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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. Using the Atlantic hurricane database for 1950-2010, TCs which 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 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 southwest portion of the MDR rather than to 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 US 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 which impact basin-wide TC activity in the North Atlantic (e.g., Gray et al. 1992, Landsea and Gray 1992, Kossin and Vimont 2007, Emanuel 2007, Swanson 2007, Holland and Webster 2007, Vecchi and Soden 2007, Vimont and Kossin 2007, Klotzbach and Gray 2008, Knutson et al. 2008, Chan 2009). However, less attention has been devoted to the environmental factors which influence the tracks of TCs within the North Atlantic and how these factors respond to natural and anthropogenic climate change.

TC tracks are determined both by the large-scale steering flow and interactions between the steering flow and storm dynamics (e.g., the $\beta$-effect, Holland 1983). Various climate features can influence the large-scale steering flow. Most notable is the North Atlantic Subtropical High (NASH) whose strength and location is 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 cause of variations on longer time scales (e.g., interannual to 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 which 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, TCs remain at low latitudes, whereas when it contracts to the east and north, TCs recurve into the western Atlantic. Numerous studies have found a decrease in both basin-wide 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 East Coast of the US becomes more susceptible to landfalling storms, whereas during the negative NAO phase the Gulf Coast of the US becomes more susceptible to landfalling storms (when the NAO phase is determined based on the May-June average, Owens 2001; Elsner 2003). More recently, Kossin et al. (2010) 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 MDR. Kossin et al. (2010) also found an increase in TC activity and 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, or 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 compliments 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 methodology for classifying TC tracks while the corresponding steering flow is presented in Section 3. Section 4 discusses the changes in TC tracks and steering flow associated with 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 Tropical Cyclone Tracks

Using the HURDAT, the position and intensity of all North Atlantic TCs is obtained for every 6 hours (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 removed from the dataset. The study focuses on TCs that formed in the Main Development Region (MDR), defined as the area between 10°N and 20°N, and 17.5°W 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 Gulf Coast of the US and Western Caribbean. Recurving Landfall (RCL) TCs cross 70°W north of 25°N or cross 65°W north of 40°N and threaten the East Coast of the US. Recurving Ocean (RCO) TCs did not cross either threat boundary but went north of 25°N and recurved into the open ocean.

Storm duration of at least 36 hours is required for the TCs to be included in this study. For storms which 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 similar results to the last two methods which account for the entire track shape over time.

Fig. 1a shows the genesis location for all the TCs in the sample color coded by track classification. The larger symbol represents the mean genesis location for each category. While the genesis locations for all 3 track types are distributed throughout the MDR, the SM and RCL tend to originate further west than the RCO. The SM storms also tend to start further south relative to RCL or RCO storms. The tracks for all 237 storms and the resulting mean track for each category are shown in Figures 1b and 1c, respectively. The solid black line in Fig 1c represents the average track and the surrounding cones delineate +/- one standard error in longitude and latitude. Overall, the classification system is successful in identifying three distinct groups of TCs emerging from the MDR based upon their threat region. For RCL storms there is 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 cross into the RCL threat region.

The probability of obtaining a given track type based on the genesis location provides insight into the influence of the genesis location on a TC’s track. Fig. 2 shows the spatial distribution of genesis locations based on track category. On the eastern portion of the MDR, a TC will have a greater chance to recurve as the $\beta$-drift will have more time to lift it northward out of the easterly trades. Conversely, the further west 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 further south a TC forms the more likely it is to be classified as SM, as the storm must drift further north in order to escape the easterly trades.
3. Characterization of the Large-Scale Steering Environment

Information on sea level pressure (SLP) and vertical profiles of zonal \((u)\) and meridional \((v)\) wind are obtained from the NCEP-NCAR reanalysis which provides data at a 2.5° and 6 hour 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 is computed from the resulting 2-dimensional wind fields \((V)\) at 850, 500 and 200 mb defined as:

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

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 between track types. The subtropical high is strongest and has its greatest westward extension for SM storms, while it is the weakest and retreats the furthest eastward during RCO storms.

The difference in the SLP and deep layer wind fields between 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 mb and so we shade differences in SLP only where they exceed this value.

A strong intensification and westward extension of the subtropical high is present during SM storms relative to RCO storms (Fig. 4a). In accordance, the deep layer steering flow exhibits a stronger northerly flow over the western portion of the basin where the SLP anomalies are largest. This inhibits recurvature resulting in more SM storms. A westward extension of the subtropical high also occurs during SM storms 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 more confined to coastal regions adjacent to Florida and the rest of the Southeastern
US. 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 East Coast of the US.

If a particular type of track is more common during a specific part of the season, the differences shown in Figure 4 may be affected by the seasonal cycle in SLP and wind fields. To address this concern, climatological average SLP and wind fields are constructed for every 6 hours from May 1st to December 31st based upon all 61 years of reanalysis. The 61-year climatological mean is then subtracted from each field to create 6 hour 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 Figure 4.

Another important feature in Figure 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 dryer mid-levels 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 Figure 5, the RCO anomalous SLP fields are calculated and plotted for 4 TC vortex removal box sizes including 7.5°, 12.5°, 17.5°, and 22.5° (Fig. 6). It becomes clear that the lower basin-wide 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 Tropical Cyclone 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 while 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 based upon the Climate Prediction Center’s (CPC) Oceanic Niño Index classification (National Weather Service: Climate Prediction Center 2011). This procedure classifies a year as being an El Niño year, if there are 5 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 5 consecutive months for that year to be classified as La Niña. Years which do not satisfy either of these conditions are classified as neutral. A given season is classified based on 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) compared to 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.

