Northern Hemisphere Surface Response to Extreme Arctic Ozone Events in a Chemistry-Climate Model

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Introduction

In recent decades, substantial springtime ozone losses in the Antarctic have had significant impacts, both on the duration of the stratospheric polar vortex and on regional surface climate. In the Arctic, an unusually large ozone depletion episode was observed in March 2011. It is therefore pertinent to investigate whether substantial ozone losses in the Arctic may impact on Northern hemisphere surface climate. This question is addressed using three modelling approaches:

(1) Time-slice experiments using HadGEM3-A with prescribed ozone losses based on 2011 observations and a 2011 "world-avoided by the Montreal Protocol" case for comparison [Chipperfield et al., 2015]

(2) A set of perpetual-year time-slice UM-UKCA experiment with interactive chemistry

(3) An ensemble of transient UM-UKCA experiments with interactive chemistry covering the period of 1980-2080.

1. Prescribed Ozone Losses

Three perpetual year-2000 simulations are carried out using HadGEM3-A, differing only in their specification of monthly zonal mean ozone, all integrated for 50 years following a 10-year 'spin-up' period:

1) A control integration using a baseline ozone climatology from a perpetual year-2000 UM-UKCA integration.

2) As in 1), but with the fractional ozone anomaly for winter 2010/2011 (relative to the 1979-2011 MERRA climatology) imposed from December until May (similar to method of Karpechko et al. (2014)).

3) As in 2), but with the fractional ozone anomaly for winter 2010/2011 taken from a model simulation for the "World Avoided by the Montreal Protocol" (i.e. with substantially higher chlorine loading) (ozone from Chipperfield et al. (2015)).

