Early indications of anomalous behaviour in the 2019 spring ozone hole over Antarctica

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ABSTRACT
The level of quasi-stationary planetary wave (QSW) activity in the Antarctic winter stratosphere provides insights into the likely behaviour of the ozone hole in the following spring months. Observation of anomalously large amplitude of the QSW in winter stratospheric temperatures is an indicator that strong disturbances to the polar vortex are likely to occur, and may lead to large reductions in both the area of the Antarctic ozone hole and the overall amount of stratospheric ozone that is depleted. In the sudden stratospheric warming (SSW) preconditions in 2019, the maximum QSW amplitude over Antarctica in August was approximately 12 K, which was only 2 K less than conditions prior to the unprecedented major SSW in 2002. The additional factors disturbing the Antarctic stratosphere in austral winter 2019 were anomalously warm sea surface temperatures in the central tropical Pacific Ocean and the western Indian Ocean, and the descending easterly phase of the Quasi-Biennial Oscillation. Under these preconditions, the Antarctic ozone hole in 2019 had the potential to demonstrate the early disruption and reduced level of the ozone depletion that has been confirmed by the satellite ozone observations. The anomalous ozone hole may also have important regional consequences for weather conditions in the Southern Hemisphere.

1. Introduction

Although the ozone hole over Antarctica develops in the austral spring (September–November), it is strongly influenced by the state of the Antarctic stratosphere in the preceding winter (June–August). Dynamical disturbance of the winter stratospheric vortex by planetary waves weakens the strength of the vortex and reduces the amount of ozone that is depleted within the ozone hole during spring (Shindell, Wong, and Rind 1997; Allen et al. 2003; Huck et al. 2005; Grassi, Redaelli, and Visconti 2008; Weber et al. 2011). Observations of quasi-stationary planetary wave (QSW) activity in the lower stratosphere during August provides
insight into the state and dynamics of the ozone hole that will take place in the following spring months. As discussed in (Grytsai, Evtushevsky, and Milinevsky 2008; Kravchenko et al. 2012), the amplitude of the QSW in stratospheric temperature serves as a key predictor of both the level of dynamical disturbance that the polar vortex is likely to display in spring and the final breakdown date of the ozone hole.

An additional factor that potentially influences the level of disturbance to the ozone hole is the state of tropical sea surface temperatures (SSTs). In (Evtushevsky et al. 2015; Evtushevsky, Grytsai, and Milinevsky 2019) it was shown that SST anomalies in the central Pacific in June can force disturbances in the temperature of the Antarctic stratosphere which have peak influence in the following October. This link arises when wave trains generated by deep convection over warm SST anomalies propagate poleward from the troposphere to the Antarctic stratosphere (Grassi, Redaelli, and Visconti 2008; Lin, Fu, and Hartmann 2012; McIntosh and Hendon 2018; Domeisen, Garfinkel, and Butler 2019). In 2019, the combination of the quasi-stationary wave 1 (QSW-1) in extratropical stratospheric temperatures having a large amplitude in August and strong surface warming in the central tropical Pacific Ocean, as well as in the western Indian Ocean, in June had the potential to cause an early disruption of the ozone hole.

The ozone hole evolution is also influenced by the Quasi-Biennial Oscillation (QBO) due to the modulation of the polar vortex strength (Holton and Tan 1980; Watson and Gray 2014). The sudden stratospheric warming (SSW) appears earlier and is more intense, and planetary wave amplitude is larger for the easterly QBO phase (Holton and Austin 1991; Anstey, Shepherd, and Scinocca 2010). In this paper, based on a SSW predictor analysis, the stratospheric preconditioning that took place in the Antarctic austral winter of 2019 is discussed.

2. Data and method

Similar to Kravchenko et al. (2012) we use the QSW amplitude in August at 50° S – 80° S and 50 hPa to provide an indication of October ozone hole area. The amplitude of the wave is obtained from a zonal monthly average temperature data from the NCEP–NCAR reanalysis (NNR; https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html). We use also NNR data to obtain the June monthly average SST for the central tropical Pacific (20° N – 20° S, 160° E – 220° E), as was done by Kravchenko et al. (2012). HadISST data for the tropical SSTs were also used from http://hadobs.metoffice.gov.uk/hadisst/.

Additional atmospheric parameters are illustrated by data from the Climate Prediction Centre (https://www.cpc.ncep.noaa.gov/products/stratosphere/polar/polar.shtml), NASA Ozone Watch (https://ozonewatch.gsfc.nasa.gov/), NASA GSFC Atmospheric Chemistry and Dynamics Laboratory (https://acd-ext.gsfc.nasa.gov/Data_services/met/qbo/), the KNMI Climate Explorer (https://climexp.knmi.nl) and Climate System Monitoring of Japan Meteorological Agency (http://ds.data.jma.go.jp/tcc/tcc/products/clisys/STRAT/).

