Climatological Variations in North Atlantic Tropical Cyclone Tracks

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ABSTRACT

This study investigates the relationship between tropical cyclone (TC) tracks and climatological variations in large-scale environmental parameters associated with the TC steering flow. By using the Atlantic Ocean hurricane database for 1950–2010, TCs that form in the main development region (MDR) are categorized into one of three track types: straight moving, recurving landfall, or recurving ocean. As expected, the straight-moving storms are associated with a westward extension and strengthening of the subtropical high, whereas the recurving ocean storms are associated with a weakening of the high. The presence of El Niño conditions in the tropical Pacific Ocean is shown to be associated with a weakening of the high, an increase in the percentage of recurving ocean TCs, and a decrease in the percentage of recurving landfall TCs. Positive phases of the Atlantic Meridional Mode are associated with an increase in the percentage of recurving ocean TCs and a decrease in the percentage of straight-moving TCs. Synthetic tracks are simulated for each storm using a beta and advection model. Sensitivity experiments using both observed and uniformly seeded genesis locations indicate that the path of straight-moving TCs is largely a reflection of their tendency to form in the southwestern portion of the MDR rather than of differences in steering flow. These experiments also suggest that the shift in TC tracks associated with El Niño/La Niña conditions is largely attributable to changes in the steering flow, whereas the track changes associated with variations in the Atlantic Meridional Mode are due to a systematic shift in genesis location.

1. Introduction

Tropical cyclones (TCs) represent a substantial economic and societal threat for the U.S. coastline (Pielke and Landsea 1998; Pielke et al. 2008). A number of studies have identified environmental factors associated with both natural and anthropogenic climate change that impact basinwide TC activity in the North Atlantic Ocean (e.g., Gray et al. 1992; Landsea and Gray 1992; Kossin and Vimont 2007; Emanuel 2007; Vecchi and Soden 2007; Knutson et al. 2010). However, less attention has been devoted to the environmental factors that influence the tracks of TCs within the North Atlantic and how these factors respond to natural and anthropogenic climate change.

Tropical cyclone tracks are determined both by the large-scale steering flow and by interactions between the steering flow and storm dynamics (e.g., the β effect; Holland 1983). Various climatic features can influence the large-scale steering flow. Most notable is the North Atlantic subtropical high (NASH) whose strength and location are influenced by a combination of local and remote factors (Chen et al. 2001; Rodwell and Hoskins 2001; Miyasaka and Nakamura 2005; Seager et al. 2003; Nigam and Chan 2009; Li et al. 2010). In addition, the causes of variations on longer time scales (e.g., interannual–decadal) and the impact of those changes on TC tracks are not well understood.

Understanding the impact of climate change on the large-scale circulation of the North Atlantic could help to identify processes that lead to secular variations in TC tracks. For example, Elsner et al. (2000) observed that when the subtropical high extends to the west and south then TCs remain at low latitudes, whereas when it contracts to the east and north then TCs recurve into the western Atlantic. Numerous studies have found a decrease in both basinwide and landfalling storms in the Atlantic during El Niño years (Bove et al. 1998; Xie et al. 2005; Kossin et al. 2010). Previous studies have also found changes in TC tracks associated with the phase of the North Atlantic Oscillation (NAO). During the positive NAO phase the U.S. East Coast becomes more susceptible
to landfalling storms, whereas during the negative NAO phase the U.S. Gulf Coast becomes more susceptible to landfalling storms [when the NAO phase is determined on the basis of the May–June average; Owens (2001); Elsner (2003)]. Kossin et al. (2010) more recently found that during a negative May–June NAO phase the western portion of the NASH is generally weaker for the duration of the hurricane season, allowing for greater recurvature of TCs when they formed north of the “main development region” (MDR; defined below). Kossin et al. (2010) also found an increase in TC activity and a higher chance for landfalling TCs during the positive Atlantic Meridional Mode (AMM) phase.

In this study we use National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis and the National Hurricane Center’s North Atlantic hurricane database (HURDAT) to study the relationship between North Atlantic TC tracks and climatological variations in large-scale environmental parameters associated with the TC steering flow. Our analysis complements previous studies in two ways. First, we jointly analyze the large-scale steering flow and the TC tracks to assess their consistency. Second, we use a beta and advection model (BAM) to separate the influence of changes in the steering flow and changes in genesis location on the resulting storm tracks.

