9D.4 CLIMATOLOGICAL ANALYSIS OF TROPICAL CYCLONE INTENSITY CHANGES UNDER MODERATE VERTICAL WIND SHEAR

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1. Introduction

Deep-layer (200–850 hPa) vertical wind shear (VWS) generally inhibits tropical cyclone (TC) intensification (e.g., Merrill 1988). This inhibition stems from the destructive effects of VWS, including: vertical misalignment of the vortex (e.g., Jones 1995), increased stability above the surface vortex (DeMaria 1996), warm core ventilation (Frank and Ritchie 2001; Kwon and Frank 2008), and dry air entrainment (Tang and Emanuel 2010, 2012; Riemer et al. 2010). Despite these negative effects, some TCs can intensify in moderately sheared environments (e.g., Rios-Berrios et al. 2016a,b). Previous studies have suggested that environmental factors, such as high sea surface temperature (SST) (Tao and Zhang 2014) and abundant moisture (Rios-Berrios et al. 2016a,b), can aid intensification under moderate VWS by promoting deep moist convection near the TC center. Other studies have suggested that TC characteristics matter, such that strong, high-latitude, and large TCs are more likely to withstand the effects of VWS by having a faster vortex re-alignment (e.g., Jones 1995; DeMaria 1996; Reasor et al. 2004). However, most of those findings are based on case studies or idealized model simulations. A climatological analysis is needed to identify factors that commonly favor intensification despite moderate VWS.

The purpose of this project is to investigate TC intensity changes under moderate VWS from a multi-case, observational perspective. A comprehensive analysis of TCs in all basins during a 33-year period is presented to elucidate which environmental (e.g., SST, precipitable water, relative humidity) *and* storm-dependent (e.g., intensity, latitude, speed, size) factors aid or inhibit intensification in moderately sheared environments.

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2. Methods

a. Datasets

This study considered six-hourly (i.e., 0000, 0600, 1200, and 1800 UTC) snapshots for any TC around the world during 1982–2014. A total of 49,968 six-hourly data points (named events hereafter) associated with 2,760 individual TCs[1] were identified with the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al. 2010) dataset. Environmental diagnostics were calculated from the Climate Forecast System Reanalysis (CFSR; Saha et al. 2014) by first removing the kinematic component of each TC vortex (Galarneau and Davis 2013), and then area-averaging relative humidity (RH), precipitable water, and winds within a 500-km radius of each TC. These diagnostics are similar to synoptic predictors of statistical-dynamical prediction models (e.g., DeMaria and Kaplan 1994), but CFSR was used here because it provided a consistent dataset for all years and all basins. An additional diagnostic, SST near each TC, was obtained from NOAA Optimum Interpolation SST (Reynolds et al. 2002) weekly analyses. Lastly, most storm-dependent factors (intensity, latitude, and speed) were obtained or calculated from IBTrACS, except for TC size (defined here as the 34-knot wind radius). This variable was obtained from the QuikSCAT Tropical Cyclone Radial Structure (QSCAT-R; Chavas and Vigh 2015; Chavas et al. 2015) dataset, which was only available between 2000–2009.

b. Analysis

Several quantities were objectively defined to facilitate the robustness of the climatological analysis. Moderate VWS was defined as 5.0–12.5 m s^{-1} based on the 20th and 80th percentiles of the 200–850 hPa shear magnitude distribution (Fig. 1). This definition was adopted because a consistent definition does not exist in previous literature. Additionally, intensity change was defined as a 24-h change in maximum sustained wind speed. Two groups

[1] Extratropical cyclones, subtropical cyclones and landfalling TCs were not included in this study.

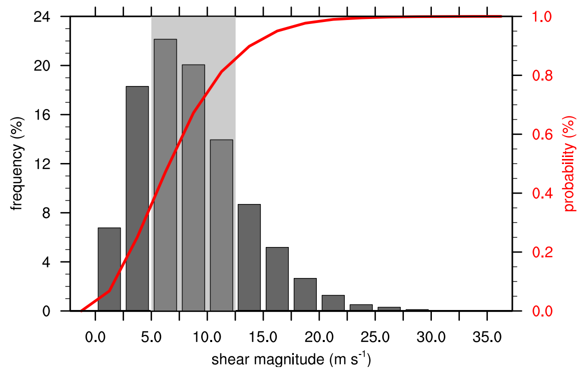

FIG. 1. Normalized distribution of 200–850 hPa shear magnitude surrounding all TCs between 1982–2014. The left ordinate corresponds to the probability density function (gray bars), while the right ordinate corresponds to the cumulative probability density function (red line). Light gray shading indicates shear values between the 20th and 80th percentiles.

