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The Response of Atlantic Tropical Cyclones to Suppression of African Easterly Waves

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Key Points:
- African easterly wave suppression produced no change in seasonal Atlantic tropical cyclone number in regional model simulations
- Atlantic TCs are not limited by AEWs on season-climate time scales and will generate by other mechanisms in the absence of AEWs
- AEWs are not a reliable predictor of variability and change in basin-wide Atlantic TC frequency but may be important regionally

Supporting Information:
- Supporting Information S1

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The Response of Atlantic Tropical Cyclones to Suppression of African Easterly Waves

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Abstract Atlantic tropical cyclone (TC) genesis is strongly linked with African easterly waves (AEWs) on the synoptic time scale. However, the TC-AEW relationship is unclear on interannual to climate time scales, and it is unknown whether AEWs are necessary to maintain climatological TC frequency, that is, whether TCs are limited by AEWs. We investigated the impact of AEW suppression on seasonal Atlantic TC activity using a 10-member ensemble of regional climate model simulations in which AEWs were either prescribed or removed through the lateral boundary condition. The climate model experiments produced no significant change in seasonal Atlantic TC number, indicating that AEWs are not necessary to maintain climatological basin-wide TC frequency even though TCs readily originate from these types of disturbances. This suggests that the specific type of "seedling" disturbance is unimportant for determining basin-wide seasonal Atlantic TC number and that in the absence of AEWs, TCs will generate by other mechanisms. The results imply that changes in the presence of AEWs may not be reliable predictors of seasonal variability and future change in Atlantic TC frequency.

1. Introduction

Tropical cyclone (TC) genesis requires several conditions, including warm near-surface ocean temperature, a moist mid-troposphere, weak vertical wind shear, and a "seedling" low-pressure disturbance (e.g., Avila, 1991; Emanuel, 1988; Frank & Ritchie, 2001; Gray, 1968; Gray, 1979; Landsea, 1993; Lin et al., 2013; Price, 1981; Wong & Chan, 2004; and many others). A common type of low-pressure disturbance in the tropical Atlantic basin is the African easterly wave (AEW). AEWs are characterized by a trough of low pressure between 850 and 600 hPa and can generate from baroclinic and barotropic instability associated with the African easterly jet (AEJ) (Burpee, 1972), convection within the intertropical convergence zone (ITCZ) (Hsieh & Cook, 2005), and localized forcing associated with latent heating upstream of AEW development (Diaz & Aiyyer, 2013; Diaz & Aiyyer, 2015; Thorncroft et al., 2008). AEWs typically occur between May and October and peak with the Atlantic hurricane season in August and September. They generate over the Sahel with a periodicity of 2–10 days and propagate westward over the Atlantic Ocean with two preferred tracks, one north and one south of the AEJ (Burpee, 1974; Carlson, 1969; Chen, Wang, & Clark, 2008; Diedhiou et al., 1998; Reed et al., 1977).

It is well understood that Atlantic TCs and AEWs are linked on the synoptic time scale, with about 85% of observed major Atlantic hurricanes and 60% of minor Atlantic hurricanes originating from AEWs (e.g., Dunn, 1940; Frank, 1970; Landsea, 1993; Russell et al., 2017). However, the relationship between AEW variability and Atlantic TC activity is unclear on the interannual time scale and is highly dependent on reanalysis product, time period considered, and AEW definition (e.g., tracking of vorticity features and 2–10 day band-pass filtered meridional wind at 600 hPa). For example, AEWs defined via tracking and Atlantic TC activity are positively correlated during the 1985–1998 period of the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (Thorncroft & Hodges, 2001) but are not correlated during 1952–2002 in the same product (Hopsch et al., 2007). On the other hand, Hopsch et al. (2007) found that the 2–6 day filtered meridional wind is significantly positively correlated with Atlantic TC activity on the interannual time scale. In addition, AEW frequency and Atlantic TC activity are significantly positively correlated in the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis but not in the NCEP Climate Forecast System Reanalysis (CFSR), whereas the relationship in ERA-Interim depends on AEW lifetime (Belanger, 2012). When AEW activity is estimated using eddy kinetic energy

(EKE), a correlation with Atlantic TC genesis is apparent in the lower troposphere, especially during weak to moderate EKE years, but is weak in the midtroposphere (Russell et al., 2017). The lack of a clear interannual relationship between AEWs and TCs may be in part because the Atlantic basin receives an abundance of AEWs each hurricane season, with only about 15–20% of AEWs developing into TCs (Agudelo et al., 2011; Dunkerton et al., 2009; Frank, 1970; Satoh et al., 2013).

