DEFINING SUDDEN STRATOSPHERIC WARMINGS

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This document is a supplement to "Defining Sudden Stratospheric Warmings," by Amy H. Butler, Dian J. Seidel, Steven C. Hardiman, Neal Butchart, Thomas Birner, and Aaron Match (*Bull. Amer. Meteor. Soc.*, **96,** 1913–1928) • ©2015 American Meteorological Society • *Corresponding author:* Amy Butler, NOAA/ESRL/CSD, 325 Broadway, Boulder, CO 80305-3337 • E-mail: amy.butler@noaa.gov • DOI:10.1175/BAMS-D-13-00173.2

TABLE ES1. Some historical references for definitions of sudden stratospheric warmings: SSW = sudden stratospheric warmings and NH = Northern Hemisphere/Northern Hemispheric.

Year	Reference	Definition and related text (quoted from the source)
1964	WMO/ IQSY (1964)	Stratospheric Warming Alert (STRATWARM) is issued when a sudden and unusual increase in temperature at 30 km or above has been detected. The general geographical region where the warming phenomena have been observed is specified; such events however, usually involve the high level circulation of the entire hemisphere at high latitudes after a period of several days, and an estimate of the area to be affected is given. (page 2)
		3. Explanation of the STRATWARM Scheme
		The most important GEOALERT messages for meteorologists are those dealing with stratospheric warmings which are issued by the IQSY [International Years of the Quiet Sun] World Warning Agency in accordance with the scheme described hereafter. In the WMO Guide to the IQSY Meteorological Programme (WMO/IQSY Report No. 1) a brief introduction to the scientific problem of the STRATWARM scheme is given.
		The organization of the STRATWARM warning centers, as well as the telecommunication arrangements for the distribution of alert messages and for the collection of the upper-air information necessary for the recognition of the warmings, are set forth below. The main object is the listing of types of warmings and their characteristics which are outlined here for the purposes of this warning scheme; the details should not be considered as scientifically definitive in view of the short period during which these phenomena have been studied. In the IQSY period stratospheric events of an unprecedented nature might be observed in either hemisphere.
		3.2.2 A GEOALERT STRATWARM message will be issued when a center of warming of major proportions, meeting the meteorological criteria given in paragraph 3.5 has been detected and appears likely in the course of time to affect conditions over much of the Northern Hemisphere. …

Table ES1. Continued.		
Year	**Reference**	**Definition and related text (quoted from the source)**
1964	WMO/ IQSY (1964)	3.5 Warming Characteristics and Alerting Criteria
		3.5.1 Stratospheric warmings have been observed and studied for only a relatively few years. Certainly the daily stratospheric charts analyzed for levels above 30 mb have shown that wintertime circulation patterns vary in a complex manner. Therefore a division into categories, as in the following discussion, should be considered only as a convenience in the practical work of attempting to distinguish phenomena for the purposes of issuing and interpreting the Alert messages. In particular it is difficult to distinguish the warmings into such categories on current schedule, while the stratospheric condition is developing.
		3.5.2 Mid-Winter Warmings
		For purposes of issuance and interpretation of Alerts, the wintertime disturbances will be classified into two general categories:
		(i) a major mid-winter warming accompanied by complete circulation reversal; and
		(ii) minor warmings with limited circulation changes.
		Some characteristics of each and the guide lines for declarations of worldwide (GEOALERTS STRATWARM) and regional (STRATALERT …) alerts are as follows:
		3.5.2.1 Major Mid-Winter Warmings
		(a) Sudden warming appears usually during middle or late January.
		(b) Contour pattern changes from and (sic) intense circumpolar vortex to a pattern of bipolar troughs and associated anticyclones, one or both of which may intensify rapidly.
		(c) Although no preferred geographical location for the initial warming has yet been identified, the highest temperatures tend to develop in the jet stream along the eastern side of one or both of the bipolar troughs that extend into middle latitudes.
		(d) The warming, once established, tends to intensify rapidly, by as much as 10°C in one day.
		(1) STRATALERT messages should be initiated when the central temperature of the warm air reaches ~30°C at 10 mb or ~35°C at 30 mb.
		(2) GEOALERT STRATWARM messages may be expected when temperatures within the warm center reach ~25°C at 10 mb or ~30°C at 30 mb.
		(e) 10-mb temperatures may reach 0°C at the climax of the warming. At this stage, the warm-air center has been observed to move toward the north or northwest, nearly perpendicular to the strong south-westerly jet in which it is located.
		(f) With the arrival of warm air in polar regions, the bipolar troughs are closed off into separate cold lows, one or both of which weaken rapidly as they move to lower latitudes. In all observed cases the major warmings and circulation changes have been associated with retrogression of systems in the middle stratosphere.
		(g) At the climax of the circulation reversal a warm anticyclonic flow is established at high latitudes.
		(h) The circulation reversal ends with cooling of the polar region and the return of weak cyclonic flow at high latitudes.
		(1) STRATALERT messages may be continued until the stratospheric circulation becomes generally stabilized, but they will in any event cover the entire period of the GEOALERT STRATWARM messages.
		(2) GEOALERT STRATWARM warning messages will be discontinued after polar temperatures again drop below ~40°C.
		3.5.2.2. Minor Mid-Winter Warmings

