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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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Again, the authors would like to thank Anonymous Referee #1 for her/his effort!

In the following we will address to the Reviewer's Specific Comments and Technical Corrections:

Specific Comments:

(1) p.11688, l.14: dispersion curves are for zero background wind

Yes, indeed! This will be clarified in the revised manuscript!

(2) p.11689, 3rd para (from l.13): Sato et al.(1994) is for short-period waves only (T$<$3days), Sato and Dunkerton (1997) quantifies the effect of those waves on the QBO and should also be cited!

The paper Sato et al. (1994) covers both periods of 8–20 days (these are dominated by Kelvin waves, e.g., their Figs. 7a and 7b) as well as shorter periods of 1–3 days (probably due to gravity waves, e.g., their Figs. 7c and 7d). Indeed, the focus of the paper by Sato et al. (1994) is on those short-period waves but nevertheless it seems justified to also cite it in the context of other equatorial waves.

Of course, the reviewer is correct: the works by Sato et al. (1994) and Sato and Dunkerton (1997) should be cited together with Maruyama (1994) and Vincent and Alexander (2000) on p.11703/11704 where the contribution of the gravity waves is discussed. Thank you very much for this advice!

For changes of the manuscript see Major Comment #1.

(3) p.11690, 3rd sentence: Sentence is wrong! Critical level filtering depends also on the zonal wavenumber and radiative relaxation is also an important process (Holton and Lindzen, 1972)!

We are sorry that this sentence was not formulated carefully enough! We will rewrite the sentence as follows:

"The waves with lower phase speeds $\hat{\omega}/k$ (longer periods for a given zonal wave number) will not propagate to higher altitudes because they will encounter critical level filtering and wave dissipation, for example, by wave breaking or radiative relaxation (e.g., Holton and Lindzen, 1972)."

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(4) p.11692, ll.11-12: 31-day time window is too short to address periods of 30 days properly!

We chose the 31-day window length as compromise between frequency resolution and time resolution and, indeed, this compromise implicates some limitations to our method. Some spectral leakage is expected if there is a mismatch between the ground based frequency of a wave and the spectral grid points used in the spectral analysis. In such cases there will be an underestimation of the 31-day component and some contamination of neighbored frequencies. On the other hand such long periods are only prominent at the lowermost altitudes (see Table 1) and the main findings presented in the manuscript are not affected by this uncertainty.

We will add the following sentences at the end of Sect. 2.1:

"It should however be noted that this compromise of a 31-day time-window implicates some limitations to our method: Some spectral leakage is expected if there is a mismatch between the ground based frequency of a wave and the spectral grid points used in the spectral analysis. In such cases there will be an underestimation of the 31-day component and some contamination of neighbored frequencies. On the other hand such long periods are only prominent at the lowermost altitudes and the main findings presented in this paper are not affected by this uncertainty."

(5) p.11694, ll.2-3: The temperature can be modified by the background static stability and Doppler effects of the mean wind as well as wave dissipation and wave generation. (similar shortcoming on p.11696, 3rd para).

Anonymous Reviewer #1 is correct! More discussion is needed on p.11694 and p.11696.

Both the spectra shown in our paper and the tropospheric observations by Wheeler

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and Kiladis (1999) or Cho et al. (2004) are ground-based frequency/zonal wavenumber spectra. Since the ground-based frequency of a wave does not change when the wave encounters vertical wind shear, the shift of the spectral contributions with respect to the troposphere indicates that at low (ground-based) frequencies there is a real loss of spectral power (Doppler shifting of the waves would have no effect on the ground-based frequencies observed).

At the same time the occurrence of higher ground-based frequencies could be an indication for processes involving longer vertical scales in the troposphere that become important only in the stratosphere and become visible due to amplitude growth with altitude but are too small effects in the troposphere to be observed.

This loss of spectral power at low ground-based frequencies can have different reasons: critical level filtering and wave dissipation due to, e.g., wave breaking or radiative relaxation and, as the reviewer points out, amplitude modulations of waves propagating conservatively induced by changes in the background wind (also see Major Comment #3).

The change in the static stability will lead to a significant increase of wave amplitudes during the transition of a wave from the troposphere into the stratosphere because the buoyancy frequency N increases by a factor of about two. In the whole stratosphere, however, this should be a minor effect because N is about constant in the stratosphere.

