Effects of the Quasi-Biennial Oscillation and Stratospheric Semiannual Oscillation on Tracer Transport in the Upper Stratosphere

JIANCHUAN SHU

Key Laboratory for Semi-Arid Climate Change of the Ministry of Education, College of Atmospheric Sciences, Lanzhou University, Lanzhou, and Institute of Plateau Meteorology, China Meteorological Administration, Chengdu, China

WENSHOU TIAN, DINGZHU HU, JIANKAI ZHANG, LIN SHANG, AND HONGYING TIAN

Key Laboratory for Semi-Arid Climate Change of the Ministry of Education, College of Atmospheric Sciences, Lanzhou University, Lanzhou, China

FEI XIE

State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

(Manuscript received 16 February 2012, in final form 12 November 2012)

ABSTRACT

Using satellite observations together with a chemistry–climate model (CCM), the effect of the stratospheric semiannual oscillation (SAO) and quasi-biennial oscillation (QBO) on the equatorial double peak in observed CH4 and NO2 is reexamined. It is concluded that the lower-equatorial Halogen Occultation Experiment (HALOE) CH4 mixing ratio of the April double peak in 1993 and 1995 was associated with the prominent first cycle of the SAO westerlies, which causes local vertical downwelling in the upper equatorial stratosphere. The observational evidences imply that the strong westerlies of the first cycle of the stratospheric SAO in 1993 and 1995 were driven by enhanced lower-stratospheric gravity wave activity in the early parts of those years. The CCM simulations further verify that the gravity wave source strength has a large impact on the development and strength of the SAO westerlies. This result suggests that the equatorial long-lived tracer mixing ratio near the stratopause (which is associated with the strength of the SAO westerlies) was not only modulated by the QBO phase, but was also significantly influenced by interannual variation in the gravity waves. It is also found that the deeper equatorial trough of the double peak is unlikely to be always accompanied by the more prominent Northern Hemispheric lobe, and the Northern Hemispheric lobe of the double peak can be mainly attributed to subtropical upwelling. The altitude of greatest chemical destruction anomalies associated with the SAO and QBO is below the trough of the double peak, implying that the effect of the chemical process on the double peak is insignificant.

1. Introduction

Important information on the transport and overall flow of mass in the stratosphere can be obtained by analysis of long-lived chemical tracers. Two such tracers are CH4 and N2O, which have considerably longer local chemical lifetimes than transport lifetimes in the middle atmosphere, making them useful tracers for middle-atmospheric transport processes (see, e.g., Brasseur and Solomon 2005). Hence, measurements of atmospheric CH4 and N2O have been used as indicators of transport processes for many years. The first global measurements of CH4 and N2O were measured by the Stratospheric and Mesospheric Sounder (SAMS) (Drummond et al. 1980). Jones and Pyle (1984) conducted analyses of the SAMS CH4 and N2O measurements and compared the 1979 data to two-dimensional model results and other measurements. They discovered a particular discrepancy between the model and the observational data, namely a double peak that occurred in the upper...
stratosphere shortly after the equinoxes, with a relatively high mixing ratio in the subtropics of both hemispheres and a local minimum at the equator.

Gray and Pyle (1986, 1987) investigated this feature using a series of experiments based on a two-dimensional model. They attributed it to local vertical advection by the circulation induced by the westerly shear of the stratospheric semiannual oscillation (SAO). This conclusion was supported in subsequent studies (Solomon et al. 1986; Holton and Choi 1988). Further observational results revealed a double minimum in water vapor measurements from the Nimbus-7 Limb Infrared Monitor of the Stratosphere (LIMS) (Remsberg et al. 1984).

Furthermore, Ruth et al. (1997, hereafter RKG) and Randel et al. (1998) analyzed CH$_4$ variability using measurements from the Halogen Occultation Experiment (HALOE) (Russell et al. 1993), and these results were summarized by Baldwin et al. (2001). Particular attention was paid to the equinoctial double peak discussed in the previous paragraphs. A strong correlation was found between the appearance of the stratopause CH$_4$ equinoctial double peak and the phase of the quasi-biennial oscillation (QBO) in the tropical lower stratosphere, with a prominent double peak in the QBO westerly phase years (April 1993, April 1995) and a barely discernible one peak in the QBO easterly phase years (April 1994, April 1996). However, this observational result seems counterintuitive since a possible mechanism for the double peak is that the vertical propagation of eastward-propagating waves (which is responsible for the SAO westerly phase) would be more strongly damped in the lower stratosphere during the westerly QBO phase. Accordingly, this would reduce the strength of the SAO westerly phase and thereby that of the local vertical downwelling induced by the SAO. The reduced downwelling over the equator would lead to a weaker double peak when the QBO was in its westerly phase rather than during the easterly QBO phase. However, the opposite result was obtained from the HALOE observations: a clear double peak was seen in the QBO westerly phase as mentioned above. To investigate this issue and to verify whether the QBO could be responsible for the observed variation in the CH$_4$ distribution near the stratopause, Kennaugh et al. (1997) reproduced the observed variability when the QBO was introduced into a two-dimensional model. They found that the QBO indeed modulated the westerly phase of the SAO by selectively damping the parameterized waves responsible for producing the westerly phase of SAO circulation because that circulation was stronger when the QBO was easterly than when it was westerly. In their simulations, the stronger westerly SAO phase descended much more rapidly during the easterly QBO phase, so that the downwelling associated with the SAO could not remain at any one level long enough for the stratospheric tracer to respond to its presence, and thus the double peak was absent. For a westerly QBO phase, the downwelling, although weaker, was also more persistent, leading to a pronounced double peak. This result appears to explain the issue introduced above—namely, the observed double peak that occurred in 1993 and 1995—when the QBO was in the westerly phase.

