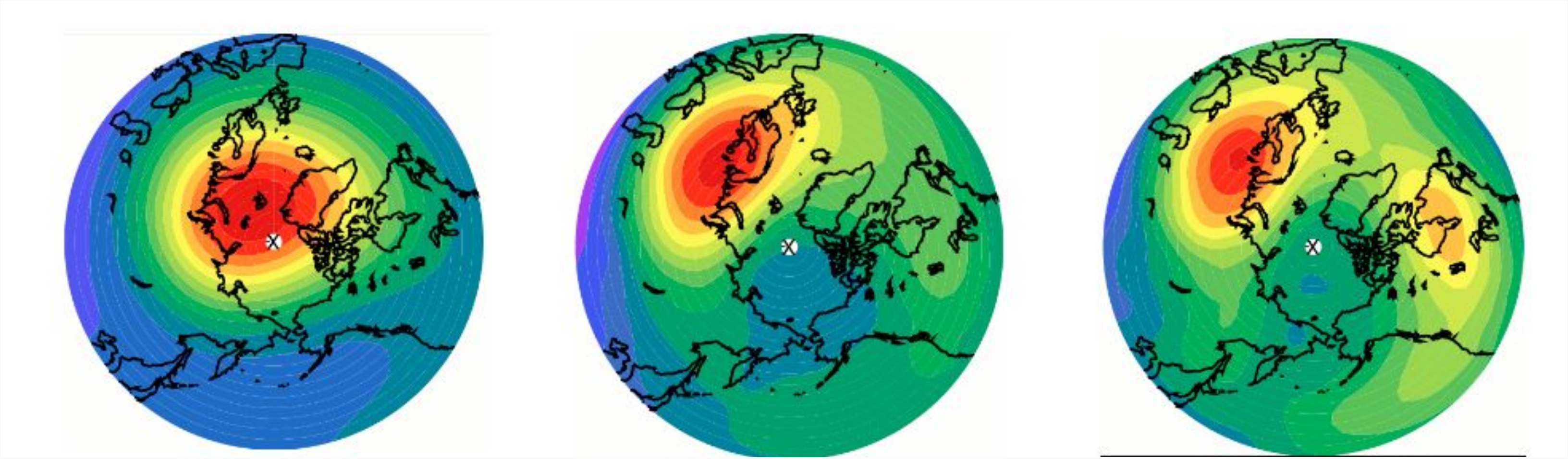
Dynamical-Chemical Feedbacks in General Circulation Models and Their Influence on Sudden Stratospheric Warming Events



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Display Outline

- SSW events and chemical dynamical coupling - a short overview.
- Scientific questions and experimental setup
- Results
- Discussion and open questions (to be discussed in the chat!)

Scientific questions: Sudden Stratospheric Warming events

- SSWs are important/interesting dynamical phenomena!

- Vertically propagating planetary waves “break” when their amplitudes become large and deposit easterly momentum on the westerly polar vortex during NH winter.

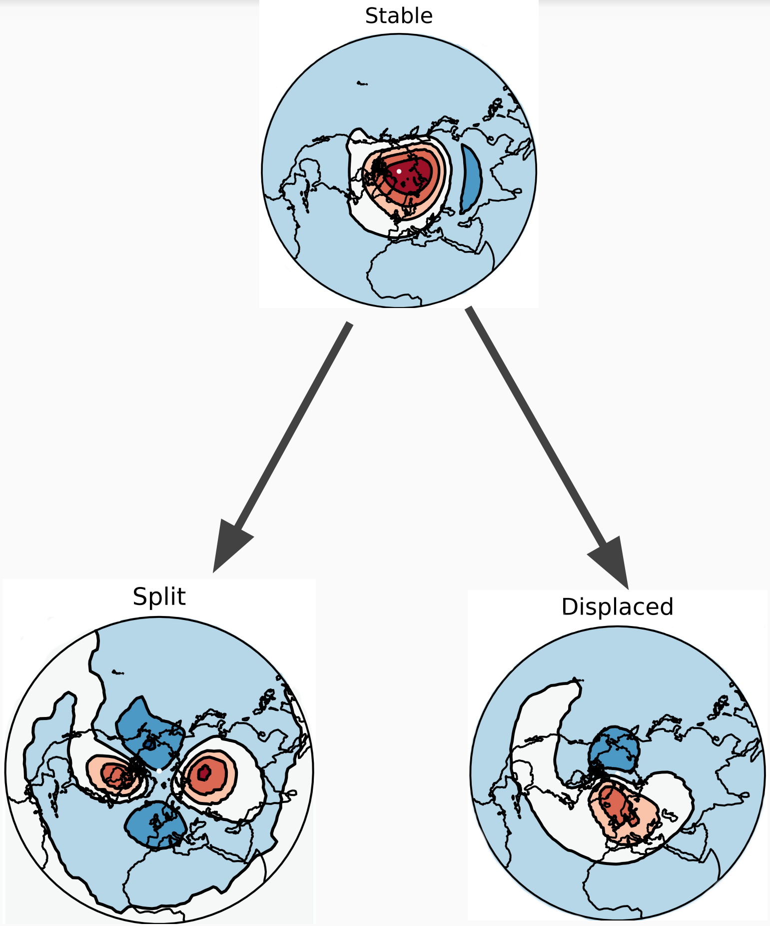
- Waves can only propagate if the background flow satisfies

$$0 < U < U_c$$

$$U_c = \frac{\beta k}{k^2 + l^2}$$

(Charney and Drazin 1961)

- If momentum deposition from breaking waves is sufficient, the vortex becomes unstable. ZMZW reverses and polar cap T increases dramatically.



Why are SSWs Important?