Table ES1. Continued.		
Year	**Reference**	**Definition and related text (quoted from the source)**
1964	WMO/ IQSY (1964)	(a) Minor warmings may be associated with several types of circulation patterns; e.g., circumpolar vortex, bipolar cyclones, and also the typical eccentric pattern in which the polar vortex is displaced southward with a diametrically opposed anticyclone at high latitudes.
		(b) The warmest air is generally associated with the anticyclone center.
		(c) The cyclonic vortex, even though displaced from polar region, remains a dominant circulation feature.
		(d) Warm air may reach the polar area but modifies over the course of a week or two.
		(l) STRATALERT messages should be initiated when the central temperature of the warm air reaches ~30°C at 10 mb or ~35°C at 30 mb. They may be continued until the stratospheric circulation becomes generally stabilized, but they will in any event cover the entire period of the GEOALERT STRATWARM messages.
		(2) GEOALERT STRATWARM messages may be expected when temperatures within the warm center reach ~25°C at 10 mb or ~30°C at 30 mb. They may be discontinued after polar temperatures in the anticyclone center again drop below ~40°C.
		3.5.3 Final Warmings (Arctic)
		The final (spring-time) warming in the Arctic* accompanies a circulation reversal to warm-season easterlies. Its characteristics seem to depend on the antecedent wintertime conditions and phenomena and may therefore be classified for the purposes of the present program into:
		(i) late final warmings following major mid-winter warmings, and
		(ii) early final warmings following one or more minor mid-winter warmings.
		Some general characteristics of each and guidelines for declaration of alerts are as follows:
		3.5.3.1 Late Final Warmings Following Major Mid-Winter Warmings
		(a) Restored polar low remains dominant feature until at least mid-April.
		(b) Temperatures gradually rise to summer-time levels as polar cyclone slowly weakens.
		(c) Polar cyclone is finally replaced by developing anticyclone.
		(1) GEOALERT STRATWARM and STRATALERT messages will probably not be issued for this type of final warming.
		3.5.3.2 Early Final Warmings Following one or More Minor Mid-Winter Warmings
		(a) Early warmings usually begin with north-eastward movement of a large anticyclone located in the Pacific.
		(b) Warming takes place at high latitudes with temperatures exceeding summertime values.
		(c) Warm anticyclone continues poleward across North America as cold cyclone moves southward over Asia.
		(d) Anticyclone reaches pole sometimes in late March or early April.
		(1) STRATALERT messages should be issued if temperatures in northern latitudes exceed ~30°C at 10 mb or ~35°C at 30 mb. They may be continued until the stratospheric circulation becomes stabilized.
		(2) GEOALERT STRATWARM messages will be issued if temperatures in any latitude exceed ~25°C at 10 mb or ~30°C at 30 mb. They will be discontinued when rapid changes in the stratospheric circulation are no longer evident.
		* For a brief discussion of the fragmentary knowledge of final warmings in the Antarctic regions, see under Section 4 and 6.2.

Table ES1. Continued.		
Year	**Reference**	**Definition and related text (quoted from the source)**
1969	Johnson et al. (1969)	A variety of possible indices were tested, including the mean zonal geostrophic winds at various latitudes, the temperature variance at various latitudes, and kinetic energy associated with various wave numbers. We finally have selected two index numbers, one for circulation (defined in terms of the geostrophic wind field), the other for temperature. . . .
		The index characterizing the circulation is, in brief, a normalized difference between the squared amplitudes of zonal wavenumber 2 and zonal wavenumber 1 of the height field at a given latitude circle (usually 60°N.) and at a given stratospheric level. . . .
		The temperature index is designed to be used in conjunction with the circulation index and indicates the mean temperature gradient from the Pole to a chosen latitude (again usually 60°N.). . . .
		The choice of 60°N. for these calculations was dictated by two considerations: 1) At levels above 100 mb and south of 60°N., there are large areas (Atlantic and Pacific Oceans, and, more importantly, mainland China) for which very little data were available for analysis. 2) Although warmings are often first observed at lower latitudes than 60°N., they usually progress fairly rapidly toward the polar basin. . . .
1971	Matsuno (1971)	A sudden warming event is a complex of many phenomena. Among them let us be concerned with three major features: 1) the distortion and the breakdown of the stratospheric polar vortex; 2) the sudden warming of the polar air, eventually resulting in the reversal of the meridional temperature gradient; and 3) the appearance of circumpolar easterly winds succeeding the weakening and disappearance of the polar night westerly jet.
1975	Quiroz (1975)	The classification of warmings as major or minor (International Council of Scientific Unions 1963) is in need of revision. Various authors agree that minor warmings are relatively common in both the Northern and Southern Hemispheres. As used here, major will connote that a circulation reversal occurred in the stratospheric polar vortex at an altitude at least as low as the 10-mb level, in association with a reversal of the meridional temperature gradient in the middle or lower stratosphere.
1978	WMO CAS (1978)	The rapporteur [K. Labitzke] commented on the criteria for issuing stratospheric warming alerts of (a) “minor” warmings when a temperature increase of at least 25 degrees is observed in a period of a week or less at any stratospheric level; (b) “major” warmings 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; and (c) “Canadian” warmings which originate through the pulsation of the Aleutian anticyclone with the reversal of the temperature gradient poleward of 60°N. The rapporteur’s study revealed that it was possible to find simple alerting criteria for all types of midwinter disturbances. The Commission therefore recommended that the system with the existing alerting scheme should continue.
1978	McInturff (1978)	In an attempt to standardize the use of the terms “major” and "minor” the World Meteorological Organization’s Commission for Atmospheric Sciences 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 (see below) 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)."