However, because of the relatively short period of the HALOE data (1992–96) introduced by RKG, there are some uncertainties in the interannual variations of the double peak. Jin et al. (2009) analyzed the interannual variation in the stratopause N$_2$O measurement obtained from the Odin Submillimeter Radiometer (SMR) between July 2001 and February 2007 and found that the SMR N$_2$O anomalies between 10°S and 10°N, characterized by the first positive N$_2$O anomaly in the calendar year, occurred at relatively higher altitudes during the years 2002, 2004, and 2006 (when the QBO was in its westerly phase) and at relatively lower altitudes during the years 2003 and 2005 (when the QBO was in its easterly phase). They argued that the latter feature corresponds to the prominent N$_2$O double peak in the extratropical stratopause. However, the zonal-mean latitude–height cross section of N$_2$O was not clearly described in their paper. Data from the Aura Microwave Limb Sounder (MLS), launched in July 2004, showed interannual variation similar to that of the SMR N$_2$O field during the overlap period from August 2004 to January 2007. These recent measurements differ from those reported by RKG and Randel et al. (1998), in which the pronounced double peak feature occurred near April of 1993 and 1995, during the westerly QBO phase. Comparison of previous and current results suggests that the relationship between the interannual variation in the tracer distribution near the stratopause (which is mainly influenced by SAO circulation) and the QBO is not well understood.

Therefore, we conducted a more comprehensive analysis of the interannual variation in the stratopause double peak, including the effects of the SAO and QBO, with particular emphasis on why a strong stratopause double peak can occur in both QBO phases. The stronger strength of the first cycle than of the second cycle of the annual stratospheric SAO (Garcia et al. 1997) can be attributed to the presence of stronger dynamical forces during the Northern Hemisphere winter than during the Southern Hemisphere winter (Gray and Pyle 1986; Delisi and Dunkerton 1988), when the magnitude of the interannual variation in the stratopause double peak near October is relatively weak.
Considering this, both previous studies (RKG; Kennaugh et al. 1997; Jin et al. 2009) and our own work focus mainly on the interannual variation in the stratopause double peak occurring near April. Section 2 describes the data used in this paper. The interannual variation in the double peak near April, calculated from the HALOE and Aura MLS measurements, as well as its connection with gravity wave activity, is discussed in section 3. In section 4, the vertical velocity at the equator and in the northern subtropics is examined, and the effects of the SAO, QBO, and annual oscillation (AO) harmonics on the equatorial and subtropical vertical velocity are evaluated by Fourier analysis. Results from the Whole Atmosphere Community Climate Model, version 3 (WACCM3) model are presented in section 5. In this section, the gravity wave contribution to SAO development and the double peak is also investigated. Section 6 is concerned with the effect of chemical destruction on the double peak. A summary and discussion of the main results are given in section 7.

2. Data and model description

The data used here are the CH₄ measurements of the HALOE and the N₂O measurements from the Aura MLS. For investigating the zonal wind and vertical velocity, monthly mean European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) data are also utilized.

The HALOE instrument has been described by Russell et al. (1993), and the CH₄ data has been discussed in detail by Park et al. (1996). HALOE was a solar occultation instrument that took 15 sunrise and 15 sunset measurements per day. The latitudinal sampling progresses over time, so that approximately one month's sunset or sunrise data will cover most of the globe. The latitude range extends to a maximum of nearly ±80°. Using the same method employed by RKG, the latitude–pressure cross sections presented in this paper are composites of data from sequences of consecutive sunset or sunrise measurements. The N₂O measurements are derived from the MLS 640-GHz retrievals on the Aura satellite, with a vertical resolution of 4–5 km between 100 and 1 hPa (Lambert et al. 2007), and the N₂O latitude–height cross sections are also composed of continuous scan data.

The ERA-Interim data (Simmons et al. 2007; Uppala 2007), from the third generation of the ECMWF reanalysis product, are advanced in many ways compared to 40-yr ECMWF Re-Analysis (ERA-40) data, providing a good representation of tropical winds up to 2–3 hPa, such that the SAO and QBO amplitudes match rawinsonde and rocketsonde observations up to 2–3 hPa and are reliable up to 1 hPa (Baldwin and Gray 2005). ERA-Interim is enhanced by higher horizontal resolution with four-dimensional variational analysis, better formulation of background error constraints, variational bias correction of satellite radiance data, and improved fast radiative transfer (Sylla et al. 2009). More details on the ERA-Interim can be found on its home page (http://www.ecmwf.int/research/era/do/get/era-interim).

In this paper, we use the WACCM3 model to study the gravity wave, QBO, and SAO effects on stratospheric trace gases. WACCM3 is a fully interactive chemistry–climate model (CCM) with 66 vertical levels, extending from the surface to approximately 145 km. It is based on the Community Atmosphere Model version 3 (CAM3) and incorporates most of the new physical processes, as well as a detailed chemistry module for the middle atmosphere, with good performance for various aspects (Eyring et al. 2006). In this model, QBO is imposed by relaxing the winds to tropical observations (Calvo et al. 2010). A spectrum of vertically propagating internal gravity waves is parameterized based on the work of Lindzen (1981), Holton (1982), Garcia and Solomon (1985), and Sassi et al. (2002). The orographic gravity wave parameterization follows the approach of McFarlane (1987). More details on this model and model configurations can be found in Garcia et al. (2007) and Shu et al. (2011).

