WHAT IS THE POLAR VORTEX AND HOW DOES IT INFLUENCE WEATHER?

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There are separate stratospheric and tropospheric planetary-scale circumpolar vortices, with differing structure, seasonality, dynamics, and impacts on extreme weather.

The term *polar vortex* has become part of the everyday vocabulary after the widespread media coverage of the extreme cold events over the United States during the early winter of 2014. However, there is some confusion in the media, general public, and even within the science community regarding what polar vortices are and how they are related to various weather events. This confusion is illustrated by the fact that the polar vortex entry in the American Meteorological Society (AMS) glossary was revised in 2000, 2014, and again in October 2015 (AMS 2015). Much of the confusion stems from the fact that polar vortex is used in the literature to explain two different features of the atmospheric circulation: one in the troposphere and the other in the stratosphere. The distinction between them is not always made clear in discussions of extreme cold events.

Another source of confusion stems from the fact that these polar vortices are neither unusual nor extreme; they are simply basic features of Earth's climatology. While some extreme weather events at some locations are related to transient displacements of the edge of the tropospheric polar vortex, these events are in no way a manifestation of major changes in the global atmospheric circulation. Here, we clarify the different structures, seasonality, and dynamics of the stratospheric and tropospheric polar vortices and discuss the connections of both to extreme weather events at Earth's surface.

TWO POLAR VORTICES. In the atmospheric science literature, the term *polar vortex* is most commonly used as an abbreviation for *circumpolar vortex* and refers to a planetary-scale westerly (west to east) flow that encircles the pole in middle or high latitudes.[1]

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[1] There are a few cases where polar vortex is used to refer to smaller and shorter-lived vortices that occur in polar regions and within the much broader tropospheric polar vortex discussed here, for example, Cavallo and Hakim (2009).
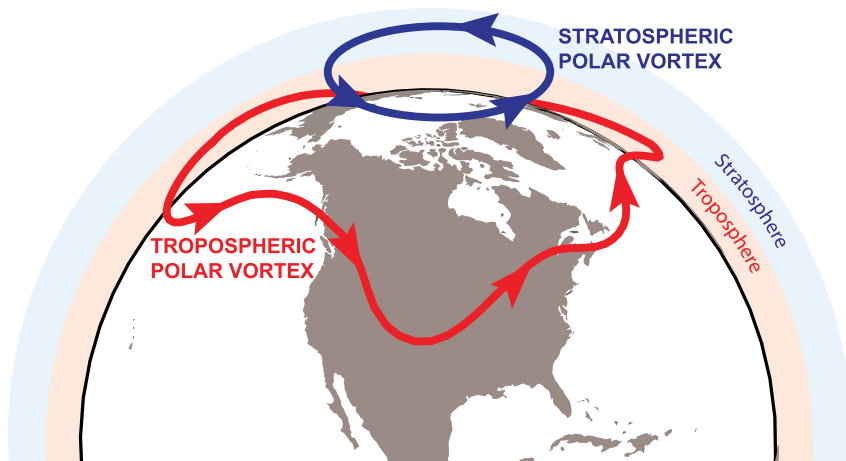
Fig. 1. Schematic of stratospheric and tropospheric polar vortices.

Although the polar vortices are sometimes described as extending from the middle troposphere to the upper stratosphere (e.g., as they were in the 2000 and 2014 versions of the AMS glossary), there are actually two quite different polar vortices in Earth's atmosphere: a tropospheric vortex and a stratospheric vortex.[2] The tropospheric and stratospheric circumpolar vortices are illustrated schematically in Fig. 1 and can be easily seen in the climatological zonal-mean zonal winds shown in Fig. 2. The latitude at which the zonal wind reaches its hemispheric maximum can be considered as marking the approximate edge of a polar vortex, and Fig. 2 shows that there is a clear vertical discontinuity in this latitude around 100 hPa. It should also be clear that the vortex in the troposphere is much larger than the vortex in the stratosphere and that the two are not directly connected. Furthermore, we wish to highlight another fundamental difference between these two vortices: their seasonal evolution. While the tropospheric vortex exists all year, the stratospheric polar vortex exists only from fall to spring. In the following sections, we describe the two vortices in greater detail.

