Reponses of middle atmospheric circulation to the 2009 major sudden stratospheric warming

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Key Points:
- The MERRA-2 data set and downward control principle were utilized to differentiate the roles of gravity waves and planetary waves during the January 2009 major sudden stratospheric warming
- Changes in gravity wave forcing are solely responsible for the anomalous mesospheric residual circulation, including the interhemispheric coupling
- Both gravity wave forcing and planetary wave forcing are important to the variability of the mean flow in the stratosphere, but with opposite effects

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Abstract: In this research, the roles of gravity waves and planetary waves in the change to middle atmospheric residual circulation during a sudden stratospheric warming period are differentiated and depicted separately by adopting the downward control principle. Our analysis shows clear anomalous poleward residual circulation patterns from the equator to high latitudes in the lower winter stratosphere. At the same time, upward mean flows are identified at high latitudes of the winter upper stratosphere and mesosphere, which turn equatorward in the mesosphere and reach as far as the tropical region, and consequently the extratropical region in the summer hemisphere. The downward control principle shows that anomalous mesospheric residual circulation patterns, including interhemispheric coupling, are solely caused by the change in gravity wave forcing resulting from the reversal of the winter stratospheric zonal wind. Nevertheless, both planetary waves and gravity waves are important to variations in the winter stratospheric circulation, but with opposite effects.

Keywords: sudden stratospheric warming; residual circulation; gravity and planetary waves

1. Introduction

Sudden stratospheric warming (SSW), the most dramatic phenomenon occurring in the winter polar atmosphere, is generally attributed to the rapid growth of planetary waves (PWs) and the momentum deposition to the mean flow (Liu and Roble, 2002). Additionally, the winter mesosphere has been shown to undergo a cooling process during the SSW period, which is caused by the variability of wave forcing resulting from gravity wave (GW) breaking (Zülicke and Becker, 2013). Nayak and Yiğit, 2019 also found that the GWs during an SSW period could reach as high as the ionospheric region. Goncharenko et al. (2010a) found that SSW-induced ionospheric variations at 200 to 1,000 km could account for 50% to 150% of the total electron content. Currently, interhemispheric coupling during the SSW period has also been verified by both observations and simulations (Karlsson et al., 2007, 2009). Thus, understanding the variation in the middle atmospheric circulation is valuable for expanding our knowledge of the full atmospheric coupling during an SSW event.

Gravity waves play a key role in maintaining a state of equilibrium in the middle atmosphere (Liu HL et al., 2009). For example, eastward GW forcing in the summer mesosphere induces an equatorward circulation caused by the Coriolis force, which results in upward flow and adiabatic cooling in the polar summer region, and vice versa for the situation in the winter mesosphere. Additionally, cross-equatorial residual circulation from the summer to the winter hemisphere has been observed in the mesosphere. The propagation of GWs is strongly dependent on the background wind, and GWs may become evanescent when a critical layer, in which the background wind is equal to its phase speed, is approaching (Fritts and Alexander, 2003). The reversal of the zonal wind in the winter stratosphere during a major SSW period will certainly strongly influence the propagation of GWs, which will shift the momentum flux deposition to the background and consequently result in variations in the middle atmospheric circulation (Yiğit and Medvedev, 2012; Chandran et al., 2014). Furthermore, Yamashita et al. (2010) showed that the amplitudes, phase speeds, and horizontal wavelengths of GWs can all have an impact on the mesospheric temperature anomaly during an SSW period. Currently, although it is generally accepted that both GWs
and PWs are responsible for the anomalous atmospheric characteristics during an SSW period, their roles still need to be differentiated and depicted separately.

The major SSW event in January 2009 is the strongest that has occurred over the past two decades. It was characterized by a rapid temperature increase of ~50 K in one week and the reversal of the zonal mean zonal wind in the polar winter stratospheric region (Goncharenko et al., 2010b). This event provides an ideal opportunity for the study of atmospheric dynamical coupling resulting from an SSW event (Funke et al., 2010; Goncharenko et al., 2010b; Nayak and Yiğit, 2019). In this work, the total residual circulation anomaly and the residual circulation patterns induced by PWs and GWs are examined in detail and depicted separately on the basis of the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis data set. The data set is described briefly in Section 2, our analytical results are presented in Section 3, and a summary follows in Section 4.

