THE IMPACT OF SUDDEN STRATOSPHERIC WARMINGS (SSW$_S$) ON UTLS COMPOSITION, LOCAL RADIATIVE EFFECTS AND AIR QUALITY

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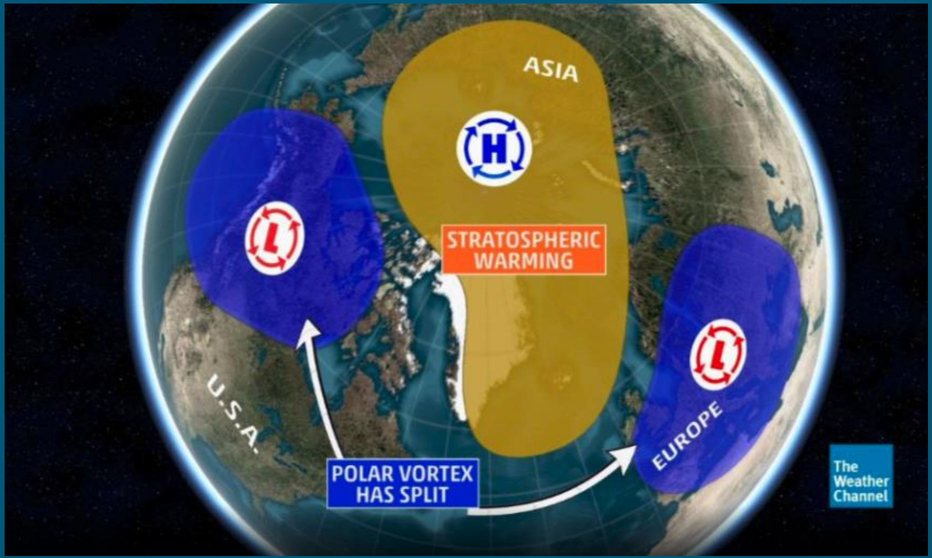

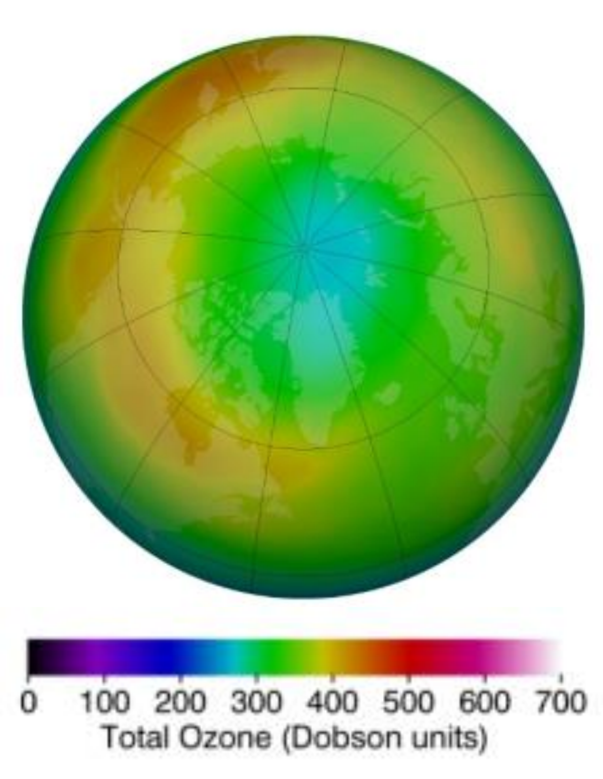

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BACKGROUND

- Sudden stratospheric warmings (SSWs) constitute the largest deviations from the mean state in the NH extratropical stratosphere.
- They are characterised by a disturbance (weakening) in the wintertime stratospheric polar vortex (SPV) due to upward wave propagation from the troposphere, where waves break and dissipate at a certain level (Matsuno, 1971).
- Such waves are associated with upper tropospheric weather disturbances (e.g. Coy et al., 2009), as well as blocking ridges (Martius et al., 2009; Castanheira and Barriopedro 2010; Woollings et al., 2010; Nishii et al., 2011).

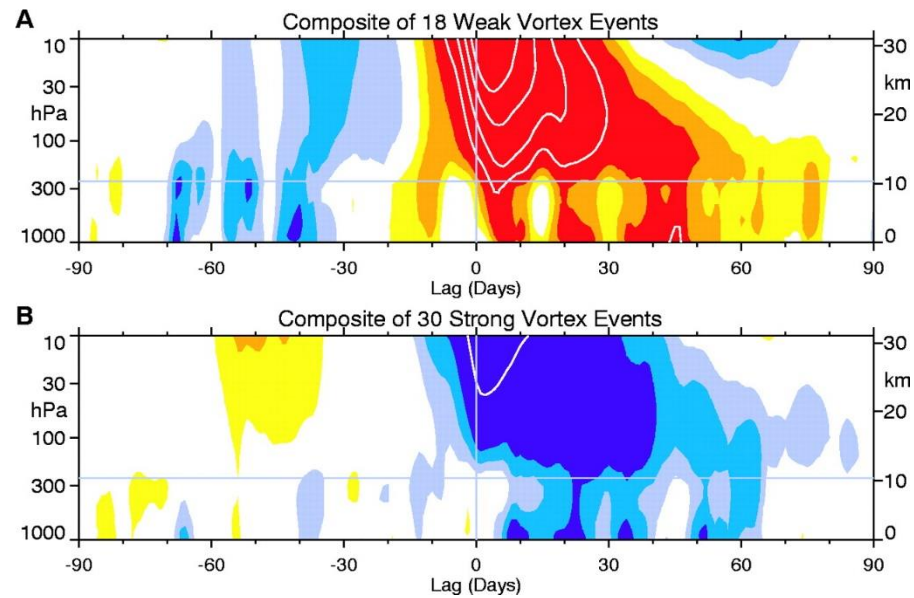

Fig 2. from Baldwin & Dunkerton (2001): Northern Annular Mode (NAM) anomalies

BACKGROUND

- **Definition:** The reversal of the temperature gradient poleward of 60°N and the reversal of the 60°N 10 hPa zonal mean wind from westerly to easterly (e.g. Andrews et al., 1987; Manney et al., 2008b).
- Two main types: Wave-1 (Vortex Displacement) and Wave-2 (Vortex Split) Events

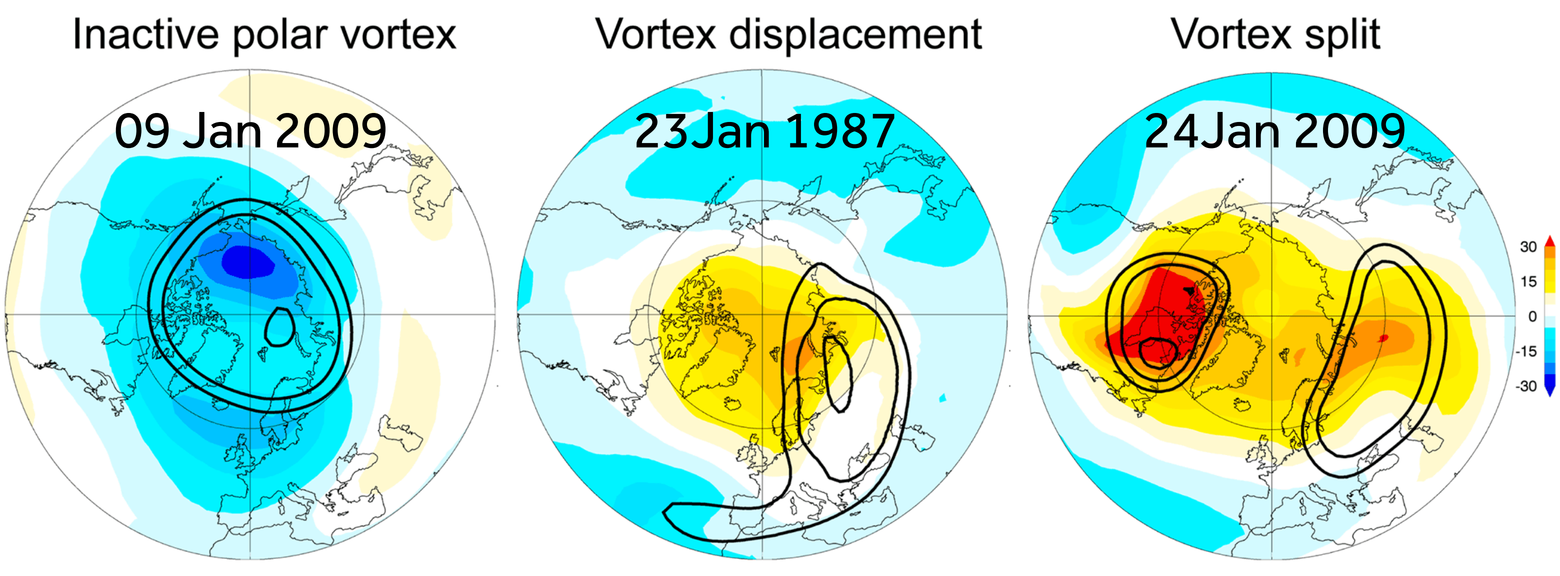

Fig 1. from Butler et al. (2017): 10 hPa temperature anomalies and 550 K Potential Vorticity during different SPV states

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- **Alternative Definition:** Events may also be distinguished by the depth to which the warming descends through the stratosphere, which is closely associated with the magnitude of the upward and poleward directed wave forcing.
- Hitchcock et al. (2013a) classified SSWs as Polar-night Jet Oscillation (PJO) events where temperature anomalies were maximised in the lower stratosphere (~ 60 hPa).
- Here, temperature and resultant dynamical perturbations to the mean state have a longer residence time (due to longer radiative relaxation timescales), of up to 3 months (Hitchcock et al., 2013b).

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Table 1. The list of Sudden Stratospheric Warmings in ERA-I including their types: split/displacement (S/D), absorptive/reflective (A/R), and PJO/nPJO.

