Introduction to Special Collection "The Exceptional Arctic Stratospheric Polar Vortex in 2019/2020: Causes and Consequences"

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Key Points:

- The stratospheric polar vortex in 2019/2020 was the strongest and longest-lasting on record as described in this special collection
- This exceptionally strong and cold polar vortex led to unprecedented Arctic ozone loss, approaching that in some Antarctic winters
- Circulation anomalies linked to the vortex spanned the mesosphere to the surface, with implications for extreme weather and predictability

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Abstract

This paper introduces the special collection in *Geophysical Research Letters* and *Journal of Geophysical Research: Atmospheres* on the exceptional stratospheric polar vortex in 2019/2020. Papers in this collection show that the 2019/2020 stratospheric polar vortex was the strongest, most persistent, and coldest on record in the Arctic. The unprecedented Arctic chemical processing and ozone loss in spring 2020 has been studied using numerous satellite and ground-based datasets and chemistry-transport models. Quantitative estimates of chemical loss are broadly consistent among the studies and show profile loss of about the same magnitude as in the Arctic in 2011, but with most loss at lower altitudes; column loss was comparable to or larger than that in 2011. Several papers show evidence of dynamical coupling from the mesosphere down to the surface. Studies of tropospheric influence and impacts link the exceptionally strong vortex to reflection of upward propagating waves, and show coupling to tropospheric anomalies including extreme heat, precipitation, windstorms, and marine cold air outbreaks. Predictability of the exceptional stratospheric polar vortex in 2019/2020 and related predictability of surface conditions are explored. The exceptionally strong stratospheric polar vortex in 2019/2020 highlights the extreme interannual variability in the Arctic winter/spring stratosphere and the far-reaching consequences of such extremes.

Plain Language Summary

The Arctic stratospheric polar vortex – a band of strong winds roughly encircling the pole at about 65°N latitude from about 15 to 50 km above the Earth's surface that forms every winter – was exceptionally strong during the 2019/2020 winter. The strong vortex in the stratosphere was linked to unusual conditions at both higher and lower altitudes. This collection of papers explores the far-reaching consequences of the exceptionally strong stratospheric polar vortex in 2019/2020, including impacts on Arctic chemical ozone loss and on surface weather conditions. Chemical ozone loss in spring 2020 matched or exceeded the most previously on record (for 2011) and showed some features similar to the larger loss that occurs over the Antarctic every spring. The exceptionally strong stratospheric polar vortex was linked to weather extremes including record heat, unusual patterns of precipitation, marine cold air outbreaks, and windstorms.

1 Introduction

The 2019/2020 Northern Hemisphere (NH) stratospheric polar vortex was exceptionally strong and cold throughout the winter and spring. The prolonged period of low vortex temperatures combined with suppressed poleward ozone transport led to record low polar cap total column ozone between February and April of 2020 (Manney et al., 2020; Lawrence et al., 2020; Feng et al., 2021). Chemical ozone depletion was more extreme than previously observed in the NH during prior cold stratospheric winters, including that in the most recent comparable year 2011 (Wohltmann et al., 2020). Extremes were also observed in the troposphere. In particular, record high positive values of the Arctic Oscillation (AO) index in early 2020 concurrent with the strong vortex (Lawrence et al., 2020) suggest significant dynamical coupling between the polar stratospheric and tropospheric circulations.

These remarkable characteristics of the 2020 winter and spring season sparked significant interest among the members of the scientific community. A special collection of papers devoted to this topic was created across the American Geophysical Union journals under the name *The Exceptional Arctic Stratospheric Polar Vortex in 2019/2020: Causes and Consequences.* The call for papers seeks contributions on topics including *detailed meteorological descriptions of 2019/2020 stratospheric vortex characteristics and evolution in the context of wave fluxes and other atmospheric modes of variability; anomalous transport in the stratospheric vortex; lower stratospheric polar processing diagnos-*

