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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 Anonymous Referee #1! The comments were found extremely helpful and the manuscript will definitely benefit from the comments! Thank you very much for the additional important references! We hope that we have addressed the issues about the Doppler effect and the effects of amplitude modulation of waves propagating conservatively in a satisfactory way. The determination of momentum fluxes from the SABER measurements, however, is beyond the scope of our paper intended to only present the data, the analysis method and some implications in a first step. The determination of momentum fluxes invokes additional theory separately for each wave type and the amount of discussion required would probably double the length of the manuscript.

In the following we will address to the Reviewer Comments:

Major Comments:

Major Comment #1: "The review of previous studies using radiosonde data should be more properly made in order to clarify the originality of this paper. Several works captured essential characteristics of short-period (small-scale) waves in the QBO..."

See also Specific Comment (8).

Thank you very much for the additional references Maruyama (1994) and Vincent and Alexander (2000)! Of course, these will be added! In addition, the papers Sato et al. (1994) and Sato and Dunkerton (1997) will also be cited in this context.

Anonymous Reviewer #1 suggested to add some discussion on p.11704, 4th para (from l.18) (see Specific Comment (8))! Instead, we suggest to add the following sentences on p.11703 after l.16:

"Indications that short-period (small-scale) waves show modulations related to the QBO were found before in radiosonde data by, for example, Maruyama (1994), Sato et al. (1994), Sato and Dunkerton (1997) and Vincent and Alexander (2000). Sato and Dunkerton (1997) estimated momentum fluxes for both Kelvin waves and 1–3 day period gravity waves based on an 8-year time series of radiosonde observations at Singapore and the association between the wave fluxes and the QBO was investigated. Vincent and Alexander (2000) carried out a similar study for small-scale waves based on a 6-year data set of radiosonde observations at Cocos Islands. In addition to strong

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annual and interannual variations they also find variations related to the QBO in wave energy and zonal momentum fluxes.

Also investigations of QBO-related variations based on satellite data have been carried out before. The temporal evolution of variances..."

Major Comment #2: "The Doppler effect of the mean wind is ignored through the analysis of this paper!... The significance of the Doppler effect needs to be clarified and the ambiguity from this effect should be discussed quantitatively!"

In our paper spectra like the ones shown in Figs. 1–3 are used. These are based on the observed ground based frequency ω. This frequency is conserved for the usually made assumption of slowly varying background wind fields and the results shown throughout the paper are not directly influenced by the Doppler effect. We discuss this in more depth below.

Why is it not essentially important for the results presented in our manuscript to consider effects of non-zero background wind?

The ground-based frequency of a wave is "defined" on the wave source level by the wave excitation process and has the value:

$$\omega = \hat{\omega}_{source} + k\,\bar{u}_{source}$$

This value does not change with altitude — even though the background wind $\bar{u}$ will change with altitude (e.g., Olbers, J. Physical Oceanography (1981), Marks and Eckermann, JAS, (1995), Moulin and Flor, Dyn. Atmos. Ocean., (2005)).

Different from this, the intrinsic frequency $\hat{\omega}$ of the wave will change with altitude according to the background wind $\bar{u}(z)$:

$$\hat{\omega}(z) = \omega - k\,\bar{u}(z) = \hat{\omega}_{source} + k(\bar{u}_{source} - \bar{u}(z))$$

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This means: If a wave is launched in the troposphere and propagates upward through the stratosphere, the "location" of the wave in the zonal wavenumber/ ground-based frequency domain will always be the same, i.e., independent of altitude.

Now let us consider the case of the different frequency bands we have defined in the ground-based frequency/wavenumber domain in our paper (see Figs. 1–3): The waves contained in one of the frequency bands at one altitude will not "leave" this band if the background wind is different at another altitude. As a consequence, if we discuss the properties of the waves contained in one of the wave bands, for example, in an altitude-time cross-section (see Figs. 5–9), it is the properties of always the same "ensemble" of waves over the whole altitude range and Doppler shifting is not important here.

Are there still some shortcomings?

Yes, indeed! In her/his Major Comment #3 Anonymous Reviewer #1 mentions the effect of temperature amplitude modulation due to changes in the background wind which can also occur for waves propagating conservatively. This effect is not taken into account, and cannot be addressed easily (also see Major Comment #3).

We will add the following text for the Doppler shifting issue in the Introduction on p.11689 after l.2:

"... It should be noted that the frequencies ω that are observed by satellite instruments and most other observing systems are ground based (Eulerian) frequencies and intrinsic wave frequencies $\hat{\omega}$ will be Doppler shifted in case of non-zero background wind according to:

$$\hat{\omega} = \omega - k\,\bar{u}$$

with k the horizontal wavenumber and $\bar{u}$ the background wind. This means that spectral features can shift considerably if plotted against intrinsic frequency instead of ground based frequency. Also the vertical wavelength of the waves considered will be Doppler

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shifted. For example, a Kelvin wave having 10km vertical wavelength for zero background wind will have about 20 km vertical wavelength if the background wind changes to -30 m/s.

