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1. INTRODUCTION

Upper-tropospheric troughs may affect tropical cyclone (TC) intensity in both positive and negative ways. Favorably, Molinari and Vollaro (1989) found that enhanced angular momentum eddy flux convergence (EFC) near the tropopause due to an approaching upper-level trough can spin up the TC outflow layer and enhance upper-level divergence. The enhanced outflow subsequently lowers the central pressure of the TC and increases the surface winds. Unfavorably, large vertical wind shear tilts the TC vortex from an upright configuration and ventilates the TC with cooler, drier air. In a three year study of Atlantic TC-trough interactions, DeMaria et al. (1993) found that sea surface temperatures (SSTs) and vertical wind shear dominated the positive effect of EFC on TC intensity, leading to more weakening than strengthening TCs following TC-trough interactions. However, in a 12-year climatology of Atlantic TC-trough interactions by Hanley et al. (2001) (hereafter H01) as many as 78% of TC-trough interactions were found to be favorable for TC intensification. The purpose of this study is to use a longer, modern dataset to address this discrepancy in the literature and determine which factors (e.g., trough morphology, EFC, shear profile) are dominant in determining the favorability of a TC-trough interaction.

2. DATA AND METHODOLOGY

Six-hourly data for years 1979–2014 were obtained from the European Center for Medium Range Weather Forecasts' ERA-Interim reanalysis dataset. Atlantic TC data were obtained from the National Hurricane Center Best Track dataset.

TC centers were calculated from the ERA-interim data using 850-hPa vorticity centroids centered on the best track center. In order 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.

Distributions of EFC were calculated for 300–600-km and 500–900-km annuli, and a trough interaction was said to occur when the EFC exceeded the 75th percentile in one of the annuli for two consecutive six-hourly periods. Trough interactions are classified into three types: superposition (EFC ≥ 7.4 -m/s/d in the inner annulus), distant interaction (EFC ≥ 10.0 -m/s/d in the outer annulus), and no trough

interaction (EFC ≤ 2.7 (3.2) -m/s/d in the inner (outer) annulus for three consecutive periods).

To address 24-h intensity change following a TC-trough interaction, intensity was normalized by potential intensity (Emanuel 1986). This non-dimensional intensity, I , controls for changes in the background thermodynamic environment. Only TCs with an initial I between .2 and .7 were included, and these TCs were then binned into strengthening ($\Delta I > .07$), steady ($-.07 \leq \Delta I \leq .07$), or weakening ($\Delta I < -.07$) cases. TC-centered composites of weakening and intensifying TCs in each trough category were compared. For brevity, only superposition cases are discussed below.

3. RESULTS

Generally, TC-trough interaction appears to have a negative effect on subsequent TC intensification compared to cases of no trough interaction (Table 1); however, more TCs still intensify than weaken following a trough interaction, possibly due to the favorability of the eligibility requirements. This result is similar to those of DeMaria (1993), but differs significantly from H01. There are two major methodological differences contributing to the discrepancy between the current study and H01. The first difference is the definition of steady state. H01 defines steady state as a pressure change of 0-hPa in 24-h, while this study defines steady state as a change in non-dimensional pressure of $\pm .07$ in 24-h. Thus, as many as 29% of weakly intensifying TCs, which in this study would be considered steady state, were listed as intensifying in the H01 study. Second, H01 assumes that any intensity change during a TC-trough interaction is due solely to the presence of the trough, rather than assuming that the trough *could* cause intensity change. These differences combine to give the impression in H01 that troughs are overwhelmingly favorable, while the results of this study show it is much less clear.

Because TC-trough interactions are not overwhelmingly favorable or unfavorable, the influence of EFC compared to shear is investigated using a joint distribution of intensity change (Fig. 1). The overall pattern indicates that shear is dominant over EFC in intensity change during TC-trough interactions. Likewise, shear also dominates the effect of 200-hPa divergence (not shown). In line with shear being the dominant control on intensification, the median 850–200-hPa shear value is 3 m/s higher in the weakening cases than the strengthening cases.

