A daily estimate of phase speed to explore the link between Arctic Amplification and Rossby waves

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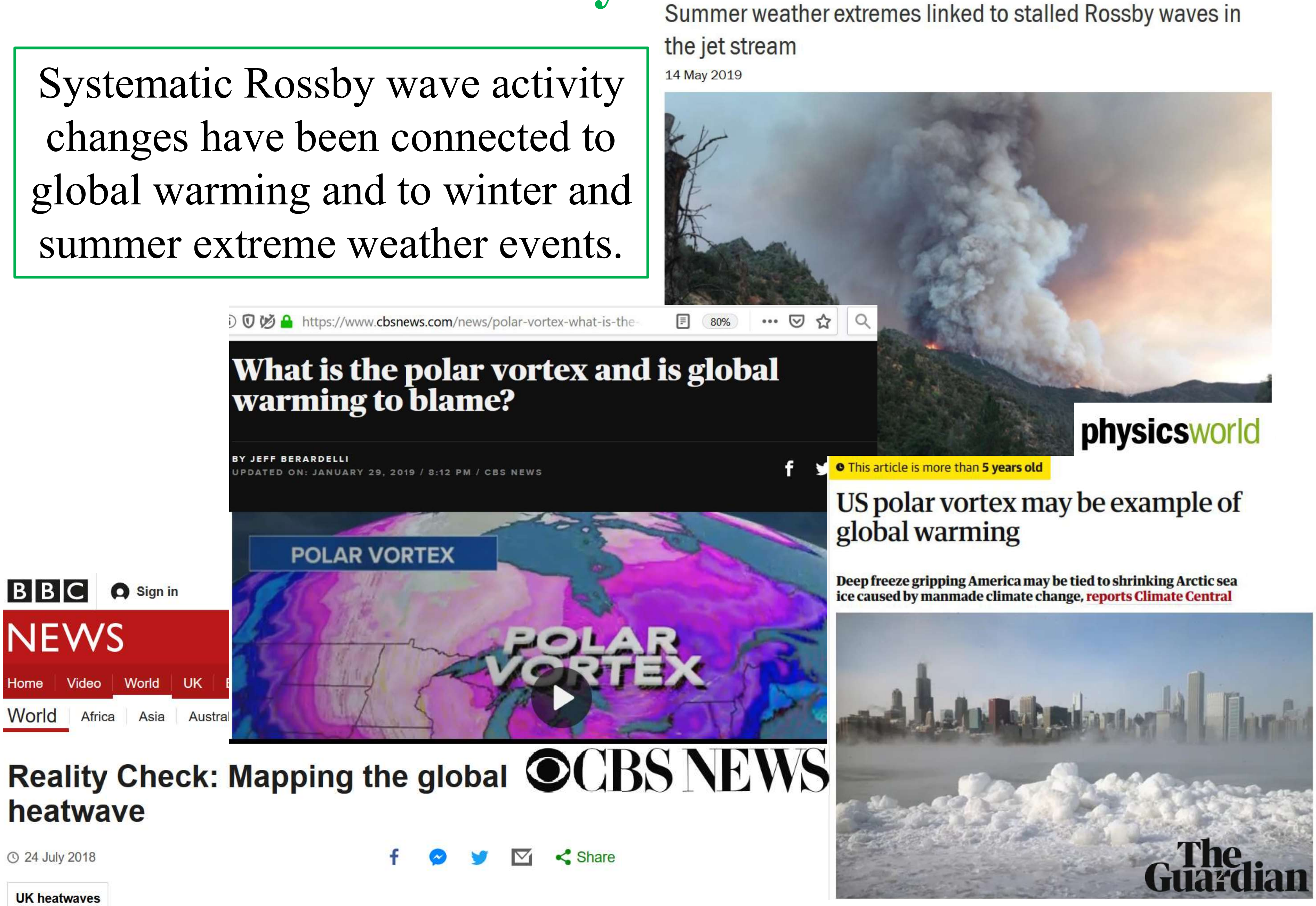
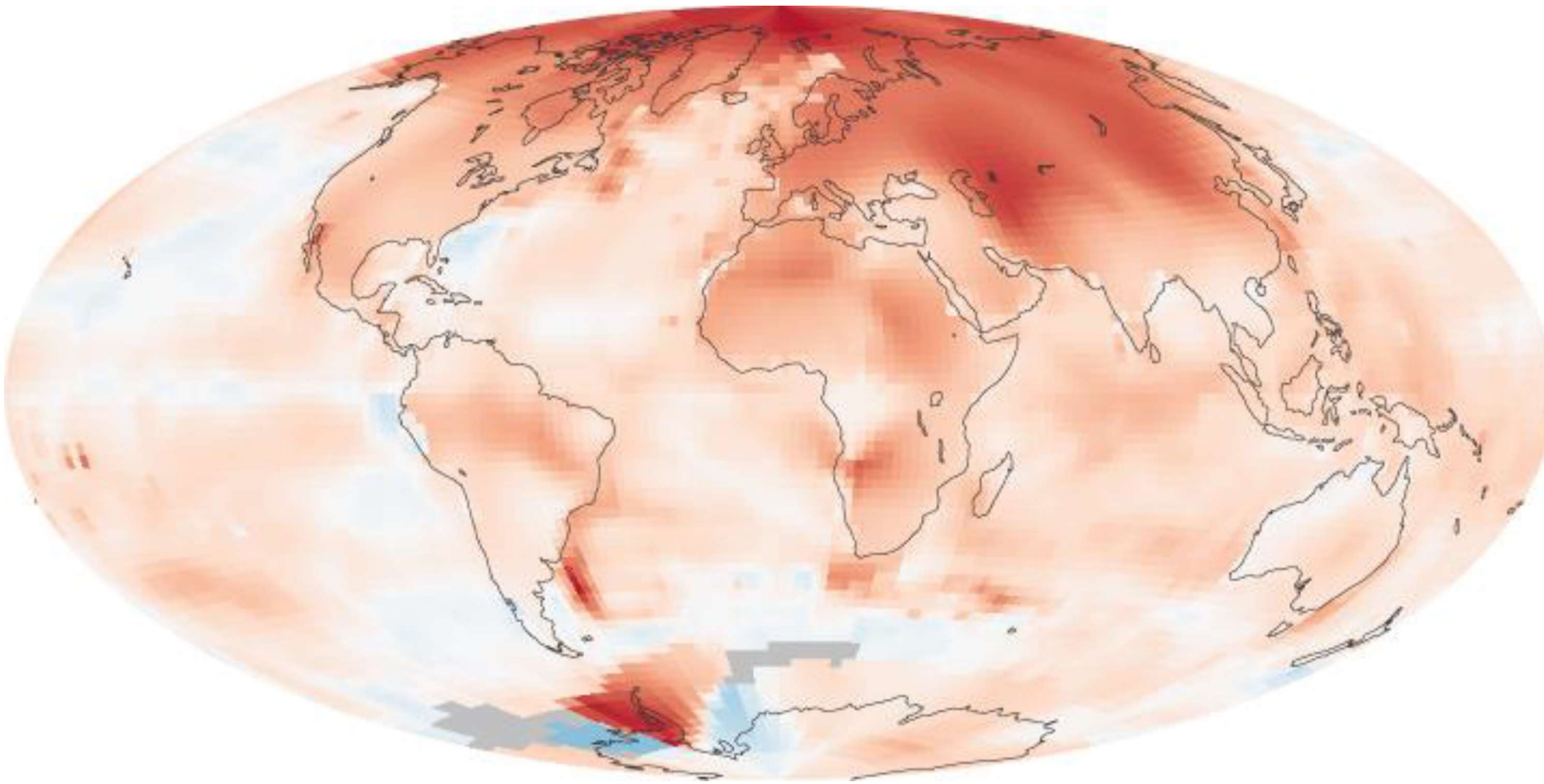
Introduction 1: Rossby waves and extreme events

Systematic Rossby wave activity changes have been connected to global warming and to winter and summer extreme weather events.



Introduction 2: Arctic Amplification



2000-2009 surface temperature trend.

Credit: NASA (Robert Simmon), based on GISS surface temperature analysis data including ship and buoy data from the Hadley Centre.

Motivation

<u>Hypothesis:</u> Arctic Amplification can reduce eastward Rossby wave propagation, inducing extreme weather events or making them more persistent (e.g., Francis and Vavrus 2012, Cohen et al. 2020).

<u>Chain of events:</u>

Surface temperature increase → Upper-level geopotential increase → Weaker meridional thickness gradient → Weaker background westerlies → Slower Rossby waves → Blocking/ Extreme events

How to assess whether Rossby waves have become slower?

$$c_p = \frac{\omega}{k} = \frac{\omega a \cos(\phi)}{n}$$

Problem: many waves with different ω and *k* co-exist in the atmosphere: how to obtain a global value?