3. Interannual variations in the stratopause double peak

Based on observations from the HALOE experiment, Fig. 1 shows the stratospheric latitude–height cross sections of the CH₄ data during the equinoctial period near April for each year from 1993 to 2004. Here we simply extend the analysis of RKG to include the CH₄ field near April from 1997 to 2004. In addition, the interannual variation in the stratospheric N₂O double peak during the years 2005–08, obtained from the Aura MLS data, is shown in Fig. 2. As mentioned above, both the N₂O and CH₄ measurements can represent the character of the circulation near the stratopause and, thus, the interannual variation in the stratospheric double peak. Since the records employed here cover a longer period than those used by RKG, Figs. 1 and 2 provide more information on the double peak from the stratospheric CH₄ and N₂O fields. To diagnose double peak more quantitatively, we use the 0.5 ppmv contour of CH₄ distributions to identify strong double peaks. When the 0.5 ppmv CH₄ contour is near or lower than 2 hPa in the equatorial stratosphere and obviously bulges upward in the subtropical stratosphere, a strong double peak is thought to exist. It is apparent that the
FIG. 1. Composite latitude–pressure cross sections of HALOE CH$_4$ measurements taken near April from 1993 to 2004. Each cross section shows data from a sweep of continuous sunset or sunrise measurements taken near April. The contour interval is 0.1 ppmv with the 0.5-ppmv contour marked, and dashed vertical (horizontal) lines have been added at the equator (at 1 hPa) for clarity.
pronounced double peak near April occurred not only during the westerly phase of the QBO (1993, 1995, 1997, 1999, and 2002) but also during the QBO easterly phase (the wind QBO phase is defined by the equatorial wind at 20 hPa) during the years 2005 and 2007. In other years, the double peak was not present, or was relatively weak. Note that the stratopause double peak was strong in 2002 but absent in 2003 and weak in 2004. This result differs from that of Jin et al. (2009), who argued that the double peak was stronger in 2003 than in 2002 or 2004, based on the SMR N2O anomalies between 10°S and 10°N. However, the equatorial CH4 anomalies below 2 hPa (the upper boundary of SMR measurements) are consistent with the SMR N2O measurements, with a relatively low equatorial mixing ratio in 2003. This result suggests that the pronounced double peak is determined not only by the low equatorial mixing ratio, but also partly depends on the subtropical lobe induced by upwelling (Kennaugh et al. 1997).

Because of the short period of the HALOE measurements (1992–96) used by RKG, there is no systematic error associated with their conclusion that the appearance of the stratopause double peak was strongly correlated with the westerly phase of the QBO. However, considering the later MLS measurements, the new double peak features found during the years 2005–08 indicate that the interannual variation in the double peak is not solely associated with the phases of the QBO. In regard to the prominent double peak occurring in the years 1993 and 1995 (westerly QBO phase), but not in 1994 and 1996 (easterly QBO phase), Kennaugh et al. (1997) argued that this feature was induced by the

FIG. 2. April zonal-mean latitude–pressure cross sections of N2O (ppmv) from the MLS for the years (a) 2005, (b) 2006, (c) 2007, and (d) 2008.
Weaker modeled SAO circulation in the QBO westerly phase (1993, 1995) than in the QBO easterly phase (1994, 1996). Nevertheless, the high-resolution Doppler imager (HRDI) wind measurements indicate that the stratospheric SAO dominates throughout the lower mesosphere (about 70 km) to the upper stratosphere, and that the stratospheric SAO during the first cycle of 1993 and 1995 (during when the wind speed peaked near 50 m s\(^{-1}\) at the onset of the stratospheric SAO westerlies) was significantly stronger than in 1994 and 1996 (Baldwin et al. 2001). Those observational results imply that the prominent double peaks of 1993 and 1995 were probably associated with the strong stratospheric SAO westerlies that occurred during those years and is at odds with the simulation of Kennaugh et al. (1997) mentioned above (in which the stratospheric SAO westerlies were stronger in 1994 and 1996 during the easterly phase of the QBO). This discrepancy may be mainly due to the absence of a gravity wave–breaking parameterization scheme in their model.

Kelvin waves are thought to be essential to westerly SAO acceleration, but both observations and model simulations have indicated that they are too weak to fully drive the westerly phase of the SAO (Hamilton and Mahlman 1988; Randel and Gille 1991; Canziani et al. 1995). Hitchman and Leovy (1988) suggested that small-scale gravity waves play an important role in the descent of the SAO westerlies. Sassi and Garcia (1997) further revealed that inertia–gravity waves provide about 50% of the force driving the westerly phase of the SAO near the stratopause. From observations in the Cocos Islands (12°S, 97°E) between September 1992 and June 1998, Vincent and Alexander (2000) investigated gravity wave activity in the lower mesosphere (18–25 km) and found that QBO-like interannual variation in wave activity was very apparent early in 1993, 1995, and 1997. In addition, the wave energy was found to be propagating upward and in a predominantly eastward horizontal direction. The observations described above suggest that the prominent double peaks of 1993 and 1995 were induced by strong rather than weak stratospheric SAO westerlies (Baldwin et al. 2001) and were probably associated with the relatively intense gravity wave activity that occurred early in 1993 and 1995 (Vincent and Alexander 2000). In the following section, we will discuss interannual variations of the SAO under different phases of the QBO and their effects on the tracer transport in the stratosphere.