The dominance of the shear as a predictor of intensification agrees well with previous studies (e.g. DeMaria and Kaplan 1999); however, the morphology of the shear-inducing trough during TC-trough interaction

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has not been well studied. Plan-view composites and composite cross-sections (Fig. 2) of intensifying and weakening TC-trough interactions suggest that unfavorable trough interactions tend to have a stronger trough that is zonally broader and vertically deeper relative to favorable trough interactions. Broader and deeper troughs induce larger environmental wind shear over the TC and lead to a more hostile environment. Additionally, the unfavorable trough is more positively tilted and more progressive, and it is associated with an upstream anticyclonic wave break. The favorable trough shows evidence of a cyclonic wave break and is slower and neutral or negatively tilted. The progressive nature of the unfavorable trough may allow less time for TC convection to erode the trough as it approaches, resulting in higher wind shear. Alternatively, the more negative tilt of the favorable trough may be a result of favorable positioning of TC convection relative to the approaching cyclonic PV anomaly. Favorable positioning of convection could allow for the low PV TC outflow to halt the progression of the trough or cause it to break, similar to TCs interacting with the midlatitude waveguide (Archambault et al. 2013). In both cases, a cutoff low forms and lingers west of the TC center, although, as expected, the cutoff is stronger in the weakening cases.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

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Category	% Intensify	% Steady	% Weaken
Superposition Interaction 1047 periods	34 (78)	47 (2)	19 (20)
Distant Interaction 1133 periods	33 (61)	48 (2)	19 (37)
No trough present 607 periods	49 (82)	47 (9)	4 (9)

Table 1. Frequency of TCs that intensify, remain steady, or weaken in the 24-h following each type of trough interaction. Below the type of interaction are the number of six-hour time periods in that category. Numbers in parentheses are the corresponding frequencies given in Hanley et al. (2001).