Central date	dSSW/nSSW	NAM1000 (days 8–52)	Daily NAM1000 (%)	Daily NAM150 (%)	S/D	A/R	PJO/ nPJO
22.02.79	**dSSW**	**−1.1**	**78**	**87**	**S**	**R**	**nPJO**
29.02.80	**dSSW**	**−0.5**	**75**	**89**	**D**	**R**	**nPJO**
04.03.81	*nSSW*	*0.5*	*36*	*53*	*D*	*A*	*nPJO*
04.12.81	**dSSW**	**−0.9**	**82**	**80**	**D**	**A**	**nPJO**
24.02.84	**dSSW**	**−0.9**	**89**	**96**	**D**	**R**	**PJO**
01.01.85	**dSSW**	**−1.8**	**100**	**100**	**S**	**R**	**PJO**
23.01.87	**dSSW**	**−0.7**	**78**	**100**	**D**	**A**	**PJO**
08.12.87	*nSSW*	*0.3*	*44*	*62*	*S*	*A*	*PJO*
14.03.88	*nSSW*	*−0.1*	*49*	*38*	*S*	*R*	*nPJO*
21.02.89	*nSSW*	*0.8*	*11*	*78*	*S*	*R*	*nPJO*
15.12.98	*nSSW*	*−0.2*	*51*	*69*	*D*	*R*	*PJO*
26.02.99	**dSSW**	**−0.5**	**51**	**100**	**S**	**A**	**PJO**
20.03.00	*nSSW*	*0.2*	*33*	*40*	*D*	*R*[a]	*nPJO*
11.02.01	**dSSW**	**−0.8**	**69**	**91**	**S**	**A**	**nPJO**
30.12.01	*nSSW*	*1.1*	*11*	*31*	*D*	*A*	*nPJO*
18.01.03	*nSSW*	*0.0*	*44*	*57*	*S*	*A*	*nPJO*
05.01.04	**dSSW**	**−0.8**	**80**	**100**	**D**	**R**	**PJO**
21.01.06	**dSSW**	**−0.3**	**62**	**96**	**D**	**A**	**PJO**
24.02.07	*nSSW*	*0.3*	*47*	*42*	*D*	*R*	*nPJO*
22.02.08	*nSSW*	*−0.0*	*64*	*60*	*D*	*R*	*nPJO*
24.01.09	**dSSW**	**−0.6**	**69**	**100**	**S**	**A**	**PJO**
09.02.10	**dSSW**	**−0.3**	**58**	**96**	**S**	**A**	**PJO**
07.01.13	**dSSW**	**−0.6**	**73**	**98**	**S**	**A**	**PJO**[b]

Also shown are the three criteria used to define tropospheric impacts. dSSW events are highlighted in bold. nSSW events are marked with Italic.
[a]This event was not studied in Kodera *et al.* (2016).
[b]This event was not studied in Hitchcock *et al.* (2013).

Table 1 from Karpechko et al. (2017): SSW distinctions (1979-2013)

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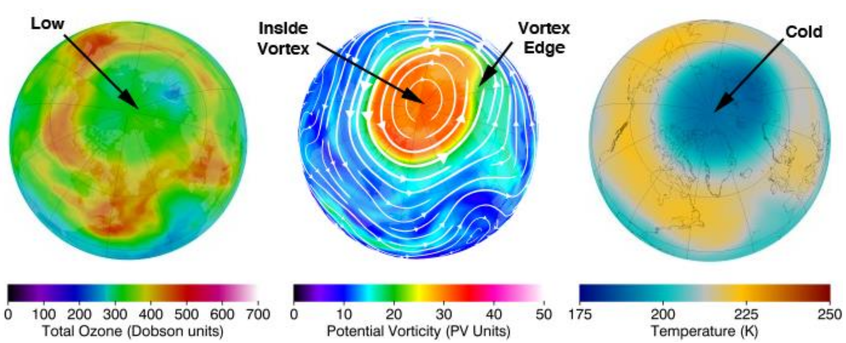
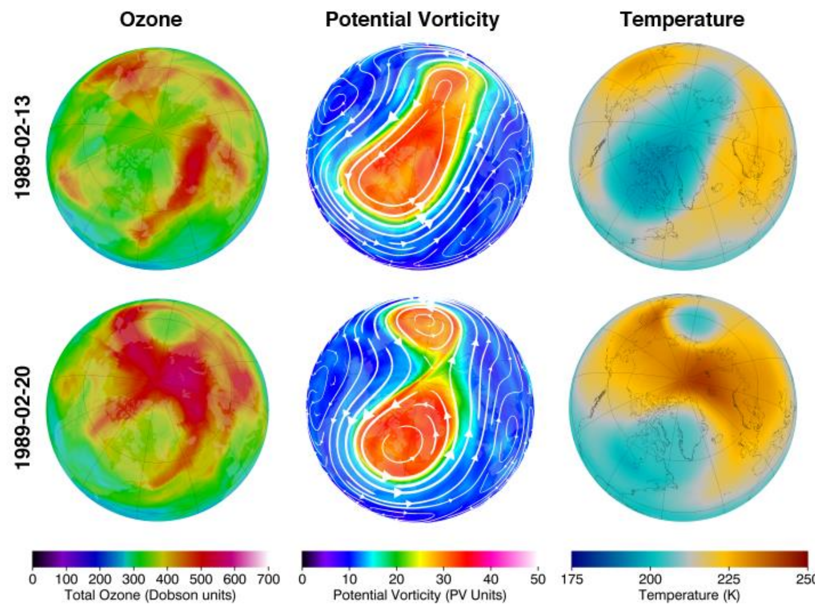
MOTIVATION

- Although it is known that SSWs are associated with changes in stratospheric O_3 (notably an enhancement over the polar-cap region), the impact on Stratosphere-Troposphere Exchange (STE) of O_3 and tropospheric O_3 has so far received little attention.
- It is also known that SSWs lead to pronounced impacts on tropospheric circulation, which leads to regional changes in temperature, precipitation etc. (e.g. Kidston et al., 2015).

Wintertime SPV mean state (below) and during an SSW event (right). Source: NASA





WHY IS TROPOSPHERIC O_3 IMPORTANT?

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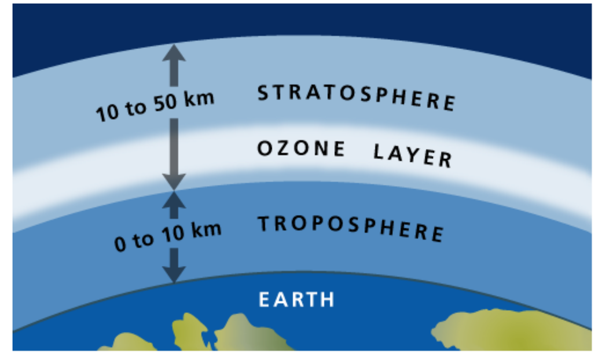
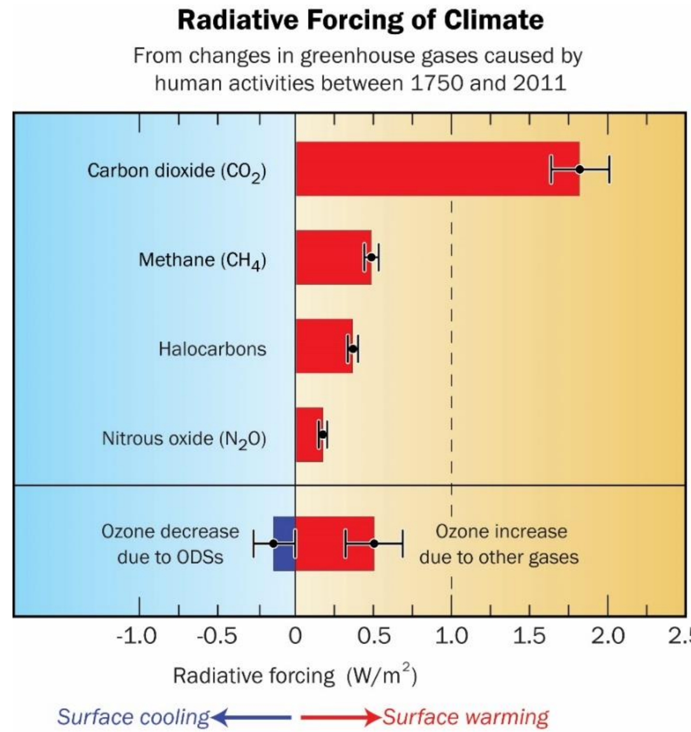
- **Ground level pollutant** – adverse effects on human health and ecosystems (Paoletti et al., 2014). Surface air quality standards ~ 60-75 ppbv.

- **Primary source of the hydroxyl (OH) radical** – important regulatory role in the oxidation and lifetime of several pollutants and greenhouse gases (GHGs) (Seinfeld & Pandis, 2006; Cooper et al., 2010).

- **GHG** – largest radiative effect in the upper troposphere – lower stratosphere (UTLS) (~ 10 km) (Lacis et al., 1990).