4. Vertical transport of tracers associated with SAO and QBO

To understand why a strong double peak occurred in the QBO westerly phase during the period 1993–96, but in the QBO easterly phase during the period 2005–08, the time series of monthly average equatorial residual vertical velocities, based on ERA-Interim data for the two periods, are shown in Fig. 3. During the period 1993–96 (Fig. 3a), equatorial downwelling in the upper stratosphere primarily occurred in the first SAO cycle, when the westerlies were stronger. As expected, the downwelling anomalies appeared at lower altitudes when the QBO easterly phase prevailed in the middle stratosphere (1994, 1996). However, upper-stratospheric downwelling was relatively pronounced in 1993 and 1995, when the QBO was in its westerly phase. Using observations from Kwajalein Island, Garcia et al. (1997) pointed out that only the altitude of maximum descent, not the strength of the SAO westerly phases in the stratosphere, was modulated by the QBO. Thus it is also accepted that a stronger descent in the upper stratosphere occurs not in the QBO easterly phase, but during the westerly phase. Prominent downwelling led to a deeper trough at the equator near April of 1993 and 1995 than in 1994 and 1996. In addition, note that the strong descent near the stratopause in 1994, which started relatively early and did not reach as low as that which occurred near April of 1993 and 1995 (although the altitude of maximum weak descent was lower in 1994), can explain the weak HALOE CH\(_4\) double peak that was observed from 5 January to 21 February, but disappeared near April in 1994 (not shown). On the other hand, the equatorial downwelling near April was evidently stronger in 2005 and 2007 during the period 2005–08 and reached a lower altitude than that observed in 2006 and 2008 in the upper stratosphere. Therefore, stronger equatorial downwelling in the upper stratosphere results in a deeper trough at the equator, thereby producing a prominent double peak. Nevertheless, it should be noted that the April N\(_2\)O mixing ratio in the upper-stratospheric subtropics was larger in 2006 and 2008 than in 2005 and 2007 (Fig. 2). This may be due to the fact that the upper-stratospheric N\(_2\)O mixing ratio was much larger in March of 2006 and 2008 than in March of 2005 and 2007, which should be associated with the interannual variation in the northern subtropical upwelling, which was stronger in March of 2006 and 2008 (not shown). It is also apparent from Figs. 1 and 2 that the deeper equatorial trough of the double peak is not always accompanied by a more prominent lobe in the Northern Hemisphere.

As discussed in section 3, there are two features that distinguish a strong double peak from a weak double peak or the absence of a double peak. One is the deep trough at the equator, induced by strong downwelling at the equator, and the other is the enhanced Northern Hemispheric lobe of the double peak, centered near
Figure 4 displays the interannual variations in the April upper-stratospheric residual vertical velocity, averaged over the equator (Fig. 4a) and 25°–30°N (Fig. 4b) for the period from 1991 to 2010. The subtropical upwelling was stronger in April of 1993 and 1995 than in April of 1994 and 1996 for the period 1993–96, and more intense in April of 2005 and 2007 than in April of 2006 and 2008 for the period 2005–08. Hence, it is clear that the combined effects of the pronounced downwelling at the equator and upwelling in the Northern Hemispheric subtropics produced the double peak. In addition, the April upper-stratospheric residual vertical velocity exhibits an evident anticorrelation between the equator and the northern subtropics, with strong/weak downwelling at the equator and enhanced/suppressed upwelling in the northern subtropics. However, the northern subtropical upwelling may not be a component of the secondary circulation corresponding to equatorial downwelling as the temporal evolution of the March residual vertical velocity does not exhibit a similar anticorrelation between the equator and the Northern Hemispheric subtropics (not shown).

To assess the contributions of the SAO, QBO, and AO to equatorial downwelling, Fourier analysis (Pascoe et al. 2005) of the equatorial zonal-mean monthly residual vertical velocity is displayed in Fig. 5. Figure 5a shows the temporal evolution of the SAO harmonics (corresponding to a period range of 4–8 months) of the
equatorial residual vertical velocity over the periods 1993–96 and 2005–08. After wave filtering, the SAO harmonics of equatorial downwelling are still stronger in 1993 and 1995 than in 1994 and 1996. Interestingly, during the period 2005–08 (Fig. 5c), the SAO variation in equatorial downwelling was relatively strong in 2006 and 2007, although the overall downwelling was more intense in 2005 and 2007. When we take the QBO harmonics (corresponding to a period range of 22–40 months) of the equatorial vertical velocity into account (Fig. 5b), the combined effects of the SAO and QBO exhibit an interannual variation similar to the overall interannual variation in the April equatorial vertical velocity. Comparing the combined interannual variation in the SAO and QBO with the overall interannual variation in the April equatorial vertical velocity over the period 1991–2010, we still obtain results similar to those mentioned above (not shown). The results reveal that the AO plays an insignificant role in the interannual variation in the equatorial vertical velocity in the upper stratosphere. This may be due to the fact that the amplitude of the equatorial AO (corresponding to a period range of 10–14 months) is much smaller than the combined effect of the SAO and QBO (Fig. 5c). However, it is worth pointing out that the AO harmonics made an important contribution to northern subtropical

