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Activity of convective coupled equatorial wave in tropical Tropopause layer in reanalysis and high-top CMIP5 models

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Abstract. The activity of convectively coupled equatorial waves (CCEWs), including Kelvin waves, Mixed Rossby-Gravity (MRG), and Equatorial Rossby (ER), in the tropical tropopause layer (TTL) is investigated in the Reanalysis and nine high-top CMIP5 models using the zonal wave number-frequency spectral analysis with equatorially symmetric-antisymmetric decomposition. We found that the TTL activities in the high-top CMIP5 models show significant difference among the high-top CMIP5 models with respect to the observation. The MIROC and HadGEM2-CC models work best in simulating Kelvin wave in the TTL, while the HadGEM2-CC and MPI-ESM-LR models work best in simulating MRG waves. The ER waves in TTL are best simulated in the MRI-CGCM model. None of the models are good in simulating all waves at once. It is concluded that the broad range of wave activity found in the different CMIP5 models depend on the convective parameterization used by each model and the representation of the tropical stratosphere variability, including the QBO.

1. Introduction
Convectively coupled equatorial waves (CCEWs) are the tropical waves generated by large-scale convective system and have strong influences on tropical rainfall and circulation [1-7]. CCEWs include Kelvin waves, Mixed Rossby-Gravity (MRG), and Equatorial Rossby (ER). CCEWs have strong influence on tropical weather system and stratospheric circulation, e.g. they play an important role in transferring momentum and energy from the troposphere into the stratosphere. In the troposphere, CCEWs control the variation of the tropopause temperature and thus determine the variability of tropical tropopause layer. Since the waves are coupled with temperature, the variation of the tropical tropopause layer can be also used as a proxy of wave activity at this level.

The efforts in developing climate model have been made recently within the Coupled Model Intercomparison Project Phase 5 (CMIP5) models. CMIP5 is one of the IPCC assessment reports, which is a continuation of the previous assessment report of AR4. CMIP5 is expected to project climate change in two groups: close group (close to 2,035) and distant group (close to 2,100 to over), adding several other factors such as cloud and carbon cycle. The representation of tropical tropopause layer is varying among CMIP5 models, and the activity of CCEWs in these models is not well
documented yet. In this study, we will identify the characteristics of tropical waves (Kelvin, MRG, ER, TD-type) in the tropical tropopause layer (TTL) and then, to examine the capability of high-top CMIP5 models in reproducing tropical waves in the TTL and its implication on transport processes in that region.

2. Data and Methods

2.1 Data
The research used reanalysis data from ERA-Interim and 9 models of High-Top CMIP5. The CMIP5 models used are CMCC-CESM, CanESM2-CC, HadGEM-CC, IPSL-CM5A-MR, MPS-ESM for January 1985 to December 1995. We focus on latitude 20S to 20N with a resolution of 2.5 x 2.5 °.

2.2 Zonal Wave Number Frequency Spectrum
This method is used to study zonal propagating waves and decompose the time-dependent data field (in this study using zonal winds) into the wave and frequency components for waves that travel west and east [8-10]. Then a further complex FFT process is performed for the function in time against the Fourier coefficients to obtain the spectrum of the number of frequencies for each latitude. Furthermore, the spectrum of zonal wind power data is averaged over the time of the study then summed for all latitude [9].

2.3 Spatial Distribution
Spatial distribution used to analyze variability of equatorial waves in space, by variance and residual values. The background spectrum analysis serves to eliminate the "red noise" found in the spectrum with small frequency values [4, 9]. The bias in this analysis comes from the difference in meteorological parameter values. Disturbance is seen as a small increment associated with a red noise spectrum or in other words can be seen at the top or bottom in the output of the zonal wave number-frequency spectrum.

2.4. Taylor Diagram
Taylor diagrams make it easy to find the best models using RMS values, correlations, and variance ratios [11]. The model having a correlation value close to 1 and the RMS value closest to the observation curve illustrates the best model. The line between RMS values marks the curve of observation. The diagram will help in summarize the relative quality of each model compared with observation.

3. Results

3.1 Basic Comparison of Temperature in Tropical Tropopause Layer
The tropopause layer is a layer with a constant temperature value with respect to height but varies with time and space. The average temperature distribution of each model when compared with observation tends to be the same with different temperature values. The highest temperature value according to observation is 200° K while the model's highest temperature of 205° K is seen in CanESM2, HadGEM, IPSL-CM5B-MR and MRI-CGCM models. When viewed from the closest value, then four of the nine models are considered good. Based on spatial distribution of temperature, the models such as HadGEM, IPSL-CM5B-LR and MIROC can be considered the best models (figure 1).
3.2 Statistical Significance and Dispersion Relation of Equatorial Waves

The symmetric component shows the frequency and wave number spectra of the Kelvin and equatorial Rossby (ER). Kelvin wave signal are observed between wave numbers 1 to 5. The difference between Kelvin and ER waves can be seen from the shape of the dispersion curve and their phase speed. Kelvin wave has mode of $n \leq 1$ whereas ER wave has mode of $n \geq 1$, this will be related to wave propagation direction. This result is consistent with the previous observationally-based analysis of CCEWs [4, 9].

