Projection of Tropical Cyclones on Wavenumber–Frequency-Filtered Equatorial Waves

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ABSTRACT

The impact of localized convection associated with tropical cyclones (TCs) on activity ascribed to equatorial waves is estimated. An algorithm is used to remove outgoing longwave radiation (OLR) signal in the vicinity of observed tropical cyclones, and equatorial wave modes are extracted using the standard wavenumber–frequency decomposition method. The results suggest that climatological activity of convection-coupled equatorial waves is overestimated where TC tracks are densest. The greatest impact is found for equatorial Rossby (ER)- and tropical depression (TD)-type waves followed by the Madden–Julian oscillation (MJO). The basins most affected are the eastern and western North Pacific Ocean where, on average, TCs may contribute up to 10%–15% of the climatological wave amplitude variance in these modes. In contrast, Kelvin waves are least impacted by the projection of TCs. The results are likely relevant for studies on the climatology of equatorial waves in observations and global climate model simulations and for those examining individual cases of TC genesis modulated by equatorial wave activity.

1. Introduction

Convection-coupled waves are an integral part of atmospheric variability in the tropics (e.g., Gruber 1974; Takayabu 1994; Wheeler and Kiladis 1999). Numerous studies have found that they modulate precipitation, atmospheric momentum transport. and tropical cyclone (TC) activity (e.g., Liebmann et al. 1994; Lin et al. 2005; Bessafi and Wheeler 2006). Accurate assessment of climatological wave activity is essential for a complete description of tropical circulation and validation of numerical models used to study the waves. Equatorial wave activity, defined as the variance of filtered signals, is typically deduced from proxies of convection using spectral decomposition methods. To the extent it can be claimed that tropical cyclones are localized vortices—distinct from equatorial waves—it is possible that their signal in convection can artificially contribute to the variance ascribed to these waves.

At higher latitudes, Rossby and inertia–gravity modes are clearly separated in the spectral domain. However, near the equator, these modes appear close to each other in the wavenumber–frequency spectrum. Consequently, it is not easy to unambiguously identify specific wave modes using raw data. It is necessary to decompose the data into components associated with known eastward- and westward-propagating waves. As shown by Zangvil (1975), and many others since (e.g., Wheeler and Kiladis 1999), peaks in observed spectral power distribution appear to match dispersion curves for inviscid shallow-water equatorial waves. Individual classes of modes are extracted through inverse Fourier transform of the portions of the spectrum where the signal-to-noise

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ratio is significant relative to red noise (e.g., Wheeler et al. 2000; Yang et al. 2003).

The method of spectral decomposition involves two implicit assumptions: 1) the waves are linearly separable; and 2) isolated, nonwavelike disturbances do not significantly project onto the decomposed modes (i.e., their power is smeared over a wide range of wavenumbers and frequencies). Apropos the former, it is possible that small amplitude equatorial waves may effectively evolve quasi independently while allowing for some measure of interaction between scale-separated modes (e.g., Hartmann and Maloney 2001; Aiyyer and Molinari 2003). However, it is the latter assumption that is of concern here, especially given that localized disturbances, such as TCs, have strong convective signals. In fact, it is quite easy to identify TCs in charts of proxies of convection, such as outgoing longwave radiation (OLR). A randomly occurring localized feature is not expected to significantly impact a particular wave mode, owing to its broad spectral projection. However, given their spatial and temporal coherency, the collective impact of multiple TCs can be substantial over a wide range of wavenumber and frequency bands. This concern is certainly not new. Zangvil (1975) highlighted the need for caution while interpreting spectral peaks around the scales of localized disturbances. This has particular significance to modes such as tropical depression (TD)-type disturbances, which are also referred to as easterly waves, and are nearly of the same scale as the TCs. Some studies (e.g., Frank and Roundy 2006) use threshold values of filtered fields to reject cases potentially dominated by noise, in part due to localized features. While this is a useful approach, experience shows that often the convective signal of TC is substantially higher than usually assumed. An alternative is to replace the fields in the vicinity of the TCs with a suitable background or with climatological values, as was done for a study on MJO modulation of TC genesis (Camargo et al. 2009).