AEW and Atlantic TC variability have also been linked on the interannual time scale through their connections with the West African monsoon and Atlantic sea surface temperature (SST) variability. The Atlantic hurricane season tends to be more active, and AEWs tend to be stronger, with a longer and more active wave season, during years when Sahelian precipitation of the West African monsoon is more intense (Grist, 2002; Landsea & Gray, 1992). Increases in AEW activity, Atlantic TC activity, and West African monsoon precipitation have all been connected with warm conditions in the northern Atlantic associated with the positive phases of the Atlantic Multidecadal Oscillation (AMO) and the Atlantic Meridional Mode (AMM) (Druyan & Fulakeza, 2011; Lamb, 1978; Lamb & Peppler, 1992; Martin & Thorncroft, 2014; Patricola et al., 2014; Rowell et al., 1995; Vizy & Cook, 2002; Vimont & Kossin, 2007; Ward, 1998). The observed covariability of these factors is unquestionable. However, causality within the AEW and TC relationship is difficult to unravel. Is it the case that Atlantic SST drives AEW variability, which in turn (with other factors including SST) drives interannual Atlantic TC variability? Or does Atlantic SST drive both AEW and TC variability, causing the latter two to be correlated?

Aside from AEWs, there are several other mechanisms of tropical cyclogenesis globally including wave breaking of the ITCZ, self-aggregation of convection, and disturbances from the Asian monsoon trough. Specifically, wavelike disturbances associated with the ITCZ, and distinct from AEWs, have been observed to provide the seeds for TCs in the Atlantic and eastern and western North Pacific (Agee, 1972; Cao et al., 2013; Kieu & Zhang, 2008; Thompson & Miller, 1976). Tropical cyclogenesis due to ITCZ breakdown has also been simulated in climate models (Yokota et al., 2012, 2015). Furthermore, TC-like phenomena can develop via self-aggregation of convection in rotating radiative-convective equilibrium simulations (e.g., Bretherton et al., 2005; Held & Zhao, 2008; Khairoutdinov & Emanuel, 2013; Nolan et al., 2007; Reed & Chavas, 2015; Wing et al., 2016; Zhou et al., 2014). Finally, disturbances from the Asian monsoon trough are a large contributor to tropical cyclogenesis in the western North Pacific, where only 10–25% of typhoons form from tropical waves (Chen et al., 2004; Chen, Wang, Yen, et al., 2008; Frank, 1987; Lander, 1994; Ritchie, 1995; Yoshida & Ishikawa, 2013).

The lack of a clear connection between AEWs and Atlantic TC activity on the interannual time scale, together with the existence of several alternative TC genesis mechanisms, leads us to pose the following question: *Are AEWs necessary to maintain climatological TC frequency? That is, are Atlantic TCs limited by AEWs?* It is important to understand how AEWs and Atlantic TCs are connected on interannual to climate time scales because it is unclear whether changes in AEWs are a source of uncertainty in seasonal predictions and future projections of TC activity. It is crucial to establish this fundamental physical understanding, as climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) project an increase in AEW strength north of the AEJ (Skinner & Diffenbaugh, 2014). In addition, global models suffer from strong biases in AEW representation (Martin & Thorncroft, 2015), which have been linked with simulated TC representation (Daloz et al., 2012). Here we investigated the impact of AEW suppression on seasonal Atlantic TC activity using regional climate model simulations in which AEWs were either prescribed or removed through the lateral boundary conditions. As described in the next section, the experimental setup is the first and perhaps best attempt to clearly delineate causality between AEWs and TCs. The results described in section 3 challenge the way we think about variability and change in TC activity by suggesting that Atlantic TCs are not limited by AEWs and pave the way for future work on this topic.

