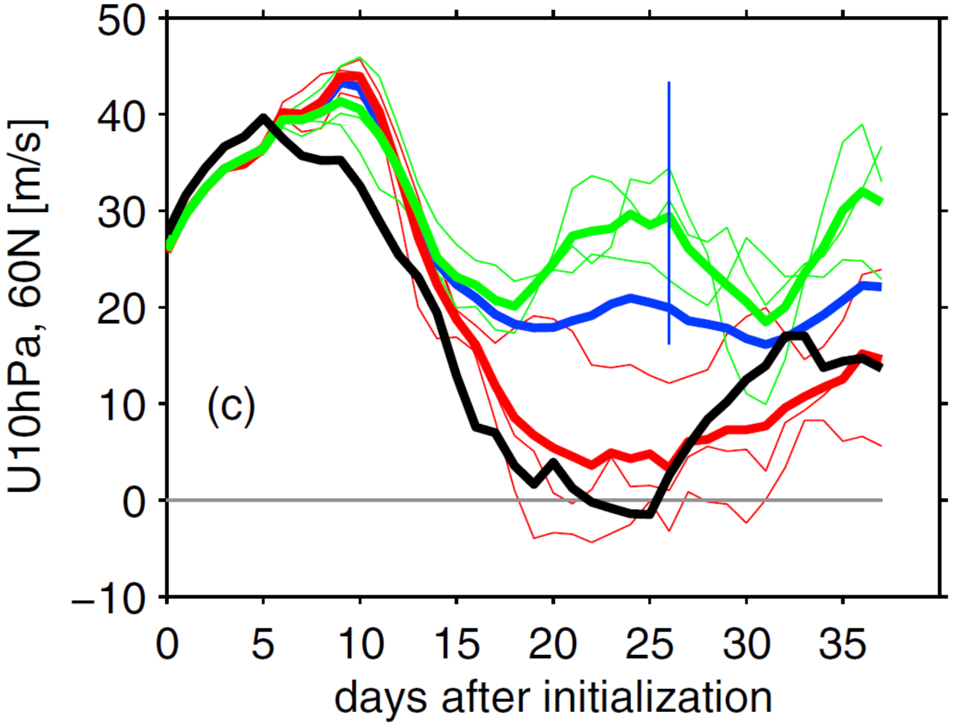
S2S (ECMWF) ens mean

reduced West Pac. convection

enhanced West Pac. convection

The 11 ECMWF ensemble members are split up into integrations with high OLR in the West Pacific and low OLR in the West Pacific.

Case study: SSW on Jan 2, 2002



MERRA

S2S (ECMWF) ens mean

reduced West Pac.
convection

enhanced West Pac.
convection

The low OLR ensemble members are much closer to reality, while the high OLR ensemble members simulate a relatively stronger vortex.

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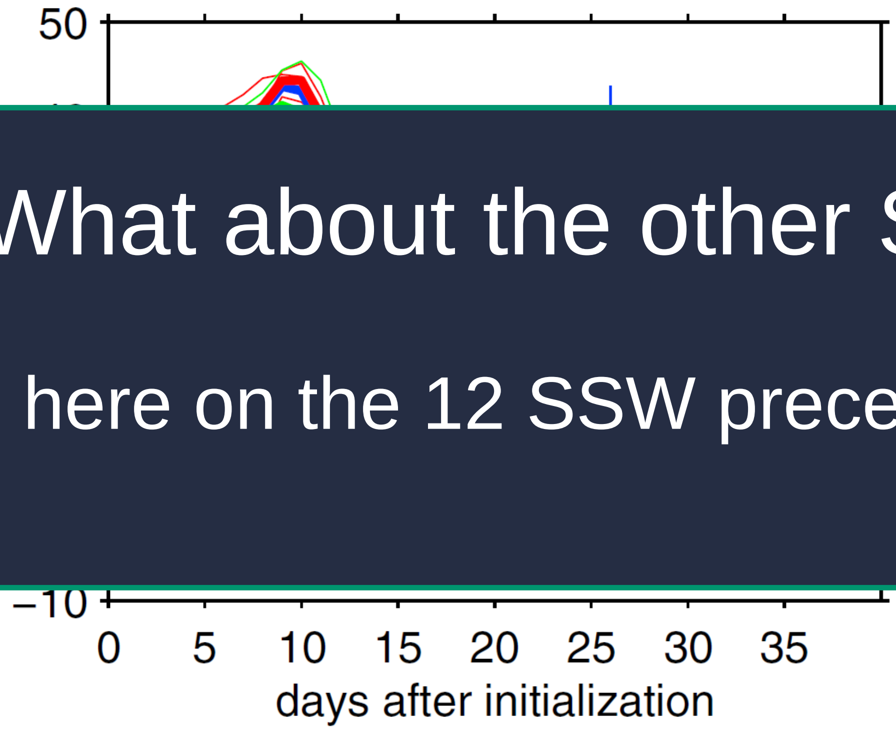
Case study: SSW on Jan 2, 2002



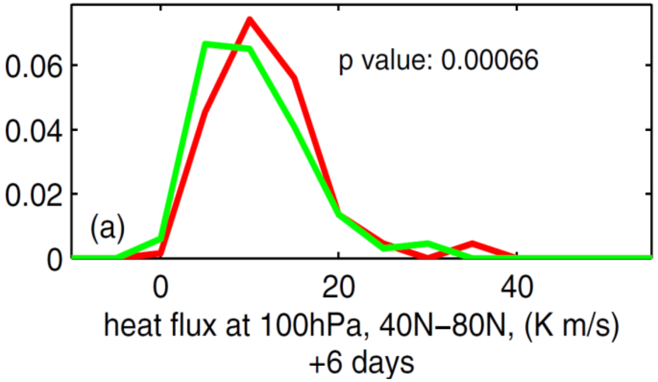
What about the other SSW events?

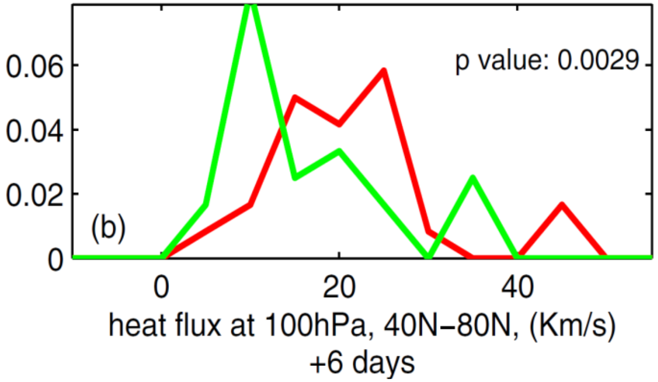
(focus here on the 12 SSW preceded by a strong MJO)

convection

The low OLR ensemble members are much closer to reality, while the high OLR ensemble members simulate a relatively stronger vortex.

PDFs for all SSWs preceded by MJO


Bureau of Meteorology
probability distribution function

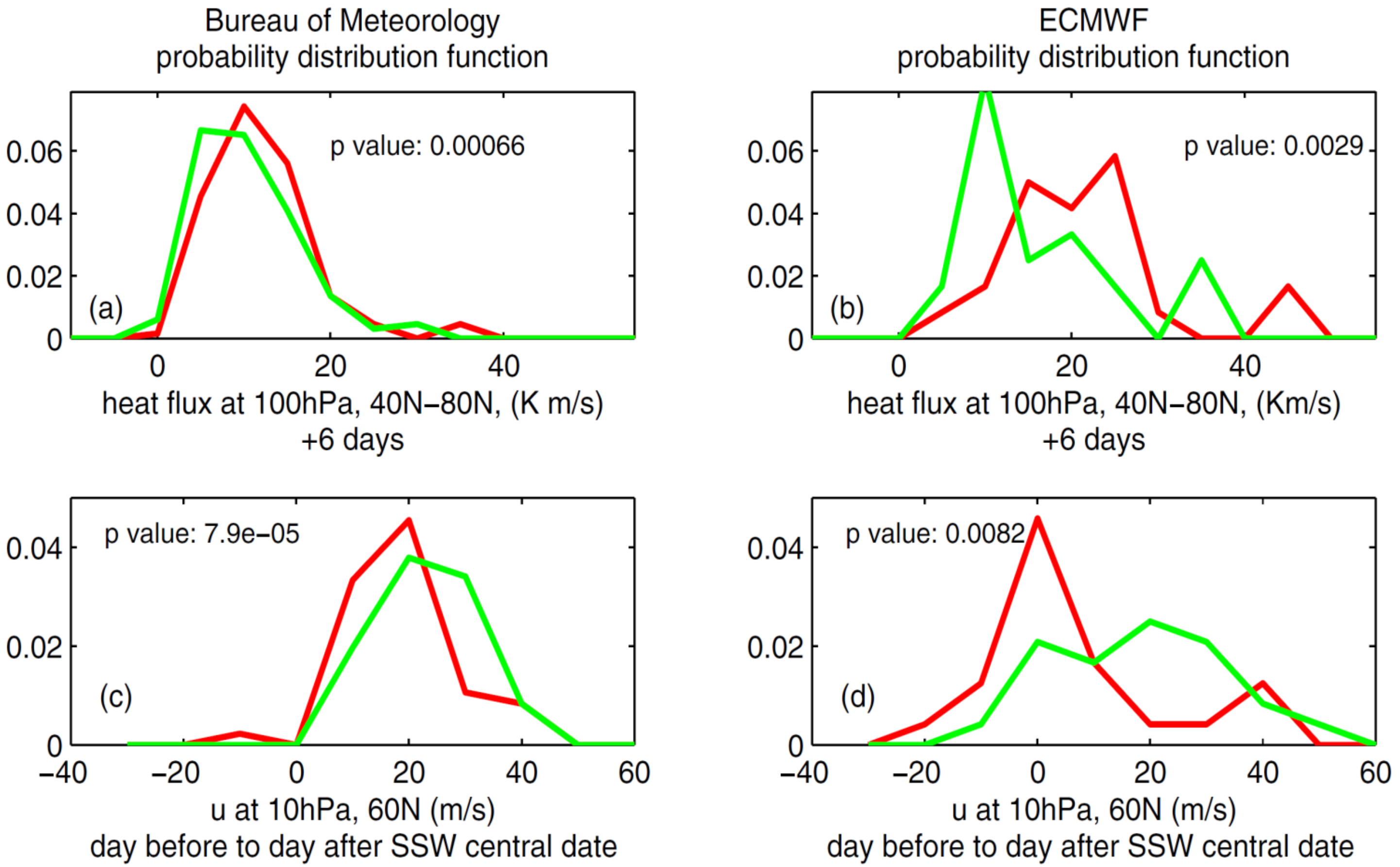

ECMWF
probability distribution function

reduced West Pac. convection

enhanced West Pac. convection

The low OLR ensemble members simulate enhanced stratospheric wave driving as to compared to high OLR ensemble members.

PDFs for all SSWs preceded by MJO


Bureau of Meteorology probability distribution function

ECMWF probability distribution function

reduced West Pac. convection

enhanced West Pac. convection

The low OLR ensemble members simulate enhanced stratospheric wave driving as to compared to high OLR ensemble members. Vortex response follows heat flux response.

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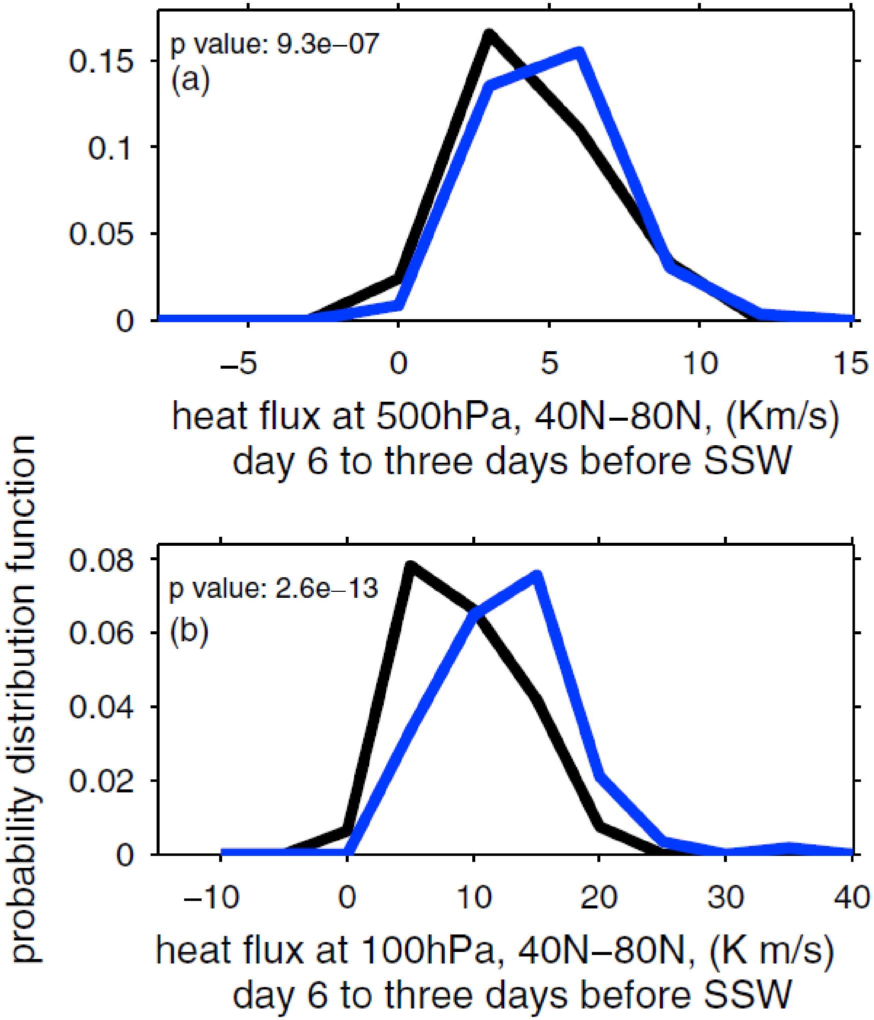
SSWs preceded by MJO are more predictable ~20 days in advance


Enhanced predictability of SSW preceded by a strong MJO

SSW without MJO (11 events)

SSW with MJO (12 events)

For initializations ~20 days before observed SSW, SSW that follow MJO have significantly more heat flux at 500hPa and 100hPa.

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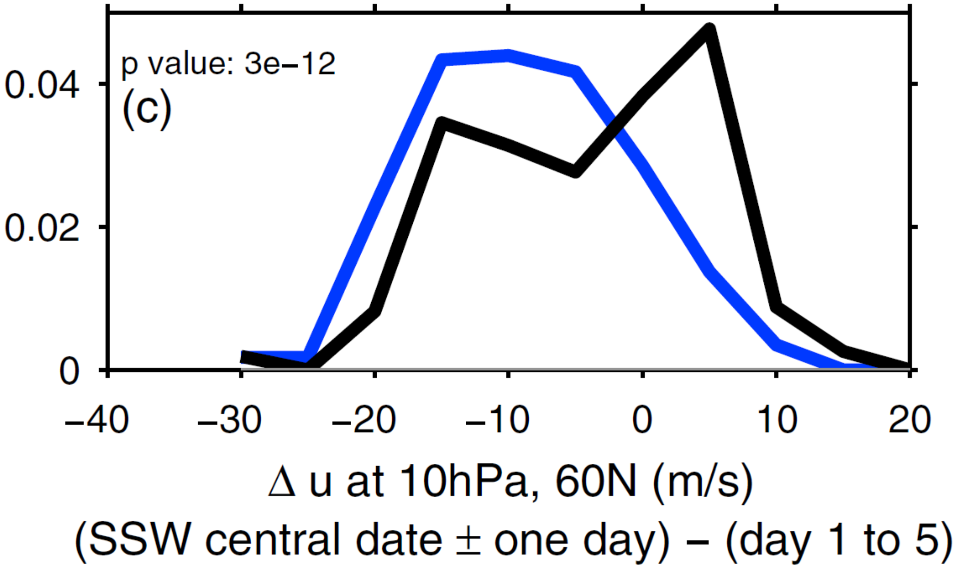

SSW without MJO (11 events)

SSW with MJO (12 events)

For initializations ~20 days before observed SSW, SSW that follow MJO have significantly stronger deceleration of the vortex.

Conclusions

The MJO modulates the vortex, with phase 6/7 (convection in west Pacific) immediately preceding Stratospheric sudden warmings.

- Reforecasts which simulate stronger MJO-related convection in the Tropical West Pacific also simulate enhanced heat flux in the lowermost stratosphere and a more realistic vortex evolution.
- The time scale on which vortex predictability is enhanced lies between 2 and 4 weeks for nearly all cases.
- Those stratospheric sudden warmings that were preceded by a strong MJO event are more predictable at ~20 day leads than stratospheric sudden warmings not preceded by a MJO event.

Garfinkel, C.I. and Schwartz, C., 2017. MJO-Related Tropical Convection Anomalies Lead to More Accurate Stratospheric Vortex Variability in Subseasonal Forecast Models. *Geophysical research letters*, *44*(19).

Schwartz, C. and C.I. Garfinkel. Relative Roles of the MJO and Stratospheric Variability in North Atlantic and European Winter Climate. J. Geoph. Res.

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Take home message

Operational subseasonal forecasts have some probabilistic skill in forecasting stratospheric vortex conditions up to a month before using the state of the MJO and QBO.

There are biases though – QBO decays in time, and upward coupling is too weak in the models

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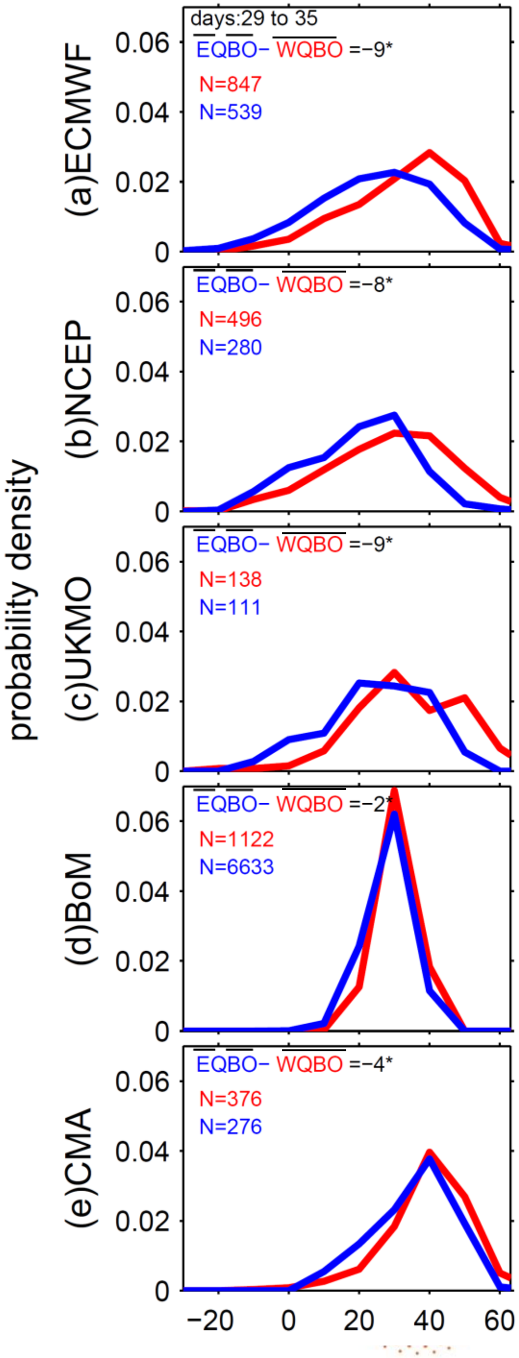
Useful for probabilistic forecasting of vortex

zonal wind at 10hPa, 60N; days 29 to 35



WQBO
EQBO;

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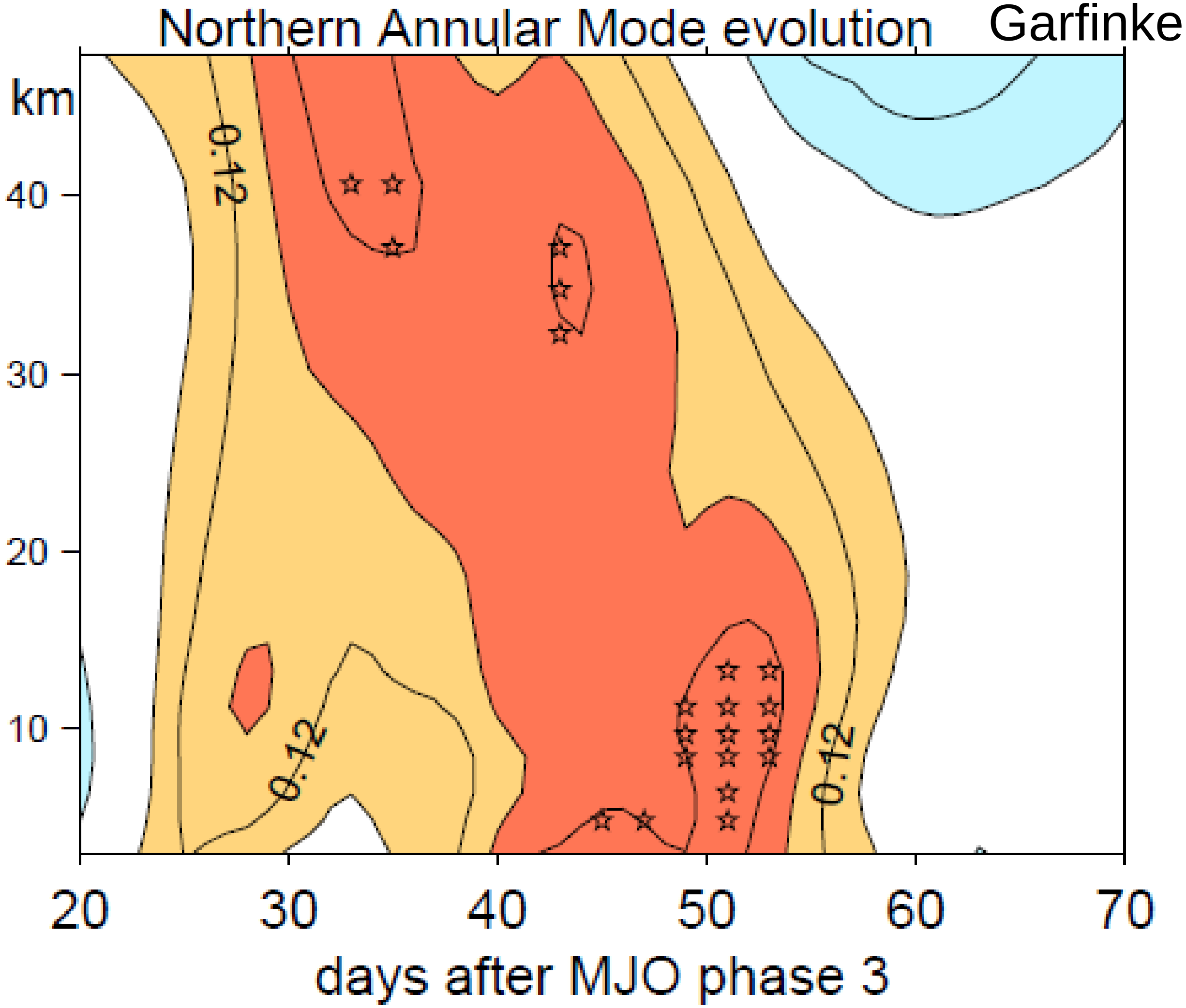
Downward Propagation of MJO Anomaly

Garfinkel et al 2012, GRL



Contours shown normalized polar cap height anomalies.

Contour interval: 0.06 standard deviations

MJO -> vortex -> tropospheric northern annular mode

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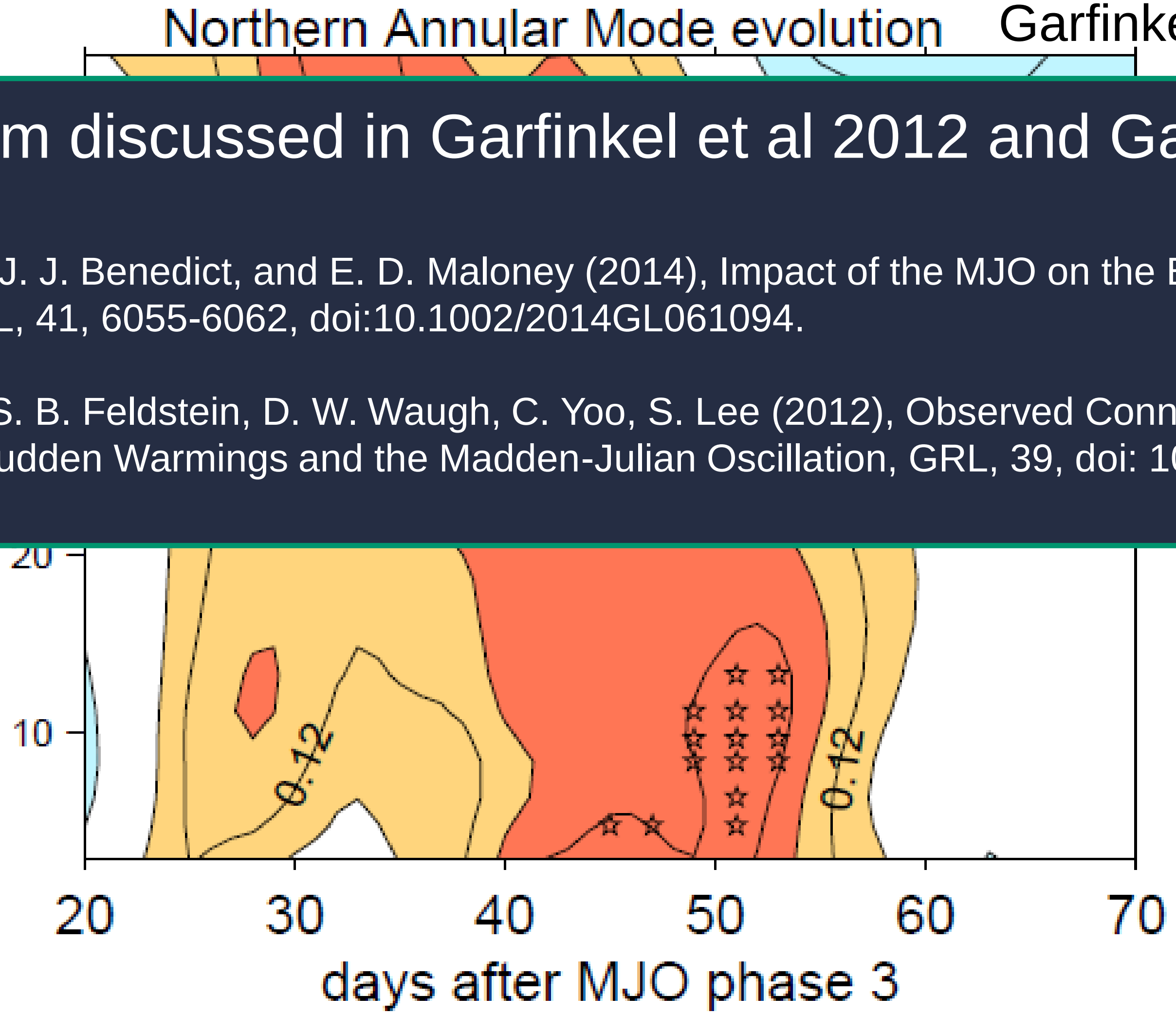
Downward Propagation of MJO Anomaly

Garfinkel et al 2012, GRL



Mechanism discussed in Garfinkel et al 2012 and Garfinkel et al 2014

Garfinkel, C. I., J. J. Benedict, and E. D. Maloney (2014), Impact of the MJO on the Boreal Winter Extratropical Circulation, GRL, 41, 6055-6062, doi:10.1002/2014GL061094.

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standard deviations

MJO -> vortex -> tropospheric northern annular mode

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Can the Impacts of the MJO and stratosphere be separated?

It has been argued that the MJO directly influences weather and subseasonal climate over Europe and the North Atlantic (e.g. Cassou 2008, Nature).

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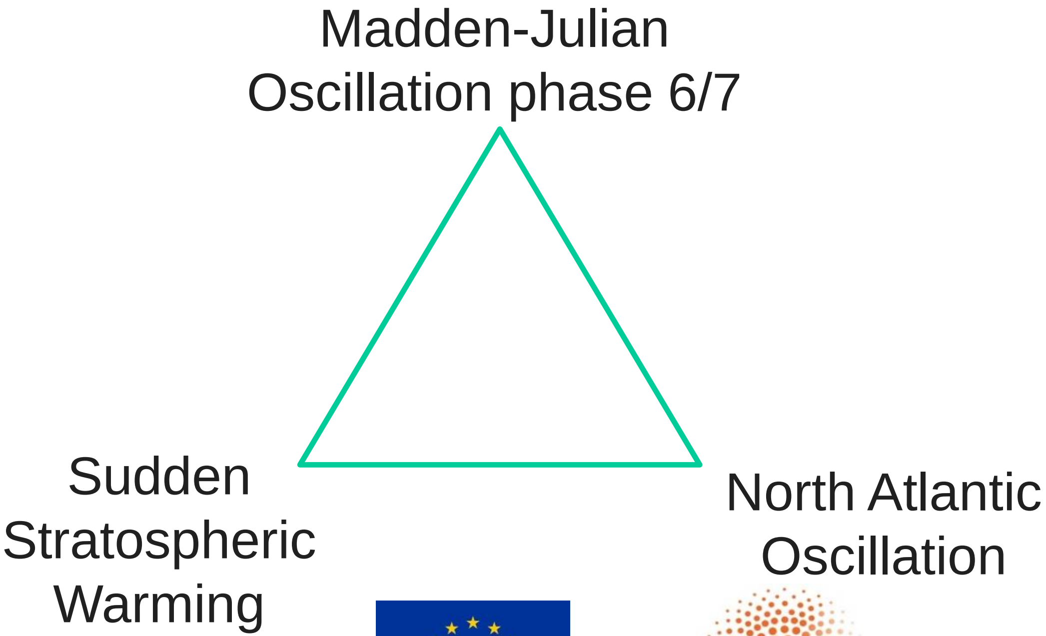
More than half of SSW events since 1979 occurred during one specific MJO phase



Madden-Julian Oscillation phase 6/7

Sudden Stratospheric Warming

North Atlantic Oscillation

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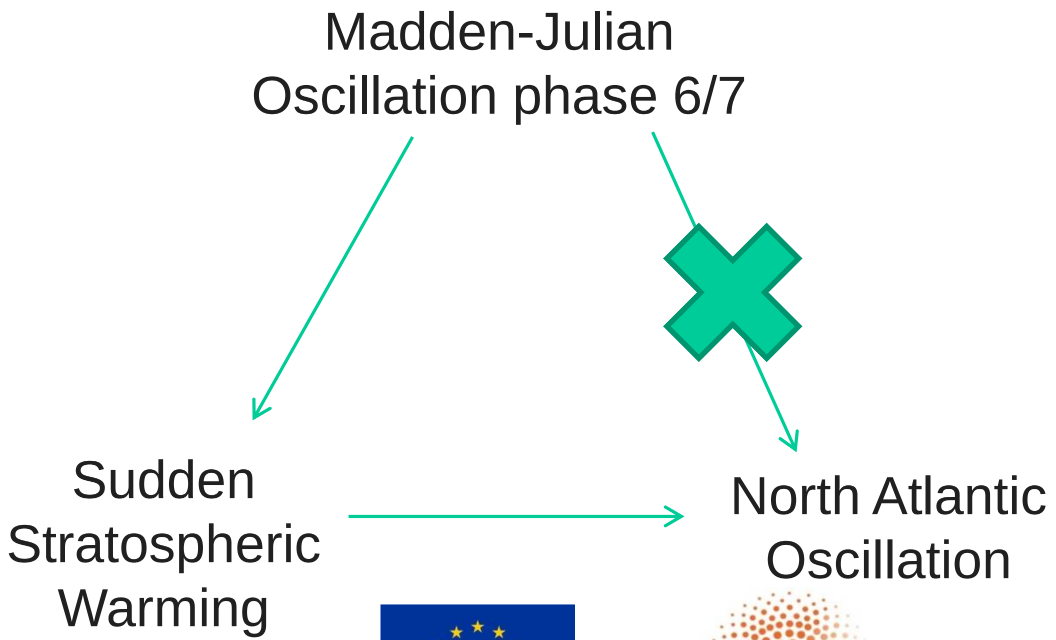
Is MJO->NAO connection an artifact of the influence of the MJO on the stratosphere?



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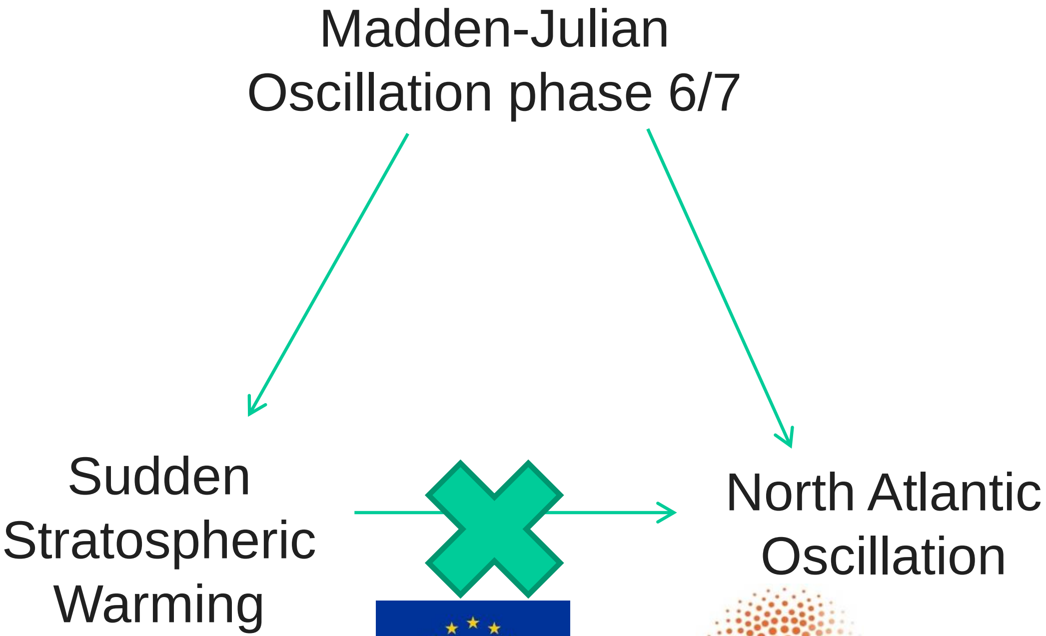
Is the apparent influence of SSW on NAO an artifact of aliasing with the MJO?



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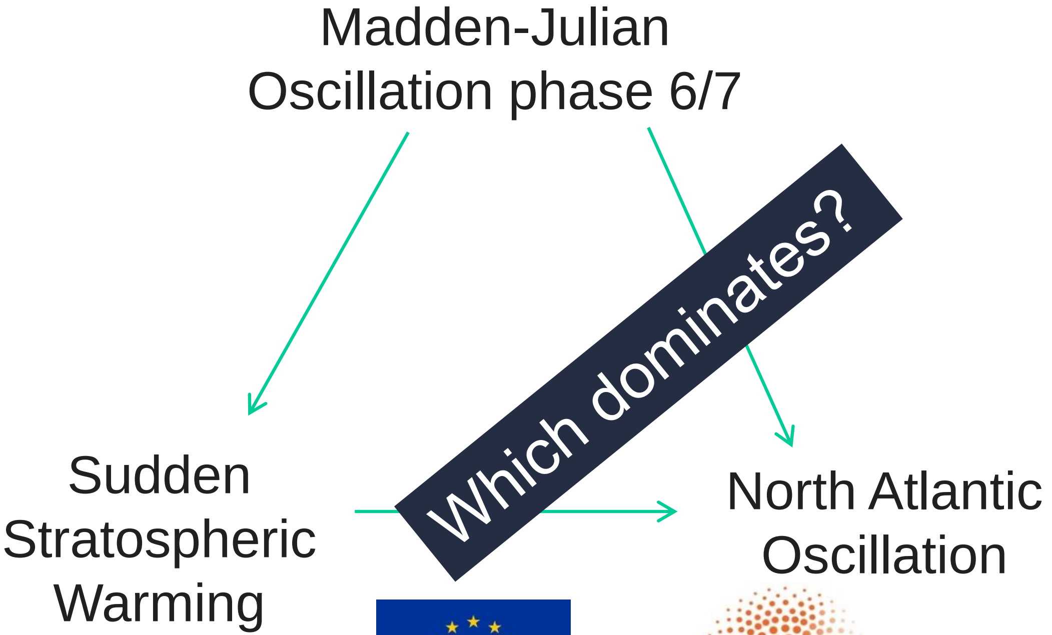
Do the MJO and SSW independently affect the NAO? Which dominates?



Madden-Julian Oscillation phase 6/7

Sudden Stratospheric Warming

North Atlantic Oscillation

Which dominates?

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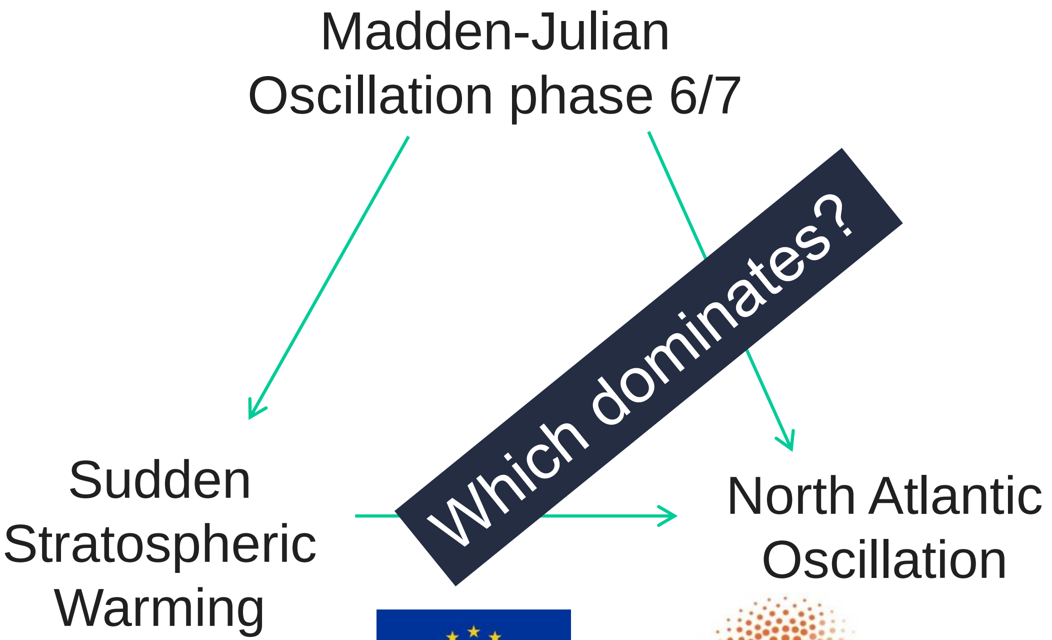
Approach

We disentangle their respective influences by comparing the tropospheric anomalies among three composite:

1. MJO phase 6/7 that preceded a SSW (MJOSSW, 12 events)
2. MJO phase 6/7 that occurred without a subsequent SSW (MJOw/oSSW, 87 events)
3. SSW events not preceded by MJO phase 6/7 (SSWw/oMJO, 11 events).