2. MERRA-2 Reanalysis Data Set

The MERRA-2 is the newest version of the atmospheric reanalysis data set released by NASA’s Global Modeling and Assimilation Office (Gelaro et al., 2017). Various kinds of satellite observations, such as temperature and ozone observations from the Microwave Limb Sounder instrument on the Aura satellite, as well as ground-based measurements, are incorporated in MERRA-2. The observational data sets are updated every 6 hours, and the synoptic output data set has a horizontal resolution of 0.5° longitude and 0.625° latitude. The data include 72 pressure levels, ranging from the ground to 0.01 hPa. Gelaro et al. (2017) showed that the SSW features are better captured in MERRA-2 compared with the previous MERRA data set. The neutral atmospheric parameters in January 2009 were utilized to study the complete atmospheric coupling during this major SSW event.

It is generally accepted that the sudden growth of PWs in the stratosphere leads to the generation of an SSW event, which alters the propagation feature of GWs through a change in the background mean flow. The total residual circulation and its variability during the 2009 SSW period can be calculated as follows (Andrews et al., 1987):

\[
v^* \equiv \bar{v} - \rho^{-1}(\rho \overline{\nabla} / \overline{\rho})_z ,
\]

\[
w^* \equiv \bar{w} + (\cos \phi)^{-1}(\cos \phi \overline{\nabla} / \overline{\rho})_\phi ,
\]

where \(v, w, a, \rho, \varphi, \theta\) are the meridional wind, vertical wind, Earth’s radius, neutral air density, and latitude in radians and potential temperature; \(\bar{v}\) and \(\bar{w}\) represent the zonal mean value; \(\nabla\) and \(\nabla\) are the deviations from the zonal mean value, and the subscripts \(z\) and \(\phi\) indicate the vertical and latitudinal gradients, respectively. In addition, according to the downward control principle, the latitudinal and vertical circulation patterns are approximately proportional to the gradients of the vertically integrated wave force above that level. Circulation is thus utilized to distinguish the contributions of GWs and PWs to the residual circulation anomaly. The meridional and vertical residual circulation patterns induced by PW and GW forcing are proportional to the vertical and horizontal gradients of the corresponding stream functions \((\psi_{pw}, \psi_{gw})\) and can be calculated as follows (Haynes et al., 1991):

\[
v^*_{(pw,gw)} = -\frac{1}{\rho \cos \varphi} \frac{\partial \psi_{(pw,gw)}}{\partial z} ,
\]

\[
w^*_{(pw,gw)} = \frac{1}{a \rho \cos \varphi} \frac{\partial \psi_{(pw,gw)}}{\partial \phi} ,
\]

where \(g\) is the acceleration caused by gravity. Considering that the GW parameters are difficult to present in the MERRA-2 reanalysis data set, the GW-induced stream function \((\psi_{gw})\) can be calculated by the difference between the total \((\psi_{total})\) and PW-induced \((\psi_{pw})\) stream functions (Karpechko and Manzini, 2012; Lubis et al., 2016), which can be calculated by

\[
\psi_{pw} = \rho \cdot \cos \varphi \int_0^\varphi (\rho \cdot a \cdot \cos \varphi)^{-1} \frac{\nabla \cdot F}{(\rho \cdot a \cdot \cos \varphi)^{-1}(\bar{u} \cdot \cos \varphi)\phi - f} dz' ,
\]

\[
\psi_{total} = \rho \cdot \cos \varphi \int_0^\varphi \psi^* dz' ,
\]

where \(\bar{u}, f, \psi^*\) are the zonal mean zonal wind, Coriolis parameter, and meridional component of the total residual circulation (Equation (1)) and \(F\) is the Eliassen–Palm flux vector attributable to PWs (Andrews et al., 1987).

