7D.1 ENVIRONMENTAL HELICITY AND ITS EFFECTS ON DEVELOPMENT AND INTENSIFICATION OF TROPICAL CYCLONES

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1. INTRODUCTION

Much attention has been given to the impact of environmental wind shear in the 850 – 200 hPa layer on tropical cyclones (TCs). However, even with the same magnitude of shear, helicity in this layer can vary significantly. TC vertical tilt is often attributed to wind shear. We find that different values of helicity modulate this tilt and certain tilt configurations are more favorable for development or intensification than others, suggesting that mean positive environmental helicity is more favorable for development and intensification than mean negative helicity. A new parameter is presented, the tropical cyclone-relative environmental helicity (TCREH). Positive TCREH leads to a tilted storm that enhances local storm scale helicity in regions of convection within the TC. This enhanced local scale helicity allows for more robust and longer lasting convection which is more effective at generating latent heat and subsequent TC intensification. Idealized modeling simulations are performed to analyze the impact of environmental helicity on TC development and intensification in the Weather Research and Forecasting (WRF) model. Results show that wind profiles with the same 850-200 hPa wind shear but different values of helicity lead to different rates of development. TCREH also is computed from Era-Interim reanalysis (1979 – 2011) and GFS analyses (2004 – 2011) to determine if a significant signal exists between TCREH and TC intensification. Mean annual helicity is averaged over various time periods and correlated with the TC intensity change during those periods. Results suggest a weak but statistically significant correlation between environmental helicity and TC intensity change with positive helicity being more favorable for intensification.

2. NUMERICAL SIMULATIONS

2.1 Modeling Techniques

To study the effects of environmental helicity on TC intensity and evolution the Weather Research and Forecasting Model (WRF; Version 3.4.1) was used with two unique configuration techniques. Point-downscaling (PDS; Nolan 2011) was used to control the environment around the TCs in the simulations performed as part of this study. It was desirable to have a background environment around the simulated TCs that was very consistent in time and space. By homogenizing the environmental state, it becomes simpler to attribute changes in TC structure and intensity to that background environment. PDS adds a forcing term to the *u* and *v* momentum equations which is equal and opposite to the pressure gradient force that would be present if temperature gradients were allowed to exist in the environment. In this way a TC can be simulated in wind shear without the typically required temperature and pressure gradients. PDS can be thought of as the Coriolis force acting only on the perturbation winds and it allows for nearly constant vertical profiles of temperature, humidity, and winds in the simulated TC environment. Another benefit of PDS is that it allows for doubly periodic boundary conditions which were used on the outermost domain in the simulations. In addition to the PDS technique, an idealized version of analysis nudging (FDDA; Stauffer and Seaman 1990,1991) was used to impose even stricter constraint on the TC environment. In this idealized version of FDDA, the environment is nudged toward the initial vertical profile to work in concert with PDS to maintain the nearly constant background state. The simulations in this study used 3 grids with 18, 6, and 2 km horizontal resolution. FDDA was applied only to the 18 km grid in an effort to restrict changes to the TC environment while still allowing the nested domains to calculate the higher resolution dynamics within the TC itself. This configuration was used in hopes that variability in TC development and evolution could be more easily attributed to environmental factors. Utilizing the PDS and FDDA techniques, 120 h simulations were performed with a prescribed vertical profile of height, temperature, humidity, *u*, and *v*. The TC was initialized as a Rankine vortex with maximum tangential velocity of 20 ms^{-1} and a radius of maximum winds (RMW) of 90 km. The environmental sounding then is held nearly constant by the PDS and FDDA techniques throughout the 120 h simulations. Figure 1 shows the environmental *u* and *v* profiles as a function of height. Variations in the magnitudes of the cosine function for the meridional wind lead to the different hodographs (Fig. 2) used in the 11 simulations. Microphysical processes are simulated with the WRF 6 class microphysics scheme, which includes graupel (WSM6, Hong and Lim 2006). Surface fluxes, friction, and vertical mixing in the planetary boundary layer (PBL) are parameterized using the Yonsei University PBL scheme (YSU, Noh et al. 2003; Hong et al. 2006). The parameterizations for surface fluxes of heat, moisture and momentum for fluxes at high wind speeds follow Dudhia et al. (2008). Longwave and shortwave radiation are not active. The Coriolis parameter is set to 5.0 x 10^{-5} s^{-1}