Hegglin et al., WMO (2015)

TROPOSPHERIC O_3 INFLUENCES

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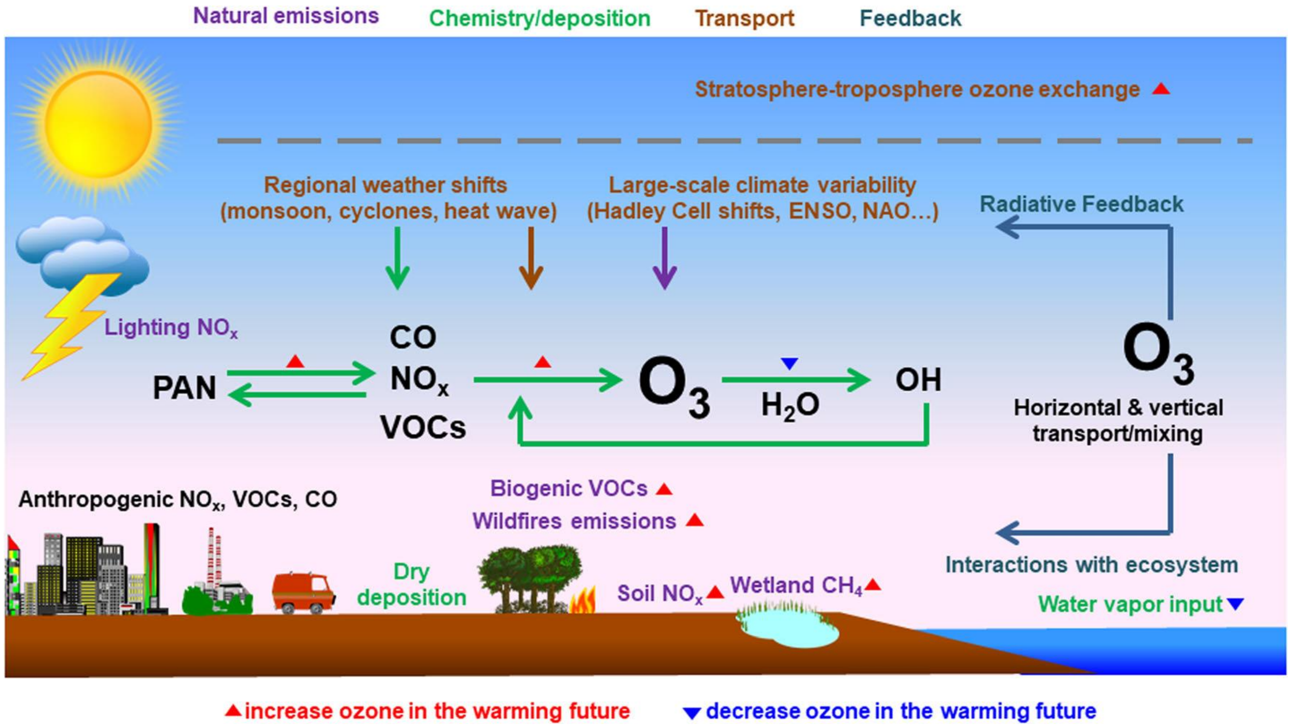

Fig. 1 from Lu et al. (2019): Factors influencing the tropospheric O_3 budget, including transport pathways.

- Although much of the ozone is formed photochemically in the troposphere from precursor molecules (e.g. NOx, CO, VOCs), downward transport of ozone-rich air from the stratosphere is known to be an important influence (Holton et al., 1995; Lamarque et al., 1999), particularly in mid-latitudes (Miles et al., 2015).

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STRATOSPHERE-TROPOSPHERE EXCHANGE (STE)

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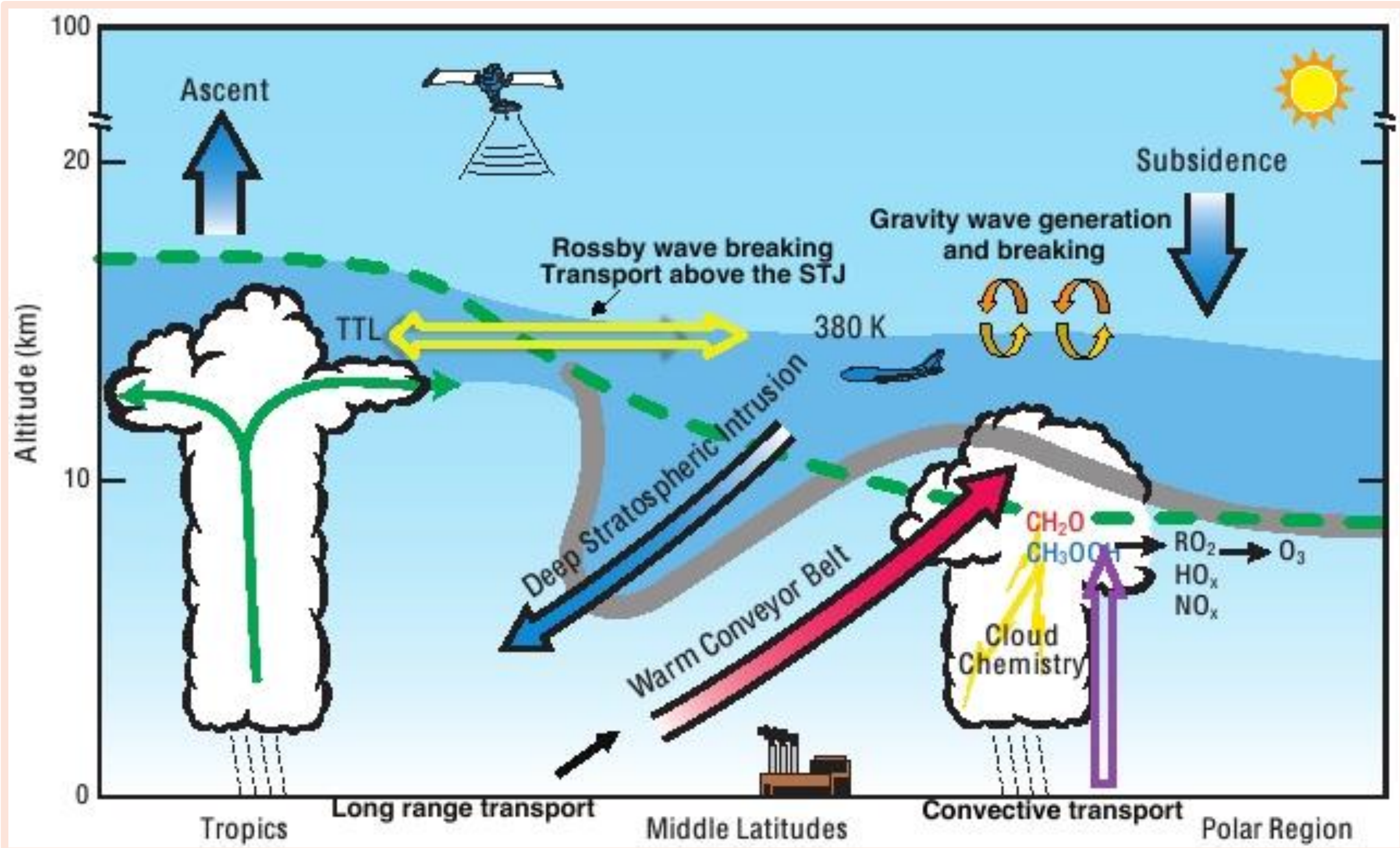

Schematic of coupling processes between dynamics, chemistry and cloud microphysics in the vicinity of the UTLS. Adapted from UCAR (2020)

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STE INFLUENCE ON THE SEASONAL CYCLE OF TROPOSPHERIC O_3

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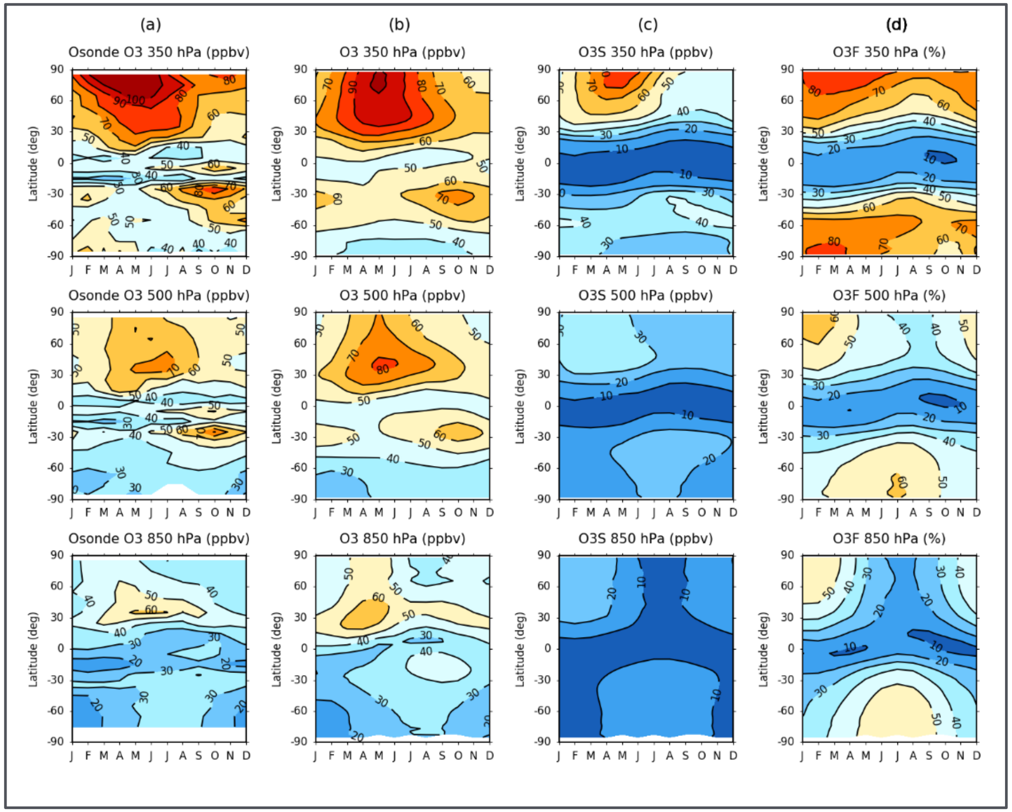

__Williams, R. S.__, Hegglin, M. I., Kerridge, B. J., Jöckel, P., Latter, B. G., & Plummer, D. A. (2019). Characterising the seasonal and geographical variability in tropospheric ozone, stratospheric influence and recent changes. Atmospheric Chemistry and Physics, 19(6), 3589-3620

Zonal-mean monthly evolution of (**a**) ozonesonde-derived O_3, (**b**) EMAC O_3, (**c**) EMAC ozone of stratospheric origin (O_3S) and (**d**) EMAC O_3 fraction of stratospheric origin (O_3F [%] = (O_3S / O_3) x 100) averaged over the 1980-2010 climatological period. Values in **(a-c)** are volume mixing ratios [ppbv]. Taken from **Fig. 7** in Williams et al. (2019).

