DEFINING SUDDEN STRATOSPHERIC WARMINGS

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Six decades after the discovery of sudden stratospheric warmings, their multiple, and somewhat ambiguous, definitions merit scrutiny in light of contemporary research and forecasting challenges and opportunities.

Sudden stratospheric warmings[1] (SSWs) are among the most impressive dynamical events in the physical climate system. Driven by the breaking of planetary waves propagating up from the troposphere, these events involve a large and rapid temperature increase (>30–40 K in a matter of days) in the mid- to upper stratosphere (30–50 km) and, in the most extreme cases, a reversal of the climatological westerly zonal-mean zonal winds associated with the stratospheric polar night jet (e.g., Scherhag 1952; Quiroz 1975; Labitzke 1977; Schoeberl 1978). Figure 1 demonstrates the rapid changes in the stratosphere during these events, which typically manifest in one of two ways (or both[2]): either the vortex is displaced entirely off the pole (Fig. 1a) or the vortex is split into two smaller vortices (Fig. 1b; see also supplement).

Impressive in their own right, SSWs are also important because associated temperature and wind anomalies can descend downward into the troposphere on time scales of weeks to months (e.g., Baldwin and Dunkerton 2001), with significant impacts on Northern Hemisphere wintertime surface climate. The tropospheric response to SSWs closely resembles the negative phase of the North Atlantic Oscillation (NAO), involving an equatorward shift of the North Atlantic storm track; extreme cold air outbreaks in parts of North America, northern Eurasia, and Siberia; and strong warming of Greenland, eastern Canada, and southern Eurasia (e.g., Thompson et al. 2002). Major midwinter SSWs rarely occur in the Southern Hemisphere, largely because of smaller planetary-wave amplitudes (Van Loon et al. 1973), though a notable exception occurred in September 2002 (Allen et al. 2003; see special issue of the *Journal of Atmospheric Sciences*, 2005, Vol. 62, No. 3). SSWs play a major role in Arctic and Antarctic ozone variability (e.g., Schoeberl and Hartmann 1991), and stratospheric transport and chemistry (e.g., Manney et al. 2009). SSWs can also influence the transport of tropospheric CO_2 and pollutants (Jiang et al. 2013), the extension of the El Niño–Southern Oscillation (ENSO) teleconnection into Eurasia (e.g., Ineson and Scaife 2009; Butler et al. 2014b), decadal variability in the North Atlantic Ocean circulation (Reichler

[1] *Stratospheric sudden warming* and *sudden stratospheric warming* have been used interchangeably in the literature. Note, however, that *sudden stratospheric warming* corresponds more closely to the original German *Stratosphärenerwärmung* (Scherhag 1952), where *stratospheric* and *warming* become one word. Clear and unambiguous acronyms may facilitate efforts by organizations such as the American Meteorological Society to maintain acronym reference lists and improve scientific communication (Heideman 2014).

[2] Split vortices are also typically displaced from the pole.

et al. 2012), equatorial tropospheric convective activity (e.g., Kodera 2006), polar tropospheric clouds (Kohma and Sato 2014), and mesospheric dynamics and the breakdown and reformation of the stratopause (e.g., Siskind et al. 2007; Manney et al. 2008).

Scientists have been trying to understand, monitor, and classify SSWs for over 60 years. As with any noteworthy weather or climate phenomena (El Niño–Southern Oscillation, hurricanes, drought, tornadoes, etc.), reaching community agreement on a standard way to define events is an extremely challenging, though useful, endeavor. We believe that improved observations and better understanding of SSWs in recent decades make this an ideal time to reevaluate and/or clarify the standard definition of SSWs and its purpose. To this end, the key objectives of this paper are 1) to describe the historical background and evolution of the SSW definition, demonstrating the lack of an unambiguous current "standard" definition; 2) to examine how differences among a number of proposed definitions can affect the interpretation of observed and simulated SSW frequency, implying a need for a standard definition for certain applications; 3) to argue that for statistical applications that depend on a robust metric of events, such as model intercomparisons of the stratosphere, a standard definition is necessary; and 4) to describe current efforts to gather community input and to suggest possible ways to proceed to update the standard SSW definition.

HISTORY OF SSW DEFINITIONS. Richard Scherhag first observed "explosive warmings in the stratosphere" (which he referred to as the "Berlin phenomenon") in radiosonde measurements in Berlin, Germany, in January/February 1952 (Scherhag 1952, p. 53). Within about a decade, and as part of the International Years of the Quiet Sun (IQSY) 1964–65, the World Meteorological Organization (WMO) Commission for Atmospheric Sciences (CAS; originally called the Commission for Aerology) developed an international SSW monitoring program called STRATALERT, based on available radiosonde and rocketsonde observations. The program, led by Karin Labitzke at the Freie Universität Berlin, involved teams at meteorological centers in Washington, D.C.; Tokyo, Japan; Berlin; and Melbourne, Australia. A major goal was to "aid in the co-ordination of normal and special observations, particularly throughout the Northern Hemisphere, relating to the physical conditions in the 20-90 km height range of the atmosphere" (WMO/IQSY 1964, p. 7) during an SSW, which by that time had been observed only a few times. From these early monitoring efforts, various definitions for SSWs were developed and appeared in the scientific literature over the latter half of the twentieth century (the STRATALERT program continued until 2004). Because some of the references are not readily available, and for historical completeness, we include a detailed table of major references stating SSW definitions in the electronic supplement to this article (http://dx.doi.org/10.1175/BAMS-D-13-00173.2; see Table ES1).

As evident from these references, definitions for SSWs have changed over time. An early definition for major SSWs based on temperature changes (WMO/IQSY 1964) evolved to one using the reversal of the stratospheric zonal-mean zonal wind circulation, the basic concepts of which have endured in some form since the late 1970s. The appeal of a definition based on the zonal circulation originates in work by Charney and Drazin (1961), Matsuno (1971), and others (O'Neill and Taylor 1979; Palmer 1981), who demonstrated that planetary-scale stationary waves cannot propagate into easterly flow. Thus, following a major SSW in which the stratospheric winds reverse from climatological-mean westerly flow to easterly flow, waves can no longer propagate upward above the level of the reversal and so subsequently break at lower and lower levels in the stratosphere, reversing the wind downward from the upper stratosphere to the lower stratosphere. The reversal of the zonal circulation is thus a fundamental characteristic of major SSWs and their associated dynamics.

