

The 2018-19 Arctic stratospheric polar vortex

Article

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1	The 2018-19 Arctic Stratospheric Polar Vortex			
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13	SCENARIO doctoral training partnership at the University of Reading (NE/L002566/1).			
14	Abstract			
15	The stratospheric polar vortex is a westerly circulation that forms over the winter pole around			
16	10-50 km above the surface, which is known to influence mid-latitude weather patterns. During			
17	2018-19, the Arctic polar vortex demonstrated an unusually large amount of variability,			
18	including a strong and persistent sudden stratospheric warming (SSW) event, a strong vortex			
19	event, and a dynamic final stratospheric warming (FSW). In this article we discuss the			
20	evolution of the vortex, placing it in the context of wider observed climatology, and comment			
21	on its apparent impacts on tropospheric weather patterns – notably, the lack of a surface climate			
22	response to the SSW of similar magnitude to the February-March 2018 "Beast from the East"			
23	cold-wave.			

24 Introduction

25 The stratospheric polar vortex (SPV) is a planetary-scale cyclonic circulation which forms over 26 the winter pole each year in the stratosphere (the layer of the atmosphere 10-50 km above the 27 surface) and is encircled by the westerly polar night jet stream. The vortex develops due to 28 seasonal radiative cooling owing to the Earth's axial tilt; air within the vortex becomes isolated 29 and can cool to below -80°C as a result of the lack of solar heating. In the Northern Hemisphere 30 (NH), the SPV is highly variable on both intra- and inter-annual timescales. The distribution 31 of the oceans, continents, and mountain ranges produces large-scale planetary waves in the 32 mid-latitude tropospheric polar jet stream. Planetary-scale waves can also be formed by 33 anomalous heating associated with tropical convection, such as the Madden-Julian Oscillation 34 (MJO) or the El Niño-Southern Oscillation (ENSO). These waves can propagate vertically into 35 the westerly winds of the SPV and break in the stratosphere (akin to waves breaking on a 36 beach), depositing their momentum there and decelerating the westerly flow. Such waves can 37 only propagate into regions of westerly flow; this communication of wave activity from the 38 troposphere to the stratosphere is absent in the summertime when stratospheric easterlies are 39 present. The stratospheric circulation typically only supports large-scale waves of wavenumber 40 1 or 2 (whereas many higher wavenumbers are present in the troposphere). Contrastingly, the Southern Hemisphere (SH) SPV is relatively strong and stable with less inter-annual variability 41 42 due to the symmetric Southern Ocean encircling Antarctica.

43

Sometimes, the SPV can break down entirely in an event known as a sudden stratospheric warming (SSW) (Scherhag, 1952). If the event is sufficiently strong to reverse the zonal-mean zonal (westerly) wind at 10 hPa and 60°N (hereafter, U10₆₀), the event is defined as major (Charlton and Polvani, 2007; Butler et al., 2015). Major SSWs occur approximately 6 times per decade in the NH though with significant longer-term absences (e.g. 1989-1998, 2013-

2018) (Butler et al., 2017), whilst only 1 has been observed in the SH in 2002 (Newman and
Nash, 2005). SSWs, as the name suggests, involve a sudden warming of the polar stratosphere
- temperatures have been observed to rise over 50°C in only a few days. The westerly
circulation of the SPV is disrupted; the vortex either splits into two or is displaced from the
pole (so-called 'split' and 'displacement' events, respectively).

54

55 The variability of the NH SPV, including SSWs and their strong-vortex counterpart, is 56 important for day-to-day weather as it can affect the state of the tropospheric Northern Annular 57 Mode (NAM)/Arctic Oscillation (AO), and the North Atlantic Oscillation (NAO) (Baldwin 58 and Dunkerton, 2001; Kidston et al., 2015) – which are essentially measures of the strength of 59 the westerly mid-latitude flow in the NH and North Atlantic respectively. The AO and the 60 NAO are associated with extratropical temperature and precipitation patterns. In general, weak 61 (strong) vortex events are followed by negative (positive) phases of the AO/NAO and colder and drier (warmer and wetter) weather in places such as Britain and northwest Europe. 62 63 However, recent work has shown that the relationship between SSWs and the AO/NAO varies 64 on a case-by-case basis, and is only a strong relationship (if at all) in approximately half of 65 observed major SSWs (Karpechko et al., 2017). The exact reasons why some stratospheric 66 events couple to the surface weather and some do not is poorly understood, and an area of 67 active research. In February 2018, the first major SSW since January 2013 occurred, and the 68 following period into March was unusually cold across Eurasia with a strongly negative 69 NAO/AO pattern (Karpechko et al., 2018). The moniker "The Beast from the East" was widely 70 used to describe the easterly flow which brought record-breaking cold temperatures to north-71 west Europe, including the UK (Greening and Hodgson, 2019). In contrast, the SSW in January 72 2019 was not followed by similarly cold conditions in Europe.

