What Governs the Interannual Variability of Recurving North Atlantic Tropical Cyclones?

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ABSTRACT

Recurving tropical cyclones (TCs) can cause extensive damage along the US East Coast and later in their life cycle over Europe as post-tropical cyclones. While the existing literature attempts to understand the drivers of basin-wide and regional TC variability, less work has been undertaken looking at recurving TCs. The roles played by the interannual variabilities of TC frequency and the steering flow in governing recurving TC interannual variability are investigated in this study. Using a track-matching algorithm, we identify observed TC tracks from the HURricane DATabase version 2 (HURDAT2) in the ERA5 and MERRA2 reanalyses. This allows for detailed analysis of the post-tropical stages of the tracks in the observational TC record, enabling robust identification and separation of TCs that recurve.

We show that over 75% of the interannual variance in annual recurving TC frequency can be explained by just two predictors – the frequency of TCs forming in the subtropical Atlantic, and hurricanes (TCs with wind speeds > 33ms\(^{-1}\)) forming in the Main Development Region. An index describing the seasonal mean meridional steering flow shows a weak, non-significant relationship with recurving TC frequency, supported by composite analysis. These results show that the interannual variability in recurving TC frequency is primarily driven by the seasonal TC activity of the MDR and the subtropical Atlantic, with seasonal anomalies in the steering flow playing a much smaller, secondary role. These results help to quantify the extent to which skillful seasonal forecasts of Atlantic hurricane activity benefit regions vulnerable to recurving TCs.

SIGNIFICANCE STATEMENT

Recurving tropical cyclones (TCs) can cause extensive damage to the East Coast of the US, eastern Canada, and Europe. It is therefore crucial to understand why some years have a higher frequency of recurving TCs than other years. In this study, we show that the frequency of recurving TCs is very strongly linked to the frequency that hurricanes (TCs with wind speeds > 33ms\(^{-1}\)) form in the Main Development Region, and the frequency that TCs form in the Subtropical Atlantic. This result suggests that skillful seasonal prediction of hurricane activity could be used to give enhanced seasonal warning to the regions often impacted by recurving TCs.

1. Introduction

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Recurving North Atlantic tropical cyclones (TCs) can pose extreme hazards to the East Coast of the US, and later in their lifecycle over Europe. For example, hurricane Sandy led to over 200 deaths, many of which were in the north-eastern US, a region which does not often see direct impacts from TCs. At the time, Sandy was the second costliest TC in US history, causing over $65 billion USD in damages (Blake et al. 2013).

The steering flow played a clear role in the unusual track of hurricane Sandy. A ridge over the north-west Atlantic Ocean drove a south-easterly steering flow towards the north-east US. The steering effect of the ridge, along with favorable interaction with an upper-level trough to the north-west, were ultimately responsible for the strength and track of Sandy in the latter stages of its lifecycle (Varlas et al. 2019). For a TC to be classified as recurving using existing methods (such as described in Archambault et al. (2013) and Riboldi et al. (2018)), a TC must change its direction of travel from westwards to eastwards while travelling poleward. TCs like Sandy which travelled north-west and then north-east for a time would therefore be classified as recurving TCs, even though they might not traditionally be thought of as recurving TCs (as they do not have the classical “C” shape track). In this study, we are interested in TCs which pose risk to land regions in the North Atlantic midlatitudes (such as the US East Coast and Europe). We therefore define a recurving TC as any North Atlantic TC which enters the North Atlantic midlatitudes in the domain 36-70°N, 82°W-30°E with no requirement for a change in zonal direction of travel.

Recurving TCs can also cause damage across Europe (Dekker et al. 2018; Laurila et al. 2020), particularly in the form of extreme precipitation, strong winds and large waves (Evans et al. 2017; Jones et al. 2003). Ex-hurricane Ophelia was responsible for Ireland’s strongest wind gust on record of 119mph in 2017, and ex-hurricane Charley brought severe flooding to parts of the UK and Ireland in 1986 (Hickney and Connolly-Johnston 2012). Post-tropical cyclones (PTCs) are a robust feature of mid-latitude and European storminess during hurricane season (Baker et al. 2021) but are also disproportionately responsible for high impact windstorm risk. Recent work has shown that, despite accounting for less than 1% of
all cyclones to impact Northern Europe during the North Atlantic hurricane season, PTCs represent 9% of all cyclones with storm-force (>25ms$^{-1}$) winds (Sainsbury et al. 2020).

Given the risk associated with recurving TCs to the East Coast of the US and later in their lifecycle over Europe, it is crucial to understand what governs the interannual variability of the frequency of recurving TCs. One possible driver of recurving TC frequency is basin-wide TC frequency. The 2005 North Atlantic hurricane season produced 16 recurving TCs, more than any other year considered in this study (1979-2018). This year also contained the highest number of TCs in the North Atlantic. The greater the number of TCs in the North Atlantic, then the more opportunities there are for TCs to recurve. It is therefore hypothesized that TC frequency is strongly associated with recurving TC frequency.

The physical drivers of basin-wide TC frequency are well understood, with contemporary statistical, dynamical (e.g. Camp et al., 2015; Murakami et al., 2016; Murakami et al., 2016a) and hybrid models now exhibiting good skill at predicting basin-wide TC activity before the onset of peak hurricane season activity (Klotzbach et al., 2019). Forecasts and observations of large-scale environmental fields over the tropical North Atlantic during and prior to hurricane season, which have been shown to have a strong physical link with hurricane season activity (Saunders et al., 2017) explain approximately 60% of the variance in hurricane season activity, allowing for skillful seasonal forecasts from July 1st (Klotzbach, 2014).

Boudreault et al. (2017), Kossin et al. (2010) and Kozar et al. (2012) use various clustering techniques to segregate North Atlantic TCs into 4 different groups, in order to understand the drivers of the interannual variability in these groups of TCs. It was found that the frequency with which TCs form in the deep tropics is strongly modulated by the Atlantic Meridional Mode (AMM) and El Niño Southern Oscillation (ENSO), whereas higher latitude TC frequency is modulated by the NAO (Elsner et al., 2000; Kossin et al., 2010). The frequency with which storms form in the Gulf of Mexico is also strongly modulated by ENSO (Boudreault et al. 2017), whereas the frequency with which storms originate in the northern and eastern parts of the basin are modulated by the subtropical high (Kozar et al. 2012).