STRATOSPHERIC POLAR VORTEX. Knowledge of these circumpolar westerlies in the stratosphere can be traced to the late 1940s (e.g., Scherhag 1948; Gutenberg 1949). The phrase *circumpolar vortex* was used in early papers (e.g., Brasefield 1950), but the abbreviation *polar vortex* became common by the late 1950s and 1960s (e.g., Palmer 1959).

The strong circumpolar westerlies that define the stratospheric polar vortex maximize at around 60°

latitude, from just above the tropopause (~100 hPa) into the mesosphere (above 1 hPa; see Fig. 2). The stratospheric vortex can also be defined by the coherent region of low geopotential height that is enclosed by the westerlies, as shown in Fig. 3a for January 2014 (the thick contour is a geopotential height representing the edge of the vortex). However, most studies in recent decades have defined the vortex by the region of high potential vorticity (PV; see Fig. 3b). PV is proportional to the product of vorticity (a measure of the rate of rotation of air parcels) and stratification (the extent to which an air parcel displaced vertically will tend to return to its starting height, as water at the surface of a lake does). PV has several useful properties for understanding vortex dynamics: 1) It is materially conserved for flow with no diabatic heating or friction, 2) other dynamical fields can be determined from PV using "PV inversion" (e.g., Hoskins et al. 1985), and 3) PV gradients, which are sharper at the polar vortex edge than at other latitudes, provide the restoring mechanism for the propagation of Rossby waves. Rossby waves are the fundamental low-frequency disturbances in the extratropical troposphere and stratosphere, and, roughly speaking, all large-scale perturbations of the polar vortex that might be of interest in discussions of the weather and climate state can be described in terms of Rossby waves.

The stratospheric polar vortex appears each winter as a consequence of the large-scale temperature gradients between the midlatitudes and the pole. It forms in fall when there is no solar heating in polar regions, strengthens during winter, and then breaks down as sunlight returns to the polar regions in spring, and the high-latitude winds become weak easterlies (Waugh and Polvani 2010; and references therein). If the solar heating exactly balanced infrared cooling (so-called radiative equilibrium), then the stratospheric polar vortex would be stronger and the pole would be colder than they are. Rossby waves excited in the troposphere propagate up into the stratosphere and perturb the vortex away from radiative equilibrium, weakening it and distorting its shape away from circular symmetry about the pole.

The larger topographic and land–sea contrasts in the Northern Hemisphere (NH) generate stronger

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[2] There are also polar vortices in the atmospheres of other planetary bodies, including Mars, Venus, Saturn, and Saturn's moon Titan (e.g., Read 2011).
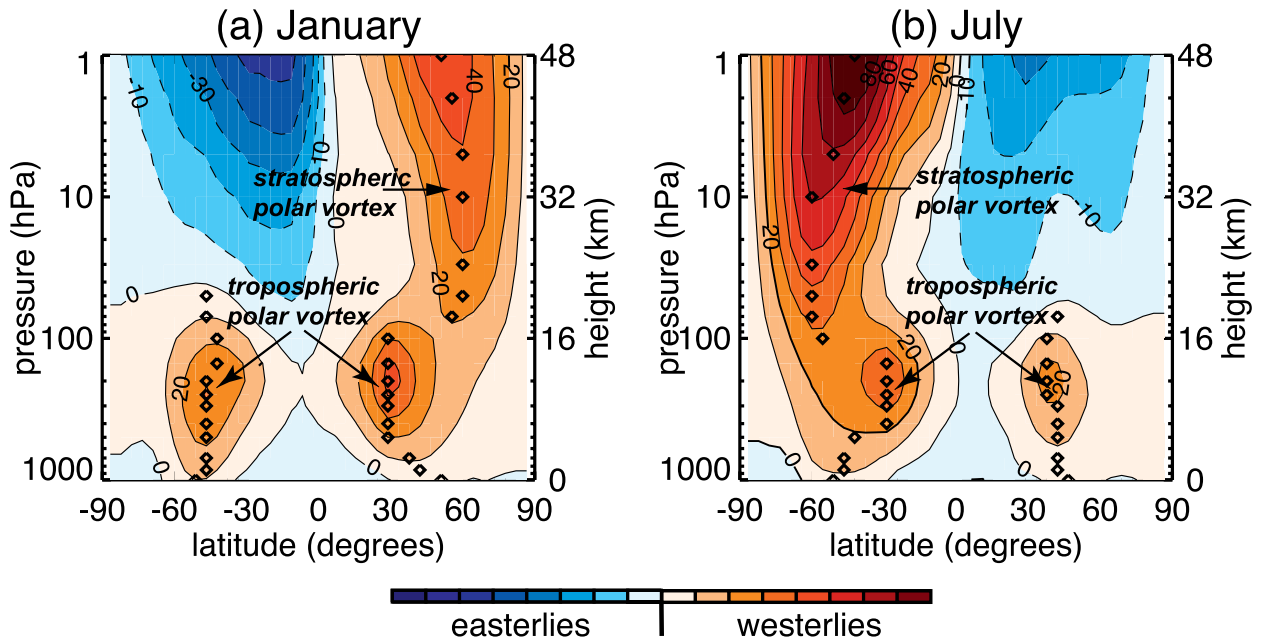
Fig. 2. Climatological zonal-mean zonal wind in Jan and Jul. The diamonds mark the hemispheric maximum of the zonal wind at each pressure level and the approximate edge of the polar vortex for that hemisphere. Data source: National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) analyses.