Section 2 describes the method for classifying TC tracks, and the corresponding steering flow is presented in section 3. Section 4 discusses the changes in TC tracks and steering flow associated with the El Niño–Southern Oscillation (ENSO), NAO, and AMM. The corresponding analysis of synthetic TC tracks generated using the BAM is presented in section 5, and the results are summarized in section 6.

2. Classification of TC tracks

Using HURDAT data, the position and intensity of all North Atlantic TCs are obtained for every 6 h (Jarvinen et al. 1984; McAdie et al. 2009). From 1950 to 2010, a total of 667 TCs occurred, 24 of which were classified as subtropical at the time of genesis and were removed from the dataset. The study focuses on TCs that formed in the MDR, defined as the area between 10° and 20°N and between 17.5° and 65°W. The TC tracks are classified into one of three categories (see Fig. 1b): straight-moving (SM) TCs stay below 25°N until they cross 80°W and threaten the U.S. Gulf Coast and the western Caribbean Sea. Recurving landfall (RCL) TCs cross 70°W north of 25°N or cross 65°W north of 40°N and threaten the U.S. East Coast. Recurving ocean (RCO) TCs do not cross either threat boundary but go north of 25°N and recurve into the open ocean.

Storm duration of at least 36 h is required for the TCs to be included in this study. For storms that dissipate before reaching one of the three boundaries, we compute a mean trajectory angle over the storm’s lifetime to extrapolate its path until reaching one of the boundaries. The addition of the shorter storm tracks to the dataset enables a larger sample and more robust statistical results. Out of 237 storms that formed in the MDR, this classification procedure yields 76 SM, 67 RCL, and 94 RCO TCs. Previous studies have used K-means clustering techniques for the longitude and latitude of two points of interest (Elsner 2003), mass moments (Nakamura et al. 2009), or a mixture regression model (Kossin et al. 2010), whereas the classification method in this study is based on defined threat regions, which have direct societal impacts, but yields results that are similar to those of the last two methods, which account for the entire track shape over time.

Figure 1a shows the genesis location for all of the TCs in the sample, color coded by track classification. The larger symbol represents the mean genesis location for each category. The genesis locations for all three track types are distributed throughout the MDR, but the SM and RCL tend to originate farther west than do the RCO. The SM storms also tend to start farther south relative to the RCL or RCO storms. The tracks for all 237 storms and the resulting mean track for each category are shown in Figs. 1b and 1c, respectively. The solid black line in Fig. 1c represents the average track, and the surrounding cones delineate ±1 standard error in longitude and latitude. Overall, the classification system is successful in identifying three distinct groups of TCs emerging from the MDR on the basis of their threat region. For RCL storms there are both substantial variability and an eastward skew to the track once they recurve. This causes the average RCL track to lie to the east of its defined boundary even though each of the individual tracks included in the average crosses into the RCL threat region.

The probability of obtaining a given track type on the basis of the genesis location provides insight into the influence of the genesis location on a TC’s track. Figure 2 shows the spatial distribution of genesis locations on the basis of track category. On the eastern portion of the MDR, a TC will have a greater chance to recurve because the β drift will have more time to lift it northward out of the easterly trades. Conversely, the farther west that a TC forms, the less time it has to recurve, resulting in an increased probability of SM TCs along the western end of the MDR. Likewise, the farther south that a TC forms, the more likely it is to be classified as SM, because the storm must drift farther north to escape the easterly trade winds.
3. Characterization of the large-scale steering environment

Information on sea level pressure (SLP) and vertical profiles of zonal \( u \) and meridional \( v \) wind components are obtained from the NCEP–NCAR reanalysis, which provides data at a 2.5° and 6-h resolution for the period 1950–2010 (Kalnay et al. 1996). To remove any influence of the TC vortex on the large-scale environment, the vortex in the SLP and wind fields is removed as described in the appendix. Then, a deep-layer steering flow \( V^* \) is computed from the resulting two-dimensional wind fields \( V \) at 850, 500, and 200 hPa, defined as

\[
V^* = 0.25V_{850\text{hPa}} + 0.5V_{500\text{hPa}} + 0.25V_{200\text{hPa}}.
\]

The average SLP and deep-layer steering flow are computed for each track type (Fig. 3). As expected, there are clear differences in the strength and location of the NASH among track types. The subtropical high is strongest and has its greatest westward extension for SM storms, whereas it is the weakest and retreats the farthest eastward during RCO storms.

