Blocking precursors to stratospheric sudden warming events

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Received 27 April 2009; revised 9 June 2009; accepted 17 June 2009; published 18 July 2009.

[1] The primary causes for the onset of major, midwinter, stratospheric sudden warming events remain unclear. In this paper, we report that 25 of the 27 events objectively identified in the ERA-40 dataset for the period 1957–2001 are preceded by blocking patterns in the troposphere. The spatial characteristics of tropospheric blocks prior to sudden warming events are strongly correlated with the type of sudden warming event that follows. Vortex displacement events are nearly always preceded by blocking over the Atlantic basin only, whereas vortex splitting events are preceded by blocking events occurring in the Pacific basin or in both basins contemporaneously. The differences in the geographical blocking distribution prior to sudden warming events are mirrored in the patterns of planetary waves that are responsible for producing events of either type. The evidence presented here, suggests that tropospheric blocking plays an important role in determining the onset and the type of warmings. **Citation:** Martius, O., L. M. Polvani, and H. C. Davies (2009), Blocking precursors to stratospheric sudden warming events, *Geophys. Res. Lett.*, *36*, L14806, doi:10.1029/2009GL038776.

1. Introduction

[2] Sudden stratospheric warming (SSW) events and blocking events are major atmospheric flow phenomena. Both entail large departures of the flow from a zonal state and occur on time scales longer than typical synoptic eddies; hence their importance for enhancing predictability. Here we present new evidence suggesting that, while occurring at different levels in the atmosphere, these two phenomena may be much more closely related than previously appreciated.

[3] In the stratosphere, SSWs are major disruptions of the polar vortex during the cold season. The high potential vorticity (PV) reservoir over the pole is either displaced equatorwards and sheared out into a comma shape (a *displacement* event), or torn into two distinct pieces (a vortex *splitting* event) [*Charlton and Polvani*, 2007]. Both types of events can have a significant impact on stratospheric ozone distribution [e.g., *Ghazi*, 1974] and surface weather evolution, up to two months following the vortex disruption [e.g., *Baldwin and Dunkerton*, 2001].

[4] In the troposphere, blocking events severely disrupt the extra-tropical circumpolar tropopause-level jet, which is either displaced poleward of or splits around the block's core of anomalously low PV (positive height) at tropopause levels. Their comparatively long duration and quasi-stationary equivalent barotropic structure is manifest at the ground as a high surface pressure system that impacts directly upon the pattern of surface weather [e.g., *Rex*, 1950].

[5] Most work to date on the link between the two phenomena has been based on case studies of individual events. For instance, in an early study, *Julian and Labitzke* [1965] found that high latitude tropospheric blocking preceded the January 1963 warming event by some 5 to 10 days, and that the block persisted beyond the breakdown of the stratospheric vortex [see also *Labitzke*, 1965]. The latter observation suggests the possibility of a two-way inter-play between the phenomena: a block might serve as the initial trigger for vertically propagating planetary waves that induce an SSW event [e.g., *O'Neill and Taylor*, 1979], and thereafter the perturbed stratospheric flow accompanying the SSW event might be conducive to a block's persistence [*Woollings and Hoskins*, 2008]. The comparatively rapid bottom-up component poses a challenge for numerical weather prediction [e.g., *Mukougawa and Hirooka*, 2004], while the longer-term top-down component has implications for extended range and seasonal forecasting [e.g., *Baldwin et al.*, 2003].

[6] In this paper we focus only on the first part of this link, namely the bottom-up precursor role of atmospheric blocking. Taking advantage of two relatively new, independently derived, multidecadal climatologies of SSW events [*Charlton and Polvani*, 2007] and atmospheric blocks [*Croci-Maspoli et al.*, 2007], we here explore the precursor role of blocks on SSW events over a much larger sample size than previously available [*Quiroz*, 1986]. We show that nearly all SSW events in the last four decades were preceded by blocking events, and that the type of SSW is very highly correlated with the geographical characteristic of the preceding block.

