1. Introduction

The extratropical stratosphere is affected by several external factors (e.g., Yoden et al. 2002). This study focuses on changes of the Northern winter stratosphere with El Niño/Southern Oscillation (ENSO) and quasi-biennial oscillation (QBO) phases, and found some interesting nonlinear relationships. Garfinkel and Hartmann (2007) observe that the ENSO’s effects on the polar vortex (weaker vortex for El Niño phase than for La Niña phase) are more apparent for the QBO westerly (and neutral) phase and that the QBO’s effects (weaker vortex for the QBO easterly phase) are more apparent for the La Niña phase. The latter result deals with the modulation of the so-called Holton–Tan relationship (Holton and Tan 1982) by the ENSO. Watson and Gray (2014) examine a transient response of a GCM to QBO-like wind conditions to show that the mechanism proposed by Holton and
Tan (QBO easterly wind refracts planetary waves to high latitudes causing strong deceleration of the westerly wind there) plays a role. The modulation is also obtained by Wei et al. (2007). The observed result (weak response of the vortex to El Niño during the easterly phase) is reproduced in the MAECHAM5 simulations especially in February (Calvo et al. 2009). Calvo et al. further emphasize the importance of studying the seasonal evolution of ENSO and QBO signals: for instance, the Holton–Tan effect occurs earlier during El Niño winters in their simulations.

The nonlinear changes in seasonal mean states also suggest combined effects of the ENSO and QBO on extreme variability, such as the occurrence of major stratospheric sudden warmings (MSSWs), but such effects remain relatively unexplored. As for QBO’s effects, the Holton–Tan relationship implies that MSSWs should be common for the QBO easterly phase, as supported by the observational studies of Labitzke (1982) and Dunkerton et al. (1988). Baldwin et al. (2001) and Anstey and Shepherd (2014), however, suggest that these results are sensitive to the definitions chosen for the QBO and MSSWs.

On the other hand, possible ENSO’s effects on the MSSW frequency are relatively unresolved. Butler and Polvani (2011, hereafter referred to as BP) use the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data to observe that the MSSW probability increases for both El Niño and La Niña phases compared to a neutral phase. Butler et al. (2014) provides an updated list of MSSWs from BP. Garfinkel et al. (2012) explain the BP’s result by the fact that both El Niño and La Niña phases lead to tropospheric anomalies over the North Pacific that similarly act to strengthen precursor signals for MSSWs. This result can also be found, albeit weak, in Barriopedro and Calvo (2014), who examine precursor signals of blocking events for MSSWs between different ENSO phases.

The result of BP is different from a GCM result of Taguchi and Hartmann (2006, hereafter referred to as TH), who claim increased frequency of SSWs (not necessarily MSSWs) for an El Niño-like phase compared to a La Niña-like phase (see also Cagnazzo and Manzini 2009). This result is based on two perpetual January experiments with a general circulation model (GCM) forced with La Niña- and El Niño-like SST conditions in the eastern equatorial Pacific. TH show that the El Niño-like SST condition leads to a Pacific-North America pattern-like response in the troposphere, which acts to strengthen the stationary planetary wave of zonal wavenumber 1. Note that SSWs in TH are defined with an arbitrary definition, since the stratospheric polar vortex in their GCM experiments is stronger on average with weaker variability (much fewer MSSWs) compared to the real world. It is also noted that the experiments of TH do not simulate or include observed-like QBO variability, whereas BP also focus on the effects of ENSO only.

The result of the enhanced wave 1 for the El Niño phase is shown in several studies. Analyzing reanalysis datasets and GCM simulations, Li and Lau (2013) find that ENSO plays an important role in modulating the frequency of stratospheric polar vortex anomalies. They show that weak vortex events (not necessarily MSSWs) during El Niño winters are preceded by enhanced wave 1 and weakened wave 2.

Such an idea of changes in stationary waves by interference between climatological waves and wave response is shown by several studies. For example, Fletcher and Kushner (2011) examine how a GCM responds to imposed warmings in the tropical Pacific Ocean or tropical Indian Ocean. Fletcher and Kushner find that the former (latter) forcing weakens (strengthens) the stratospheric jet through constructive (destructive) interference of the wave response with climatological waves. Nishii et al. (2011) investigate the influence of blocking events on the stratospheric variability. They show that blocking events over the Euro-Atlantic sector strengthen planetary waves resulting in polar stratospheric warming, whereas the situation is opposite for blocking events over the western Pacific and the Far East sector.

A modeling study by Richter et al. (2011) examine the role of ENSO and QBO in the frequency of MSSWs. Richter et al. show that removing only one of the ENSO and QBO variations yields a MSSW frequency similar to that in a control simulation while removing both results in a significantly reduced frequency.

