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Revisiting trough interactions and tropical cyclone intensity change

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Abstract An updated climatology of Atlantic basin tropical cyclone (TC) intensity change in the presence of upper tropospheric trough forcing is presented. To control for changes in the background thermodynamic environment, a methodology that normalizes intensity change by the potential intensity of the TC is used to more narrowly focus on the effect of troughs compared to previous studies. Relative to the full sample of Atlantic TCs, troughs are a negative influence on intensification: trough interaction cases are 4% less likely to intensify and 5% more likely to weaken. Troughs are especially detrimental compared to TCs without trough forcing: trough interaction cases are 14% less likely to intensify and 13% more likely to weaken. Additionally, eddy flux convergence of angular momentum, previously shown to positively affect TC intensity change, is shown to be a weak predictor of intensity change compared to vertical wind shear, which is enhanced during a trough interaction.

Key Points:
- Upper level troughs have a negative influence on tropical cyclone intensification
- Angular momentum eddy flux convergence is a weak predictor of tropical cyclone intensity change
- Vertical wind shear is the main control on intensification during trough interactions

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1. Introduction

Tropical cyclone (TC) intensification following an interaction with an upper tropospheric trough remains a significant forecast challenge. Previous studies have shown that TC intensity change in the presence of a trough can range from rapid weakening to rapid intensification, though most studies report favorable TC-trough interactions [e.g., *McBride*, 1981; *Molinari and Vollaro*, 1989; *DeMaria et al.*, 1993, hereinafter D93; *Bosart et al.*, 2000; *Hanley et al.*, 2001, hereinafter H01; *Yu and Kwon*, 2005; *Leroux et al.*, 2013]. Forecasting TC intensity change in the presence of a trough is challenging because troughs may affect TC intensity in both positive and negative ways [*Molinari and Vollaro*, 1989; D93; H01]. Favorably, *Molinari and Vollaro* [1989, 1990] found that near the tropopause, the approaching trough causes enhanced eddy flux convergence of angular momentum (EFC),

$$\mathrm{EFC} = \frac{-1}{r^2}\frac{\partial}{\partial r} r^2 \overline{u_L' v_L'}\ , \tag{1}$$

where r is the radius from the TC center, u and v are the storm-relative radial and tangential wind, respectively, and primes indicate perturbations from the azimuthal mean.

Enhanced EFC can spin up the TC outflow layer and increase upper level divergence through a Sawyer-Eliassen balanced response. The Sawyer-Eliassen balanced vortex model applies to a vortex in gradient wind balance, such as a TC, in which the azimuthally averaged tangential wind is in balance with the azimuthally averaged pressure gradient [*Eliassen*, 1952]. The balanced vortex model describes how a secondary (radial-vertical) circulation evolves in the presence of a heat or momentum source in order to maintain balance. In the case of a trough interaction, the trough serves as a momentum source and the balanced vortex response leads to enhanced upper level outflow and concomitant evacuation of mass from the TC core, subsequently lowering the TC's central pressure and increasing its surface winds. Unfavorable for intensification, high vertical wind shear tilts the TC vortex from an upright configuration and ventilates the TC with cooler, drier air, which reduces the entropy gradient between the environment and TC core and weakens the TC [*Molinari and Vollaro*, 1989; *Frank and Ritchie*, 2001; *Riemer et al.*, 2010; *Riemer and Montgomery*, 2011; *Tang and Emanuel*, 2010, 2012a, 2012b; D93; H01].

Two previous studies, D93 and H01, used multiple years worth of Atlantic basin TC data to determine the general favorability of TC-trough interactions on TC intensity change. In a limited (39 trough interaction events), 3 year study of TC-trough interactions, D93 defined a trough interaction as any time that EFC exceeded $10\,\mathrm{m\,s^{-1}\,d^{-1}}$ within 1500 km of the TC center. This threshold was determined based on the EFC value approximately one standard deviation higher than the mean EFC in the sample. They found that trough interactions generally led to more weakening (38%) than strengthening (33%). Using a multiple-regression technique to control for shear and sea surface temperatures (SSTs), they found that trough-induced EFC