Objectives

1) **Develop a phase speed diagnostic accounting for Rossby waves variability** (planetary vs synoptic waves, Rossby wave packets, blocking, etc...)**.**

2) **Assess whether Arctic Amplification impacted phase speed trends.**

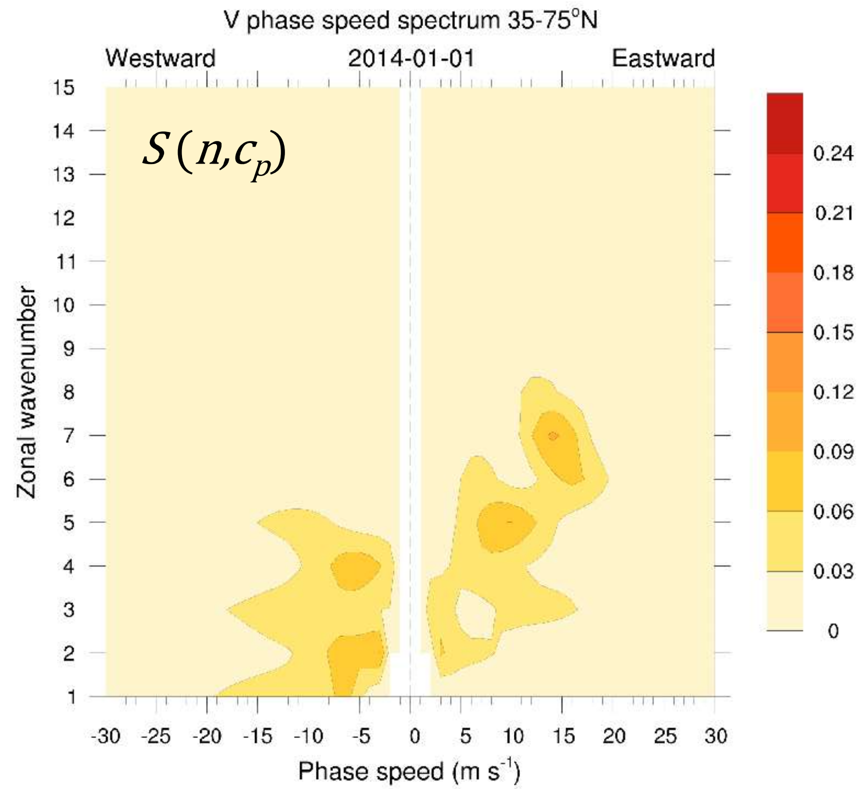
A ERA-I daily spectral climatology

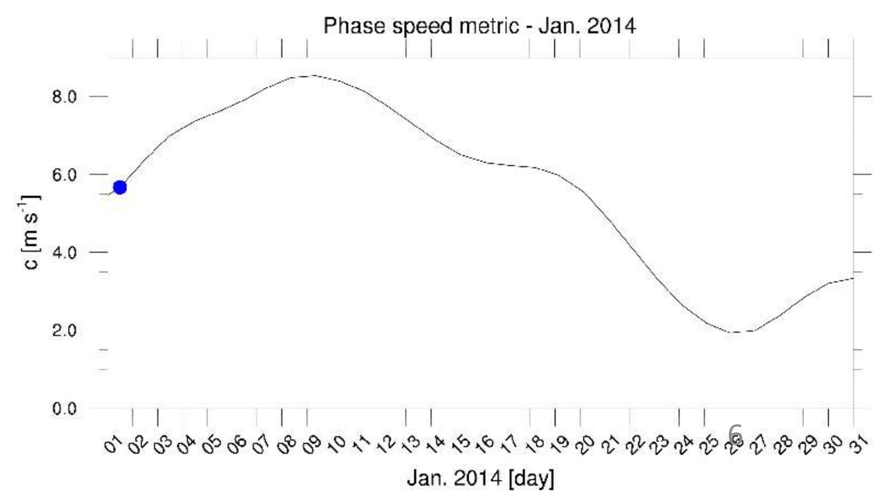
Units: Rescaled V variance [$m^2\ s^{-2}$]

- ERA Interim, V250hPa (meridional wind)
  - 35-75°N, 0.75° resolution
- Consecutive 61 days time intervals
  - Feb 1979 → Nov 2018

(Randel and Held 1991)

Spectral analysis indicates how each (n, c_p) harmonic contributes to the overall phase speed in a given time period.



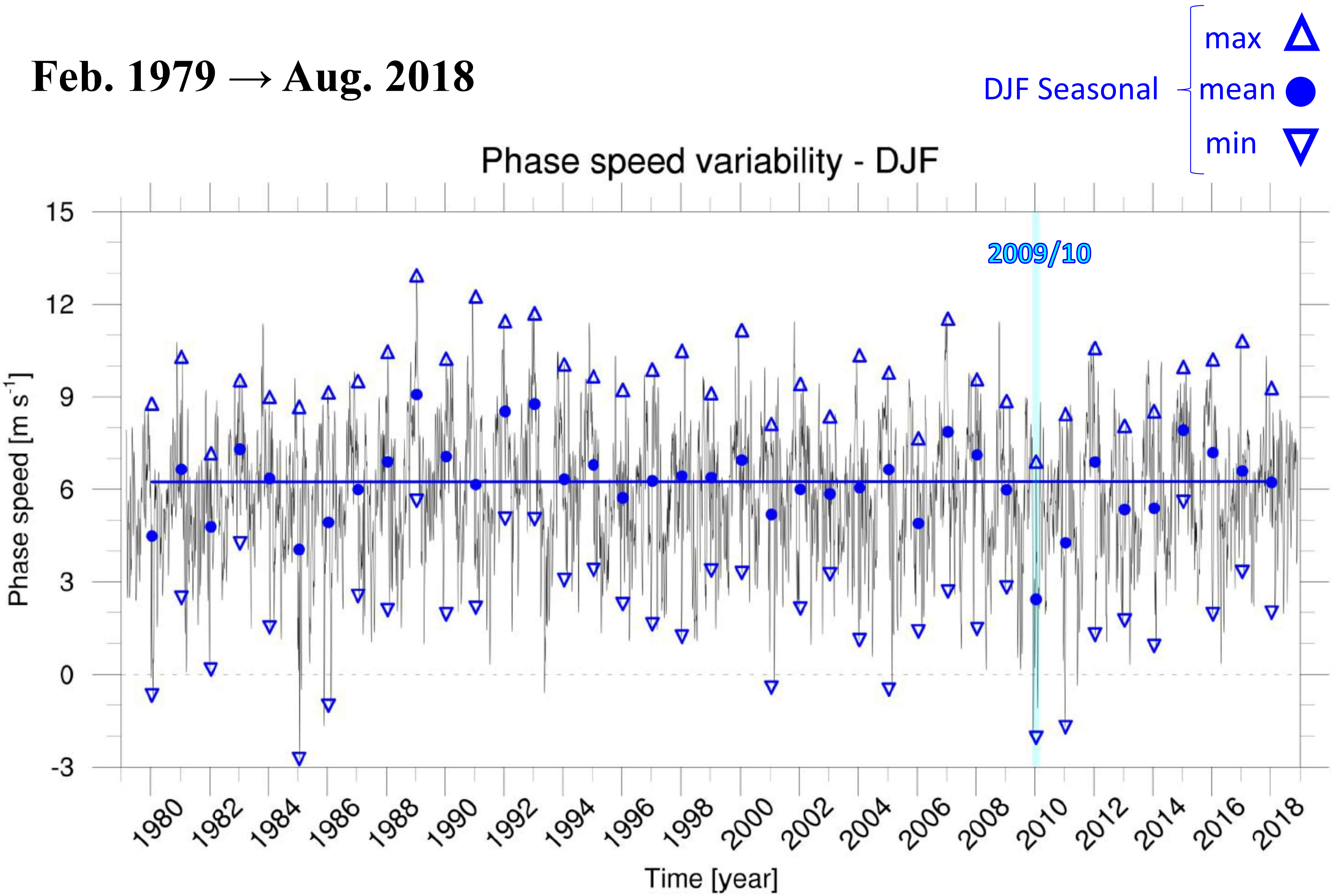


Phase speed metric

$$\boxed{c} = \frac{\sum_{n=1}^{15} \sum_{c_p=-30}^{30} S(n, c_p) \cdot c_p}{\sum_{n=1}^{15} \sum_{c_p=-30}^{30} S(n, c_p)}$$