This study seeks to explore changes in the MSSW occurrence with ENSO and QBO using a reanalysis dataset. Our approach is thus close to that of BP, but takes additional account of QBO. In the following, our result reveals that both the seasonal mean polar vortex and the MSSW probability experience nonlinear changes with ENSO and QBO. Although the statistical significance of our results is limited in places due to the data length, observational results should be documented as a benchmark for longer model simulations.

We do not take account of effects of other factors such as the solar cycle, volcanic eruptions, extratrop-
ical SST anomalies, global warming, and so on, which will also affect the Northern extratropical stratosphere (e.g., Yoden et al. 2002). In particular, the combination of the QBO and solar cycle is known to induce nonlinear changes of the Northern polar vortex (e.g., Baldwin et al. 2001; Anstey and Shepherd 2014). For example, Labitzke (1987) and Naito and Hirota (1997) demonstrate that MSSWs tend to occur for the QBO westerly and solar maximum condition, and the QBO easterly and solar minimum condition. It is desirable to take account of all possible factors, but it would be too demanding to obtain meaningful results in such an approach using observational data of limited length. We here focus on the effects of ENSO and QBO as these are likely to be the main natural factors in observational records for the present climate, whereas we also briefly demonstrate that our results are not strongly contaminated by other factors.

The rest of the paper is organized as follows. Section 2 explains the data analyzed in this study, and the analysis method. Sections 3 and 4 describe results for seasonal mean states and MSSW occurrence, respectively. Section 5 is for discussion, and Section 6 is for summary.

2. Data

2.1 NCEP/NCAR reanalysis data, and definition of MSSWs

This study makes use of daily averages of the NCEP/NCAR reanalysis data (Kalnay et al. 1996) for Northern winters for 56 years from 1957/58 to 2012/13. We use the year to which the month of January belongs, in short when we refer to a Northern winter season of interest. The use of the daily averaged data is reasonable to examine changes (including MSSWs) of the polar vortex, of which time scales are typically much longer than a day.

We adopt a similar definition of MSSWs as in BP, who follow the adaptation of the World Meteorological Organization definition of MSSWs outlined in Charlton and Polvani (2007). In short, an MSSW is detected when the zonal mean zonal wind at 60°N, 10 hPa changes its direction from the westerly wind to the easterly wind during the extended winter season of November to March (NDJFM). The central date of the MSSW is defined as the first day on which the zonal wind is easterly. The central date is also referred to as lag = 0 day. To identify two MSSWs for one season, we use an additional condition that the zonal wind must recover above 20 m s⁻¹ between them. This condition aims to ensure that the polar vortex is sufficiently re-established between the two events. As a result, this study identifies 34 MSSWs during NDJFM for the entire 56 years, and 27 of the 34 MSSWs occur from December to February (DJF). The average probability (the number of MSSWs divided by the number of years) is thus 0.61 for NDJFM and 0.48 for DJF.

The MSSWs examined in this study are almost identical to those in Butler et al. (2014), except for one case. The list of Butler et al. (2014) includes a case in March, 2010. This case is excluded here, because it does not satisfy the additional condition that the zonal wind must recover above 20 m s⁻¹ after the preceding MSSW in February, 2010. The exclusion/inclusion of this case does not affect our main results especially for DJF.

We mainly target the mean polar vortex and MSSWs for the winter season of DJF, because such an approach focusing on a more limited period (season) will be more useful to understand the changes in the mean vortex condition and MSSW occurrence in terms of their ENSO and QBO dependences. MSSWs in early winter and spring may have different characteristics from those in DJF, reflecting the mean seasonal evolution of the stratospheric and tropospheric circulation. We also examine results for the extended winter season of NDJFM as in BP, and find that our argument basically holds for both cases. Considering possible seasonal dependences of ENSO and QBO effects can be a next step beyond the scope of this study.

2.2 ENSO and QBO phases

In order to define ENSO phases, we use the monthly NINO3.4 SST index archived by the National Oceanic and Atmospheric Administration (NOAA)/Climate Prediction Center (CPC) as in BP. We calculate DJF- or NDJFM-means of the SST index, depending on the seasons of interest (Fig. 1, solid line for the DJF means). The La Niña (LA) and El Niño (EL) winters are defined as when the seasonal mean SST index falls in the bottom or top 25th percentile (14 winters) of all values in the 56 year time series, respectively (Fig. 1), while all remaining winters are classified as ENSO neutral (NT). The 25 % threshold corresponds to about 0.72 K anomaly, or 0.70 standard deviation, of the DJF mean SST
We further test the sensitivity of our results to this threshold using 15 % and 35 % values: the 15 % threshold corresponds to about 1.1 K (1.0 standard deviation), and 35 % to about 0.47 K (0.46 standard deviation). Our case of the 35 % threshold roughly corresponds to the BP’s case, as BP used the ± 0.5 K threshold for the NDJFM mean NINO3.4 time series to obtain 18 LA and 18 EL cases (34.0 %) of their 53 target winters. Although our 25 % threshold tends to focus on stronger LA and EL phases, it turns out that our argument holds regardless of the exact choice of the threshold value as shown below.

