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African Easterly Wave Strength and Observed Atlantic Tropical Cyclone Genesis and Characteristics

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Key Points:

- Tropical cyclogenesis occurs farther west for weaker developing African easterly waves (AEWs) than for stronger developing AEWs
- Tropical cyclones (TCs) from weaker developing AEWs are more likely to make landfall due to their genesis proximity to the Americas
- Weaker developing AEWs tend to develop into TCs over warmer sea surface temperatures than stronger developing AEWs

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Abstract

African easterly waves (AEWs) are known precursors to Atlantic tropical cyclones (TCs), and are therefore often directly connected to extreme weather events that can be both deadly and destructive. It is well established that not all AEWs develop into TCs, and there has been substantial research that has addressed the different characteristics and environments of developing and non-developing waves. In this study, however, we specifically examine 41-years of developing AEWs to provide a better understanding of the relationship between the developing wave and the environment, and the resulting TC. To conduct this research, we identified TCs with AEW origins from the observational record between 1980 and 2020. We then used an objective tracking algorithm to identify the developing AEWs in reanalysis data. We found a statistically significant relationship between the strength of the developing AEWs, TC genesis location and landfall, and sea surface temperature (SST) during TC genesis. Weaker AEWs tend to develop into TCs closer to the Americas in a region with warmer SSTs than those of the stronger AEWs, which tend to develop into TCs closer to Africa. Consequently, the TCs that develop from weaker AEWs are more likely to make landfall due to the close proximity of their genesis locations to the Americas.

Plain Language Summary

African easterly waves (AEWs) are atmospheric disturbances that often develop into Atlantic tropical cyclones (TCs). Although each year there are many AEWs, only a fraction of these waves develop into TCs. In this study, we examine only developing AEWs to provide a better understanding of the relationship between the developing AEW and the environment, and the resulting TC. To conduct this research, we identified TCs with AEW origins from the observational record between 1980 and 2020 and tracked the developing AEWs in reanalysis data. We found a statistically significant relationship between the strength of the developing AEWs, TC characteristics, and the sea surface temperature (SST). Weaker AEWs develop into TCs closer to the Americas with SSTs that are notably warmer than those of the stronger AEWs, which develop closer to Africa. Consequently, the TCs that develop from weaker AEWs are more likely to make landfall because they form closer to the Americas.

1. Introduction

Atlantic tropical cyclones (TCs) are both deadly and destructive, leading to hundreds of fatalities and billions of dollars in losses each year (Klotzbach et al., 2018, 2022; Mendelsohn et al., 2012). The genesis of Atlantic TCs is often associated with African easterly waves (AEWs), which are synoptic-scale disturbances that propagate westward over North Africa and out into the Atlantic Ocean (Burpee, 1972; Carlson, 1969). AEWs have been shown to serve as the initial disturbances needed for Atlantic TCs (Avila & Pasch, 1992; Landsea, 1993), with approximately 60% of TCs and 85% of major hurricanes developing from AEWs (N. L. Frank, 1970; Landsea, 1993; Russell et al., 2017). There has been a considerable amount of research on the relationship between AEWs and TCs (Carlson, 1969; Enyew & Mekonnen, 2022; W. M. Frank & Roundy, 2006; Hopsch et al., 2007; Núñez Ocasio et al., 2021; Russell et al., 2017; Thorncroft & Hodges, 2001; Wu et al., 2012). However, recent work has shown that environmental conditions may be the driving factor behind tropical cyclogenesis (Emanuel, 2022; Helms & Bosart, 2021; Hoogewind et al., 2020; Mei et al., 2019; Rajasree et al., 2023; C. Wang et al., 2019) and that AEWs are not necessary to maintain basin-wide TC frequency (Bercos-Hickey & Patricola, 2023; Danso et al., 2022; Patricola et al., 2018). Although the observational record clearly indicates that AEWs can indeed develop into TCs, the complex relationship between AEWs, the environment, and tropical cyclogenesis warrants further investigation.

Previous research has primarily focused on the differences between AEWs that do and do not develop into TCs, largely owing to the fact that each year only a fraction of AEWs in existence actually develop into TCs (N. L. Frank, 1970). For example, out of a 23-year average of 58 tropical waves that moved across the Atlantic during hurricane season, only 30% developed into TCs (Avila, 1991). Many studies have therefore examined the characteristics and environments of developing and non-developing waves in an effort to understand the circumstances under which AEWs lead to tropical cyclogenesis (Asaadi et al., 2016, 2017; Bercos-Hickey et al., 2023; Dunkerton et al., 2009; Enyew & Mekonnen, 2022; Hopsch et al., 2009; Núñez Ocasio et al., 2021; Peng et al., 2012; Ross et al., 2009; Z. Wang et al., 2012). Dunkerton et al. (2009) found that the preferred region of storm formation was the Kelvin cat's eye within the critical layer of a tropical easterly wave, where the cat's eye was defined as a region enclosed by a bounding streamline crossing a saddle point in a wave-centric framework. Building on these results, Z. Wang et al. (2012) suggested that a deep Kelvin cat's-eye extending from the mid-troposphere to the boundary layer was a necessary condition for tropical cyclogenesis. Asaadi et al. (2016) further extended this work by examining 54 developing AEWs from reanalysis data. They found that the coexistence of a nonlinear critical layer and a region of weak meridional potential vorticity gradient over a period of several days might be a major factor to distinguish developing and non-developing disturbances. In a subsequent study, Asaadi et al. (2017) determined that approximately 91% of non-developing waves were not located on a critical layer.