tics and chemical processing, including polar stratospheric clouds (PSCs) and ozone extremes; tropospheric/surface precursors and feedbacks; surface impacts via downward stratosphere/troposphere coupling; effects on Arctic upper tropospheric flow and stratosphere/troposphere exchange; relationships to anomalous quasi-biennial oscillation (QBO) variations in 2020; implications for subseasonal to seasonal predictability; and possible relationships to climate change and/or climate interventions. These research topics reflect the known interconnections between the state of the stratospheric polar vortex and other elements of the Earth's system and its modes of variability. The vortex strength is controlled by variations in the intensity and propagation of planetary waves of mainly tropospheric origin (Matsuno, 1970; Polvani & Waugh, 2004) and non-linear dynamical processes within the stratosphere (Albers & Birner, 2014; de la Cámara et al., 2019). Vortex variability in turn impacts polar stratospheric ozone via both transport and chemical mechanisms (Weber et al., 2011; WMO, 2018). Variability of the the stratospheric polar vortex also influences the surface weather on timescales of weeks to months, providing a source of subseasonal to seasonal predictability.

The present paper introduces this special collection. In addition to the motivation for it presented in this Introduction, this work provides a broad summary, categorized by main research topics, of the publications accepted to the collection so far. At the time of writing there are 26 papers in this special collection on subjects ranging from the dynamics and chemistry of the 2019/2020 polar stratosphere and mesosphere, to surface impacts of the stratospheric polar vortex and implications for subseasonal and seasonal forecasting, to connections with the Montreal Protocol and climate change.

The dynamics of the stratospheric polar vortex and the exceptionally low values of total column ozone emerge as the central themes of the research results discussed in this special collection. Both topics have found their way into the mainstream media and popular science outlets, prompting several authors to reevaluate the language that researchers use to communicate these topics to the public. Specifically, many experts express their concerns about the often imprecise and sometimes misleading use of the terms "polar vortex" and "ozone hole" in public discourse and scientific reporting.

A commentary in this special collection (Manney, Butler, et al., 2022) discusses the uses and misuses of the term "polar vortex" in popular media as well as scientific literature. They argue that while this well-established term accurately describes a well-defined major feature that dominates the circulation in the polar winter stratosphere, attempting to use this term to describe the tropospheric circulation is misguided, as that circulation is best characterized in terms of regional undulations of jet streams and the conventional language of ridges and troughs.

The term "ozone hole" when applied to instances of extreme ozone loss in the Arctic is equally problematic. While several metrics of ozone loss in 2020 approached values typical for the Antarctic (Section 3), occurrences of extremely low ozone were spatially localized and short-lived compared to those in the Antarctic. Wohltmann et al. (2020), as well as discussion published with Dameris et al. (2021, not in this special issue), briefly present arguments against referring to the polar ozone anomaly in 2020 as an "ozone hole", echoing previous arguments made in light of the 2011 Arctic ozone depletion (e.g., Solomon et al., 2014). These sources argue that the term "ozone hole" is inappropriate and potentially misleading for even the most extreme instances to date of low ozone resulting from chemical loss over the Arctic.

This paper is organized as follows. Section 2 summarizes and elucidates links among the contributions focused on dynamical processes in and affected by the stratospheric polar vortex. Section 3 summarizes the results of contributions focused on chemical processing and ozone loss in the 2019/2020 stratospheric polar vortex, including the observed ozone extremes. Section 4 discusses papers that focus on further implications, including subseasonal to seasonal predictability in the context of the 2019/2020 NH winter and spring, and effects of chemical processing in the stratospheric vortex on the troposphere and surface. Section 5 provides a brief summary and discusses broad implications in the context of ozone recovery and climate change.