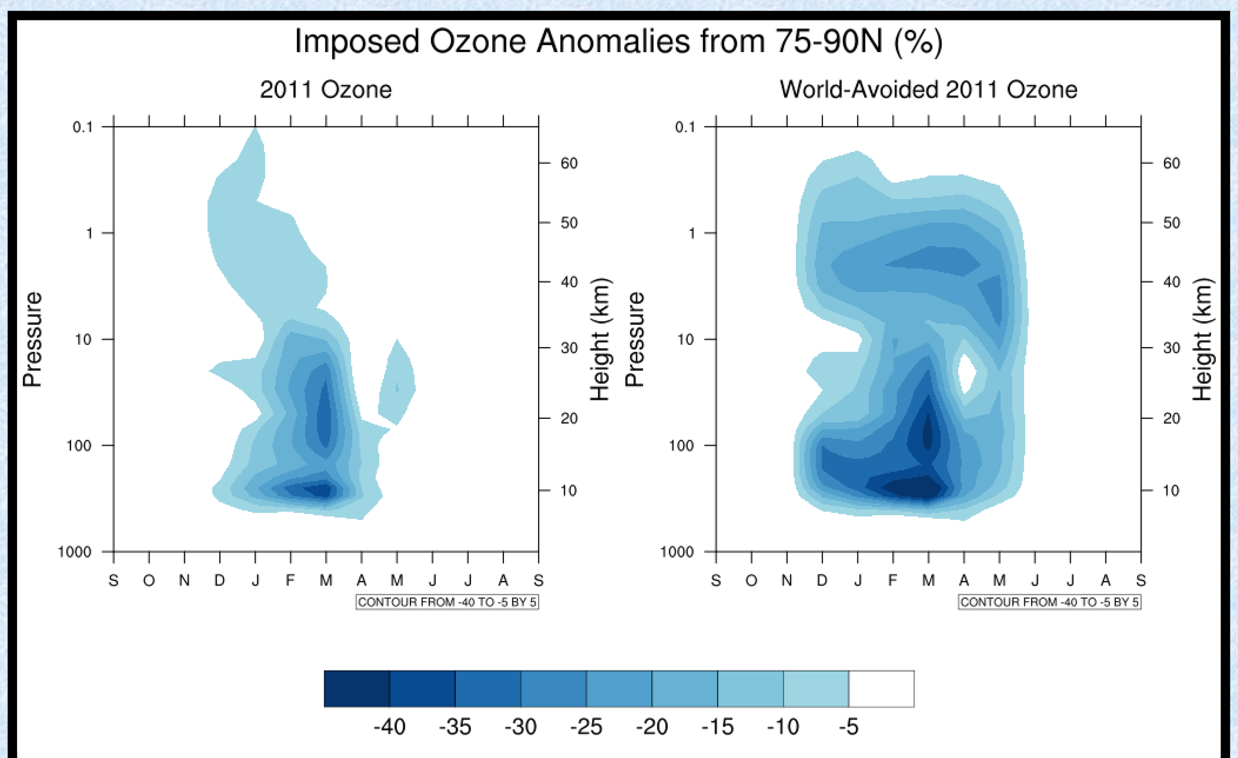


Figure 1: *The seasonal cycle of fractional ozone anomalies averaged from 75-90°N. (Left) ozone anomaly for winter 2010-11 from MERRA reanalysis. (Right) ozone anomaly for the 'World-Avoided' winter 2010-11 calculated with projected ODS levels assuming no Montreal Protocol by Chipperfield et al. (2015).*

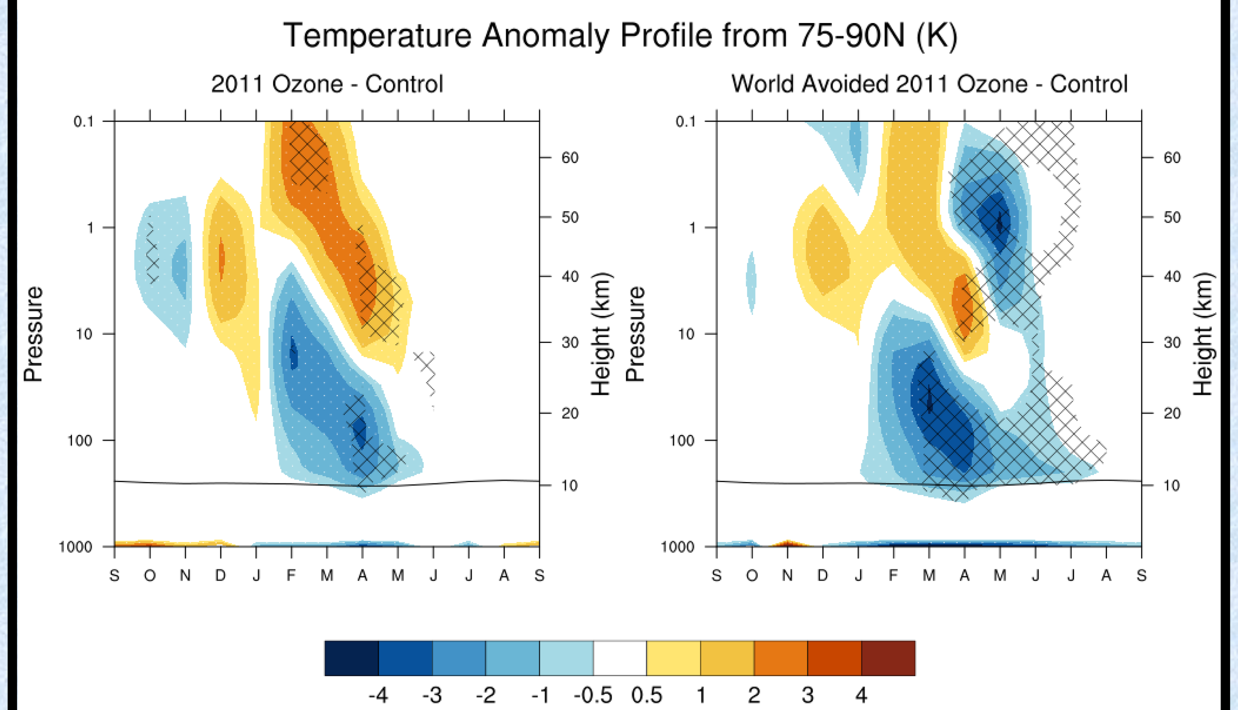


Figure 2: *The seasonal temperature responses averaged from 75-90°N to the imposed ozone anomalies in Figure 1. Hatching indicates statistical significance at the 95% confidence level, as measured by a two-tailed Student's t-test. The baseline tropopause is plotted as a solid black line.* ***This response is largely confined to the stratosphere, with insignificant response in the troposphere.***