Madden-Julian Oscillation phase 6/7

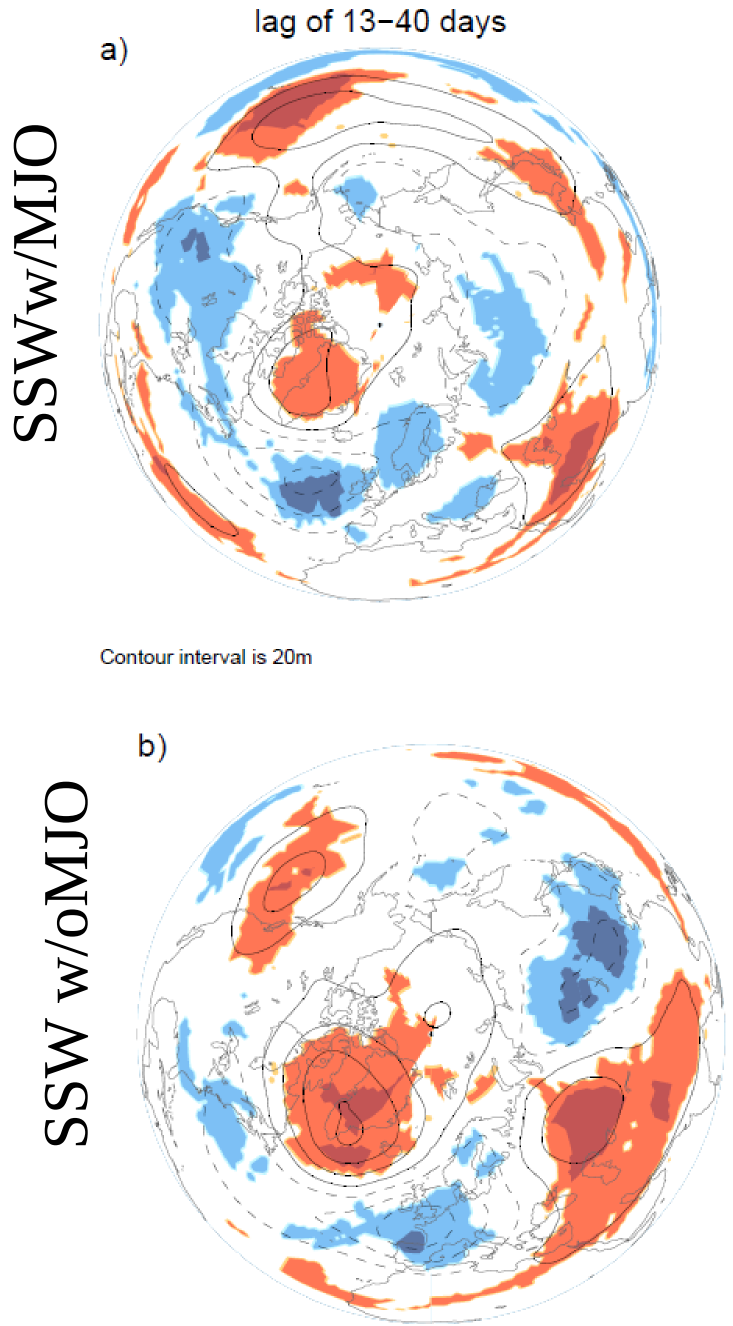
Sudden Stratospheric Warming

North Atlantic Oscillation

Which dominates?

MJO modulates the impact of SSWs in troposphere

Geopotential height at 500hPa



While SSW events lead to a negative NAM signal regardless of MJO phase, the spatial patterns are subtly different.

SSWw/MJO is associated with an East Atlantic type pattern, while SSWw/oMJO is associated more with a more conventional negative NAO phase

Different sea level pressure and surface temperature impacts.

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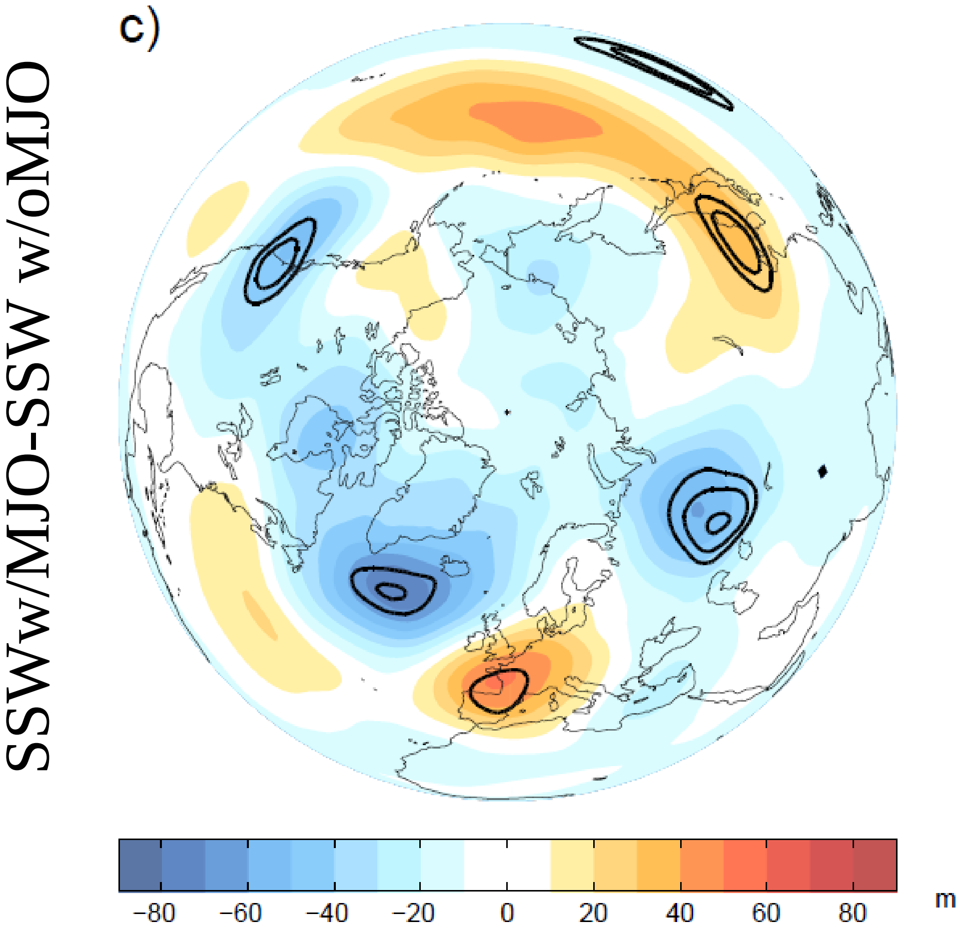
MJO modulates the impact of SSWs in troposphere
Geopotential height at 500hPa



Difference between SSWw/MJO and SSWw/oMJO is statistically significant at the 95% level (black contours) in the North Atlantic

Significantly different sea level pressure and surface temperature impacts.

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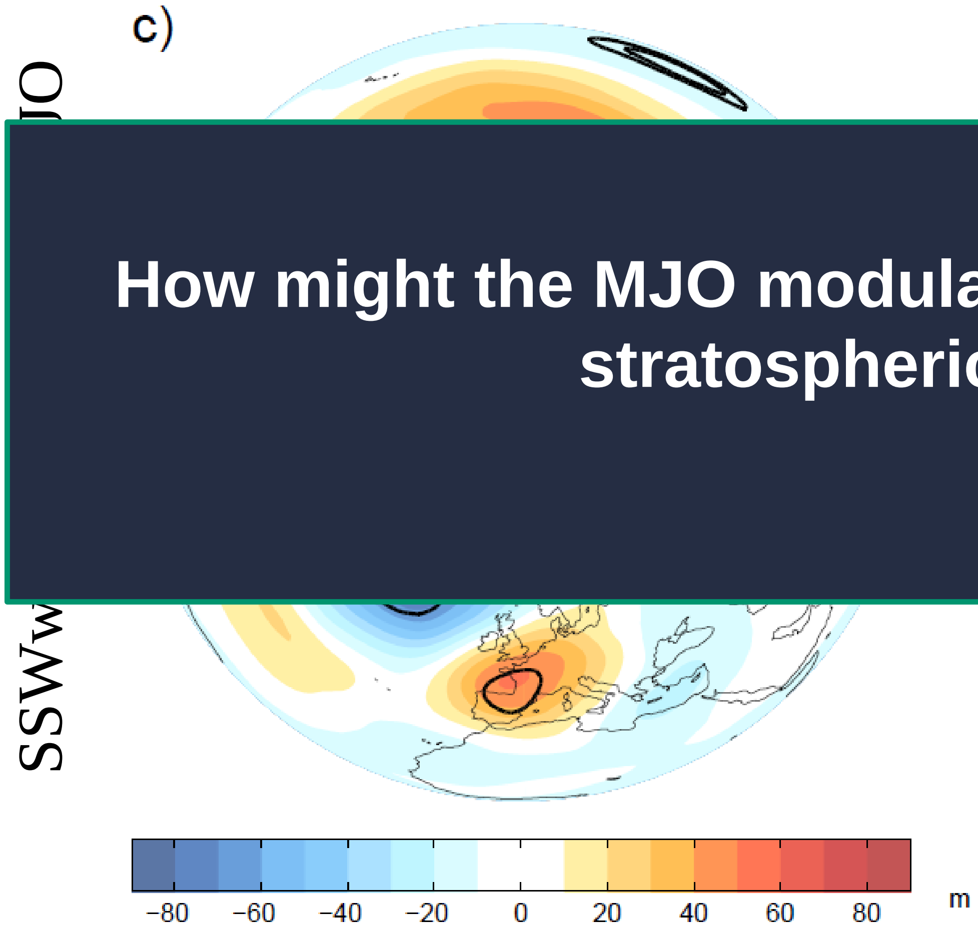
MJO modulates the impact of SSWs in troposphere
Geopotential height at 500hPa



How might the MJO modulate the downward impact of stratospheric variability?

pressure and surface temperature impacts.

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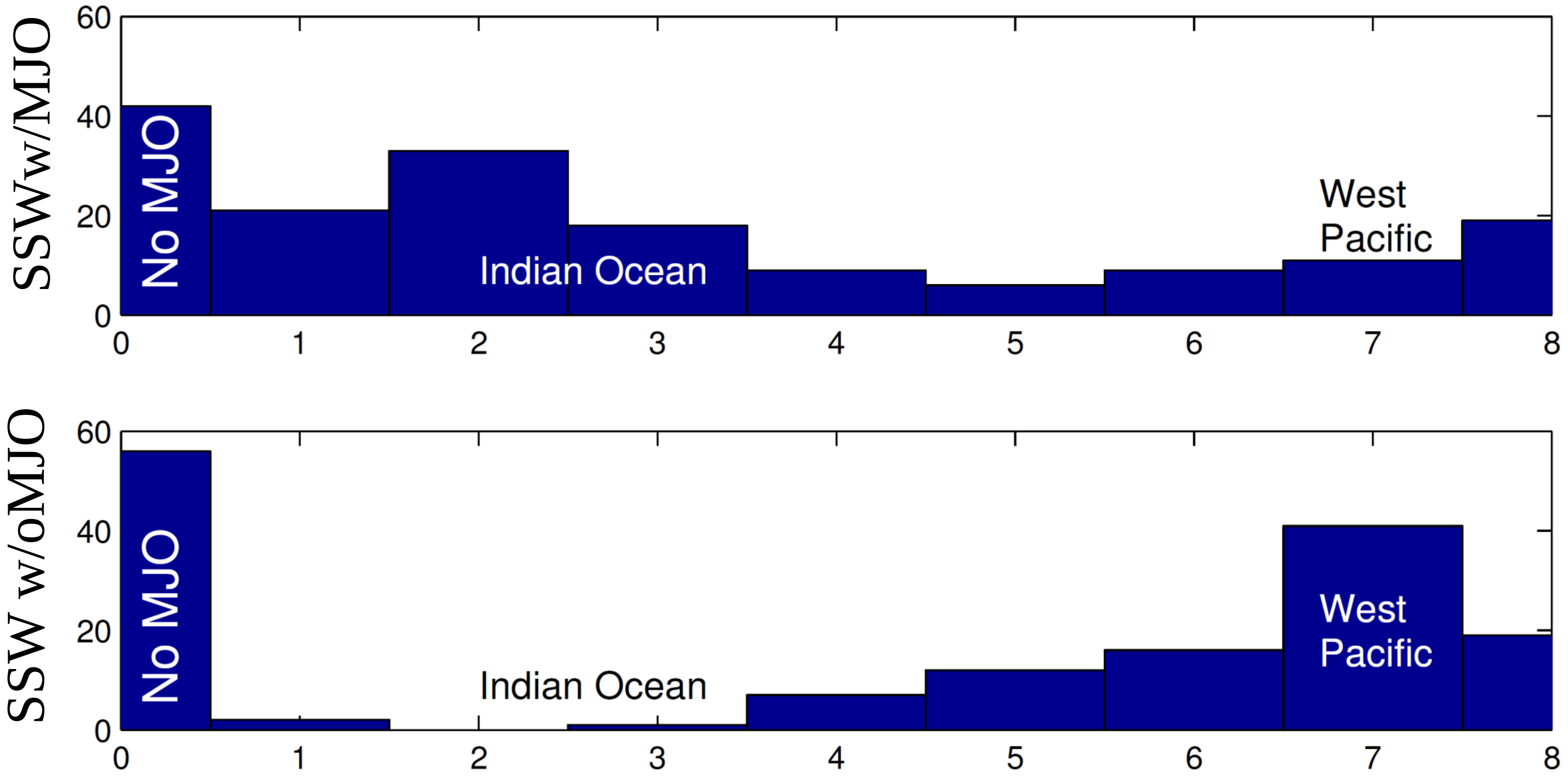
Why does the MJO modulate the impact of SSWs?

Number of occurrences of each MJO phase 13-26 days after SSW

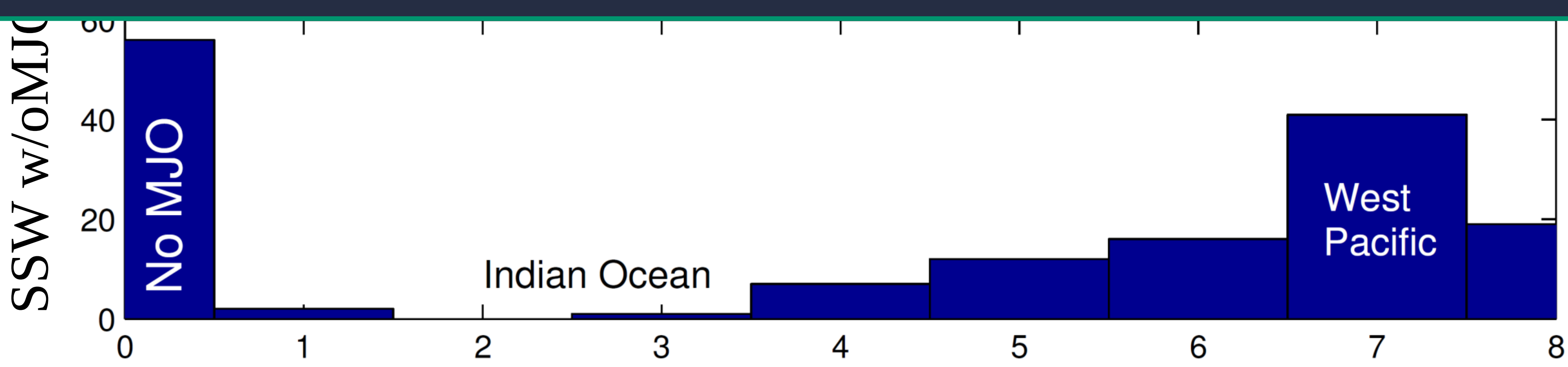


Large difference in convective activity following SSWs.

Why does the MJO modulate the impact of SSWs?

Number of occurrences of each MJO phase 13-26 days after SSW

These convective anomalies launch a Rossby wavetrain within the troposphere



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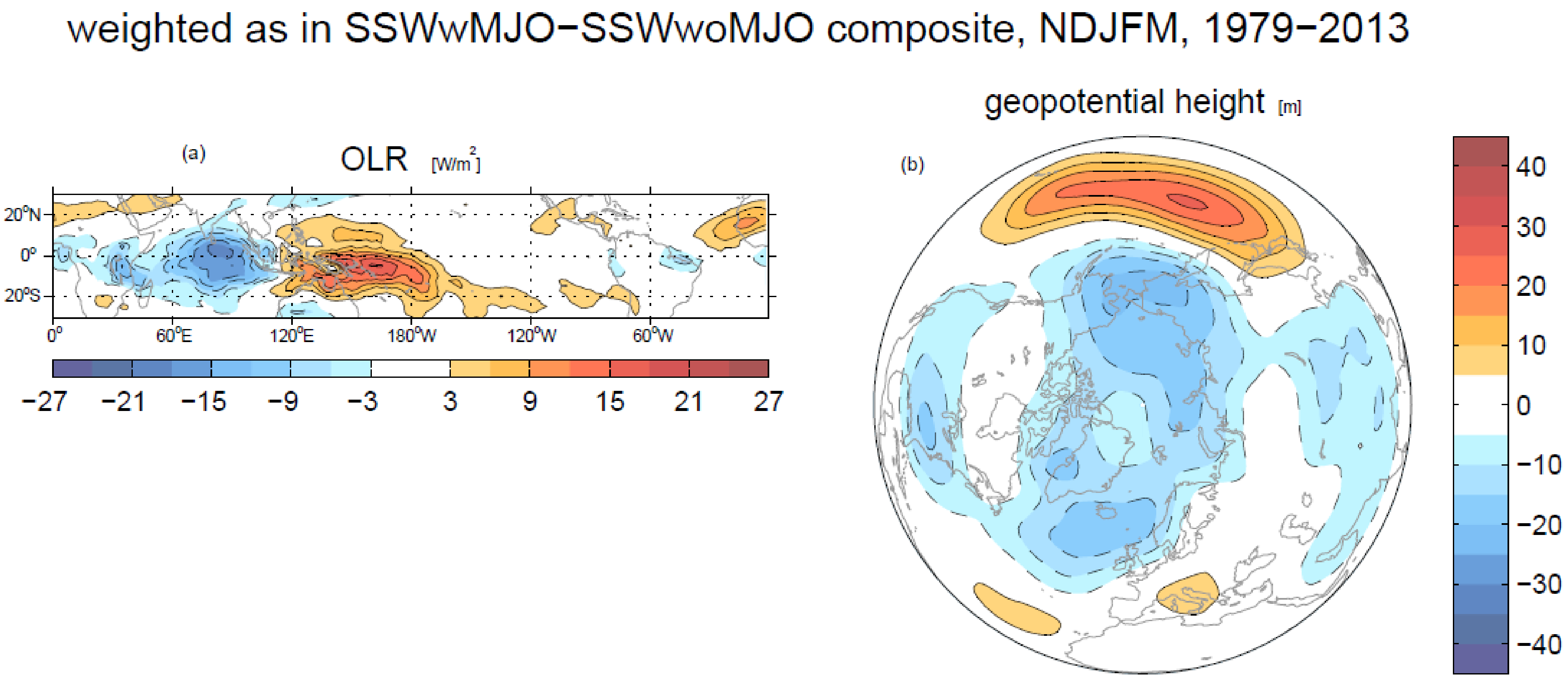


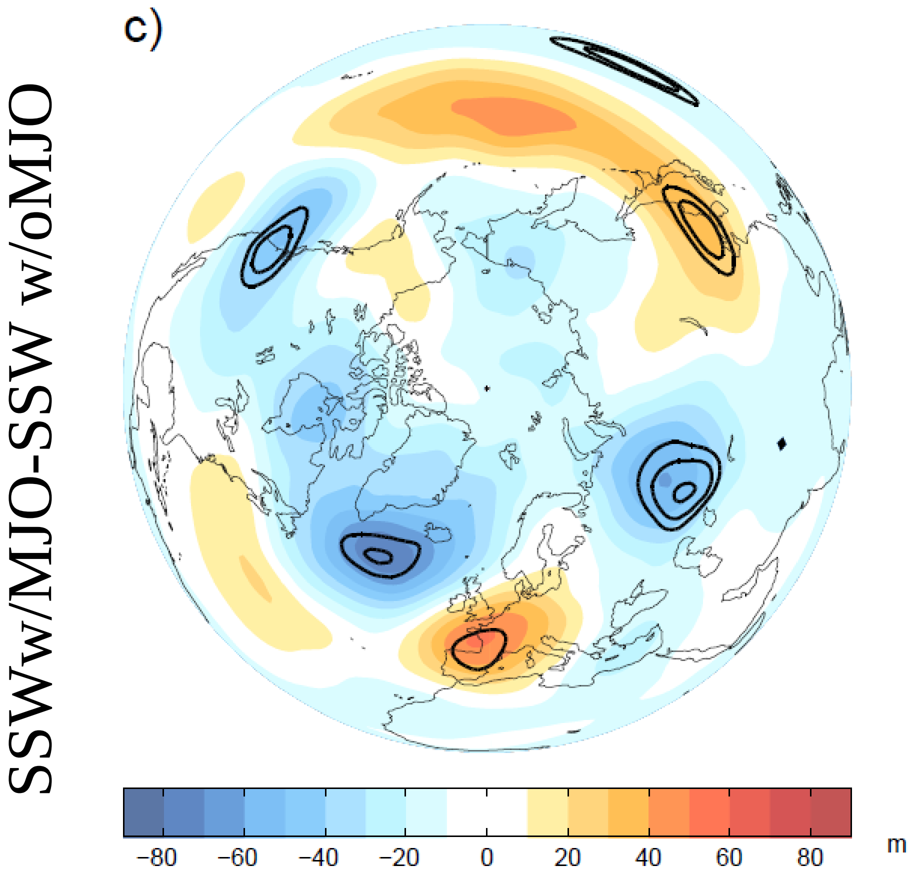
weighted as in SSWwMJO−SSWwoMJO composite, NDJFM, 1979−2013

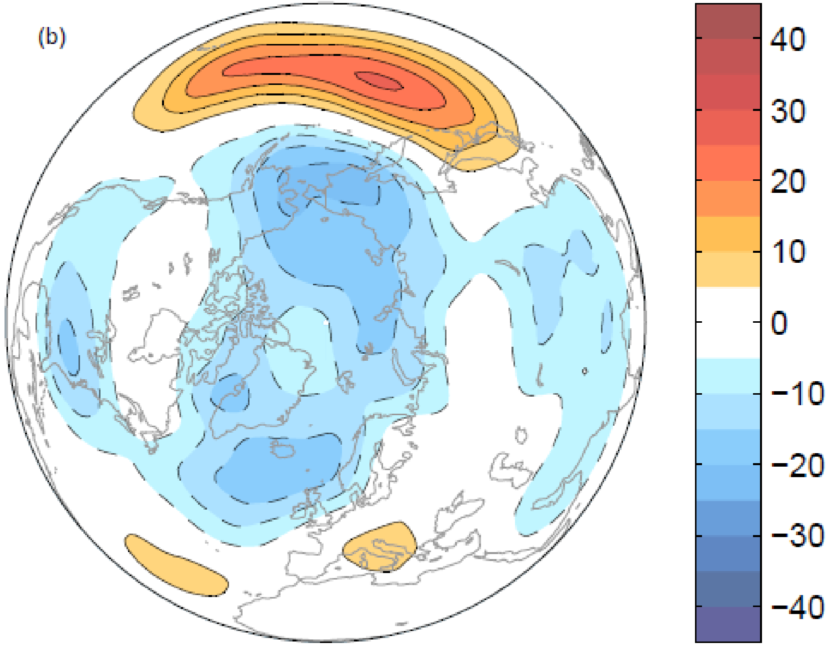
(a) OLR [W/m²]

(b) geopotential height [m]

If we examine the anomalies generally associated with these MJO phases, we find large extratropical anomalies

Why does the MJO modulate the impact of SSWs?





The extratropical anomalies associated with these MJO phases are similar to (though weaker than) the actual difference between the SSWw/MJO and SSW w/oMJO composites.

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Conclusions

- The MJO modulates the vortex, with phase 6/7 (convection in west Pacific) immediately preceding Stratospheric sudden warmings.
- After the stratospheric vortex is modulated, the anomalies propagate downwards to the troposphere and influence the surface Arctic Oscillation.
- This pathway can be disentangled from a purely tropospheric pathway, and for lags of 5-7 weeks the stratospheric pathway is dominant.
- The MJO modulates the regional structure of the surface impact of stratospheric sudden warmings events.

Garfinkel, C. I., J. J. Benedict, and E. D. Maloney (2014), Impact of the MJO on the Boreal Winter Extratropical Circulation, GRL, 41, 6055-6062, doi:10.1002/2014GL061094.

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Schwartz, C. and C.I. Garfinkel. Relative Roles of the MJO and Stratospheric Variability in North Atlantic and European Winter Climate. J. Geoph. Res.

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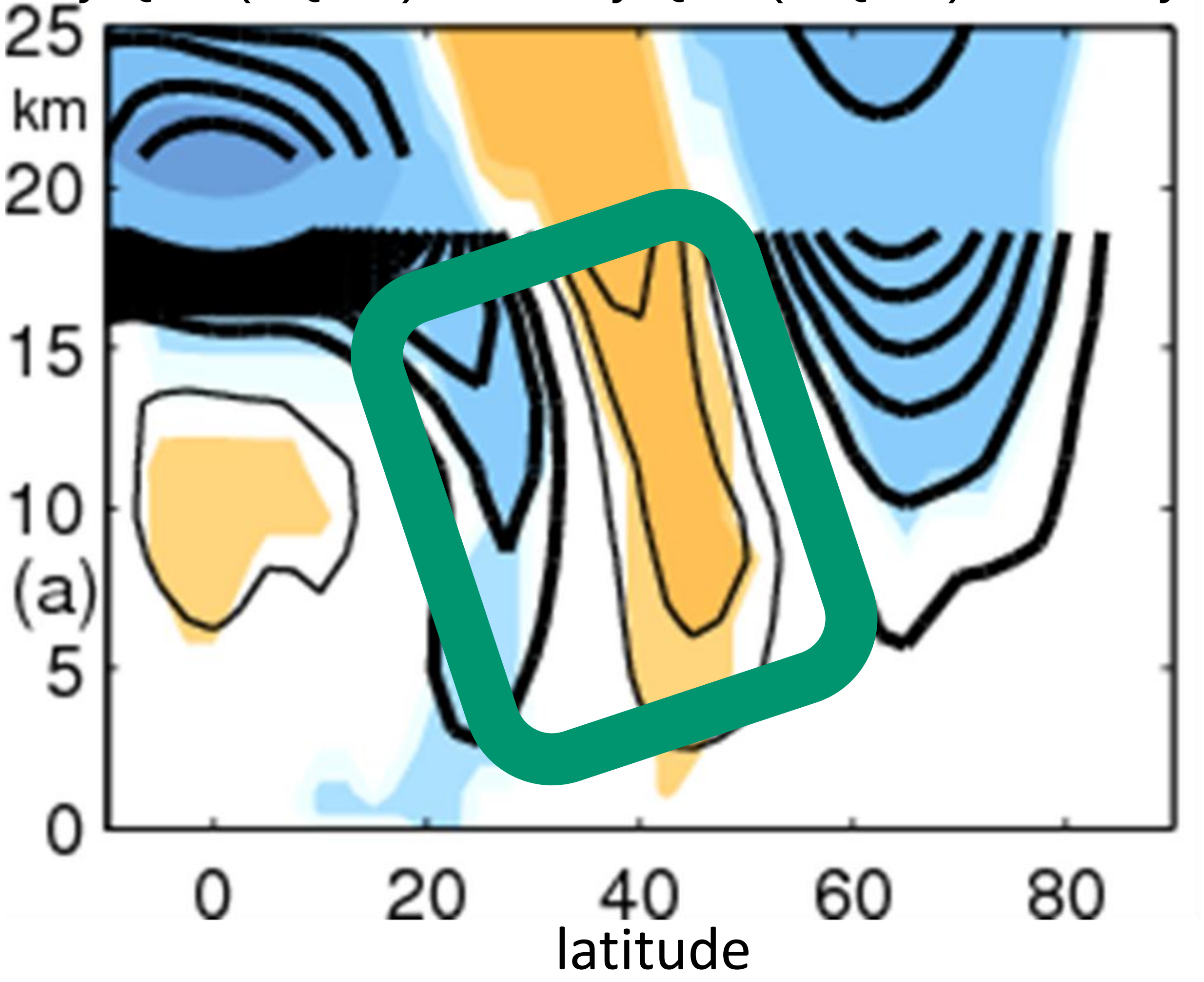
Easterly winds in the tropical lower stratosphere lead to a weaker vortex

Easterly QBO(EQBO)-Westerly QBO(WQBO), Reanalysis, NDJF



C.I.=0.5m/s in trop
5m/s in strat

Garfinkel and Hartmann 2011ab

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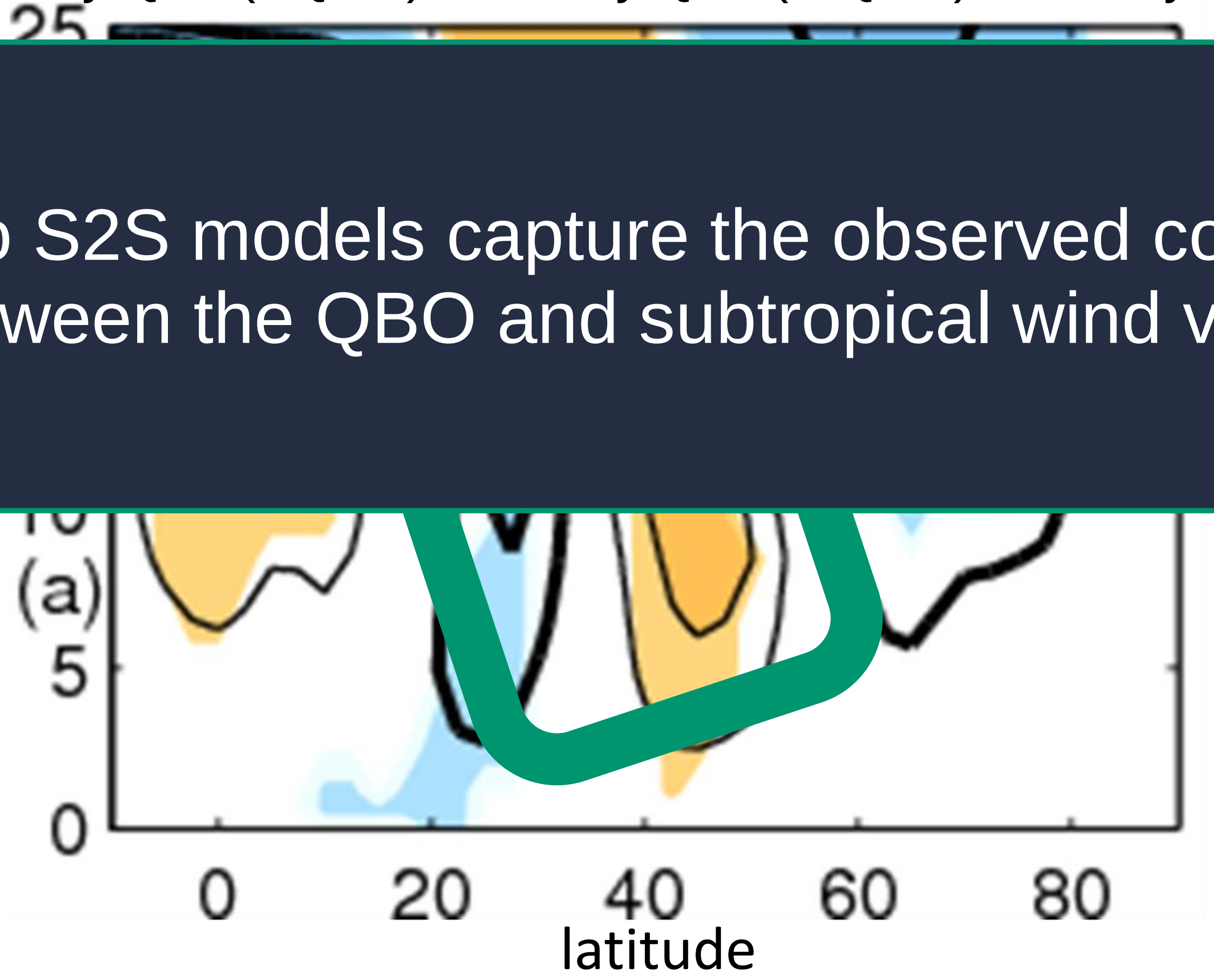

Do S2S models capture the observed connection between the QBO and subtropical wind variability?

Garfinkel and Hartmann 2011ab

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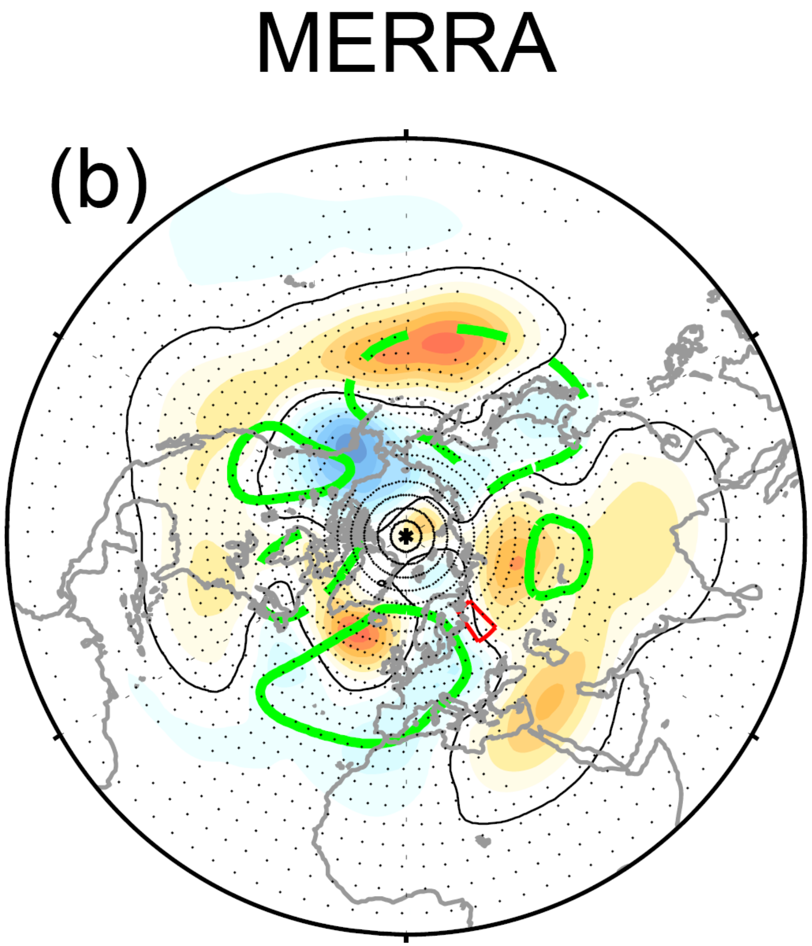
Higher geopotential heights near 35N

Easterly QBO(EQBO)-Westerly QBO(WQBO), Reanalysis, February



C.I.=0.5m/s in trop
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After Garfinkel and Hartmann 2011ab

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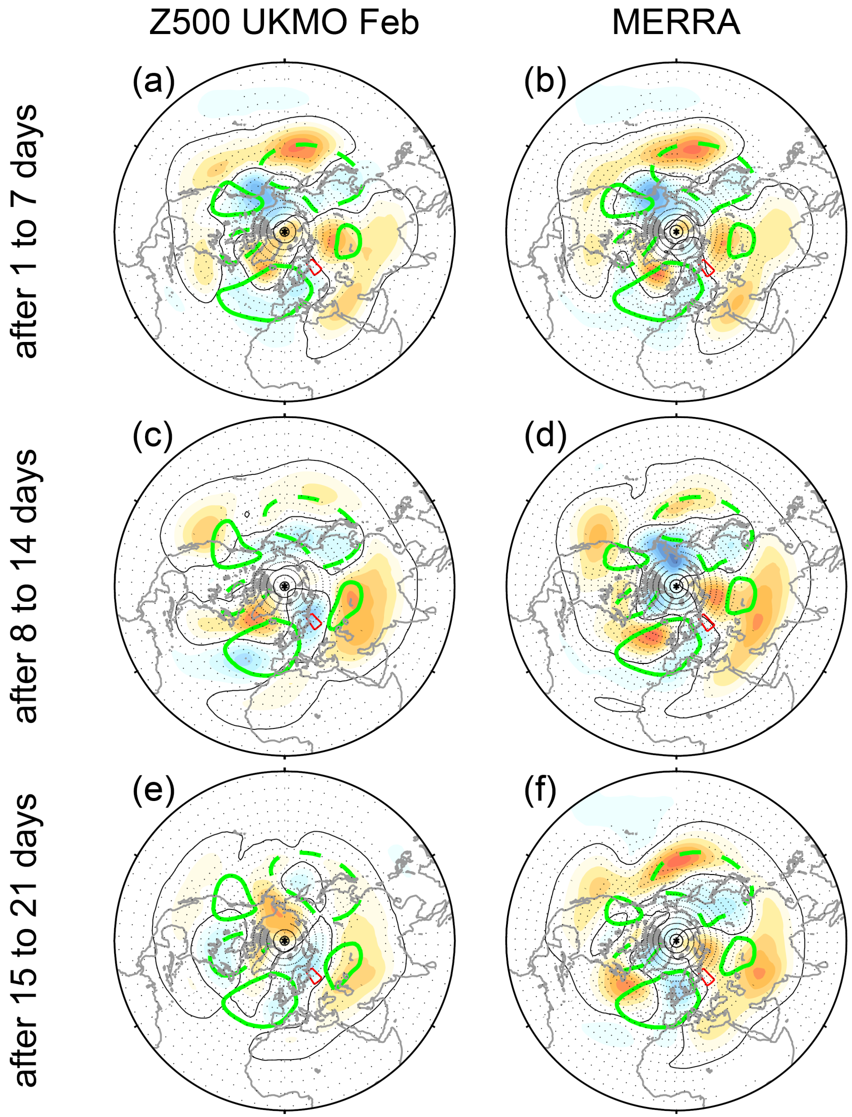

tmann 2011ab

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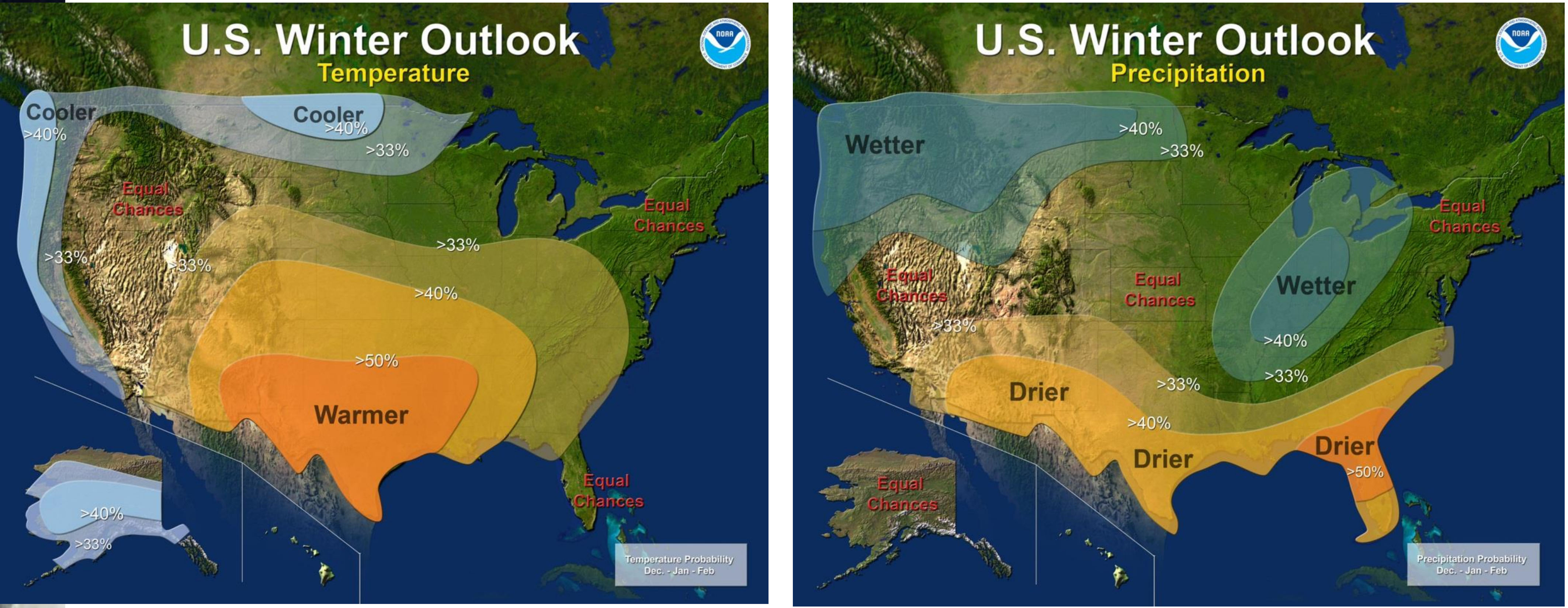
(Towards) Understanding Seasonal Variability



Projection for DJF 2011-2012, issued October 2011.