2. Regional Climate Model Simulations

We conducted regional climate model simulations with the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) configured with a TC-permitting horizontal resolution of 27 km. The regional model is particularly well suited to address this problem, because it allows us to configure a model domain (Figure 1a) that covers the Atlantic basin only, thereby including TC development regions and excluding the AEW genesis region over the Sahel. By placing the eastern domain edge just off the west coast of northern Africa, we can control the presence of AEWs entering the domain through the lateral boundary conditions (LBCs). The

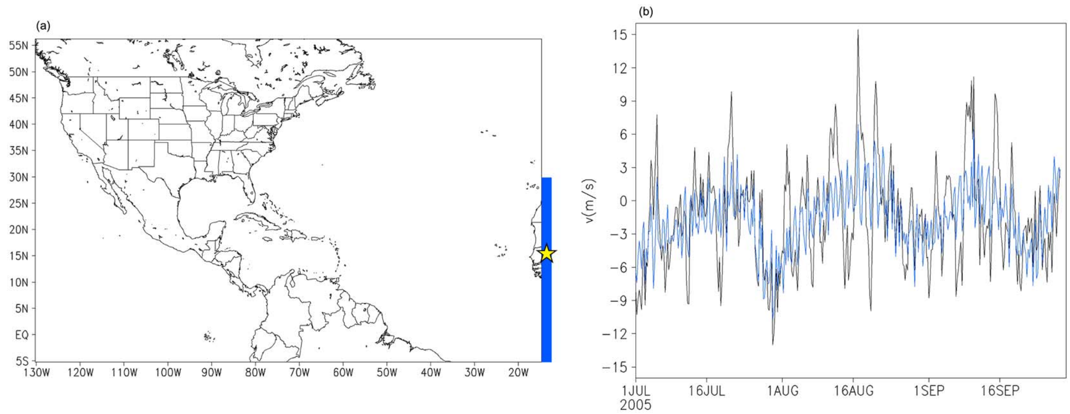

Figure 1. (a) The regional climate model domain. The blue rectangle denotes the latitude over which a 2–10 day Lanczos filter was applied to the eastern LBC in the AEW suppressed experiment. (b) The time series of 6-hourly meridional wind (m s^{-1}) at 15°N, 15°W (denoted by star in Figure 1a) and 700 hPa prescribed in the eastern LBC for the (black) control simulation and (blue) AEW suppressed experiment.

longitude of the eastern LBC coincides with the observed peak of AEW genesis (Thorncroft & Hodges, 2001). The control simulation allows AEWs to enter the model domain by prescribing 6-hourly NCEP-CFSR (Saha et al., 2010) on the LBCs, whereas the experiment suppresses AEWs by forcing the LBCs with the same data, except with a 2–10 day Lanczos filter applied over 5°S–30°N on the eastern LBC. The filter removes the 2–10 day time scale from all variables and all levels in the vertical. The effect of retaining and filtering AEWs can be seen by comparing the two time series of meridional wind at 700 hPa, 15°N, and 15°W (Figure 1b).

In addition, we examined the impact of the LBC filtering within the regional model domain from the eastern lateral edge (near 15°W), westward to 50°W. The standard deviation of the July–October 10-day high-pass filtered meridional wind at 700 hPa and 15°N changes little from 15°W to 50°W in the control simulations, whereas the AEW suppressed simulations produce a standard deviation that is reduced by more than 50% from 15°W to 30°W (relative to the control simulation) and is close to the control values from 35°W to 50°W (Figure S1 in the supporting information). This indicates that while AEWs are largely suppressed within the domain in the experiment, there is some amount of variability on approximately the diurnal time scale (as would be expected), which may provide potential seedling disturbances for TCs. As discussed in section 4, additional studies to investigate this further would be valuable. Despite the 2–10 day filtering applied to the tropical eastern LBC, the model generates synoptic variability of a similar magnitude compared with the control within 20° of longitude downstream from the lateral edge. This is expected, as there is no nudging applied within the regional model domain. Therefore, we emphasize that the AEW suppressed experiment specifically evaluates the impact of suppression of tropical easterly waves that generate over Africa and permits diurnal variability, as well as synoptic variability, well downstream from the AEW genesis region.