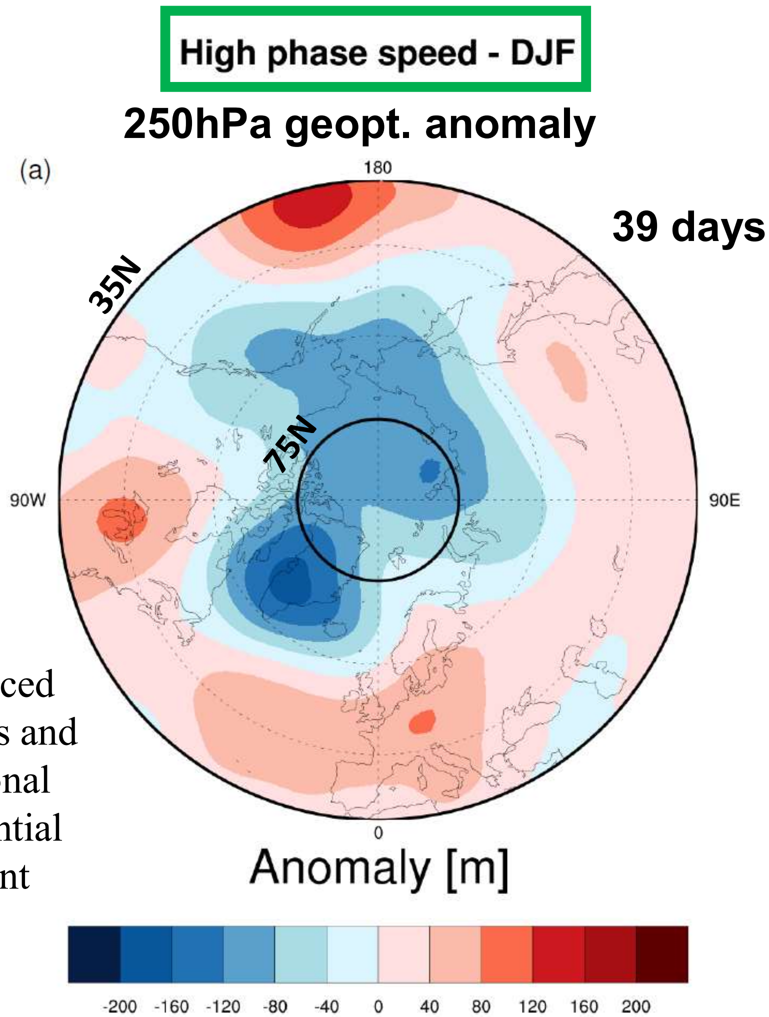
Daily phase speed evolution

Feb. 1979 → Aug. 2018

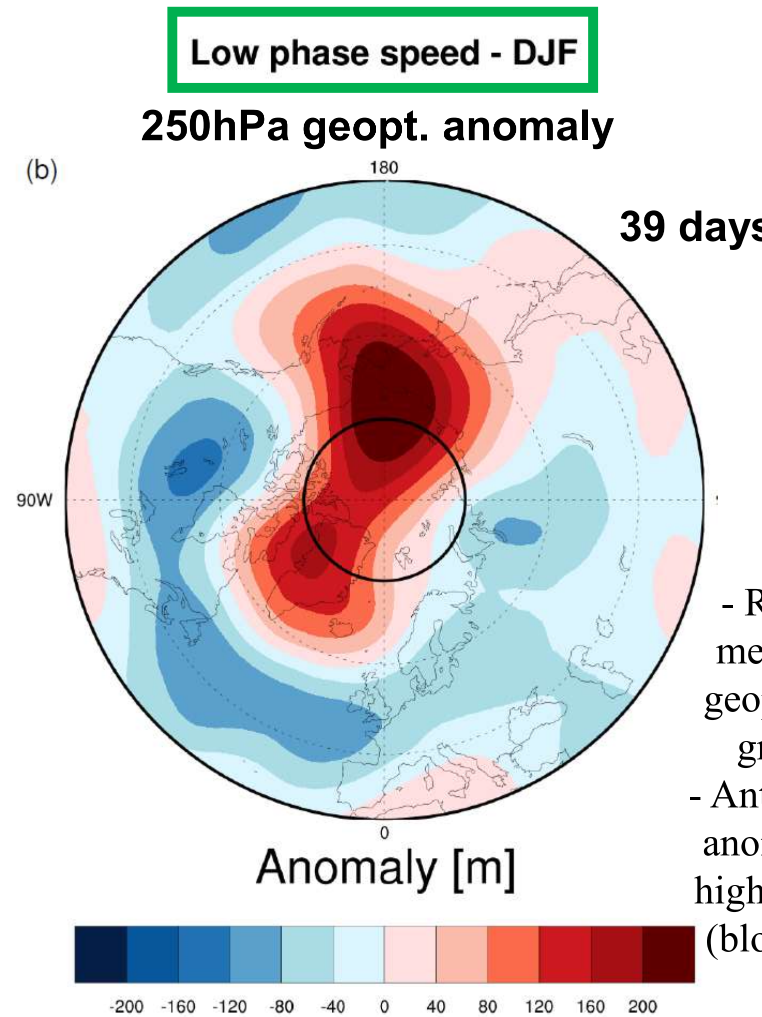


Large-scale circulation during high/low phase speed days (1)

DJF 1979/80→2017/18 (39 winters): composite days of phase speed maximum and minimum for each winter



- Enhanced westerlies and meridional geopotential gradient



- Reduced meridional geopotential gradient
- Anticyclonic anomalies at high latitudes (blocking ?)

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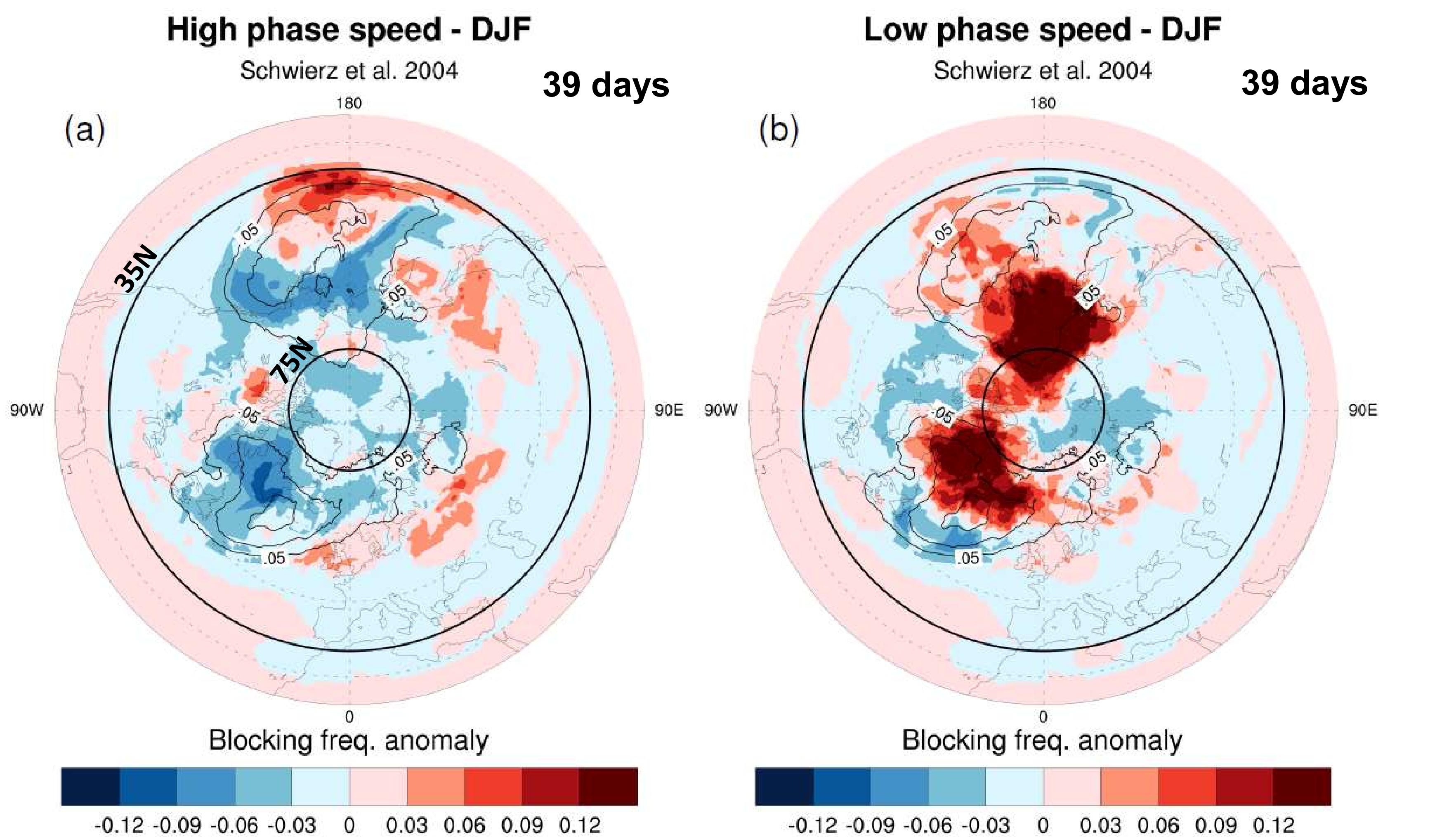
Large-scale circulation during high/low phase speed days (2)

Low phase speed occurrence is linked to anomalous blocking activity.