In this article, we discuss the evolution of the Arctic SPV during 2018-19. The SPV exhibited an unusually high level of variability during this winter, including a major SSW, a strong vortex event, and a dynamically-driven final stratospheric warming. We place these events in the wider context of the observed climatology of the vortex, and comment on the impact on tropospheric weather patterns.

- 79
- 80 **Data**

We use data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim reanalysis (ERA-Interim) (Dee et al., 2011), retrieved from the ECMWF MARS archive (via <u>https://apps.ecmwf.int/datasets/</u>). Climatological values are those observed between January 1979 and June 2018 inclusive. NAO and AO data indices are accessed from the National Centers for Environmental Prediction Climate Prediction Center (NCEP CPC) website (https://www.cpc.ncep.noaa.gov/).

87

88 The Polar Vortex in 2018-19

89 The evolution of the SPV during 2018-19 can be readily sorted into five distinct phases:

90 1) The spin-up and development of the SPV during August-October 2018.

- 91 2) Pre-SSW evolution (so-called 'pre-conditioning') of the SPV during November92 December 2018.
- 3) The onset and evolution of the major SSW during January 2019.
- 4) The subsequent recovery and development of a strong SPV event during March 2019.
- 5) The final stratospheric warming and vortex dissipation during April 2019.
- Timeseries of the evolution of $U10_{60}$ and 45-75°N mean eddy heat flux (denoted [v*T*]) at

97 100 hPa are shown in Figure 1 and Figure 2. The latter quantity is commonly used as a

98 diagnostic of vertically propagating wave activity in the lower stratosphere. It is computed by

- calculating the area-weighted average across 45-75°N of the zonal-average of the products of
 the departures from the zonal-mean T and v.
- First, we describe the stratospheric evolution during 2018-19, and then discuss the impacts onthe troposphere.
- 103

104 September-October 2018: Vortex spin-up

Daily mean U10₆₀ first became westerly on 22 August (see **Figure 1**), indicating the development of the SPV for the 2018-19 season. This was 3 days earlier than the climatological mean date of 25 August – however, variability at this time of year is small, and in all cases in ERA-Interim climatology, the SPV spins up by 30 August. Zonal-mean zonal winds tracked slightly below normal during September, before strengthening towards date-record strong values by the second half of October 2018. Though some fluctuations occurred, U10₆₀ remained mostly stronger than average through November.

112

113 November-December 2018: Preconditioning

114 During November 2018, vertically propagating wave activity began to increase. By the 115 beginning of December, the effect of this wave activity was evident in a deceleration of $U10_{60}$ to below-normal values. Notably, the beginning of the weakened SPV occurred during the 116 117 period of climatological maximum wind speed, although this is also when observed variance 118 markedly increases. In early December, the amplitude of wavenumber-1 increased to above-119 average values (i.e., a strengthened Aleutian high), and the SPV was displaced towards Eurasia 120 and became elongated (Figure 3). This is consistent with the structure and positioning of the SPV prior to major SSWs. Anomalously high heat flux persisted, reaching daily 90th percentiles 121 122 in the second half of the month, as shown in **Figure 2**. Individual daily or seasonal heat flux 123 records were not broken at 100 hPa; this pre-SSW evolution was not an example of one large 124 wave pulse, but prolonged elevated wave activity. Polar cap temperatures subsequently 125 warmed, and westerly zonal winds began to rapidly decrease during the final week of 126 December. At the same time, polar cap total column ozone increased (not shown). Stratospheric 127 ozone levels and polar vortex variability are strongly coupled – the regularity of NH SSWs and 128 the weaker SPV compared with its SH counterpart are key reasons why the Arctic does not 129 regularly see a large ozone hole. Increasing polar cap ozone is a common occurrence during 130 stratospheric vortex disruption; it is driven primarily by enhanced poleward transport from 131 equatorial regions (owing to the amplified stratospheric wave field and mixing from wave 132 breaking) where concentrations are higher (de la Cámara et al., 2018).

