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# Global estimates of equatorial inertia-gravity wave activity in the stratosphere inferred from ERA40 reanalysis

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[1] A new methodology is applied to ERA40 reanalysis in order to quantify large-scale inertia-gravity wave activity in the equatorial lower stratosphere. Both eastward and westward propagating waves are identified in the data set and a good agreement is found with previously published in situ observations. Global estimates of vertical fluxes of zonal momentum associated with such waves are obtained. Typical amplitudes of order  $10^{-2} \text{ m}^2 \cdot \text{s}^{-2}$  suggest that the forcing of the Quasi-Biennial Oscillation by large-scale inertia-gravity waves is tantamount to that by Kelvin waves. This method can be used to document the space-time variability of the wave-activity in order to improve the wave-drag parameterizations in climate models. **Citation:** Le Sommer, J., H. Teitelbaum, and V. Zeitlin (2006), Global estimates of equatorial inertia-gravity wave activity in the stratosphere inferred from ERA40 reanalysis, *Geophys. Res. Lett.*, 33, L07810, doi:10.1029/2005GL024873.

## 1. Introduction

[2] Gravity waves are known to play a fundamental role in driving the large-scale circulation in the stratosphere in the mid-latitudes [Andrews *et al.*, 1987]. The interest to the gravity wave forcing in the tropical stratosphere, as compared to the forcing by Kelvin waves and mixed Rossby-gravity waves, was renewed recently [Dunkerton, 1997]. By taking into account the mean upward motion in the equatorial stratosphere associated with the Brewer-Dobson circulation, Dunkerton [1997] concluded that almost a half of the zonal momentum flux required to drive the Quasi-Biennial Oscillation (QBO) should be attributed to gravity waves. On the basis of the estimation of the momentum flux associated with gravity waves performed by Sato and Dunkerton [1997], Dunkerton [1997] supposed that the contribution of large scale equatorial inertia-gravity waves [Gill, 1982] was important. This supposition has recently been corroborated by Alexander and Rosenlof [2003].

[3] Such equatorial inertia-gravity waves were observed in the stratosphere by Cadet and Teitelbaum [1979]. On the basis of radiosoundings collected over the Atlantic ocean, they gave evidence of large-scale eastward propagating inertia-gravity waves with period between 1 and 3 days. Likewise, several observational studies identified eastward and westward propagating inertia-gravity waves with about

2-days period and 3 to 6 km vertical wavelength in the lower-stratosphere over Indonesia [Tsuda *et al.*, 1994; Shimizu and Tsuda, 1997] and during TOGA-COARE campaign [Pires *et al.*, 1997; Wada *et al.*, 1999]. Though restricted to localized observations both in space and in time, radiosounding measurements suggest that the wave-activity is related to tropospheric convection [Wada *et al.*, 1999] and varies in correlated manner with the phase of the QBO [Sato and Dunkerton, 1997; Vincent and Alexander, 2000].

[4] A promising improvement of current wave-drag parameterizations in climate models is the implementation of spatially varying forcings based on local flow parameters [Kim *et al.*, 2002; Fritts and Alexander, 2003]. This requires both a global climatology of inertia-gravity wave-activity and a quantification of the relative contribution of their possible sources. For this purpose, we propose in this letter a method to quantify at the global scale the inertia-gravity wave activity in the lower equatorial stratosphere.

