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Key Points:
- Waves with eastward phase speeds are preferred for upward propagation into the stratosphere
- Split SSW events are preceded by an eastward tendency in zonal phase speed of wave 1 and wave 2
- Extreme eastward phase speeds likely favored the record upward EP flux before the 2009 SSW

Supporting Information:
- Supporting Information S1

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Rossby Wave Propagation into the Northern Hemisphere Stratosphere: The Role of Zonal Phase Speed

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Abstract Sudden stratospheric warming (SSW) events are to a dominant part induced by upward propagating planetary waves. While theory predicts that the zonal phase speed of a tropospheric wave forcing affects wave propagation into the stratosphere, its relevance for SSW events has so far not been considered. This study shows in a linear wave diagnostic and in reanalysis data that phase speeds tend eastward as waves propagate upward, indicating that the stratosphere preselects eastward phase speeds for propagation, especially for zonal wave number 2. This also affects SSW events: Split SSW events tend to be preceded by anomalously eastward zonal phase speeds. Zonal phase speed may indeed explain part of the increased wave flux observed during the preconditioning of SSW events, as, for example, for the record 2009 SSW event.

1. Introduction

Upward propagating planetary-scale Rossby waves are the dominant cause of day-to-day variability in the extratropical winter stratosphere. Anomalous wave forcing can lead to strong disruptions of the stratospheric flow, so-called sudden stratospheric warming (SSW) events, which in turn affect tropospheric variability (e.g., Baldwin & Dunkerton, 2001) and predictability (e.g., Domeisen et al., 2015; Karpechko et al., 2017). The magnitude and duration of the wave forcing can be diagnosed from the vertical component of the Eliassen-Palm (EP) flux (e.g., Vallis, 2006), which is proportional to the meridional heat flux and often considerably enhanced for a sustained period before SSW events (Polvani & Waugh, 2004; Sjoberg & Birner, 2012). The anomalous wave forcing has been linked to tropospheric anomalies such as blocking (Martius et al., 2009; Nishii et al., 2011; Quiroz, 1986; Woollings et al., 2010). However, both tropospheric forcing (Davies, 1981) and internal stratospheric variability (de la Cámara et al., 2017) have to be considered as factors playing a role in preconditioning SSW events.

While both the magnitude and duration of a wave forcing can influence the preconditioning of SSW events, it is known from theoretical considerations (Charney & Drazin, 1961) that the vertical propagation of waves into the stratosphere is also affected by their zonal phase speed. Waves with nonzero zonal phase speed, that is, traveling waves, are ubiquitous in the stratosphere, especially in the Southern Hemisphere (Labitzke, 1981). In the absence of longitudinally asymmetric surface forcing such as topography, Domeisen and Plumb (2012) show that the generation of traveling planetary-scale waves is dominated by nonlinear interaction among synoptic-scale baroclinic eddies in the troposphere, as suggested by Scinocca and Haynes (1998). In the Northern Hemisphere, the majority of the wave spectrum consists of stationary waves (e.g., Watt-Meyer & Kushner, 2015a). Traveling waves are, however, also observed, for example before the 1979 SSW event (Madden & Labitzke, 1981). Traveling waves have in addition been linked to resonant behavior before SSW events (e.g., Geisler, 1974; Plumb, 1981).

The aim of this study is to elucidate the role of traveling Rossby waves for the Northern Hemisphere winter stratosphere. The paper is structured as follows: Section 2 introduces the role of phase speed in upward wave propagation, section 3.1 expands the analysis using a two-dimensional wave propagation diagnostic, and section 3.2 compares these results to reanalysis. Section 3.3 examines the role of zonal phase speed ahead of SSW events, and section 3.4 discusses the results in the framework of the 2009 SSW event. Section 4 provides a summary and discussion of the results. The supporting information provides further details on the methods used in this study.