The difference in the SLP and deep-layer wind fields among track categories illustrates the changes in the NASH more clearly (Fig. 4). To gauge the significance of these differences, we plot the standard error of the SLP field as contours. For most regions of interest, the standard error is less than 0.5 hPa, and so we shade differences in SLP only where they exceed this value.

A strong intensification and westward extension of the subtropical high relative to RCO storms is present during SM storms (Fig. 4a). In accordance, the deep-layer steering flow exhibits a stronger northerly flow over the western...
FIG. 2. The spatial TC genesis location distribution for (a) SM, (b) RCL, and (c) RCO TCs, in number of TCs per 2.5° box.
portion of the basin where the SLP anomalies are largest. This inhibits recurvature, resulting in more SM storms. During SM storms, a westward extension of the subtropical high also occurs relative to RCL storms (Fig. 4b), although the SLP differences are weaker than for RCO storms. The shift in anomalous circulation is also smaller and is more confined to coastal regions adjacent to Florida and the rest of the southeastern United States. Relative to RCO, RCL storms tend to be associated with a westward extension in the northern portion of the NASH (Fig. 4c). This causes increased northeasterly flow over the mid-Atlantic, steering TCs into the U.S. East Coast.

If a particular type of track is more common during a specific part of the season, the differences shown in Fig. 4 may be affected by the seasonal cycle in SLP and the wind fields. To address this concern, climatological average SLP and wind fields are constructed for every 6 h from 1 May to 31 December on the basis of all 61 yr of reanalysis. The 61-yr climatological mean is then subtracted from each field to create 6-h anomaly fields for both the SLP and deep-layer steering flow. The average SLP and wind anomaly fields for each track type are composited (Fig. 5). Similar patterns of wind and pressure anomalies are observed, indicating that the aliasing of the seasonal cycle is not a primary cause of the differences seen in Fig. 4.

Another important feature in Fig. 5 is the anomalously lower pressure throughout much of the basin when TCs are present (even with the TC vortices removed), suggesting that the lower pressure is a contributing factor to TC genesis and development. Knaff (1997) found that higher SLP anomalies are linked to drier midlevels and stronger vertical wind shear, making the environment less conducive for TC development. The anomalous low pressure seen for all track categories supports this finding.

To verify the robustness of the results in Fig. 5, the RCO anomalous SLP fields are calculated and plotted for four TC vortex removal box sizes including 7.5°, 12.5°, 17.5°, and 22.5° (Fig. 6). It becomes clear that the
lower basinwide SLP is a robust and significant result, regardless of the box size used to remove the presence of the TC vortex in the reanalysis data. Although the intensity at the maximum contour changes slightly depending on box size, the overall feature remains consistent. This reinforces the findings in Fig. 5 that lower SLP occurs throughout the basin when a TC is present.

4. Climatological variations in TC tracks

As shown in the previous section, changes in the position and intensity of the NASH can affect TC tracks through changes in the large-scale steering flow. Several sources of climate variability, such as ENSO, NAO, and AMM, impact the large-scale circulation of the North Atlantic and, in turn, may influence TC tracks. In this section, the TC tracks are categorized according to the phase of each of these climate anomalies. A two-tailed binomial test is conducted to determine the statistical significance of the changes in track-type frequency, and the standard error (with a temporal autocorrelation taken into account) is used to evaluate the statistical significance of the SLP fields.

