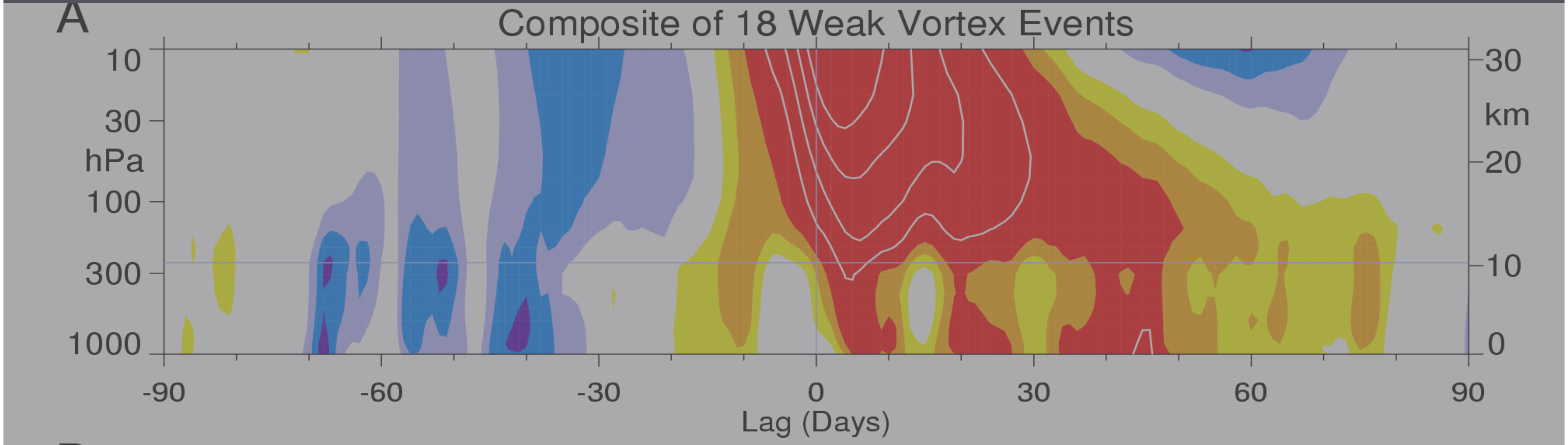
METEOROLOGY

IMPORTANCE OF THE STRATOSPHERE FOR EXTENDED-RANGE PREDICTION



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European Research Council
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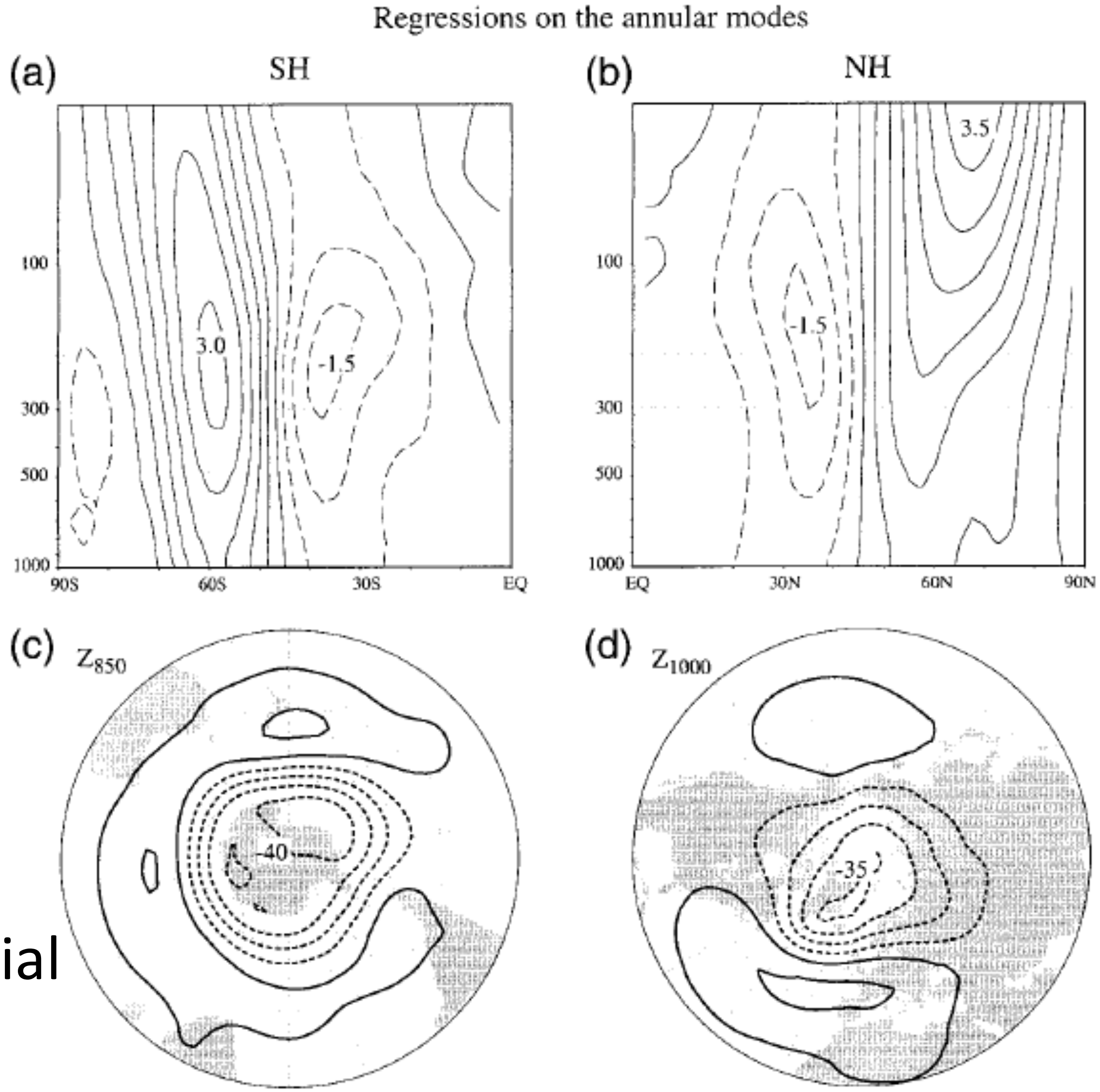
- In both hemispheres, **stratospheric polar vortex variability is connected to the troposphere**: in the NH, the effect is strongest over the North Atlantic

Zonal wind

Surface geopotential

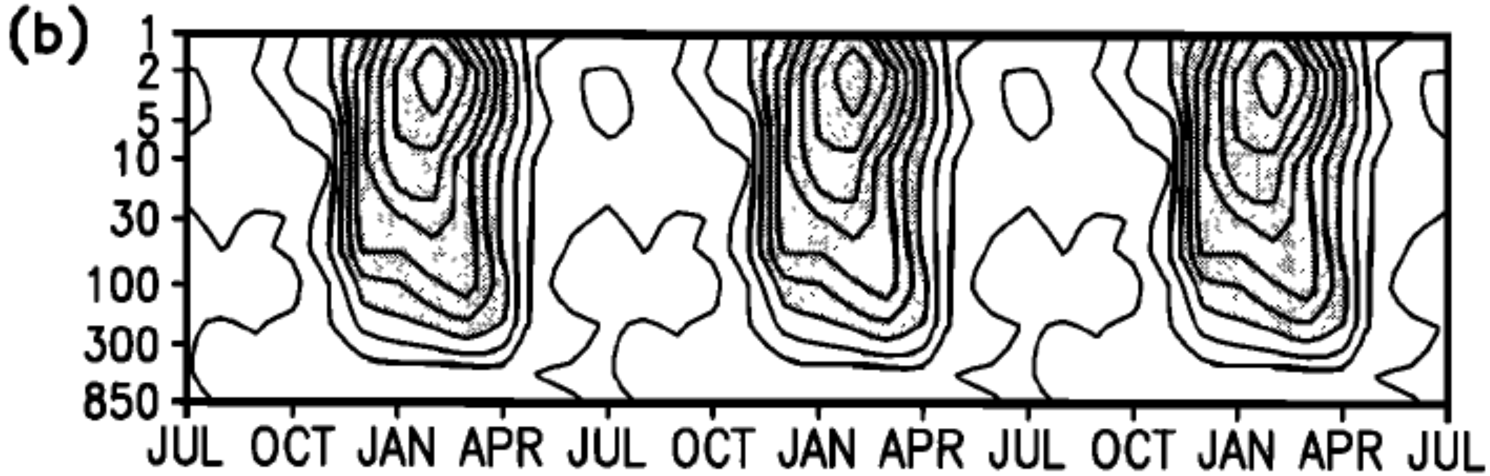


Southern and Northern Hemisphere “annular modes” (SAM and NAM), based on hemispheric EOFs

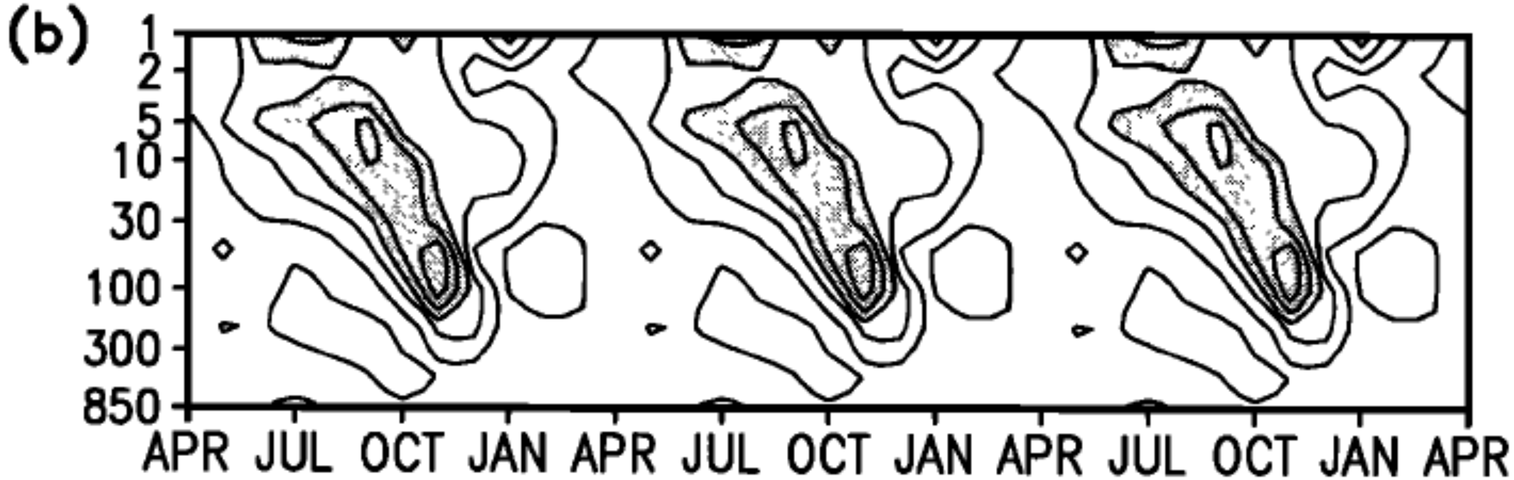
Thompson & Wallace (2000 J. Clim.)

- Stratospheric polar vortex variability has a strong seasonal dependence, which is **quite different in the two hemispheres**
  - Figure shows interannual std dev of monthly mean polar T

NH

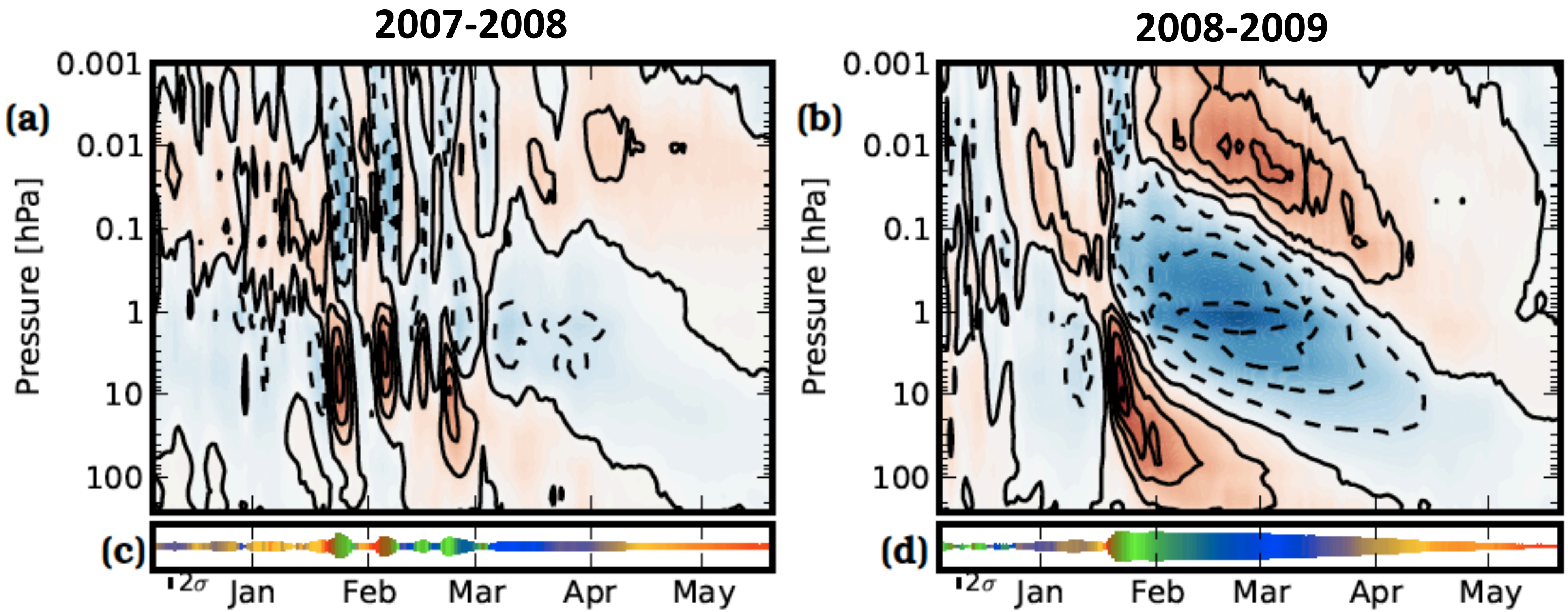


SH



Kuroda & Kodera (2001 JGR)

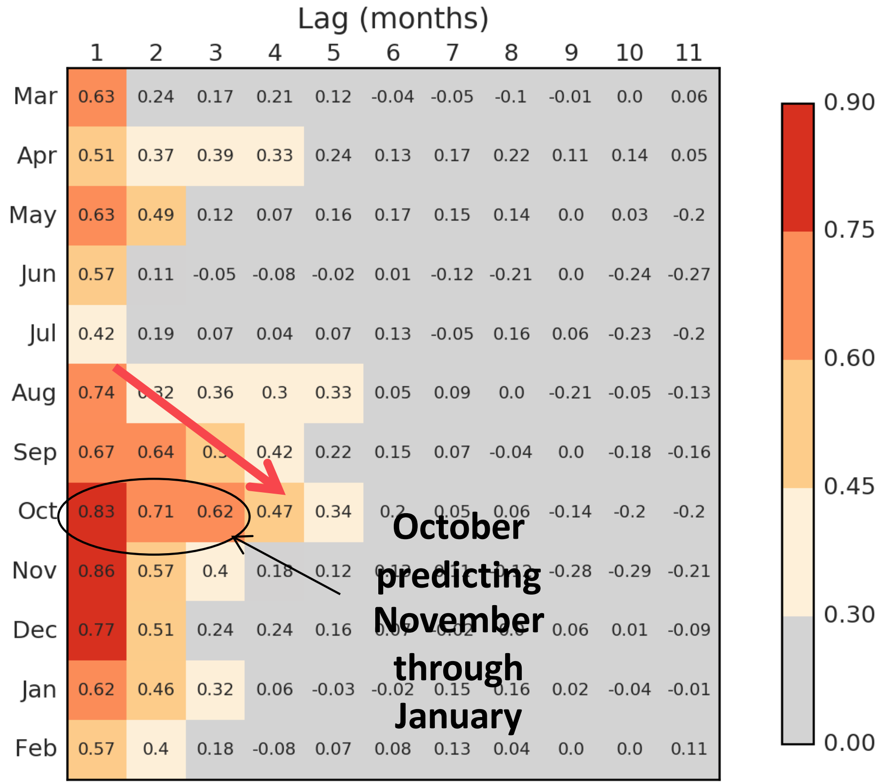
- In the NH, the main form of stratospheric polar vortex variability occurs through **Stratospheric Sudden Warmings** (SSWs)
  - About half of all SSWs are short-lived, as in 2007-2008, while half have extended recovery periods, as in 2008-2009, which provide a source of extended predictability (PJO life cycle)
  - Figures show Aura-MLS polar-cap average temperatures



Hitchcock, Shepherd & Manney (2013 J. Clim.)