For both the control simulation and the AEW-suppressed experiment, SST was prescribed from the daily NOAA Optimum Interpolation (OI) V2 SST. The simulations were performed for the extremely active 2005 hurricane season, when AEWs contributed directly or indirectly to about 75% of Atlantic TC genesis (Beven et al., 2008). A 10-member ensemble of both the control and AEW-suppressed experiment were generated by initialing the model with different initial conditions corresponding to 15, 18, 22, 25, and 28 April and 1, 4, 8, 12, and 15 May. Output up to 1 June 2005 was discarded for model spin-up, leaving 1 June to 1 December 2005 for analysis.

Simulated TCs were identified using the tracking algorithm of Walsh (1997), which includes criteria for a minimum 10 m wind speed of 17.5 m/s, a closed minimum in surface pressure, a minimum 850 hPa vorticity threshold over a 5° by 5° region over the TC center, and a warm core. In addition, we applied a duration threshold of at least 2 days and included only TCs that originated south of 30°N.

Similar configurations of the WRF model at 27 km resolution have demonstrated ability to represent the climatology and interannual variability of Atlantic TC activity, as well as the response of TCs and the

Table 1
Measures of Atlantic TC Activity From the Ensemble Average of the Control and AEW Suppressed Simulations

	Control	AEW suppressed	% change	*p* value
Number of TCs/season	19.5	20.2	+4%	0.64
Number of TC days/season	105	117	+11%	0.17
ACE (10^4 kt^2)	168	192	+15%	0.07

Note. This includes the percent change relative to the control simulation and the *p* value corresponding to a *t* test for difference of the means.

tropical circulation to modes of climate variability including the AMM and El Niño–Southern Oscillation (Patricola et al., 2014, 2016, 2017). In addition, WRF hindcasts of 1980–2000 that were forced with observed SST and lateral boundary conditions (Patricola et al., 2014) reproduced the magnitude of observed interannual correlations between AEW activity and number of Atlantic TCs well. Specifically, the interannual correlation between observed Atlantic TC number (according to the Revised Hurricane Database; HURDAT2; Landsea & Franklin, 2013) and a metric of June–October averaged AEW activity from the NCEP CFSR (standard deviation of 2–10 day meridional wind at 850 hPa, averaged 15°W–10°W and 6°N–18°N) is $R = 0.41$. The correlation of the same quantities, but both from the WRF model, is $R = 0.37$. Similarly, the correlation is $R = 0.38$ in observations and $R = 0.48$ in the model for wind instead at 700 hPa.

3. Results

Compared with the simulations in which AEWs were prescribed through the eastern LBC, the simulations in which AEWs were suppressed produced no significant changes (5% level) in the ensemble-averaged seasonal Atlantic TC number, number of TC days, and accumulated cyclone energy (ACE), which is defined as the sum of the squares of the 6-hourly maximum TC wind speed throughout the life of a TC and for all TCs in a season (Bell et al., 2000) (Table 1). Figure S2 shows a large overlap in the ensemble spreads between the control and AEW suppressed simulations for each of these quantities. This indicates that AEWs are not necessary to maintain climatological basin-wide TC frequency, even though TCs readily originate from these types of disturbances. Further, the results suggest that interannual variability in AEWs may not influence seasonal Atlantic TC frequency and that changes in AEWs may not be reliable predictors of future changes in Atlantic TC numbers.

These findings are supported by results from the synthetic TC track model of Emanuel et al. (2008) and Emanuel (2010). Input to the synthetic track model includes atmospheric thermodynamic state, vertical wind shear, and ocean temperature. TC genesis is initiated by seeding the model with weak warm-core vortices, which is done randomly in time and space, meaning that no information about AEW variability is given to the model. Even without the AEW information, the synthetic track model is able to largely reproduce the interannual variability of Atlantic TC activity, suggesting that the monthly mean atmospheric and oceanic states are the dominant predictors of interannual TC activity (Emanuel et al., 2008). Additional support for our findings is provided by a statistical model that largely reproduces the interannual variability of Atlantic hurricane activity using only monthly atmospheric and oceanic variables as input, that is, without information about AEW variability (Saunders et al., 2017).