a. El Niño–Southern Oscillation

To determine the influence of ENSO on TC tracks, we classify each North Atlantic hurricane season to be El Niño, La Niña, or neutral on the basis of the Climate Prediction Center’s (CPC) oceanic Niño index classification (Climate Prediction Center 2011). This procedure classifies a year as being an El Niño year if there are five consecutive months in which the smoothed (3-month running mean) Niño-3.4 index is greater than 0.5°C. Likewise, the index must remain below −0.5°C for five consecutive months for that year to be classified as La Niña. Years that do not satisfy either of these conditions are classified as neutral. A given season is classified on the basis of the phase during the November, December, January 3-month mean, where November and December are of the same year as the hurricane season being classified.
Using this procedure, the 61 years were divided into 19 El Niño seasons, 20 La Niña seasons, and 22 neutral seasons. Consistent with previous studies, a decrease in TC activity occurs during El Niño with 54 TCs (2.84 TCs per season) as compared with 94 TCs (4.70 TCs per season) for La Niña and 89 TCs (4.05 TCs per season) for neutral seasons. We note that there is no statistically significant difference in the number of TCs forming in the MDR between La Niña and neutral seasons.

Figure 7a shows the track frequency with respect to the ENSO phase. For neutral seasons, each of the three track categories has roughly the same percentage (~33%) of storms. This distribution is not significantly different from the full distribution in which 32% of the TCs are SM, 28% are RCL, and 40% are RCO TCs. Likewise, for La Niña seasons, SM and RCL tracks are approximately 29% and 30%, respectively, of the track distribution and RCO tracks represent the remaining 41% of the distribution. However, for El Niño seasons, a statistically significant drop in RCL track frequency to 15% and a rise in RCO tracks to 48% are observed.

Figure 8a highlights the difference in the August, September, October (ASO) average SLP and deep-layer steering flow fields for El Niño minus La Niña. During El Niño seasons there is a weakening of the NASH that results in anomalous cyclonic flow in the eastern mid-Atlantic. This change in steering flow is consistent with a decreasing percentage of RCL TCs and an increasing percentage of RCO TCs during El Niño relative to La Niña. The average La Niña track extends farther westward than the average El Niño track, consistent with the difference in frequency of track types from Fig. 7a. Note that both the El Niño and La Niña storm tracks have similar mean genesis locations, suggesting that the difference in tracks is associated with the change in large-scale steering flow (rather than genesis location).
b. North Atlantic Oscillation

Similar to the ENSO analysis, the 237 TC tracks are divided into positive and negative phases of the NAO determined using the CPC’s monthly mean NAO index where the phase of the NAO at the month and year of genesis for the TC is used. This results in 122 TCs during the positive phase and 115 TCs during the negative phase of the NAO. Figure 7b displays the track probability distribution with respect to the phase of the NAO. For the positive phase of the NAO, 28% of the TCs are SM, 30% are RCL, and 42% are RCO. For the negative phase of the NAO, a slight increase in the SM tracks to 37% and slight decreases to 26% and 37% for RCL and RCO tracks, respectively, occur.

These slight shifts are consistent with Elsner (2003); however, they are not statistically significant in this study.

One reason for this disparity could be the difference in timing of the NAO index used between the two studies. Elsner (2003) looks at the May–June predictive nature of the NAO, whereas this study examines the NAO’s phase at the time of storm genesis. To better compare results, the May–June average NAO index was used to define the phase for an entire season. However, no statistically significant shifts in TC track frequencies were found. The lack of statistical significance is most likely related either to differences in the sample of storms [Elsner (2003) only considers hurricanes] or to the difference in the classification of TC tracks. Elsner (2003) used a $K$-means analysis with a hurricane’s location at maximum intensity and location at final hurricane intensity to sort tracks into straight moving and recurving.

The differences in SLP and deep-layer steering flow are largest north of 30°N and are consistent with the
FIG. 7. The percentage of TCs for each track type by (a) ENSO season (El Niño, La Niña, or neutral), (b) NAO phase (positive or negative) for a given month and year of genesis, and (c) AMM phase (positive or negative) for a given month and year of genesis. The values in parentheses denote the number of TCs included in the frequency distribution for each season or phase.
definition of the NAO (Fig. 8b). Moreover, since the NAO index measures the difference between the subtropics and subpolar regions, it is weakest during the late summer. During the positive phase, anomalously low SLP occurs over the southeastern United States and is associated with weak anomalous southeasterlies along the coast of Florida which could encourage the recurvature of storms into the East Coast. During the negative phase, anomalous southeasterlies in the Caribbean may steer TCs into the Gulf of Mexico. Despite these changes in SLP, the average tracks of the two phases are nearly identical, suggesting that the NAO has little influence on TC tracks that form in the MDR. This may reflect the northerly location of the largest circulation changes, consistent with Kossin et al. (2010).

