Connection of predictability of major stratospheric sudden warmings to polar vortex geometry

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1. Introduction

Extensive studies have investigated the predictability of major stratospheric sudden warmings (MSSWs), and suggested its considerable case-to-case variations (e.g. Tripathi et al., 2015). For example, predictability time limits for MSSWs obtained by recent case studies vary as follows:

- about 5 days to a week for the September 2002 Southern Hemisphere case (Allen et al., 2006; Taguchi, 2014a) and the January 2009 case (Kim and Flatau, 2010; Taguchi, 2014a),
- about 10 days to 2 weeks for the December 2001 case (Mukougawa et al., 2005) and the December/January 2003/2004 case (Hirooka et al., 2007), and
- about a month for the December 1998 case (Mukougawa and Hirooka, 2004).

The intermediate time scale of about 2 weeks is also obtained by other studies, each of which includes several MSSWs (Jung and Leutbecher, 2007; Stan and Straus, 2009; Marshall and Scaife, 2010). One should note here that these studies use different models/systems and apply different methods to calculate the limits. Regarding the case-to-case variations in the predictability limits, Mukougawa and Hirooka (2004) suggested that the type of MSSWs is important: MSSWs with an amplified zonal wavenumber 2 component (wave 2) are associated with shorter limits. Hirooka et al. (2007) suggested that the predictability limit is shorter when the time evolution of the extratropical stratosphere is more complicated. It has been yet inadequately understood to what features of MSSWs such variations are connected.

2. Method

2.1. Data

To represent the real world, this study makes use of daily averages of the JRA-55 reanalysis data (Kobayashi et al., 2015), with 2.5°×2.5° horizontal grids and 37 levels up to 1 hPa. The daily averaged data of the spatial resolution can well capture large-scale dynamical features associated with MSSWs (e.g. Limpasuvan et al., 2004).

This study therefore investigates how such case-to-case variations in the predictability of MSSWs occur. To be more specific, we seek to connect error variations of medium range (≈14 day) forecasts for MSSWs during Northern winter to the geometry of the polar vortex. To this end, we examine 1-month hindcast (HC) experiment data from 1979 to 2012 of the Japan Meteorological Agency (JMA) in comparison to the Japanese 55-year Reanalysis (JRA-55) data.

Keywords: predictability variations; major SSWs; polar vortex geometry
not impact the results of this study because results from HC1 and HC2 are similar as shown below.

2.2. Analysis

We identify MSSWs in the JRA-55 data from 1979 to 2013 based on the procedure of Charlton and Polvani (2007), as it is widely used. The 2012/2013 season is included, as the HC2 data produce forecasts for January 2013. In short, this procedure identifies reversals of the zonal mean zonal wind \( [U] \) at 60°N, 10hPa. We focus on MSSWs during Northern winter (December to February), as MSSWs in other months may have different characteristics reflecting the mean seasonal evolution. As a result, 21 MSSWs are identified, and their key dates, when a zonal wind reversal occurs, are listed in Table 1. They mostly match the recent result of Butler et al. (2014). The key day is also referred to as lag = 0 day.

In order to examine forecast error in the extratropical stratosphere for the MSSWs, we calculate the root-mean-square error (RMSE) of 10 hPa geopotential height (Z10) poleward of 20°N on each forecast day for each ensemble set (JMA, 2013):

\[
RMSE = \sqrt{\frac{\sum_i w_i D_i^2}{\sum_i w_i}}.
\]  

Here, \( D_i \): the difference of ensemble mean Z10 in HC1 or HC2 from the JRA-55 counterpart, \( w_i = \cos \phi_i \) (\( \phi_i \): latitude), \( i \): index for spatial grid points, and \( I \): total number of grid points poleward of 20°N. Both JRA-55 and HC Z10 data are averaged in time around the key day of each MSSW, from lag = −\( \mu \) to \( \mu \) days. We use \( \mu = 2 \) days as a standard case, but we confirmed that our results hold for \( \mu = 0 \sim 4 \) days (not shown).