2. Data and Methodology

[7] All analyses are based on the ERA-40 reanalysis dataset [*Uppala et al.*, 2005] interpolated onto a 1° Gaussian grid which is available at 6-hour intervals. The blocking data set of *Croci-Maspoli et al.* [2007] covers the period from 1957–2001 and was compiled using the PV-base algorithm developed by *Schwierz et al.* [2004]. Two versions of this blocking climatology are used for this analysis: one containing blocks with a life-time exceeding 5 days and the other containing blocks with a life-time exceeding 10 days. Little difference in the key conclusions was found and, unless otherwise stated, all results shown below are based on the climatology of blocks lasting longer than 5 days.

[8] Blocking composites are then constructed for ERA-40 SSW events, and stratified into displacement (D) and splitting (S) events following *Charlton and Polvani* [2007].

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0094-8276/09/2009GL038776$05.00

Table 1. Geographic Location of Tropospheric Blocking for the Period −10 to 0 Days Prior to the Central Date of the Corresponding Stratospheric Sudden Warming Event[a]

Displacement Events		Splitting Events	
Event (Central Date)	Precursor Blocking (Location)	Event (Central Date)	Precursor Blocking (Location)
15 January 1960	Pacific/Atlantic	31 January 1958	Pacific/Atlantic
16 December 1965	Atlantic[b]	28 January 1963	Pacific/Atlantic
28 November 1968	Atlantic	23 February 1966	Pacific/Atlantic
13 March 1969	Atlantic[c]	7 January 1968	Pacific
1 January 1970	Atlantic	18 January 1971	Pacific/Atlantic
19 March 1971	Atlantic[b]	31 January 1973	Pacific/Atlantic
29 February 1980	Atlantic	9 January 1977	Atlantic
4 March 1981	Atlantic	22 February 1979	Pacific
4 December 1981	Atlantic	1 January 1985	Pacific[d]
24 February 1984	Atlantic	7 December 1987	
23 January 1987	Atlantic	14 March 1988	Atlantic[b]
15 December 1998	Atlantic	21 February 1989	Pacific
20 March 2000		26 February 1999	Pacific
		11 February 2001	Atlantic[d]

[a]Blocking is identified using the PV-based algorithm of *Schwierz et al.* [2004], and sudden warmings using the algorithm of *Charlton and Polvani* [2007], applied to the ERA-40 reanalyses for the period 1958–2001.
[b]Blocking is present over Asia.
[c]Blocking is present over Newfoundland.
[d]Blocking over the pole.

Only SSW events that overlap temporally with the blocking climatology are used (see Table 1 for a list of all events). The composite analysis is performed for the time period −10 to 0 days prior to the SSW events. The statistical significance of the composites with respect to a climatological state is examined using a Monte Carlo approach where the composited fields are compared to 300 random composites that take into account the seasonal distribution of individual events in the original composites. The statistical significance of the difference between the displacement and the splitting composite is determined following the Monte Carlo approach described in detail in the appendix of *Martius et al.* [2006]. For the wavenumber $m = 1, 2$ height composites, a Fourier decomposition of the waves in the zonal direction is first performed for each time instance, and these fields are then averaged.

[9] This compositing approach helps to highlight features that are common to all SSW events, while dampening those associated with only few isolated cases. It should be kept in mind, however that the signal extracted through the compositing approach is diluted due to several factors. First, SSW events exhibit a significant case-to-case variability, both in their temporal evolution and their spatial structure. Second, the distinction between splitting and displacement events is not clear-cut in some cases; the central date of the event and the time when the character of the event (splitting vs. displacement) becomes distinct can differ.

3. Results

[10] In Table 1, the SSW events considered in this study are listed. We also report whether each event was preceded by atmospheric blocking at tropopause level, and in which ocean basin the respective blocks were located. Two facts are immediately apparent from Table 1. First nearly all SSW events are preceded by atmospheric blocking, and even for the two exceptions the tropospheric flow was highly perturbed prior to the SSW event (although is no blocking was reported in the *Croci-Maspoli et al.* [2007] climatology). Specifically, in December 1987, the tropopause level flow was characterized by a large-scale ridge over central Asia 10 days before the SSW event, and a shorter lived ridge over the western Atlantic 6 to 2 days before the event; for the March 2000 event a block-like, temporally sustained, large amplitude, high latitude ridge situated over Alaska and extending towards the pole was present prior to the SSW event.