- The EMAC model accurately captures the seasonality in tropospheric O_3, with a simulated stratospheric contribution > 50 % near the surface during winter in the extratropics.

STE INFLUENCE ON LONG-TERM RECENT CHANGES IN TROPOSPHERIC O_3

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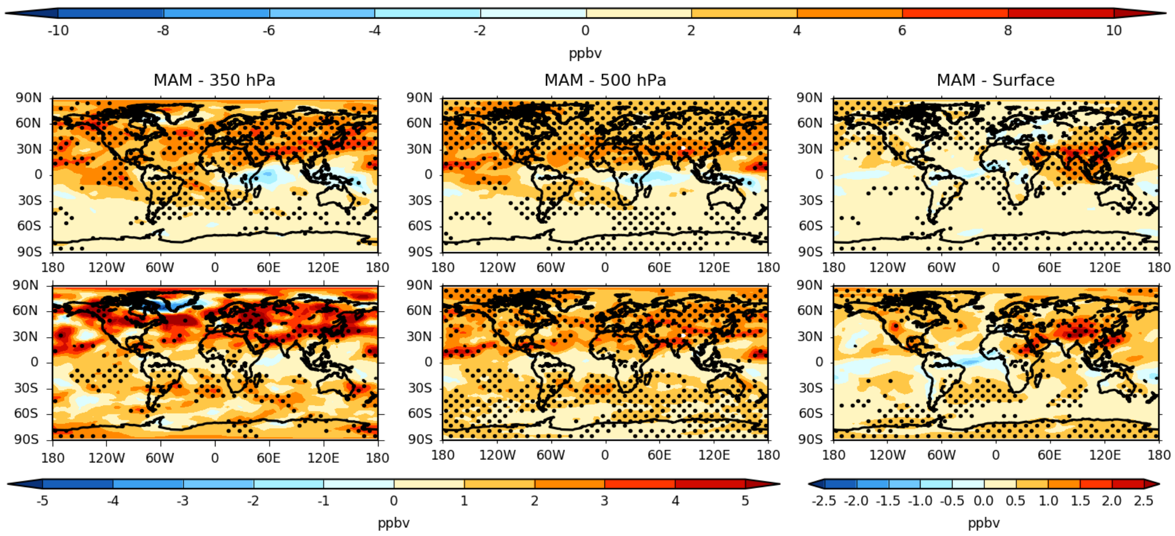

Boreal springtime (MAM) recent changes (2001-2010 minus 1980-1989) in EMAC O_3 (top row) and O_3S (bottom row). Taken from **Fig. 8** and **Fig. 10** in Williams et al. (2019).

- Recent changes in tropospheric O_3 reflect not only changes in emission precursors, but also an increased influx of O_3 from the stratosphere, as indicated using a tagged stratospheric ozone (O_3S) model tracer.

***Williams, R. S.**, Hegglin, M. I., Kerridge, B. J., Jöckel, P., Latter, B. G., & Plummer, D. A. (2019). Characterising the seasonal and geographical variability in tropospheric ozone, stratospheric influence and recent changes. Atmospheric Chemistry and Physics, 19(6), 3589-3620*

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SSW INFLUENCE ON STE: DATA SOURCES

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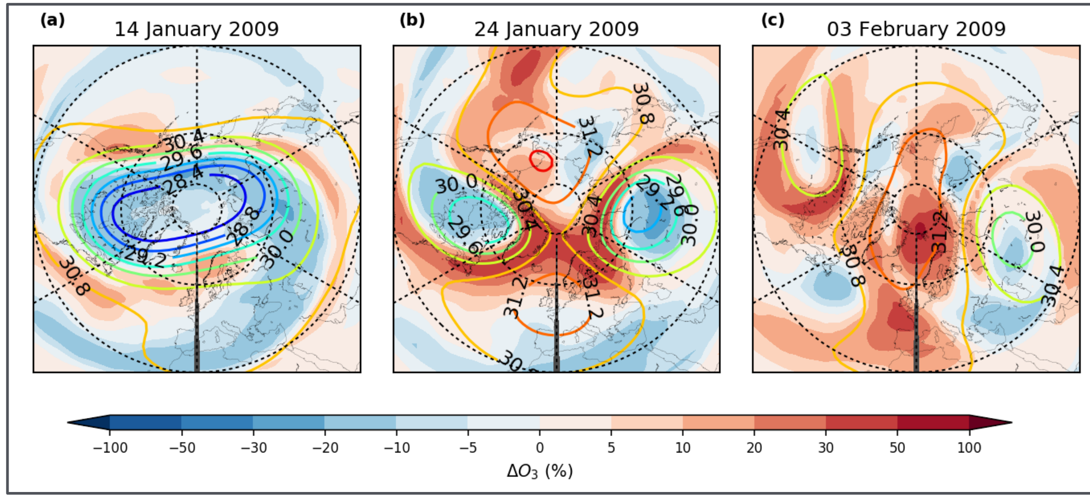
- **CAMS Reanalysis (2005-2013):** O_3 & H_2O at 3 hr temporal resolution. 80 km horizontal resolution and 60 vertical levels (up to 0.1 hPa). Used for model validation and verifying signals.



CAMS 10 hPa O_3 anomaly and geopotential height (km) evolution during the onset of the 2009 SSW

- **EMAC Chemistry-Climate Model Simulations (1979-2013):** Hindcast specified-dynamics simulations (nudged to ERA-Interim) of O_3, H_2O and ‘stratospheric’ tagged O_3 (O_3S) at 10 hr temporal resolution. 2.8°(~ 275 km) horizontal resolution and 90 vertical levels (up to 0.01 hPa).
- **Ozonesondes:** Vertical profiles of O_3 from four long-running Arctic stations. Typical frequency of one sounding weekly at ~ 150 m resolution up to ~ 35 km (Worden et al., 2007; Nassar et al., 2008).

OBSERVATIONAL EVIDENCE: CAMS

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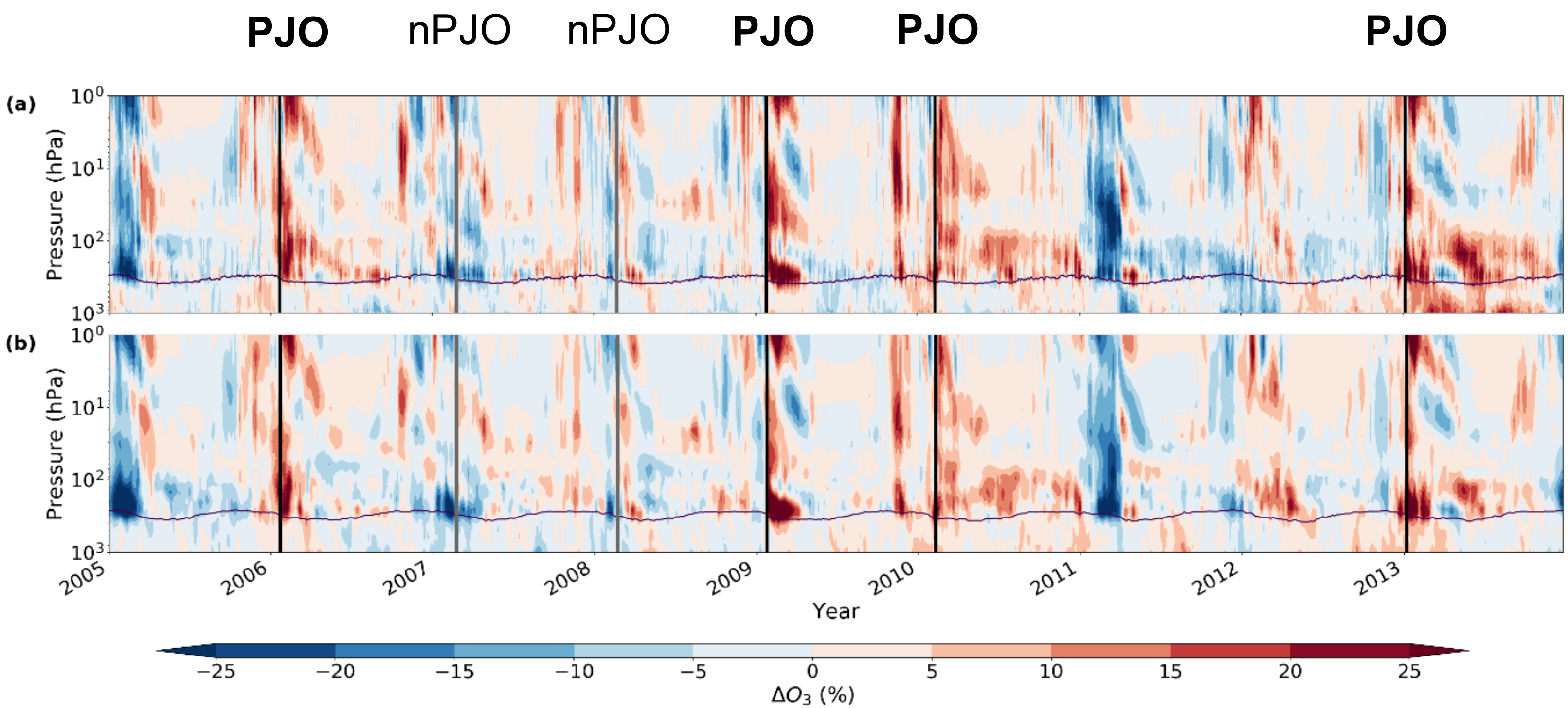

Time series of polar-cap (60-90°N) O_3 (%) anomalies for (**a**) the CAMS reanalysis and (**b**) from the EMAC model (2005-2013). An approximation for the tropopause height purple line is indicated (100 ppbv ozone contour).

- Good agreement, particularly in the stratosphere, with evidence that EMAC adequately captures O_3 variability associated with SSW events (solid lines).

