Atmos. Chem. Phys. Discuss., 7, S6436–S6447, 2007
www.atmos-chem-phys-discuss.net/7/S6436/2007/

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.

Received and published: 30 October 2007

Again, we would like to thank both Referees for their careful review of the manuscript and for the comments we highly appreciated!

Most of the Referees comments were already answered in detail in the ACPD open discussion. Now, in the final comment we will also list in detail the remaining changes that are required (see below).

All changes will be incorporated in the revised version of the paper.

We hope that the revised manuscript will meet the requirements for publication in ACP.

Manfred Ern (on behalf of all co-authors)

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Further changes of the manuscript:

(1) For Substantial Concern #2 by George Kiladis we will introduce two new figures using the 8-2000m equivalent depth equatorial wave bands. The changes of the manuscript are listed in detail below:

Para.2 in Sect. 3.1 has to be rewritten (p.11697, ll.24):

"In a first step we integrate the squared spectral amplitudes over the spectral band between 8 and 2000 m equivalent depth to calculate the "total" temperature variances of the different wave modes. For both SABER and ECMWF we integrate only over zonal wavenumbers 1–6. The choice of 8 and 2000m is somewhat arbitrarily and the reason for this spectral range is that most of the contributions of a given wave mode will be contained in this spectral band in the whole altitude range of 20-40km (see Figs. 2 and 3). And the choice of an upper limit of 2000m equivalent depth, for example, would also include the ultrafast Kelvin waves identified by Salby et al. (1984), having wavenumber 1 and periods of about 3.5 days."

And the paragraph about the frequency cutoffs to avoid overlaps (p.11699, ll.2) will be moved up and will immediately follow the new para.2 in the revised manuscript.

The paragraph starting on p.11689, l.13 will be rewritten, giving some more explanation:

As expected there is an evident modulation of the temperature variances by the QBO below about 40 km altitude. Eastward propagating wave modes like Kelvin waves (panels "a") or n=0 inertia-gravity waves (panels "b") show enhanced values during QBO *east phases (i.e., phases of westward directed zonal winds) while westward propagating wave modes like n=1 equatorial Rossby waves (panels "c") or Rossby-gravity waves (panels "d") are enhanced during QBO west phases (i.e., phases of eastward directed zonal winds). ...*

The "slow" and the "fast" spectral bands will be introduced with the following text that will be added after p.11698, l.21:

"In the following the 8-2000m equivalent depth spectral band will be split up into a "slow" spectral band, ranging from 8–90m equivalent depth (about the same range as used by Wheeler and Kiladis (1999)) and a "fast" spectral band, ranging from 90–2000m equivalent depth. We distinguish between the "slow" and the "fast" wave bands because we expect different responses of the "slow" and the "fast" waves to the QBO. "Slow" and "fast" in this context means: slower, respectively, faster (ground based) phase speeds of the waves at a given zonal wavenumber.

Figures 7 and 8 show the same as Figs. 5 and 6 but for the contribution of only lower equivalent depths between 8 and 90m in the "slow" wave bands, whereas Figs. 9 and 10 show the contribution of only the higher equivalent depths between 90 and 2000m in the "fast" wave bands. Please note that the color scales in Figs. 7–10 are different from the ones in Figs. 5 and 6."

The paragraph starting on p.11698, l.22 will be removed and is partly contained in the rewritten text.

At the end of Sect. 3.1 the following text will be added:

"...again showing the surprising agreement between both data sets — even though ECMWF data are partly based on assimilated TOVS/ATOVS satellite measurements, which provide information at least about atmospheric waves with longer vertical wavelengths (see Sect. 2.3)."

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(2) In Specific Comment (9) by Anonymous Referee #1 it was recommended to include an example for QBO westerly phase in Sect. 5. The changes of the manuscript are listed in detail below:

In the revised manuscript two figures will show Hovmoeller plots for Kelvin, equatorial Rossby (n=1) and Rossby-gravity waves for the examples of both a QBO easterly and a QBO westerly phase. Because in the old manuscript only Kelvin waves for a QBO easterly phase were discussed part of Sect. 5 will be rewritten and discussion of the QBO westerly phase and the other wave modes has to be added.

The title of Section 5 will be changed to:

"Examples for equatorial wave activity during QBO easterly and QBO westerly phases"

And we will introduce two subsections:

"5.1 QBO easterly phase (period of the SCOUT-O3 tropical aircraft campaign)"

starting after para.2 (after p.11705, l.4) and after the end of former Sect. 5:

"5.2 QBO westerly phase"

Further the text will be changed in para.3 (starting from p.11705, l.5) as follows:

"First, we present the example of equatorial wave activity during the SCOUT-O3 tropical aircraft campaign in Darwin/Australia during November and December 2005. During this period we are in QBO easterly phase at 21 km altitude.