3. Results

Figure 1a shows the temporal variations in the zonal mean zonal wind at 60°N during January and February of 2009, which is eastward in the stratosphere prior to January 20 and becomes westward between January 20 and 30. The reversed zonal wind reaches ~40 m/s at ~1 hPa on January 23, which coincides with the peak of the temperature increase shown in Figure 1b. We can see that the zonal mean temperature is nearly constant between January 1 and January 12, indicating the steadiness of the mean flow prior to the occurrence of the SSW. Nevertheless, the zonal mean temperature at 70°N increases dramatically from ~200 K on January 12 to ~250 K on January 23, and then recovers slowly to its climatological state. The SSW features in our analysis agree well with previous publications that have included both observations and model simulations (Funke et al., 2010; Goncharenko et al., 2010b; Pedatella et al., 2014). Thus, we conclude that the MERRA-2 reanalysis data set captured the January 2009 major SSW event well.

Figure 1 shows that the SSW reached its crest on January 23 and that the mean state was still quiet on January 9. Thus, the atmospheric conditions on these two days were compared to determine the responses of the middle atmosphere to this major SSW event. Figure 2a and 2c show the latitudinal and vertical distribution of the zonal mean temperature on January 9 and 23, respectively. The stratospheric temperature is clearly higher in the summer hemisphere than in the winter hemisphere on January 9, which is due to the stronger solar absorption by ozone in the summer hemisphere. Nevertheless, the temperature in the mesosphere is evidently lower in the summer hemisphere than in the winter hemisphere, which is related to the pole-to-pole (from the summer to winter hemisphere) residual circulation induced by GW breaking (Liu HL et al., 2009). Thus, the zonal mean temperature on January 9 shows a typical climatological middle atmo-
Figure 1. Temporal variations of the zonal mean (a) zonal wind at 60°N and (b) temperature at 70°N and 10 hPa during January and February of 2009. The dashed lines indicate the dates of January 9 and January 23.

Figure 2. The zonal mean (a, c) temperature and (b, d) zonal wind on (a, b) January 9 and (c, d) January 23. (e, f) Differences of the zonal mean temperature and zonal wind, respectively.

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spheric state under austral summer conditions. However, the zon- 
al mean temperature in the winter stratosphere becomes much warmer and the mesospheric temperature becomes cooler on January 23 compared with that on January 9. The temperature anomaly during this major SSW period is more clearly exhibited by the temperature differences, as shown in Figure 2e. The figure clearly shows that the stratospheric warming and the mesospheric cooling in the winter polar region could reach ~60 K and ~40 K, respectively. Additionally, the zonal mean temperature shows weak warming in the tropical and subtropical regions in both hemispheres.

The zonal wind conditions on January 9 and 23 are shown in Figure 2b and 2d, respectively. The zonal mean zonal wind on January 9 is eastward in the winter middle atmosphere and westward in the summer hemisphere, but the winter westerly decreases significantly and is even reversed on January 23. This difference (Figure 2f) shows that the net change in the zonal wind in the winter middle atmosphere is even larger than 120 m/s during the January 2009 SSW period, whereas the change in the zonal wind in the summer hemisphere is much weaker.

Limpasuvan et al. (2012) have suggested that the momentum flux from PWs brings westward forcing onto the mean flow during the SSW period, which decelerates the winter westerly. At the same time, the westward forcing induces a downward circulation at high latitudes, which results in adiabatic heating and thus stratospheric warming. In contrast, the deceleration or reversal of the eastward wind in the winter stratosphere enables more eastward GWs to reach higher regions (Limpasuvan et al., 2012), which promotes an anomalous equatorward and upward motion, and thus cooling in the mesosphere. We then examined the variations in the residual circulation $(v^*, w^*)$ during the January 2009 major SSW event.

