Influence of African Easterly Wave Suppression on Atlantic Tropical Cyclone Activity in a Convection-Permitting Model

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Abstract African easterly waves (AEWs) are strongly linked to Atlantic tropical cyclones (TCs) on the synoptic timescale by serving as seedling disturbances for TC genesis. However, it is unclear whether climatological TC frequency is limited by AEWs. We investigated the impact of suppressing AEWs using a 3-member ensemble of convection-permitting regional model simulations, in which AEWs were either retained or removed through the lateral boundary conditions. Suppressing AEWs did not substantially change seasonal TC number, but did influence TC intensity, genesis time and location. Suppressing AEWs produced stronger TCs, shifted peak TC genesis from September to August, and reduced (increased) TC genesis in the eastern Atlantic (Gulf of Mexico). Without AEWs, TCs generated under more favorable large-scale atmospheric conditions. These results indicate that AEWs may not be reliable predictors of basin-wide seasonal TC frequency. However, simulations provide evidence that AEWs could influence the large-scale environment that is important for TCs.

Plain Language Summary African easterly waves (AEWs) serve as precursors for tropical cyclones (TC) in the Atlantic. However, it is unclear whether the seasonal TC number is limited by AEWs. To investigate the connection between AEWs and Atlantic TCs, we used an ensemble of regional climate model simulations in which AEWs were either retained or removed. The simulations revealed no changes in the seasonal TC number after removing AEWs. However, the peak of TC genesis was shifted from September to August, suggesting that AEWs could influence the timing of TC genesis. Similarly, removing AEWs led to changes in TC genesis location, with TC genesis increased in the Gulf of Mexico and decreased near the western coast of northern Africa. Finally, by removing AEWs, TCs generated under more favorable atmospheric conditions, suggesting that environmental favorability could be the primary determinant of the seasonal TC number. Thus, AEWs on their own may not be reliable predictors of seasonal TC frequency but may control the variability of the atmospheric environment.

1. Introduction

Understanding the physical controls on tropical cyclone (TC) frequency represents a major challenge, as there is no theory to explain why the global annual number of TCs is relatively constant in historical observations and no consensus on future changes in TC frequency (Sobel et al., 2021). Pre-existing low-pressure disturbances, or TC “seeds,” may trigger TC genesis, and have been identified as one possible factor in determining TC frequency. The typical Atlantic TC seed is provided by African easterly waves (AEWs), which are synoptic–scale disturbances that grow off of the baroclinic and barotropic instability of the African easterly jet (AEJ) (Burpee, 1972). AEWs generate between 5°N and 30°N over tropical northern Africa (Kiladis et al., 2006) and propagate westward over the tropical Atlantic Ocean.

There is a strong connection between AEWs and Atlantic TCs on the synoptic time scale (Dieng et al., 2017; Landsea et al., 1998), with about 60%–80% of major Atlantic hurricanes originating from AEWs (Landsea, 1993; Russell et al., 2017). However, some studies have suggested that the relationship between TC frequency and AEWs may not be as straightforward as previously thought, especially on climate time scales. For instance, results from Thorncroft and Hodges (2001) and Hopsch et al. (2007) suggest that the relationship between AEWs and Atlantic TC activity could depend on the period considered, with the former finding them to be correlated for one period whereas the latter found them to be uncorrelated for a different period using the same data product. Moreover, Thorncroft and Hodges (2001) showed that only AEWs leaving the West African coast with significant low-level amplitudes, rather than the total number of AEWs, may influence the seasonal Atlantic
TC activity. Meanwhile, Caron and Jones (2012) found the large-scale atmospheric environment as the primary control of seasonal Atlantic TC activity in a series of simulations. In addition, Patricola et al. (2018) investigated the AEW-TC relationship using a 27 km resolution regional climate model in which a filter was applied to the eastern lateral boundary along the coast of northern Africa to suppress the propagation of AEWs into the tropical Atlantic region. They found no significant difference in seasonal basin-wide Atlantic TC frequency, suggesting that TCs will develop from alternative mechanisms in the absence of AEWs. Indeed, TCs can also form from other seed generation mechanisms, including the breakdown of the intertropical convergence zone (Wang & Magnusdottir, 2005), convective self-aggregation (Muller & Romps, 2018), and variations of the Asian monsoon trough (Molinari & Vollaro, 2013).