Other studies have focused on the location, role of convection, and strength of developing and non-developing AEWs (Agudelo et al., 2011; Brammer & Thorncroft, 2015; Brammer et al., 2018; Chen et al., 2008; Dieng et al., 2014; Hopsch et al., 2009; Núñez Ocasio et al., 2021; Ross et al., 2009; Semunegus et al., 2017). For example, Chen et al. (2008) manually backtracked developing AEWs in reanalysis data and found that the conversion rate of AEWs to TCs from the south wave track was more effective than from the drier north wave track. Recent work has also shown that developing AEWs are more likely to be from the south wave track, and additionally that AEWs that initiate over eastern Africa are more likely to undergo tropical cyclogenesis than those that initiate over central or West Africa (Núñez Ocasio et al., 2020a, 2021). Ross et al. (2009) examined three AEWs and found that although all of the waves experienced a burst of diabatic heating, the barotropic energy conversion was positive for the two developing waves and negative for the one non-developing wave. Hopsch et al. (2009) performed a composite analysis of developing and non-developing AEWs over the period 1979–2001 which indicated that the wave characteristics at the coast of Africa influence downstream tropical cyclogenesis. Hopsch et al. (2009) concluded that developing AEWs are stronger and convectively active as they reach the Guinea highlands region, whereas non-developing AEWs are weaker and less convectively active with dry mid- to upper-level air ahead of the wave trough before reaching the coast. Indeed the topography in Africa has been shown to play a significant role in AEW development (Hamilton et al., 2017, 2020). Similar to Hopsch et al. (2009), Agudelo et al. (2011) found that AEW amplitude is a major determinant for tropical cyclogenesis and that genesis potential increased when the wave was preceded by moist convection. This relationship between AEW strength and convection was further addressed by Semunegus et al. (2017), who hypothesized that the progression of convection from disorganized to mesoscale convective systems (MCSs) may play a critical role in AEW development.

Multiple other studies have also examined the role of convection in developing and non-developing AEWs (Arnault & Roux, 2010; Brammer & Thorncroft, 2015; Brammer et al., 2018; Dieng et al., 2014; Lawton et al., 2022; Leppert et al., 2013; Núñez Ocasio & Rios-Berrios, 2023; Núñez Ocasio et al., 2020b; Schwendike & Jones, 2010; Zawislak & Zipser, 2014). For example, some studies have emphasized the importance of moisture ahead of AEWs exiting or about to exit coastal West Africa as a characteristic of developing waves (Brammer & Thorncroft, 2015; Dieng et al., 2014). Indeed, previous research has shown that dry air advection can inhibit AEW development (Arnault & Roux, 2010; Brammer et al., 2018), and that a positive net moisture flux within the boundary layer toward the center of the AEW is a critical step toward tropical cyclogenesis (Núñez Ocasio & Rios-Berrios, 2023). The role of convection in tropical cyclogenesis was also examined by Schwendike and Jones (2010), who found that the MCS-AEW interaction was crucial for the development of Hurricane Helene. Leppert et al. (2013) found that increased fractional cloud coverage, large-scale moisture, and upper-level divergence were the most important parameters for distinguishing between developing and non-developing AEWs. Similarly, Zawislak and Zipser (2014) found that developing and non-developing AEWs were better characterized by the areal coverage of convection rather than the overall intensity of convection. Additionally, Lawton et al. (2022) found that convective coverage around AEWs changed in phase with convectively coupled

Kelvin wave crests, and Núñez Ocasio et al. (2020b) found that developing AEWs over West Africa were associated with a larger number of convective cloud clusters than non-developing AEWs.

In addition to examining the characteristics of developing and non-developing AEWs, previous studies have also investigated the environmental conditions associated with the waves (Bercos-Hickey et al., 2023; Enyew & Mekonnen, 2022; Kerns & Zipser, 2009; Leppert et al., 2013; Peng et al., 2012; Vizy & Cook, 2009). Kerns and Zipser (2009) found that the 925 hPa vorticity and the mid-level mixing ratio were the best predictors for discriminating between developing and non-developing disturbances in the Atlantic. Vizy and Cook (2009) simulated two successive AEWs from August 2006 and concluded that environmental conditions associated with the Saharan air layer hindered the development of the stronger wave into a TC, whereas favorable conditions led the weaker wave to quickly intensify into a TC. More recently, Enyew and Mekonnen (2022) revisited the relationship between AEWs and TCs through a composite analysis where AEW strength was measured using the relative vorticity at pressure levels with high AEW activity. They found that developing AEWs are stronger, associated with well-organized deep convection, and have environments with high relative humidity. Similarly, Bercos-Hickey et al. (2023) examined developing and non-developing AEWs in High-Resolution Model Intercomparison Project models (Haarsma et al., 2016) and also found that developing waves were stronger than non-developing waves, as measured by eddy kinetic energy (EKE) and curvature vorticity (CV). Additionally, they found that environmental conditions were more favorable for tropical cyclogenesis for developing AEWs, indicating that development may be a function of both the wave and the environment.

Previous research has clearly shown a consensus that developing AEWs tend to be stronger than non-developing AEWs (Agudelo et al., 2011; Bercos-Hickey et al., 2023; Enyew & Mekonnen, 2022; Hopsch et al., 2009). Indeed, Atlantic hurricane season reports often cite vigorous AEWs as the initial disturbances of Atlantic TCs. For example, Hurricane Fabian in 2003, which was reported to be the worst hurricane to affect Bermuda since 1926, was attributed to a vigorous tropical wave that emerged from western Africa (Lawrence et al., 2005). However, there are also numerous instances of weak AEWs serving as the precursors to Atlantic TCs, such as Tropical Storm Matthew in 2004, whose precursor was a weak tropical wave that moved across the west coast of Africa (Franklin et al., 2006). Brammer and Thorncroft (2015) also found through an analysis of favorable AEWs that not all strong waves develop into TCs. This suggests that other factors, such as environmental conditions, are playing a role in tropical cyclogenesis from AEWs. Additionally, the development of both strong and weak AEWs demonstrates that within the subset of developing AEWs, there is a broad range of wave characteristics and environments.

Although a great deal of research has focused on the differences between developing and non-developing AEWs, little attention has been paid to the variations within the spectrum of developing AEWs. In this study, our objective is to examine only developing AEWs to provide a better understanding of the relationship between the initial disturbance and the environment, and the resulting impact on TCs. We aim to answer the following questions: How does the strength of developing AEWs affect the characteristics of the TCs with AEW origins? And, what role do the environmental conditions have on developing AEWs? To address these questions, we use the observational record combined with reanalysis data to examine known developing AEWs and their corresponding TCs. The paper is organized as follows: Data and methods are discussed in Section 2. Our results are presented in Section 3, and the conclusions are presented in Section 4.

2. Data and Methods

National Hurricane Center (NHC) TC reports and Monthly Weather Review Atlantic Hurricane Season articles were used to identify TCs that developed from AEWs between 1980 and 2020 (NHC, 2023). All tropical storms and hurricanes were surveyed during this time period. A TC was considered to have developed from an AEW if the report stated that the TC originated from a tropical wave that exited the western coast of Africa. This method allowed us to create a data set of 310 known TCs with AEW origins based on the observational record, and is similar to the methodology of Russell et al. (2017), who only examined the years 1995–2015.