c. Atlantic Meridional Mode

Similar to the analysis performed with the NAO, the TCs are divided into positive and negative phases of the AMM, determined using the CPC’s monthly mean AMM index at the month and year of genesis. This results in 175 TCs during the positive AMM phase and 62 TCs during the negative AMM phase. Figure 7c shows the probability distribution of tracks with respect to the phase of the AMM. For the positive phase, the recurving TCs are slightly increased (with 29% RCL and 43% RCO) and SM TCs are slightly decreased to 28%. For the negative AMM phase, there is a statistically significant (at the 90% confidence level) increase in SM TCs to 43% and a decrease in recurving TCs to 26% and 31% for RCL and RCO TCs, respectively. The track frequency distribution
during the positive AMM phase is similar to that observed during La Niña (Fig. 7a), consistent with Kossin et al. (2010), who found a strong relationship between the positive AMM phase and La Niña for deep tropic TC activity.

Figure 8c shows a lowering of SLP over the U.S. East Coast and upper tropics across the Atlantic during the positive AMM phase for ASO. There is no clear pattern in the steering-flow winds associated with the changes in SLP, suggesting that differences in genesis location between the two AMM phases may be an important contributor to the track differences. As noted in Kossin and Vimont (2007), a positive AMM phase resulted in a basinwide shift of cyclogenesis (defined as the point at which the TC first reaches tropical storm strength) eastward and toward the equator. This corresponds to an increase in MDR genesis during the positive AMM phase, whereas the negative AMM phase shows an increase in near-land (southeastern United States) genesis.

5. Track simulations using the beta and advection model

a. BAM

In this section, the BAM is used to examine the relative importance of the large-scale steering flow and genesis location in reproducing the observed TC tracks. The NCEP–NCAR reanalysis $u$ and $v$ vertical wind profiles and a specified $\beta$ drift are used in the BAM. The mean steering flow is computed as described in section 3. To remove the effect of the storm circulation on the steering flow, the TC vortex is removed from the $u$ and $v$ wind fields before computing the steering flow (see the appendix).

A $\beta$ drift is imposed to include the effects of planetary vorticity advection by the storm’s circulation on storm movement. Marks (1992) experimented with an empirical $\beta$ drift with angles ranging from 295° to 315° and speeds of 1–3 m s$^{-1}$ to impose a northwest deviation of the TC vortex from the environmental flow. In this study, the speed of the $\beta$ drift is tuned to provide the best match between the observed and simulated mean track on the basis of the 1950–2010 historical climatology. This model uses a constant angle of 315° and allows the $\beta$ drift speed to vary from 1.5 to 5 m s$^{-1}$ depending on the TC’s current angle of trajectory. The advection model uses a second-order Runge–Kutta time step, which is integrated forward in time at 1-h intervals for the full step. The $u$ and $v$ components are calculated as an average value over a 7.5° × 7.5° box centered on the vortex location to reflect a realistic vortex size from the given reanalysis data for each half and full time step.

For each historical TC, a 10-day synthetic track is generated by initializing the model at the historical genesis date and location. In addition, for each historical TC, we generate 100 synthetic tracks by uniformly seeding the MDR (every 2.5° grid box) at the date of genesis for that TC. The first set of simulations allows one to evaluate the ability of the BAM to reproduce the mean distribution and climatological variations in storm tracks. The uniformly seeded experiment allows us to evaluate the impact of genesis location on the distribution and climatological variations in storm tracks.