Blocking diagnostics from ETH Zürich (Sprenger et al. 2017).

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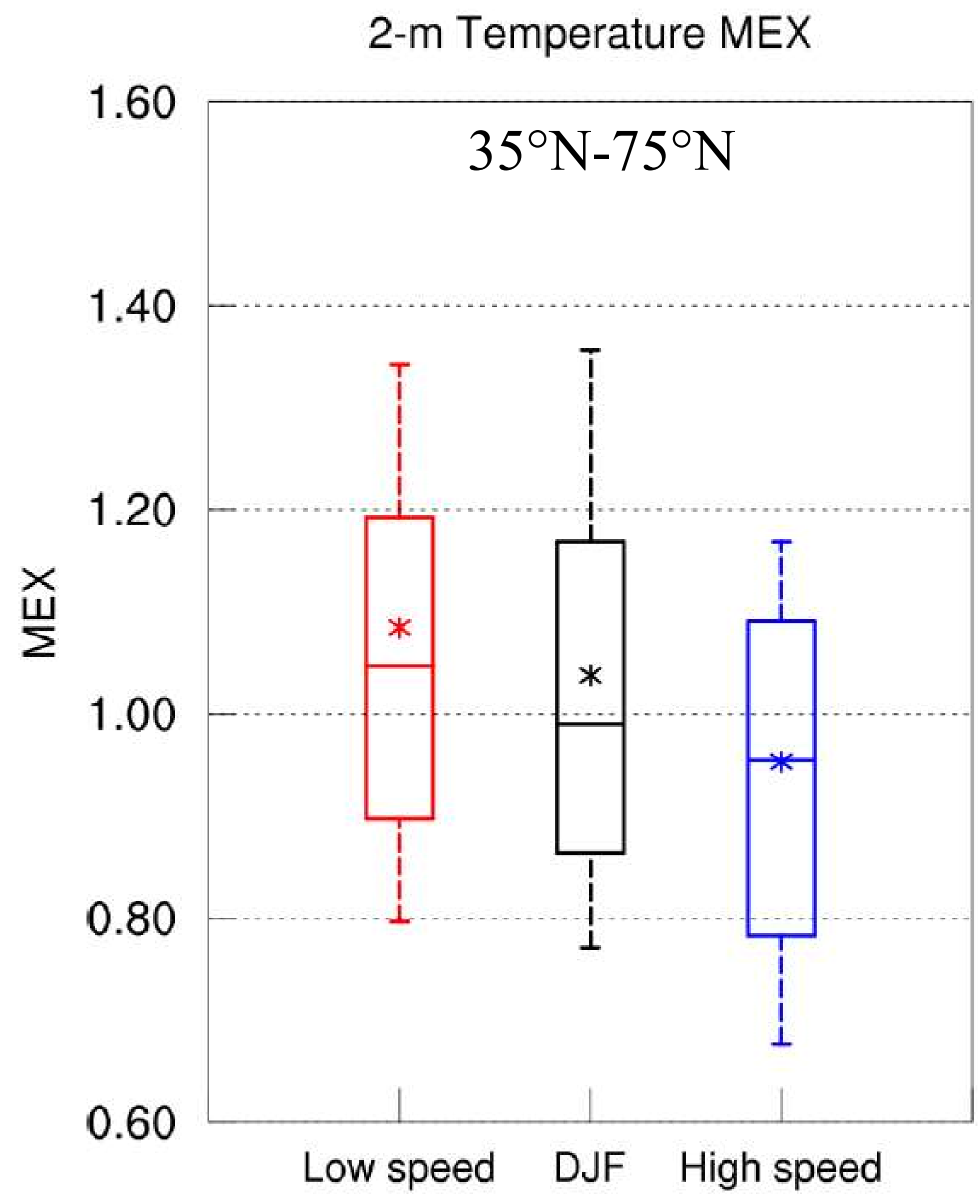
Extreme temperatures during high/low phase speed days

Midlatitude EXtreme (MEX) index: Areally averaged (over N gridpoints between 35°N and 75°N) squared standardized 2-m temperature anomalies (see also Coumou et al. 2014).

$$MEX(T,t) = \frac{1}{N}\sum_{i}^{N}\left(\frac{T_i(t)-\overline{T_i(t)}}{\overline{\sigma}(T_i(t))}\right)^2$$

Low phase speed → high MEX values → stronger/more extended temperature anomalies than normal.



MEX definition:
Coumou D., Petoukhov V., Rahmstorf S., Petri S., Schellnhuber H. J.: *Quasi-resonant circulation and extreme weather* PNAS, (2014) DOI: 10.1073/pnas.1412797111

Summary (1)

The developed phase speed metric can realistically represent extratropical flow variability:

- ***Realistic intra-seasonal and inter-annual variability, winter 2009/10 stands out with particolarly slow Rossby waves.***
- ***Low phase speeds are associated with atmospheric blocking and with extreme temperature events over midlatitudes.***

Now, let's explore the links between phase speed and Arctic Amplification.

Arctic Amplification metrics

Relate two different metrics of Arctic Amplification to phase speed:

1) **Thermal metric:** 850hPa temperature anomaly difference (65°N-90°N minus 35°N-65°N)

2) **Dynamical metric:** 250hPa geopotential anomaly difference (65°N-90°N minus 35°N-65°N)

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T850 temperature difference and phase speed trends