Because STRATALERT was organized under the WMO CAS, we have searched all meeting reports of those commissions, and of the WMO Executive

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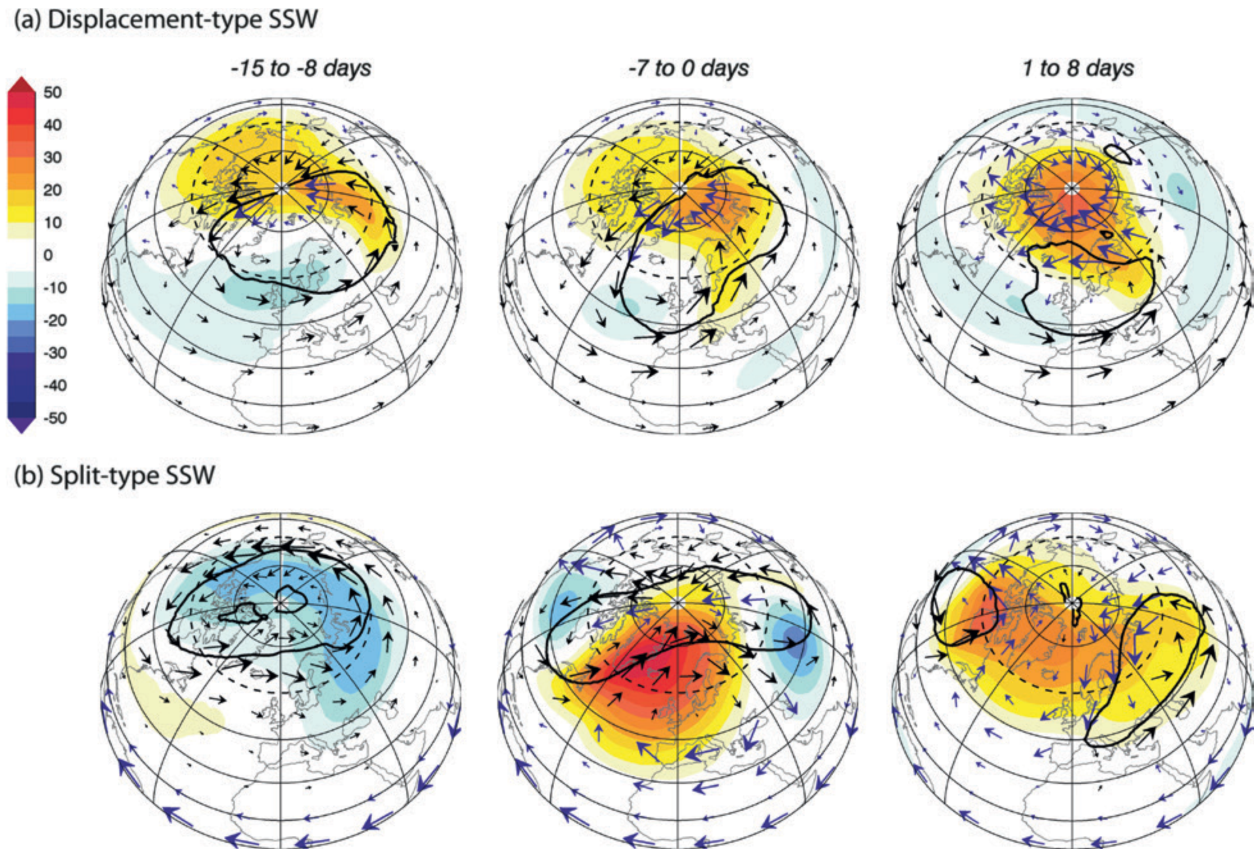

Fig. 1. (a) A displacement-type SSW event on 21 Jan 2006 and (b) a split-type SSW event on 24 Jan 2009, for the average of (left) 8–15 days prior to the event, (middle) 7 days prior to the event, and (right) 1–8 days following the event. ERA-Interim temperature anomalies (based on 1979–2012 climatology) at 10 hPa (K) are shaded. The black solid line marks the 7-PVU contour (1 potential vorticity unit = 10^{-6} K kg^{-1} m^2 s^{-1}) at 10 hPa and indicates the shape of the polar vortex. The arrows indicate the full zonal and meridional wind fields at 10 hPa (arrows with a westerly zonal component are black; arrows with an easterly zonal component are blue). The 60°N latitude line is dashed. A complete movie of these events can be found online (http://dx.doi.org/10.1175/BAMS-D-13-00173.2).

Committee and Congress, since the 1950s for language related to the SSW definition. The SSW definition was last formalized by the CAS in 1978, but two reports published that year offer two different interpretations. McInturff (1978, p. 19) (published in January 1978) states that the WMO CAS

> has adopted the following definitions: 1. A stratospheric warming is called minor if a significant temperature increase is observed (i.e., at least 25 degrees in a period of a week or less) at any stratospheric level in any area of the wintertime hemisphere, measured by radiosonde or rocketsonde data and/or indicated by satellite data; and if criteria for major warmings are not met. Less extreme warmings will be referred to as warming pulses. 2. A stratospheric warming can be said to be major if at 10 mb or below the latitudinal mean temperature increases poleward from 60 degrees latitude and an associated circulation reversal is observed (i.e., mean westerly winds poleward of 60° latitude are succeeded by mean easterlies in the same area).

Yet a WMO CAS report (WMO CAS 1978, p. 36, item 9.4.4) published two months later, while stating the same definition for minor SSWs, states: "'major' warmings [occur] with a temperature increase of at least 30 degrees in a week or less at 10 mb or below, or by at least 40 degrees above 10 mb." No criteria about the circulation reversal are mentioned in this WMO CAS report.

These discrepancies between two closely timed early publications are emblematic of the sorts of variations in definitions of SSWs that are pervasive in the literature over the last three decades. While the zonal wind reversal diagnostic (e.g., McInturff 1978) has been the dominant basis for the definition of major SSWs in recent decades, the application of the SSW

TABLE 1. Nine SSW definitions used in this paper, the details of their calculations, and the average number of major SSWs per year for each definition using 57 winters in NCEP–NCAR (NNR; Jan 1958—Apr 2014) and ERA-40 (Jan 1958–Mar 1989)/ERA-interim (Mar 1989–Apr 2014). Abbreviations for each definition are used in Figs. 2 and 5b.