upward-propagating waves than in the Southern Hemisphere (SH), causing the northern stratospheric vortex to be weaker and more distorted than its southern counterpart (i.e., the SH stratospheric vortex is larger and more axisymmetric than the NH vortex; e.g., Waugh and Randel 1999). This also causes more temporal variability in the NH vortex, including so-called sudden stratospheric warmings (SSWs), which consist of a sudden rise in the polar temperatures and a breakdown of the stratospheric vortex during midwinter. These SSWs occur on average around once every two years in the Northern Hemisphere (Charlton and Polvani 2007). A SSW in the Southern Hemisphere, in contrast, has been observed only once, in September 2002 (e.g., Charlton et al. 2005).

Scientific interest in the stratospheric polar vortices increased dramatically in the mid-1980s because of their importance for stratospheric ozone depletion. The low temperatures within the vortices and reduced mixing of polar and midlatitude air across the vortex edge are crucial ingredients for the formation of the Antarctic ozone hole as well as the less dramatic (but still significant) winter–spring depletion over the Arctic (e.g., Schoeberl and Hartmann 1991).

In more recent years research on the stratospheric polar vortices has broadened far beyond the ozone issue. It has been increasingly recognized that while the stratospheric polar vortices are distinct from the tropospheric ones, the stratospheric vortices do influence the troposphere and even surface weather. We discuss this further below.

TROPOSPHERIC POLAR VORTEX. While the scientific literature on tropospheric meteorology is much larger than that on stratospheric meteorology, the term *polar vortex* is much less common in the tropospheric literature. Nonetheless, the earliest scientific papers describing the tropospheric circumpolar flow as a vortex are as old as those describing the stratospheric polar vortex, with initial papers dating back to the late 1940s and early 1950s (e.g., Rossby and Willett 1948; LaSeur 1954), followed by a series of papers by Angell et al. from the 1970s to 2000s [see Angell (2006); and references therein]. The majority of these studies refer to a tropospheric circumpolar vortex, but it is not uncommon to find it referred to simply as the polar vortex (e.g., Angell and Korshover 1975; Angell 1992; Kashki and Khoshhal 2013).