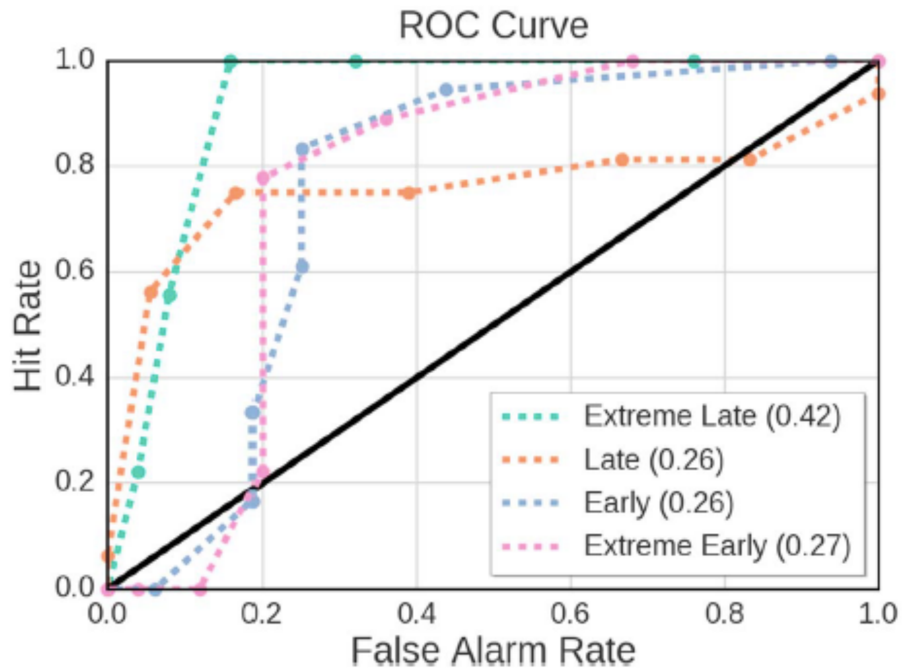
- In the SH, the variability is in the **springtime seasonal evolution**
- Anomalies build up through late winter/early spring, provide predictability through late spring/early summer **See Nick's talk**

Autocorrelations of monthly mean 30 hPa Z polar vortex anomalies



Byrne & Shepherd (2018 J. Clim.)

Hindcasts from ECMWF SEAS4, with August 1 initializations, of 30 hPa Z seasonal evolution

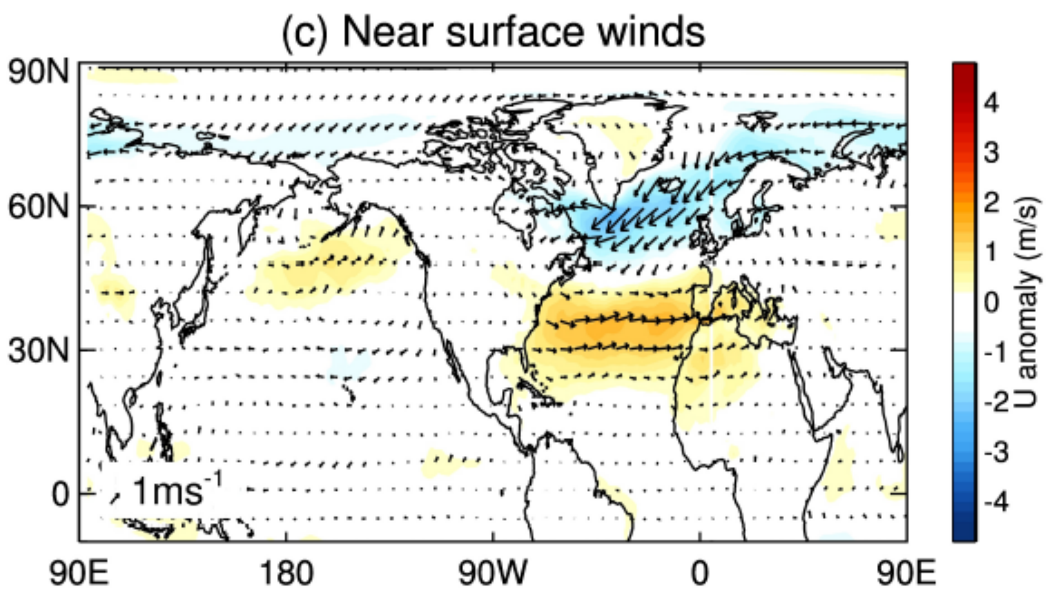


Byrne, Shepherd & Polichtchouk (2019 JGR)

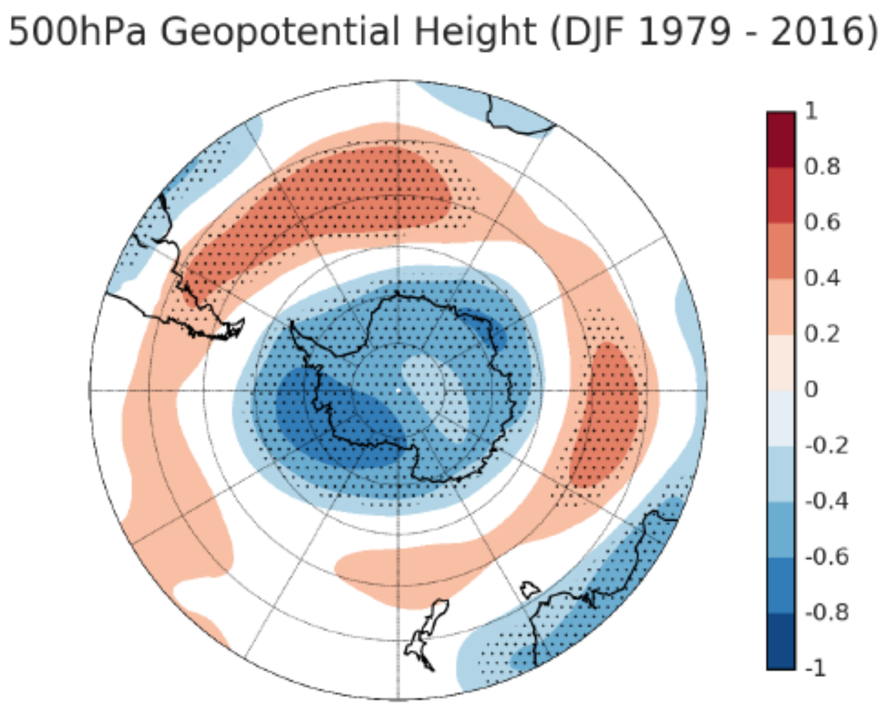
- **Stratosphere-troposphere coupling:** stratospheric polar vortex variability affects tropospheric circulation (here in observations)
  - Weakened vortex induces equatorward jet shift, in both hemispheres

SH: correlation with vortex breakdown date

NH: response for 30 days after SSW

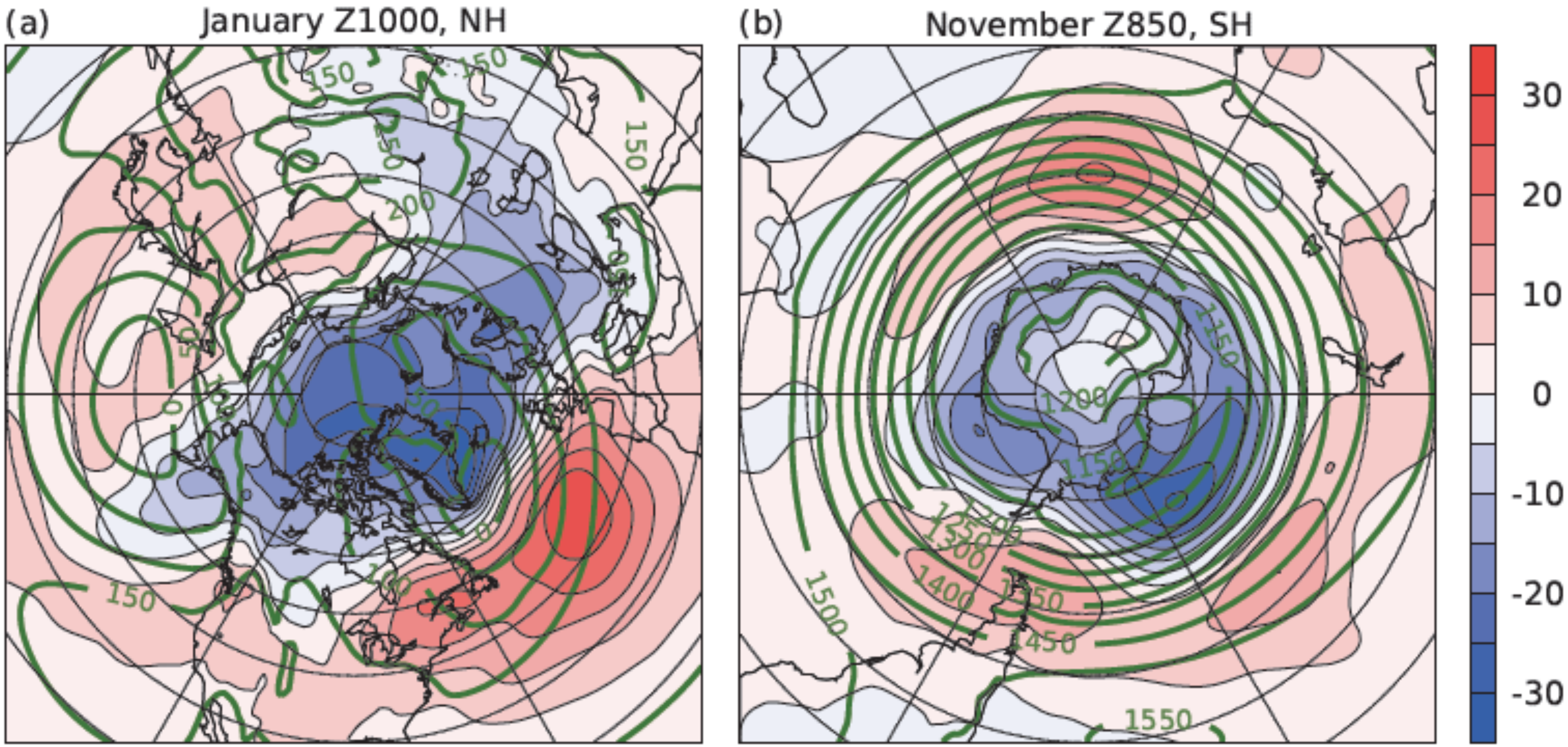


Hitchcock & Simpson (2014 JAS)



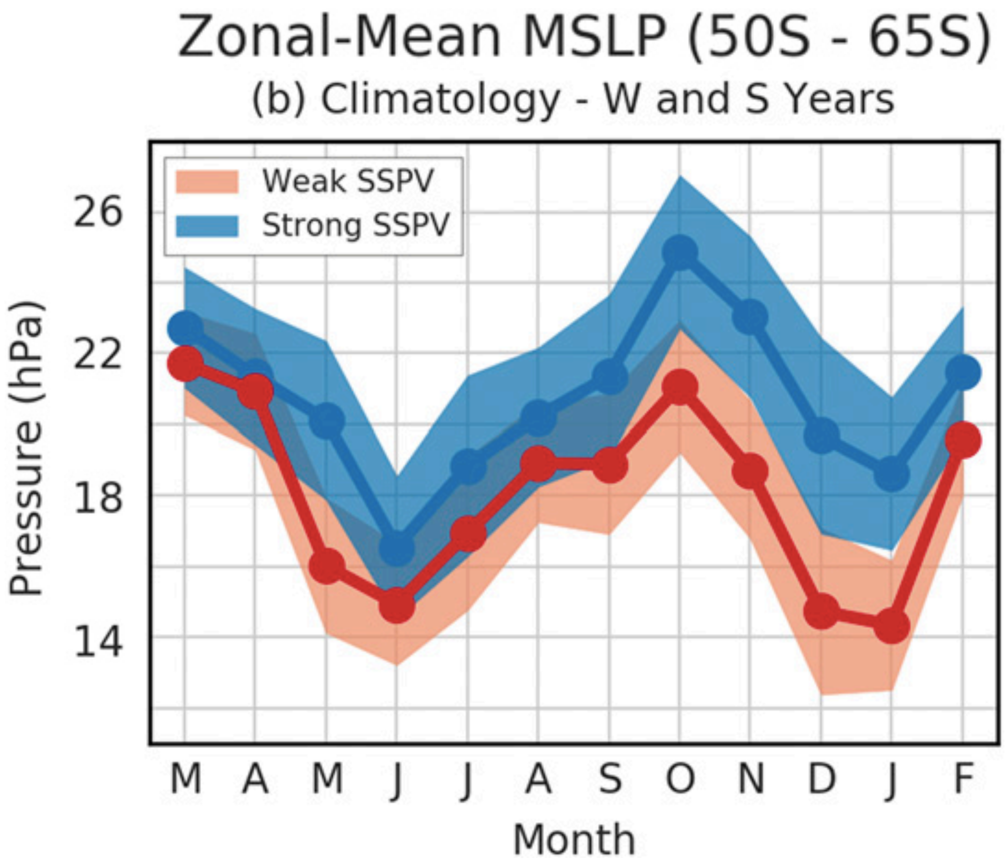
Byrne & Shepherd (2018 J. Clim.)

- Through its impact on polar vortex variability, the **Quasi-Biennial Oscillation** (QBO) in stratospheric tropical zonal winds affects surface climate, in both hemispheres
  - Figure shows W-E differences, updating Holton & Tan (1980)



Anstey & Shepherd (2014 QJRMS)

- The **SH semi-annual oscillation (SAO) in MSLP** — a common measure of the SH storm track — is notably different in spring and summer between weak and strong polar vortex years
  - In SH, BAM responds to SAM on quasi-steady timescales, i.e. > 1 month (Boljka, Shepherd & Blackburn 2018 JAS)
  - True for both the shifting and the strengthening SAM modes

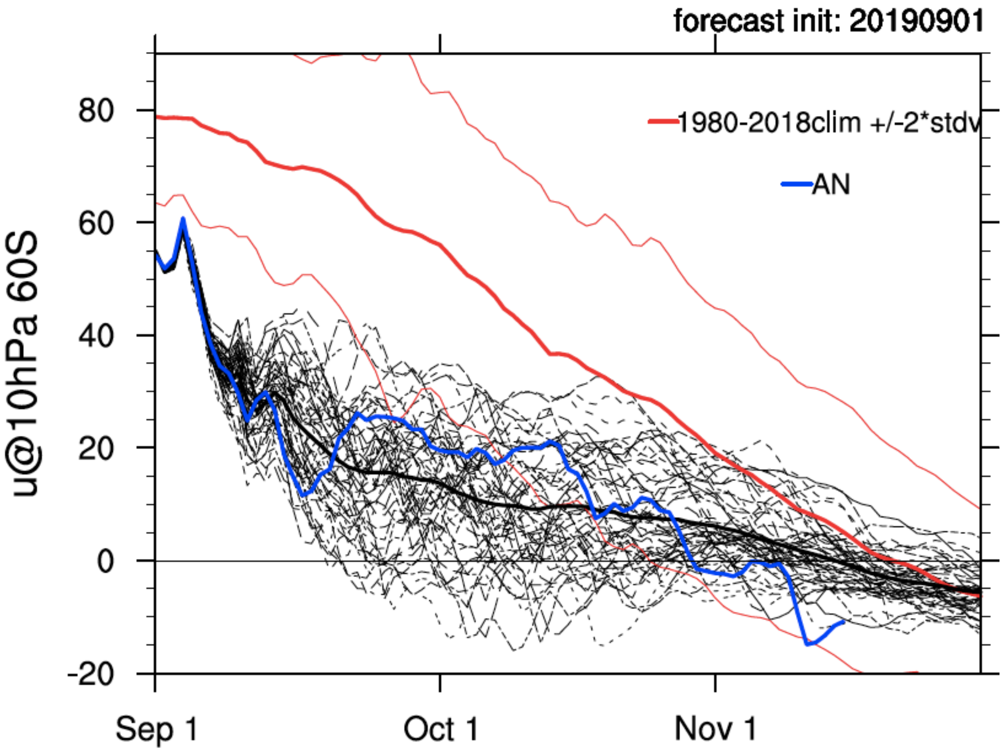


Strong polar vortex years correspond to a late vortex breakdown

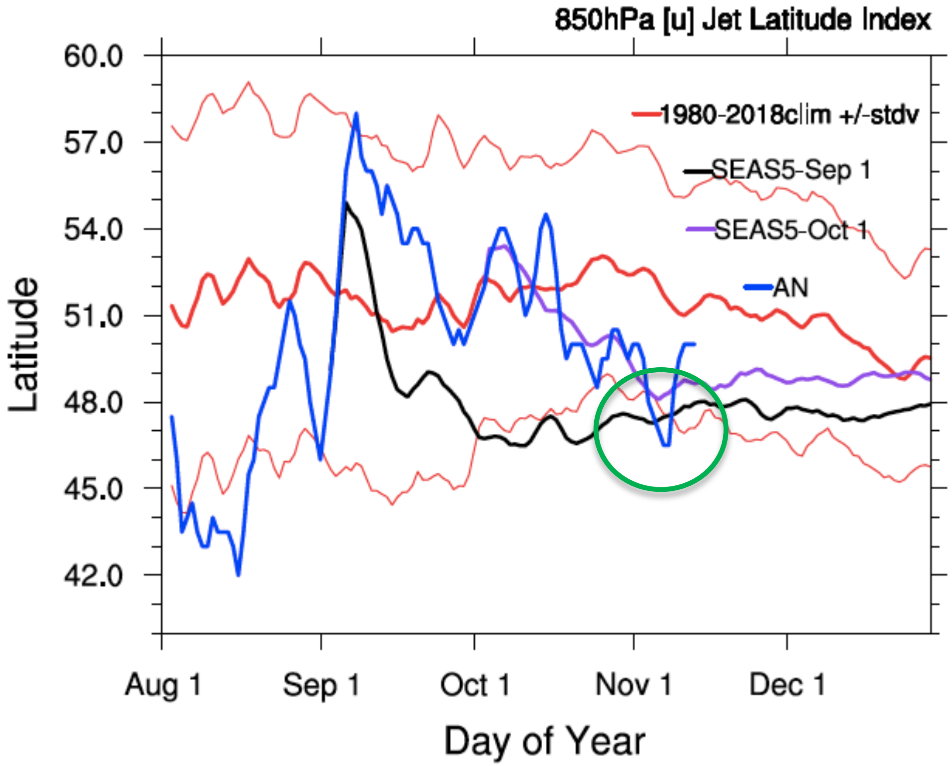
Byrne & Shepherd (2018 J. Clim.)