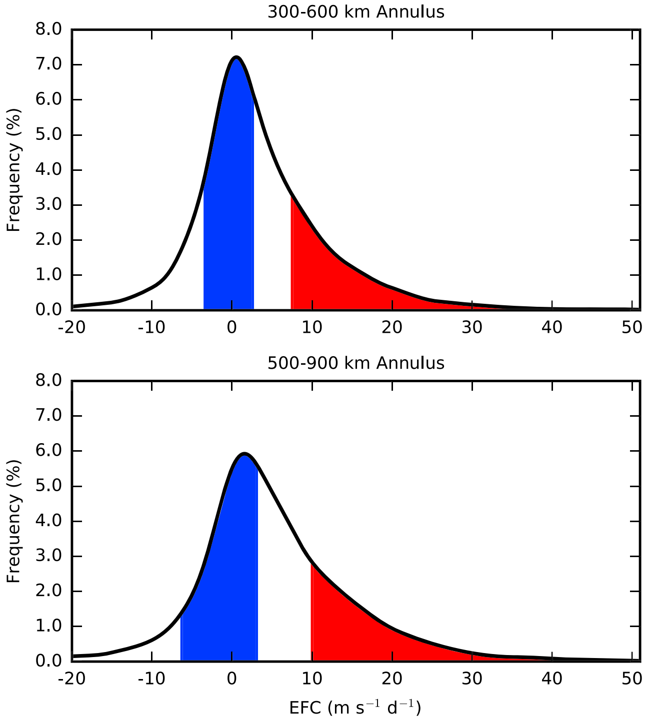

Figure 1. Distributions of 200 hPa EFC in the (top) 300–600 km annulus and (bottom) 500–900 km annulus for all eligible 6 h time periods. Red shading indicates EFC ≥ 75th percentile. Blue shading indicates EFC within ±20 percentiles of EFC = 0 m s^{-1} d^{-1}.

was, in fact, positively correlated with TC intensification; however, the effect was too small to offset the effect of higher shear induced by the trough or to offset lower SSTs encountered by the TC. Despite finding troughs slightly unfavorable overall, D93 found high variability in intensity change during trough interactions, with several TCs rapidly intensifying under the influence of a trough.

In a 12 year climatology of TC-trough interactions, H01 employed D93's trough interaction threshold of 10 m s^{-1} d^{-1} but added the temporal threshold that the period of enhanced EFC must have lasted for two consecutive reanalysis periods. In their study, as many as 78% of TC-trough interactions were found to be favorable for TC intensification. The apparent highly favorable results of trough interactions in H01 are partially an artifact of two methodological choices that bias the results toward intensification, rather than weakening or steady state. First, the times at which 24 h intensity changes were calculated were not chosen based on when periods of enhanced EFC began. Rather, any time TC pressure started rising or falling, the value of EFC was considered under the assumption that the approaching trough must be solely responsible for the pressure change. Such a methodology presupposes that a TC-trough interaction must cause intensity change, rather than hypothesizing that it could. Given the favorable conditions for eligibility in H01 (e.g., high SSTs and not over land), most of the TCs in the H01 sample are intensifying. Second, steady state TCs were defined as having a 0 hPa pressure change in 24 h, much smaller than the uncertainty of pressure estimates, which are between 3 and 10 hPa depending on the strength of the TC and the type of instrument(s) used in the estimation [*Landsea and Franklin*, 2013]. The purpose of this study is to address these two methodological issues and the discrepancy between D93 and H01, as well as update the climatology of TC-trough interactions using a much longer, higher-resolution data set.

2. Data and Methodology

Six-hourly data for the years 1979–2014 were obtained from the European Centre for Medium Range Weather Forecasts' ERA-Interim (ERA-I) reanalysis data set, which has a horizontal resolution of 0.7° × 0.7° and a vertical resolution of either 25 or 50 hPa for the levels used in this study [*Dee et al.*, 2011]. Atlantic TC wind speed and minimum central pressure were obtained from the National Hurricane Center Best Track data set.

New TC centers were calculated from the ERA-I data using the 850 hPa vorticity centroid within a 2.8° × 2.8° box centered on the Best Track center. This center finding method accounts for the fact that the Best Track center may not coincide precisely with the ERA-I reanalysis center. To be included in this study, TCs can never have been subtropical and they had to be more than 24 h from landfall or extratropical transition at the time period of interest. The deep-layer, environmental vertical wind shear was calculated between 850 and 200 hPa and a 200–800 km annulus by interpolating ERA-I winds onto a 5° × 50 km cylindrical grid and averaging over the 200–800 km annulus to remove the shear associated with the TC vortex itself.

