Relation between Equatorial Mesospheric Wind Anomalies during Spring and Middle Atmosphere Variability Modes

Christoph Zülicke and Erich Becker
Leibniz Institute of Atmospheric Physics, Kühlungsborn, Germany

Abstract

Strong easterly wind anomalies in the equatorial upper mesosphere were observed during northern hemispheric spring equinox. While the anomalies are mainly related to the semi-annual oscillation (SAO) in the stratopause region and to the quasi-biennial oscillation (QBO) in the stratosphere, an additional influence of sudden stratospheric warmings (SSWs) was recently suggested.

In order to analyze this relation, we use an 18-year simulation of the Kühlungsborn Mechanistic Circulation Model (KMCM) that includes these middle atmosphere variability modes. We compute composites for the different phases of the QBO and intensities of SSWs. The results support the notion that easterly equatorial mesospheric wind anomalies occur during spring equinox if the QBO is in its westerly phase. In addition we show that this relation does not hold when the preceding winter is characterized by strong SSWs. We interpret this phenomenon as a result of a persistent strengthening of the residual circulation in the equatorial stratopause region.

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1. Introduction

The variability of the zonal wind in the equatorial middle atmosphere is driven by the annual cycle of solar insolation and by waves. Equatorially trapped Kelvin waves and Rossby-gravity waves, as well as mesoscale gravity waves (GWs) are responsible for the quasi-biennial oscillation (QBO). In addition, they modulate the semi-annual oscillation (SAO) in the stratopause region and contribute to the wind variations in the mesosphere (Andrews et al. 1987; Baldwin et al. 2001; Plumb 2002; Fritts and Alexander 2003; Haynes 2005; Shepherd 2007). Observations of inter-annual (year-to-year) variations of winds in the equatorial upper mesosphere (80–100 km) are available for the last decades (Garcia et al. 1997; Day and Mitchell 2013; de Wit et al. 2013; Kishore Kumar et al. 2014). Strong easterly wind anomalies during early spring (so-called Mesospheric Spring Equinox Enhancements, MSEE) are usually observed during the westerly phase of the QBO (hereafter: QBO-West) (Garcia et al. 1997), but not in all years. As suggested in Kishore Kumar et al. (2014) (referred to as KK14), MSEEs are lacking during QBO-West when the northern hemisphere was subject to strong sudden stratospheric warmings (SSWs). In the present study we analyze this relation in model data and propose a dynamical mechanism.

This task requires a general circulation model (GCM) that includes the entire middle atmosphere and has a proper representation of the QBO. Such models were used to study the vertical coupling between stratosphere and mesosphere for the QBO (Kawatani et al. 2010; Kawatani and Hamilton 2013; Richter et al. 2014), the SAO (Peña-Ortiz et al. 2010; Smith 2012), and SSWs (Liu and Roble 2002; Harada et al. 2010; Richter et al. 2010; Miller et al. 2013; Zülicke and Becker 2013).

Though linked to the annual cycle, the SAO is strongly wave-driven and interacts with the cross-equatorial residual circulation around the stratopause. Since this nonlinear advection is approximately angular-momentum conserving and emanates in the summer subtropics, it is characterized by a distinct easterly maximum above the equator (Dunkerton 1989; Semeniuk and Shepherd 2001a, 2001b). This “easterly nose”, as it was termed by Sassi et al. (1993), does usually not occur during the transition phases between winter and summer which are characterized by weak westerlies. The mean winds in the stratosphere and stratopause region determine the propagation conditions for equatorial planetary waves and GWs, and they thereby affect the mesospheric winds (Dunkerton 1982). For example, the filtering of easterly GWs by the “easterly nose” supports the appearance of westerlies at greater height in the mesosphere.

The QBO shows up as a vertically and temporally alternating pattern in the equatorial stratosphere. Sometimes, even three vertically aligned QBO phases can be identified (Pascoe 2005). Corresponding correlations were found, e.g., in simulations with the Hamburg Model of the Neutral and Ionized Atmosphere (HAMMONIA) of Peña-Ortiz et al. (2010) (referred to as PO10).