- This year's SH weak-vortex evolution **was quite well forecast** (here for ECMWF SEAS5), including the extreme equatorward midlatitude jet location in early November

Stratospheric zonal wind

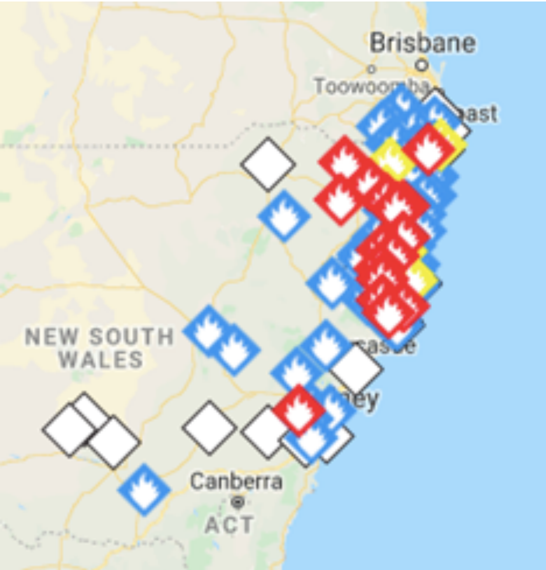


Tropospheric zonal wind

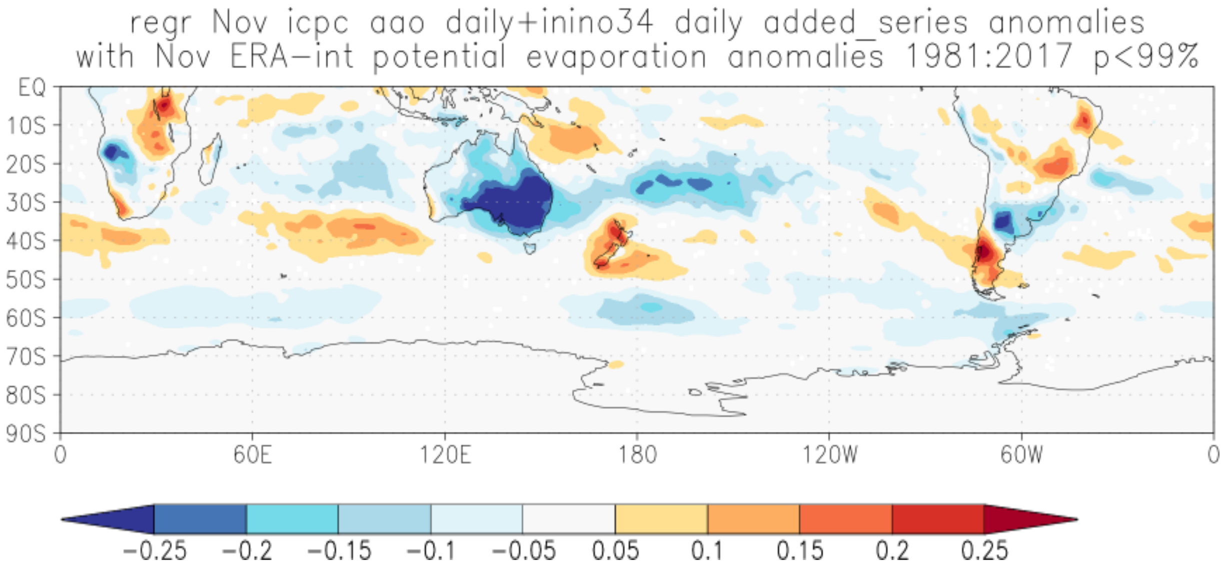


Figures courtesy of Inna Polichtchouk, ECMWF

- Westerly winds (and associated low humidity) over Australia are recognized as a **key driver of bushfire risk** at this time of year, acting on top of dry conditions and rising temperatures

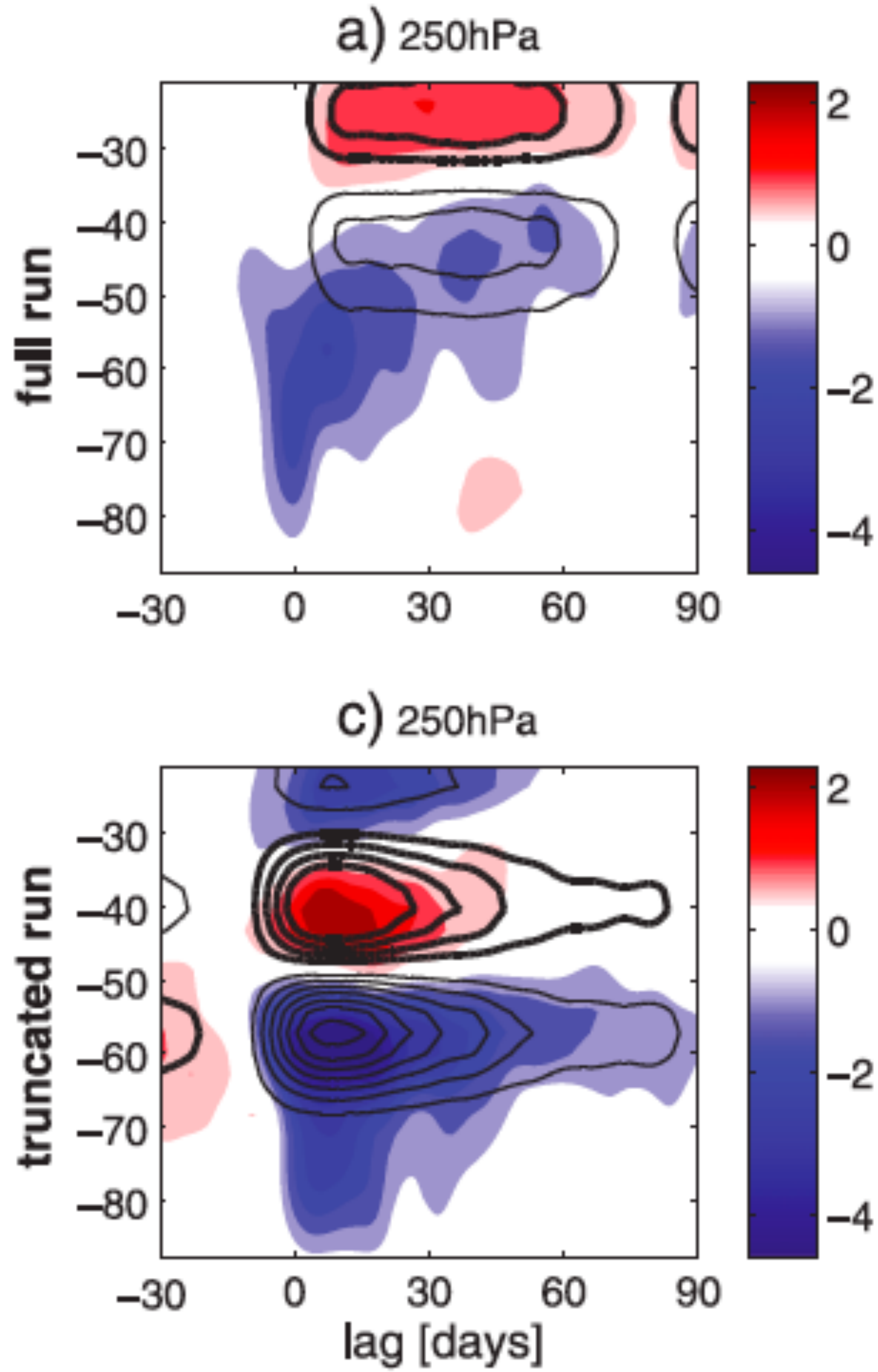


8 Nov 2019



November potential evaporation anomalies from AAO (SAM+) after controlling for ENSO

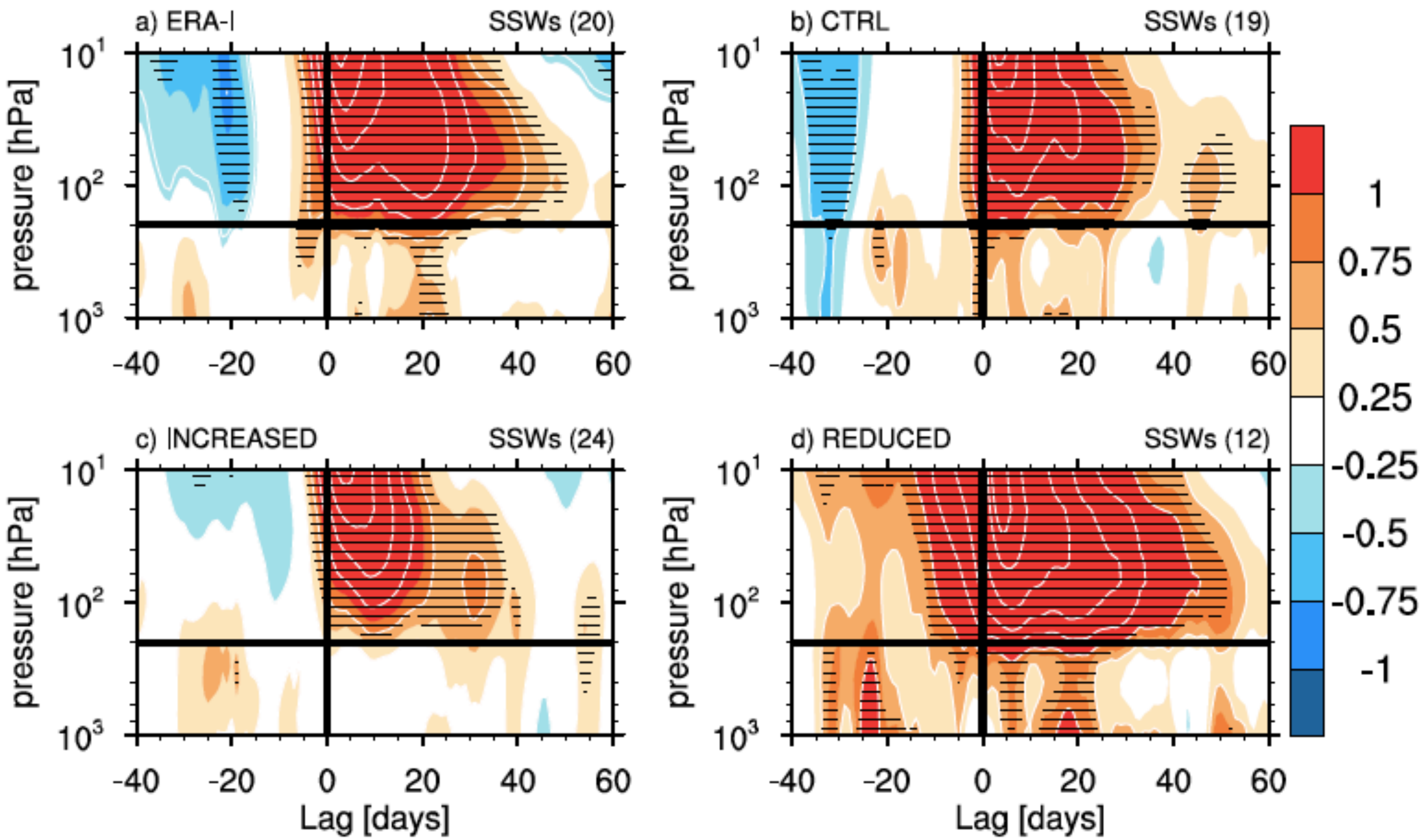
Courtesy of Harry Hendon, BOM (Aus)



- The exact **mechanism** for strat-trop coupling remains unclear
- Results from idealized model: tropospheric jet shifts equatorward in response to SSW in full run (top), but shifts poleward when only the planetary waves are allowed to respond (bottom)

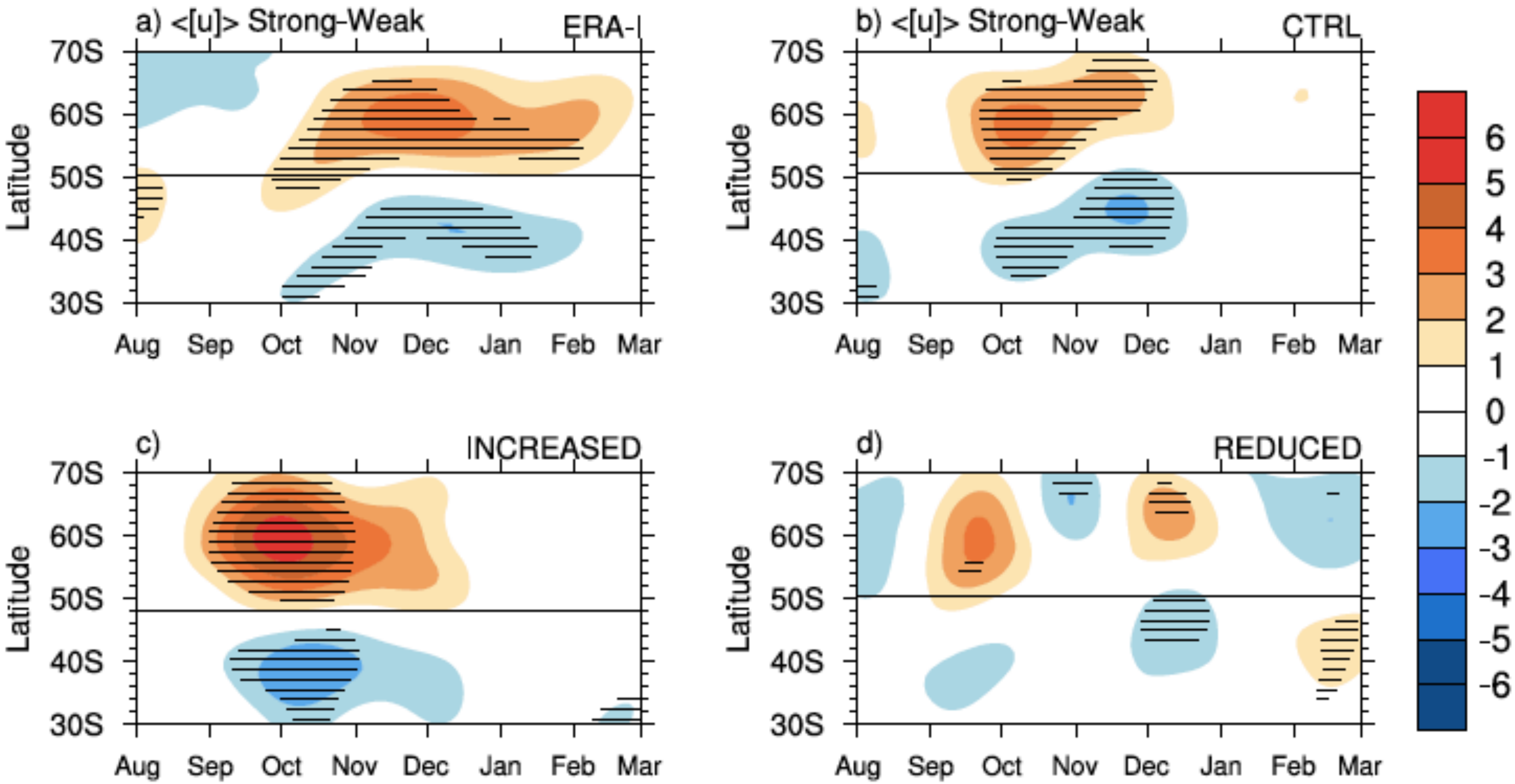
Domeisen, Sun & Chen (2013 GRL)