[11] Second, there is a significant difference in the spatial distribution of atmospheric blocking prior to each type of SSW event. The majority of blocks occurring in the time period prior to displacement events are located in the Atlantic basin, while splitting events are predominantly preceded by blocks occurring over the Pacific or over the Pacific and the Atlantic contemporaneously.

3.1. Blocking Composites

[12] The results of the composite analysis, shown in Figure 1, confirm and elucidate these findings, while the event based analysis presented in the Table 1 ensures that the composite signal is not dominated by only a small number of events. The blocking frequency composites for displacement and splitting events (Figure 1) exhibit major differences.

[13] Prior to displacement events blocks occur predominantly in the Atlantic basin along the Atlantic storm track, with frequency maxima to the east of Greenland and over Scandinavia. Areas of statistical significance with respect to the climatology (at the 95% confidence level, two-sided) are identified over Scandinavia, with the frequency exceeding a climatological sample, and over parts of the northeastern Pacific, where the frequencies are significantly below climatology (not shown).

[14] Prior to splitting events, on the other hand, the majority of blocks are located in the Pacific basin, with frequency maxima along the Pacific storm track, the eastern Pacific and over Alaska. A secondary weaker maximum is found in the Atlantic basin west of Greenland. Neither frequency maximum is anomalous compared to a climato-

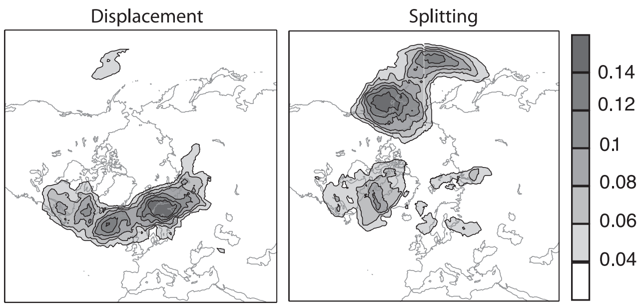

Figure 1. Blocking frequency composites for the period −10 to 0 days *prior* to (left) displacement and (right) splitting stratospheric sudden warming events. The shading indicates the fraction of the time that a block is identified, in that period, at each grid point.

logical distribution. Composites for an earlier time period (−20 to −10 days) yield a very similar picture. For this earlier time period, small areas of statistical significance with respect to the climatology are found south of Greenland and over the northeastern Pacific.

[15] The differences between the two composites are highly significant, above the 99% confidence level, for all major blocking areas. These differences in the frequency of blocks are reflected in the tropopause level flow: anomalously low PV values (positive height anomalies) are found over the Atlantic basin prior to displacement events and over the eastern Pacific prior to splitting events. These anomalies are related to changes in the jet location and strength. Amplitude-wise, the largest differences are found over the eastern Pacific (not shown).

[16] In an earlier study, *Quiroz* [1986] suggested, that long lasting blocks are the most effective in triggering SSW events. To investigate this idea, we repeated the above analysis with blocks lasting longer than 10 days (instead of 5 days). We found that the composite analysis of these longer lasting blocks yields the same spatial patterns as in Figure 1, but with lower blocking frequencies. Prior to displacement events, longer lasting blocks constitute about 50% of the Atlantic blocking signal, with the frequency of such blocks significantly exceeding a climatological distribution over Scandinavia. Similarly, more than 60% of the blocking frequency maximum in the eastern Pacific prior to splitting events can be attributed to long lasting blocks. From this we conclude that while blocking duration matters to some degree, it is not the dominant factor in the upward link between blocks and SSWs.