As our QBO index, we use the monthly equatorial zonal wind data at 50 hPa archived by Free University of Berlin. The zonal wind data is compiled from radiosonde observations at equatorial stations (see, e.g., Taguchi 2010 for more details of the data). We apply the same seasonal (DJF or NDJFM) means to the monthly data (Fig. 1, broken line for the DJF means). It is notable that the QBO index has clear bimodality with great frequencies around +10 and −20 m s$^{-1}$. Values around −10 m s$^{-1}$ are absent (see also Fig. 2).

We adopt a threshold of 0 m s$^{-1}$ to classify QBO easterly (ELY) and westerly (WLY) phases, because this is a natural and meaningful choice from a physical perspective. The zero wind line acts as a critical line for stationary planetary waves that play a role in the extratropical stratosphere and troposphere. In this case, ELY or WLY phases are when the index is smaller or larger than the threshold, respectively.

We also examine our results when using another threshold of −10 m s$^{-1}$ to separate the two QBO phases. This threshold is unlikely to have a physical meaning, but is based on the clear bimodality of the QBO index without values around −10 m s$^{-1}$. The examination below shows that our results are robust to the changes in the threshold. It is also possible to use other thresholds, e.g., to isolate stronger QBO wind conditions, which are not tested to avoid decreases in the sample size.

Thus, we define six groups using the ENSO and QBO indices (3 ENSO by 2 QBO phases). We show results for the standard case (25 % threshold for ENSO, and 0 m s$^{-1}$ threshold for QBO), unless stated otherwise. Note that the data points distribute unevenly in the scatter plot (Fig. 2), and the sample size (how many seasons exist for each group) differs by the groups.

### 3. Seasonal mean states

Figure 3 shows the DJF composite zonal mean zonal wind in the six groups for the entire 56 years: the composites are shown in terms of the differences from the DJF climatology. The six groups are defined by the 3 ENSO and 2 QBO phases as stated in Section 2. The figure also plots gray dots to denote statistically significant differences at the 90 % level (based on two-side Student’s t-test). The results basically confirm the known nonlinear changes of the Northern stratosphere with the two factors (e.g., Garfinkel and Hartmann 2007; Wei et al. 2007).

During the WLY phase, the polar night jet

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3http://www.geo.fu-berlin.de/met/ag/strat/produkte/qbo/qbo.dat.
strengthens for the LA compared to the NT phase (Figs. 3a, b): the wind response for the LA/WLY group is particularly characterized by the stronger-than-normal westerly wind (Fig. 3a). The zonal wind difference is similarly small in magnitude and insignificant at the 90 % level in the extratropical stratosphere for both NT and EL phases (Figs. 3b, c). On the other hand, during the ELY phase, the polar night jet weakens for LA (Fig. 3d), and negative anomalies are also found for EL in the extratropical stratosphere although the significance is limited around mid-latitudes (Fig. 3f). The NT/ELY group does not have significant differences in the extratropical stratosphere.

One can also see in Fig. 3 that the so-called Holton–Tan relationship depends on the ENSO phase. The relationship (i.e., stronger polar night jet for WLY and weaker jet for ELY) is most evident when the ENSO phase is in LA. Such a difference is relatively weak or absent, when the ENSO phase is in NT or EL. It is also noted that significant differences from the climatology exist in the troposphere for a few groups (e.g., LA/WLY, EL/WLY, and LA/ELY). These differences in the troposphere have varying magnitudes and latitudinal locations, e.g., between LA/WLY and LA/ELY.

These results are generally consistent with existing studies on changes of the polar vortex with ENSO and QBO phases (Garfinkel and Hartmann 2007; Wei et al. 2007). For example, our results reproduce the dependence of the ENSO effect on QBO: the difference between LA and EL winters is larger in magnitude during WLY than during ELY. A key here is that the polar vortex weakens for both LA/ELY and EL/
ELY groups compared to the climatology. The modulation of the Holton–Tan effect with ENSO is also reproduced as mentioned above (stronger QBO effects during the ENSO LA phase compared to the NT or EL phase). Wei et al. (2007) speculate that only LA winters, when planetary wave activity tends to be weak, are susceptible to QBO phases.