For the example of Kelvin waves, which satisfy the same dispersion relation as gravity waves, we can make use of Eq. 55 in Fritts and Alexander (2003), which was originally derived for gravity waves. Following Eq. 55 in Fritts and Alexander (2003) for the transition from troposphere into stratosphere a change of the temperature variances according to:

$$(\overline{T'^2})_{strato}/(\overline{T'^2})_{tropo} \approx N^3_{strato}/N^3_{tropo}$$

would be expected. In this equation changes in temperature and atmospheric density are neglected. Since in the stratosphere the buoyancy frequency N_{strato} is about twice

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the value in the troposphere N_{tropo} this would be an increase in variances (and power spectral densities) of almost an order of magnitude.

For the case of enhanced spectral contributions at higher ground-based frequencies in the stratosphere with respect to the troposphere this will be a significant effect in addition to the amplitude growth with altitude expected due to the decrease of atmospheric density with altitude (see also Eq. 55 in Fritts and Alexander (2003)). At lower ground based phase speeds obviously critical level filtering and wave dissipation or amplitude modulation due to changes in the background wind are more important.

We will rewrite the text, starting on p.11693 last line as follows:

"In Fig. 2 we can see that already in the lower stratosphere spectral contributions are somewhat shifted with respect to the tropospheric observations by Wheeler and Kiladis (1999) or Cho et al. (2004). There are also contributions of the different wave types outside the 8–90 m equivalent depth wave bands and a large portion of the faster stratospheric signals are likely independent of the tropospheric waves studied by Wheeler and Kiladis (1999). Both the spectra shown in Fig. 2 and the tropospheric observations by Wheeler and Kiladis (1999) or Cho et al. (2004) are ground-based frequency/zonal wavenumber spectra. Since the ground-based frequency of a wave does not change when the wave encounters vertical wind shear, the shift of the spectral contributions with respect to the troposphere indicates that at low (ground-based) frequencies there is a real loss of spectral power (Doppler shifting of the waves would have no effect on the ground-based frequencies observed).

At the same time the occurrence of higher ground-based frequencies could be an indication for processes involving longer vertical scales in the troposphere that become important only in the stratosphere and become visible due to amplitude growth with altitude but are too small effects in the troposphere to be observed.

The loss of spectral power at low ground-based frequencies can have different rea-

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sons, such as critical level filtering and wave dissipation due to, e.g., wave breaking or radiative relaxation. Another reason could be wave amplitude modulations of waves propagating conservatively caused by changes in the background wind.

The change in the static stability will lead to a significant increase of wave amplitudes during the transition of a wave from the troposphere into the stratosphere because the buoyancy frequency N increases by a factor of about two. In the whole stratosphere, however, this should be a minor effect because N is about constant in the stratosphere.

For the example of Kelvin waves, which satisfy the same dispersion relation as gravity waves, we can make use of Eq. 55 in Fritts and Alexander (2003), which was originally derived for gravity waves. Following Eq. 55 in Fritts and Alexander (2003) for the transition from troposphere into stratosphere a change of temperature variances according to:

$$(\overline{T'^2})_{strato}/(\overline{T'^2})_{tropo} \approx N^3_{strato}/N^3_{tropo}$$

would be expected with $(\overline{T'^2})_{tropo}$ the tropospheric and $(\overline{T'^2})_{strato}$ the stratospheric value. In this equation changes in temperature and atmospheric density are neglected. Since in the stratosphere the buoyancy frequency N_{strato} is about twice the value in the troposphere N_{tropo} this would be an increase in variances (and power spectral densities) of almost an order of magnitude.

For the case of enhanced spectral contributions at higher ground-based frequencies in the stratosphere with respect to the troposphere this will be a significant effect in addition to the amplitude growth with altitude expected due to the decrease of atmospheric density with altitude (see also Eq. 55 in Fritts and Alexander (2003)). At lower ground based phase speeds obviously critical level filtering and wave dissipation or amplitude modulation due to changes in the background wind are more important."