2. Theory

The main factor influencing upward wave propagation is the background state of the stratosphere, that is, the slowly evolving state of the stratospheric wind and temperature, which influences the behavior of the propagating waves. In turn, waves affect the mean flow through the deposition of momentum when they break. Charney and Drazin (1961) showed that there exists a limited range of the zonal phase speed c and zonal background wind speed u_0 for which upward propagation of waves is possible: For a spatially uniform background wind speed,

$$0 < u_0 - c < u_c := \frac{\beta}{k^2 + l^2 + f_0/4H^2N^2}\,, \tag{1}$$

where k and l are the zonal and meridional wave numbers of the propagating wave, respectively, $f_0 := 2\Omega \sin \phi_0$ is the Coriolis parameter at a fixed latitude ϕ_0 with $\Omega = \frac{2\pi}{24h}$, $\beta := \frac{2\Omega}{a} \cos \phi_0$ with a the Earth's radius, H is the scale height of the atmosphere, and N is the Brunt-Väisälä frequency for the undisturbed motion. For stationary waves (i.e., $c = 0$), propagation is limited to background winds that are eastward (i.e., $u_0 > 0$) and smaller than the critical velocity u_c, which is determined by the structure of the background state (e.g., through N^2) and the wave numbers of the propagating wave (right-hand side in equation (1)). Waves with large zonal wave numbers k are inhibited from propagating into strong background winds, limiting vertical propagation to zonal wave numbers 1 and 2 (hereafter wave 1 and wave 2) in the Northern Hemisphere upper stratosphere (Plumb, 1989).

As an example, an eastward phase speed of $c = 10$ ms^{-1} allows wave 2 to propagate into winds that are faster by around 10 ms^{-1} as compared to a stationary wave. The effect is smaller for wave 1, but wave 1 tends to be less limited in its vertical propagation in the Northern Hemisphere as indicated by the wider propagation window. In addition to the larger magnitude of the effect for wave 2, the effect for wave 2 occurs within a range of background wind speeds that are typical for zonal mean winds in the extratropical midstratosphere after an initial weakening of the flow, which is often induced by wave 1 (e.g., Bancalá et al., 2012).

While the analysis of upward wave propagation in the Northern Hemisphere is often reduced to stationary waves, the question addressed in this study is to what extent an observed change in the zonal phase speed c of the wave forcing alters the propagation characteristics.

3. Results

3.1. Wave Propagation Analysis in Two Dimensions

The assumption of a background flow that is uniform in space as assumed in section 2, especially with respect to height and latitude, is, however, rather limiting. Upward wave propagation is therefore explored in the wave geometry diagnostic developed in Harnik (2001) in order to understand if a preference for upward propagation by waves with an eastward phase speed can indeed be found. For further details on the diagnostic see the supporting information and Harnik (2001), Harnik and Lindzen (2001), and Lubis et al. (2016).

Zonal mean temperature and wind fields averaged over December–February for each winter from 1958 to 2016 from the Japanese 55-year reanalysis (Kobayashi et al., 2015) are used as the background state. Wave 1 and wave 2 anomalies with a prescribed phase speed relative to the ground are forced separately at the reference level (500 hPa). The model is then used to compute the equilibrium quasi-geostrophic upward EP flux for each winter and for phase speeds between −8 ms^{-1} and 8 ms^{-1} at intervals of 1 ms^{-1}.

Figure 1a shows the relative change in the vertical EP flux component at 100 hPa, as computed from the wave diagnostic, for a finite phase speed of the forcing relative to a stationary forcing ($c = 0$). A clear increase in upward propagation is observed for eastward phase speeds and a decrease for westward phase speeds. The effect is considerably stronger for wave 2: A phase speed of 5 ms^{-1} yields an increase in the upward EP flux for wave 2 by more than 50% with respect to $c = 0$. A higher year-to-year variability (indicated by the shaded regions in Figure 1a) is observed for eastward phase speeds, indicating that the exact configuration of the background flow more strongly controls the amount of upward propagation for eastward phase speeds.