FIG. 4. Evolution of the monthly mean residual vertical velocity (m s\(^{-1}\)) calculated from the ERA-Interim data in April of each year, averaged over (a) the equator (5°S–5°N) and (b) 25°–30°N. Positive values represent upwelling and negative values indicate downwelling. The plotted data range from 10 to 1 hPa.
FIG. 5. SAO harmonics calculated via Fourier analysis of the equatorial (5°S–5°N) ERA-Interim monthly mean residual vertical velocity for the periods (a) 1993–96 and (c) 2005–08. The combined SAO and QBO harmonics are shown for the periods (b) 1993–96 and (d) 2005–08. The black dashed lines indicate April of each year. (e) SAO amplitude calculated via Fourier analysis of the residual vertical velocity. The amplitude is a function of the ratio of the sum of the squares of the SAO harmonics to the sum of the squares of all harmonics; this ratio is then multiplied by the standard deviation of the residual vertical velocity to yield the SAO amplitude. The QBO, AO, and combined SAO and QBO amplitudes are also shown in (e). (f) Same Fourier analysis of the zonal wind is plotted. The lines represent the different harmonics, as indicated in the legend.
upwelling, with the maximum AO amplitude contribution ranging from 70% to 80% in the upper stratosphere (not shown). In addition, the combined SAO and QBO variations during the period 2005–08 are very significant with relatively pronounced downwelling in 2005 and 2007 (Fig. 5d). This suggests that the QBO not only modulates the SAO strength to influence the equatorial vertical velocity near the stratopause, but also has a direct impact on it. This result seems reasonable, since Pascoe et al. (2005) also concluded that the QBO response can reach as high as 50 km in the ERA-40 data. Note that the amplitudes QBO, AO, and SAO in residual vertical velocities are all peaked at the upper stratosphere at around 2–3 hPa (Fig. 5e), while the maximum QBO amplitude in the tropical zonal occurred in the middle stratosphere.

Regarding the SAO impact on the upper stratosphere, there are no symmetric vertical velocity features about the equator (not shown), which is probably related to the asymmetric SAO zonal wind. The observations suggest that the westerly phase of the stratopause SAO descends farther on the southern side of the equator during the northern spring and farther on the northern side of the equator during the northern autumn (Garcia et al. 1997). Previous studies reported that the asymmetry of the SAO is due to gravity waves (Hitchman and Leovy 1988), but gravity wave activity varies with position and time (Allen and Vincent 1995). Furthermore, we note the vertical velocity difference between the QBO easterly and westerly phases (not shown). The difference plot indicates a threefold vertical structure of the QBO vertical velocity anomalies. At the equator, the east-minus-west residual vertical velocity difference is positive in the lower and upper stratosphere and negative in the middle stratosphere; the same pattern holds in the subtropics, but with opposite signs. Pascoe et al. (2005) inferred a similar threefold structure of the QBO zonal wind differences between the two QBO phases. Baldwin et al. (2001) had noted the presence of a return arm of the local equatorial QBO circulation, with ascent (descent) in the subtropics associated with westerly (easterly) equatorial shear. It is clear that the subtropical residual vertical velocity anomalies between the QBO easterly and westerly phases are related to the circulation of equatorial anomalies, which are associated with the threefold structure of the zonal wind differences.

5. Effects of gravity waves on the double peak

In section 3, we inferred that the deep trough of the prominent double peak that appeared in 1993 and 1995 was induced by the strong westerlies of the stratospheric SAO, which were likely associated with the more intense gravity wave activity observed early in 1993 and 1995, compared with that in 1994 and 1996 (Vincent and Alexander 2000). To further quantify the effect of gravity wave forces on the stratospheric SAO westerlies and the double peak, we conducted three experiments using the WACCM3 model. In this model, unresolved gravity waves are prescribed with 64 phase speeds, and the default source amplitude is $6 \times 10^{-3}$ Pa. Moreover, the strength of the gravity wave source will vary with this tunable parameter. In the control run R0, the gravity wave source amplitude was set at the default value ($6 \times 10^{-3}$ Pa). Two additional sensitivity experiments, R1 and R2, were performed with a 20% reduction and a 20% enhancement, respectively, of the prescribed gravity wave source strength. It should be pointed out that changes in the gravity wave source strength will induce changes in wave transmission properties via changing the wind structure. However, our analysis reveals that zonal wind differences in the stratosphere between run R1 and R2 are small owing to the nudging of the same observed zonal winds (not shown).

Since the model cannot spontaneously generate the QBO (Richter et al. 2008), we employed the same method used by Calvo et al. (2010) to force the QBO signals by the observed zonal winds between 3 and 90 hPa. Although the nudging to observed zonal winds has deficiencies, for instance, it may not allow the tropical and midlatitude stratosphere to adjust spontaneously and realistically to changes in the QBO phase. However, this technique offers the advantage that the background wind field that modulates the SAO is as realistic as possible (Kennaugh et al. 1997), and the forced QBO with nearly realistic strength and synchronization allows us to make meaningful comparisons of influence on the SAO for a specific period between the net QBO modulation and actual atmosphere. On the other hand, the main focus of this study is the effect of the QBO on the tracer transport in the stratosphere rather than the two-way interaction between the QBO and the stratospheric circulation. Therefore, the WACCM3 model with forced QBO is able to address the main issue of this study. All the three experiments were run for 20 years and the QBO was forced by observed zonal winds from January 1980 to December 2000. Figure 6 displays the equatorial time series of the modeled zonal-mean zonal winds in the last 10 years of model simulation, and Fig. 6b presents the ERA-Interim reanalysis zonal winds in the tropics for the time period from January 1991 to December 2000. The tropical zonal winds in the nudged experiment are overall in agreement with the ERA-Interim in the structure of the QBO jets below 3 hPa, where wind observations exist. The descending shear regimes of the QBO can be seen, with
those of the SAO overlying them (Fig. 6a). In particular, the SAO westerlies are suppressed in the nudged QBO experiment when there are westerlies at 20 hPa, but strengthen and descend lower during the QBO easterly phase. This result is consistent with the mechanism that the vertically propagating waves responsible for the westerly phase of the SAO will be more strongly filtered in the lower stratosphere when the QBO is westerly than when the QBO is easterly (Andrews et al. 1987; RKG). Note that in the ERA-Interim data, the annual asymmetry between the two SAO cycles is more pronounced than in the model experiments, and is generally more variable, whereas the evolution of SAO is relatively regular in the simulation owing to the fact that the gravity wave source strength is fixed in the model and there are no interannual variations in SSTs and greenhouse gas (GHG) conditions. In addition, the position of the simulated SAO maximum is about 10 km higher than that of the ERA-Interim data. This is a consequence of the too-low-resolved driving wave in the WACCM3 model, which is one reason why the model does not produce the QBO spontaneously. However, the higher position of the SAO maximum in the model may not significantly affect the main conclusions of this work, as we are mainly concerned with verifying that the gravity wave can directly influence SAO strength, thereby modulating the interannual variation in the double peak. Since the model is unable to reproduce the observed SAO, the relative weakness and high location of the maximum imply that equatorial downwelling did