While the steering flow on the daily timescale is important for the evolution and track of recurving TCs (such as in the case of Sandy), the role of the steering flow on the seasonal timescale is not as well understood. However, as the mean steering flow may alter the typical trajectory of TC tracks over the hurricane season, it may modulate recurving TC frequency.
The seasonal mean steering flow is therefore a second possible driver of recurving TC frequency.

By subsampling the HURDAT database to investigate Main-Development Region (MDR) storms only, Colbert & Soden (2012) investigate the role of the steering flow on North Atlantic hurricane tracks by segregating storms into three categories based on recurvature: straight moving, recurving land and recurving ocean. It was found that recurving ocean storms were associated with a weakening of the North Atlantic subtropical high (NASH) on the timescale of individual storms. On the seasonal timescale, the fraction of storms which ended up in the recurving ocean category was highest during El Niño years and years with a positive AMM. Recent work has also shown that during strong Indian Monsoon years, the strength of the NASH is enhanced, leading to increased landfall probability of MDR TCs (Kelly et al. 2018).

The relative importance of the interannual variabilities in hurricane season activity (TC frequency) and steering flow in the North Atlantic to recurving TCs remains unknown from a climate perspective. In this paper, we investigate the relative importance of both the interannual variabilities of the seasonal mean steering flow and TC frequency in governing recurring TC frequency in the North Atlantic. This is achieved by constructing a statistical model to quantify the variance in recurring TC frequency that can be explained by regional TC activity, and by presenting a composite analysis to investigate the role of the steering flow on the seasonal timescale.

The paper continues in section 2 with a description of the data used, along with details of the TC feature-tracking scheme, the spectral filtering technique used to isolate the background flow, and an objective track-matching algorithm used to identify recurvature. Section 3 contains an analysis of track and genesis differences between recurving and non-recurving TCs, a composite analysis to investigate the role of the steering flow, and an analysis of the statistical model. The paper concludes with a summary and discussion in section 4.

2. Methods and Data

Observational best track data do not always contain information on the position and intensity of TCs after they have been designated as post-tropical (Hagen et al. 2012; Delgado et al. 2018). In addition, the eastern boundary of the National Hurricane Center (NHC) area
of responsibility was only extended eastward from 35°W to the coasts of Africa and western Europe in 2005 (Rappaport et al. 2009), possibly introducing more inhomogeneities to the observational record for TC tracks. TC tracks are often limited to their tropical phase, making it difficult to consistently separate the TCs which recurve from those that do not when using best track data. To overcome this, we first track all Northern Hemisphere cyclonic features in two reanalysis datasets. We then use an objective track matching method to identify the TCs in the HURricane DATabase version 2 (HURDAT2) (Landsea and Franklin 2013) that are present in these reanalyses, thereby giving us an extended track that includes the storms’ post-tropical evolution. A TC is then classified as either recurving or non-recurving depending on whether the corresponding track in the reanalysis enters a domain in the North Atlantic from 36-70°N, 82°W-30°E. A boundary of 36°N was chosen because almost all (~98%) TC genesis in the North Atlantic occurs equatorward of this latitude band (see Figure 1), so for a TC to enter this domain it (almost always) gains latitude. A western boundary of 82W is used because this allows for all TCs traversing the East Coast to be identified as recurving, along with those that recurve farther east in the basin. The sensitivity of the results presented here have been tested on a second domain, extending from 36-70°N, 70°W-30°E, to ensure that results are robust to changes in the definition of recurvature.

a. Datasets

Two different reanalyses are used to test the sensitivity of our results to the reanalysis product. We use the ERA5 (Hersbach et al. 2020) and MERRA2 (Molod et al. 2015; Gelaro et al. 2017) reanalyses to provide the 6-hourly relative vorticity fields which are necessary for the cyclone detection and tracking scheme (600, 700 and 850hPa, vertically averaged). We also use 6-hourly wind (u and v) fields at 200, 500, 700 and 850hPa pressure levels to construct seasonal mean wind fields for composite analysis and for the construction of a meridional steering flow index. The 6-hourly mean sea level pressure (MSLP) data is also used after removing the TC vortices to construct seasonal means for composite analysis.

ERA5 is based on the Integrated Forecasting System cycle 41r2. Data from 1979 to 2018 are used because despite being available, the back-extension to 1950 is not yet deemed suitable by the ECMWF for TC analysis due to an unrealistic representation of TC intensity (Bell et al. 2021). ERA5 is chosen based on its high horizontal resolution and four-dimensional variational data assimilation scheme, which have been shown in previous reanalyses to improve the representation of the location and intensity of tropical cyclones (TCs). MERRA2

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uses the GEOS 5.12.4 data assimilation system, which comprises the GEOS atmospheric model and GSI analysis scheme (Gelaro et al. 2017). MERRA2 data is used from 1980-2016. The figures presented in this paper contain ERA5 data only, and corresponding figures created using MERRA2 data are available in the supplementary material (Figures S1-S4, S10). This is done for simplicity and to avoid duplication, because the MERRA2 results in the supplement are very similar to the results presented in the main manuscript. Observational best track data from the HURDAT2 are also used between 1979 and 2018.

b. Spectral filtering

Spectral filtering using a spectral transform based on spherical harmonics is utilized in two different ways in this study, using the functionality of the cyclone detection and tracking scheme, TRACK (section 2c). In the first instance, spectral filtering is applied to the relative vorticity fields necessary to detect and track the cyclones. The vertically averaged 600-850hPa relative vorticity field is spectrally filtered to a spectral resolution of T63 (approximately equivalent to 200km in the midlatitudes), and waves with a total wavenumber of less than 6 are removed. This removes the smallest horizontal scales and the planetary scale waves, isolating the vorticity scales relevant for cyclone detection and tracking.