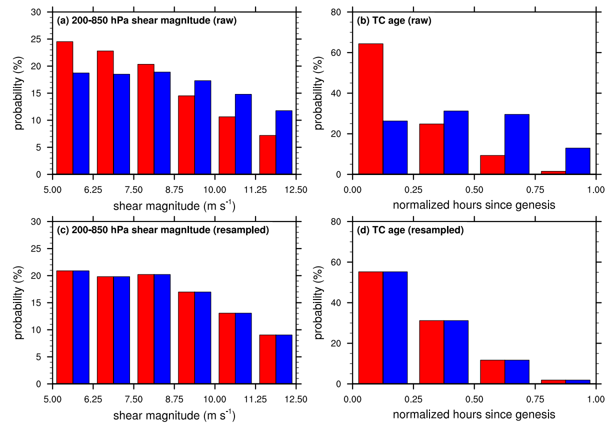

FIG. 2. Normalized distributions of (a,c) 200–850 hPa shear magnitude and (b,d) TC age (top) before and (bottom) after randomly resampling the database to control for shear magnitude and TC age. Red (blue) color depicts intensifying (steady state) events. TC age is defined as the number of hours since genesis normalized by the number of hours between genesis and dissipation.

with different intensity changes were compared: intensifying events (intensity changes greater than 5 m s^{-1}) and steady state events (intensity changes between -5 m s^{-1} and 5 m s^{-1}).

An initial comparison of intensifying and steady state revealed the following: (a) intensifying events encountered weaker shear magnitude than steady state events (Fig. 2a), (b) intensifying events happened closer to their genesis time than steady state events (Fig. 2b), and (c) intensifying events (6,018) happened less often than steady state events (10,160). Because these aspects could introduce biases to the analysis, a random resampling approach was employed in which the same number of events with the same shear and age distributions were drawn from each group (Fig. 2c,d). This step was repeated 1,000 times to consider all events.

After controlling for shear magnitude and age, a statistical analysis was performed to compare environmental and storm-dependent factors of intensifying and steady state events. All factors were evaluated at the beginning of each 24-h period (named t_0 hereafter) under the assumption that conditions at t_0 influenced the intensity at $t_0 + 24h$. Results were tested for statistical significance using the bootstrap resampling method of Rios-Berrios et al. (2016a).

3. Results

The comparison of intensifying and steady state events confirmed that environmental factors can influence intensity changes in sheared environments. Intensifying events experienced significantly higher SSTs and greater precipitable water than steady state events (Fig. 3a,b and Table 1). A further look at the moisture field revealed that, on average, intensifying events had 1.48% greater RH in the lower troposphere (600–900 hPa), but 5.14% greater RH in the middle troposphere (400–600 hPa) (Fig. 3c,d and Table 1). These discrepancies between events could indicate that intensifying events entrained less environmental dry air and promoted more convective activity to aid intensification. A detailed analysis, possibly with parcel trajectories, is needed to verify this hypothesis.

The analysis of storm-dependent factors both validated and contradicted previously proposed theories on TC resiliency to VWS. As predicted by theory, intensifying events were significantly stronger than steady state events (Fig. 3e and Table 1). However, intensifying events were further equatorward and moving faster than steady state events (Fig. 3f,g and Table 1). Moreover, there was no significant difference in size between intensifying and steady state events (Fig. 3h and Table 1). These results do not support theoretical prediction that larger TCs at higher latitudes are more likely to resist VWS than smaller TCs at lower latitudes. The coarse resolution of the analyses employed in this study prevents a further examination of this result, but future work will seek to clarify these contradictions with alternate datasets and/or idealized modeling.

4. Summary

This study combined best tracks, reanalysis, and satellite data to investigate factors influencing TC