The edge of this vortex is often defined by specified geopotential contours, on the 300- or 500-hPa pressure levels, that typically lie within the core of the westerlies (e.g., Angell 2006; Frauenfeld and Davis 2003; and references therein). The values of the contours chosen vary, but the tropospheric vortex edge generally lies between 40° and 50°N (see thick contour in Fig. 3c). On monthly or longer time scales the tropospheric vortex usually has one or two centers (Fig. 3c), but on daily time scales the vortex may have several centers (Fig. 4). The climatological winter
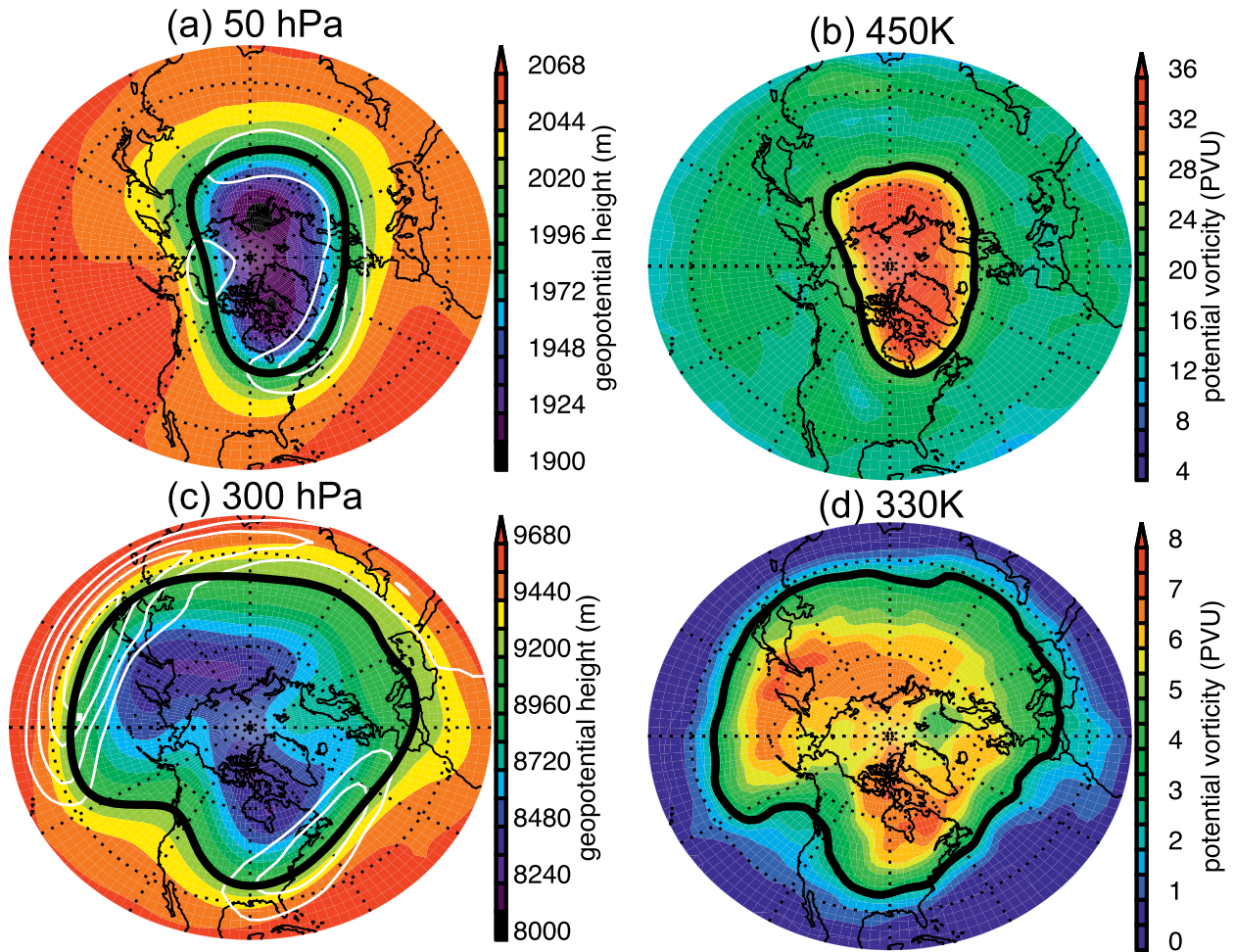
Fɪɢ. 3. Maps illustrating the (a),(b) stratospheric and (c),(d) tropospheric vortices in Jan 2014 using (left) geopotential height (shading) and zonal winds (white contours for 30, 40, 50, and 60 m s⁻¹) at (a) 50 and (c) 300 hPa and (right) potential vorticity at (b) 450 and (d) 330 K. The thick black contours illustrate the edge of the vortices defined using geopotential height or potential vorticity. Data source: National Centers for Environmental Prediction (NCEP) reanalyses.