3.2. Wave Composites

[17] The dynamical link between the above precursor blocking patterns and the subsequent SSW event is established by examining the planetary waves with zonal wave number m = 1, 2 that accompany the blocking events. In Figure 2, we show the composite m = 1, 2 signals in the height field prior to displacement and splitting SSW events respectively. The wave composites exhibit the same structure previously reported for individual cases [e.g., *Quiroz*, 1986], with m = 1 tilting westward with height by approximately 180° between 500 and 10 hPa, and m = 2 exhibiting a more barotropic structure, tilting westward by approximately 90° in the displacement composite and only by about 45° in the splitting composite. Also typical is the amplification of the wave signal with height. For the displacement composite it is very strong for m = 1, but nearly absent for m = 2. For the splitting composite both m = 1 and m = 2 show strong amplification, with m = 2 being larger up to 100 hPa and m = 1 slightly exceeding it above that height; this indicates that both m = 1 and m = 2 contribute to these warming events.

[18] The link between these planetary scale waves and the corresponding atmospheric blocks is easily made by considering their relative spatial location. For splitting events an almost perfect collocation of the blocking maximum in the Pacific with the positive m = 2 wave peak is found at the lower levels. Moreover for the splitting events the relative locations of the blocking regions together with the differing westward slope with height of the two waves leads to a constructive interference of m = 1 and m = 2 in the upper stratosphere resulting in the splitting of the vortex.

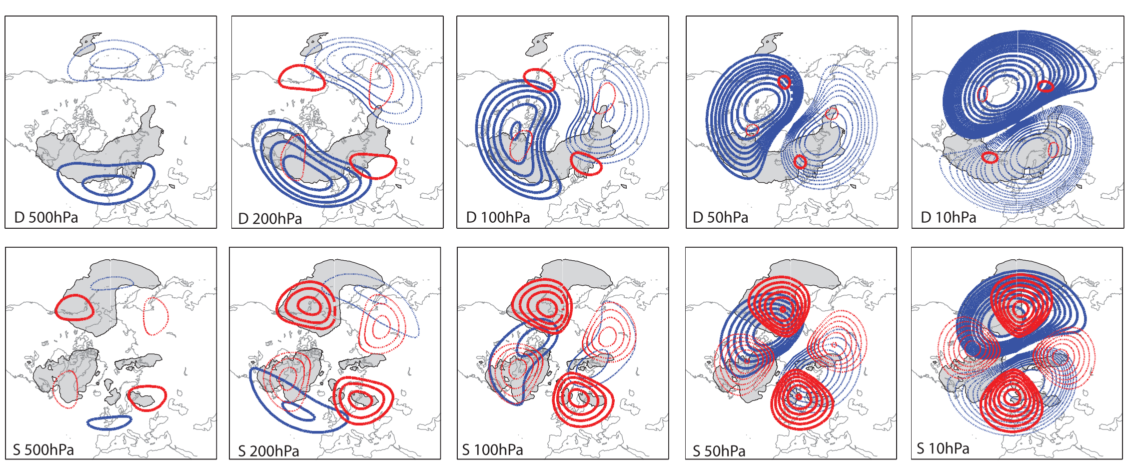

Figure 2. Geopotential height fields, zonal wave number 1 in blue and 2 in red, composited for the period −10 to 0 days prior to (top) vortex displacement events and (bottom) vortex splitting events, at 500, 200, 100, 50 and 10 hPa, from left to right, respectively. Contour levels shown are: 100, 130, 160, 190, 220, 250, 300, 350, 400, 500, 600, 700, 800 and 900 m, solid contours indicate positive values. Gray shading shows blocking frequency greater than 0.4, from Figure 1.

[19] For displacement events an overlap of the positive wave peak and maxima in the blocking frequency is found on 200 hPa. It is important to add that the maximum blocking amplitude is located approximately at 200 hPa [*Schwierz et al.*, 2004] and blocks exhibit an almost barotropic structure [e.g., *Schwierz et al.*, 2004, Figure 1; *O'Neill et al.*, 1994, Figure 13].

[20] The geographical location (i.e., the phasing) of the blocks relative to the climatological stationary planetary waves is very important. For displacement cases the positive PV (negative height) anomaly that is a feature of the climatological mean flow over the western Pacific contributes significantly to the $m = 1$ signal. Hence the favorable phase shift of about 180° between this positive PV anomaly and negative (blocking) PV anomalies in the Atlantic contribute constructively to the $m = 1$ signal. The opposite is true for the presence (absence) of blocks in the eastern Pacific with a phase shift of approximately 90° which projects favorably onto $m = 2$ ($m = 1$). Hence the block location relative to the stationary planetary wave pattern is important in determining the amplitude of $m = 1$ and $m = 2$.

