14C.4 ANALYSIS OF ATMOSPHERIC ENVIRONMENTS ASSOCIATED WITH TROPICAL CYCLONE SIZE CHANGES USING ERA-INTERIM REANALYSIS

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1. Introduction

Tropical cyclones (TCs) are sometimes observed to vary considerably in their wind field intensity, size and structure through the course of their lifetime. The most intense winds dictate the extremity of the damage that a TC may exert. However, the extent of damaging winds and the associated storm surge mostly determine the total impact of an individual TC. Impacts include, but are not limited to, high winds and waves at sea that can impact air and sea traffic, and damaging winds, heavy rainfall, and storm surge upon landfall that can sometimes extend well inland of the landfall location. Understanding how the size of the TC wind field varies will help to better predict size changes before the proximity of a TC becomes a threat to either oceanic or continental interests.

Generally, the structure of a TC is divided into three parts: the inner-core, quantified by the radius of maximum winds; the outer-core, measured by either the radius of 64- or 50-kt winds, and the overall size, defined here by the radius of 34-kt winds (R34) (Merrill, 1984; 1992; Holland and Merrill 1984; Kimball and Mulekar; 2004). Whereas inner core structure is closely associated with the intensity of the strongest winds and is generally linked to forcing mechanisms internal to the TC, the size of the outer wind field is more related to interactions with the near environment (Holland, 1983; Holland and Merrill, 1984; Weatherford and Gray 1988a,b; Liu and Chan, 2002). Understanding the relationship between changes in the environment and changes in the TC size, and the associated physical mechanisms is of considerable importance as it is the totality of the damaging winds that leads to the overall TC impact and it is the extent of the strong winds that drives associated storm surge upon landfall. While accurate representation of TC-scale processes remains problematic for numerical weather prediction models, the large-scale environment is usually well represented. Thus, an improved understanding of the underlying physical mechanisms that enable TC size changes associated with well-predicted environmental changes should enable better overall forecasts of TC impacts over the ocean and upon landfall.

a. Background and previous research

Numerical modeling studies conducted within the last decade have generally shown that high relative humidity and surface energy fluxes favor TC size expansion (i.e. Kimball, 2006; Hill and Lackmann, 2009; Xu and Wang 2010a,b). Variables that adversely impact TC size and structure changes by producing asymmetries in the wind field include high vertical wind shear and dry-air intrusion, and environmental flow relative to the TC (i.e. Frank and Ritchie 1999; 2001; Bender 1997; DeMaria 1996; Shapiro 1983; Jones, 1995; Kimball, 2006).

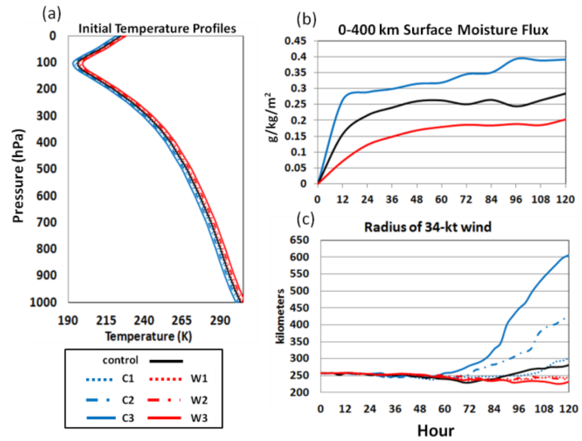

Figure 1: *(a) Atmospheric temperature profiles used to initialize a model vortex of tropical cyclone strength. (b) Temporal evolution of the surface moisture fluxes within 0-400 km of the storm center (g/kg/m^2) and (c) radius of 34-kt winds (km) associated with the initial temperature profiles.*

Numerical simulations designed to supplement this study of idealized tropical cyclones using V3.2 of the Advanced Research WRF- Weather Research and Forecasting Mdoel (WRF-ARW) show that a relatively cool atmosphere over warm SSTs favor an expanding TC wind field (Stovern and Ritchie, 2014). Figure 1a shows the atmospheric temperature profiles used to initialize each environment of the model vortex. Each incremental reduction in the atmospheric temperature while maintaining the same underlying SST of 302 K leads to an increase in surface energy fluxes in the storm region and its environment (fig. 1b). The physical mechanisms associated with the higher latent and sensible heat fluxes are theorized to be causal to the expansion of the entire wind field of the storm (i.e. fig. 1c).

Based on the results from past and present numerical modeling studies, the analysis is performed on environmental fields of: surface and mid-level atmospheric temperature; mid-level relative humidity and specific humidity; sea surface temperature; and vertical wind shear. Part 2 describes the datasets and methods we use to define size changes and our method for creating the

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environmental composites. Part 3 discusses the results applied to an initial set of 11 storms. A short summary and future work are provided in part 4.