133

134 January 2019: Major SSW

135 Following the period of vortex weakening, daily-mean U10₆₀ became easterly on 2 January, indicating a major SSW was underway. This was the 6th earliest date (out of 26 events) for a 136 137 major SSW since 1979 (the earliest being 4 December 1981) according to ERA-Interim 138 reanalysis. The vortex was displaced towards the Atlantic sector by the strong Aleutian 139 anticyclone, and then split into two smaller vortices (Figure 4). Unlike the SSW in February 140 2018, where an unusually strong vortex was abruptly torn in two by an amplified wavenumber-141 2 pattern (i.e., both Atlantic and Aleutian ridges), the January 2019 major SSW resulted from 142 the splitting of a weak vortex by a wavenumber-1 pattern without wavenumber-2 amplification. 143 This is consistent with the prolonged elevated heat flux weakening the vortex over a longer 144 period, rather than a single extreme pulse.

145

The easterly zonal-mean zonal winds persisted for 21 days until 23 January (slightly longer than the February 2018 event, and tied with February 1999 for 7th longest in 26 events in ERA-Interim, see **Table 1**), with U10₆₀ reaching a minimum of -10.2 m s⁻¹ on 10 January (16th most 149 easterly). The duration was above the mean of 14 days, but lies within 1 standard deviation (10 days), whilst the minimum $U10_{60}$ was slightly above the mean of -12.1 m s⁻¹, though also within 150 1 standard deviation (7.9 m s⁻¹), as shown in **Figure 5**. Considering all events in ERA-Interim, 151 the minimum U10₆₀ and the duration of the easterlies are inversely correlated (Pearson's r = -152 0.62, Spearman's ranked correlation r = -0.69, p < 0.001), indicating SSWs which more 153 154 strongly disrupt the stratospheric circulation and generate stronger easterly zonal-mean 155 momentum tend to take longer to recover to westerlies. The main exception to this is the SSW 156 of 24 February 1984, which was the longest lived (39 easterly days) but had a below-average 157 minimum wind.

158

Following the split of the SPV, the two smaller vortices resided over Eurasia and North America. The North American lobe was associated with a surface circulation that lead to record-breaking cold temperatures in the northern U.S. and Canada during late January 2019 (BBC News, 2019).

163

164 February-March 2019: Strong Vortex Event

165 Following the recovery of the SPV, a strong vortex event ensued on 5 March, which is defined as U10₆₀ exceeding 41.2 m s⁻¹, following Tripathi et al. (2015). This peaked on 12 March 166 (Figure 6), when daily-mean U10₆₀ reached 52.2 m s⁻¹ which set new daily records (c.f. Figure 167 168 1) with the SPV forming an almost perfect annulus around the Arctic. The strong recovery of the SPV following the SSW is dynamically consistent with the prolonged period of easterly 169 170 winds – these effectively 'shield' the mid-to-upper stratosphere from tropospheric planetary 171 wave activity which can only propagate into westerly flow, allowing the vortex to be undisturbed and re-develop through radiative cooling. A secondary component pertains to the 172 173 timing of the SSW – being relatively early-season, minimal solar radiation reached the Arctic during the following weeks, allowing further enhanced radiative cooling. For example, a similar SSW-to-strong vortex transition was seen following the early-season SSW of 8 December 1987 ($U10_{60}$ reached a date-record 70.4 m s⁻¹ on 13 February 1988). Associated with the strong SPV were date-record-cold 10 hPa 60-90°N average temperatures from 16 February to 19 March, with a minimum of -75°C on 24 February.

179

180 April 2019: Final Stratospheric Warming

181 U10₆₀ became easterly again on 23 April in the final stratospheric warming (FSW), which is 182 defined to be the first day of easterly $U10_{60}$ that is not followed by a recovery to westerlies for 183 at least 10 consecutive days until the following winter season (following Butler and Gerber, 184 2018). The 2019 date is 8 days later than the climatological mean date of 15 April, which is 185 typical of seasons with a mid-winter SSW owing to the following recovery (Hu, Ren and Xu, 186 2014). FSWs are radiatively driven as the sun returns to the Arctic pole, but can also be driven 187 by dynamic wave forcing akin to a major SSW. The FSW in April 2019 had a substantial 188 dynamic component, with high wave activity preceding the event (Figure 2). This developed 189 an unusually intense Aleutian high which displaced the weakening SPV (Figure 7) and produced date-record strong easterly $U10_{60}$ in early May (a minimum of -20.4 m s⁻¹ was reached 190 191 on 4 May). Although the envelope of variability becomes smaller into the summer, $U10_{60}$ 192 remained close to date-record minima through June.