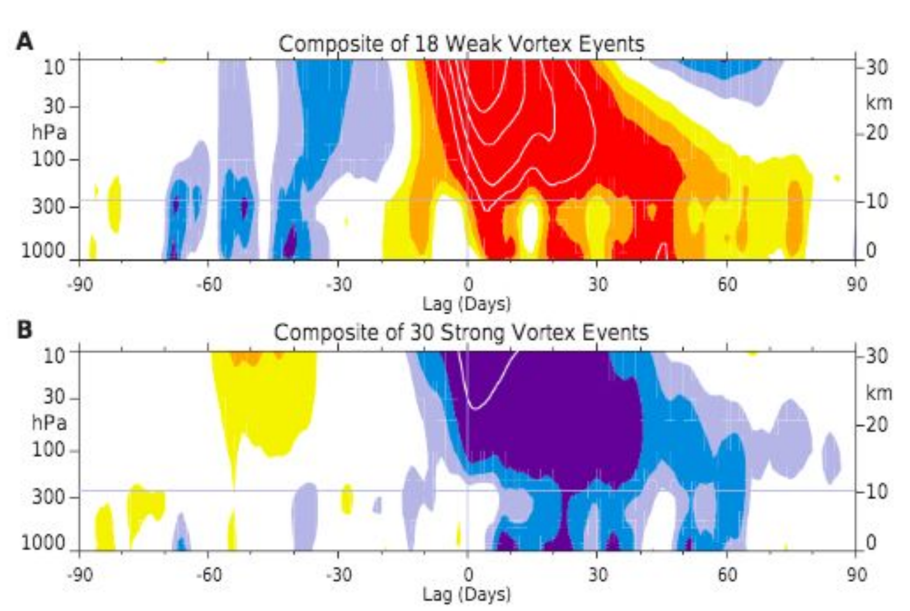


Figure from Baldwin et al. 2001

Oxford, March 2018

- Anomalies associated with SSWs can propagate vertically downwards to the surface (the dripping paint picture).
- Associated with a negative NAO phase and cold snaps over Northern Europe
- Representing/understanding these events is key to improve S2S predictability.

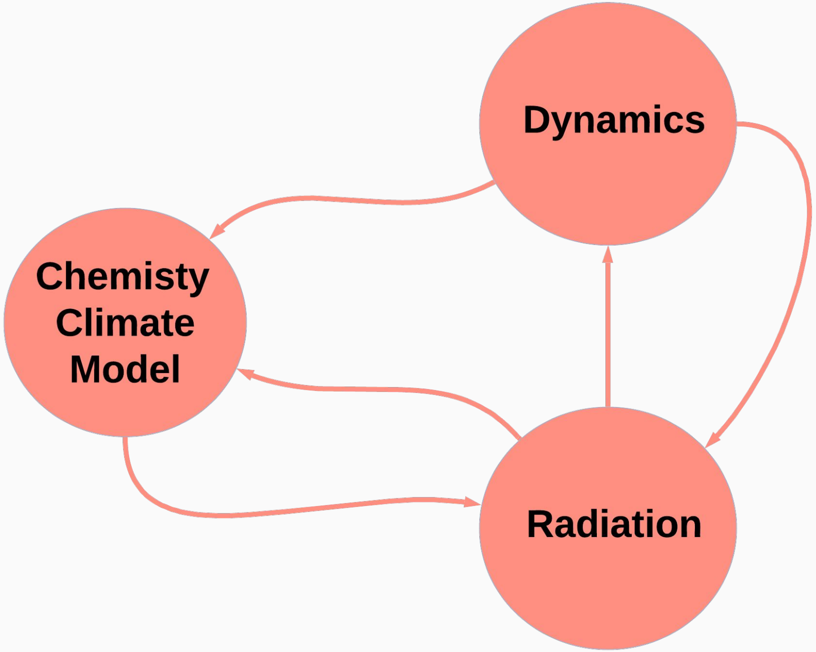
Chemical-Dynamical Coupling

- Trace gases influence atmospheric (diabatic) heating rates according to their molecular structure
- Shortwave heating via absorption: $\rho Q_{\nu}^{SW}(z) = F_{\nu\infty}^{\downarrow} k_{\nu} \rho_a(z) e^{-\chi_{\nu}(z)}$
- Common (and important) example is ozone.
- Highly coupled with stratospheric dynamics. Ozone coupling with dynamics appears to:
  - Account for approximately 25% of the QBO amplitude (Huang et al. 2008)
  - Strengthen the Holton-Tan relationship in some simulations (Silverman et al. 2018)
- Variability of the Polar Vortex drives interannual variability in the size of the NH ozone hole. E.G. this year, the largest on record cause by, among other factors, an anomalously strong vortex.

Representing Atmospheric Chemistry in GCMs: 2 Methods

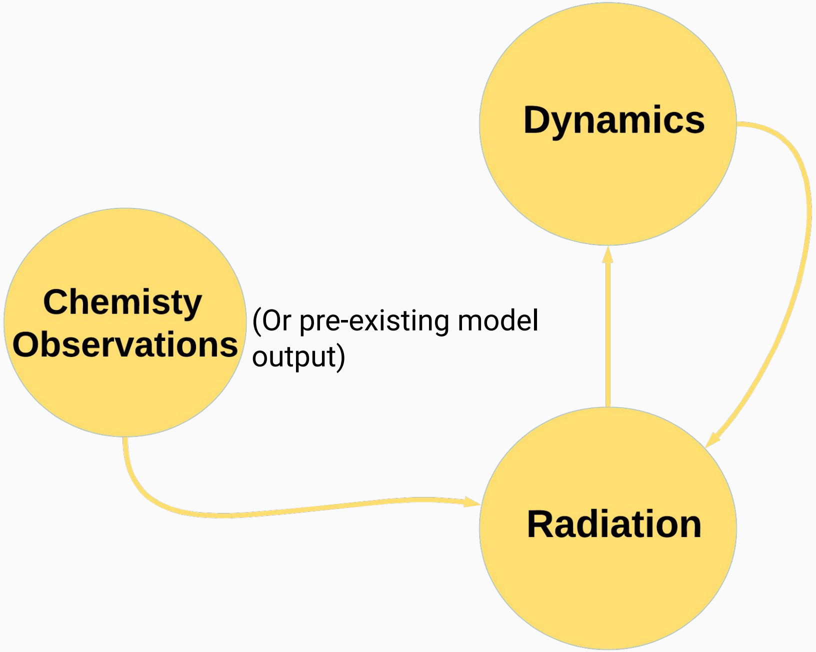
Interactive Chemistry

Captures chemical-dynamical feedbacks



Prescribed Chemistry

No feedbacks



(Or pre-existing model output)

Experimental Setup: Analysing SSW representation in Prescribed and Coupled Chemistry MetOffice Models

- Compare the representation of SSW events and the polar vortex in MetOffice contributions to CMIP6.

- HadGEMGC3.1 (GC3) coupled ocean-atmosphere model prescribes seasonally repeating chemical distributions.