The objective of this study is to examine wave activity after artificially removing the TC-related signal using an objective algorithm in global OLR fields. The motivating hypothesis is that the convection signal of TCs will project significantly onto filtered modes of equatorial waves. This, however, is not at odds with the observations that equatorial waves can modulate TC formation. The assumption here is that once a TC forms it is no longer reasonable to consider it to be a part of an equatorial wave, and thus it must be treated separately from the parent wave. The equatorial modes considered are TD-type disturbances, MJO, equatorial Rossby (ER) waves, mixed–Rossby gravity (MRG) waves, and Kelvin waves. The results suggest that the presence of TCs can

artificially enhance the activity ascribed to these waves. These results are broadly consistent with Schreck et al. (2011), who used a variant of the method described here and found that TC-related precipitation can significantly project onto shorter wavelength equatorial waves. It should be noted that the spectral filtering does not isolate the specific modes since the inverse Fourier transform also includes contributions from other overlapping modes, organized convection not related to equatorial waves, and the background red noise. As such, the results presented here should be viewed as a rough estimate of the projection of nonwave-related convection onto equatorial wave activity.

2. Data and method

Daily OLR fields are used as a proxy for convection. Global tropical cyclone tracks are taken from the World Meteorological Organization (WMO) subset of the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al. 2010), and only the 1200 UTC positions are used. All data span January–December 1979–2009. The TC-removed fields are created by replacing the OLR in the vicinity of TCs with climatological values. A Gaussian weighting function is used to remove the anomalies from climatology near each TC and is given as

$$w(x, y) = 1 - \exp\left[-\frac{r^2 \ln(4)}{2R^2}\right], \qquad (1)$$

where $r = r(x, y)$ is the distance of a given grid point from the storm center and $R = 500$ km sets the length scale for the weighting function. Anomalies at the storm center are reduced to zero, while at a distance R they are reduced by half.

This method entails two main sources of uncertainty. The first is the occasional mismatch between the IBTrACS position and the OLR minimum associated with the TC in the daily mean field. The second source is the choice of the envelope used to define the TC's OLR contribution. The specific choice of the decay function gives a reasonable representation of the TC signal. This was confirmed by examining numerous specific cases of TCs subjectively. In this regard, a complete removal of the OLR signal in the vicinity of the TC may overestimate the TC's projection since part of the removed OLR may well be associated with one or more equatorial wave modes. As noted earlier, the results presented here should be viewed as an estimate of the TC projection onto the waves. A wavenumber–frequency decomposition is performed using the technique outlined in Wheeler and Kiladis (1999). To provide a more
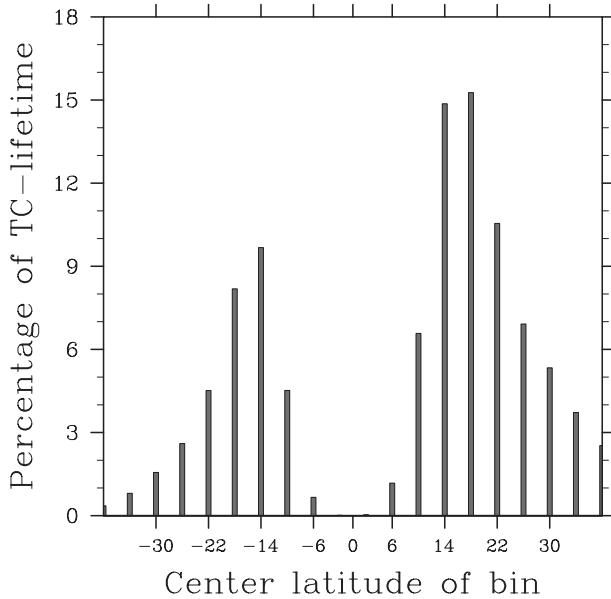
FIG. 1. Residence time (expressed as percent of storm lifetime) of all tropical cyclones averaged in 4° latitude bins.

complete picture of the signals, the filtered fields are not decomposed by equatorial symmetry (Frank and Roundy 2004). As in Wheeler et al. (2000), the variance of the filtered OLR fields is taken to be a measure of wave activity.

