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Sudden Stratospheric Warmings and Anomalous Upward Wave Activity Flux

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Abstract

Abrupt breakdowns of the polar winter stratospheric circulation such as sudden stratospheric warmings (SSWs) are a manifestation of strong two-way interactions between upward propagating planetary waves and the mean flow. The importance of sufficient upward wave activity fluxes from the troposphere and the preceding state of the stratospheric circulation in forcing SSW-like events have long been recognized. Past research based on idealized numerical simulations has suggested that the state of the stratosphere may be more important in generating extreme stratospheric events than anomalous upward wave fluxes from the troposphere. Other studies have emphasized the role of tropospheric precursor events. Here reanalysis data are used to define events of extreme stratospheric mean flow deceleration (SSWs being a subset) and events of extreme lower tropospheric upward planetary wave activity flux. While the wave fluxes leading to SSW-like events ultimately originate near the surface, the *anomalous* upward wave activity fluxes associated with these events primarily occur within the stratosphere. The crucial dynamics for forcing SSW-like events appear to take place in the *communication layer* just above the tropopause. Anomalous upward wave fluxes from the lower troposphere may play a role for some events, but seem less important for the majority of them.

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1. Introduction

Sudden stratospheric warmings (SSWs) – abrupt disruptions of the predominantly westerly polar winter stratospheric circulation – are known to enhance predictability near the surface (e.g., Baldwin and Dunkerton 2001; Thompson et al. 2002). SSWs themselves, however, remain hard to predict (e.g., Mukougawa and Hirooka 2004; Simmons et al. 2005; Inatsu et al. 2015). Furthermore, the generation of SSWs is still not fully understood. An improved understanding of the generation of SSWs is important for a better understanding of stratospheric variability, but also of surface effects due to SSWs.

From a dynamical perspective, the most outstanding feature of SSWs is the concomitant sudden stratospheric deceleration (SSD) of the polar night jet, which must be mechanically forced. SSWs are therefore sometimes thought of as being caused by anomalously large upward fluxes of (planetary) wave activity emanating from the troposphere below (Matsuno 1971). Support comes from the comparison of the two hemispheres: only the northern hemisphere has strong enough planetary wave forcing due to topography and land-sea contrast to regularly produce SSWs, whereas only one SSW has ever been observed in the southern hemisphere where planetary wave amplitudes are generally much smaller. Many studies have investigated the link between tropospheric precursor signals and SSWs (e.g., Garfinkel et al. 2010; Cohen and Jones 2011; Sun et al. 2012). Tropospheric blocking has often been implied as a tropospheric precursor, going back to at least (Quiroz 1986). However, most tropospheric blocking episodes are not associated with SSWs (Martius et al. 2009).

Scott and Polvani (2004, 2006) found in idealized numerical model experiments that the state of the stratosphere is crucial in determining the amount of upward wave activity flux entering it. By suppressing all tropospheric variability they showed that the stratosphere is capable of controlling the upward wave activity flux near the tropopause, thereby creating its own SSW-like events. From this perspective the role of the troposphere is to merely provide a sufficient amount of background upward wave activity flux. This situation also corresponds to the classic Holton-Mass vacillations (Holton and Mass 1976), which come about due to the combined action of positive and negative feedbacks between the wave field and the mean flow (Sjoberg and Birner 2014). Specifically, an initial amount of upward wave activity flux leads to mean flow deceleration, which enhances the wave activity flux, decelerating the flow further, and so on – a positive feedback. In this sense stratospheric mean flow decelerations, such as those leading to SSWs, are as much causing enhanced upward wave activity fluxes as they are caused by these enhanced upward wave activity fluxes. This positive feedback acts until the flow has been decelerated sufficiently to form critical lines, which then act to suppress upward wave propagation – a negative feedback (Matsuno 1971; Plumb and Semeniuk 2003). The importance of these wave-mean flow feedbacks has long been recognized (e.g. Clark 1974; Geisler 1974; Holton and Mass 1976; Plumb 1981). Note that this is a nonlinear effect that comes about due to the coupling between two quasi-linear fields – the mean flow and the waves. This nonlinear coupling ultimately limits (deterministic) predictability of SSW-like events.