Definition	Description	SSW per year NNR	SSW per year ERA
Zonal wind and temperature gradient reversal (U&T)	Events occur when the zonal-mean zonal winds at 10 hPa and 60°N fall below 0 m s^{-1} from Nov to Mar. Events that do not also have a meridional temperature gradient reversal (defined as the zonal-mean temperatures averaged from 80° to 90°N minus the temperatures averaged from 60° to 70°N) within ~10 days of the circulation reversal are excluded. Events must return to westerly (>0 m s^{-1}) for at least 20 consecutive days between events. The winds must return to westerly for at least 10 consecutive days prior to 30 Apr (or an event is considered a final warming).	0.58	0.65
Zonal wind reversal at 60°N (CP07)	Events occur when the zonal-mean zonal winds at 10 hPa and 60°N fall below 0 m s^{-1} from Nov to Mar. Events must return to westerly (>0 m s^{-1}) for at least 20 consecutive days between events. The winds must return to westerly for at least 10 consecutive days prior to 30 Apr (or an event is considered a final warming).	0.61	0.65
Zonal wind reversal at 65°N (U65)	Identical to CP07, except using zonal-mean zonal wind at 65°N.	0.77	0.84
Zonal winds averaged from 60° to 90°N (U6090)	Events occur when the zonal-mean zonal winds at 10 hPa, cosine weighted and averaged from 60° to 90°N, fall below 0 m s^{-1} from Nov to Mar. Identical to U60 except using the 60°–90°N averaged zonal-mean zonal wind.	0.81	0.91
Vortex moments* (MOM)	Details can be found in Mitchell et al. (2011) and Seviour et al. (2013). The gridded geopotential height field at 10 hPa is used to find vortex moments: the aspect ratio and centroid latitude. The vortex edge is taken to be the mean value of the Dec–Mar (DJFM) heights at 10 hPa and 60°N. Displacement events occur when the centroid latitude is equatorward of 66°N for 7 days or more. Split events occur when the aspect ratio is greater than 2.4 for 7 days or more. If splits or displacements occur within 30 days of each other, then only the first event qualifies.	0.49	0.68
Polar cap–averaged geopotential height anomalies (ZPOL)	Anomalies of zonal-mean geopotential heights at 10 hPa are found following Gerber et al. (2010). The polar cap anomalies are found by averaging (cosine weighted) anomalies from 60° to 90°N. This (year-round) time series is standardized about the JFM mean (as in Thompson et al. 2002). Events occur when the time series exceed plus three standard deviations. An event that occurs within 60 days after another is excluded.	0.65	0.61
EOF of zonal-mean geopotential height anomalies (EOFZ)	Anomalies of zonal-mean geopotential heights at 10 hPa are found following Gerber et al. (2010). The first EOF is then calculated for anomalies 20°–90°N, after weighting by the square root of the cosine of latitude. The first principal component time series (PC1) is then found by projecting the unweighted original anomaly data onto the first EOF and then standardizing the resulting time series (see Baldwin and Thompson 2009). Events occur when the PC1 index falls below –3 standard deviations (where the negative phase of the EOF is defined by anomalously high heights over the polar cap). An event that occurs within 60 days after another is excluded.	0.65	0.60

Table 1. Continued.			
Definition	**Description**	**SSW per year NNR**	**SSW per year ERA**
EOF of zonal-mean zonal winds (EOFU)	The method for EOFZ (above) is used, but zonal-mean zonal wind anomalies at 50 hPa and 20°–90°N (PC1 < ~3 std dev) are instead analyzed. Similar to Limpasuvan et al. (2004).	0.46	0.49
Temperature changes >40°C in a week or less (TMP)	Zonal-mean temperatures, Nov–Mar, 100–10 hPa, poleward of 60°N. Events occur when any grid cell in this region exceeds a 40°C change in one week. An event that occurs within 60 days after another is excluded.	0.37	0.35

* The SSW dates using the vortex moments definition have been calculated by W. Seviour, Department of Physics, University of Oxford (Seviour et al. 2013), through 2012; dates for 2013–14 have been calculated by A. Butler.

definition varies considerably. Some of these interpretations include the following: using only the 10-hPa level (very common; data at pressures less than 10 hPa are rarely used); using zonal-mean zonal winds at a single latitude (60° or 65° latitude; e.g., Labitzke and Naujokat 2000) rather than zonal winds poleward of 60°; using polar cap–averaged zonal winds poleward of 60° latitude (vs the more stringent requirement that zonal-mean zonal winds reverse at each latitude poleward of 60°); and evaluating minor warmings not by a temperature tendency but rather as those warmings that do not reverse the circulation (e.g., Andrews et al. 1987). This evolutionary history suggests that a true standard definition of SSWs is at best ambiguous and at worst nonexistent.

Additional warming classifications (beyond minor and major) also appear in the literature (e.g., Labitzke 1981; Meriwether and Gerrard 2004). These include Canadian warmings (early winter warmings marked by an eastward shift of the Aleutian high) and final warmings (abrupt, dynamically forced warmings in both hemispheres, after which the winter cyclonic vortex does not recover). But different studies implement these classifications in different ways. For example, some studies (e.g., Charlton and Polvani 2007, hereafter CP07) classify Canadian warmings as major warmings if a circulation reversal occurs, while Labitzke (1977) argues against this based on differences in synoptic development.

The determination of final warmings also varies. Some studies (e.g., CP07; Bancalá et al. 2012) consider some March events to be major midwinter[3] events rather than final warmings if the vortex returns to a westerly state or to a certain amplitude for a certain number of days before the end of winter. Both midwinter and final warmings have important (and often similar) influences on the atmosphere. The frequency of major midwinter SSWs is an important metric of polar stratospheric wintertime variability (final warmings occur every winter, so they do not contribute to the total frequency). The seasonal timing of final warmings each winter is also an important metric of interannual stratospheric variability. What constitutes "midwinter" and how to determine which warmings are final are aspects of current definitions that remain imprecise.

New diagnostics[4] for characterizing SSWs (including minor, major, and final warmings) have been proposed as a result of technological advances and scientific needs. Freie Universität Berlin produced continuous daily stratospheric maps since the late 1950s for STRATALERT activities based largely on radiosonde measurements, which are unique because unlike reanalyses, there are no jumps or irregularities due to model updates, different streams, or upper-boundary effects (Labitzke et al. 2002; Labitzke and Kunze 2005). Like other traditional synoptic analyses, these contain a certain degree of subjectivity. More comprehensive observations from satellites and improved stratospheric model simulations (e.g., Rind et al. 1988; Manzini and Bengtsson 1996; Erlebach et al. 1996; Charlton et al. 2007) have

[3] The adjective *midwinter* in the recent literature has often been used to refer to all, or most, wintertime (November–March) warmings except the final warming—not, as might be assumed, to those warmings occurring only in the middle of winter.

[4] Here, we use *diagnostics* to refer to any technique that may be used to examine particular aspects of SSWs and their evolution; in combination with threshold limits and usage guidelines, diagnostics may form "definitions."