Fig. 6. Zonal-mean zonal wind (m s\(^{-1}\)) at the equator, averaged between 5°S and 5°N for (a) the control run R0 and (b) the ERA-Interim. Note that the vertical ranges of the two panels are different.
not last until the end of April in some years, as will be explained below. Thus, to evaluate the effect of the SAO on the double peak, we mainly focus our analysis on the model results for March. The modeled stratospheric CH₄ mixing ratios in March for the easterly QBO phase, the westerly QBO phase, and the difference between the two QBO phases are shown in Fig. 7. In contrast to the 1993–96 observations of RKG and the model results obtained by Kennaugh et al. (1997), our simulated double peak is evidently more prominent during the QBO easterly phase, with a lower CH₄ mixing ratio at the upper-stratospheric equator and a higher value in the subtropics (Fig. 7c). This feature is associated with the stronger downwelling at the equator (at the same position where the relatively low CH₄ mixing ratio occurs) and the stronger upwelling in the subtropics during the easterly phase in March, compared to the westerly phase in March (not shown). The simulated results suggest that the net effect of the QBO gives rise to stronger SAO westerlies during the easterly QBO phase (when a relatively prominent double peak occurs) but not during the westerly QBO phase (Fig. 7). The difference between the modeled and the observational anomalies during 1993–96 suggests that other interannual variations also play an important role in modulating interannual SAO variation, thereby affecting the interannual variation in the double peak. Regarding these interannual variations, as was noted in section 3, Vincent and Alexander (2000) found that the interannual variation in gravity wave activity occurred early in 1993 and 1995, with maximum energy densities of about 25 J kg⁻¹, and that the wave energy propagated upward, with predominantly eastward horizontal propagation. Thus, we restrict our attention primarily to a discussion of the gravity waves and are particularly interested in the effect of gravity waves on the SAO and the double peak. In addition, there is a CH₄ mixing ratio difference between the QBO westerly and easterly phases in the middle and lower stratosphere (Fig. 7c). This result is related to the secondary circulation induced by the QBO. A more comprehensive analysis of the QBO and the lower and middle stratospheric CH₄ mixing ratio differences is outside the scope of this paper.

Figure 8 shows time series of zonal-mean zonal winds for R1 (20% gravity wave reduction) and R2 (20% gravity wave increase) at the equator for the same period used in Fig. 6. As expected, the strength of the SAO westerlies generally decreased in R1 and increased in R2. Furthermore, the SAO westerlies extended to lower altitudes in R2 as the gravity wave amplitude is increased (Fig. 8a). Changes in gravity wave activities can directly influence the strength and evolution of the SAO westerlies (Sassi and Garcia 1997). On the other hand, changes in the gravity wave source can influence the SAO indirectly via the BD circulation. Figure 9 shows annual mean EP flux vectors in run R1 and the differential EP flux vectors between runs R2 and R1. We can see a 20% increase in the gravity wave source tends to strengthen the BD circulation and the residual vertical velocity \( \hat{w} \) at 100 hPa averaged over the tropics in run R2 is increased by about 8% in comparison to the run R1. Apart from the significant change in the BD circulation in the tropics caused by increased gravity wave source, the EP flux at middle and high latitudes is also largely altered by the gravity wave source change. The
altered BD circulation also may have an impact on the SAO through meridional advection of zonal wind. In any case, comparison of the results of these experiments verifies that gravity waves have a significant impact on the SAO westerlies.

Compared to the control run R0, the SAO westerlies generally became more intense in R2, even during the QBO westerly phase, when the vertically propagating waves that drive the SAO westerly phase were strongly damped. However, the SAO westerlies were weaker in R1 than in R0, when there were easterlies at 20 hPa. Comparison of R0, R1, and R2 confirms the possibility that SAO westerlies during the QBO westerly phase can be more pronounced than in the QBO easterly phase when gravity waves are significantly stronger in the former QBO phase than in the latter. Although the model results regarding the SAO and gravity waves do not directly validate the stronger SAO westerlies, the anomalies of 1993 and 1995 (QBO westerly phase) were driven mainly by the interannual variation in the gravity

FIG. 8. (a) Maximum pressure of SAO westerlies descent in run R1 (solid line) and R2 (dash line), and the evolution of the equatorial average zonal wind in run (b) R1 and (c) R2. A horizontal black dashed line has been added at 0.5 hPa for clarity in (b),(c).
waves. At the very least, this suggests that the interannual variation in gravity waves was a robust factor driving the SAO westerly anomalies during the period 1993–96.