The total residual circulation of the middle atmosphere on January 9, which is prior to the occurrence of the SSW, is shown in Figure 3a. The pole-to-pole circulation from the summer to winter hemisphere is clearly exhibited. The upward and downward flows in the polar mesopause region are responsible for the warm winter and cold summer phenomena, respectively, as shown in Figure 2a. In addition, the residual circulation moves upward in the equatorial region, which then merges into the pole-to-pole circulation in the mesosphere. The difference between the total residual circulation on January 9 and January 23 is shown in Figure 3b and represents the mean flow anomaly during the SSW period. We can observe strong upward circulation patterns at high latitudes in the winter mesosphere, which then turn equator-
ward in the upper mesosphere (between 0.01 and 0.05 hPa). At the same time, poleward circulation patterns at ~1 hPa sink at the middle and high latitudes. The high-latitude downward circulation below ~1 hPa and upward circulation above ~1 hPa result in corresponding stratospheric warming and mesospheric cooling during the SSW period (as also shown in Figure 2e), respectively. Specifically, we found that the anomalous residual circulation in the upper mesosphere could even reach low-latitude regions in the summer hemisphere, suggesting interhemispheric coupling during the SSW period (Karlsson et al., 2007, 2009). In addition, we found poleward and downward circulation patterns at middle and high latitudes in the summer hemisphere between 0.01 and 0.05 hPa.

Figure 3b clearly shows anomalous residual circulation during the January 2009 major SSW period, which results in both vertical and latitudinal atmospheric coupling. The downward control principle was then utilized to differentiate the contributions of the GWs and PWs to the residual circulation anomaly.

Figure 3c shows the difference in residual circulation induced by PWs on January 9 and 23, which includes all the PWs with zonal wavenumbers 1–6. We can see that the anomalous mean flows induced by PWs during the SSW period are mostly confined to the winter hemisphere below 0.1 hPa. Specifically, the mean flow is downward between 60°N and 90°N, which is most likely responsible for the high-latitude winter stratospheric warming during the SSW period (shown in Figure 2c). The corresponding residual circulation anomaly induced by GWs is shown in Figure 3d. The anomalous GW activities during the SSW period clearly result in an upward circulation at high latitudes of the winter hemisphere from the stratosphere to mesosphere, which then turns equatorward and reaches as far as the low-latitude regions in the summer hemisphere. A comparison of Figures 3b and 3d shows that the patterns of the total residual circulation anomaly in the mesosphere (e.g., above 0.5 hPa) agree well with that induced by GWs.

In other words, our analysis indicates that the residual circulation anomalies in the mesosphere are solely driven by the change in forcing attributable to GW breaking. Even so, Figures 3c and 3d show that both PWs and GWs are important to the formation of the total mean flow anomalies (Figure 3b) in the stratosphere (e.g., below 0.5 hPa). For example, the anomalous mean flow induced by GWs is upward at winter high latitudes between 0.5 and 3 hPa (Figure 3d), which counteracts the upward residual circulation induced by PWs (Figure 3c) and results in a net effect of poleward mean flow in the winter stratosphere (Figure 3b). In our analysis, the maximum downward circulation induced by PWs was ~3.9 cm/s and the maximum upward circulation induced by GWs was ~4.4 cm/s at high latitudes in the stratosphere.

The variability of the zonal wind in the winter hemisphere during the SSW period and its influence on GW propagation are illustrated in Figure 4. We can see that the zonal mean zonal wind at 60°N on January 9 (before the SSW) is eastward from the ground to the mesosphere, with a maximum value of ~90 m/s at ~0.5 hPa (Figure 4a). The GWs become evanescent during propagation when a critical layer is approaching (Fritts and Alexander, 2003). Thus, all the eastward GWs with a phase speed of less than 90 m/s are blocked by the background wind in the troposphere and stratosphere, and only the westward GWs are able to propagate upward into the mesosphere. As a result, the net GW forcing resulting from the momentum flux deposition before the occurrence of the SSW is westward in the mesosphere, which results in a poleward and downward circulation attributable to the Coriolis force at the middle and high latitudes of the winter hemisphere (as shown in Figure 3a). Nevertheless, at the warming peak on January 23, the zonal wind clearly decelerates in the troposphere and lower stratosphere and is reversed in the upper stratosphere and

