Influence of QBO on stratospheric Kelvin and Mixed Rossby gravity waves in high-top CMIP5 models

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Abstract. It is well established that quasi-biennial oscillation (QBO) has a substantial influence on Kelvin and mixed Rossby gravity (MRG) wave activity in the tropical lower stratosphere. In this study, we examined how QBO influences Kelvin and MRG wave activity in the lower stratosphere, based on nine high-top CMIP5 models. The results show that the Kelvin and MRG wave signals are stronger in the models with QBO, and relatively weaker in the models without QBO. The results are consistent with established theory, whereby upward-propagating Kelvin waves occur more frequently during the easterly QBO phase, while upward-propagating MRG waves occur during the westerly QBO phase. Without the QBO, the mean flow exhibits a near-zero easterly wind, which prevents the waves from propagating and penetrating into the stratosphere. Our analysis also shows that models with the QBO tend to have more robust signatures (in terms of amplitude and phase speed) of Kelvin and MRG waves.

1. Introduction

Equatorial planetary waves (EPWs) are atmospheric waves that are trapped close to the Equator, generated by a large-scale convective system. EPWs contribute to the western and eastern phases of quasi-biennial oscillation (QBO) [1]. QBO is a stratospheric oscillation, with a period of two years, which occurs simultaneously around the equatorial belt. Observational data have shown that Kelvin waves can transfer their momentum to the mean flow, resulting in an easterly phase of the QBO. In contrast, mixed Rossby gravity (MRG) waves can produce momentum that contributes to the westerly phase of the QBO [2-4].

The stratosphere plays a significant role in both global atmospheric circulation and surface climate. The fifth-comparison coupled model intercomparison project (CMIP5) improves the representation of the stratosphere by expanding the lid of the model up into this region. In general, most CMIP5 models include the stratosphere and QBO. This type of model can be used to analyse the effect of QBO on generating larger-amplitude waves better than models without QBO [5].

The focus of this study was to examine the characteristics of Kelvin and MRG waves in the lower stratosphere (level 50 hPa), and their interaction with QBO activity, with the main focus being on horizontal structure, based on high-top CMIP5 models. In addition, we evaluated the ability of the CMIP5 models to represent Kelvin and mixed Rossby gravity wave activity on a subset of high-top CMIP5 models.
2. Methods
The data used in this research are daily zonal wind and temperature data from nine high-top CMIP5 models, and ERA-Interim reanalysis obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF), for the period January 1985 to December 1995. We focused on the equatorial latitudinal band between 10°LU and 10°LS, at a height of 50 hPa.

2.1 Space-Time Spectral Analysis (STSA)
STSA was used to study the zonal propagation of waves by decomposing tropical disturbances as a function of frequency and zonal wavenumber into symmetric and asymmetric components. This technique decomposes the time-dependent data fields (zonal winds) into wave and frequency components for eastward and westward travelling waves [6-8].

2.2 Amplitude Distribution
We also examined the amplitude variations of Kelvin and MRG waves associated with the zonal wind in the tropical lower stratosphere during different QBO phases. The amplitude was calculated as the variance of filtered fields, wherein a high value of variance indicates that the effect of the associated waves is large.

2.3 Composite Analysis
Composite analysis is a method used to determine atmospheric distribution under certain conditions [9].

3. Results

3.1 Determining the Phases of QBO
High-top CMIP5 models can represent the stratosphere and QBO vertically. Some models may indicate a good enough QBO signal, but there are also models that are unable to simulate the QBO. Kelvin wave activity is very strong in the easterly phase of QBO, while MRG wave activity is relatively stronger during the westerly phase of QBO. To determine whether the model could simulate the presence of QBO, or vice versa, we first calculated the wind speed anomaly for each model in the lower stratosphere [5]. In principle, in the equatorial lower stratosphere, EPW waves (including Kelvin and MRG waves) can propagate vertically, or grow, if there is a favorable windshear associated with the QBO.

![Figure 1. Time-series of monthly zonal-mean wind anomalies for 11 years (1985-1995), averaged at 10°N-10°S (50 hPa) from ERA-Interim data and nine high-top CMIP5 models.](image)

The time-series of the tropical stratopheric wind, from ERA-Interim data and nine high-top CMIP5 models, is shown in figure 1. In this study, the westerly and easterly phases of QBO were defined as zonal wind velocity anomalies of less than -5 m/s, or more than 5 m/s, respectively [10]. Figure 1 shows
that the ERA-Interim and MPI-ESM-MR, HadGEM2-CC, and MIROC-ESM models, provided wind speeds of above 5 m/s and below -5 m/s. In contrast, the line graph, representing the models CanESM2, CMCC, MPI-ESM-LR, IPSL-CM5B-LR, IPSL-CM5A-MR, MRI-CGCM3, does not indicate the presence of QBO. Therefore, from figure 1, we can see that there are two groups of models; the first group (MPI-ESM-MR, HadGEM2-CC, MIROC-ESM) simulated QBO, but the second (CanESM2, CMCC, MPI-ESM-LR, IPSL-CM5B-LR, IPSL-CM5A-MR, MRI-CGCM3) did not.