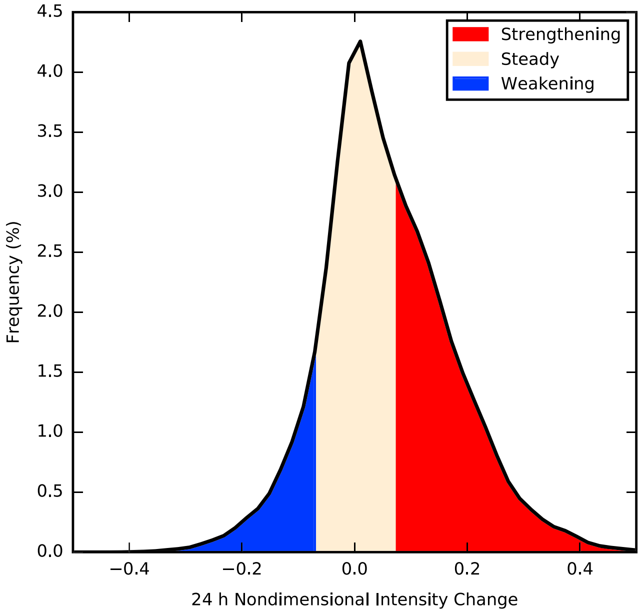

Figure 2. Distribution of 24 h nondimensional intensity change, ΔI, for all eligible 6 h periods. Red shading indicates strengthening, blue shading indicates weakening, and tan shading indicates steady state.

To determine whether a trough interaction occurred, distributions of 200 hPa EFC were calculated for 300–600 km and 500–900 km annuli for all eligible time periods, consistent with H01 (Figure 1). D93 and H01 defined a trough interaction as having 200 hPa EFC $\geq 10\ \mathrm{m\ s^{-1}\ d^{-1}}$, and H01 added that this EFC threshold be met for two consecutive 6 h periods in a given annulus. This study follows a similar procedure, but a trough interaction is defined as when the EFC was in the upper quartile of the full distribution of EFC calculated for all eligible periods (red areas in Figure 1) in either of the annuli for two consecutive 6 h periods. The 75th percentile EFC was $7.4\ \mathrm{m\ s^{-1}\ d^{-1}}$ for the 300–600 km annulus and $10.0\ \mathrm{m\ s^{-1}\ d^{-1}}$ for the 500–900 km annulus. "No trough interaction" cases were required to maintain EFC in both annuli for 18 consecutive hours within ±20 percentiles of where EFC $= 0\ \mathrm{m\ s^{-1}\ d^{-1}}$, which corresponds to a range of -3.5 to $2.7\ \mathrm{m\ s^{-1}\ d^{-1}}$ for the inner annulus and a range of -6.4 to $3.2\ \mathrm{m\ s^{-1}\ d^{-1}}$ for the outer annulus (blue areas in Figure 1). Trough interactions are thus classified into three types: superposition (EFC $\geq 7.4\ \mathrm{m\ s^{-1}\ d^{-1}}$ in the inner annulus), distant interaction (EFC $\geq 10.0\ \mathrm{m\ s^{-1}\ d^{-1}}$ in the outer annulus), and no trough interaction (defined above). To clarify further, the superposition (distant) interactions must have had two consecutive periods of EFC within the red range of the top (bottom) graph in Figure 1, and the no trough interactions must have had three consecutive periods within the blue range of both graphs simultaneously.

A major methodological difference between H01 and this study is the removal of a minimum SST constraint. D93 found that the effect of EFC during a trough interaction was largely masked by the effect of the changing underlying SST, and H01 restricted TCs to SSTs ≥ 26°C to account for this issue. To control for changes in the thermodynamic environment of the TC, the current study uses a nondimensional intensity metric. By normalizing TC intensity by the potential intensity (PI) [*Emanuel*, 1986], changes in the underlying SST and outflow layer temperature are taken into account in intensity change calculations. For example, a TC with a wind speed of $40\ \mathrm{m\ s^{-1}}$ and a PI of $60\ \mathrm{m\ s^{-1}}$ has nondimensional intensity $(I) = 0.67$. If this TC moves into a less favorable thermodynamic environment (PI decreases by $20\ \mathrm{m\ s^{-1}}$) and weakens by $10\ \mathrm{m\ s^{-1}}$ over the next 24 h, the resulting I of 0.75 suggests that the TC is actually strengthening, in a nondimensional sense. This methodology is a significant point of differentiation from D93 and H01, in which the previous example would be considered a weakening case due to the reduction of wind speed.