Statistical significance of the ENSO- and QBO-dependent zonal wind differences at 60°N, 10 hPa is evaluated as follows. The zonal wind at the grid point can be used as a proxy of the polar vortex strength, and shows large differences for some groups (Fig. 3). It is also used to define MSSWs (Sections 2 and 4). For the statistical evaluation, we randomly shuffle the seasonal mean zonal wind at the same grid point (60°N, 10 hPa) for the 56 winters in terms of year while holding the observed yearly ENSO and QBO phases that determine the six groups. Namely, this artificial dataset assumes that the zonal wind variations are independent of the two factors. We obtain the mean zonal wind value for multiple winters in each group using the artificial dataset. We repeat this procedure 10,000 times, and obtain significance estimates by comparing the observed wind differences to the artificially created differences (Fig. 4a). For example, the observed wind difference between the groups LA/ELY and LA/WLY (20.8 and 37.1 m s⁻¹, respectively) is estimated to be significant at the level higher than 99 %, because only 0.17 % of the 10,000 random trials yields differences exceeding the observed value (one-side test). The test thus shows that the observed wind differences is significant for some combinations at the level of about 90 % or higher, although the significance is more marginal (or absent) for other combinations.

Examining the Eliassen–Palm (EP) flux and its divergence/convergence of waves 1–3 (zonal wave-numbers 1–3) as in Fig. 3, Fig. 5 shows that the wave propagation and driving also change with ENSO and QBO in a consistent manner. We here focus on the planetary waves, since they can propagate to the stratosphere and affect the extratropical stratosphere. The EP flux convergence, or wave driving, is stronger than normal, when the polar night jet is weaker (Figs. 5d, f), and vice versa (Fig. 5a). This is an expected result in the sense that the wave driving acts to weaken the polar night jet. It is common between LA/ELY and EL/ELY that the stronger wave driving is associated with more poleward wave propagation in high latitudes of the stratosphere (Figs. 5d,
f). The vertical wave propagation is different between the two groups. The LA/ELY group experiences anomalously upward propagation in mid-latitudes, whereas the situation is opposite for the EL/ELY group.

We examine the sensitivity of these results of the mean zonal wind to the analysis parameters, and find that the above results are robust. In particular, a re-examination of the zonal wind differences, when the QBO phases are defined with the $-10 \text{ m s}^{-1}$ threshold for the equatorial zonal wind, indicates that the wind differences of the QBO from the climatology are overall similar, whereas the EL/ELY has significant differences extending over a wider region (not shown). A separate examination for early and later winter mean states suggests some seasonality of the stratospheric changes with ENSO and QBO as pointed out by the simulations of Calvo et al. (2009) and Manzini et al. (2006), but a more detailed analysis is beyond the scope of this study.

4. Occurrence of MSSWs

4.1 MSSW probability for the six groups

We now move to an examination of the occurrence of MSSWs. In the scatter plot between the SST and QBO indices (Fig. 2), stars indicate years when one or two MSSWs occur, and dots indicate years when no MSSW occurs. Table 1 shows the number of winters and MSSWs in DJF for the six groups. Figures 6a and
6b present graphical demonstrations of the MSSW probability for the DJF season based on the 25% threshold for ENSO. Here, the probability is given by the number of MSSWs divided by the number of winters for each group (expressed in %).

It is the central result in this paper that the MSSW probability changes differently with ENSO between the QBO ELY and WLY phases. The DJF MSSW probability for WLY increases with the ENSO SST index, while such a simple increase is not the case for ELY. The MSSW probability for NT is similar between ELY and WLY. When the QBO is WLY, the probability increases for EL and decreases for LA, compared to NT. When the QBO is ELY, on the other hand, the MSSW probability increases much more for LA compared to NT, whereas the probability is

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**Table 1.** Numbers of winters (denominator) and MSSWs (numerator) for DJF in the six groups defined by the three ENSO (LA, NT, and EL) and two QBO (WLY and ELY) phases. LA and EL winters are the bottom and top 25% (14 years) of the 56 years with the NINO3.4 SST index, respectively, and the others are classified as NT. The QBO WLY and ELY phases are based on the 0 m s⁻¹ threshold. Numbers in parentheses denote the MSSW probabilities in percent. Numbers in the square brackets denote the results for NDJFM. The rightmost column sums the numbers with respect to the ENSO phases (total QBO effect), whereas the bottom row sums the numbers with respect to the QBO phases (total ENSO effect). The lower-right box denotes the sums for all groups.

|          | LA (1/9, 11.1%) | NT (6/16, 37.5) | EL (6/9, 66.7) | Total QBO effect |
|----------|-----------------|-----------------|---------------|-----------------|
| WLY      |                 |                 |               |                 |
|          | 1/9 (11.1%)     | 6/16 (37.5)     | 6/9 (66.7)    | 13/34 (38.2)    |
|          | [3/9, 33.3 %]   | [6/16, 37.5]    | [7/9, 77.8]   | [16/34, 47.1]   |
| ELY      |                 |                 |               |                 |
|          | 6/5 (120)       | 5/12 (41.7)     | 3/5 (60)      | 14/22 (63.6)    |
|          | [6/5, 120]      | [7/12, 58.3]    | [5/5, 100]    | [18/22, 81.8]   |
| Total ENSO effect | 7/14 (50) | 11/28 (39.3) | 9/14 (64.3) | 27/56 (48.2) |
|          | [9/14, 64.3]   | [13/28, 46.4]  | [12/14, 85.7] | [34/56, 60.7]  |