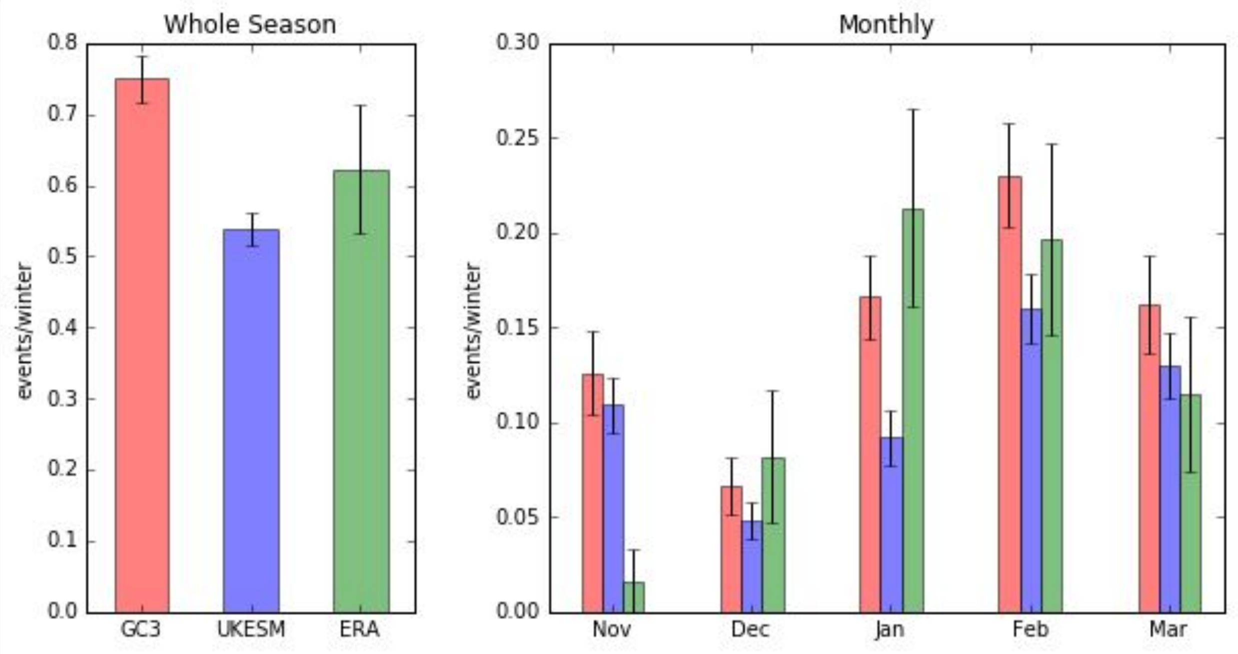
- UKESM1 uses the same dynamical core and ocean component as GC3. Couples radiation and dynamical components to the UK chemistry and aerosols model (UKCA).

- Consider pre-industrial control runs (500 years of GC3, 1000 years of UKESM).

- **Does the inclusion of couple chemistry influence model SSWs?**
    - What physical mechanisms are responsible for any differences?
    - What can differences tell us about chemical-dynamical coupling and stratospheric variability?

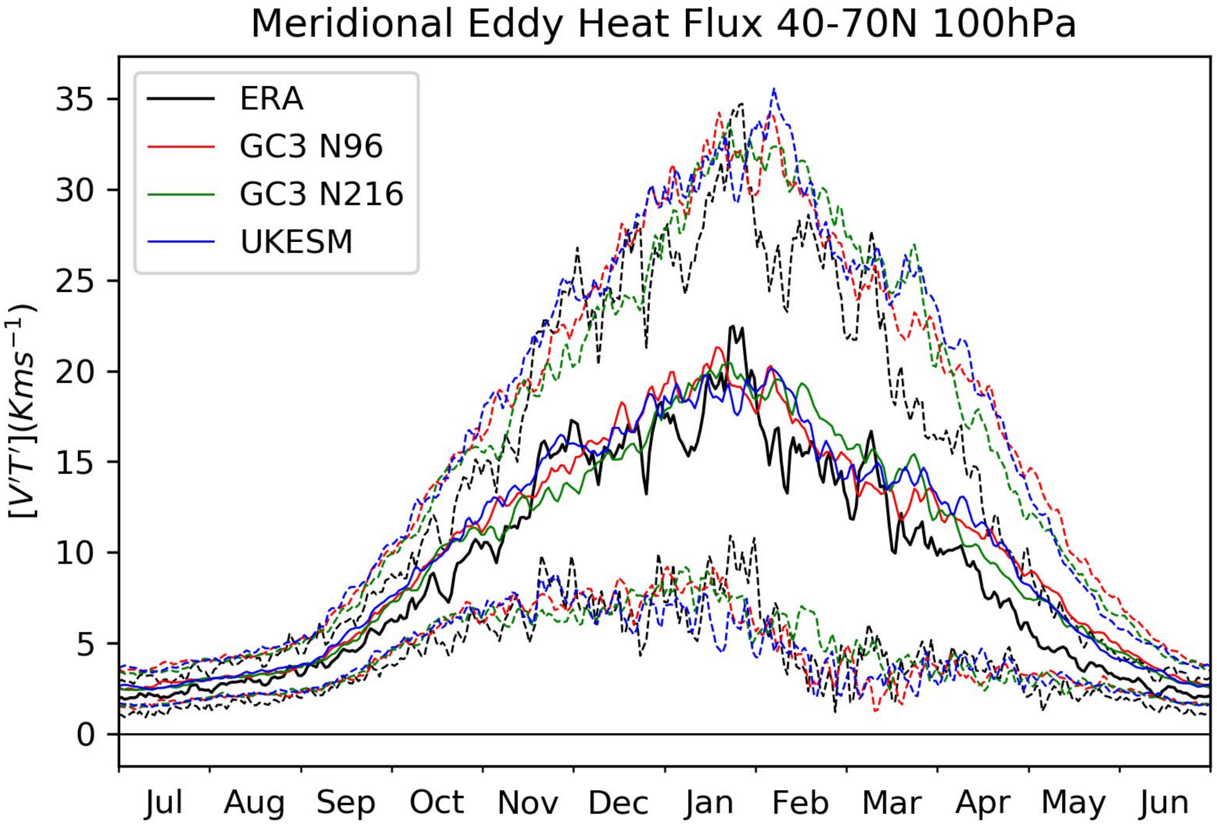
SSW rates in GC3 and UKESM1

- GC3 (prescribed chemistry) Exhibits a significantly higher SSW rate than UKESM (coupled chemistry)
- Both models overestimate SSW rate in early winter compared to ERA (November).
- Differences between UKESM and GC3 are concentrated in mid winter (Jan and Feb).
- This is during Polar night when diabatic effects of polar cap ozone influence are minimal.



Left: *Mean SSWs per winter in GC3, UKESM and ERA datasets.* ***Right***: *Mean SSW rates per month for all datasets.*

Wave Driving of the Vortex



- Eddy heat transport polewards indicates planetary wave activity.
- Both models show overestimated wave activity in Sep-Oct which may account for the early winter overestimation of SSWs
- No significant differences between UKESM and GC3 over the whole season.