(courtesy:NOAA/CPC)

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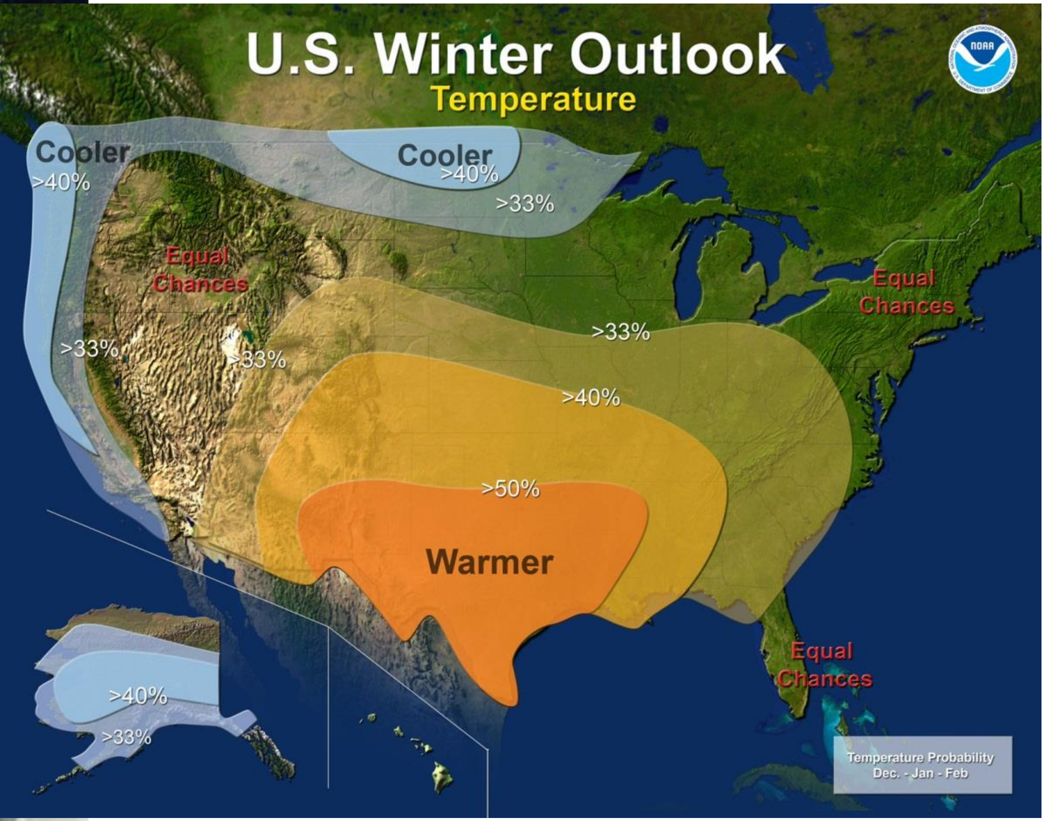

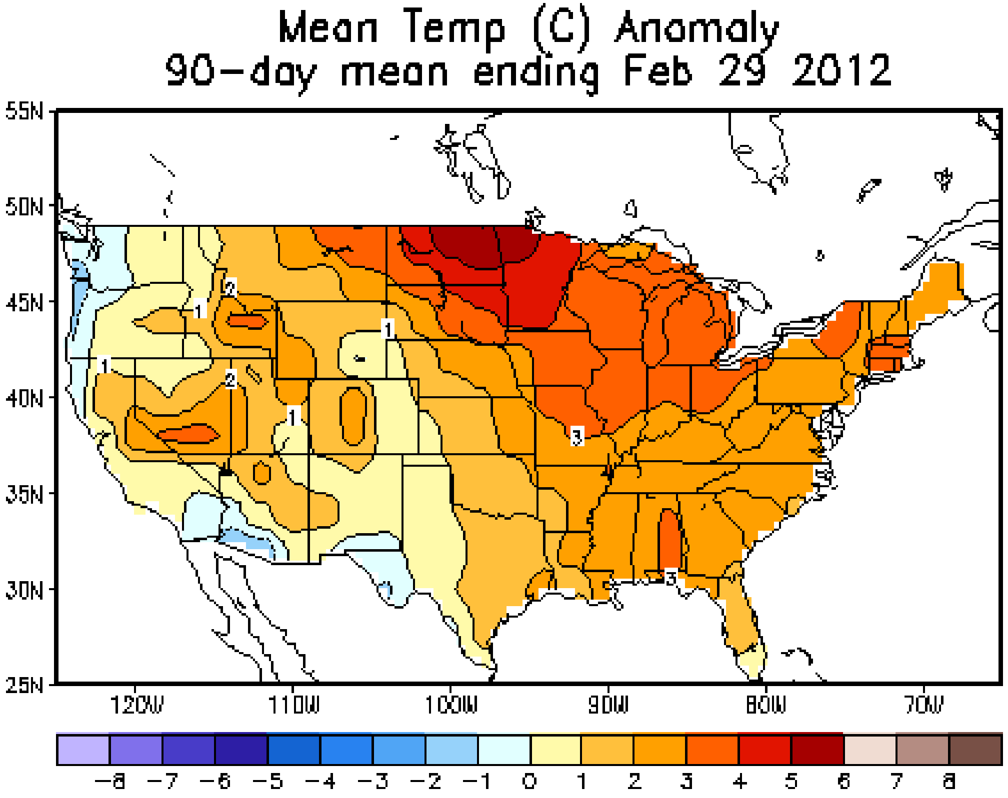

(courtesy:NOAA/CPC)

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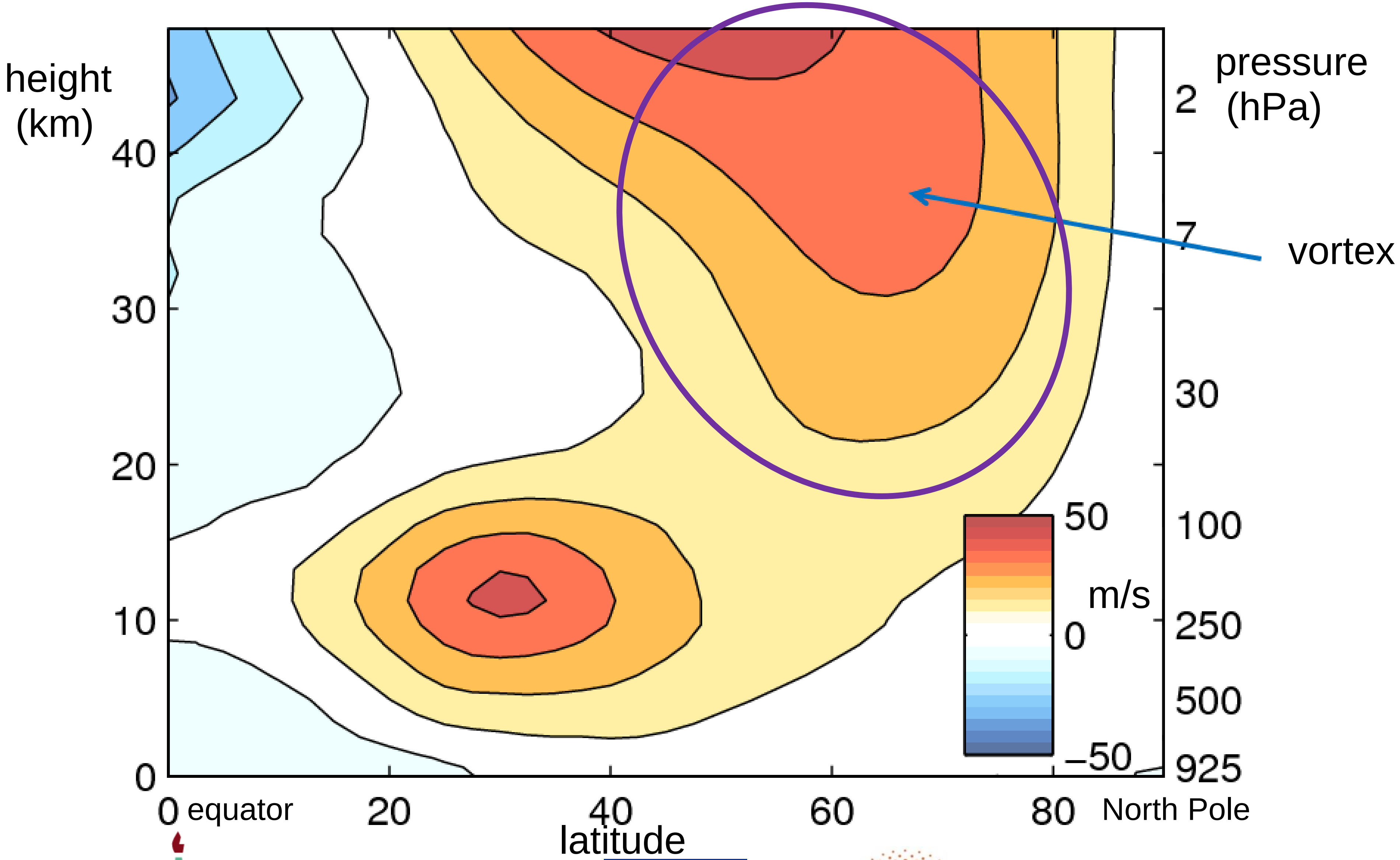
Climatological wintertime zonal wind



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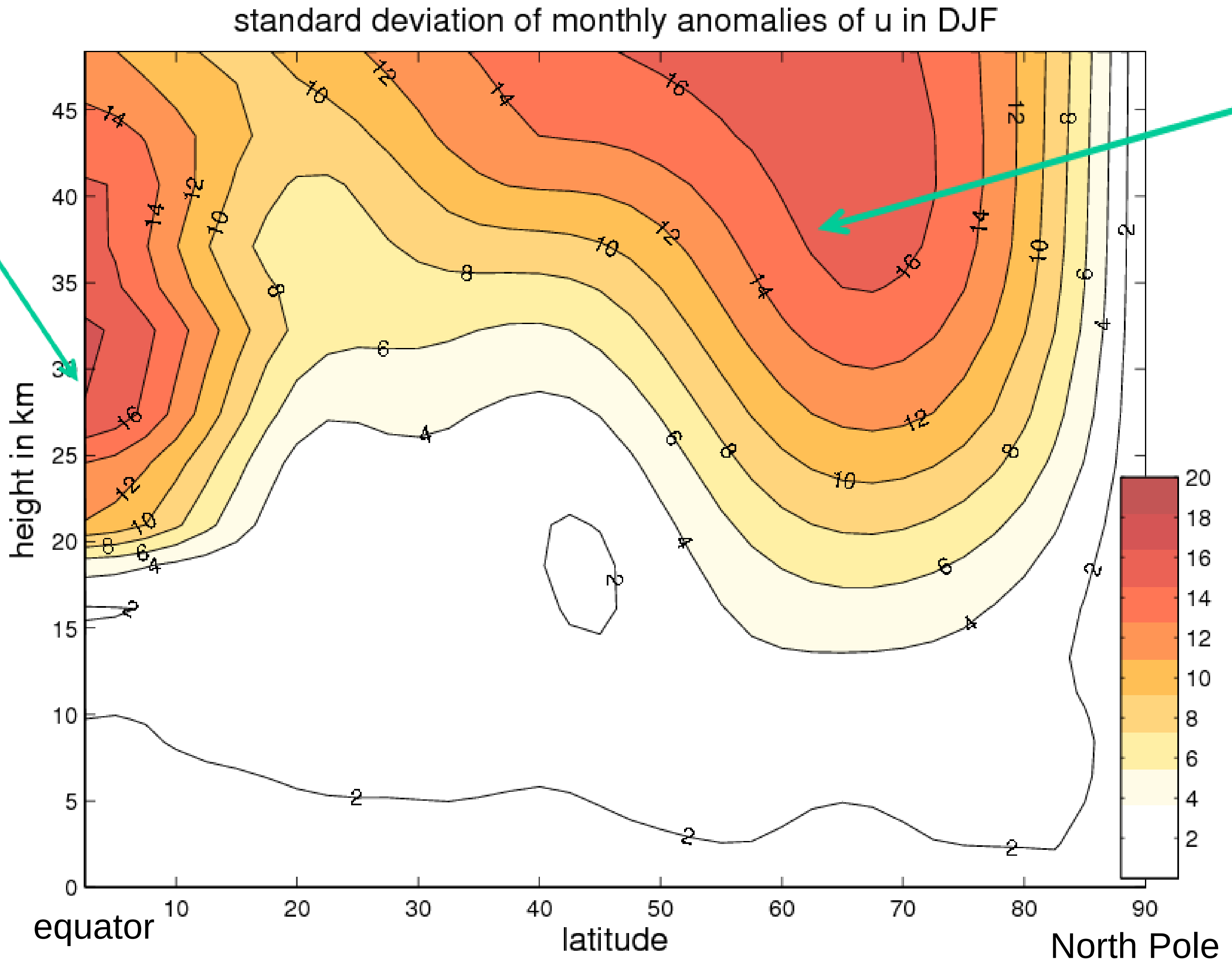
Standard Deviation, 1957-2007

(after Nigam, 1990)



Quasi-Biennial Oscillation (QBO)

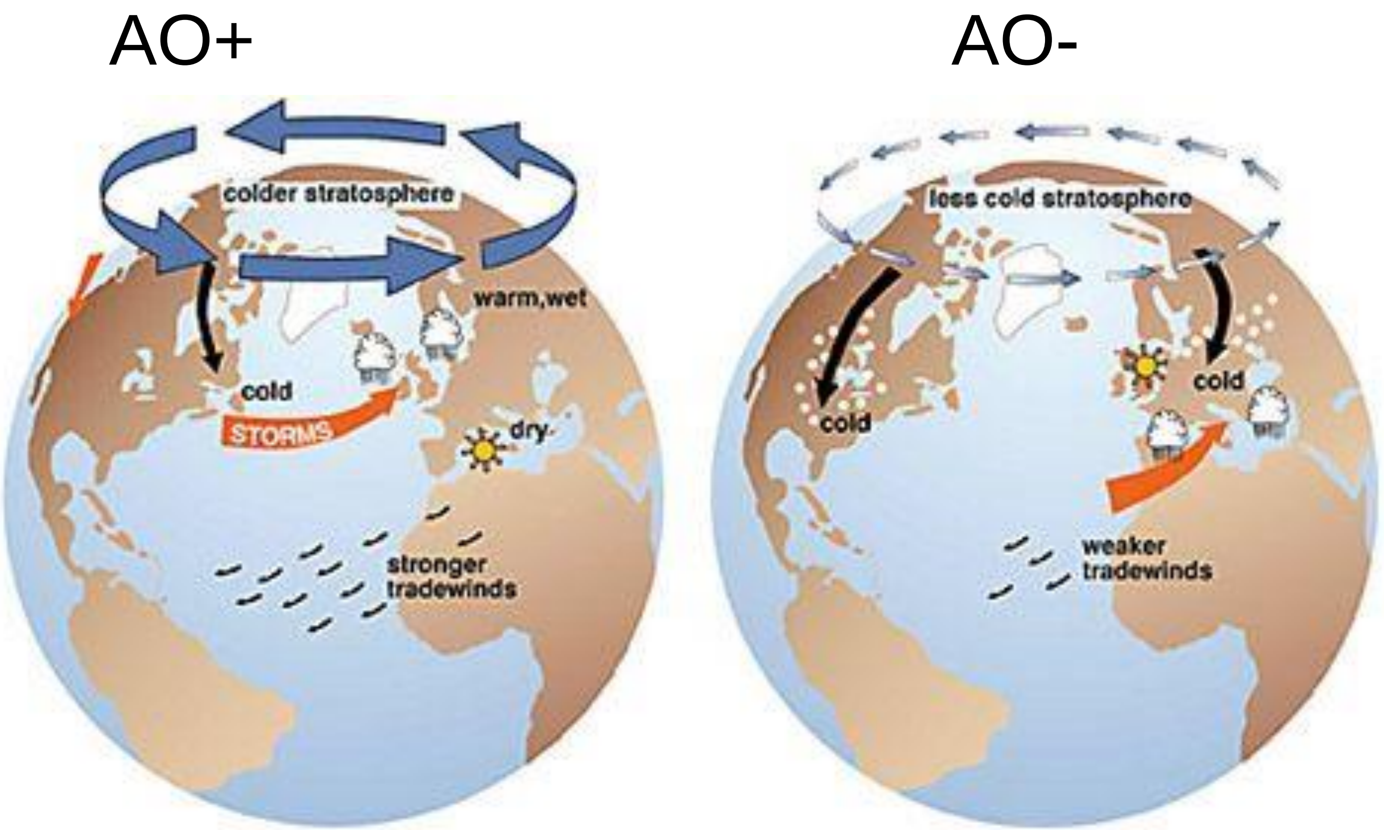
vortex

m/s

equator

North Pole

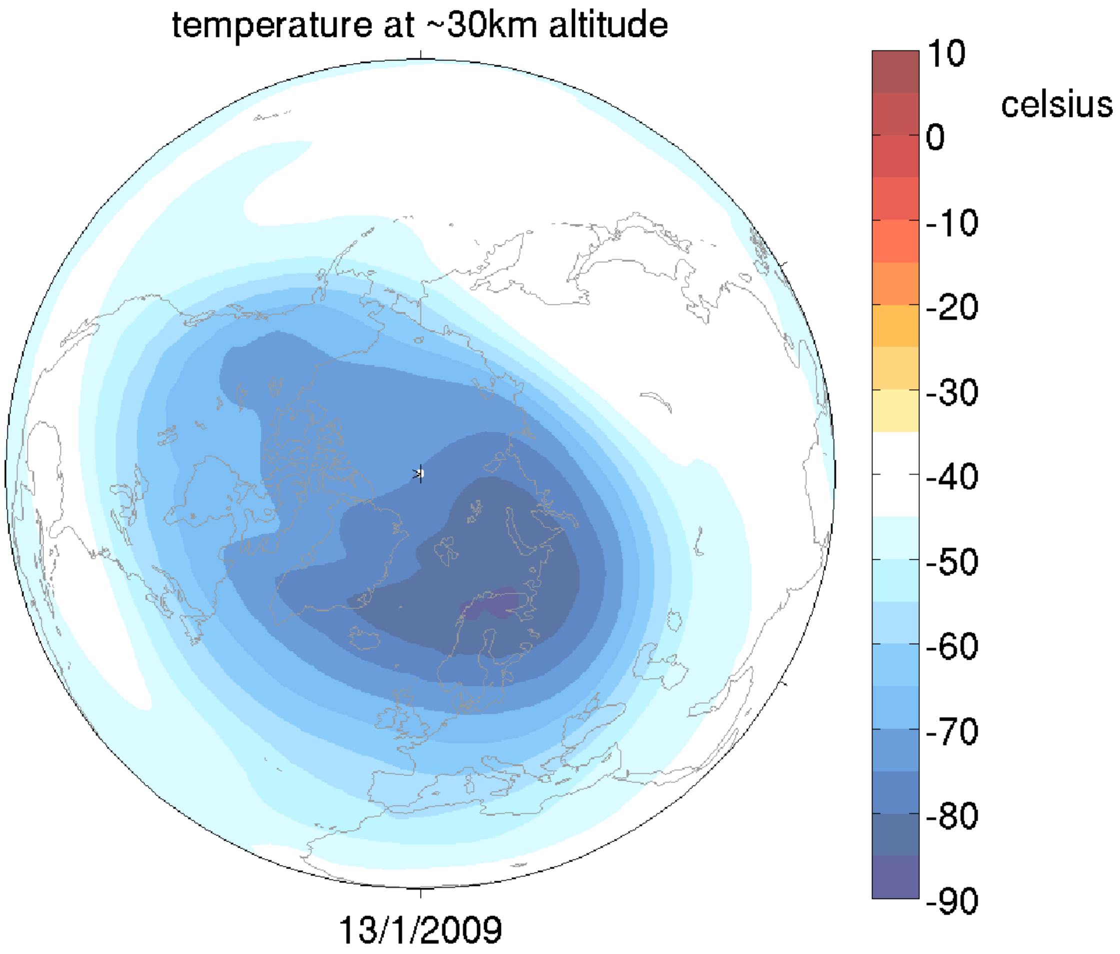
Stratospheric anomalies can affect surface climate



(Figure courtesy of Mike Wallace)

Better predictability of vortex variability may lead to better forecasts of surface climate on monthly timescales.

Stratospheric Variability in the Extratropics: Case Study, January 2009



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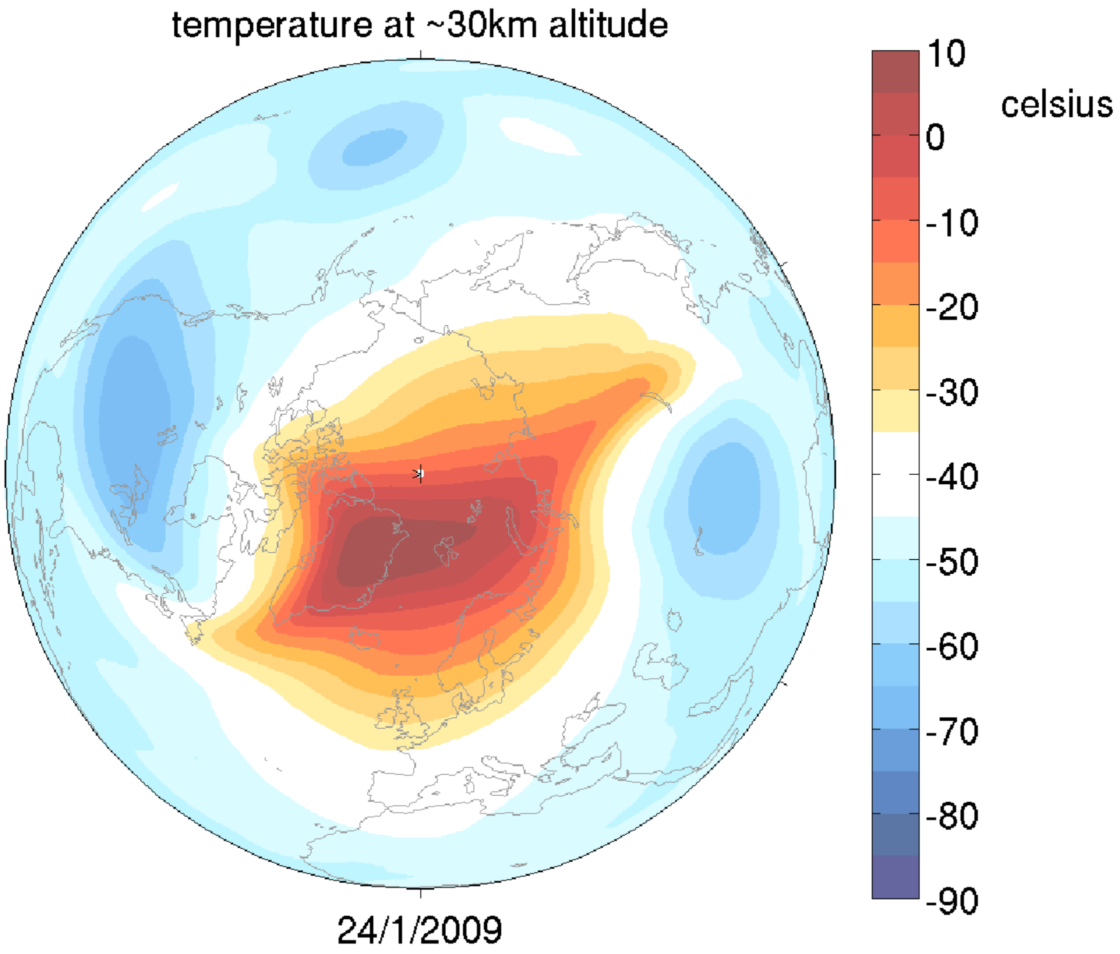
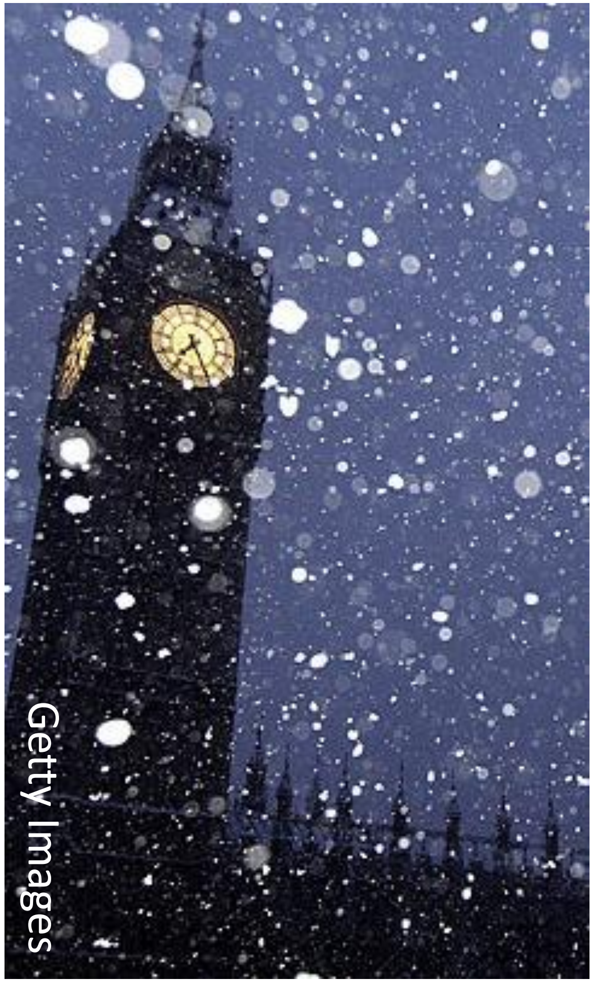


Importance for Surface



Getty Images

February 1-12:
Heaviest snowfall in over 18 years in Britain

Forecasted 5 days in advance,
but we should do better!

Importance for climate change: Models capable of simulating stratospheric warmings project qualitatively different impacts of increased CO_2 for the US and Europe.

Subseasonal to Seasonal (S2S) Project

11 operational subseasonal forecasting models share their forecast data over the past few decades.

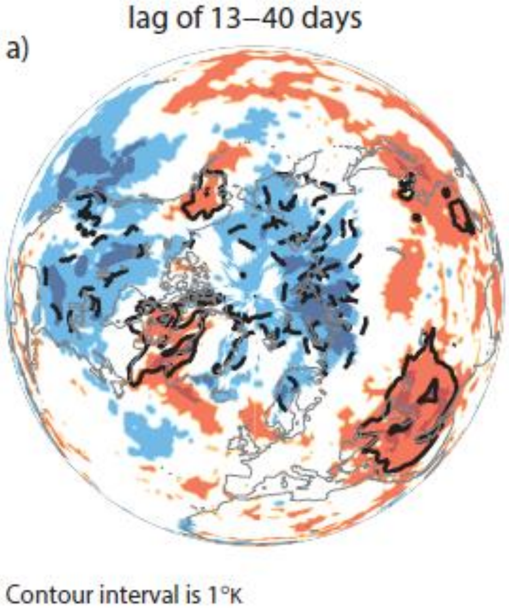
How predictable is stratospheric variability in these models?

Garfinkel, C.I. and Schwartz, C., 2017. MJO-Related Tropical Convection Anomalies Lead to More Accurate Stratospheric Vortex Variability in Subseasonal Forecast Models. *Geophysical research letters*, *44*(19). **MJO**

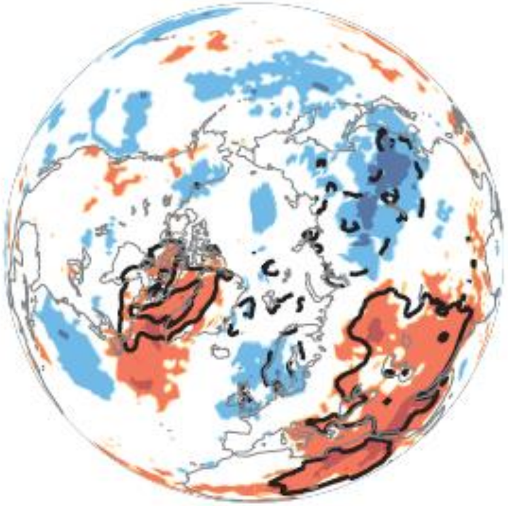
Garfinkel, C.I., Schwartz, C., Domeisen, D.I., Son, S.W., Butler, A.H. and White, I.P., 2018. Extratropical Atmospheric Predictability From the Quasi-Biennial Oscillation in Subseasonal Forecast Models. *Journal of Geophysical Research: Atmospheres*, *123*(15), pp.7855-7866. **QBO**

MJO modulates the impact of SSWs in troposphere
2 meter temperature

SSWw/MJO



SSW w/oMJO



While SSW events lead to a negative NAM signal regardless of MJO phase, the spatial patterns are subtly different.

SSWw/MJO is associated with cooling over Eastern US and subpolar Eurasia, while SSWw/oMJO is associated more with anomalies over Southwest Asia.

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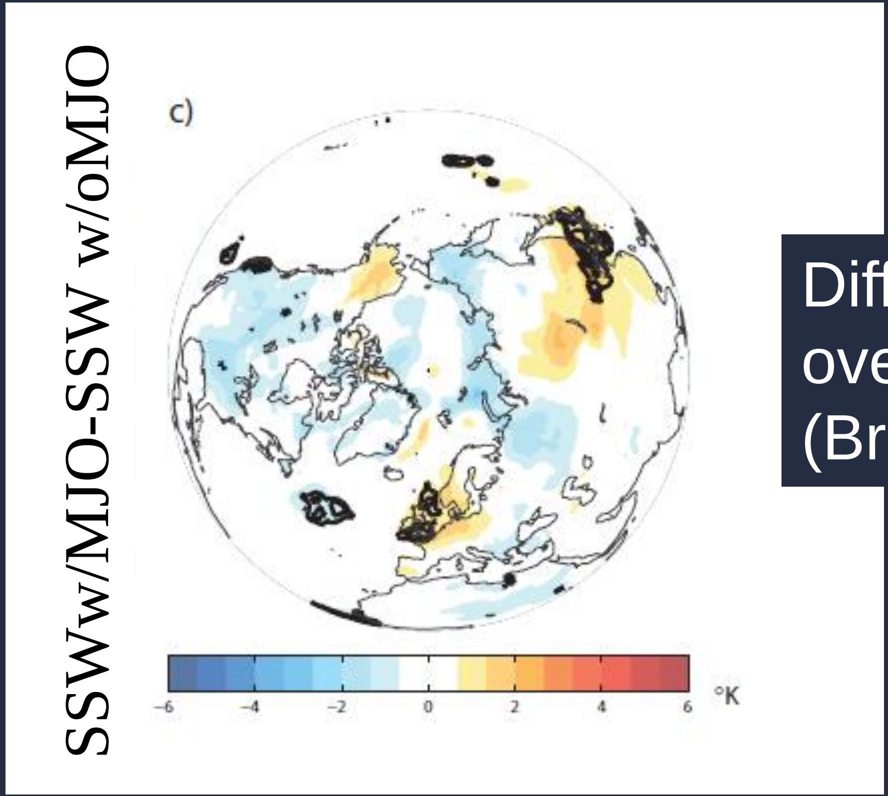
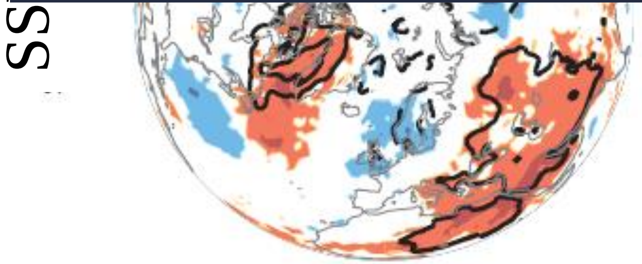
MJO modulates the impact of SSWs in troposphere
2 meter temperature

While SSW events lead to a negative NAM signal regardless of MJO phase



Difference is statistically significant over several populated regions (Britain and East Asia)



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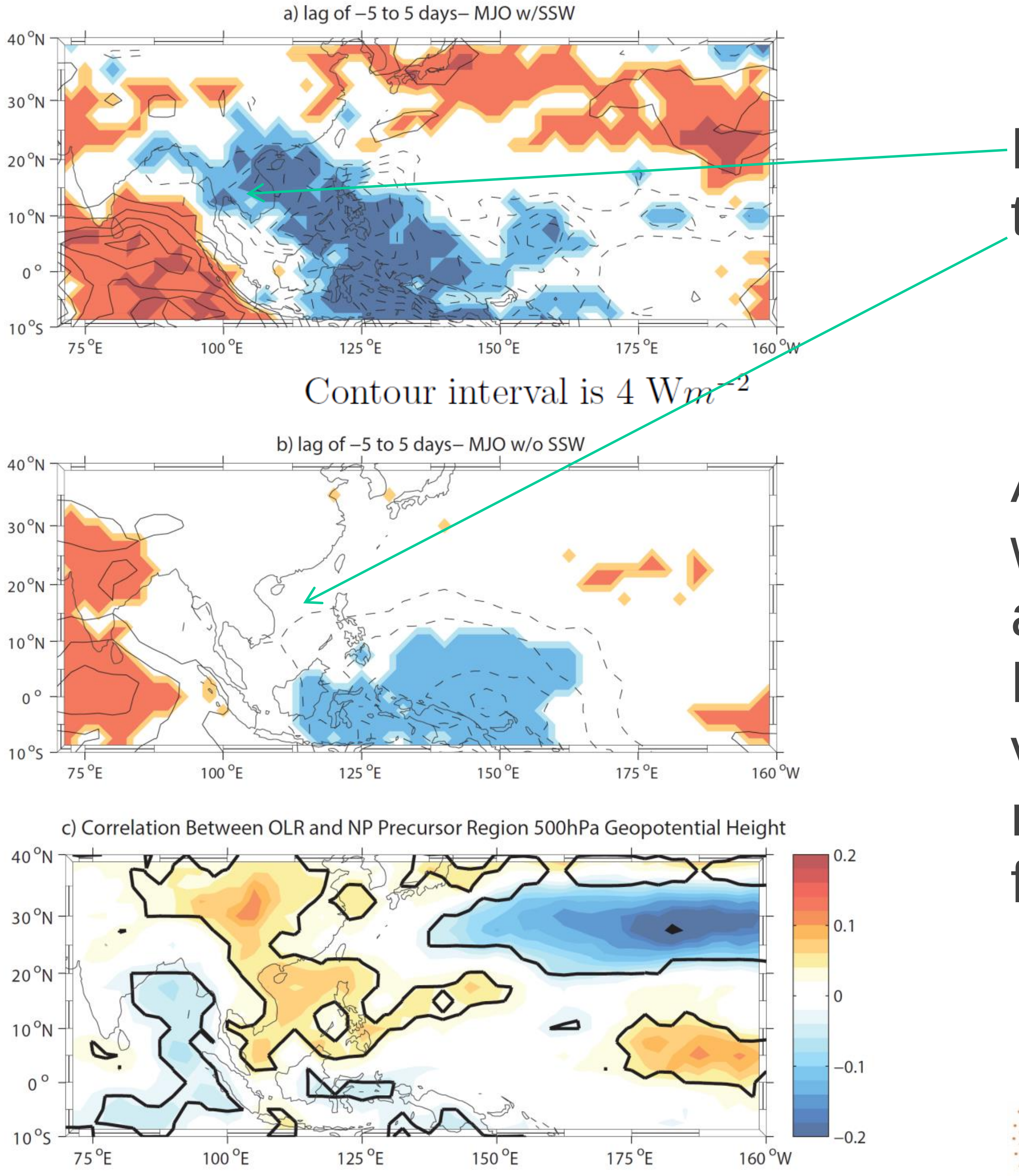
Why do only some MJO events force SSWs?



a) lag of −5 to 5 days– MJO w/SSW

Contour interval is 4 Wm^{-2}

b) lag of −5 to 5 days– MJO w/o SSW

c) Correlation Between OLR and NP Precursor Region 500hPa Geopotential Height

Different OLR anomalies in the South China Sea region

Anomalies in this region are well correlated with height anomalies in the subpolar Northwest Pacific, where variability efficiently modulates planetary wave flux into stratosphere.