The possible effect of SSWs on the residual circulation in the equatorial stratosphere can be deduced from a composite analysis based on a permanent January simulation with the Kühlungsborn Mechanistic Circulation Model (KMCM). Becker (2012) compared in his Fig. 8 the SSW composite against the model climatology in order to illustrate the global pattern of the interhemispheric coupling mechanism (e.g. Körnich and Becker (2010) and Karls- son and Becker (2016)). Focusing on the equatorial region, we can conclude that SSWs are not only associated with an intensification of the extratropical residual circulation in the stratosphere, but are also linked to a significant amplification of the residual circulation in the equatorial stratopause region, and hence, to a stronger “easterly nose”. Hence, it is possible that when the “equatorial nose” persists until early spring due to strong Rossby-wave activity (and SSWs), the MSEE is suppressed due to filtering of easterly GWs around the stratopause.

In this paper we aim to analyze the relations between MSEE and SAO, QBO and SSWs. For this purpose we employ a new version of the KMCM that is run with a full annual cycle and a self-generated QBO. In particular, we aim to provide evidence that strong SSWs suppress the occurrence of MSEE during QBO-West.

2. Model description

The KMCM is a mechanistic GCM from the surface to about 130 km height (uppermost level around 0.000025 hPa). It is used here with a horizontal spectral resolution of T42 and with 116 hybrid levels including a level spacing of about 650 m in the stratosphere. In combination with a parameterization of GWs, such a level spacing is required for a self-generated QBO. The KMCM employs an extended Doppler-spread parameterization (Becker and McLandress 2009) for non-orographic GWs and the scheme of McFarlane (1987) for orographic GWs. As usual in models with a self-generated QBO, the parameters for the non-orographic GWs are adjusted in the tropics independently from the extratropics.

The KMCM includes explicit computations of radiative transfer and the tropospheric moisture cycle. Land–sea contrasts
are taken into account in terms of orography, land–sea masks for several parameters (relative humidity, heat capacity, and albedo), and a slab ocean with prescribed lateral heat flux convergence. Though these model components are strongly idealized compared to comprehensive models, they allow to simulate the general circulation quite reasonably. Further details of the model can be found in Becker et al. (2015) and Karlsson and Becker (2016).

After equilibration to the model climatology, it was integrated for another 18 years. The model output was archived every 3 hours. We computed time series of zonal-mean fields averaged over subsequent 5-day bins. This way we suppress fluctuations which are faster than the approximate radiative time scale in the middle atmosphere (~7 days).

3. Results and discussion

As an illustration of the simulated equatorial dynamics, Fig. 1a shows the first 5 years of the zonal wind. The QBO signal at about 10 hPa and the SAO signal at about 1 hPa are evident. At about 0.01 hPa the dynamics is quite complex while a SAO signal is also prominent in the upper model domain. The vertical profile of the corresponding quasi-amplitude (defined here as the standard deviation times square-root of two $A_{\text{quasi}} = \sqrt{2}\sigma_u$, Fig. 1b) indicates high variability between 10 and 0.001 hPa. The level of 0.01 hPa is taken to diagnose the MSEE variability.

The time series of the zonal wind at the “MSEE level” of 0.01 hPa (Fig. 2a) shows one strong easterly peak with $-57$ m s$^{-1}$ at 2.1 years (actually, the strongest in the record) and another one with $-25$ m s$^{-1}$ at 4.07 years. In order to select the spring equinox anomalies, we define the spring as the time-of-year from 0.05 to 0.35 (respectively mid-January to mid-May). With this definition and a threshold of $-20$ m s$^{-1}$ as in KK14, we find in Fig. 2a MSEE events in 5 out of 18 years - roughly every third year.

The mean annual cycle of the monthly-mean zonal wind at 0.01 hPa is shown in Fig. 2b. It ranges between about 5 and 20 m s$^{-1}$ but has inter-annual fluctuations of about $\pm 15$ m s$^{-1}$. The maximum easterly wind amounts to about $-60$ m s$^{-1}$ which is about two thirds of the largest observed peak value (KK14). From our model data we can find 60 events of easterly wind anomalies if we apply a threshold value of $-20$ m s$^{-1}$. Out of these, 16 events occur during spring, including the three strongest events.