And on p.11696 the third paragraph will also be rewritten:

"This probably indicates that part of the Kelvin waves at lower ground based phase

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speeds (i.e., lower equivalent depths) is absorbed in the lower stratosphere, thereby transferring ... The effects observed for the other wave modes are similar. For the differences between the spectra at 21 km and 41 km altitude amplitude modulations of waves propagating conservatively caused by changes in the background static stability can be neglected because the buoyancy frequency N is about constant throughout the whole stratosphere. Also amplitude modulations due to the vertical shear of the background wind will most likely be small compared to the expected increase of wave variances due to the decrease of atmospheric density over three pressure scale heights. For example, for Kelvin waves an increase of wave variance of about a factor of 20 would be expected according to Fritts and Alexander (2003), Eq. 55. This equation was derived for gravity waves but can also be applied for Kelvin waves because gravity waves and Kelvin waves satisfy the same dispersion relation."

(6) p.11697, 2nd para: How are spectral densities obtained (normalization issue)?

We are sorry if this paragraph has caused some confusion. "Normalized" is not the correct term in this context since just a conversion of physical units was applied.

One of the fundamentals of Fourier analysis is that the complete integral (sum) over the power spectral densities gives the total variance of the data set analyzed (Parseval's theorem). If we carry out a Fourier analysis we have a certain set of independent spectral grid points, each carrying a certain part of the total variance contained in the data set. If we use a frequency sampling distance of our data set, for example, better by a factor of three, the average variance carried by a single grid point is reduced by this factor of three simply because of the fact that the total variance of the original data set is unchanged and there is a factor of three more independent frequency grid points.

What does this mean for our space-time Fourier analysis method?

As discussed above, on average, the spectral squared amplitudes delivered by the FFT

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or the least-squares method also used in this paper are dependent on the frequency resolution used (i.e. the length of the time window). A longer analysis time window will result in reduced squared amplitudes. Since we chose to use physical units for the axes of Figs. 2 and 3 (and not the number of grid points) the integration boundaries for integrating the power spectral density remain unchanged (ECMWF: zonal wavenumbers 0–20 and frequencies -2 cpd...2 cpd, SABER: zonal wavenumbers of 0–7 and frequencies -1 cpd...1 cpd) no matter how long the time-window (i.e., how dense the frequency resolution) is chosen. This means: to conserve the integral over the spectral power density we have to scale the squared spectral amplitudes obtained from FFT or LSQ by the factor:

(number of frequency grid points) / (frequency range in cpd)

and strictly speaking also by this second factor which is, however, exactly unity in our case and independent of the time-window length chosen:

(number of zonal waveno. grid points) / (waveno. range)

So this "normalization" is just necessary to account for the use of physical units for the axes and to calculate power spectral densities in K^2/waveno./cpd instead of K^2/(frequency-gridpoint)/(waveno.-gridpoint)

We will reword the sentence on p.11697, para.2 in the following way:

"However, it should be noted that the relative deviations shown in Table 1 and Fig. 4 are calculated for squared spectral amplitudes given in K^2/waveno./cpd (see also Figs. 2 and 3). Since the relative deviation doubles by squaring the values, relative deviations would be lower by a factor of two if Kelvin wave amplitudes are considered."

We have also found a minor inconsistency in our Figs. 2 and 3 because the spectral values given in Figs. 2 and 3 strictly speaking are squared spectral amplitudes and not power spectral densities. Power spectral density is exactly half the squared amplitudes shown. The calculation of variances in later parts of the paper is done correctly —

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so this has no effect on the numbers given there. But for consistency reasons we will change the legend of Figs. 2 and 3 as well as Table 1 accordingly.

And also the text of the manuscript has to be changed on p.11693 l.12ff:

"... show space-time spectra of symmetric and antisymmetric squared spectral amplitudes in K^2/wavenumber/cpd (i.e., two times power spectral density) at 21 km altitude..."

Some facts of the normalization discussion will be given on p.11694 after l.4:

"The fact that the values shown in Figs. 2 and 3 are squared spectral amplitudes (in units of K^2/wavenumber/cpd) means that we can apply Parseval's theorem to calculate variances from the spectral values given by integrating the spectral values over a given area in the wavenumber/frequency domain. According to Parseval's theorem the spectral density integrated over the whole spectral domain is equal to the overall variance of the data set analyzed. In our case it has to be kept in mind that the squared spectral amplitudes we use are two times power spectral density and the integration result has to be divided by two to obtain the variance. In addition, symmetric and antisymmetric spectra have to be treated separately.