Figure 2 shows the distribution of 24 h nondimensional intensity change (ΔI) for all eligible 6 h periods. The value of ΔI for steady state is hereafter defined as ±0.07, which corresponds to a dimensional intensity change of ~$5\ \mathrm{m\ s^{-1}}$ for a mean PI of ~$70\ \mathrm{m\ s^{-1}}$ for our sample. The TCs were then binned into strengthening ($\Delta I > 0.07$), steady ($-0.07 \leq \Delta I \leq 0.07$), or weakening ($\Delta I < -0.07$) cases. The sensitivity of the results to different thresholds of steady state was tested. Using steady state values of ±0.04 and ±0.0, the percentage of TCs that remained steady decreased as expected, but the proportion of intensifying to weakening TCs remained similar.

3. Results and Discussion

Figure 3 shows the frequency of intensity change for 6 h time periods in each category: superposition trough, distant trough, no trough, and all eligible time periods. The 95th confidence interval was calculated using a

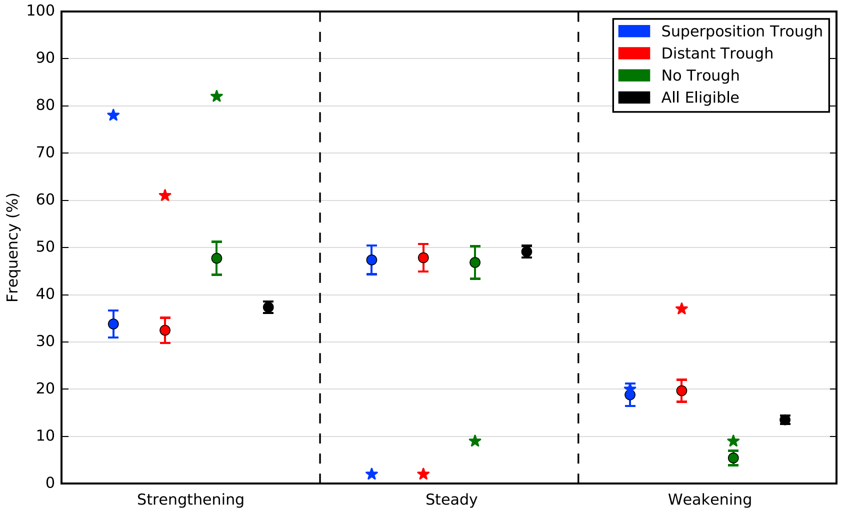

Figure 3. The frequency of 6 h periods that strengthen, remain steady, or weaken in the subsequent 24 h for each of the trough interaction categories: superposition trough interaction (1047 periods, blue), distant trough interaction (1133 periods, red), no trough interaction (790 periods, green), and all eligible times (6146 periods, black). Circles indicate the observed frequency, and bars indicate the 95th confidence interval calculated using a Monte Carlo random resample test. Stars indicate values of H01 for the corresponding categories. Note: H01 did not provide an all eligible category equivalent.

Monte Carlo random resample test with replacement, in which 6146 time periods were drawn at random from the "all eligible" category (6146 total periods) and then sorted into the proper interaction category. This test was repeated 10,000 times. Generally, trough interactions, either superposition or distant, were unfavorable for intensification compared to all eligible time periods. Not only were TCs less likely to intensify following superposition or distant interactions compared to all eligible times (33%, 32%, and 37%, respectively) but TCs were also more likely to weaken following superposition and distant interactions than all eligible times (18%, 19%, and 13%, respectively). These results cannot be compared directly to those of H01 in terms of how trough interactions affect intensity change relative to the full sample of all eligible TCs, as such a category was not included. However, the raw numbers of intensification and weakening can be compared between the trough categories in the current study and H01. In this study, superposition (distant) interactions were 45% (29%) less likely to intensify, but also 2% (18%) less likely to weaken than in H01. Though both superposition and distant trough interactions were slightly less likely to weaken than in H01; the net favorability of trough interactions is still much more unfavorable in the present study considering the larger reduction in strengthening frequency. Likewise, D93 did not provide an all eligible category for comparison, but that study found that 33% of TCs intensified following a trough interaction and 38% weakened. The results of this study thus agree with the finding of D93 that troughs are unfavorable for intensification, although our values are not quite as unfavorable.