193

194 Connection to the Troposphere

The dynamic connection between the stratosphere and troposphere can be readily shown by a vertical cross-section of a timeseries of polar cap geopotential height anomalies. These are often referred to as "dripping paint" plots, as they show the downward propagation of stratospheric anomalies over time. The evolution in 2018-19 is shown in **Figure 8**. Prior to the 199 SSW, there is little indication of coupling between the troposphere and stratosphere, though 200 from September to November there are anomalously high geopotential heights in the 201 troposphere. This indicates a tendency toward blocked and amplified mid-latitude flow, which 202 may have helped drive the high wave activity during autumn 2018. Following the SSW, the 203 associated anomalies did not propagate downwards below ~200 hPa into the troposphere until 204 a brief, weak spell in early February, indicating the SSW did not couple persistently to surface 205 weather patterns. However, it should also be noted that anomalously low geopotential heights 206 were also absent from the Arctic troposphere during this time. Afterwards, the strong vortex 207 event coupled strongly to the troposphere during March, and the final warming in late April 208 also produced a very strong response at the surface that persisted through May (even though 209 the middle-stratospheric anomalies were not as strong as during the SSW, suggesting the 210 importance of lower-stratospheric anomalies in stratosphere-troposphere coupling).

211

212 The response of the troposphere to SPV variability is traditionally discerned in terms of the 213 behaviour of the hemispheric AO pattern, and the more regionalised NAO pattern. The sign of 214 these, on average, is negative following major SSWs and positive following strong SPV events. 215 For example, following the February 2018 SSW, a strong and persistent negative AO/NAO 216 pattern developed, indicating anomalously weak tropospheric westerlies. For deep and 217 persistent cold in Europe, a negative NAO is usually required. The evolution of the two indices 218 in 2018-19 is shown in Figure 9. Neither index transitioned into a strongly negative state 219 following the SSW. However, during January 2019, the AO was persistently more negative 220 than the NAO. This indicates that whilst anomalously high pressure developed over higher 221 latitudes, this did not project onto the NAO pattern. The opposite followed during February 222 into early March, when the strongly positive AO was not reflected in a strongly positive NAO; 223 however, it is unlikely that during this time the AO was responding to the strong vortex at 10 224 hPa, as lower stratospheric winds remained weak (c.f. positive height anomalies during this 225 time in Figure 8), possibly indicating other tropospheric drivers. During both periods, the NAO 226 remained persistently neutral or weakly positive. Indeed, the distribution of the daily NAO 227 index during February was unusual in the historical record; no other February since 1950 228 exhibited the combination of both a weakly positive mean state and weak variance about the 229 monthly mean. Following mid-March, the AO and NAO began to be more in-phase as the 230 strong vortex event propagated downwards, and evolved similarly through April into May. A 231 negative NAO/AO pattern then developed following the final warming. The NAO was more 232 negative following the final warming than following the SSW or at any other point in the 233 extended winter period (the mean NAO index for May 2019 was -2.62 σ , the lowest for the 234 month of May in the CPC record stretching back to 1950) giving an unusual example of late-235 season stratosphere-troposphere coupling. May 2019 was also the first month for the UK with 236 a mean temperature below the 1981-2010 average since September 2018, and had the largest 237 negative anomaly of any month since March 2018 (Met Office, 2019) (during which the "Beast 238 from the East" cold-wave occurred).

239

240 Conclusions

241 During 2018-19, the stratospheric polar vortex (SPV) was highly variable, with a major split-242 type sudden stratospheric warming (SSW) in January, followed by a strong vortex event in 243 March, culminating in a dynamic final stratospheric warming (FSW) in April. The major SSW 244 did not strongly couple with tropospheric weather patterns. The North Atlantic Oscillation 245 (NAO), which typically responds to stratospheric events, did not transition to a strong negative 246 phase following the event like in February 2018, which resulted in less notable impacts to 247 Europe in particular. In contrast, the strong vortex event did couple to the surface and generate 248 a strongly positive Arctic Oscillation (AO) and NAO in during March. Following the later than

- average dynamically driven FSW in April, the AO and NAO transitioned into strongly negativestates.
- 251