2 Dynamical Features and Impacts of the Stratospheric Vortex in 2019/2020

Some measures of the anomalous stratospheric polar vortex strength and longevity are shown in Fig. 1. According to several diagnostics of vortex strength (including the NAM index shown in Fig. 1a, vortex-edge averaged wind speeds in Fig. 1b, and potential vorticity gradients shown in Fig. 1e,f), the vortex was the strongest and most persistent in a record of over 40 years (Lawrence et al., 2020; Manney et al., 2020). Lawrence et al. (2020) noted that it represented the most extreme case of two-way stratosphere-troposphere coupling on record. Figure 1a shows that anomalies related to the exceptionally strong vortex extend from the lower mesosphere to the surface, as discussed in detail in several papers described below. The stratospheric vortex was also unusually large in the lower through middle stratosphere, especially in spring (Fig. 1c), demonstrating its exceptional persistence, as well as unusually pole-centered (Fig. 1d). Further examination of vortex "moments" calculated as in Lawrence and Manney (2018) indicate that it was more circular (less distorted) than is typical. Lawrence et al. (2020) introduce many of the "causes and consequences" discussed further in individual focused papers. The upward influence on and of the stratosphere is apparent in the combination of weak tropospheric wave driving (Lawrence et al., 2020; Weber et al., 2021) and downward coupling events following the development of a reflective configuration of the stratospheric vortex, which resulted in the extreme robustness and persistence of the 2019/2020 Arctic stratospheric vortex (Lawrence et al., 2020). The persistent low temperatures and vortex confinement accompanying the exceptionally strong and long-lasting stratospheric polar vortex in 2019/2020 drove chemical processing leading to unprecedented lower stratospheric ozone loss (e.g., Lawrence et al., 2020; Inness et al., 2020; Manney et al., 2020; Weber et al., 2021; Wohltmann et al., 2020), as analyzed further in the papers discussed in section 3.

In addition to Lawrence et al. (2020) and discussion in papers related to polar processing (see section 3), several papers in the special collection discuss aspects of vertical dynamical coupling, including coupling to the troposphere and surface impacts (Lawrence et al., 2020; Dahlke et al., 2022; Rupp et al., 2022), connections to the upper stratosphere and mesosphere lower-thermosphere (MLT) (Lukianova et al., 2021; Ma et al., 2022), and vertical coupling during the spring vortex breakup (Matthias et al., 2021).

While much focus has been given to surface impacts following a disrupted stratospheric polar vortex, or sudden stratospheric warming, the winter/spring of 2020 demonstrated that persistent coupling of a strong polar vortex to the tropospheric circulation also has substantial effects on weather and extremes. In particular, the 2020 strong polar vortex was associated with the most positive January-March averaged Arctic Oscillation (AO) in the 70-year reanalysis record, and record high temperatures over Siberia (Lawrence et al., 2020). Other weather extremes were also observed during this time period, including extreme marine cold air outbreaks over the Fram Strait (Dahlke et al., 2022). Wetter than average conditions over northern Europe and drier than average conditions over southern Europe were consistent with the strongly positive phase of the AO (Lawrence et al., 2020). However, whether these anomalous patterns and extremes can be directly attributed to the downward influence of the stratosphere on the surface is less clear; while circulation extremes from the troposphere to the stratosphere were vertically coupled, they may have arisen by "fortuitous alignment" (Rupp et al., 2022). Nonetheless spring 2020 exemplified how strong vertical coupling in the atmosphere can result in diverse extremes.