In the following we relate the MSEE to middle atmosphere variability modes in terms of SAO, QBO, and SSWs. The time series of the zonal wind at the “SAO level” of 1 hPa is shown in Figure 3a. It shows the typical semi-annual cycle, including mainly westerly winds during spring as expected. For the detection of the vertical SAO influence we fit a harmonic function

$$u_{\text{SAO}}(t) = A_{\text{SAO}} \cos(\omega_{\text{SAO}} t + \phi_{\text{SAO}})$$

with $\omega_{\text{SAO}} = 2\pi/(0.5 a)$ at each level to the zonal wind. The amplitude profile (Fig. 3b) shows a distinct peak of 28 m s$^{-1}$ around 1 hPa which falls between the observed value of 33 m s$^{-1}$ given by Baldwin et al. (2001) (referred to as B01) and a value of $20-25$ m s$^{-1}$ given by KK14. The SAO amplitude minimizes at 0.01 hPa (80 km) and then increases with altitude, reaching 23 m s$^{-1}$ at the model top (~130 km). The compilations of B01 show a peak value of 31 m s$^{-1}$ at 81 km, while the data of KK14 (their Fig. 3) vary between 10 and 25 m s$^{-1}$ above 80 km. Both datasets show a decrease of the SAO amplitude farther above which is not present in Fig. 3b. In the height-time plot of annual variability (Fig. 3c)
1c) instead we identify SAO-related variations around $5 \times 10^{-3}$ and $10^{-2}$ hPa. Similar structures are found in satellite data (Smith 2012; Smith et al. 2017) and in other model simulations (PO10). The agreement of these mesospheric SAO structures with the present simulation is only qualitative.

The QBO timing is analyzed from the zonal wind time series at 10 hPa (see Fig. 4a). During the first 5 years of the simulation we find during spring 3 years with QBO-East, and 2 years with QBO-West. Taking into account all 18 spring seasons of the simulations, we find 13 QBO-East and 5 QBO-West. The continuous time series exhibits 10 minima and 12 maxima which corresponds to quasi-periods of 1.8 and 1.5 years. Both estimates are well below the observed values of 28 months respectively 2.3 years (B01). Hence, the simulated QBO is clearly faster than observed but qualitatively well reproduced. A harmonic analysis

$$u_{\text{QBO}}(t) = A_{\text{QBO}} \cos(\omega_{\text{QBO}} t + \phi_{\text{QBO}})$$

with the period from the minimum count ($\omega_{\text{QBO}} = 2\pi/(1.8 \text{ a})$) is used to construct the amplitude profile shown in Fig. 4b. The stratospheric peak (16 m s$^{-1}$ at 10 hPa) is at a higher altitude compared to the B01 observations (19 m s$^{-1}$ at 29 hPa) and smaller than in the PO10 simulations (25 m s$^{-1}$ at 10 hPa). Farther above, the amplitude is small and oscillates with altitude which is similar to the behavior found by PO10. A distinct mesospheric peak as found by B01 is missing in both models. We can conclude that the stratospheric QBO signal is sufficiently well simulated in both models, while the mesospheric QBO signal is too weak.

SSWs are detected in the simulation as follows: The 10 hPa zonal-mean zonal wind at 70$^\circ$N is tested for easterlies in the winters between time-of-year 0.88 (middle of November) and 0.25 (end of March) of the following year. If there is at least one 5-day bin with easterlies, the winter is classified as “strong SSW”, otherwise as “weak SSW” (including the absence of warmings). With this ad-hoc criterion, we find 8 strong-SSW cases for the 16 simulated winters. This is only slightly less than the observed 0.60 major warmings per year according to the WMO definition (Charlton and Polvani 2007). Although we use a slightly higher altitude and longer temporal sampling, we may consider the simulated SSW frequency as nearly realistic.

Before constructing composites we verify that the years with strong and weak SSSWs and with easterly and westerly QBO are sufficiently well distributed. Actually we find 8 QBO-East and 2 QBO-West phases in weak-SSW winters, while in strong-SSW winters we find 5 samples with QBO-East and 3 with QBO-West. Hence, for each SSW–QBO combination we have at least 2 samples and a composite analysis can be performed. From this analysis we expect a hint on the underlying physical mechanisms rather than statistically robust results.

Figure 5a shows the QBO composite difference of the zonal-mean zonal wind,

$$\Delta u_{\text{QBO}} = \langle u \rangle_{\text{QBO-East}} - \langle u \rangle_{\text{QBO-West}}$$

during spring. Several vertically aligned dipole-like patterns with a westerly wind maximum on top of an easterly wind maximum are found above the equator. The first dipole extends from 70 to 5 hPa, the second dipole reaches up to about 0.5 hPa, and the third dipole extends up to about 0.05 hPa. A fourth dipole with weak wind maxima can be seen in the upper mesosphere.

This equatorial pattern corresponds well to Fig. 9a of PO10. It is also interesting to note that de Wit et al. (2013) found similar structures in correlations between the mesospheric and stratospheric monthly-mean winds. In particular, they found a positive correlation of the 90 km wind with the 70 hPa wind, while the correlation was negative for 20 hPa. This corresponds in our Fig. 5a to the combination of a negative anomaly at 0.01 with a negative anomaly at 50 hPa and with a positive anomaly at 10 hPa.