Because trough interactions comprise 24% of all eligible periods, the intensification of TCs following trough interactions was also compared against periods with no trough interaction. Superposition (distant) trough interactions were less likely to intensify than TCs without trough interactions, 33% (32%) compared to 47%, respectively, and superposition (distant) trough interactions were also more likely to weaken than TCs without trough interactions, 18% (19%) compared to 5%, respectively. Thus, trough interactions of any sort make weakening more likely, and strengthening less likely, compared to cases of no trough interaction.

It should be noted that more TCs still intensified than weakened following a trough interaction in this study. Given that this result was also true for all eligible periods, it is likely that the eligibility criteria biased the results toward intensification. As stated, the TCs considered eligible had to have been at least 24 h from land or extratropical transition, both of which could contribute to weakening. Additionally, SSTs were controlled for by the use of nondimensional intensity. Therefore, most of the major environmental weakening mechanisms in TCs were removed, with the exception of vertical wind shear, thus biasing TCs in the sample toward intensification. As we have previously considered the results in relation to all eligible periods, the bias of eligibility criteria was largely removed. Herein lies another differentiation from both D93 and H01, which

Table 1. Percentages of 6 h Periods That Strengthen, Remain Steady, or Weaken for Each Trough Interaction Category Using Eligibility Requirements, Trough Interaction Thresholds, and Steady State Definition of H01 With Our Data Set[a]

Category	% Strengthen	% Steady	% Weaken
Superposition interaction, 464 periods	54 (78)	12 (2)	33 (20)
Distant interaction, 907 periods	51 (61)	12 (2)	36 (37)
No trough present, 1368 periods	65 (82)	17 (9)	17 (9)
All eligible periods, 5425 periods	57	27	15

[a] The number of 6 h time periods is listed beside the category name. Values in parentheses are the corresponding values from H01. H01 did not include an all eligible category.

did not define an all eligible category to which results could be compared, making it difficult to account for sample biases.

We speculate that two major methodological differences are contributing to the discrepancy between the current study and H01. First, H01 determined initial times of interest using periods of increasing or decreasing pressure change, rather than periods of enhanced EFC. The methodology of H01 is, therefore, problematic because it attributed any pressure change to EFC. Additionally, the conditions for eligibility in their sample (e.g., warm SSTs) and the requirement that the pressure must change, resulted in very few steady state TCs and a bias toward intensifying TCs even before considering the effects of the trough. Without an all eligible category, these differences combined to give the impression in H01 that troughs were overwhelmingly favorable, which the results of this study do not support. The second major methodological difference possibly contributing to the differences in results is the definition of steady state. H01 defined steady state as a pressure change of 0 hPa in 24 h, while this study defines steady state as a change in the magnitude of the nondimensional intensity of less than 0.07 in 24 h. Thus, even a 1 hPa pressure change, well within observational uncertainty, would cause a TC to be listed as either intensifying or weakening in H01.

To determine whether the differences in intensification frequency are the result of the choice of steady state criteria or the choice of when to define the initial time period of interest, the trough interaction category threshold values, the eligibility criteria, and the steady state value of H01 were applied to our data set to define the categories. Additionally, as in H01, pressure was used as the intensity change metric. Unlike H01, however, the 24 h intensity change was still calculated from when the period of enhanced EFC began rather than when pressure started changing. Table 1 shows the results of this modification and indicates that troughs are still not as favorable as suggested in H01. We, therefore, surmise that it is not the difference in steady state definition that contributes significantly to the differences between the studies, but rather the difference in how the initial times were defined. Thus, a number of the intensifying trough interaction cases in H01 were likely intensifying due to factors other than enhanced EFC.

To elucidate the relative importance of EFC compared to vertical wind shear on TC intensity change, the influence of 300–600 km EFC and deep-layer shear is investigated using a joint distribution of nondimensional intensity change (Figure 4). The overall pattern, which is similar for 500–900 km EFC (not shown), shows that the gradient in nondimensional intensity change is mostly aligned along the shear axis (horizontal), rather than the EFC axis (vertical). This pattern indicates that nondimensional intensity change is much more sensitive to shear than EFC, in agreement with D93.