As a test of our experimental design, we examined the influence of AEW suppression on Atlantic TCs on the synoptic time scale. If the design is suitable for addressing our question, we would expect to see that the AEW information communicated to the Atlantic basin in the control simulation can provide synoptic TC predictability and that removal of the AEW information in the experiment eliminates that predictability. (Note that we are not quantifying synoptic predictability in general, which is a separate topic from this study.) Figure 2 shows the sum of positive 6-hourly relative vorticity at 850 hPa over a 1 week period in late August, with contours of daily 10 m wind speed at 00*z* (colored by time) from four ensemble members of each of the control and AEW suppressed simulations. The control simulation clearly shows a vorticity maximum that enters the regional model domain at the eastern lateral edge (near 15°W and 12°N) and moves northwestward as it develops into a TC in all 10 ensemble members (Figures 2a–2d and S3). This vorticity maximum corresponds in time with a peak in the 2–10 day meridional wind (Figure 1b), indicating its

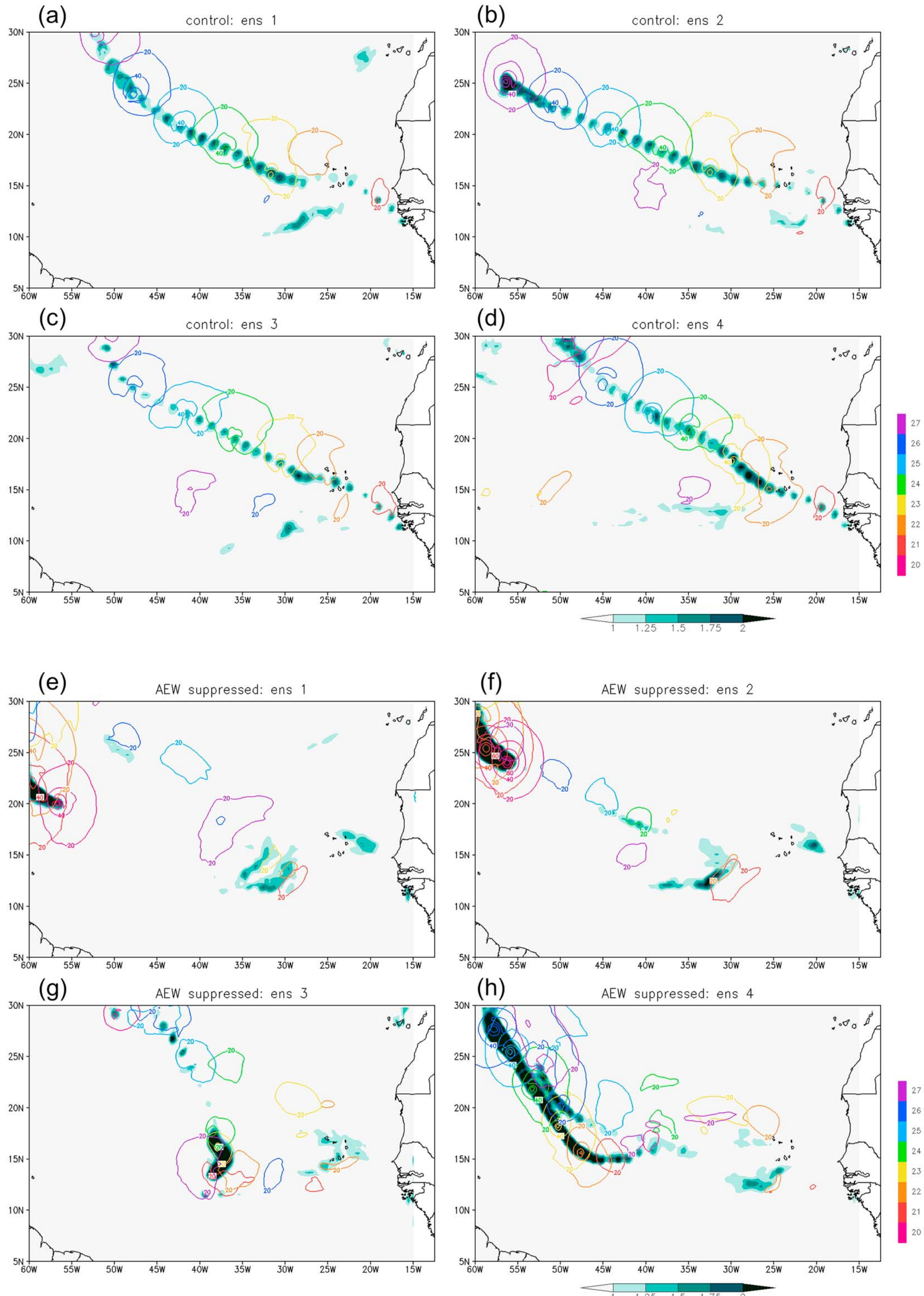

Figure 2. The sum of 6-hourly positive relative vorticity values at 850 hPa (10^{-3} s^{-1}; shaded green) and daily snapshots of 10 m wind speed at 00z (m s^{-1}; contour; color denotes day of August) over 20–27 August 2005 from four ensemble members of the (a–d) control and (e–h) AEW suppressed simulations. The eastern lateral boundary of the regional model is emphasized by shading regions outside of the model domain white.