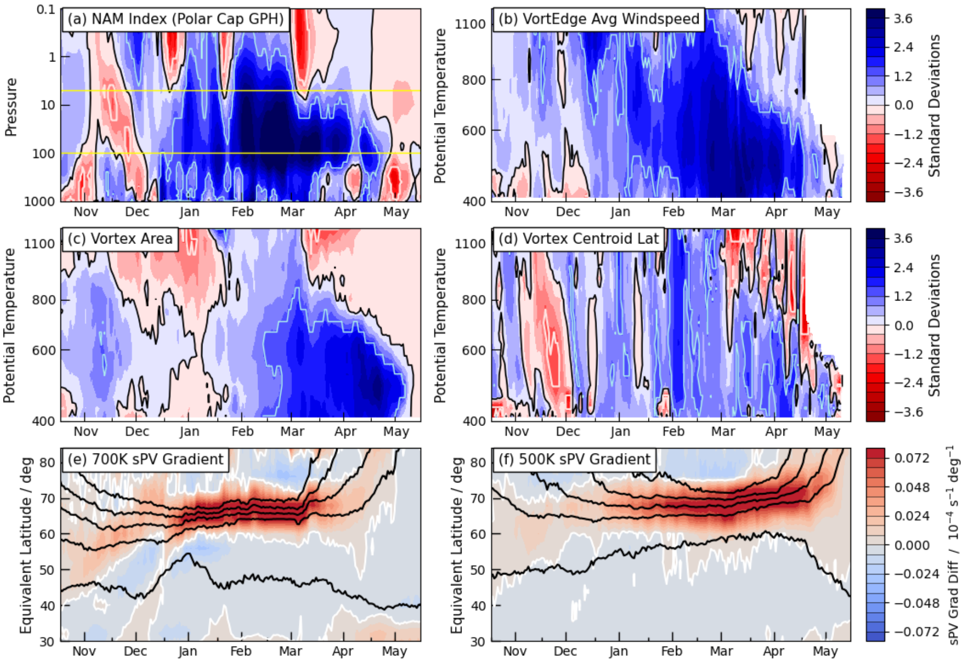

Figure 1. Example metrics of stratospheric polar vortex strength in 2019/2020 calculated from the MERRA-2 reanalysis (Gelaro et al., 2017): standard anomalies of (a) polar cap geopotential height (calculated as in Lawrence et al., 2020), (b) vortex-edge averaged wind speed, (c) vortex area, and (d) vortex centroid latitude; remaining panels show anomalies from climatology of scaled PV (sPV) gradients in the (e) middle (700 K) and (f) lower (500 K) stratosphere; black overlays show sPV contours in the vortex edge region. Fields in (b), (c), and (d) are calculated as in Lawrence and Manney (2018). Yellow horizontal lines in (a) show approximate vertical range shown in (b) through (d).

The effects of vertical coupling are also seen up into the mesospheric/lower thermosphere (MLT). A study of the climatology and characteristic patterns of the springtime transition in the stratosphere and mesosphere showed 2019/2020 to be a key example of a springtime transition for a "no negative NAM" case Matthias et al. (2021). In this class of spring transition, as in 2020, a minor warming in the upper stratosphere/lower mesosphere in early spring is unable to propagate downward due to the strong winds in the mid-stratosphere, thereby delaying the spring transition in until late spring, when it progresses smoothly downward. The most distinct features of the composite of no negative NAM cases arose from features of the evolution in 2019/2020, highlighting the unique extremes of the 2019/2020 polar vortex.

Additional unusual aspects of the circulation extending above the stratosphere were seen in the evolution of disturbances in winds and temperatures in the upper stratosphere/lower mesosphere (USLM) and the MLT: Lukianova et al. (2021) showed USLM disturbances in December 2019 and early January 2020 similar to those often preceding SSWs, but which in 2019/2020 were instead followed by episodic USLM and MLT zonal wind accelerations and rapid cooling of the entire stratospheric layer. Their results appear consistent with an extension into the MLT of the "split" upper stratospheric jet reported by Lawrence et al. (2020) that played a role in the wave reflection. Quasi-10-day waves in the MLT also showed anomalous behavior, especially in that they were unusually weak during a minor SSW that affected the upper stratosphere in February 2020, whereas they are typically enhanced following polar warming in the stratosphere (Ma et al., 2022). Ma et al. (2022)'s analysis suggested that the extremely strong stratospheric vortex was instrumental in inhibiting upward propagation of quasi-10-day waves from the stratosphere.

These papers provide a broad view of the dynamics of the exceptional Arctic stratospheric polar vortex in 2019/2020, including its upward influence through the mesosphere and downward influence to the surface. In the following sections we synthesize work on further consequences of the exceptional vortex strength in 2019/2020.