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across the domain and sea surface temperature (SST) was held constant throughout the simulations at 29° C.

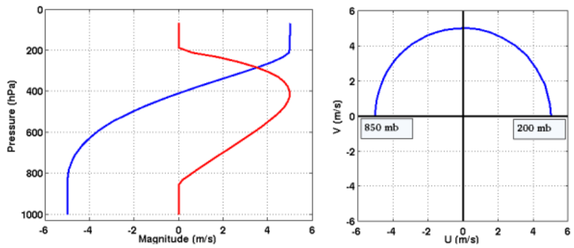

Fig. 1. Vertical profiles of *u* (blue) and *v* (red) wind components (ms^{-1}) for a simulation with positive helicity (left panel) and the corresponding hodograph (right panel).

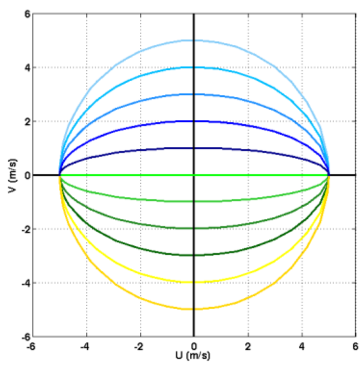

Fig. 2. The 11 hodographs (850 – 200 hPa) used for the prescribed environmental flow in the WRF simulations.

One concern when controlling the environment in a numerical model is gradual changes to environmental parameters. Because mean annular TCREH was calculated from reanalyses, it was also computed for the simulations and time plots were created to check for changes during the 120 h simulations. TCREH is formulated identically as storm-relative helicity in the mid-latitudes except that the movement of the TC is used rather than some form of storm cell motion. To calculate mean TCREH in an annulus around the TC, a mean vertical profile of wind was calculated in the annulus centered on the TC. This mean wind was defined simply by the average of the *u* and *v* components at all available model grid points inside the annulus. TCREH was then computed as the TC-relative helicity in the mean wind profile. The environmental helicity was quite constant throughout the simulations as TCREH remained in a 2.5 m^2s^{-2} range (10.5 ± 1.25, for example, in the simulation corresponding to figure 2) through each of the entire 120 h simulations.

In addition to TCREH, another parameter to consider when simulating the effects of different wind profiles is TC tilt. Both observational studies and numerical simulations (e.g., Huntley and Diercks 1981; Reasor et al. 2004, 2013; Braun and Wu 2007; Rappin and Nolan 2012; Rogers et al. 2013) demonstrate that wind shear affects the vertical alignment of TCs. Different wind profiles with equal magnitude 850 – 200 hPa shear (e.g., Fig. 2) lead to different distributions of convection in TCs. One way to consider this is to horizontally shift the wind fields from a simulation with no environmental flow (and no vertical shear) outside the TC. A simulation with zero background flow and constant SST was performed and this simulation yields a vortex that is vertically aligned. The wind fields from this model output at different heights then are shifted as they would be if wind shear were present. Figure 3 shows a diagram of how a TC is tilted in different background flows; one with positive helicity and one with negative helicity. By shifting the wind fields to mimic a tilted vortex the effects on local storm scale helicity become evident. Figure 3 demonstrates how the environment around a TC can lead to a tilted TC which then modulates the storm scale helicity. Row *a* shows how a vertically aligned vortex becomes tilted downshear in a way that increases the amount of positive local scale helicity in the downshear quadrants of the vortex. These quadrants typically are where convection is the most common and most intense (Corbosiero and Molinari 2002). The opposite occurs in the presence of negative

