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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.

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Anonymous Referee #2

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Referee report on "Investigation on the abnormal quasi-two day wave activities during sudden stratospheric warming period of January 2006"

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Discussion paper

This paper examines the unusual quasi two-day wave (QTDW) behavior during sudden stratospheric warming (SSW) period of January 2006, and reaches two main conclusions:

1. The unusually strong W2 QTDW is identified during the 2006 Austral summer, along with the conventional W3 component. 2. The strongest W2 signal occurs due to: (a) a manifestation of the summer easterly jet instability induced by SSW event via interhemispheric coupling and (b) a nonlinear interaction between W3 QTDW and wave number 1 stationary planetary waves (SPW1).

Neither of these findings is new and the first is definitely not new. One can find a similar description in Limpasuvan and Wu (2009) and other previous studies by the same first author (e.g., Gu et al., 2016a,c). In particular, the unusual QTDW behavior during the 2006 Austral summer has been well documented in Limpasuvan and Wu (2009), where they showed that the conventionally dominant mode of QTDW with zonal wavenumber 3 (W3) is followed by a strong W2 component traveling westward (at nearly the same phase speed). In addition, the characteristic features of the QTDW (W2 and W3) found in this study are very similar to the previous findings of Gu et al. (2016c), who considered a large number of SSW events (including the warming episode of 2006). This also includes interpretation related to W2 generation by a nonlinear interaction between W3 and SPW1 during SSW events (Gu et al., 2016c). The authors will need to argue the significance of their work, with an emphasis on their novel findings. Because of these concerns, the manuscript requires a major and mandatory revision. If these concerns cannot be addressed, I would not recommend publishing this manuscript in ACP.

Reply: Our present work is in fact 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 stratospheric 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 situ-

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ation 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 mecha-

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nism 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.

Other major points:

1. The interpretation of Fig. 7, regarding the source of W2 is not convincing. The EP flux vectors associated with W2 QTDW in the summer hemisphere are far from the instability source and the critical layers. Therefore, the argument for the amplification of QTDW via wave-mean flow interaction near the critical layer seems flimsy and requires

further investigation. In addition, the QTDW activity in the winter branch seems to be partly originating from the tropical (0-20N) mesosphere. Can the authors explain this?

Reply: We agree that there are differences between the W2 and W3 QTDWs. For one thing, the W3 QTDW is more obviously amplified by the mean instabilities, while the W2 QTDW looks more like a free traveling planetary wave, whose amplitude grows with the decrease of atmospheric density. For another, the W3 QTDW is only favored to propagate in the southern (summer) hemisphere, while the W2 QTDW is capable of propagating in both hemispheres. This is partly due to the larger phase speed of W2, which results in weaker dissipation when propagating upward. In fact, there are some (though weak) clues at 20-40S and 0.1-0.01 hPa showing the W2 EP flux propagating away from the instability region, which indicates weak amplification through wave-mean interaction. There are two possible sources for the winter branch of W2: One, it is generated by the nonlinear interaction between W3 and SPW1; Second, it may originate from the source region in the lower atmosphere, and then directly propagates upward into the mesosphere. The differences between W2 and W3 are expressed more clearly in the revision.

2. The authors also argued that the stronger W2 QTDW in austral summer 2006 is due to enhanced inter-hemisphere coupling induced by SSW in the winter hemisphere; however, such evidence is not clear from Fig. 9 and Fig. 10. I would suggest the authors prove it quantitatively, e.g., by calculating the residual mass-stream function induced by resolved planetary wave drag (via downward control principle), as outlined by Lubis et al. (2016, Eq. 5), and the associated diabatic heating ($d\theta/dz$ w*). If the authors' argument is correct, hence, after the SSW event, we do expect an enhanced residual (inter-hemispheric) circulation in the summer hemisphere along with increased diabatic heating near the austral mesospheric jet.

Reply: The W2 QTDW has a larger phase speed compared with other QTDWs, which needs a stronger summer easterly to sustain a critical layer of W2. The inter-hemispheric couplings during SSW period result in an enhanced summer easterly, which facilitates the existence of W2 critical layer and the wave-mean interaction.

We calculated the stream function induced by wave number 1 planetary wave, and the corresponding vertical and meridional residual circulations. The results show that the winter planetary wave induced circulations are confined in the winter hemisphere. This agrees well with the inter-hemispheric mechanism that the inter-hemispheric coupling arises from a feedback between the gravity wave breaking and the zonal wind in the mesosphere. We thus should calculate the stream function induced by gravity wave drag to illustrate the inter-hemispheric couplings. It is a pity that the gravity wave drag is not included in the publicly accessed NOGAPS-ALPHA dataset. In the revision, we showed the difference between the total meridional circulations during and before SSW. It is clear that there is an anomalous cross-equator mesospheric meridional circulation from the northern (winter) to southern hemisphere during SSW period, which provides evidence for the inter-hemispheric coupling.