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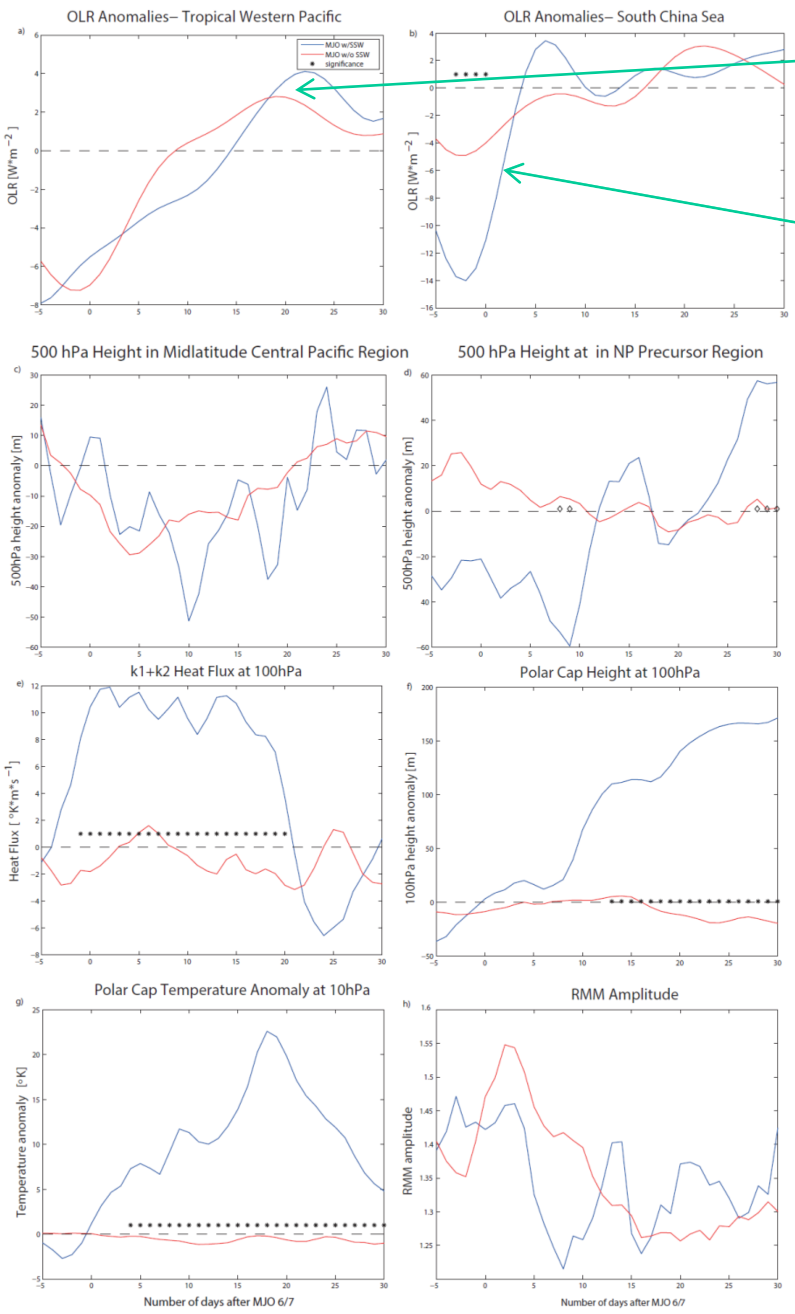
Why do only some MJO events force SSWs?



OLR in deep tropics is the same for both

Significant difference in south china sea

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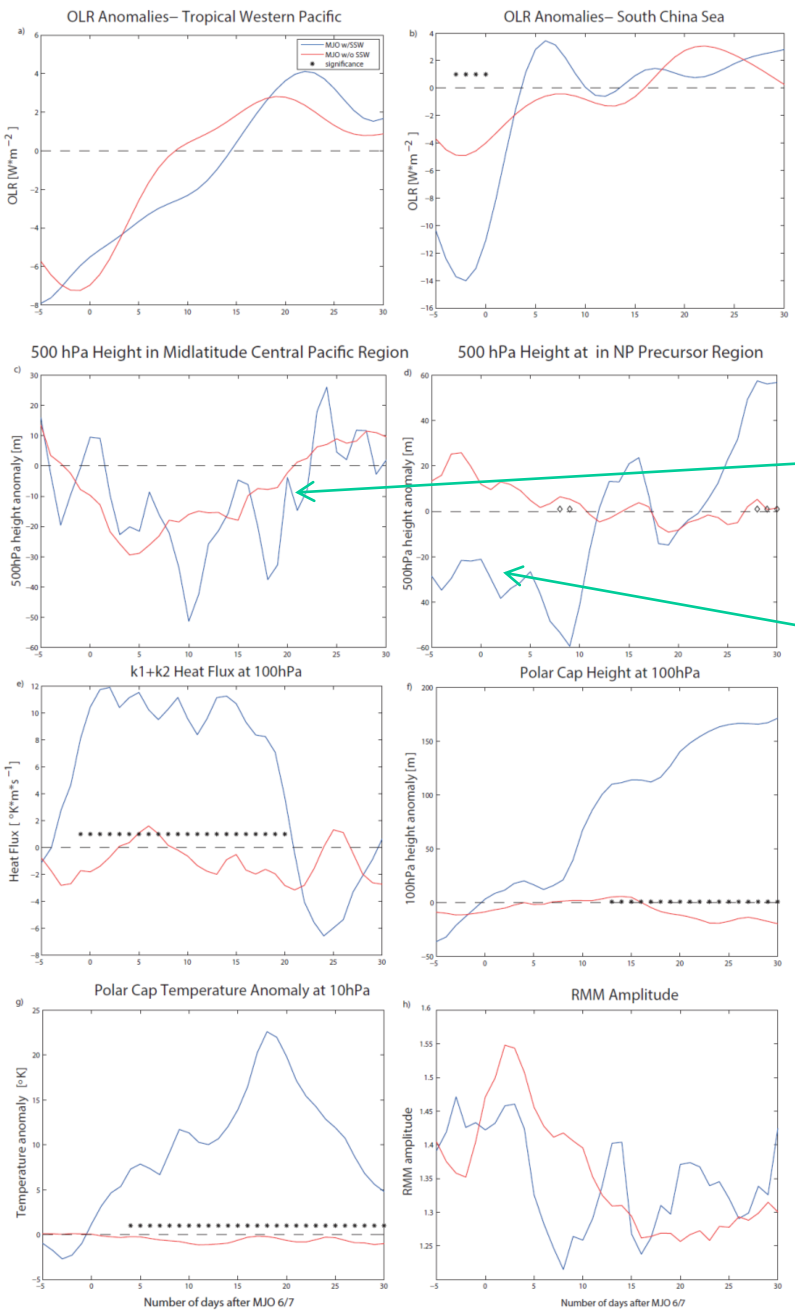
Why do only some MJO events force SSWs?



500hPa Height anomalies in central midlatitude Pacific is the same for both

Significant difference in subpolar Northwest Pacific

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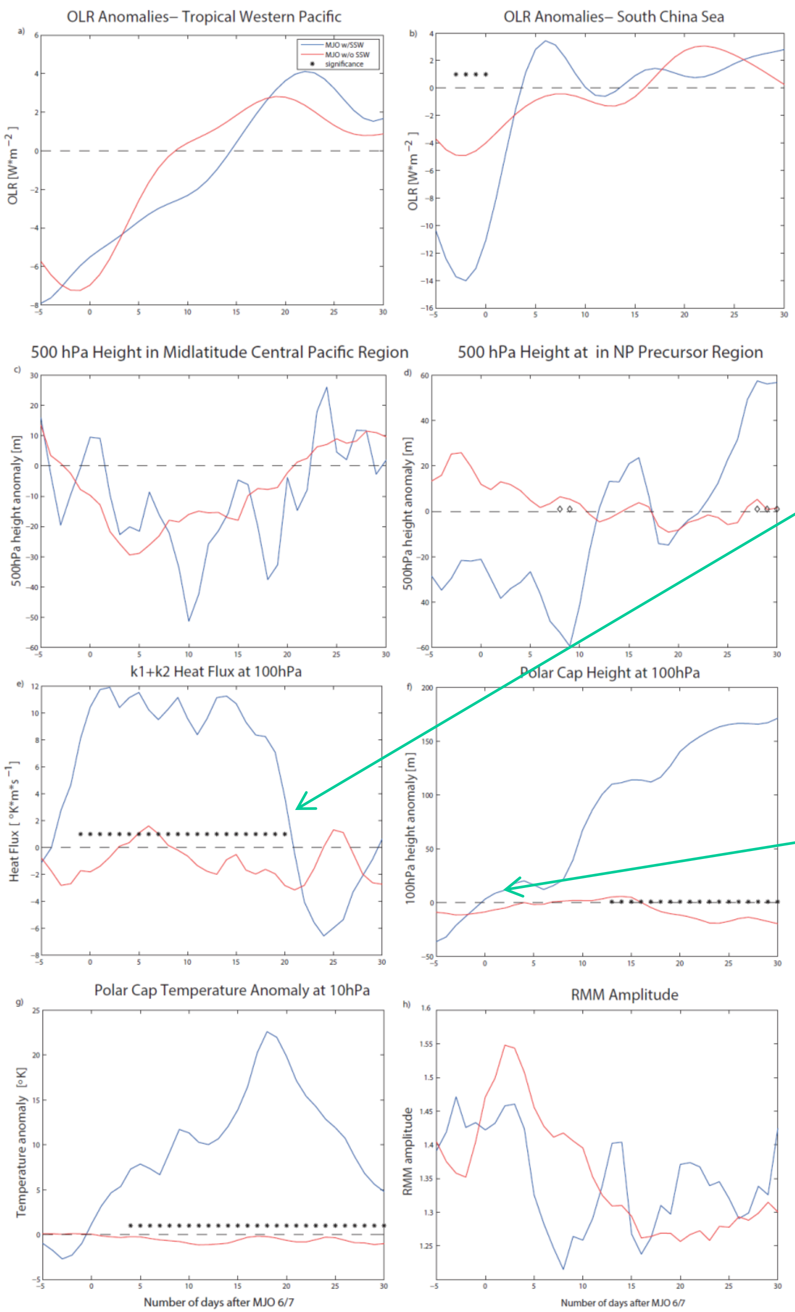
Why do only some MJO events force SSWs?



Large difference in heat flux at 100hPa (wave flux entering stratosphere)

Significant difference in stratospheric polar cap height

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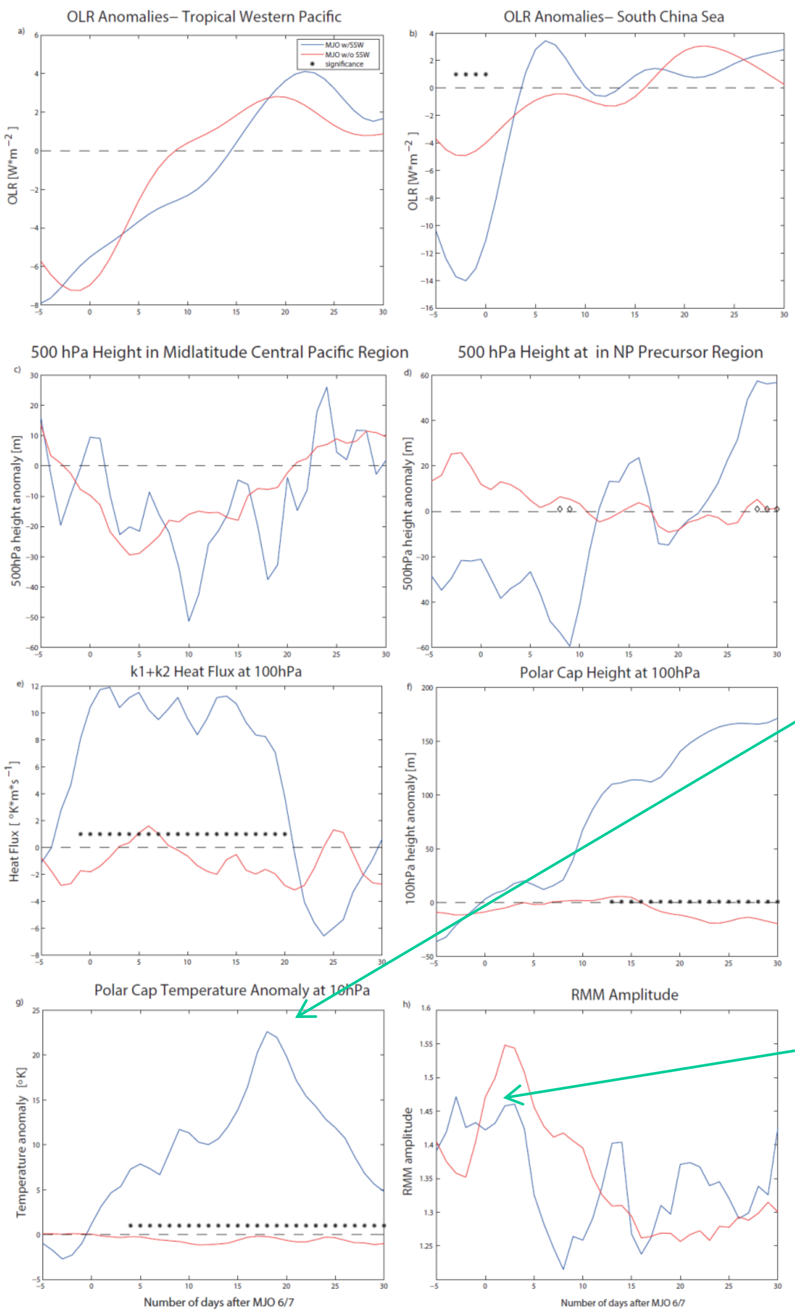
Why do only some MJO events force SSWs?



Significant difference in stratospheric zonal wind at 10hPa, 60N

SSWw/oMJO are somewhat stronger events

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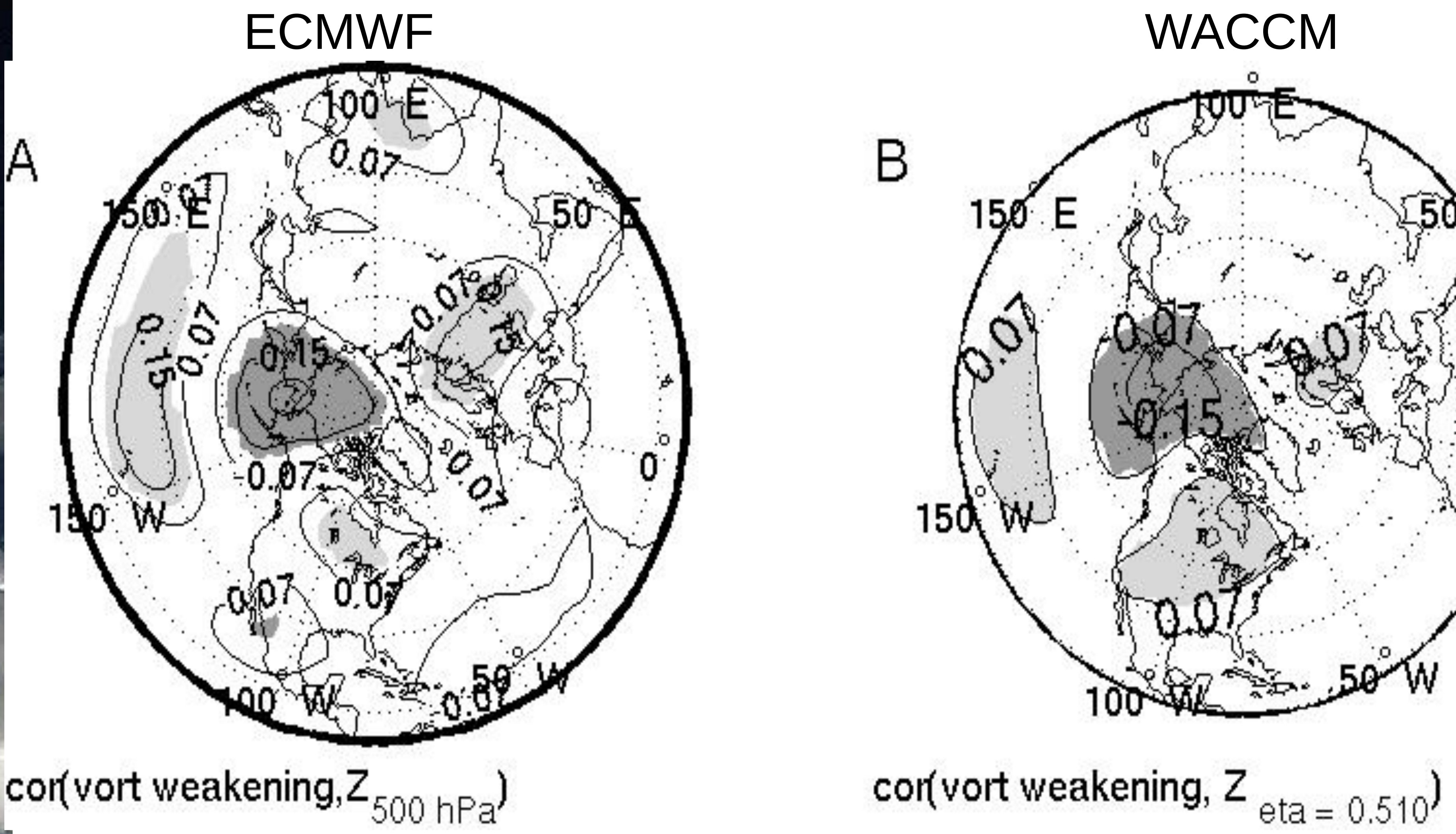
Key Questions

- What are the underlying pathway(s) through which the MJO can affect planetary wave driving of the polar vortex?

Objective Search for Tropospheric Patterns

1. Define a vortex weakening index as the change in vortex strength over a ten day period.
2. Correlate tropospheric geopotential height over the entire Northern Hemisphere with this index of vortex weakening.
3. Analyze the subsequent patterns in both the reanalysis record and in a 126 year general circulation model run.

Tropospheric geopotential height correlated with vortex weakening



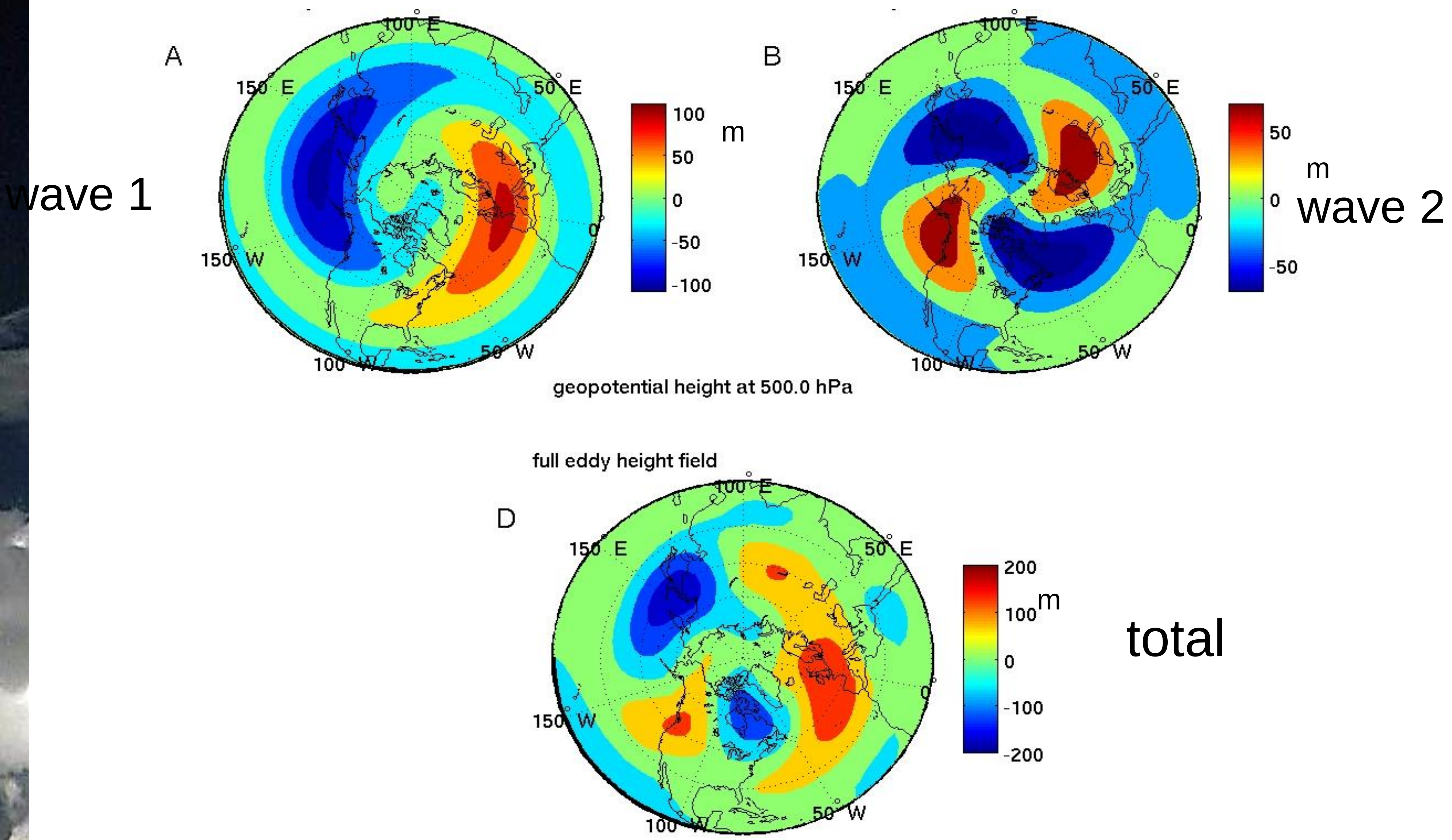
ECMWF

WACCM

Garfinkel et al 2010, J. Clim.

Why do low anomalies over the North Pafic and high anomalies over Eastern Europe weaken the vortex?

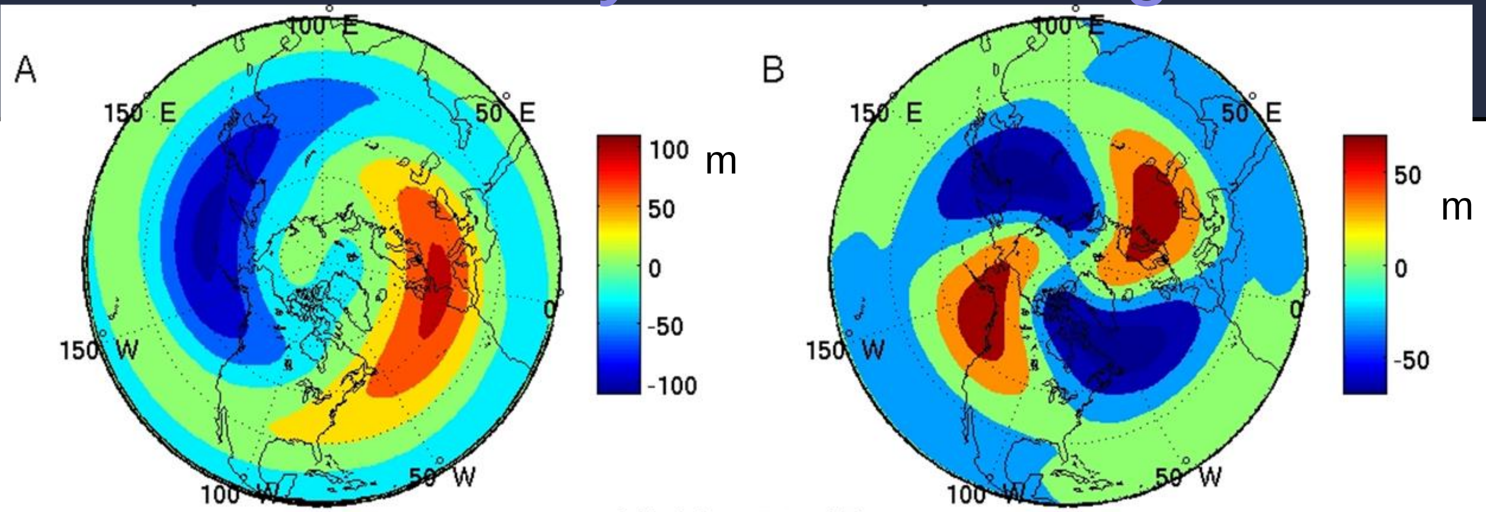
Climatology of NDJF Tropospheric Geopotential Height



- Stationary planetary waves that are generated by surface forcing can propagate upwards to the stratosphere (Charney and Drazin, 1961).

Source of Planetary Wave Driving of Stratosphere

wave-1

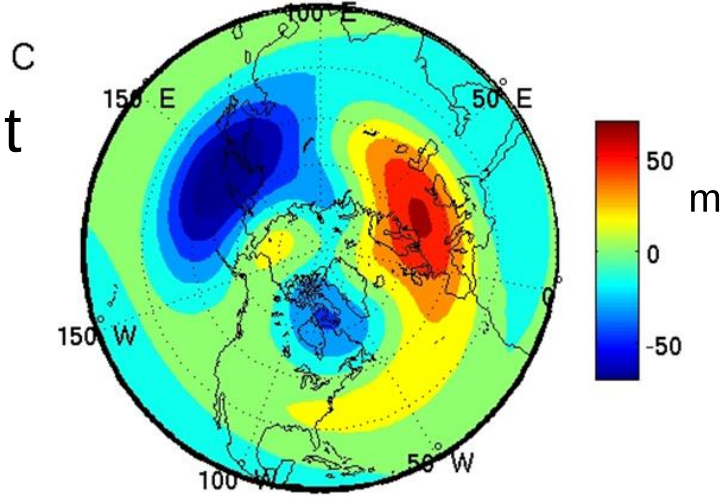


geopotential height at 500.0 hPa

wave-2

Low wavenumber height field

avg. of wave1, wave2, and wave3



Anomalies collocated with these climatological regional asymmetries will enhance wave-1 and wave-2 EP flux leaving the troposphere and affecting the stratosphere.

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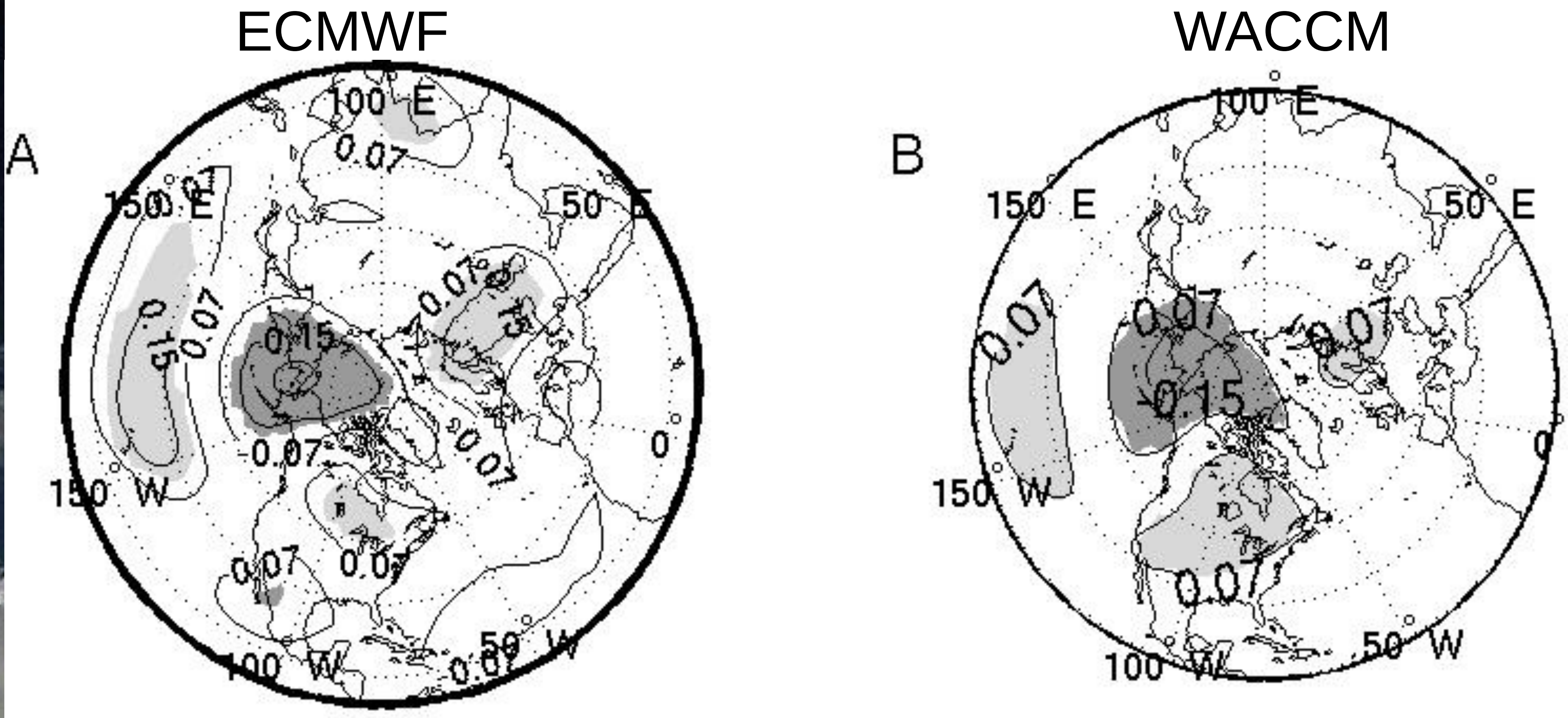
Chaim I. Garfinkel

Tropospheric geopotential height correlated with vortex weakening-revisited

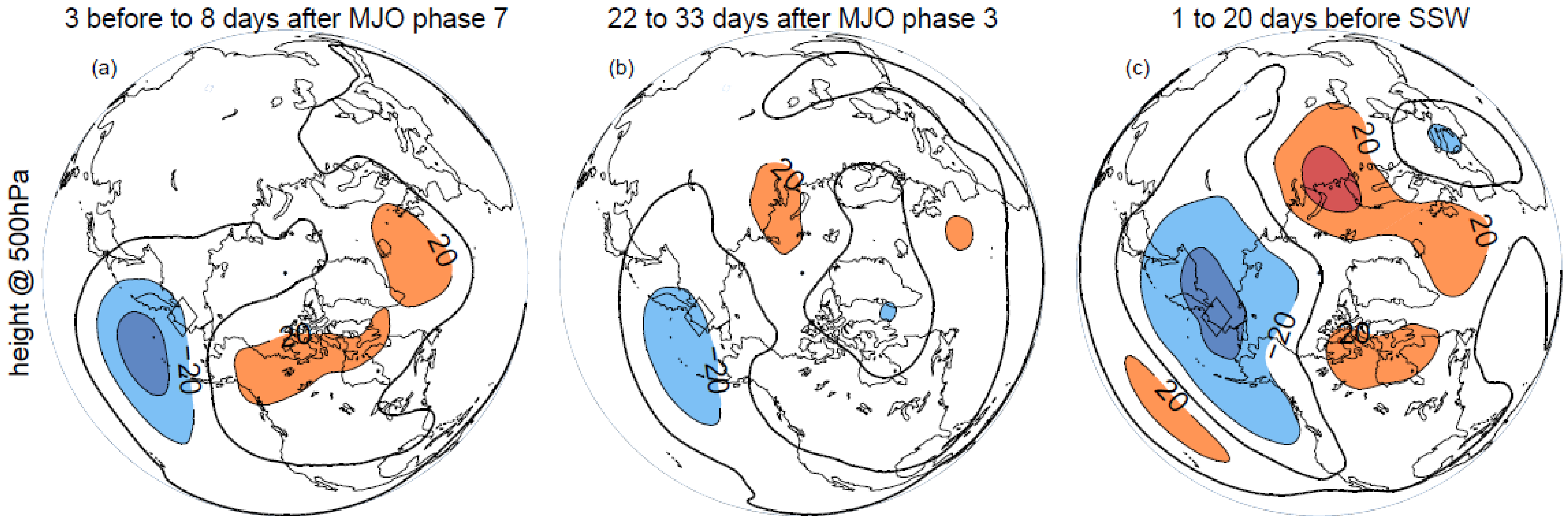


cor(vort weakening, $Z_{500\ \mathrm{hPa}}$)

cor(vort weakening, $Z_{\mathrm{eta}\,=\,0.510}$)

The North Pacific and Eastern European extrema are collocated with the climatological planetary wave extrema, and thus they represent particularly effective conduits for enhancing upward planetary wave activity. (Garfinkel et al 2010, J. Clim)

MJO influences the tropospheric North Pacific

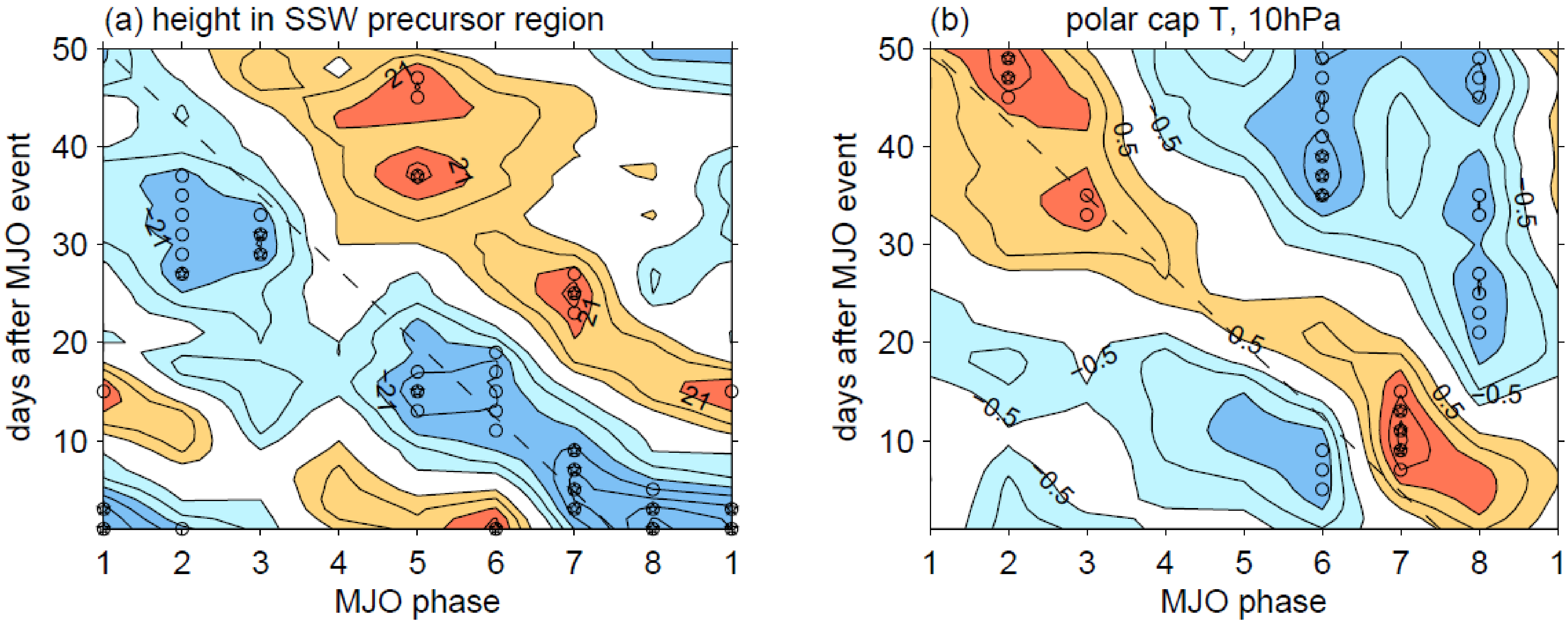


contour interval 10m

Garfinkel et al 2012, GRL

Variability in the North Pacific can account for the influence of the MJO on the polar stratosphere.

Summary of MJO-North Pacific-vortex connection



contour interval 7m

contour interval 0.5K

Garfinkel et al 2012, GRL

A variety of MJO phases influence variability in the North Pacific and subsequently affect the polar stratosphere.

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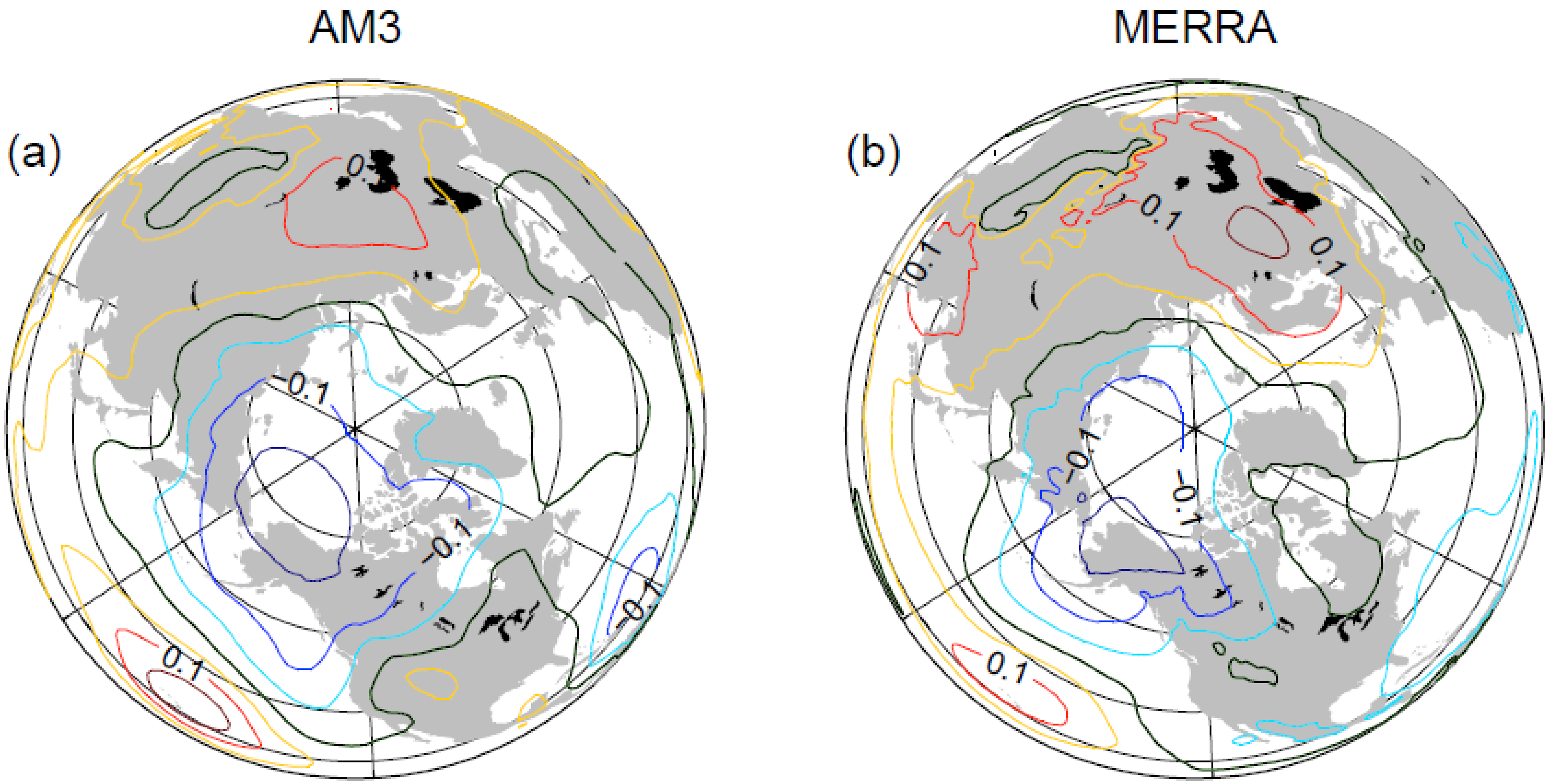
AM3 Simulations

Recent tests with the AM3 atmospheric model simulate a fairly realistic MJO (Benedict et al., 2013, Journal of Climate) .

The model also has a realistic stratospheric circulation and realistic variability (though the variability is slightly smaller than observed).

Realistic tropopspheric precursors.