Table ES1. Continued.		
Year	**Reference**	**Definition and related text (quoted from the source)**
1978	McInturff (1978)	It might seem that the mode of establishing categories ought to depend on the special interests of particular research groups. However, since consistency in nomenclature is essential, and a certain degree of arbitrariness is inevitable in any taxonomical system, the WMO definition will be adhered to throughout this paper.
1978	Schoeberl (1978)	The World Meteorological Organization (WMO) definition of a major warming requires that at the 10-mbar level or below, there are (1) a latitudinal mean temperature increase poleward of 60° latitude and (2) an associated circulation reversal. . . .
		A major warming which occurs in late winter is often called a 'final warming.'
		A third category of warming events is the 'minor warming.' In a minor warming the zonal winds in the stratosphere and the meridional temperature gradient usually weaken but do not reverse. Otherwise, these events seem to have all of the same characteristics of major warmings but with lesser intensity.
1981	Labitzke (1981)	(Definition of midwinter warmings according to CAS/WMO: A stratospheric warming can be said to be major if at 10 mbar or below the zonal mean temperature increases poleward from 60° latitude and an associated circulation reversal (breakdown of the polar vortex) is observed. Minor warmings may reach comparable intensities (i.e., high temperatures) but do not lead to a breakdown of the circulation as is defined above. Another type of midwinter warmings not belonging to either of the above criteria is called the Canadian warming (C.W.), which originates through the pulsation of the Aleutian anticyclone with a possible reversal of the temperature gradient poleward of 60°N. Final warmings (F.W.) are those events that lead into the summer circulation pattern in the middle stratosphere.)
1982	McIntyre (1982)	[A] major warming . . . can itself be looked at from the viewpoint of potential-vorticity mixing (Davies 1981). From this viewpoint the difference between a minor warming and a major warming is simply that middle latitudes are mixed in the first case, but the polar cap is mixed in the second. . . .
		The forecasting of a major warming seems certain to depend equally crucially on two separate things. One is an accurate estimate of the initial potential-vorticity gradients in the polar-night jet, together with relevant phase speeds and critical-line positions. The other is an accurate estimate of just how long the anomalous forcing from the troposphere will persist. It is hardly surprising that no simple rule of thumb for predicting major warmings has been found.
1987	Andrews et al. (1987)	A major SSW is defined by Andrews et al. (1987, p. 259) as when "at 10 mb or below the zonal-mean temperature increases poleward from 60° latitude and the zonal-mean zonal wind reverses. If the temperature gradient reverses but the circulation does not, it is defined to be a minor warming."
1999	Labitzke and Van Loon (1999)	From the abundance of observations which have accumulated since Scherhag's discovery it has become clear that the warmings can be arranged into four types, as defined by the World Meteorological Organization (WMO):
		Major Midwinter Warmings occur mostly in January-February. In addition to warming of the north polar region and reversal of the temperature gradients, they are also associated with a breakdown of the polar westerly vortex, which is replaced by a high. That is, the definition of a Major Midwinter Warming requires not only the warming but also a total change of circulation.
		The definition of a breakdown of the polar vortex is that the usual westerlies in the Arctic at 10 hPa are replaced by easterlies so that the center of the vortex moves south of 60°N-65°N. The vortex is either displaced entirely or split into two. This type of warming has not been observed in the Antarctic.
		Minor Warmings. These warmings can indeed be intense and sometime also reverse the temperature gradients, but they do not result in a reversal of the circulation at the 10-hPa level. They are found on the Southern Hemisphere as well.

