IMPORTANCE OF THE STRATOSPHERE FOR EXTENDED-RANGE PREDICTION

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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.

Regressions on the annular modes

- **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

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

**Autocorrelations of monthly mean 30 hPa Z polar vortex anomalies**

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**See Nick’s talk**

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

**Byrne & Shepherd (2018 J. Clim.)**

**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

**NH: response for 30 days after SSW**

500hPa Geopotential Height (DJF 1979 - 2016)

**SH: correlation with vortex breakdown date**

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

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**Zonal-Mean MSLP (50S - 65S)**

(b) Climatology - W and S Years

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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.

**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.
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

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Zappa & Shepherd (2017 J. Clim.)
• The same, for wintertime **central European windiness**
  (95\textsuperscript{th} 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.

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.

Mindlin, Shepherd, et al. (in preparation)

See Julia’s poster
• An issue with correlations: non-stationarity
  – Composited tropospheric circulation anomalies are completely different for early and late breakdown events

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.)

\[ X_t = aX_{t-1} + \varepsilon_t^X, \quad Y_t = bY_{t-1} + cX_{t-1} + \varepsilon_t^Y, \]

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

\[
\rho_{\text{MIT}}^{X\rightarrow Y}(\tau) = \begin{cases} 
\frac{c\sigma_X}{\sqrt{c^2\sigma_X^2 + \sigma_Y^2}} & \text{if } \tau = 1 \\
0 & \text{otherwise}
\end{cases}
\]
- Lagged correlations between monthly circulation anomalies (as in Byrne & Shepherd 2018 J. Clim.) show lots of structure.

![Heatmap](image)

**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

\[
\begin{align*}
\overline{PoV}_t &= a \overline{PoV}_{t-1} + \varepsilon_{P,t} \\
\overline{Jet}_t &= c \overline{PoV}_{t-1} + \varepsilon_{J,t}
\end{align*}
\]

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

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