Fig. 7a shows the track frequency with respect to the ENSO phase. For neutral seasons, each of the three track categories has roughly the same percent (~ 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 compose approximately 29% and 30%, respectively, of the track distribution, while 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 58% are observed.

Fig. 8a highlights the difference in the August, September, and 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 which 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 further westward than the average El Niño track, consistent with the difference in frequency of track types from Fig. 7a. It is worth noting 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. Fig. 7b displays the track probability distribution with respect to the phase of the NAO. For the positive phase of the NAO, 28% are SM, 30% are RCL, and 42% are RCO TCs. 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, occurs.

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 to either 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 definition of the NAO (Fig. 8b). Moreover, since the NAO index measures of 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 US and is
associated with weak anomalous south-easterlies along the coast of Florida which could encourage the recurvature of storms into the East Coast. During the negative phase, anomalous south-easterlies 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 is 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. Fig. 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) while 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.

Fig. 8c shows a lowering of SLP over the East Coast of the US 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 basin-wide shift of
cyclogenesis (defined as the point when 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 (southeast US)
genesis.

5. Track Simulations Using the Beta and Advection Model

a. Beta and Advection Model

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
zonal (u) and meridional (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 Appendix).

A β-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 β-drift with
angles ranging from 295° to 315° and speeds of 1-3 m/s to impose a northwest deviation of the
TC vortex from the environmental flow. In this study, the speed of the β-drift is tuned to provide
the best match between the observed and simulated mean track based on the 1950-2010 historical
climatology. This model uses a constant angle of 315° and allows the β-drift speed to vary from
1.5 to 5 m/s 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 one hour intervals for
the full step. The u and v are calculated as an average value over a 7.5° by 7.5° box centered on
the vortex location to reflect a realistic vortex size from the given reanalysis data for each half
time step 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 versus 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 based on 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

Fig. 9a compares the observed TC tracks to 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.
Fig. 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 RCO storms recurving more, on average, than the RCL storms, indicate that the difference in steering flow between these storms contribute to their differing tracks. However, the RCO storms form, on average, ~10° further west 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 northwesterly 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. Fig. 10a compares the average track 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. Fig. 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 which is responsible for the difference in TC tracks.

For the NAO, only a small difference is found in the observed tracks between storms which 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 phase. 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 southwestward 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 does 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 the HURDAT for the period 1950-2010, we categorize Atlantic TCs which 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 influences the 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 number 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 where the MDR was uniformly-seeded, a difference between RCL and RCO tracks remained, with RCL tracks recurving further westward compared to RCO storms. However, the uniform-seeding simulations for SM storms yield an average track that is much further north than observed and very similar to the average RCO track. This suggests that the tendency for SM storms to form further south and west within the MDR is a key factor in determining their track; i.e., tracks that threaten the Western Caribbean and Gulf Coast of the US. Tracks are an essential aspect to consider for determining trends in hurricane activity, especially when examining TC intensity, as 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 further west when compared to 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 due to 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 does 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 as 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

Using the best track location from the HURDAT, the TC vortex is identified in the corresponding SLP field. A 12.5° by 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, in order to remove the TC vortex, the vorticity

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

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, \( \nabla^2 \psi = \xi \), is computed using the Jacobi iteration method and finite differences. This streamfunction is used to calculate the zonal (u) and meridional (v) wind fields

\[ u = \frac{\partial \psi}{\partial y}, \quad v = \frac{\partial \psi}{\partial x}. \]

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

In order to isolate the vorticity of the TC vortex, a 12.5° by 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 mb, 500 mb, and 200 mb pressure levels.
References


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_____, ______, and M. Sitkowski, 2010: Climate modulation of North Atlantic hurricane


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FIG. 1. The track boundaries for classifying TC tracks. The straight-moving (SM, Green) TCs threatened the Gulf Coast and Western Caribbean. The recurving landfall (RCL, Red) TCs threatened the East Coast of the US. The recurving ocean (RCO, Blue) TCs never threatened the US. All TCs had to form in the Main Development Region (MDR, Gray). a) The TC genesis location for all TCs color coded by category. The larger symbols represent the average genesis location for that track type. b) All 237 TC 10-day (or less) tracks in the sample, color coded by track classification with the track category boundaries. c) The 10 day composite plot of the average track by category with the track category boundaries. The solid black line represents the average track and the cones are +/- one standard error in longitude and latitude for each day.

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FIG. 7. a) 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 value in parentheses denotes the number of TCs included in the frequency distribution for each season or phase.

FIG. 8. The difference colored contours show the average SLP field for August, September, and October of a) all El Niño years subtracted from all La Niña years, b) all NAO negative years subtracted from all NAO positive years, and c) all AMM negative years subtracted from all AMM positive years. The gray contours are the standard error for the SLP field at 0.25, 0.5, 0.75, and 1 mb. The black arrows depict the difference in the average deep layer steering flow. The two tracks represent the 10-day average track of all TCs in the sample during the respective years with the ellipses being +/- one standard error for 0,3,6, and 9 days, respectively. The points show the genesis location for every TC included in the average track.
FIG. 9. a) The average tracks for the three track categories from observations and reproduced by the BAM with a deep steering flow. For the BAM runs, each TC was started at the historical genesis location and run for 10 days. b) The average tracks for the three track categories where the MDR is uniformly seeded in the BAM.

FIG. 10. a) The average tracks for El Niño and La Niña from observations and reproduced by the BAM with a deep steering flow. For the BAM runs, each TC was started at the historical genesis location and run for 10 days. b) The average tracks for El Niño and La Niña where the MDR is uniformly seeded in the BAM.

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