3. Preconditions

In the SSW preconditions in 2019, the maximum QSW amplitude in stratosphere temperature over Antarctica in August was similar to conditions prior to the unprecedented major Antarctic SSW in 2002 first described by Varotsos (2002, 2003) and later by Allen...
et al. (2003). The high QSW amplitude in temperature at 50 hPa in August 2019 was similar to the precondition in 2002 in both meridional section (Figure 1(a), thick and thin solid curves, respectively) and time series for 60° S (Figure 1(b)) and suggested the possibility of a significant reduction of the area of the ozone hole in the forthcoming spring. Based on the QSW amplitude level in August 2019 (Figure 1), the possible ozone hole area in October 2019 could be between that in 1988 and 2002.

The second additional index to predict the behaviour of the ozone hole 2019 is the index of the SST variability in the central tropical Pacific (Evtushevsky et al. 2015; Evtushevsky, Grytsai, and Milinevsky 2019). In June 2019, the SST in this region from the NNR data increased to +28.5°C, the highest in the last 4 decades (Figure 2(a)). Note that the HadISST data reveals anomalous high SST level of +29.1°C in the tropical western Indian Ocean (10° S – 10° N, 50° E – 90° E) for June (Figure 2(b)). Anomalous thermal forcing from tropical convection over the central Pacific or the Indian Ocean can modulate the stratospheric response due to teleconnection (see Section 1). Figure 3 shows how the 10-hPa zonal wind anomalies progressively propagate poleward (dashed lines). Negative anomaly in zonal mean (−5 ms⁻¹ to −10 ms⁻¹) propagates between the tropics and SH high latitudes during the winter months (June–August, Figure 3(a)).

![Figure 1](image1.png)

**Figure 1.** (a) Latitudinal QSW amplitude variations in temperature at 50 hPa (~20 km) in August for the four anomalous years 1988, 2002, 2017 and 2019 versus the 1979–2019 climatology (grey curve with the standard deviation shown by vertical bars); (b) time series 1979–2019 of the QSW amplitude in August in the Antarctic stratosphere at 50 hPa, 60° S.

![Figure 2](image2.png)

**Figure 2.** The mean June sea surface temperature (SST) in (a) the central Pacific Ocean (20° S – 20° N, 160° E – 220° E) and (b) the western Indian Ocean (10° S – 10° N, 50° E – 90° E). In 2019, the temperatures in these regions were the highest in 40 years of observations: +28.5°C (central Pacific Ocean) and +29.1°C (western Indian Ocean).
This tendency is mainly contributed by the strong negative anomalies migrated from the tropical Indian Ocean and central Pacific (Figure 3(b,c), respectively), not from the tropical Atlantic Ocean (Figure 3(d)) or other tropical regions (not shown). Negative anomaly in the Pacific sector (Figure 3(c)) starts to propagate poleward from the subtropics in mid-August. This time lag compared to the Indian Ocean sector (Figure 3(b)) could be due to upper-stratospheric and downward propagation in June–July such that anomaly reaches the middle stratosphere in mid-August. More detailed analysis is needed in future work for the upper-level circulation within the Pacific sector.

In the late August, the negative wind anomalies reach the polar vortex at about 60° S (Figure 3(a–c)) and weaken it allowing more waves to propagate into the stratosphere (Figure 4(a)).

This is seen from the strong increase in the wave 1 amplitude in geopotential height (Z1) at 60° S and heat flux (HF) towards the South Pole (45° S – 75° S) at 100 hPa (Figure 4(a), solid and dashed curves, respectively). Simultaneously, sudden late-August deceleration of the zonal wind...
wind and SH polar cap warming occur (Figure 4(b), dashed and solid curves, respectively). Note that both Z1 and HF pulses in June and July (Figure 4(a)) do not lead to such changes in the polar zonal wind and temperature (Figure 4(b)). On the other hand, the late-August vortex deceleration is a precondition for further zonal wind weakening and stratospheric warming in September and October (Figure 4(b)). Strong warming in the Antarctic stratosphere in the early spring of 2019 is associated with anomalous poleward heat flux (dashed curve in Figure 4(a)). Strong negative fluxes indicate poleward transport of heat via eddies that may result in a smaller polar vortex and an earlier transition from winter to summer circulations (https://www.cpc.ncep.noaa.gov/products/stratosphere/polar/polar.shtml; Limpasuwan et al. 2005).

