What's in a name? On the use and significance of the term "polar vortex"

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Key Points:

- The stratospheric polar vortex is a well-defined feature dominating the cool-season circulation in each hemisphere from ~15–50 km altitude
- The tropospheric circulation does not constitute a single coherent structure and is most aptly described by regional jet stream variations
- Accuracy in defining and describing "the polar vortex" and its effects is key to improving understanding by non-specialist audiences

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Abstract

The mainstream media and popular science platforms are rife with misunderstandings about what a "polar vortex" is. The term most aptly describes the stratospheric polar vortex, a single feature dominating the cool-season circulation at $\sim$15–50 km altitude. Regional upper tropospheric jet stream variations dominate the tropospheric circulation, which is not well-described by the idea of a polar vortex; indeed, there is no single consistent definition of a tropospheric polar vortex in the literature. Stratospheric polar vortex disturbances profoundly influence extreme weather events such as cold air outbreaks (CAO); how the stratospheric polar vortex affects the tropospheric jets, local excursions of which drive CAOs, is not yet fully understood. The most public-facing parts of publications describing research on this topic are sometimes unclear about how the "polar vortex" is defined; greater clarity could help improve communications both within the community and with non-specialist audiences.

Plain Language Summary

What is a "polar vortex"? The atmospheric science community most commonly uses this term to describe the stratospheric polar vortex, a band of winds extending from about 15 to 50 km altitude that flows around the pole of each hemisphere during their respective fall through spring seasons. However, the term "polar vortex" has been used in mainstream media and popular science platforms to instead describe local variations in the upper tropospheric jet streams (winds that blow most strongly between about 8 and 13 km altitude) and even individual extreme cold weather events. We argue that the term should be used only in reference to the stratospheric polar vortex, which is a single feature that predominantly controls dynamical and chemical variability in the winter polar stratosphere. The stratospheric polar vortex is related to but distinct from more regional jet stream excursions and associated weather extremes; further study is needed to fully understand these relationships.

1 The stratospheric polar vortex, tropospheric jet streams, and cold air outbreaks

The Special Collection in which this commentary appears focuses on the Arctic stratospheric "polar vortex" in the 2019/2020 winter. But how clear are we about what constitutes a "polar vortex"? Confusion persists in the popular press about what a polar vortex is, how many of them there are, and how they relate to extreme weather events. This confusion stems in part from imprecise descriptions by the scientific community.

In January 2014, a cold air outbreak (CAO) extending through the southern central and eastern US set record-low minimum temperatures as far south as Georgia and Texas (e.g., Screen et al., 2015). Headlines hailed it as "the polar vortex", and this language became commonplace in the news media and on popular science platforms (e.g., Lillo et al., 2021, describe some of this media frenzy). At the time, the term "polar vortex" in scientific literature typically described the stratospheric polar vortex (e.g., Wang et al., 2014) (also discussion in Waugh et al. (2017) and Lillo et al. (2021)), but some studies also used the term to describe the "tropospheric polar vortex" (e.g., Wallace et al., 2014; Yu & Zhang, 2015), in both cases often without further qualification. Waugh et al. (2017) sought to dispel the confusion by describing the stratospheric and tropospheric "circumpolar" vortices as the terms had been commonly used in scientific literature, highlighting their differences and relationships to extreme weather events and providing recommendations for describing them in public forums. While this work is widely cited, the two concepts are still often conflated or confused, with examples found on educational websites and in climate change communication studies (e.g., Shepherd, 2016; Lyons et al., 2018; UCDavis, 2019; UCAR, 2021). Even recent papers within the atmospheric science community are not always immediately clear about which circulation feature(s) they are discussing, and some have used the term "polar vortex" to describe synoptic-scale disturbances associated with CAOs, echoing the inaccurate usage in popular media (e.g., Bushra & Rohli, 2019, 2021; Overland & Wang, 2019; Dai et al., 2021; Jiang, 2021; Juzbašić et al., 2021; Kömüşcü & Oğuz, 2021; Nielsen-Gammon et al., 2021; Overland, 2021; Zhang et al., 2021;

Xiong et al., 2021). In some cases, the most public-facing parts of research papers – abstracts, plain language summaries, and/or key points – do not make the definitions or distinction clear.

Figure 1 shows characteristics of the stratospheric and tropospheric circulation on two occasions when CAOs were described in the popular press as some form of a polar vortex "outbreak" or "attack", but which were associated with very different stratospheric polar vortex conditions. This figure shows the stratospheric polar vortex, upper tropospheric jet streams, and the circulation that is sometimes described as a "tropospheric polar vortex".