In the present study, we seek to quantify to what extent SSW-like events are preceded by anomalously strong upward wave fluxes in the troposphere. While it is clear that the stratospheric wave fluxes need to be anomalously strong to force SSW-like events, it is not clear whether an additional amount of wave flux (above climatological levels) needs to be provided from the troposphere below. The above referenced work by Scott and Polvani has clearly demonstrated that an anomalous tropospheric wave pulse is *not* required to force SSW-like events, at least in idealized numerical models. Here we revisit this question by analyzing reanalysis data.

2. Data and event definitions

We use 38 years (1979−2016) of data from the European Center for Medium Range Weather Forecasting Interim Reanalyses (hereafter ERAi for short) (Dee et al. 2011). We calculate the Eliassen-Palm flux (EP flux) as a measure of the wave activity flux based on 6-hourly model level data (interpolated onto the nearest pressure levels) on the native Gaussian grid with approximate horizontal resolution of 0.7°. The underlying equations are given in the supplement. For the analyses presented below we focus on extended Northern winter (November–March).

Figure 1a illustrates that, climatologically, most of the upward planetary EP flux (waves 1+2) originating in the lower extratropical troposphere converges just below the tropopause, corresponding to wave dissipation there (EP flux convergence). Stratospheric EP flux vectors are much smaller than in the troposphere. A small part of the tropospheric planetary wave fluxes is refracted

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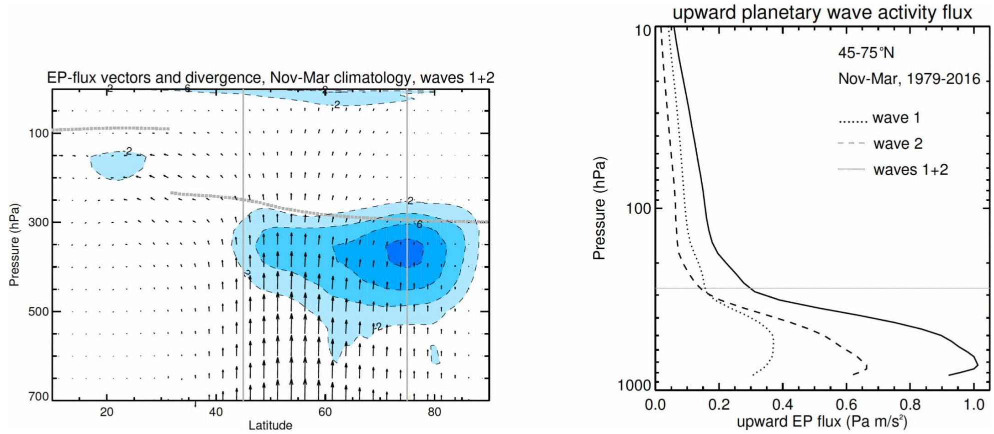

Fig. 1. (Left) Climatological November through March northern hemispheric wave activity flux (EP fluxes, vectors) and wave-induced force (EP flux divergence, color shading, in m s^{-1} day^{-1}) for planetary waves (wave numbers 1 & 2). The units for the EP fluxes are arbitrary – the purpose here is to highlight the relative difference in magnitude between troposphere and stratosphere. Gray dots mark the thermal tropopause position. Note the linear y-axis scaling. (Right) Climatological November through March upward planetary EP flux, averaged over 45°N−75°N (latitude range marked in left panel by gray vertical lines). Horizontal gray line marks approximate tropopause position. Note this panel uses a logarithmic y-axis.

equatorward and dissipates near the subtropical tropopause – this part "escapes" upward propagation into the mid- and high latitude stratosphere.

