Quantification of the contribution of equatorial Kelvin waves to the QBO wind reversal in the stratosphere

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[1] Both global scale waves (e.g., Kelvin, equatorial Rossby, or Rossby-gravity waves) and mesoscale gravity waves contribute to the wind reversals of the quasi biennial oscillation (QBO). The relative contributions of the different wave types are highly uncertain. In our work we quantify the contribution of equatorial Kelvin waves to the reversal from stratospheric easterlies to westerlies averaged over two QBO cycles in the period 2002–2006. Our analysis is based on longitude-time spectra of temperatures measured by the SABER satellite instrument, as well as temperatures from ECMWF operational analyses. Kelvin waves of zonal wavenumber 1–6 and periods longer than 2.5 days are covered. It is found that the contribution of Kelvin waves is about 30–50% of the observed wind reversal and only 20–35% of the expected total wave forcing. The larger part of the wave forcing therefore has to be contributed by other waves, likely mesoscale gravity waves. **Citation:** Ern, M., and P. Preusse (2009), Quantification of the contribution of equatorial Kelvin waves to the QBO wind reversal in the stratosphere, *Geophys. Res. Lett.*, *36*, L21801, doi:10.1029/2009GL040493.

1. Introduction

[2] The quasi biennial oscillation (QBO) is an oscillation of the zonal wind in the tropics between equatorial easterlies and westerlies with a period of about 28 months. Our work will be focused on the stratospheric QBO which is observed at altitudes of about 18–40 km. Effects of the QBO are found not only in the tropics in the latitude range between about 15°S and 15°N where the equatorial wind jets are located, but also at mid and high latitudes. For a more detailed discussion of the QBO and its effects and mechanisms, see *Baldwin et al.* [2001].

[3] It has been shown by *Lindzen and Holton* [1968] and *Holton and Lindzen* [1972] that the QBO is a wave driven oscillation. Waves of both global scale (equatorial wave modes like Kelvin waves, equatorial Rossby waves, or Rossby-gravity waves) as well as mesoscale gravity waves contribute to the observed wind reversals. It was pointed out by *Dunkerton* [1997] that the total wave flux should be about 2–4 times as high as the flux of the global scale wave modes alone. This means that the effect of mesoscale gravity waves in the forcing of the QBO should be about 50–75% of the total wave forcing.

[4] This large range of uncertainty given by *Dunkerton* [1997] demonstrates that the relative contributions of the different types of waves are still highly uncertain. This is the case because until recently there were no long-term high spatial resolution measurements in the stratosphere covering at least one full QBO cycle. For quantifying reliable global averages of these relative contributions high resolution global measurements, for example from satellites, are required. These observational values of the wave forcing are urgently needed as reference for general circulation models (GCMs).

[5] Kelvin waves are the by far dominant global scale equatorial wave mode during QBO easterly phases and responsible for the largest part of the wind accelerations contributed by global scale waves during wind reversals from QBO easterlies to westerlies. First attempts to quantify the effect of zonal wind acceleration due to Kelvin waves from global satellite measurements were carried out by *Hitchman and Leovy* [1988] and *Canziani and Holton* [1998]. These analyses were however limited in several ways. First, the data did not cover a full QBO cycle. Second, the analysis by *Hitchman and Leovy* [1988] covers only zonal wavenumbers 1–3 and the analysis by *Canziani and Holton* [1998] only zonal wavenumbers 1–2. Third, the amplitudes of Kelvin waves were not corrected for mesoscale gravity waves and might therefore be biased.

[6] In our work we will quantify the contribution of equatorial Kelvin waves to the wind reversal from QBO easterlies to westerlies averaged over two QBO cycles. Zonal wavenumbers 1–6 and wave periods longer than 2.5 days are taken into account and therefore the bulk of the total contribution due to Kelvin waves should be covered. Our analysis is based on five years of temperature measurements of the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) satellite instrument. These data are the first global long-term high-resolution data set in the stratosphere that can serve as observational reference for GCMs in the tropics. For comparison the same analysis is carried out for temperature data from European Centre for Medium-Range Weather Forecasts (ECMWF) operational analyses to find out whether the results obtained from SABER temperatures can be reproduced by a model data set highly constrained by assimilation of measurements. ECMWF temperatures and winds also serve as background atmosphere and are used to quantify the expected total wave forcing needed to balance the zonal mean flow.