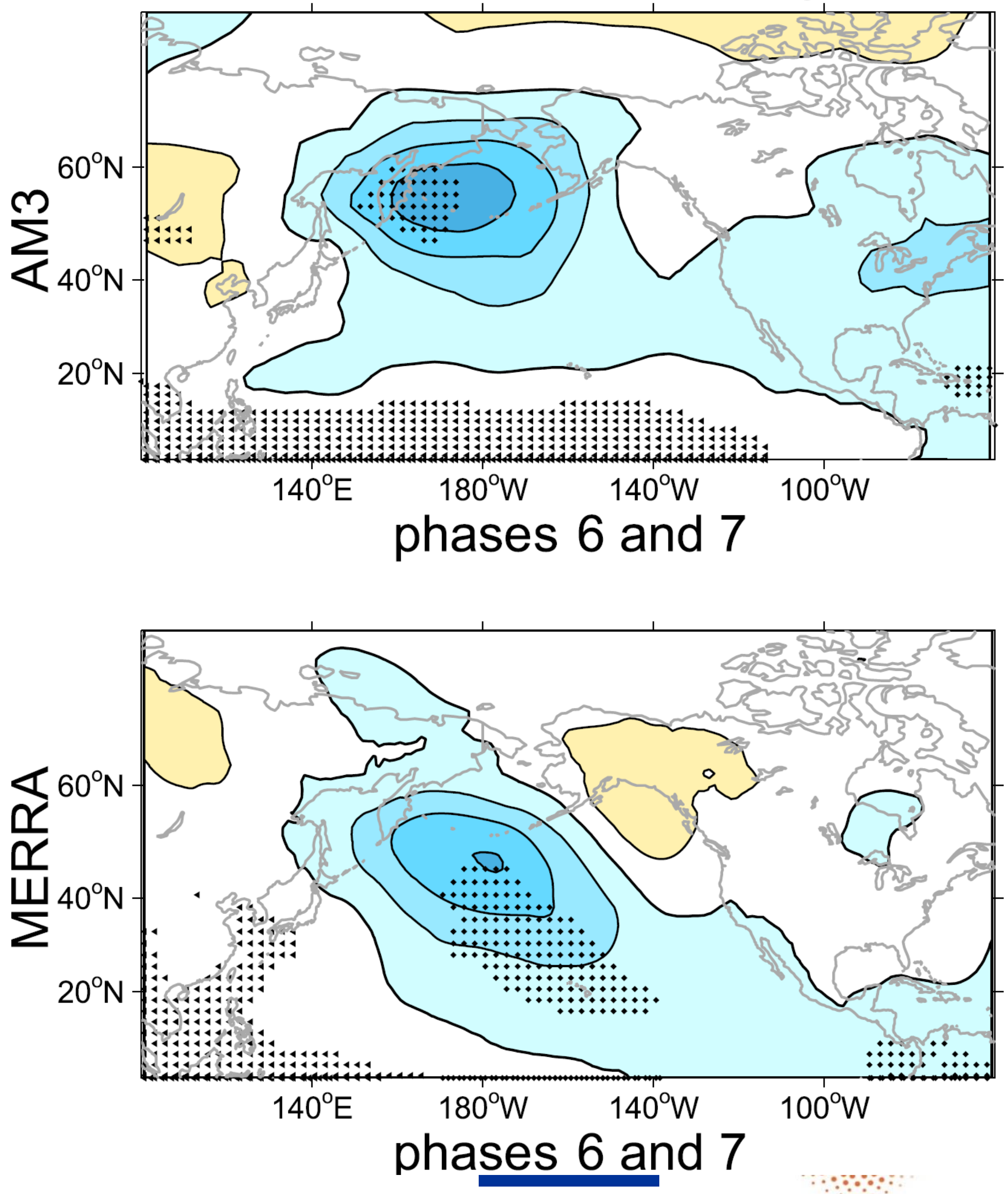


Correlation between vortex weakening index and SLP

AM3 Simulations

AM3 simulates a realistic North Pacific response to the MJO

Composite SLP response following MJO phase



C.I. 1hPa

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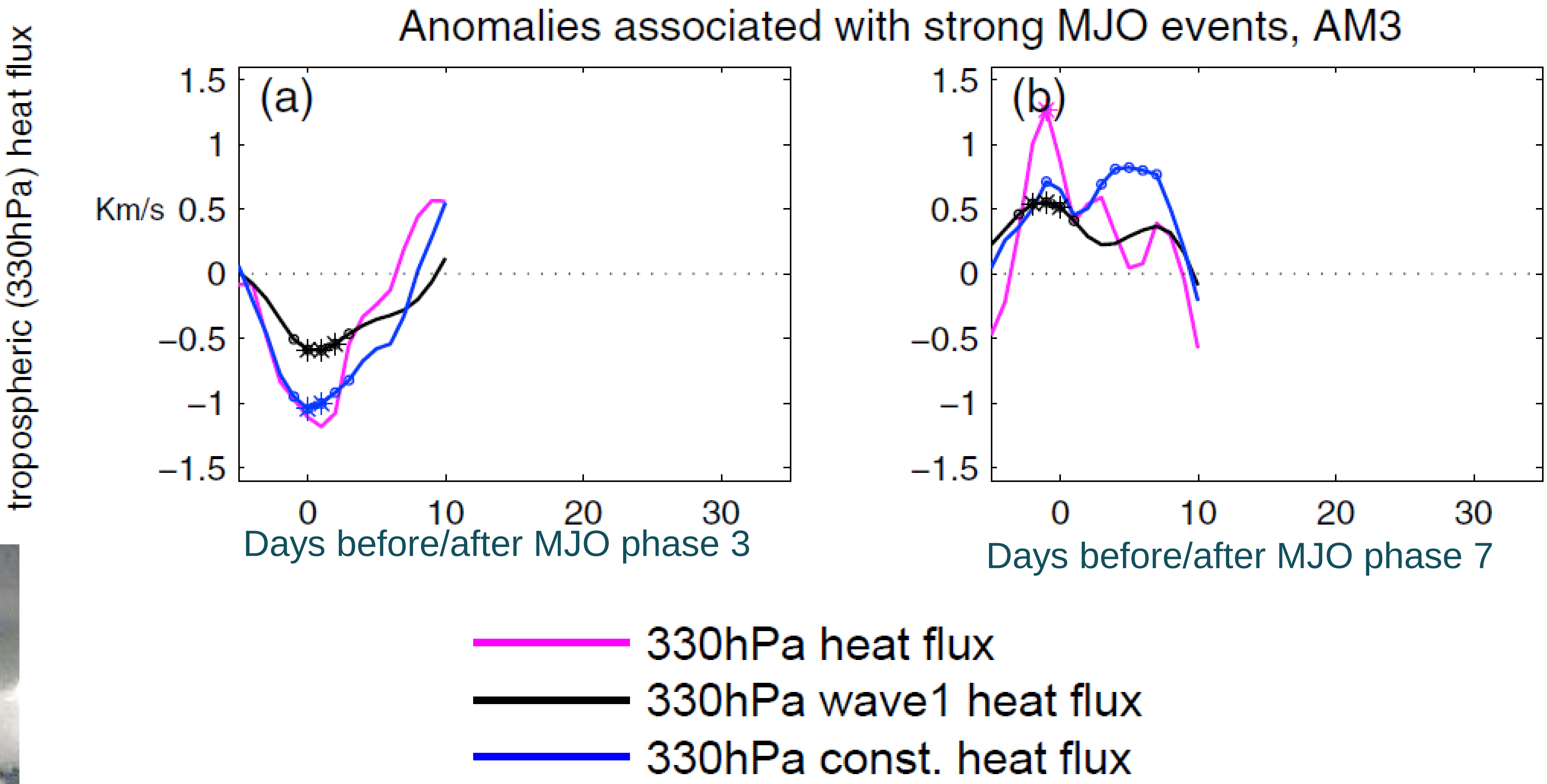
AM3 Simulations

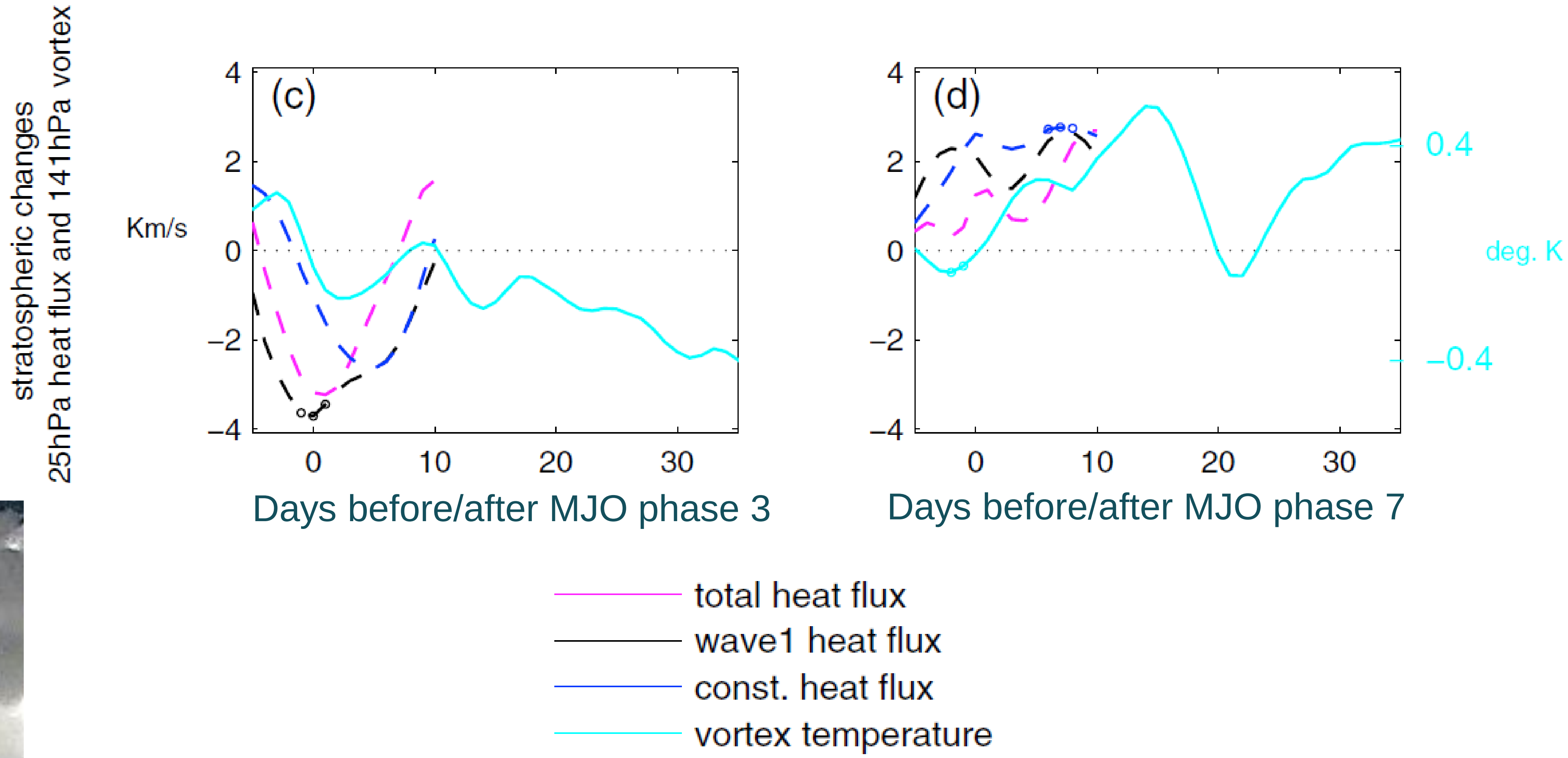
Lagged Response to MJO phases 3 and 7



Less tropospheric heat flux after MJO phase 3, and more heat flux after MJO phase 7

AM3 Simulations

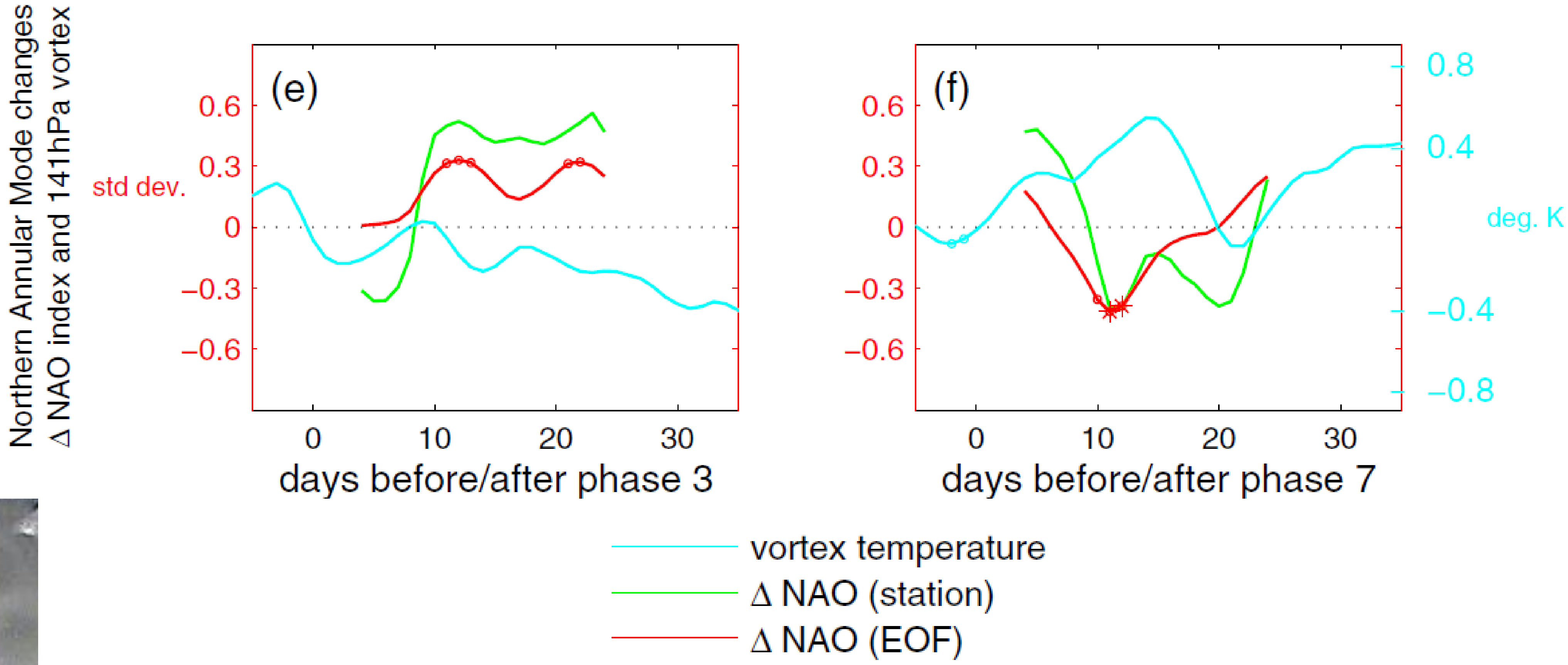
Lagged Response to MJO phase 3 and 7



Heat flux anomalies reach the stratosphere where they interact with the vortex, causing it to cool (phase 3) or warm (phase 7).

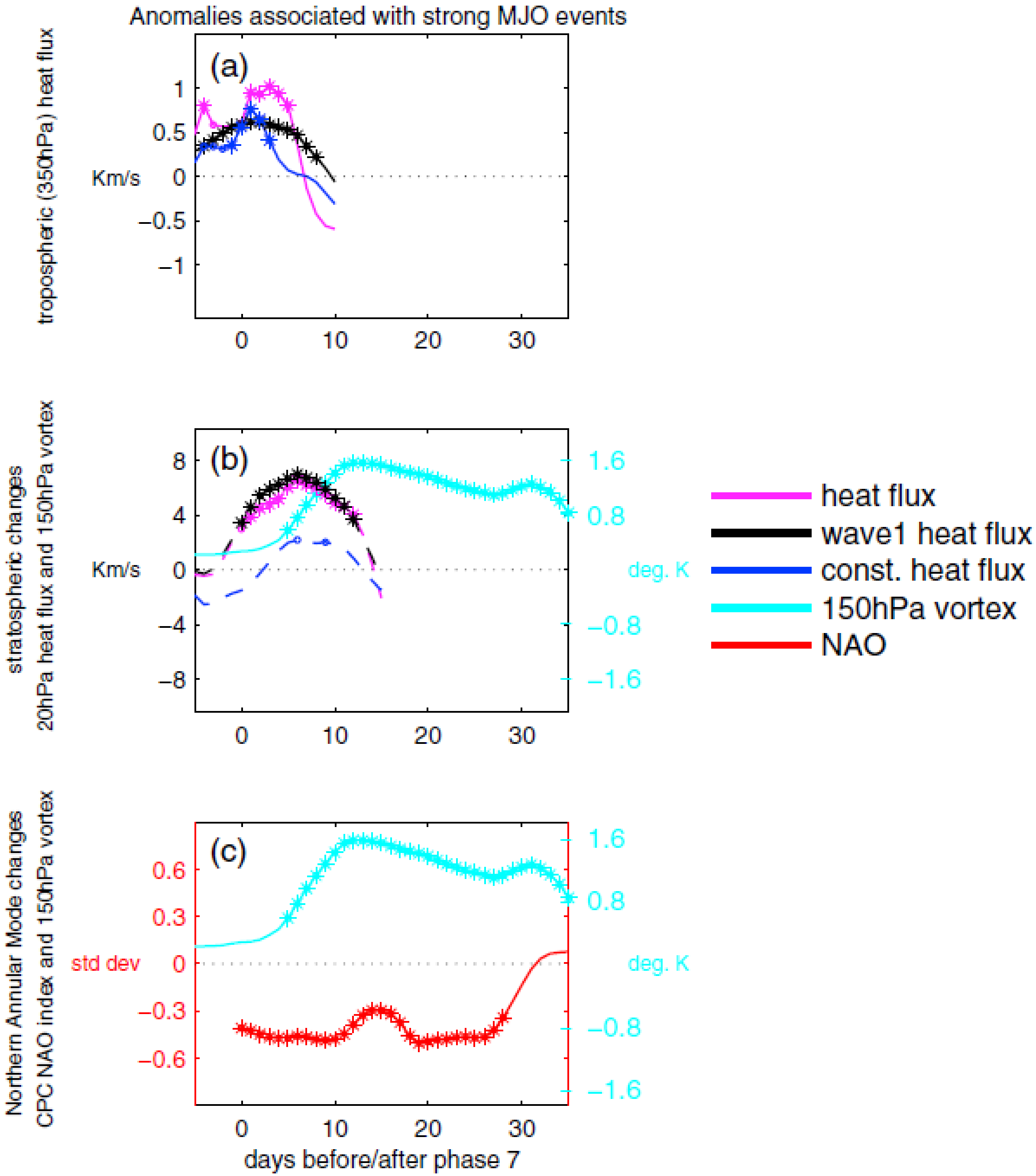
AM3 Simulations

Lagged Response to MJO phase 3 and 7



Once the vortex cools (phase 3) or warms (phase 7), the tropopspheric annular modes are affected: negative NAO after phase 7, and positive NAO after phase 3

Lagged Response to Phase 7 in MERRA



Once the vortex starts to warm during phase 7, the tropopspheric annular modes are affected, and a pre-existing negative NAO persists.

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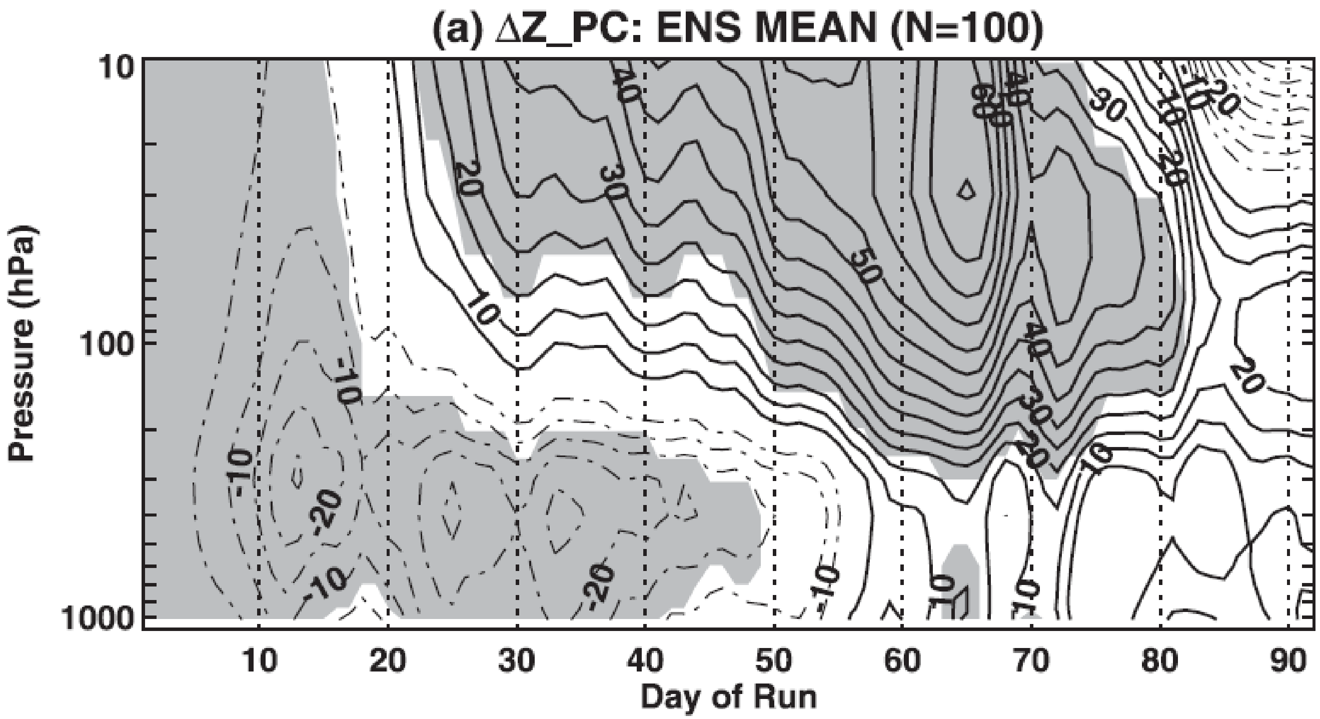
Many phenomena have been linked to the strength of the stratospheric polar vortex

October Eurasian snow cover

North Atlantic sea surface temperatures
Arctic sea ice
North Pacific sea surface temperatures
ENSO
Indian Ocean sea surface temperatures
Quasi-Biennial Oscillation
Incoming Solar Radiation
Madden Julian Oscillation

More extensive snow cover leads to a weaker vortex and subsequently to anomalies in the troposphere (Cohen et al., 2007; Fletcher et al., 2009).



Contours shown polar cap height anomalies after the imposition of a snow cover anomaly.

(from Fletcher et al., 2009)

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Arctic sea ice

North Pacific sea surface temperatures

ENSO

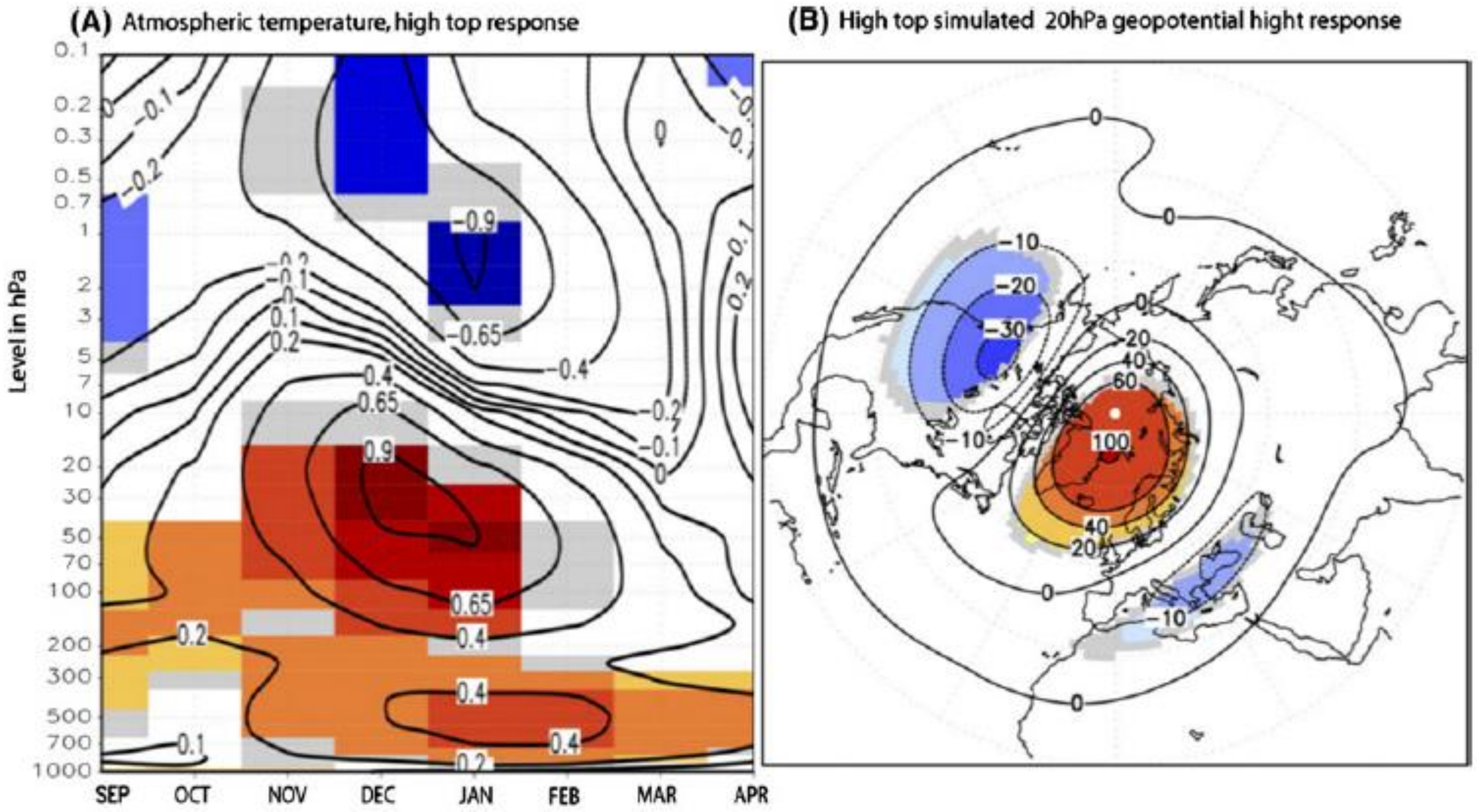
Indian Ocean sea surface temperatures

Quasi-Biennial Oscillation

Incoming Solar Radiation

Madden Julian Oscillation

Warm phase of Atlantic multi-decadal variability leads to a weakened early winter vortex (Schimanke et al., 2011; Omrani et al., 2013).



Modeling response to warm Atlantic SSTs as compared to cold SSTs

Figure from Omrani et al., 2013

Many phenomena have been linked to the strength of the stratospheric polar vortex

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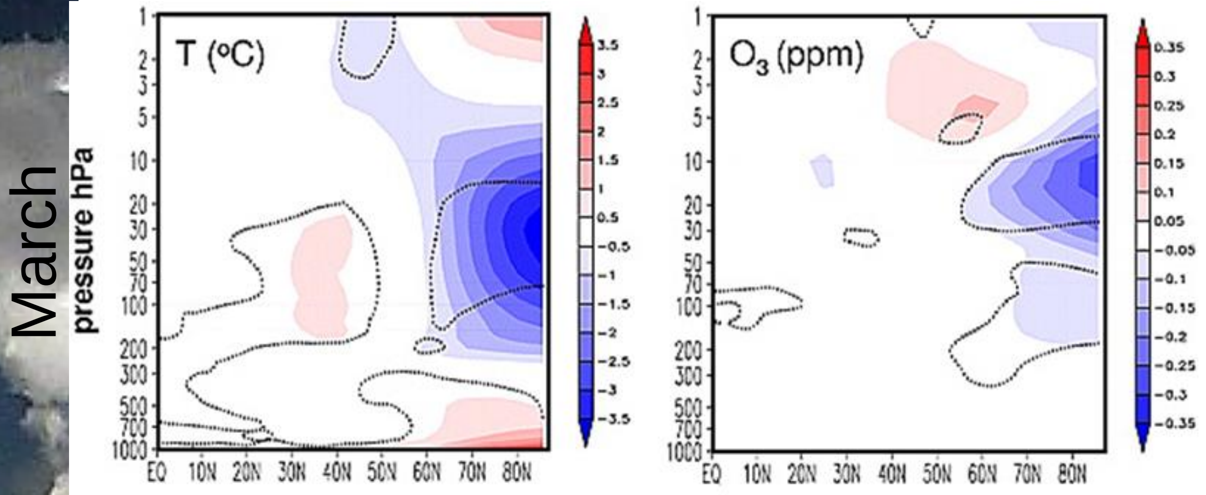
Declining sea ice cover leads to a stronger and colder vortex due to a reduction in wave forcing from the troposphere.

sea-ice perturbation - control



Note that the seasonality differs among different studies: Scinocca et al., 2009 and Screen et al., 2013 find a significant effect primarily in late winter, while Orsolini et al., 2012 and Cai et al., 2012 find a significant effect primarily in early winter.

Figure from Scinocca et al., 2009

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Colder sea surface temperatures in the North Pacific lead to a weakened vortex (Jadin et al., 2010; Hurwitz et al., 2011, 2012).

Temperature at 80N, Warm– Cold NP SSTa

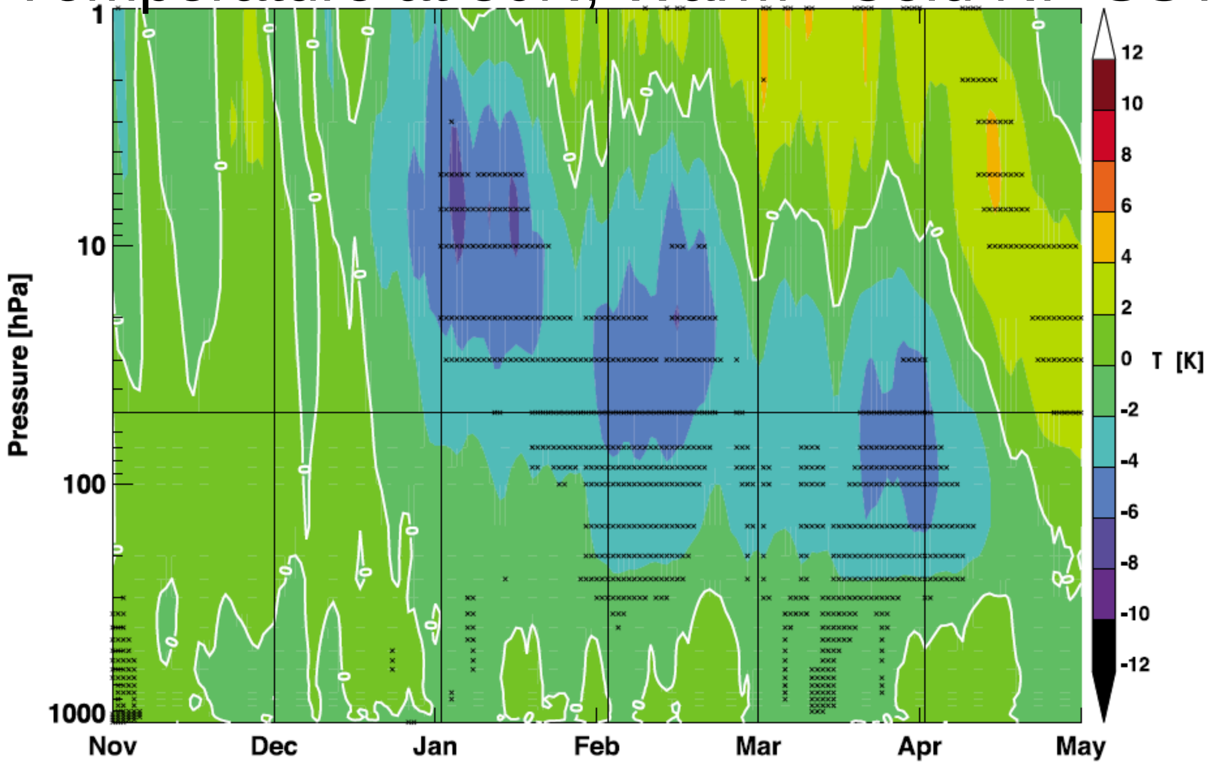

Figure is from the modeling experiments of Hurwitz et al., 2012, and it shows the difference between 40 winters with warm SSTa and 40 winters with cold SSTa

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Many phenomena have been linked to the strength of the stratospheric polar vortex

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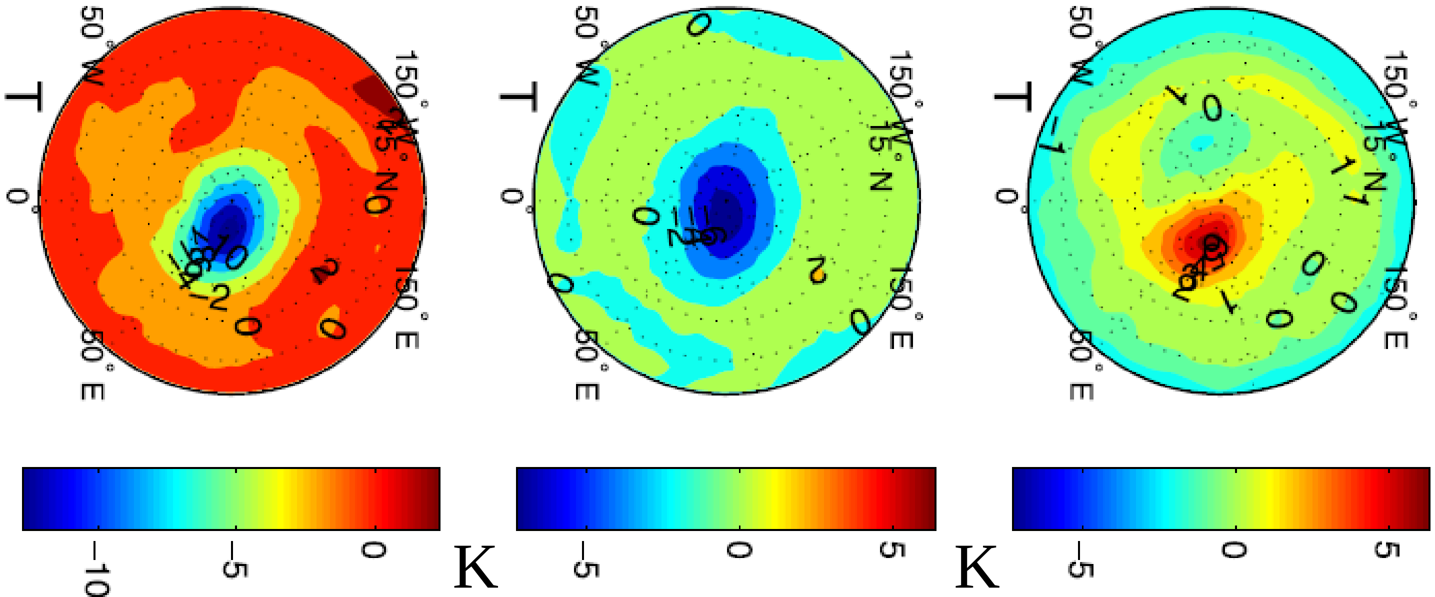
El Nino leads to a weaker vortex, and La Nina (possibly) to a stronger vortex (Manzini et al., 2006, Garfinkel and Hartmann 2007).



El Nino-La Nina

La Nina

El Nino

NDJF Temperature anomalies at 10hPa

Figure from Garfinkel and Hartmann (2007)

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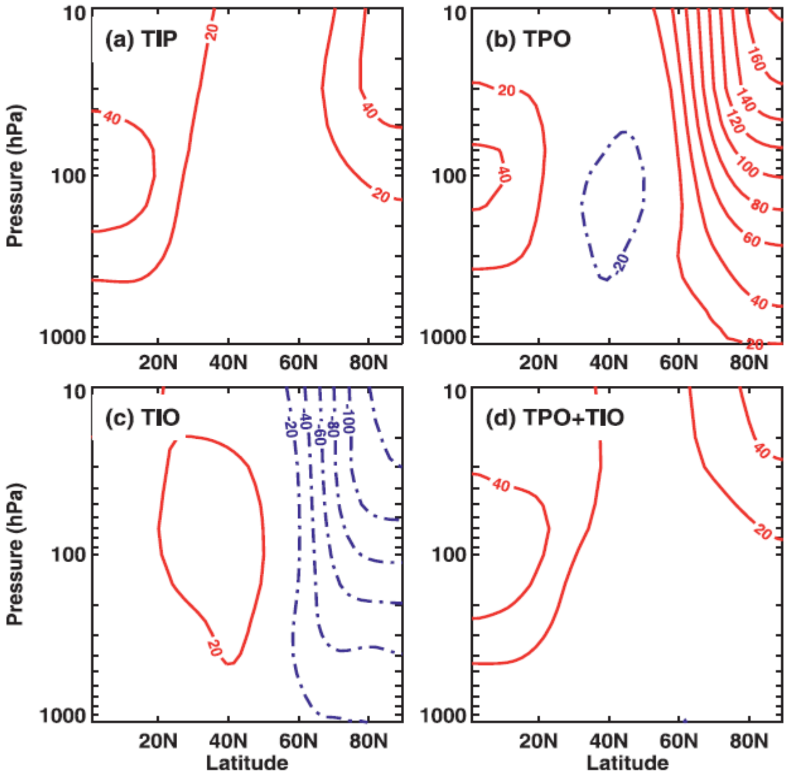
Warmer Indian Ocean SSTs lead to a stronger vortex (Fletcher and Kushner 2011). As El Nino events typically include warmer Indian Ocean temperatures as well, this effect reduces the apparent impact of El Nino on the stratospheric vortex.