3. Results

The residence time of TCs as a function of latitude is shown in Fig. 1. To compute this, all TC positions from the IBTrACS dataset were binned in 4° latitude intervals, and the residence time in each bin is expressed as
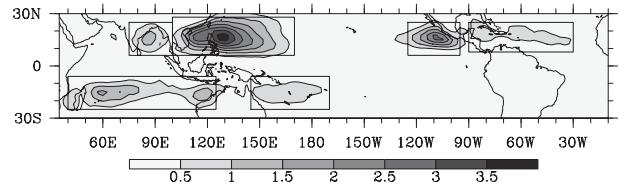

FIG. 2. Mean OLR (W m^{-2}) associated with all TCs (January–December 1979–2010), defined as the difference in climatological average OLR before and after TC removal. Boxes demarcate the various basins referred to within the text.

a percentage of the total lifetime of all TCs. It can be seen that the bulk of the TC lifetime is spent within 20° of the equator. Furthermore, TCs are located most frequently around 14° from the equator, a region where equatorial waves are also very active (e.g., Wheeler et al. 2000). Thus, in addition to physically based connections between the two, it also raises the potential for artificial projection of TC-related convection onto equatorial waves.

Figure 2 shows the mean OLR field associated with just the TCs and essentially depicts the tropical storm track. As expected, the largest anomalies are found over the western and eastern Pacific Ocean where the tracks are densest. In these locations, the peak anomalous OLR associated with TCs ranges from 3 to 4 W m^{-2}. These values are comparable with the OLR standard deviation for many wave modes (Wheeler et al. 2000). The coverage of OLR anomalies equal or greater than 1.0 W m^{-2} is extensive over the western Pacific and Indian Oceans. This figure also highlights the contribution of TCs on the tropical radiation budget and points to potentially significant effects, should there be systematic changes in the intensity or tracks of these storms.
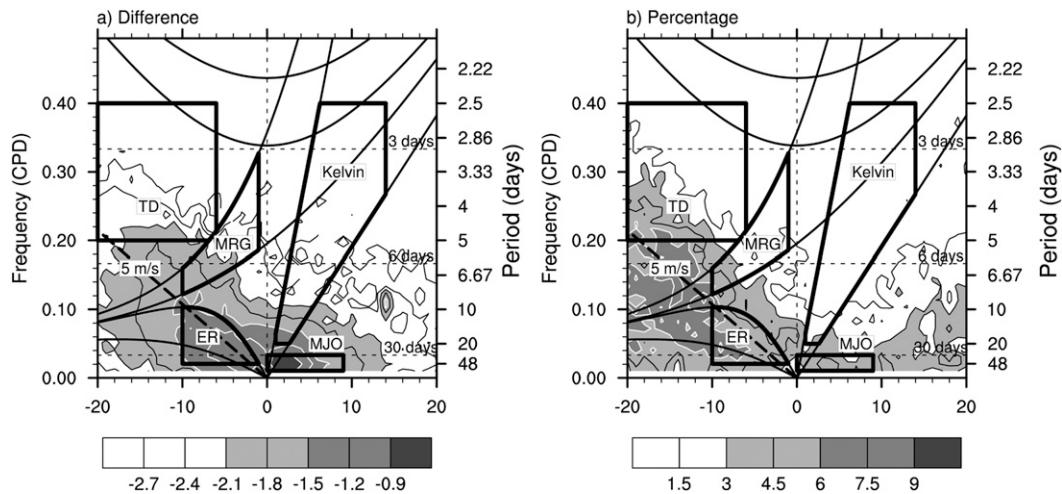