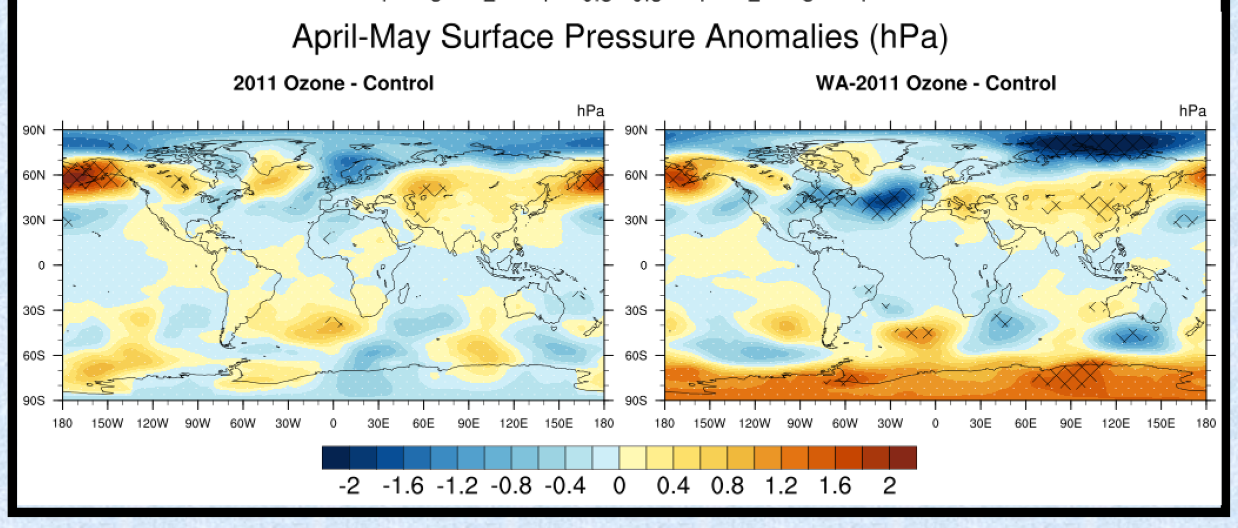


Figure 3: *The April-May MSLP response from the imposed ozone anomalies in Figure 1. Hatching as before.* ***Slight decrease in Arctic cap MSLP, increase in strength of north Pacific high, but largely insignificant over high latitudes.***

2. Interactive Ozone (Time-Slice)

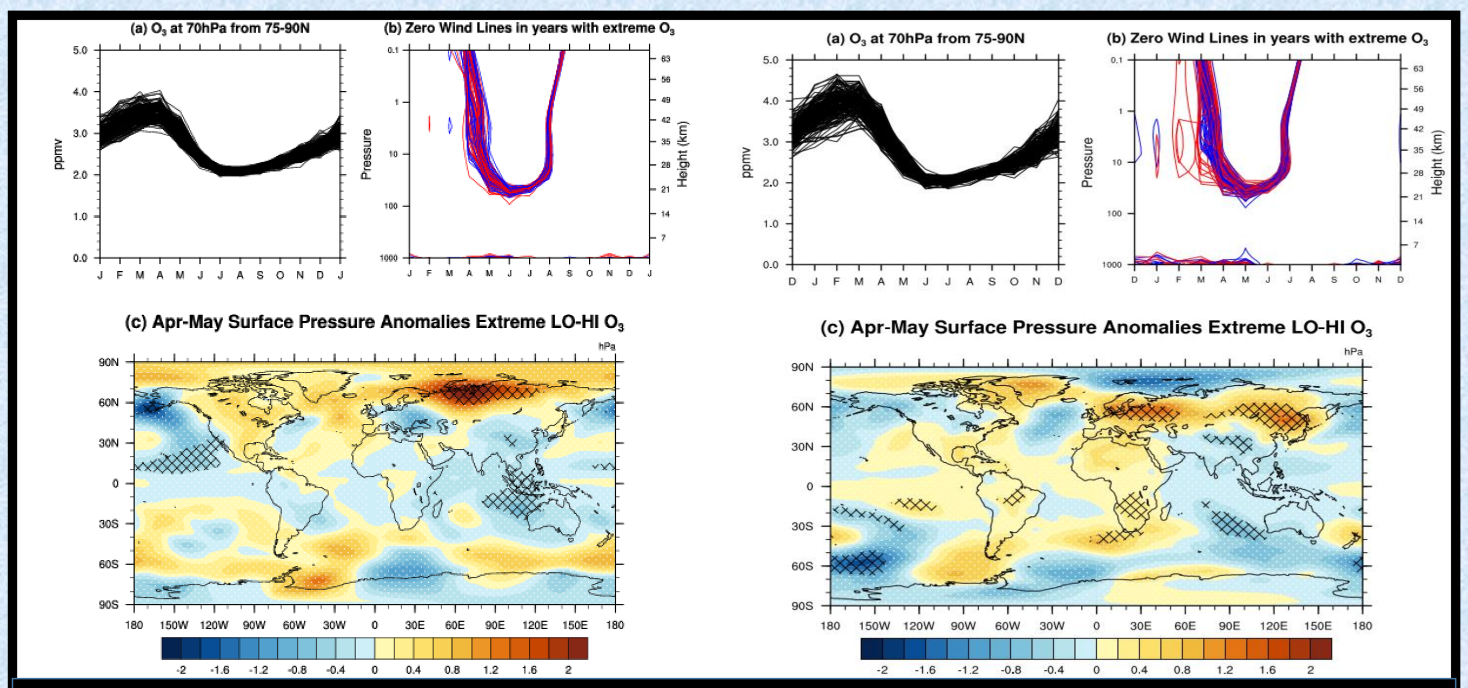
A set of long perpetual-year integrations produced by the UM-UKCA chemistry-climate model (version 7.3) are analysed for differences in spring-time tropospheric circulation and surface conditions following winters with extreme values of Arctic stratospheric ozone (defined as quartiles of 75-90°N 70hPa April ozone, as in Calvo et al., (2015)). Four integrations with different boundary conditions are considered, all with coupled atmosphere-ocean:

- Preindustrial control (PI), 160 years
- Abrupt $4xCO_2$ ($4xCO_2$), 160 years (after 43 years of 'spin-up')
- Fixed year-2000 conditions (TS2000), 100 years
- Fixed year-2000 conditions + 2.5x more ODS (TS2000+ODS), 100 years

No ODS

Left:
PI Control

Right:
Abrupt $4xCO_2$



With ODS

Left:
TS2000

Right:
TS2000+ODS

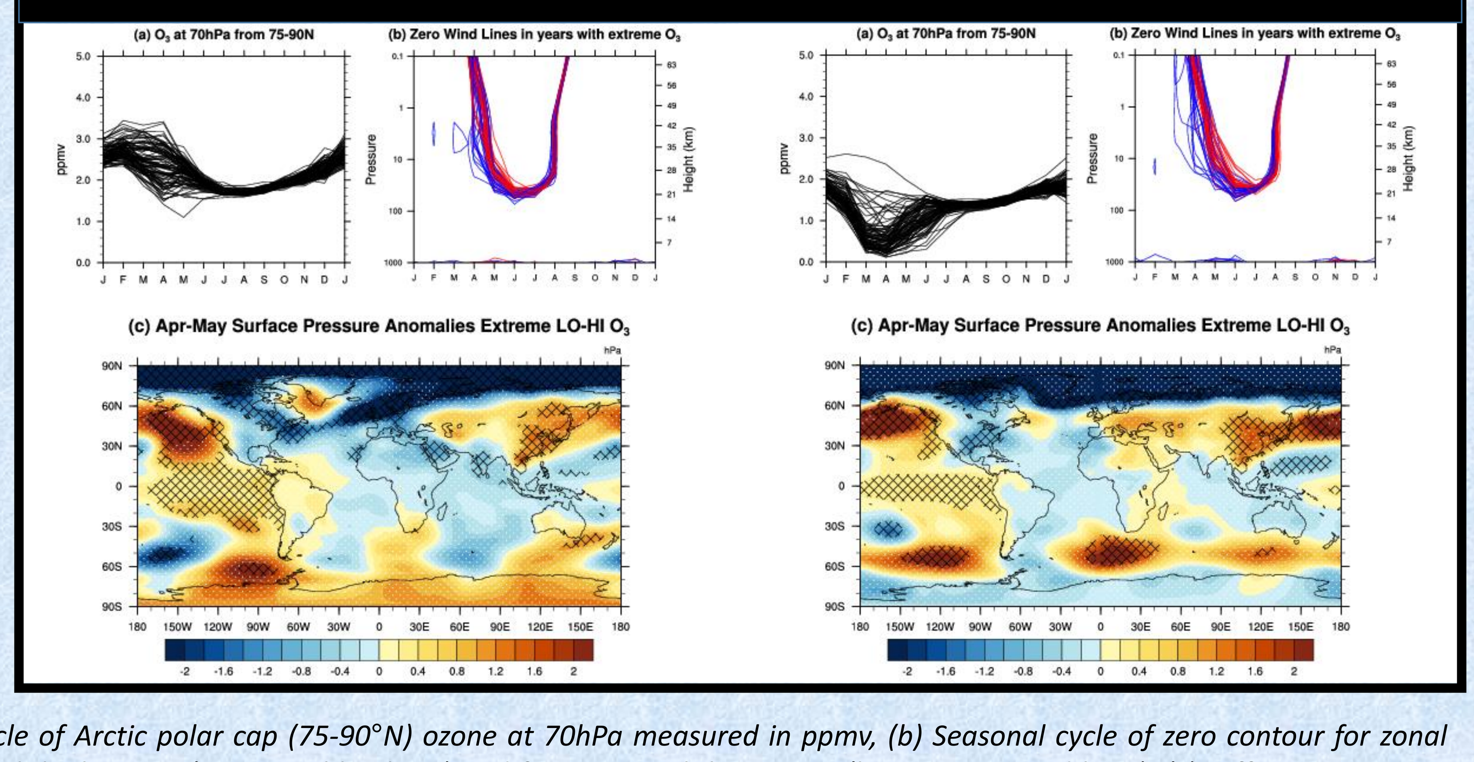
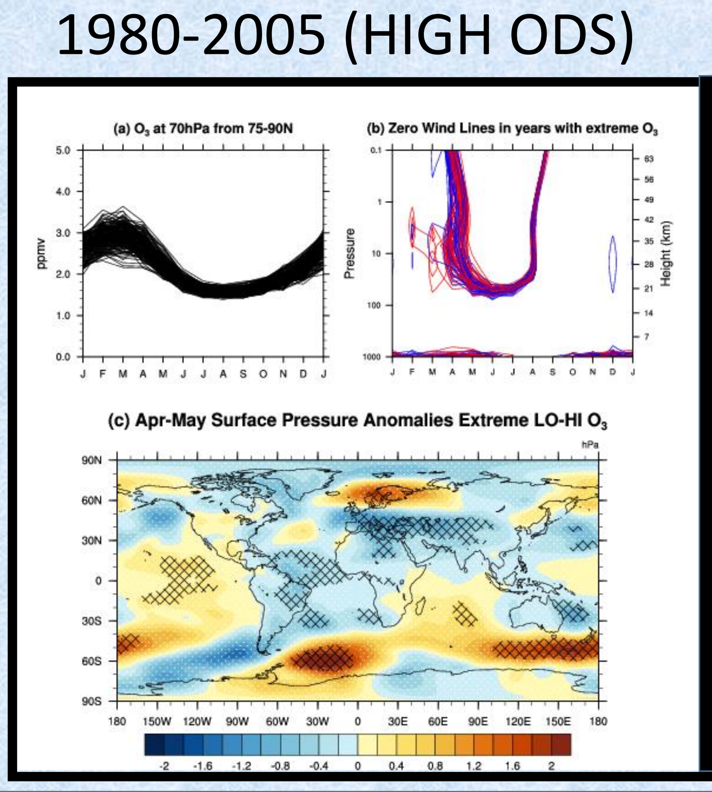


Figure 4: *(a) Seasonal Cycle of Arctic polar cap (75-90°N) ozone at 70hPa measured in ppmv, (b) Seasonal cycle of zero contour for zonal wind at 60°N for years with high ozone (top 25%; blue lines) and for years with low ozone (bottom 25%; red lines), (c) Difference in MSLP between years with low ozone and high ozone, measured in hPa.* ***An annular-mode-like pressure anomaly is present only in integrations containing ODS, which is associated with a slight delay in the seasonal cycle of zonal wind in the stratosphere (Table 1).*** *Hatching same as Figure 2.*

3. Interactive Ozone (Transient Ensemble)

An ensemble of 7 transient atmosphere-only UM-UKCA integrations covering 1980-2080 are analysed as above. The boundary conditions follow CCMI REF-C2 with RCP6.0 greenhouse gases. For two 25-year periods, differences in springtime tropospheric circulation and surface conditions are characterized following winters with extreme values of Arctic stratospheric ozone (similar to Calvo et al. (2015)).