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Fig. 5. As in Fig. 3, but for the differences in the EP flux (arrows) and its divergence (contours and shades, m s⁻¹ d⁻¹) of waves 1–3. Contour interval is 0.5 m s⁻¹ d⁻¹. Gray dots denote statistically significant differences of the divergence at the confidence level of 90%.
similar between EL and NT. These changes in the MSSW probability are generally consistent with those in the seasonal mean polar vortex (i.e., the vortex tends to be weaker when the probability is higher; Figs. 3 and 4), although details of the relationship between the seasonal mean state and MSSW occurrence are beyond this study. The highest probability occurs for LA/ELY, and will be examined in detail below.

Figures 6a and 6b also indicates that the dependence of the MSSW probability on the QBO changes with the ENSO. A comparison between ELY and WLY for given ENSO phases in DJF shows that the probability difference is largest for LA. This reflects the highest probability for LA/ELY, and the lowest probability for LA/WLY. For NT and EL winters, the MSSW probability is relatively similar between ELY and WLY.

When we obtain an average probability for each ENSO phase (i.e., take averages independent of the QBO phases) as denoted in Table 1, both EL and LA have higher probabilities than NT (higher for EL). This result is roughly consistent with BP. When we obtain an average probability for each QBO phase, the ELY phase has a much higher probability than the WLY counterpart. This result agrees with the early observations of Labitzke (1982) and Dunkerton et al. (1988).

Statistical significance of the differences of the MSSW probability is evaluated in a similar manner.
as for the differences of the seasonal mean states (Fig. 4b). The evaluation reasonably supports the QBO-dependent changes in the MSSW probability with ENSO. In this case, we randomly shuffle the observed yearly frequency (0, 1, or 2) of DJF MSSWs in terms of year to examine the significance of the probability differences. The test clarifies the degree to which the difference of the MSSW probability between each combination of two adjacent groups of interest is significant (or insignificant). For example, the probability increase for LA/ELY compared to NT/ELY is significant at an approximate 95 % level. The probability decrease for LA/WLY compared to NT/WLY is also significant at approximately 95 %, whereas the increase for EL/WLY compared to NT/WLY is marginal. The difference between LA/ELY and LA/WLY is also highly significant.

We test two other threshold values (15 % and 35 %) to classify the ENSO phases, and find that the changes in the MSSW probability are generally insensitive to the changes in the threshold (Figs. 6c, d). Furthermore, the change in the threshold for the QBO phases does not strongly affect the result either (Figs. 6e, f). We also repeat the analysis for the extended winter season (NDJFM), and confirm that the results are basically similar between DJF and NDJFM (numbers in square brackets in Table 1).

### 4.2 Characterization of LA/ELY winters

In the following, we further seek to characterize the LA/ELY winters, with the highest MSSW frequency, from two perspectives. For the first perspective, we examine case-to-case variations in wave forcings that induce MSSWs and other weak vortex events. For the second perspective, we compare changes in the EP flux and amplitude of stationary waves among the six groups.

For the first perspective, we examine the relationship between the occurrence of MSSWs and wave forcings as follows. For years when an MSSW occurs, we look for a minimum zonal wind value at 60°N, 10 hPa in the entire DJF winter period, and obtain the cumulative EP flux similarly. We refer to these cases as non-MSSW weak vortex events. The 31-day period is determined, so that the minimum zonal wind and cumulative EP flux (vertical component, FZ) in the lower stratosphere has the maximum correlation (cf. Fig. 7a). This is consistent with the result of Polvani and Waugh (2004) that the 10 hPa Northern Annular Mode index (proxy for the strength of the polar vortex, Thompson and Wallace 2000) is highly correlated with poleward eddy heat flux in the lower stratosphere when the heat flux is cumulated for several weeks. The heat flux is used as a proxy of FZ, since the latter is proportional to the former. The result also agrees with Newman et al. (2001), who find high correlations of the zonal mean zonal wind and temperature with the poleward eddy heat flux when the heat flux leads by about one month.

Figure 7a is a scatter plot between the minimum zonal wind at 60°N, 10 hPa (y-axis) and cumulative FZ in 40–80°N, 100 hPa (x-axis) obtained as above. It is clear that the two quantities show a quasi-linear relationship as expected. The correlation coefficient is −0.70, which is statistically significant at the confidence level well higher than 99 % according to a Student t test (the 58 data points are treated as 58 independent samples). That is, the zonal wind response experiences greater weakenings for stronger FZ on average. A least square method shows that the best-fit line to the distribution is $y = -(3.1 \times 10^{-4})x + 36$ ($x$: cumulative FZ in kg m$^{-1}$ s$^{-2}$; $y$: minimum zonal wind in m s$^{-1}$). This indicates that on average, the cumulative FZ of about $1.2 \times 10^5$ kg m$^{-1}$ s$^{-2}$ results in the zero wind response, or occurrence of an MSSW.