![Figure 4](image-url)
4. Discussion and Summary

Figure 2e shows that the temperature exhibits a positive increase in the tropical mesosphere during the SSW period, a result that agrees well with the interhemispheric patterns presented by Karlsson et al. (2009) and Körnich and Becker (2010). It is also argued that the corresponding increase in temperature gradients in the summer mesosphere accelerates the zonal wind in the summer subtropics, which then transmits the impact of the winter SSW to extratropical regions of the summer hemisphere through feedback between the mean flow and GW breaking. The results of our analysis show that the GW-induced meridional circulation in the winter hemisphere reaches as far as the tropical region in the summer hemisphere. It then sinks in the subtropical zone and grows again in the extratropical region of the summer mesosphere (Figure 3b and 3d). This result suggests the occurrence of feedback between GW breaking and the background wind in the summer mesosphere, which agrees well with the interhemispheric coupling mechanism proposed by Karlsson et al. (2009) and Körnich and Becker (2010). We thus conclude that interhemispheric coupling occurs in the mesosphere during the SSW period and that this coupling results solely from the variability in GW forcing in the winter hemisphere.

In summary, the MERRA-2 reanalysis data set was utilized to identify the variability in residual circulation during the January 2009 major SSW event. The novelty of this work lies in the fact that we applied the downward control principle to differentiate the roles of PWs and GWs in the mean flow variation in both the stratosphere and mesosphere. Our results clearly show that the change in GW forcing in the winter mesosphere, which is induced by the reversal of the winter westerly in the stratosphere, is solely responsible for the variability of the mesospheric residual circulation during the 2009 major SSW event, including the interhemispheric coupling. Specifically, the anomalous southward GW-induced residual circulation in the winter mesosphere is able to reach as far as the tropical region in the summer mesosphere, where it sinks at the subtropics and grows again at the extratropical zones. This finding illustrates the role of the GW–mean flow interaction in the interhemispheric coupling process (Karlsson et al., 2009; Körnich and Becker, 2010). Nevertheless, both PW and GW forcing were found to be important to variations of the mean flow in the stratosphere. In particular, we found that the downward and upward residual circulation patterns induced by PWs and GWs counteract each other and result in a net poleward circulation in the winter stratosphere at the middle and low latitudes. In the polar winter stratosphere, the GW-induced circulation is upward and opposite the circulation induced by PWs, but the total anomalous residual circulation is downward, which is responsible for the winter stratospheric warming during the SSW period. The findings from the January 2009 major SSW event in this work shed new light on the complete atmospheric coupling during the SSW period, which also applies to other SSW events.

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References

Andrews, D. G., Holton, J. R., and Leovy, C. B. (1987). Middle Atmosphere Dynamics (pp. 490). San Diego: Academic Press.

Chandran, A., Collins, R. L., and Harvey, V. L. (2014). Stratosphere-mesosphere coupling during stratospheric sudden warming events. Adv. Space Res., 53(9), 1265–1289. https://doi.org/10.1016/j.asr.2014.02.005

Fritts, D. C., and Alexander, M. J. (2003). Gravity wave dynamics and effects in the middle atmosphere. Rev. Geophys., 41(1), 3–1.

Funke, B., López-Puertas, M., Bermejo-Pantaleón, D., García-Comas, M., Stiller, G. P., von Clarmann, T., Kiefer, M., and Linden, A. (2010). Evidence for dynamical coupling from the lower atmosphere to the thermosphere during a major stratospheric warming. Geophys. Res. Lett., 37(13), L13803. https://doi.org/10.1029/2010GL043619

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., and Zhao, B. (2017). The modern-era retrospective analysis for research and applications, Version 2 (MERRA-2). J. Climate, 30(14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

Gonzarenko, L. P., Chau, J. L., Liu, H. L., and Coster, A. J. (2010a). Unexpected connections between the stratosphere and ionosphere. Geophys. Res. Lett., 37(10), L10101. https://doi.org/10.1029/2010GL043125

Gonzarenko, L. P., Coster, A. J., Chau, J. L., and Valladares, C. E. (2010b). Impact of sudden stratospheric warmings on equatorial ionization anomaly. J. Geophys. Res. Space Phys., 115(A10), A00G07. https://doi.org/10.1029/2010ja15400