The stratospheric polar vortex is bounded by the polar night jet, a band of strong eastward winds throughout the stratosphere that forms in fall in each hemisphere and weakens and reverses in spring. Any of the diagnostics used to define the stratospheric polar vortex edge (Lawrence & Manney, 2018, and references therein) select a similar physically meaningful boundary (Fig. 1a, left panels, defined using a potential vorticity contour coincident with the strongest potential vorticity gradients, as in Lawrence et al. (2018)). The stratospheric polar vortex constitutes a single feature that dominates the circulation and transport throughout the polar stratosphere from fall through spring.

The so-called "tropospheric polar vortex", as most often defined, exists year-round, but there is no single definition that uniquely identifies it or the altitude(s) at which it exists (the characteristics described herein do not depend substantially on which of numerous definitions is used). Waugh et al. (2017) (and references therein) used one common definition whereby its edge approximately follows the axis of an upper tropospheric jet stream. These jets have maxima that are very localized in altitude compared to the stratospheric polar night jet, and they vary strongly with longitude (e.g., Manney, Hegglin, et al., 2011; Manney et al., 2014, and references therein; Fig. 1a, right panels). Because smaller-scale motions dominate tropospheric dynamics, definitions of a tropospheric polar vortex do not generally describe a coherent circumpolar circulation. Further confusion arises from the distinction between tropospheric "polar" (primarily eddy driven) and "subtropical" (largely radiatively driven) jets. While some recent papers define the "tropospheric polar vortex" as following the tropospheric polar jet, numerous studies show that the tropospheric jets are not well-represented by this simplified conceptual division into two types but rather form a seasonally and regionally varying complex that has hybrid radiatively and eddy-driven features and is rarely continuous around the globe (S. Lee & Kim, 2003; Manney et al., 2014; Spensberger & Spengler, 2020, and references therein).

These differences are reflected in windspeeds, which peak sharply along the stratospheric polar vortex edge (Fig. 1a and 1b, left panels). On the other hand, a tropospheric polar vortex defined on an isentropic surface as in Waugh et al. (2017) meanders through regions of weak and strong winds (Fig. 1a, right panels), leading to a broad, flat distribution of "vortex-edge" windspeeds (Fig. 1b). Potential vorticity gradients (indicating the strength of the polar vortex) are consistently strong along the circumference of the stratospheric polar vortex but have many very localized maxima in small portions of the tropospheric vortex edge and elsewhere in the extratropics (Figure 1c). This results in relatively stronger mean potential vorticity gradients along the stratospheric vortex edge, as opposed to weaker mean potential vorticity gradients and most frequent values near zero in the troposphere (Fig. 1d). Further, the tropospheric panels in Fig. 1a show a single jet at many longitudes, indicating that separate tropospheric polar and subtropical jets do not always exist; the variations are such that a "tropospheric polar vortex" might follow the polar jet in one region and the subtropical jet in another, thus traversing areas dominated by different dynamical processes because of the differing driving mechanisms of those jets.

The concept of the stratospheric polar vortex is critical for transport, particularly in relation to stratospheric polar vortex confinement, chemical processing, and ozone loss. Chemical processes related to ozone depletion are commonly analyzed from a vortex-centered perspective because the stratospheric vortex acts as a strong transport barrier that isolates chemical species involved in ozone destruction (e.g., Schoeberl et al., 1992; Manney, Santee, et al., 2011; Manney et al., 2020, and references therein), and the amount of polar ozone loss in a given spring depends critically on the strength and coldness of the winter/springtime stratospheric polar vortex. In contrast, upper tropospheric ozone variability is dominated by regional variations in stratosphere-troposphere exchange and the amount of ozone in the lower stratosphere that can be transported into the troposphere (e.g., Albers et al., 2018; Olsen et al., 2019; Breeden et al., 2021). Figures 1e and 1f illustrate these differences: Ozone values within the stratospheric polar vortex are very distinct from those in mid-latitudes, leading to sharply-peaked distributions along the stratospheric polar vortex edge. In contrast, tropospheric ozone distributions indicate fairly well-mixed air from the subtropics to the pole, with strong regional variations in windspeeds resulting in a broad distribution of ozone along the path that would define a "tropospheric polar vortex."