In a second experiment, instead of using a background state averaged over the entire winter season, the period before a SSW event is used as a background state, which is obtained by averaging over all 37 SSW events in the Japanese 55-year reanalysis database for the period 1958–2016 (according to Butler et al., 2017; Charlton & Polvani, 2007) (Figure 1b). The zonal mean zonal wind and temperature fields are low-pass filtered with a cutoff of 5 days prior to averaging over the events. The linear model is run for each lag with respect

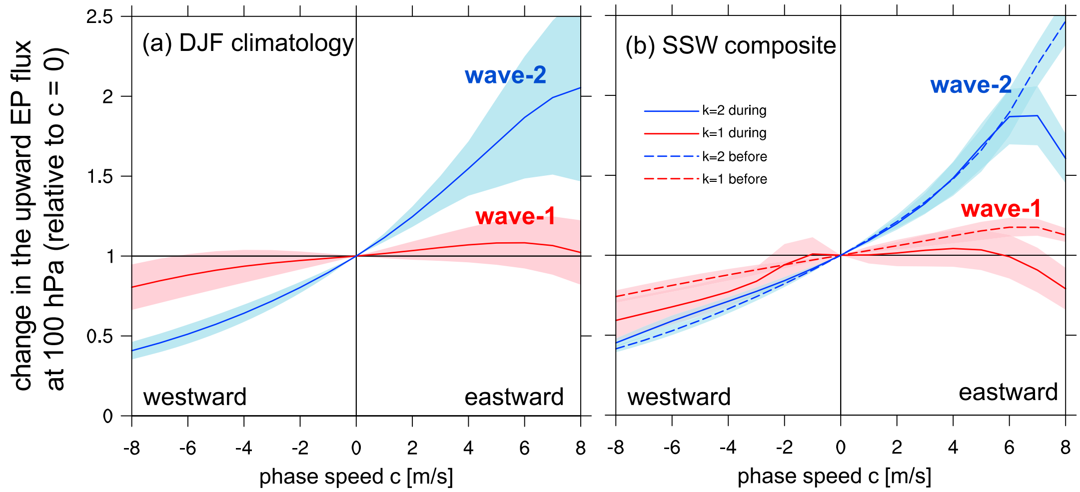

Figure 1. Relative upward Eliassen-Palm (EP) flux (100 hPa) averaged between 40 and 80°N (normalized by the upward EP flux for $c = 0$) for wave 1 (red) and wave 2 (blue) for a range of phase speeds defined at 45°N for (a) the December–February (DJF) background flow. Shading indicates year-to-year variability defined by $\pm\sigma$, where σ is the standard deviation. (b) The same as (a) but using a background state before (dashed; days −20 to −6) and during (solid; days −5 to 5) a sudden stratospheric warming event. Shading indicates daily variability defined by $\pm\sigma$ for the respective periods.

to the central date of the SSW composite. The relative upward EP flux change is averaged over two representative periods, that is, before (days −20 to −6) and during (days −5 to 5) the SSW event. The results confirm the notion that the background state before SSW events is more susceptible to changes in phase speed, while during the SSW event, phase speed has a weaker effect on facilitating upward wave propagation. In more detail, upward propagation is enhanced in particular for large eastward phase speeds before the SSW event, while it is diminished during the event (cf. Figure 1a). This effect is again stronger for wave 2 as compared to wave 1. These findings indicate that for a given background flow, a change in phase speed—as indicated by theory—may indeed be a significant factor for facilitating upward wave propagation, in particular for wave 2.

3.2. Zonal Phase Speed Statistics in Reanalysis

We now explore if the above behavior is observed in the real atmosphere. The Hayashi spectra (Hayashi, 1979) (computed following Randel & Held, 1991) show the density power of geopotential height for the observed range of phase speeds (relative to the ground) and wave numbers (Figure 2). More details about