Haynes, P. H., McIntyre, M. E., Shepherd, T. G., Marks, C. J., and Shine, K. P. (1991). On the “downward control” of extratropical diabatic circulations by eddy-induced mean zonal forces. J. Atmos. Sci., 48(4), 651–678. https://doi.org/10.1175/1520-0469(1991)048<0651:OTDCOE>2.0.CO;2

Karlsson, B., Körnich, H., and Gumbel, J. (2007). Evidence for interhemispheric stratosphere-mesosphere coupling derived from noctilucent cloud properties. Geophys. Res. Lett., 34(16), L16806. https://doi.org/10.1029/2007gl030282

Karlsson, B., McLandress, C., and Shepherd, T. G. (2009). Inter-hemispheric mesospheric coupling in a comprehensive middle atmosphere model. J. Atmos. Sol.-Terr. Phys., 71(3–4), 518–530. https://doi.org/10.1016/j.jastp.2008.08.006

Karpachevo, A. Y., and Manzini, E. (2012). Stratospheric influence on tropospheric climate change in the Northern Hemisphere. J. Geophys. Res.: Atmos., 117(D5), D05133. https://doi.org/10.1029/2011JD017036

Körnich, H., and Becker, E. (2010). A simple model for the interhemispheric coupling of the middle atmosphere circulation. Adv. Space Res., 45(5), 661–668. https://doi.org/10.1016/j.asr.2009.11.001

Gu SY et al.: Atmospheric circulation due to SSW
Limpasuvan, V., Richter, J. H., Orsolini, Y. J., Stordal, F., and Kvissel, O. K. (2012). The roles of planetary and gravity waves during a major stratospheric sudden warming as characterized in WACCM. J. Atmos. Sol.-Terr. Phys., 78-79, 84–98. https://doi.org/10.1016/j.jastp.2011.03.004

Liu, H. L., and Roble, R. G. (2002). A study of a self-generated stratospheric sudden warming and its mesospheric-lower thermospheric impacts using the coupled TIME-GCM/CCM3. J. Geophys. Res. Atmos., 107(D23), ACL 15-1–ACL 15-18. https://doi.org/10.1029/2001JD001533

Liu, H. L., Marsh, D. R., She, C. Y., Wu, Q., and Xu, J. (2009). Momentum balance and gravity wave forcing in the mesosphere and lower thermosphere. Geophys. Res. Lett., 36(7), L07805. https://doi.org/10.1029/2009GL037252

Lubis, S. W., Omrani, N. E., Matthes, K., and Wahl, S. (2016). Impact of the antarctic ozone hole on the vertical coupling of the stratosphere-mesosphere-lower thermosphere system. J. Atmos. Sci., 73(6), 2505–2528. https://doi.org/10.1175/jas-d-15-0189.1

Nayak, C., and Yiğit, E. (2019). Variation of small-scale gravity wave activity in the ionosphere during the major sudden stratospheric warming event of 2009. J. Geophys. Res.: Space Phys., 124(1), 470–488. https://doi.org/10.1029/2018JA026048

Pedatella, N. M., Raeder, K., Anderson, J. L., and Liu, H. L. (2014). Ensemble data assimilation in the Whole Atmosphere Community Climate Model. J. Geophys. Res.: Atmos., 119(16), 9793–9809. https://doi.org/10.1002/2014JD021776

Yamashita, C., Liu, H. L., and Chu, X. Z. (2010). Responses of mesosphere and lower thermosphere temperatures to gravity wave forcing during stratospheric sudden warming. Geophys. Res. Lett., 37(9), L09803. https://doi.org/10.1029/2009GL042351

Yiğit, E., and Medvedev, A. S. (2012). Gravity waves in the thermosphere during a sudden stratospheric warming. Geophys. Res. Lett., 39(21), L21101. https://doi.org/10.1029/2012GL053812

Zülicke, C., and Becker, E. (2013). The structure of the mesosphere during sudden stratospheric warmings in a global circulation model. J. Geophys. Res.: Atmos., 118(5), 2255–2271. https://doi.org/10.1002/jgrd.50219