[7] In section 2 our analysis method is described. Results are presented in section 3. A summary and discussion is given in section 4.

2. Analysis Method

[8] In our study we make use of the longitude-time spectral analysis method described by *Ern et al.* [2008, 2009a, 2009b] and *Ern and Preusse* [2009]. The SABER

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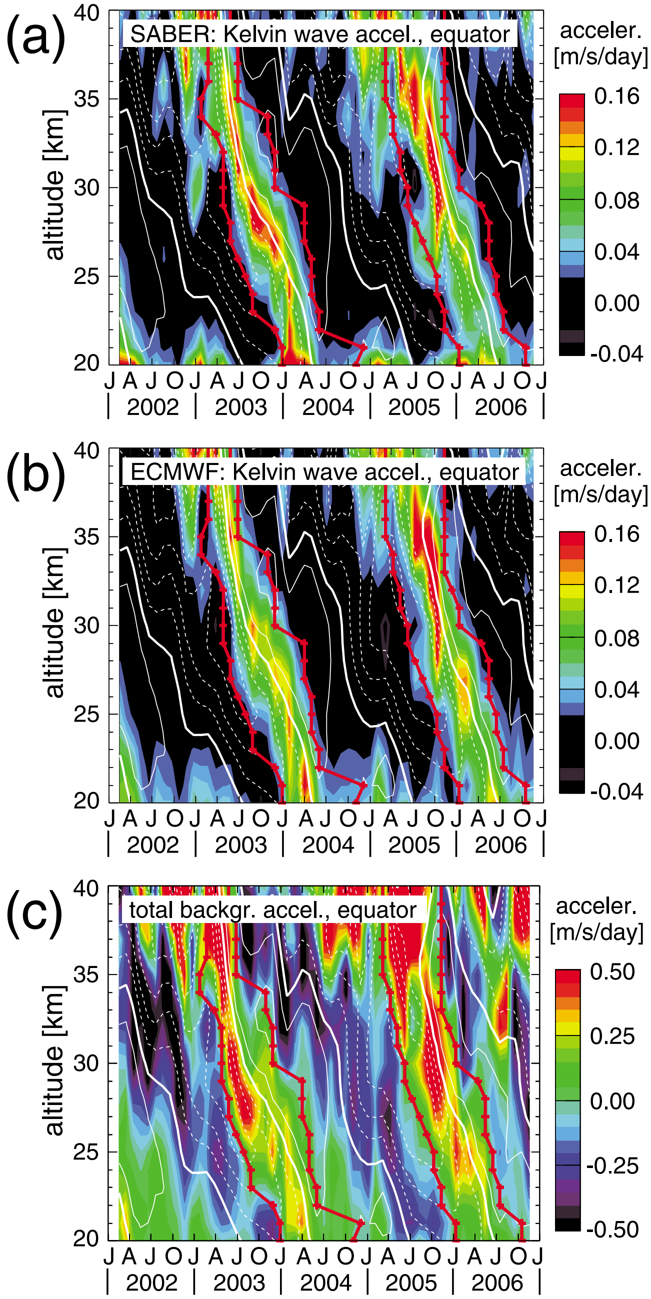

Figure 1. Zonal wind accelerations in m/s/day due to Kelvin waves at the equator derived from (a) SABER and (b) ECMWF temperature spectra. (c) The expected total wave forcing derived from the ECMWF background atmosphere. White contour lines indicate the ECMWF zonal wind at the equator. Easterlies are dashed, westerlies are solid, and the zero wind line is bold solid. Contour increment is 10 m/s. The bold red lines give the integration limits for determining zonal wind contributions during westerly wind shear. For details, see text.