JF polar cap height anomalies in 3 modeling experiments that isolate the impact of anomalous SSTs in the tropics

Fletcher and Kushner (2011)

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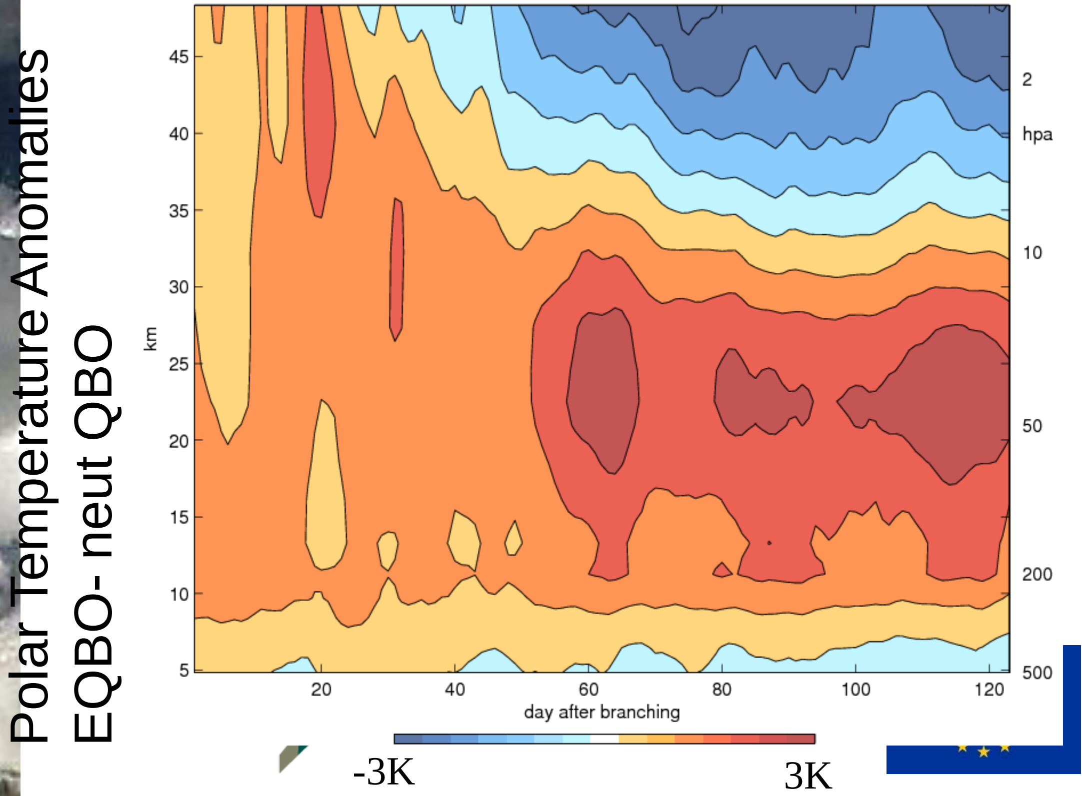

Lower stratospheric easterlies lead to a weaker vortex (Holton and Tan, 1980; Garfinkel et al, 2012)

Temperature anomalies from 70N and poleward after switching on easterly QBO winds (based on Garfinkel et al, 2012)

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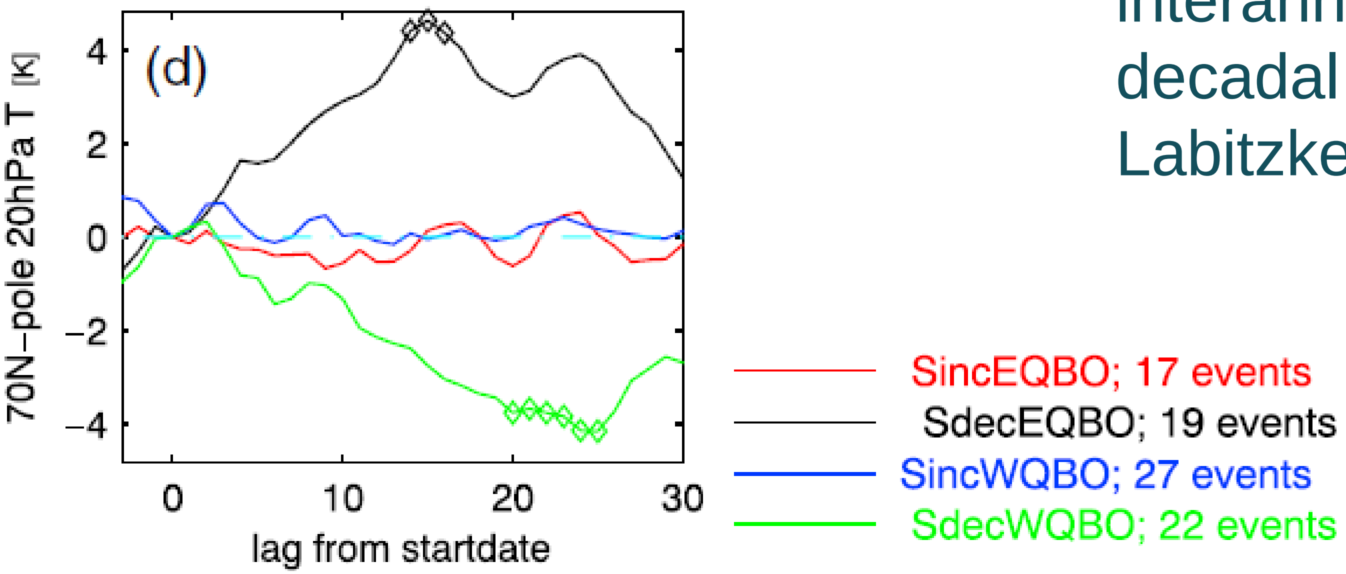
Decreasing solar flux leads to polar warming during EQBO, while decreasing solar flux leads to polar cooling during WQBO. Similar response on interannual timescale as on decadal timescales (e.g. Labitzke 2006)



Garfinkel et al., 2015

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Madden-Julian Oscillation

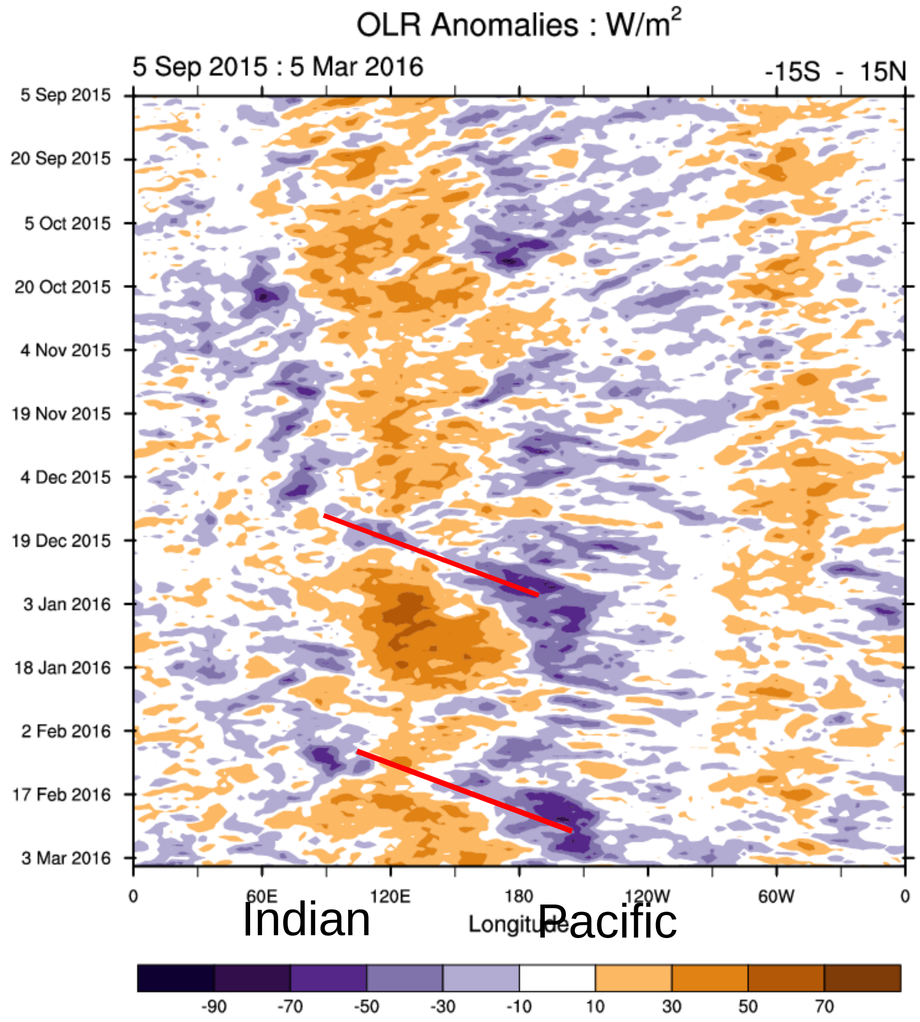
Indian

Pacific

Courtesy of NCAR

MJO is the dominant mode of intraseasonal tropical variability, and it is manifested as eastward propagating anomalies in the tropical Indian and Pacific Oceans.

Madden-Julian Oscillation



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MJO is the dominant mode of intraseasonal tropical variability, and it is manifested as eastward propagating anomalies in the tropical Indian and Pacific Oceans.

Many phenomena have been linked to the strength of the stratospheric polar vortex

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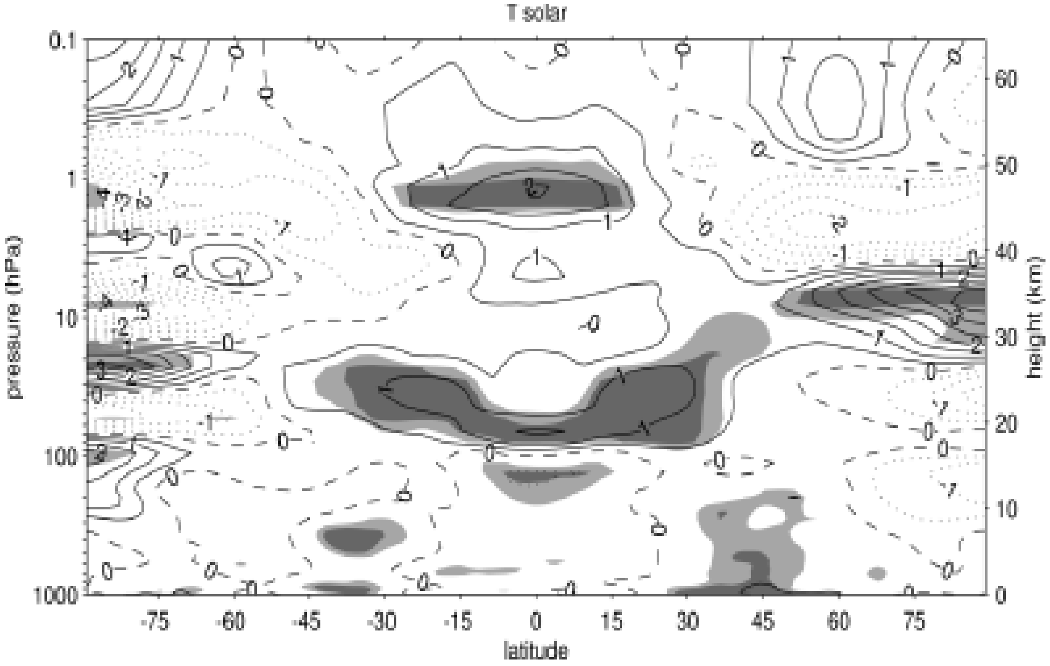
Madden Julian Oscillation

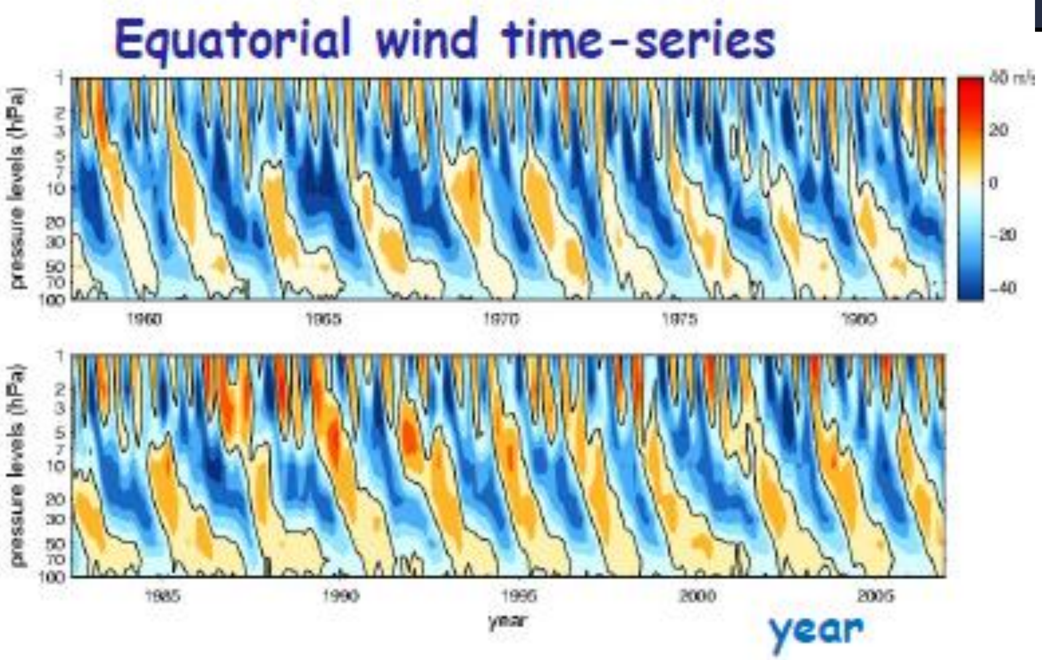
Incoming solar radiation varies on an 11-year timescale. More incoming solar radiation leads to warmer tropical and polar stratosphere. Effect is particularly pronounced in late winter and early spring.



ERA-40
temperature response
Smax minus Smin (K)
annual average 1979-2008

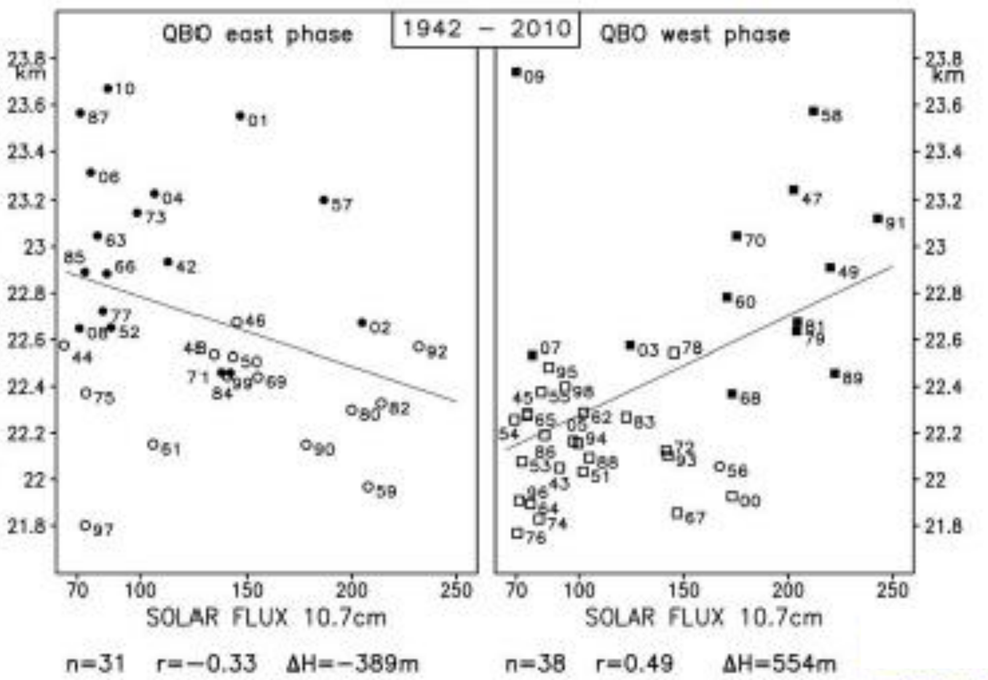
Gray et al 2009 and Frame and Gray 2010

The Quasi Biennial Oscillation (QBO)



Weaker vortex

Stronger vortex



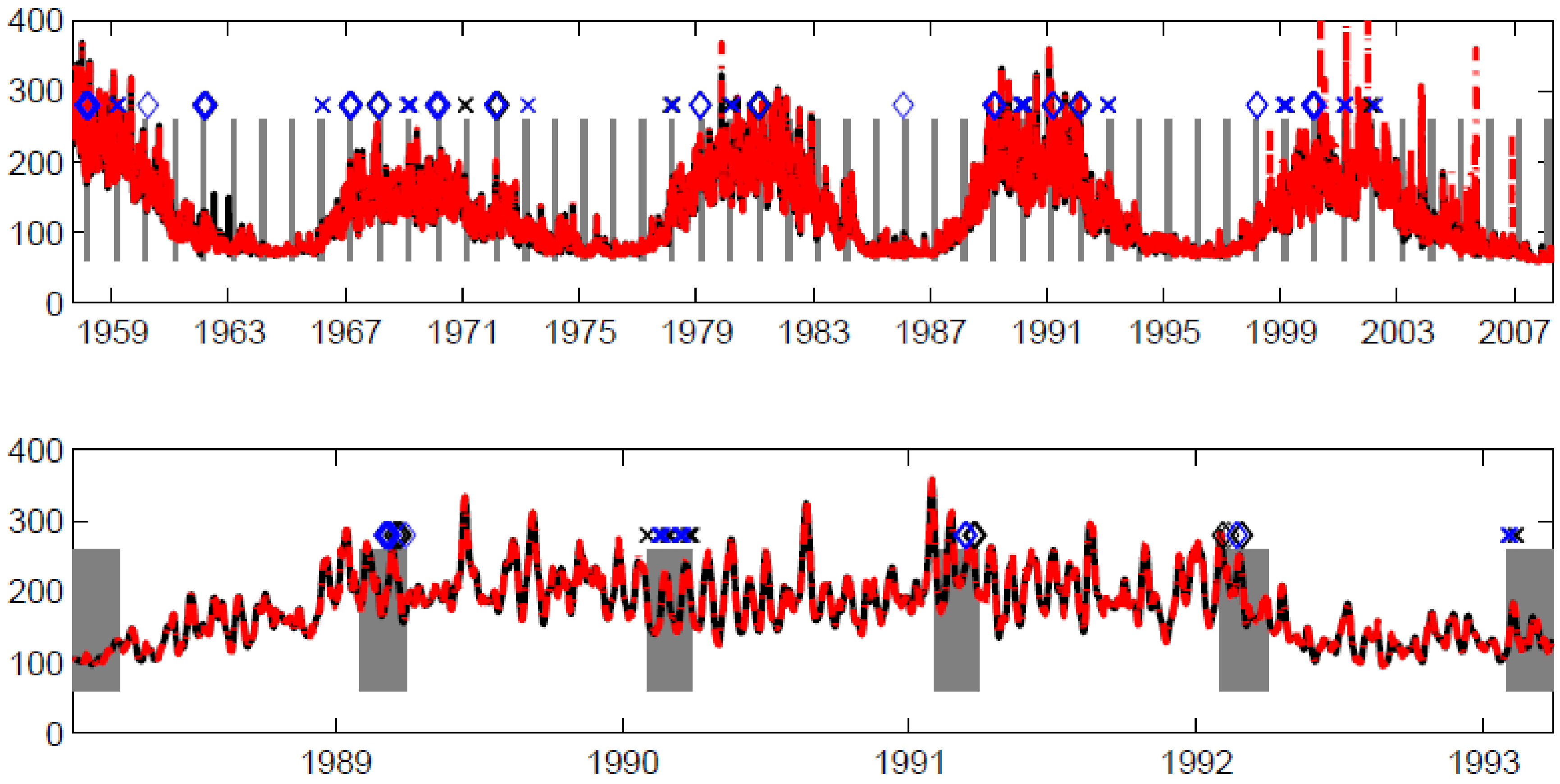
During EQBO, Smin produces weaker vortex in FM

During WQBO, Smin produces stronger vortex in FM

Examining Smax-Smin blurs this difference.

Gray et al 2009

Variability in solar input (in SFU)



We are interested in intraseasonal solar variability: does the response on intraseasonal timescales resemble that on the 11-year timescale? Can the mechanism(s) be deduced?

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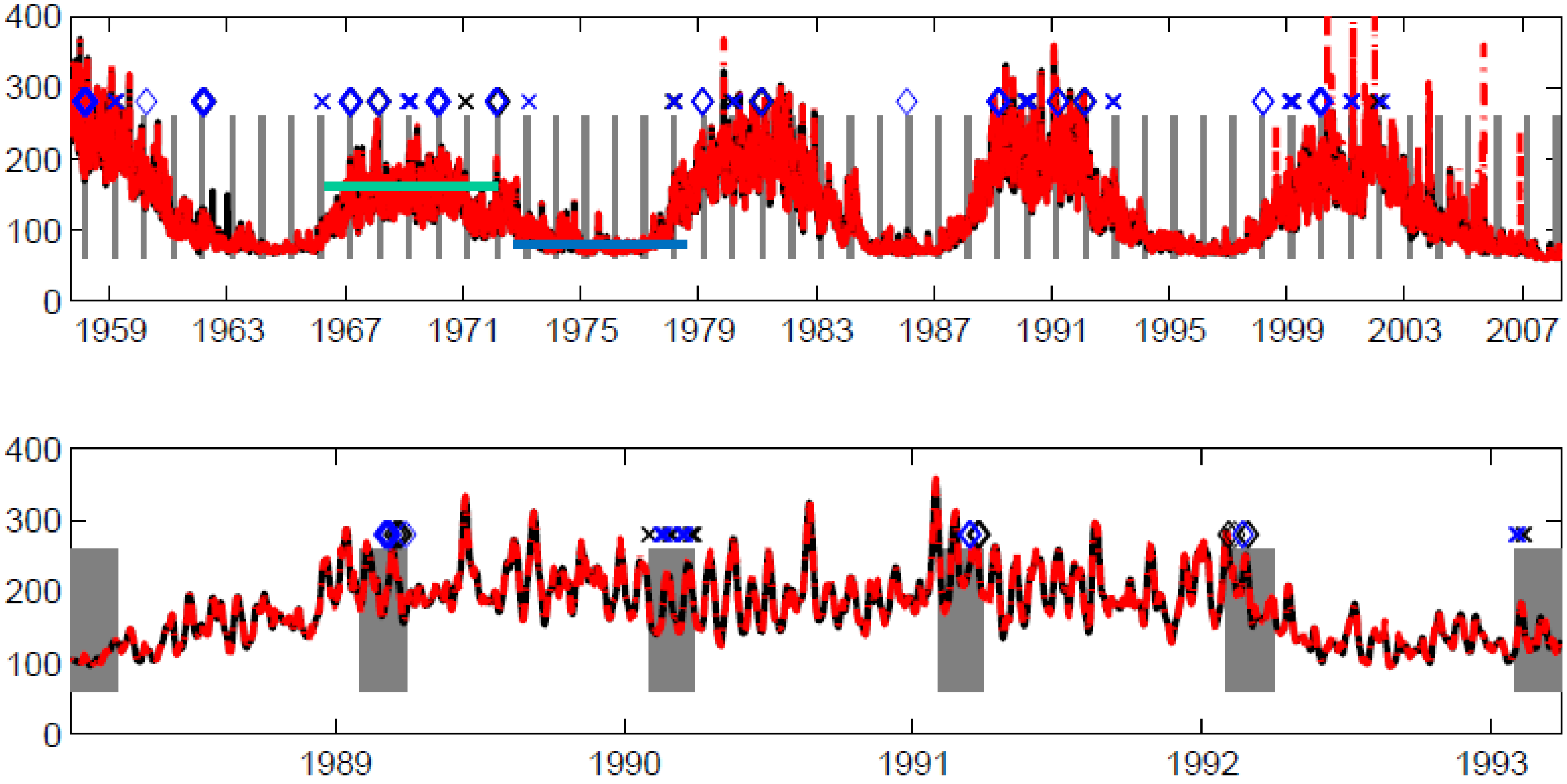
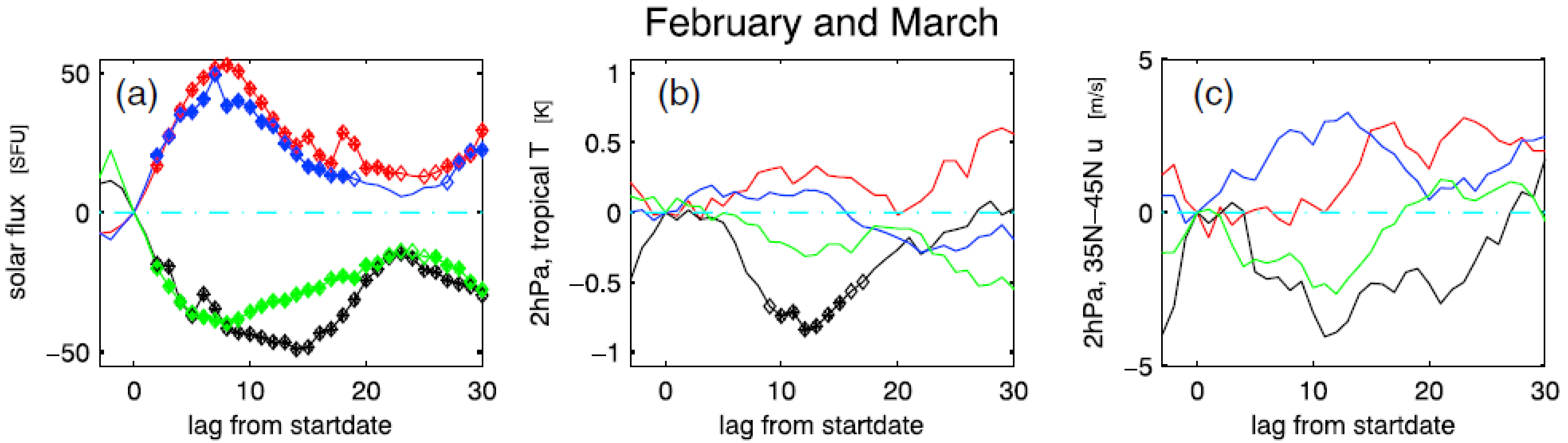
Variability in solar input (in SFU)



We are interested in intraseasonal solar variability: does the response on intraseasonal timescales resemble that on the 11-year timescale? Can the mechanism(s) be deduced?

We form composites of events in which solar flux is increasing and solar flux is decreasing, and we investigate the stratospheric response

Response to Intra-seasonal solar variability

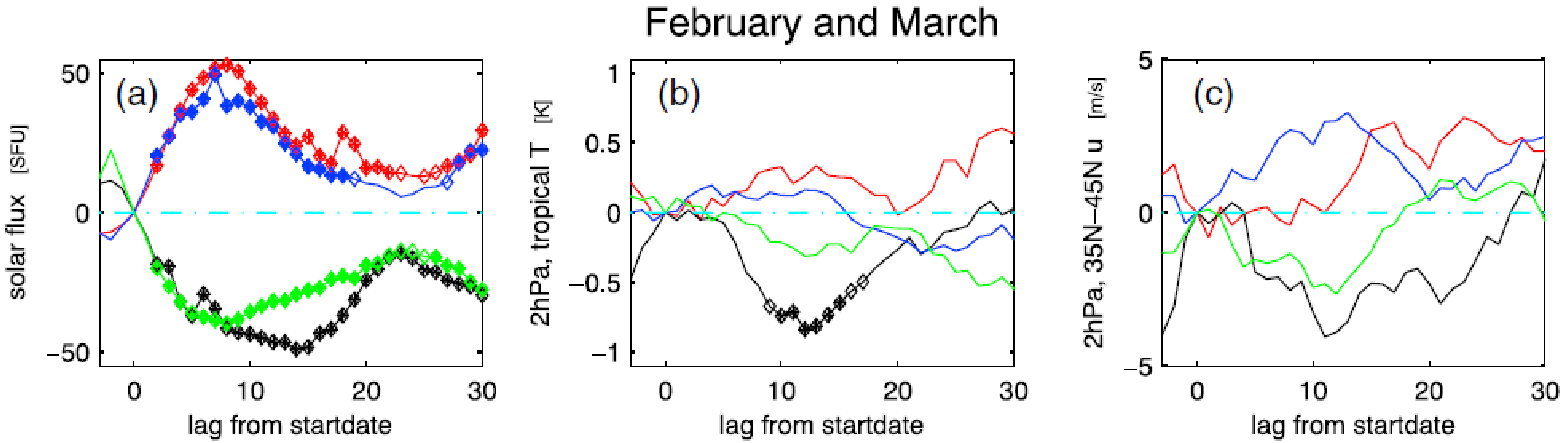


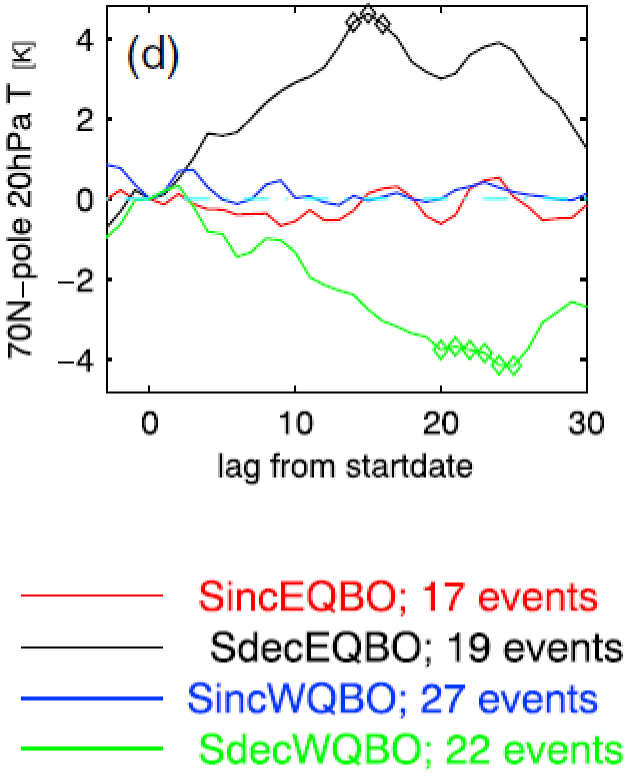
Tropical upper stratosphere warms in response to increasing flux, and cools in response to decreasing flux. Subtropical winds are in thermal wind balance with the tropical temperature anomalies.

SincEQBO; 17 events
SdecEQBO; 19 events
SincWQBO; 27 events
SdecWQBO; 22 events

Response to Intra-seasonal solar variability

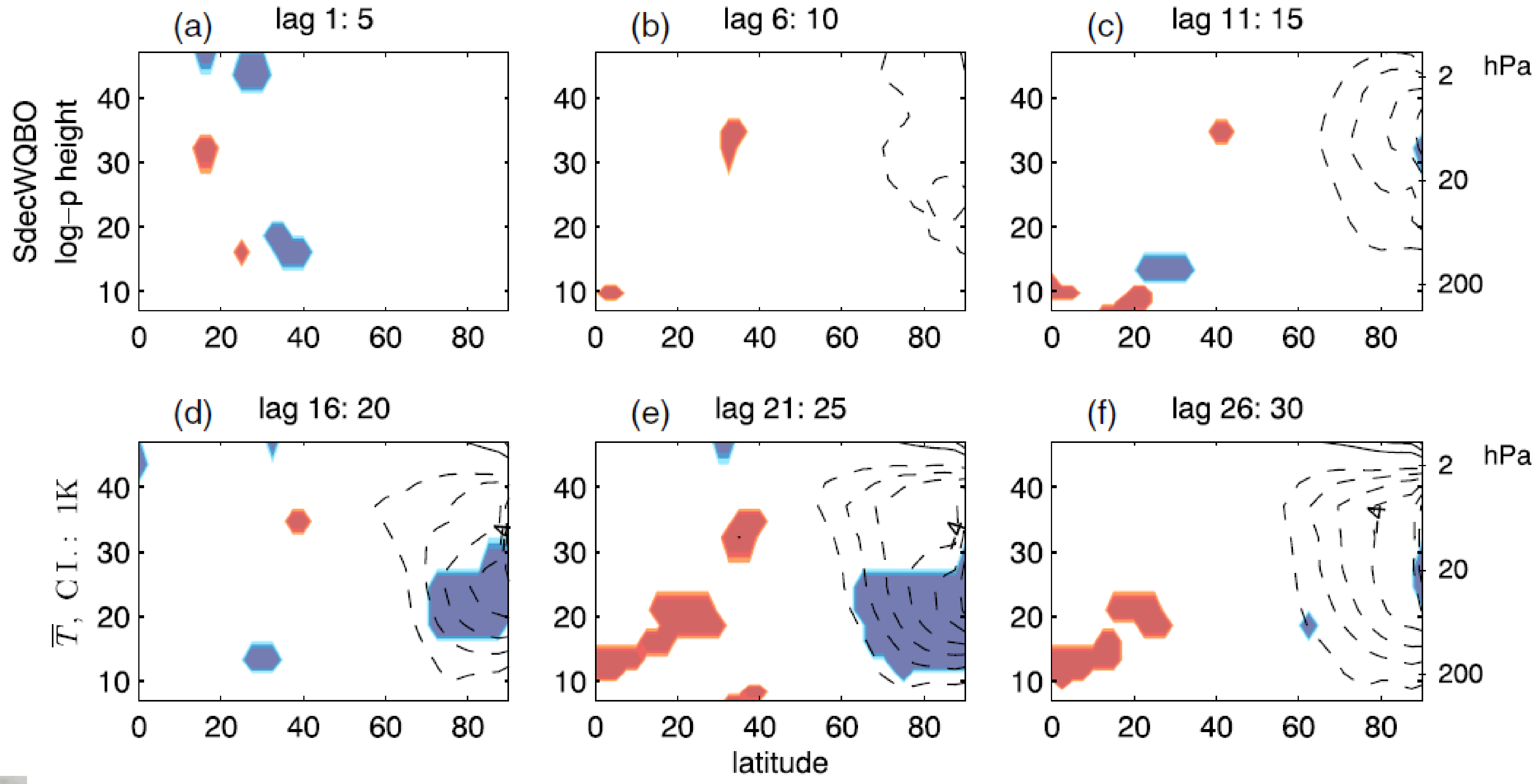
February and March





Similar response on interannual timescale as on decadal: SdecEBO leads to polar warming, while SdecWQBO leads to polar cooling.

Solar decreasing and WQBO – cooling of vortex



Polar anomaly exceeds 6K and is significant at the 95% level 16 to 20 days after the event begins.

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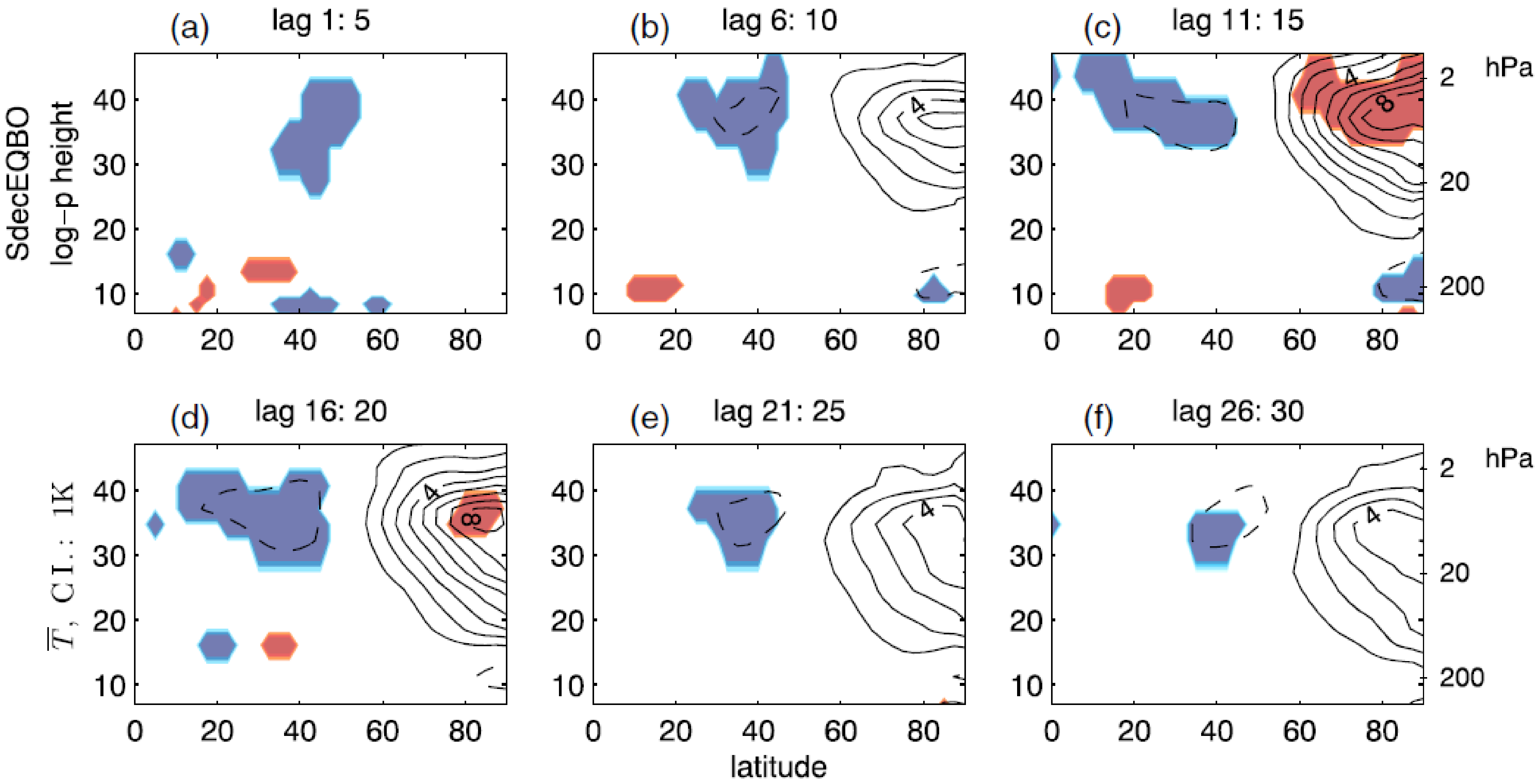
Solar decreasing and EQBO – warming of vortex



Polar anomaly exceeds 6K and is significant at the 95% level 11 to 15 days after the event begins.

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Conclusions

- Nearly a dozen long-lived phenomena have been linked to polar stratospheric vortex variability and surface annular mode variability. The potential for better seasonal forecasting exists.
- The MJO modulates the vortex by deepening the North Pacific Low, which in turn leads to enhanced upwards wave activity flux due to constructive interference with the climatological planetary waves.
- The magnitude of the polar cap averaged effect at 10hPa is ~4K, which is comparable to the effects of the QBO and ENSO.
- Intraseasonal variability in incoming solar radiation leads to anomalies in the polar stratosphere exceeding 6K. The phasing resembles that seen on the 11 year timescale.

Garfinkel, C. I., J. J. Benedict, and E. D. Maloney (2014), Impact of the MJO on the Boreal Winter Extratropical Circulation, GRL, 41, 6055-6062, doi:10.1002/2014GL061094.

Garfinkel C. I., S. B. Feldstein, D. W. Waugh, C. Yoo, S. Lee (2012), Observed Connection between Stratospheric Sudden Warmings and the Madden-Julian Oscillation, GRL, 39, doi: 10.1029/2012GL053144.

Garfinkel, C.I., V. Silverman, N. Harnik, C. Erlich, Y. Riz (2015), Stratospheric Response to Intraseasonal Changes in Incoming Solar Radiation**, J. Geophys. Res. Atmos., 120, 7648-7660. doi: 10.1002/2015JD023244.

Thanks for listening!

Chaim I. Garfinkel

Conclusions

- The MJO modulates the vortex by deepening the North Pacific Low, which in turn leads to enhanced upwards wave activity flux due to constructive interference with the climatological planetary waves.
- The magnitude of the polar cap averaged effect at 10hPa is ~4K, which is comparable to the effects of the QBO and ENSO.
- After the stratospheric vortex is modulated, the anomalies propagate downwards to the troposphere and influence the surface Arctic Oscillation.
- A similar mechanism has been implicated in the effect of ENSO on the vortex (Garfinkel and Hartmann 2008, and many others).

Garfinkel, C. I., J. J. Benedict, and E. D. Maloney (2014), Impact of the MJO on the Boreal Winter Extratropical Circulation, GRL, 41, 6055-6062, doi:10.1002/2014GL061094.

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Garfinkel, C.I., D.L. Hartmann, and F. Sassi (2010), Tropospheric Precursors of Anomalous Northern Hemisphere Stratospheric Polar Vortices, J. Clim.

Thanks for listening!