The European Centre for Medium-range Weather Forecasts reanalysis five (ERA5) (Hersbach et al., 2020) was used to identify the tracks of the developing AEWs that preceded the TCs between 1980 and 2020 with AEW origins. To identify the waves, we ran an objective AEW tracking algorithm on the ERA5 data in advance of each TC with AEW origins between 1980 and 2020. The objective tracking algorithm is a modified version of the algorithm used by Brammer and Thorncroft (2015), has been used in multiple other studies, and has been shown to accurately identify AEWs (Bercos-Hickey & Patricola, 2021; Bercos-Hickey et al., 2023; Brannan & Martin, 2019; Brammer & Thorncroft, 2015). The domain of the tracking algorithm spans the African continent as well as the Atlantic Ocean. The tracking algorithm utilizes CV maxima, which is similar to the AEW tracker that was recently developed by Lawton et al. (2022). CV has been shown to distinguish the trough of a wave from the background shear vorticity and removes any bias associated with the strength of the African easterly jet (Bain et al., 2014; Berry et al., 2007). At each time step, locations of unique CV maxima on multiple pressure levels are determined and the stream function is then used to advect the maxima to find the next point in time. Locations of the advected maxima are corrected through a comparison with the unique CV maxima at the next time step. A magnitude-weighted centroid is calculated to select the CV centroid if multiple weak CV maxima are present (Brammer & Thorncroft, 2015). Consistent with Brannan and Martin (2019), the algorithm considers CV maxima to have magnitudes greater than or equal to 0.15×10^{-5} s^{-1}. Analysis of the genesis locations for the tracked developing AEWs indicates that 86% of waves develop east of 0°, in agreement with Núñez Ocasio et al. (2021), who found that AEWs that form over eastern Africa are more likely to develop into TCs.

To assess the strength of the developing AEWs, we used the CV associated with the wave tracks. CV has previously been used as a measure of AEW strength, with larger values of CV indicating stronger waves (Bercos-Hickey & Patricola, 2021; Brannan & Martin, 2019). Bercos-Hickey and Patricola (2021) used both CV and EKE to examine the strength of simulated AEWs and found that the CV and EKE were in agreement with each other. For this study, we measured the strength of the individual AEWs using the CV when the wave departs the coast of Africa. We use this measurement of strength because it allows for a fair comparison between AEWs of varying track lengths. There is also a strong positive correlation between the CV at the coast of Africa and the average CV along the AEW track ($r = 0.6$, $p < 0.05$), indicating that the CV at the coast is representative of the entire wave track. Additionally, we examined ERA5 outgoing longwave radiation (OLR) at the coast of Africa, as convective activity is another indicator of AEW strength (Enyew & Mekonnen, 2022; Hopsch et al., 2009; Semunegus et al., 2017). We chose ERA5 OLR because of the 1980–2020 data availability and to be consistent with the other data used for analysis. We found that the OLR is in good agreement with the CV at the coast of Africa (see Section 3). To assess the characteristics of the TCs with AEW origins, we used the International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al., 2010). IBTrACS is the largest collection of global TC observations, and merges recent and historical data from multiple agencies. From IBTrACS, we specifically examined TC track location, landfall, and maximum sustained wind speed. Lastly, to assess the environmental conditions of the developing AEWs and their corresponding TCs, we used the ERA5 reanalysis.

3. Results

3.1. AEW Strength and TC Characteristics

We begin our analysis by examining the relationship between developing AEW strength and the location of tropical cyclogenesis. Figure 1 shows (a) the locations of tropical cyclogenesis and the CV at the African coast of the corresponding AEWs between 1980 and 2020 and (b) probability density function (PDF) curves of the developing AEW CV at the African coast for TCs that form east and west of 40°W. The vertical red line in Figure 1a indicates the location of 40°W. We chose 40°W based on Figure 1a, but found that the results shown in Figure 1b are not sensitive to the choice of longitude within a reasonable range. From Figure 1a, there is a clear difference between the CV of the AEWs that develop into TCs in the eastern Atlantic and those that develop into TCs in the western Atlantic. AEWs that develop in the eastern Atlantic near Africa have a tendency to have greater CV than those that develop farther afield, suggesting that TCs with AEW origins that form in the deep tropics (i.e., Cape Verde hurricanes) often develop from stronger waves. Figure 1b further demonstrates the relationship between the location of tropical cyclogenesis and wave strength. TCs with AEW origins that form east of 40°W (purple curve) have statistically significantly larger AEW CV values than TCs that form west of 40°W (red curve), thus confirming that stronger AEWs tend to develop into TCs in the eastern Atlantic closer to Africa. It is important to note that stronger (weaker) AEWs can and do develop into TCs in the western (eastern) Atlantic, but here we are showing that there is a relationship between developing AEW strength and the longitudinal location of tropical cyclogenesis. These results suggest that stronger AEWs are able to develop into TCs not long after they exit the coast of Africa, whereas weaker AEWs may require additional factors to develop into TCs, such as more favorable environmental conditions (Vizy & Cook, 2009), that may not be available upon immediately exiting the coast of Africa.

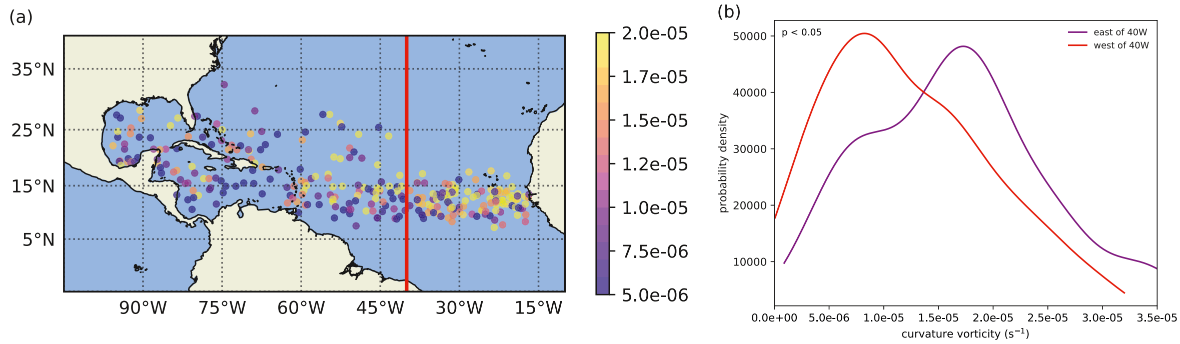

Figure 1. (a) Genesis locations of Atlantic tropical cyclones (TCs) with African easterly wave (AEW) origins between 1980 and 2020 and the curvature vorticity (CV) (s^{-1}) at the African coast of the associated AEWs (colors); the vertical red line shows the location of 40°W. (b) Probability density function curves of developing AEW CV at the African coast for TCs that form east (purple) and west (red) of 40°W; $p < 0.05$ from a two-sided t-test.