For the period of this measurement campaign the question of the reliability of meteorological analyses like ECMWF is of particular interest: A pronounced Kelvin wave is found in the ECMWF data and it is being discussed whether this Kelvin wave has a

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large impact on the dehydration of the tropical tropopause region during the period of the measurement campaign (Brunner at al., 2007).

Again, we average ...
...containing the whole time period shown. To get more reliable results also for the weaker equatorial wave modes like equatorial Rossby waves or Rossby-gravity waves we taper the data to zero at both ends of the time windows (over 10 days at each end) using a split cosine-bell window.

Tapering was not possible for the results shown in Sects. 2–4 because tapering reduces the variances with respect to the original time series. But to allow a more accurate comparison of the wave phases on a limited part of the time window tapering can reduce the spectral leakage due to edge effects caused by the finite length of the time windows."

Because Fig. 13 (former Fig. 10) now contains further panels para.4 also has to be rewritten:

"... Figure 13d shows residual ECMWF temperatures averaged over the latitudes 15S–15N which can also be compared to the symmetric wave modes, whereas Fig. 13g shows residual ECMWF temperatures averaged over 15S–15N antisymmetrically, i.e., the sign is reversed for residual temperatures south of the equator before averaging. Therefore Fig. 13g can be compared with the signatures of the antisymmetric wave modes."

Signatures of equatorial Rossby and Rossby-gravity waves will be described after the last para. of Sect 5(.1):

"Figures 13e and 13f show the signatures of equatorial Rossby waves (the n=1 symmetric wave mode) and Figs. 13h and 13i the signatures of Rossby-gravity waves for ECMWF and SABER, respectively. Please note that the color scales are different from

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Figs. 13b and 13c because Rossby and Rossby-gravity waves have lower amplitudes.

In the residual temperatures (Figs. 13d and 13g) we do not find obvious signatures of equatorial Rossby waves and Rossby-gravity waves. Since the variances for those wave modes in Figs. 5 and 6 are low in November and December 2005 this is as expected. Consequently, the amplitudes found in Figs. 13e, 13f, 13h, and 13i are relatively small compared to the Kelvin wave amplitudes.

There is a certain agreement between the ECMWF and the SABER distributions of equatorial Rossby and Rossby-gravity waves. But there are also significant differences. In particular, the SABER residual temperatures found in the Rossby (n=1) and Rossby-gravity wave bands are considerably higher and somewhat noisier than in ECMWF. This most likely can be attributed to the spectral background due to gravity waves present in the SABER spectra. This spectral noise overlays the signatures of Rossby (n=1) and Rossby-gravity waves and can probably explain most of the differences between SABER and ECMWF."

The text for the second subsection will be as follows:

"5.2 QBO westerly phase

Figure 14 shows the same as Fig. 13 but for the period from October 12 until December 11 2004. During this period we are in QBO westerly phase at 21 km altitude. From Figs. 5–10 we can see that in this period there is enhanced activity of equatorial Rossby waves (n=1) as well as enhanced variances due to Rossby-gravity waves. This can also be seen in Figs. 14e and 14f where (different from Figs. 13e and 13f) we find a very pronounced Rossby n=1 wave with a period of about 25 days. Also the activity of Rossby-gravity waves is enhanced in Figs. 14h and 14i with respect to the QBO easterly phase (see Figs. 13h and 13i).

There is good agreement between the Rossby wave structures found in ECMWF and SABER. The Rossby-gravity wave signatures are qualitatively the same in Figs. 14h

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and 14i but there are differences in details which can probably be attributed to distortions by the spectral background due to gravity waves which can be as high as about 50% of the Rossby-gravity wave variances (see Fig. 5).

However, the agreement between SABER and ECMWF Rossby-gravity waves and Rossby n=1 waves is much better than in Figs. 13h and 13i and Figs. 13e and 13f. First, the amplitudes of the Rossby-gravity waves and Rossby n=1 waves are higher in the period from October 12 until December 11 2004, and, second, at 21 km altitude temperature variances due to gravity waves are much lower (about 2 K^2, see Fig. 11a) than in the period from 27 October until 26 December 2005 (about 3 K^2, see also Fig. 11a).

It should also be noted that even during the QBO westerly phase there is still a large signal due to Kelvin waves (Fig. 14c and 14d) — lower than during the QBO easterly phase (see Sect. 5.1) but still as large as the variations due to the Rossby n=1 wave during the QBO westerly phase.

Both the signatures of the Kelvin waves and the Rossby n=1 waves can be found in the symmetric residual temperatures from ECMWF (see Figs. 14a, 14d). Even the signatures of the Rossby-gravity waves can be found in the antisymmetric ECMWF residual temperatures (see Fig. 14g) in spite of the relatively low amplitudes on average.