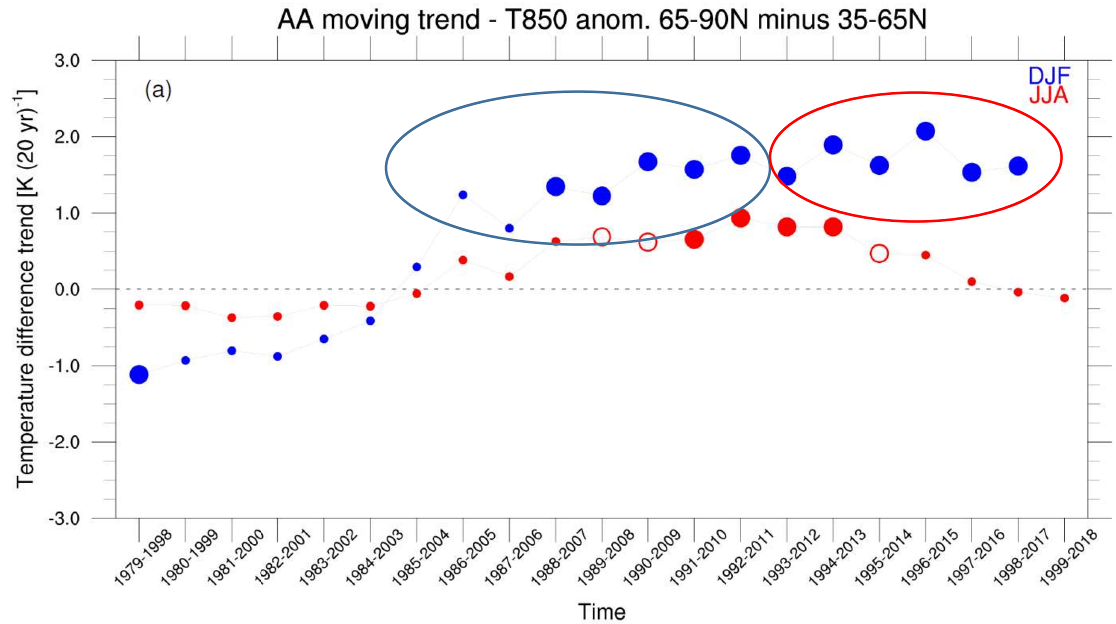
95% significance
90% significance

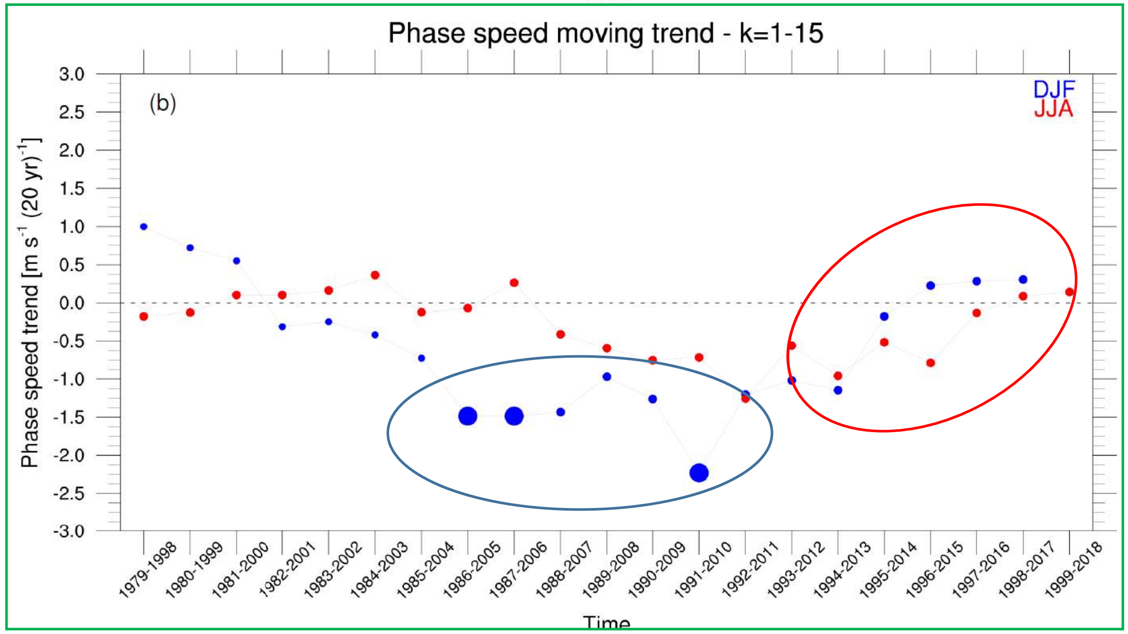
Trends over consecutive 20-year periods

- Day-to-day Pearson correlation
  $r\,(c, \text{T850 anom.}) = -0.39$

- Temperature difference consistently increasing since 1988-2007 period.

- <u>No corresponding phase speed trend in recent decades.</u> Significant negative trend in 1991-2010 period (likely because of 2009/2010 winter).





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Z250 temperature difference and phase speed trends

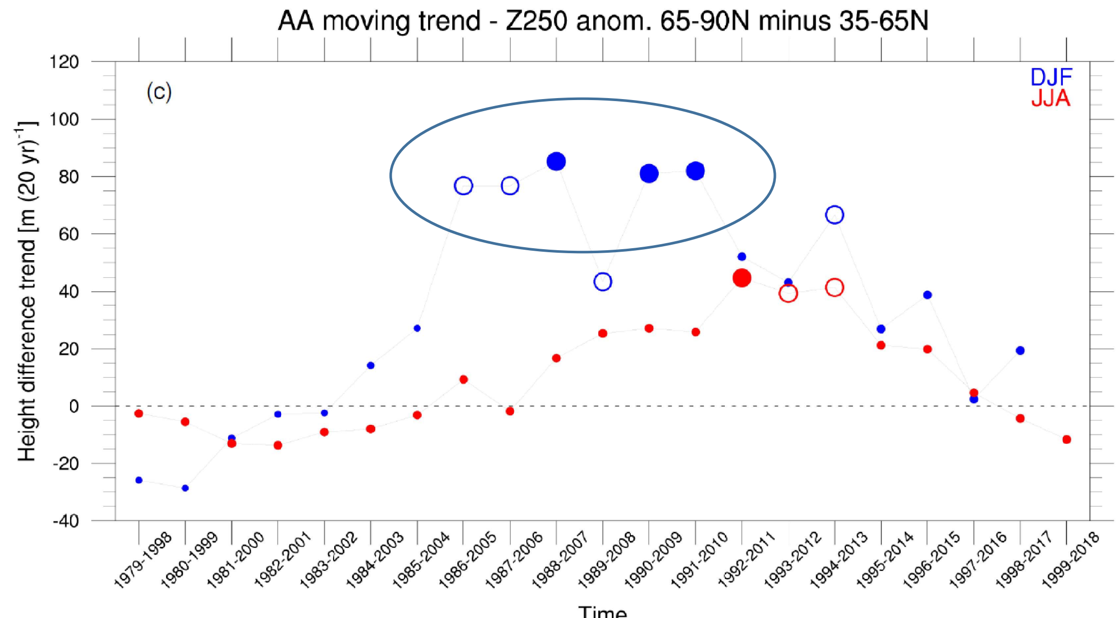
95% significance
90% significance

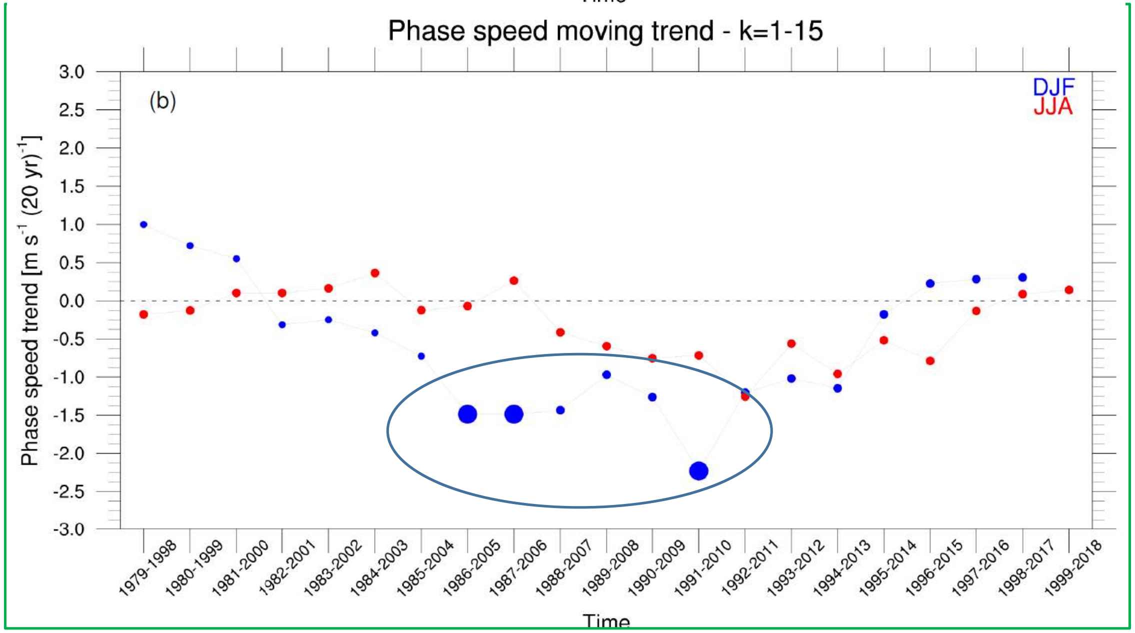
Trends over consecutive 20-year periods

- Day-to-day Pearson correlation
  $r(c, \text{Z250 anom.}) = -0.70$

- Geopotential anomaly trends occur in similar decades as phase speed trends.

- Phase speed trend follows evolution of Z250 gradient, rather than of T850.





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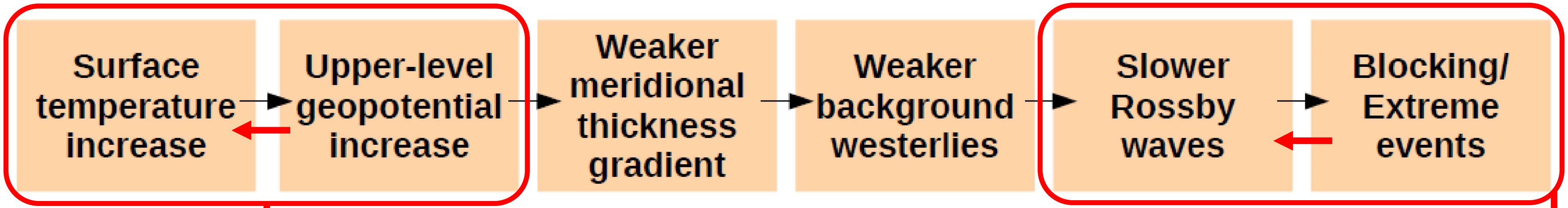
Conclusions



- **Reduction of low-level meridional T gradient not related to reduction in Rossby wave phase speed.**

Extratropical variability/other processes have affected phase speed more strongly than Arctic Amplification.