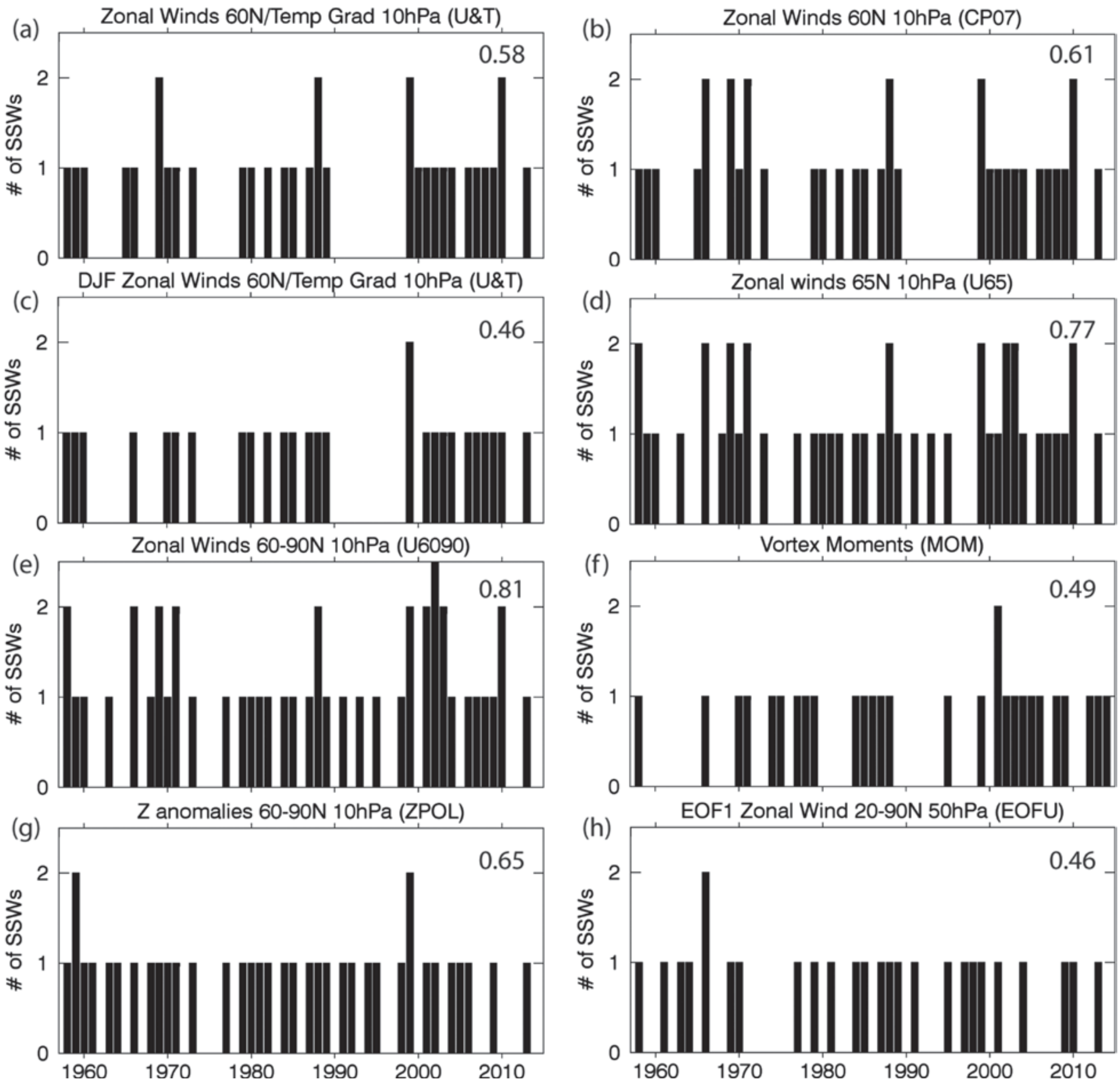

Fig. 2. Time series (using NCEP–NCAR reanalysis from 1958 to 2014) of major midwinter SSWs as defined using seven different definitions (described in Table 1): (a) zonal-mean zonal winds at 60°N and 10 hPa, and a temperature gradient reversal; (b) zonal-mean zonal winds at 60°N and 10 hPa, following guidelines by CP07; (c) as in (a), but for Dec–Feb only; (d) zonal-mean zonal winds at 65°N and 10 hPa; (e) zonal-mean zonal winds at 10 hPa and averaged from 60° to 90°N; (f) vortex moment diagnostics; (g) geopotential height (Z) anomalies averaged from 60° to 90°N at 10 hPa, exceeding three standard deviations of the Jan–Mar (JFM) mean climatology; and (h) the leading EOF of zonal wind anomalies from 20° to 90°N and 50 hPa. The abbreviations correspond to those in Table 1. The average number of SSWs per winter is given in the top-right corner of each panel (corresponding values for ERA-40/ERA-Interim are given in Table 1).

led to an improved understanding of SSWs and their impacts. Diagnostics, many of which are the basis for various SSW definitions (Table 1), include the following:

- Zonal-mean zonal winds at 10 hPa and 60° latitude (Christiansen 2001; CP07)
- Reversal of the meridional zonal-mean temperature gradient poleward of 60° latitude, usually used in combination with a reversal of the zonal-mean zonal winds at or poleward of 60° latitude (e.g., Labitzke 1981; Ayarzagüena et al. 2013)
- Empirical orthogonal functions (EOFs) of a) gridded pressure-level data of either geopotential height

anomalies (Baldwin and Dunkerton 2001; Baldwin 2001) or zonal wind anomalies (Limpasuvan et al. 2004); b) zonal-mean geopotential height anomalies (Baldwin and Thompson 2009; Gerber et al. 2010); and c) vertical profiles of polar cap–averaged temperature (Kuroda and Kodera 2004; Hitchcock and Shepherd 2013; Hitchcock et al. 2013)

- Polar cap–averaged geopotential height anomalies at 10 hPa (e.g., Thompson et al. 2002)
- Tendency of the northern annular mode index at 10 hPa (Martineau and Son 2013), polar cap temperature (Nakagawa and Yamazaki 2006), or the zonal-mean zonal wind at 10 hPa near 60°N (Birner and Albers 2015)
- k-means clustering technique (Coughlin and Gray 2009)
- Vortex geometry, including vortex moments (Waugh and Randel 1999; Matthewman et al. 2009; Hannachi et al. 2011; Mitchell et al. 2011, 2013; Seviour et al. 2013)
- Wavenumber of the disturbed vortex (Johnson et al. 1969; O'Neill and Taylor 1979)
- Supervised learning approach/neural networks (Blume et al. 2012)

Each diagnostic has unique characteristics; for example, EOFs of stratospheric height anomalies may be more strongly coupled to the troposphere compared to zonal-mean zonal winds (Baldwin and Thompson 2009), and vortex moment diagnostics are more physically linked to potential vorticity dynamics. Diagnostics that capture stratosphere–troposphere coupling are appealing from the perspective of physical understanding and potential societal impacts, as are those that provide a simple metric of SSW occurrence for climate model intercomparison and validation.