Whereas the best-fit line extracts an average picture of the distribution, the actual data spread about it. A further inspection of Fig. 7a reveals that the data points for the LA/ELY MSSWs (downward triangles in blue) are biased toward the lower-left side of the best-fit line. This is notable by comparing the two ellipses: the black ellipse represents the distribution of all data points whereas the blue ellipse represents that of the data points only for LA/ELY. The directions of the major and minor axes of each ellipse are determined by applying an empirical orthogonal function (EOF) analysis to the target data points. The length of each axis of each ellipse is set as 1.5 standard deviation of the relevant principal component. This feature indicates that the mean zonal wind tends to experience greater-than-average weakenings for a given value of FZ. Some of the LA/ELY MSSWs (in 1984/85,
Fig. 7. (a) Scatter plot between the minimum zonal wind in the stratosphere (60°N, 10 hPa, y-axis) and associated vertical component of the cumulative EP flux of waves 1–3 in the lower stratosphere (40–80°N, 100 hPa, x-axis). A best-fit line is denoted. Panel (b) is the same as in (a), but the x-axis uses the meridional component of the cumulative EP flux of waves 1–3 in 60°N, 10–100 hPa. Blue, gray, and red symbols denote LA, NT, and EL winters, respectively. Upward and downward triangles denote WLY and ELY winters, respectively. Black ellipse denotes a representative distribution of all data points using the two EOF vectors. The length of each axis is set as 1.5 standard deviation of the relevant principal component. Blue ellipse is similar, but only for the LA/ELY data. See text for details on how the minimum wind and wave forcings are obtained and the ellipses are determined.
1998/99, 2005/06, and 2007/08) occur with FZ around $1.2 \times 10^5$ kg m$^{-1}$ s$^{-2}$. The 2006 MSSW shows the strongest easterly wind response in this group. FZ of similar magnitudes result in non-MSSW weak vortex events in other winters. In other words, the LA/ELY MSSWs are characterized by stronger easterly wind responses for average cumulative FZ forcing of about $1.2$ to $1.3 \times 10^5$ kg m$^{-1}$ s$^{-2}$. Conversely, there are only three cases where a relatively strong FZ (e.g., larger than $1.5 \times 10^5$ kg m$^{-1}$ s$^{-2}$) do not result in an MSSW.

Figure 7b is a similar scatter plot to Fig. 7a, but uses the meridional component of the cumulative EP flux (FY) at 60°N, 10–100 hPa for the x-axis to quantify meridional wave propagation in the stratosphere. It is notable that most of the LA/ELY MSSWs are biased toward the +x-axis side representing poleward wave propagation (also see the two ellipses). The 2006 MSSW shows the second largest value of FY in all MSSWs. These features are consistent with the fact that the LA/ELY MSSWs tend to show the stronger easterly wind responses, since enhanced planetary waves are likely to affect the extratropical stratospheric circulation strongly when propagating to high latitudes.

As the second perspective, we further compare changes in the EP flux and amplitude of stationary waves among the six groups. We here examine changes in stationary waves during DJF, as the occurrence of MSSWs and FZ during DJF of interest (Fig. 7a) is closely related to them: such large cumulative FZ leading to MSSWs will be more likely when the stationary waves are stronger. TH use the same reasoning to explain the frequency changes in SSWs and strong wave events in their simulations.

Similar to Fig. 4a, Fig. 8a compares FZ of DJF stationary wave 1–3 in the extratropical stratosphere (40–80°N, 100 hPa) among the six groups. It shows that the changes in the stationary wave activity (Fig. 8a) are largely consistent with those in the MSSW frequency (Fig. 4b). During the QBO WLY phase, FZ increases with the ENSO SST condition, whereas during the ELY phase it increases from NT to LA and EL.

Figures 8b and 8c separately examine FZ changes of DJF stationary wave 1 and 2. It is notable that the FZ changes of stationary waves 1–3 are largely explained by those of wave 1, as almost all arrows are in the same directions between Figs. 8a and 8b. In particular, the wave 1 FZ decreases from NT to LA during WLY whereas it increases from NT to LA during ELY, although the statistical significance is marginal. On the other hand, the changes in the wave 2 FZ are smaller in magnitude than the wave 1 counterpart, and the statistical significance is generally more limited. The wave 2 FZ decreases from NT to LA during WLY as does the wave 1 FZ. It also decreases from NT to EL as opposed to the increase in the wave 1 FZ. The changes in the wave 2 FZ with ENSO are insignificant during ELY.