So Far....

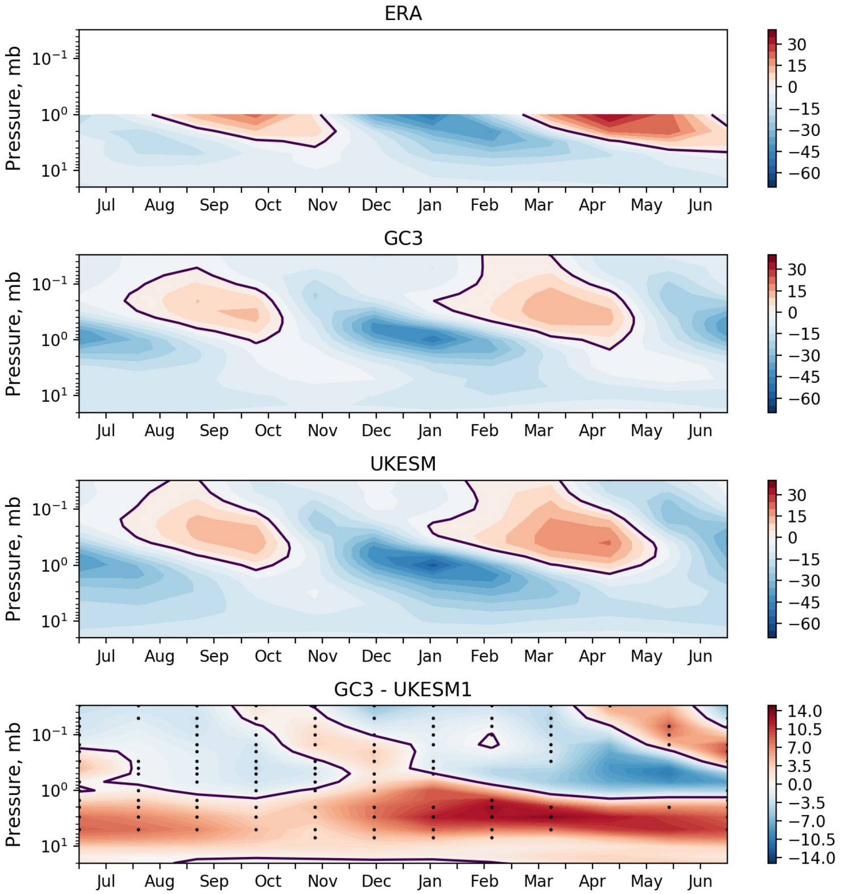
- SSWs appear suppressed in Interactive chemistry models compared to prescribed.

- Differences peak in mid-winter (polar night).

- Mid-latitude tropospheric wave driving is similar across the models.

- Physical mechanisms responsible for the differences in SSWs may originate elsewhere. We therefore also assess the representation of the equatorial stratosphere, an important region when considering vortex variability, in each model. namely;
    - The Semi Annual Oscillation (SAO) in mesospheric zonal mean zonal wind.
    - The Quasi Biennial Oscillation (QBO) and its links to ozone variability.

The SAO in GC3 and UKESM1



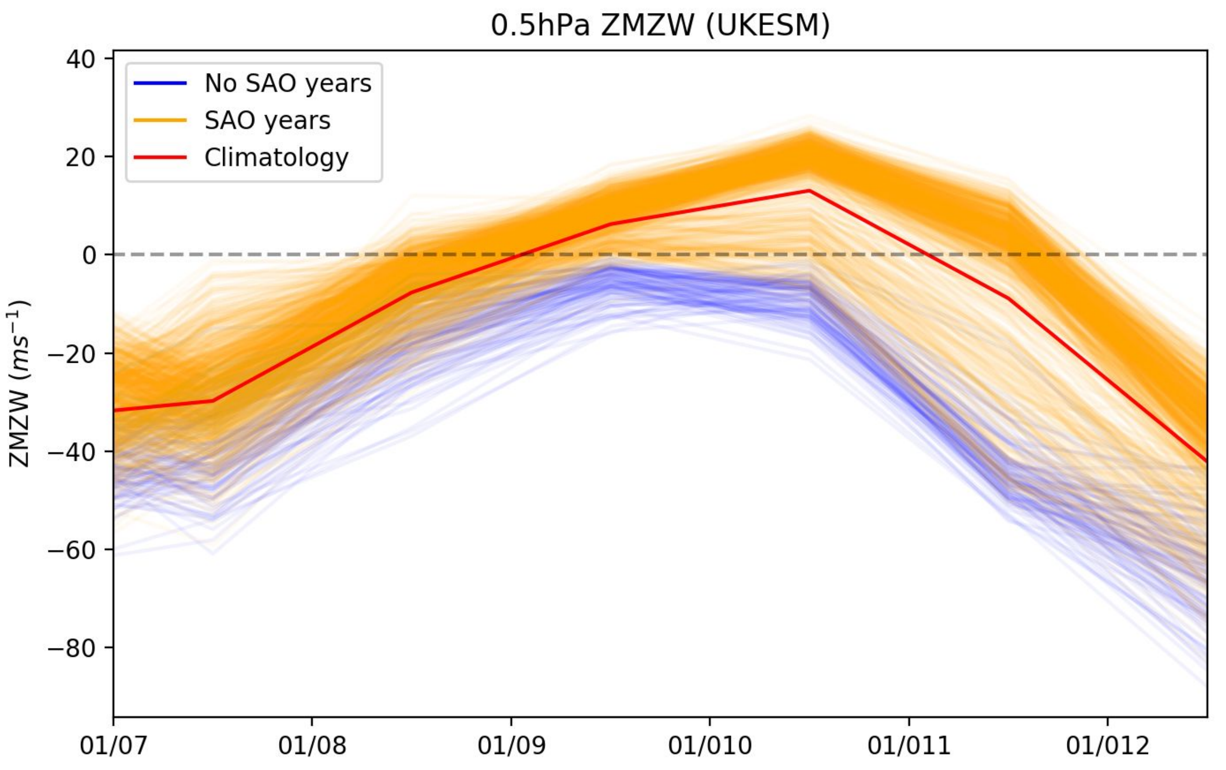
- Both models exhibit biases compared to ERA-interim
- Underestimated westerly phase amplitude
- Late W-E phase transitions
- Biases marginally reduced in UKESM

monthly climatological, equatorial ZMZW for ERA-interim, GC3 and UKESM. Coloured contours signifies ZMZW value and black contours denote the 0ms−1 contour level.The bottom panel shows differences between GC3 and UKESM. Stippling denotes 95%confidence interval defined by a 2 tail student's t-test.