One of the most commonly used SSW definitions (pertaining to major midwinter SSWs) in the recent literature is based on the diagnostic of zonal-mean zonal wind at 60° latitude and 10 hPa and is described in detail by CP07. The CP07 definition is likely popular because of its simplicity (one variable at one latitude and pressure level) and because it includes detailed implementation guidelines pertaining to a) the separation of closely timed events[5] (i.e., if the zonal-mean zonal wind reverses twice within a short period of time, are those events considered separate and independent?), b) exclusion of final warmings, and c) identification of split-type events. In recent years, this definition has commonly (but mistakenly) been cited as "the WMO definition." However, it lacks the meridional temperature gradient reversal requirement and the consideration of zonal winds poleward of 60° latitude in the McInturff (1978) definition. Moreover, the CP07 definition clearly distinguishes between late midwinter and final warmings, requiring zonal-mean zonal winds to return to westerly for at least 10 days prior to 30 April to be classified as a major midwinter event. As demonstrated in the next section, these distinctions matter.

SENSITIVITY OF SSW CLASSIFICATION TO THE DEFINITION.

If identification of major midwinter SSWs were not sensitive to definition, then the differences in the literature would be moot. But this is not the case because of the highly variable nature of SSW events and of wintertime stratospheric dynamics. Figure 2 shows the number of major SSWs per year for seven different definitions described in Table 1, applied to the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) from 1958 to 2014 (Fig. 2c is the same as Fig. 2a, but for December–February events only). The average number of major SSWs per winter for this 57-yr period range from 0.46 to 0.81 per winter among the seven definitions, and the dates of major SSWs for each definition differ substantially (see also Table ES2). In fact, of the 26–46 SSWs identified in each definition, only 13 SSWs are identified by all seven definitions using NCEP–NCAR reanalysis data. Using different reanalyses (or six-hourly winds rather than daily-averaged winds, or data on a coarser horizontal grid) produces slightly different results. Tables 1 and ES2 compare the number of major SSWs per winter in NCEP–NCAR and in the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40)[6] (Uppala et al. 2005)/ERA-Interim (Dee et al. 2011) from 1958 to 2014[7] and demonstrate that certain definitions are more sensitive to differences between reanalysis products than others.

Some definitions show noticeably more decadal variability than others. For example, the definitions

[5] Note the corrected guidelines in the corrigendum to Charlton and Polvani (2007).

[6] We employ the NCEP–NCAR and ERA-40 reanalyses here because they extend prior to 1979, and thus they allow better statistics of SSW events. Many of these events have been independently verified in prior studies. However, these reanalysis datasets may poorly represent polar stratospheric processes (e.g., Manney et al. 2003) and may be poorly constrained prior to 1979 when satellite observations became abundant.

[7] Here ERA-40 is used from 1958 to 1 March 1989, and ERA-Interim thereafter, following the justification for combining the datasets in Blume et al. (2012).

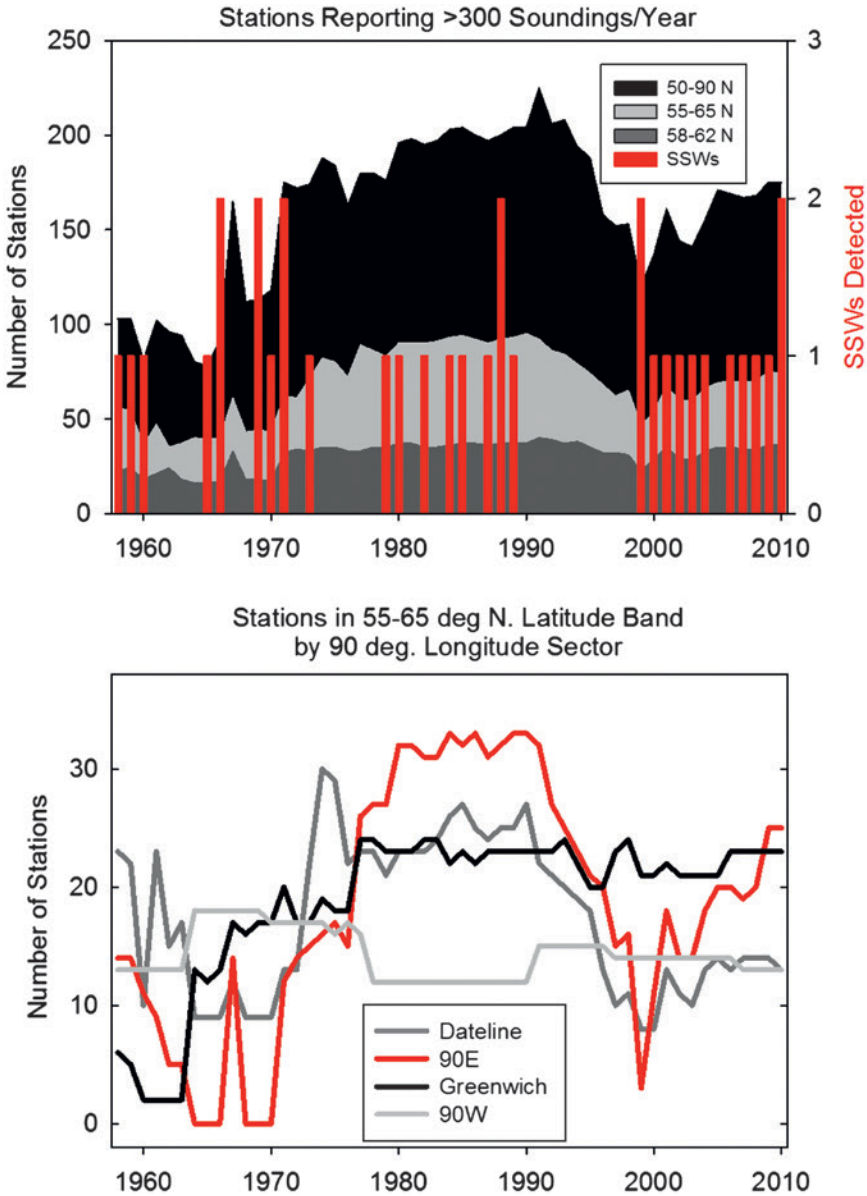

Fig. 3. (top) The number of radiosonde stations reporting >300 soundings per year in different latitude bands, from 1958 to 2010. Red bars indicate the occurrence of SSWs (from Fig. 2b, the CP07 method). (bottom) The number of stations reporting in the 55°–65°N latitude band as a function of longitude quadrant (centered on the given longitude).