The BAM provides a tool for examining the relative importance of different factors (e.g., steering flow vs. genesis location) in governing climatological changes in TC tracks but is not meant for operational forecasting. Previous studies have used more complex algorithms to generate TC tracks. One uses a statistical downscaling method in which tracks are randomly produced on the basis of the historical distributions and then fit to the large-scale circulation of a global climate model (Emanuel 2006; Emanuel et al. 2006). Another approach employs a statistical model in which the synthetic tracks are propagated using information from historical storm displacements (Hall and Jewson 2007, 2008).

b. North Atlantic subtropical high

Figure 9a compares the observed TC tracks with those simulated from the BAM using historical genesis locations. The BAM successfully reproduces the primary differences between the three track categories, although the simulated tracks exhibit a slight westward bias for the RCO TCs, a slight eastward bias for the RCL TCs, and a slight northeastward bias for the SM TCs.

Figure 9b displays the average tracks for each track category when the MDR is uniformly seeded. This set of simulations removes the influence of genesis location on the TC track and permits a better understanding of the impact of the large-scale circulation alone. Under the uniform-seeding experiments, the RCL and RCO TCs still exhibit distinctly different tracks. The fact that the RCO storms recurve more, on average, than the RCL storms indicates that the difference in steering flow between these storms contributes to their differing tracks. However, the RCO storms form, on average, a few months farther east than RCL storms, which also greatly reduces their landfalling threat.

When the MDR is uniformly seeded for SM genesis dates, the averaged simulated track exhibits a more northeasterly projection than the tracks computed using historically observed genesis location. Indeed, under
a uniform-seeding scenario, the SM storms exhibit a mean track similar to RCO storms, emphasizing the importance of the more southwestern genesis location in contributing to the track of SM TCs. Once this difference in genesis location is removed, the average SM track no longer threatens the Gulf Coast and western Caribbean.

This analysis clearly illustrates the importance of genesis location within the MDR on the resulting track of a TC. It further suggests that changes in the location of genesis associated with anthropogenic changes in climate could be an important impact on TC tracks in addition to changes in the large-scale steering flow.
c. ENSO, NAO, and AMM

We now use the BAM to examine the extent to which changes in the large-scale circulation associated with ENSO can explain the observed differences in TC tracks associated with these events. Figure 10a compares the average tracks for El Niño seasons and La Niña seasons for both the observed and historically seeded BAM simulations. The BAM is successful in reproducing the westward displacement of storms during La Niña seasons relative to El Niño seasons, although there is a slight eastern bias for the simulated El Niño track. Figure 10b compares the average La Niña and El Niño TC tracks for the uniformly seeded experiment. When removing the influence of genesis location through uniform seeding, there remains a clear difference between the two tracks.
suggesting that it is primarily the change in the deep-layer steering flow between La Niña and El Niño seasons that is responsible for the difference in TC tracks.

For the NAO, only a small difference is found in the observed tracks between storms that form during a positive or negative phase, with the mean track during a negative phase being slightly west of the mean positive phase track. The simulated tracks are qualitatively consistent with observations in this respect; however, there is a noticeable westward bias for the negative-phase NAO average track after 7 days (Fig. 11a). When the MDR is uniformly seeded, no significant track differences are found (Fig. 11b). As with the observational results for the NAO, the BAM results further suggest a lack of influence of the NAO phase on the track of TCs that form in the MDR.

As discussed in section 4c, there is a statistically significant difference in average track between the positive and negative AMM phases. When using the historical
genesis locations, the BAM captures this difference very well, with slight differences after 8–9 days (Fig. 12a). However, when the MDR is uniformly seeded, the difference in the average tracks between the two phases is removed, suggesting that the southwestern displacement of genesis locations during the negative AMM phase is the primary cause for the westward shift in tracks (Fig. 12b). This is consistent with the results for SM TCs, which dominate the negative AMM phase tracks. It is important to note that these results focus on shifts in genesis within the MDR region and do not include the scope of storms examined in Kossin and Vimont (2007).

6. Summary

This study examined the impact of natural climate variability on North Atlantic TC tracks. Using data from HURDAT for the period 1950–2010, we categorize
Atlantic TCs that form in the MDR into one of three track types: SM, RCL, or RCO. As expected, the SM storms are associated with a westward extension and strengthening of the subtropical high whereas the RCO storms coincide with a weakening of the subtropical high. This supports the hypothesis that the location and intensity of the subtropical high directly influence a TC track (Elsner et al. 2000; Kossin et al. 2010).

