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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Equatorial wave analysis from SABER and ECMWF temperatures" *by* M. Ern et al.

M. Ern et al.

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The authors would like to thank George Kiladis for his extremely helpful comments! We hope that the confusion we have caused by some inaccuracies and by introducing the "tropospheric" wave band is settled in the revised manuscript. We also totally agree with the request for more discussion of the QBO variation of gravity wave variances and hope that the additional evidence given is sufficient.

In the following we will address to the Reviewer's Substantial Concerns:

Substantial Concerns:

Substantial Concern #1: Distinguish between the various "free" and the "convectively coupled" (here called "tropospheric") waves more clearly!

It seems that some inaccuracies and the use of two different spectral bands, one called "tropospheric" have caused some confusion — sorry for that!

Alone from the data presented in this manuscript it is difficult to decide whether the waves seen only by their spectral information in the space-time spectra are "free" waves or "convectively coupled" waves. In addition, the waves observed in the stratosphere are most likely "free" Kelvin waves and only in the lower stratosphere there may be still some contributions of convectively coupled waves at low phase speeds. Therefore we suggest to use an additional broad filter for the different wave types (8–2000m equivalent depth as suggested in Substantial Concern #2) in two new Figures, presenting the total variances for the different wave types in SABER and ECMWF data and show the different behavior of the temporal variations of the variances in the "slow" and the "fast" wave bands afterwards. We will further remove any interpretation that is beyond the scope of this paper and the potential of the data presented.

In the Introduction we will add the following text on p.11686 after l.3:

"... As a consequence in the troposphere we find significant contributions of convectively coupled equatorial waves, directly linked to the convective systems acting as wave sources (e.g., Wheeler and Kiladis (1999), Straub and Kiladis (2003), Cho et al. (2004)).

Equatorial waves also propagate vertically into the stratosphere. Equatorial waves observed in the stratosphere are dominated by "free" wave modes, which are excited by deep convection in the troposphere but not longer linked with the space-time patterns of the convective forcing (Randel and Wu (2005)).

Together with a broad spectrum of gravity waves equatorial waves are..."

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Interactive Comment

In Section 4 we will rewrite the first paragraph of Sect. 4.1 (see also Specific Comment (15) concerning p.11701):

"As mentioned in Sects. 2.2–2.4 the general behavior of the spectral signatures observed in SABER and ECMWF temperatures in the stratosphere is as follows: In the lowermost stratosphere the spectral features are already somewhat shifted towards higher phase speeds or equivalent depths compared to the observations in the troposphere by, for example, Wheeler and Kiladis (1999) or Cho et al. (2004), which are dominated by convectively coupled equatorial waves. With increasing altitude higher phase speeds and equivalent depths (dominated by free equatorial wave modes) become even more important because slow phase speed waves will more and more encounter critical level filtering and wave dissipation. Higher phase speed waves have been observed before by, e.g.,... "

For further changes required in the manuscript see Substantial Concern #2.

Substantial Concern #2: Waves with equivalent depth shorter than 90m are not necessarily convectively coupled waves, maybe use only one broad filter 8–2000m!

Also see Substantial Concern #1. It seems wise not to attribute different wave types to the different spectral bands. The manuscript will be changed in the following way:

(1) Two additional figures will be included for SABER and ECMWF in Sect. 3.1 based on a broad filter 8–2000m, showing the total contribution due to the different wave types.

(2) The term "tropospheric" wave band will be replaced by the term "slow" wave band for the 8–90m equivalent depth band. The other wave band (90–2000m) will still be called the "fast" wave band.

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(3) The motivation for two different wave bands will be reduced mainly to the fact that the waves contained in those two wave bands react in different ways to changes of the background wind.

This will imply several changes in the manuscript not listed here in detail.

Substantial Concern #3: "It seems to me that the gravity wave signal analyzed in Sections 3.2 and 4.2 may not be cleanly separated from the Kelvin wave signal."

See also reply to Specific Comments (14a) and (14b). In the revised manuscript we will give further evidence for a clean separation and that contamination of the gravity wave signal by Kelvin waves is not very likely.

Some facts:

(1) The amplitude of gravity waves is expected to be modulated by the background wind. In a stronger background wind gravity waves can attain larger amplitudes before the amplitude limit critical for wave breaking is reached (e.g., Preusse et al., JASTP, 2006). In QBO easterly phases the background wind is stronger than in the westerly phases. Therefore some kind of QBO modulation of gravity wave variances would be expected.

(2) Short period waves (gravity waves) have been found to be modulated by the QBO before in analyses of radiosonde data (Maruyama (1994), Sato et al. (1994), Sato and Dunkerton (1997), and Vincent and Alexander (2000)). In addition, Krebsbach and Preusse (2007) found a variation of gravity wave temperature variances with the QBO, also using SABER data but an approach different from the one used in our manuscript.

(3) If we calculate median values only from the antisymmetric spectra and for frequencies$<$ 0cpd especially in SABER data we still see the QBO variation similar to the variation of the Kelvin waves with the QBO — although frequencies $<$ 0cpd

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should be dominated by westward propagating equatorial waves with enhanced variances during the QBO westerly phases (different from the Kelvin waves) and the effect of Kelvin waves should be strongly suppressed in the antisymmetric spectra. Like in Fig. 9 for ECMWF there is only a weak signature. We will show this in another Figure in the revised manuscript.

(4) Not likely, but also possible: For SABER we cannot rule out completely that even antisymmetric spectra and frequencies $<$ 0cpd might be contaminated by Kelvin waves having zonal wavenumbers $>$7 due to aliasing effects. Zonal wavenumbers $>$7 are not properly resolved by the SABER sampling, but there is no indication for such contributions in Figs. 2 and 3.