Table ES1. Continued.		
Year	**Reference**	**Definition and related text (quoted from the source)**
1999	Labitzke and Van Loon (1999)	Canadian Warmings often happen in early winter. They take place when the Aleutian stratospheric high intensifies and moves poleward. The Canadian warmings can reverse the temperature gradients and sometimes briefly change the wind direction, but they do nevertheless not lead to a breakdown of the cyclonic polar vortex.
		Final Warmings mark the transition from the cold cyclonic vortex in winter to the warm high centered on the pole in summer. Their intensity varies much and they can be divided into major and minor Final Warmings. The time when the Final Warmings take place – when the westerlies of winter are replaced by the easterlies of summer – also varies a good deal, so they are further divided into early and late Final Warmings. Naturally, there are also final warmings on the Southern Hemisphere but they differ from those on the Northern Hemisphere . . . .
2003	O'Neill (2003)	Major midwinter warmings occur mostly in January and February. In addition to a warming of the North Polar region and the reversal of the normal wintertime temperature gradient (cold pole; warm tropics), they lead to a breakdown of the polar westerly vortex, which is replaced by an anticyclone (usually the Aleutian High). The World Meteorological Organization classifies warmings as major when the usual westerly winds of the Arctic at 10 hPa are replaced by easterlies as far south as 60°N. The polar vortex is either displaced entirely from the pole or split in two. These warmings are therefore referred to respectively as 'wave-1' warmings and 'wave-2' warmings. Some major warmings exhibit a hybrid character, with the polar vortex being displaced asymmetrically from the pole and then split.
		Minor warmings occur every winter in the stratosphere of both hemispheres. They share many of the characteristics of 'wave-1' major warming, except that the polar vortex is not broken down and the wind reversal from westerly to easterly is less extensive.
		Canadian warmings occur in early winter in the stratosphere of the Northern Hemisphere, typically from mid-November to early December. (They have no counterpart in the Southern Hemisphere.) . . . The warm Aleutian High is advected eastward in a few days from its normal position over the dateline towards the 90°W line of longitude over Canada. The polar vortex is displaced from the pole and strongly distorted, but does not break down. Temperature changes are modest compared with major warmings, and affect mainly the middle and lower stratosphere. As the Aleutian High collapses, the vortex regains its usual polar position.
2004	Limpasuvan et al. (2004)	Variability in the strength of the stratospheric polar vortex is defined on the basis of the leading principal component (PC) time series of daily zonal-mean zonal wind anomalies at 50 hPa during the extended winter season (October-April). When forming the temporal covariance matrix for the PC, the grid points in the horizontal data domain were weighted by the square root of the cosine of latitude.
		By construction, the selected events coincide closely to sudden stratospheric warmings as defined by the World Meteorological Society (WMO). According to the WMO definition, a stratospheric warming occurs when the latitudinal gradient in 10-hPa zonal-mean temperatures between 85° and 60°N is positive for more than 5 days. If the 10-hPa zonal-mean zonal wind at 65°N is concurrently easterly, the warming event is categorized as a "major warming"; otherwise, the warming event is categorized as "minor" (see Andrews et al. 1987). A total of 26 of the 39 events used in this study correspond to WMO-defined major warmings and 2 of the events correspond to WMO-defined minor warmings. The remaining 11 events correspond to weakenings of the polar vortex that are neither WMO-defined major nor minor warmings.

Table ES1. Continued.		
Year	**Reference**	**Definition and related text (quoted from the source)**
2005	Krüger et al. (2005)	Midwinter warmings have been classified on the basis of their NH synoptic appearance up to 10 hPa (Julian 1967; Labitzke 1968). They were grouped into major and minor warmings, depending on their influence on the wintertime circulation of the stratosphere:
		• Major warmings are associated with a breakdown of the polar vortex as well as a warming of the polar region and the reversal of the meridional temperature gradient between 60° latitude and the Pole. The vortex breakdown is defined by the reversal of the mean zonal westerlies poleward of 60° latitude into easterlies, at least down to 10 hPa [this was implemented by using zonal mean zonal winds at 60° latitude only; K. Krüger 2014, personal communication]. This can happen when the vortex center is either displaced to midlatitudes or entirely split into two centers.
		• Minor warmings can be as intense as their major counterparts in terms of temperature increase, and they sometimes also reverse the temperature gradient, but they do not result in a reversal of the circulation at 10 hPa.
		These categories are based on zonal means of temperatures and winds, which might obscure the dynamical structure of the systems involved. However, the terminology first adopted by the International Council of Scientific Unions for the alerts of stratospheric warmings during the International Quiet Sun Year (IQSY) 1963, was later taken over by the World Meteorological Organization (WMO) and is still most applicable when classifying the warming phenomena.
2007	Charlton and Polvani (2007)	[W]e here adhere to the more widely used World Meteorological Organization (WMO) definition of SSWs (easterly winds at 10 hPa and 60°N). . . .
		[W]e also distinguish between different types of SSWs, based on the synoptic structure in the middle stratosphere. Following O'Neill (2003), one type, a vortex displacement, is characterized by a clear shift of the polar vortex off the pole, and its subsequent distortion into a "comma shape" during the extrusion of a vortex filament. . . .
		We have decided to follow the WMO definition (Andrews et al. 1985, p. 259), also used for the widely known STRATALERT messages (Labitzke and Naujokat 2000) in order to detect the occurrence of the SSWs: a major midwinter warming occurs when the zonal mean zonal winds at 60°N and 10 hPa become easterly during winter, defined here as November–March (NDJFM). Note that our definition differs from that used by Labitzke and others in several studies in that we do not attempt to exclude Canadian warmings from our definition and that we also include events in March that would be rejected by some authors. The first day on which the daily mean zonal mean zonal wind at 60°N and 10 hPa is easterly is defined as the central date of the warming. Note that this definition differs from that of [Limpasuvan et al. 2004], who identify warmings by reduction in strength of a stratospheric zonal index, based on the first empirical orthogonal function of 50-hPa geopotential height.
		We note that the WMO definition, in addition to the reversal of the winds at 60°N and 10 hPa, requires that the 10-hPa zonal mean temperature gradient between 60° and 90°N be positive (Krüger et al. 2005) for an event to be designated as a major midwinter warming. Including this additional constraint makes only a small difference to the number of SSWs identified (only three events in the NCEP–NCAR dataset and one in the ERA-40 dataset do not meet this criterion). Thus, to avoid unnecessary complexity, we have not included the temperature gradient criterion in our algorithm.