Figure 1b shows vertical profiles of climatological November-March upward planetary wave EP flux (waves 1, 2, and their sum) averaged between 45−75°N. Less than ~15% of the climatological lower tropospheric wave 1+2 EP flux remains just above the tropopause.

Figure 1 also highlights that fluctuations in tropospheric upward wave activity fluxes will tend to easily overwhelm those in the stratosphere, simply because the background fluxes are so much larger in the troposphere. For example, a mere 10% increase in lower tropospheric wave 2 flux, when translated into an absolute increase, would correspond to more than a doubling in the lower stratosphere (if all of this anomalous flux propagated into the lower stratosphere). It is therefore crucial to consider anomalous wave fluxes in a relative sense. We will consider standardized anomalous upward wave activity fluxes, i.e. normalized by their standard deviation. By definition this quantifies more appropriately how anomalous a given wave flux anomaly is at a given pressure level.

In this study we explore the fate of extreme events in lower tropospheric upward planetary wave activity (EP) flux and to what extent they lead to strong decelerations of the mid-stratospheric polar night jet. Since individual planetary scale waves may not be independent (e.g. waves 1 and 2 have often been reported to show a degree of anti-correlation, e.g. Labitzke (1978)), we define events based on individual wave numbers. In what is shown below we use the 45°N−75°N averaged de-seasonalized upward EP flux near 700 hPa for waves 1 and 2 individually, and define an extreme wave event when the 10-day averaged upward EP flux exceeds the value corresponding to two standard deviations. The qualitative features of the results are not very sensitive to the choice of tropospheric level. The 10-day time scale used here is motivated by Sjoberg and Birner (2012), who found SSWs to be preferentially associated with order of 10-day forcing.

A total of 21 wave 1 events and 32 wave 2 events have been identified near 700 hPa in the 38 year record (event dates are provided in the supplement). We distinguish wave events that are followed by a strong deceleration of the mid-stratospheric polar night jet from those that are not. In order to do so we define sudden stratospheric deceleration events (SSDs) based on the 10-day deceleration of the de-seasonalized 10 hPa zonal mean flow averaged over 45°N−75°N (results are virtually the same when using the zonal mean flow at 60°N). SSDs are used instead of the conventional SSWs to better capture the mechanically forced explosive dynamics of these events. An SSD is defined to occur when this 10-day deceleration exceeds a critical threshold – here we use 2 m s^{-1} day^{-1} (i.e. 20 m s^{-1} over 10 days), which corresponds to ~2.2 standard deviations based on the available November–March data record. The center date of the event is assigned to the maximum 10-day deceleration value within 20 days of first exceedance of the threshold. A minimum separation time scale of 20 days is used between the events. A qualitatively similar tendency-based index to define events was recently used by Martineau and Son (2013). We identify a total of 32 SSD events – their dates are provided in the supplement. 21 of these SSD events are followed within 10 days by an SSW (including some final warming events).

Lower tropospheric wave events (LTWEs) and SSDs provide alternative perspectives on the wave coupling between the troposphere and stratosphere. The table in the supplement shows that a total of only 11 LTWEs (7 wave 1 and 4 wave 2) are followed by SSDs within 10 days[1]. These LTWEs are in the following referred to as being associated with that SSD, although a clear mechanistic link between the LTWEs and SSDs cannot be established from the quasi-observational data used here. Tropospheric precursory wave fluxes might therefore play an important role in forcing about a third of the 32 identified SSDs. The corresponding statistic is similar for SSWs: 7 out of a total of 28 SSWs (25%) are preceded by an LTWE (see supplement).

3. Results

Figure 2 shows the composite evolution of standardized anomalous upward EP flux and wind tendency averaged over wave 1 (top row) and 2 (bottom row) LTWEs, but decomposed into those associated with SSDs (left column), those not associated with SSDs (middle column), and their difference (right column).