To further examine the relationship between developing AEW strength and the location of tropical cyclogenesis, we look specifically at the weakest and strongest developing AEWs. Figure 2 shows PDF curves of the longitude of tropical cyclogenesis from the weakest and strongest developing AEWs, as measured by taking the bottom and top 10% of all developing AEWs based on their (a) CV and (b) OLR at the coast of Africa. From Figure 2a, there is a very clear, statistically significant difference in the longitude of tropical cyclogenesis between the weakest and strongest developing AEWs. The weakest developing AEWs develop into TCs farther west (purple curve), while the strongest developing AEWs develop into TCs closer to Africa (red curve). Not only is Figure 2a in agreement with the results presented in Figure 1, but it also demonstrates that the difference in the longitudinal location of tropical cyclogenesis is more pronounced when we examine the weakest and strongest developing AEWs. Although it may be surprising that weaker developing AEWs tend to traverse the Atlantic before tropical cyclogenesis occurs, previous research has shown that as AEWs propagate westward, they may experience regions of weak wave growth that are likely associated with the ITCZ and therefore the diabatic generation of eddy available potential energy (Thorncroft & Hodges, 2001). In addition to CV, convective activity is also an indicator of AEW strength (Enyew & Mekonnen, 2022; Hopsch et al., 2009; Semunegus et al., 2017), which we measure here using OLR. Figure 2b indicates that the developing AEWs with the largest OLR, or least convective activity, develop into TCs farther to the west (purple curve), while developing AEWs with the smallest OLR, or most convective activity, develop into TCs closer to Africa (red curve). The results presented in Figure 2 are in strong agreement with each other, and we therefore use only the CV for the remainder of our analysis.

We next consider the relationship between developing AEW strength and whether or not a TC makes landfall. Figure 3a shows PDF curves of developing AEW CV at the coast of Africa for TCs that do and do not make

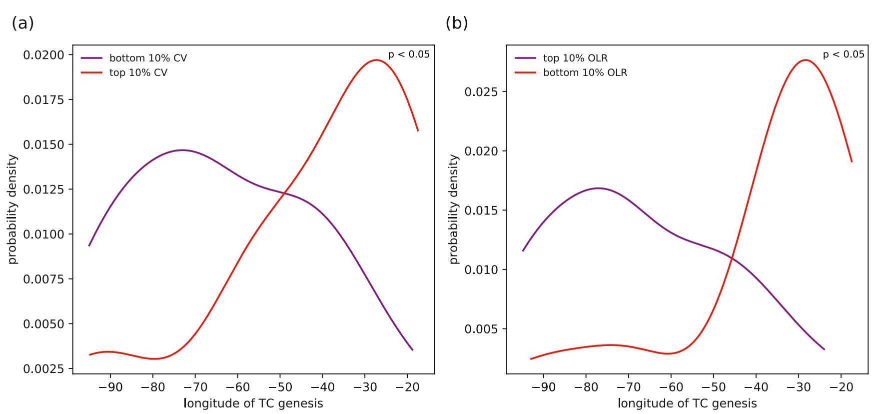

Figure 2. Probability density function curves of the longitude of tropical cyclogenesis from the weakest and strongest developing African easterly waves (AEWs), as measured by taking the bottom and top 10% of all developing AEWs based on their (a) curvature vorticity and (b) outgoing longwave radiation at the coast of Africa. $p < 0.05$ from a two-sided t-test for both panels.

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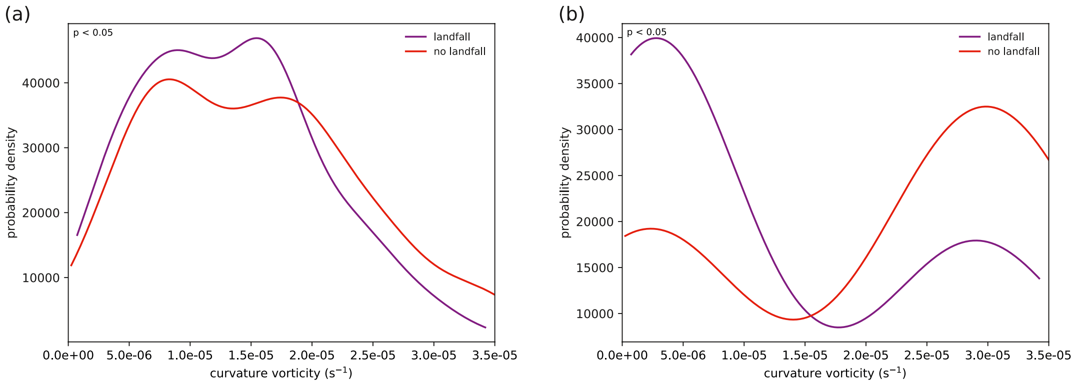

Figure 3. Probability density function curves of (a) developing African easterly wave (AEW) curvature vorticity (CV) (s^{-1}) at the African coast for tropical cyclones (TCs) that do (purple) and do not (red) make landfall between 1980 and 2020 and (b) the top and bottom 10% of all developing AEWs based on their CV at the coast of Africa for TCs that do (purple) and do not (red) make landfall between 1980 and 2020; $p < 0.05$ from a two-sided t-test for both panels.

landfall based on the IBTrACS data set. From Figure 3a, there is a statistically significant difference in CV magnitude between the TCs that make landfall (purple curve) and those that do not (red curve). The distribution of TCs that make landfall is shifted to have lower developing AEW CV values when compared to the distribution of TCs that do not make landfall. This indicates that weaker developing AEWs may be more likely to develop into landfalling TCs, although we note that there is overlap between the two curves. To examine only the weakest and strongest developing AEWs, Figure 3b shows PDF curves of the top and bottom 10% of all developing AEWs based on their CV at the coast of Africa for TCs that do and do not make landfall. Figure 3b shows a very clear and statistically significant difference in CV magnitude between TCs that do (purple curve) and do not (red curve) make landfall, indicating that the weakest developing AEWs are more likely to result in landfalling TCs than the strongest developing AEWs. Indeed, when we look specifically at the bottom and top 10% of all developing AEWs based on their CV at the coast of Africa, landfalling TCs result from approximately two thirds of the weakest waves but only one third of the strongest waves.

