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

Gloria L Manney[1,1], Amy Hawes Butler[2,2], Zachary Duane Lawrence[2,2], Krzysztof Wargan[3,3], and Michelle L. Santee[4,4]

[1]Northwest Research Associates
[2]CIRES/NOAA
[3]Science Systems and Applications, Inc.
[4]Jet Propulsion Laboratory

November 30, 2022

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 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.

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Gloria L. Manney[1,2], Amy H. Butler[3], Zachary D. Lawrence[4,5,6], Krzysztof Wargan[7,8], Michelle L. Santee[9]

[1]NorthWest Research Associates, Socorro, NM, USA
[2]New Mexico Institute of Mining and Technology, Socorro, NM, USA
[3]NOAA Chemical Sciences Laboratory, Boulder, CO, USA
[4]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA
[5]NOAA Physical Sciences Laboratory, Boulder, CO, USA
[6]NorthWest Research Associates, Boulder, CO, USA
[7]NASA Goddard Space Flight Center, Greenbelt, MD, USA
[8]Science Systems and Applications, Inc., Lanham, MD, USA
[9]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Key Points:

- The stratospheric polar vortex is a well-defined feature dominating the cool-season circulation in each hemisphere from ∼1550 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

Corresponding author: Gloria L. Manney, `manney@nwra.com`

Abstract

Mainstream and popular science media 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 from ∼15–50 km. Regional jet stream variations dominate the tropospheric circulation, which is not well-described as 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, including cold air outbreaks (CAOs). How the stratospheric polar vortex affects tropospheric jets, whose local excursions drive CAOs, is not fully understood. Public-facing parts of publications describing research on this topic are not always clear about how the "polar vortex" is defined; greater clarity could 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

This commentary appears in the Special Collection focusing on the Arctic stratospheric "polar vortex" in 2019/2020. But how clear are we about what constitutes a "polar vortex"? Confusion persists in the popular press about what a polar vortex is 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) set record-low minimum temperatures throughout the south central and eastern US (e.g., Screen et al., 2015). Headlines hailed it as "the polar vortex", and this language became commonplace in news and popular science media. At the time, the term "polar vortex" in scientific literature typically described the stratospheric polar vortex (see, e.g., Waugh et al., 2017; Lillo et al., 2021, for discussion of this), but some studies 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 confusion, describing the stratospheric and tropospheric "circumpolar" vortices as these terms had been commonly used in scientific literature, highlighting their differences and relationships to extreme weather events, and providing recommendations for describing them. While this work is widely cited, the two concepts are still often confused, including on educational websites and in climate change communication studies (e.g., Shepherd, 2016; Lyons et al., 2018; UC-Davis, 2019; UCAR, 2021). Even recent papers within the atmospheric science community are not always clear about which circulation feature(s) they are discussing, and some use 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). Sometimes the most public-facing parts of research papers (abstracts, plain language summaries, key points) do not clearly define how the term "polar vortex" is used.

Figure 1 shows characteristics of the stratospheric and tropospheric circulation on two occasions the popular press described CAOs as 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" (i.e., the 2 and 3 PVU potential vorticity contours on the 330-K isentropic surface, one possible definition discussed by Waugh et al., 2017).

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 vanishes in spring. Different diagnostics of the stratospheric polar vortex edge (e.g., Lawrence & Manney, 2018) select similar physically meaningful boundaries (Fig. 1a, left, 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 no single definition 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). We show one common definition (Waugh et al., 2017, and references therein) whereby its edge follows the axis of an upper tropospheric jet on an isentropic surface in the middle to upper troposphere. The maximum winds of these jets 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, Fig. 1a). Because regional variability of discontinuous jet streams governs the extratropical tropospheric circulation, *"tropospheric polar vortex" definitions do not describe a single dominant circumpolar circulation.* Further confusion arises from the distinction between tropospheric "polar" (primarily eddy driven) and "subtropical" (largely radiatively driven) jets. While some recent papers and popular science pieces identify the "tropospheric polar vortex" with the tropospheric polar jet (e.g., Waugh et al., 2017; Bushra & Rohli, 2021; UCAR, 2021), numerous studies show that tropospheric jets are not well-represented by this simplified conceptual division but rather form a seasonally and regionally varying complex with hybrid radiatively and eddy-driven features that 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 (Fig. 1a,b), which peak sharply along the stratospheric polar vortex edge; in contrast, a "tropospheric polar vortex" defined as noted above meanders through regions of weak and strong winds, leading to a broad, flat distribution of "vortex-edge" windspeeds. Potential vorticity gradients (indicating polar vortex strength) are consistently strong along the circumference of the stratospheric polar vortex but have many 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, versus weaker mean potential vorticity gradients and most frequent values near zero in the troposphere (Fig. 1d). Further, tropospheric windspeeds (Fig. 1a) often show a single jet (or no strong jet) because separate tropospheric polar and subtropical jets do not always exist. A "tropospheric polar vortex" might therefore follow the polar jet in one region but the subtropical jet in another, thus traversing regimes controlled by different dynamical processes.