Interannual Variability in the SAO in GC3 and UKESM1

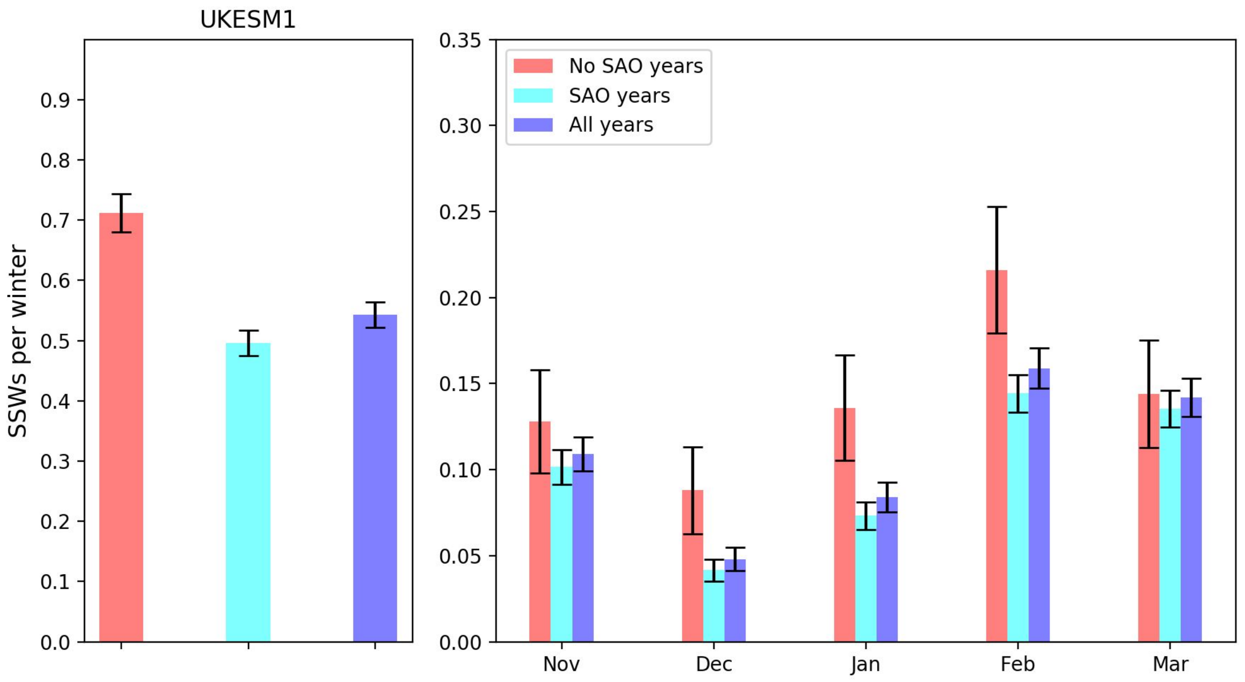
- 124 years out of 1000 display no westerly SAO phase (at 0.5 hPa) in early winter for UKESM. We term these “No SAO years”

- 109 years out of 500 show no SAO in GC3 (not shown). twice the rate of no SAO years as in UKESM



UKESM Jul-Dec equatorial ZMZW on the 0.5hPa separated into SAO years which exhibit a westerly phase (orange) and no SAO years which exhibit only easterlies (blue). The mean state climatological winds are shown in red.

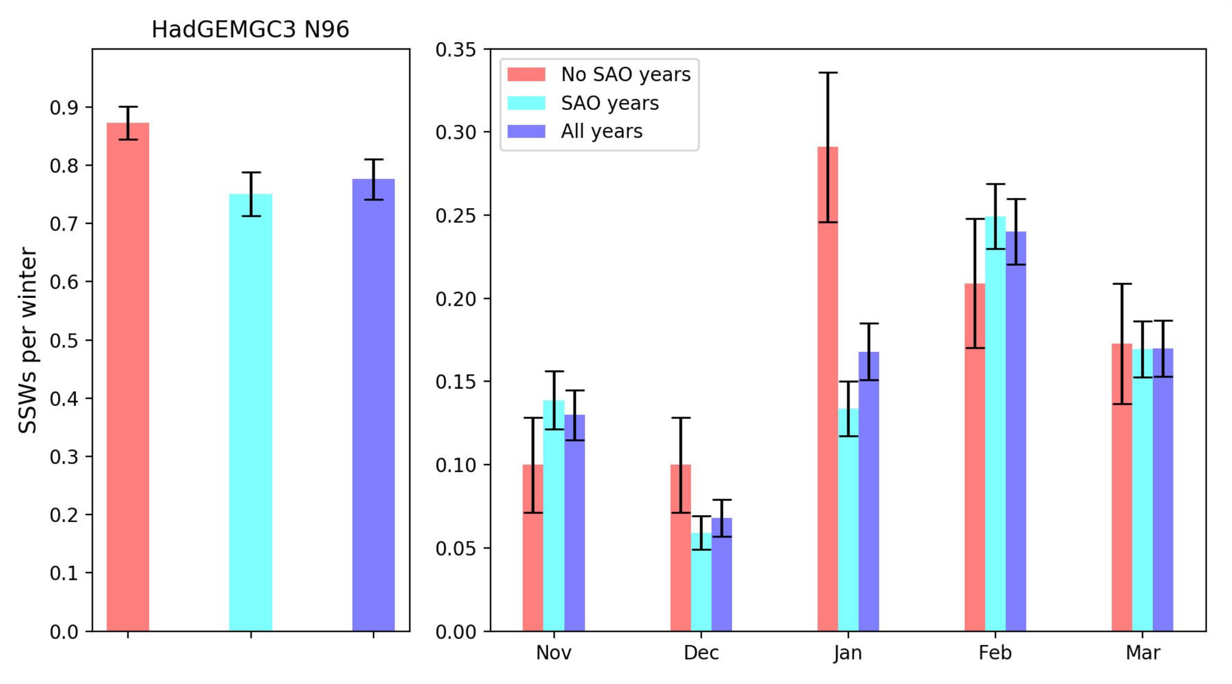
SAO Influences on the Vortex



SSW rates for no SAO years, SAO years (years in which the westerly phase of the SAO forms at 0.5 hPa) and all years of the UKESM simulation.

- How do these “No SAO years” influence the vortex?
- We separate winters into those No SAO years and SAO years - measure SSW rates in each group.
- In UKESM, years with no westerly SAO phase exhibit significantly higher SSW rates.