The calculation of variances will now be demonstrated in an example: Beneath the abovementioned spectral peaks... would be equal to a contribution of about 2 K^2 of SABER temperature variances. The contributions from symmetric and antisymmetric backgrounds (both 0.15 K^2/waveno./cpd) are added in the following way:

$$(0.15 + 0.15)K^2\text{/waveno./cpd} \times 7 \text{ wavenos.} \times 2\text{cpd} \times 0.5 \approx 2K^2$$

"

(7) p.11698, 4th para (from l.13): The QBO modulation of equatorial waves observed in Figs. 5 and 6 is consistent with results for long-period Kelvin waves by

Wallace and Kousky (1968) and Rossby-gravity waves by Sato et al. (1994).

This sentence will be added on p.11698, 4th para.

(8) p.11704, 4th para (from l.18): Give credit to QBO and annual variations observed in radiosonde data by Maruyama (1994) and Vincent and Alexander (2000).

Thank you very much for these additional references! Of course, these will be added! See also Major Comment #1.

(9) p.11704, Sect. 5: It is not clear why the authors chose the time period of the SCOUT-O3 campaign. It may be more interesting to show the wave structures in the QBO easterly and westerly phases, for example.

The time period of the SCOUT-O3 campaign was chosen to give some climatological information to the participants of the SCOUT-O3 campaign.

The period of the SCOUT-O3 campaign is an example of enhanced Kelvin wave activity in a QBO easterly phase.

We suggest to add another example for a QBO westerly phase with little Kelvin wave activity but enhanced Rossby-gravity wave activity. Maybe a good example would be the period September/October 2004 (see Fig. 5).

Another figure and some discussion will be added, accordingly.

(10) p.11707, discussion on Fig. 10: Satellite data in the stratosphere (TOVS) are assimilated in ECMWF. Therefore consistency for 10-15 day period Kelvin waves is not surprising. Comparison of shorter period waves would be more informative for the readers.

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Yes, indeed, satellite data are assimilated in ECMWF. Since the TOVS/ATOVS radiances used are sounded using a nadir viewing geometry with broad vertical weighting functions (see Li et al., J. Appl. Meteorology, 2000), it would be expected that long vertical wavelength waves are better represented in ECMWF.

It should be noted, however, that (given a fixed zonal wavenumber) shorter period Kelvin waves have longer vertical wavelengths, which can be seen from the dispersion relation:

intrinsic frequency:

$$\hat{\omega} = \omega - k\bar{u} = -N * k/m$$

gives:

$$m = -Nk/\hat{\omega}$$

or:

$$\lambda_z = 2\pi\hat{\omega}/(Nk) = 2\pi(2\pi/\hat{\tau})/(Nk)$$

with $\hat{\tau}$ the intrinsic Kelvin wave period.

So we have the interesting fact that ECMWF analyses agree better with the SABER observations at low altitudes (about 20–30 km, see Table 1 and Fig. 4) where the vertical wavelength of Kelvin waves is shorter on average, while at higher altitudes (about 40 km) where Kelvin waves have longer vertical wavelengths on average there is some disagreement with the SABER Kelvin waves — although the assimilated satellite data should even improve the representation of Kelvin waves in ECMWF at higher altitudes.

The following text will be added on p.11694 after l.24:

"Some agreement between SABER and ECMWF is expected. Even though SABER data are not assimilated in the operational ECMWF analyses, other satellite data

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(TOVS/ATOVS radiances) are used for data assimilation in the stratosphere. The TOVS/ATOVS radiances are sounded in nadir viewing geometry with broad vertical weighting functions in both troposphere and stratosphere (see Li et al. (2000)). Therefore it would be expected that long vertical wavelength waves (higher equivalent depths) are better represented in ECMWF than short vertical wavelength waves (lower equivalent depths).

The ECMWF data offer..."

This will again be discussed in Sect. 5 where the Hovmoeller plots from SABER and ECMWF are compared. Changes of the manuscript are not given in detail here.

Technical Corrections:

p.11702, l.23: Singapur -> Singapore

Will be changed.

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