Table ES1. Continued.		
Year	**Reference**	**Definition and related text (quoted from the source)**
2007	Charlton and Polvani (2007)	Once a warming is identified, no day within 20 days of the central date can be defined as an SSW. The length of the interval is chosen to approximately equal two radiative time scales at 10 hPa (Newman and Rosenfield 1997). This condition prevents the algorithm from counting the same SSW twice, as the zonal mean zonal winds might fluctuate between westerly and easterly values following the onset of the warming.
		Finally, it is important to highlight that only midwinter warmings are considered in this study. To ensure this, cases where the zonal mean zonal winds become easterly but do not return to westerly for at least 10 consecutive days before 30 April are assumed to be final warmings, and as such are discarded. This criterion ensures that following SSWs, a coherent stratospheric vortex is reestablished.
		From the corrigendum: An important step in the methodology presented in Charlton and Polvani (2007) was incorrectly reported. The first sentence in the last paragraph in the right column on page 451 reads, "Once a warming is identified, no day within 20 days of the central date can be defined as an SSW." This is incorrect and should read, "Once a warming is identified, an interval of 20 consecutive days with westerly winds must exist before the following central date can be defined."
2009	Coughlin and Gray (2009)	The k-means clustering technique has been used to study the nature of NH winter SSW events in the ERA-40 dataset. . . .
		[T]he method did not further divide the 10% grouping in order to distinguish between major and minor SSWs or to distinguish between displaced and split vortex (waves 1 and 2) SSWs. This suggests that there is not a well-designated threshold between these types of SSWs and they are simply different manifestations of a continuum of SSWs.
		It was shown that the zonally averaged zonal wind in the polar upper stratosphere averaged over 70–80°N near 7 hPa can be used, with a threshold value of ~4 m s^{-1}. This is similar to the WMO definition for major SSWs of less than 0 m s^{-1} at 65°N and 10 hPa, thus confirming the WMO definition as an appropriate measure of the two different states.
2011	Mitchell et al. (2011)	The analysis undertaken in this study builds on previous work by further developing and refining the methods for calculating the moments, applying them to a longer period reanalysis dataset, and extending their interpretation to further examine behavior during extreme events. The characteristics of the NH moment diagnostics, especially during SSW events, are compared and contrasted with the more traditional diagnostics used to define SSWs, namely the zonal mean zonal wind at 60°N and the 60°–90°N polar cap temperatures.
		One of the major conclusions drawn from this study is that traditional definitions of SSW events often miss extreme behavior of the vortex. The analysis of the distributions of each of the moment diagnostics has shown that so-called minor SSW events often have a larger influence on the geometry of the vortex than major SSW events. Likewise, the subdivision of splitting and displacement events is not always as well defined as the names suggest. Often a vortex displacing event will split into two daughter vortices before the vortex returns to its stable state, and vice versa. It is therefore not only the use of such traditional diagnostics that often leads to poor characterization of the vortex, but the very binary definition of SSW events that is used in the mainstream literature.