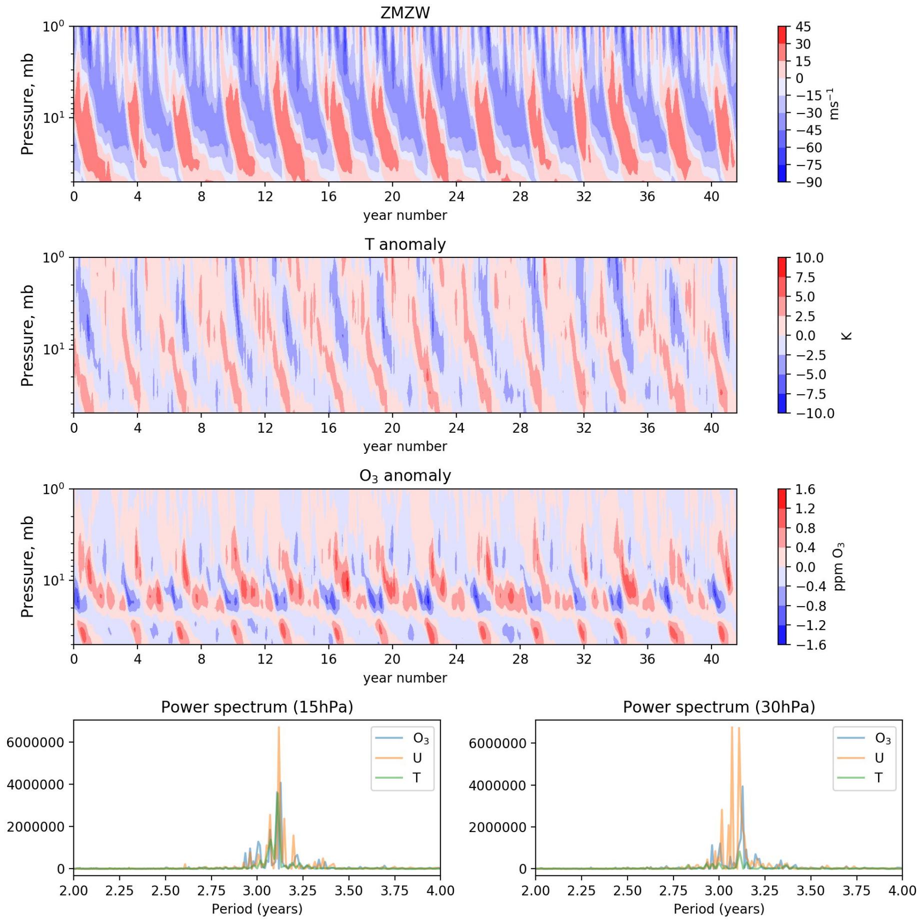
SAO influences on the Vortex



SSW rates for no SAO years, SAO years (years in which the westerly phase of the SAO forms at 0.5 hPa) and all years of the GC3 simulation.

- Large response to no SAO years concentrated in January for GC3
- This could account for differences between models in mid winter?
- Higher rate of no SAO years in HadGEM than in UKESM (almost double)
- Supports previous work by Gray et al. highlighting the coupling between SAO phase timing and vortex variability
- Further work is required to link these differences to atmospheric chemistry.

Equatorial Ozone Variability in UKESM



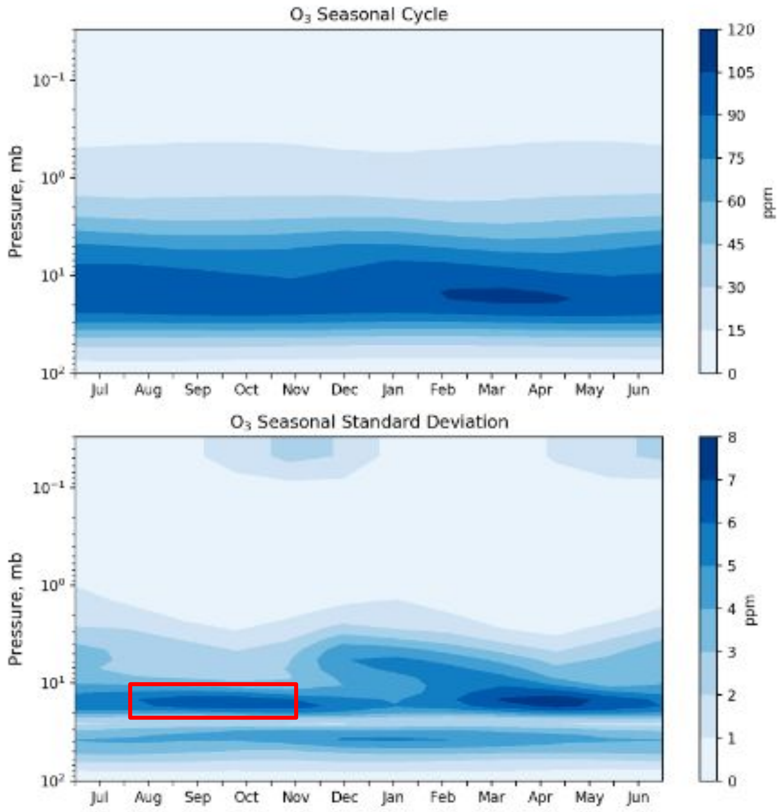
- QBO like variations in ozone mole fraction can be observed in equatorial ozone in UKESM.

- This variability is absent in GC3 (Not shown) as this model prescribes seasonally repeating ozone fields. I.E. only a seasonal cycle is present (see next slide).

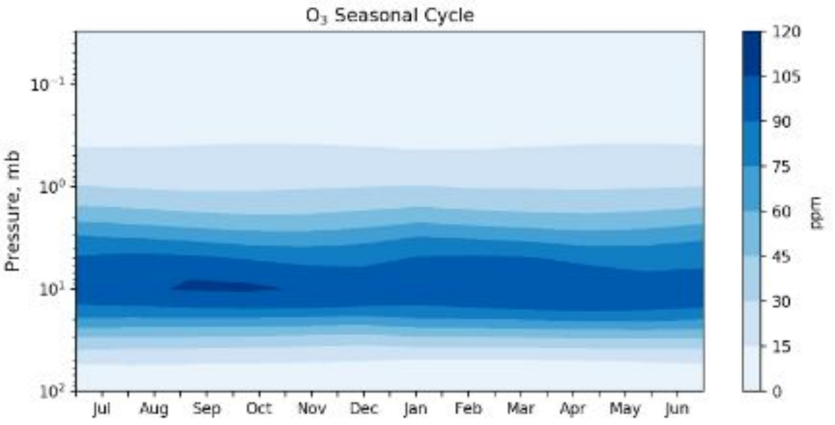
- This QBO in ozone is a well understood effect (refs) and has been shown to account for approximately 20% of the QBO amplitude.