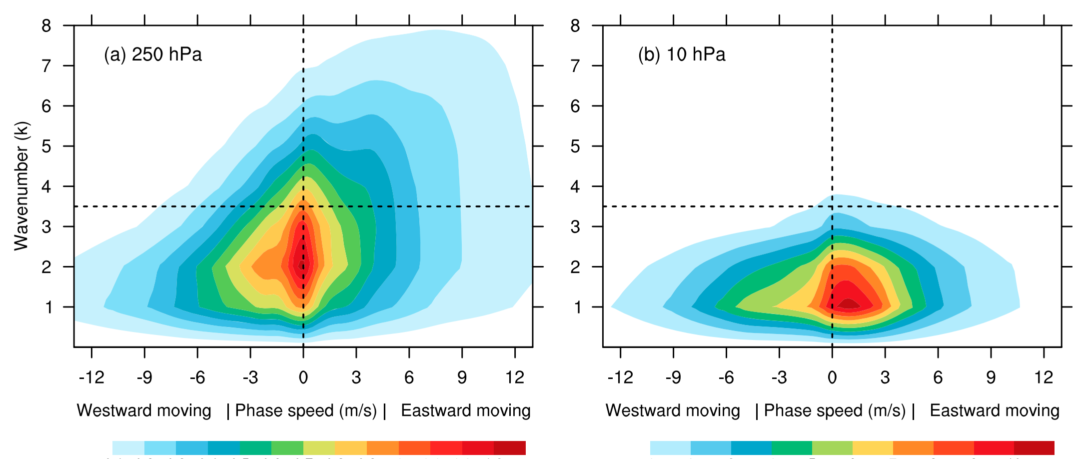

Figure 2. Hayashi spectra of phase speed (ms^{-1}) relative to the ground versus zonal wave number k for (a) 250 hPa and (b) 10 hPa averaged over 30–75°N. Units are $m^2 \cdot \Delta c^{-1}$, where $\Delta c = 0.33\ ms^{-1}$ is the phase speed interval.

