Atmospheric
Chemistry
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Discussions

Interactive comment on "Investigation on the abnormal quasi-two day wave activities during sudden stratospheric warming period of January 2006" *by* Sheng-Yang Gu et al.

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We thank the reviewer for the constructive comments. Our responses are listed below. Interactive comment on "Investigation on the abnormal quasi-two day wave activities during sudden stratospheric warming period of January 2006" by Sheng-Yang Gu et al.

Anonymous Referee #1

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Review of "Investigation on the abnormal quasi-two day wave activities during sudden stratospheric warming period of January 2006" by Gu et al. The paper investigated the

impact of the SSW on QTDW at other hemisphere. The authors have carried out a number of analyses using satellite observations and reanalysis data to establish their conclusions. However, the findings do not illustrate any novelty in their characteristics. In this context it should be pointed out that earlier study by Gu et al. (2016c) already investigated on the SSW and QTDW (W2, W3) relationship using greater number of warming events including the present warming episode of 2006. Noting the listed issues the paper requires substantial revision before it could be considered for publication.

Major points:

1) Characteristic features of the QTDW (W2 and W3) over both hemispheres during warming period as found from the present study are very similar with the past findings as expected. Explanation and interpretation related to the W2 and W3 components bear significant resemblance with the past study of Gu et al. (2016c).

Reply: Motivated by the observational work of Limpasuvan et al. (2009) entitled "anomalous two-day wave behavior during the 2006 austral summer", we would like to further investigate the reasons for the anomalous QTDW activities and whether they are related to the major SSW event during the same time. To perform diagnostic analysis on the propagation and amplification of QTDW, we need synoptic wind and temperature model datasets from the stratosphere to the mesosphere. As far as we know, the NOGAPS-ALPHA reanalysis dataset is the only reported dataset that is capable of capturing both SSW in the stratosphere and QTDWs in the mesosphere during January 2006 (McCormack et al., 2009), which can also be freely accessed on the website (ftp://map.nrl.navy.mil/pub/nrl/nogaps). Thus we choose to utilize the NOGAPS-ALPHA reanalysis dataset to further analyze the QTDWs during January 2006 with a focus to answer whether the anomalous QTDWs are related to the major SSW event during the same time.

In the previous ACP paper (Gu et al., 2016), we studied the influence of sudden strato-

spheric warming on quasi-two day wave with theoretical TIME-GCM numerical simulations. Our present results from NOGAPS-ALPHA reanalysis dataset show both similarities and differences.

The similarities include:

(1) the summer easterly is enhanced during the SSW period, which may provide stronger instabilities and thus lager forcing for the amplification of QTDW; (2) the nonlinear interaction between W3 QTDW and zonal wave number 1 stationary planetary wave (SPW1) could generate a W2 QTDW.

Our new findings and new work in this paper include:

(1) The TIME-GCM simulations showed that the W3 becomes weaker during SSW periods due to the nonlinear interaction and the energy transfer from parent wave (W3) to child wave (W2). Note that the forcing of W3 at the lower boundary of TIME-GCM is constant in the previous simulations. Nevertheless, in real atmosphere, the planetary wave signals in the winter stratosphere, where the source of QTDW exists, are very strong during a major SSW event. In this case, the QTDW forcing in the lower atmosphere may not be constraints for the QTDW oscillations in the upper atmosphere. On the contrary, the strong planetary wave activities during SSW periods would provide strong QTDW sources in the lower atmosphere and result in strong QTDW oscillations (including both W2 and W3) in the upper atmosphere, such as the January 2006 situation presented in this paper.

(2) The previous TIME-GCM simulations show that the W2 peaks earlier than W3 due to the larger phase speed and thus weak dissipation of W2. We should note that the W2 is generated immediately when the W3 and SPW1 are forced at the lower model boundary. In real atmosphere, the W2 QTDW may peak later than W3 according to the occurrence time of the nonlinear interaction between W3 and SPW1, such as the situation during January 2006.