The strength of developing AEWs is also related to the location of TC landfall. Figure 4 shows (a) the locations of TC landfall and the CV at the African coast of the corresponding AEWs between 1980 and 2020 and (b) PDF curves of the developing AEW CV at the African coast for TCs that make landfall east and west of 81.5°W. The longitude 81.5°W was chosen because it corresponds to the middle of the state of Florida and separates the TCs that make landfall in the Gulf of Mexico from those that make landfall farther east. From Figure 4a, it appears that TCs from stronger developing AEWs are more likely to make landfall along the eastern coast of North America,

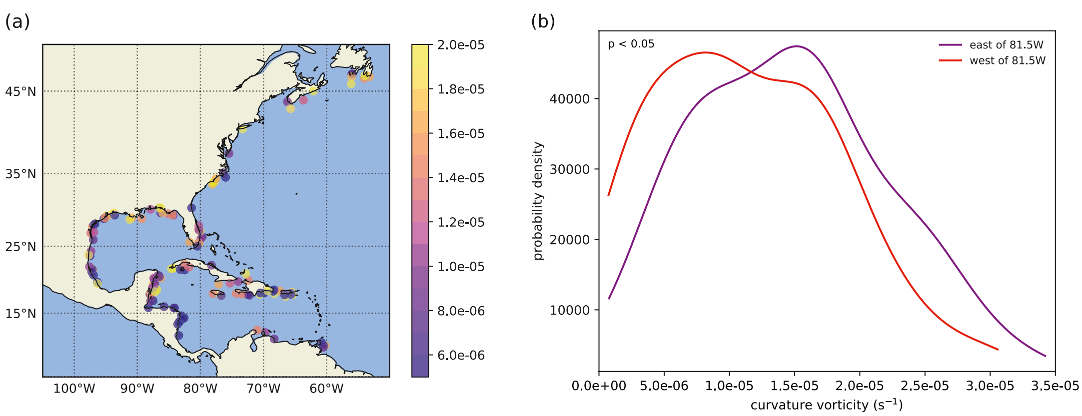

Figure 4. (a) Landfall locations of Atlantic tropical cyclones (TCs) with African easterly wave (AEW) origins between 1980 and 2020 and the curvature vorticity (CV) (s^{-1}) at the African coast of the associated AEWs (colors). (b) Probability density function curves of developing AEW CV at the African coast for TCs that make landfall east (purple) and west (red) of 81.5° W; $p < 0.05$ from a two-sided t-test.

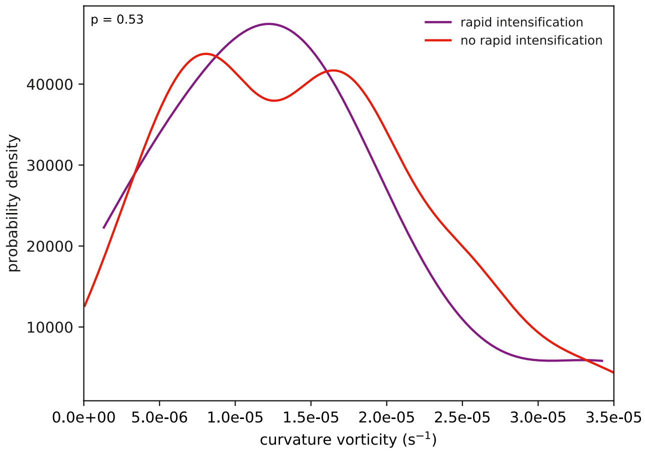

Figure 5. Probability density function curves of developing African easterly wave curvature vorticity at the African coast for tropical cyclones that do (purple) and do not (red) experience rapid intensification between 1980 and 2020; $p = 0.53$ from a two-sided t-test.

while TCs from weaker developing AEWs are more likely to make landfall along the coast of Mexico. Figure 4b shows a statistically significant difference in developing AEW strength for TCs with AEW origins that make landfall east and west of Florida. TCs with AEW origins that make landfall east of Florida are more likely to have larger AEW CV values at the coast of Africa than TCs that make landfall to the west. There is overlap between the two curves in Figure 4b, which we would expect given that not all landfalling TCs with weaker (stronger) AEW origins make landfall west (east) of Florida. The results presented in Figures 3 and 4 demonstrate a relationship between AEW strength and TC landfall potential, which is supported by the results presented in Figures 1 and 2. In Figures 1 and 2, we found that weaker developing AEWs are more likely to develop into TCs closer to the Americas, which in turn positions the TCs closer to land and therefore increases the likelihood of landfall.

Unlike tropical cyclogenesis location and landfall, we found that there is little relationship between developing AEW strength and TC strength. For example, when comparing the AEW CV with the TC maximum sustained wind speed (not shown), the Pearson's correlation coefficient is 0.17 ($p < 0.05$). This low coefficient represents almost no correlation, which indicates that stronger developing AEWs do not necessarily lead to stronger TCs, and suggests that environmental favorability may be a more important factor for TC intensity than AEW strength. Additionally, we found little evidence of a relationship between the interannual variability of TCs with AEW origins and the strength of the developing AEWs. Figure 5 shows PDF curves of developing AEW CV at the African coast for TCs that do and do not experience rapid intensification. Here we defined TC rapid intensification according to the NHC as an increase in the maximum sustained wind speed of at least 30 kt in a 24-hr period. From Figure 5, there is a slight, but not statistically significant ($p = 0.53$), difference in developing AEW CV for TCs with AEW origins that do (purple curve) and do not (red curve) experience rapid intensification. When we look specifically at the bottom and top 10% of all developing AEWs based on their CV at the coast of Africa, TCs that experience rapid intensification result from approximately 11% of the weakest waves and only 4% of the strongest waves. A possible relationship between AEW strength and TC rapid intensification may be related to the tendency for weak AEWs to develop into TCs further west than strong AEWs, and therefore experience more favorable environmental conditions for rapid intensification, such as the warm Loop Current and associated warm core eddies in the Caribbean and Gulf of Mexico (Jaimes & Shay, 2009; Scharroo et al., 2005; Shay et al., 2000). This is a topic that warrants further investigation.