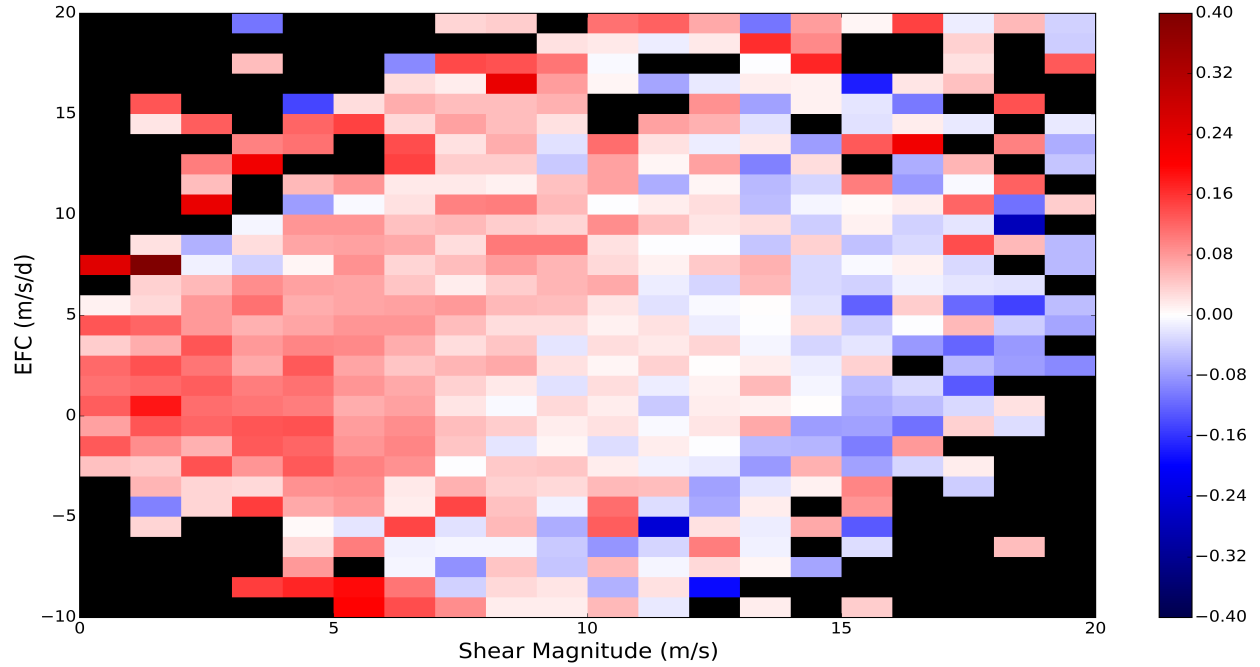


Figure 1. Mean 24-hour non-dimensional TC intensity change (shaded) for all eligible TC periods binned by 850–200-hPa vertical wind shear and 300–600-km eddy flux convergence. Black indicates no data.

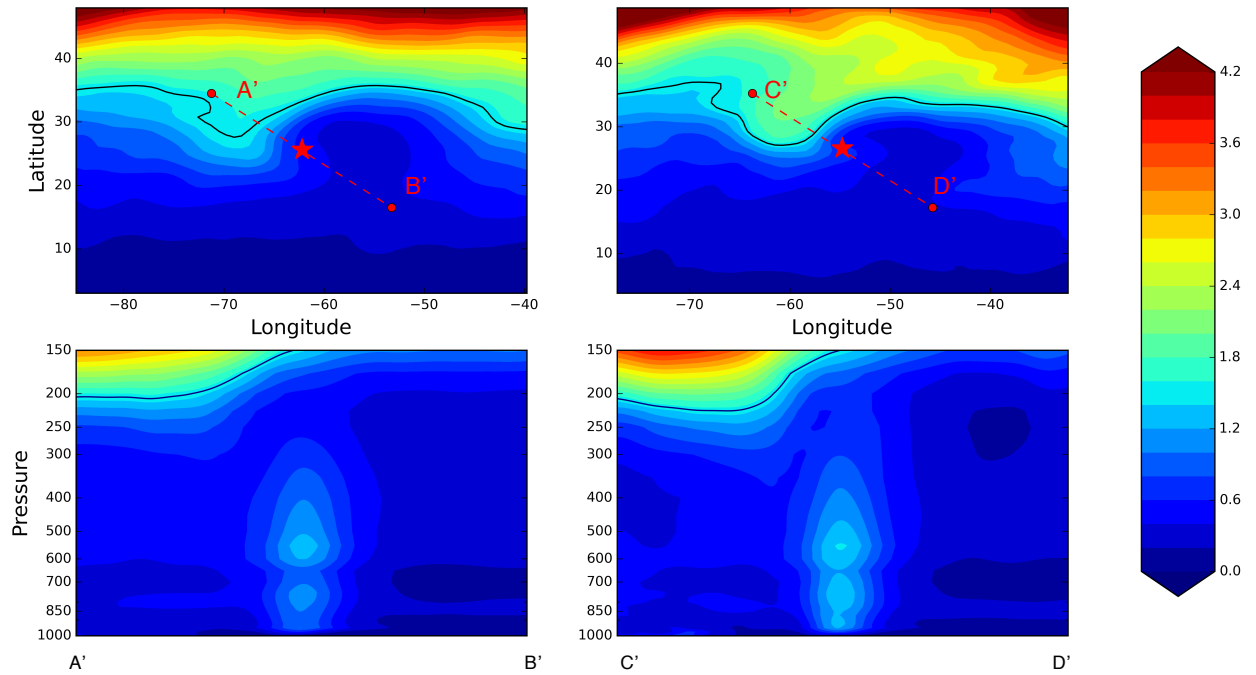


Figure 2. TC-centered superposition trough interaction composites of potential vorticity at the initial time of trough interaction. Top panels are 200-hPa potential vorticity (PVU). Bottom panels are vertical cross sections of potential vorticity along the red dashed line from A' to B' or C' to D' in the top panels. Strengthening composites shown in left panels and weakening in right panels. Star indicates composite mean TC location. 1.5 PVU surface contoured (thin black line).