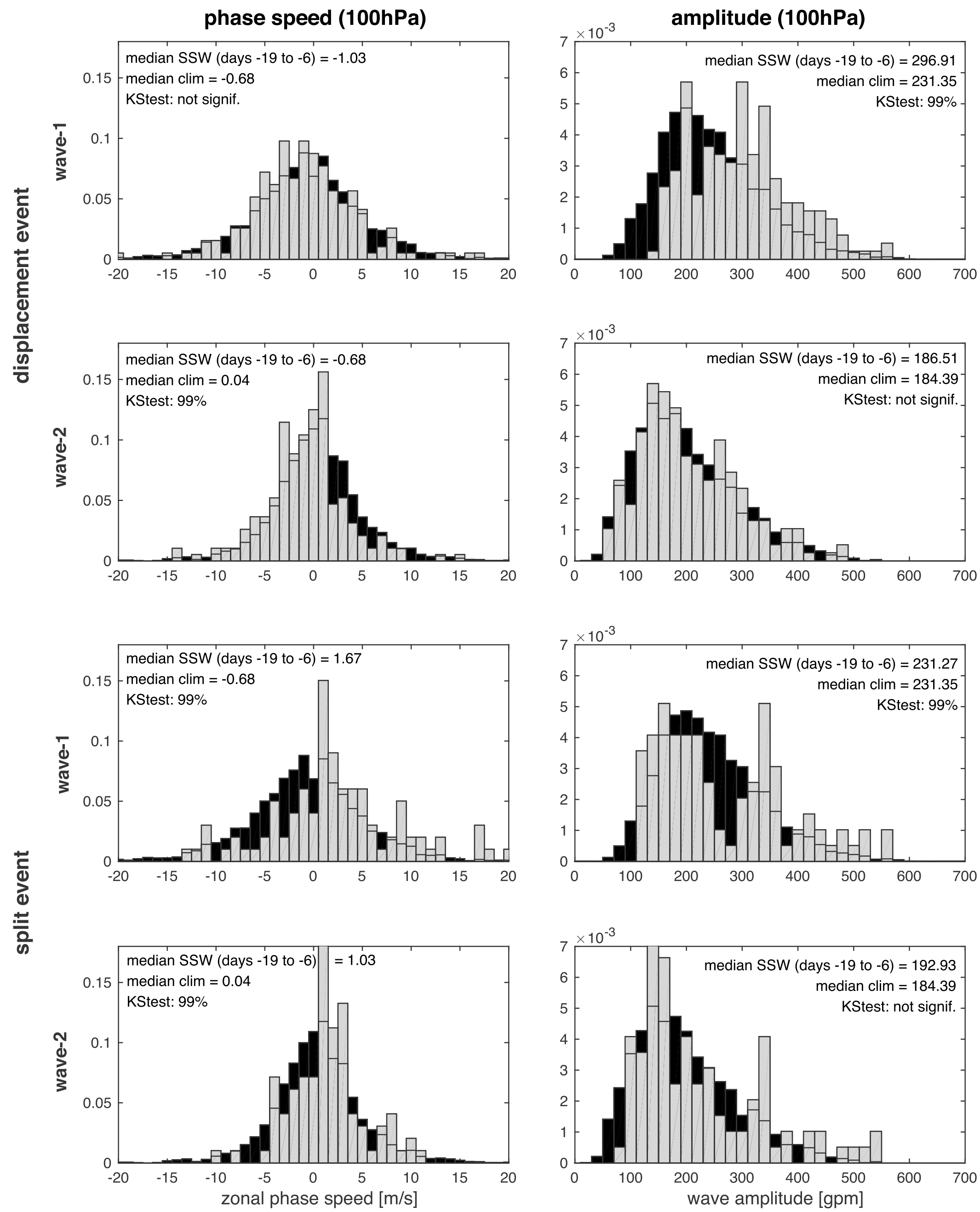

Figure 3. Phase speed (ms^{-1}) (left) and amplitude (gpm) (right) at 100 hPa for daily average values for days −19 to −6 before a sudden stratospheric warming event (gray bars) and for the November–March climatology (black bars). Additional horizontal bars indicate the climatology where the gray bars are taller than the black bars. The median values for the respective distributions and significant differences between the distributions according to a two-sample Kolmogorov-Smirnov test are indicated. Values of 90%, 95%, and 99% significance are tested. Significance values below 90% are indicated as “not significant.” All distributions are normalized for comparison.

the computation can be found in the supporting information. Synoptic waves ($k = 4$–8) exhibit a strong eastward propagating component in the troposphere, as expected from the eastward movement of synoptic systems with the storm track. Note that the mean flow is included in the analysis. The majority of the planetary-scale waves are stationary in the troposphere (Figure 2a), with a skewness toward westward propagation for wave 1 and wave 2. Dell’Aquila et al. (2005, 2016) obtain comparable results for the National Centers for Environmental Prediction (Kalnay et al., 1996) and ERA40 (Uppala et al., 2006) reanalyses.

In the stratosphere (10 hPa, Figure 2b), propagation is limited to planetary-scale waves as predicted by equation (1). More interestingly, the spectral density maximum moves toward eastward phase speeds for all wave numbers, while the long tail for wave 1 toward westward phase speeds persists with height. The eastward shift in phase speed with height can clearly be observed from evaluating additional pressure levels (Figure S1) for wave 1 and wave 2. Note that while the eastward shift in phase speed with height may in part be explained by the increasing wind speed with height in the stratosphere, for example, between 100 and 10 hPa, this behavior is less clear across the tropopause, where different methods yield different results for the change in phase speed with height (Figure S1a), though these are well contained within the error bars.

3.3. Phase Speed Behavior Before SSW Events

The above results lead to the notion that during periods of strong upward wave propagation, for example, before SSW events, waves with eastward phase speed may dominate, as they are more likely to propagate into the stratosphere. To test this hypothesis, we composite the phase speeds of wave 1 and wave 2 signals in the geopotential height field before SSW events. The results from this method for the computation of zonal phase speed agree well with the Hayashi method; see supporting information for a comparison of the climatologies. The events are separated into 12 split (wave 2) and 23 displacement (wave 1) SSW events (according to Butler et al., 2017; Charlton & Polvani, 2007; were excluded as they could not be unambiguously identified).

It could be expected that the dominant wave number for each SSW event is associated with a more eastward phase speed. The results confirm this notion for split events: Ahead of split SSW events, phase speed in the lower stratosphere (100 hPa) increases significantly for both wave numbers (Figure 3), consistent with the dominant precursor role that wave 1 often plays ahead of split events in preconditioning the mean flow (Bancalá et al., 2012; Watt-Meyer & Kushner, 2015b). This increase does not occur simultaneously for wave 1 and wave 2 (not shown), consistent with the observed anticorrelation of wave 1 versus wave 2 in the stratosphere (Labitzke, 1977).