Such changes in FZ of stationary waves are partly explained by those in amplitude of the waves (Fig. 9) in the high-latitude upper troposphere (60°N, 300 hPa). The latitude is used to extract representative features in high latitudes, as the changes in the EP flux are large there, e.g., for LA/ELY (not shown). The upper troposphere is used to examine the plan-
etary wave changes in terms of tropospheric wave responses to different ENSO and QBO phases, but results for the lower stratosphere such as 100 hPa are similar (not shown).

The increase in the wave 1 FZ from NT to EL during WLY is consistent with that in the amplitude (Fig. 9b), whereas the wave structure (including the amplitude) is roughly similar between NT and LA. During ELY, both LA and EL phases experience increases in the wave 1 amplitude (Fig. 9a) consistent with those in FZ (Fig. 8b). The QBO WLY phase shows decreases in the wave 2 amplitude for both LA and EL compared to NT (Fig. 9d), consistent with Fig. 8c. The wave 2 structure is similar among the three ENSO phases during ELY (Figs. 8c, 9c).

The results in Figs. 8 and 9 partly correspond to existing studies. Our result of the increase in the wave 1 activity during EL compared to NT, obtained for both QBO phases (Figs. 8b, 9a, b), is consistent with the precursory signal of wave 1 for MSSWs during EL shown by Barriopedro and Calvo (2014). They also show that MSSWs during LA are predominantly associated with wave 2 amplification: a corresponding signal is unclear in our result of stationary wave 2 (Figs. 8c, 9c, d). The increase in the wave 1 amplitude (deepening of the trough near 180°E) for both EL and LA compared to NT during ELY (Fig. 9a) is consistent with the tropospheric negative anomalies over the North Pacific, which Garfinkel et al. (2012) claim play a role in triggering MSSWs for the ENSO phases (Section 1). The stationary wave activity flux FZ may be also related to phase structure in addition to wave amplitude (Eq. 5.2.6 of Andrews et al. 1987), but a further examination on detailed phase structure,
as done in Lin and Lau (2013), is beyond the scope of this paper.

5. Discussion

This study examined interannual changes in the seasonal mean state and MSSW frequency in the Northern winter stratosphere with ENSO and QBO, as well as explored changes in stationary wave forcings (as summarized in Section 6). We here discuss a possible underlying mechanism for the changes, and two possible problems of the present results: contaminations of effects of other factors, and limitation of the statistical significance.

5.1 Possible underlying mechanism

A key result in this study is that in contrast to a possible expectation that MSSWs tend to be absent during LA, the MSSW probability is very high when LA is combined with ELY (Figs. 4b, 6). The high MSSW frequency for LA/ELY is consistent with the strengthening of stationary waves (in particular wave 1) compared to NT/ELY (Fig. 9). On the other hand, the wave 1 structure is similar between LA and NT during WLY.

A preliminary analysis of zonal mean zonal wind and precipitation distributions is made to better understand the strengthening of the stationary wave for LA/ELY. The analysis shows that the mean zonal anomalies for LA (from the climatology) are different in the subtropical upper and middle troposphere between ELY and WLY (Figs. 3a, d), whereas precipitation anomalies (proxy of atmospheric heating) are not significantly different (not shown). This suggests that the different wave responses could be induced by differences in the mean zonal wind in the troposphere: stationary waves may show different responses to a given forcing (anomalous SST or heating distribution) when the mean wind, or basic state is different.

A similar idea is tested by Garfinkel and Hartmann (2010), who use a shallow water model to understand QBO-dependent teleconnection response over the North Pacific to El Niño.

A further investigation on this aspect is left to a future work, since some uncertainty remains in the preliminary analysis, e.g., about the interpretation of causality. The different zonal wind anomalies in the subtropical troposphere may reflect the different MSSW frequencies.

5.2 Possible contaminations of other effects

While this study focuses on the changes with ENSO and QBO, it is known that the Northern winter stratosphere is also affected by other factors. We examine whether or not the present results are contaminated by such effects: solar cycle (e.g., Labitzke 1987; Naito and Hirota 1997; Anstey and Shepherd 2014), volcanic eruptions (e.g., Graf et al. 1994), October Eurasian snow cover (e.g., Cohen et al. 2007), and extratropical SST variations (e.g., Hurwitz et al. 2012; Omrani et al. 2014).

To this end, it is desirable to composite the target quantities (seasonal mean zonal wind and MSSW occurrence) by considering all possible factors, but such an approach is too demanding for current observational data. Instead, we take composites of each of the other factors (excluding volcanic eruptions) for the six groups defined by the ENSO and QBO phases to see if these factors are significantly biased from climatology and/or different from one group to another. For volcanic effects, we re-examine the MSSW frequency by removing a few years after major volcanic eruptions. It is overall suggested that our key results are not strongly contaminated by the volcanic eruptions, Eurasian snow cover, or extratropical SST variations.