When HC data are needed in the time average but are unavailable, the JRA-55 data are substituted. For example, a HC set initialized one day before the key day does not have data for lag = −2 days. The JRA-55 data are substituted for the day, as it is needed for the key day. It turns out that the increase is roughly linear.

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We also use forecast error of \( [U] \) at 60°N, 10 hPa, which is simply a difference of HC ensemble mean \( [U] \) from JRA-55 \([U]\) averaged around the key day. The zonal wind at the grid point is a simple and important index, e.g. to identify MSSWs.

In order to understand case-to-case variations of the forecast errors, we calculate several measures that characterize the geometry of the polar vortex using JRA-55 Z10 around the key day: vortex moment parameters [centroid latitude (CL) and aspect ratio (AR)] and amplitudes of waves 1 and 2 at 60°N. The calculation for the moment parameters is based on the Z10 method of Sveirou et al. (2013). The CL measures the latitude of the vortex center, whereas the AR is a measure of how stretched the vortex is. Displaced (split) vortex states, which are predominantly associated with wave 1 (wave 2), are captured by low CL (high AR).

3. Results

Figure 1 plots RMSE for all HC sets initialized 30 to 1 day before the MSSWs. Downward and upward triangles denote results from HC1 and HC2, respectively. When both HC1 and HC2 are available, the average is denoted by a square. When only one is available, the result is also denoted by a square. In the following, these results are referred to as average RMSE for brevity. It is clear, as expected, that RMSE basically increases with the lead time, or time difference of each initial day from the key day. It turns out that the increase is roughly linear.

A representative value of observed interannual variability of Z10 for Northern winter is about 380 m (denoted by a horizontal line in Figure 1), when calculated as in Equation (1) by using the JRA-55 Z10 variance, averaged from December to February, for \( D_i^2 \). The best-fit line reaches this value around lag = −16 days. This indicates that RMSE for the MSSW onset phase becomes comparable to the observed variability for HC data initialized about 2 weeks before. It is noted that RMSE can be very large for lag = −15 to −10 days in some cases exceeding the observed variability, when RMSE is defined for the spatial average in each HC set (Equation (1)).

It is also important to notice that RMSE varies from one case to another when HC data of similar lead times, such as 10−20 days, are compared. We therefore focus on the HC data of these lead times below, because these HC data have large case-to-case RMSE variations.

To do this, we choose, for each MSSW, only one HC set that has a minimum lead time larger than 10 days (Table 1). The RMSE variations for HC data of shorter lead times are much smaller. It is also noted that the RMSE differences between HC1 and HC2 are smaller than the case-to-case variations.

The RMSE variations for these HC data are shown in a scatter plot with the \([U]\) error (Figure 2). The average results from HC1 and HC2 are used as mentioned above. The plot shows that RMSE approximately ranges from 200 to 600 m together with an outlier of about 900 m. The \([U]\) error is strongly correlated with RMSE, with a correlation coefficient (CC) of +0.94. A CC is judged to be statistically significant at the 95% confidence level in a two-sided \( t \)-test when exceeding ±0.44 for 21 data points.

To better understand the RMSE variations, Figure 3(a) presents a scatter plot between the CL and AR for the 21 MSSWs. Each data point is colored according to the relevant average RMSE value. First, it is notable that the data points form a linear distribution, with a CC of +0.82. The situation in the upper right corresponds to vortex split MSSWs as characterized by...
Table 1. Key dates of the MSSWs, and lead times (given in parentheses, unit: day) of the HC data used in Figures 2–4.