The SSW composite of wind anomalies is constructed from the difference between strong-SSW winters and weak-SSW winters according to

$$\Delta u_{\text{SSW}} = \langle u \rangle_{\text{strong-SSW}} - \langle u \rangle_{\text{weak-SSW}}$$

Figure 5b shows the result. In addition to the expected easterly anomaly of the polar night jet north of 50$^\circ$N extending from 100 to 0.1 hPa, we find an easterly anomaly in the tropics between 10 and 40 hPa that is indicative of the Holton-Tan effect (e.g., Baldwin and Dunkerton (1998)). Around the equatorial stratosopause (between 1 and 0.3 hPa) there is another easterly anomaly which corresponds to the aforementioned “easterly nose”. Hence, the notion that the residual circulation around the equatorial stratosopause is amplified during SSWs is confirmed by the present model simulation.

To analyze the effect of SSSWs on MSEE, we split the QBO composite difference into weak-SSW and strong-SSW winters (Fig. 6). The dipole-structure in the tropical lower stratosphere, with a westerly wind maximum on top of an easterly wind maximum, is very similar in both panels and hence hardly affected by SSSWs. At greater heights in the tropics, however, the QBO composite difference for weak-SSW winters deviates significantly from that for strong-SSW winters. In particular, the dipole structure from about 0.03 to 0.0001 hPa, with easterlies around 0.01 hPa (the MSEE) is well pronounced for weak-SSW winters, but is no longer visible in the QBO composite difference for strong-SSW winters. In other words, the MSEE is less likely when the polar vortex is perturbed by SSSWs. This is consistent with the finding of KK14.

Our model simulation allows to interpret this phenomenon with the following mechanism: During strong-SSW winters the cross-equatorial circulation and the “easterly nose” are stronger than...
During weak-SSW winters (Fig. 5b). This gives rise to enhanced breakdown of easterly tropical GWs around the stratopause such that these GWs are no longer available to force an MSEE around 80 km. Figure 6 furthermore indicates that the “easterly nose” around 0.3 hPa above the equator is more persistent during springtime after a winter with strong SSWs when the QBO is in its westerly phase.

4. Summary and conclusions

In this paper we analyze variability modes of the middle atmosphere with respect to the QBO, the SAO, and SSSW during northern hemispheric spring on the basis of an 18-year model simulation. For this purpose, the KMCM as described in Becker et al. (2015) is used in a version with increased resolution and a special tuning of GWs in the tropics such as to simulate a self-generated QBO. We find that the wind amplitudes of the stratospheric QBO and SAO are roughly realistic, that the QBO period is too short, and that SSSWs occur with nearly realistic frequency. In the mesosphere, the comparison with observations suggests a qualitative agreement. The model data also show the strong easterly wind anomalies in the equatorial upper mesosphere around northern hemispheric spring equinox (so-called MSEE) that were observed by KK14.

The composite difference between strong-SSW and weak-SSW winters is found to be correlated with the easterly phase of the QBO, as is expected from the Holton-Tan effect (Fig. 5b). Additionally, this composite difference shows that the cross-equatorial circulation, which is associated with an easterly wind maximum around 0.3 hPa, is amplified during strong-SSW winters. The composite difference between QBO-West and QBO-East during northern hemispheric spring confirms the easterly wind maximum in the tropical upper mesosphere (MSEE). Splitting this composite difference into the contributions from strong-SSW and weak-SSW winters (Fig. 6), we confirm the suggestion of KK14 that the MSEE does not occur after a strong-SSW winter. We interpret this phenomenon as a result of the filtering of eastward GWs by the aforementioned persistent easterly wind maximum around the tropical stratopause that is amplified during phases of a stronger residual circulation in the northern stratosphere as is the case during SSSWs.

Although MSEE, SSW, QBO, and SAO are reproduced by the model, their amplitudes are smaller than observed. Furthermore, their seasonal dependence is not as clear as in observations and a statistically robust quantification of the proposed mechanism is not possible on the basis of the 18-year-long model dataset. Further improvement of the model is therefore required for a more realistic simulation of the relevant dynamical components. Nevertheless, we consider it encouraging that middle atmosphere GCMs with parameterized GWs can simulate a complex phenomenon of long-term internal variability like MSEE that results from the interaction of several variability modes.

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