It was also shown that El Niño seasons are associated with a weakening of the NASH. This change in steering flow is consistent with an increase in the percentage of RCO storms and reduction in the percentage of RCL storms during hurricane seasons in which an El Niño occurs. The change in steering flow occurs in addition to an overall reduction in the number of TCs that form during El Niño seasons and thus further reduces the threat of landfalling storms. These track modulations further support ENSO’s influence on TC tracks in the Atlantic, as noted by Elsner (2003) and Kossin et al. (2010).

In agreement with Kossin et al. (2010), we found no significant change in TC tracks associated with the phase of the NAO for TCs that formed in the MDR. A distinct difference in average TC tracks was found between the positive and negative AMM phases. In accordance with Kossin et al. (2010), a larger subsample occurred during the positive AMM phase, with a track frequency distribution similar to the La Niña track frequency distribution. The negative AMM phase resulted in an increase in the percentage of SM TCs, skewing the average genesis location to the southwest of the corresponding positive AMM phase genesis location.

Simulations of TC tracks were performed using the BAM with both historically observed and uniformly seeded genesis locations. In simulations in which the MDR was uniformly seeded, a difference between RCL and RCO tracks remained, with RCL tracks recurving farther westward relative to RCO storms. However, the uniform-seeding simulations for SM storms yield an average track that is much farther north than is observed and that is very similar to the average RCO track. This suggests that the tendency for SM storms to form farther south and west within the MDR is a key factor in determining their track (i.e., tracks that threaten the western Caribbean and U.S. Gulf Coast). Tracks are an essential aspect to consider for determining trends in hurricane activity, especially when examining TC intensity, because they can account for a large amount of the variability in a given trend (Kossin and Camargo 2009). Thus, any assessments of systematic variations in TC tracks for either natural or anthropogenic climate change must consider the impact of both changes in the genesis location and changes in the large-scale steering flow.

In the uniformly seeded MDR experiment, the average track for La Niña seasons was found to recurve farther west when compared with the El Niño track, in a manner consistent with the historically observed tracks. This suggests that the primary cause for reduced landfalling TCs during El Niño seasons is the change in the large-scale steering flow. Consistent with observations, we did not find an influence of the NAO phase on TC tracks of storms that formed in the MDR in either set of simulations. This result is consistent with the findings of Kossin et al. (2010) and supports the conclusion that NAO modulations of TC tracks do not occur for MDR-forming storms. For the AMM, the uniform-seeding experiment removed the variation in the average track between the two phases, suggesting that shifts in genesis location are determining the differences in the average tracks opposed to changes in the large-scale steering flow, in accordance with Kossin and Vimont (2007). This is expected, because the positive AMM phase is associated with a warm anomaly in tropical Atlantic sea surface temperatures, resulting in increased genesis within the MDR (Kossin and Vimont 2007).

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APPENDIX

Tropical Cyclone Vortex Removal

By using the best-track location from HURDAT, the TC vortex is identified in the corresponding SLP field. A 12.5° × 12.5° box centered on the vortex is defined, and the SLP values within the box are removed. The SLP values on the outer edges of the box are bilinearly interpolated, in the latitudinal and longitudinal directions, to remove the TC’s influence. This process is repeated at every time step for the duration of the TC.

For the wind fields, to remove the TC vortex, the vorticity

\[ \zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \]

is calculated for the entire field. A second vorticity field is constructed by subtracting the TC vorticity that is separated from the environment as described below. For each field, the streamfunction, \( \nabla^2 \psi = \zeta \), is computed using the Jacobi iteration method and finite differences. This streamfunction is used to calculate the \( u \) and \( v \) wind fields:
\[ u = \partial \phi / \partial y \quad \text{and} \quad v = \partial \phi / \partial x. \]

The wind fields associated with the TC vortex can then be computed and removed from the original reanalysis wind fields.

To isolate the vorticity of the TC vortex, a 12.5° × 12.5° box is constructed around the HURDAT best-track center, and the maximum vorticity center of the TC in the reanalysis field is located. Using a radial distance of 15° from the maximum vorticity center, the vorticity of the TC vortex is isolated and the rest of the field is set to zero. The TC vortex is removed from the reanalysis wind fields at every time step for the duration of the TC at the 850-, 500-, and 200-hPa pressure levels.

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