- **Conversely, Rossby wave phase speed correlates well with upper-level geopotential gradient and blocking activity.**

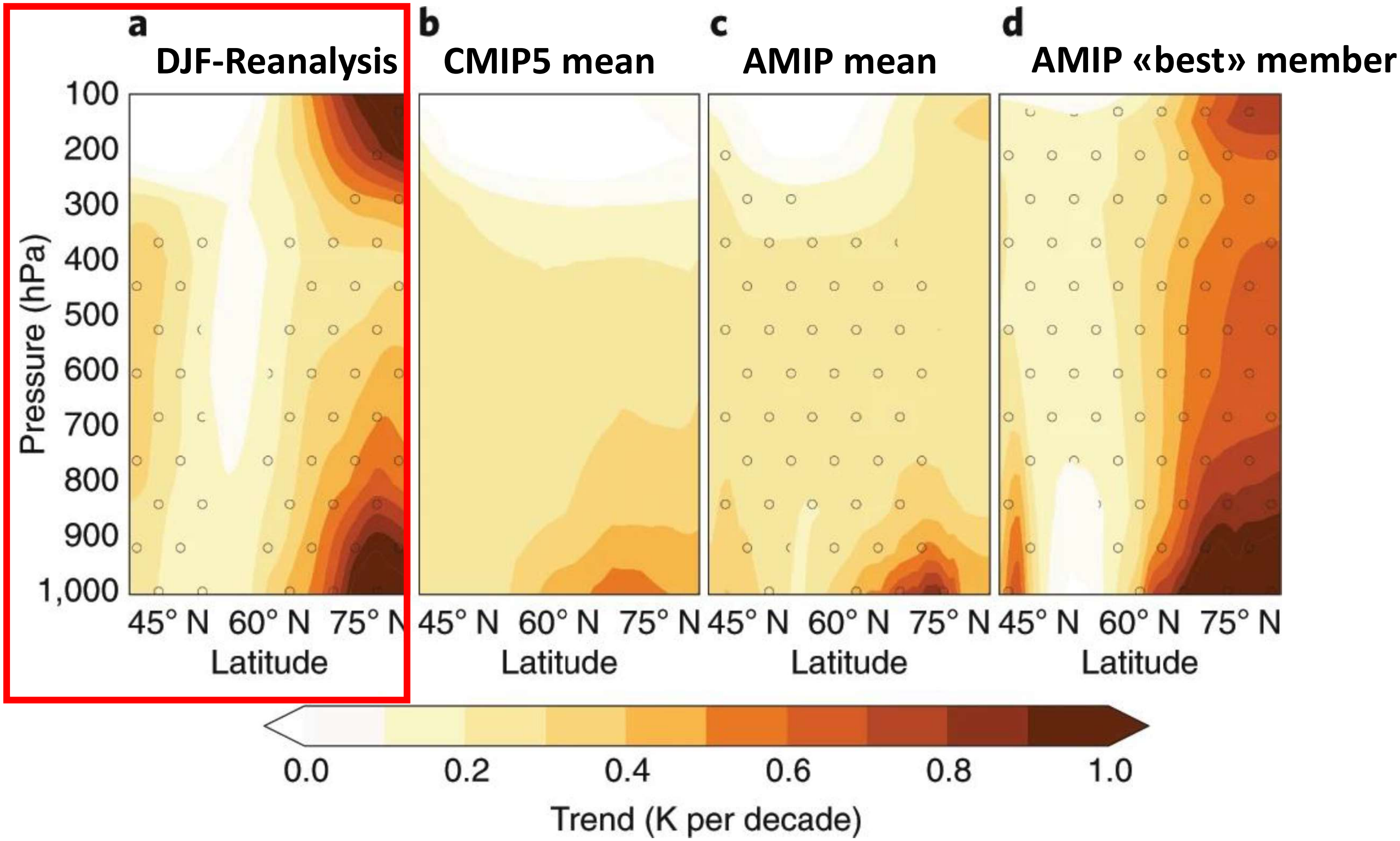
Upper-level processes and atmospheric blocking seem to modulate Rossby wave phase speed, rather than low-level temperature change.

Bibliography

- Francis, J. A., and Vavrus, S. J. (2012), Evidence linking Arctic amplification to extreme weather in mid-latitudes, *Geophys. Res. Lett.*, 39, L06801, doi:10.1029/2012GL051000.

- Cohen J., Zhang X., Francis J., et al. ARCTIC CHANGE AND POSSIBLE INFLUENCE ON MID-LATITUDE CLIMATE AND WEATHER: A US CLIVAR White Paper. *US CLIVAR Rep*. (2018) doi:10.5065/D6TH8KGW

Vertical warming structure (Cohen et al. 2019)



Winter (December, January, February: DJF) and zonal-mean air-temperature trends from December 1980 to February 2019 for the average of MERRA-2, ERA5, JRA-55 and CFSR reanalysis products for DJF. **b**, Same as **a** but for the CMIP5 multimodel ensemble mean historical simulation through 2004 and RCP8.5 simulation thereafter. **c**, Same as **a**, but for the AMIP multimodel mean. **d**, Same as **c** but for the AMIP ensemble member that best matches the reanalysis mean based on pattern correlation. Stippling indicates significant trends with $P < 0.05$ after the correction for false discovery rate was applied[135].

A ERA-I daily spectral climatology

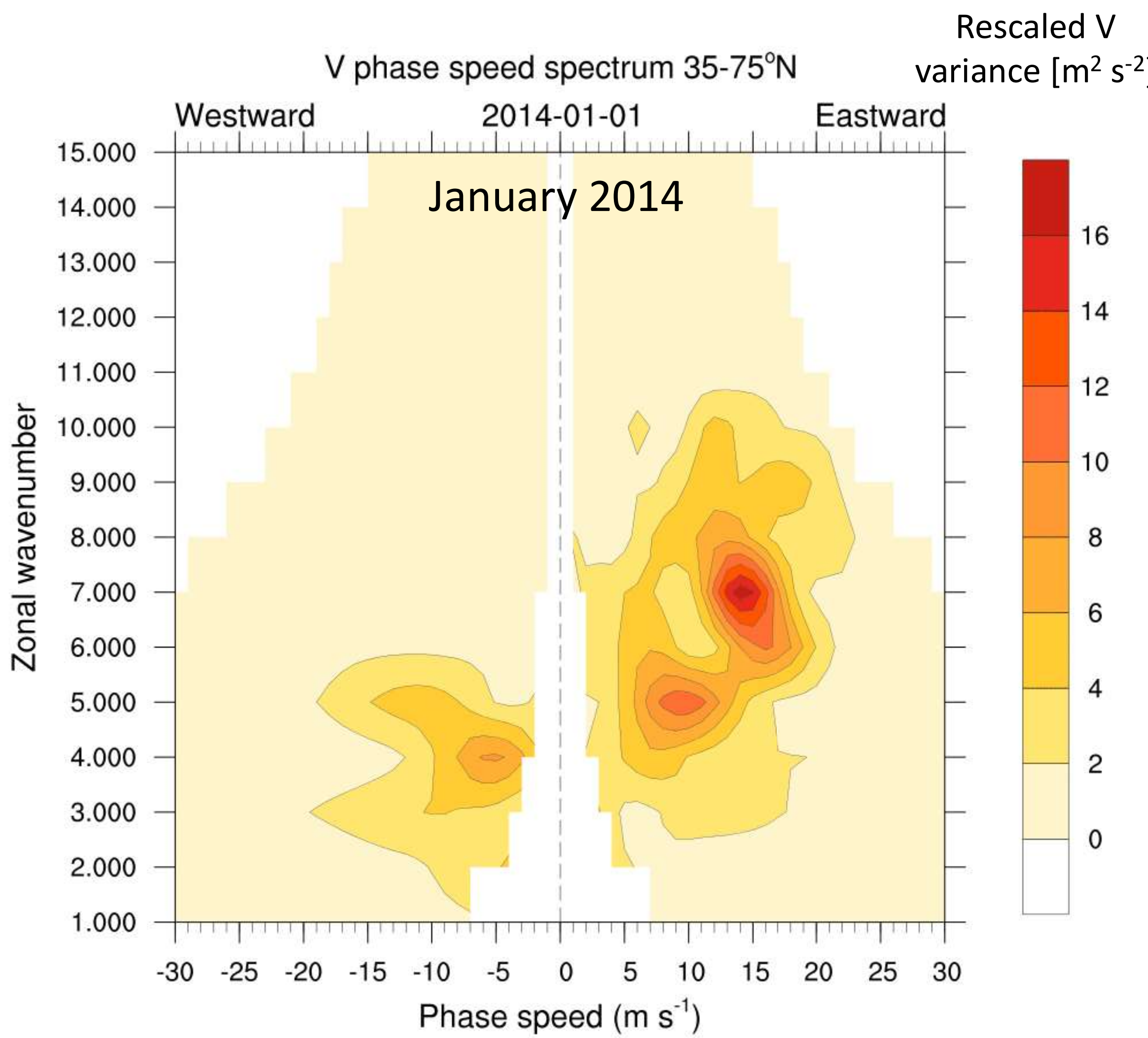
- ERA Interim,
- 35-75°N, 0.75°x0.75°
- 6-hourly, consecutive 61 days periods
- 250hPa meridional wind
- Jan 1979 → Dec 2018

→ **A spectrum each day to partition extratropical flow in**

(n, c_p)
(wavenum., phase speed)

harmonics.