3.3. Heat Flux Composites/Analysis

[21] Finally, we examine the vertical component of the Eliassen Palm flux anomalies during blocking days prior to SSW events to further illuminate the link between blocks and tropopause level wave forcing. Such heat flux anomalies, averaged over the northern hemisphere (45N–75N), are in general positive prior to both the splitting and the displacement events [see, e.g., *Polvani and Waugh*, 2004].

[22] The probability distribution functions of heat flux anomalies for blocking days preceding SSW events have a larger positive amplitude than for blocking events unrelated to SSW events. It is interesting to note that the difference in heat flux between these two types of blocks is nearly insignificant at 500 hPa, but increases substantially with height, with a very clear signal at 100 hPa (not shown). This is in accordance with the results in Figure 2, showing relatively weak planetary wave amplitudes at 500 hPa which progressively amplify into substantial amplitudes by 100 hPa.

4. Discussion

[23] This study, based upon the ERA-40 data set, reveals a clear linkage between major SSW events and blocks, with the former being almost always preceded by the latter. Separate composites compiled for displacement and splitting SSW events indicate that displacement events are associated with block occurrence in the eastern North Atlantic, and splitting events associated with either the occurrence of blocks in the eastern North Pacific or the contemporaneous occurrence of blocks in the eastern North Pacific and the North Atlantic.

[24] Examination of composites of the geopotential height signal of the $m = 1, 2$ planetary waves in the period preceding SSW events link the triggering of these waves and their longitudinal phase in the upper-troposphere to the presence of blocks, and in addition hint at the relative contribution of $m = 1$ and $m = 2$ waves to the spawning of displacement and splitting SSW events.

[25] These results might, at first sight, be difficult to reconcile with a recent study by *Taguchi* [2008], who suggested that there is no statistically significant connection between SSW events and tropospheric blocks. The apparent contradiction is, however, easily resolved by noting that most of the analysis in that study was done using 500 hPa fields. As we have shown (cf. Figure 2) the wave amplitudes at that level are very weak, and one needs to look at 200 hPa or above for clear signals to emerge.

[26] How might this precursor role of atmospheric blocks be exploited to enhance the predictability of SSW events? To answer this, one would start by asking how often blocks are followed by SSW events, and if specific characteristics of the blocks preceding the SSW events distinguish them from non-event blocks. The climatology we have used contains 782 blocking events, between November and April: of these, only 52 occurred during the 10-day period prior to SSW events. Hence, while there is a strong indication that blocks can exert a significant influence on circulation in the stratosphere, a very large number of blocks are not, in fact, followed by SSW events.

[27] Some reasons for this can easily be suggested. First, we have here considered only major, mid-winter, SSW events. It is plausible that the stratospheric flow is disturbed by waves emitted from blocked areas on a regular basis, but that most of the time these disturbances do not reach sufficiently large amplitudes to induce a SSW. Second, the pre-existing flow structure in the stratosphere could crucially influence the propagation of planetary waves [e.g., *Davies*, 1981; *McIntyre*, 1982], and the impact that such waves (when triggered by a block) will have on the polar vortex. Hence, the presence of a blocked flow might be a necessary but not sufficient condition for the occurrence of a SSW event.

[28] In sum, the results of the present study serve on the one hand to underline the strong link between major sudden stratospheric warming events and the occurrence of a block at tropopause elevation, and point on the other hand to the need to elicit and calibrate the factors that determine whether the occurrence of an individual block will trigger an SSW event.

[29] **Acknowledgments.** The authors would like to thank MeteoSwiss for granting access to the ERA-40 data set. O. Martius is funded by the NCCR Climate project. Special thanks go to Mischa Croci-Maspoli and Conny Schwierz for providing the blocking data set and to Tim Woollings for helpful comments. LMP is supported, in part, by the US National Science Foundation.

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