3 Polar Processing and Arctic Ozone Loss in 2019/2020

The process of chemical ozone loss in the lower stratospheric polar vortex is well understood and depends critically on heterogeneous chlorine activation on liquid aerosols and polar stratospheric clouds (PSCs) (e.g., Tritscher et al., 2021, not in this special issue). This process typically becomes significant below the formation temperature of Nitric Acid Trihydrate (NAT) PSCs, therefore this threshold temperature is commonly used to locate areas of stratospheric ozone loss. When integrated over the winter, 2019/2020 had the largest so-defined PSC potential on record in the Arctic (Lawrence et al., 2020; Wohltmann et al., 2020) because, while temperatures low enough for PSC existence persisted similarly long in 2020 to those in 2011, in late 2019 temperatures dropped below the PSC threshold in a large vertical region much earlier than they did in late 2010 (Lawrence et al., 2020; Manney et al., 2020; Wohltmann et al., 2020; Weber et al., 2021). PSC potential at some times during the Arctic winters of both 2011 and 2020 (including during fall and early winter 2019/2020) matched or exceeded that in some Antarctic winters (Wohltmann et al., 2020). Consistent with these results inferred from temperatures, DeLand et al. (2020) and Bognar et al. (2021) used observations of PSCs to document unprecedented Arctic PSC activity in March, comparable to the average in mid-August in the Antarctic.

Also critical to polar processing and ozone loss is the degree of confinement of air that is primed for ozone depletion inside the polar vortex, and how it is transported within the vortex. In addition to the metrics already discussed of exceptional polar vortex strength and longevity (Fig. 1e, f, Lawrence et al., 2020; Manney et al., 2020, also show diagnostics that are indicative of unusually low mixing), Manney, Millán, et al. (2022) discussed the unusual transport throughout the 2019/2020 winter, showing that in early winter unusual long-lived trace gas distributions arose primarily from descent of preexisting anomalies entrained into the vortex as it formed, whereas in spring trace gas anomalies arose primarily from inhibited mixing into the polar regions related to the late polar vortex breakup. Further, Curbelo et al. (2021) explored aspects of the evolution of and transport within the polar vortex during a vortex-split event in the lower to middle stratosphere in the period preceding the springtime vortex breakup. They detailed the lower-stratospheric vortex evolution and transfer of air from the main to offspring vortex during the split event, showing that air in the offspring vortex originated well inside the main vortex, but the air with lowest ozone values remained confined within the main vortex (which then persisted into mid-May). These results, in conjunction with the evidence of unprecedented Arctic ozone destruction summarized below, have important implications for how ozone-depleted air may be transported as the vortex is eroding in spring, possibly affecting (e.g., through enhanced surface UV, see section 4) densely populated regions.

Studies in this special collection focusing on observations and/or modeling of chemical ozone loss in the Arctic in 2019/2020 use satellite datasets including those from: the Aura Microwave Limb Sounder (MLS) (Manney et al., 2020; Manney, Butler, et al., 2022; Wohltmann et al., 2020, 2021; Feng et al., 2021; Grooß & Müller, 2021), the Atmospheric Chemistry Experiment-Fourier Transform Spectrometer (ACE-FTS) (Manney et al., 2020; Bognar et al., 2021; Grooß & Müller, 2021), the Aura Ozone Monitoring Instrument (Bernhard et al., 2020), the TROPOspheric Monitoring Instrument (TROPOMI), the Global Ozone Monitoring Experiment-2 (GOME-2), the SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY (SCIAMACHY), and the Ozone Mapping and Profiler Suite - Limb Profiler (OMPS-LP) (last four by Weber et al., 2021). In addition, several studies use ground- and/or balloon-based datasets (Bognar et al., 2021; Wohltmann et al., 2020). Inness et al. (2020) presented results from the Copernicus Atmosphere Monitoring service (CAMS) chemical reanalysis and the ERA5 reanalysis, both of which assimilate many of the satellite datasets listed above.