Stratosphere-troposphere coupling (e.g., Baldwin & Dunkerton, 2001; Kidston et al., 2015; D. I. V. Domeisen & Butler, 2020, and references therein) dynamically links many CAOs to extreme disruptions of the stratospheric polar vortex called sudden stratospheric warmings (SSWs) (e.g., Butler et al., 2017; King et al., 2019; Baldwin et al., 2021; Huang et al., 2021, and references therein). Another unique aspect of the stratospheric polar vortex is that, because of the longer radiative timescales in the lower stratosphere, large polar vortex anomalies can persist there for weeks to even months, providing potential subseasonal to seasonal forecast skill for CAOs (e.g., D. I. Domeisen et al., 2019), whereas CAOs driven solely by local jet stream excursions may only be predictable on deterministic (less than about 10-day) timescales. However, one complication in using information about the stratospheric polar vortex to predict CAOs is that its influence depends strongly on their location (e.g., North America versus Eurasia) and on other stratospheric polar vortex characteristics (e.g., Kretschmer et al., 2018; S. H. Lee et al., 2019; Cohen, Agel, Barlow, Garfinkel, & White, 2021). In fact, CAOs can occur during both strong and weak stratospheric polar vortex conditions (e.g., S. H. Lee et al., 2019; Cohen, Agel, Barlow, Furtado, et al., 2021): Fig. 1 shows an example of a CAO (January 2014) linked to a strong (but distorted) stratospheric vortex and another of a CAO occurring in the aftermath of an SSW (February 2021). Some recent work indicates that, while Eurasian CAOs are more closely linked to stratospheric polar vortex patterns characteristic of SSWs, North American CAOs are more often associated with a regime indicative of a polar vortex elongation that might or might not accompany an SSW (e.g., Kretschmer et al., 2018; S. H. Lee et al., 2019; Cohen, Agel, Barlow, Garfinkel, & White, 2021).

CAOs are often described as "polar vortex events" in the media and in venues such as peer-reviewed papers on communication of climate change risks (e.g., Lyons et al., 2018), but, based on the dynamical processes involved, they are best described as equatorward excursions of the tropospheric jet streams and southward advection of cold Arctic air. These features are not generally correlated with the strength of any globally defined "tropospheric polar vortex" (e.g., Cellitti et al., 2006; Waugh et al., 2017; Bushra & Rohli, 2021, and references therein), so the usefulness of this concept in relation to CAOs is limited at best. CAOs are indeed more likely in some regions, and more likely to be severe, following strong SSWs (e.g., King et al., 2019; S. H. Lee et al., 2019; Huang et al., 2021), which may explain why the media often hails reports of an SSW with "the polar vortex is coming" even though an SSW actually represents a rapid deceleration, or disappearance, of the stratospheric polar vortex winds. While the relationship to stratospheric polar vortex disturbances is valuable for improving the lead time for probabilistic forecasts of CAO occurrence, more extensive mechanistic understanding of how stratospheric polar vortex anomalies affect the tropospheric jet streams and their regional excursions is needed to further improve our ability to predict when and where CAOs will occur.

Conversely, several studies show links between strong stratospheric polar vortices and events related to anomalously high temperatures (including heat waves and destructive wildfires) in the Northern Hemisphere extratropics (Limpasuvan et al., 2005; Lawrence et al., 2020; Overland & Wang, 2021, and references therein). Thus anomalies in the strength or shape of the stratospheric polar vortex are associated with warm as well as cold weather extremes.

It is worth noting that the term "polar vortex" is used in another way that is not directly related to any planetary-scale circumpolar vortex, but is directly linked to many CAOs (e.g., Lillo et al., 2021, and references therein). A "tropopause polar vortex" (TPV) is a sub-synoptic scale feature characterized by a deep depression of the tropopause (sometimes to near the surface) bounded by an "Arctic jet stream" poleward of and below the tropospheric polar jet stream (Shapiro et al., 1987; Lillo et al., 2021). Lillo et al. (2021) showed that the North American CAO in late January 2019 was a direct consequence of a TPV that moved southward into the US from its high-latitude origins; several recent papers have shown that TPVs play a role in many (but by no means all) CAOs (e.g., Papritz et al., 2019; Biernat et al., 2021). While the existence of yet another feature termed a polar vortex may engender confusion, the direct links of these very localized vortices to CAOs emphasize the importance of local / regional circulation anomalies (typically associated with excursions of the jet streams) for such extreme weather events.