based on zonal-mean zonal winds at 60°N yield no major warmings during most of the 1990s, when other definitions, including one based on zonal-mean zonal wind reversal at 65°N, show two to five major SSWs during that decade (Fig. 2). Why do these differences—among the definitions and over time—exist? One contributing factor may be changes in the observations assimilated into reanalyses. Definitions based on one latitude or region may be more sensitive to this than definitions based on larger domains. This explanation appears possible in light of changes in the Northern Hemisphere radiosonde network (Fig. 3). The number of regularly reporting radiosonde stations in the region 50°–90°N increased from the 1960s to the 1980s, but then it dramatically decreased in the 1990s in association with the collapse of the Union of Soviet Socialist Republics (USSR; ~45°–135°E) and parts of its meteorological networks. The timing of the largest reduction in radiosonde observations from 55° to 65°N (which is especially noteworthy in the region of the former USSR; not shown) roughly coincides with the period when few major SSWs are detected using the zonal-mean zonal wind reversal at 60°N. We find it worth noting that the definition most dependent on this particular latitude detects the fewest major SSWs during a decade that experienced the greatest loss of measurements there.

Arguably, assimilation of satellite data into the reanalysis products used to calculate SSW events here should somewhat mitigate the sampling inhomogeneities in radiosonde observations. Moreover, major SSW events are still detected in the early 2000s despite reduced numbers of radiosonde stations. The mid-1990s are known to have been particularly cold years in the Arctic stratosphere (e.g., Pawson and Naujokat 1999), which argues against invoking sampling issues to explain the lack of detected SSWs in the 1990s. On the other hand, the fact that the zonal-mean zonal wind diagnostic at 65°N rather than 60°N does detect major SSWs in the 1990s suggests sensitivity to this particular latitude.

This begs the question: Is 60° latitude a reasonable choice for defining SSWs, particularly now that

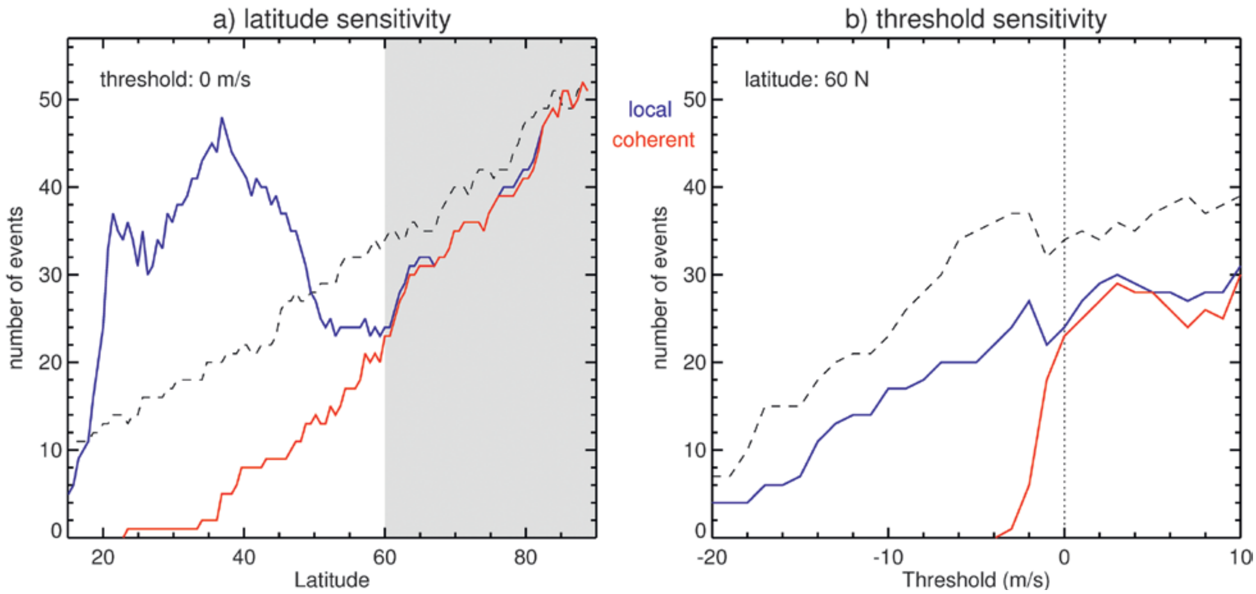

Fig. 4. (a) The number of SSWs (during 1979–2012, in ERA-Interim) as a function of latitude where the zonal wind reverses from westerly to easterly (0 m s^{-1} critical threshold). (b) The number of SSWs as a function of critical threshold (i.e., the wind speed below which a warming is considered to occur), for zonal wind at 60°N. "Local" events (blue) occur when the zonal winds at one particular latitude fall below the critical threshold. "Coherent" reversals (red) occur when the zonal winds at every latitude poleward of the given latitude also fall below the critical threshold within 20 days. "Averaged" reversals (black dashed) occur when the zonal winds averaged from a particular latitude to 90°N fall below the critical threshold. Note: no temperature gradient criterion is applied here, Nov–Mar zonal winds are used, and we follow the CP07 criteria for separation of events and determination of final warmings.

near-global satellite measurements are available? Does this latitude represent some key physical feature of stratospheric circulation? Or does it make sense to choose a more poleward latitude, average over a larger latitude region, or (more stringently) require a reversal of the zonal winds everywhere poleward of a particular latitude? Figure 4a shows the dependence of major SSW frequency on the latitude of circulation reversal. When major SSWs are diagnosed using the reversal of the zonal-mean zonal winds at one latitude only (local reversal, blue line), the number of major SSWs (1979–2012) minimizes if that latitude is between 50° and 60°N. To understand this result, we also consider the number of major SSWs that occur if instead the zonal winds everywhere poleward of a particular latitude must also reverse direction (coherent reversals, red line). Poleward of 60°N, the local and coherent reversal requirements yield nearly identical numbers of SSWs; anywhere in this region, if the wind reverses from westerly to easterly at one latitude, it is also almost certain that the wind is reversing everywhere poleward of that latitude. Equatorward of 60°N, however, the number of coherent reversals continues to decrease while the number of local reversals increases. This bifurcation can be explained by noting that these latitudes mark the surf zone (McIntyre and Palmer 1984), where breaking waves can drive local reversals in the stratospheric circulation, which is not associated with coherent polar vortex dynamics. Thus, 60°N is near the average edge of the coherent polar vortex.