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OBSERVATIONAL EVIDENCE: CAMS

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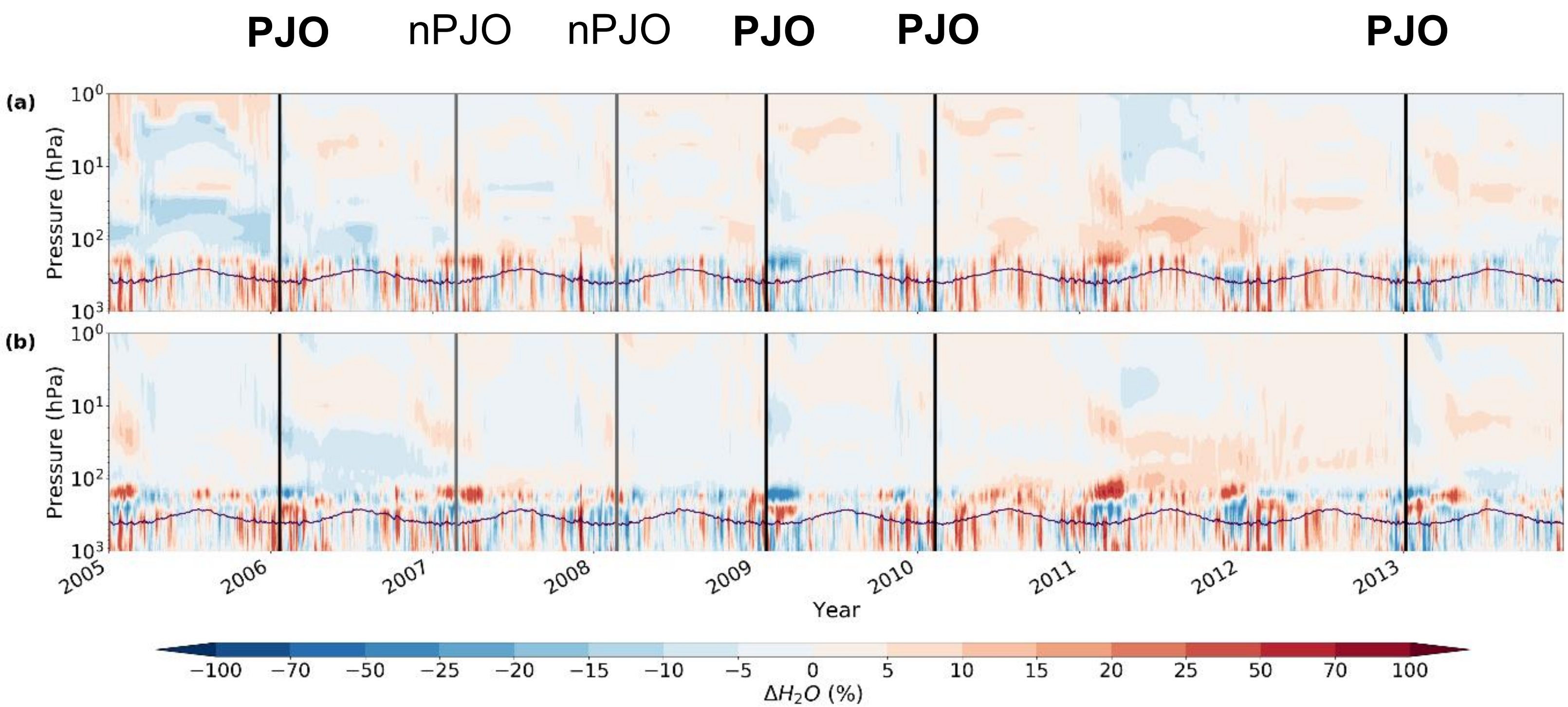

Time series of polar-cap (60-90°N) H_2O (%) anomalies for (**a**) the CAMS reanalysis and (**b**) from the EMAC model (2005-2013). An approximation for the tropopause height purple line is indicated (100 ppbv ozone contour).

- Broad agreement, again particularly in the stratosphere, with evidence for a dipole in water vapour anomalies within the lowermost stratosphere (LMS) frequently during winter (between 100 hPa and tropopause).

OBSERVATIONAL EVIDENCE: SONDES

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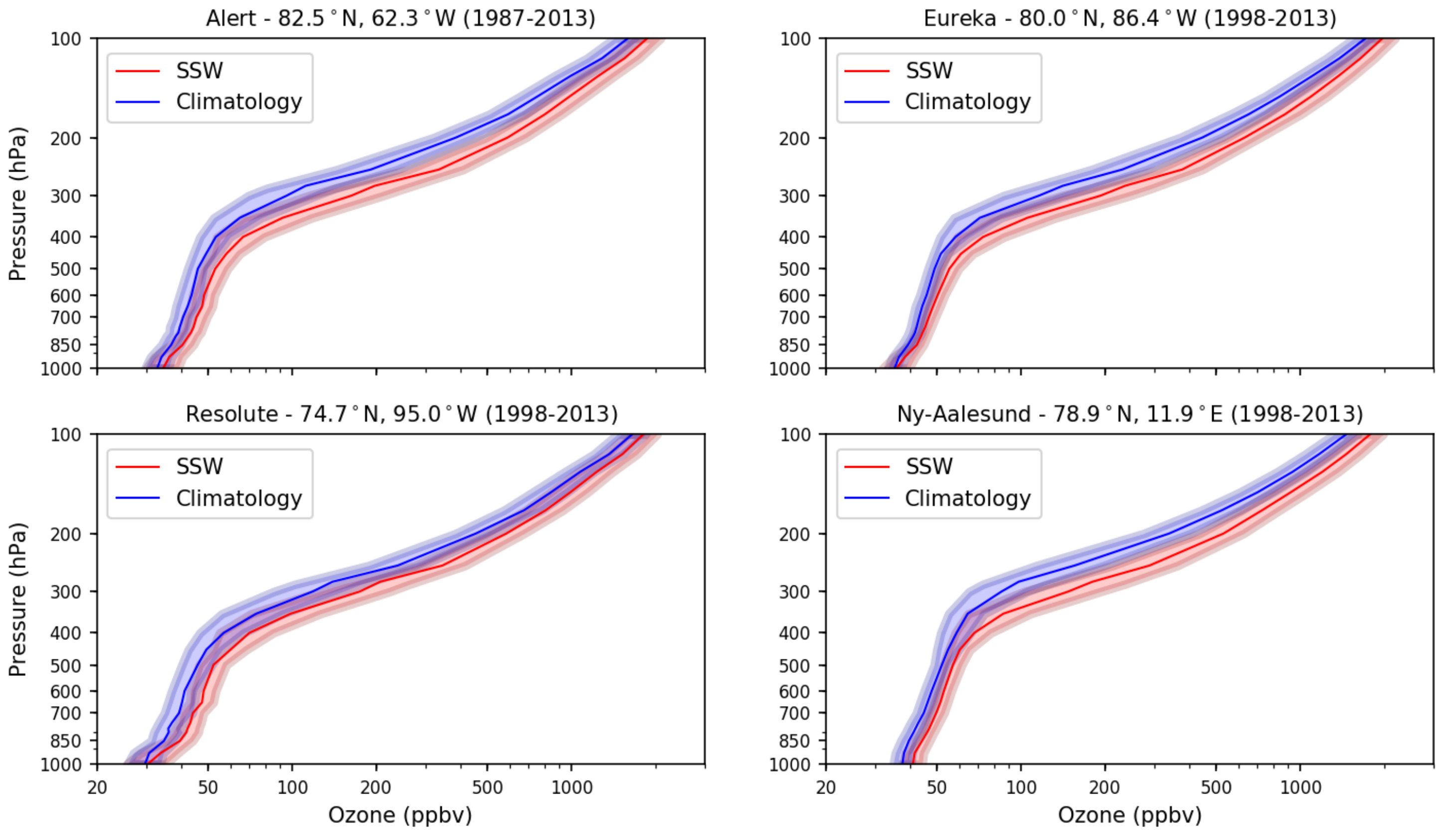

Arctic station mean ozonesonde profiles during SSW events and from climatology (excluding SSWs) with 1σ intervals indicated (shaded regions).

- Clear signal for an O_3 enhancement when comparing SSW averaged and climatology averaged profiles (Jan-Feb)