Section 3c contains composite analysis which is used to investigate the large-scale environmental flow during years of high and low recurving TC activity. To ensure that the fields used contain a minimal signature of the recurving TC vortices themselves, the reanalysis data is also spectrally filtered. This is performed on the global, 6-hourly reanalysis fields for MSLP and wind (u and v). The data are truncated to a T11 spectral resolution (approximately 10 x 10 degrees) globally (but output on the original grid), which removes approximately 95% of the circulation associated with the vortices. For further information, see Bhatia et al. (2020). On the seasonal timescale used in this paper the differences between the spectrally filtered flow and the non-filtered flow are relatively small. Some differences exist in the composite plots (Figures 4-6) depending on whether spectrally filtered data is used or not (see Figure S9 in the supplementary material). However, these differences do not alter the interpretation of the figures. For consistency, the spectrally filtered data is used throughout.

c. Cyclone detection and tracking

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Cyclone detection and tracking is performed using the tracking scheme of Hodges (1994, 1995, 1999) (named TRACK) configured for TCs. Vertically averaged 6-hourly relative vorticity fields at the 600, 700 and 850hPa pressure levels are used to perform the tracking. The vertically averaged vorticity is first spectrally filtered as described in section 2b. Features are first identified with a T63 vorticity maximum exceeding $0.5 \times 10^{-5} \text{s}^{-1}$, and then refined by identifying the off-grid locations using B-spline interpolation and maximum ascent optimization (Hodges 1994). These features are tracked and retained as cyclones. Tracks which have a lifetime less than two days are then removed. Further details on the configuration of the tracking scheme used in this study are available in Hodges et al. (2017). Cyclone detection and tracking is performed for the entire Northern Hemisphere for both reanalyses, and systems which pass though the North Atlantic basin are then selected.

d. Objective track matching

A reanalysis cyclone track matches that of a HURDAT2 track if there is temporal overlap of the 6-hourly time steps and the mean separation distance between the reanalysis track and the HURDAT2 track is less than 4 geodesic degrees for all overlapping time steps. If there is more than one reanalysis cyclone track which satisfies this criterion, then the reanalysis cyclone track which has the smallest mean separation distance to the HURDAT2 track is chosen (Hodges et al., 2017; Hodges & Emerton, 2015). A small proportion (~5%) of the TCs in HURDAT2 are not identified in the ERA5 and MERRA2 reanalyses and are excluded from the analysis. These tend to be weak, short-lived systems (Sainsbury et al. 2020) and their exclusion does not affect the results of this study.

e. Track and genesis density statistics

The spherical kernel method of Hodges (1996) is used to show the spatial distribution of the TC tracks. Statistical significance in the spatial distribution differences of recurving and non-recurving TCs is tested using the Monte Carlo approach described in Hodges (2008). Densities are calculated per unit area per year, where the unit area is equivalent to a spherical cap with a radius of 5 degrees.

f. Regional selection and recurvature definition

The matched TCs are separated according to 3 regions (shown in Figure 1), based on their genesis location in HURDAT2. These 3 regions are the MDR (10-70°W, 6-20°N), Subtropical Atlantic (SUB, 10-82°W, 20-50°N), and the region comprising the Gulf of
Mexico and South Caribbean, denoted WEST ((8°N, 70°W), (8°N, 90°W), (16°N, 90°W),
(16°N, 100°W), (33°N, 100°W), (33°N, 82°W), (20°N, 82°W) and (20°N, 70°W)). The
choice of 3 regions is subjective, but the regions themselves each have a physical basis. The
MDR TCs typically form from African Easterly Waves unlike the TCs in the other two
regions (Caron and Jones 2012; Arnault and Roux 2011). In the SUB region, TCs often form
under marginal conditions for tropical cyclogenesis. This region also contains TCs which
form via tropical transition, with precursors of extratropical origin (Kossin et al. 2010). The
TCs forming in region WEST often encounter the most favorable thermodynamic conditions
for intensification (for example, see potential intensity map (Figure 3) in Camargo et al.,
(2013)), with the main inhibitor of intensification often being the proximity to land. The 3
regions also have broadly different seasonal mean values of vertical wind shear (e.g. Figure
3, Aiyyer & Thorncroft, (2006)). The 3 chosen regions therefore allow for a zonal and
meridional separation of tracks based on genesis, thermodynamic and dynamic conditions,
and precursor type.

The choice is made to group storms into these three regions based on the factors which may
be important for recurvature. An obvious factor is proximity to the mid-latitudes – a TC
forming at higher latitudes is unlikely to be influenced by the strongest easterly trades which
steer TCs zonally, and thus may be more likely to recurve. A second justification is the
differing thermodynamical and dynamical conditions in the three regions, which largely
control the lifetime maximum intensity (LMI) of the TCs. TCs which form in regions
climatologically more conducive for intensification will often attain higher intensities, and
the resilience associated with stronger TCs is likely key to their longevity and ability to
maintain their structure in hostile environments, which may lead to an increased probability
of recurvature.

Many studies (e.g. Boudreault et al., 2017; Kossin et al., 2010; Kozar et al., 2012) use
clustering methods to group TCs, rather than regional boundaries which are used here and in
Colbert & Soden (2012). Despite these differences in methodology, the three TC regions used
here can be related to the TC classifications used in other studies. TCs in SUB, WEST and
MDR are closely related to clusters 1, 2 and 3 respectively in Kossin et al. (2010) and Kozar
et al. (2012). Cluster 4 in these studies mainly relates to TCs forming in the MDR and WEST
regions. TCs forming in the SUB and WEST regions are similar to clusters 1 and 2 in
Boudreault et al. (2017), with clusters 3 and 4 in this study relating to MDR recurving and
MDR non-recurving TCs respectively. These three previous studies all used a similar clustering technique, which is more readily able to distinguish tracks based on their genesis location than the K-means method used in many other studies of TC clustering (e.g. Harr & Elsberry, 1995).