A more subtle aspect of the definitions based on zonal-mean zonal wind diagnostics also affects SSW identification. If one interprets the McInturff (1978) definition, for example, as meaning that the zonal-mean zonal winds everywhere poleward of 60°N must coherently reverse from westerly to easterly, then Fig. 4a suggests that using just 60°N will yield essentially the same events. On the other hand, if one interprets this definition as meaning that the zonal-mean zonal winds averaged from 60° to 90°N must reverse (black dashed line), then about 30% more events will be detected compared to using 60°N only (or coherent reversals from 60°N). Defining the reversals near 65°N rather than 60°N reduces that difference to about 10%, thus minimizing the effect of the different interpretation.

The stratosphere experiences low-frequency variability on interannual and decadal time scales, as well as long-term trends, due to both natural variability like the solar cycle (e.g., Labitzke et al. 2006) and anthropogenic change (e.g., Butchart et al. 2000; Scaife et al. 2005). It is possible then that the polar vortex edge also varies, so that during some years or decades 60°N may be within the surf zone and therefore not

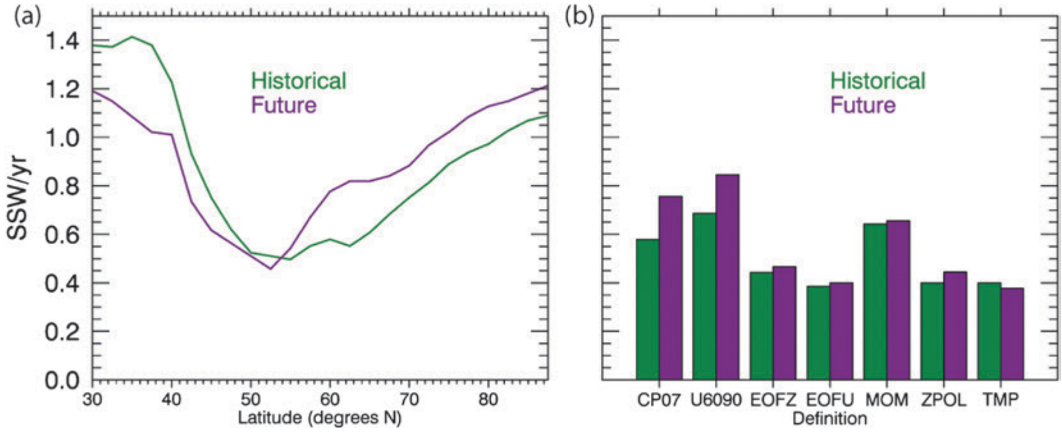

Fig. 5. (a) Average number of SSWs per year using the CP07 zonal wind definition (local reversals) evaluated at different latitudes, for the historical simulation (1860–2005, green) and the climate change simulation (2006–99, purple) in HadGEM2-CCS. (b) Average number of SSWs per year for seven different definitions (described in Table 1), for the historical and climate change simulations.

a suitable place at which to evaluate SSWs. Using historical (1860–2005) and future [2006–99; representative concentration pathway 8.5 (RCP8.5)] climate simulations from the Hadley Centre Global Environment Model, version 2—Carbon Cycle Stratosphere (HadGEM2-CCS) model (Hardiman et al. 2012; Osprey et al. 2013), we consider the frequency of major SSWs using the zonal-mean zonal wind reversal definition at a particular latitude (Fig. 5a). We find that a) in the historical simulation, the separation between the surf zone and the coherent vortex zone resembles the observations (Fig. 4a); and b) in the future simulation, the frequency of major SSWs detected using the zonal wind reversal at a particular latitude increases at every latitude poleward of ~55°N, and that there is a slight equatorward shift in the region experiencing a minimum of reversals between the surf and coherent zones. In other words, whereas 60°N is historically at the edge of the polar vortex, this model simulation suggests 60°N will be well within the coherent vortex in a future climate.

SSW classification is also sensitive to the threshold used to determine an extreme event. In some cases, like EOF-based definitions, the threshold (usually two or three standard deviations) is not dynamical but statistical. For definitions based on zonal wind reversal, the threshold is the speed to which the zonal winds must decelerate. From a dynamical perspective, an appealing threshold represents the wind speed below which waves cannot propagate, leading to wave breaking and descent of the circulation anomalies. In linear planetary-wave theory (Charney and Drazin 1961) and critical-layer theory (Matsuno 1971), stationary planetary waves (i.e., waves with zero phase speed) cannot propagate into easterly winds, and the current threshold of 0 m s^{-1} seems an obvious choice. One question to consider, particularly for impact or stratosphere–tropospheric coupling studies, is whether the dynamical impacts following a wind deceleration to 1–5 m s^{-1} (or some other nonzero value, i.e., minor warmings) are essentially equivalent to the impacts of a complete wind reversal. Figure 4b also suggests that the major SSW frequency is (perhaps surprisingly) not highly sensitive to the critical threshold (for threshold values between 0 and 10 m s^{-1}). Nonetheless, for a standard definition, which by construction requires some threshold criteria, the 0 m s^{-1} threshold seems justifiable based on dynamical arguments.

Finally, certain SSW definitions can be sensitive to changes in the background climatology of the polar wintertime stratosphere. In Fig. 5b, we consider the average number of major SSWs per year, using seven different definitions from Table 1, for historical and future climate simulations from the HadGEM2-CCS model. Whereas the definition using zonal-mean zonal wind at 60°N (CP07), or the polar cap–averaged winds (U6090), shows a significant (at the 90% confidence level) increase in major SSWs in the future, other definitions like those using EOF-based diagnostics show insignificant changes. This result is in agreement with other modeling studies (McLandress and Shepherd 2009; Bell et al. 2010) that indicate an increased major SSW frequency in future climate using the zonal-mean zonal wind reversal criteria, though this result appears to be model dependent (Mitchell et al. 2012; Ayarzagüena et al. 2013). McLandress and Shepherd (2009) also note that the increase in major SSW frequency occurs only for definitions based on zonal wind diagnostics but not for definitions based on anomalies relative to the contemporaneous climatology. They argue that simulated weaker climatological westerly winds in the polar wintertime stratosphere allow variations in the zonal wind to fall below the 0 m s^{-1} critical threshold more easily, so the increase in major SSW frequency for those definitions may be at least partially due to changes in the climatological state rather than changes in polar wintertime stratospheric variability.

Two perspectives are prevalent regarding the effect of changes in climatology on the SSW definition (e.g., Mitchell et al. 2012). One viewpoint maintains that using the absolute sign change of the stratospheric winds as a measure of major SSW frequency can be interpreted as a change in stratospheric variability, but that it may actually only reflect changes in the climatological state of the vortex; therefore, long-term changes in climatology need to be considered (an analogous example is the adaptation by the National Oceanic and Atmospheric Administration of the ENSO definition to update sea surface temperature climatologies, to account for warming that might erroneously suggest that warm El Niño events are increasing; L'Heureux et al. 2013). The alternative viewpoint is that even if more major SSWs occur only because the thresholds are easier to meet in a weaker westerly climatology, that the stratospheric zonal circulation is still reversing, which has real dynamical implications following the events.