A favourable factor for an unstable polar vortex over Antarctica in spring 2019 was also the evolution of the QBO, which was in the easterly descending phase (Figure 5). As noted in Section 1, the polar vortex and ozone hole disappear earlier in the easterly QBO phase (Holton and Tan 1980; Holton and Austin 1991; Anstey, Shepherd, and Scinocca 2010; Watson and Gray 2014). The QBO wind at 10 hPa was easterly from May 2019 (Figure 5(a)) and contributed to the polar vortex destabilization. Along with the easterly descent through the stratosphere (Figure 5(b)), progressive poleward expansion of the easterly is observed (marked by dashed lines in Figure 5(c)) in consistency with Figure 3. Thus, the QBO acts in winter–spring 2019 in the same direction (to earlier SSW occurrence) as the stratospheric QSW in August and tropical SST anomalies since June.

This development of stratospheric processes indicated a possible major SSW in September–October 2019, similar to that observed in September 2002 (Varotsos 2002, 2003; Allen et al.

![Figure 5](https://acd-ext.gsfc.nasa.gov/Data_services/met/qbo/).
which has occurred only once during observations of the ozone hole. We published this prediction in September 2019 (Milinevsky et al. 2019) and compare it with the observed ozone evolution in September–November 2019 in the next Section.

4. Observations

As shown in Figure 6, the total column ozone distribution over the Southern Hemisphere in the early part of spring in anomalous years (1988, 2002, 2012, 2017 and 2019) exhibited strong zonal asymmetry. A relatively small ozone hole and high total ozone values in the mid-latitudes of the eastern hemisphere are observed (Figure 6(a,b,d–f), respectively) under the influence of the meridional transport associated with the preconditioned quasi-stationary waves (Figure 1). Unlike this, large ozone hole centred over the South Pole and weak midlatitude ozone maximum were observed in 2006 (Figure 6(c)) due to weak wave activity (Figure 1(b)).

In the late spring, the ozone hole had collapsed much earlier in anomalous years (Figure 6(g,h,j–l)) than more typically observed (usually late November to early December; https://ozonewatch.gsfc.nasa.gov/meteorology/SH.html) as confirmed by the strong vortex conditions in 2006 (Figure 6(i)).

As seen from Figure 7, ozone hole sizes in 2002 and 2019 appear to be very close in August, October, and November (green and red curves, respectively, in Figure 7(a); see also Figure 8(b) for October) and the excess of 2019 over 2002 was only 0.3% in August, 2.6% in October, and 2.1% in November (Figure 7(b)). Large reduction of the ozone size occurred in September 2019, by 27.3% relatively September 2002: \(10.4 \times 10^6 \text{ km}^2\) and

![Figure 6](image-url)
~14.3 × 10^6 km^2, respectively (Figure 7 and Figure 8(a)). The complete recovery of the Antarctic ozone hole in early November 2019 is close to the completion dates of the 2002 event (Figure 7(a), red and green curves).

In general, the ozone hole in the spring 2019 had the record small size since the 1980s (Figure 8) in agreement with the ranks of the preconditioning indices based on the QSW amplitude and SST anomalies (Figure 1 and Figure 2).

5. Discussion

As known, short-term forecasts provide fairly reliable data on the development of stratospheric processes on a synoptic timescale (5–10 days). This is confirmed by the ozone hole parameters in 2019 forecasted, for example, by the Tropospheric Emission Monitoring Internet Service (TEMIS, http://www.temis.nl/protocols/O3 forecast.html), the NASA Modern-Era Retrospective analysis for Research and Applications (MERRA2, https://acd-ext.gsfc.nasa.gov/Data_services/met/ann_data.html), National
Oceanic and Atmospheric Administration (NOAA, https://www.cpc.ncep.noaa.gov/products/stratosphere/strat-a_f/#emcoz) and Copernicus Atmosphere Monitoring Service (CAMS, https://atmosphere.copernicus.eu/monitoring-ozone-layer).

On a seasonal scale, existing forecasts are less reliable and can determine general trends in the atmospheric conditions (Marshall and Scaife 2010; Tripathi et al. 2015; Karpechko, Tummon, and Secretariat 2016; Lim et al. 2020). In this case, cyclical phenomena with reasonably predictable seasonal and annual variability of phases and trends, such as El Niño or QBO (Trenberth et al. 2002; Marshall and Scaife 2010) are used. The identification of the factors that limit the seasonal predictability of stratospheric processes is an urgent problem in global climate forecasting (Tripathi et al. 2015). Our forecast indices are based on statistically established patterns of winter preconditions, which determine to large extent the state of the Antarctic stratosphere in spring (Kravchenko et al. 2012; Evtushevsky et al. 2015; Evtushevsky, Grytsai, and Milinevsky 2019).