3. Based on Figs 10-11, it is clear that the regions where the PV gradient is negative are potentially baroclinically or barotropically unstable, and thus represent potential sources of QTDW activity; however, it is still unclear which types of instability are more dominant for such processes; is it barotropic or baroclinic mode? Also, what causes the negative PV gradient in that region? Is this associated with changes in vertical shears or wind curvature? Please clarify.

Reply: In the revision, we added a Figure to show the barotropic and baroclinic instability separately. We found that the barotropic instability is usually ∼60-80% as strong as the baroclinic instability at middle latitudes in the southern mesosphere, where it is more effective for the amplification of QTDW. In other words, the wind vertical shears contribute more to the growth of QTDW, but the wind curvatures are also very important.

4. The interpretation of Figs 13-14 is very confusing. The results shown in Figs 13 and 14 do not indicate that the W2 QTDW is generated via nonlinear advection interaction

between W3 and SPW1. This is due to the fact that enhanced meridional nonlinear advection in the summer hemisphere (Fig. 13) is not accompanied by enhanced SPW1 activity (in u and v) in the same region (Fig. 14), rather only a prominence of W3 activity. Therefore, the generation of W2 QTDW via meridional nonlinear advection seems to be unlikely.

Reply: In fact, there is a minor peak of 6-9 m/s for the zonal component of SPW1 at 40S nearby the enhanced nonlinear advection. The enhanced nonlinear advection between W3 and SPW1 in the summer hemisphere corresponds to the nearby major peak of W3 and this minor peak of SPW1. We use the nonlinear advection between W3 and SPW1 as a substitute to study their nonlinear interaction. Our point is that the nonlinear interaction between W3 and SPW1 is more likely to occur in the region with strong nonlinear advection, whereas we are not sure whether there is a one to one correspondence between each other. For example, the enhanced nonlinear advection in winter polar mesosphere is probably not a source for W2, since the W2 is more favored to propagate at middle and low latitudes. We thus suggest that the enhanced nonlinear advections between W3 and SPW1 at 40-50S and 0-10S are possible sources for W2, while the enhanced nonlinear advection at 30N is a more conceivable source for W2.

Specific points:

L47: Delete “to exist”

Reply: Deleted in the revision.

L57-58: Missing references

Reply: Added in the revision.

L59-L60: A similar finding was also reported by Lossow et al. (2015) and Lubis et al. (2016).

Reply: These references are added in the revision.

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L87-L99: In addition to inter-hemispheric coupling induced by SSW events, a strengthening of summer mesospheric easterlies can also be induced by stratospheric ozone depletion in spring, leading to an increased instability of the summer mesospheric easterly jet and, thus, enhanced QTDW activity (see Lossow et al., 2015; Lubis et al., 2016).

Reply: We agree that the ozone deletion in the southern hemisphere stratosphere will result in stronger easterlies in the mesosphere, which may also contribute to the enhancement of planetary wave activities. Nevertheless, this does not influence our conclusion that the enhanced summer easterly and QTDW activities during January 2006 are most likely related to the SSW event. For one thing, the O3 depletion occurs mainly during southern spring (Sep-Nov), whereas the QTDW is a summer phenomenon (Dec-Feb). Thus the enhanced instabilities induced by the ozone depletion may be ineffective for the amplification of QTDW; For another, the O3 mixing ratios during January 2005 and 2006 from Aura/MLS do not show significant differences that may account for the enhanced summer mesospheric easterly in 2006. Both the two references are cited and discussed in the revision.

L206-L207: Why is the latitudinal structure of W2 more symmetrical, compared to W3? Is this due to the characteristic of the instability-normal mode of the wave? Please explain.

Reply: The phase speed of W2 is larger, and therefore its waveguide has a broader latitudinal extension, which enables the propagation of W2 in both hemispheres. The larger phase speed also makes W2 less vulnerable to dissipation and critical layer filtering by the background wind when propagating upward (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.

L236-L237: Please clarify this result by plotting a latitude-height structure of the refractive index associated with W2?

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Reply: A new Figure with refractive index of both W2 and W3 is added in the revision.

L287: Why does positive EP flux divergence indicate the source of planetary waves?

Reply: The ‘source’ here means energy conversion to planetary waves due to mean flow interactions. When the planetary wave is amplified by the mean flow instabilities, the EP flux divergence usually shows a positive value near the instability region. It is expressed more clearly in the revision.

L293: Please provide the nonlinear advection equation that you used in the manuscript.

Reply: Added in the revision.

Please also note the supplement to this comment:
https://www.atmos-chem-phys-discuss.net/acp-2017-563/acp-2017-563-AC2-supplement.pdf

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Interactive comment on Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-563, 2017.