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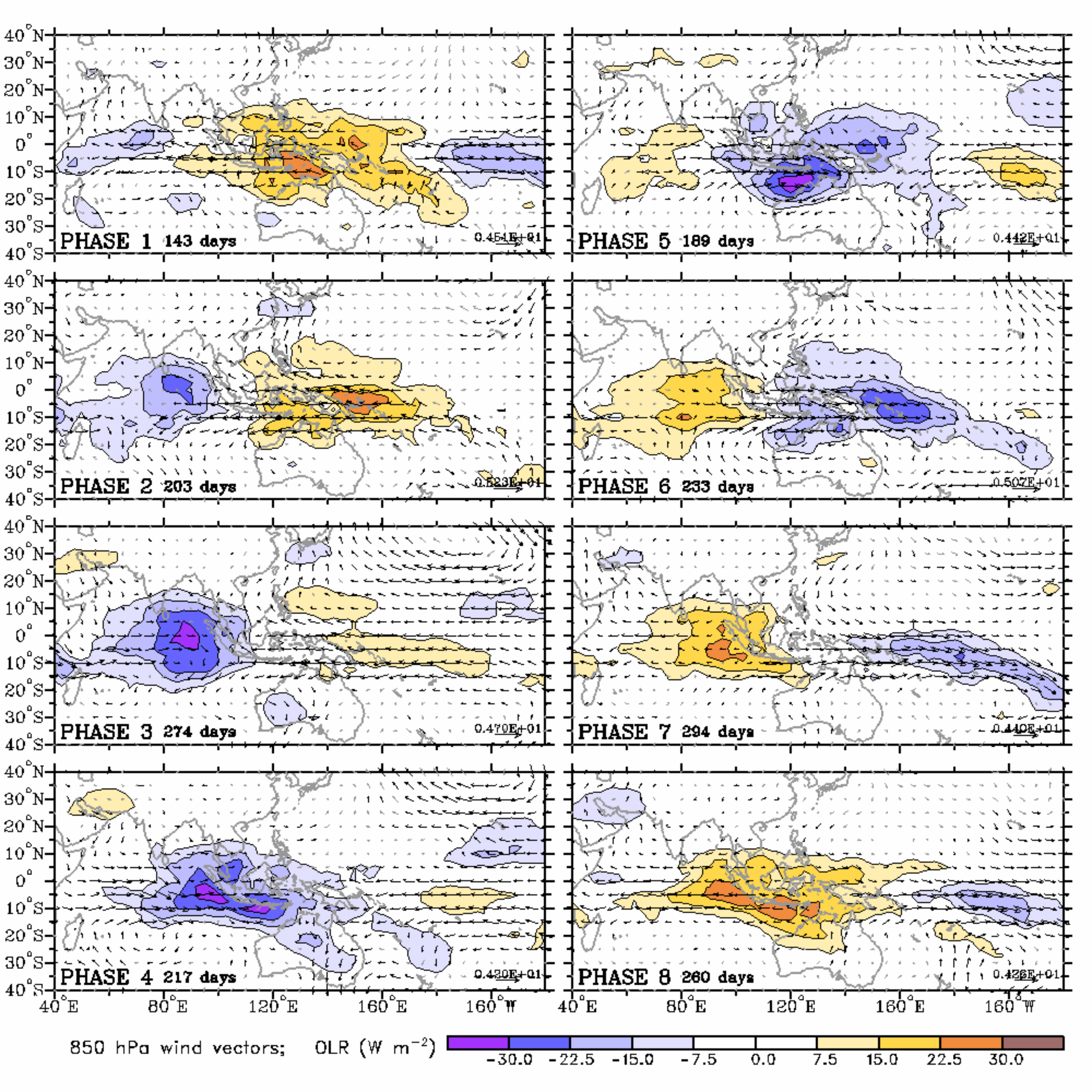
Madden-Julian Oscillation



Courtesy of Matthew Whee

On monthly to seasonal timescales, El Nino and Madden-Julian Oscillation (MJO) dominate)

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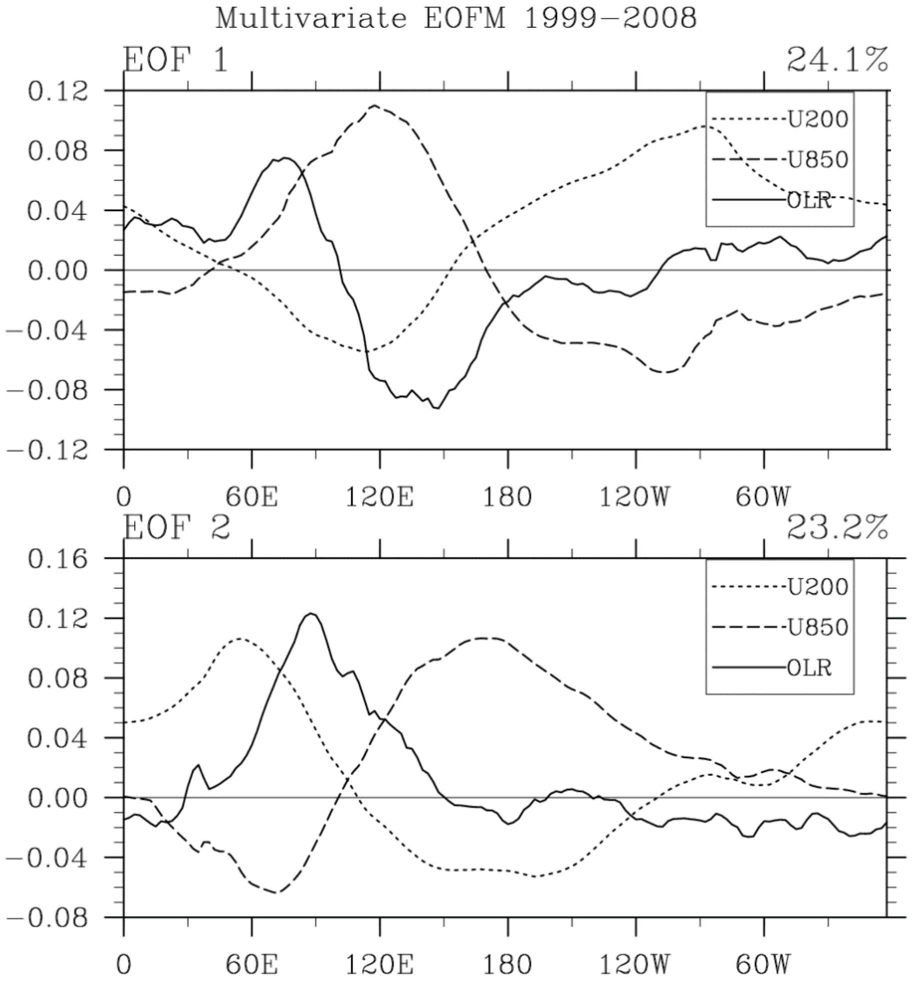
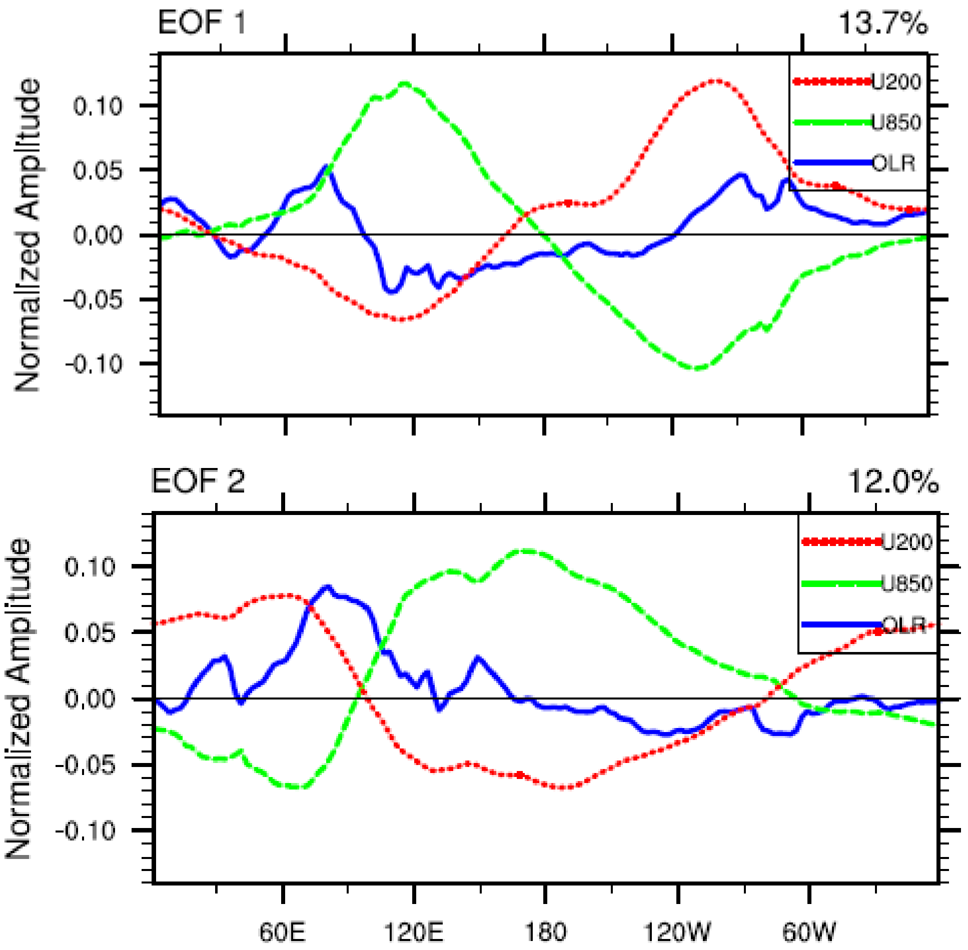
MJO Structure

NOAA OLR and ERA-I winds



AM3 (altered from standard version)



OLR, lower level wind, and upper level wind all act in concert to give localized convection anomalies

AM3 simulates the MJO reasonably well (though there is too much high frequency variability, not shown)

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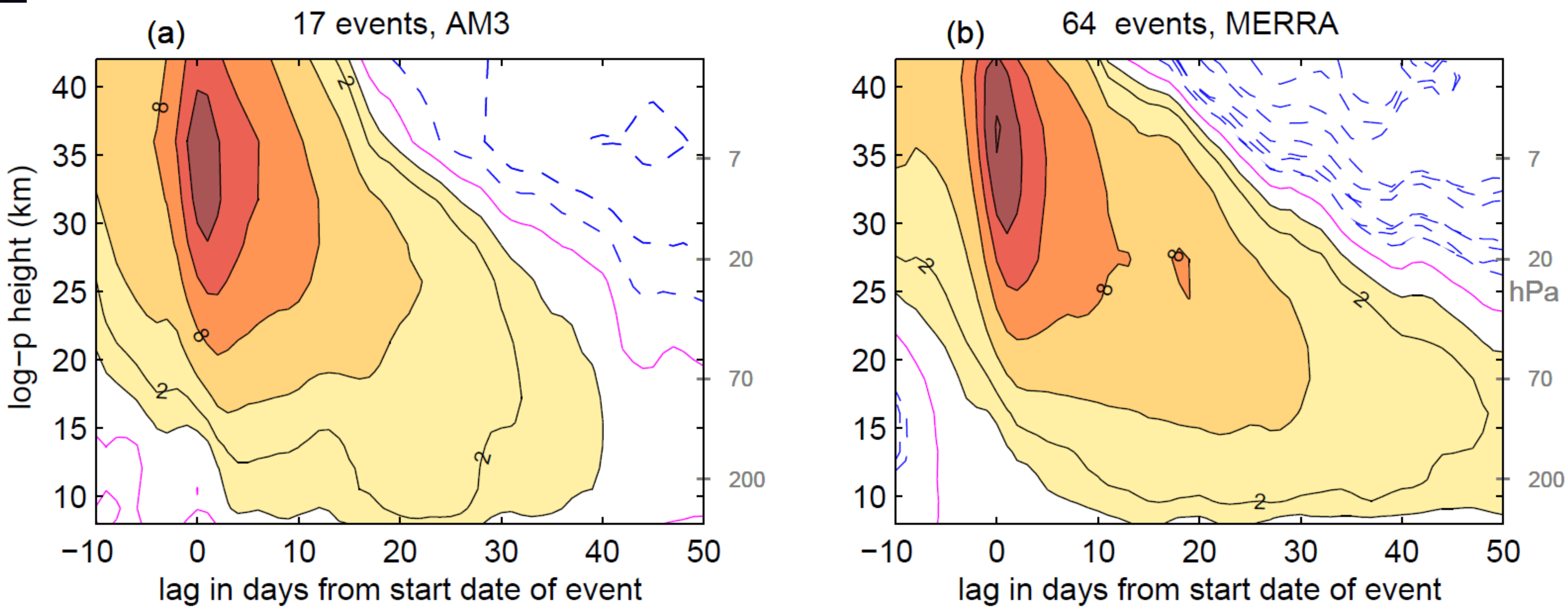
Downward Propagation of Stratospheric Anomalies

AM3

MERRA



Geopotential height anomalies propagate downwards to the tropopause in AM3

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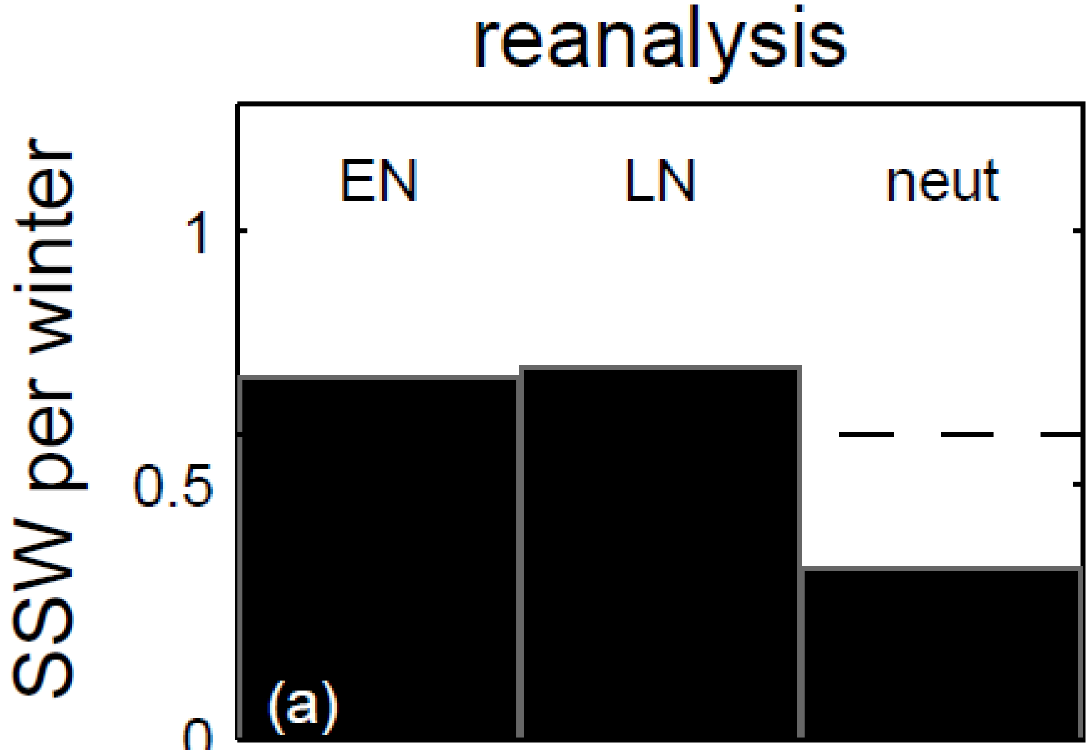
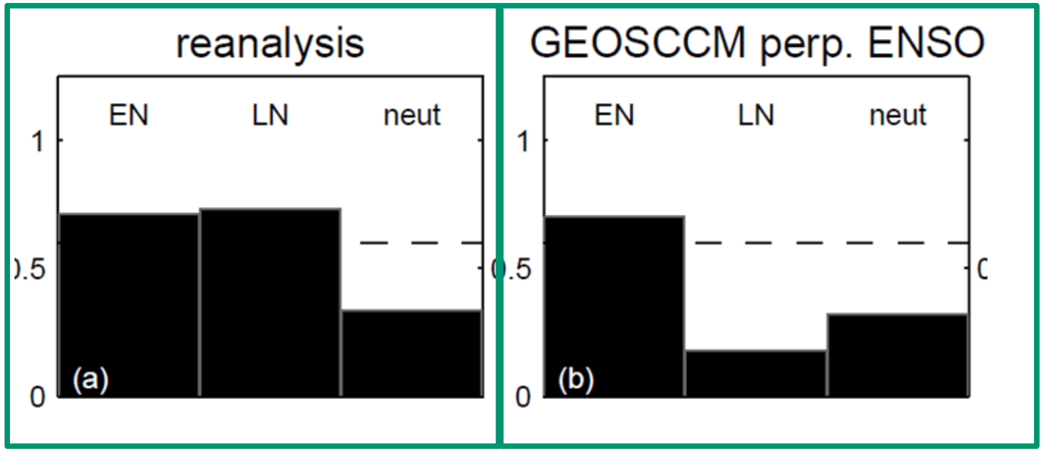
ENSO’s Impact on SSW, reanalysis



Butler and Polvani (2011)

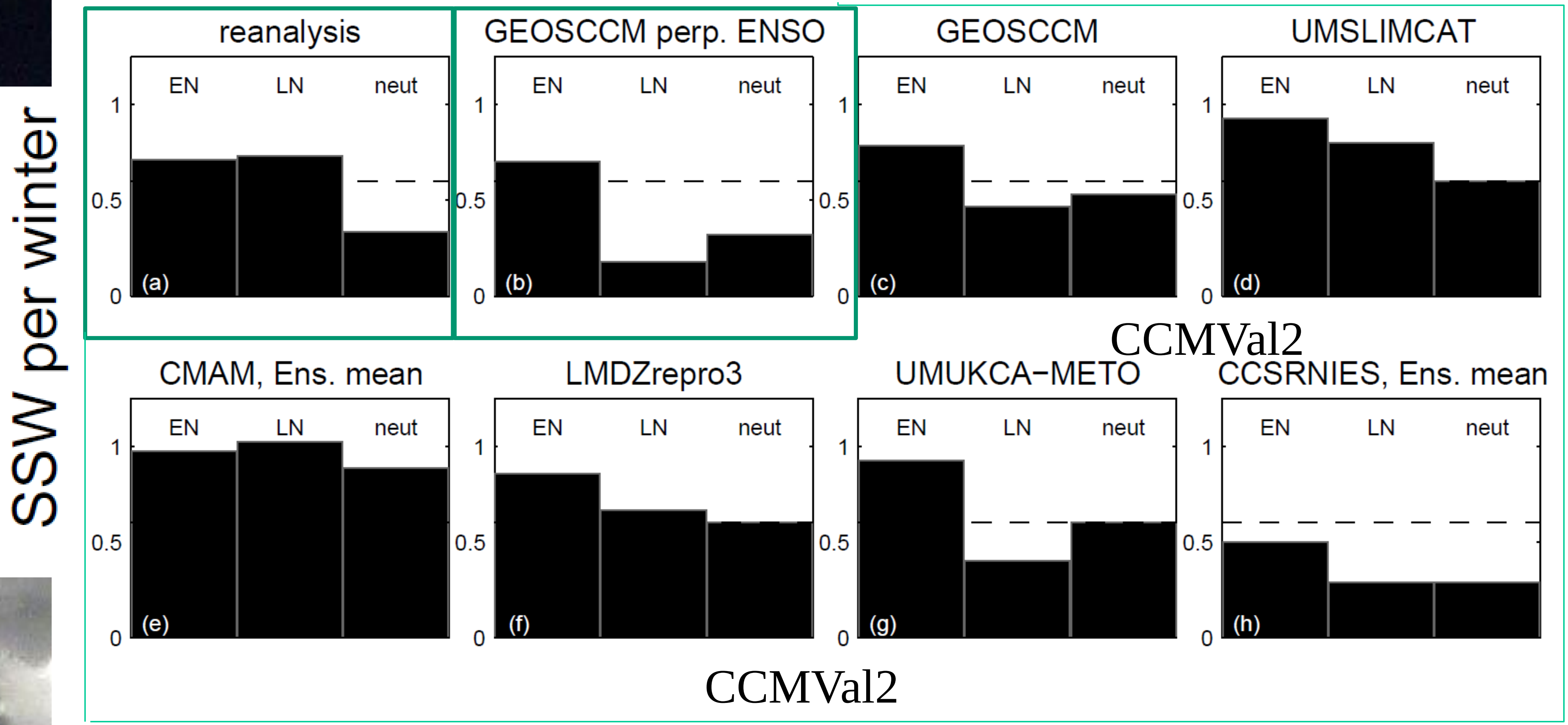
- Apparent Contradiction! Why should both El Nino and La Nina lead to more SSW?
- Why should SSW frequency be lower during neutral ENSO than La Nina?

ENSO’s Impact on SSW, perpetual ENSO GEOSCCM



- 3, 50-year long integrations, one forced with perpetual El Nino sea surface temperatures, one forced with perpetual La Nina sea surface temperature, and one forced with perpetual neutral ENSO sea surface temperatures.
- More SSW in El Nino than in La Nina, contrary to reanalysis result (but as in Taguchi and Hartmann, 2006). Can we understand why GEOSCCM may fail to capture the observed effect?

ENSO’s Impact on SSW, models



- Why should both El Nino and La Nina lead to more SSW in reanalysis and in some models but not others?

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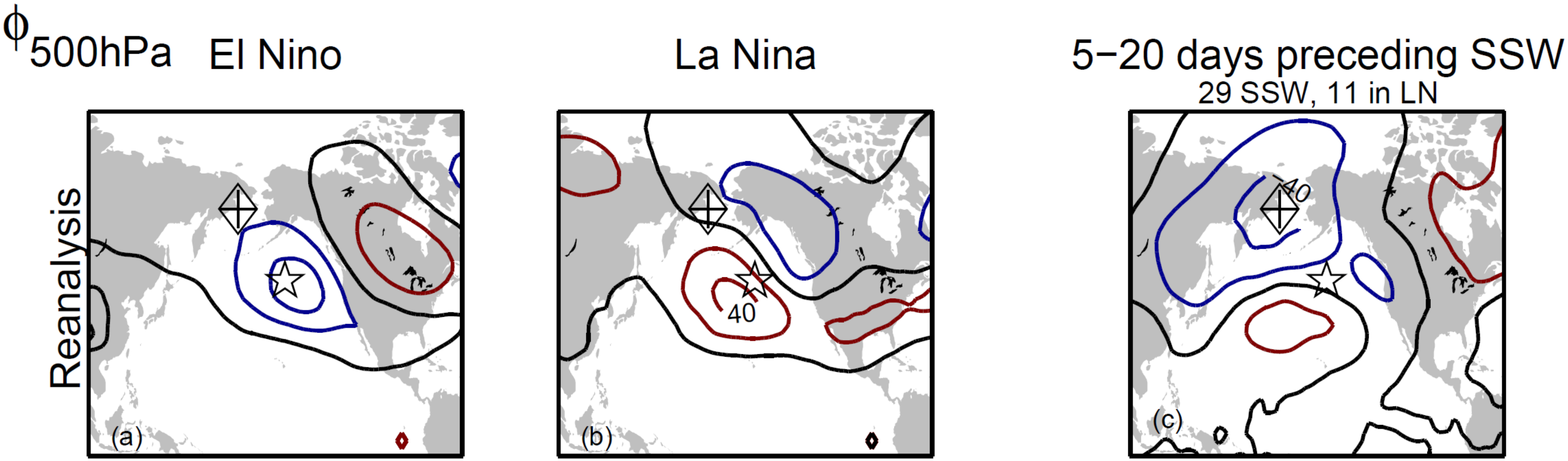
ENSO teleconnections and SSW Precursors

Height anomalies at 500hPa



ϕ_{500hPa} El Nino

La Nina

5−20 days preceding SSW

29 SSW, 11 in LN

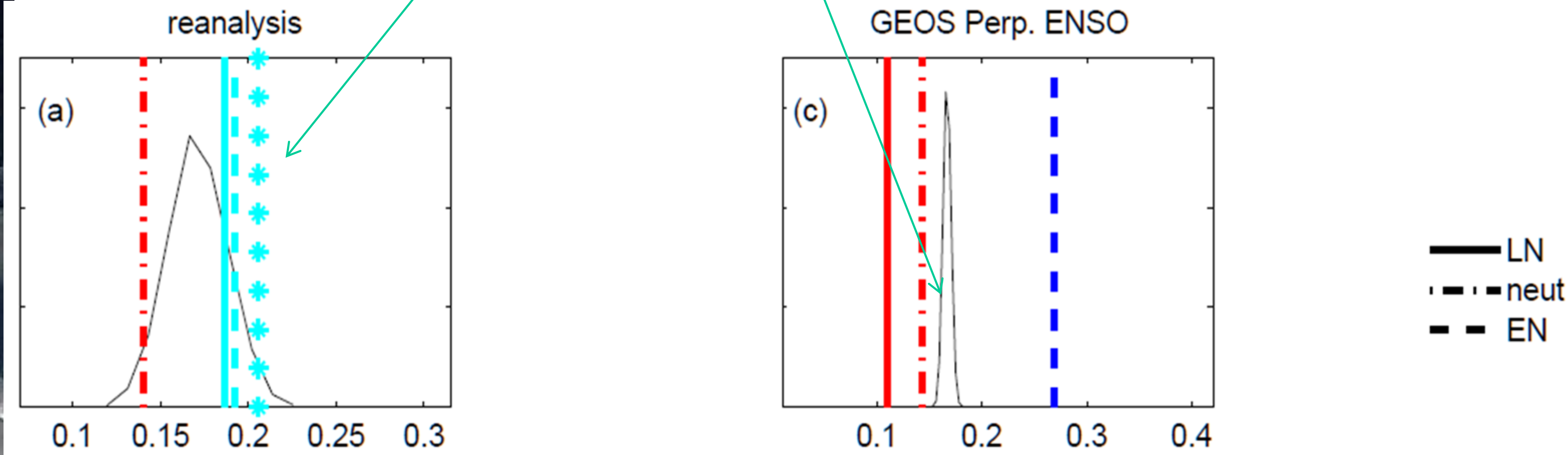
C.I.: 20m

- La Nina’s North Pacific ridge does not reach into the SSW precursor region in the reanalysis (pattern correlation of the La Nina panel and the SSW precursor panel is 0.01)

Frequency of Extreme Lows in SSW Precursor Region

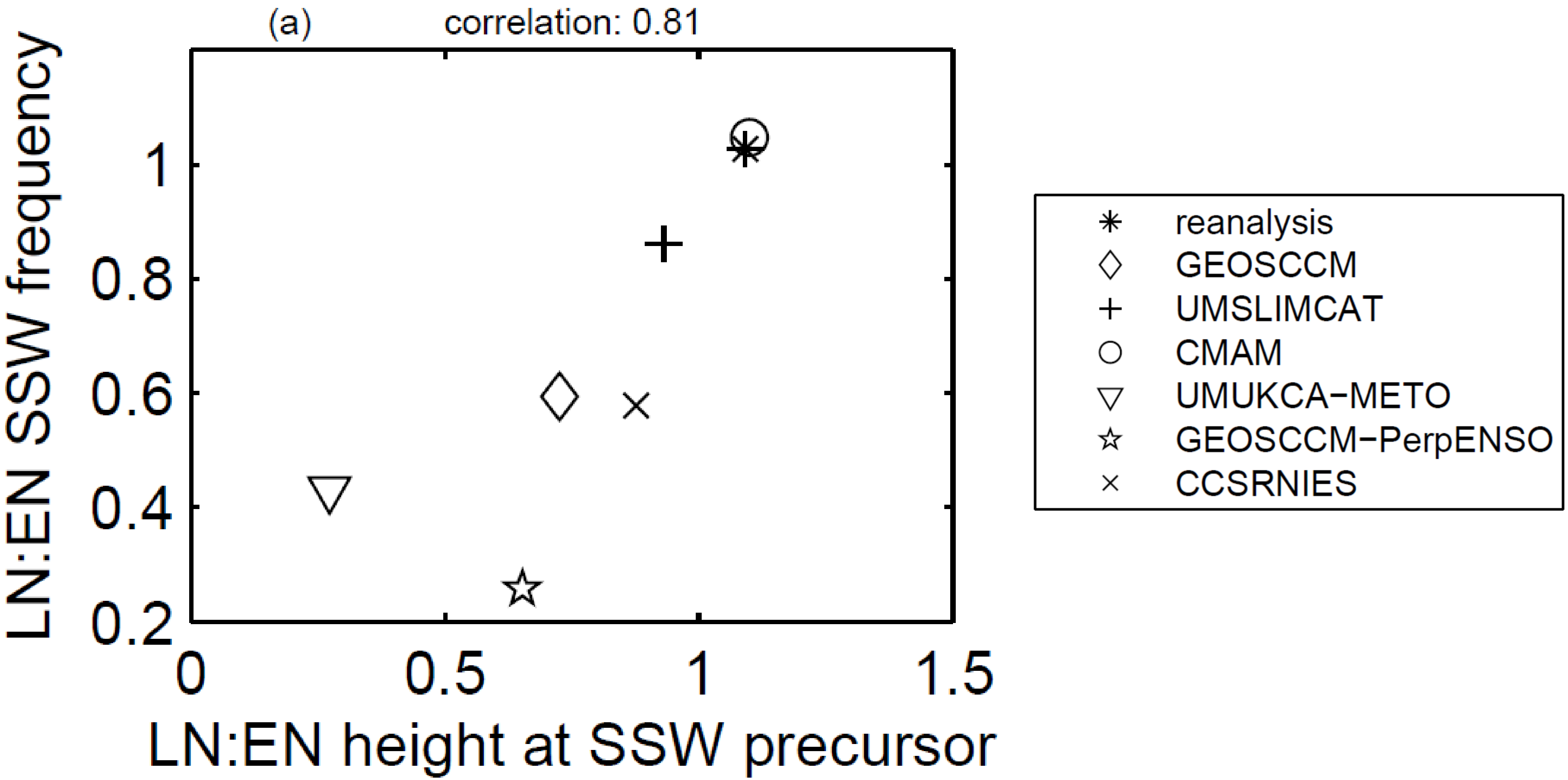
Strong La Nina

Monte Carlo PDF



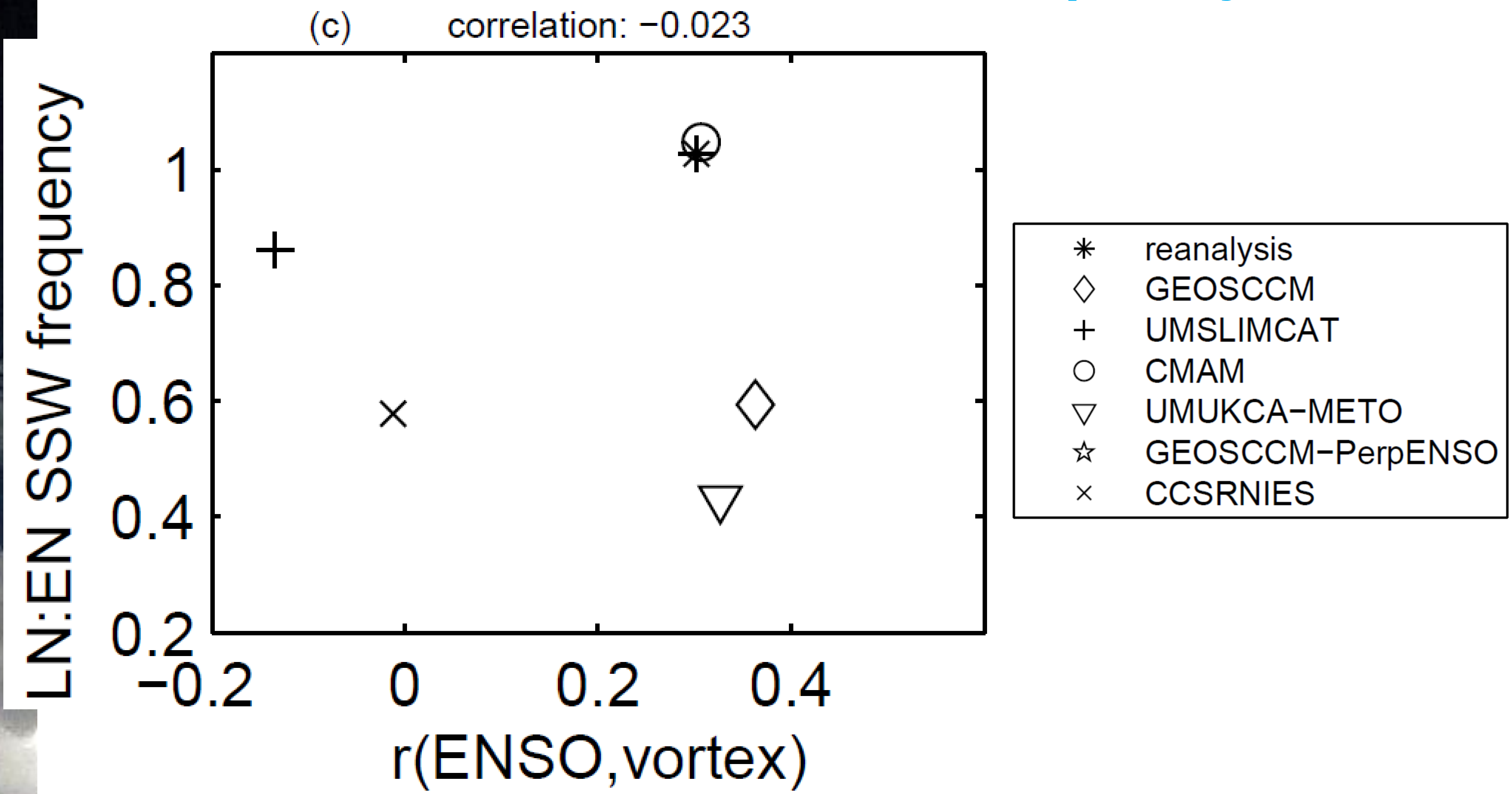
- Extreme negative anomalies in the SSW precursor region occur nearly equally often in La Nina and El Nino, and less often in neutral ENSO, in reanalysis, consistent with SSW frequency.
- In GEOSCCM, extreme negative anomalies occur most often during El Nino, consistent with SSW frequency..

ENSO teleconnections and SSW Precursors, models



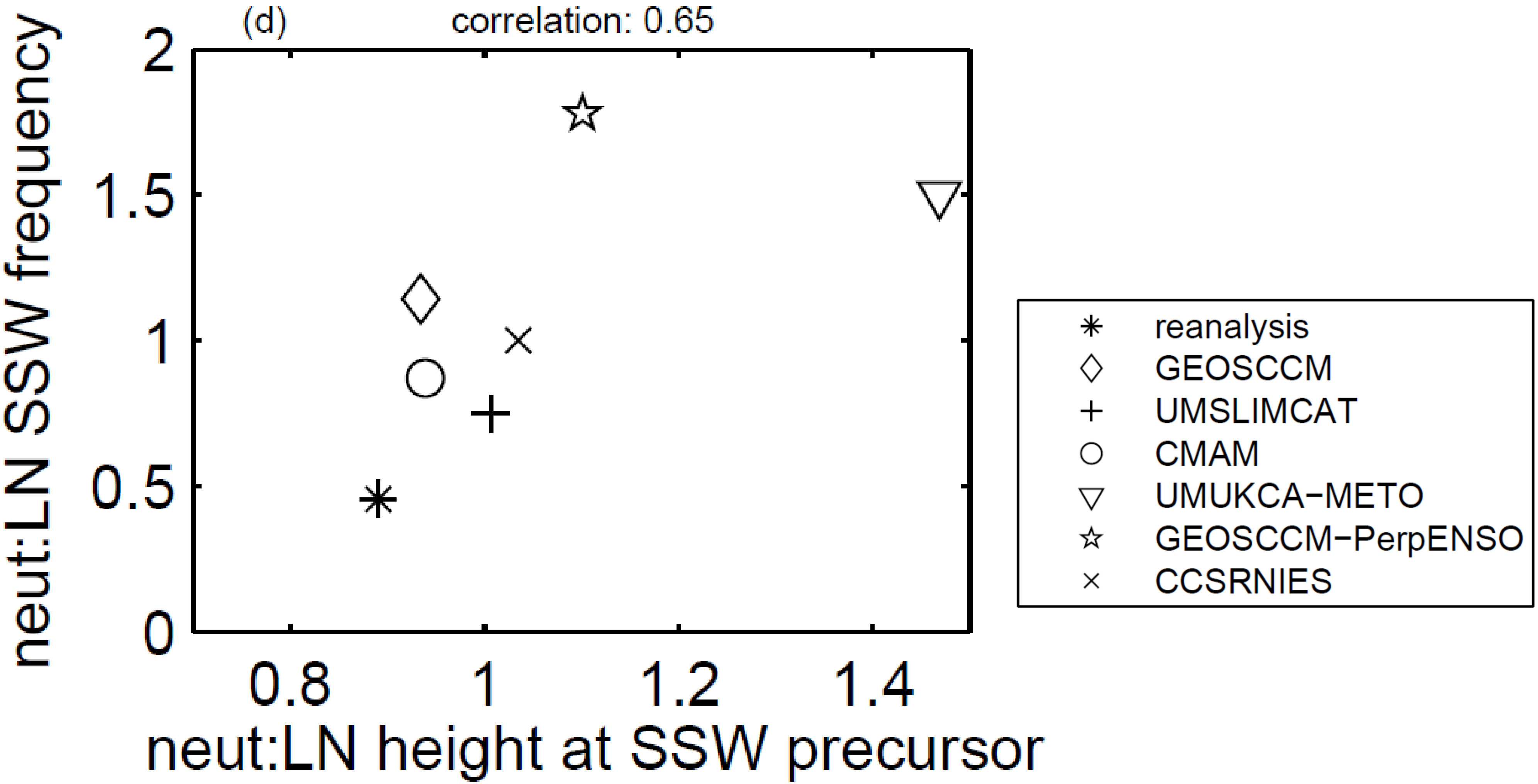
- When La Nina, relative to El Nino, has little impact on extreme negative anomalies in the SSW precursor region, then there is ittle difference between La Nina and El Nino SSW frequency.

No relationship between ENSO impact on seasonal mean vortex and SSW frequency



- Data sources with a large seasonal mean impact from ENSO do not necessarily have a large SSW response to ENSO, and vice versa.

Explanation for Reduced SSW frequency during neutral ENSO winters



- Frequency of occurrence of large negative anomalies in SSW precursor region largely determines SSW frequency during neutral ENSO winters.

Key Question:

- What are the underlying pathway(s) through which tropospheric variability can affect planetary wave driving of the polar vortex?

Objective Search for Tropospheric Patterns

1. Define a vortex weakening index as the change in vortex strength over a ten day period.
2. Correlate tropospheric geopotential height over the entire Northern Hemisphere with this index of vortex weakening.
3. Analyze the subsequent patterns in both the reanalysis record and in a 126 year general circulation model run.