Northern Hemisphere vortex features two centers: one near Baffin Island and the other over northeastern Siberia (associated with the Icelandic and Aleutian surface lows). Analogous circumpolar asymmetry is not usually observed in the climatological Southern Hemisphere vortex (e.g., Burnett and McNicoll 2000).

While not discussed in the abovementioned tropospheric vortex studies, the edge of the tropospheric vortex can (as in the stratosphere) be defined from potential vorticity contours on an isentropic surface or (equivalently) potential temperature on a surface of constant potential vorticity (Hoskins et al. 1985). The 300–500-hPa geopotential height contours used to define the vortex are similar to the intersection of the PV = 2 or 3 potential vorticity units (PVU; $1 \, PVU = 10^{-6} \, K \, kg^{-1} \, m^2 \, s^{-1}$) surface—commonly used to define the dynamical tropopause in the extratropics—with the 320- or 330-K isentropic surfaces

(see Fig. 3d). As is the case in the stratosphere, the PV field shows finer-scale structure than does the geopotential height and enables more detailed analysis of the dynamics of Rossby waves and related extratropical weather disturbances.

As for the stratospheric vortex, the tropospheric polar vortex and the associated strong westerly airflow are largely manifestations of the thermal wind relation and the pole-to-equator temperature gradient. However, in contrast to the stratospheric vortex, baroclinic instability (and the resulting waves) plays a key role in the variability and long-term maintenance of the large-scale tropospheric jet stream (Robinson 2006). Baroclinic instability is the process by which most extratropical tropospheric weather systems extract energy from the basic pole-to-equator temperature gradient, but these weather systems are largely confined to the troposphere. Only the Rossby waves
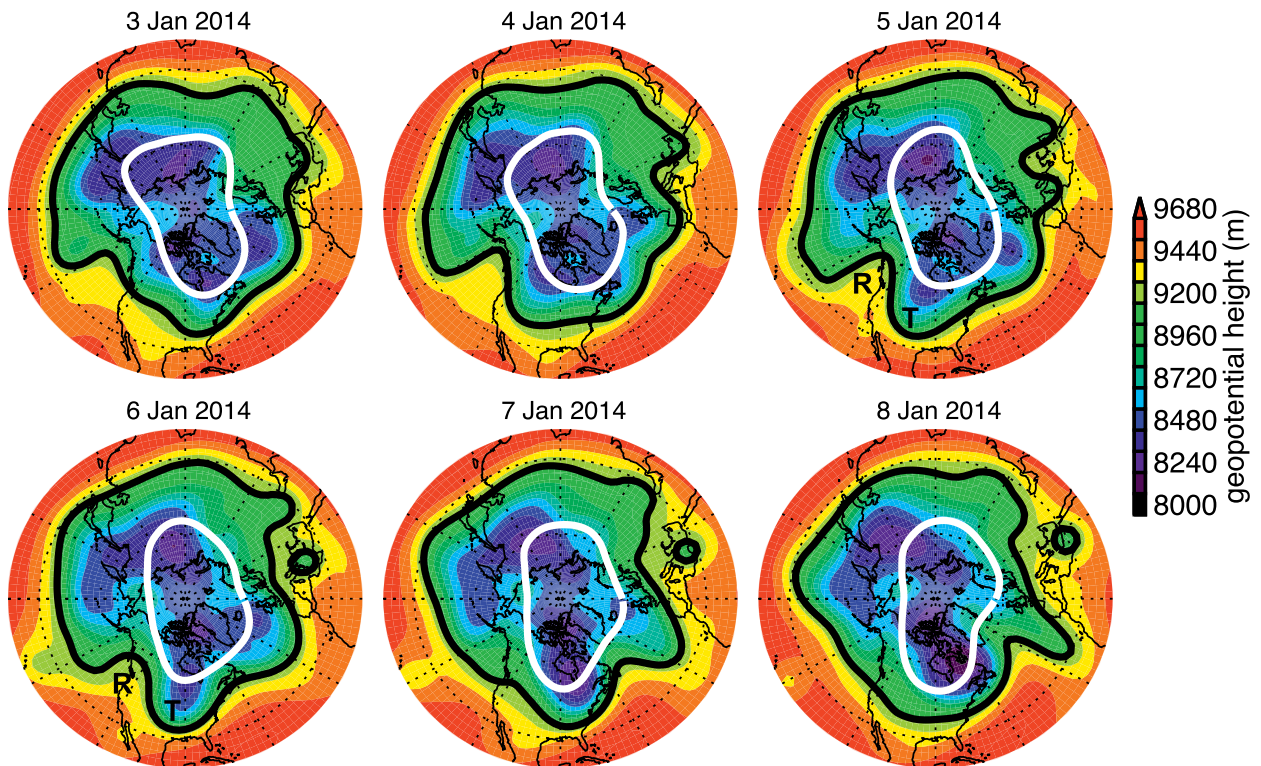
Fig. 4. Maps of 300-hPa geopotential height for 3–8 Jan 2014. Black contours mark the tropospheric vortex edge at 300 hPa and white contours mark the stratospheric vortex edge at 50 hPa. The R and T on 5 and 6 Jan indicate the location of ridge and trough, respectively, discussed in the text. Data source: NCEP reanalyses.

