Features of vortex split MSSWs that are problematic to forecast

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Abstract
A companion paper demonstrated that it is more difficult to forecast major stratospheric sudden warmings (MSSWs) of the vortex split type on medium range time scales of about 2 weeks than other MSSWs. As its extension, this study further investigates more specific features of planetary waves for the greater difficulty through a composite analysis using the Japanese 55-year reanalysis data and the Japan Meteorological Agency 1-month hindcast data. Results show that the hindcast data of about two week lead times to the MSSWs largely underestimate the vortex stretching and split at 10 hPa, and the forcing and propagation of planetary wave of zonal wavenumber 2 to the stratosphere. The underestimation in the wave forcing largely reflects a deficiency in simulating a nonlinear, or quadratic, term in wave anomalies (meridional wind and temperature) from the climatology.

Keywords: predictability; major SSWs; planetary waves

1. Introduction
There has been a growing interest in predictability of the extratropical stratospheric circulation, as numerical weather forecast models/systems have been developed to well represent the stratosphere (e.g. Gerber et al., 2012; Tripathi et al., 2015). Examining predictability of extreme stratospheric states, such as major stratospheric sudden warmings (MSSWs), is useful to better understand the nature of the stratosphere–troposphere system. This includes assessment of the possible importance of the stratosphere in extended range weather forecasts as suggested by, e.g. Baldwin and Dunkerton (2001). It will be also useful to improve the numerical forecast models/systems themselves.

Companion papers have extensively investigated predictability of the Northern winter stratosphere using the Japanese 55-year reanalysis (JRA-55) data and the Japan Meteorological Agency (JMA) 1-month hindcast (HC) data. Taguchi (2015) compared stratospheric forecast errors between vortex weakening and strengthening conditions. Some of these conditions correspond to MSSWs (their types were not considered) and vortex intensifications (e.g. Limpasuvan et al., 2005). The study showed that it is more difficult to forecast vortex weakening conditions than strengthening conditions. This reflects greater difficulty in forecasting planetary wave amplifications in the upper troposphere and lower stratosphere leading to weakening conditions.

Taguchi (2016) examined a possible connection of predictability of MSSWs to their types. It was speculated that predictable time limits are shorter for vortex split MSSWs including a large contribution from the zonal wavenumber 2 component (wave 2; Mukuougawa and Hirooka, 2004), although the speculation was not conclusive because it relied on just a few cases. Taguchi (2016) demonstrated that errors of medium range (approximately 2 weeks) forecasts of 21 actual MSSWs are larger when the vortex is highly stretched or split with high aspect ratio and amplified wave 2. It hypothesized that amplified wave 2 events in the troposphere for vortex split MSSWs are more difficult to forecast than wave 1 events, although it left detailed features and mechanisms open.

MSSWs are observed to typically occur in either of the vortex displacement or split type (Charlton and Polvani, 2007; Mitchell et al., 2011; Seviour et al., 2013). The former is characterized by the vortex moving far from the pole, and the latter by the vortex dividing into two separate vortices. Vortex displacement and split events tend to be predominantly associated with amplified wave 1 and wave 2, respectively (e.g. Charlton and Polvani, 2007). Extensive studies showed that these two types have different surface impacts (e.g. Mitchell et al., 2013; O’Callaghan et al., 2014; Seviour et al., 2016), suggesting importance of a better understanding of differences in the predictability of MSSWs of the two types. Maycock and Hitchcock (2015) suggested possible importance of lower stratospheric wind anomalies for diagnosing surface impacts of MSSWs.

As an extension of the companion papers (Taguchi, 2015, 2016), this study further explores more specific features especially of planetary waves for the greater difficulty in forecasting the vortex split MSSWs. To this end, we contrast these characteristic cases to the other cases though a composite analysis using the same reanalysis and HC data.

The rest of the paper is organized as follows. Section 2 explains the data used in this study. Section 3 describes the results. Section 4 provides summary and discussion.
2. Data
This study largely uses the same JRA-55 reanalysis and JMA HC data as in Taguchi (2016).