- **Interaction** between gravity-wave drag and strat-trop coupling
  - In the ECMWF IFS, reducing NOGWD *strengthens* strat-trop coupling in the NH
  - Results from effect on amplitude and persistence of lower-stratospheric SSW anomalies (Polichtchouk et al. 2018 JAS)



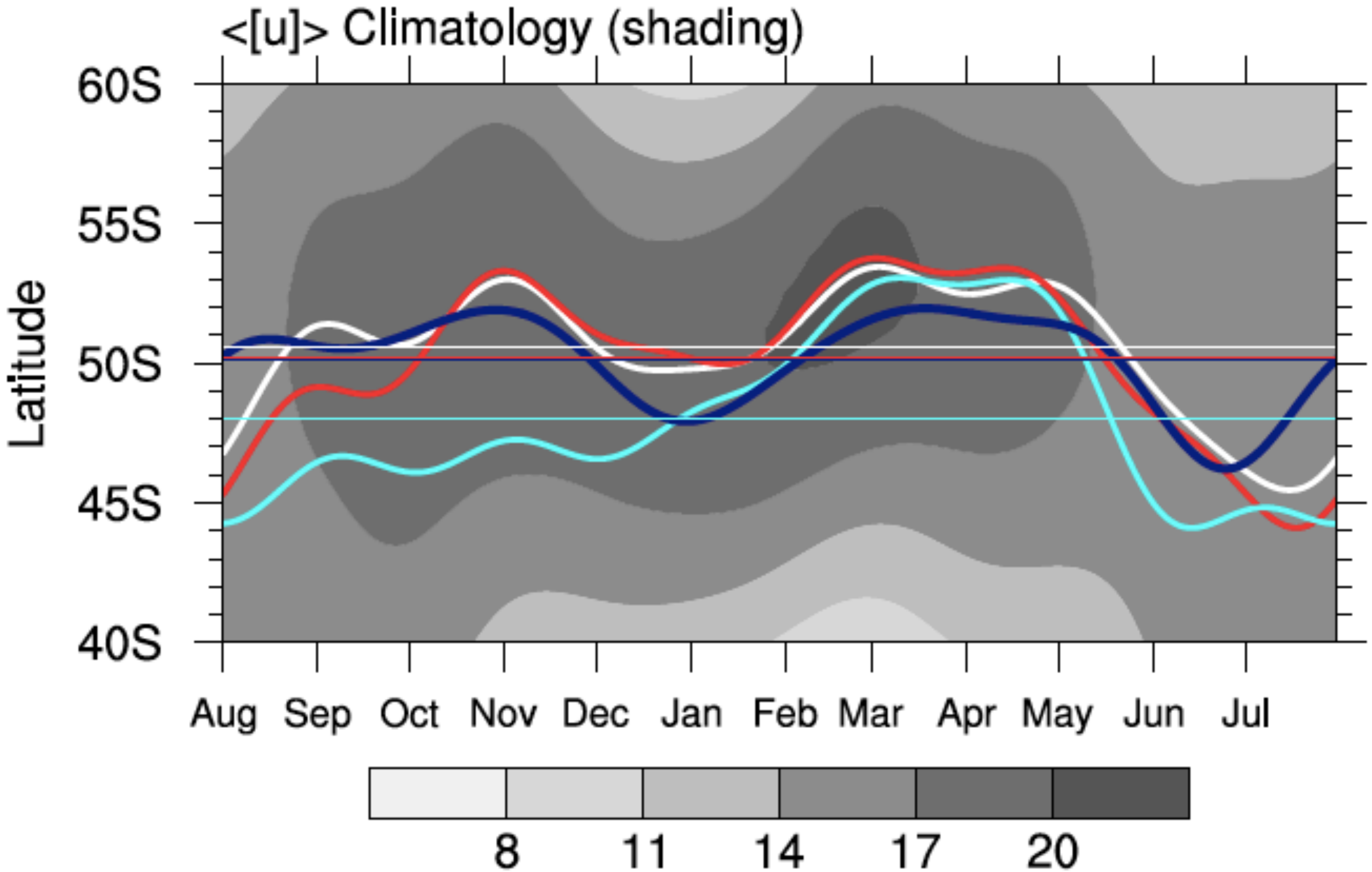
Polichtchouk, Shepherd & Byrne (2018 GRL)

- In the SH, in contrast, reducing NOGWD *weakens* strat-trop coupling
  - Results from changes in the sensitivity of the tropospheric circulation to lower stratospheric anomalies



Polichtchouk, Shepherd & Byrne (2018 GRL)

- NOGWD also affects the seasonal cycle of the SH tropospheric jet and thus the climatological biases
  - SAO disappears with increased NOGWD (cyan), hence **is not a purely tropospheric phenomenon** as conventionally argued



Dark blue: ERA-I
White: CTRL
Red: Reduced
Cyan: Increased

Polichtchouk, Shepherd & Byrne (2018 GRL)

- Further evidence of the SH strat-trop linkage being causal: the **equatorward jet bias** ([u] at 500 hPa) in ECMWF SEAS5 during late spring/summer (left) — which is consistent with its overly accelerated stratospheric seasonal evolution — is much reduced when the stratosphere is nudged to reanalysis (right)

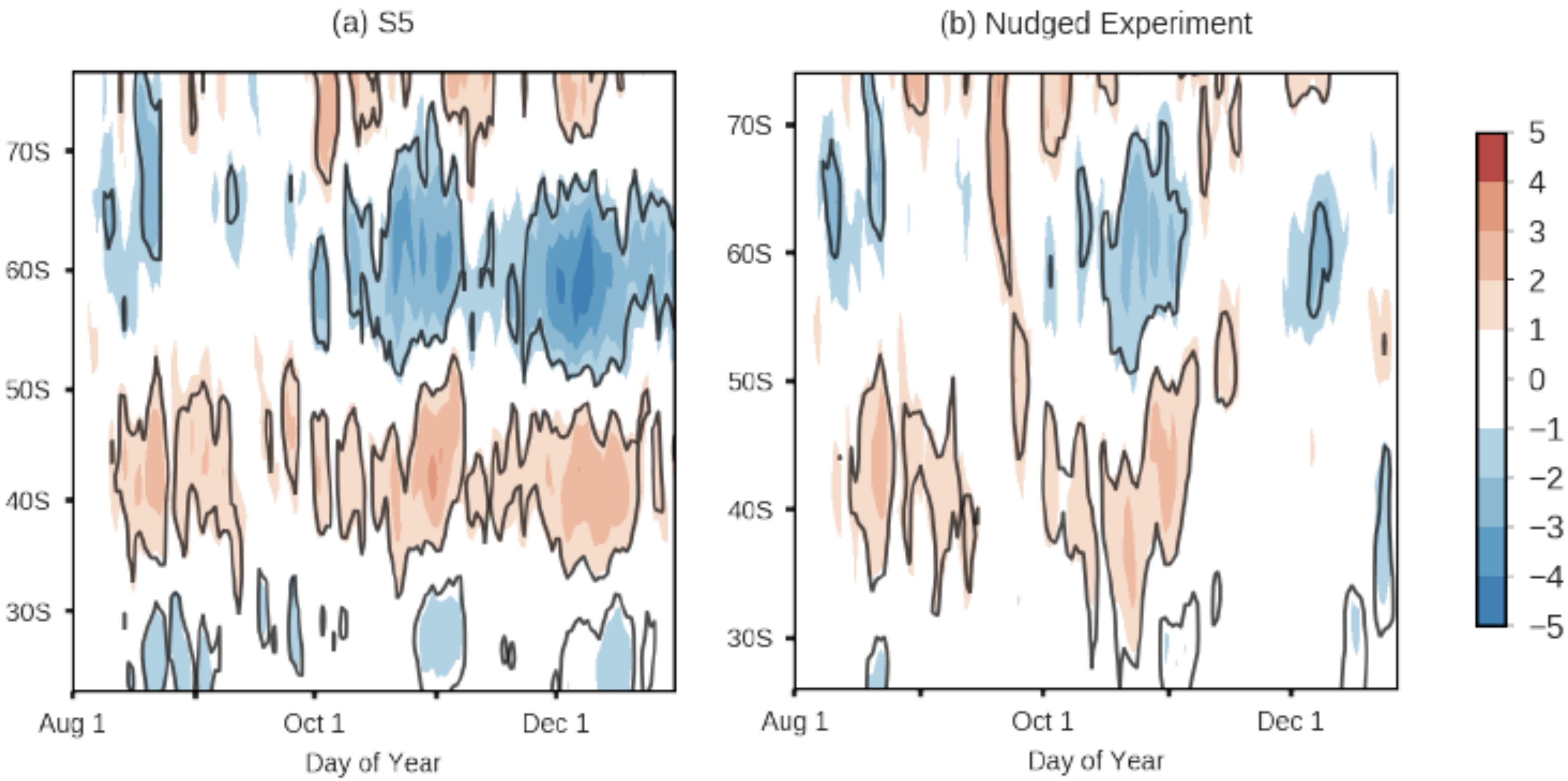
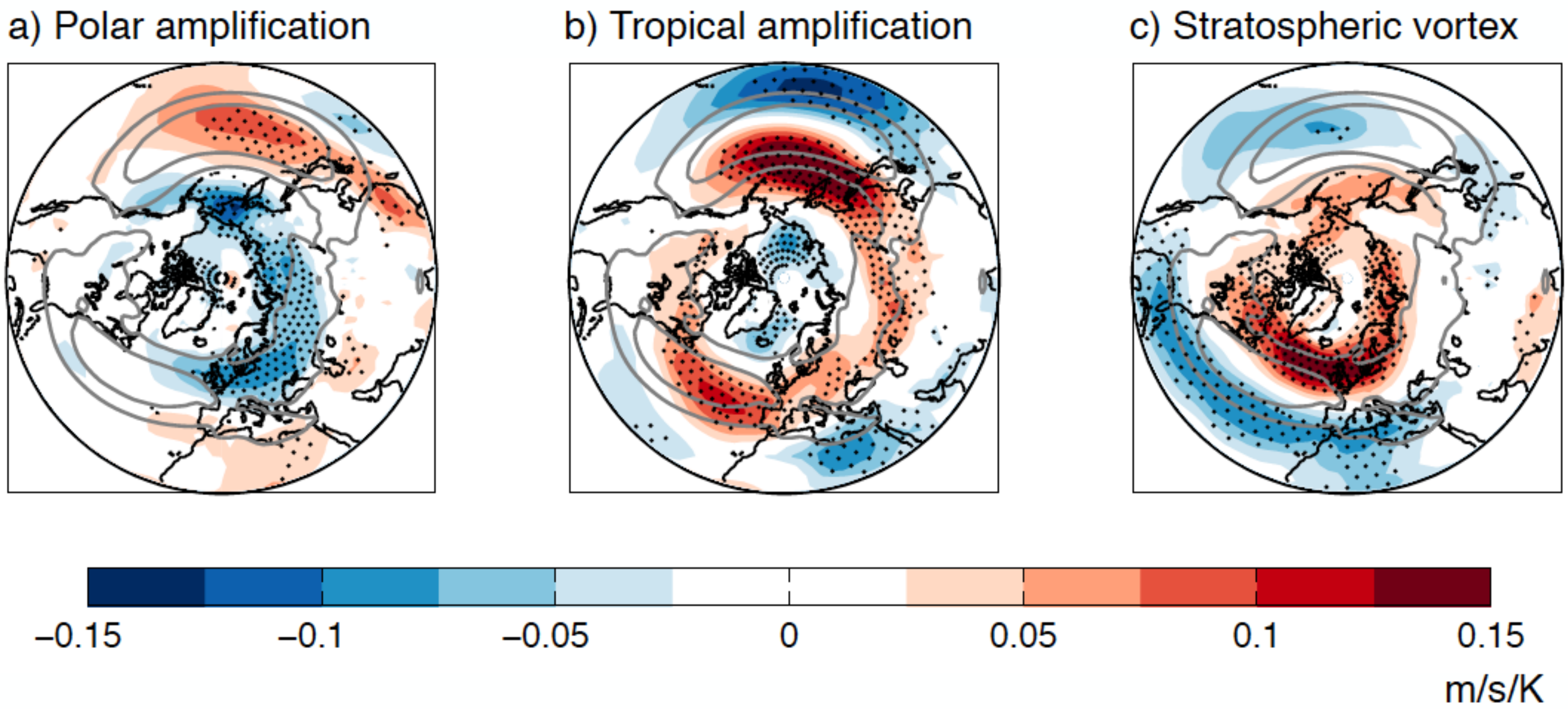


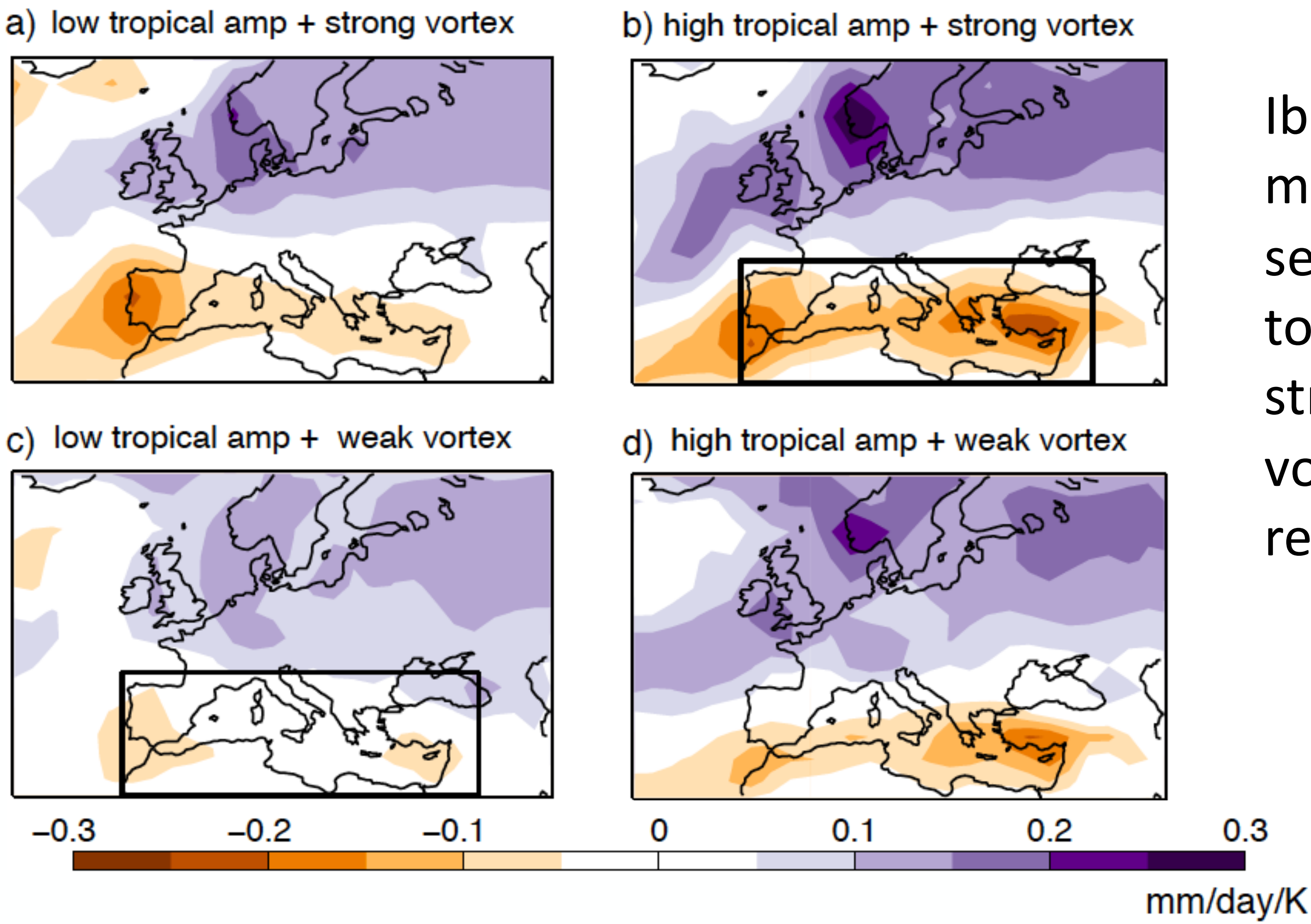
Figure courtesy of Inna Polichtchouk, ECMWF

- The **stratospheric vortex response to climate change** is a major driver of the uncertainty in the NH midlatitude circulation response during the cold season (Manzini et al. 2014 JGR)
- The patterns (here U850) are similar to those expected from single-forcing experiments, and from seasonal prediction



Zappa & Shepherd (2017 J. Clim.)