The TCs in each region are designated as recurving if their ERA5/MERRA2 matched track enters the domain defined as 36-70°N, 82°W-30°E (shaded box, Figure 1). This method for identifying recurvature is different to that used by Colbert & Soden (2012), in which the degree of recurvature (either straight moving, recurving-land or recurving-ocean) associated with a TC is determined based on which spatial boundary the HURDAT TC track intersects. Our method of vorticity-based tracking allows us to extrapolate the TC tracks present in HURDAT2, giving us a more robust separation of tracks based on their recurvature.

g. Multiple linear regression model

We use multiple linear regression to quantify the variability in recurving TC frequency that is associated with TC activity in the North Atlantic. There are several candidates for predictors, including basin wide TC frequency and regional TC frequency in the North Atlantic, with and without intensity constraints. Using the analysis presented in sections 3a and 3b, a multiple linear regression model is fit using the two most suitable predictors.

\[
\text{Rec}_{TC} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \epsilon, \quad (1)
\]

where \(\beta_0, \beta_1\) and \(\beta_2\) are coefficients to be fitted, \(x_1, x_2\) are the two chosen predictors, and \(\epsilon\) represents the residuals.

3. Results

a. Historical TC recurvature statistics

Figure 1 shows the genesis location for all TCs in HURDAT2 between 1979 and 2018, along with the boundaries for each of the 3 regions that the TCs are separated into. The shaded region represents the domain used to define recurvature. It should be noted that there is an overlap between the SUB region and the recurvature domain, with 12 TCs (<2% of all TCs considered in this study) identified as recurving by virtue of their genesis location. The sensitivity of the results to these overlapping TCs has been tested, and the results remain
unchanged whether they are excluded from the analysis or not. As a result, we include these TCs in the analysis of this paper. The SUB region is the largest spatially and contains the largest number of recurving TCs of any of the 3 regions. It also contains the highest fraction of recurving TCs at 76.6% (Table 1). TCs forming in this region form poleward of the strongest easterly trade winds and are also closer to the midlatitude westerly flow. The mean genesis latitude of recurving SUB TCs is 4 degrees farther poleward than for the non-recurving TCs (29.5°N and 25.5°N for recurving and non-recurving TCs respectively), and this difference is significant to 95% using a student’s t-test.

![Figure 1: Genesis location (HURDAT2) of all recurving (red) and non-recurving (blue) TCs forming in the North Atlantic from 1979-2018. The 3 domains overlaid represent the 3 sampling regions used in this study: MDR (lower right), SUB (upper right), and WEST (left). Shaded region represents the domain used to define recurvature. Larger dots represent the mean genesis location in HURDAT2 for the tracks in the region.](image)

The MDR contains the largest number of TCs of any of the 3 regions, approximately 48% of which recurve. The mean longitude of genesis for TCs in this region is similar for both recurving and non-recurving TCs at 38.3°W and 38.5°W, respectively. Although small, the
differences in the mean genesis latitude of recurving and non-recurving TCs in the MDR (13.2°N and 12.5°N) are also statistically significant to 95%.

Only a quarter of TCs forming in the WEST region recurve, and TCs in the WEST region account for only 15% of the overall number of recurving TCs. No significant differences in mean position exist between the recurving and non-recurving TCs in this region. Overall, Figure 1 suggests that both the zonal and meridional location of TC genesis are associated with TC recurvature, with TCs forming in regions farther polewards and eastwards in the basin comprising the highest proportion of recurving storms. A summary of this information can be found in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>MDR</th>
<th>SUB</th>
<th>WEST</th>
<th>Whole North Atlantic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recurring</td>
<td>121</td>
<td>144</td>
<td>48</td>
<td>313</td>
</tr>
<tr>
<td>Non-recurring</td>
<td>130</td>
<td>44</td>
<td>122</td>
<td>296</td>
</tr>
<tr>
<td>Total</td>
<td>251</td>
<td>188</td>
<td>170</td>
<td>609</td>
</tr>
<tr>
<td>% Recurring</td>
<td>48.2%</td>
<td>76.6%</td>
<td>28.2%</td>
<td>51.4%</td>
</tr>
</tbody>
</table>

**Table 1:** Summary of the number of recurving (top), non-recurving (second row), and total (third row) TCs, along with the % TCs which recurve in each of the 3 sampling regions displayed in Figure 1. Right hand column gives the basin-wide statistics.

**b. Regional historical TC statistics**

1. **HISTORICAL TC TRACK AND PRECURSOR GENESIS DENSITIES**

Track and genesis densities are calculated for recurving and non-recurving TCs using the ERA5 reanalysis tracks which have been separated by their region of formation as defined by HURDAT2. Genesis densities outside of each region (which are denoted by the red boxes) are non-zero in some areas. This is because we are assigning storms to a region using HURDAT2 genesis location but calculating genesis and track density using the corresponding ERA5 tracks, where the pre-TC lifecycle stages are identified. Figure 2 is therefore showing the TC precursor genesis density. Another reason for the non-zero
densities outside of the regions is because the densities are calculated for a unit area using the kernel method, with kernels that spread the influence of a data point depending on their bandwidth. Differencing (recurving minus non-recurving) the track and genesis densities will highlight if there are important differences in genesis within regions and will also indicate where in the TCs lifecycle the trajectories start to differ. In the MDR and SUB regions, the differences in the track density are meridional – with significant negative (lower recurving TC density) differences equatorward, and positive differences (higher recurving track density) poleward. However, in the WEST region the differences are much more zonal, with more recurving TCs in the east of this region (Figure 3).

![Figure 2](image_url)

**Figure 2**: Normalized genesis density for the recurving (top) TCs, non-recurving (middle) TCs and recurving minus non-recurving (bottom) in the 3 sampling regions displayed in Figure 1. Boundaries for each region are displayed in red. Densities (and differences) less than 1 have been masked for clarity. Stippling denotes significance at the 95% level. Densities are calculated as the number of cyclones per year per unit area, where the area is a 5-degree radius spherical cap. The densities are normalized to account for differences in sample sizes in the difference panels (a-f) by dividing by the number of cyclones in the sample.
Most of the recurving TCs forming in the MDR cross the northern boundary of the region, whereas the non-recurving MDR TCs mainly track out of the western edge (Figures 3a,d). Track density values for the non-recurving TCs decrease substantially to the west and north of the MDR region, in part due to a broadening of the distribution from east to west, but also because approximately 40% of the non-recurving MDR TCs dissipate before leaving the region. Despite these differences in track density, the difference in precursor genesis density in this region is small (Figure 2g).