The stratospheric polar vortex is critical for transport, chemical processing, confinement of processed air, and ozone loss. Processes promoting ozone depletion are commonly analyzed from a vortex-centered perspective because the stratospheric vortex represents a strong transport barrier, isolating air primed for ozone destruction (e.g., Schoeberl et al., 1992; Manney, Santee, et al., 2011; Manney et al., 2020); the amount of polar ozone loss in a given spring depends critically on the strength and coldness of the winter/spring stratospheric polar vortex. In contrast, upper tropospheric ozone variability is dominated by regional variations in stratosphere-troposphere exchange and the amount of lower stratospheric ozone available for transport 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 gradients change abruptly across the stratospheric polar vortex edge but are quite uniform within it. In contrast, ozone gradients are strong in many localized regions within the "tropospheric polar vortex", with highly variable gradients often appearing well poleward of the "vortex" edge. These characteristics are reflected in sharply-peaked ozone distributions along the stratospheric polar vortex edge, and large variability in ozone along the "tropospheric vortex" edge (Fig. 1f). Note that the broad change from uniform gradients to highly variable gradients across the "tropospheric vortex edge" as defined here is a reflection of vertical ozone gradients and the tilt of the 330 K isentropic surface in the subtropics.

Stratosphere-troposphere coupling (e.g., Baldwin & Dunkerton, 2001; Kidston et al., 2015) dynamically links variability of the polar vortex to extremes at the surface (e.g., Domeisen & Butler, 2020). For example, extreme stratospheric polar vortex disruptions (sudden stratospheric warmings, SSWs) are associated with increased risk of mid-latitude CAOs (e.g., Butler et al., 2017; King et al., 2019; Baldwin et al., 2021; Huang et al., 2021), and unusually strong stratospheric polar vortices are associated with anomalously high extratropical surface temperatures (including heat waves and destructive wildfires) (Limpasuvan et al., 2005; Lawrence et al., 2020; Overland & Wang, 2021). Because radiative timescales are longer in the lower stratosphere, disruptions to the circulation can persist there for weeks to months, potentially providing subseasonal-to-seasonal forecast skill for extremes like CAOs (e.g., Domeisen et al., 2019). Using information about the stratospheric polar vortex to predict CAOs is, however, complicated because the timing and location of individual CAOs varies significantly following polar vortex disruptions, perhaps related to details of the stratospheric polar vortex characteristics and evolution. Recent work suggests that Eurasian CAOs are more closely linked to SSWs, while North American CAOs are more strongly associated with stratospheric 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). It is worth emphasizing that 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): Figure 1 shows a CAO (January 2014) linked to a strong (but distorted) stratospheric vortex and one (February 2021) following an SSW.

CAOs are often termed "polar vortex events" in the news, popular science media, and less specialized peer-reviewed papers (e.g., Lyons et al., 2018, on communication of climate change risks), but the dynamical processes involved argue that they are best described as equatorward excursions of the tropospheric jets 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), so the utility of the latter concept in relation to CAOs is questionable. CAOs in some regions are indeed more likely, and more likely to be severe, following SSWs (e.g., King et al., 2019; S. H. Lee et al., 2019; Huang et al., 2021), explaining 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 can improve lead times for probabilistic forecasts of CAO occurrence, more extensive mechanistic understanding of how stratospheric polar vortex anomalies affect regional excursions of tropospheric jet streams is needed to further improve prediction of when and where CAOs will occur.