and ECMWF residual temperatures used in our analysis are arranged into non-overlapping latitude-altitude bins. For SABER we use the latitude bins -8 ± 2, -4 ± 2, 0 ± 2, 4 ± 2, and 8 ± 2 degs corresponding to the horizontal sampling distance of about 500 km along the satellite track. SABER temperatures are given on fixed geometric altitudes from 15 to above 100 km in 1-km altitude steps. The ECMWF data are given on a $1° \times 1°$ longitude-latitude grid and a set of pressure levels which we convert to pressure altitudes with a fixed pressure scale height of 7 km. We use the full latitudinal resolution of the ECMWF data but only a reduced longitude resolution of 9° which is sufficient to resolve global scale equatorial waves. Longitude-time spectra are determined in a series of non-overlapping 31-day time windows in the period 1/2002–11/2006 for the latitudes and altitudes of the bin centers.

[9] The method to calculate Kelvin wave accelerations and expected wave forcing is described in depth by *Ern and Preusse* [2009] and is briefly summarized in the following: From the temperature space-time spectra momentum flux spectra of equatorial Kelvin waves can be determined via the polarization relations for a linear wave approach. Mesoscale gravity waves not resolved by the sampling pattern or the model grid act as some kind of white noise and induce an almost uniform spectral background. Therefore the Kelvin wave spectral contributions have to be corrected for this spectral background to avoid a bias of the momentum fluxes.

[10] For ECMWF data this spectral background is only minor, but it is highly relevant in the SABER temperature space-time spectra. Even though in our study only periods of high Kelvin wave temperature variances are considered, on average the calculated SABER temperature variances would be overestimated by about 20–30% if this background would not be subtracted. Also Kelvin wave momentum fluxes and accelerations would be overestimated and SABER Kelvin wave zonal wind contributions would be high-biased by about 5 m/s.

[11] The total momentum flux due to Kelvin waves is estimated by integrating the momentum flux spectra over zonal wavenumbers 1–6 and between ground based phase speeds of 9 and 140 m/s (according to equivalent depths of $h_e = 8$ and 2000 m under zero background wind conditions, respectively). In addition, a high frequency cutoff is introduced at 0.4 cycles/day to avoid non Kelvin wave contributions at higher frequencies, i.e., only periods longer than 2.5 days are considered.

[12] From vertical gradients of Kelvin wave momentum flux the acceleration of the background wind due to Kelvin waves is deduced. Before calculating accelerations the SABER data are smoothed vertically by a 4-km running mean to remove an oscillation, which is likely an artifact of the temperature retrieval. This oscillation, however, has only little effect on the results presented here. For a more detailed discussion and an error estimation, see *Ern and Preusse* [2009]. Altitude-time cross sections of total Kelvin wave accelerations at the equator are shown in Figure 1a for SABER and in Figure 1b for ECMWF. In Figure 1c the expected total wave forcing derived from the ECMWF background atmosphere is shown. This total wave forcing term is the sum of the wind tendency term, as well as the meridional and the vertical advection terms of the background atmosphere that have to be balanced by wave forcing for momentum conservation. While the zonal wind tendency term can be determined with only little error from the zonal wind values, the accuracy of the meridional and vertical advection terms largely depends on the accuracy of the zonal mean meridional and vertical winds that are used. These

values depend on the equilibria and the physical processes represented in the model employed and will be somewhat different from model to model.

[13] In Figures 1a and 1b for clarity reasons small, insignificant wind tendencies are given in black. In Figure 1 the white contour lines indicate the zonal mean wind taken from ECMWF at the equator, averaged over the 31-day time windows of our analysis. The contour increment is 10 m/s, easterly winds are indicated by dashed contours, and the zero wind line is highlighted by a bold solid line. It is evident that westerly accelerations due to Kelvin waves form pronounced bands during westerly wind shear, thus contributing to the reversal from QBO easterly winds to QBO westerlies.