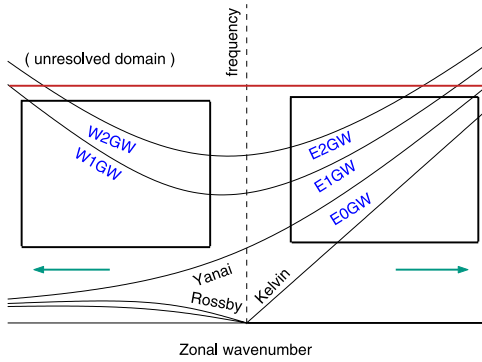
[5] Recently, Yang *et al.* [2003] have developed a methodology based on the equatorial shallow water theory which extracts from a gridded data set the dynamical fields associated with equatorial waves. Applying the method to ERA40 data set, the authors have focused on low frequency ( $\sim 0.1 \text{ day}^{-1}$ ) tropospheric waves, namely Kelvin waves, Rossby waves and mixed Rossby-gravity waves. Our first observation is that for higher frequency motions, the numerical resolution currently used in the ECMWF dynamical model is such that synoptic-scale inertia-gravity waves are now being computed with a reasonable accuracy in the mid-latitudes [Plougonven and Teitelbaum, 2003]. GCM simulations by Sato *et al.* [1999] suggest such result to hold in the tropics as well. We demonstrate below that the method proposed by Yang *et al.* [2003] may be successfully applied to higher frequency waves ( $\sim \text{day}^{-1}$ ) in the stratosphere and show how to obtain global estimates of the wave activity. In section 2, we present the method of data processing. A case study of identification of wave parameters is presented and compared with in situ measurements in section 3. We then show in section 4 how the method can be used to obtain global estimates of momentum fluxes associated with inertia-gravity waves and briefly discuss the results in section 5.

## 2. Data Processing

[6] The method is based on a decomposition of ERA40 dynamical fields. Considering horizontal winds and geopotential ( $u, v, \phi$ ) in the band between  $20^\circ\text{S}$  and  $20^\circ\text{N}$ , the purpose is to display coherent wave modes in the data set. For this, we perform a two-step decomposition on each pressure level: namely a *space-time filtering* and a *projection* onto prescribed meridional modes. The

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**Figure 1.** Scheme of the space-time filtering. Dispersion curves of equatorial waves with vertical wavenumber  $m$  corresponding to a given trapping scale  $y_0$  are plotted. In order to extract meridional modes 0, 1 and 2 of eastward propagating equatorial inertia-gravity waves (resp. E0GW, E1GW and E2GW), the analysis retains only the part of the variability of  $(u, v, \phi)$  included in the right window. The same analysis for westward propagating waves (W1GW and W2GW) with the left window respectively. Remind that the eastward branch of the Yanai wave dispersion curve corresponds to the inertia-gravity wave E0GW while its westward branch corresponds to the mixed Rossby-gravity wave. The sampling frequency of ERA40 data excludes periods shorter than 24 hours (red line).

procedure is adapted from Yang *et al.* [2003] but is applied within a different context. Indeed, we show that the method can be used to identify *stratospheric* waves and allows for the study of their *vertical propagation*, which was not addressed in the original paper.

[7] The first step of the data processing is to separate the relevant scales by means of space-time spectral analysis. Space-time spectral analysis [Hayashi, 1982] is used to extract both eastward and westward propagating components of  $(u, v, \phi)$  within given zonal wavenumber and frequency windows. As illustrated on Figure 1, we extract periods between 1 and 3 days in order to capture equatorial inertia-gravity waves. Moreover, we only consider zonal wavelengths between  $5^\circ$  and  $100^\circ$ . The procedure is applied to time-series from 10 to 30 days long.

[8] The second step, which is the key point of the procedure proposed by Yang *et al.* [2003], consists in the projection of the remaining fields onto prescribed meridional modes. We first define the variables  $(q, r)$  for a given meridional trapping scale  $y_0$  such that:

$$q = \alpha\phi + u \text{ and } r = \alpha\phi - u \text{ with } \alpha = (2\beta y_0^2)^{-1}. \quad (1)$$

[9] Then  $(q, v, r)$  are projected onto the parabolic cylinder functions with the meridional scale  $y_0$ . This yields  $(q_n, v_n, r_n)$  for each  $n \geq 0$ . Finally, for a given meridional mode  $n$ , we use a synthesis formula to rebuild the associated wave field  $(\tilde{u}, \tilde{v}, \tilde{\phi})$ . For  $n = 1$ , this formula is

$$\tilde{u} = (q_2 - r_0)/2, \quad \tilde{v} = v_1 \quad \text{and} \quad \tilde{\phi} = (q_2 + r_0)/2. \quad (2)$$

[10] Hence, the only free parameter in the whole procedure is the meridional scale  $y_0$ . Here, we chose  $y_0/R = 6^\circ$ ,

with  $R$  the Earth radius, but, as noticed by Yang *et al.* [2003], in the troposphere the results are essentially independent of that choice. Preliminary tests (not shown) indicate that this result is likely to hold for the stratosphere as well.