- We aim to analyse whether the inclusion of this ozone variability in UKESM (and not GC3) drives SSW differences.

Equatorial Ozone Variability in UKESM



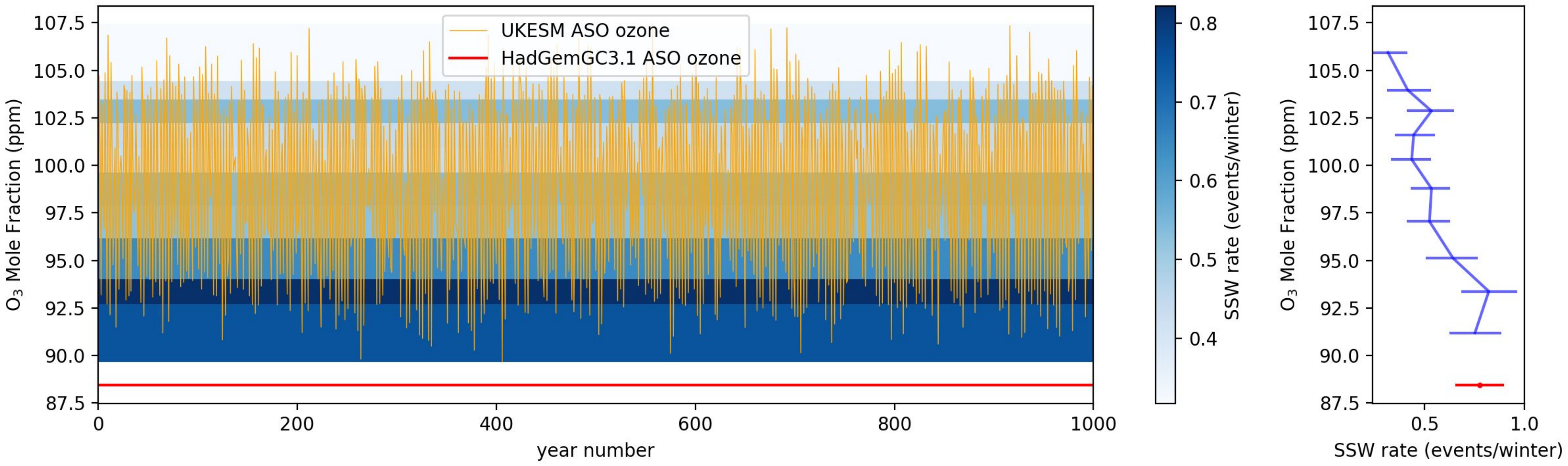
(a) UKESM



(b) GC3

- Both models exhibit a broadly similar equatorial ozone seasonal cycles.
- UKESM exhibits high interannual variability in early winter (Aug-Oct) between 10hPa and 20hPa (red rectangle). This variability is absent in GC3.
- Does this interannual variability influence SSW probability in the following NH winter?

Ozone Links With the Vortex.

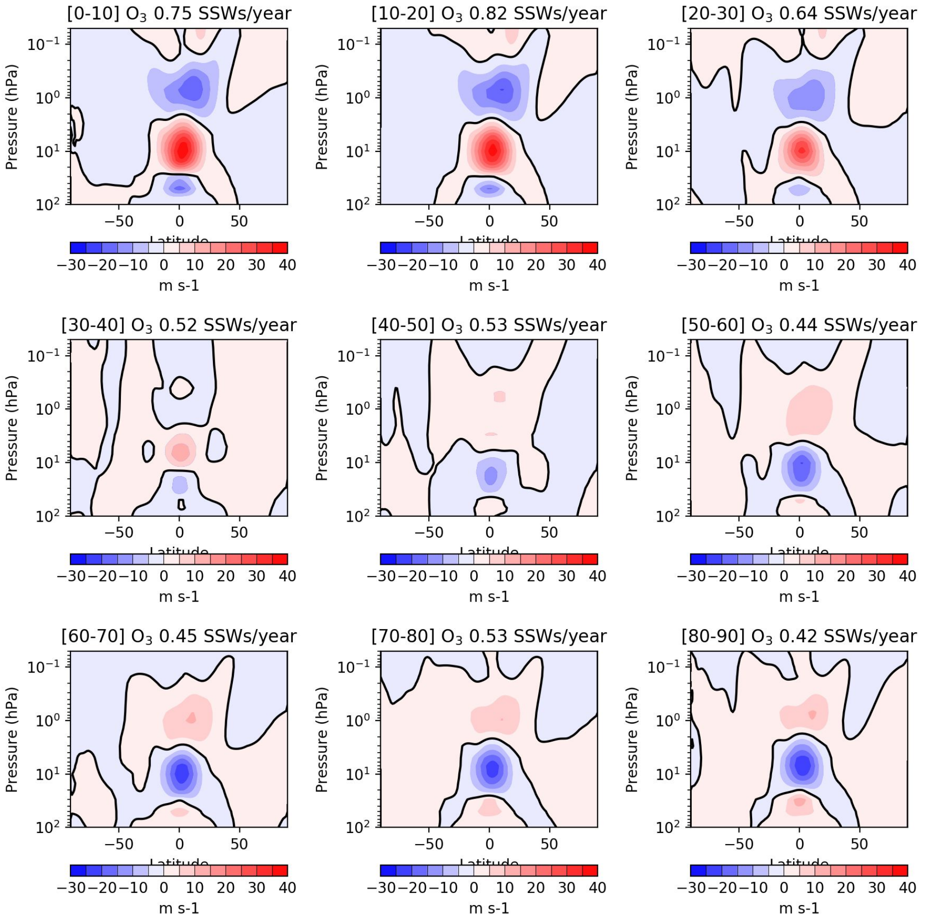


Left: *Time series of annual mean Aug-Oct ozone mole fraction averaged between 10 and 20hPa levels (orange), shading represents SSW rates in sets of 100 winters sorted by percentile bands of the timeseries.*
Right: *SSW rates vs timeseries 10 percentile band middles.*

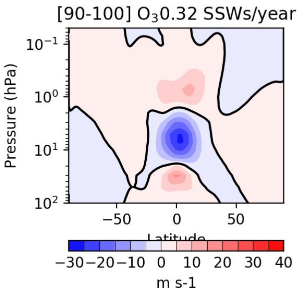
- Interannual variability in Aug-Oct mean ozone between 10 and 20hPa levels associated with SSW probability in following winter.