Considering the global scale, Hoogewind et al. (2020) suggested that the geography of favorable environments, without the explicit inclusion of TC seeds, could support a higher number of TCs than are currently found in the present-day Earth climate. Similarly, Emanuel (2022) argued that the climatological TC frequency is controlled more by the environmental conditions of the basin in which the TC forms rather than the frequency of TC seeds. Despite this, other studies have shown that frequency of TC seeds strongly influences TC frequency (Hsieh et al., 2022), although this relationship could depend on the definition of “seeds” and the time scale considered.

It is unclear how the frequency of AEWs will change in future, with studies projecting both increasing (Bercos-Hickey & Patricola, 2021; Hannah & Aiyyer, 2017; Skinner & Differnbaugh, 2014) and decreasing (Kebe et al., 2020) AEW activity. This is further complicated by a projected multi-model average increase and decrease of the northern and southern AEW tracks respectively, albeit with a large spread among individual climate models (Brannan & Martin, 2019). In all the above studies, it is unclear how changes in TC frequency and intensity, whose response to climate change is already associated with uncertainties (Knutson et al., 2020). Some studies, however, have projected decreasing TC seeds and TC frequency (Sugi et al., 2020; Yamada et al., 2021) but the definition of “seeds” does not explicitly account for AEWs.

Understanding the causality between AEWs and Atlantic TC activity could therefore be crucial to improving projections of the latter. The study of Patricola et al. (2018), which used climate model experiments that controlled AEW activity, was the first attempt of its kind to clearly untangle the causality between TC activity and AEWs. However, the simulations used a horizontal resolution of 27 km, in which convection was parameterized. This is a source of uncertainty, as convective parameterization has challenges in representing some cloud and precipitation processes, especially in the tropics (Fosser et al., 2015). Additionally, convective parameterization can introduce errors into simulated AEWs, as the initiation and consequent development of AEWs may require a triggering mechanism such as convection (Hsieh & Cook, 2005). For example, shallow cumulus convection and moist convection beneath and south of the AEJ, respectively, can trigger barotropic conversions that provide energy for AEW genesis (Hsieh & Cook, 2007). Other studies have also shown a spatial correlation between AEW genesis locations and the areas of peak convection in West Africa and the Atlantic (Diedhiou et al., 1999; Mekonnen et al., 2006).

Given the strong connection between AEWs and convection, it is unclear whether the response of TC frequency to AEW suppression in simulations with parameterized convection will be replicated in a convection-permitting model. Thus, the main aim and novelty of this study is to investigate the response of Atlantic TC frequency to AEW suppression in a convection-permitting model. An added value of using a convection-resolving model is the ability to reproduce extremely intense TCs such as Category 5 hurricanes, which are often not captured at coarser resolutions (Davis, 2018; Mohan et al., 2022). In addition, simulating TCs at higher resolutions may lead to better representations of the overall climate system as suggested by Li and Sriver (2018). Thus, this study will also investigate the influence of AEW suppression on the intensity of Atlantic TCs, which is currently unknown, and the environmental conditions in which TCs exist.

2. Convection-Permitting Regional Model Simulations

We performed regional model simulations with the Weather Research and Forecasting (WRF) model (Skamarock et al., 2019) version 4.2.2. The initial and lateral boundary conditions, as well as sea surface temperature, were prescribed from the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) ReAnalysis (ERA5) (Hersbach et al., 2020). The model is configured with 3.5 km resolution and 45 vertical levels.
Figure 1. (a) Regional model domain. The thick green line at the eastern lateral boundary denotes the region over which a 2–10-day Lanczos filter was applied. (b) Number of tropical cyclones during August–October 2020 in International Best Track Archive for Climate Stewardship observations and the 3-member ensemble mean from the Weather Research and Forecasting control simulation.