The tropospheric evolution of the anomalous upward EP fluxes is very similar between those events that are associated with an SSD and those that are not. However, the composite evolution in the stratosphere differs markedly: those LTWEs associated with SSDs (left column) show even stronger wave flux anomalies in the stratosphere than in the troposphere. There is a strongly positive vertical gradient in anomalous upward EP flux just above the tropopause, between 300−200 hPa, in particular for the wave 1 events. On the other hand, those LTWEs that are not associated with SSDs (middle column) show strong wave dissipation in the upper troposphere (confirmed by analyzing their EP flux diver-

[1] These statistics are not very sensitive to this 10-day time scale, see discussion in the supplement.

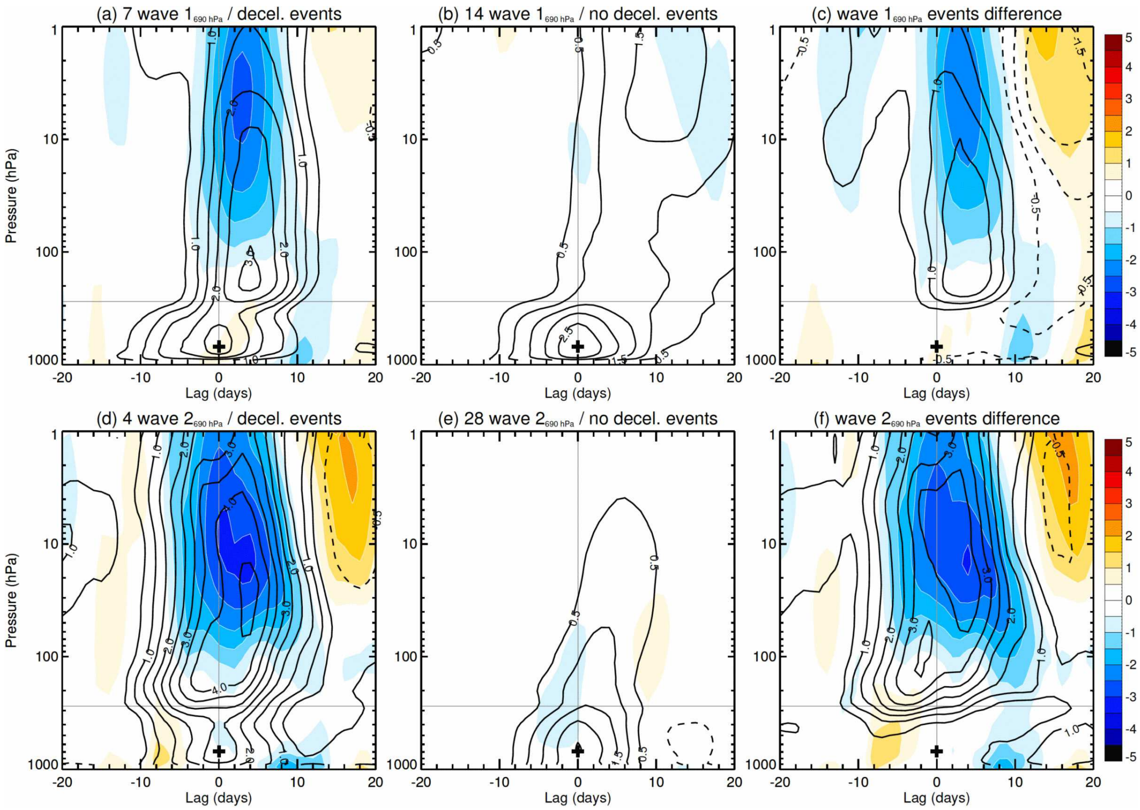

Fig. 2. Composite evolution, as a function of lag and pressure level, of extreme upward EP flux events (LTWEs) near 700 hPa (marked at lag zero by the plus sign). The 10-day averaged upward EP flux is shown in black contours, with the 10-day integrated wind tendency in colors. (left; a, d) Subset of those LTWEs associated with a deceleration event at 10 hPa (SSD). (middle; b, e) Subset of those LTWEs not associated with an SSD. (right; c, f) difference between (left) and (middle). Top row (a−c) shows wave 1 LTWEs, bottom row (d−f) shows wave 2 LTWEs. Fields are standardized, i.e. high values indicate high statistical significance. Horizontal gray lines mark approximate tropopause level.