The term “polar vortex” is used in another way that is not directly related to any planetary-scale circumpolar vortex, but is related to many CAOs (e.g., Lillo et al., 2021). 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 (Shapiro et al., 1987). Lillo et al. (2021) showed that the North American CAO in late January 2019 resulted directly from a TPV moving southward from its high-latitude origins; 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 link of these localized vortices to CAOs emphasizes the importance of local/regional circulation anomalies (and associated jet stream excursions) to extreme weather events.

Points such as those above regarding the stratospheric polar vortex have been highlighted in studies using theoretical fluid-dynamical or dynamical systems approaches (e.g., Scott & Dritschel, 2006; Serra et al., 2017; Mester & Esler, 2020). It is not clear that similar approaches could usefully describe what some have termed a “tropospheric polar vortex”.

2 Best Practices for Describing the Polar Vortex

It is clearly appropriate and useful to describe the stratospheric polar vortex as dominating stratospheric cool-season variability and exerting influence on the surface on subseasonal to seasonal timescales, including probabilistic links to extreme weather events. Jet stream excursions 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 conclude:

- The term “polar vortex” is most appropriate for describing the stratospheric polar vortex, but given its broad use and misuse, “stratospheric” should be specified explicitly.
- The stratospheric polar vortex is a climatological feature that exists throughout the cool seasons (though sometimes temporarily disrupted) and thus should not be described as an “event” with a sub-seasonal time scale.
- 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”. More accurate and appropriate terminology for referring to such events would be “Arctic cold air outbreak” (or more simply a CAO) or a “polar front”.
- While the term “tropopause polar vortex” has been used to describe sub-synoptic scale vortices that are sometimes linked to CAOs, local features might be more clearly described in relation to their provenance, e.g., a “Canadian tropopause vortex”.
- Scientists should be careful in the public-facing parts of our communications (e.g., titles, abstracts, plain language summaries, web sites) to be clear and precise about what we mean by the term “polar vortex”.
- In communications with the media, atmospheric scientists should emphasize that stratospheric polar vortex variability is indeed helpful in predicting CAOs and other extreme weather events, but stratospheric influence is exerted via regional jet stream variations that cannot in themselves be called a “polar vortex”.

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

Acknowledgments

We thank the MLS team at JPL, especially Brian Knosp, Luis Millán, and Ryan Fuller, for data management, processing, and analysis support; NASA's GMAO for the MERRA-2 dataset; Ken Minschwaner, Jessica George, and Kody Gray for helpful discussions; and two anonymous reviewers for their insightful comments. We are grateful to B. J. Hoskins, M. E. McIntyre, and A. W. Robertson (Hoskins et al., 1985) for inspiring the title of this commentary. G.L.M. was partially supported by the JPL Microwave Limb Sounder team under a JPL subcontract to NWRA. Z.D.L. was partially supported under a NWS OSTI Weeks 3–4 Project (NA20NWS4680051). G.L.M. and Z.D.L. were partially supported by NSF Climate and Large-scale Dynamics Grant #2015906. K.W. was supported by NASA's GMAO core funding. Work at the Jet Propulsion Laboratory, California Institute of Technology, was carried out under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

Data Availability Statement The MERRA2 data set used here is publicly available: `https://disc.sci.gsfc.nasa.gov/uui/datasets?keywords=\%22MERRA-2\%22` (Global Modeling and Assimilation Office (GMAO), 2015).