The real world is represented by daily averages of the JRA-55 reanalysis data (Kobayashi et al., 2015), with $2.5^\circ \times 2.5^\circ$ horizontal grids and 37 levels up to 1 hPa. Twenty-one MSSWs are identified during December–January–February (DJF) from 1978/79 to 2012/13 using the method outlined in Charlton and Polvani (2007). This method identifies a MSSW as when the zonal mean zonal wind [$U$] at $60^\circ N$, 10 hPa reverses from a westerly flow to an easterly flow. Here, $U$ denotes the zonal wind, and squares brackets denote the zonal mean. The day when the zonal wind reverses is referred to as the key or onset day of the MSSW (denoted as lag = 0 day).

As a forecast data set, this study mainly uses the HC data from the March 2014 version of the JMA 1-month HC experiments (The newer version is ‘March 2014’, which was mistyped in Taguchi (2016) as ‘March 2013’). The experiments employ the JMA global model with a horizontal grid size of about 55 km. A set of five ensemble forecasts is performed for one month from each of the 10th, 20th, and last day of each month from 1981 to 2012.

Whereas Taguchi (2016) use two versions (March 2011 and March 2014) of the HC experiments, for the sake of simplicity this study basically uses only the newer one. Two exceptions are the MSSWs in February 1979 and in February 1980: these are not covered by the newer version, and the older version is used. Taguchi (2016) showed that the differences in stratospheric forecast errors between the two versions are not large, e.g. when compared to case-to-case variability.

This study examines ensemble mean fields in the HC data of lead times of about 2 weeks to the 21 MSSWs. For each of them, we choose only one HC set that is initialized about 2 weeks (ranging from 11 to 20 days) before the onset day.

In order to characterize the vortex geometry around the MSSWs, two vortex moment parameters, centroid latitude (CL) and aspect ratio (AR), are calculated for 10 hPa height Z10 (Seviour et al., 2013). Whereas CL measures the latitude of the vortex center, AR is a measure of vortex stretching. It is noted that the calculation is impossible or will not work well, e.g. when the vortex completely breaks down. Such cases occur for time lags of approximately 5–25 days of some MSSWs, and are excluded from the results. This treatment hardly affects our argument since we are interested in the period before and around the onset day.

3. Results
Figure 1 confirms the main result in Taguchi (2016) that errors of about two week forecasts for the MSSWs are larger for vortex split MSSWs. It is a scatter plot between CL and AR for the JRA-55 10 hPa height averaged for lag = ±2 days of the 21 MSSWs. The errors are quantified by the root mean square error (RMSE$_{Z10}$) calculated for the 10 hPa height difference field between the JRA-55 and HC data on each forecast day poleward of $20^\circ N$.

In order to better understand how/why the larger errors occur for the vortex split MSSWs, we perform a composite analysis by classifying the 21 MSSWs into two groups (Figure 1). The group 1 is the target group for the seven vortex split MSSWs located in the upper right with the larger errors. The group 2 is for the other 14 MSSWs. The classification seeks to maximize the RMSE$_{Z10}$ difference between the two groups. The following results do not depend on a few outliers, since the results hold when a few randomly chosen cases are artificially removed from each group (this is repeated 100 times, not shown).

Figure 2(a)–(c) shows composite time series of CL and AR, as well as [U], for the two groups in the JRA-55 data. For both groups, the polar vortex is characterized by high CL and low AR about 3 weeks before the onset day, with westerly wind around 40 m s$^{-1}$, before the zonal wind reverses on lag = 0 day.

For the group 1, AR exhibits a peak around the onset day, with CL remaining high. The situation is opposite for the group 2 as both CL and AR are low. These differences in CL and AR between the two groups are statistically significant at the 90% level according to a Student’s $t$-test as denoted by magenta squares. Here, the relaxed confidence level of 90% is used since the sample size is not large. These results are consistent with Mitchell et al. (2011), who apply a vortex moment analysis to potential vorticity on potential temperature surfaces.