2. Methodology

a. Description of datasets

i. Extended Best-Track dataset

The extended Best track (EBT) archive is used to characterize the size and subsequent size changes of a database of 189 TCs between 1988-2011. The EBT provides a number of relevant quantities including: the radius of 34-, 50-, and 64-kt winds in all four quadrants; the radius of maximum wind; and the pressure and radius of the outer-most closed isobar. (http://rammb.cira.colostate.edu/research/tropical_cyclones/tc_extended_best_track_dataset; Demuth et al. 2006). The EBT is compiled by the Cooperative Institute of Research in the Atmosphere (CIRA) at Colorado State University using HURDAT data provided by the National Hurricane Center (NHC). HURDAT is a climatology maintained by the NHC with Atlantic storm information dating back to 1851. A big limitation of HURDAT is that it does not contain storm structural information. It provides each storms intensity, given by the MSLP and 1-minute sustained maximum wind speed (MWS), along with latitudinal and longitudinal coordinates of the storm center. EBT supplements HURDAT by providing information on the RMW, R64, R50, R34 in four quadrants, the eye diameter, and the radius and pressure of outer-most closed isobar (ROCI). In our study, we define size by the radius of the 34-kt (R34) winds, structure variously using the radius of 50-, 64-kt (R50, R64) and maximum winds (RMW), and intensity by the maximum sustained surface winds (MWS). Although the ultimate goal is to assess size changes for the radius of 64- 50- and 34- kt winds, particular attention is focused on the 6-hourly change in the radius of 34-kt winds for the current analysis.

ii. ERA-Interim Reanalysis data

The mean environmental fields for TCs with significant size changes are composited using variables derived from the 6-hourly, nominally 0.75°x0.75° (~83 km x 83 km) ERA-Interim global reanalysis dataset (ERA). ERA-interim is the latest global atmospheric reanalysis produced by the European Center for Medium Range Weather Forecasting (ECMWF) which covers the period from January 1989 onwards (Dee et al. 2011). The low spatial resolution of ERA leads to shortcomings in capturing basic TC intensity and structural characteristics. However, it is suitable for the purpose of this experiment which looks at the synoptic environment of a TC which is known to be resolved fairly well in the model (Dee et al. 2011). In order to ensure that the storms environment is well-captured, storm-centered grids of size ~40° by 40° are extracted from the ERA-Interim dataset for times that immediately precede a significant 6-hour size change (i.e. fig. 2c). The environmental fields extracted and analyzed include: 850 hPa temperature, relative humidity, and specific humidity; 2 meter temperature and sea-surface temperature as a gauge for surface energy fluxes; and 850-200 hPa vertical wind shear.

b. Statistical method for binning storms

The size for each 6-hourly period in the EBT is calculated by averaging the 4-quadrant R34 values for all TCs, excluding zero or missing values. The 6-hourly size change is calculated for each storm that maintained an intensity of 50 kts or greater during its lifetime and then separated into bins of "zero change", "size decrease", and "size increase". The statistics associated with the "size increase" and "size decrease" bins are provided in Table 1. Essentially, a large increase (LI) or large decrease (LD) has occurred if the absolute value of the 6-hour size change exceeds the mean plus half the standard deviation of the corresponding bin. A small increase (SI) and small decrease (SD) occurs when the size change is less than the mean minus half the standard deviation. Values that fall within the range of the mean plus/minus half the standard deviation are considered medium size changes (MI,MD).

	Size increase (nm/6 hours)	Sample Size #	Size decrease (nm/6 hours)	Sample Size #
Mean	19.3	969	18.9	516
Standard Deviation	15.9		16.1	
Small	≤ 11.35	323	≤ 10.85	183
Medium	11.35-27.25	468	10.85 - 26.95	231
Large	≥27.25	178	≥26.95	102

Table 1: *Size change statistics for the 6-hour size increases and decreases in nautical miles. Sample size represents the number of 6-hour size changes in bin corresponding to a dataset of 189 storms.*

For our dataset containing 189 storms there are 969 6-hour periods of size increase and 516 periods of decrease. Large size increases occur when the value of the size change is greater than 27.25 nautical miles in a 6-hour period. Medium size increases are those which fall between 11.35-27.25 nm/6 h and small size increases are less than 11.35 nm. A large size decrease occurs when the R34 decreases 26.96 nm/6 h and medium size decreases in the R34 wind field are between 26.95 and 10.85 nm/6 h. Small size decreases are less than 10.85 nm in 6 hours. Interestingly, although the sample size in the "size decrease" bin is smaller than the "size increase" bin, the mean and standard deviation change very little (Table 1).