Ahead of displacement events, strong eastward phase speeds of wave 2 occur much less frequently, as expected, while wave 1 does not exhibit a significant phase speed signal. For wave 1, changes in wave amplitude play a much more important role, with significant increases of wave 1 amplitude ahead of both displacement and split events. The conclusion does not change when considering the 10 hPa level instead (Figure S3). The tendency toward more negative (positive) phase speeds of wave 2 ahead of displacement (split) SSW events can also be observed in the troposphere (250 hPa, Figure S2), though the signal is not significant there. The only strongly significant signal at 250 hPa is the increase in wave 1 amplitude ahead of displacement events.

For comparison, Dunn-Sigouin and Shaw (2015) found westward propagation of wave 1 at 500 hPa during upward wave events (which do, however, not need to correspond to the SSW events defined here) and weak eastward propagation at 10 hPa.

3.4. Case Study: Phase Speed Preconditioning of the 2009 SSW Event

The presence of anomalously eastward phase speeds in the lead-up to a SSW event can be demonstrated for a prominent example: The SSW event on 24 January 2009 was the strongest split event on record in terms of the observed heat flux (Ayarzaguena et al., 2011). Before the event, a wave 2 pattern dominated the Northern Hemisphere tropopause-level flow, with anticyclonic anomalies over western North America and Scandinavia. These ridges were colocated with blocking anticyclones and are suggested to have played a role in exciting upward propagating wave packets (Ayarzaguena et al., 2011; Harada et al., 2010; Schneidereit et al., 2017) by projecting onto the climatological planetary-scale wave 1 and wave 2 patterns.

The blocking high over North America showed a comparably large eastward phase speed between 15 and 20 January, which was shown in the last section to be a crucial period for phase speed preconditioning of a SSW event. Both wave numbers exhibit anomalously eastward phase speeds before the SSW event (Figure 4). While the amplitude of wave 1 remains comparably low and the positive phase speeds occur for a shorter period only, for wave 2, however, anomalously eastward phase speeds occurred up to 20 days before the SSW event, growing up to 2 weeks before the event and then slowly approaching smaller values with exceptionally high amplitude. Wave 2 phase speeds remain above the median for the entire period, that is, days −20 to −5 before the SSW event. The 2009 event is therefore an exception to the notion that wave 1 tends to be responsible to weaken the flow ahead of split events.

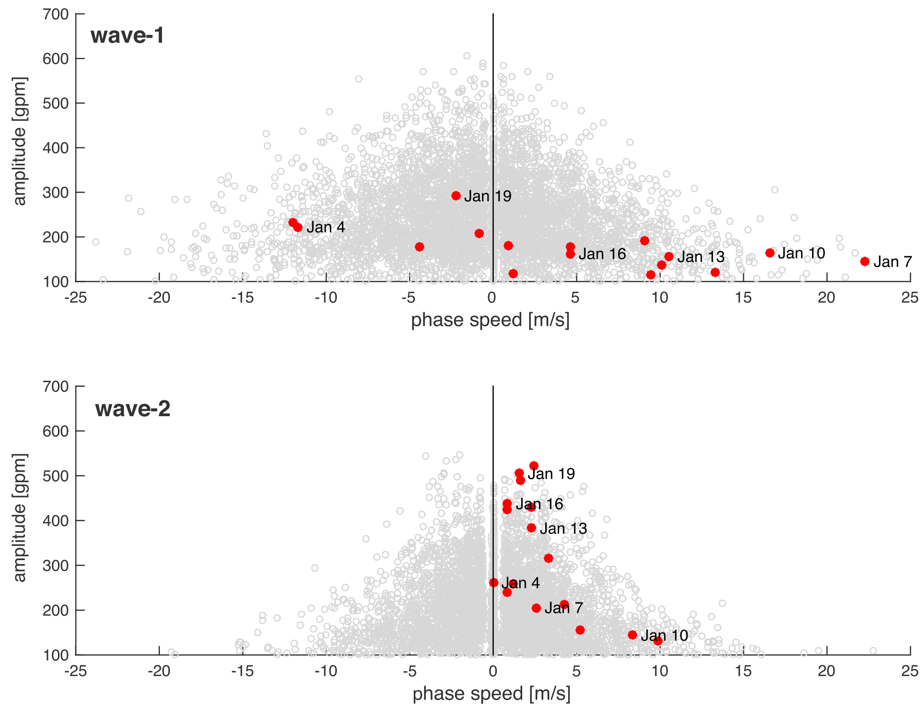

Figure 4. Daily zonal phase speed (ms^{-1}) versus wave amplitude (gpm) for November–March 1958–2013 (gray circles) and for days −20 to −5 before the 2009 sudden stratospheric warming event (red circles) for wave 1 (top) and wave 2 (bottom) at 100 hPa. Every circle represents a daily average value, and every third day before the 2009 sudden stratospheric warming event is indicated.