with the largest spatial scales are able to propagate upward into the stratosphere (Charney and Drazin 1961), and these tend to be mostly those generated by westerly flow over mountains and continental land–sea contrasts. Thus, the variability of the stratospheric polar vortex lacks the "synoptic scale" structures that dominate the tropospheric variability, with typical horizontal scales from one to a few thousand kilometers. This is easily seen by comparing the edges of the tropospheric (black contours) and stratospheric (white contours) polar vortices in Fig. 4.

The focus of the majority of tropospheric vortex studies has been on the hemispheric-scale circulation and on the seasonal and interannual variations in size and shape of the vortex. There has been much less attention to synoptic-scale weather in papers that explicitly refer to a polar vortex, although there are some exceptions (e.g., Gardner and Sharp 2007; Kashki and Khoshhal 2013).

EXTREME WEATHER EVENTS. While the tropospheric and stratospheric polar vortices are clearly distinct, they are able to interact on certain occasions, and both vortices can be influenced by the same large-scale wave events. Furthermore, both vortices can, in some circumstances, play a role in

extreme weather events at the surface, though the tropospheric vortex is generally the more important one for surface weather. In those circumstances, the presence of two vortices necessitates a very subtle discussion as to the relative role of each vortex, if any at all. Frequent references to the stratospheric vortex in discussions of surface weather events are sometimes a result of confusing the tropospheric and stratospheric vortices or even the simple lack of recognition that two distinct vortices are present at very different heights in the atmosphere. The stratospheric vortex can play a role, though typically an indirect one, in some (though not all) surface weather events. This can occur through one or more of a variety of mechanisms of stratosphere–troposphere interaction.

Although the coherent region of high PV associated with the stratospheric polar vortex lies in the stratosphere, it can influence the tropospheric flow below it (e.g., Black 2002; Ambaum and Hoskins 2002). This influence includes trends in summer circulation and weather in the Southern Hemisphere due to an ozone hole–induced strengthening of the Antarctic polar vortex (Thompson et al. 2011) as well as connections between weak and strong Arctic stratospheric vortex events and extreme surface weather (Baldwin and Dunkerton 2001). The latter

Arctic connection involves the movement of an extremely cold air mass from the polar regions to the midlatitudes at the surface (cold-air outbreaks), and it has been shown that the probability of such events increases following periods when the stratospheric vortex is highly disturbed and weakened (Thompson et al. 2002; Kolstad et al. 2010). Many of the studies linking the stratospheric vortex to surface climate describe the connection in terms of the so-called annular modes (e.g., the Arctic or Antarctic Oscillation), with the negative phase of the mode corresponding to a weak vortex and vice versa. Despite this statistical link between occurrence of cold-air outbreaks and weak stratospheric vortices, there is not a one-to-one relationship between them. Cold-air outbreaks are fundamentally tropospheric events, and they can and often do occur in the absence of any detectable stratospheric influence.