(Randel and Held 1991)



Coexisting **progressive and retrogressive, synoptic and planetary Rossby waves.**

Daily phase speed diagnostic

Superposition principle:

Large-scale flow evolution results from a superposition of waves across a broad range of wavenumbers and frequencies (and, therefore, of phase speeds).

Spectral analysis tells us how much each (n,c_p) harmonic contributes to the overall phase speed.

Phase speed metric

$$\boxed{c} = \frac{\sum_{n=1}^{15}\sum_{c_p=-30}^{30} S(n,c_p)\cdot c_p}{\sum_{n=1}^{15}\sum_{c_p=-30}^{30} S(n,c_p)}$$

Sum over wavenumbers and phase speeds

Spectral coefficients as weights

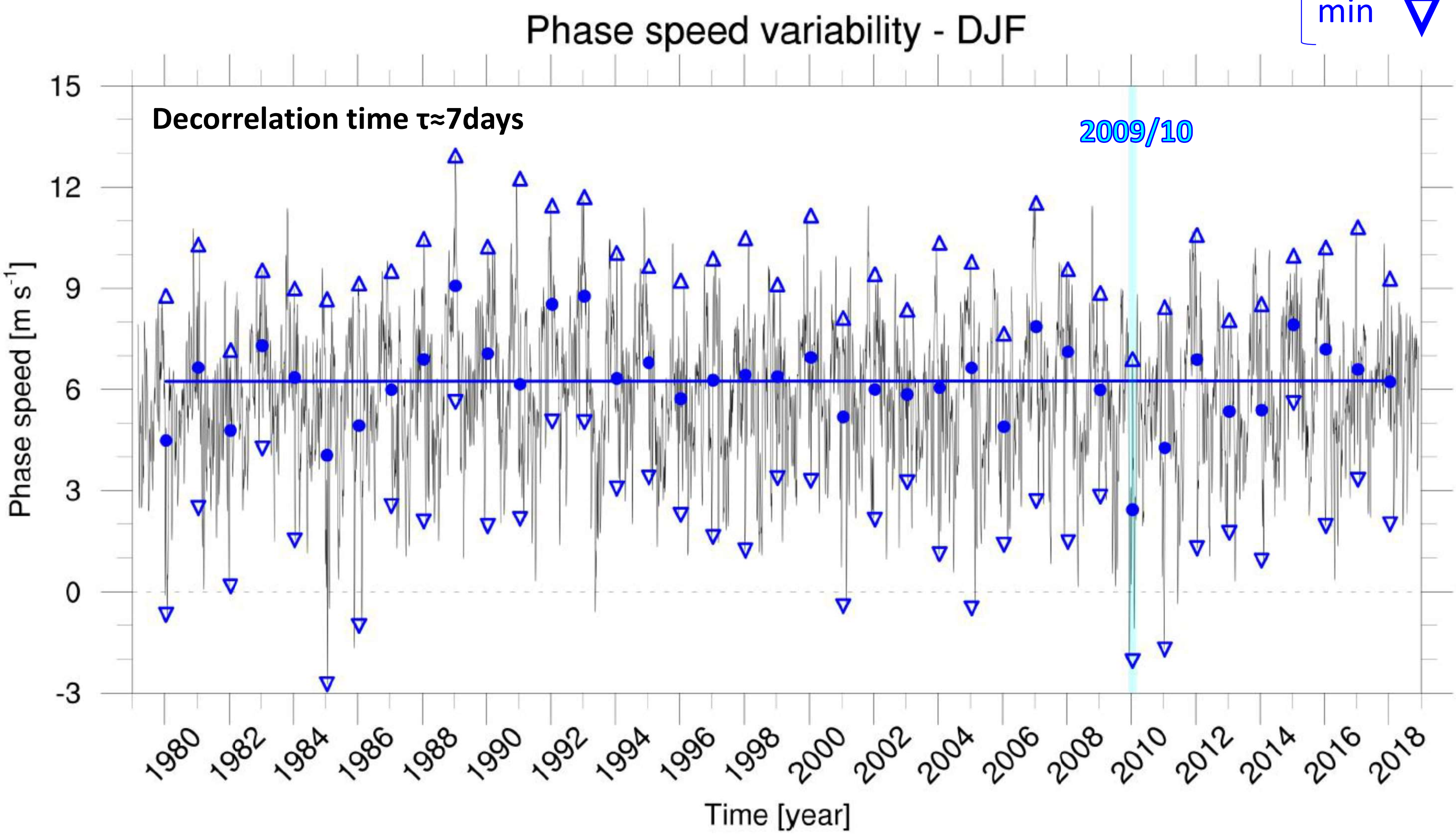
n	a-dimensional zonal wavenumber
c_p	phase speed
$S(n,c_p)$	spectral coefficients of meridional wind for 61 days period (37 days with tapering), as in Randel and Held (1991).

Daily phase speed diagnostic

Daily phase speed evolution from Feb. 1979 to Aug. 2018

Blue line is linear regression (trend is absent, p<0.01).

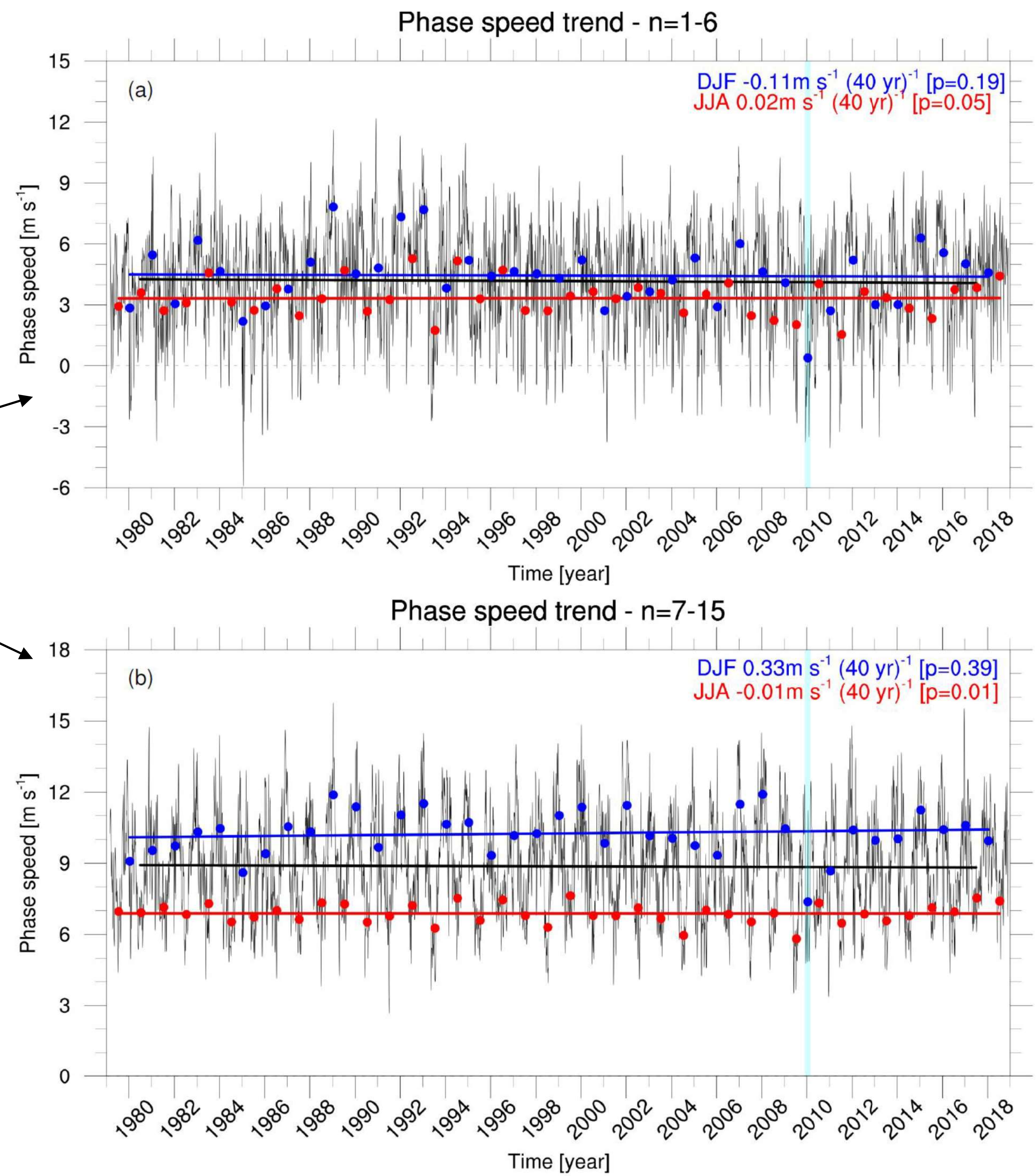
Seasonal: max △, mean ●, min ▽



c for subsets of harmonics

Phase speed considering only harmonics in the wavenumber range

(a) wave 1-6
(b) wave 7-15



However, the difference between a planetary wave and a synoptic wave is in the physical processes driving it, rather than just the different wavenumber.