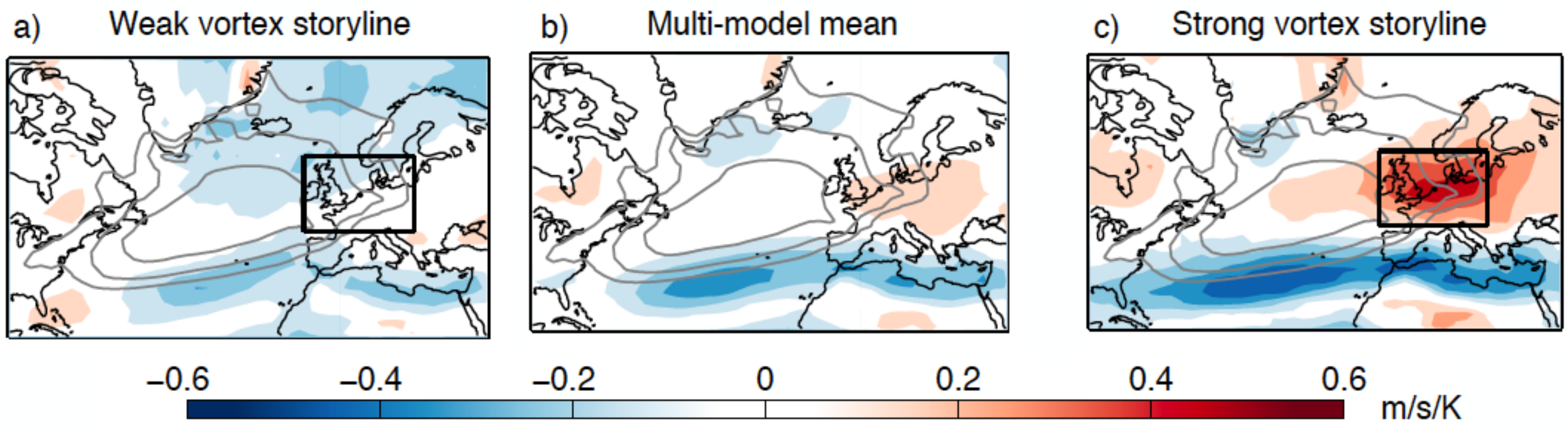
- Four **storylines of cold-season Mediterranean drying**
  - So far as we know, any one of these could be true



Iberia is mainly sensitive to the stratospheric vortex response

Zappa & Shepherd (2017 J. Clim.)

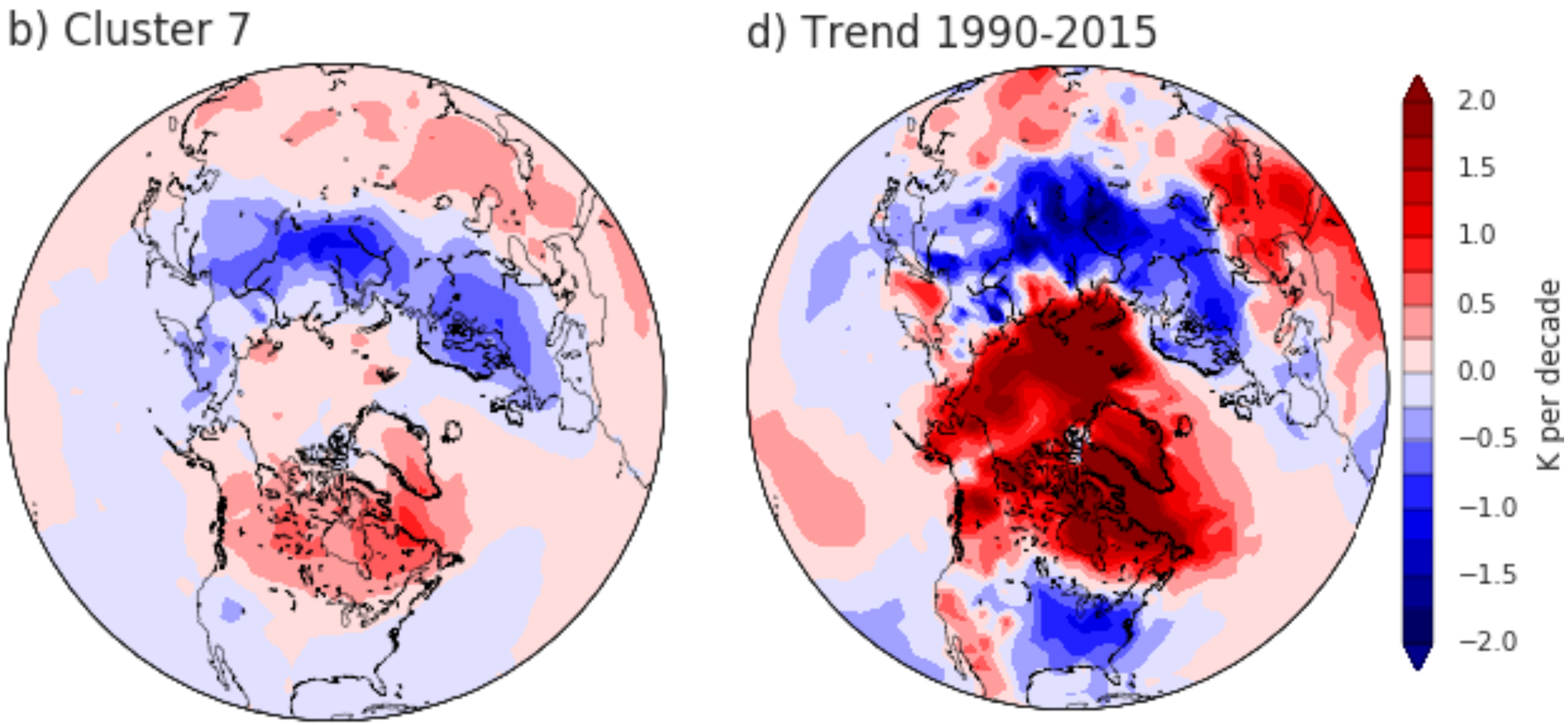
- The same, for wintertime **central European windiness** (95th percentile of daily mean windspeed at 850 hPa)
  - Here the stratospheric vortex response is the dominant source of uncertainty across the CMIP5 models!



Zappa & Shepherd (2017 J. Clim.)

- **Decadal variability:** increased frequency of weak stratospheric-vortex states (Cluster 7) over the last 25 years can account for most of the observed mid-late winter cooling over Eurasia

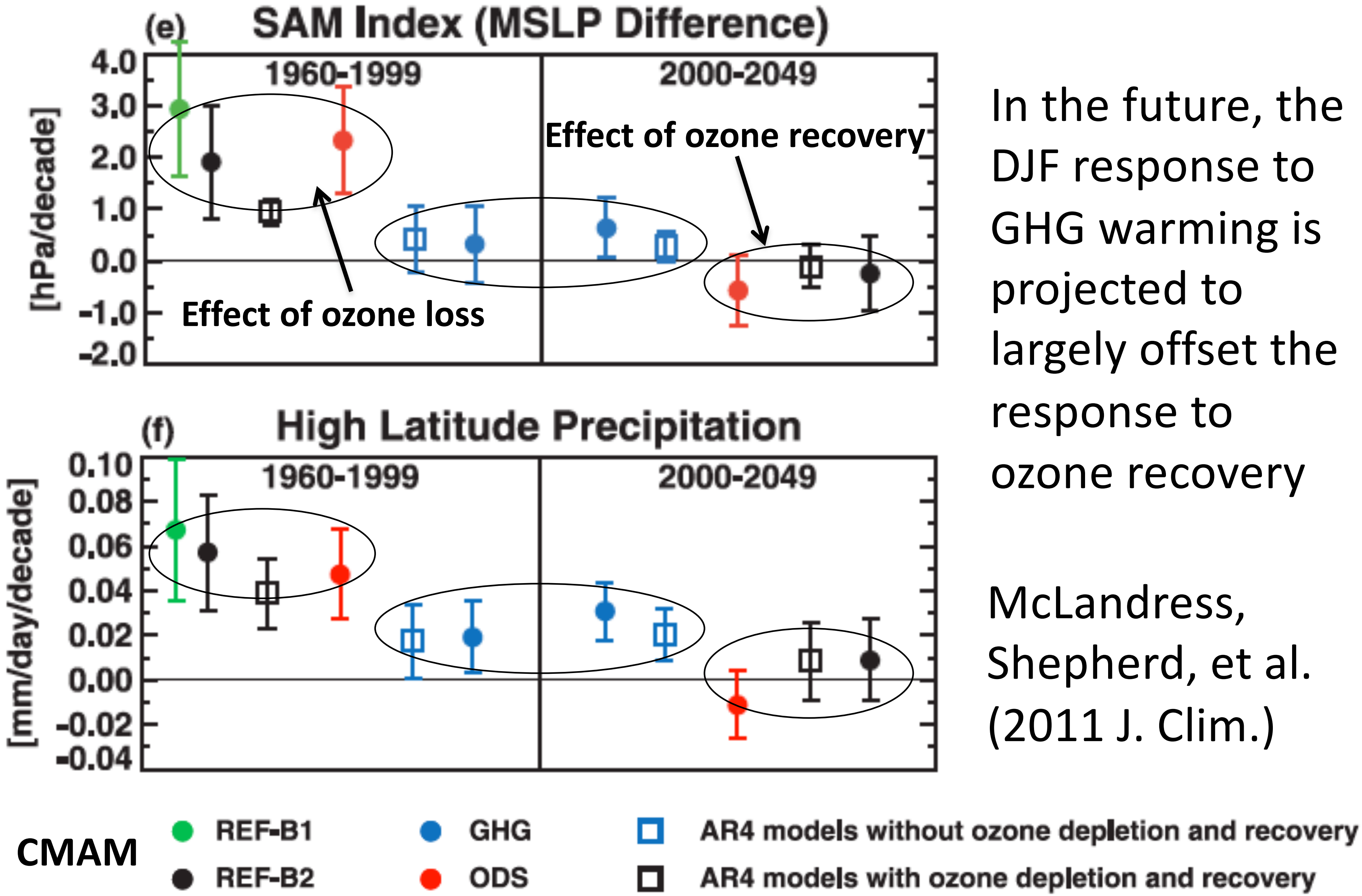
Predicted **Observed**



See Marlene's talk

Kretschmer et al. (2018 BAMS)

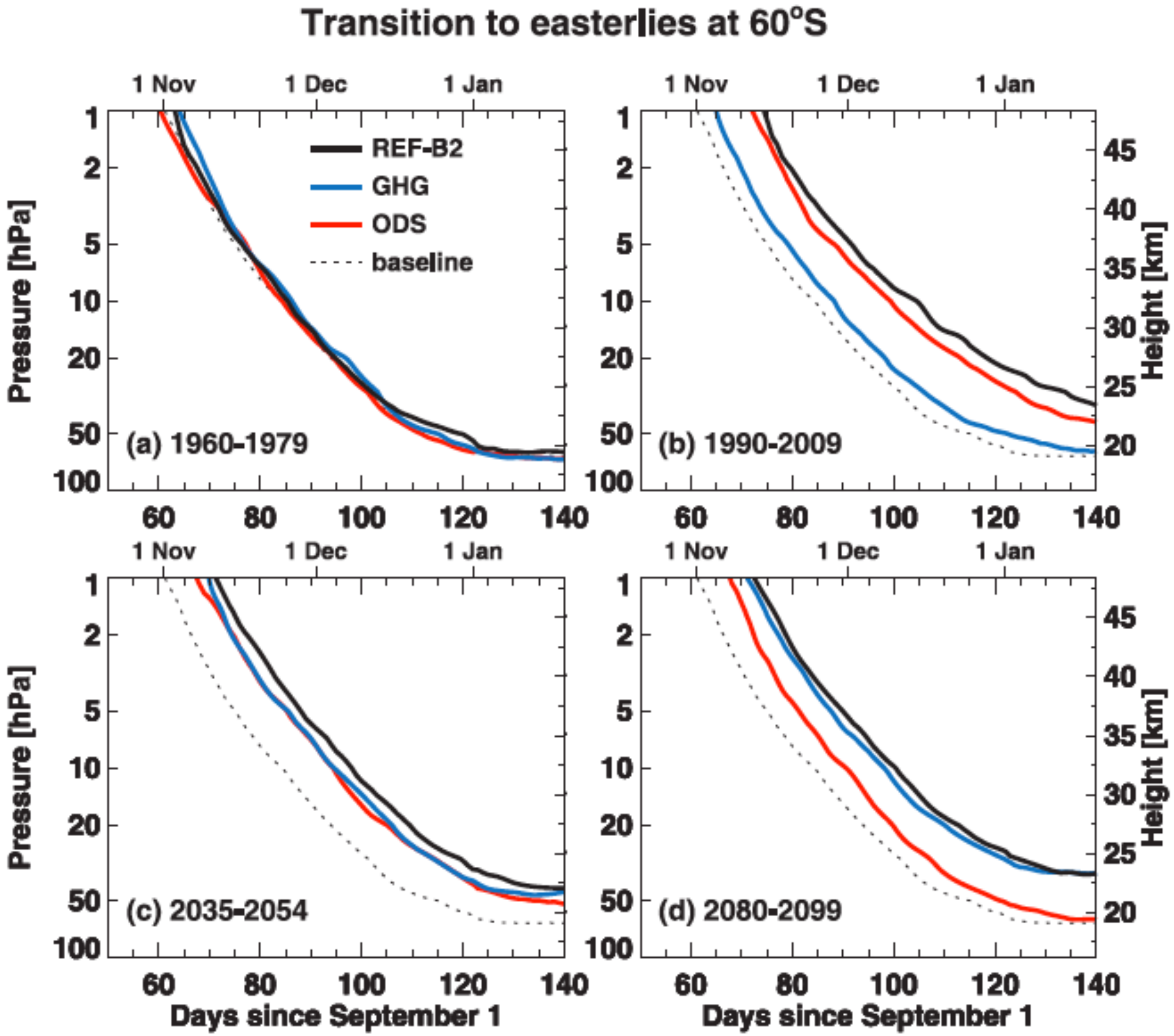
- In the SH, the **ozone hole** provides unambiguous evidence (since exogenous) for the causal nature of strat-trop coupling



In the future, the DJF response to GHG warming is projected to largely offset the response to ozone recovery

McLandress, Shepherd, et al. (2011 J. Clim.)

