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THE INFLUENCE OF AFRICAN EASTERLY WAVES ON ATLANTIC TROPICAL CYCLONE TRACKS AND LANDFALL IN LARGE ENSEMBLES

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1. INTRODUCTION

African Easterly Waves (AEWs) often serve as precursors for Atlantic tropical cyclone (TC) development, with 60-80% of major hurricanes observed to originate from AEWs (Landsea, 1993; Russell et al., 2017). However, some climate model simulations indicate that AEWs have no significant effect on annual Atlantic TC frequency (Patricola et al., 2018; Danso et al., 2022). Furthermore, small ensembles of simulations suggest that AEWs may influence TC genesis location and the environmental conditions favorable for TCs (Danso et al., 2022; Bercos-Hickey and Patricola, 2023), suggesting that AEWs may have an impact on the spatial distribution and landfall of Atlantic TCs. Here, we investigated the influence of AEWs on the spatial distribution of Atlantic TC tracks and landfall using 50-member ensembles of TC-permitting regional model simulations. The control simulations are seasonal hindcasts in which AEWs are prescribed through the eastern lateral boundary condition using reanalysis. In the experiments, we suppressed AEWs by applying a 2-10 day filter to the eastern lateral boundary condition. We found significant increases in annual Atlantic TC frequency, along with changes in the spatial distribution of TC genesis and tracks due to the AEW suppression. In addition, we will evaluate how suppressing AEWs influences large-scale environmental favorability for TCs and TC steering flow. Our analysis aims to uncover potential shifts in the spatial distribution of TC genesis to understand changes in environments that TCs will experience in the absence of AEWs, which will provide insight into changes in TC tracks and landfall. By uncovering the connections between TC precursors and the likelihood of TC landfall and impacts, this research can provide Atlantic coastal and island communities with useful information to prepare for the risk of TCs.

2. BRIEF LITERATURE REVIEW

Tropical cyclone (TC) genesis requires an initial low pressure disturbance. North Atlantic TCs initiate from a variety of physical mechanisms, with the majority of Atlantic TCs originating from African Easterly Waves (AEWs). AEWs are characterized by a trough between 800 and 650 hPa that generally form upstream from the African Easterly Jet and grow as a result of baroclinic instability that occurs between the Saharan Desert and the Sahel due to sharp moisture and temperature gradients combined with abundant moist convection (Burpee, 1972; Thorncroft et al., 2008). AEWs then propagate, typically with a periodicity of around 2-10 days, across Africa and exit the west African coast into the North Atlantic, often serving as initial “seedlings” for TC development. Potential TC precursor disturbances that then move into regions of warm sea surface temperatures, weak vertical wind shear, sharp temperature lapse rates, and moist mid-tropospheric profiles can experience TC genesis (Kaplan and DeMaria 2003), intensifying and possibly becoming major hurricanes.

Extensive research has been done investigating the relationship between Atlantic TCs and AEWs on interannual timescales. Patricola et al. (2018) concluded that Atlantic TC annual frequency is unaffected by AEWs based on climate model simulations. A ten-member, 27 km horizontal resolution ensemble was used to simulate the active 2005 Atlantic TC season. In the control, AEWs were prescribed in the eastern lateral boundary conditions. In the experiment, AEWs were suppressed in the eastern lateral boundary conditions using a Lanczos filter that removed the 2-10 day variability of variables consistent with AEW signatures. They found that, in the absence of AEWs, other atmospheric mechanisms would initiate TCs, indicating that AEWs do not influence basin-wide Atlantic TC variability on seasonal time scales.

These findings were supported by Danso et al. (2022), which used a 3-member ensemble of convection-permitting (3.5 km resolution) regional climate model simulations to simulate the peak TC months (Aug-Oct) of the 2020 Atlantic TC season, following similar methodology as Patricola et al. (2018). The convection-permitting simulations produced similar results to Patricola et al. (2018) in that, when AEWs were suppressed along the lateral boundary conditions, other synoptic and mesoscale features were present to serve as low-pressure disturbances for TC genesis. AEW suppression also led to an increase in TC intensity, indicating that large-scale conditions in the North Atlantic became increasingly favorable for

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the genesis and intensification of TCs in the AEW-suppressed simulations compared to the control. Interestingly, deviations in the spatial distribution of TC genesis location were present between the simulations, indicating that the suppression of AEWs may impact locations in which TCs undergo genesis. This could have implications on the overall track and landfall of TCs, as shifts in intra-basin variability could lead to TCs being influenced by the steering flow depending on their genesis location, resulting in altered TC tracks and changes in landfall (Kossin et al. 2010).