Arctic Amplification and phase speed trends

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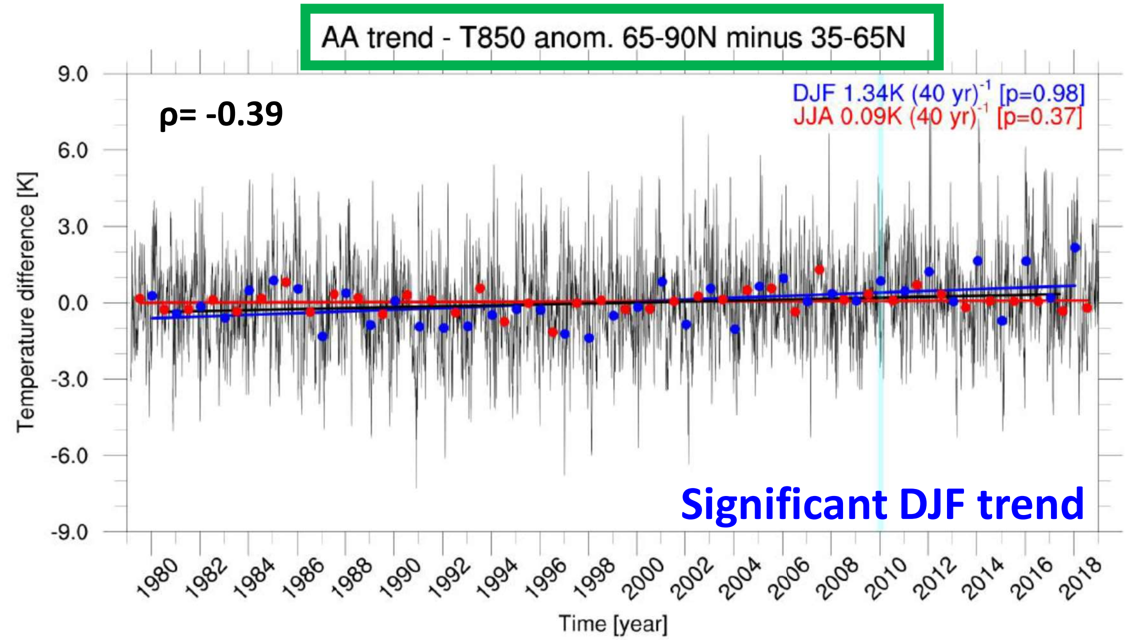

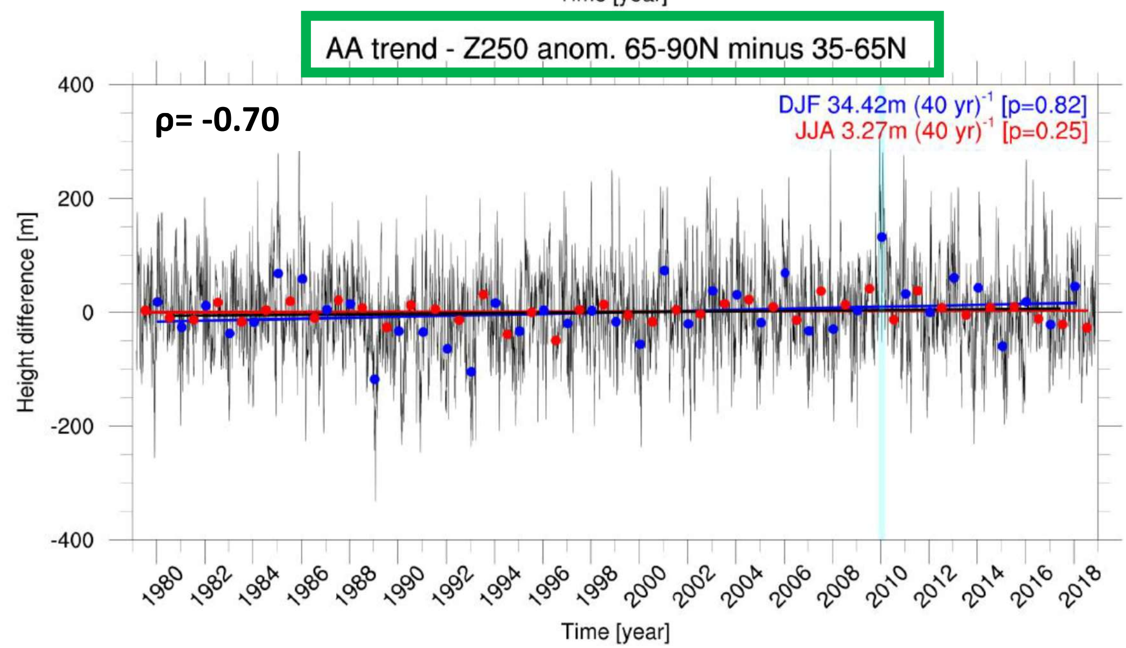

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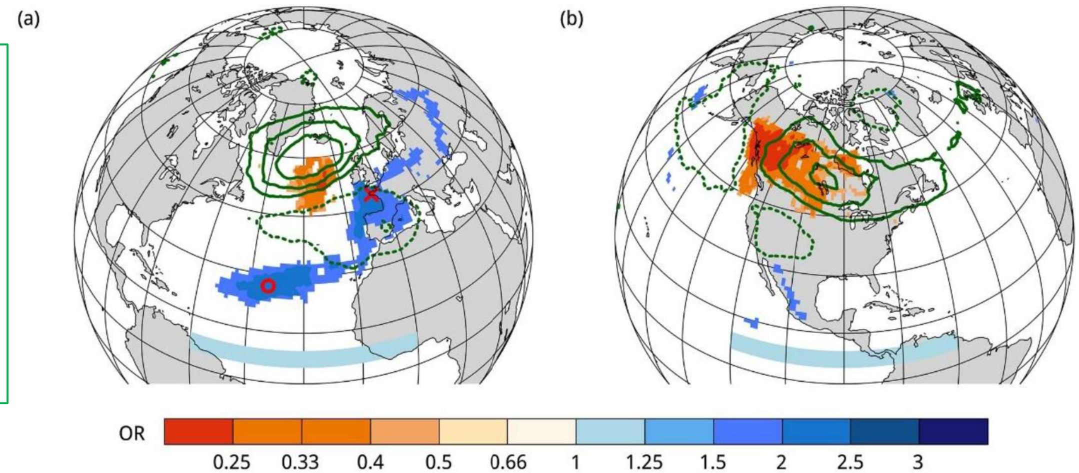
1) Introduction

Roethlisberger and Pfahl (2016)
→ amplified Rossby waves related to extreme events via weather systems, with regional differences.

Francis and Vavrus (2012) and following papers
→ sea ice melt, reduction of meridional temperature/PV gradient, weaker jets, more amplified waves → extremes.
<u>Very debated</u>

Cold events/high waviness odds ratio



Arctic amplification

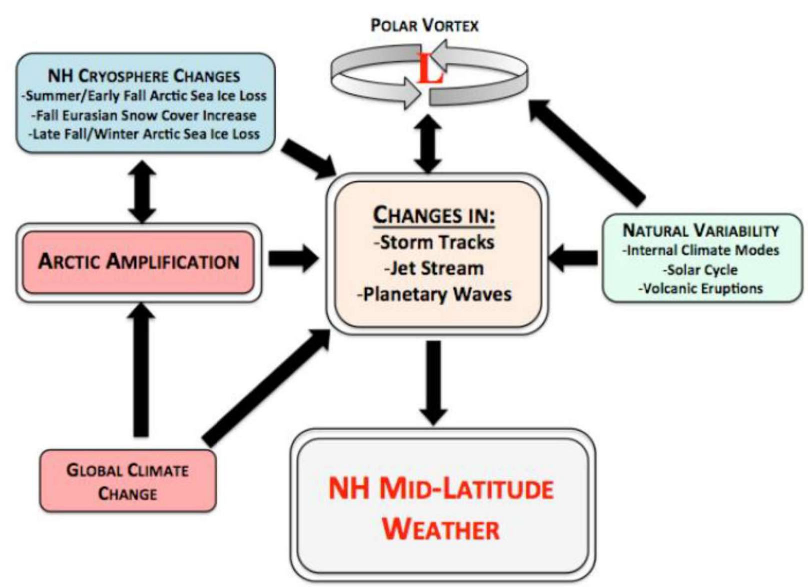


Figure 5. Complexity of linkage pathways. (Figure from Cohen et al. 2014).