Figure 2(d)–(f) shows forecast errors of these quantities, together with RMSE$_{Z10}$ in Figure 2(g). A notable feature is that the HC data largely underestimate the observed increase in AR for the group 1. This is likely to contribute the larger errors in [U] and Z10. The HC data also underestimate the observed weakening and equatorward displacement of the vortex for the group 2.
Since the changes in CL and AR are related to those in planetary waves, Figure 3(a)–(c) shows observed anomalies (deviations from the seasonally varying climatology) of the vertical component (FZ) of the Eliassen-Palm (EP) flux in Northern high latitudes (40–90°N) at 100 hPa. The MSSWs are associated with positive FZ anomalies of waves 1–3 in both groups (Figure 3(a)) as is well known (e.g. Limpasuvan et al., 2004). The FZ anomalies are predominantly contributed by wave 1 and wave 2 for the group 2 and 1, respectively. These features are consistent with the fact that vortex displacement and split MSSWs are contributed by wave 1 and wave 2, respectively (e.g. Charlton and Polvani, 2007).

The HC data tend to underestimate FZ for both groups, but the underestimation is larger in magnitude for the group 1 (Figure 3(d)). This reflects that the underestimation in wave 2 FZ for the group 1 is larger than that in wave 1 FZ for the group 2 (Figure 3(e) and (f)). The large underestimation in wave 2 FZ for the group 1 is consistent with that in AR (Figure 2(f)).

The underestimation in 100 hPa FZ is further examined by calculating budgets of EP flux anomalies in 40–90°N, 100–300 hPa from lag = −10 to 0 days as

\[
FZ300 = FZ100 - FY40 + CONV \quad (1)
\]

Here, FZ300 and FZ100 denote FZ anomalies at 300 and 100 hPa, respectively, integrated from 40 to 90°N, FY40 denotes FY (meridional component of the EP flux) anomalies at 40°N from 300 to 100 hPa, and CONV denotes the convergence. Equation (1) states that some part of wave forcing from the extratropical troposphere enters the lower stratosphere while the rest propagates to lower latitudes or converges in the region. The budget resolves the lower stratosphere and upper troposphere, since this region modulates the propagation of planetary waves (Chen and Robinson, 1992).

Table 1 shows the composite results for the two groups averaged from lag = −10 to 0 days when the FZ anomalies and their forecast errors are large in magnitude to the onset day (Figure 3). The dominant wave component, wave 2 for the group 1 and wave 1 for the group 2, is used. One sees that the HC data underestimate FZ at 100 and also 300 hPa in both groups and that the underestimation is stronger for the group 1. The difference in the underestimation between the two groups is statistically significant above or near the 90% level (p value is 2.1 × 10^{-3} at 100 hPa and 0.11 at 300 hPa).

It is also possible to examine the budgets when normalizing them by the relevant FZ300 term. This suggests that the HC data overestimate the equatorward propagation and convergence for both groups, which act to decrease the efficiency of the wave propagation between 300 and 100 hPa. It is also suggested that the underestimation of the propagation is stronger for the group 1. However, such normalization makes it difficult
to obtain statistical significance for these errors and their differences between the two groups, as it leads to larger case-to-case variability (not shown).

In order to better understand the underestimation in the tropospheric wave forcing (FZ300), the poleward eddy heat flux is examined when the meridional wind $V$ and temperature $T$ are decomposed into the seasonally varying climatology and anomaly fields (denoted by subscripts c and a, respectively). The heat flux is examined for simplicity using its proportional nature to FZ. Anomalous eddy heat flux on an arbitrary day can be expressed as

$$\left[V^* \cdot T^*\right]_a = \left[V^* \cdot T^*\right]_c + \left[V^* \cdot T^*\right]_c + \left[V^* \cdot T^*\right]_c$$

(e.g. Nishii et al., 2009). Here, asterisks denote waves. The first and second square bracket terms on the r.h.s. are linear and nonlinear (quadratic), respectively, with respect to anomalies.

Figure 4(a) shows the decomposition results for the two groups. The same time and latitudinal averages are taken for the dominant wave component as in the EP flux budgets (Table 1). The linear term contributes to the positive heat flux anomalies in both groups. Furthermore, the nonlinear term plays a more important role for the group 1 than for the other ($p = 0.11$). These results are consistent with previous studies, as the importance of the linear term in driving SSWs was pointed out by, e.g. Garfinkel et al. (2010), Nishii et al. (2009) and Smith and Kushner (2012). The important role of the nonlinear term for vortex split SSWs was also claimed by Smith and Kushner (2012).