This issue of a variable background state may be relevant even on shorter interannual to decadal time scales. For example, the Northern Hemisphere stratospheric polar vortex was particularly strong during the 1990s (Shindell et al. 1999; Pawson and Naujokat 1999; Manney et al. 2005). Though it is possible that the polar vortex winds were stronger because there were fewer SSWs, it is also conceivable that SSW definitions based on zonal wind diagnostics, particularly at a single latitude like 60°N, might have been less likely to meet the threshold value of 0 m s^{-1} during an extended period of stronger-than-normal westerly flow (particularly because other SSW definitions detect major events during this decade; Fig. 2). Another example may be modeling studies that find fewer major SSWs in models with an overly strong climatological polar vortex using zonal-mean zonal wind diagnostics (Charlton et al. 2007).

We have demonstrated that major SSW identification can be quite sensitive to the definition used and its interpretation and implementation. Aside from latitude and wind speed threshold, results are also sensitive to the pressure level (altitude) considered, the climatology chosen for definitions involving anomalies, and the climatological-mean state of the stratosphere itself and its low-frequency variability.

RECOMMENDATIONS AND OPPORTUNITIES.

Is a "standard" SSW definition necessary? The analysis above suggests that it would be impossible to find a single definition to serve every purpose or describe every event perfectly. We believe that the primary purpose of a standard SSW definition should be to characterize polar stratospheric wintertime variability; examining other aspects, like the stratosphere–troposphere coupling of these events, arguably requires different diagnostics. Some applications, like forecasting SSWs, may benefit from a standard definition for the sake of consistency across international operating centers, but they also require further detailed diagnosis for each event.

A standard definition is useful primarily for statistical applications, such as the robust assessment and intercomparison of major SSW frequency in observational datasets and historical/future climate simulations, and between different model generations. For example, Fig. 5b shows the large differences in SSW frequencies for different definitions when applied to historical and future climate simulations. A standard definition allows for consistency across observational and modeling studies. Without consistency, it is difficult to evaluate which models reasonably represent polar stratospheric wintertime variability. Other analyses that depend on the frequency (i.e., statistics) of major SSWs should also use a standard definition for consistency. It should be noted that while a standard definition should be able to detect the vast majority of major SSWs, more detailed diagnostics may be needed to determine a complete set of historical SSWs.

If the community agrees that a standard definition is useful and that the purpose of the standard definition is to characterize wintertime stratospheric variability, then the next step is to consider details of the definition. What qualities are desirable in a standard definition? Our analysis suggests these three characteristics:

- Simplicity: Easily calculated and applicable to reanalyses and model output, both retrospectively and in real time (operationally)
- Relevance: Serves primarily as a metric of polar stratospheric variability, rather than a metric of associated phenomena such as stratosphere–troposphere coupling
- Robustness: Not highly sensitive to details, such as an exact latitude, background climatology,

threshold wind speed, spatial extent, or pressure level

It has been over 35 years since the WMO offered a definition of SSWs, during which time many more SSWs have been observed. We suggest the time is ripe for improvements and updates. A clear reference for the original WMO definition is lacking, and how the definition should be applied is vague, resulting in different interpretations and inconsistent identification and classification of SSWs. We believe a new definition should include, at a minimum, guidelines for determining a) the independence of closely timed events; b) the classification of split-type versus displacement-type events; and c) precise distinctions among major, minor, final, and Canadian SSWs.

In addition to these new guidelines, we propose several options as a starting point for updating the SSW definition.

1) Among the definitions surveyed here, the CP07 definition provides a strong basis for a definition of major SSWs because of its simplicity and relevance. However, it lacks robustness. Using a latitudinal average of zonal winds rather than one particular latitude, or using 65°N instead of 60°N, may decrease sensitivity to changes in the vortex edge.
2) The McInturff (1978) definition, including the temperature gradient criterion, could be clarified and enhanced to address current ambiguities (e.g., How closely timed do the temperature gradient and zonal wind reversals need to occur for major SSWs? During which months? How do we separate closely timed events?). An advantage to this technique is that this definition has a strong historical basis and familiarity; a disadvantage is that more data are required (both temperature and zonal wind), which can be computationally expensive when considering large model intercomparisons.
3) Further consideration could also be given to developing a new kind of stratospheric index, along which a continuum of stratospheric events could be defined, including minor warmings and polar vortex intensification (Limpasuvan et al. 2005). Research would be needed to develop such an index, but it could allow the user to choose the threshold at which extreme events occur in a particular analysis, and it may have a broader application. Still, we argue in this case it would be useful to have a "standard threshold" for major SSWs or for major vortex intensification events to ensure a consistent metric of polar stratospheric variability.
4) We also think it worthwhile and timely to reflect on the name sudden stratospheric warming and whether this terminology is the most useful in light of the fact that major SSWs are now identified primarily on the basis of a circulation reversal, rather than some unspecified measure of a sudden temperature increase. While the historical context (SSWs were first observed in temperature data; e.g., Scherhag 1952) and the need for continuity are important and valid reasons for the maintaining the term sudden stratospheric warming, wording that focuses on circulation rather than the temperature change, and thus more accurately reflects to the public what is being defined, should be considered.

Under the auspices of the World Climate Research Programme's core project on Stratosphere–Troposphere Processes and their Role in Climate (SPARC), efforts are underway to gather community ideas and to develop consensus on an updated standard SSW definition. An initial meeting was held during the SPARC General Assembly in Queenstown, New Zealand, in January 2014 to discuss a timeline and process for gathering input (Butler et al. 2014a). Three additional townhall discussions were held in 2015 (at the American Meteorological Society Annual Meeting, the European Geophysical Union General Assembly, and the Asia Oceania Geosciences Society Annual Meeting) to gather community feedback. The input from these forums will be compiled into a recommendation for an updated standard definition, to be finalized at the SPARC Dynamic Variability (DynVar) meeting in June 2016, prior to submitting recommendations to the WMO. Anyone who is interested can join the e-mail LISTSERV (visit https://sites.google.com/site/stratosphericwarmings/ and following the links therein). Ideas are welcome from anyone who may use the SSW definition for research and operational purposes.

The challenges in understanding the SSW definition and its history, applications, and interpretations are not unique. Other standard definitions face or will face reevaluation in light of new and improved observations, modeling capabilities, and understanding of physical processes. Community involvement and discussion will be essential in determining state-of-the-art definitions for these phenomena to enable improved understanding of past and future climate.

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