- In CMAM, the delay in the SH polar vortex breakdown induced by the ozone hole is not reversed during ozone-hole recovery

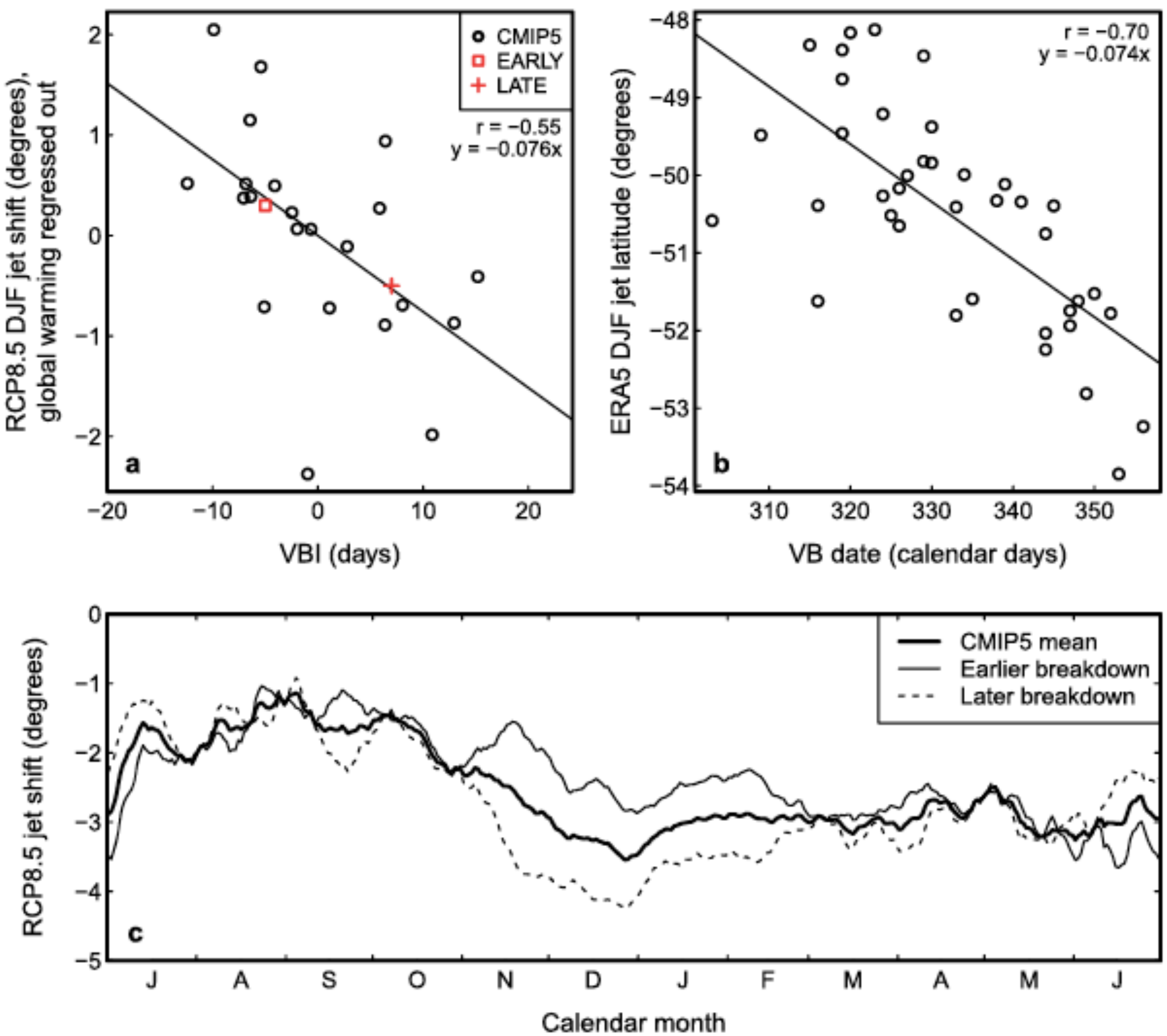


Increasing GHGs also lead to a delay in vortex breakdown

Are these two cancelling effects on circulation perhaps related?

McLandress et al. (2010 J. Clim.)

- CMIP5 models all predict a **delayed vortex breakdown from GHG**
- Explains about 30% of the model variance in the DJF jet shift and 45% of the mean shift (see bottom panel)

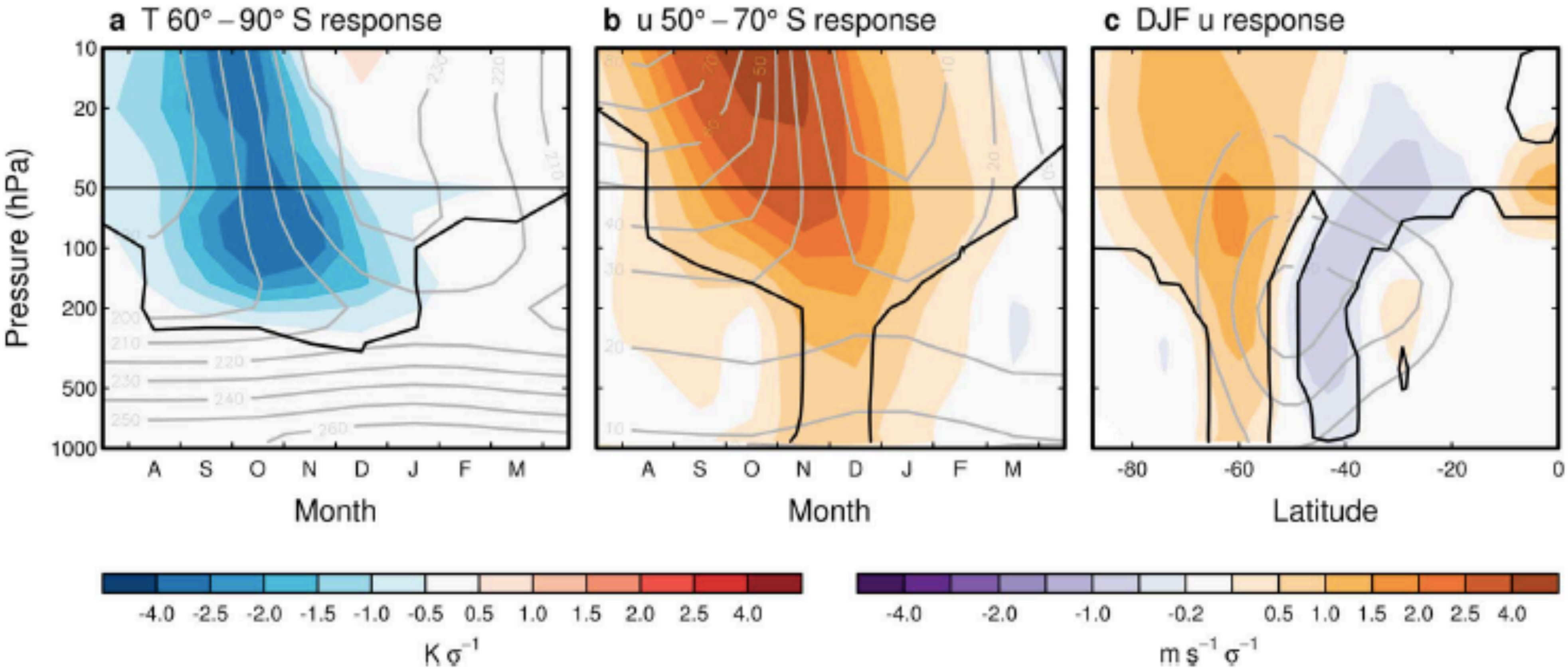


CMIP5 changes between piControl and 2080-2099

VB-jet relation in the trend (upper left) is the same as the observed relation in the interannual variability (upper right)

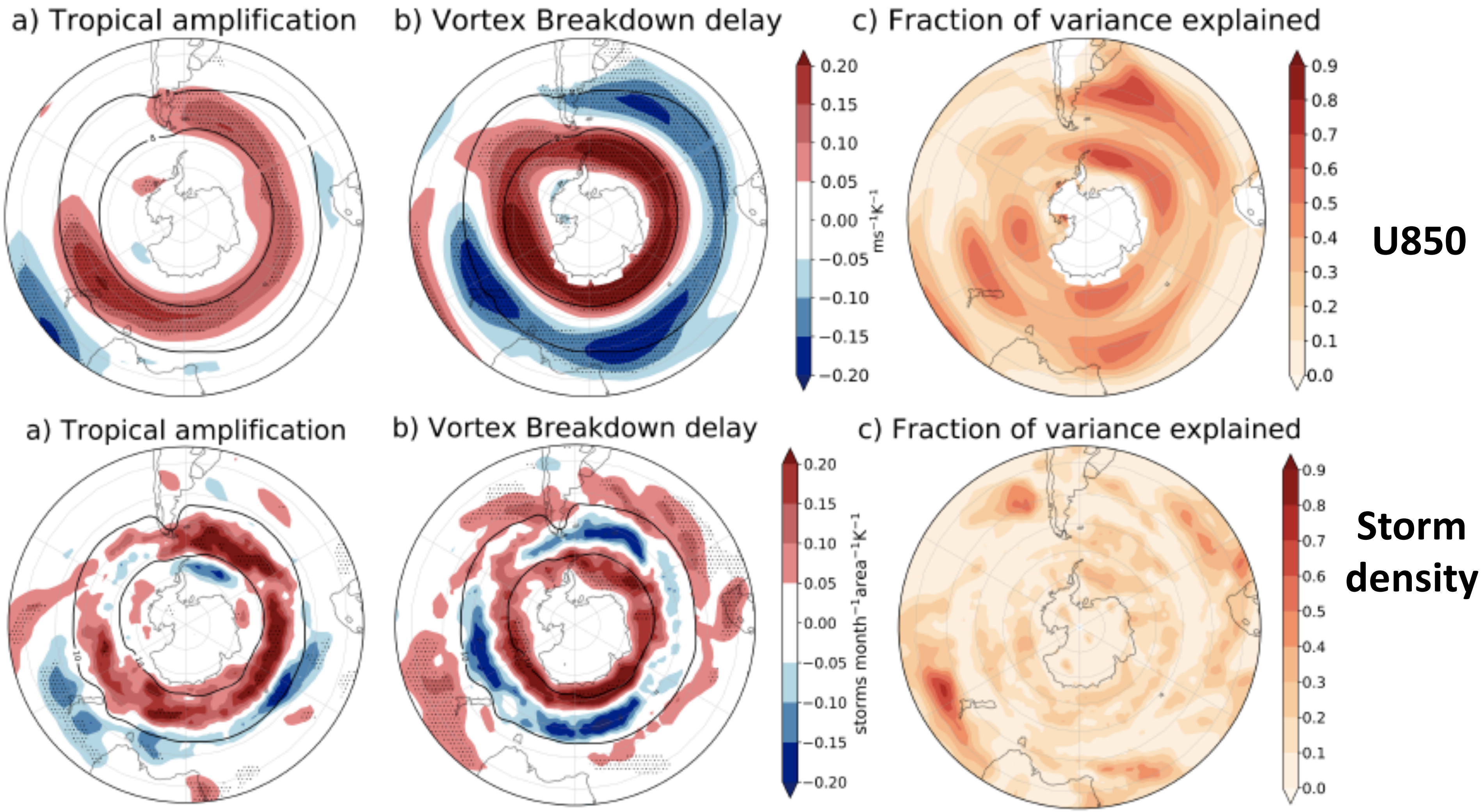
Ceppi & Shepherd (2019 GRL)

- That the effect is causal is proven with nudging experiments



Ceppi & Shepherd (2019 GRL)

- Uncertainty in vortex breakdown delay is a major contributor to **uncertainty in SH DJF midlatitude regional changes from GHG**

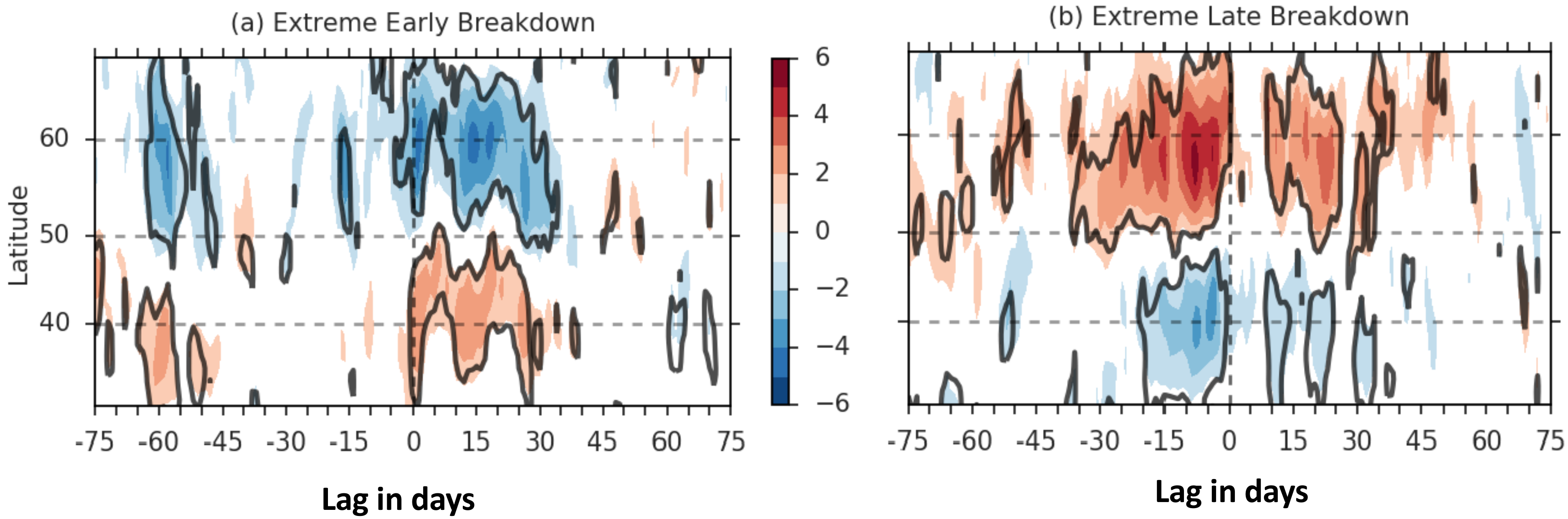


See Julia's poster

Mindlin, Shepherd, et al. (in preparation)

- **An issue with correlations: non-stationarity**
  - Composited tropospheric circulation anomalies are completely different for early and late breakdown events

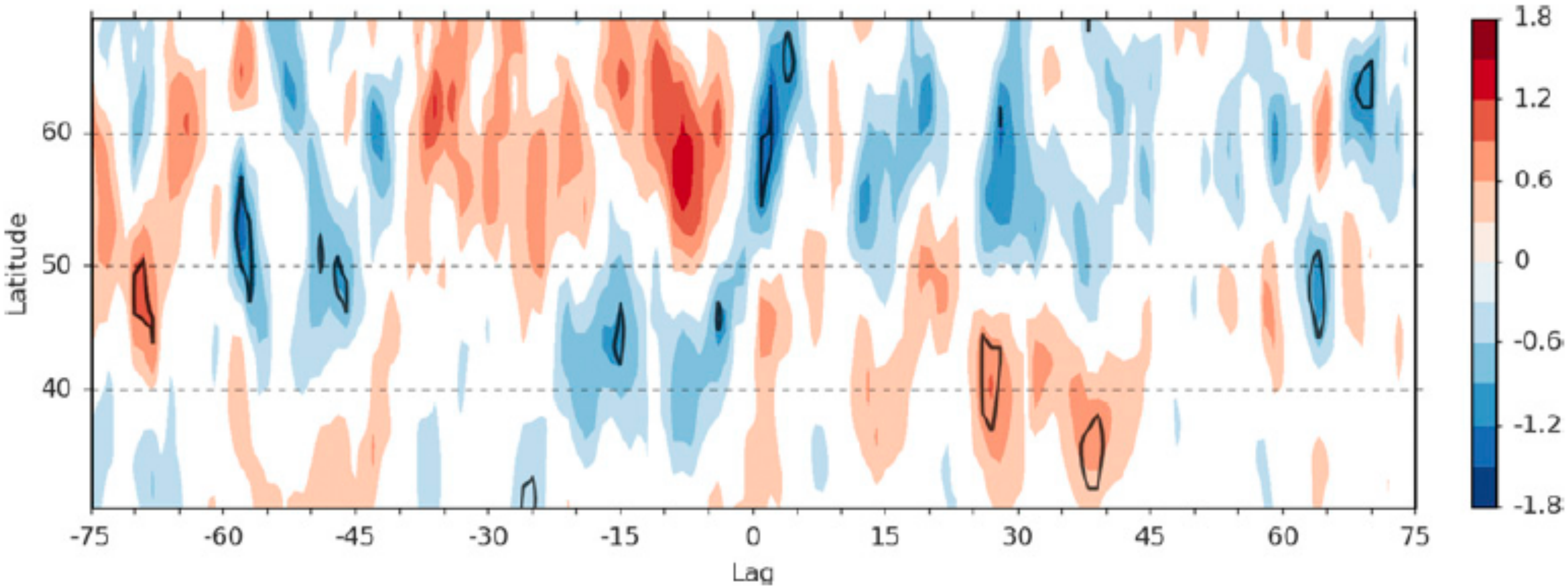
Tropospheric average zonal mean zonal wind



Byrne, Shepherd, Woollings & Plumb (2017 J. Clim.)