(3) The TIME-GCM simulations show strong nonlinear advection between W3 QTDW and SPW1 at the lower model boundary (~10 hPa), which is weak in NOGAPS-ALPHA reanalysis datasets. Our present work made it clear that the strong nonlinear advection at ~10 hPa in TIME-GCM is due to the lower boundary effect, which will possibly not occur in real atmosphere.

(4) According to previous statistical results (Gu et al., 2013), the period of QTDW is extremely short during 2006. Our analysis reveals that the short QTDW period is related to the enhanced summer easterly jet during the 2006 major SSW event. In other words, we found that the SSW can not only result in abnormally strong QTDW activities with different zonal wave numbers, but also influence the period of QTDW.

(5) Following the reviewers' comments, the barotropic and baroclinic instabilities are investigated separately. We found that the barotropic is ~60-80% as strong as the baroclinic instability. In other words, the baroclinic instability would play a more important role in the amplification of QTDW, whereas the role of barotropic instability is also very important.

(6) In the revision, we also calculated the meridional and vertical circulations induced by the wave number 1 stationary planetary wave by using the downward control principle following Haynes et al. (1991) and Lubis et al. (2016). We found that the winter planetary wave induced circulations are confined to winter hemisphere, which would be ineffective for the inter-hemispheric coupling. This agrees well with the mechanism that the inter-hemispheric coupling is induced by the feedback between gravity wave breaking and zonal mean zonal wind in the mesosphere (Karlsson et al., 2009; Körnich and Becker, 2010). We also calculated the meridional component of the total residual circulation during and before the SSW event. Their difference shows that there is an anomalous cross-equator circulation from the winter to summer hemisphere in the mesosphere, which clearly suggests the inter-hemispheric coupling during SSW period.

(7) According to the analysis in this paper, we conclude that the abnormal QTDW activities during January 2006 are related to the major SSW event during the same time. The differences between the TIME-GCM and NOGAPS-ALPHA results are strengthened in the revision, and it is suggested that our present work with reanalysis dataset is a further contribution to the previous study with theoretical numerical simulation.

Limpasuvan, V., and D. L. Wu (2009), Anomalous two day wave behavior during the 2006 austral summer, Geophys. Res. Lett., 36, L04807.

McCormack, J. P., L. Coy, and K. W. Hoppel (2009), Evolution of the quasi 2-day wave during January 2006, J. Geophys. Res., 114, D20115.

Gu, S.-Y., T.Li, X. Dou, N.-N.Wang, D. Riggin, and D. Fritts (2013), Long-term observations of the quasi two-day wave by Hawaii MF radar, J. Geophys. Res. Space Physics, 118, 7886–7894, doi:10.1002/2013JA018858.

Gu, S. Y., H. L. Liu, X. Dou, and T. Li (2016), Influence of the sudden stratospheric warming on quasi-2-day waves, Atmos. Chem. Phys., 16(8), 4885-4896.

2) The correlation analysis between zonal mean temperature (70N, 10 hPa) and zonal wind shown in Figure 9 looks very crude which does not entail any firm physical background, rather it is a chance occurrence. High anticorrelation is observed at several regions in the plot and cannot be considered as instability zones to excite QTDW. It is not clear why the interval is chosen from 1 Jan to 20 Feb when SSW activity is selected during 10-30 Jan for rest of the analyses.

Reply: According to the definition of World Meteorological Organization, a SSW event is usually identified by the increase of temperature at 10 hPa (or below) poleward of 60N. Thus it is reasonable to choose a reference temperature point at 10 hPa and 70N to show the interhemispheric patterns during a SSW event. For example, Tan et al. [2012] also used a reference temperature point at 10 hPa and 76N-80N to study the interhemispheric couplings patterns during SSW periods. We focus on the zonal wind

due to the fact that the zonal wind is essential for the propagation and amplification of planetary waves.