We suggest that the eastward acceleration of the zonal phase speed may have increased the possibility for upward propagation for wave 2 ahead of the 2009 SSW event, contributing to the record heat flux injection into the stratosphere. At the same time, the tendency toward smaller phase speeds just before the event is reminiscent of resonance behavior, as discussed in the next section.

4. Summary and Discussion

Theory predicts that a wave forcing with an eastward zonal phase speed can propagate more readily upward due to the refractive properties of the background flow. This is confirmed in a two-dimensional wave propagation diagnostic by forcing planetary-scale waves with a range of phase speeds, while keeping the background flow constant: Upward wave flux increases with increasing eastward phase speed and decreases with increasing westward phase speed of the forcing. The effect is considerably stronger for wave 2 compared to wave 1 for Northern Hemisphere mean flow climatologies. Indeed, phase speeds of geopotential height anomalies in reanalysis data tend eastward with height, indicating a preselection of eastward propagating waves by the stratosphere. Note that this effect is in part explained by the change in the background wind.

An investigation of wave propagation before SSW events in the wave diagnostic indicates a preference for waves with eastward phase speed up to 5 days before a SSW event. Indeed, an eastward shift in phase speed before SSW events is also observed in reanalysis data: Phase speeds for wave 2 in the stratosphere tend to decrease (increase) ahead of displacement (split) SSW events, while the changes in amplitude are not significant. Wave 1 tends to experience a significant increase in amplitude ahead of both split and displacement events and a significant increase in phase speed before split events. Phase speed is therefore suggested to play a role in enhancing upward wave propagation before SSW events, especially for wave 2.

While these results are based on reanalysis data and a simple wave diagnostic, they remain to be validated for comprehensive climate models. It can be expected that the impact of a nonzero phase speed of wave disturbances is even greater in the Southern Hemisphere, where traveling waves account for the dominant portion of the stratospheric wave spectrum, and winds in midwinter tend to be too strong for wave propagation (Plumb, 1989). A separate study will look into the role of zonal phase speed in the Southern Hemisphere stratosphere.

Zonal phase speed has also been suggested to play a role in resonant excitation (Esler & Scott, 2005; Geisler, 1974; Plumb, 1981; Tung & Lindzen, 1979a, 1979b) for both split (Matthewman & Esler, 2011) and displacement events (Esler & Matthewman, 2011). Indeed, some of the effects observed for the 2009 SSW event may be linked to resonant wave excitation: The exceptional eastward phase speed and amplitude of wave 2 may have facilitated upward wave propagation until about 5 days before the event, thereby nudging the stratosphere toward resonance that then caused the SSW event, as suggested by Albers and Birner (2014) and Matthewman and Esler (2011). The decreasing zonal phase speed shortly before the event is also suggestive of resonant behavior, possibly caused by an assimilation in phase speed between a stationary wave and a free mode (Geisler, 1974; Plumb, 1981). A similar mechanism has been proposed for the 1979 SSW event (Smith, 1989), in line with the mechanism for resonant self-tuning (Plumb, 1981).

In terms of possible tropospheric precursors, this study represents a note of caution when considering the effect of tropospheric blocking anomalies as precursors for stratospheric anomalies, noting that the definition of the threshold of how much a block is allowed to move within a given time frame may affect the results. It should, however, be noted that the observed shift in phase speed is only found to be significant above the tropopause for the reanalysis data considered here, while a significant increase in wave amplitude can be observed already at 250 hPa, in particular ahead of displacement events (Figure S2).

So far, research has focused on large-scale quasi-stationary wave forcing as preconditioning for SSW events. This study suggests that zonal phase speed, that is, the phase speed of zonally traveling waves, has to be considered along with the duration and amplitude of a wave forcing when evaluating precursors to stratospheric variability.

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