c. Environmental Composites

The environmental composites in this analysis are created from a dataset of 11 Atlantic hurricanes that underwent significant size expansions and contractions during their lifetime including: Helene (1988); Felix (1995);

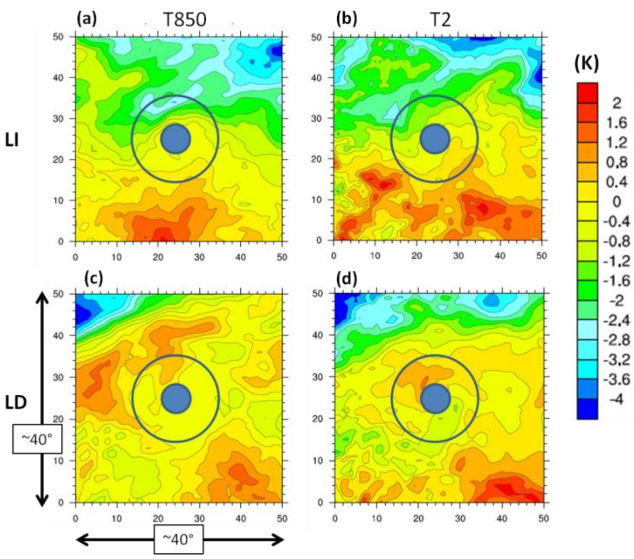

Figure 2: *Composite of the 48-hour change in 850-hPa and 2-meter temperature (K) that preceded a size change for moments of: a-b) large increase (LI); and c-d) large decrease (LD). Each composite contains 11 periods of large size change. Blue contours represent a region between 300-1000 km from the storm center.*

Iris (1995); Luis (1995); Georges (1998); Jeanne (1998); Olga (2001); Kyle (2002); Ivan (2004); Noel (2007); and Igor (2010). Helene and Igor are two examples of storms that made large expansions in their wind field as they underwent extratropical transition. Because the size-change dynamics during extratropical transition may be substantially different from the size changes that occur in the deep tropics, we only composited environments of storms equatorward of 32°N. This reduces the impact of the midlatitude baroclinicity in the composites. In addition, TC landfall produces drastic changes in the wind field so we perform our composites on storms centered at least 300 nm from land.

Finally, all images, except for the SSTs, are composites of the 48-hour environmental change that precedes a size change in the R34 wind field.

3. Results

Figures 2 and 3 show the composited 48-hour environmental change associated with TC cases that experienced a large increase (LI) or large decrease (LD) in the R34 in a 6-hour period during their lifetime. It is important to note that features in the MI and MD composites closely resemble those in the LI and LD composites. Also, we exclude discussion of the results from the SI and SD bins since the environmental changes associated with size changes are generally negligible.

Figure 2 shows the atmospheric temperature for the LI and LD cases at two levels: 850 hPa and 2 meters. Results from the numerical modeling studies of Stovern and Ritchie (2014) suggest that a relatively cool atmosphere over warm sea-surface temperatures (SSTs) favor size increases due to mechanisms associated with increased surface energy fluxes. It can be seen in figure 2a-b that asymmetric cooling, primarily in the northern quadrant of the storm environment, generally precedes large size increases. There is cooling in the northern sector between -2.4 and -2.8 K (Fig. 2a), and the average cooling over a 300-1000 km annulus from the center, is -0.75 K/48 h. In contrast, the LD case shows slight warming in the northern quadrant of the storm, yet the average 300-600 temperature change is near zero (fig. 2c). The temperature at 2 meters (fig. 2b, d) show a similar pattern except the 300-1000 km temperature change for the LI case is -0.6 K/48 h.

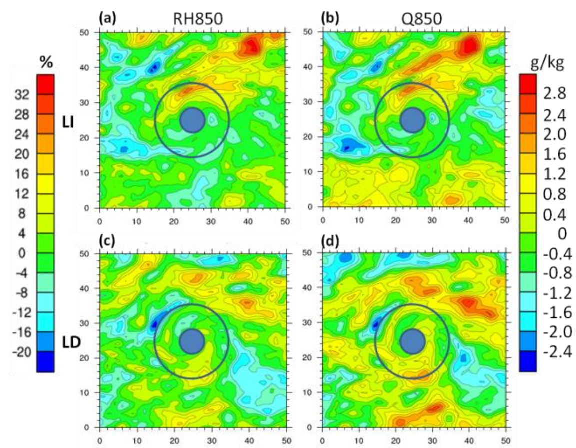

Figure 3: *Composite of the 48-hour change in 850 hPa relative (RH850 - %) and specific humidity (Q850 - g/kg) that preceded a size change for moments of: a-b) large increase (LI); and c-d) large decrease (LD). Blue contours represent an annulus of 300-1000 km from the storm center.*