We should note that a region with high anticorrelation does not mean instabilities there. The instability only occurs where the latitudinal gradient of the potential vorticity is negative. The diagnostics show that the mean flow instabilities during January 2006 exist in the summer easterly at middle and high latitudes, and in polar winter stratosphere due to the reversal of westerly. And the instabilities in the summer hemisphere are most effective for the amplification of QTDW. The high correlation patterns in other regions show that the SSW also has strong impact on the zonal wind there, but these variations are ineffective for the amplification of QTDWs.

Both the warming and QTDW peaks lie between Jan 10 and 30 of 2006, and we thus choose the dataset during Jan 10-30 when discussing the mechanism about QTDW amplification and its difference with that during 2005. We use a longer dataset (from Jan 1 to Feb 20) in the correlation analysis just to increase the reliability.

Tan, B., X. Chu, H.-L. Liu, C. Yamashita, and J. M. Russell III (2012), Zonal-mean global teleconnection from 15 to 110 km derived from SABER and WACCM, J. Geophys. Res., 117, D10106, doi:10.1029/2011JD016750.

3) The instability contours (Figures 7, 10, 11) do not suggest any evident link between the southern and northern hemispheres, rather southern hemispheric instabilities (to excite W3 and W2 QTDW near 40S and 20S, respectively) are found to be linked with highest instability southern polar mesosphere and stratosphere regions. Therefore from the present results it seems SSW has little to do with the summer hemisphere QTDW activity except coincidence and hence it requires substantiation.

Reply: We agree that Figures 7, 10 and 11 only show how the summer easterly and the corresponding instabilities influence the amplification of QTDW. In fact, the influence of the winter SSW on summer QTDW is realized just by the modulation on summer easterly through inter-hemispheric couplings. In other word, the QTDW is not trig-

gered directly by the SSW, and the influence of SSW on QTDW is an indirect process. Our further correlation analysis in this paper, and the control TIME-GCM simulations in previous literature have confirmed the enhancement of summer easterly during the SSW period. In the revision, we also calculated the meridional component of the residual circulation, which shows an anomalous cross-equator circulation from the winter to summer mesosphere. This clearly suggests the inter-hemispheric coupling during SSW period.

4) Section 3.3: Fig. 14, Authors have mentioned that the present study could provide more realistic view of nonlinear interaction between SPW1 and W3 resulting generation of W2 QTDW as compared to the past study by Gu et al. (2016c). The present results (Figure 14) shows prominence of W3 in southern hemisphere and SPW1 in northern hemisphere indicating unlikely generation of W2 QTDW due to nonlinear interaction between SPW1 and W3 QTDW. Furthermore, nonlinear advection as shown in Figure 13 seems to be unreliable for identification of W2 generation as authors ruled out one such possibility in the text at winter polar region. Therefore using nonlinear advection to identify W2 QTDW generation looks incorrect in the present scenario.

Reply: The present analysis makes it clear that the strong nonlinear advection between W3 and SPW1 at ∼10 hPa, which is exhibited by previous TIME-GCM simulations, is due to the unrealistic wave forcing at the lower model boundary.

We note that the W3 peak mainly in the southern hemisphere and the SPW1 shows maximum wave amplitude in the northern hemisphere. We should also note that the zonal component of W3 has a weaker branch in the northern hemisphere with maximum amplitude at 20N, and the meridional wind perturbations of W3 can also propagate across the equator to as far as 40N in the northern hemisphere. Thus we suggest that the nonlinear advection between W3 and SPW1 most probably occur in the northern hemisphere equatorward of 40N. This generally agrees with the enhanced nonlinear advection at ∼20N in both previous TIME-GCM simulation and current NOGAPS-ALPHA reanalysis dataset.

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Keep in mind that the nonlinear advection between W3 and SPW1 in fact represent the nonlinear effect on the mean flow tendencies. We use the nonlinear advection between W3 and SPW1 as a substitute to study their nonlinear interaction. We suggest that the nonlinear interaction most possibly occurs in the region with high nonlinear advection. We rule out the contribution of the nonlinear advection in polar winter region to the generation of W2 mainly due to that the W3 is extremely weak there and the W2 is not inclined to propagate in the polar region [Gu et al., 2016].