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EMAC MODEL: SSW COMPOSITES

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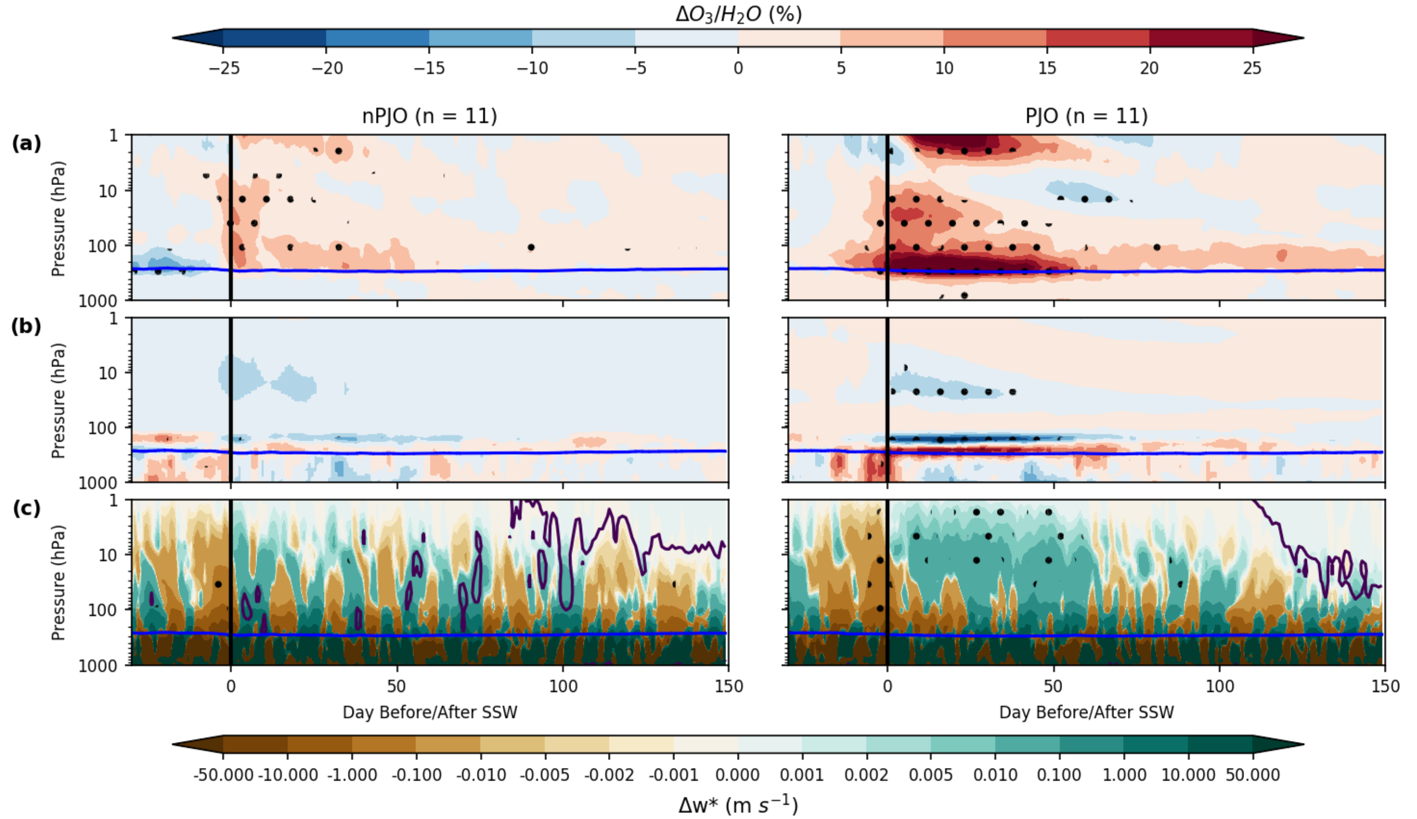
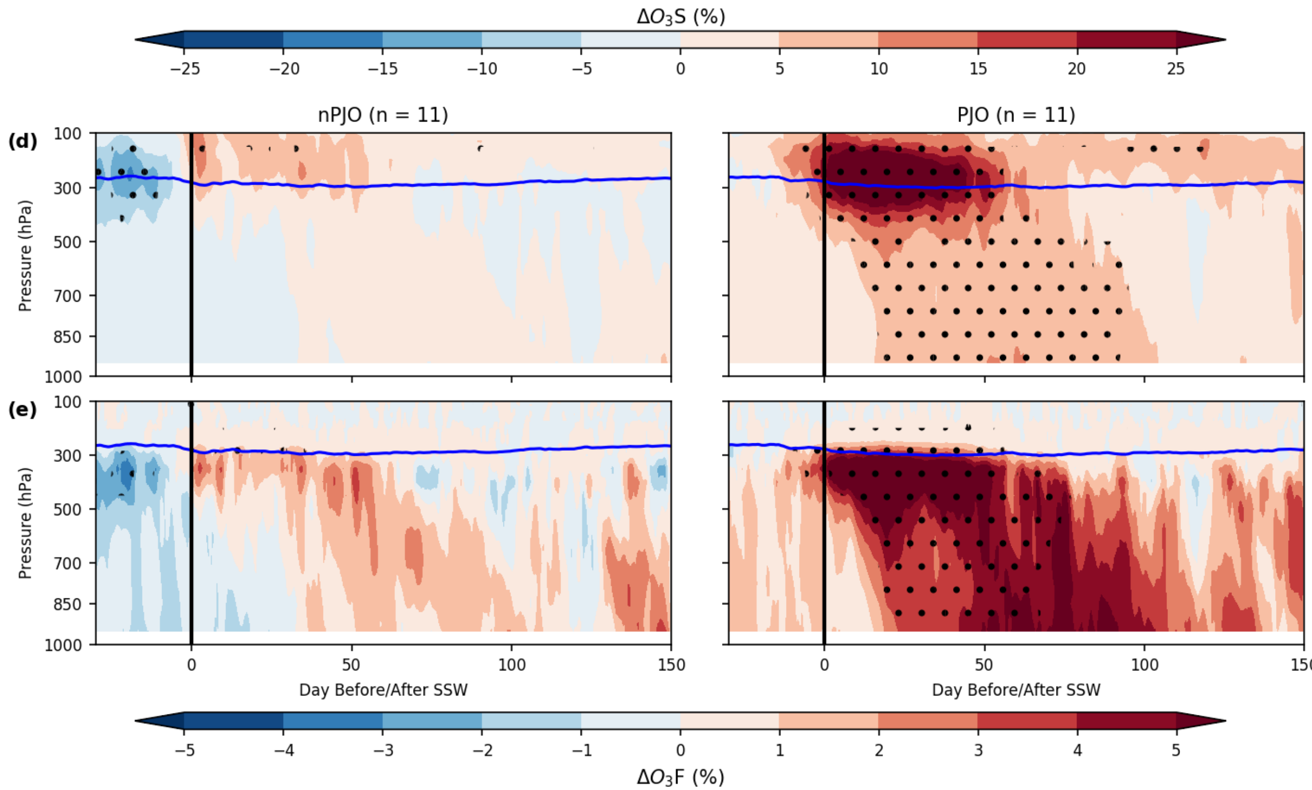


Evolution of polar-cap (60-90° N) mean (a) O_3, (b) H_2O and (c) $\overline{w}^*$(residual vertical velocity) anomalies during an SSW life cycle from the EMAC model (1980-2013). Statistically significant regions ($p < 0.05$) (stippling) and the WMO thermal tropopause are indicated (blue solid line).

- Relative anomalies in O_3 and H_2O of > 25 % and ± 25 % respectively in the UTLS are simulated for PJO events, which persist for up to 2-3 months. This is preceded by a period of enhanced polar downwelling (negative $\overline{w}^*$ anomalies).

EMAC MODEL: SSW COMPOSITES



Evolution of polar-cap (60-90° N) mean (a) ozone of stratospheric origin (O_3S) and (b) the fraction of ozone of stratospheric origin ($O_3F = O_3S/O_3 \times 100$) anomalies during an SSW life cycle from the EMAC model (1980-2013). Statistically significant regions ($p < 0.05$) (stippling) and the WMO thermal tropopause (blue solid line) are indicated.

- An enhancement in tropospheric O_3, maximised around a 50 day lag, is inferred for these events with an increase of ~ 5-10 % in the ozone of stratospheric origin (O_3S). This equates to a stratospheric ozone fraction (O_3F) anomaly > +5 %.

OZONE DISTRIBUTION CHANGES

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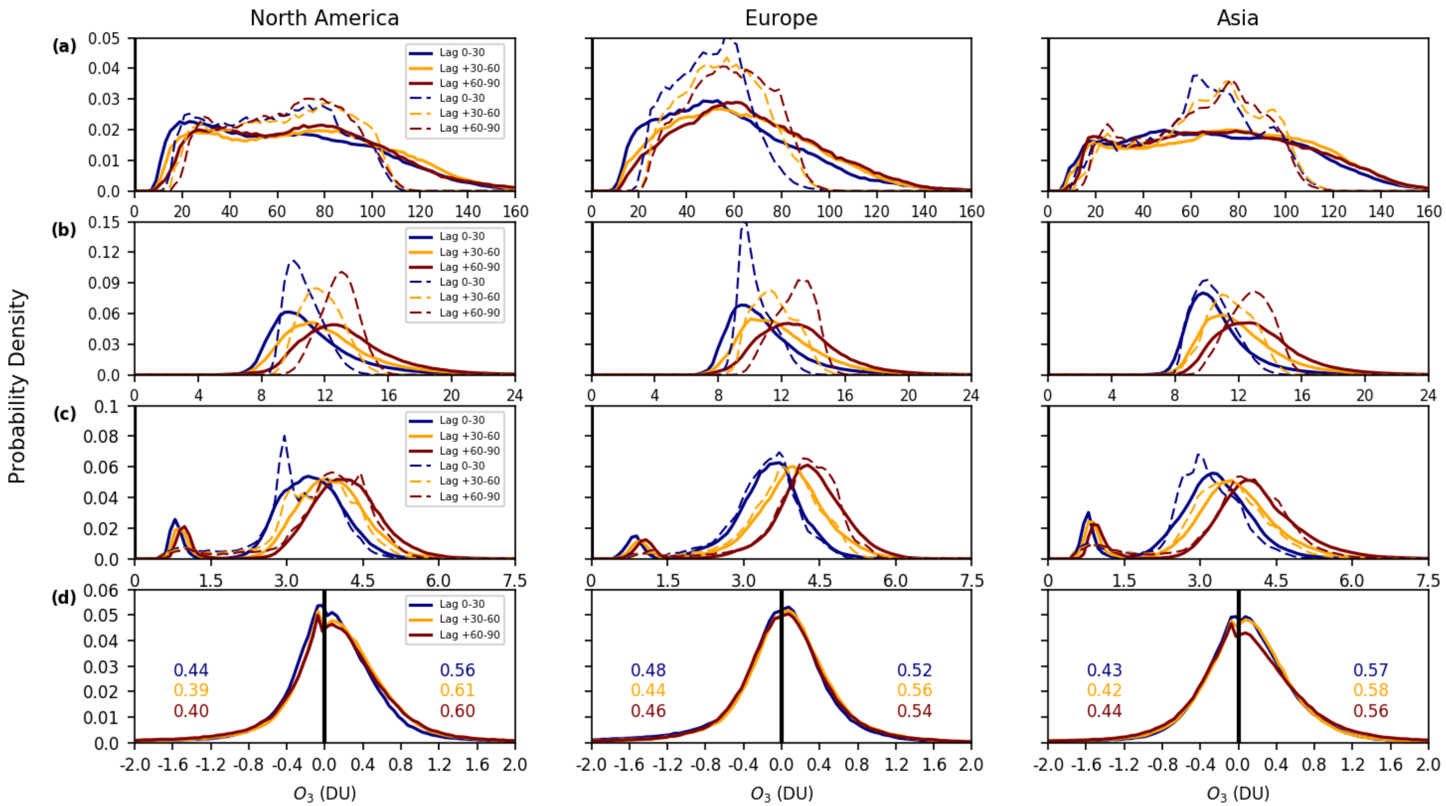

Regional EMAC subcolumn O_3 SSW (solid lines) and climatological (dashed lines) probability density functions (PDFs) for (a) 100-300 hPa (LMS), (b) 300-500 hPa (UT), (c) 900-1000 hPa (PBL) and (d) same as (c) but plotted as an anomaly PDF. Numbers in (d) indicate the ratio of each distribution either side of zero.