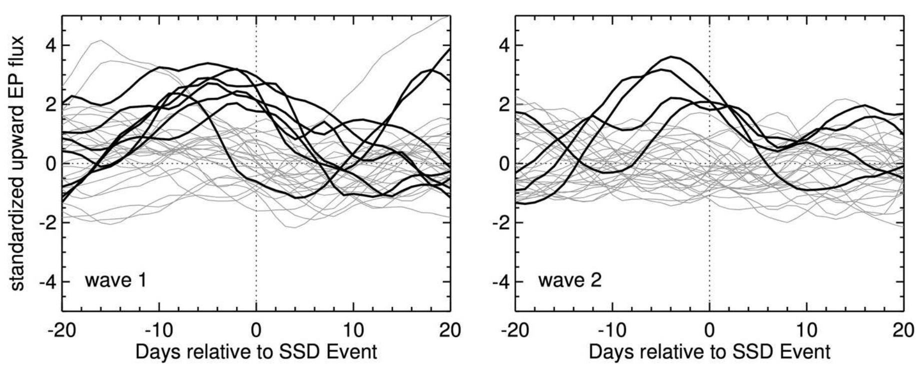

Fig. 3. Evolution of standardized upward EP flux near 700hPa (averaged over 45°N−75°N) relative to the center date of SSD events. Left: wave 1, right: wave 2. Individual events are shown as thin gray lines with thick black lines highlighting those SSDs that are preceded by a wave event within 10 days.

gence), such that only a small fraction of the lower tropospheric EP flux reaches the stratosphere. Furthermore, the composite wave flux evolution in the middle panels shows a clear upward progression with time, indicative of upward propagation of a lower tropospheric wave pulse. There are hardly any mean flow changes for this subset, indicating the linear wave propagation paradigm to be appropriate. In contrast, the composite wave flux evolution in the left panels does not show much upward progression with time in the stratosphere: strongly anomalous upward EP fluxes appear nearly instantaneously at all stratospheric levels. The duration of the wave event is longer in the stratosphere than in the troposphere (the opposite of the behavior in the middle panels). Mean flow changes are substantial, as expected given that these events are associated with SSDs. The difference between the composite LTWE evolutions between SSDs and no SSDs (Fig. 2, right panels), shows that it is the stratospheric part of the wave-mean flow evolution that distinguishes SSDs. The strongest differences exceed two standard deviations.

As pointed out in the previous section, most of the SSD events (21 out of 32) are not preceded by extreme lower tropospheric planetary wave fluxes. To compare the evolution of lower tropospheric wave fluxes between those SSDs that are preceded by LTWEs and those that are not, Fig. 3 shows the individual time series of standardized lower tropospheric wave 1 and 2 fluxes relative to the central SSD dates. The time series corresponding to the 7 wave 1 events making up the composite in Fig. 2a, as well

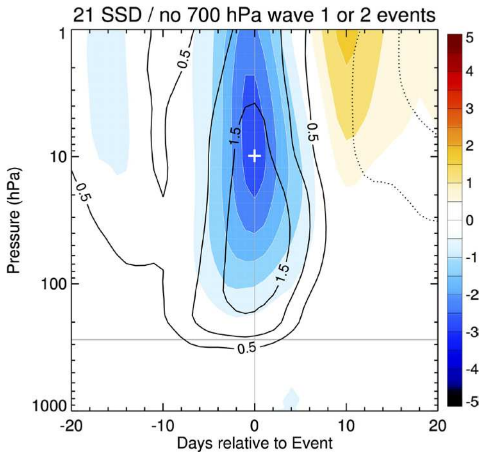

Fig. 4. Composite evolution as a function of lag and pressure level of the subset of SSDs at 10 hPa that were *not* preceded by an LTWE within 10 days. Colors show 10-day integrated wind tendency, black contours show 10-day averaged upward planetary EP flux (waves 1+2, negative dotted). All fields are standardized. All values correspond to latitudinal averages over 45°N−75°N.