To further investigate the strength of the SAO westerlies and the vertical velocity, monthly mean climatologies of the equatorial zonal wind and vertical velocity in the last 10 years of simulation in control run R0 are shown in Fig. 10, together with the equatorial zonal wind and vertical velocity differences between R0, R1, and R2. The simulated equatorial zonal wind exhibits a semiannual oscillation (Fig. 10a) similar to that of the earlier SAO study, but the amplitude of the modeled SAO (which was stronger during the Northern Hemisphere winter, according to observations) and ERA-40 data (Delisi and Dunkerton 1988; Pascoe et al. 2005; Swinbank and O’Neill 1994) showed a much smaller difference between the first semiannual cycle (beginning in the Northern Hemisphere winter, December–May) and the second semiannual cycle (beginning 6 months later, June–November) (Delisi and Dunkerton 1988). In the ERA-40 data, the first cycle of the SAO westerlies lasted until July, and the second cycle of the SAO westerlies lasted until December (Pascoe et al. 2005). In this case, possibly for the same reason that contributed to the higher position of the simulated SAO maximum mentioned above (Fig. 6), the persistence of the simulated SAO westerlies is also relatively weak. Consequently, the first cycle of semiannual downwelling begin in November and could not last until April (Fig. 10c).

In our simulations, the altered strengths of the gravity wave source in the different runs lead to noticeable differences in the SAO equatorial zonal winds (Figs. 10b,c,d). Regarding the equatorial zonal winds ranging from 100 hPa to the upper stratosphere, wherever the zonal winds are driven by observed data, there is little variation among the three runs. The changes in the SAO westerlies and easterlies are concentrated at their respective lower limits, as shown in Fig. 10a, but are not close to the SAO maximum. This may be because the

![Fig. 9. (a) Annual mean EP flux (kg s\(^{-2}\)) vectors from run R1 and (b) the differential EP flux vectors between runs R2 and R1. The unit vectors are shown to the top right of each panel. Note that the unit vectors are different between two panels.](image-url)
strengths of both the westward-propagating and eastward-propagating gravity waves are altered in the different runs. As the eastward-propagating gravity waves are enhanced, the westerlies should become stronger and reach lower altitudes in comparison to the simulated results obtained with the relatively weak gravity waves of the source strength experiment. At the same time, the easterlies should exhibit similar evolution features as the westward-propagating gravity waves increase. Thus, the upper region of the background westerlies and easterlies, exhibited in the control run R0 (Fig. 10a), is weakened when the strength of the gravity waves increased, while the lower region reaches lower altitudes and displays a stronger signal. This result explains why the differences between the positions of the westerlies and easterlies in the three experiments are not consistent with those of the background westerlies and easterlies. Corresponding to the zonal wind anomalies, the vertical velocity shows similar evolutionary differences among the three runs, with strengthened downwelling/upwelling near the lower region of background downwelling/upwelling (Figs. 10f,g,h).

The SAO westerlies cause anomalous downwelling, which increases as the SAO westerlies strengthen.

FIG. 10. Seasonal variations in the equatorial wind in (a) the control run R0, and the differences (b) R0 – R1, (c) R2 – R0, and (d) R2 – R1. (e)–(h) Vertical velocity (m s\(^{-1}\)) results corresponding to (a)–(d). The data plotted are 10-yr (1991–2000) average climatologies.
Therefore, the equatorial vertical velocity displays a downwelling anomaly as gravity wave activities are enhanced, and the anomaly descends with the SAO westerlies. In particular, the downwelling anomaly difference between R1 and R2 is generally larger than the other two equatorial vertical velocity discrepancies (R0–R1 and R2–R0).

Recall that in an earlier study mentioned above (Vincent and Alexander 2000), gravity wave activity in the lower stratosphere occurred early in 1993, 1995, and 1997, with maximum energy densities of about 25 J kg\(^{-1}\). The wave energy was found to be propagating upward and in a predominantly eastward horizontal direction. In contrast to this, because of deficiencies in the model, we are only able to change the strength of the gravity source in our simulations. In this case, the altered strength of the gravity waves is almost isotropic in the horizontal direction for the three runs. However, based on the present simulated results, we can assume that if only the eastward-propagating gravity wave activity are increased, there would be a more profound SAO westerlies anomaly, as well as stronger and more persistent downwelling induced by the SAO westerlies.

The CH\(_4\) mixing ratio is directly affected by the SAO circulation. In the tropics, the CH\(_4\) mixing ratios in March (Fig. 11) decrease with enhanced gravity wave strength, which is induced by tropical downwelling anomalies. In the subtropics, there are upwelling anomalies (not shown), accompanied by tropical downwelling anomalies when the strength of the gravity waves increased. However, gravity wave changes also have a significant impact on Brewer–Dobson circulation, which strengthens as wave activities increase (Fig. 9). Therefore, the CH\(_4\) mixing ratios are generally lower in the Northern Hemispheric upper stratosphere, and although subtropical upwelling is enhanced, the subtropical CH\(_4\) mixing ratio still decreases because of the enhanced BD circulation when the gravity wave strength increased.

6. Chemical budget contribution to the equatorial CH\(_4\) mixing ratio

The model can also be used to study the contribution of chemical processes to the development of the double peak. The decreasing CH\(_4\) mixing ratios in the middle and upper stratosphere can also be caused by chemical destruction (Röckmann et al. 2004). Although dynamical processes play a significant role in the formation of the double peak, the anomalous chemical reaction induced by SAO downwelling may also have an impact on the double peak. Downwelling reduces the upper-stratospheric ozone column, and thinning of the upper-stratospheric ozone column can undoubtedly cause an increase in O(\(^1\)D) and OH levels, resulting in more efficient CH\(_4\) oxidation (Röckmann et al. 2004). There is a similar chemical destruction effect for N\(_2\)O caused by the enhanced photolysis reaction with the thinner ozone column and increased O(\(^1\)D). Röckmann et al. (2004) found that a reduction of the upper-stratospheric partial ozone column by only 5% in the 1–10-hPa region can lead to more efficient oxidation of CH\(_4\).