Bercos-Hickey and Patricola (2023) further investigated the AEW–TC relationship by suppressing north-track AEWs (north of the African easterly jet; AEJ), south-track AEWs (south of the AEJ), as well as both south and north-track AEWs using a similar regional modeling methodology as Patricola et al. (2018) and Danso et al. (2022). They found that, suppressing south-track AEWs and both south-track and north-track AEWs produced a statistically significant increase in Atlantic TC frequency, supported by increases in mid-tropospheric moisture and decreases in vertical wind shear. Potential mechanisms for TC genesis in the absence of AEWs were also discussed, in which increased convective activity off the West African coast was associated with a potential increase in the number of precursors needed for TC genesis.

Although the previous studies provided substantial evidence for the influence of AEWs on Atlantic TC frequency, the ensemble sizes were too limited to evaluate the significance of any responses in the location of TC genesis, tracks, and landfall. This leads us to pose the question, how do AEWs influence Atlantic TC tracks and the likelihood of TC landfall on the seasonal-climate timescale? Our study attempts to investigate how changes in TC steering flow and TC environment in the absence of AEWs can impact Atlantic TC tracks. We performed a large-ensemble of simulations to quantify the statistical significance of responses in the spatial patterns of TCs.

3. REGIONAL MODEL SIMULATIONS

We performed regional model simulations using the Weather Research and Forecasting (WRF) Model version 4.3.3 (Skamarock et al., 2008). The initial and lateral boundary conditions, along with prescribed SSTs, were based on the ECMWF Reanalysis v5 (ERA5; Hersbach et al., 2020). WRF was configured with TC-permitting 27 km horizontal resolution and 48 vertical levels over a domain that includes the Atlantic TC basin and most of North America. The domain was designed so that the eastern lateral boundary was located along the West African coast (5°S-55°N, 135°W-15°W). The domain allows for the model to simulate the semi-permanent Bermuda High, which plays a role in the steering flow for North Atlantic TCs. The simulations were performed over a period that includes the 2010 Atlantic hurricane season, from June 1 through November 30. We performed a 50-member ensemble, to generate sufficient data to investigate any spatial shifts in TC tracks and landfall. Each ensemble member was initialized every 6 hours starting from May 1 through May 14, with data before June 1 disregarded for model spin up. Model output was saved 3-hourly, allowing enough data to analyze TC tracks, environmental favorability, and steering flow.

The following parameterizations were used: Purdue-Lin microphysics (Lin et al. 1983), Kain-Fritsch cumulus scheme (Kain and Fritsch 1990, 1993), RRTMG shortwave and longwave radiation (Lacono et al., 2008), YSU Boundary layer (Hong et al., 2006), Revised MM5 Monin-Obukhov surface layer (Monin and Obukhov, 1954), and the Unified Noah land-surface model (Niu et al., 2011). These schemes were chosen for their ability to adequately simulate TCs at 27 km horizontal resolution. We performed tests of two convective parameterizations to determine which scheme more closely represented the observed number of 19 TCs. The simulation using the Simplified Arakawa-Schubert scheme produced 4 TCs, whereas the simulation using the Kain-Fritsch scheme produced 22 TCs. We decided to use the Kain-Fritsch scheme, as it was much closer to representing the observed number of TCs.

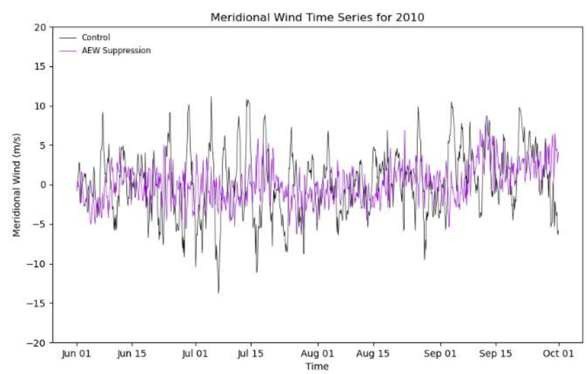

Figure 1. Time series of 3-hourly 700 hPa meridional wind at 15°N, 15°W from the control (black) and AEW suppression (purple) simulations.