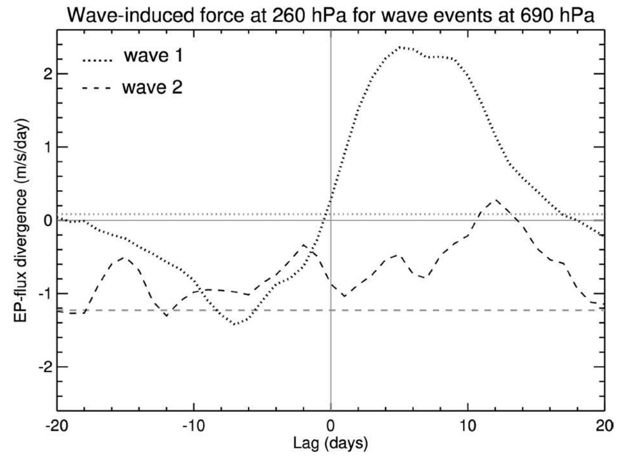

Fig. 5. Composite evolution, as a function of lag, of the total 10-day averaged wave-induced force (EP-flux divergence) just above the tropopause (at 260 hPa) corresponding to those LTWEs near 700 hPa that are associated with an SSD at 10 hPa (see Figs. 2a and 2d). Wave 1 events dotted, wave 2 events dashed. Total quantities are shown (anomaly plus climatology), in order to highlight the source of wave activity (positive EP-flux divergence) at positive lags for wave 1 events. Background climatologies for wave 1 and 2 are shown as gray dotted and dashed lines, respectively.

as the 4 wave 2 events making up the composite in Fig. 2d are highlighted. In almost all other cases these wave fluxes fluctuate within ± 2 standard deviations. For 2 SSD events the wave 1 evolution shows extreme events more than 10 days before the SSD central date, indicating that they may have provided precursory forcing. Including these 2 events in the composite shown in Fig. 2a does not strongly modify the evolution.

Figure 4 shows the composite evolution of the subset of SSD events that are *not* preceded by LTWEs. While the composite evolution of the wind tendency in the stratosphere is similar to that for the wave events shown in Figs. 2a and 2d, the upward wave fluxes (here wave 1+2) do not show a tropospheric signal for this subset of SSD events. Instead, upward wave fluxes are only significantly enhanced above the tropopause where they evolve in a qualitatively similar fashion to those shown in Figs. 2a and 2d (albeit less strong). Interestingly, there is hardly any near-surface circulation signal for this subset of SSD events.

4. Summary and discussion

Abrupt transitions in the wintertime stratospheric circulation such as those associated with SSWs are sometimes thought of as being caused by anomalously large fluxes of upward (planetary) wave activity emanating from the troposphere below. However, it is important to note that climatologically – at least in the northern hemisphere – the troposphere contains a reservoir of wave activity flux multiple times bigger than those wave fluxes existing in the stratosphere. From this perspective it is questionable whether an additional amount of upward tropospheric wave activity fluxes is needed to force SSW-like events; what is climatologically available may be sufficient. Our analysis supports the viewpoint that the extent to which the stratosphere is able to tap into the tropospheric reservoir is in most cases more important for forcing SSW-like events than an additional amount of upward wave activity fluxes from the troposphere.