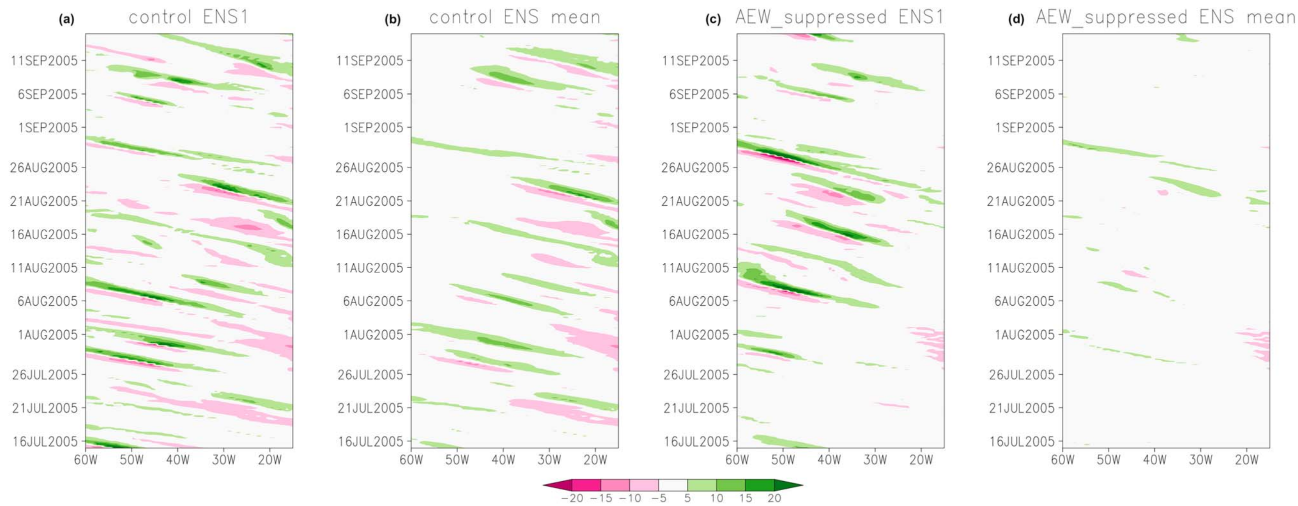

Figure 3. Hovmöller diagrams of meridional wind (m s^{-1}) at 700 hPa and averaged 14°N–16°N from (a) an individual ensemble member and (b) the 10-member ensemble mean of the control simulation, and (c) an individual ensemble member and (d) the 10-member ensemble mean of the AEW suppressed experiment.

association with an AEW. That vorticity maximum does not enter the regional model domain in any of the 10 ensemble members of the AEW suppressed simulations (four shown in Figures 2e–2h). Furthermore, although TCs develop in the AEW suppressed experiments, the TCs are not temporally and spatially coherent as in each of the control ensemble members. (Note that plotting over 20–27 August shows only part of the life span of TCs that originated before 20 August; e.g., TC genesis is not shown for TCs exiting the northwestern portion of the maps around 20–22 August in Figures 2e and 2f). Therefore, we indeed find that AEWs and TCs are linked on the synoptic time scale by retaining AEWs in model's LBC and that this predictability is lost by filtering the AEWs, providing support for the experimental design. We note the caveat that although the model is capable of generating TCs from AEWs in a spatially and temporally coherent manner, it is possible that the model could be biased toward TC genesis from non-AEW sources, as the percentage of simulated TC genesis associated with AEWs was not quantified.