High mid-level moisture favors the formation of rainbands and a larger TC wind field. The 48-hour change in 850 hPa relative humidity (RH850) and specific humidity (Q850) are shown in figure 3. In approximately the same region as the atmospheric cooling there is an increase in both the relative humidity and specific humidity in the LI case (fig. 3a, b). The average 300-1000 km specific humidity change is negligible with a value of -0.16 g/kg while the RH change is +1.6 %. The average RH increase may be largely due to the average decrease in atmospheric temperature. However small the average moisture changes may be, it seems likely that the increased RH850 and Q850 located in the same region as the atmospheric cooling region is favorable for size increases.

The 48-hour atmospheric moisture change in the LD composite is negligible with respect to both RH and Q (Fig.

3c, d). The 300-1000 km specific and relative humidities increase by 0.07 g/kg and 0.3 %, respectively. Dry air-intrusion is known to cause size contractions, yet no evidence of that is found in these particular cases.

SST composites associated with large size changes are shown in figures 4a and 4c. The average environment associated with LI has higher SSTs than the environment associated with LD. The average 0-600 km (indicated by the blue circle) SST in the LI composite is 300.9 K whereas the average SST in the LD composite is 299.8 K. The SSTs generally did not change over the 48-hour period that preceded the size changes (not shown). The 0-600 km average SST change is -0.2 K/6 h for the LD case and -0.3 K/6 h for the LI case indicating negligible overall change. It is possible that the slightly cooling atmosphere may have resulted in higher latent and sensible fluxes producing a favorable environment for TC wind field expansion, but this is pure speculation at this time. However, if this were indeed the case, the higher surface energy fluxes may have triggered size increases similar to the mechanisms proposed by Xu and Wang (2010a,b) and explored in Stovern and Ritchie (2014).

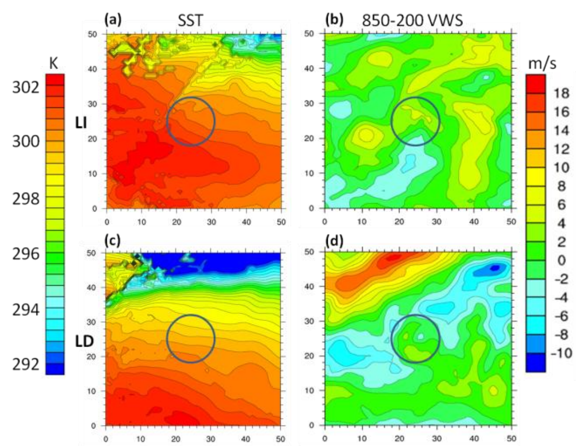

Figure 4: *Composite of: a) instantaneous sea-surface temperature (K) and b) 48-hour change in the vertical wind shear for the large increase (a, c) and large decrease (b, d) cases. Blue circles indicate a region approximately 0-600 km from the storm center.*

Finally, figures 4b and 4d show the composited 48-hour change in vertical wind shear associated with the LI and LD cases. Interestingly, the average shear in the LI case increases by 2.3 m/s but experiences negligible change (-0.01 m/s) in the LD case. Although high values of vertical shear are known to have negative impacts on TC intensity, moderate values of shear may favor size increases through a process of "ventilation". Clearly, more exploration into the mechanisms that cause TC size contractions is needed in order to eliminate the factors that cause size expansion.

4. Summary

This study is a first attempt to identify key features in TC environments that may be associated with significant size changes in the TC wind field. Data from the EBT was used to calculate 6-hourly size changes which were separated into bins of 6-hour size increase and 6-hour size decrease. This made it possible to develop a statistically significant way of determining what a "large", "medium", and "small" 6-hour size change is in the Atlantic basin. Once the periods of large increases and large decreases were identified, the environments from 11 storms were extracted from the ERA-Interim dataset to produce composites of the 48-hour environmental change in the atmosphere associated with TC size changes. In general, the environments that preceded a large TC size increase experienced a slight reduction in atmospheric temperature located in the northern sector of the storm region. A corresponding slight increase in relative and specific humidity occurs in approximately the same region. However, although modeling studies have linked these factors to TC wind field increases, the analysis in this study does not overwhelmingly support this concept. Potentially adding more cases to the composites and performing EOF analyses will help to better separate and identify the environmental factors associated with TC size increases. We do note that there are few modeling studies that actually simulate TC size *decreases*.