Nevertheless, a subset of our identified SSD events (11 out of 32) is preceded by extreme anomalous upward planetary wave fluxes in the lower troposphere. It remains an open question whether these preceding wave fluxes are causal for these SSD events or whether they arise as part of the evolution of the events due to deep vertical coupling across the entire troposphere-stratosphere system, especially for split/wave 2 events for which the anomalous upward EP fluxes emerge essentially simultaneously at all levels (Fig. 2d) (O'Neill and Pope 1988; Charlton et al. 2005; Hitchcock and Haynes 2016).

Overall our results support the viewpoint that the non-linear positive feedback between upward propagating planetary waves and the stratospheric mean flow is crucial in forcing SSW-like events. The majority of LTWEs do not manage to kick off this positive feedback – they only produce weak stratospheric mean flow changes (Figs. 2b and 2e), i.e. they fall into the linear wave propagation paradigm with standard group velocities of 3−7 km/day. On the other hand, the wave events that do produce strong stratospheric mean flow changes extend nearly instantaneously over all heights (Figs. 2a and 2d). Indeed these events do not have group velocity signatures that would be indicative of vertically propagating waves generated by anomalously large forcing from the troposphere below in that the anomalous upward wave activity flux occurs almost concurrently at all stratospheric levels without a clear upward propagating signal. Both group velocity signatures, falling under the linear propagation paradigm and the nonlinear wave-mean flow interaction paradigm, are clearly identifiable during the onset (preconditioning) time period and actual event time period of the 2009 split SSW (Albers and Birner 2014).

Our results show that the dynamics in the layer between the tropopause and the bottom of the polar vortex (~300−200 hPa), which may be thought of as a "communication layer", are crucial in determining whether the nonlinear wave-mean flow feedback leading to SSW-like events is kicked off. An interesting feature arises for wave 1 events, for which the strongly positive vertical gradient in the anomalous upward wave activity flux between ~300−200 hPa (Fig. 2a) turns out to correspond to a wave source signature just above the tropopause. This is revealed by the significant positive EP flux divergence (in a total sense, i.e. mean plus anomaly) shown in Fig. 5. Wave 2 events do not show such a feature. It is presently unclear why these two planetary wave numbers show such qualitatively different behavior. We note that the background meridional gradients of potential vorticity are near zero in the layer just above the tropopause (Birner 2006) and may reverse from time to time, such that the necessary condition for instability and hence wave generation is fulfilled (Charney and Stern 1962). Sjoberg and Birner (2014) found that reversals of the potential vorticity gradient near the tropopause may be created by the wave-mean flow interaction itself, at least in highly idealized models, leading to local wave generation. Localized positive EP flux divergence may also indicate a reflecting surface and reflection has been found to be more prevalent in the wave 1 fields (e.g. Shaw et al. 2010; Dunn-Sigouin and Shaw 2015).

Our results also suggest that it is misleading to think of the anomalous upward wave activity flux in the lower stratosphere as the ultimate cause of SSW-like events. For the most part lower stratospheric wave fluxes are simply a signature of the mean flow event itself. Viewed in this way, correlating lower stratospheric wave fluxes with mid-stratospheric mean flow events – e.g. correlating 100 hPa wave fluxes with the 10 hPa mean flow – is equivalent to correlating the event with itself. In certain cases a precursory planetary wave signal from below may represent the ultimate trigger of the event, while in other cases the event may be triggered by other processes. A preconditioned vortex that is anomalously strong, as found for our subset of LTWEs that precede SSDs (Fig. 1 in supplement) may help trigger the feedback. However, given the multitude of possible trigger signals and the generic sensitivity to initial conditions of nonlinear feedback processes, deterministic predictability of SSW-like events is essentially limited to the lead time of the onset of the positive feedback (~10 days, cf. Sjoberg and Birner 2014 – this time scale agrees with that from deterministic predictability experiments, see e.g., Taguchi 2014; Tripathi et al. 2015), although probabilistic forecast are possible at much longer time scales (Scaife et al. 2016).

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Supplements

The supplement provides the relevant equations and a table listing all event dates used and/or discussed in this study.

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