The time series of the equatorial CH\(_4\) chemical net production rate in the control run R0 is shown in Fig. 12a. Note that CH\(_4\) chemical net production rate also displays a semiannual behavior, with minima near March.
and September. The \(^4\text{CH}\) chemical net production rate is negative throughout the stratosphere, with a minimum centered at around 1.5 hPa, which is lower than the lowest position attainable by SAO-induced downwelling, and also lower than the altitude of the simulated double peak trough (Fig. 7). To determine whether or not the position of the \(^4\text{CH}\) chemical net production rate minimum is impacted by SAO downwelling, we performed a free-running experiment, which does not reproduce the QBO (non-QBO). The corresponding result from non-QBO experiment indicates that the SAO is more pronounced than in the QBO experiment (not shown), and extends farther down, in accordance with results obtained by Punge and Giorgetta (2008). Corresponding to the lower SAO downwelling in the non-QBO experiment, the \(^4\text{CH}\) chemical net production rate minimum concentrates at 2 hPa and exhibits a semiannual behavior similar to that of the QBO experiment (not shown). These results reveal that the \(^4\text{CH}\) chemical net production rate minimum is associated with SAO downwelling, which induces a thinner ozone column and hence leads to intensified destruction of \(^4\text{CH}\), as noted above.

To distinguish the relative importance of transport and chemical processes in the modeled \(^4\text{CH}\) mixing ratio, it is instructive to quantify the transport contribution. The total transport contribution can be obtained by summing the advection and eddy transport terms in the
transformed Eulerian mean (TEM) formulation of Andrews et al. (1987), which has been used to evaluate CH4 and N2O transport (Strahan et al. 1996). It is clear that the CH4 transport tendency is linked with SAO downwelling, with a minimum centered at 0.5 hPa (Fig. 12b), which is close to the lower limit of SAO downwelling. The transport tendency is of the same order of magnitude as the chemical tendency, but its minimum is approximately 2 times larger than the chemical tendency minimum. The combined transport and chemical contribution to the CH4 tendency is shown in Fig. 12c, and the tendency minimum is still located at 0.5 hPa, where the double peak trough occurs. It appears that transport (both the advection and eddy components) is the dominant factor impacting on semiannual behavior of CH4 field in the tropics, which is consistent with the conclusions of Randel et al. (1998).

7. Summary and discussion

Stratospheric CH4 observations from HALOE and N2O measurements obtained by the MLS have led to differing accounts of interannual variation in the stratosphere. In 1993 and 1995 was induced by the strong westerlies of the stratospheric SAO, in contrast to the speculation in Kennevagh et al. (1997) that a pronounced double peak was associated with the weak stratospheric SAO westerlies during the westerly QBO phase. However, this result raised the question of what caused the SAO westerlies during the period 1993–96 to be stronger in 1993 and 1995 (westerly QBO phase), when the vertically propagating waves driving these westerlies were strongly damped in the lower stratosphere. The strong SAO westerlies in early 1993 and 1995 can be attributed to gravity wave activity but not only modulation by the QBO phase.

Using the WACCM3 model, it is further verified that gravity waves have an important impact on the strength and lower limit of the SAO westerlies. Because of the limitations of the model, the changes in gravity wave strength are almost isotropic in the horizontal direction. As the gravity wave source strength increased, the lower limit of the SAO westerlies strengthened and moved further downward, owing to the enhanced eastward propagation combined with the increased westward propagation of gravity waves (which intensifies the evolution of the SAO easterlies and thereby weakens the upper region of the SAO westerlies). We assume that if only eastward-propagating gravity wave activity increased, there would be a more profound SAO westerlies anomaly as well as stronger and more persistent downwelling induced by the SAO westerlies.

The stratospheric double peak of long-lived chemical constituents consists of an equatorial low mixing ratio and an enhanced northern subtropical constituent field — namely, the Northern Hemispheric lobe of the double peak. In comparison to the strong northern subtropical lobes of 1993 and 1995, when the double peak occurred, later observational features imply that the deeper equatorial trough of the double peak does not always correspond to a more prominent northern subtropical lobe, which is mainly influenced by northern subtropical upwelling. As explained above, northern subtropical upwelling is also modulated by the SAO, QBO, and AO. Both the SAO and QBO harmonics have large impacts on the northern subtropical upwelling. The AO makes a significant contribution to northern subtropical upwelling, with a maximum amplitude contribution ranging from 70% to 80% in the upper stratosphere.

The SAO westerlies cause equatorial downwelling, which decreases the upper-stratospheric ozone column at the equator. Thinning of the upper-stratospheric ozone column leads to increased O(1D) and OH levels and thereby induces more efficient CH4 destruction. According to the model results, the equatorial chemical trend shows a semiannual variation, with minima near March and September. However, the altitude of maximum chemical destruction is located below the trough of the double peak, which is dominated by advection and eddy transports, according to the transformed Eulerian mean formulation.

Acknowledgments. This work was supported by the National Science Foundation of China (41175042 and 41225018) and National Basic Research Program of China (2010CB428604). We thank the Fundamental Research Funds for the Central Universities of China (lzujbky-2012-k04). We also thank two anonymous reviewers and the editor for their helpful comments.

REFERENCES


Jin, J. J., and Coauthors, 2009: Comparison of CMAM simulations of carbon monoxide (CO), nitrous oxide (N2O), and methane (CH4) with observations from Odin/SMR, ACE-FTS, and Aura/MLS. Atmos. Chem. Phys., 9, 3233–3252.


Simmons, A., S. Uppala, D. Dee, and S. Kobayashi, 2007: The ERA interim reanalysis. ECMWF Newsletter, No. 110, ECMWF, Reading, United Kingdom, 25–35.