FIG. 3. (a) Difference and (b) percent difference in wavenumber–frequency power spectrum for OLR before and after TC removal. Spectral power is averaged over 15°S–15°N.
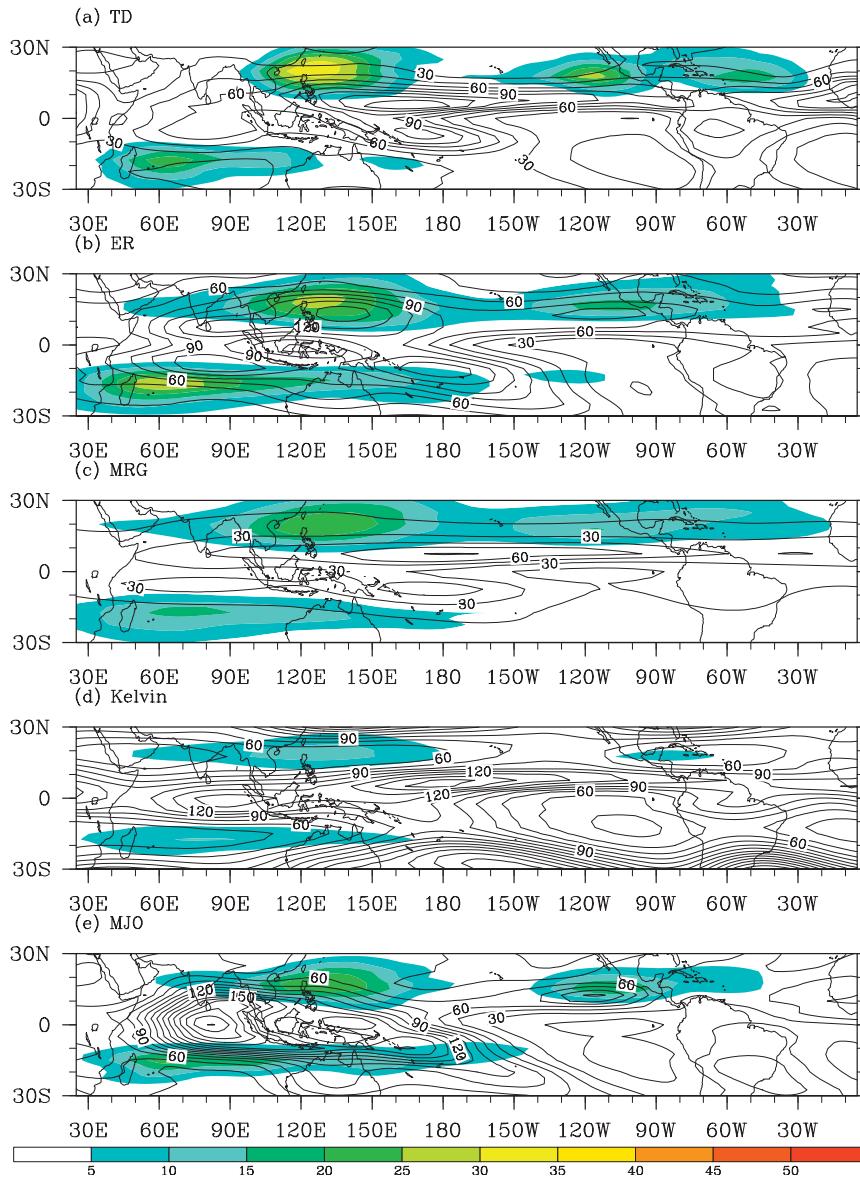
FIG. 4. Variance of each wave mode (contours; interval: 15 W^2 m^{-4}) in the TC-removed OLR data and percent difference in variance after removing TCs (statistically significant values are shaded).

The impact of TCs on equatorial wave activity is depicted in the difference in the spectral power in the wavenumber–frequency domain computed from the two sets of OLR data (Fig. 3). Also shown are the shallow-water dispersion curves and frequency–wavenumber domains for various modes. It can be seen that ER and TD modes show the greatest sensitivity to the removal of TCs, with differences in spectral power ranging from 3% to 7.5%. The impact on MJO and MRG is smaller and generally below 6%. In contrast, Kelvin waves appear to be least sensitive to the TC removal. These

differences are expected to be locally greater in the physical (i.e., space–time) domain.

Figure 4 shows the variance of wave-filtered modes in the TC-removed OLR dataset (contours) and the percent difference in the variance after TC removal (shaded). Statistical significance of the difference is assessed using the Ansari–Bradley test of dispersion with the null hypothesis that the full OLR and TC-removed OLR fields have the same variance for each wave mode. The test statistic, computed at the 5% significance level, is used to assess the validity of the null hypothesis. Only areas

where the null hypothesis can be rejected are shaded. These areas represent a significant difference in wave activity due to the projection of TCs onto filtered wave modes. The difference in variance of wave-filtered OLR is almost uniformly positive in the TC storm-track regions. This suggests that the presence of TCs can artificially increase the variance attributed to equatorial waves. The area covered by the variance difference greater than 10% is most extensive for TD and ER waves, followed by MJO and MRG modes, while the smallest difference is seen for Kelvin waves, consistent with Fig. 3.