3.2. Environmental Conditions

To better understand the mechanisms driving the relationship between developing AEWs and TCs with AEW origins, we next examine environmental conditions that are favorable for tropical cyclogenesis. Such conditions include warm sea surface temperatures (SSTs), a moist mid-troposphere, and weak vertical wind shear (Avila, 1991; Emanuel, 1988; W. M. Frank & Ritchie, 2001; Gray, 1968; Landsea, 1993). For Figures 6–8, we spatially averaged the SST, relative humidity, and vertical wind shear in a 500 km radius box around the location and during the time of tropical cyclogenesis. We chose a 500 km radius box because this encompasses the typical size of a TC and its surrounding environment (NOAA, 2023) and focus on the time during tropical cyclogenesis because we are interested in the environments that directly lead to TC formation.

Figure 6a shows the genesis locations of TCs with AEW origins and the spatially averaged SST for each tropical cyclogenesis point during the time of tropical cyclogenesis. There is a distinct difference in the SST at genesis for TCs developing in the eastern Atlantic versus those that develop in the western Atlantic. TCs that develop to the east have cooler SSTs at genesis by several degrees Celsius than TCs that develop closer to the Caribbean and the Gulf of Mexico (Figure 6a). Although Figure 6a is representative of the North Atlantic SST climatology, and therefore expected, it serves as a clear illustration of the difference in SST between TCs that form in the eastern and western parts of the basin. Recall from Figures 1 and 2 that AEWs that develop into TCs closer to the Americas tend to be weaker than AEWs that develop into TCs to the east near Africa. The combined results from Figures 1, 2, and 6a suggest that there may be a relationship between developing AEW strength and SST that

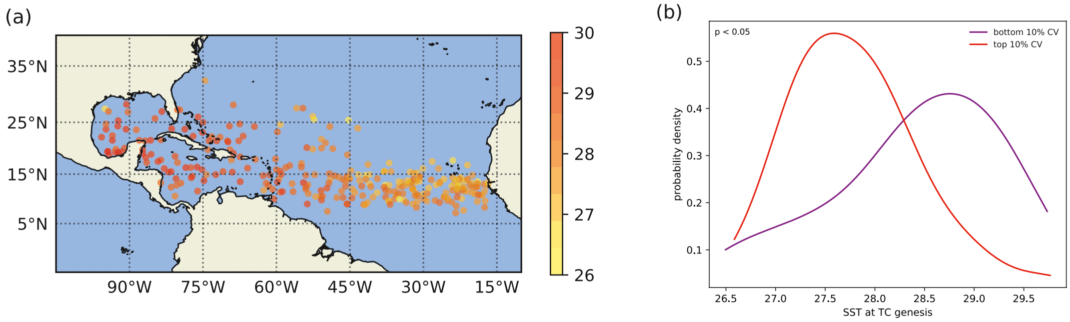

Figure 6. (a) Genesis locations of Atlantic tropical cyclones with African easterly wave (AEW) origins between 1980 and 2020 and sea surface temperature (SST) (°C, colors) during the time of tropical cyclogenesis spatially averaged in a 500 km radius box around the point of tropical cyclogenesis. (b) Probability density function curves of the spatially averaged SST during tropical cyclogenesis from the weakest and strongest developing AEWs, as measured by taking the bottom and top 10% of all developing AEWs based on their curvature vorticity at the coast of Africa; $p < 0.05$ from a two-sided t-test.

could impact tropical cyclogenesis, highlighting the importance of understanding AEW intensity before and as the wave exits the coast of Africa.

To further explore the relationship between developing AEW strength and SST, Figure 6b shows PDF curves of the spatially averaged SST during tropical cyclogenesis from the weakest and strongest developing AEWs, as measured by taking the bottom and top 10% of all developing AEWs based on their CV at the coast of Africa. Figure 6b shows that TCs that originate from the weakest developing AEWs (purple curve) experience a higher SST during tropical cyclogenesis than TCs that originate from the strongest developing AEWs (red curve). This difference between the SST during tropical cyclogenesis for the weakest and strongest developing AEWs is