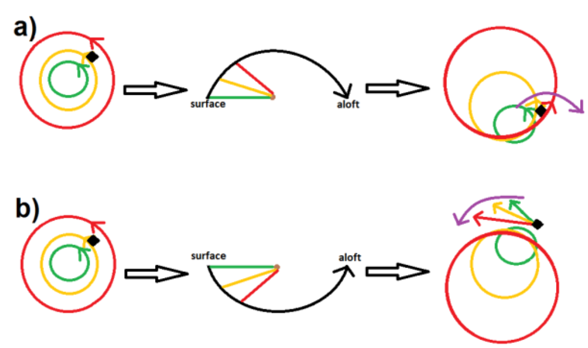

Fig. 3. Idealized vortex tilting. The green circles (and corresponding lines and arrows) represent the vortex near the surface. The yellow circles and lines represent the vortex at approximately 1500 m and the red circles and lines represent the vortex at approximately 3000 m. In both the top and bottom sections, the left panel shows a vertically aligned vortex. The middle panel shows the imposed environmental wind profile. The right panel shows the resulting vortex alignment. The top diagram shows the effects of positive TCREH and the bottom diagram shows the effects of negative TCREH. The purple curves demonstrate the orientation of the resulting local hodograph (clockwise for positive TCREH and counterclockwise for negative TCREH) in the downshear left quadrant.

TCREH (row *b* of fig. 3) where negative local scale helicity (or at least a reduction in the magnitude of positive helicity) is introduced. Even though the hodographs are quite different in fig. 3 the deep layer shear vectors are identical and the downshear regions are the same. It should be noted that the idealized shifting shown in fig. 3 does not account for boundary layer effects which would turn low-level winds inward leading to an increase in local scale helicity.

After taking the vertically aligned vortex and horizontally shifting the model wind fields to mimic the effects of TCREH, local scale helicity then is calculated to show what regions experience the largest increase or decrease in helicity and how these correspond to regions of enhanced convection. Increased TCREH in regions of enhanced convection may lead to organization of vorticity and amplified TC intensification. Figure 4 compares TCREH for shifted wind fields in a clockwise (top) and a counterclockwise (bottom) sense. It is apparent that a clockwise hodograph promotes increased TCREH that is collocated with regions of enhanced convection while the counterclockwise hodograph yields predominantly negative helicity over regions of convection.

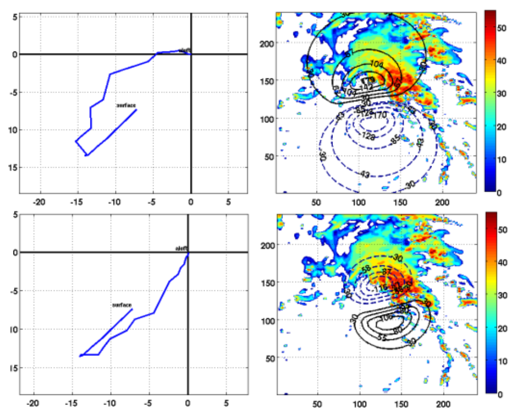

Fig. 4. Comparison of change in local scale helicity (contoured) for shifted wind fields in a clockwise (top) and a counterclockwise (bottom) sense. The hodographs on the left correspond to a vertical wind profile near the location of maximum convection and show the *u* and *v* wind components in ms^{-1}. The color contoured field is simulated reflectivity at the 700 hPa level (dBZ).