The control simulations are seasonal hindcasts of the 2010 TC season, a relatively active Atlantic TC season, with AEWs prescribed through the eastern lateral boundary condition. In addition, we performed "AEW-suppressed" experiments, in which a 2-10 day Lanczos filter was applied along the eastern lateral boundary edge from 5°S–30°N to remove both kinematic and thermodynamic signatures of AEWs at all vertical levels, similar to the methodology of Patricola et al. (2018), Danso et al. (2022), and Bercos-Hickey and Patricola (2023). Figure 1 shows a time series of the 700 hPa meridional wind, one of the variables that illustrates AEW signatures, from the lateral boundary condition in the region where AEWs occur. The control simulation in black contains variations in the 700 hPa meridional wind that are consistent with AEWs, as expected since they were prescribed through reanalysis. The AEW-suppression experiment in purple shows reduced amplitude in the 2-10 day variability, verifying that the filter was effective at suppressing AEWs. This restricts AEWs from propagating into the Atlantic Ocean, allowing for TCs to form only from non-AEW origins. This also allows us to investigate large-scale environmental conditions over the Atlantic Ocean that may be affected by the suppression of AEWs, as indicated by Bercos-Hickey and Patricola (2023).

We tracked simulated TCs using a revised TC tracking algorithm implemented by Bercos-Hickey and Patricola (2023) and based on criteria from Walsh (1997) including: a closed minimum in sea level pressure, a minimum 10-m wind speed of 17.5 m/s, a warm core, and a minimum 850 hPa vorticity threshold over the TC center. In addition, TCs that formed over land and spent over 50% of their lifetime over land were discarded. TCs that formed over the Pacific Ocean were also discarded, along with any TC tracks over the Pacific. Each TC was characterized as either a landfalling or non-landfalling TC, to compare the changes between both the landfalling and non-landfalling TCs between the control and AEW suppressed simulations. The tracking algorithm produced 3-hourly TC track coordinates and timestamps, along with intensity parameters including minimum sea level pressure, maximum 10-m windspeed, and relative vorticity at the TC center.

4. TC FREQUENCY

The number of Atlantic total TCs, landfalling TCs, and non-landfalling TCs significantly increased in response to AEW suppression (Figure 2). Compared to the control simulation the AEW suppressed simulation produced an ensemble-mean increase of +7.5 total TCs (26.0%), +2.3 landfalling TCs (19.3%), and +5.2 non-landfalling TCs (30.6%), which were all statistically significant ($p<0.05$). These results indicate that in the absence of AEWs, other low pressure disturbances will serve as TC precursors, consistent with Bercos-Hickey and Patricola (2023), Patricola et al. (2018), and Danso et al. (2022). This also reaffirms the notion that favorable environmental conditions are primarily responsible for TC frequency (Emanuel, 2022).

The increase in Atlantic TC frequency due to AEW suppression was not uniform throughout the hurricane season. The difference in ensemble-mean Atlantic TC frequency was relatively small between the control and AEW suppressed simulations, with the exception of July. Interestingly, there was a stark increase in TC frequency in July in the AEW suppressed simulation compared to the control (Figure 3).

This indicates that the suppression of AEWs could produce increased environmental favorability earlier in the Atlantic TC season that is supporting enhanced TC genesis. On the other hand, this could also suggest a higher frequency of other TC precursors during July in response to the suppression of AEWs. Both of these could also be true. We plan to investigate the large-scale environmental favorability for TCs and the frequency of TC precursors to better understand how the suppression of AEWs produced significant changes in Atlantic TC frequency and the seasonal cycle of TCs.

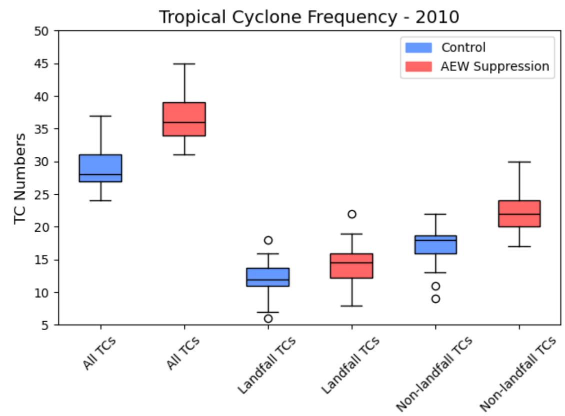

Figure 2. Boxplots of all Atlantic TCs, landfalling Atlantic TCs, and non-landfalling Atlantic TCs from the 50-member ensemble of control and AEW suppressed simulations. Black lines represent the median.