[11] It is worth noting that the whole two-step procedure is applied independently to each pressure level so that no vertical structure is imposed while performing the decomposition. Moreover, no a priori phase correlation between  $q$ ,  $v$  and  $r$  is assumed. In what follows, we apply the decomposition method to data corresponding to December 1992. This choice is motivated by the possible comparison of our results with the in situ measurements during the TOGA-COARE campaign. One can also expect that the quality of ERA40 reanalysis is improved at this period due to the assimilation of TOGA-COARE data. Note that the zonal wind vertical profile in December 1992 above the western Pacific is typical of the easterly shear phase of the QBO, with easterly wind above 40hPa and westerly wind below.

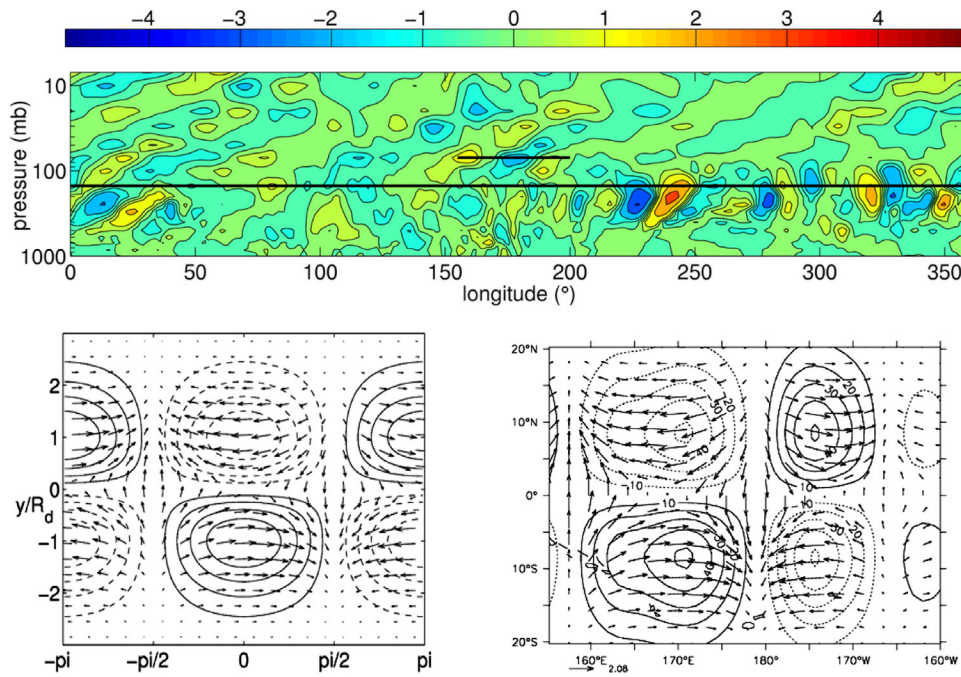
### 3. Identification of Equatorial Inertia-Gravity Waves

[12] The decomposition method allows to extract a coherent wave signal from the data set with wave parameters which are consistent with in situ observations. Figure 2 presents the results of the analysis for the eastward propagating mode 0 on 26 December 1992. As noticed in the previous section, no vertical structure nor horizontal phase correlation between the velocity and the geopotential are imposed. However, horizontal phase correlation of  $u$ ,  $v$  and  $\phi$  are consistent with the horizontal structure of E0GW predicted by the theory (see Figure 1 for the notations). Moreover, the vertical coherence of the wave signal which is organized along clearly visible phase lines shows that the wave is dynamically consistent and is not an artifact of the data processing.