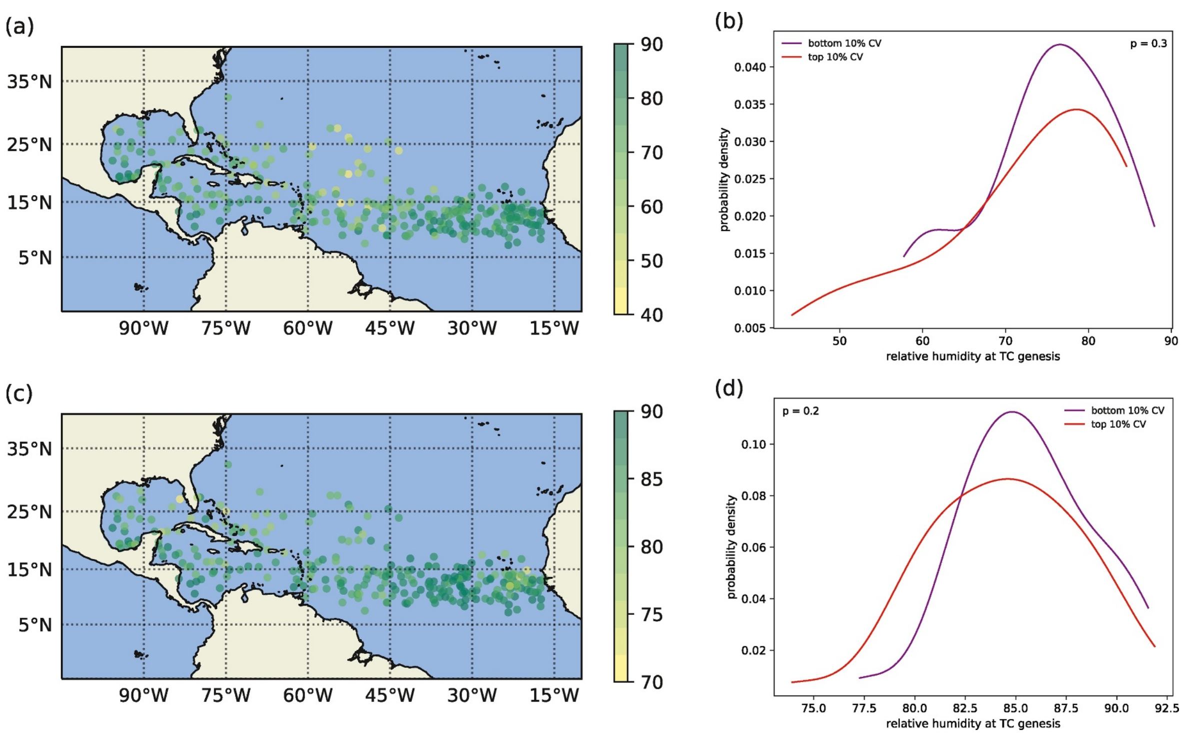

Figure 7. Genesis locations of Atlantic tropical cyclones with African easterly wave (AEW) origins between 1980 and 2020 and (a) 600 and (c) 900 hPa relative humidity (%, colors) at the time of tropical cyclogenesis spatially averaged in a 500 km radius box around the point of tropical cyclogenesis. Probability density function curves of the spatially averaged (b) 600 and (d) 900 hPa relative humidity during tropical cyclogenesis from the weakest and strongest developing AEWs, as measured by taking the bottom and top 10% of all developing AEWs based on their curvature vorticity at the coast of Africa; $p = 0.3$ and $p = 0.2$ from a two-sided t-test for the 600 and 900 hPa relative humidity, respectively.

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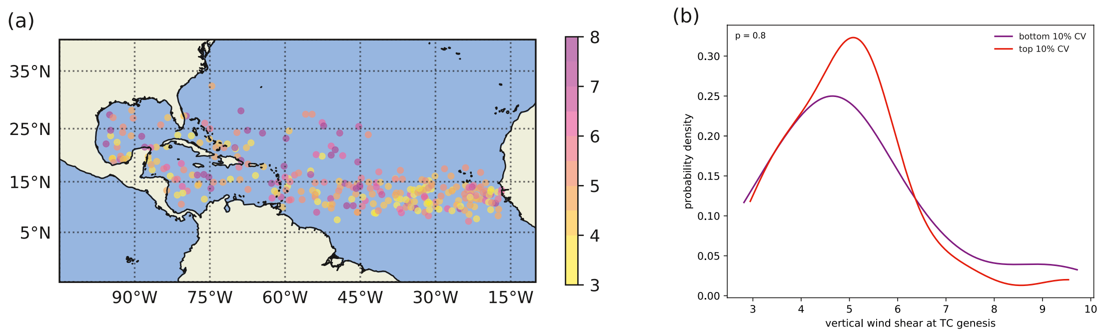

Figure 8. (a) Genesis locations of Atlantic tropical cyclones with African easterly wave (AEW) origins between 1980–2020 and 850–200 hPa vertical wind shear (m s^{-1}, colors) at the time of tropical cyclogenesis spatially averaged in a 500 km radius box around the point of tropical cyclogenesis. (b) Probability density function curves of the spatially averaged 850–200 hPa vertical wind shear during tropical cyclogenesis from the weakest and strongest developing AEWs, as measured by taking the bottom and top 10% of all developing AEWs based on their curvature vorticity at the coast of Africa; $p = 0.8$ from a two-sided t-test.

statistically significant ($p < 0.05$). The results presented in Figure 6b demonstrate a clear relationship between developing AEW strength and the SST during tropical cyclogenesis. It is challenging to know if this relationship is causal, where weaker developing AEWs would potentially require more favorable SSTs for tropical cyclogenesis to occur than stronger developing AEWs. The relationship could also be a covariation of developing AEW strength and the location of tropical cyclogenesis with the climatology of SSTs, where weaker developing AEWs tend to develop closer to the Americas where the SSTs are warmer and stronger developing AEWs tend to develop closer to Africa where the SSTs are cooler.

Figures 7a and 7c show the genesis locations of TCs with AEW origins and the spatially averaged (a) 600 and (c) 900 hPa relative humidity for each tropical cyclogenesis point during the time of tropical cyclogenesis. At 600 hPa (Figure 7a), there is a clear relationship between the tropical cyclogenesis location and the relative humidity, where TCs with AEW origins that form near the Americas and Africa have higher mid-tropospheric relative humidity than those that form in the middle of the Atlantic. At 900 hPa (Figure 7c), the relationship between tropical cyclogenesis location and relative humidity is less clear, indicating little difference in the lower-tropospheric relative humidity between TCs with AEW origins that form in the eastern and western North Atlantic. Recall from Figures 1 and 2 that weak and strong developing AEWs tend to develop closer to the Americas and Africa, respectively. The combined results presented in Figures 1, 2, 7a, and 7c suggest that there is no clear relationship between the relative humidity during tropical cyclogenesis and developing AEW strength.

As with our analysis of the SST, we next utilize PDF curves to further explore the relationship between developing AEW strength and relative humidity. Figures 7b and 7d show PDF curves of the spatially averaged (b) 600 and (d) 900 hPa relative humidity during tropical cyclogenesis from the weakest and strongest developing AEWs, as measured by taking the bottom and top 10% of all developing AEWs based on their CV at the coast of Africa. From Figures 7b and 7d, there is little difference between the mid- and lower-tropospheric relative humidity during tropical cyclogenesis for TCs that originate from the weakest (purple curve) and the strongest (red curve) developing AEWs. Indeed, a two-sided t-test reveals that the differences between the weakest and strongest developing AEWs are not statistically significant for the 600 hPa ($p = 0.3$) and the 900 hPa ($p = 0.2$) relative humidity during tropical cyclogenesis. In contrast to the SST (Figure 6b), Figures 7b and 7d indicate that the mid- and lower-tropospheric relative humidity during tropical cyclogenesis is similar for weak and strong developing AEWs. These results suggest that relative humidity may not be a driving factor for why weak developing AEWs tend to travel farther across the Atlantic before tropical cyclogenesis occurs.

Lastly, we examine the relationship between the vertical wind shear and TCs with AEW origins, where large vertical wind shear values are unfavorable for TCs (Rios-Berrios & Torn, 2017; Tao & Zhang, 2014, 2015; Zhang & Tao, 2013). Figure 8a shows the genesis locations of TCs with AEW origins and the spatially averaged 850–200 hPa vertical wind shear for each tropical cyclogenesis point during the time of tropical cyclogenesis. Unlike Figures 6a and 7a, there is not a clear relationship between the location of tropical cyclogenesis and the magnitude of the vertical wind shear. There is some indication of lower vertical wind shear values for TCs that develop east of 40°W, however many instances of low vertical wind shear can also be seen to the west. The results presented in

Figure 8a suggest that there is not a clear relationship between the vertical wind shear during tropical cyclogenesis and developing AEW strength.