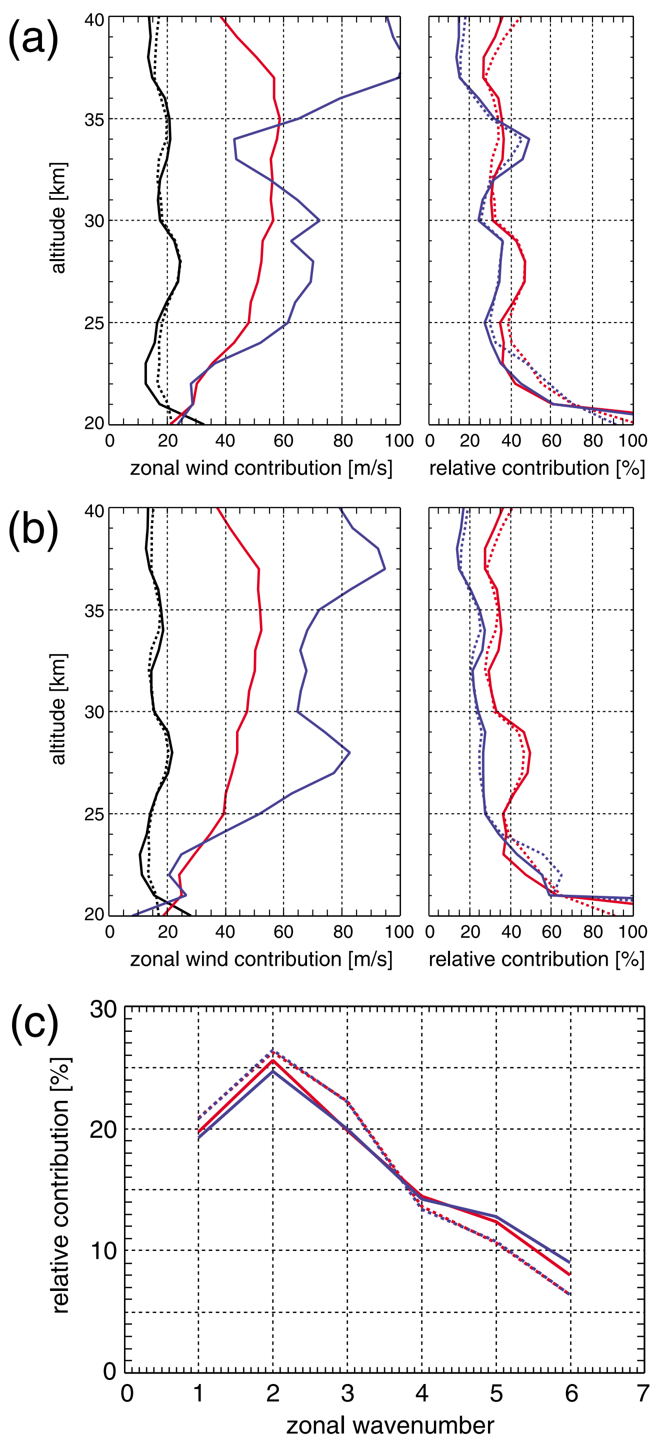

Figure 2. Altitude profiles of zonal wind contributions (a) at the equator as well as (b) averaged over 10°S–10°N. Values are averages over two QBO cycles. (left) The total Kelvin wave contribution in m/s determined from SABER (ECMWF) is given by the black solid (dashed) lines. The red line is the observed wind reversal; the blue line is the contribution expected from the total wave forcing. (right) Relative Kelvin wave contributions in percent. Red lines are with respect to the observed wind reversal; blue lines are with respect to the expected total wave forcing. Solid lines are for SABER; dashed lines are for ECMWF. Figure 2c shows the relative contribution of the single zonal wavenumbers to the total Kelvin wave forcing during westerly wind shear averaged over two QBO cycles and over the altitude range 20–40 km. Red lines are for the equator and SABER (solid) as well as for ECMWF (dashed). Blue lines show the same but averaged over 10°S–10°N. For details, see text.