Significant differences can be seen in the track and genesis densities for TCs forming in the SUB region, with recurving TCs forming farther north and west than non-recurving TCs, which form primarily on the border between the MDR and SUB regions (Figures 2b,e). This agrees with the significant difference in the genesis latitude of recurving and non-recurving TCs seen in Figure 1 and indicates that the location of precursor genesis is also significantly different for the recurving and non-recurving TCs in the SUB region. The non-recurving TCs in the SUB region gain little latitude and either travel eastwards and decay in the subtropical North Atlantic or reach the Caribbean and southeast US (Figure 3e).

![Figure 3](image_url)

**Figure 3**: Normalized track density for the recurving TCs (top), non-recurving TCs (middle), and recurving – non-recurving (bottom) TCs in the 3 sampling regions displayed in Figure 1. Boundaries for

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Each region are displayed in red. Densities (and differences) less than 5 have been masked for clarity. Stippling denotes significance at the 95% level. Densities are calculated as the number of cyclones per year per unit area, where the area is a 5-degree radius spherical cap. The densities are normalized to account for differences in sample sizes in the difference panels (a-f) by dividing by the number of cyclones in the sample.

Few differences exist between the recurving and non-recurving TC genesis densities in the WEST region, but track density differences are seen. The recurving TCs forming in WEST impact the states bordering the eastern side of the Gulf of Mexico, whereas the non-recurving TCs forming in this region often impact Central America. This can be seen in the differenced track density plots for this region (Figure 3i).

2. LIFETIME MAXIMUM INTENSITY DISTRIBUTIONS

Inherent to TC recurvature is longevity (particularly for storms forming in the MDR) – stronger TCs may be more resilient to hostile environments, and as a result, last longer. For a MDR TC to recurve, it often must endure less than ideal sea surface temperatures, an environment which may be too hostile for most weak TCs. We therefore investigate the lifetime-maximum intensity (LMI) distributions for recurving and non-recurving TCs in the 3 genesis regions used to partition the TCs. These are shown in Figure 4. Across much of the North Atlantic basin (WEST and SUB regions), there are small (but statistically significant at 95% by a Kolmogorov-Smirnov test) differences between the LMI distributions of recurving and non-recurving TCs. However, in the MDR there is a large significant difference (Fig. 4a). The non-recurving TCs tend to be considerably weaker at their LMI than recurving TCs. 40% of non-recurving TCs which form in the MDR dissipate before leaving the region, attaining a low LMI.
Figure 4: Probability distributions of Lifetime maximum Intensity (LMI) for all recurving (red) and non-recurving (blue) TCs in the North Atlantic, 1979-2018, for the 3 regions displayed in Figure 1. Densities have been calculated using a kernel density estimation.

Recurvature of TCs in the MDR is linked to the strength and westward extent of the North Atlantic subtropical high (NASH) (i.e. the steering flow), with TCs often recurving around the western edge of the high (Colbert and Soden 2012). Some MDR TCs die out before reaching the western edge of the subtropical high and as a result, are classified as non-recurving. Another possible reason that recurving TCs have higher LMI is beta drift (Wang et al. 1998). This drift is usually of the order of a few meters per second (Wang et al. 1997) with stronger TCs drifting poleward out of the easterly trade winds faster than weaker TCs (Colbert and Soden 2012). The recurving TCs also have a longer track over the ocean, potentially allowing those tracking over the warm Gulf Stream to attain greater intensities.

c. Predictors of recurving TC frequency

In this section, we first explore the role of the steering flow in modulating the number of recurving TCs. In section 3c.1. the focus is on TCs forming in the MDR, and in section 3c.2. we investigate TCs forming in the SUB region.

1. THE STEERING FLOW (MDR)

To investigate the role of the seasonal mean steering flow on TC recurvature for storms originating in the MDR, we use the deep-layer flow, $\mathbf{V}_{DLS}$ (Equation 2), defined previously by Colbert and Soden (2012). The subscripts represent the pressure level (in hPa) at which the flow is used. The MSLP is also used to determine the strength and position of the NASH, the westward extent of which was shown by Colbert and Soden (2012) to modulate TC
recurvature from the MDR. In the construction of Figures 5 and 6, spectral filtering is performed on the MSLP and wind field data as described in section 2b.

\[ \mathbf{V}_{DLS} = 0.25\mathbf{V}_{200} + 0.5\mathbf{V}_{500} + 0.25\mathbf{V}_{850} \]  

(2)

Figures 5a and 6a show the difference in the composite mean August, September, October (ASO) deep layer flow and MSLP respectively, between years which have a very high number and a very low number of recurving TCs originating in the MDR, defined as (number > mean + 1 standard deviation) and (number < mean – 1 standard deviation).

Figures 5b and 6b show the differences between years which have a high (number > mean) and low (number < mean) number of recurving TCs originating in the MDR. Of the 40 years used in our analysis, 9 years have very high activity, 11 years have very low activity, 17 years have high activity and 23 years have low activity.

Figure 5: Composite differences in the deep layer flow (wind vectors), calculated from T11 spectrally filtered wind fields, based on the number of recurving TCs which form in the MDR. (a): very high minus very low, (b): high minus low. Red lines represent the 1550m contour for the ASO 850hPa geopotential height during years of very high (solid) and very low (dashed) recurving TC frequency originating in the MDR (5a) and during years of high (solid) and low (dashed) recurving TC frequency originating in the MDR (5b). Filled contours show the composite difference in the meridional component of the ASO deep layer steering flow.