Table ES1. Continued.		
Year	**Reference**	**Definition and related text (quoted from the source)**
2012	Báncala et al. (2012)	A major warming is identified by the reversal of $\bar{U}$ at 10 hPa and 60°N, with the first day of easterlies defined as the central date of the warming. As after the onset of the warming $\bar{U}$ may fluctuate between weak easterlies and westerlies, to prevent counting the same event twice, Charlton and Polvani [2007] introduced a 20 day mask starting from the central date within which no other major SSW is counted. In our algorithm, this 20 day interval, which approximately equals two radiative time scales at 10 hPa (i.e., the time necessary for restoring the polar vortex) [Newman and Rosenfield 1997], starts instead from the first day of westerly winds after the central date. Additionally, if the first day after this 20 day mask has easterly wind, the algorithm searches for the next day with westerly wind exceeding 5 m s^{-1} and starts from that day to search for other major SSWs. These additional constraints are introduced because occasionally the wind fluctuates around the zero value during the recovery of the vortex, thus it should avoid counting mere wind oscillations as major SSWs. To avoid the overestimation of spring major SSWs, we also modified the final warming detection criterion of Charlton and Polvani [2007]. To distinguish major SSWs from final warmings the algorithm considers the number of consecutive days of westerlies and wind intensity after major warming events. Cases after which $\bar{U}$ becomes westerly for at least 10 consecutive days, but during which the wind does not reach, at least for 1 day, the intensity of 5 m s^{-1}, are assumed to be final warmings, and as such are discarded.
2012	Kuttippurath and Nikulin (2012)	There are different definitions for a SSW to be called major or minor. According to the World Meteorological Organisation (WMO) a SSW can be said to be major if at 10 hPa or lower altitudes the latitudinal mean temperature increases abruptly poleward from 60 latitude with an associated circulation reversal in a short period of time. If the reversal of temperature gradient does not follow the zonal-mean wind reversal, then it is a minor SSW (e.g., WMO 1978, item 9.4, 35–36; Andrews et al. 1987; Labitzke and Naujokat 2000). In some cases the increase in temperature near the pole can be up to 40–60K in a week at 10 hPa (Limpasuvan et al. 2004; Andrews et al. 1987). The followed zonal wind reversal displaces or splits the polar vortex toward midlatitudes (e.g., Kuttippurath et al. 2010; Charlton and Polvani 2007). Since the WMO definition considers the major SSWs (hereafter major warmings–MWs) from November to February, studies have slightly modified this criterion to account for the warmings from October through May (e.g., Charlton and Polvani 2007; Bancalá et al. 2012). Also, there is an ambiguity regarding the temperature gradient criterion of the WMO definition (e.g., the difference between Limpasuvan et al. 2004 and Krüger et al. 2005). Apart from these, classifications of MWs based on the northern annular mode (Baldwin and Dunkerton 2001) and external atmospheric forcings (Blume et al. 2012) are also being proposed.
		Although studies use different definitions for MWs, there is a general agreement on the poleward temperature increase from 60 N. Some studies are critical about the timing of wind reversal that it must last for 5 days (e.g., Limpasuvan et al. 2004), but no strict time condition is followed by some others (e.g., Labitzke 1981; McInturff 1978). Regarding the wind reversal, the latter two use a circulation reversal poleward of 60 N whereas Charlton and Polvani (2007) consider that the winds must reverse at 60 N. Nevertheless, Limpasuvan et al. (2004) applied the same condition of temperature increase and wind reversal with a slight difference in latitude, 65 N instead of 60 N.