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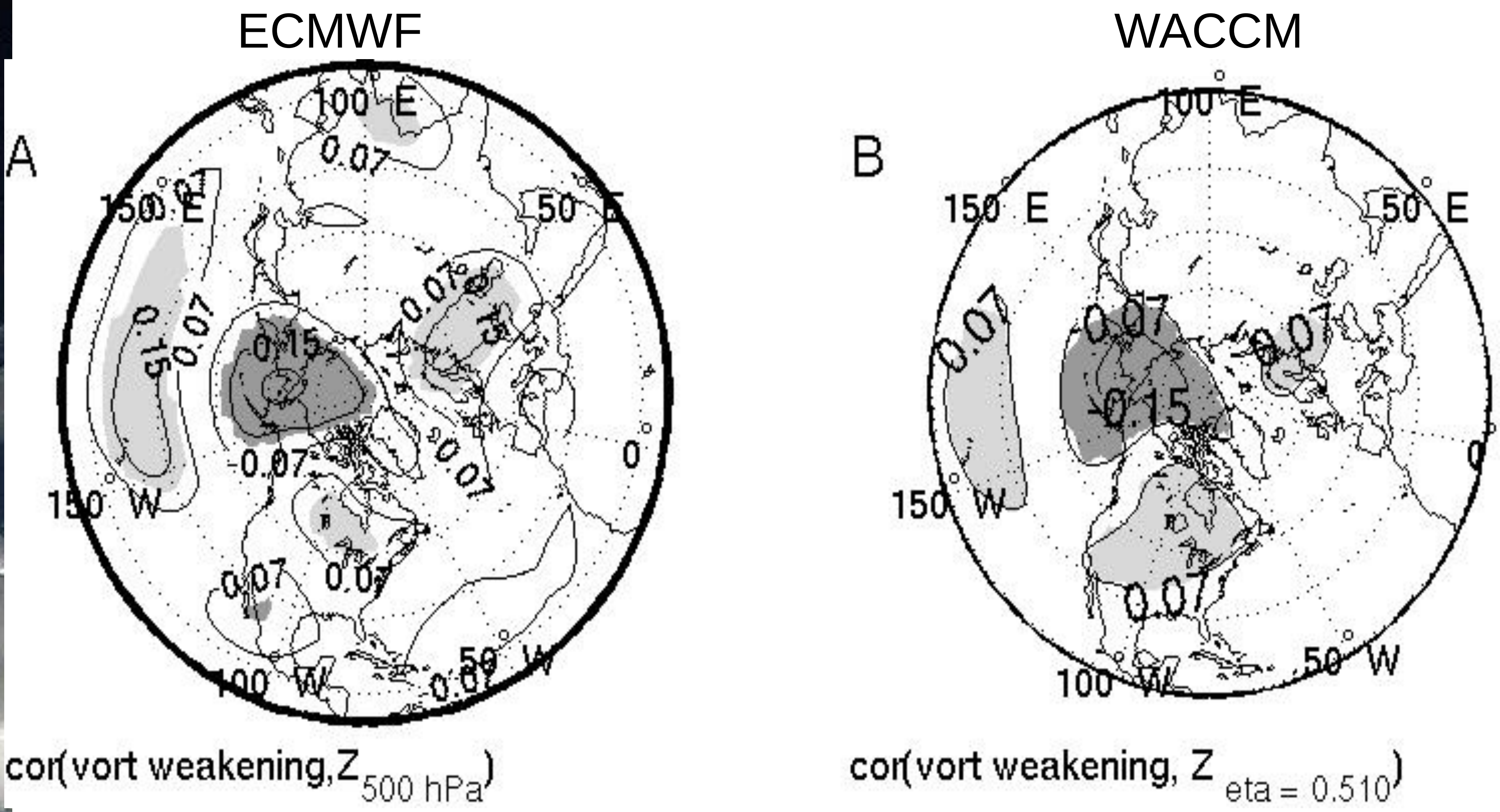
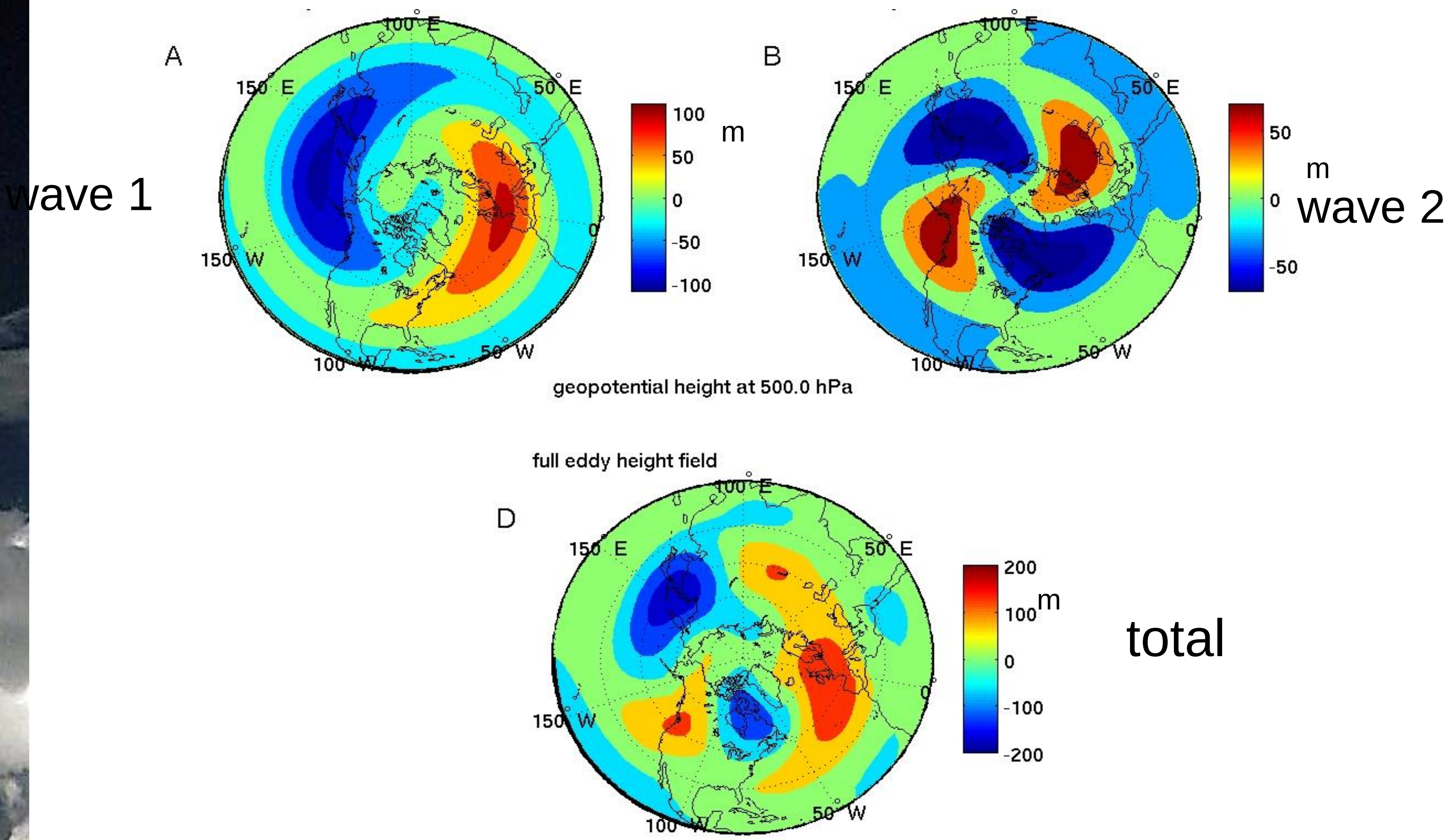
Tropospheric geopotential height correlated with vortex weakening



Garfinkel et al 2010, J. Clim.

Why do low anomalies over the North Pafic and high anomalies over Eastern Europe weaken the vortex?

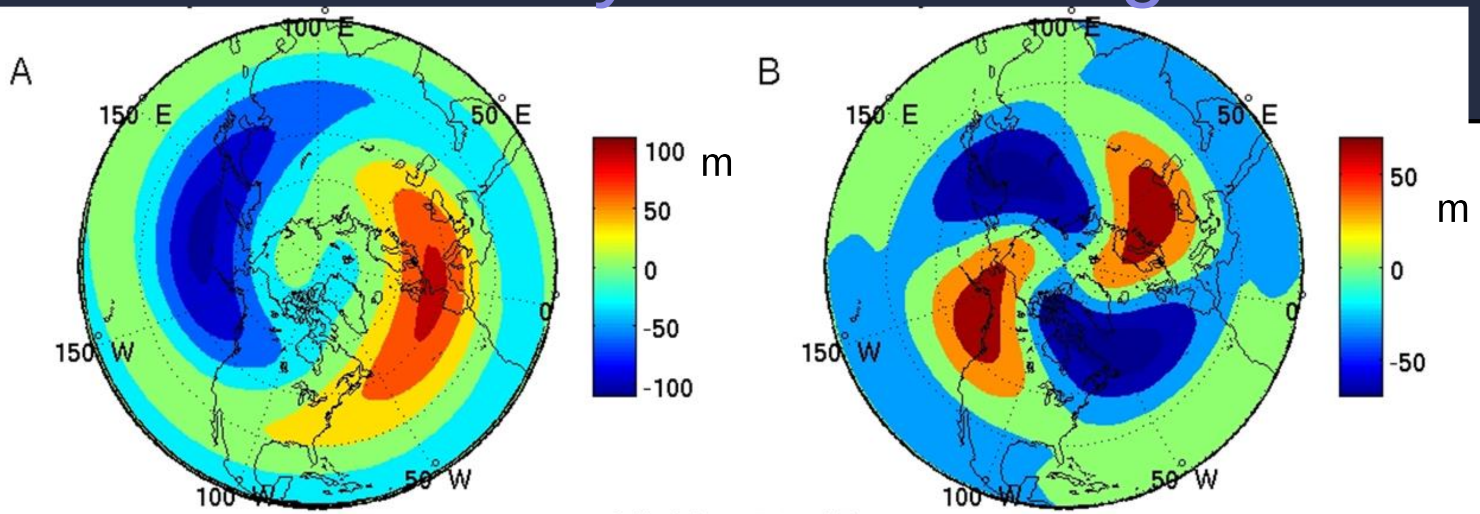
Climatology of NDJF Tropospheric Geopotential Height



- Stationary planetary waves that are generated by surface forcing can propagate upwards to the stratosphere (Charney and Drazin, 1961).

Source of Planetary Wave Driving of Stratosphere

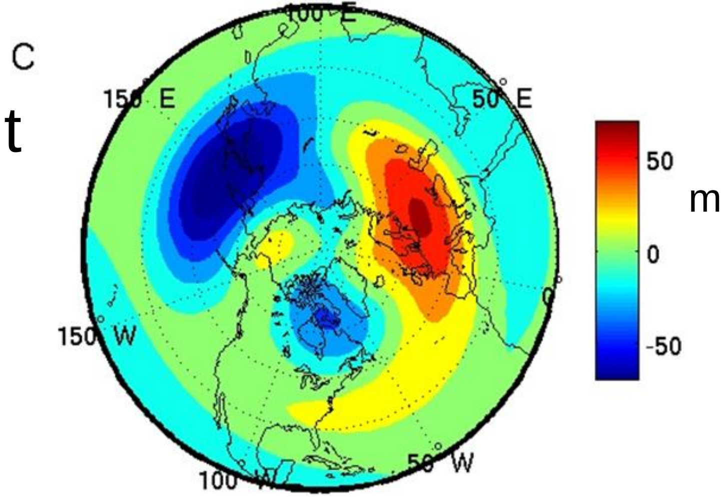
wave-1



geopotential height at 500.0 hPa

wave-2

avg. of wave1, wave2, and wave3



Low wavenumber height field

Anomalies collocated with these climatological regional asymmetries will enhance wave-1 and wave-2 EP flux leaving the troposphere and affecting the stratosphere.

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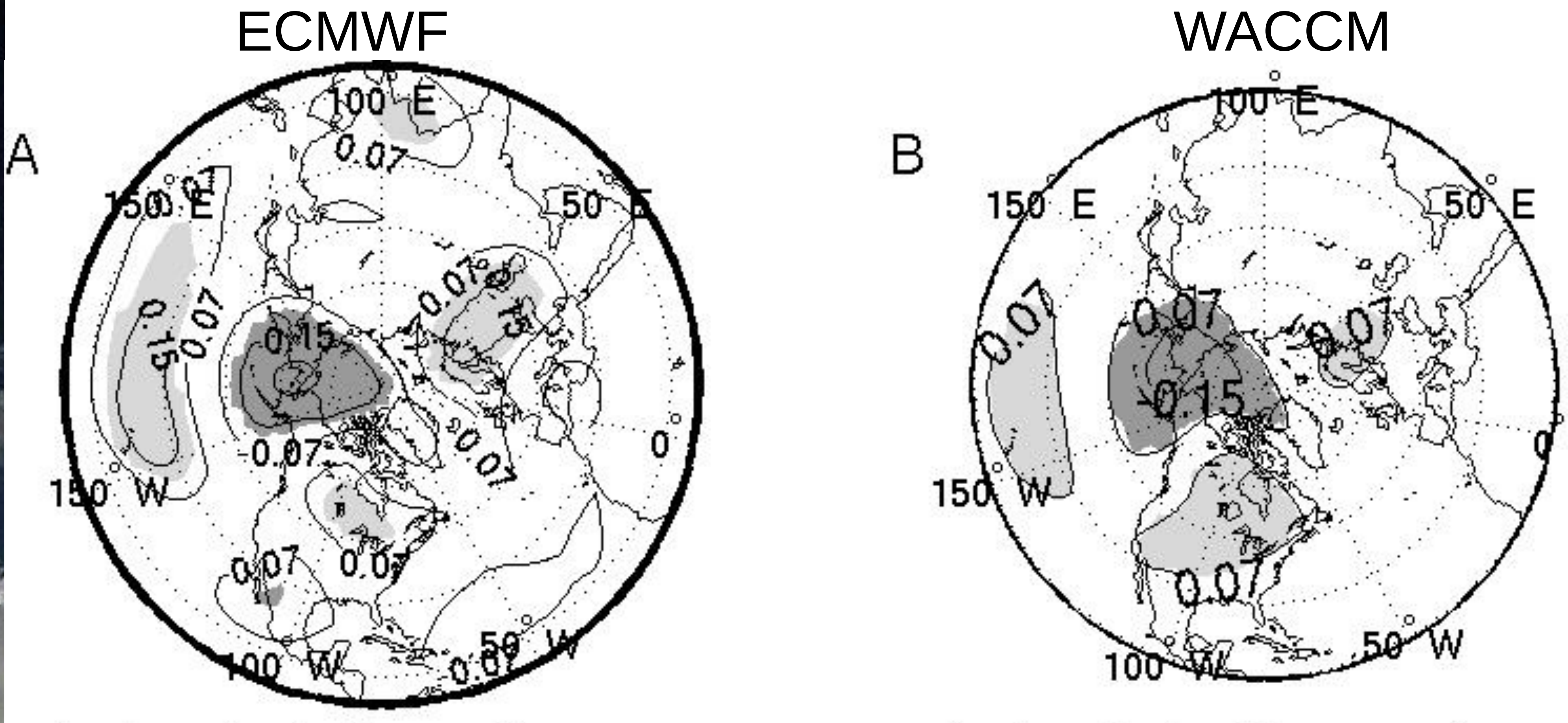
Tropospheric geopotential height correlated with vortex weakening-revisited



cor(vort weakening,$Z_{500\ hPa}$)

cor(vort weakening, $Z_{eta\ =\ 0.510}$)

The North Pacific and Eastern European extrema are collocated with the climatological planetary wave extrema, and thus they represent particularly effective conduits for enhancing upward planetary wave activity. (Garfinkel et al 2010, J. Clim)

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What role has SST variability played in trends of the polar vortex over the satellite era?

- Four of the aforementioned phenomena are based on SST variability. Is there a connection between trends in SST over the satellite era (1980-2010) to trends in wave driving of the polar vortex?

- We examine a seven-member ensemble of Goddard Earth Observing System Chemistry-Climate Model, Version 2 (GEOSCCM) in which the sea surface temperatures in the years January 1980 to December 2009 force each 30-year integration. Other than the SST forcing, there is no externally forced variability (e.g. greenhouse gas and ozone-depleting substance concentrations represent the year 2005). We compare these trends to those found in the MERRA reanalysis and in satellite data.

Many tropospheric phenomena have been linked to the strength of the stratospheric polar vortex

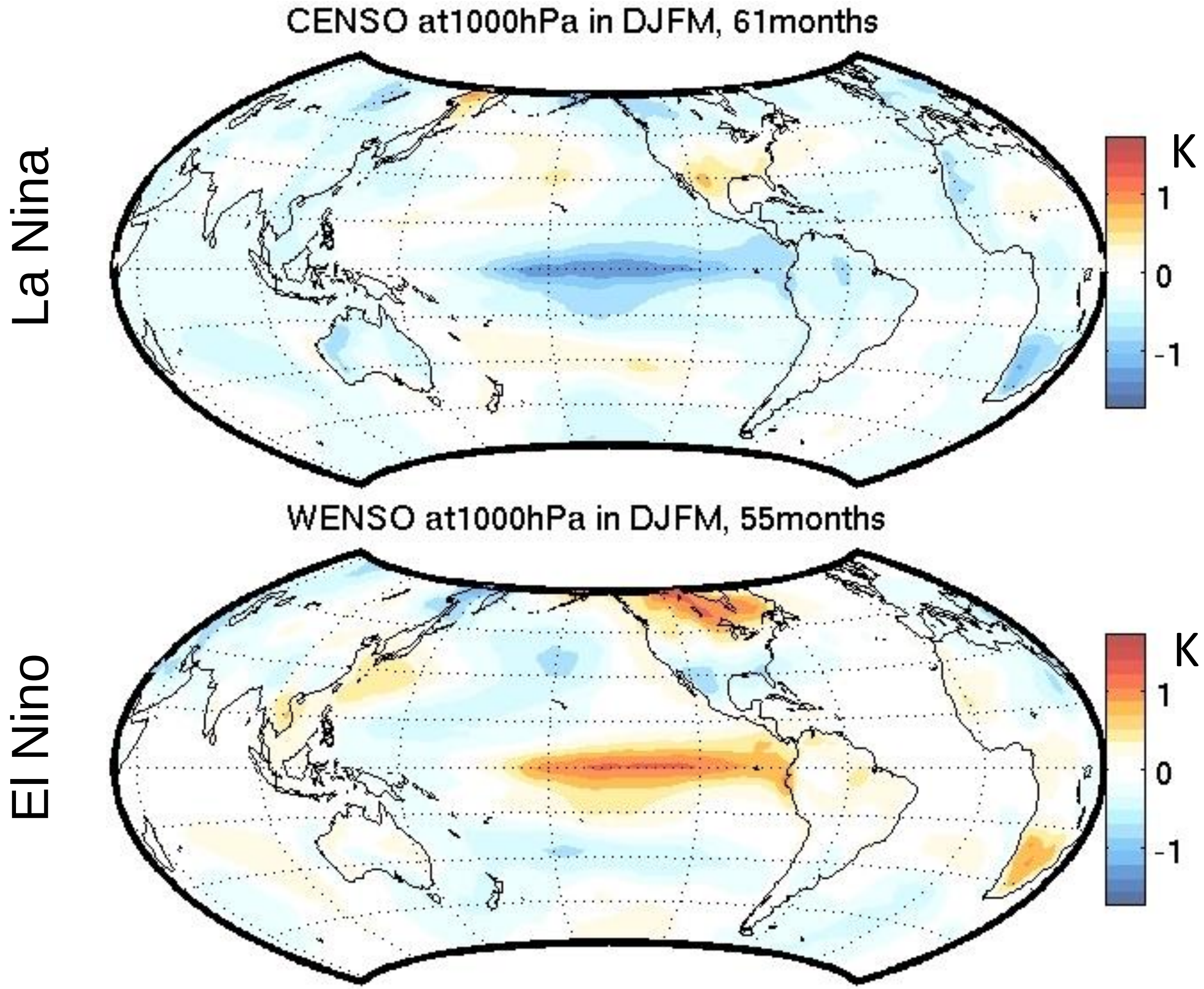
- ENSO: El Nino leads to a weaker vortex, and La Nina (possibly) to a stronger vortex. (Manzini et al., 2006, Garfinkel and Hartmann 2007)
- October Eurasian snow cover: More extensive snow cover leads to a weaker vortex (Cohen et al., 2007)
- North Pacific sea surface temperatures: colder temperatures lead to a weakened vortex ???? (Hurwitz et al., 2012)
- Indian Ocean sea surface temperatures: colder temperatures lead to a ??? (Fletcher and Kushner 2011)
- North Atlantic sea surface temperatures: warmer temperatures lead to a weakened vortex (Schimake?? Omra??)
- Madden Julian Oscillation: MJO phase 7 (anomalous convection propagating into central Pacific) leads to a weakened vortex (Garfinkel et al., 2012)
- Arctic sea ice: more extensive ice cover leads to a weaker vortex (??? Seok woo)

Model Experiments

- is an eight-member ensemble of Goddard Earth Observing System Chemistry-Climate Model, Version 2 (GEOSCCM) in which the sea surface temperatures in the years January 1980 to December 2009 force each 30-year integration. The GEOSCCM couples the GEOS-5 atmospheric GCM (Rienecker et al. 2008) with a comprehensive stratospheric chemistry module (Pawson et al. 2008), and has been graded highly as compared to observations and to the multi-model mean of an ensemble of CCMs (SPARC-CCMVal, 2010). Other than the SST forcing, there is no externally forced variability (e.g. greenhouse gas and ozone-depleting substance concentrations represent the year 2005).

ENSO

Difference in surf. T by ENSO phase



- SST anomalies in Tropical Pacific causes anomalies in convection

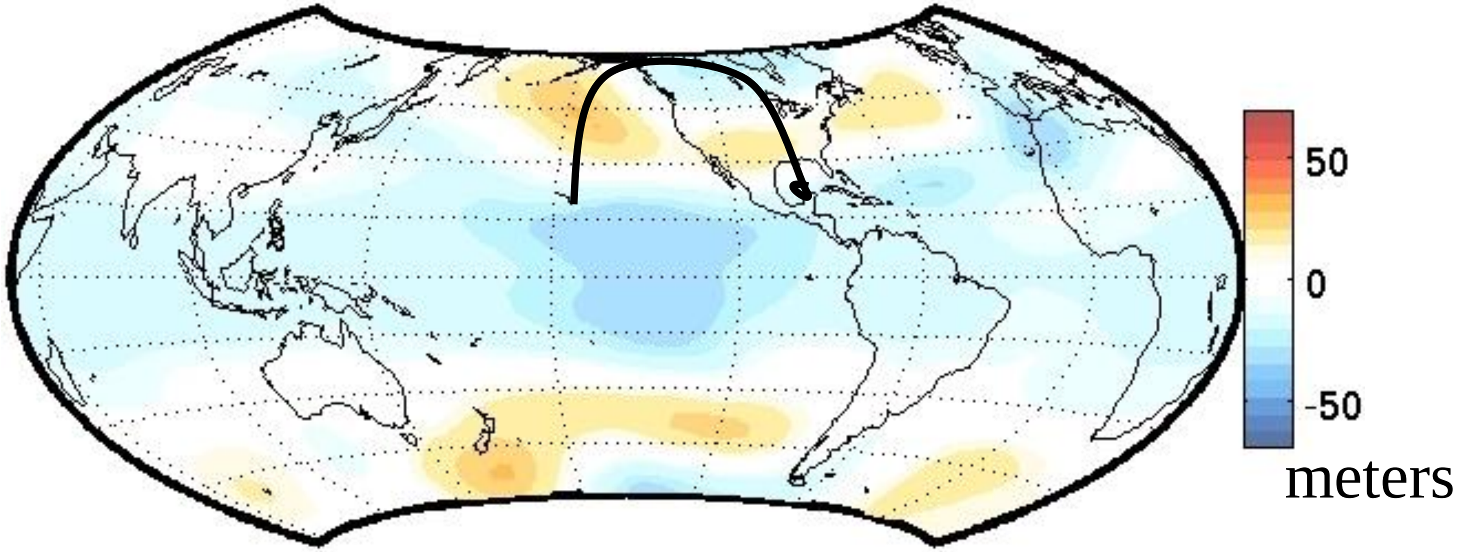
ENSO's wintertime teleconnection

Height at 300hPa

Rossby wave train propagating from tropical Pacific

CENSO at300hPa in DJFM, 61months

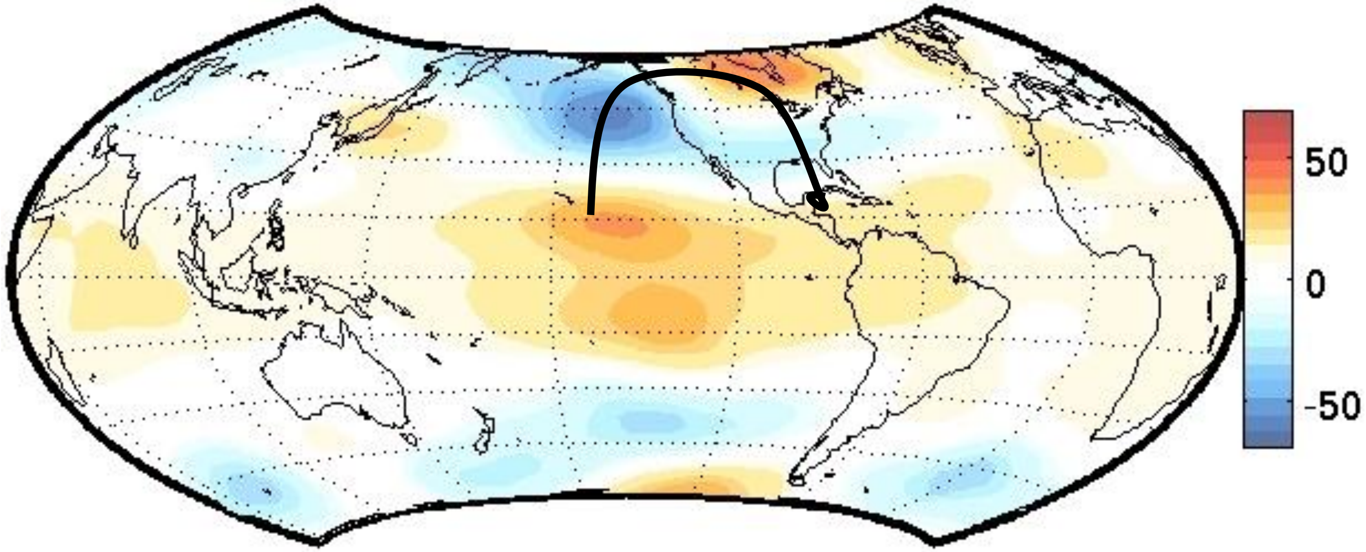
La Nina



- Results in anomalies in North Pacific height.

WENSO at300hPa in DJFM, 55months

El Nino



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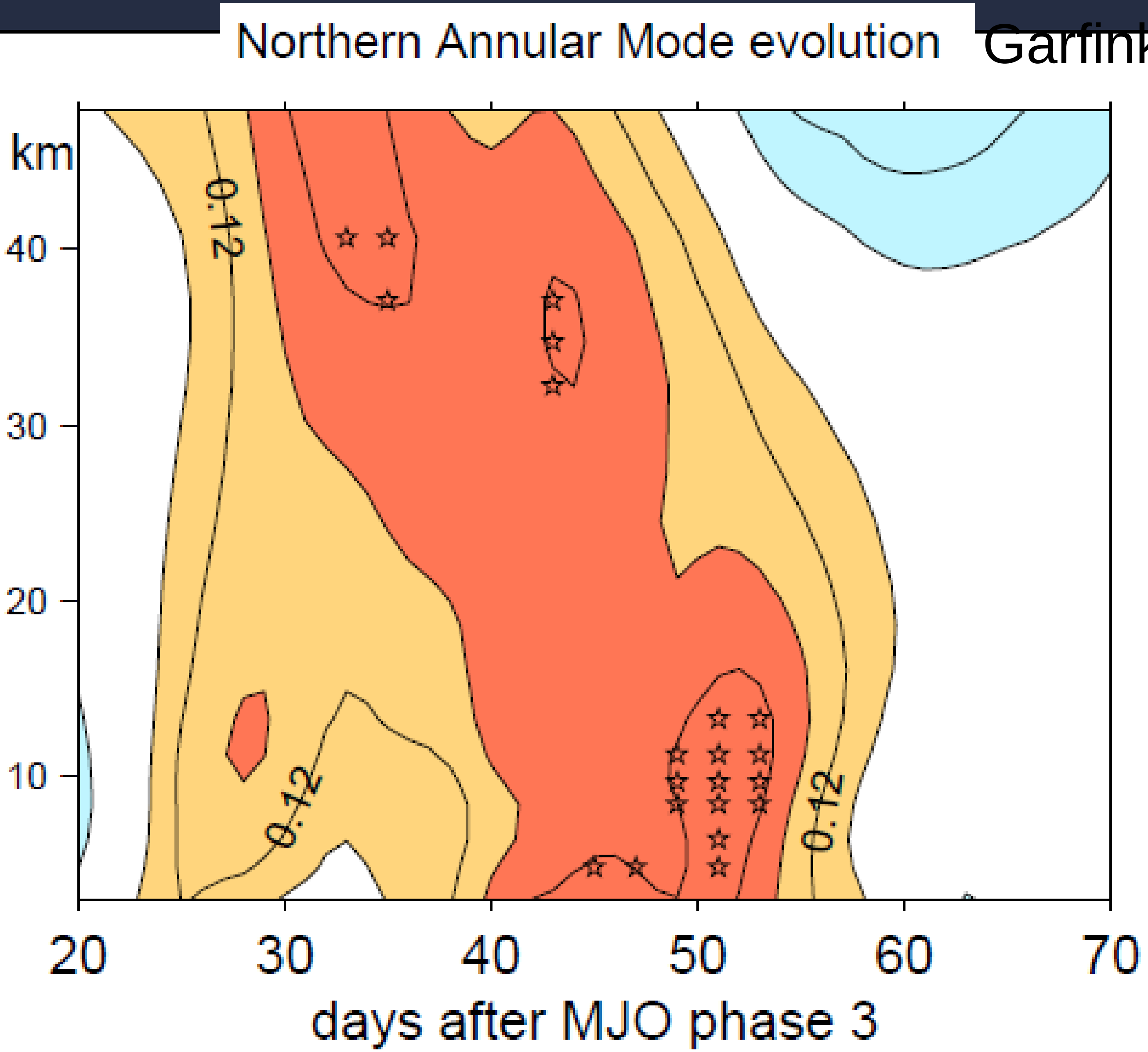
Downward Propagation of MJO Anomaly

Garfinkel et al 2012, GRL

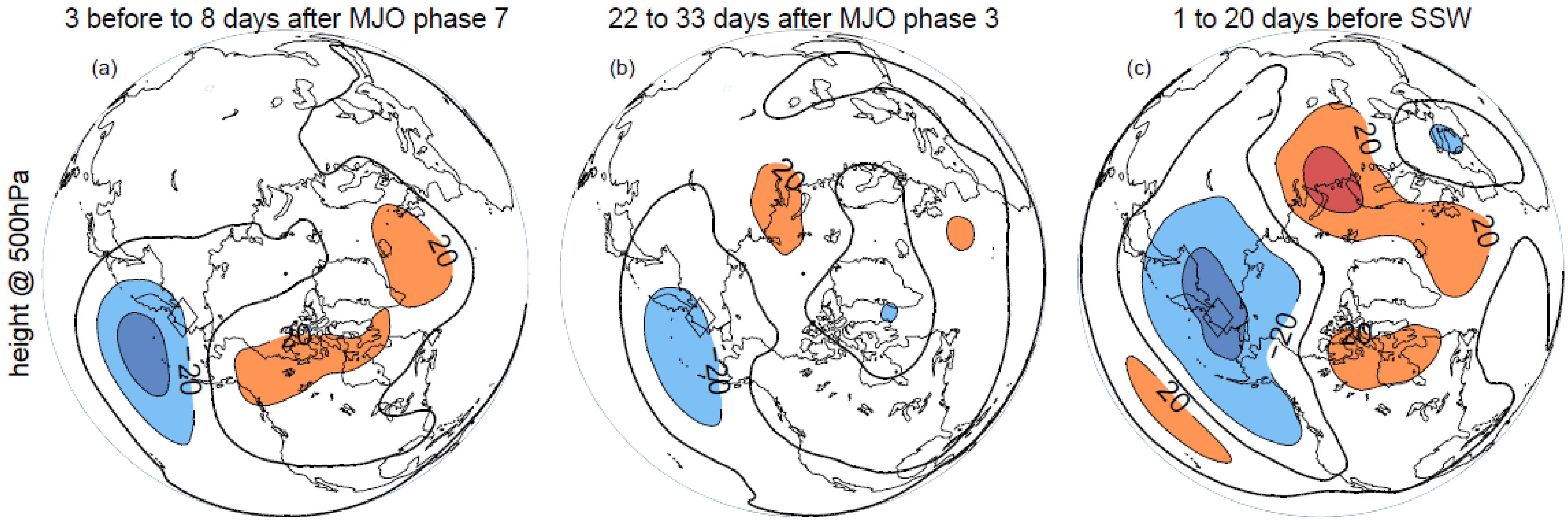

Northern Annular Mode evolution

Contours shown normalized polar cap height anomalies.

Contour interval: 0.06 standard deviations

The vortex anomalies following certain MJO phases reach the troposphere and impact the Northern Annular Mode.

MJO influences the tropospheric North Pacific

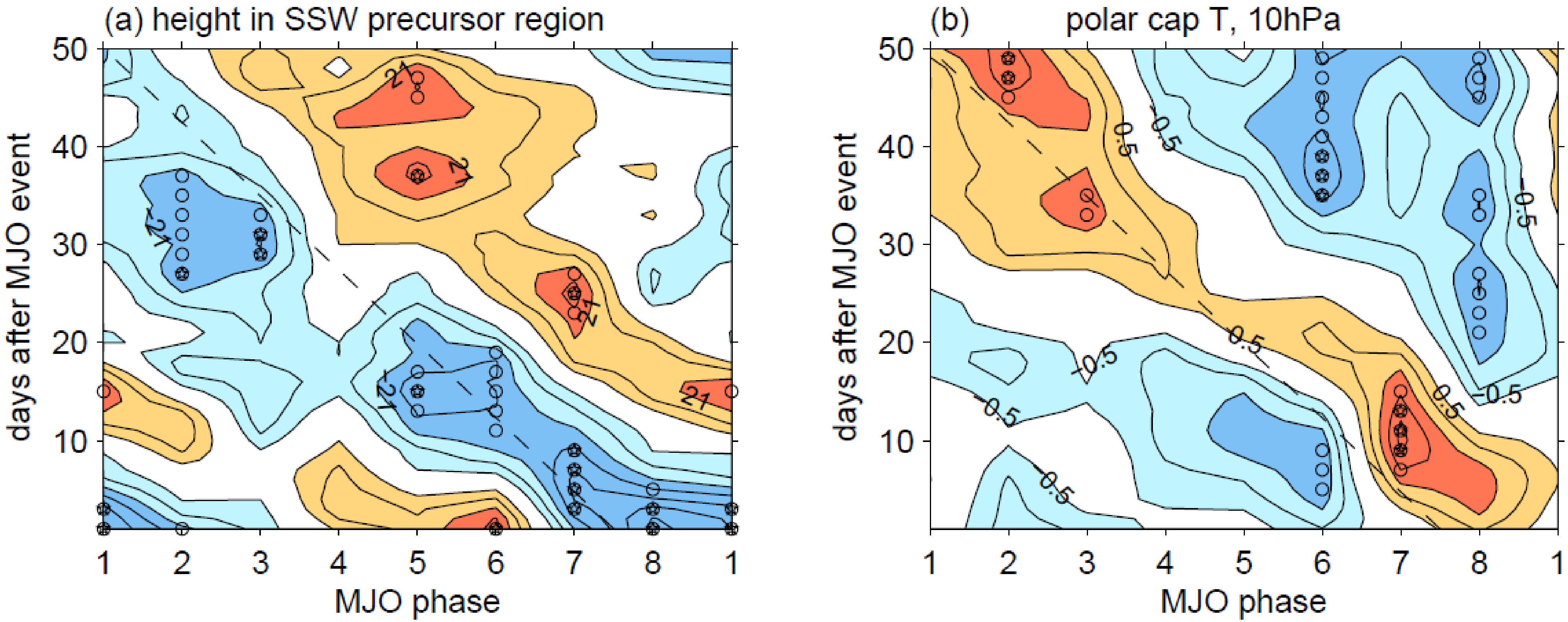


contour interval 10m

Garfinkel et al 2012, GRL

Variability in the North Pacific can account for the influence of the MJO on the polar stratosphere.

Summary of MJO-North Pacific-vortex connection



contour interval 7m

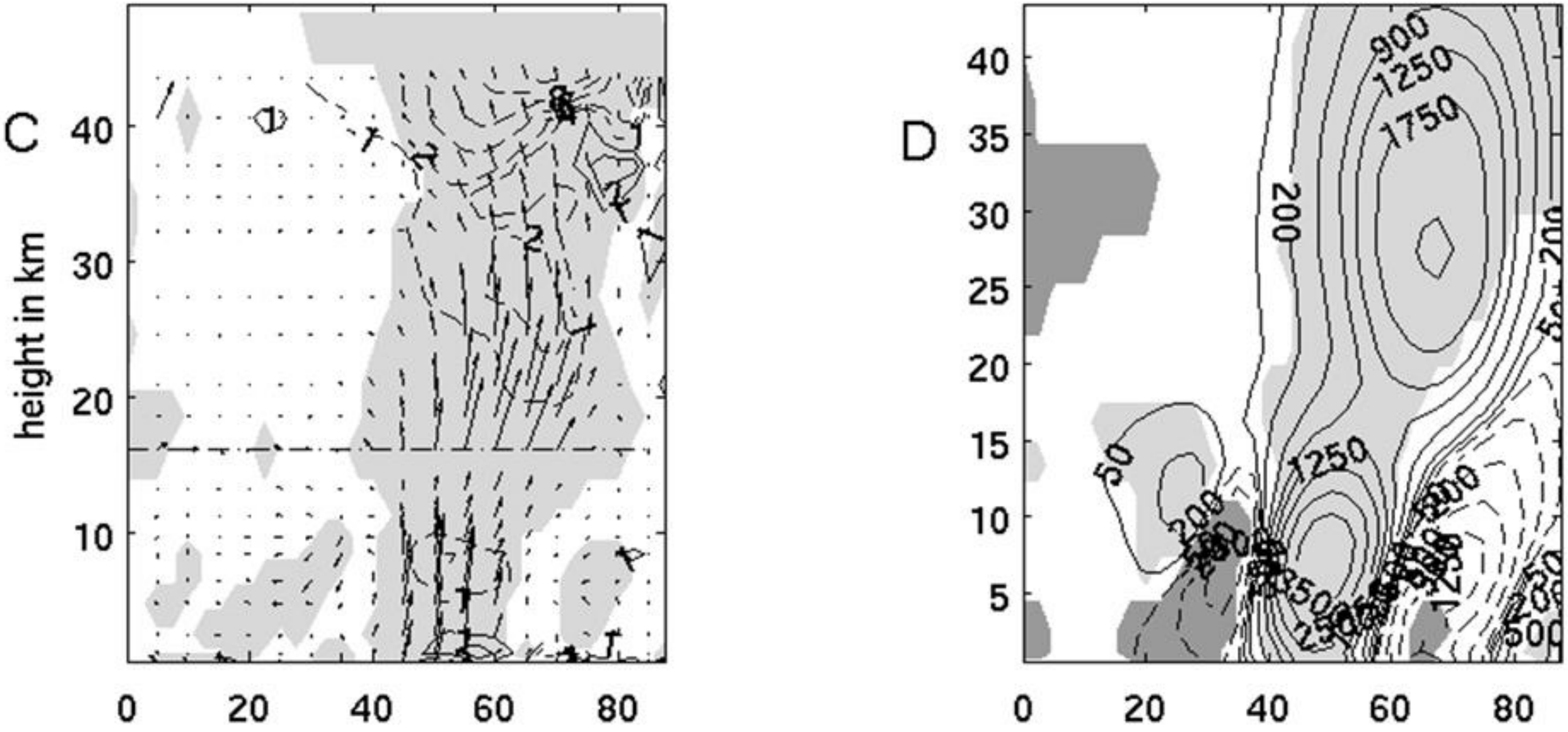
contour interval 0.5K

Garfinkel et al 2012, GRL

A variety of MJO phases influence variability in the North Pacific and subsequently affect the polar stratosphere.

Wave-1 EP flux and height variance

anomalous low in the Pacific – anomalous high in the North Pacific



Garfinkel et al 2010, J. Clim.

North Pacific height anomalies lead to a strong wave-1 signature that is coherent into the stratosphere.