3.2 Characteristics of Kelvin Waves

Kelvin waves are generated by large-scale convective heating oscillations in the equatorial tropospheric layer. Based on previous research [2,3,11], the Kelvin wave is the oscillation of the zonal wind component near the Equator, in the form of eastward propagating waves, having a period of between 12 and 20 days, a vertical wavelength of 10 km, and a zonal wavelength of 40,000 km [12].

Figure 2 shows the symmetric component of the STSA. The color spectrum shows the wave power, and the dispersive curve shows the relation between the frequency and the wave number. The STSA results show that the Kelvin wave moved eastward, characterized by a positive wave number and strong Kelvin wave activity, based on the ERA-Interim data and model with QBO; it is indicated by the dominance of red in the color spectrum.

The models that could not simulate QBO show weaker amplitude, dominated by green in the color spectrum. CanESM2, IPSL-CM5B-LR, IPSL-CM5A-MR, MPI-ESM-LR, and MRI-CGCM3 are the models wherein the period of propagation was longer than for the other models, but which had weaker wave strength. It is interesting to examine the spatial distribution of each wave amplitude. Figure 3 shows the variance distribution of Kelvin waves in the ERA-Interim (reference) and high-top CMIP5 models.

MPI-ESM-MR has the greatest variance, compared to the other models that could simulate QBO. Models that could not simulate QBO seem to be underestimated, since the value of its variance is smaller than in the ERA-Interim model. The higher the value of variance, the greater the wave activity. Figure 3 shows that strong Kelvin wave activity occurs at longitudes 30°-120°E, over the Indian Ocean and the Maritime Continent. The presence of cloud cover, due to the effects of the Asian monsoon, evokes Kelvin wave over the Maritime Continent. This may be a reason why the Kelvin wave signal in that region is stronger than in other regions [13].

Figure 4 shows Kelvin wave variance as a function of longitude. Almost all models that could simulate QBO tend to follow the ERA-Interim (black line) model. The variance shows the maximum value at longitude 70°, and its minimum at 227.5°. Almost all of the models overestimated the amplitude, with the MPI-ESM-MR (purple line) and MIROC-ESM (turquoise line) indicating a very distant representation of the ERA-Interim model. Based on the residual graph (figure 4b), the closer the line is to zero, the better the model in representing the Kelvin waves. The IPSL-CM5B-LR, IPSL-CM5A-MR, and CANESM2 models have residual values close to zero, while models that simulated QBO have residual values far from zero. Almost all of the models overestimated the amplitude, except for MRI-CGCM3, and IPSL-CM5A-MR. Similar results were found, based on filtered temperature data.

Furthermore, we wanted to examine the propagation of Kelvin waves, using the Hovmoeller diagram. Based on the results of composite analysis, all of the models were able to simulate the presence of eastward zonal wind propagation. Models that could simulate QBO have stronger wave signals and longer propagation phases than non-QBO models. This shows that the Kelvin wave is moving eastward and has a long period (figure 5).
Figure 2. STSA (symmetric) daily zonal wind at 10°S-10°N (50 hPa), from (a) ERA-Interim as base, (b-d) models with QBO, and (e-j) models without QBO. The y-axis shows the frequency of the wave, while the x-axis shows the number of waves in the west and east zonal direction.

Based on the wave’s magnitude, as indicated by the composite results, MPI-ESM-MR exhibits a longer propagation phase and lighter color than the ERA-Interim model. This indicates that the MPI-ESM-MR wave signal is stronger than the ERA-Interim (overestimate). In contrast, HadGEM2-CC shows weaker signals than the ERA-Interim. Overall, almost all of the models show Kelvin wave signal propagation. The models that could simulate QBO show stronger signals and longer propagation phases than models that could not demonstrate QBO.
3.3 Characteristics of MRG Waves

The MRG wave is a short-period wave, clearly visible in the meridional wind component, propagating westward and downward. This wave has a period of between four and five days, a zonal wavelength of 10,000 km, and a vertical wavelength of approximately 5 km [14]. MRG waves are detected by STSA (anti-symmetric) each season, under all conditions [4].