Future work includes performing the composites using all applicable storms in the Atlantic Ocean as identified by the EBT. Our next step involves using EOF analysis techniques to separate size changes that occur in the deep tropics from those that happen during extra-tropical transition. We also plan to calculate composites of the -6, -12, and -24 hour environmental change associated with the size changes in order to more effectively identify environmental triggers of size change.

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5. References

Bender, M. A. 1997: The effect of relative flow on the asymmetric structure of the interior of hurricanes. *J. Atmos. Sci.*, **54**, 703-724.

Dee, D. P., S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. A. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A. J. Geer, L. Haimberger, S. B. Healy, H. Hersbach, E. V. Hólm, L. Isaksen, P. Kållberg, M. Köhler, M. Matricardi, A. P. McNally, B. M. Monge-Sanz, J.-J. Morcrette, B.-K. Park, C. Peubey, P. de Rosnay, C. Tavolato, J.-N. Thépaut and F. Vitar, 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system*, J. Roy. Met.,* **137**, 553-597.

DeMaria, M., 1996: The effect of vertical shear on tropical cyclone intensity change. *J. Atmos. Sci*., **53**, 2076-2087.

Demuth, J. L., Demaria, M., and J. A. Knaff, 2006: Improvement of advanced microwave sounding unit tropical cyclone intensity and size estimation algorithms, *J. Applied Met. And Clim*., **45**, 1573 – 1581.

Frank, W. M. and E. A. Ritchie, 1999: Effects on environmental flow upon tropical cyclone structure. *Mon. Wea. Rev.,* **127**, 2044-2061.

Frank W. M. and E. A. Ritchie, 2001: Effects of vertical wind shear on the intensity and structure of numerically simulated hurricanes. *Mon. Wea. Rev*., **129**, 2249-2269.

Hill, K. A., G.M. Lackmann, 2009: Influence of Environmental Humidity on Tropical Cyclone Size. *Mon. Wea. Rev.*, **137**, 3294–3315.

Holland, G.J, 1983: Angular momentum transports in tropical cyclones. *Quart J. Roy. Meteor. Soc*., **109**, 187-209.

Holland, G. J., and R. T. Merrill, 1984: On the dynamics of tropical cyclone structure changes. *Quart. J. Roy. Meteor. Soc.,***110**, 723-745.

Jones, S. C., 1995: The evolution of vortices in vertical shear. I: Initially barotropic vortices. *Quart. J. Roy. Meteor. Soc.*, **121**, 821-851.

Kimball, S. K., and M. S. Mulekar, 2004: A 15-year climatology of North Atlantic tropical cyclones. Part 1: Size parameters. *J. Climate*, **17**, 4590-4602.

Kimball, S. K., 2006: A modeling study of hurricane landfall in a dry environment. *Mon. Wea. Rev.*, **134**, 1901-1918.

Liu, K. S., and J. C. L. Chan, 2002: Synoptic flow patterns associated with small and large tropical cyclones over the western North Pacific. *Mon. Wea. Rev*., **130**, 2134-2142.

Merrill, R. T., 1984: A Comparison of Large and Small Tropical Cyclones. *Mon. Wea. Rev.*, **112**, 1408–1418.

Merrill, R. T., 1992: Chapter 2: Tropical cyclone structure. *A global guide to tropical cyclone forecasting.* G. J. Holland, ed., World Meteorological Organization, pp.

Shapiro, Lloyd J., 1983: The Asymmetric Boundary layer Flow Under a Translating Hurricane. *J. Atmos. Sci.*, **40**, 1984–1998.

Stovern, D. R. and E. A. Ritchie, 2014: Influence of atmospheric temperature on the size and structure of a numerically simulated TC. *In progress.*

Weatherford, C., and W. M. Gray, 1988a: Typhoon structure as revealed by aircraft reconnaissance. Part 1: Data analysis and climatology. *Mon. Wea. Rev*., **116**, 1032-1043.

Weatherford, C., and W. M. Gray, 1988b: Typhoon structure as revealed by aircraft reconnaissance. Part 2: Structural variability. *Mon. Wea. Rev.*, **116**, 1044-1056.

Xu, J. and Y. Wang, 2010a: Sensitivity of tropical cyclone inner-core size and intensity to the radial distribution of surface entropy flux. *J. Atmos. Sci*., **67**, 1831-1852.

Xu, J., and Y. Wang, 2010b: Sensitivity of the simulated tropical cyclone inner-core size to the initial vortex size. *Mon. Wea. Rev*., **138**, 4135-4157.