To more generally examine the simulated relationship between AEWs and individual TC genesis, we consider Hovmöller diagrams of meridional wind at 700 hPa averaged over 14°N–16°N from the control and AEW suppressed simulations. Several TCs (apparent as adjacent positive/negative features) propagate from east to west in individual ensemble members of both the control and AEW suppressed simulations (e.g., Figures 3a and 3c, respectively). The spatial and temporal patterns of the wind features in the individual ensemble members of the control simulation (e.g., Figure 3a) resemble that of the ensemble mean (Figure 3b), indicating that the AEWs prescribed in the LBC initiated TC genesis in a coherent way throughout the season, as was shown for an individual TC (Figures 2a–2d). On the other hand, the spatial and temporal patterns of TC genesis in the individual ensemble members of the AEW suppressed simulations (e.g., Figure 3c) differ from those of the control simulations (e.g., Figure 3a). Moreover, the ensemble mean of the AEW-suppressed simulations (Figure 3d) shows weak winds throughout the season, indicating little spatial and temporal coherence among individual ensemble members and again more generally supporting the finding that suppression of AEWs eliminates the predictability for individual TCs present in the control simulation.

4. Discussion

The results presented here by no means suggest that AEWs are unimportant for understanding and predicting individual TC genesis on synoptic scales. Rather, we put forth the specific idea that AEWs do not influence *basin-wide* Atlantic TC variability on *seasonal-climate time scales*. In addition, the climate model experiments suggest that although there is covariability between Atlantic TCs, AEWs, and Atlantic SST, there is no causal relationship between AEW variability and basin-wide TC numbers on interannual time scales. The simulations suggest that instead, AEW and TC variability may both be driven by ocean variability. Furthermore, we do not suggest that TC genesis requires no preexisting disturbance; rather, we conclude that the *specific type* of disturbance is unimportant for determining basin-wide seasonal Atlantic TC numbers. Although Atlantic TCs readily generate from AEWs, in the absence of AEWs the TCs can and will generate by other mechanisms (e.g., those discussed previously) or the "next greatest" low-pressure disturbance when environmental conditions (e.g., upper-ocean temperature and vertical wind shear) are favorable for TCs.

The regional climate model experiments conducted here, considered together with the synthetic TC track simulations of Emanuel et al. (2008), provide strong evidence for our conclusions. However, this research also opens questions that are beyond the scope of a single study. In particular, we focused on one active hurricane season, which was characterized by SST conditions highly favorable for TCs. We did not examine whether AEW variability would become more important for influencing TC activity during near-average TC seasons, although we hypothesize that AEWs are not a limiting factor for TCs under a range of oceanic and atmospheric conditions. Investigating the influence of AEWs on interannual TC prediction skill in a broader sense would require decades-long model simulations. However, despite focusing on 1 year, our results are sufficient to conclude that seasonal Atlantic TC numbers can be maintained in the absence of AEWs, at least for some hurricane seasons.

In addition, we did not investigate how different types of AEWs, that is, those characterized by northern or southern tracks, may influence TC activity. For example, Russell et al. (2017) found that midtropospheric AEW activity is a poor predictor of seasonal TC number, whereas low-level southern-track AEW activity is correlated with seasonal Atlantic TC number and may be useful for seasonal TC prediction. Additional studies are needed to fully quantify the role, if any, of AEWs in seasonal TC prediction.

Finally, while the analysis here focused on basin-wide Atlantic TC numbers, it is not fully understood how AEW variability influences the spatial clustering of TCs and landfall statistics. There is evidence to believe that although the AEWs do not influence basin-wide TC number, they may be important in determining TC genesis location within the Atlantic basin. Specifically, the TC tracks generated with the synthetic track model have difficulty representing the observed seasonal cycle of Cape Verde TCs, which typically generate from AEWs (Daloz et al., 2015). Furthermore, AEW location influences TC genesis and landfall locations, with AEWs north of the AEJ associated with "cluster 4" TCs (Figure 1 of Kossin et al., 2010). If AEWs north of the AEJ intensify in the future as projected (Skinner & Diffenbaugh, 2014), this could translate to increased TC landfall in the Gulf of Mexico (Kossin et al., 2010). A much larger ensemble size of climate model simulations (on the order of 10^2) would be required to investigate how the location, periodicity, and timing of AEWs influence the spatial patterns of Atlantic TC activity. These topics will be the focus of future research.

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