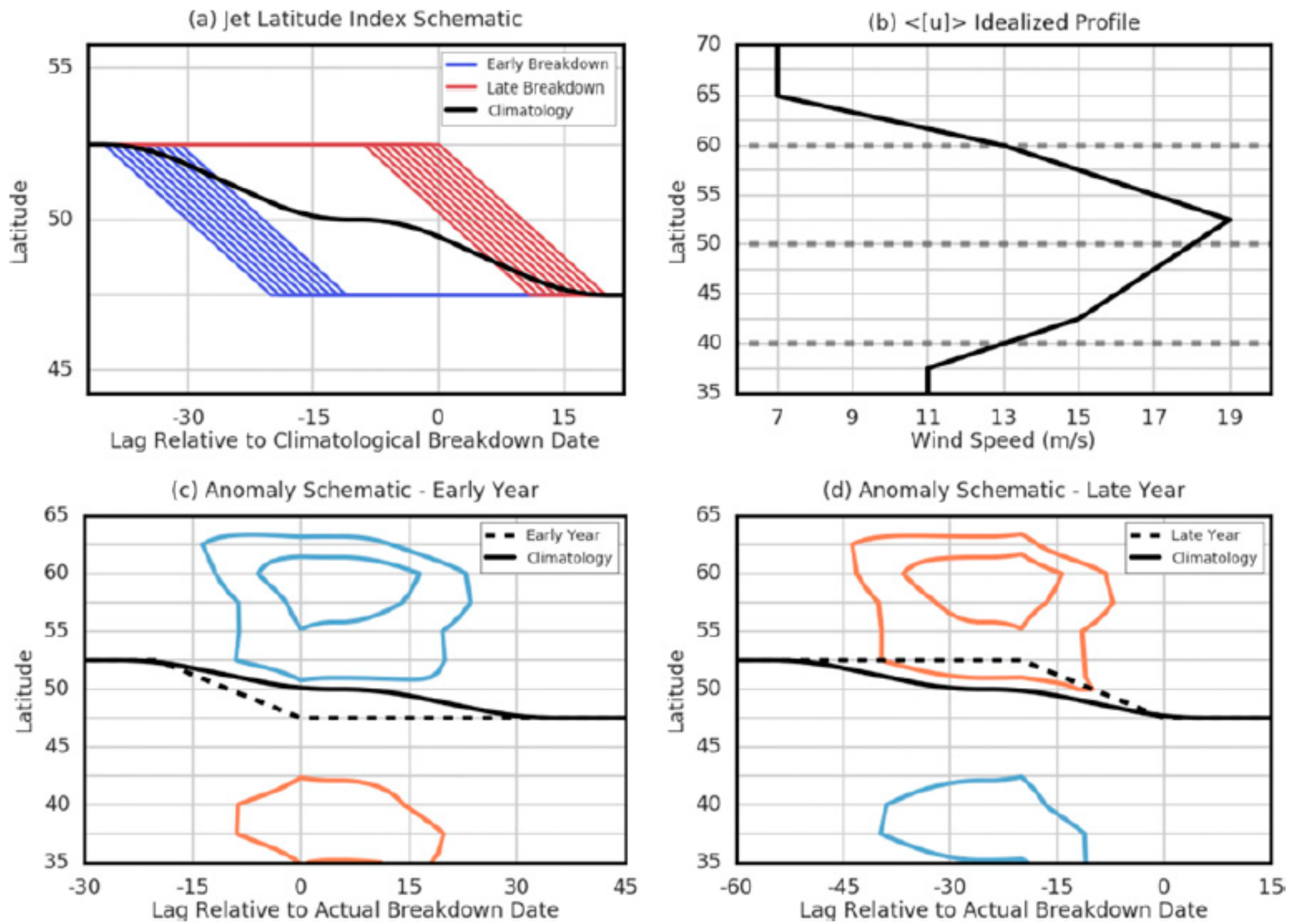
- When all anomalies are composited together (as in Black & McDaniel 2007 JAS), the very different features get diluted and lose statistical significance (note different colour scale)
  - This is *prima facie* evidence for non-stationarity

Tropospheric average zonal mean zonal wind



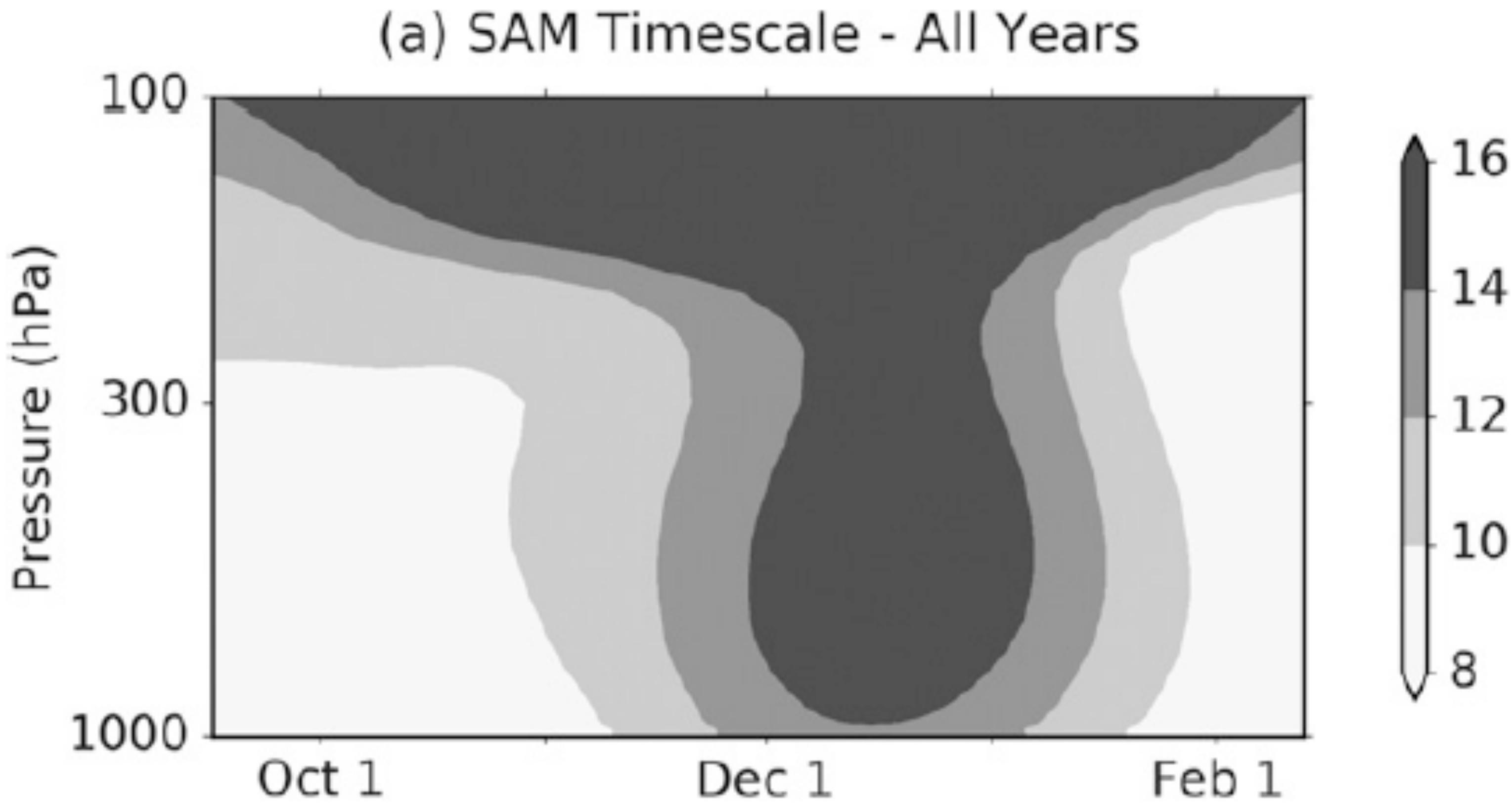
Byrne, Shepherd, Woollings & Plumb (2017 J. Clim.)

- The summertime equatorward shift of the tropospheric jet is a **regime transition**, mediated by the vortex breakdown
  - Explains anomaly patterns; the regime transition is a rapid phenomenon, but gets smoothed out in the climatology



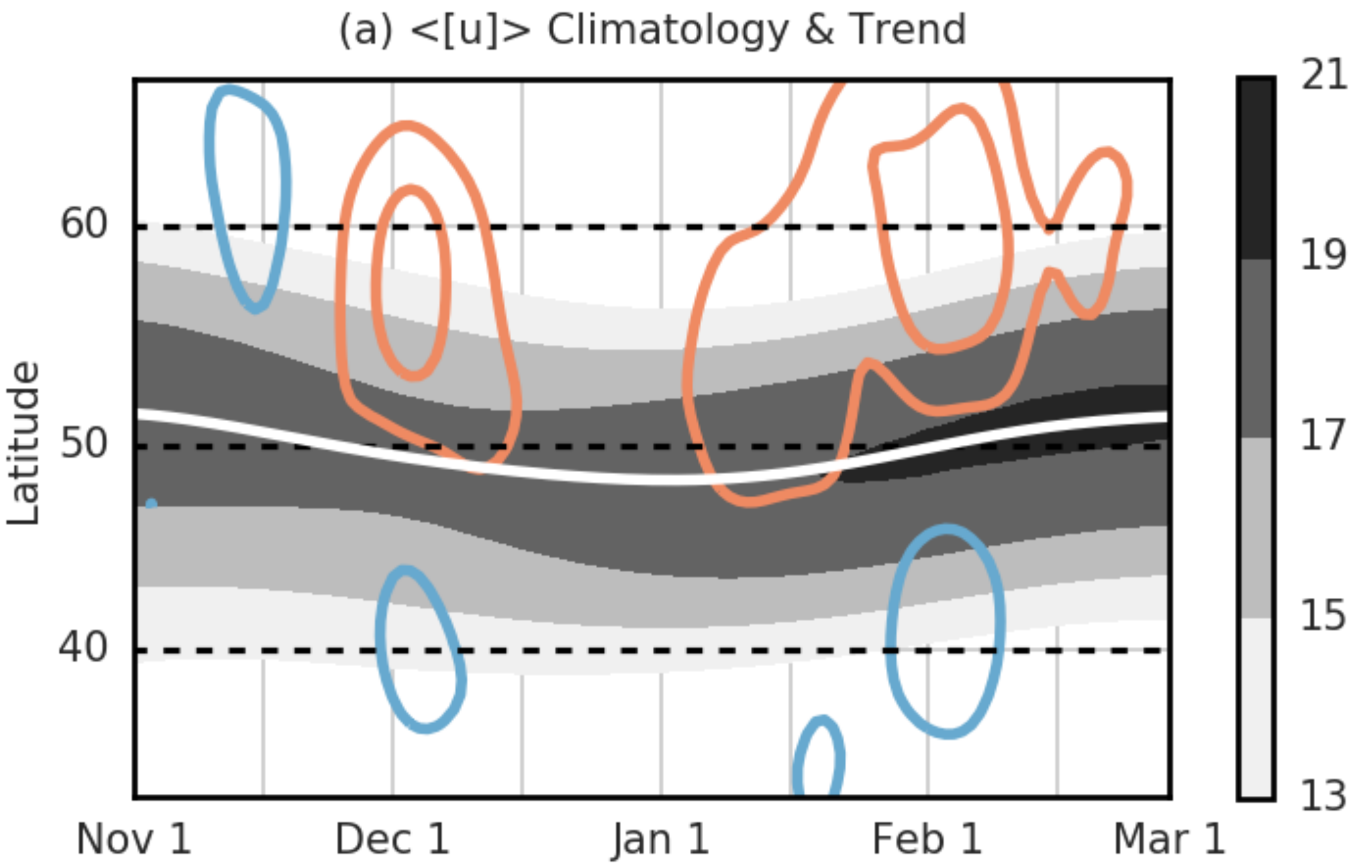
Byrne, Shepherd, Woollings & Plumb (2017 J. Clim.)

- This phenomenon heuristically accounts for the **very long SAM persistence timescales** (deduced from anomaly autocorrelations) around the time of the vortex breakdown
  - No need to invoke tropospheric eddy feedback mechanisms



Byrne, Shepherd, Woollings & Plumb (2017 J. Clim.)

- Also offers an alternative (much simpler) interpretation of the observed poleward shift of the summertime SH eddy-driven jet
  - It is rather a **delay of the seasonal equatorward transition**, induced by delayed vortex breakdown



Shading shows climatology of tropospheric [u] from 1979-2016, contours the long-term change, C.I. 0.6 m/s/decade

Byrne, Shepherd, Woollings & Plumb (2017 J. Clim.)

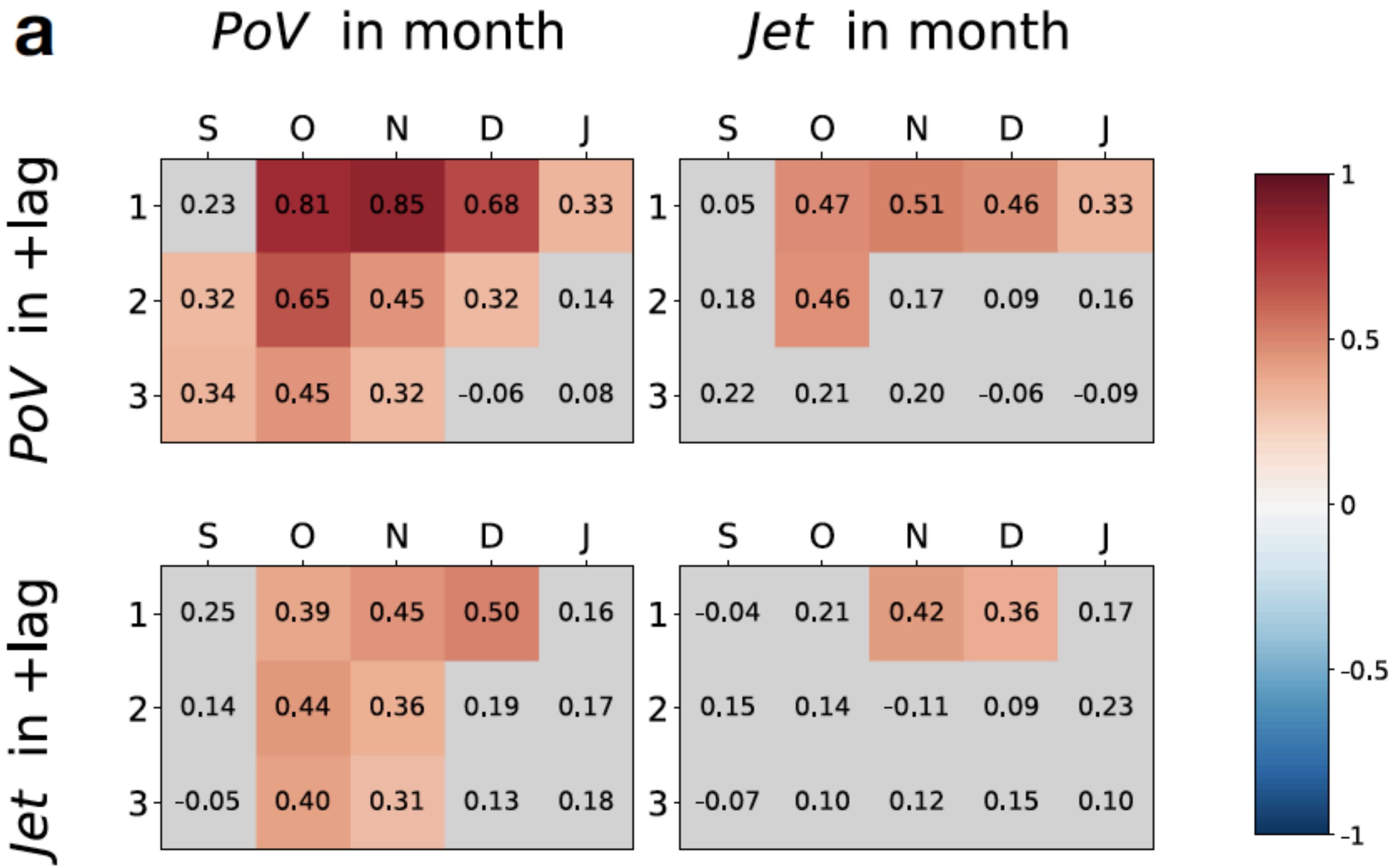
- **An issue with correlations: confounding influences**
  (Runge et al. 2014 J. Clim.)

$$X_t = aX_{t-1} + \varepsilon_t^X, \qquad Y_t = bY_{t-1} + cX_{t-1} + \varepsilon_t^Y,$$

$$\rho(X_{t-\tau}, Y_t) = \begin{cases} \dfrac{c\sigma_X^2 a^{1+|\tau|}}{(1-a^2)(1-ab)} / \sqrt{\Gamma_X \Gamma_Y} & \text{if } \tau \leq 0 \\ \dfrac{c\sigma_X^2 [a^{|\tau|}(1-ab) - b^{|\tau|}(1-a^2)]}{(1-a^2)(a-b)(1-ab)} / \sqrt{\Gamma_X \Gamma_Y} & \text{if } \tau > 0 \end{cases}$$