- Years with ozone closest to prescribed value exhibit an SSW rate closest to that of GC3.

Ozone Links With the Vortex - Winter ZMZW composites for ozone bands

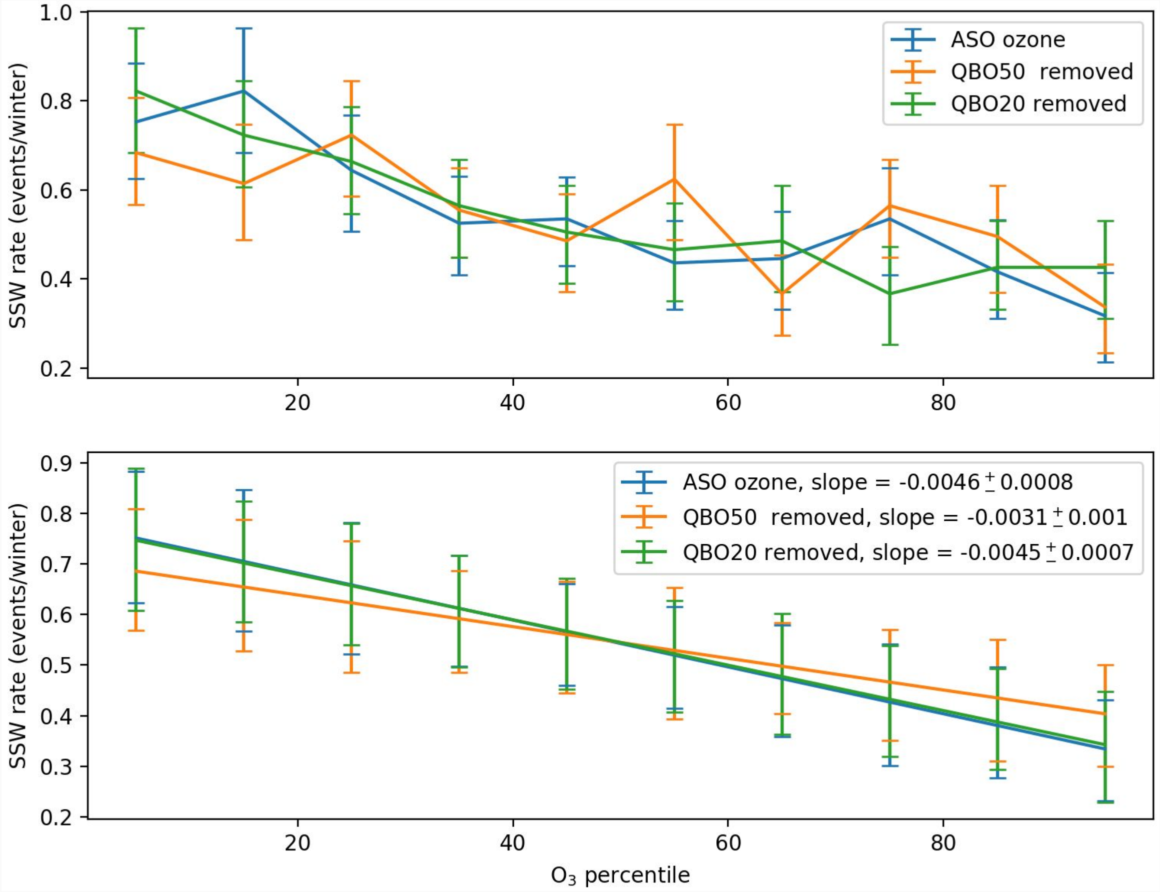


- ZMZW composites of winters following Aug-Oct ozone values from each 10 percentile band shows a clear QBO pattern.
- Ozone bands with elevated SSW rate correspond to Easterly phase QBO at 50 hPa below a descending easterly phase. The opposite is true to the bands with lowest SSW rates.
- This suggests the association with SSW rates is driven by a Holton-Tan like mechanism.



Nov-Mar lat-pressure ZMZW anomaly composites for years in ozone 10 percentile bands defined in the previous slide. Ranges in square brackets represent the ozone percentile band range, also noted is the SSW rate in years from that band.

Ozone Links With the Vortex.



- We also assess whether the ozone-SSW association (previous slide) is due to an ozone response to residual upwelling of ozone rich air caused by existing QBO phase or whether chemical feedbacks are also significant.

- We remove the QBO at 50hPa and 20hPa from the Aug-Oct and observe that this weakens the association between ozone and SSWs. However, it does not reduce to 0 suggesting the cause is not purely due to upwelling. Diabatic effects could still be important

Ozone percentile from Aug-Oct ozone metric vs SSW rate in following winters with the Aug-Oct mean QBO at different levels regressed out from the ozone metric. Bottom: linear fits of the series from above.

Conclusions and Future Work

- SSW representations are different in MetOffice models with prescribed and interactive chemistry schemes.
  - **Coupled chemistry suppresses SSW rates.**

- Representations of key modes of variability in the equatorial stratosphere, **the SAO and QBO, could account for these differences**.

- Coupled chemistry models appear to reduce biases in SAO representation (both in mean state and interannual variability) which may influence SSWs.
  - explicit analysis of ozone in this region is needed to link these differences to chemical feedbacks.
  - Future work using a set of sensitivity experiments in which a model is run for a case study winter containing an SSW with and without coupled chemistry will give a more direct comparison.

- Equatorial zone variability in early winter may influence SSW probability via the QBO.
  - The response appears to be partially due to ozone response to QBO.
  - Diabatic effects may also play a role though.

References

Baldwin, M. P. & Dunkerton, T. J. (2001), ‘Stratospheric harbingers of anomalous weather regimes’, *Science* **294**(5542), 581–584.

Charney, J. G. & Drazin, P. G. I. (1961), ‘Propagation of Planetary-Scale Disturbances from theLower into the Upper Atmosphere’, *Journal of Geophysical Research* **66** (1), 83–109.

Huang, F. T., Mayr, H. G., Reber, C. A., Russell, J. M., Mlynczak, M. G. & Mengel, J. G. (2008), ‘Ozone quasi-biennial oscillations (QBO), semiannual oscillations (SAO), and correlations with temperature in the mesosphere, lower thermosphere, and stratosphere, based on measurementsfrom SABER on TIMED and MLS on UARS’, *Journal of Geophysical Research: Space Physics* **113** (1), 300–316.

Silverman, V., Harnik, N., Matthes, K., Lubis, S. W., and Wahl, S.: Radiative effects of ozone waves on the Northern Hemisphere polar vortex and its modulation by the QBO, *Atmos. Chem. Phys.*, **18**, 6637–6659, 2018.