2 Best Practices for Describing the Polar Vortex

Table 1 summarizes the contrast between the scale and characteristics of the stratospheric and tropospheric circulations as described above. It is clearly appropriate and useful to describe the stratospheric polar vortex as the primary factor dominating stratospheric cool-season variability and exerting influence on the surface on sub-seasonal to seasonal timescales, including probabilistic links to extreme weather events. Excursions of the jet streams and related troughs and ridges are suitable for describing the genesis and evolution of CAOs, whereas the concept of a "tropospheric polar vortex" is typically not helpful in describing extreme weather events or elucidating their causes. We make the following recommendations:

- The term "polar vortex" is most useful for describing the stratospheric polar vortex, but given its broad use and misuse, "stratospheric" should be specified at the outset.
- The stratospheric polar vortex is a climatological feature that exists throughout the cool seasons (though it may be temporarily disrupted) and thus should not be described as an "event" with a sub-seasonal time scale.
- The salient features of the tropospheric circulation, especially in relation to extreme weather events, can most clearly be described in relation to the tropospheric jet streams, without invoking the term "tropospheric polar vortex".
- While the term "tropopause polar vortex" has been widely used to describe sub-synoptic scale vortices that originate in the Arctic and often move into mid-latitudes in advance of CAOs, we suggest that local features might be more clearly described in relation to their provenance, e.g., a "Canadian tropopause vortex" or a "Greenland Sea tropopause vortex".
- Scientists should be particularly careful in the most public-facing parts of our communications (e.g., titles, abstracts, plain language summaries, web sites directed at or used by general audiences) to be clear and precise about what we mean by the term "polar vortex".
- In communications with the media, atmospheric scientists should strive to emphasize that variability in the stratospheric polar vortex is indeed helpful in predicting CAOs and other extreme weather events, but that stratospheric influence is exerted via regional variations in the jet streams that cannot in themselves be described as a "polar vortex".

Further study is needed to elucidate the relationship of the stratospheric polar vortex to underlying regional tropospheric jet stream variations and ultimately to extreme weather events. Because of the important, but distinct, roles the stratospheric polar vortex and tropospheric jet streams play in understanding and forecasting extreme weather events, accurate description of these circulation features is critical to improving communication, both within the scientific community and with the public, regarding events that can have profound human impacts.

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Table 1. Major characteristics of the primary features that control circulation and transport in the stratosphere (the stratospheric polar vortex) and troposphere (tropospheric jet streams).

Stratospheric Circulation / Polar Vortex	**Tropospheric Circulation / Jet Streams**
Deep vortex bounded by circumpolar polar night jet extending from the tropopause (about 12–15 km) to the stratopause (about 50–60 km)	Circulation influence of upper tropospheric jets is limited vertically by localized jet windspeed maxima that fall off rapidly above and below. Typically defined at single level, commonly between about 5 and 10 km
Unique feature whose variations in strength, size, and position dominate the stratospheric circulation in late fall through spring	No single simply-connected feature; impactful circulation systems / weather (e.g., winter storms) primarily linked to local jet stream excursions rather than to an overall strong or weak circumpolar vortex.
Trace gas transport is closely aligned with the vortex; the vortex edge is a global transport barrier whose strength determines the degree of mixing across it	Transport controlled by upper tropospheric jet and tropopause variations; these jets represent a transport barrier only in regions where they are strong, not around the globe
Provides the "containment vessel" in which lower stratospheric chemical ozone loss occurs, thus variations in strength / coldness dominate interannual variability in ozone	Upper tropospheric ozone variability primarily controlled by ozone abundances in the lowermost stratospheric reservoir and local jet and tropopause variations that lead to stratosphere-troposphere exchange