2.2 Modeling Results

Positive TCREH favors development in the simulations performed. Figure 5 shows the evolution of minimum surface pressure for the 11 120 h simulations along with their corresponding hodographs. Clockwise (positive TCREH) wind profiles are represented with the blue colors while counterclockwise (negative TCREH) wind profiles are represented by green and yellow colors. Clearly the positive helicity is more favorable for development. When negative environmental helicity falls below approximately -10.5 m^2s^{-2} (orange line) the TC no longer develops. Interestingly, while negative TCREH seems to delay intensification, several of the these cases rapidly develop in the 72 – 110 h time range suggesting that during this period these storms may overcome their less favorable environment.

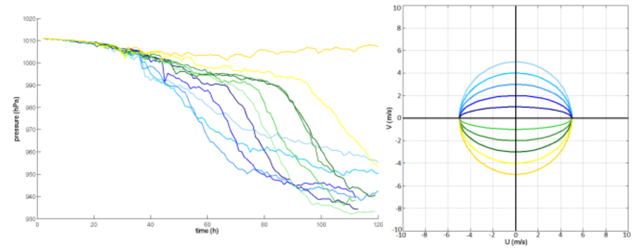

Fig. 5. Evolution of surface pressure (left) for the 11 120 h simulations with varying TC-relative helicity and their corresponding 850 – 200 hPa hodographs (right).

TC vortex vertical tilt also was computed for each case. Tilt was defined as the horizontal distance between the vortex centers at 850 hPa and 300 hPa. The vortex center was identified as the centroid of vorticity on the innermost (2 km) nest. Because the simulations are initialized from a weak, precursor vortex, tilt was often large (~200 km) until the TC underwent significant strengthening. Figure 6 shows a tilt and minimum central pressure diagram for several of the simulations.

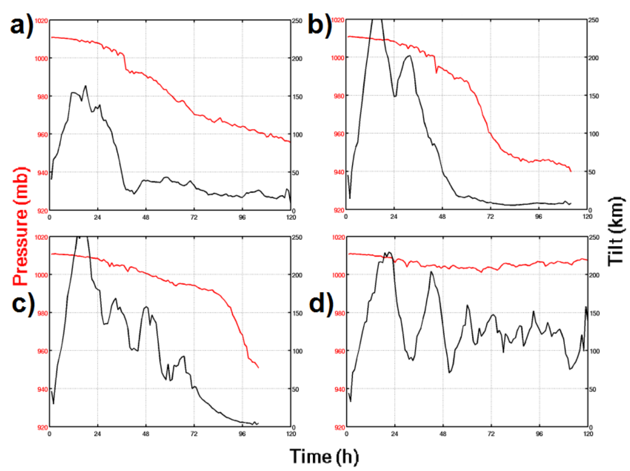

Fig. 6. 850 – 300 hPa tilt (km, 9 h running mean) in black and minimum central pressure (hPa) in red vs. time (h) for 4 simulations with different environmental TCREH: +11 m^2s^{-2} (a), +6 m^2s^{-2} (b), -6 m^2s^{-2} (c), -11 m^2s^{-2} (d). Tilt is defined as the horizontal distance between the vorticity centroids at 850 and 300 hPa.

For cases that developed, tilt was small once development occurred and this delay was longer for cases with larger negative values of TCREH. It is interesting to compare the upper right and lower left panels of fig. 6 where the magnitude of TCREH is equal but of opposite sign. Though 850 – 200 hPa wind shear was identical in the environments of both simulations, tilt remained large considerably longer for the case with negative helicity (lower right panel). This lag suggests that negative helicity in the environment can delay the process of intensification, presumably due to the fact that convection is not collocated with areas of positive helicity. For the case with -11 m^2s^{-2} development did not occur and the weak vortex remained strongly tilted throughout the entire 5 day simulation.