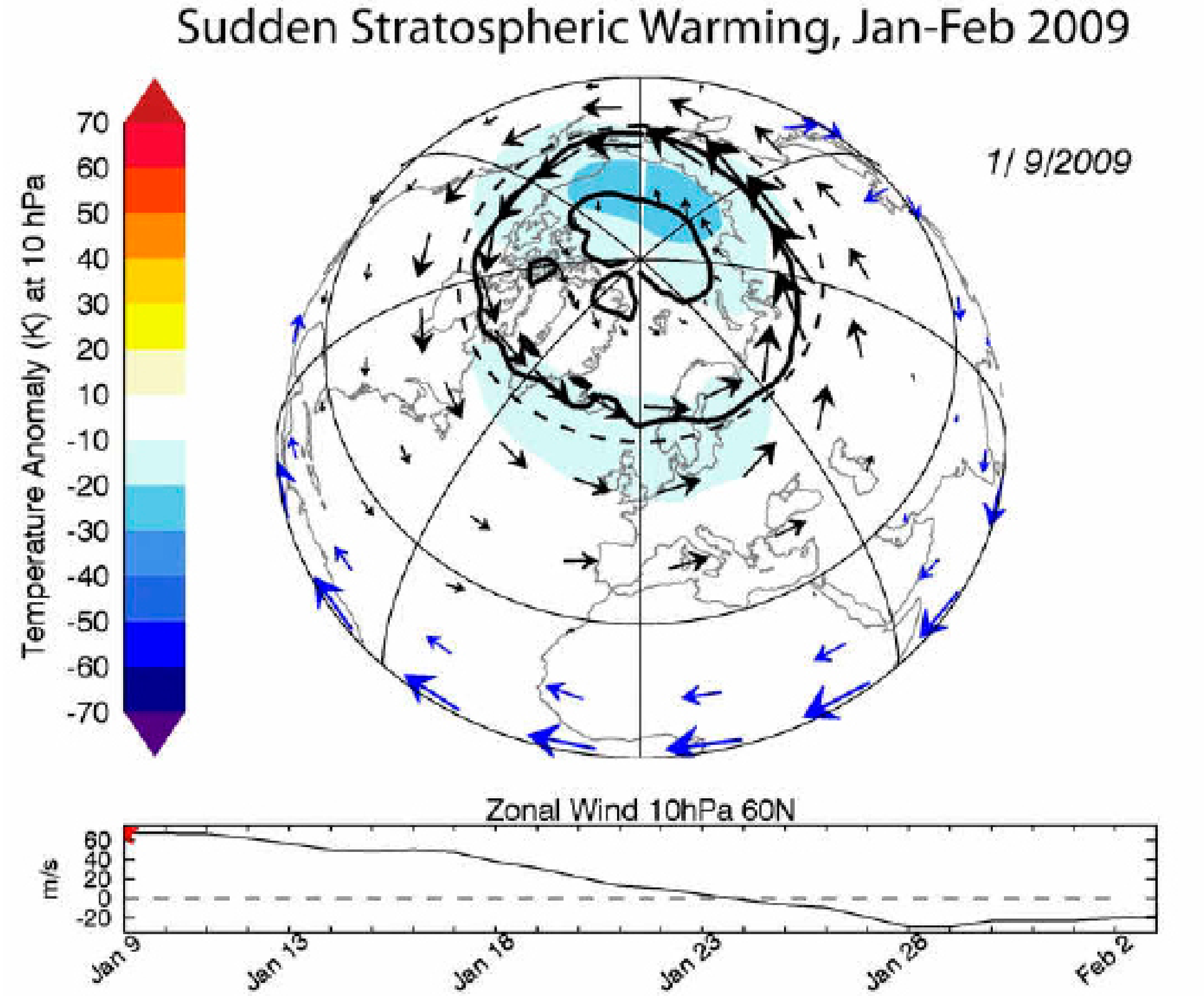

Fig. ES1. Animation (click image to view) showing the time evolution of the Northern Hemisphere stratosphere (at 10 hPa) during the sudden stratospheric warming of 9 Jan–3 Feb 2009. Temperature anomalies and wind fields are shown as colored areas and vectors, respectively. Black contours show regions of potential vorticity at 7 PVU (1 potential vorticity unit = 10^{-6} K kg^{-1} m^2 s^{-1}). Note the strong warming of the polar cap region and the associated reversal of the polar vortex in late Jan.

Table ES2. Dates when SSWs occur for seven SSW diagnostics using NCEP–NCAR (1958–2014; red) and ERA-40 (1958–1 Mar 1989)/ERA-Interim (2 Mar 1989–2014; blue). Major SSW dates that are detected in both reanalyses are shown in black (the average date is used). Explanations and abbreviations for each diagnostic are provided in Table 1, and the number of major SSWs per year for NCEP–NCAR reanalysis is shown in Fig. 2. Events detected by all seven diagnostics in NCEP–NCAR reanalysis are bolded. CP07 = Charlton and Polvani (2007).

U&T	CP07	U6090	U65	MOM	ZPOL	EOFU
30 Jan 1958	30 Jan 1958	28 Jan 1958	29 Jan 1958	29 Jan 1958	30 Jan 1958	28 Jan 1958
		23 Feb 1958	24 Feb 1958			
30 Nov 1958	30 Nov 1958	29 Nov 1958	30 Nov 1958		29 Nov 1958	
					17 Mar 1959	
16 Jan 1960	16 Jan 1960	11 Jan 1960	11 Jan 1960		12 Jan 1960	
		20 Dec 1960			16 Dec 1960	
				9 Mar 1961	13 Mar 1961	21 Mar 1961
				30 Jan 1962		
				7 Mar 1962		
28 Jan 1963	28 Jan 1963	5 Feb 1963	6 Feb 1963		28 Jan 1963	10 Feb 1963
				15 Mar 1964	19 Mar 1964	25 Mar 1964
23 Mar 1965	23 Mar 1965	31 Mar 1965				
12 Dec 1965	**12 Dec 1965**	**6 Dec 1965**	**8 Dec 1965**	**9 Dec 1965**	**12 Dec 1965**	**18 Dec 1965**
23 Feb 1966	23 Feb 1966	19 Feb 1966	21 Feb 1966	26 Feb 1966		20 Feb 1966
7 Jan 1968	7 Jan 1968	6 Jan 1968	6 Jan 1968	29 Dec 1967	3 Jan 1968	8 Jan 1968
27 Nov 1968	27 Nov 1968	24 Nov 1968	25 Nov 1968		4 Dec 1968	28 Nov 1968
13 Mar 1969	13 Mar 1969	12 Mar 1969	12 Mar 1969			
2 Jan 1970	**2 Jan 1970**	**1 Jan 1970**	**1 Jan 1970**	**14 Jan 1970**	**1 Jan 1970**	**3 Jan 1970**
17 Jan 1971	17 Jan 1971	13 Jan 1971	16 Jan 1971	15 Jan 1971	13 Jan 1971	
20 Mar 1971	20 Mar 1971	18 Mar 1971	18 Mar 1971			
				4 Feb 1972		
1 Feb 1973	1 Feb 1973	31 Jan 1973	31 Jan 1973	4 Feb 1973	31 Jan 1973	
				12 Mar 1974		
				16 Mar 1975		
				31 Mar 1976		
		23 Nov 1976				
9 Jan 1977	9 Jan 1977	1 Jan 1977	2 Jan 1977	10 Jan 1977	24 Dec 1976	7 Jan 1977
				25 Mar 1978		

Table ES2. Continued.