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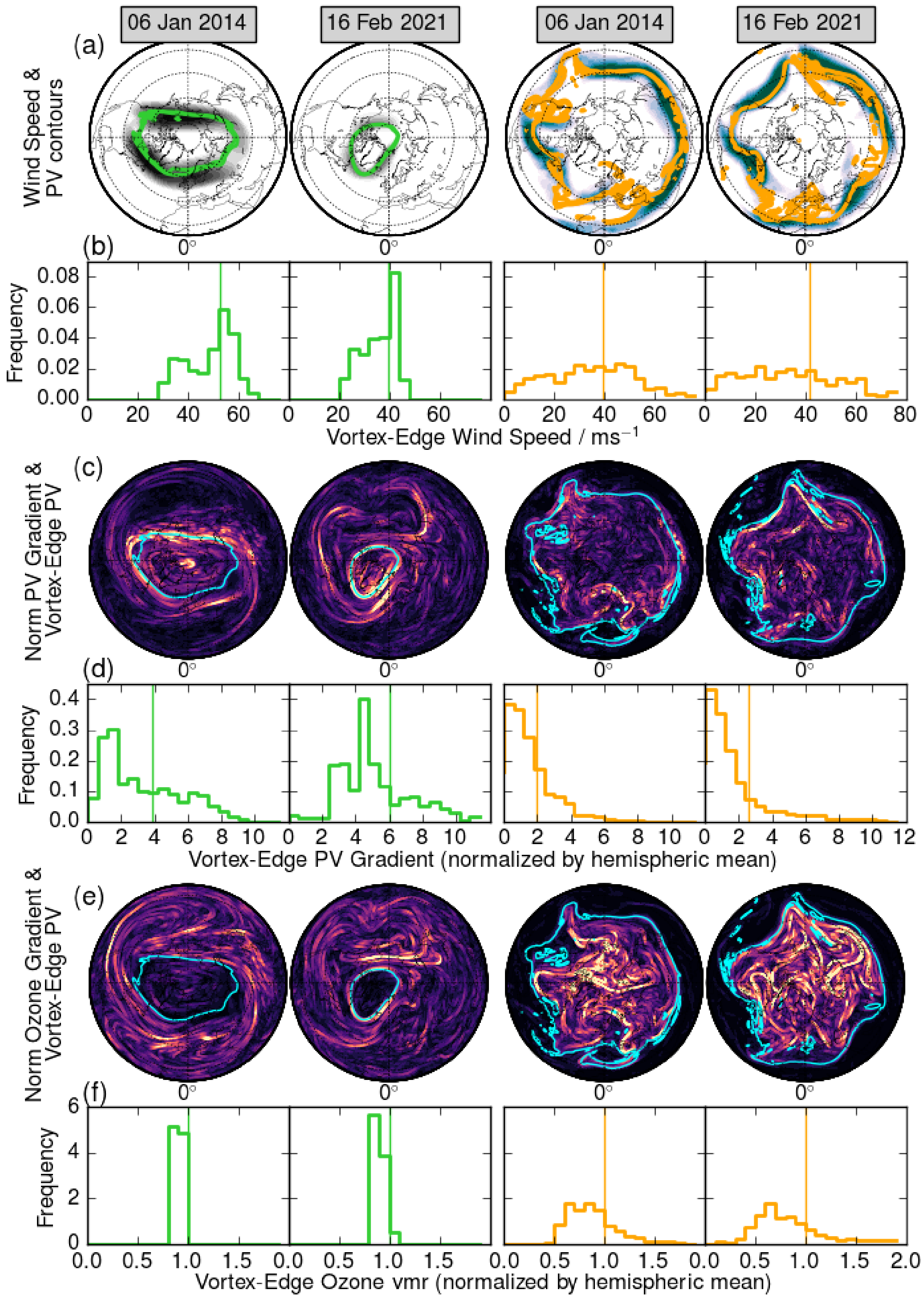

Figure 1. Characteristics of (left to right) 6 Jan 2014 and 16 Feb 2021 stratospheric and upper tropospheric circulations: (a) Windspeeds (colorfill) and two potential vorticity (PV) contours representing the stratospheric polar vortex edge (green) and boundary of tropospheric "global" circulation (orange). (b) Windspeed histograms along the "vortex edge" (most equatorward PV contour shown in (a)); vertical lines show mean around that PV contour. (c) Normalized PV gradient magnitudes. (d) Normalized PV gradient magnitude along the "vortex edge" (hemispheric mean is 1 by definition; vertical lines as in (b)). (e) Normalized ozone gradient magnitudes. (f) Normalized ozone mixing ratios along the "vortex edge" (vertical lines as in (b)). Cyan contours in (c) and (e) show "vortex edge" PV. 600 K (330 K) fields are shown for stratosphere (troposphere), except windspeeds are at 345 K (near level of maximum tropospheric jet stream winds). Data are from MERRA-2 (Gelaro et al., 2017).