3. TCREH IN REANALYSIS DATA

3.1 Reanalysis Methods

The modeling cases of section 2 motivated the next section of this research which investigated to what degree environmental helicity could be correlated to intensity change in TCs as represented in analysis and reanalysis data. Two data sets were chosen to analyze environmental helicity around TCs. The first was ERA-Interim data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the second was GFS analyses. The ERA-Interim data period was from 1979-2011 (10,162 Best Track 6 h periods greater than 100 km from land) while the GFS analyses data covered 2004-2011 (2278 Best Track 6 h periods greater than 100 km from land). Both data sets were global in coverage. However, only tropical depressions, tropical storms, and hurricanes in the Atlantic were considered (i.e., no tropical waves, sub-tropical systems, etc.). The ERA-Interim data are 0.75 by 0.75 degrees in horizontal resolution while the GFS analyses are 0.5 by 0.5 degrees.

For each Best Track time, TCREH was calculated in an annulus centered on the TC location. A TC motion vector was derived from the Best Track data and this vector was used in calculating the TC-relative helicity (TCREH). Multiple annuli were tested including a 200-800 km annulus, 500-1000 km annulus, and a 500-1500 km annulus. TCREH calculated from the 500-1500 km annulus correlated most strongly with TC intensity change. In additional to varying the annulus size different regional subsets of the Atlantic basin were tested for correlation between TCREH and intensity change. TCs north of 25°N may not correlate well since these storms often are more sheared and less tropical in nature and thus were not included in the statistical analysis. It was desirable to have a TC environment that changed as little as possible during the analysis periods so that the impacts of environmental helicity could be more easily evaluated. The impacts of land were also reduced by considering only Best Track points greater than 100 km from land. This prevented rapidly weakening storms from skewing the results.

When computing correlations between TCREH and intensity change, different time periods were considered. Mean annular TCREH was computed around each Best Track point (6 h intervals), averaged over different lengths of time, and then compared to the change in TC intensity during the same period. For example, TCREH could be calculated for each Best Track point for a single TC over a 96 h period and then compared to the change in intensity which was defined as the intensity at t = 96 h minus the intensity at t = 0 h. The longer the time period becomes, the fewer cases that are available, since it was required that Best Track data was available at all 6 h periods within the correlation period being considered. Correlations for all time periods from 12 h to 168 h were computed to see for which time period TCREH best correlates with TC intensity change. One thing to consider when correlating these factors is whether or not the sign of TCREH changes during the correlation period. For example, it was quite uncommon for TCREH to remain entirely positive or entirely negative for a continuous 96 h period. TCREH remained constantly signed for only 10.2% (168 of 1646 available periods) of the 96 h periods in the ERA-Interim data, and for only 11.5% (64 of 557 available periods) of the periods in the GFS data.

By calculating TCREH from both model simulations and reanalysis with the same methodology, comparisons can be drawn. How important is environmental helicity over time periods of several days? Can the impact of TCREH compare to that of 850-200 hPa shear? Is there a meaningful signal between TCREH and intensity in reanalysis like there is in the simulations? Answers to these questions are provided in the following sections.

3.2 Reanalysis Results

Results from reanalyses showed a weak but statistically significant correlation between time averaged TCREH and TC intensity change. 1646 concurrent 96 h periods were available from the 8324 best track times south of 25° N and east of 65° W in the Era-Interim data. Correlating the mean value of TCREH during these 96 h periods to the intensity change during the same periods yielded a correlation coefficient (R-value) of -0.2844 (R^2 = 0.0809). While this correlation is quite weak, the large number of 96 h periods available provided very statistically significant results which were significant beyond the 99% confidence level. Results from the GFS analyses were similar with an R-value of -0.2226 (R^2 = 0.0496). Figure 7 shows a scatter plot of 96 h mean annular TCREH vs. intensity change. The red best-fit line demonstrates that larger values of TCREH correspond most with intensifying TCs while larger negative values correspond to weakening storms (note that negative values of pressure change on the y-axis implies a strengthening TC). Clearly there were many cases in which the magnitude of TCREH was quite small (<5 m^2s^{-2}). The relationship between intensity change and TCREH became stronger when these cases were removed and correlations were recomputed. When considering only cases with 96 h mean TCREH absolute value > 5 m^2s^{-2} in the ERA-Interim data, the R-value improved to -0.4172 (R^2 = 0.1741) and the result remained statistically significant. These results suggest that for larger positive (negative) values of annular mean TCREH strengthening (weakening) is more likely. The R-values computed for 96 h TCREH are quite similar to correlation coefficients computed for 850 – 200 hPa wind shear. For example, DeMaria (1996) reports correlation coefficients on the order of 0.3 at forecast ranges of 24 – 72 h. The similar R-values suggest that TCREH may have nearly as much predictive capability as the value of 850 – 200 hPa shear.