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- 254 SCENARIO doctoral training partnership at the University of Reading (NE/L002566/1).
- 255
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302	2019 according to ERA-Interim reanalysis. Climatological values are also indicated.		
303			
304	Figure 2: Timeseries of meridional eddy heat flux at 100 hPa, averaged across 45-75°N, from		
305	July 2018 through June 2019, according to ERA-Interim reanalysis. Climatological values are		
306	also indicated.		
307			
308	Figure 3: 10 hPa wind (filled) and geopotential height (contoured) for 00Z 12 December 2018		
309	according to ERA-Interim reanalysis. Also indicated are the 60°N zonal-mean zonal-wind ([U]		
310	60°N) and the minimum and maximum geopotential height in the domain (Z_{min} and Z_{max}).		
311			
312	Figure 4: As in Figure 3 but for 2 January 2019 at the onset of the major SSW.		
313			
314	Figure 5: (a) Persistence of each SSW as defined by cumulative easterly zonal-mean zonal		
315	wind days at 10 hPa 60°N, (b) minimum 10 hPa 60°N zonal-mean zonal wind during each		
316	SSW, and (c) a scatter plot of duration versus minimum zonal-mean zonal wind, for all major		
317	SSWs in ERA-Interim reanalysis 1979-2019. Red (blue) indicates the SSW is classified as		
318	(non-)downward propagating in Karpechko et al. (2017), extended to include the 2018 and		
319	2019 events. The SSW of 24 March 2010, shown in grey, was not classified in that study. In		
320	(a) and (b) the black dashed (dotted) lines denote the mean (standard deviations) of each		
321	quantity. In (c) the linear regression is shown with a solid black line.		
322			
323	Figure 6: As in Figure 3 but for 12 March 2019 at the peak of the strong vortex event.		
324			
325	Figure 7: As in Figure 3 but for 23 April at the onset of the final warming.		
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Figure 1: Evolution of 10 hPa 60°N zonal-mean zonal winds from July 2018 through June

326	Figure 8: Timeseries of 60-90°N average geopotential height anomalies from 1 August 2018
327	through 31 May 2019 in ERA-Interim. Anomalies are standardized departures expressed with
328	respect to the daily mean and standard deviation from 1979-2019. Vertical dashed lines indicate
329	(from left-to-right) the vortex spin-up, the major SSW, the peak of the strong vortex event, and
330	the final warming.
331	

- **Figure 9:** Timeseries of daily North Atlantic Oscillation (NAO, left-hand axis in blue) and
- Arctic Oscillation (AO, right-hand axis in red) for 1 November 2018 to 31 May 2019.

Table 1: Top 10 (of 26) major SSWs in ERA-Interim ranked by persistence of easterlies. 2019

is indicated in bold. The duration is defined following Charlton and Polvani (2007) – these are

the total number of easterly days associated with the event and are not necessarily consecutive.

Rank	Major SSW	Persistence (days)
1	24 Feb 1984	39
2	24 Jan 2009	30
3	23 Jan 1987	29
4	21 Feb 1989	28
5	21 Jan 2006	26
6	6 Jan 2013	22
7 (tied)	2 Jan 2019	21
	26 Feb 1999	21
9	12 Feb 2018	19
10	22 Feb 2008	15

337



340 Figure 1: Evolution of 10 hPa 60°N zonal-mean zonal winds from July 2018 through June 2019





Figure 2: Timeseries of meridional eddy heat flux at 100 hPa, averaged across 45-75°N, from
July 2018 through June 2019, according to ERA-Interim reanalysis. Climatological values are
also indicated.



Figure 3: 10 hPa wind (filled) and geopotential height (contoured) for 00Z 12 December 2018
according to ERA-Interim reanalysis. Also indicated are the 60°N zonal-mean zonal-wind ([U]
60°N) and the minimum and maximum geopotential height in the domain (Zmin and Zmax).



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352

353 Figure 5: (a) Persistence of each SSW as defined by cumulative easterly zonal-mean zonal 354 wind days at 10 hPa 60°N, (b) minimum 10 hPa 60°N zonal-mean zonal wind during each 355 SSW, and (c) a scatter plot of duration versus minimum zonal-mean zonal wind, for all major 356 SSWs in ERA-Interim reanalysis 1979-2019. Red (blue) indicates the SSW is classified as 357 (non-)downward propagating in Karpechko et al. (2017), extended to include the 2018 and 358 2019 events. The SSW of 24 March 2010, shown in grey, was not classified in that study. In 359 (a) and (b) the black dashed (dotted) lines denote the mean (standard deviations) of each 360 quantity. In (c) the linear regression is shown with a solid black line.



361

362 Figure 6: As in Figure 3 but for 12 March 2019 at the peak of the strong vortex event.









Figure 8: Timeseries of 60-90°N average geopotential height anomalies from 1 August 2018 through 31 May 2019 in ERA-Interim. Anomalies are standardized departures expressed with respect to the daily mean and standard deviation from 1979-2019. Vertical dashed lines indicate (from left-to-right) the vortex spin-up, the major SSW, the peak of the strong vortex event, and the final warming.



372

373 Figure 9: Timeseries of daily North Atlantic Oscillation (NAO, left-hand axis in blue) and