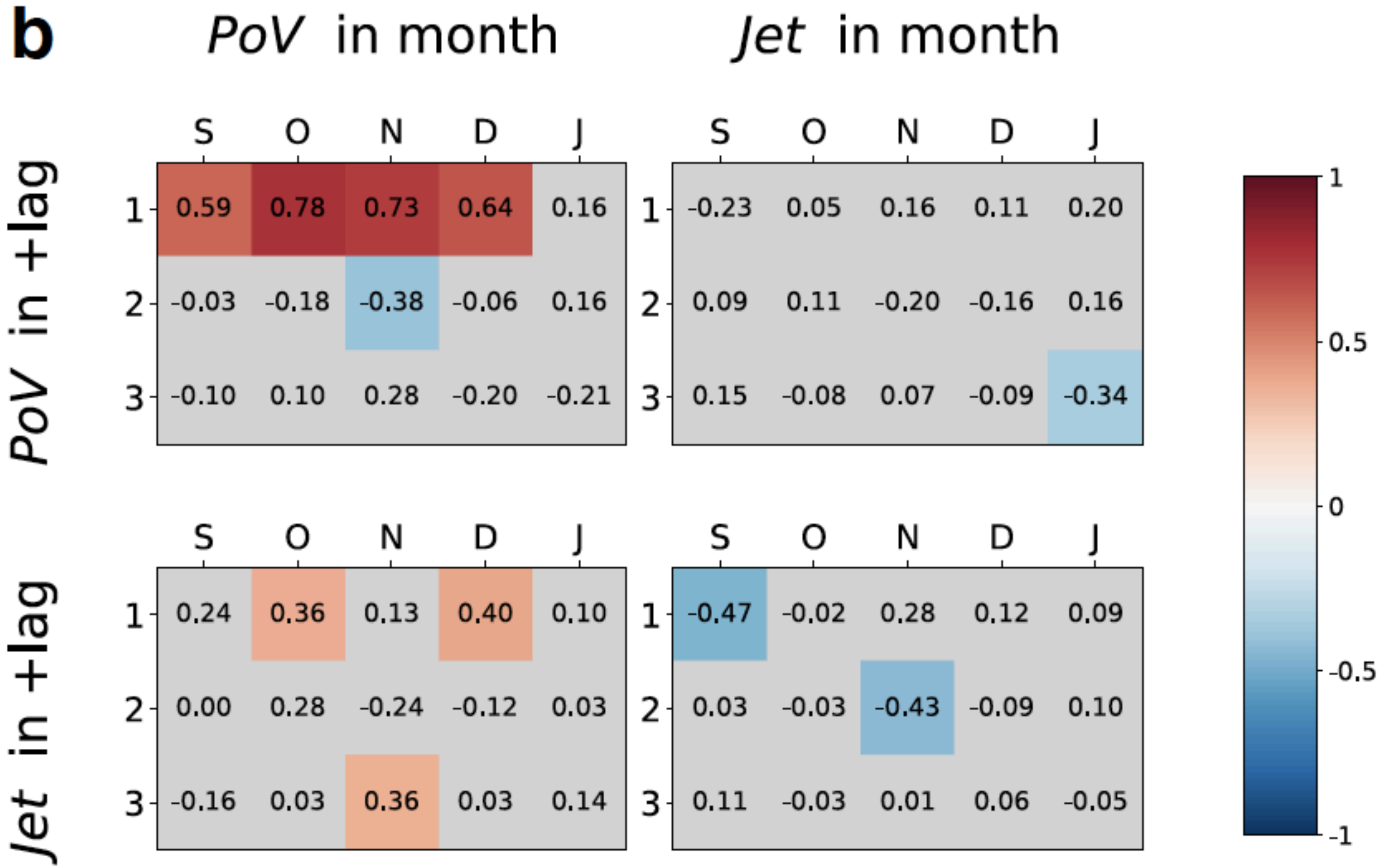
$$\rho_{X\to Y}^{\mathrm{MIT}}(\tau) = \begin{cases} \dfrac{c\sigma_X}{\sqrt{c^2\sigma_X^2 + \sigma_Y^2}} & \text{if } \tau = 1 \\ 0 & \text{otherwise} \end{cases}$$

- Lagged correlations between monthly circulation anomalies (as in Byrne & Shepherd 2018 J. Clim.) show lots of structure



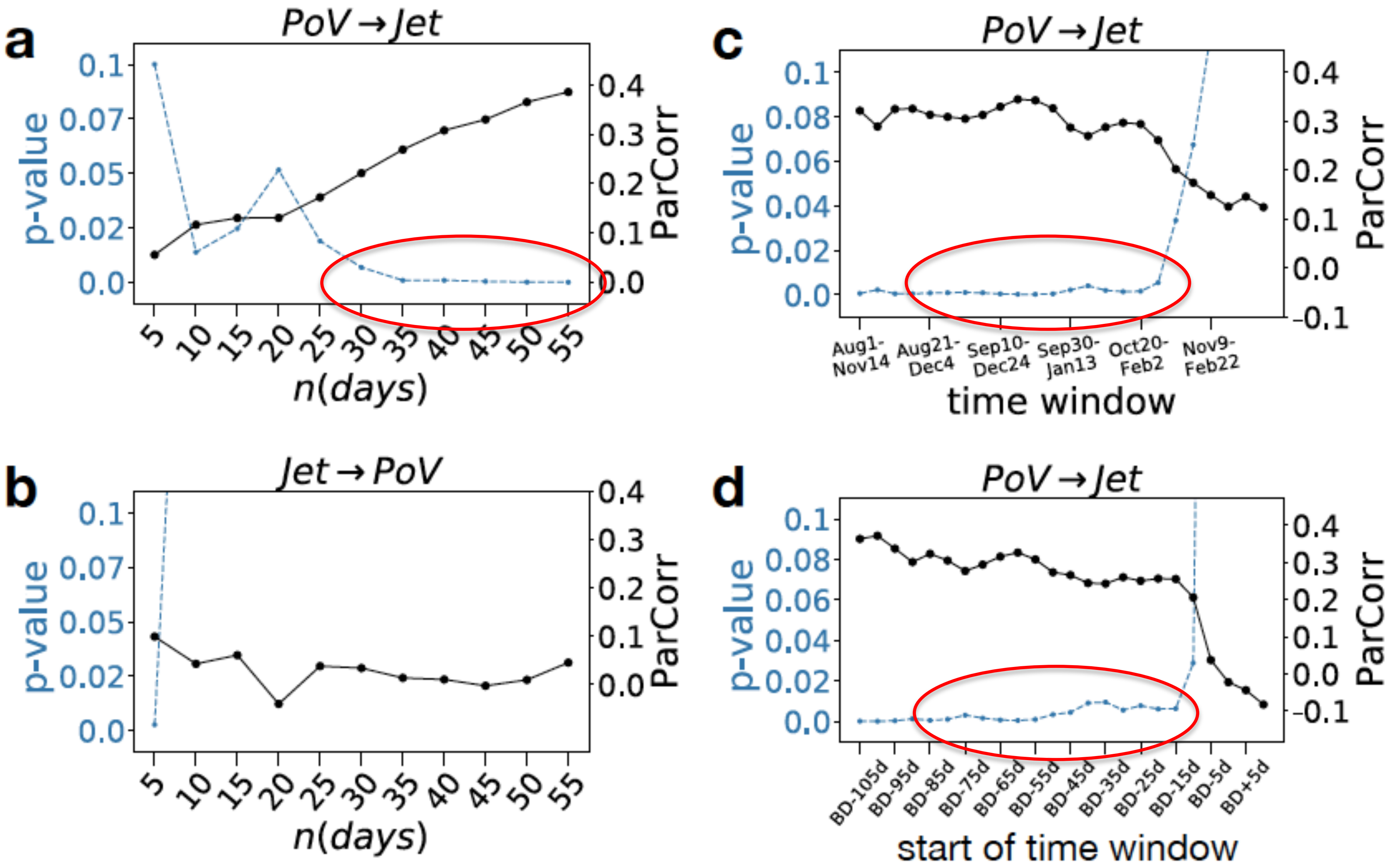
Saggioro & Shepherd (GRL, in press)

- Controlling for autocorrelation of the polar vortex eliminates most of that structure



Saggioro & Shepherd (GRL, in press)

- Allows isolation of timescale and extent of strat-trop coupling



Saggioro & Shepherd (GRL, in press)

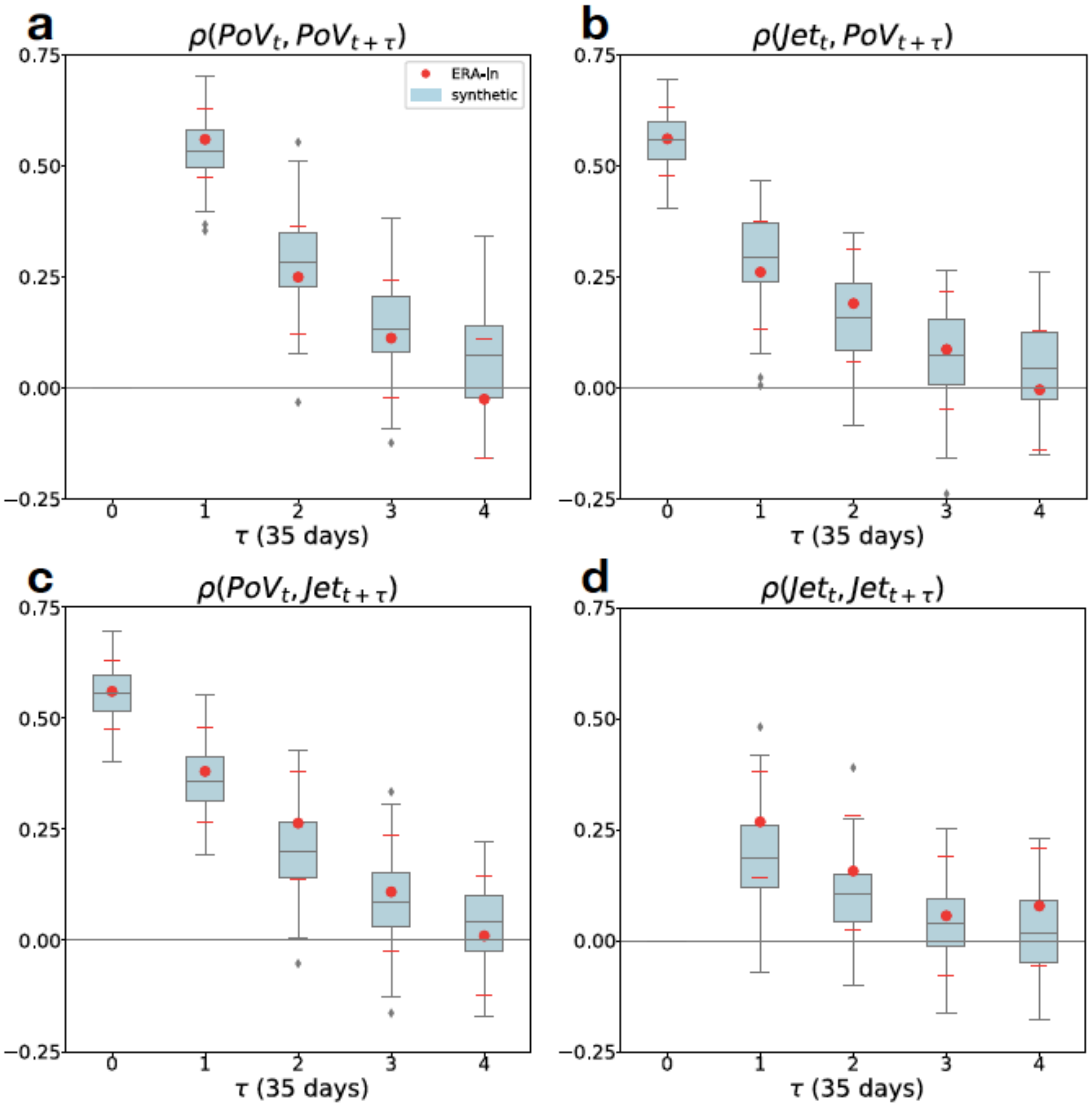
- Leads to a **parsimonious statistical model** for monthly (35-day) strat-trop coupling
  - Vortex variability explains nearly 40% of the monthly jet variability in spring and summer
  - No auto-dependence detected in jet variability on this timescale; so, no need to invoke tropospheric eddy feedbacks
  - Analytical solution explains high autocorrelation of tropospheric jet variability during this time of year purely from strat-trop coupling

$$\begin{cases} \overline{PoV}_t & = a\,\overline{PoV}_{t-1} + \varepsilon_{P,t} \\ \overline{Jet}_t & = c\,\overline{PoV}_{t-1} + \varepsilon_{J,t} \end{cases}$$

$$a = 0.55 \pm 0.11 \text{ and } c = 0.37 \pm 0.15.$$

Saggioro & Shepherd (GRL, in press)

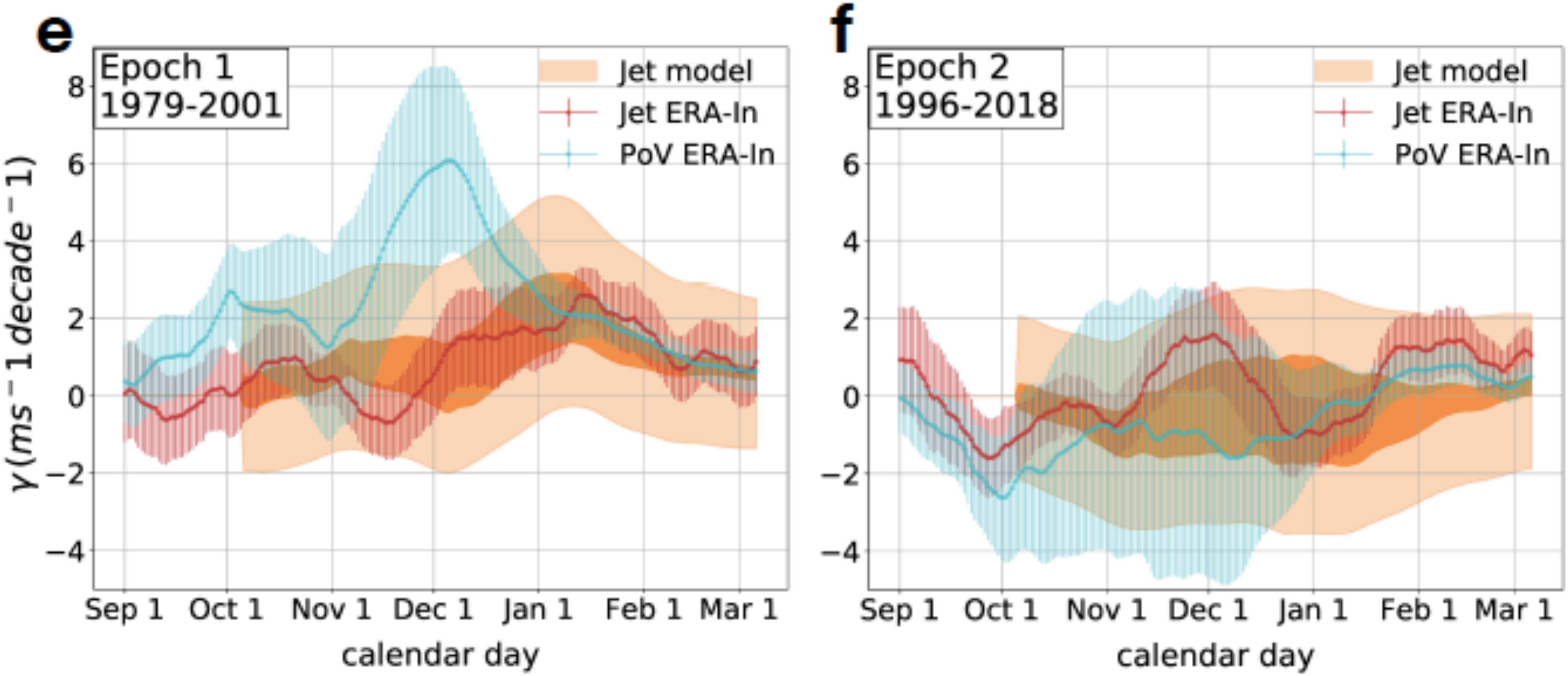
- **Observed correlation structure reproduced** by the simple model



Explains why FDT arguments using autocorrelation timescale do not work for the SAM response to forcing during DJF (Simpson & Polvani 2016 GRL)

Saggioro & Shepherd (GRL, in press)

- The same statistical model can **quantitatively connect the observed stratospheric and tropospheric trends**
- Shows how short-term variability can be used to understand statistical links in long-term changes
  - Now examining biases in seasonal prediction models



Saggioro & Shepherd (GRL, in press)

Summary

- Stratospheric polar vortex variability has a profound effect on midlatitude circulation and weather
  - Exact mechanism still not understood, but is robust
  - Basic phenomenon is similar in the two hemispheres, though there are important differences in how it is manifest
  - Basic phenomenon seems to be the same across timescales
- In what sense is the stratospheric influence causal?
  - In the real system, true causality can only be exogenous
  - However, the stratosphere does provide memory; influence can be quantified through conditional dependence
  - And model error can be causal!
- Causal network approaches offer a promising way to use short-term variability to relate long-term changes (or biases?)

  See Marlene’s talk