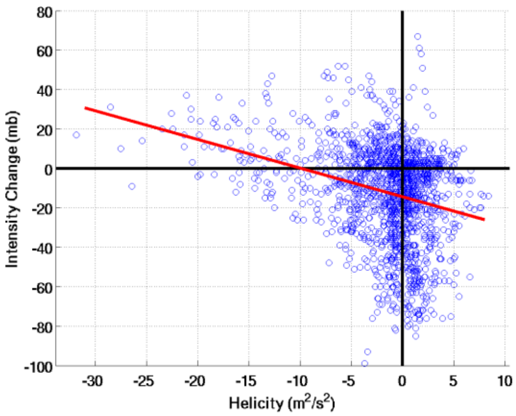

Fig. 7. Scatter plot of 0 – 3 km 96 h annular mean TCREH (m^2s^{-2}) vs. Intensity Change (hPa) for 1646 96 h periods in ERA-Interim reanalysis data. The red line is the best-fit line with R = -0.2844. An annulus of 500 – 1500 km centered on the TC was used.

TCREH was computed for different time periods and fig. 8 shows correlation coefficients vs. time period. Figure 8 in this manuscript is quite similar to fig. 8 of DeMaria (1996) which shows a similar analysis for 850 – 200 hPa wind shear.

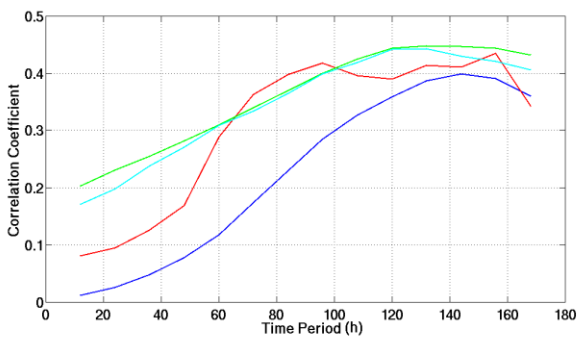

Fig. 8. Absolute value of correlation coefficient (between TCREH and TC intensity change and between 850 – 200 hPa wind shear and TC intensity change) vs. time period length. The red line is for cases where absolute values of TCREH of less than 5 m^2s^{-2} are not considered while the blue line considers all magnitudes of TCREH. The green line represents 850 – 200 hPa wind shear correlation vs. time period and the cyan line is for cases where shear magnitudes of less than 5 ms^{-1} are not considered.

While DeMaria shows that wind-shear correlates on shorter timescales (0 – 72 h), our results suggest that TCREH becomes useful at longer forecast ranges (96 – 168 h). It is important to note that fewer cases with concurrent Best Track points are available as the time period lengthens. However, the results shown in fig. 8 are statistically significant beyond the 99% level even when considering 168 h forecast periods. The blue and cyan lines of fig. 11 show correlation coefficient vs time period length for 850 – 200 hPa wind shear. While wind shear generally correlates slightly more strongly with TC intensity change when compared to TCREH, a 24 h period from 72 to 96 h exists in which TCREH (cases for which magnitude greater than ±5 m^2s^{-2} are not considered) correlates more strongly. The correlation between TCREH and 850 – 200 hPa wind shear also is small with R = -0.3339. This small inter-correlation suggests that wind shear and TCREH both are explaining variance in TC intensity change and that the combination of these factors explains more variance than does just one or the other by itself.