|   | Key Date   | Lead Time |
|---|------------|-----------|
| 1 | 19790222   | 12        |
| 2 | 19800229   | 19        |
| 3 | 19810204   | 14        |
| 4 | 19811204   | 14        |
| 5 | 19840224   | 14        |
| 6 | 19850101   | 12        |
| 7 | 19870123   | 13        |
| 8 | 19871208   | 18        |
| 9 | 19890221   | 11        |
|10 | 19981215   | 15        |
|11 | 19990226   | 16        |
|12 | 20001231   | 11        |
|13 | 20030118   | 18        |
|14 | 20040105   | 16        |
|15 | 20060121   | 11        |
|16 | 20070224   | 14        |
|17 | 20080222   | 12        |
|18 | 20090124   | 14        |
|19 | 20100209   | 20        |
|20 | 20130107   | 18        |

Figure 1. RMSE of Z10 around the key day of the MSSWs (averaged from lag = −2 to +2 days) as a function of the timing of the initial day of each HC data. Downward and upward triangles denote RMSE for HC1 and HC2, respectively. Squares denote average RMSE values. The best-fit line is determined with the least-square method and denoted by the broken line. The horizontal line denotes the representative value (about 380 m) of the observed interannual variability.

Figure 2. Scatter plot between average RMSE of Z10 and error of [U] at 60°N, 10hPa for the MSSWs. Some MSSWs are labeled. The HC data of lead times of about 15 days are used. The best-fit line is determined with the least-square method and denoted by the broken line.

high AR, whereas the opposite situation in the lower left corresponds to vortex displacement MSSWs of low CL (Seviour et al., 2013).

Furthermore, it is a central result in this article that data points of large RMSE values, e.g. those larger than 400 m, are located in the upper right. That is, RMSE is larger for MSSWs of the vortex split type of high AR when the polar vortex is highly stretched. RMSE is relatively small for other MSSWs. Such a feature is also seen in Figure 3(c), where RMSE is shown as a function of the CL or AR. The strong correlation between Z10 RMSE and [U] error (Figure 2) implies that the [U] error similarly varies with the vortex moment parameters.

An equivalent result is also obtained when the amplitudes of wave 1 and 2 are used (Figure 3(b) and (d)). Again, the data points roughly form a linear distribution, although they are more scattered (CC = −0.70). Large RMSE values tend to occur for data points in the upper left: RMSE is larger for MSSWs when wave 2 has clearly larger amplitudes than wave 1. This result is consistent with vortex split MSSWs being predominantly associated with wave 2. In addition, large RMSE values also occur when the wave 2 amplitude is comparable to or smaller than the wave 1 amplitude, such as in #11, #14, and #21.

Although the HC data examined in Figure 3 have different lead times, the difference is not likely a prime determinant of the RMSE variations. The HC data that are located in the upper right with large RMSE values in Figure 3(a) have variable lead times (Table 1). The same holds true for the HC data in the opposite situation.

Figure 4 illustrates synoptic Z10 maps in the JRA-55 and HC2 ensemble mean data for three MSSWs. The two MSSWs (#16 and #19) are chosen near each end of the distribution in Figure 3(a), whereas the third (#12) is chosen near the center (Figure 2). Results from HC1 are similar (not shown). For the #16 MSSW, the polar vortex in the HC2 data is too strong and close to the pole, with a maximum error of about −1500 m (Figure 4(a)). The pattern difference is reflected in the higher CL for the HC2 data. For the #19 MSSW, the HC2 data fail to show the observed vortex split, with the too strong vortex staying over the pole (Figure 4(c)). This results in very large differences in magnitude especially in polar latitudes, up to about −2500 m. These features are consistent with the much lower AR for the HC2 data. Similar results are obtained for other vortex split MSSWs of large RMSE values, e.g. #09 and #21 (not shown). For the #12 MSSW, the HC2 data reproduce the observed vortex structure relatively well (Figure 4(b)).