The calculation based on Eq. (2) is repeated for the HC data to obtain forecast errors (Figure 4(b)). Here, all climatological fields are taken from the JRA-55 data. Both linear and nonlinear terms are underestimated in the two groups. A notable feature is that the nonlinear term plays an important role in the group 1. The underestimation in the nonlinear term is judged to be statistically different, albeit weakly, between the two groups at $p = 0.15$. The significance for the difference in the linear term underestimation is much weaker or absent.

Synoptic Z300 maps support the underestimation in the linear term for the two groups (Figure 5). The observed anomalies enhance the climatological waves (wave 2 for the group 1 and wave 1 for the group 2) through constructive interference (Figure 5(a)–(c)), consistent with the contribution from the linear term (Figure 4(a)). The significance for the group 1 is not high. This may suggest that the phase of wave

Figure 3. (a)–(c) As in Figure 2(a)–(c), but showing anomalous FZ (in $10^5 \text{kg m}^{-1} \text{s}^{-2}$) averaged in 40–90°N, 100 hPa for the JRA-55 data: (a) waves 1–3, (b) wave 1, and (c) wave 2. Panels (d)–(f) plot forecast errors in the same unit.

Figure 4. (a) Composite poleward eddy heat flux anomalies over 40–90°N, 100 hPa from lag $= -10$ to 0 days for the two groups in the JRA-55 data. Contributions from the linear (LIN) and nonlinear (NONLIN) terms, and their sum (ALL) are plotted (Eq. (2)). Panel (b) is similar, but for forecast errors. Results for the dominant component in each group (wave 2 for the group 1, and wave 1 for the group 2) are plotted as in Table 1.
anomalies before these MSSWs are not coherent with the climatology but are variable from one case to another (recall the importance of the nonlinear term in Figure 4(a)). The HC data tend to underestimate the observed Z300 anomalies for both groups (Figure 5(d) and (e)), consistent with the underestimation in the linear term (Figure 4(b)).

Future studies could examine if the observed anomalies and forecast errors of the nonlinear term ($V_a^* T_a^*$, before taking the zonal mean) have distinct zonal distributions.

4. Summary and discussion

This study has explored more specific features especially of planetary waves for the greater difficulty in forecasting vortex split MSSWs (Taguchi, 2016). To this end, we characterize these cases in a composite analysis using the JRA-55 reanalysis and JMA HC data. We have shown that for the vortex split MSSWs, the HC data largely underestimate the vortex stretching and split at 10 hPa, and the wave 2 forcing and propagation to the stratosphere. This result may be expected, because these are just different aspects of the same problem. A large underestimation of the nonlinear term in the 300 hPa heat flux (or FZ) occurs for the group 1. The underestimation of the wave 2 forcing and propagation for the group 1 is suggested to be larger than those of wave 1 for the group 2, although the statistical significance is limited for some quantities.

The present results are relevant to a recent study by Tripathi et al. (2016). Tripathi et al. examined predictability of the January 2013 MSSW of a vortex split feature in five numerical weather prediction systems. They show that the models have reasonably good skill in forecasting amplified wave 2 associated with tropospheric blocking features, but have limited skill for amplified wave 2 in the stratosphere. This may be interpreted as difficulty in forecasting the upward propagation of wave 2.

This study may be extended in forcing and propagation of wave 2. Whereas we examined wave 2 forcing for the MSSWs, one can examine such wave events regardless of MSSWs. This will deal with predictability of tropospheric circulation anomalies in more general. We also suggest that wave 2 propagation may be more difficult to forecast than wave 1 counterpart. This may be rephrased as higher sensitivity of wave 2 propagation, e.g. to changes in mean zonal wind and wave forcing. This possibility can be pursued using linear model calculations of planetary wave propagation.

Acknowledgements

The JRA-55 data are developed by the JMA, and obtained from Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. The HC data are provided by way of the Meteorological Research Consortium, a framework for research cooperation between the JMA and Meteorological Society of Japan. Comments from two reviewers improve the manuscript. This work was supported by JSPS KAKENHI Grant Numbers JP24224011 and JP15K05286.

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