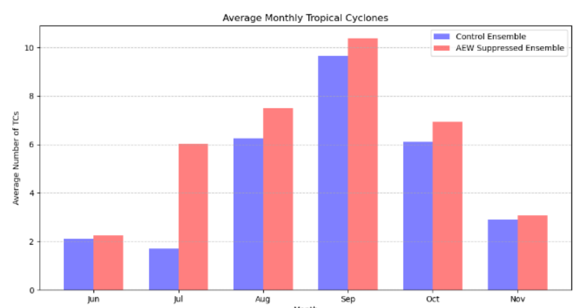

Figure 3. Ensemble-averaged monthly Atlantic TC frequency from the 50-member ensemble of control and AEW suppressed simulations.

5. TC TRACK AND LANDFALL

AEW suppression produced substantial responses in the location of TC tracks, illustrated by the TC track density (Figure 4a). This is unsurprising given the response in basin-wide TC frequency together with TCs forming closer to land and potentially being subjected to different steering flow, as discussed in the next section.

We found significantly different probabilities of TC occurrence in response to AEW suppression across multiple regions in the Atlantic basin, including evidence of TCs preferentially targeting specific regions as they make landfall (Figure 4b). These probabilities were calculated using a Bayesian geospatial analysis following the same statistical methodology used by Rhoades et al. (2021), which creates probability distributions of TC counts. The Carolinas, southeastern Caribbean Sea, and the northeastern United States coast have higher probabilities of TCs when AEWs were suppressed, whereas there are increased probabilities of TCs over the West African coast, Gulf of Mexico, and the southwestern Caribbean Sea when AEWs are permitted. This indicates an increased risk of TC landfall over the Carolinas and northeastern U.S. coast when AEWs are suppressed. The enhanced landfall risk is especially pronounced close to the Carolinas, where the difference in probability of one TC occurrence per year between the AEW suppressed and control ensemble exceeds 35% (Figure 4b). These results could indicate that the absence or presence of AEWs modulates the risk of landfalling TCs for different Atlantic coastal regions. We highlight that the 50-member ensemble allows us to capture statistically significant responses in the TC tracks between the control and AEW suppressed simulations.

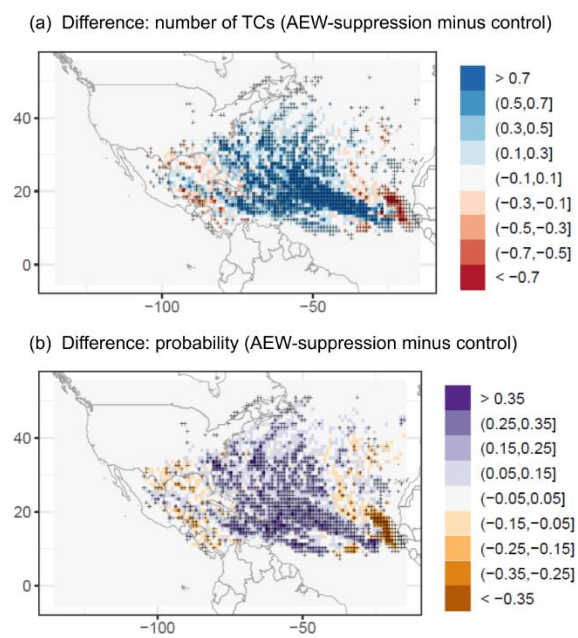

Figure 4. Atlantic TC track density showing the (a) average number of TC occurrences per year and (b) probability of experiencing at least one TC per year from the 50-member ensemble of the AEW suppressed minus control simulations. Hatched grid points indicate that the 95% credible interval does not include 0.

6. TC GENESIS LOCATION

Significant changes were also found in the spatial distribution response of TC genesis across the Atlantic basin between the control and AEW suppressed simulations. We found greater TC genesis closer to the West African coast (22-25°W) in the control simulation, indicating that TCs are forming from AEWs that were prescribed from the lateral boundary conditions, along with a decrease in TC genesis close to the West African coast in the AEW suppressed simulation compared to the control simulation (Figure 5). These responses physically make sense, as we would expect to find reduced TC genesis close to the West African coast in the AEW suppressed simulation due to the removal of the main TC precursor in this region.