Figure 5a shows anomalously strong south-easterlies over the central Subtropical Atlantic during years where there is a very high number of recurving TCs originating in the MDR. Figure 5b also shows the same anomalous meridional flow in the subtropical Atlantic, but this time centered approximately 10 degrees farther west. This anomalous flow may steer TCs which formed in the MDR on a poleward trajectory, directing them away from the easterly trade winds before they have tracked to the western side of the basin. This is consistent with Fig. 3a, in which the recurving TCs originating in the MDR see an increase in

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their poleward translation speed in the central Atlantic. At this point in their life cycle, some of the TCs may still be weak. Red contours in Figures 5a and b show the 1550m 850hPa geopotential height contour for the composites, to illustrate the westward extent of the NASH. During years of high MDR-originating recurving TC frequency, the westward extent of the NASH is reduced (solid lines) compared to years of low frequency (dashed), in agreement with Colbert and Soden (2012).

The sensitivity of the measure used to characterize the steering flow is tested by replicating the composites using a lower level flow (such as described in Chan & Gray, 1982). Recreating Figure 5 using the 700hPa flow shows the same anomalous flow pattern as seen in the subtropical Atlantic in Figure 5, however in this case the anomalous poleward flow extends farther equatorward in to the MDR (see Figure S7, supplementary material).

**Figure 6:** Composite differences in the ASO mean MSLP field, constructed from 6-hourly T11 spectrally filtered MSLP data. Composites are based on the number of recurving TCs which form in the MDR. (a): very high minus very low, (b): high minus low. Stippling denotes significance at 95% using a student’s t-test.

Both Fig. 6a and 6b show a significant negative difference in the ASO MSLP field in the tropical Atlantic and the western subtropical North Atlantic towards the east of the south-east US. This suggests that during years when there are a larger number of recurving TCs originating in the MDR, the MSLP in the western subtropical Atlantic is anomalously low. This is physically consistent with the results of Colbert and Soden (2012) and Figure 5 and is indicative of higher TC recurvature coinciding with reduced westward extent of the NASH. The anomalously low MSLP in the western subtropical North Atlantic may promote the development of MDR-originating recurving TCs during years of high MDR-originating recurving TC frequency, whilst the anomalously high MSLP in this region suppresses their
development and prohibits their northward migration during years of low MDR-originating recurving TC frequency. However, the significant difference between the composites is not confined to the western subtropical Atlantic and can also be seen in the tropical Atlantic and Caribbean. Negative MSLP anomalies in these regions are associated with decreased atmospheric stability (and therefore increased vertical motion), reduced vertical wind shear, and increased mid-level humidity and temperature, leading to higher TC frequency in the MDR (Klotzbach, 2007; Knaff, 1997; Saunders et al., 2017). Despite compositing based on recurving TC frequency, the difference between the composites could also arise due to differences in the suitability for TC genesis in the MDR, which leads to differences in recurving TC frequency and indicate a strong association between the TC frequency and recurving TC frequency.

When repeating the analysis in section 3c.1 using MERRA2 spectrally filtered fields (Figures S1 and S2) instead of ERA5, the results are like those presented here (Figures 5 and 6), with an anomalous south-easterly flow being present during years which have a high number of recurving TCs. There is a negative difference in MSLP in the western subtropical Atlantic, tropical Atlantic and Caribbean as is shown in Figure 6, however the MERRA2 composites have slightly larger differences, and the largest differences are centered more over the Caribbean for the very high minus very low activity composite.

2. THE STEERING FLOW (SUB)

The analysis shown in section 3c.1 is expanded, this time with composites constructed around the number of recurving TCs which form in the SUB region. Composites are comprised of 6 years which have very high and very low activity, 19 years which have high activity, and 21 years which have low activity. As TCs forming in the SUB region often have much lower LMI (Figure 4) than those forming in the MDR, they may not extend the entire depth of the troposphere. As a result, the lower tropospheric flow may be a better proxy for their steering flow than the average flow over the entire depth of the troposphere. Figure 7 shows the composite mean difference in the ASO 700hPa flow for years which have been separated based on SUB recurving TC activity. Anomalous cyclonic flow exists in the subtropical Atlantic during years with many recurving TCs originating in the SUB region. This leads to an anomalous north-easterly flow along the coast of eastern Canada and the northeast US. This flow is in the opposite direction to which the recurving TCs forming in the SUB region track (Fig 3a) and as a result, it does not appear that the anomalous flow pattern...
would aid TC recurvature. It is therefore unlikely that the seasonal mean steering flow plays a
direct role in modulating the recurving TC frequency in the SUB region during the 1979-
2018 period. Figure 7 is repeated using the deep layer flow (Equation 2), and the flow pattern
is the same (Figure S8).

Figure 7: Composite differences in the ASO mean 700hPa wind field (wind vectors), constructed
from 6-hourly T11 spectrally filtered 700hPa (u and v) data (all days in ASO). Composites are based on
the number of recurving TCs which form in SUB. (a): very high activity minus very low activity, (b): high
activity minus low activity. Filled contours show the composite difference in the meridional component of
the ASO 700hPa flow.

The anomalous cyclonic circulation that exists in the subtropical North Atlantic during
years in which there are a high number of recurving SUB TCs is associated with a reduction
in the intensity of the NASH. This may lead to increased TC activity in the SUB region. This
contrasts with Figure 5, wherein the NASH intensity does not differ between years of high
and low MDR-originating recurving TC frequency, but where instead the location of the
NASH may be more important. The potential relationship between NASH intensity and SUB
TC genesis agrees with Kossin et al. (2010), who suggested that a negative NAO (weaker
NASH, higher SLP over Iceland) is associated with a higher TC frequency in the subtropical
North Atlantic (‘cluster 1’ therein). Correlation maps between annual SUB TC frequency and
the meridional 700hPa flow show that whilst correlations do exist in the subtropical North
Atlantic between the circulation anomalies and TC activity, these correlations are weak
(r~0.3) (Figure S6, supplementary material). Figure 7 is not sensitive to the reanalysis used,
with the MERRA2 composite supporting the analysis presented here (Figure S3).