3. Kelvin Wave Zonal Wind Contribution

[14] The total contribution of Kelvin waves to the QBO wind reversal is determined by integrating over the Kelvin wave accelerations along the time axis during the periods of westerly wind shear. We integrate separately over the two periods of westerly wind shear covered by our data sets. The boundaries of the integration intervals are indicated by the bold red lines shown in Figure 1. These lines roughly follow the maxima and minima of the QBO wind jets, respectively. The integration is always carried out starting from most negative (strongest easterly) winds until most positive (strongest westerly) winds, covering the complete westerly shear zone of a QBO wind reversal. Since the zonal wind minima and maxima considered here correspond to centers of the 31-day time windows of the spectral analysis, we use at the ends of the integration time intervals only half of the first and half of the last time window, respectively.

[15] The results of this integration are shown as altitude profiles in Figure 2. Figure 2a shows the values for the equator. The black solid (dashed) line in Figure 2a (left) gives the SABER (ECMWF) contribution to the zonal wind reversal in units of m/s due to Kelvin waves obtained by integrating over the Kelvin wave accelerations shown in Figure 1a (Figure 1b) averaged over the two QBO cycles covered by our data. In a similar way the zonal wind contribution expected from the total wave forcing (blue solid line) is determined by integrating over the total wave forcing term estimated from the ECMWF background atmosphere shown in Figure 1c. Also shown (red solid line) is the observed wind reversal in m/s taken from ECMWF averaged over the two QBO cycles. Values are determined by calculating the differences between the zonal winds at both ends of the integration intervals, which is about the difference between maximum QBO westerlies and the maximum QBO easterlies. This choice makes sure that the values given for the observed wind reversal and the wind values obtained by integration are compatible.

[16] For most altitudes the zonal wind contribution of the expected total wave forcing is considerably higher than

the observed wind reversal itself. This is the case because the total wave forcing does not only have to balance the observed zonal wind tendency. It also has to compensate for the meridional and vertical advection terms of the background atmosphere. At the equator the meridional advection term plays only a minor role below about 35 km altitude, however the vertical advection term counteracts the downward propagation of the QBO zonal wind bands because of the mean upwelling of air masses in the tropics and an enhanced total wave forcing is required.

[17] Total Kelvin wave wind reversal contributions are about 20 m/s for SABER with only little altitude dependence, and there is good agreement between SABER and ECMWF. The expected error of the values given is about 20%. For a detailed error discussion, see *Ern and Preusse* [2009]. The relative contribution in percent with respect to the observed wind reversal is given in Figure 2a (right) for SABER (red solid line) and ECMWF (red dashed line). The relative contribution is about 30–50% for both SABER and ECMWF almost over the whole altitude range 20–40 km. Only in the lower stratosphere (below about 23 km altitude) is the contribution of Kelvin waves considerably higher and can even exceed 100%. This could, for example, be explained by waves contributing also easterly accelerations to the total wave forcing (e.g., equatorial Rossby waves), but since the primary focus of the current study is the wind reversal at higher altitudes this topic will not be further discussed.

[18] The observed wind reversal is however only a lower limit to the amount of zonal wind that is expected to be contributed by atmospheric waves. An estimate for what is really expected from wave forcing is given by the blue line in Figure 2a (left), representing the integral over the expected total wave forcing. The relative contribution of Kelvin waves with respect to the total wave forcing in percent is given in Figure 2a (right) by the blue lines for SABER (solid) and ECMWF (dashed). This relative contribution is in the range of about 20–35% over almost the whole altitude interval 20–40 km, i.e., considerably lower than the relative contribution with respect to the observed wind reversal.

[19] Since equatorial values represent only a single latitude and therefore are somewhat noisy, we also provide the same values as for the equator, but averaged over the latitude band 10°S–10°N. Those average values are shown in Figure 2b. As can be seen values are similar. The zonal wind contribution by Kelvin waves is about 15 m/s over the whole altitude range. The relative contributions of Kelvin waves in almost the whole altitude range 20–40 km are about 30–50% with respect to the observed wind reversal and about 15–30% with respect to the integral over the expected total wave forcing, i.e., even somewhat lower than at the equator.