The impact of TC removal is highest over the western North Pacific. Here, TCs can locally contribute up to 30% of variance in TD waves and MJO, 25% in ER and MRG waves, and 15% in Kelvin bands. In comparison, the TC contribution in these modes is about 5% lower in the eastern Pacific and south Indian basins. In the North Atlantic, TD, ER, and MRG waves show a 5%–20% variance difference, while Kelvin waves and MJO are relatively less affected. Table 1 shows the area-averaged differences calculated for each basin as demarcated in Fig. 2. The basin averages clearly show the potential for a substantial projection of TC convection onto equatorial modes, in particular the TD and ER waves in the Pacific. The areas highlighted above are of concern since they represent uncertainty in the attribution of OLR signals to wave modes in the presence of TCs.

4. Discussion

This study estimates the projection of TC convection onto equatorial wave activity under the assumption that the two classes of phenomena are distinct in their morphology, intensification mechanism, and evolution. TCs appear to impact TD and ER modes most consistently. The impact on the MJO, MRG, and Kelvin waves is relatively smaller. However, it should also be noted that the areas of greatest impact are not always collocated with the peak in wave activity. For example, in the case of the TD (Fig. 4a), the peak variance is located in the southwest Pacific, but the greatest difference is found in northeast and northwest Pacific. In part, the large TD activity there may reflect other organized convection within the South Pacific convergence zone (SPCZ) that also project onto this mode. Nevertheless, the TD variance is still large in the northwestern Pacific, ranging from 45 to 90 W^2 m^{-4}, and TCs can account for up to 30% of this. However, in the case of ER waves, the areas of peak wave activity and variance difference are nearly collocated in both the west and east North Pacific. This raises a concern regarding the accurate characterization of ER wave climatology in these regions. In the case of the MJO, the main area of concern is the eastern North

TABLE 1. Average percent difference in variance of filtered modes in OLR data with and without TCs for each basin demarcated in Fig. 2. The data span January–December 1979–2010.

Basin	TD	ER	MJO	MRG	Kelvin
Northwestern Pacific	15	15	14	12	6
East Pacific	12	10	9	10	3
Atlantic	9	8	7	5	3
North Indian Ocean	2	7	8	6	5
South Indian Ocean	8	13	9	9	5
Southwestern Pacific	2	7	4	5	3

Pacific, where the areas of peak MJO activity and highest variance difference are nearly overlapping (Fig. 4e).

Several past studies have suggested that a large percentage of tropical storms, especially in the Pacific, form in association with TD-type disturbances (e.g., Fu et al. 2007). ER waves have been implicated in multiple TC outbreaks in the Pacific (e.g., Molinari et al. 2007; Schreck and Molinari 2009). In general, equatorial wave activity appears to be enhanced during TC genesis (Bessafi and Wheeler 2006; Frank and Roundy 2006). However, several studies have reported that Kelvin waves are least effective in modulating TCs. Interestingly, the results in this study show that TCs project also the least onto Kelvin waves. While it is outside the scope of this study to examine individual cases of TC genesis and their association with equatorial waves, the relatively large projection of TCs suggests that caution should be exercised when attributing one or more wave modes to cyclogenesis. Such studies on the TC–wave relationship could benefit from sensitivity tests of relevant statistics to TC removal in the convection data.

In summary, the results show that climatological wave activity is sensitive to TC removal, albeit with varying degrees of sensitivity based on the location and wave type. In particular, off-equatorial regions in the western and eastern Pacific are most sensitive to the removal of TCs in the OLR data. Assuming a mean threshold of a 10% difference and a mean variance of 45–60 W^2 m^{-4}, a rough estimate of approximately 4–6 W^2 m^{-4} is attributable to TCs. Given that this is an average estimate, individual TCs are likely to contribute at a much higher level. These results are relevant to studies attempting to evaluate equatorial wave activity in global climate model simulations. Models that are too coarse to simulate TCs or that have significant errors in TC numbers and tracks are likely to exhibit larger biases in climatological equatorial wave activity.

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