Doppler shifting of intrinsic frequencies and vertical wavelengths is not considered throughout the whole paper since the ground based frequency of a wave is "defined" on the wave source level by the wave excitation process and (assuming slowly varying background wind fields) does not change with altitude — even though the background wind $\bar{u}$ will change with altitude (e.g., Olbers (1981), Marks and Eckermann (1995), Moulin and Flor (2005)). This means: If a wave is launched in the troposphere and propagates through the stratosphere, the "location" of the wave in the zonal-wavenumber/ground-based frequency domain will always be the same, i.e., independent of altitude. Only the intrinsic frequencies (and vertical wavelengths) will change with the background wind.

The waves contained at one altitude in one of the frequency bands defined in Fig. 1 will not "leave" this band if the background wind is different at another altitude. As a consequence, if we discuss the properties of the waves contained in one of the wave bands, for example, in an altitude-time cross-section (see Sect. 3), it is the properties of always the same "ensemble" of waves over the whole altitude range and Doppler shifting affects only the amplitudes by, e.g., amplitude modulation, changing the saturation amplitude and critical level filtering (in the latter case the wave is completely obliterated).

This would be different for the determination of momentum fluxes, which is an important issue to quantify the effect of the analyzed waves on the QBO. Momentum flux cannot be determined from the temperature spectra (temperature variances) presented in our paper alone. Additional information like vertical wavelengths or spectra of wind perturbations would be required. However, this is beyond the scope of this paper."

Of course, the intrinsic frequency $\hat{\omega}$ can differ significantly from the ground-based (ob-

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served) frequencies ω shown in Figs. 1-3. Here are two examples for the effect of non-zero background wind (also see new text above):

(a) intrinsic frequency shift of spectral features:

For example, let us assume a background wind speed of about $\bar{u}$=-30 m/s (a typical value for the QBO easterly phase at 30 km altitude). The line of ground-based phase speed ω/k=0 m/s (positive x-axis in Figs. 1-3) would correspond to a line of intrinsic phase speed $\hat{\omega}/k = \omega/k - \bar{u}$ =30 m/s (k is the zonal wavenumber). In an $\hat{\omega}$/wavenumber diagram (axes scaling also cycles/day and integer zonal wavenumbers like in Figs. 1-3) this line would have an angle of 24 deg with the positive x-axis, corresponding to a rotation of 24 deg (counterclockwise) with respect to the ω/k spectra. At the same time the line of ground-based phase speed ω/k=100 m/s, which would have an angle of 56.5 deg with the positive x-axis, would correspond to a line of intrinsic phase speed $\hat{\omega}/k = \omega/k - \bar{u} = 130$ m/s. In an $\hat{\omega}$/wavenumber diagram this line would have an angle of about 63 deg with the positive x-axis, corresponding to a rotation of only 6.5 deg (counterclockwise) with respect to the ω/k spectra. Please note that the angles given were calculated for the case that for the plotted diagram 1 cpd has exactly the same length as 1 zonal wavenumber and the angles cannot be transferred directly to Figs. 1-3. Nevertheless there can be considerable shifts of spectral features of the intrinsic frequency/zonal waveno. spectra compared with the ground-based frequency/zonal waveno. spectra.

(b) vertical wavelength:

The vertical wavelength of a Kelvin wave is given by:

$$\lambda_z = 2\pi * \hat{\omega}/(Nk) = 2\pi * (\omega - k\bar{u})/(Nk)$$

with N the buoyancy frequency. Let us assume a Kelvin wave, having 10 km vertical wavelength at maybe 20 km altitude with background wind about zero (in this case:

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$\omega = \hat{\omega}$). If we further assume a background wind of about -30 m/s at 30 km altitude (see above) the vertical wavelength will be shifted to a value λ_z' given by:

$$\lambda_z' = \lambda_z - \bar{u}/N$$

inserting the values assumed above we obtain:

$$\lambda_z' \approx 10 \text{ km} + 2\pi * (30 \text{ m/s})/(0.02 \text{ s}^{-1}) \approx 19 \text{ km}$$

So the vertical wavelength is also shifted considerably by a factor of 2 in our example.

Major Comment #3: "Some discussion about the effects of analyzed waves on the QBO is weak and not beyond speculation! ...The temperature amplitude is "not conserved" for conservative waves propagating vertically in the mean wind having vertical shear. Thus, it is generally difficult to discuss the wave dissipation only from the temperature data. This point should be more carefully taken into account in the discussion!"

For a complete discussion of the effect of the analyzed waves on the QBO it would be required to determine momentum fluxes for the different wave types and acceleration of the zonal mean wind from momentum flux vertical gradients. Momentum flux, however, cannot be determined from the temperature spectra (temperature variances) presented in our paper alone. For the calculation of momentum fluxes additional information like wind amplitudes of the waves would be required. Since these are not available we would have to use the polarization relations for the different wave types to calculate momentum fluxes from the temperature information alone. But also for this second approach additional information like vertical wavelengths would be required, which currently are also not available.

Since our paper was only thought to present the method and the direct results from temperature spectral analyses the estimation of momentum fluxes is beyond the scope

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of the current manuscript. The determination of momentum fluxes is an important issue that deserves a more detailed treatment. Therefore this point regrettably has to remain unsolved for now. But we will address this issue by adding the above discussion (see Major Comment #2).

The momentum flux issue will be treated in the additional text suggested for Major Comment #2. The amplitude modulation issue will be treated in text added in the discussion on p.11694 and p.11696. For changes of the manuscript see Specific Comment (5).

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

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