There is a more direct connection between the tropospheric polar vortex and extreme surface weather events in the midlatitudes than between the stratospheric vortex and such events, although most of the literature referring explicitly to tropospheric polar vortices has generally not examined this connection. One exception is Cellitti et al. (2006), who showed that there is a weaker-than-average tropospheric polar vortex preceding cold-air events. However, in that study, the vortex was defined as a small, closed circulation centered just north of Baffin Island, which is quite different from the larger-scale hemispheric circumpolar tropospheric vortex considered in the abovementioned climatological studies. Because of this, it remains unclear at present if and to what degree the size and/or strength of the hemispheric-scale tropospheric vortex is actually connected with cold-air outbreaks.

The most direct connection between the tropospheric polar vortex and extreme weather events is that distortions of the edge of that polar vortex are often closely related to extreme weather events at particular locations near that edge. These "distortions" correspond to large-amplitude planetary-scale waves propagating along the jet stream and are traditionally described in terms of troughs and ridges. Recent studies of extreme events (e.g., Francis and Vavrus 2012; Barnes 2013) have examined the meridional displacement of geopotential height contours similar to those used to define the hemispheric-scale tropospheric vortex and, while not discussed in these terms in those studies, could be understood as distortions of the polar vortex. During cold-air outbreaks the edge of the tropospheric vortex is displaced farther equatorward than usual in some particular range of longitudes; this is accompanied by anomalously cold air at the surface, often resulting from synoptic-scale disturbances whose paths follow the displaced vortex edge. Note that during these events the tropospheric vortex can be displaced poleward, with warmer-than-average surface conditions at other longitudes.

An example of this is the cold-air event over the eastern United States in early January 2014, which brought the term *polar vortex* into the general public's vocabulary. That event was the result of a large-amplitude ridge–trough system over the United States, with the trough bringing extremely cold air south over the eastern United States on 6 January, illustrated in Fig. 4. Although often attributed to the movement of the whole polar vortex, this event cannot be directly attributed to changes in the stratospheric vortex or even to hemispheric changes to the tropospheric vortex. However, it may be appropriate to describe it in terms of waves on the edge of the tropospheric vortex and the deformation of part of that vortex (or "a lobe") over the eastern United States on 6 January, as shown in Fig. 4.

CONCLUDING REMARKS. It is not clear that describing cold-air-outbreak events, such as the one shown in Fig. 4, in terms of a polar vortex adds significant new insights compared to the traditional descriptions in terms of ridges and troughs or in terms of waves propagating along the jet stream. As there are two distinct polar vortices, and the stratospheric one can play a significant role but often does not, introducing the term may, in fact, cause some misunderstanding. Additionally, since surface weather disturbances are associated only with displacements of the vortex edge in limited areas rather than hemispheric-scale changes to the vortex, it is not clear that invoking the term *vortex* clarifies anything, given that the vortex is a hemispheric-scale structure. Use of the term without adequate explanation can suggest a more dramatic change to the global tropospheric circulation than has actually occurred (e.g., "The polar vortex is back!").

That said, the term has become rapidly ingrained into the vocabulary of popular weather journalism and appears to be coming more common in the science literature of extreme weather (Wallace et al. 2014). We encourage those who use it to do the following:

1) Distinguish clearly between the stratospheric and tropospheric polar vortices. Many surface weather events involve only the tropospheric vortex, yet most scientific literature using the term *polar vortex* refers to the stratosphere. Thus, the distinction must be made with some care,

and any chosen references or quotations should refer to the correct vortex (which is normally the tropospheric one). The stratospheric vortex may play a role in some events, but that role is typically more subtle and indirect and requires further specific explanation.

2) Make clear that any individual extreme weather event is not the consequence of either the existence or gross properties of either polar vortex, whether tropospheric or stratospheric, as both vortices are normal climatological features of Earth's atmospheric circulation. Rather, as in the case of 2014, the events of interest tend to be associated only with transient and localized displacements of the tropospheric vortex edge.

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