Gu, S. Y., H. L. Liu, X. Dou, and T. Li (2016), Influence of the sudden stratospheric warming on quasi-2-day waves, Atmos. Chem. Phys., 16(8), 4885-4896.

5) Overall, the authors have pointed out stronger W2 and W3 QTDW in summer hemisphere in 2006 (SSW) in comparison with 2005 (no SSW), but it is not clear how the disturbance propagates from winter to summer hemisphere. Therefore the authors are suggested to look into the latitudinal-temporal evolution of the dynamical parameters and attempt to link these two entities (SSW and QTDW in summer hemisphere) which could reduce present understanding gap and add significance to the present work since the past study by Gu et al. (2016c) already reported southern hemisphere QTDW enhancement through easterly wind strengthening during northern hemispheric SSW.

Reply: The SSW in the winter stratosphere induces inter-hemispheric couplings through the feedback between zonal mean state and gravity wave breaking in the mesosphere, which causes an abnormal mesospheric meridional circulation from the winter to summer hemisphere (Karlsson et al., 2009; Körnich, H., and E. Becker, 2010). The gravity wave drag is needed to illustrate the inter-hemispheric coupling processes in detail. It is a pity that the gravity wave drag is not included in the publicly accessed NOGAPS-ALPHA datasets. In the revision, we showed the difference between the meridional circulation during and before SSW, from which we can clearly see the cross-equator coupling from the winter to summer mesosphere during SSW period. The role of gravity wave breaking and the feedback between zonal mean state and the gravity

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wave breaking needs our further investigation with other datasets.

Körnich, H., and E. Becker (2010), A simple model for the interhemispheric coupling of the middle atmosphere circulation, Advances in Space Research, 45(5), 661-668.

Karlsson, B., C. McLandress, and T. G. Shepherd (2009), Inter-hemispheric mesospheric coupling in a comprehensive middle atmosphere model, Journal of Atmospheric and Solar-Terrestrial Physics, 71(3–4), 518-530.

6) Figure 2, Instead of absolute temperature it is better to plot temperature deviation from mean wind.

Reply: Does the reviewer mean temperature deviation from mean temperature? In the revision, we showed the temperature deviation from seasonal (90-day) mean.

7) Fig 7, 10, 11: Authors should describe how critical layers of W2 and W3 are calculated

Reply: Added in the revision.

8) Fig 12. It is not clear why EP flux divergence for W3 is plotted for the interval 23-30 Jan, whereas in all other cases it is 12-19 Jan for W3.

Reply: Figure 12 is the previous manuscript is utilized to show whether instabilities related with the wind reversal during SSW period contribute significantly to the amplification of both W2 and W3. The wind reversal is much stronger during day 23-30 than during day 12-19, and thus we showed the EP flux divergence of both W2 and W3 during day 23-30.

Other points 9) L29: Replace "provides stronger" by "strengthen"

Reply: Done.

10) L40: Replace "oscillation" by "significant variability"

Reply: Done.

11) L40: Replace "with a period: : :." By " with the period: : :."

Reply: Done.

12) L45-46: "with different wavenumbers: : :: : :". Please mention the wavenumbers

Reply: Added in the revision.

13) L-175: Correct "_40N" to "40S"

Reply: Corrected.

14) L-214-215: Replace "in the mechanical study of the" by "in studying"

Reply: Done.

15) L-333: Correct "Their TIME-GCM simulations use" to "Their TIME-GCM simulations used"

Reply: Corrected.

16) L-355: Correct "may also exhibits" to "may also exhibit"

Reply: Corrected.

17) L-360-365: Both the links of data sources for NOGAPS-ALPHA and MLS-AURA are inaccessible. Please correct them.

Reply: The links are updated in the revision.

Please also note the supplement to this comment:
https://www.atmos-chem-phys-discuss.net/acp-2017-563/acp-2017-563-AC1-supplement.pdf

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