From August 2019, wave 1 dominated in the SH (Figure 4a, solid curve), largely contributed to the QSW preconditions (Figure 1) and provided steady displacements of the ozone hole towards South America and Atlantic ocean during the spring (Krummel and Fraser 2019). This distinguishes the event 2019 from event 2002, which characterized by wave 2 activity with the ozone hole split (Varotsos 2002; Allen et al. 2003). Another difference is in the duration of the SSW. If the SSW in 2002 corresponded to the criterion of the major SSW with rapid (in several days) 10-hPa zonal wind reversal (Allen et al. 2003), then the easterly wind at 10 hPa appeared only in the late phase of the slowly evolved SSW in 2019 (Figure 4(b)) and the warming in 2019 did not meet the criterion of a major SSW (Lim et al. 2020). So, our assumption on the possible major SSW in 2019 (Milinevsky et al. 2019) was exaggerated, although the zonal winds at 10 hPa and 60° S came close to reversing during the main part of the warming in mid-September (Figure 4(b), dashed curve, and Figure 5(c)).

Tropical convection perturbations caused by tropical temperature anomalies, as known by the El Niño phenomena, have a global impact (see Section 1). Our studies showed that the June tropical disturbance through the stratospheric circulation branch reaches the Antarctic stratosphere and creates the greatest impact on its temperature after 4 months, in October (Evtushevsky et al. 2015; Evtushevsky, Grytsai, and Milinevsky 2019). In 2019, as seen from poleward migration of the negative zonal wind anomalies, tropical influences reached the SH polar stratosphere earlier, in late August–September (Figure 3). This occurred possibly due to the intense tropical SST anomalies in June 2019 (Figure 2). The warm tropical SST anomalies in the Pacific and Indian Ocean basins are associated with increased tropical deep convection and enhanced Rossby wave activity (Trenberth et al. 2002; Grassi, Redaelli, and Visconti 2008; McIntosh and Hendon 2018; Lim et al. 2020). The SST anomalies in both the Pacific and Indian oceans appear to generate poleward propagating wave trains seen in zonal and meridional winds at 200 hPa and geopotential height at 500 hPa (not shown). The simultaneous poleward wave driving and negative zonal wind anomaly migration from both the Pacific and Indian Ocean regions (Figure 3) may be the unique aspect of the SSW 2019. It is interesting that descending easterly phase of the QBO (Figure 5(b)) is associated with easterly poleward expansion (Figure 5(c), dashed lines) that could be an additional factor of the early deceleration of the SH stratospheric polar vortex in the spring.
6. Conclusions

In this study, we have demonstrated an influence of the winter preconditioning on the spring ozone hole over Antarctica and the ability to predict the possible ozone hole area and ozone depletion level in the austral spring 2019. The two proposed predictors, the quasi-stationary wave amplitude in the SH polar stratospheric temperature in August and sea surface temperature in the tropical Pacific and Indian Oceans in June were used. They indicated that ozone hole size in 2019 may be between those in 1988 and 2002, the years of the historically lowest ozone loss in the Antarctic spring, and this prediction has been confirmed by satellite observations used for the ozone hole size estimation (Figure 7 and Figure 8). Our estimate is close to the results by Krummel and Fraser (2019), who use different ozone hole metrics and conclude that the ozone hole 2019 was one of the smallest, weakest and shortest since the mid- to late-1980 s. However, as follows from a zonal wind analysis at 10 hPa, 60° S (Figure 4(b)), the SSW in 2019 did not meet the criterion of a major SSW (Lim et al. 2020).

As distinct from the major SSW 2002 in Antarctica, which was classified as vortex split event due to wave 2 dominance (Varotsos 2002, 2003; Allen et al. 2003), the SSW 2019 appears to be the vortex displacement event (Figure 6(f)) under the wave 1 influence (Figure 4(a)). In September–October 2019, Antarctic ozone hole has been completely displaced off of the pole towards South America and Atlantic Ocean (Krummel and Fraser 2019). Over the Arctic, due to the unstable atmosphere, such events as major SSWs occur every second year and result in a strong change in the regional surface climate (Charlton and Polvani 2007; Thompson, Baldwin, and Wallace 2002; Tripathi et al. 2015). The recent event of a major SSW over the Arctic was observed in February 2018 and brought a cold outbreak to Canada, the United States, and Ukraine in March (Karpechko et al. 2018; Vargin and Kiryushov 2019; Wang et al. 2019). Recent work suggests a link between weak stratospheric vortex conditions and extremes in the SH climate and especially Australian summer weather (Lim, Hendon, and Thompson 2018; Lim et al. 2019, 2020). Unprecedented warm and dry conditions occurred in parts of eastern Australia and northern New Zealand during the 2019/20 summer (Climate summary archive, 2020). Additionally, Abram et al. (2020) have shown that long-term changes are taking place in the strength of the Indian Ocean Dipole, and this has implications for the propagation of Rossby wave trains to the Antarctic region. These results provide guidance for further investigation of weather and climate effects of the disturbed Antarctic stratosphere during 2019 and other recent years.

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