- PDF analysis confirms that the enhancement in LMS O_3 extends into the mid-latitude troposphere. Planetary boundary layer (PBL) increases of ~ 0.5-1 DU (~ 12-25 % of surface AQ standards: ~ 120 µg m³ or 60 ppbv) are simulated (**c**).

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RISK RATIO (RR) CALCULATION

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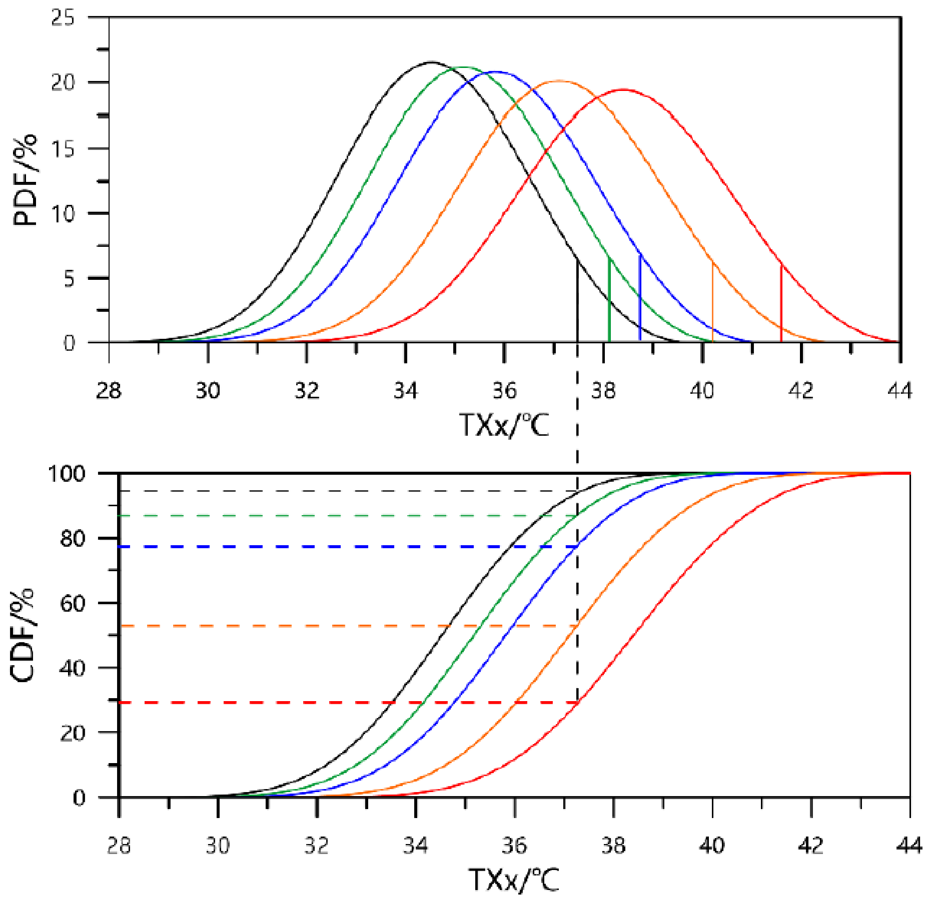
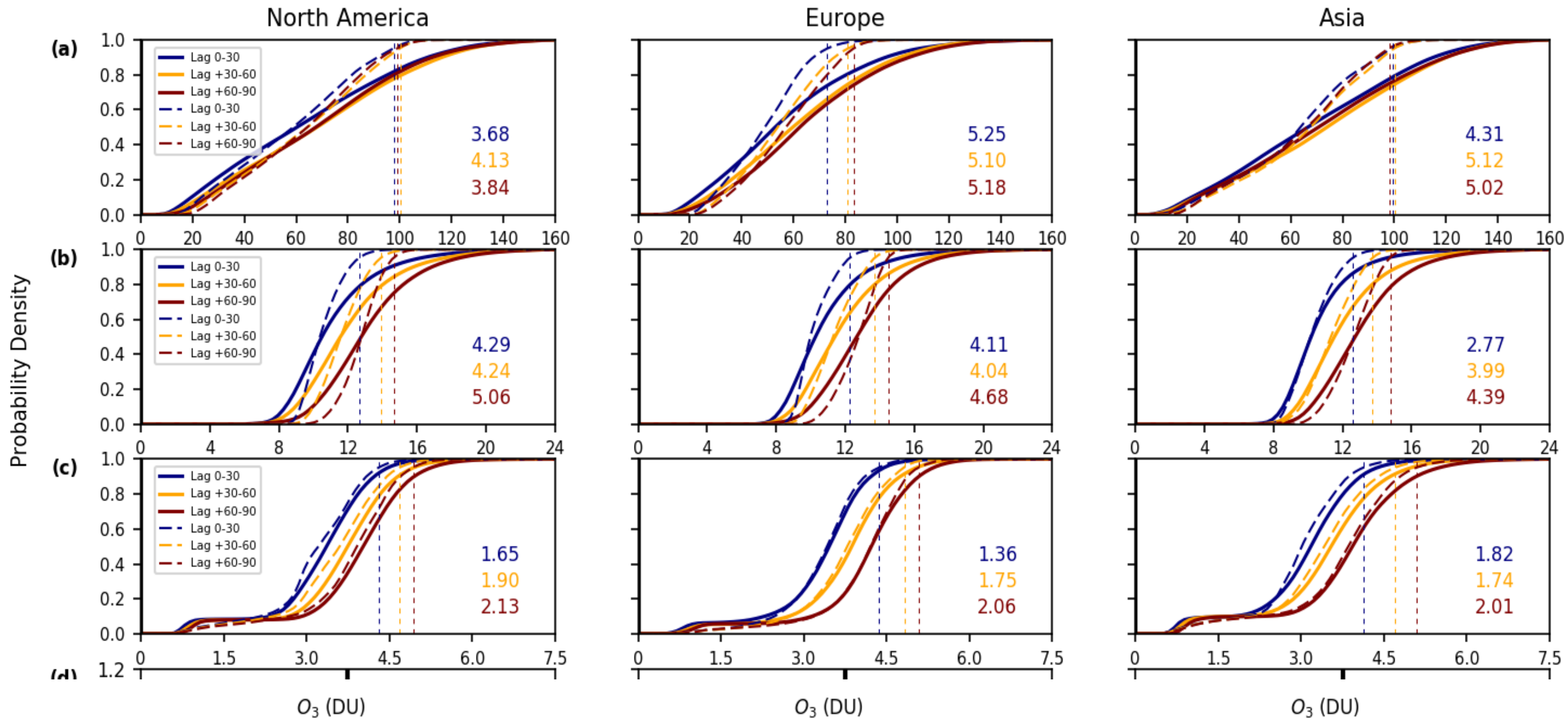


$$RR = \frac{1 - X_{ssw}}{1 - 0.95}$$

Compare distributions to calculate a risk ratio (RR) of the occurrence of an extreme event (95-percentile exceedance)

Using approach detailed in Zhang and Wang (2019, Fig. 1)

OZONE DISTRIBUTION CHANGES



Regional EMAC subcolumn O_3 SSW (solid lines) and climatological (dashed lines) cumulative density functions (CDFs) for (a) 100-300 hPa (LMS), (b) 300-500 hPa (UT), (c) 900-1000 hPa (PBL) and (d) same as (c) but plotted as an anomaly PDF. Numbers in (d) indicate the ratio of each distribution either side of zero.

- The risk ratio (RR) analysis indicates that the probability of a 95-percentile exceedance in O_3 increases by a factor of 3-5 in the LMS and UT and up to a doubling in the PBL of the mid-latitude troposphere.

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RADIATIVE EFFECTS

Using the Fixed Dynamical Heating (FDH) Technique: Forster and Shine (1997)