At 3.5 km, the convection parameterization was turned off. The following parameterization schemes were used: Purdue-Lin microphysics (Lin et al., 1983), Rapid Radiative Transfer Model for general circulation models (RRTMG) longwave and shortwave radiation (Iacono et al., 2008), Yonsei University planetary boundary layer scheme (Hong et al., 2006), revised MM5 surface scheme (Jiménez et al., 2012), and Noah land surface model (Chen & Dudhia, 2001).

The model domain (Figure 1a) covers the Atlantic main TC development region extending from the Gulf of Mexico to the western boundary of northern Africa (5°N–30°N and 100°W–15°W). The model domain is particularly suitable for this study as the eastern lateral boundary is located just off the western edge of northern Africa, where AEWs propagate over the Atlantic. We can therefore allow or restrict the entry of AEWs into the model domain via the lateral boundary condition. In the control simulation (“control”), AEWs were prescribed by forcing the model with the ERA5 data through the eastern lateral boundary. Following the methodology of Patricola et al. (2018), AEWs were then suppressed in an experiment (“AEW-suppressed”) by applying a Lanczos filter at the eastern lateral boundary (thick green line in Figure 1a, from 5°N to 30°N). The filter removes the 2–10-day variability from all variables and on all vertical levels. The effect of filtering AEWs is seen by comparing the meridional wind at 700 hPa between the control and the AEW-suppressed experiment (Figure S1 in Supporting Information S1).

The simulations were performed for the peak of the 2020 TC season (August 1–October 31). We limited the simulations to this time frame because the majority of Atlantic TCs are concentrated within this period (Yang et al., 2021), and due to the high computational cost of the convection-permitting simulations. Unlike the 2005 season simulated by Patricola et al. (2018), several TCs generated near the western coast of northern Africa during 2020 (Klotzbach et al., 2021). Those TCs likely generated from AEWs that had just propagated over the Atlantic Ocean from the African continent. Given the high resolution and expensive nature of such runs, the control and AEW-suppressed simulations were limited to three ensemble members each. The three ensemble members were generated by initializing the model on different dates (i.e., July 18, 19, and 20). Output from 1 August to 31 October (ASO) is used for the analysis, with July discarded as model spin-up.

Simulated TCs were identified with an objective detection algorithm Walsh (1997). The number of simulated TCs was compared with observations from the International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al., 2010) version 4. For the analysis period, 16 TCs were recorded in the observations within the part of the Atlantic included in the WRF domain. The ensemble mean TC number in the WRF control simulation was 16. This shows that the WRF control simulation has good skill in reproducing the observed TC number despite slight differences in monthly frequency (Figure 1b). Additionally, the observed TC intensities are reproduced well in the control simulation, though the frequency of weak TCs and major hurricanes is slightly underestimated and overestimated respectively (by ~8%, see Figure 3b).

3. Response of TCs to Easterly Wave Suppression

We first evaluate the response of Atlantic TCs to AEW suppression over the period considered. Despite filtering out AEWs, there were no considerable changes in the total number of Atlantic TCs produced during ASO between the control and experiment. The ensemble mean TC numbers were 16 and 16.7 in the control and AEW-suppressed simulations, respectively, representing a TC frequency change of +4% after filtering AEWs. This result agrees with the findings of Patricola et al. (2018) and provides robust evidence that TCs will generate by other mechanisms in the absence of AEWs, independent of whether convection is parameterized or resolved. AEW frequency may thus not be a reliable predictor of climatological TC frequency.

Although AEWs have little influence on Atlantic TC number during ASO, a breakdown of TC frequency for individual months reveals considerable differences between the two simulations. Figure 2a shows the monthly ensemble mean TC numbers. In August, the number of TCs generated in the AEW-suppressed experiment is more than twice that in the control. In contrast, fewer TCs generate in AEW-suppressed than in the control during September, which usually corresponds to the maximum AEW activity near the western coast of northern
The number of TCs in October is relatively similar between the control and AEW-suppressed. We also note that the intra-seasonal TC distribution is shifted, with the most TCs occurring in September for the control but in August for the AEW-suppressed experiment, suggesting that AEWs can influence the timing of TC genesis.