4. DISCUSSION

When comparing the modeling results to the results from reanalysis some inferences can be made. Reanalysis data supports the idealized cases in that increased positive environmental helicity leads to intensifying TCs. The reanalysis data also suggest that the relationship becomes stronger when longer time periods (particularly those longer than 72 h) are considered. In the modeling cases TCs with positive TCREH environments tended to intensify most during the 36 – 72 h time frame. This may be a function of the initial precursor vortex state but this was not tested. Reanalysis data suggests that TCREH is playing a role on longer time scales but does agree with the general result that positive helicity encourages TC intensification. One of the primary differences between the modeling studies and the TCs in reanalysis is the strict control and steadiness of the environment that is present in the simulations. Never in nature is a TC environment truly steady for any meaningful amount of time, let alone for five days. This, perhaps, is why TCs in the model respond a bit more quickly to the TCREH in their environments. While it takes longer in nature, TCREH does seem to play an important role with correlations at 96 – 156 h that are on the same order of magnitude as 850 – 200 hPa shear.

5. SUMMARY

WRF simulations of tropical cyclones in environments of varying helicity suggest a relationship exists between TC intensification and TC-motion relative helicity. 11 simulations with TCREH varying from -11 m^2s^{-2} to +11 m^2s^{-2} show that development occurs sooner for cases of positive TCREH, later for cases with negative helicity, and not at all when the value of TCREH drops below -10.5 m^2s^{-2}. These simulations all are performed with identical values of environmental 850 – 200 hPa wind shear showing that the shape of the vertical wind profile is important, not just the magnitude of the shear vector. Correlations derived from 33 years of reanalysis data suggest that this signal is apparent, though primarily at longer time scales than shown in the modeling simulations. Era-Interim reanalysis data shows increasing correlation between annular TCREH around TCs and TC intensity change through 156 h. Previous studies have demonstrated the relationship between 850 – 200 hPa wind shear and intensity change through 72 h. TCREH appears to provide useful information about intensity at longer ranges out to 156 h and perhaps even longer. It is important to point out that these relationships were derived from reanalyses and may not exist when comparing long range forecasts of TCREH to verifying intensity change.

The reason that positive environmental TC-motion relative helicity is more favorable for intensification is most likely tied to the distribution of convection. Idealized horizontal shifting of the wind fields in a TC embedded in an environment of no flow (thus no shear) demonstrate how convection and positive *local-scale* (i.e., thunderstorm scale) helicity coexist when *environmental* helicity is positive. This overlap of positive helicity and convection potentially leads to longer lasting and more vigorous thunderstorms that can more efficiently generate latent heating. This more persistent heating can then lead to intensification of the TC. The opposite is true when TCREH is negative which leads to regions of convection being displaced from regions of positive local-scale helicity. This unfavorable alignment can retard intensification and perhaps even lead to weakening, as suggested by the reanalysis data.

Finally, the modeling simulations suggest that TC-motion relative environmental helicity affects TC intensification on the order of 36 – 72 h. Reanalysis data suggest that TCREH affects TC intensity on longer time scales of 96 – 156 h. We believe this difference arises due to the nearly constant state of the environment in the model which is imposed by the point-downscaling and analysis nudging techniques. In nature the environment around a TC is always changing and thus relationships between TCREH and intensity only appear when data are averaged over longer time periods. For example, it was quite rare for TCREH to remain of constant sign for periods longer than 72 h. However, despite the sign of TCREH changing in most long range time periods, correlation still exists between the *average* value during the period and intensity change during the corresponding period. These results suggest that the magnitude of the 850 – 200 hPa wind shear alone is not optimal for diagnosing the favorability of the kinematic environment around a TC and the shape of the vertical profile of wind (TCREH) also should be considered.

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