For all wave modes shown at 21 km altitude we find qualitatively good agreement between SABER and ECMWF not only in the wave amplitudes but also in the phases of the waves for both QBO easterly and westerly phases. Some disagreements can be explained by the gravity wave background which is much higher in the SABER data than in ECMWF. Certain agreement between SABER and ECMWF was expected since TOVS/ATOVS satellite data are assimilated in the ECMWF operational analyses. Nevertheless, it is somewhat surprising that already in the lower stratosphere there is such good agreement between SABER and ECMWF, taking into account that in the lower stratosphere equatorial waves on average have lower equivalent depths and,

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consequently, shorter vertical wavelengths. Since TOVS/ATOVS data are measured in nadir viewing geometry with broad vertical weighting functions especially short vertical wavelengths should be somewhat degraded in the TOVS/ATOVS measurements entering the ECMWF analyses."

Also the conclusions section has to be rewritten on p.11707 ll.15–19:

"... There is agreement not only in the spectra, but also in the temporal evolution of the temperature variances and even in the longitudinal distribution of residual temperatures and their temporal evolution in the lower stratosphere. This has been demonstrated at 21 km altitude in QBO westerly phase (period October–December 2004) as well as QBO easterly phase (November/December 2005, period of the SCOUT-O3 tropical aircraft campaign in Darwin/Australia) for different equatorial wave modes (Kelvin, equatorial Rossby (n=1), and Rossby-gravity waves). ..."

And the last sentence of the abstract has to be changed:

"For the examples of a QBO westerly phase (October–December 2004) and a QBO easterly phase (November/December 2005, period of the SCOUT-O3 tropical aircraft campaign in Darwin/Australia) in the lower stratosphere we find qualitatively good agreement between SABER and ECMWF in the longitude-time distribution of Kelvin, Rossby (n=1), and Rossby-gravity waves."

Further minor changes:

(1) Abstract, p. 11686, l.5:

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suggest to write: *"...SABER satellite instrument..."*

(2) p.11689, ll.20+21:

Sentence will be shortened:

"... and wind data: Higher zonal wavenumbers 4–7 also contribute significantly to the momentum flux of the waves. ..."

(3) p.11692, l.5:

We will replace the reference Coy and Swinbank, which is more general about data assimilation, with a better one giving more information about ECMWF. We will use the reference Jung and Leutbecher, QJRMS, 2007, instead. In this reference some information about the ECMWF model and the recent changes of the ECMWF assimilation system are listed. The reference Coy and Swinbank will also be replaced by Jung and Leutbecher (2007) in the References section.

(4) The spectral coverage of the reduced ECMWF data set should be stated clearly in Sect. 2.3 (p.11695 after l.5):

"...we simply omit ECMWF grid points in our analysis. This reduced data set covers zonal wavenumbers up to 20 and frequencies up to 2 cycles/day."

(5) Text for our reply to Specific Comment (4) by Anonymous Reviewer #1 will be improved by adding another sentence for explanation:

"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. Especially cases with periods close to 31 days (maybe

even longer than the time windows used) could be problematic. 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."

(6) Specific Comment (9) by George Kiladis: EC background issue

For clarification we will also reword the sentence on p.11695 ll.24+25 as follows:

"Partly this is an effect of the larger spectral region covered by ECMWF so that the total background variance is distributed on a larger number of spectral grid points."

(7) Specific Comment (10) by Anonymous Referee#1: Data assimilation issue in ECMWF

Another paragraph will be added on p.11694 after l.24. Different from the version given in the ACPD open discussion before we will do some rewording for clarity:

"Although SABER data are not assimilated in ECMWF some agreement between SABER and the ECMWF operational analyses is expected because other satellite data (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..."

(8) Sentence on p.11696, ll.5–8 will be reworded for clarity:

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"The largest contribution, however, is most likely due to the broad spectrum of gravity waves which has been found before in SABER temperature data (e.g., Preusse et al., 2006; Krebsbach and Preusse, 2007) and other limb sounding satellite data sets (e.g., Fetzer and Gille, 1994; Eckermann and Preusse, 1999; Preusse et al., 2000, 2002; Ern at al., 2004, 2005, 2006; Wu et al., 2006) but is obviously underrepresented in the ECMWF data used."

(9) Specific Comment (5) by Anonymous Referee#1: 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).

Text given in the ACPD Open Discussion for the third paragraph on p.11696 will be shortened because the estimation given is valid not only for Kelvin waves:

"...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: An increase of wave variance of about a factor of 20 would be expected."

And the last paragraph of the text given in the ACPD Open Discussion that will be rewritten, starting on p.11693 last line, will be reworded for clarity as follows:

"Both fast and slow waves will encounter amplitude amplification due to this change in N as well as due to the decrease of atmospheric density with altitude. However for the slow waves obviously critical level filtering and wave dissipation or amplitude modulation due to changes in the background wind are more important and a relative shift of the spectral signatures is observed."

(10) Substantial Concern#3 by George Kiladis: Gravity wave issue

The last two paragraphs of the text given in the ACPD Open Discussion that will be added on p.11701 at the end of Sect. 3.2 will be somewhat reworded for clarity and used in reversed order.

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