Taking all these facts we are convinced that the background variations shown in Fig. 9 are due to gravity waves not resolved by the satellite sampling. We will add the above discussion (including the aliasing cautionary note) in the revised manuscript on p.11701 at the end of Sect. 3.2 as follows:

"Since the variation of gravity wave variances with the QBO is similar to the observed variation of Kelvin wave variances (see Figs. 5–8) the question arises whether the variation of gravity wave variances are just some contamination of the background variances by Kelvin waves. There are several reasons why the observed QBO-related variations of gravity wave variances should be real and not only an artifact.

First, from theoretical considerations a variation of gravity wave variances with the QBO would be expected because the amplitude of gravity waves is expected to be modulated by the background wind. In a stronger background wind gravity waves can attain larger amplitudes before the amplitude limit critical for wave breaking is reached (e.g., Preusse et al. (2006)). In QBO easterly phases the background wind is stronger than in the westerly phases. Therefore some kind of QBO modulation of gravity wave variances would be expected. In particular, an increase of temperature variances in *a layer below the lines of zero zonal wind about 2 km thick would be expected from amplitude growth arguments (see Randel and Wu (2005), Appendix A). Such layers can also be found during the phases of eastward shear in the westward wind of the QBO east phases at altitudes of 20–30 km in the SABER gravity wave variances shown in Fig. 9a. In the ECMWF data (Fig. 9b) this is only weakly indicated.*

Indeed, short period waves (gravity waves) have been found to be modulated by the QBO before in analyses of radiosonde data (Maruyama (1994), Sato et al. (1994), Sato and Dunkerton (1997), and Vincent and Alexander (2000)). In addition, Krebsbach and Preusse (2007) found a variation of gravity wave temperature variances with the QBO using SABER satellite data but an approach different from the one used in our manuscript.

Nevertheless, there might be some contamination due to Kelvin waves left in the total spectral background variances shown in Fig. 9 and we will do some kind of cross-check in the following. To further suppress the effect of Kelvin waves we estimated background variances only from frequencies $<$0 cpd in the antisymmetric spectra (again using the median method described above). By using only frequencies $<$0 cpd we also avoid contamination due to eastward propagating wave modes other than Kelvin waves. Since this part of the spectrum is dominated by westward propagating equatorial waves enhanced variances during the QBO westerly phases (different from the Kelvin waves) would be expected if the spectral background was contaminated by those waves.

Different from Fig. 9 where both symmetric and antisymmetric background values as well as almost the whole frequency range were used we now estimate total variances by taking twice the variances determined from only the frequency $<$0 cpd parts of the antisymmetric spectra. By doing so we assume that symmetric and antisymmetric backgrounds as well as the background for frequencies $<$0 cpd and frequencies $>$0 cpd should be all about equal (which is approximately the case) and the background variance of the original data can be estimated from the frequency $<$0 cpd part

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of the antisymmetric spectra alone.

These total background variances are shown in Fig. 10a for SABER and Fig. 10b for ECMWF. Especially in the SABER background variances (Fig. 10a) we still see the QBO variation similar to the variation of the Kelvin waves with the QBO. For the ECMWF variances (Fig. 10b) the QBO-related variation is also still there but even less pronounced than in Fig. 9b. Please note that the color scales in Fig. 10 are somewhat lower than in Fig. 9, accounting for minor asymmetries in the spectral background values.

The fact that QBO-related variations are also found in the variances shown in Fig. 10 indicates that the QBO-related variations found (especially for SABER) are a robust feature that can be attributed to QBO-related variations of gravity wave variances.

It should be noted that for SABER we cannot rule out completely that even antisymmetric spectra and frequencies $<$0 cpd might be contaminated by aliasing effects from Kelvin waves with zonal wavenumbers $>$7 not properly resolved by the satellite sampling. However, this is not a likely effect since the spectra shown in Figs. 2 and 3 indicate that the contributions due to Kelvin waves strongly decrease at zonal wavenumbers $>$5 for 21 km altitude (Fig. 2) and even more for 41 km altitude (Fig. 3)."

Why is our approach better than the approach by Wu (2006) and de la Torre et al. (2006)?

In these papers the horizontal structure of the waves is completely neglected, only vertical smoothing of the measured temperature altitude profiles is applied to separate residual temperatures from the background. These residual temperatures are a mixture of waves of all kind with vertical wavelengths shorter than about 10 km. This mixture of waves is found to exhibit significant variations with the QBO. Kelvin waves and gravity waves are the waves dominating the temperature variances in the equatorial stratosphere so these waves will dominate the observed fluctuations. However, because Kelvin waves show substantial variation with the QBO, from these two papers you cannot tell that gravity waves also show QBO variations.

In the approach presented in our paper we use the space-time spectral analysis to identify the spectral signatures attributed to global-scale equatorial wave modes and try to estimate the spectral background as discussed above. Several cross-checks ((1) QBO variation also found for SABER based on frequencies $<$ 0cpd in antisymmetric spectra alone, (2) about the same variations found by Krebsbach and Preusse (2007), (3) QBO variations also seen in radiosonde data (see above)) indicate that the separation of this background attributed to gravity waves is successful.

For clarification the text on p.11703, ll.20–23 will be rewritten:

...very similar to the one observed for Kelvin waves. In these analyses the horizontal structure of the waves is completely neglected. Only vertical smoothing of the measured temperature altitude profiles is applied to separate residual temperatures from the background. Therefore the results show a mixture between global equatorial wave modes (mainly Kelvin waves) and gravity waves. This is improved in our results presented in Sect. 3.2. We cleanly separate the contribution due to gravity waves from global-scale equatorial wave modes by determining the spectral background in the space-time spectra (see Sect. 3.2).

Interactive comment on Atmos. Chem. Phys. Discuss., 7, 11685, 2007.