Similar to Figures 6b, 7b, and 7d, Figure 8b shows PDF curves of the spatially averaged 850–200 hPa vertical wind shear during tropical cyclogenesis from the weakest and strongest developing AEWs, as measured by taking the bottom and top 10% of all developing AEWs based on their CV at the coast of Africa. Figure 8b does not show a clear difference in vertical wind shear during tropical cyclogenesis for TCs that develop from the weakest (purple curve) and the strongest (red curve) developing AEWs. As with the relative humidity, the differences between the weakest and strongest developing AEWs are not statistically significant for the vertical wind shear during tropical cyclogenesis ($p = 0.8$). Figure 8b therefore indicates that the 850–200 hPa vertical wind shear during tropical cyclogenesis is similar regardless of the strength of the developing AEW. These results suggest that the locational differences in tropical cyclogenesis between weak and strong developing AEWs are not likely driven by the vertical wind shear.

4. Conclusions

Atlantic tropical cyclogenesis involves the co-occurrence of multiple factors, including favorable environmental conditions and an initial disturbance, which is often an AEW. Although there has been considerable previous research on the differences between AEWs that do and do not develop into Atlantic TCs, little attention has been paid to the variations within the subset of developing AEWs and their possible relationship with TC characteristics. The objective of this study is to provide a better understanding of the relationship between developing AEWs and the environment, and the resulting impact on Atlantic TCs. To address this objective, we examined Atlantic TC observational records between 1980 and 2020 to identify which events had AEW origins. We then used an objective AEW tracking algorithm to identify the developing waves in the ERA5 reanalysis. Our results indicate the following: There is a clear relationship between the strength of developing AEWs as they exit the coast of Africa and the characteristics of the resulting TCs. TCs that form from weak AEWs tend to develop closer to the Americas and are more likely to make landfall, whereas TCs that form from strong AEWs tend to develop closer to Africa and are less likely to make landfall. These differences occur in an environment where SSTs near the Americas are warmer than those near Africa, indicating a potential relationship between developing AEW strength, tropical cyclogenesis location, and SST.

We found a robust relationship between the longitudinal location of tropical cyclogenesis and the strength of the developing AEWs, as measured by individual wave CV and OLR at the coast of Africa. Stronger developing AEWs are more likely to develop into TCs shortly after exiting the coast of Africa. The TCs that develop from these waves, however, are less likely to make landfall, which may in part be due to their genesis occurring thousands of kilometers east of the Americas. These TCs must have both favorable environmental conditions and steering flow during their journey across the Atlantic in order to reach land. When TCs that develop from strong AEWs do make landfall, this tends to occur along the U.S. east coast and over islands east of Florida, as these locations are often the first land masses in the path of the TC. In contrast, weaker developing AEWs are more likely to develop closer to the Americas and thus often travel across the Atlantic before the occurrence of tropical cyclogenesis. The TCs that develop from these waves are more likely to make landfall, owing to the close proximity of their genesis locations to land. The landfall locations of TCs that develop from weak AEWs tend to occur west of Florida near the Gulf of Mexico as this is often close to the location of tropical cyclogenesis. We found little difference in the strength of TCs from strong and weak developing AEWs, although it is possible that TCs with weak AEW origins may be more likely to experience rapid intensification. This is an important area for future research. Our results indicate that the strength of developing AEWs is not a good indicator of TC strength, however it is a good indicator of tropical cyclogenesis location as well as landfall likelihood and location.

To further investigate the relationship between developing AEWs and TCs with AEW origins, we examined environmental conditions favorable for tropical cyclogenesis. In addition to the initial disturbance, which for our purposes is an AEW, TCs also need warm SSTs, a moist mid-troposphere, and low vertical wind shear (Avila, 1991; Emanuel, 1988; W. M. Frank & Ritchie, 2001; Gray, 1968; Landsea, 1993). We found a clear relationship between developing AEW strength and the SST during tropical cyclogenesis by examining the bottom and top 10% of all developing AEWs based on their CV at the coast of Africa. TCs that develop from the weakest developing AEWs have statistically significantly warmer SSTs during genesis than TCs that develop from the strongest developing AEWs. It is possible that there is a casual relationship between the strength of developing AEWs and the SST, where weaker developing AEWs may require a more favorable environment, such as warmer SSTs, than stronger developing AEWs for tropical cyclogenesis to occur. In this case, weaker developing AEWs would be more likely to travel farther across the Atlantic to SSTs that are warmer than those by the coast of Africa. It is also possible that the relationship between developing AEW strength and SST is rather a covariation of developing AEW strength and the location of tropical cyclogenesis with the climatology of SSTs in the North Atlantic, without causation. The relationship between developing AEW strength, tropical cyclogenesis location, and SST is an important area for future research. In contrast, there was little to no clear relationship between developing AEW strength and the relative humidity and vertical wind shear during tropical cyclogenesis.

Our results demonstrate important relationships between developing AEW strength, the environment, and the resulting TC characteristics. Developing AEW strength is a good indicator of the SST during tropical cyclogenesis as well as tropical cyclogenesis location and landfall. Indeed, weaker developing AEWs tend to develop into TCs closer to the Americas. Although perhaps counterintuitive, this suggests that weaker developing AEWs are more likely to precede dangerous landfalling TCs than stronger developing AEWs, which tend to form closer to Africa and are less likely to precede TCs that make landfall. It may therefore be advisable to closely monitor weaker AEWs that are traversing into regions with high environmental favorability during Atlantic hurricane season. The results presented in this study are of course limited by the 41 years of observational records used in our analysis. However, our results indicate the importance of examining developing AEWs within the context of the environmental conditions that occur during tropical cyclogenesis.

Data Availability Statement

The Atlantic tropical cyclone summaries are available via NHC (2023). The International Best Track Archive for Climate Stewardship (IBTrACS) is available via Knapp et al. (2018). The ERA5 reanalysis is available via Copernicus Climate Change Service (2023). The AEW tracks are available via Bercos-Hickey and Patricola (2024). The tracking code used for analysis is available on GitHub via Bercos-Hickey (2024).

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