4. Summary and discussion

In summary, this study has explored case-to-case variations of forecast errors for 21 actual MSSWs by using...
Figure 3. (a) Scatter plot between the CL and AR of JRA-55 Z10 averaged from lag $= -2$ to $+2$ days for each MSSW as labeled. Each dot is colored according to the average RMSE value. The best-fit line is determined with the least-square method and denoted by the broken line. Panel (c) shows RMSE as a function of the CL, when each data point is projected perpendicularly onto the best-fit line. Another x-axis is also denoted for the AR, which is measured along the best-fit line. Panels (b and d) are the same, but use the wave 1 and 2 amplitudes of Z10 at 60°N.

Figure 4. (a–c, top) Synoptic maps of JRA-55 Z10 in colors, averaged from lag $= -2$ to $+2$ days for the three MSSWs. (a–c, bottom) Panels are similar, but for the HC2 data. Contours show differences, HC2 minus JRA-55: solid and dashed contours denote positive (including zero) and negative values, respectively. Contour interval is 250 m. Values of the CL and AR are denoted in each panel.

The JMA 1-month HC data from 1979 to 2012: we seek a possible connection of the variations to the polar vortex geometry. Our results have presented unprecedented evidence that the error variations of medium range ($\approx 14$ day) forecasts do depend on the polar vortex geometry: the errors are larger for MSSWs of the vortex split type when the polar vortex is highly stretched as measured by high AR and large wave 2 amplitude. For such cases, the HC data tend to miss observed vortex splits, with the too strong vortex staying over the pole. On the other hand, the errors are relatively small for other MSSWs, e.g. those of the vortex displacement type. This study is the first, to the author’s knowledge, that shows clear evidence, although it has been suggested in the literature (Mukougawa and Hirooka, 2004; Tripathi et al., 2015).
One may suspect that the current examination is not a fair test for a predictability difference between wave 1 and 2 MSSWs: wave 2 events may show larger RMSE for a given phase error because they have more structures than wave 1 events. However, our results do show larger errors in the zonal mean zonal wind for wave 2 MSSWs (Figures 2 and 3), which is not subject to the simple explanation. Errors in the wave 1 and 2 amplitude (especially in the latter) are also large for several wave 2 MSSWs (not shown).

This study prompts further investigation in several respects as follows:

- It will be more interesting if a local RMSE minimum exists for intermediate data points (colored in cyan and blue) as may be hinted in Figure 3(a). This point is speculative and has only limited statistical significance in the present datasets, however, and this question is left open.

- The moment diagnosis appears better than the wave amplitudes to summarize the RMSE variations with the vortex geometry. The data points are more tightly distributed when the moment parameters are used. The RMSE values also appear better separated with them.

- Further details of the connection, such as how/why the forecast errors vary with the vortex geometry, should be investigated. A possible hypothesis is that amplified wave 2 events in the troposphere, leading to vortex split MSSWs, are more difficult to forecast than wave 1 events.

- It would be interesting to see if the same geometry dependence is observed when other reanalysis datasets are used. This is beyond the scope of this article and is left for a possible future work.

- It is worthwhile to improve the ensemble size and/or frequency of the initialization for more robust results. Comparing multimodel/system forecasts will be also useful as proposed by Charlton-Perez and Jackson (2012).

- There will be more general questions about these forecast data, such as whether they reproduce the observed frequency of displaced and split vortex MSSWs, and whether the ratio varies with lead time as model error grows. Our companion paper shows that the HC data tend to underestimate or oversimplify the vortex polar night jet over extended-range time scales (Taguchi, 2014a, 2014b).

- Our results have an important implication when one seeks to use MSSW forecasts to improve extended-range weather forecasts (e.g. Baldwin and Dunkerton, 2001; Kolstad et al., 2010; Hardiman et al., 2011; Sigmund et al., 2013), because the predictability of MSSWs varies with the polar vortex geometry.

Acknowledgements

The JRA-55 data used for this study are provided by the JMA. 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. This work is supported by the Grant-in-Aid for Scientific Research (S) 2422401101 and (C) 15K05286.

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