1980-2005 (HIGH ODS)



2055-2080 (LOW ODS)

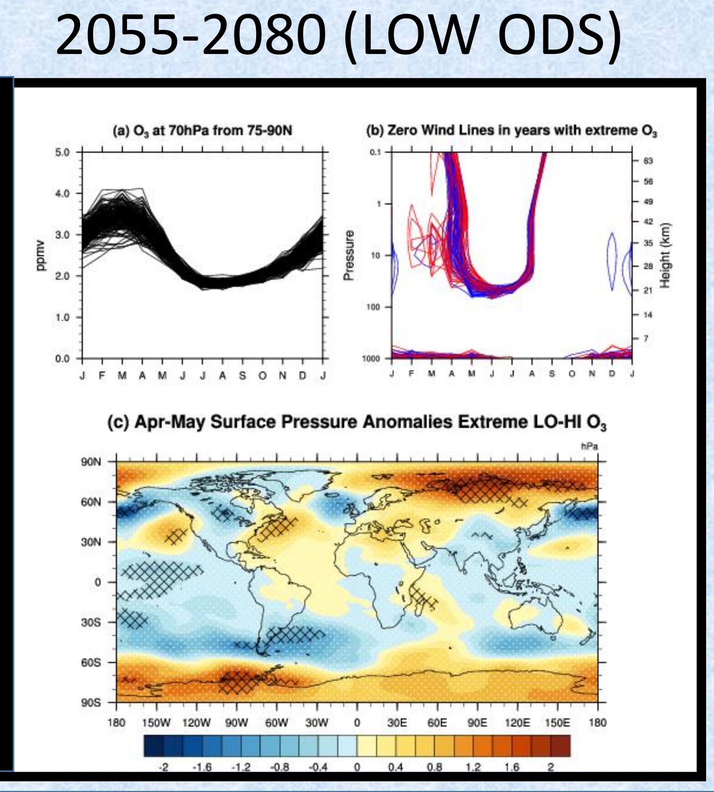


Figure 5: *As in Figure 4, but comparing the transient ensemble periods for (left) 1980-2005 and (right) 2055-2080, representing high and low ODS periods, respectively.* ***Although ODSs are higher in the first period, the frequency of large springtime Arctic depletion events, as measured by 75-90°N 70hPa ozone, does not increase compared to the later period (as was seen in perpetual year simulations containing ODSs above and in observations).*** *This may explain why there is no change in vortex breakup date and no consistent differences in MSLP patterns between low and high ozone regimes.*

Table 1: *Vortex breakup date estimated from monthly zonal wind values (linear interpolation) at 10hPa based on Charlton and Polvani (2007) criterion for vortex breakup, measured in days since 01/01.* ***Delaying the breakup of the polar vortex has been shown to be an important factor for tropospheric coupling in the southern hemisphere, in response to stratospheric ozone depletion [Sheshadri and Plumb, 2016].***

Control	Winter 2011	WA2011	PI		4xCO2		TS2000		TS2000 +ODS		1980-2005		2055-2080	
ALL	ALL	ALL	HI	LO	HI	LO	HI	LO	HI	LO	HI	LO	HI	LO
107 ± 12	110 ± 15	110 ± 13	122 ± 9	121 ± 8	128 ± 6	125 ±14	122 ± 9	130 ± 5	125 ±14	140 ±10	109 ±12	111 ±13	112 ± 8	110 ±13

Conclusions

The presence of a pressure signal at the surface is associated with a delayed stratospheric vortex breakup date. In chemistry climate models, this delay is present when sharp 'dips' are apparent in the seasonal cycle of Arctic cap ozone at 70hPa. This is reinforced by the observed delay in breakup date between the TS2000 and TS2000+ODS integrations, with the only difference being a 2.5-fold change in available reservoir chlorine species in the atmosphere. The transient ensemble demonstrates that even in the presence of moderate levels of ODS in the atmosphere, the stratospheric polar vortex needs to be strong/persistent enough to allow for springtime chlorine activation and subsequent chemical ozone depletion to delay its final breakup (e.g. Winter of 2015/2016). The delay in polar vortex breakup date and subsequent MSLP anomaly are only present when there is significant chemical ozone depletion occurring in the Arctic stratosphere. Understanding the seasonal dynamical variability that drives polar vortex evolution is crucial for understanding the impacts of chemical ozone depletion, from the stratosphere down to the surface.

References

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Acknowledgements

This work was made possible by the U.K. Natural Environment Research Council. This work used the ARCHER UK National Supercomputing Service (http://www.archer.ac.uk). I would also like to acknowledge P. J. Nowack, E. M. Bednarz, and N. L. Abraham for their contributions of large UKCA datasets, without which this analysis could not have been possible.

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