U&T	CP07	U6090	U65	MOM	ZPOL	EOFU
		7 Dec 1978	7 Dec 1978			6 Dec 1978
22 Feb 1979	**22 Feb 1979**	**21 Feb 1979**	**21 Feb 1979**	**18 Feb 1979**	**23 Feb 1979**	**22 Feb 1979**
29 Feb 1980	29 Feb 1980	29 Feb 1980	29 Feb 1980		29 Feb 1980	
4 Mar 1981	4 Mar 1981	20 Feb 1981	1 Mar 1981		5 Feb 1981	2 Mar 1981
4 Dec 1981	4 Dec 1981	3 Dec 1981	3 Dec 1981			
					26 Jan1982	
24 Feb 1984	**24 Feb 1984**	**22 Feb 1984**	**23 Feb 1984**	**25 Feb 1984**	**26 Feb 1984**	**15 Mar 1984**
1 Jan 1985	**1 Jan 1985**	**30 Dec 1984**	**31 Dec 1984**	**25 Dec 1984**	**28 Dec 1984**	**29 Dec 1984**
				7 Jan 1986		
				22 Mar 1986		
23 Jan 1987	**23 Jan 1987**	**22 Jan 1987**	**22 Jan 1987**	**21 Jan 1987**	**22 Jan 1987**	**23 Jan 1987**
8 Dec 1987	**8 Dec 1987**	**7 Dec 1987**	**7 Dec 1987**	**10 Dec 1987**	**3 Dec 1987**	**8 Dec 1987**
14 Mar 1988	14 Mar 1988	12 Mar 1988	12 Mar 1988			
21 Feb 1989	21 Feb 1989	20 Feb 1989	20 Feb 1989		19 Feb 1989	12 Mar 1989
		3 Feb 1991	4 Feb 1991		28 Jan 1991	3 Feb 1991
					16 Jan 1992	
				22 Mar 1992		
		5 Mar 1993	5 Mar 1993			
		2 Jan 1994	2 Jan 1994		1 Jan 1994	
		23 Jan 1995	4 Feb 1995	2 Feb 1995	2 Feb 1995	22 Jan 1995
		29 Mar 1996				
		20 Nov 1996	22 Nov 1996			23 Nov 1996
		6 Jan 1998	7 Jan 1998		6 Jan 1998	4 Jan 1998
15 Dec 1998	15 Dec 1998	15 Dec 1998	15 Dec 1998	15 Dec 1998	14 Dec 1998	
25 Feb 1999	**25 Feb 1999**	**25 Feb 1999**	**25 Feb 1999**	**25 Feb 1999**	**26 Feb 1999**	**3 Mar 1999**
20 Mar 2000	20 Mar 2000		20 Mar 2000			
		23 Nov 2000	23 Nov 2000			
11 Feb 2001	**11 Feb 2001**	**2 Feb 2001**	**3 Feb 2001**	**7 Feb 2001**	**15 Feb 2001**	**13 Feb 2001**
				14 Mar 2001		
31 Dec 2001	31 Dec 2001	29 Dec 2001	29 Dec 2001		25 Dec 2001	
		16 Feb 2002	16 Feb 2002			

Table ES2. Continued.

U&T	**CP07**	**U6090**	**U65**	**MOM**	**ZPOL**	**EOFU**
		27 Mar 2002		21 Mar 2002		
18 Jan 2003	18 Jan 2003	17 Jan 2003	17 Jan 2003	17 Jan 2003		
		17 Feb 2003	18 Feb 2003			
6 Jan 2004	**6 Jan 2004**	**2 Jan 2004**	**3 Jan 2004**	**2 Jan 2004**	**3 Jan 2004**	**4 Jan 2004**
				11 Mar 2005	16 Mar 2005	
21 Jan 2006	21 Jan 2006	14 Jan 2006	18 Jan 2006	17 Jan 2006	22 Jan 2006	
24 Feb 2007	24 Feb 2007	23 Feb 2007	23 Feb 2007			
22 Feb 2008	22 Feb 2008	22 Feb 2008	22 Feb 2008	18 Feb 2008		
24 Jan 2009	**24 Jan 2009**	**24 Jan 2009**	**24 Jan 2009**	**18 Jan 2009**	**23 Jan 2009**	**28 Jan 2009**
9 Feb 2010	9 Feb 2010	24 Jan 2010	26 Jan 2010			8 Feb 2010
24 Mar 2010	24 Mar 2010	21 Mar 2010	22 Mar 2010			
				12 Mar 2012		
6 Jan 2013	**6 Jan 2013**	**7 Jan 2013**	**7 Jan 2013**	**6 Jan 2013**	**6 Jan 2013**	**31 Dec 2012**
				2 Feb 2014		

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