[13] Once the reliability of the analysis is checked, we can estimate the parameters of the identified wave. The wave which is observed at 70 hPa between 150E and 160W on 26 December 1992 has a horizontal wavelength  $\lambda_x \sim 3500$  km and a vertical wavelength  $\lambda_z \sim 5$  km with typical geopotential anomaly about  $80 \text{ m}^2 \cdot \text{s}^{-2}$ . As a supplementary consistency check, we use the formula relating the trapping scale  $y_0$  and the vertical wavelength  $\lambda_z$ ,  $N = 4\pi\beta y_0^2/\lambda_z$ , to be sure that the chosen value of  $y_0$  is relevant. From Figure 2, the estimated vertical wavelengths range from 5 km to 8 km. Taking  $y_0/R = 6^\circ$ , this formula gives  $N$  ranging from  $0.015 \text{ s}^{-1}$  to  $0.025 \text{ s}^{-1}$  which is consistent with in-situ measurements in the lower stratosphere.

[14] An important piece of information is given by the vertical phase tilt of the wave signal. Considering that the wave is propagating eastward, the phase tilt shows that energy is propagating upward above 250 hPa which suggests that the wave should be emitted about this intermediate level.

[15] Such wave parameters obtained in the TOGA-COARE area are consistent with in situ measurements made in December 1992 [Wada *et al.*, 1999]. Indeed, these authors found E0GW with horizontal wavelength of three to four thousand kilometers and vertical wavelength of 4–



**Figure 2.** (top) The  $(x, z)$  vertical section along the equator ( $y = 0$ ) of the eastward propagating meridional velocity anomaly ( $\text{m.s}^{-1}$ ) associated with meridional mode 0 on 26 December 1992 at 12:00 UT. The short black line indicates the  $(x, y)$  section shown in the lower right plot. (bottom left) The  $(x, y)$  horizontal section of wind and geopotential anomaly associated with an E0GW as predicted by the shallow water theory (arbitrary contours).  $R_d = y_0\sqrt{2}$  is the equatorial Rossby radius. (bottom right) The  $(x, y)$  horizontal section of the eastward mode 0 wind and geopotential anomaly at 70 hPa corresponding to the top plot. The long black line indicates the average tropopause level.

5 km in the lower stratosphere over the TOGA-COARE Large-scale Soundings Array. Considering the coarse vertical resolution of the model used to produce ERA40 reanalysis, it is worth emphasizing the consistency of the estimated vertical wavelength with the vertical wavelength obtained by *Wada et al.* [1999]. They also observed the prominence of eastward propagating waves at this period. The latter observation is corroborated by our analysis as will be shown in section 4.

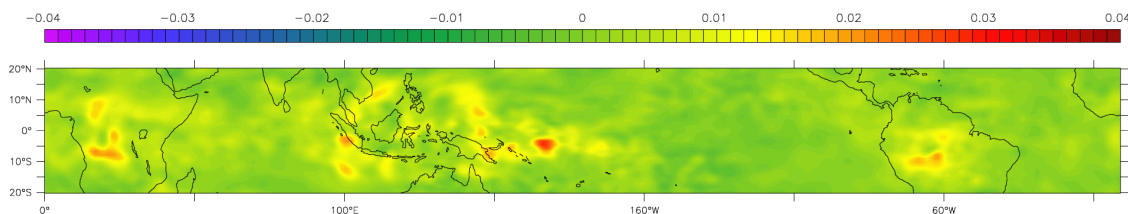
[16] The same analysis has been carried out for E1GW, E2GW, W1GW and W2GW with similar conclusions (not presented). Thus, the decomposition method allows for the identification of inertia-gravity waves within ERA40 data set and for the estimation of their parameters.

#### 4. Space-Time Variability of the Vertical Flux of Zonal Momentum

[17] The decomposition method can also be used to estimate the vertical flux of zonal momentum due to the

quasi 2-day wave field and to determine its space-time variability. In principle, it is possible to compute the vertical velocity perturbation associated with the each wave mode, however this requires a reconstruction of  $\tilde{w}$  on the basis of the hydrostatic condition, or from the continuity equation. We rather present the vertical fluxes obtained from the whole 1–3 day period wave field with  $w$  taken directly from ERA40 data set. It is to be noted that the fluxes are originally computed in  $\text{Pa.m.s}^{-2}$  and converted in  $\text{m}^2.\text{s}^{-2}$  using a dimensional coefficient  $-1 \text{ m.Pa}^{-1}$  which is typical of the lower stratosphere.