We next examine the response of TC genesis location to the AEW filtering. Figure 2b shows the ensemble mean probability density of TC genesis longitude for the two experiments. TC genesis in the eastern North Atlantic (i.e., east of about 40°W) is reduced in response to filtering out AEWs, which effectively removed all low-pressure disturbances with the potential to develop into TCs from the eastern lateral boundary condition. In the central North Atlantic (around 60°W), both simulations show a similar peak in probability density. As shown by Patricola et al. (2018), seedling disturbances may exist in the central Atlantic in the AEW-suppressed experiment, as the filtering procedure only removes AEWs that generate over northern Africa and not synoptic disturbances that develop over the Atlantic. This could partly explain the similar probability densities of TC genesis between the two simulations in the central Atlantic. Lastly, TC genesis increases in the western North Atlantic (west of 80°W) in AEW-suppressed compared to the control. The higher number of western Atlantic TC genesis can also be seen by comparing Figures 2c and 2d, which show the genesis locations (blue dots) of all TCs in the three ensemble members of the control (Figure 2c) and AEW-suppressed (Figure 2d) simulations. Moreover, the collection of TC tracks (gray lines) in the western Atlantic, especially within the Gulf of Mexico, is denser in the AEW-suppressed experiment than the control. Consequently, this could indicate an increase of landfalling TCs since most of such storms usually originate in the Gulf of Mexico (Kossin et al., 2010). The results presented in Figures 2a–2d indicate that AEWs can influence the location of Atlantic TC genesis.

Figure 2. Comparison of (a) ensemble mean tropical cyclone (TC) number and (b) probability density function of TC genesis longitudes in the control and African easterly wave (AEW)-suppressed simulations, and tracks and genesis locations (blue dots) of all tropical cyclones from the three ensemble members of the (c) control and (d) AEW-suppressed simulation from 1 August–31 October.

Africa (Thorncroft & Hodges, 2001). The number of TCs in October is relatively similar between the control and AEW-suppressed. We also note that the intra-seasonal TC distribution is shifted, with the most TCs occurring in September for the control but in August for the AEW-suppressed experiment, suggesting that AEWs can influence the timing of TC genesis.
To determine the response of TC intensity to the AEW filtering, we compared probability density distributions of the maximum wind speeds for each 6-hourly interval throughout the lifetimes of all TCs for the two simulations (Figure 3a). Both simulations show a peak in probability density for wind speeds between 20 and 25 m s\(^{-1}\), although the probability is much lower in AEW-suppressed. The probability density remains lower in AEW-suppressed for wind speeds up to 40 m s\(^{-1}\), after which it becomes higher than the control, increasing steadily until it reaches a second peak between 50 and 55 m s\(^{-1}\). Interestingly, the probability density reaches zero around 70 m s\(^{-1}\) for the AEW-suppressed experiment, although it remains above zero in the control. This is consistent across all ensemble members of the AEW-suppressed experiment (Figure S2 in Supporting Information S1) and could indicate a wind speed cap that can be attained by TCs generated by mechanisms other than AEWs. The lower probability of lower wind speeds in the AEW-suppressed experiments translates to a lower relative frequency of “Weak TCs” (defined as tropical storms and Category 1 and 2 hurricanes) as shown in Figure 3b. On the other hand, the relative frequency of “Major Hurricanes” (defined as Category 3 hurricanes and higher) is higher for AEW-suppressed compared to the control. Figures 3a and 3b indicate that the presence or lack of AEWs in the convection-permitting simulations has a substantial influence on TC intensity. This novel result was not possible to investigate in previous studies that used coarser resolution simulations, which often fail to simulate Category 4 and 5 hurricanes. For example, a 27 km resolution simulation with the same physics options used for the 3.5 km resolution (but with convection parameterization) revealed an absence of intense storms with wind speeds above 50 m s\(^{-1}\) (not shown).