A notable feature is that the DJF mean solar index (observed radio emission from the Sun at a wavelength of 10.7 cm provided by Natural Resources Canada4) is significantly different at the 90 % level between LA/ELY and NT/ELY (smaller for the former). The 5 LA/ELY winters have an average of anomalous solar index values of $-23.8$ in the solar flux unit, or $10^{-22}$ W m$^{-2}$ Hz$^{-1}$. Since the combination of the QBO easterly phase and solar minimum condition is known to favor MSSWs (Labitkze 1987; Naito and Hirota 1997), the highest MSSW probability for LA/ELY may be partly contributed by the low solar condition.

5.3 Limitation of the statistical significance

Even when we focus on the effects of ENSO and QBO, the statistical significance of the differences in the seasonal mean state and MSSW probability, e.g., at the 90 % level, is obtained for some combinations whereas the significance is marginal or absent for other combinations. The latter feature (weakness or absence of the significance) results from two possibilities. One is that the real atmosphere is insensitive to such combinations, whereas the other is that the observational data of about 60 years is not long enough to obtain significant differences. It should also be pointed out that exact MSSW probability and its

4http://www.spaceweather.ca/solarflux/sx-5-eng.php.
ENSO/QBO-dependent differences may be somewhat sensitive to analysis details: target period and season, criterion for MSSWs, and definitions for ENSO and QBO phases as cautioned by Anstey and Shepherd (2014). We have nonetheless considered different criteria of ENSO and QBO thresholds, and found that our main results are robust.

The limitation in the data length can be overcome by using long model simulation data, provided that the simulation data reproduce basic aspects of large-scale dynamics. An examination of the seasonality of the stratospheric changes, including a comparison between observations and model simulations, will be also useful as suggested by the numerical studies of Calvo et al. (2009) and Manzini et al. (2006). Taking seasonal means as done here is useful to smooth out month-to-month fluctuations and hence obtain average conditions.

Such reproducibility can be also examined in terms of predictability of several characteristic MSSWs. It is possible that some MSSWs may be more difficult to predict than others, depending on conditions of external forcings such as ENSO and QBO. The 2006 MSSW is a candidate for such a predictability study (e.g., Taguchi 2014), since the event is a characteristic case for LA/ELY. The observed fact that a MSSW (or two) occurs every LA/ELY winter could be also used for this purpose.

Seeking dynamical understanding of the ENSO- and QBO-dependent changes will be another approach to overcome the data limitation. For example, linear model calculations of stationary waves will be useful to understand wave responses to SST forcings under various mean zonal wind distributions as mentioned above (Section 5.1).

6. Summary

This study has investigated observed changes in the seasonal mean states and also variability (i.e., MSSW occurrence) in the Northern winter stratosphere with ENSO and QBO. We reveal the following complex changes in the MSSW probability as well as in the seasonal mean states, although the statistical significance is limited for some conditions due to the limitation of the observations. In spite of the limitation, it is important to document the observational results as a benchmark for longer model simulations.

When the QBO is in the WLY phase, the MSSW probability increases with the ENSO SST condition (the significance of the increase for EL compared to NT is marginal). When the QBO is in the ELY phase, on the other hand, such a simple relationship is not the case: the probability increases for LA a lot compared to NT whereas the probability is not significantly different between NT and EL. In other words, only during the LA phase, there is a larger or smaller number of the MSSW probability than the climatology for the ELY or WLY phase, respectively. These changes in the MSSW probability are generally consistent with those in the seasonal mean polar vortex. Whereas the existing studies document nonlinear changes of the extratropical stratosphere with ENSO and QBO in terms of seasonal or monthly mean states, the present study reveals that the occurrence of MSSWs also does change in a complex manner.

The results thus suggest nonlinear changes of the MSSW occurrence in the Northern winter stratosphere with ENSO and QBO. Such changes suggest necessity to take account of both ENSO and QBO conditions when MSSW frequency in the real world is examined: such an approach may be a key for the apparent difference between BP and TH about the frequency changes of MSSWs (or equivalents) with ENSO.

A characteristic feature is the high MSSW probability for LA/ELY, although the solar cycle may also contribute to the high probability. Those MSSWs for the LA/ELY winters tend to show a stronger easterly wind response. Associated with poleward wave propagation in the stratosphere, the mean zonal wind in the extratropical stratosphere during the events tends to experience greater weakenings (stronger easterlies) for given wave forcings from the troposphere than an average picture of MSSWs and non-MSSW weak vortex events. The MSSW in January, 2006 is a notable example of these features in the LA/ELY MSSWs.

A further dynamical analysis of stationary waves has characterized the LA/ELY winters compared to a few other conditions. The comparison shows that the differences in the MSSW probability are generally consistent with those in the stationary wave 1 response: compared to the climatology, the stationary wave 1 strengthens for LA/ELY and weakens for LA/WLY. These wave responses for LA/ELY and LA/WLY occur for similar precipitation (or heating) distributions, and it is speculated that the mean zonal wind differences in the subtropical troposphere may play a role.

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