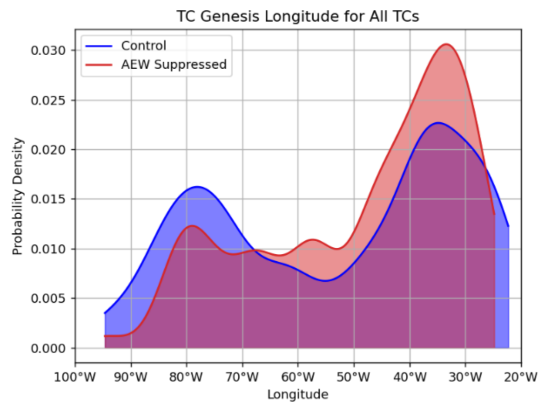

Figure 5. Kernel density distribution of TC genesis across longitudes from the 50-member ensemble of control (blue) and AEW suppressed (red) simulations.

A large response in TC genesis was produced across the Atlantic basin in the AEW suppressed simulation, with a large peak of maximum TC genesis occurring at 33°W and a small secondary peak at 79°W. The control simulation produced two peaks in TC genesis at 35°W and 78°W. We speculate that the increased TC genesis between 25°W and 50°W in response to AEW suppression could be explained by enhanced convection resulting in wave-breaking in the Intertropical Convergence Zone (ITCZ) (Agee, 1972) in the absence of AEWs. The first peak in the control simulation could be explained by AEWs (prescribed from the lateral boundary condition) encountering the Atlantic Ocean close to the African coast. The second peak can be explained by AEWs propagating across the Atlantic basin into the Caribbean Sea and encountering favorable environmental conditions for TC genesis, for example, climatologically warmer sea surface temperatures.

The latitude of Atlantic TC genesis also responded to AEW suppression (Figure 6). The control simulation produced two main peaks in TC genesis, likely associated with TC genesis from north-track AEWs (17.5°N) and south-track AEWs (13°N), as expected (Chen et al. 2008; Bercos-Hickey and Patricola, 2023). Interestingly, the AEW suppressed simulation produced enhanced TC genesis at 16°N. This could be associated with the latitude at which TC genesis mechanisms in the absence of AEWs would be located, which will be analyzed further in the future to understand what is causing TCs to form in the absence of AEWs.

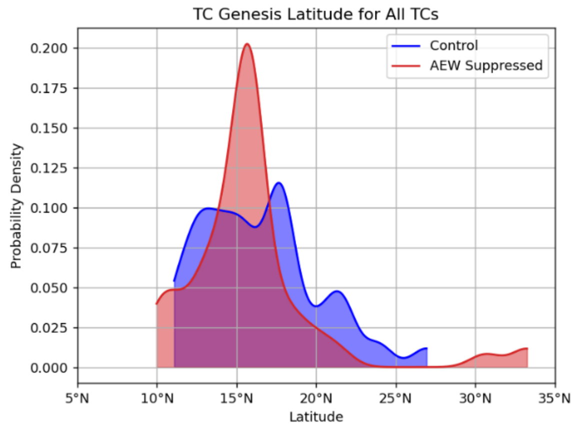

Figure 6. Similar to Figure 5, but for TC genesis across latitudes.

7. SUMMARY

Regional model simulations produced a substantially more active 2010 Atlantic TC season in response to AEW suppression compared to the control, with statistically significant increases in the number of total TCs, landfalling TCs, and non-landfalling TCs. In addition, we found changes in the spatial distribution of Atlantic TC genesis and TC tracks, suggesting that the lack of AEWs plays a role in the location of TC genesis in the Atlantic basin both close to the West African coast and downstream. Our results indicate that specific regions across North America could be more susceptible to landfalling TCs in the absence of AEWs.

Our simulations also provide evidence that AEWs may influence the formation of non-AEW TC precursors and/or the large-scale environmental favorability for TCs on seasonal timescales. This suggests that the suppression of AEWs could result in more favorable environments for TC genesis and intensification. This also indicates that TC genesis may be more reliant on the large-scale environment than the frequency of the typical TC precursor.

For future work, we plan to simulate four additional Atlantic TC seasons, characterized by different TC activity levels, as well as different numbers of TCs spawned from AEWs, landfalling TCs, and landfalling TCs spawned from AEWs. Further work is also planned to identify TC genesis mechanisms in the absence of AEWs and to investigate the influence of AEW suppression on the large-scale environmental conditions and steering flow.

Our results thus far provide evidence that the type of TC precursor may be an important indicator in predicting the frequency and spatial distribution of TC tracks and genesis on seasonal and interannual timescales.

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