The STSA (antisymmetric) results indicate the presence of MRG waves propagating in the lower stratosphere layer (figure 6). These also show that the models that could simulate QBO have stronger wave signals than the models that could not, characterized by lighter spectrum colors. The zonal wavenumber for the MRG wave has a negative value, indicating that the MRG wave propagates from east to west. The spectral value of the ERA-Interim dispersive curve, and the model that could simulate QBO, is larger than the spectrum value of the model that was unable to simulate QBO.
HadGEM2-CC is one of the models determined to be overestimated because it shows strong MRG wave activity with the highest spectrum value than ERA-Interim, which is equal to 2.78-5. Overall, not all models exhibit strong MRG wave signals, but figure 6 shows that the period of the MRG wave, as shown by the models (b-d), is longer.

Figure 7 shows the MRG wave spatial distribution based on zonal wind filter data. The variance results show that almost all models that could simulate QBO have higher variance values. Based on the results of the variance distribution of the ERA-Interim model, MRG wave propagation shows high activity in the Pacific Ocean region, characterized by a dominant red contour in this region. Based on the results of the variance values, models capable of simulating QBO have a higher variance value, compared to the reference variance value (ERA-Interim), whereas models that could not simulate QBO show lower variance values than that of the reference.

Figure 8 shows the value of the MRG wave amplitude as a function of longitude. Almost all of the models that could simulate QBO tend to follow the ERA-Interim model (black line). The variance shows the maximum value at 140° longitude, but almost all of the models show peak variance at 270° longitude. All of the models exhibit overestimation, with MPI-ESM-MR (purple line) showing a very far-reaching representation of the ERA-Interim model. Based on the residual graph (figure 8b), if the line is closer to zero, then the model represents Kelvin waves better (approaching the ERA-Interim). IPSL-CM5B-LR has residual values close to zero, while the other models have residual values far from zero.

Based on Hovmoeller analysis (figure 9), Kelvin wave signals show longer periods, compared to the MRG wave period; this is consistent with the STSA results. All of the models are able to show MRG wave signals. HadGEM2-CC, MIROC-ESM, and MPI-ESM-LR show longer MRG wave phases than the ERA-Interim model. In contrast, ERA-Interim, MPI-ESM-MR, CanESM2, CMCC-ESM, IPSL-CM5B-LR, IPSL-CM5A-MR, and MRI-CGCM3 indicate a shorter wave period. Each model shows a wave signal with different magnitudes. MPI-ESM-LR, HadGEM2-CC, and MIROC-ESM overestimate the amplitude of the propagation.
Figure 6. STSA (antisymmetric) daily zonal wind at 10°S-10°N (50 hPa), from (a) ERA-Interim as base, (b-d) models with QBO, and (e-j) models without QBO.

Figure 7. Spatial distribution of MRG wave amplitude, based on filtered zonal-mean wind in (a) the ERA-Interim, and (b-j) nine high-top CMIP5 models.
Figure 8. MRG wave variance as a function of longitude, based on filtered zonal winds at 50 hPa (a), and the residual Kelvin wave variance, i.e., model minus observation (b).

Figure 9. Composite analysis of the MRG wave, using a filtered seasonal zonal wind (DJF) basepoint at 0°N and 270°E at 50 hPa. (a-d) models with QBO, (e-j) models without QBO.

Figure 7 also illustrates that the spatial distribution of MRG waves that dominate the Pacific Ocean region. Strong MRG waves are detected for most of the year in the Pacific Ocean region. This is because the Pacific Ocean region experiences high convective activity, due to the high sea-surface temperature distribution, and its coincidence with the ITCZ region [15].

4. Conclusions
We studied the characteristics of Kelvin waves and mixed Rossby-Gravity waves in nine high-top CMIP5 models, with and without QBO. The wave properties were analysed using STSA and composite analysis. The key results of this study are:
1) Models with QBO better represent Kelvin and MRG waves, the best being the MPI-ESM-MR, HadGEM2-CC, and MIROC-ESM models.
2) Models with QBO produce larger-amplitude Kelvin and MRG waves, compared to those without QBO.
3) Consistent with established theory, upward-propagating Kelvin waves occur more frequently during the easterly QBO phase, while upward-propagating MRG waves occur during the westerly QBO phase.

4) Without QBO, mean flow exhibits a near-zero easterly wind, preventing the waves from propagating and penetrating into the stratosphere, thus weakening Kelvin and MRG wave activities in the models without QBO.

Future studies are aimed at understanding the mechanisms that control upward propagation of Kelvin and MRG waves from the troposphere to the stratosphere in CMIP5 models.

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