Quantitative estimates of Arctic ozone loss are highly uncertain and difficult to compare because of many factors including different methods and datasets (e.g., WMO, 2007; Griffin et al., 2019) and the strong influence of dynamical and transport processes that themselves may be represented differently in different meteorological datasets used in the calculations (and references therein Santee et al., 2022). Papers in this special collection (Manney et al., 2020; Wohltmann et al., 2020; Grooß & Müller, 2021) used MLS-Match (method as described in Livesey et al., 2015), vortex-averaged descent, and CTM passive subtraction methods to estimate chemical loss in ozone profiles. Given differences in datasets, methods, time periods, and definitions of vortex regions, their results are very consistent, estimating 2.3–2.8 ppmv of chemical loss in spring 2020, comparable in magnitude to that in 2011, but with maximum loss at a lower altitude. Several papers also presented estimates of chemical loss in column ozone. Again these span numerous datasets and methods, including differences in the geographic or vertical domains for which the estimates are calculated, but show good consistency, with estimates of maximum vortex or local loss ranging from about 108 to 130 DU (Wohltmann et al., 2020; Bognar et al., 2021; Feng et al., 2021; Grooß & Müller, 2021; Weber et al., 2021).

The above estimates of ozone loss each include comparisons with 2011, the previous year with the largest Arctic chemical ozone loss on record. In general the conclusions indicate that the amount of chemical loss was comparable in the two years, with some studies stating that each one showed slightly more. Several of the studies noted an unusually weak dynamical resupply of ozone via descent in the vortex in 2020 compared to that in previous winters including 2011 (Manney et al., 2020; Wohltmann et al., 2020; Feng et al., 2021), which may also contribute to the difficulty in making comparisons and the large uncertainties. Nevertheless, the overall picture of chemical ozone loss that emerges is very consistent across the studies.

The temperature and PSC evolution in the 2019/2020 Arctic winter, as well as evidence of vortex-wide denitrification (Manney et al., 2020; Wohltmann et al., 2021), suggests that it was more "Antarctic-like" than any previous Arctic winter on record (including 2010/2011). Chlorine from observations (e.g., Manney et al., 2020) and models (Grooß & Müller, 2021; Wohltmann et al., 2021) shows a more Antarctic-like pattern of chlorine deactivation in that the reformation of $ClONO_2$ was slower and HCl reformed very rapidly and to high values that far overshot those in fall before chlorine activation – similar to patterns seen in Antarctic spring under very low ozone and denitrified conditions (e.g., Douglass et al., 1995; Douglass & Kawa, 1999). Both observational and modeling results in this special collection thus indicate a progression of polar processing and ozone loss that was in between those typical for the Northern and Southern Hemispheres, and emphasize the exceptionally low ozone (Manney et al., 2020; Grooß & Müller, 2021; Wohltmann et al., 2021), with Wohltmann et al. (2021) noting that "only an additional 21–46 h below PSC temperatures and in sunlight would have been necessary to reduce ozone to near zero locally". Though unprecedented in the Arctic, the extreme ozone loss in spring 2020 was still far from the conditions seen in the Antarctic that we refer to as an "ozone hole".

4 Further Implications

Impacts of the strong 2019/2020 stratospheric polar vortex extend to effects of anomalous ozone evolution (via transport, chemistry, and radiative processes) on surface variability, including changes in UV (Bernhard et al., 2020), possible impacts of stratospheric ozone loss on surface temperatures (Xia et al., 2021) and tropospheric ozone (Steinbrecht et al., 2021; Bouarar et al., 2021), and possible implications for subseasonal to seasonal prediction (Lee et al., 2020; Rao & Garfinkel, 2020, 2021b).