3. REGIONAL TC ACTIVITY

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In this section, we explore the association between basin-wide TC frequency and recurving TC frequency. To quantify the variability in recurving TC frequency that is associated with TC activity, a multiple linear regression (MLR) model for recurving TC frequency is constructed using two predictors: The number of hurricanes forming in the MDR each year, and the number of TCs (storms of any intensity if present in HURDAT2) forming in the SUB region each year. These predictors are chosen because 85% of recurving TCs originate in either the MDR or SUB regions (Table 1). The majority (81%) of recurving TCs originating in the MDR are of hurricane strength (1-min sustained winds > 33 ms\(^{-1}\)) at their LMI (Figure 4). Whilst Figure 4 indicates that recurving TCs have a statistically significantly higher LMI in all 3 regions, the difference between the distributions is considerably larger in the MDR. While stronger TCs are more likely to recurve, MDR major hurricane frequency is not as strongly associated with recurving TC frequency as MDR hurricane frequency ($R^2$ of 44.2% and 19.7% for MDR hurricane frequency and MDR major hurricane frequency, respectively). This may be because much of the North Atlantic capable of supporting major hurricanes resides in the western side of the basin, where storms have a higher probability of making landfall and subsequently dying out. As a result, the predictors used are MDR hurricane frequency and SUB TC frequency.

Ordinary least squares assumptions are satisfied – there is no collinearity between MDR hurricane number and SUB TC number. The residuals are approximately normally distributed, tested using a Kolmogorov-Smirnov test, and both predictor terms are significant, each explaining a comparable amount of variance of recurving TCs. The variance in the residuals also does not depend on the value of the predicted variable. The fitted MLR model is shown in Equation 3, where $Rec_{TC}$, $MDR_H$, and $SUB_{TC}$ denote recurving TC frequency, MDR hurricane frequency and SUB TC frequency, respectively.

$$Rec_{TC} = 1.053MDR_H + 0.7539SUB_{TC} + 0.964 + \epsilon$$  \(3\)

As this model uses only two predictors, it is unlikely that there is any substantial overfitting. This is tested and confirmed in Figure 8b and 8c. Using 20 years of data, randomly selected to train the MLR model, the model is then tested on the remaining 20 years of data. This process is iterated 100,000 times to produce the $R^2$ distribution shown, which has a mean of 75% and a 95% confidence interval of 56-88%, indicating that there is

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no substantial overfitting and that the model performs well on the test data. Iterating the
process gives us approximately 50,000 predictions for the number of recurving TCs for each
year, which are used to construct the 95% confidence interval shown by the shading in Figure
8.

The resulting MLR model explains 81% of the variance (using all data for the MLR fit)
and has an $R^2$ of 79% when using a leave-one-out cross-validation. Using all data in the
regression, the individual $R^2$ values for the relationship with recurving TC frequency are
33.9% and 42.2% for SUB TC frequency and MDR hurricane frequency, respectively. Figure
8 shows that the interannual variability in the recurving TC number is captured extremely
well by the model, indicating that activity in the MDR and SUB regions of the North Atlantic
explain most of the variance in the interannual variability of recurving TC frequency.
Figure 8: (a): Recurring TC frequency in the North Atlantic basin between 1979 and 2018 (red) and expected recurring TC frequency in the North Atlantic basin over the same time period, predicted using the multiple linear regression model described in Equation 3 (blue). Probability distributions of $R^2$ (b) and RMSE (c), calculated using a half-and-half test iterated 100000 times. Shaded region represents the 95% confidence interval, calculated from the half-and-half test.

Poisson regression is often used to investigate the drivers of TC activity (Boudreault et al., 2017; Elsner et al., 2000; Elsner, 2003; Elsner et al., 2001; Elsner, 1993; Kossin et al., 2010; Kozar et al., 2012; Murakami, et al., 2016a) due to the discrete nature of TC counts. To establish robustness, the results presented in Figure 8 were also reproduced using a Poisson regression model with a logarithmic link function and the results support the analysis presented in this paper (Figure S12, supplementary info).

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The sensitivity of the results in figure 8 have been tested extensively by changing the domain used to define TC recurvature (Figure S13), changing the reanalysis used to track the post-tropical stage of the TCs (Figure S10), and changing the TCs used in the analysis (all TCs in HURDAT vs named storms only, Figure S11). All of these changes lead to a model which has a fit just as good as presented in Figure 8.

As TC frequency explains a large fraction of the variance of recurving TC frequency, we investigate the SST anomalies in the North Atlantic during years of high and low MDR hurricane frequency and SUB TC frequency. The SUB TC frequency is not strongly related to tropical Atlantic SSTs and the ENSO state, agreeing with Kossin et al. (2010), however positive SST anomalies exist along the midlatitude US East Coast during high SUB TC frequency years (Figure S16). MDR hurricane frequency is highest during La Nina years and years in which there is a positive SST anomaly in the tropical North Atlantic (Figure S15), which is anticipated based on previous studies (Klotzbach et al. 2017; Landsea et al. 1999; Vecchi et al. 2011).

While the focus of this study is on recurving TCs, it is sensible to ask whether such a strong relationship is seen between TC activity and non-recurving TC frequency. Separating our 40-year dataset into the 20 years which have a frequency of recurving TCs above and below the mean, we find that the ratio (recurving TCs/non-recurving TCs) is over twice as high for years which have a recurving TC frequency greater than the mean (1.7 and 0.8 for years above and below the mean respectively). This indicates that years which have a high recurving TC frequency do not necessarily have a high non-recurving TC frequency. However, the correlation between non-recurving TC frequency and basin-wide TC frequency is extremely high (r~0.8). For recurving TCs, the relationship is with TC activity in the MDR and SUB regions, however for non-recurving TC frequency, we would anticipate the relationship to be with TC activity in the WEST region, in which most TCs do not recurve (Figure 1). This would explain why there is a significant relationship between both recurving and non-recurving TC frequency and basin-wide TC frequency, but no significant relationship between recurving and non-recurving TC frequency directly.

d. Relative importance of steering flow and TC activity

Figures 5 and 6 indicate that the MSLP and deep layer flow differences exist in the central and western subtropical Atlantic between years associated with high and low recurving TC activity in the MDR, and some of these differences are physically consistent.
With our understanding of how the westward extent of the NASH modulates TC recurvature. To quantify the role that the interannual variability of the steering flow plays in modulating recurving TC frequency, we define a steering flow index. This index is created by standardizing the mean ASO meridional component of the deep layer steering flow (Equation 2) in a box from 25-35°N, 45-65°W. This region was chosen as it captures the largest meridional flow differences in Figures 5 and 7 and is the region in which the correlation between recurving MDR TC frequency and ASO meridional deep layer steering flow is highest. It is assumed that the meridional (poleward) component of the flow will determine the poleward propagation of TCs rather than the magnitude of the full (u,v) field. We therefore only consider the meridional component of the flow for the index.