[18] Figure 3 shows the flux associated with 1–3 day period waves between the 14 December 1992 and the 25 December 1992 calculated at 100 hPa. At that time, the absolute value of the flux associated with eastward propagating waves  $|\overline{u'_e w'_e}|$  is higher than that of westward propagating waves  $|\overline{u'_w w'_w}|$  (not shown). Moreover,  $\overline{u'_e w'_e}$  varies with longitude in a way that maximum amplitudes are located above the continents. It should be stressed that typical amplitudes of the flux  $3.10^{-2} \text{ m}^2.\text{s}^{-2}$  are comparable



**Figure 3.** Vertical flux of zonal momentum  $\overline{u'_e w'_e}$  of eastward propagating waves with periods between 1 and 3 days from 14 December 1992 to 25 December 1992 at 100 hPa ( $\text{m}^2.\text{s}^{-2}$ ).



with that of Kelvin waves or mixed Rossby-gravity waves [Andrews *et al.*, 1987].

[19] An interesting property of the decomposition method is its ability to distinguish between the upward transport of eastward (resp. westward) momentum and the downward transport of westward (resp. eastward) momentum. Indeed, as follows from Figure 2, the waves are mainly propagating upward at 100 hPa. Therefore positive values of  $u'_e w'_e$  associated with eastward propagating waves indicate an upward transport of eastward momentum.

[20] Hence, the proposed method allows for the direct calculation of vertical fluxes of zonal momentum due to equatorial inertia-gravity waves and reveals their space variability. In principle, a similar analysis can be carried out to study the time variability of momentum fluxes. Nonetheless, we should emphasize that, given the sparseness of the observations used to validate the procedure, the estimate of momentum flux we propose should be taken with caution.

## 5. Summary and Discussion

[21] We have applied a new methodology based on ERA40 reanalysis data set to quantify inertia-gravity wave activity in the equatorial lower stratosphere. The method consists in a two-step decomposition of the dynamical fields: space-time spectral analysis and projection onto prescribed meridional modes. The procedure was applied to waves with periods from 1 to 3 days in the lower equatorial stratosphere during December 1992. Coherent wave signals corresponding to both eastward and westward propagating inertia-gravity waves of meridional modes 0, 1 and 2 were identified in the data set and were found to be consistent with in situ observations collected in the TOGA-COARE campaign at that time. It is shown that the vertical flux of zonal momentum associated with large-scale equatorial inertia-gravity waves is tantamount to that of Kelvin waves and mixed Rossby-gravity waves. The procedure can be used to document the space-time variability of wave activity which could improve the wave-drag parameterizations in climate models.

[22] Two comments on the distinction between our work and the paper by Yang *et al.* [2003] are necessary. First, we apply the procedure to *high frequency* waves in the *stratosphere*. Second, we apply it at several pressure levels, and show that the identification of the *vertical propagation* and the estimation of momentum fluxes of the wave field are possible.

[23] We should also emphasize that for the first time the lower stratospheric inertia-gravity wave activity over the whole equatorial belt is exhibited. Previous studies based on in situ measurements were mainly focused on the Atlantic ocean [Cadet and Teitelbaum, 1979] or on the TOGA-COARE region [Wada *et al.*, 1999] with the noticeable exception of the data collected with pressurized balloons [Hertzog and Vial, 2001]. To our knowledge, the high level of inertia-gravity wave activity found in the whole lower equatorial stratosphere was never displayed before.

[24] Let us also mention that we extracted high frequency wave motions with relatively small vertical wavelength ( $\lambda_z \sim 5$  km) from ERA40 reanalysis data set. Though an extensive comparison with radiosoundings is required to

assess the reliability of the data set in this regime, the gross consistency of the results suggests that ERA40 data do carry information about inertia-gravity wave activity. The T159 spectral resolution of the ECMWF model is sufficient to capture the typical horizontal scales of equatorial inertia-gravity waves. However, the vertical resolution of the ECMWF model, which typically corresponds to 1 km in the lower stratosphere, is likely to underestimate wave motions with  $\lambda_z \lesssim 5$  km. We nonetheless believe that the ERA40 reanalyses contain the climatology of the large-scale inertia-gravity waves, at least for a part of the spectrum.

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