One very direct consequence of exceptionally low ozone in the Arctic springtime polar vortex is on surface UV. Bernhard et al. (2020) found monthly mean low total ozone column anomalies up to ∼45% colocated with high UV index (UVI) anomalies of over ∼80% in March and April 2020, as compared to 30% and 35%, respectively, in 2011. High UVI anomalies exceeded 9 standard deviations in daily data at some stations underlying the polar vortex. Because the solar elevation was still relatively low when the vortex broke up, these anomalous values did not result in high absolute UVI values (in contrast to those in the Antarctic spring, when the ozone-depleted vortex persists longer into spring/summer than any on record in the Arctic, even in 2020).

Given the strong coupling between dynamics, ozone, and radiation in the springtime polar stratosphere, and the influence of these feedbacks on surface climate variability and trends in the Southern Hemisphere, efforts have been increasing to better understand if these feedbacks also play a role in the Arctic (e.g., WMO, 2018, Chapter 5). Dynamical coupling appears to dominate over direct influences of stratospheric ozone on surface climate [ref]. However, ozone feedbacks may be important for fully capturing the stratospheric influence on the surface. For example, Arctic ozone loss such as observed in 2019/2020 can reduce lower stratospheric static stability, which may increase high clouds and thus longwave radiation at the surface, contributing to surface warming (Maleska et al., 2020; Xia et al., 2021, former not in this special collection). Not all of the complex feedbacks among processes lead to negative impacts. For example, the strong polar vortex/positive AO (Section 2) led to reductions in tropospheric ozone comparable to or greater than those due to the influence of COVID19-associated emission reductions (Steinbrecht et al., 2021; Bouarar et al., 2021).

The persistence of the two-way coupling between the troposphere and stratosphere in 2020 suggests that the strong polar vortex event and its connection to surface climate may have shown enhanced predictive skill on subseasonal to seasonal timescales. For subseasonal (2–3 weeks) forecasts, surface temperatures and precipitation were better predicted for forecasts initialized during the strong polar vortex (Rao & Garfinkel, 2021b). For seasonal forecasts, it was found that ensemble members that better predicted destructive wave interference had better forecasts of the strong polar vortex, and ensemble members that better predicted the strong stratospheric polar vortex better predicted the anomalously strong AO (Lee et al., 2020). Hardiman et al. (2020, not in this special collection) also noted improved seasonal predictability of the North Atlantic Oscillation (NAO) and hence the exceptionally warm and wet 2019/2020 European winter, partly via a stratospheric pathway of the second strongest Indian Ocean dipole on record in late 2019, which they argue led to the strengthening of the polar vortex and its persistent influence on the NAO.

Because polar vortex strength is a proxy for stratospheric ozone amount, sub-seasonal forecasts initialized during polar vortex extremes should contain some information to constrain chemistry-climate interactions in the following weeks (Rao & Garfinkel, 2021b). Indeed, empirical relationships between the strength of the polar vortex and Arctic ozone can be used with some skill to forecast Arctic ozone extremes on sub-seasonal timescales (Rao & Garfinkel, 2020). However a better prediction of Arctic ozone by itself does not appear to produce better sub-seasonal forecasts of surface climate (Rao & Garfinkel, 2020).

5 Summary and Longer View

Though the 2019/2020 Arctic winter/spring represents one dynamical coupling event with links to numerous extremes, it's worth considering it in the broader context of ozone recovery and climate change. As the concentrations of ozone depleting substances (ODSs) in the stratosphere gradually decrease following the implementation of the Montreal Protocol and its amendments (MP) the stratospheric ozone layer is expected to recover to its pre-1980 levels (WMO, 2018). While the onset of ozone recovery has already been observed in the midlatitude upper stratosphere, trend detection over the Arctic is complicated by significant year-to-year dynamical variability and possible confounding factors arising from increasing concentrations of greenhouse gases (GHGs)(von der Gathen et al., 2021, not in this special collection). Nonetheless, chemistry model simulations suggest that the 2020 Arctic ozone loss, while intense, was to some degree mitigated by the decrease in the ODSs since their peak concentrations around the year 2000. Feng et al. (2021) estimate that the MP ameliorated the March 2020 ozone depletion by about 20 DU. Even more strikingly, Wilka et al. (2021, not in this special collection) found that the dynamical conditions observed in 2019/2020 would have produced areas of about 20 million km^2 of total ozone below 220 DU if the ODSs had continued to grow at a 3.5% annual rate since 1985 as they did before the implementation of the Montreal Protocol. This is close to the typical maximum size of the 21st-century Antarctic ozone holes. In comparison, the maximum area of total ozone below 220 DU reported in the Arctic in 2020 was below 1 million km^2 (Wohltmann et al., 2020; Kuttippurath et al., 2021, latter not in this special collection).