**Figure 9:** Annual recurving TC frequency basin wide (left), originating in the MDR (middle) and originating in the SUB region (right), against the steering flow index (top) and basin-wide TC activity (bottom left), hurricanes originating in the MDR (bottom middle) and TCs originating in the SUB region (bottom right). Meridional component of the deep layer flow in the region 45-65°W, 25-35°N is used to create the steering flow index.
Figures 9a, b and c show the relationship between the number of recurving TCs (basin-wide, originating in the MDR, and originating in SUB respectively) and the steering flow index. Basin wide (Figure 9a), there is no link between recurving TC frequency and the ASO mean steering flow index. A weak relationship may exist in the MDR and SUB regions (Figures 9b, c), but correlations between the ASO mean steering flow index and recurving TC frequency are not significant at 95%.

In Figure 9e, the MDR hurricane frequency is shown instead of MDR TC frequency based on the results of Figure 4a, which shows that many weak MDR originating TCs die out, and as a result, hurricane number is likely a better predictor. Figure 9 clearly highlights that the interannual variability of recurving TC frequency is modulated by the frequency with which hurricanes form in the MDR and TCs form in SUB (Figures 9e, f), with interannual variability in the seasonal mean steering flow potentially playing a small, secondary role. A second order effect may also come from interannual variability in genesis location, particularly within the SUB region. The result remains unchanged when Figure 9 is reproduced using MERRA2 data (Figure S4), indicating that it is not sensitive to the reanalysis used.

The TC activity and the seasonal mean steering flow are not completely independent. The NAO index, which in part depends on the strength and location of the NASH is (weakly) associated with TC frequency in the subtropical Atlantic. A weaker NASH may also reduce the pressure gradient between the subtropical Atlantic and the equator, reducing trade wind strength, leading to higher SSTs and enhanced TC frequency. Correlation maps (Figure S14) have shown that these correlations are weak (r~0.2-0.3) and not significant, so collinearity between steering and TC activity in the MLR model is unlikely. Interannually, the steering flow is not strongly or significantly associated with basin-wide TC frequency, but TC frequency is strongly and significantly associated with recurving TC frequency.

4. Discussion and conclusions

The aim of this paper is to investigate the relative importance of the interannual variability of TC frequency and the steering flow in governing North Atlantic recurving TC frequency. This is achieved using a track matching algorithm to identify observed TC tracks from HURDAT2 in the ERA5 and MERRA2 reanalyses. This provides extended information about the precursor and post-tropical stages of storms beyond what is available in HURDAT2.
alone, which is then used to objectively identify the recurving TCs. We then partition the storms into three sub-regions based on genesis location (Main Development Region (MDR), Subtropical North Atlantic (SUB) and the region comprising of the Gulf of Mexico and South Caribbean (WEST)). The main conclusions of this study are as follows:

- Over 75% of the variance in seasonal North Atlantic recurving TC frequency can be explained by just two predictors – seasonal TC frequency originating in the subtropical Atlantic region, and seasonal hurricane (1 min sustained winds > 33ms\(^{-1}\)) frequency originating in the main development region. The individual R\(^2\) (using all data) are 33.9% for subtropical Atlantic TC frequency and 42.2% for main development region hurricane frequency.

- Only a weak relationship between the meridional component of the seasonal mean deep layer steering flow and recurving TC frequency is found, which is not significant.

- TC frequency explains most of the variability in recurving TC frequency, with interannual variability in the steering flow and genesis latitude potentially playing smaller, secondary roles.

The methods used here are robust to the different reanalyses used to track the TCs, to the boundaries of the domain used to define recurvature, and to the cyclones in HURDAT2 used (all TCs or just those with winds > 17ms\(^{-1}\)).

We are not suggesting that the steering flow is unimportant for TC recurvature - on the timescales of individual TCs, the steering flow is crucial for their steering and evolution. But on the seasonal timescale, the interannual variability in TC frequency is much more strongly associated with the interannual variability of recurving TC frequency than the interannual variability in the steering flow. This result suggests that skillful seasonal forecasts of Atlantic hurricane activity could also increase seasonal forecast skill in regions primarily impacted by recurving TCs, such as the east coasts of the US and Canada, and Europe.

The results presented here may also help us to understand how recurving TC frequency might change in the future. A small decrease is expected in TC counts in the North Atlantic due to climate change; particularly a decrease in weaker, short lived TCs (Knutson et al. 2019). However, the TCs that do form will likely be more intense at their LMI than in the current climate (Knutson et al. 2019). There already appears to be a poleward migration in

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the latitude at which TCs attain their LMI (Kossin et al. 2014) and if anthropogenically driven, this will likely persist into the future. Given the poleward shift in LMI and expected increase in the average intensity of TCs (suggesting increased longevity), coupled with the knowledge that weak, short-lived TCs (particularly those forming in the MDR) are unlikely to recurve, the North Atlantic may see more recurving TCs in the future, proportionally and possibly also in terms of absolute counts. Climate model projections should be utilized to further understand how recurving TC frequency and their direct and downstream impacts may change in the future, using high-resolution climate models in particular (such as in Haarsma et al. (2013) and Roberts et al. (2020)) which better capture the intensity of TCs.

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Data Availability Statement.

HURDAT2 data can be downloaded at aoml.noaa.gov/hrd/hurdat/. Reanalysis data used for cyclone tracking and composite analysis can be obtained from https://disc.gsfc.nasa.gov/ (MERRA2) and from the Copernicus C3S Date store (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5) for ERA5. Both reanalyses are freely available. TRACK is available for use with permission (see https://gitlab.act.reading.ac.uk/track/track, version 1.5.2 used).
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