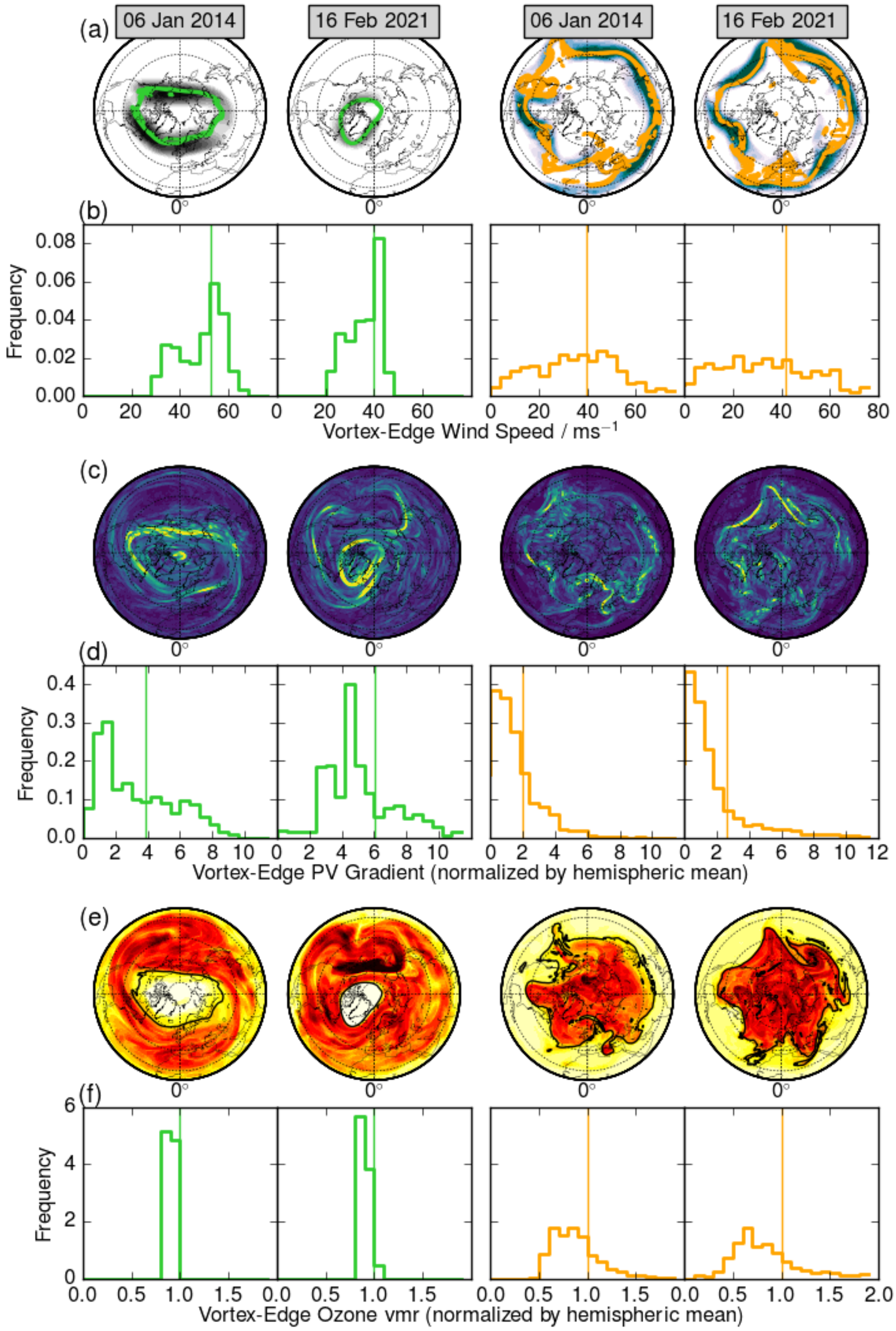

Figure 1. Characteristics of stratospheric (left two columns) and upper tropospheric (right two columns) circulations, on 6 Jan 2014 (left of each pair) and 16 Feb 2021 (right of each pair). The rows show (a) windspeeds (colorfill) and two potential vorticity (PV) contours representing the stratospheric polar vortex edge (green) and upper tropospheric "global" circulation (orange). (b) Histograms of windspeeds along the "vortex edge", defined as the lower (most equatorward) PV contour shown in each panel of (a). Vertical lines show mean around that PV contour. (c) Normalized PV gradient magnitudes. (d) Histograms of normalized PV gradient magnitude along the "vortex edge" (hemispheric mean is 1 by definition; vertical lines as in (b)). (e) Ozone volume mixing ratio (vmr; black contour shows "vortex edge" PV). (f) Histograms of normalized ozone vmr along the "vortex edge" (vertical lines as in (b)). Stratospheric fields are shown at 600 K (lower/mid-stratosphere); tropospheric fields are shown at 330 K (level used for a "tropospheric polar vortex" definition, see text), except for windspeed in (a), which is shown at 345 K (near the level of maximum tropospheric jet stream winds). Data are from MERRA-2 (Global Modeling and Assimilation Office (GMAO), 2015; Gelaro et al., 2017).