The best models that have similar signatures of Kelvin and ER wave spectra as in observation are IPSL-LR, HadGEM, MRI-CGCM, and MIROC (figure 2). In addition, the asymmetric component shows the frequency and wave number spectra of the MRG and Inertia Gravity Waves. The MRG wave has $n \geq 1$ mode, similar to ER wave. The difference between MRG and ER waves lies in its frequency and wave period. The best models that have similar signatures of MRG wave spectra as in observation are IPSL-LR, HadGEM, MPI-ESM-LR, MPI-ESM-MR, and MIROC (figure 3).

3.3 The Characteristics of Kelvin Waves

Kelvin wave amplitudes maximize in the equator from 10S to 10 N latitude. There are 5 CMIP models that well represent the distribution of Kelvin wave activity compared to the observation (figure 4). They are including the CMCC, HadGEM, MPI-ESM-MR and MIROC. Among these models, the MPI-ESM-MR model is the most representative model with respect to ERA-Interim. MIROC is the model with residual value farther than the ensemble mean model’s value.
Figure 2. Space-time spectral analysis (Symmetric) of daily temperature at 20°S-20°N (1,000 hPa) from (a) ERA-Interim as base (b-d) with QBO models (e-j) without QBO models.
Figure 3. Space-Time Spectral Analysis (Antisymmetric) daily temperature at 20°S-20°N (1000 hPa) from (a) ERA-Interim as base (b-d) with QBO models (e-j) without QBO models.
Figure 4. Spatial distributions of Kelvin wave variances using temperature filter from (a) ERA Interim and (b-j) nine high-top CMIP5 models.

3.4 The Characteristics of Mixed Rossby-Gravity Waves
Mixed Rossby-gravity (MRG) is a wave with zonal wavenumber of 3-5, period of 3-5 days, travels westward with center point above the equator and with maximum activity at 110-190 hPa [4, 5, 9]. It has a zonal wavelength is 10,000 km and has vertical wavelength approximately 5 km [12]. In contrast to kelvin wave that has high distribution and easily identifiable between 10S-10N latitude, the MRG wave distribution is seen at higher latitudes and spreading over the Pacific Ocean region. Figure 5 shows high MRG wave activity at 0-20 N latitudes from June to October. In particular, the MRG waves in northern Pacific Ocean have exceptionally high values (figure 5). MRG waves are most easily identified in the boreal autumn [4, 9]. In the CMIP5 models, the MPI-ESM-MR is the worst model in showing the wave activity of MRG waves that tend to overestimate the amplitudes. This model also has the farthest residual value away from the ensemble mean (not shown).

3.5 The Characteristics of Equatorial Rossby Waves
The largest ER wave activity lies in the off equatorial regions. Some models have overestimated the ER wave amplitudes compared to the ERA-Interim model. The largest ER wave activity occurs in the northeast of the Pacific Ocean during boreal summer [4, 9].

Based on the spatial distribution of ER waves, the ER wave activity in TTL from the high-top CMIP5 model is best simulated in the MRI-CGCM, IPSL-ESM-LR and CAN-ESM2 models (figure 6).
Figure 5. Spatial distributions of Mixed Rossby-Gravity wave variances using temperature filter from (a) ERA-Interim and (b-j) nine high-top CMIP5 models.

Figure 6. Spatial distributions of Equatorial Rossby wave variances using temperature filter from (a) ERA-Interim and (b-j) nine high-top CMIP5 models.

4 Conclusion
In this study, the characteristics of Kelvin waves, Mixed Rossby-gravity waves, and Equatorial Rossby waves in the tropical tropopause layer are analyzed using the ERA-Interim reanalysis dataset and high-top CMIP5 models from 1985-1995. We implemented the space-time spectral analysis (STSA) technique in order to understand their horizontal characteristics. The key results of this research are concluded as follow:

- TTL wave activities show significant difference among the high-top CMIP5 models with respect to the observation.
The MIROC and HadGEM2-CC models work best in simulating Kelvin wave in the TTL, while the HadGEM2-CC and MPI-ESM-LR models work best in simulating MRG waves.

- The ER waves in TTL are best simulated in the MRI-CGCM model.
- It is concluded that the broad range of wave activity found in the different CMIP5 models rely on the convective parameterization used by each model and the representation of the tropical stratosphere variability, including the QBO and MJO.

Future studies are still required in order to understand the mechanisms causing the strong biases of the CCEWs in the CMIP5 models, and to investigate whether such biases have a significant impact on the variability (synoptic time scale) of the tropical tropopause layer.

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