We further examine the response of other TC characteristics, including TC lifetime and distance traveled, to AEW filtering. The control and AEW-suppressed simulations have a similar mean TC lifetime of about 7 days (white dot), but a median lifetime of 5 and 4 days, respectively (Figure 3c). However, the changes in the mean and median are statistically insignificant (Table S1 in Supporting Information S1). Additionally, the variation of TC lifetime in AEW-suppressed is higher with an interquartile range (length of the colored box) of 2.5–11 days compared to 3–8 days in the control. The variation of distances traveled by TCs is slightly higher in AEW-suppressed, however, both simulations exhibit similar mean values for the TC traveled distance of around 2,000 km (Figure 3d). The median distance traveled by TCs is shorter in the AEW-suppressed experiment (about 1,000 km) than in the control (about 1400 km). This means that more TCs in the AEW-suppressed experiment traveled shorter distances than in the control simulation. We attribute this to the higher TC genesis in the western Atlantic (Figure 2b), which limits TCs to travel shorter distances before making landfall and/or eventually dissipating. Nevertheless, the differences between the two experiments were found to be statistically insignificant.

4. Role of Large-Scale Atmospheric Conditions

We next examine large-scale atmospheric conditions associated with TC genesis and evolution in the two simulations (e.g., Emanuel & Nolan, 2004). Figure 4 presents the composite means of 850–200 hPa vertical wind shear, potential intensity (PI), 700 hPa water vapor mixing ratio, and 850 hPa absolute vorticity during the lifetimes of all TCs. Land areas are masked out to show only the fields over the ocean. Generally, weak vertical wind shear, and high mid tropospheric moisture, PI and vorticity favor TC development and intensification (Emanuel, 2003). Here, the aim is to present the differences in these well-documented environmental factors between the two simulations.

First, the spatial pattern of all the variables changes little between the two simulations (Figure S3 in Supporting Information S1). However, the AEW-suppressed experiment is associated with weaker wind shear than the control in many areas (Figure 4b). This is true over the Gulf of Mexico and between 10°N and 20°N from the...
eastern to central North Atlantic. The difference between the two simulations is significant in a few areas across the domain (areas within green contours). Unlike the vertical shear, PI is slightly higher over most areas in the control simulation, especially in the southern part of the Gulf of Mexico (Figure 4d). However, PI is higher over the northern part of the Gulf of Mexico adjacent to the Florida coast when AEWs are suppressed. Considering the range of PI values in the two simulations, these differences, though statistically significant in some areas, are relatively weak (~0.5 m/s). On the other hand, the suppressed experiment is associated with higher mixing ratio in most areas especially in the Gulf of Mexico and southeastern North Atlantic (Figure 4f). Lastly, the vorticity is generally higher in the AEW-suppressed simulation than the control over most of the Gulf of Mexico (Figure 4h). There are, however, a few spots in the control simulation where the vorticity is higher, which may be due to TCs that were very intense (as shown in Figure 3a). It should be noted that these results are for the entire ASO. A breakdown into monthly composites revealed that the seasonal variation of vertical wind shear and vorticity are strongly connected to the timing of TCs (Figure S4–S7 in Supporting Information S1).

The results shown in Figure 4 and Figure S3 in Supporting Information S1 provide useful insights into Atlantic TC activity. First, the lack of changes in the spatial patterns of atmospheric fields between the control and AEW-suppressed gives further evidence to support previous studies that have suggested that the regional environment mainly controls the climatological TC frequency (Emanuel, 2022). Second, except for the PI, TCs that formed without AEWs required higher favorable conditions. Since PI estimation considers several environmental parameters, it is necessary to further investigate, in future studies, the contribution of the individual components. We note that higher environmental favorability in the absence of AEWs is not an implication that TC genesis does not require a seed, as there may be other TC seeds or generation mechanisms in the Atlantic. We, however, did not investigate the occurrence of such mechanisms in this work. Therefore, our results suggest that the type of seedling disturbance that generates TCs could determine the extent of environmental favorability required to generate and sustain TCs.