To test whether shear is a better intensity change predictor than EFC, the normalized multiple linear regression technique described in D93 is employed. Multiple linear regression allows for the linear dependence of shear (EFC) to be taken into account while controlling for EFC (shear). Using multiple linear regression analysis on the normalized variables indicates that shear (regression coefficient = −0.28) is a strong predictor of 24 h intensity change. Underscoring the importance of shear, the mean (median) 850–200 hPa shear value of 11.1 m s^{-11} (10.9 m s^{-1}) for weakening superposition interaction cases is 1.1 m s^{-11} (1.7 m s^{-11}) higher than strengthening cases; this result is significant at the 99% confidence level using a Mann-Whitney *U* test (Mood's median test).

Conversely, 300–600 km EFC (regression coefficient = 0.05) and 500–900 km EFC (regression coefficient = 0.04) are weak predictors of 24 h intensity change, although they do support the theory that EFC is favorable for intensification upon controlling for shear. These results are statistically different from zero at the 95th confidence interval using a standard *F* statistic. These findings are similar to D93, with the exception that the EFC was only statistically significant at the 95% level in D93 for 48 h intensity change and only for EFC calculated

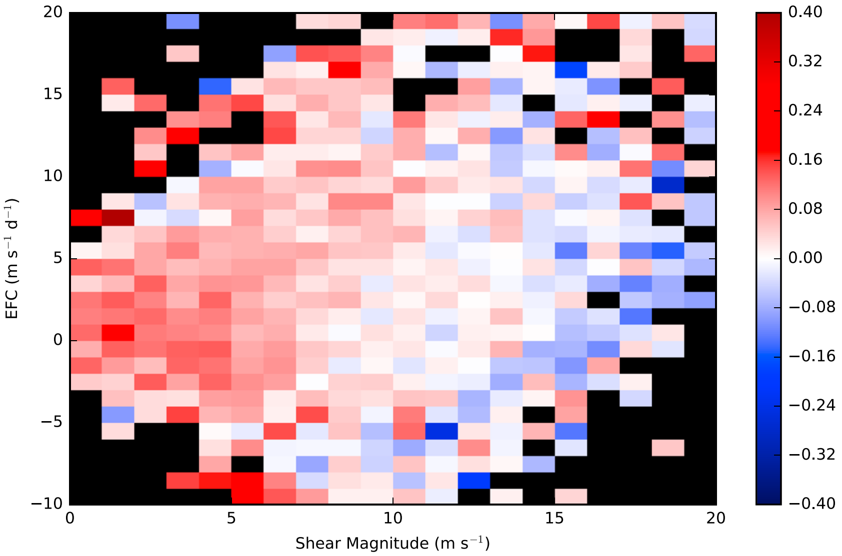

Figure 4. Mean 24 h nondimensional intensity change (shaded) for all eligible TC periods binned by 850–200 hPa vertical wind shear and 300–600 km eddy flux convergence at 200 hPa. Black indicates no data.

in the 100–300 km and 400–600 km annuli. Consistent with the result that EFC is a weak predictor of intensity change, EFC was removed as a predictor in the Statistical Hurricane Intensity Prediction Scheme in 2002 because it was no longer a statistically significant predictor [*DeMaria et al.*, 2005].

4. Conclusions

This study addresses the discrepancy between previous trough interaction climatologies, updates the climatology with a modern reanalysis data set, and assesses whether trough-induced EFC is a bigger factor in intensity change than trough-induced shear. The results of this study indicate that trough interactions, using either dimensional or nondimensional intensity, are not nearly as favorable as suggested in H01, but not as unfavorable as found by D93. EFC, as in D93, is found to be a poor predictor of intensity change, especially compared to vertical wind shear. The importance of wind shear as a predictor of intensification agrees well with previous studies [e.g., *DeMaria and Kaplan*, 1999; *Zeng et al.*, 2010]; however, the morphology of the shear-inducing trough during TC-trough interactions has not been well studied. Preliminary research has found differences in the convective evolution of TCs during favorable versus unfavorable trough interactions. Additionally, there are significant differences between the strength, depth, and wavelength of favorable and unfavorable troughs, as well as in the evolution of the midlatitude waveguide. Future research will investigate these differences.

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