[20] According to the error discussion by *Ern and Preusse* [2009] the relative error of the Kelvin wave contributions given in m/s is about 20%. Therefore this is also the minimum relative error that is expected for the percentage values given in Figures 2a and 2b. Since the magnitude of the wind reversal can be determined with little uncertainty, this error estimate will hold for the percentages indicated by red lines in Figures 2a (right) and 2b (right). Estimates for the total wave forcing, however, rely also on the accuracy of the zonal mean vertical and zonal mean meridional wind taken from ECMWF operational analyses. Both these quantities are very small (about ~1 mm/s and ~1 m/s, respectively) and highly uncertain. Relative errors for the relative contribution to the total wave forcing (blue lines in Figures 2a (right) and 2b (right) will therefore be significantly larger than 20%).

[21] Figure 2c shows the relative contribution of the single zonal wavenumbers to the total Kelvin wave forcing in the wave band discussed above (zonal wavenumbers ≤ 6 and wave periods longer than 2.5 days) integrated over the periods of strong QBO westerly wind shear and averaged over the two QBO cycles covered by our study, as well as over the whole altitude range 20–40 km. Red lines are for the equator and SABER (solid) as well as ECMWF (dashed). Blue lines show the same but averaged over the latitude band 10°S–10°N. Obviously zonal wavenumber 2 Kelvin waves play the most important role for the Kelvin wave contribution to the QBO wind reversal, followed by zonal wavenumbers 1 and 3, which are about equally important. The results shown confirm the results of *Ern and Preusse* [2009] that zonal wavenumbers 1 and 2 combined contribute less than 50% of the total Kelvin wave forcing, and that zonal wavenumbers 4–6 contribute about one third, and cannot be neglected. The decrease of the relative contributions at high zonal wavenumbers also indicates that in the stratosphere the bulk of the Kelvin wave forcing is located at zonal wavenumbers 1–6 and is therefore covered by our analysis. Obviously the twice daily asynoptic sampling pattern of satellite instruments in low Earth orbit (for example, the SABER instrument) are capable to resolve the relevant part of Kelvin wave activity with their sampling pattern, which is limited to zonal wavenumbers lower than about 6–7 [e.g., *Salby*, 1982a, 1982b].

4. Summary and Discussion

[22] In this study we have determined the contribution of Kelvin waves to the QBO wind reversal from QBO easterlies to westerlies in the altitude range 20–40 km from five years of high resolution temperature measurements by the SABER satellite instrument and of temperatures from ECMWF operational analyses. The results shown represent averages over the two QBO cycles covered by our data. The values are corrected for the spectral background due to waves not resolved by the satellite sampling or the model grid. A wide range of Kelvin waves with zonal wavenumbers 1–6 and periods longer than 2.5 days is considered. This means that our analysis covers a larger spectral range than previous studies. It is shown that the bulk of the total Kelvin wave forcing is likely covered by satellite measurements from low Earth orbit, which can resolve zonal wavenumbers up to about 6–7 with their sampling pattern. The maximum forcing is contributed by Kelvin waves with zonal wavenumber 2.

[23] The contribution of Kelvin waves is about 20 m/s at the equator and 15 m/s for 10°S–10°N averages (the range 10°S–10°N is about the half-width of the QBO). At the equator relative contributions are about 30–50% with respect to the observed wind reversal and about 20–35% with respect to the contribution expected from the total wave forcing estimated from an ECMWF background atmosphere. The respective ranges for 10°S–10°N averages are about 30–50% and about 15–30%, i.e., somewhat lower.

Values given are valid for almost the whole altitude range 20–40 km. Only in the lower stratosphere relative contributions are higher. One reason could be that waves providing easterly accelerations might also contribute in the lower stratosphere during phases of westerly wind shear. Another reason could be that other wave types (e.g., gravity waves) might only have an impact above 23 km.

[24] The low contribution of Kelvin waves to the wind reversal compared with the contribution expected from the total wave forcing supports the estimates by *Dunkerton* [1997], who concluded that forcing by global scale equatorial waves should be only about 25–50% of the total wave forcing. Our results are at the lower end of the range given by *Dunkerton* [1997], confirming the importance of mesoscale gravity waves or intermediate scale waves for the forcing of the QBO over almost the whole stratosphere.

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