The work of Jucker et al. (2021) relates to questions of how extreme stratospheric vortex states may change in the future. They focus primarily on assessing the likely frequency of future SSWs in the Antarctic, with comparison to the Arctic. While Antarctic SSWs and other stratospheric vortex weakening events are expected to become much less likely in the next century with accompanying strong and longer-lived polar vortices, it is unclear what may happen in the Arctic – while the results of Jucker et al. (2021) do not suggest a large change in Arctic SSW frequency in the future, other studies show disagreement even in the sign of the SSW frequency response across models (e.g., Ayarzagüena et al., 2019; Ayarzagüena et al., 2020; Rao & Garfinkel, 2021a, papers not in this special collection). Correspondingly, we have no consensus as to whether exceptionally strong vortices such as that in 2019/2020 may become more or less common in the future.

Also subject to ongoing debate is how the human-induced increase of GHGs concentrations influence the stratospheric polar vortex and polar ozone depletion. There is currently little agreement in scientific literature regarding the future projections of the Antarctic polar vortex strength and temperature (Wohltmann et al., 2020, and references therein). Some published results suggest that "cold Arctic winters are getting colder (in the stratosphere)" under climate change (von der Gathen et al., 2021, not in this special collection). If correct, these results project that the wintertime Arctic will see even colder polar vortices than that in 2019/2020 and that extreme chemical ozone losses associated with these cold winters will continue to occur sporadically for the next several decades despite the decreasing ODSs.

A common thread among most of the studies in this special collection is the extensive use of satellite composition and temperature data to elucidate the evolution and important consequences of the exceptional 2019/2020 stratospheric polar vortex. These analyses are made possible by the wealth of satellite data currently available, and the increasing length of many of these data records. Continuity of satellite observations with near global daily coverage has thus been critical for understanding the 2019/2020 winter, and continued long-term measurements will be invaluable for future exceptional events. This is true not only for ozone data, but also both for additional species important to polar chemical processing and evaluation of transport, and for temperatures and dynamical information in the upper stratosphere and mesosphere where observations are sparse and thus data assimilation models are not well-constrained. While continuing ozone records will be provided by some newer platforms and scheduled launches, this is not the case for high-altitude temperatures or for other chemical species that are critical to understanding the immediate and potential future environmental and human impacts of extreme conditions / events in the middle atmosphere.

The papers in this special collection on "The Exceptional Arctic Stratospheric Polar Vortex in 2019/2020: Causes and Consequences" provide a broad view of the evolution of an exceptionally strong Arctic stratospheric polar vortex and processes that affected and were affected by it. They also raise questions that will be fruitful avenues for further investigation including possible impacts of the strong polar vortex on tropopause variations and stratosphere-troposphere exchange and possible links to the QBO disruption in 2019/2020. Exceptionally strong stratospheric polar vortex states have been much less studied than SSWs and weak vortex states, and understanding the vast interannual variability in the Arctic winter stratosphere poses unique challenges, including for key topics such as the importance of stratospheric variability to human and environmental impacts, to climate change impacts and trend evaluation, and to predictability of future strong vortex states on subseasonal to seasonal and longer time scales.

6 Open Research

The data used herein are from MERRA-2 and are publicly available at `https://disc.sci.gsfc.nasa.gov/uui/datasets?keywords=%22MERRA-2%22` (Global Modeling and Assimilation Office (GMAO), 2015)

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