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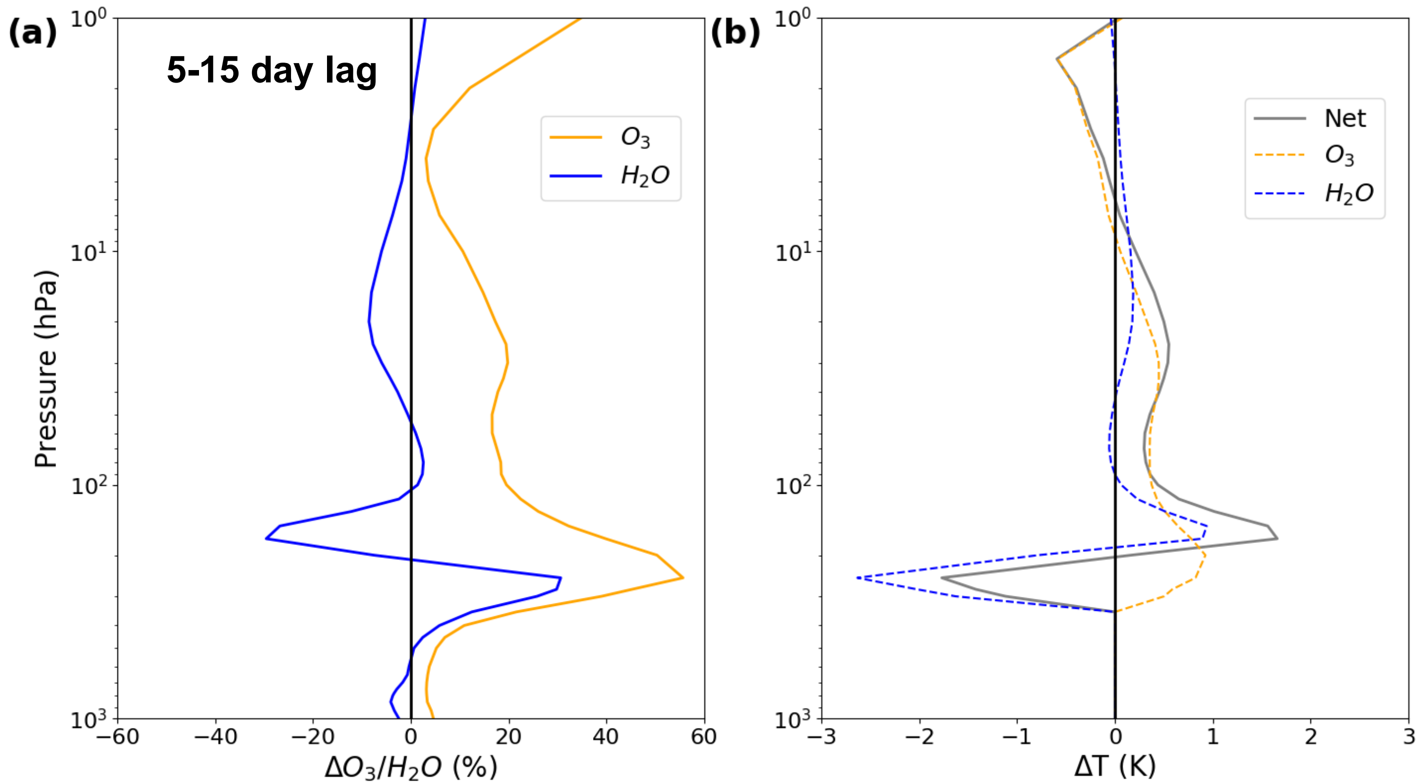

Polar-cap (60-90° N) mean perturbations (%) in (a) O_3 and H_2O and (b) the resultant radiatively-driven stratospheric temperature changes averaged 10 (± 5) days after a PJO-type SSW. The net radiative effects are also indicated.

- UTLS perturbations in O_3 and H_2O lead to local temperature changes of up to ± 2K, averaged 10 days after an SSW onset. A warming effect is induced between 100-200 hPa and a cooling effect below (~ 200-300 hPa).

RADIATIVE EFFECTS

Using the Fixed Dynamical Heating (FDH) Technique: Forster and Shine (1997)

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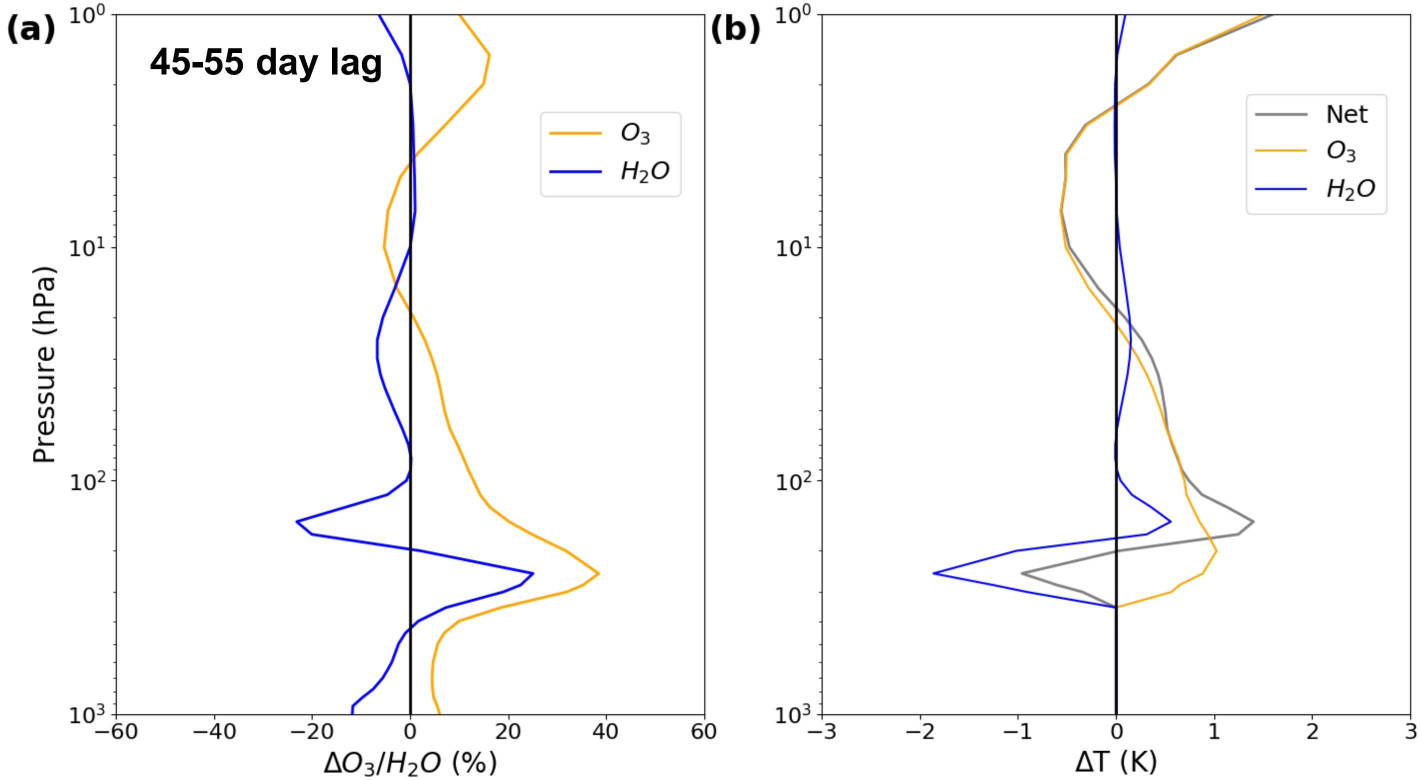

Polar-cap (60-90° N) mean perturbations (%) in (a) O_3 and H_2O and (b) the resultant radiatively-driven stratospheric temperature changes averaged 50 (± 5) days after a PJO-type SSW. The net radiative effects are also indicated.

- The simulated O_3 & H_2O anomaly profiles and resultant heating changes remain similar some 50 days after the onset of a PJO-type SSW. The results imply that such radiative impacts are relatively long-lasting.

ONGOING WORK

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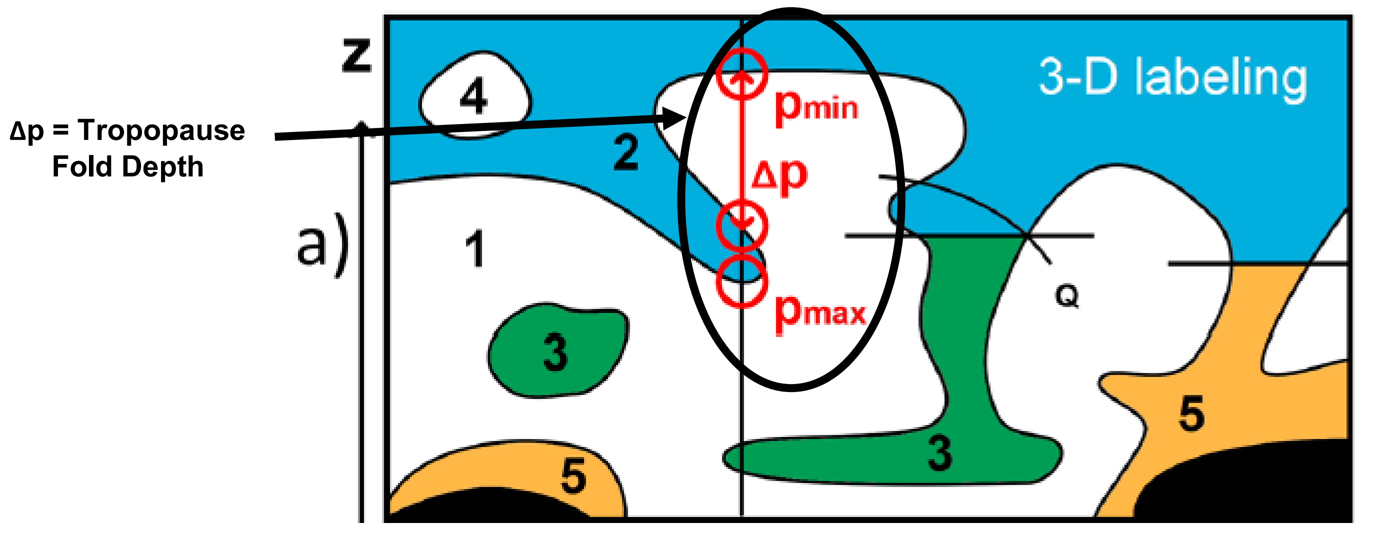
- Use of output from a tropopause fold identification algorithm (Škerlak et al., 2014), as applied to the ERA-Interim reanalysis, to elucidate STE transport pathways following SSWs.
- Assessment of changes in the frequency, distribution and extent of tropopause folding during such events.



A 3-D labelling algorithm applied to every grid point to diagnose tropopause fold activity

CONCLUSIONS

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- Persistence of O_3 and H_2O anomalies for ~ 2-3 months in the polar LMS, consistent with known dynamical perturbation timescales in response to PJO-type (long-lived) SSWs (Hitchcock et al., 2013b).

- Enhanced tropospheric O_3 is found between 20-80 days after the onset of an event, centred around a +50 day lag, which we show may be important for AQ during spring when O_3 reaches a seasonal maximum.

- Heating changes in the LMS of ~ ±2 K may be important for Numerical Weather Prediction (NWP), in representing the downward coupling of the anomalous stratospheric circulation to the dynamical pattern of the troposphere. O_3 poorly represented or missing in these models so effect not captured.

Williams, R. S., Hegglin, M. I., Jöckel, P., Garny, H. & Shine, K. P. (2020). Composition feedbacks on air quality and weather instigated by sudden stratospheric warmings. *In Review*

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