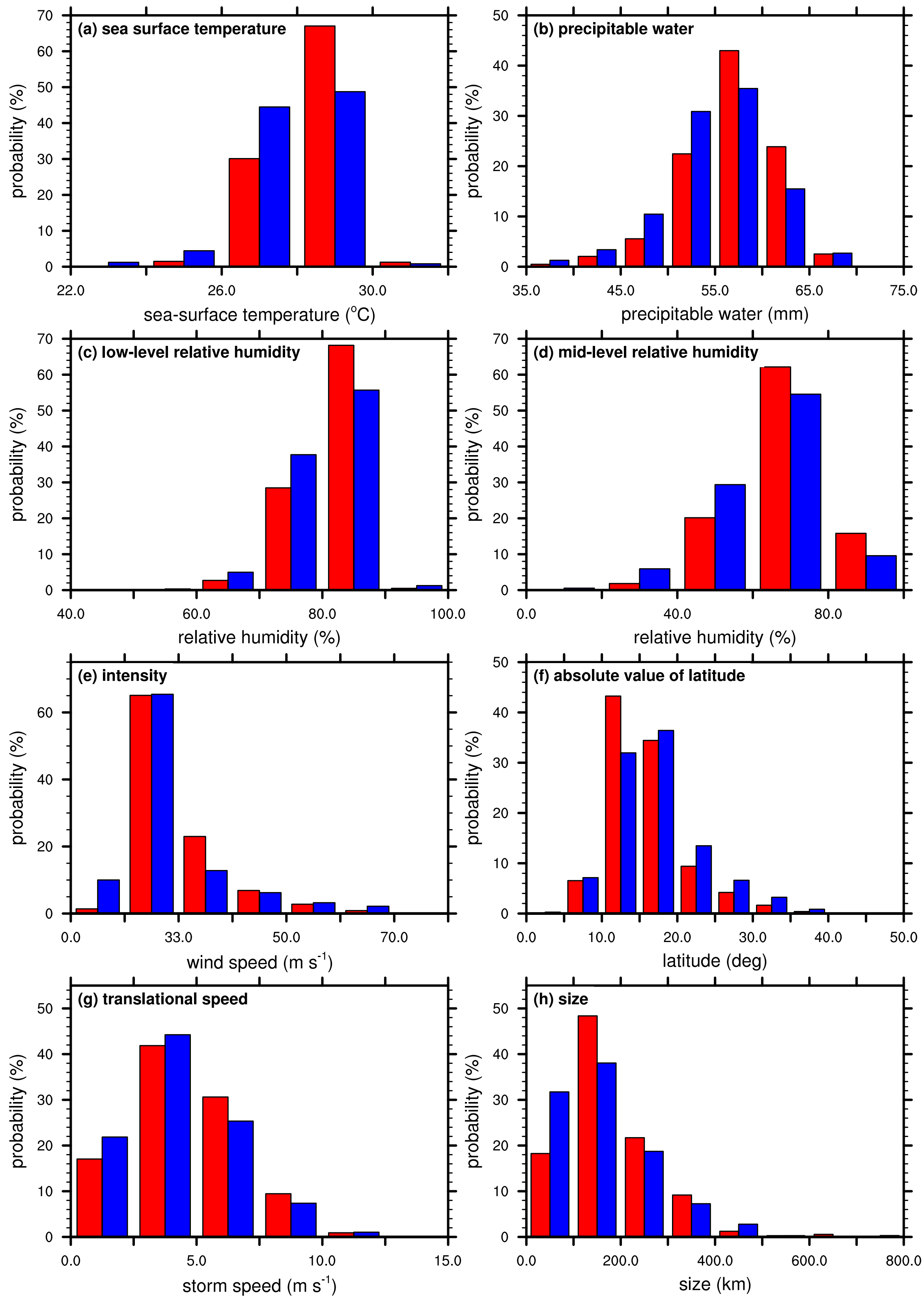

FIG. 3. Normalized distributions of (a) sea surface temperature, (b) precipitable water averaged within a 500-km radius, (c) 900–600 hPa relative humidity averaged within a 500-km radius, (d) 600–400 hPa relative humidity averaged within a 500-km radius, (e) maximum sustained wind speed, (f) absolute value of latitude, (g) translational storm speed, and (h) 34-knot wind radius. Red (blue) color depicts intensifying (steady state) events.

TABLE 1. Comparison of averaged quantities for intensifying and steady state events. Bold text indicates statistically significant differences at the 99% level.

Variable (units)	Sample size	Intensifying	Steady state	Difference
Sea surface temperature (°C)	4789	28.86	27.84	**1.02**
Precipitable water (mm)	4789	57.40	55.15	**2.25**
Low-level relative humidity (%)	4789	82.04	80.56	**1.48**
Mid-level relative humidity (%)	4789	68.35	63.21	**5.14**
Intensity (m s^{-1})	4789	29.40	26.99	**2.41**
Latitude (absolute deg.)	4789	15.81	17.09	**-1.28**
Speed (m s^{-1})	4789	4.63	4.31	**0.32**
Radius of 34-kt winds (km)	514	182.38	174.57	7.81

intensity changes under moderate VWS. A global, climatological analysis confirmed that high SSTs and moisture favor intensification under moderate VWS. However, the relationship between intensity changes and storm-dependent factors is less clear than previously proposed, thus demanding further research to clarify the role of TC characteristics on intensity changes amid moderate VWS.

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