5. Conclusions

The physical controls on TC frequency remains an unsolved problem, with one possible contributor from variability and change in TC “seeds.” However, previous studies indicate a lack of consensus regarding the role of TC seeds in determining TC frequency. Some major challenges in addressing this problem include difficulty in determining causality in observations and uncertainties associated with the often-used convective parameterization in climate model simulations. Here, we investigated the relationship between North Atlantic TCs and their typical seed, AEWs, on the seasonal timescale using convection-permitting regional climate model simulations designed to isolate the role of AEWs as clearly as possible. In particular, the eastern lateral
boundary of the model domain is located near the western coast of northern Africa, an entry region for AEWs into the Atlantic. AEWs are thus prescribed or removed from the eastern lateral boundary of the model domain, as in Patricola et al. (2018). Compared with previous investigations, an important novelty here is the use of convection-permitting, high-resolution simulations, which allows us to simulate and evaluate intense TCs and to reduce uncertainties associated with convective parameterization, which can impact simulated TCs, AEWs, and the large-scale climate.

We found that suppressing AEWs did not change the seasonal frequency of North Atlantic TCs, in agreement with previous research (i.e., Patricola et al., 2018). This provides robust evidence that TCs will generate by other mechanisms in the absence of AEWs, independent of whether convection is parameterized or resolved. Therefore, AEWs may not be a reliable predictor of the climatological North Atlantic TC frequency or the changes in future TC activity based on current AEW projections. However, we did find that AEWs can influence several TC characteristics. In particular, suppressing AEWs caused the distribution of TC intensity to shift toward stronger TCs. In addition, AEWs influenced the location of TC genesis, with our simulations revealing an increase (decrease) of genesis events in the western (eastern) North Atlantic after filtering AEWs. This could explain the higher number of short-lived TCs in the AEW-suppressed experiment, since TCs in the western North Atlantic are closer to the eastern coast of North America and could potentially make landfall quicker. Additionally, suppressing AEWs led to a substantial increase and decrease in the TC number in August and September, respectively, notably shifting the peak genesis frequency from the latter to the former. AEWs could thus influence the timing of TCs in the North Atlantic.

We then investigated the differences in the large-scale environmental favorability throughout the lifetime of all TCs, when AEWs were prescribed or suppressed. For this, we examined composites of atmospheric fields that favor TC genesis and maintenance. Generally, the atmospheric conditions associated with TCs generated in the AEW-suppressed experiment were enhanced toward greater favorability. That could explain further the higher number of stronger storms in the AEW-suppressed experiment. This result is important, as it suggests that the large-scale environment could be the main determining factor of the seasonal TC frequency, as suggested by previous studies (e.g., Emanuel, 2022).

Our findings do not suggest that AEWs are unimportant for TCs in general. In their absence, however, the lack of change in the seasonal TC frequency is a strong indication that TCs may generate if the large-scale environment is favorable enough. It could also mean that there may be other seed generation mechanisms that may strongly depend on the large-scale atmospheric environment to trigger TC genesis. Our results provide evidence that variability in AEWs could drive variability in one or more large-scale environmental fields. Therefore, investigating the interplay between the large-scale environment and TC seeds in future studies could further improve our understanding of tropical cyclogenesis. Lastly, 2020 was a very active season for both TCs and AEWs. Therefore, it would be necessary to investigate in future studies whether our experiment will lead to similar results in a mild TC season in which environmental favorability is moderate.

Data Availability Statement

WRF model code is available at https://www2.mmm.ucar.edu/wrf/users/download/get_sources.html. The ERA5 data used to provide boundary conditions is available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview. TC tracks and atmospheric composites output from climate model simulations are available at https://doi.org/10.5281/zenodo.7150386. IBTrACS data is available at https://www.nci.noaa.gov/products/international-best-track-archive. The TC tracking code is located on GitHub, https://github.com/mehtut/.

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