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Analysis of Hurricane Track Forecast Accuracy During the 2018 Season

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1. Introduction

The human impact of tropical cyclones is substantial. The primary and secondary effects of tropical cyclones, from environmental and structural damage and hazard-related fatalities to mass human displacement and prolonged economic incapacity can linger for months to years after the occurrence of such an event. Therefore, hurricane track and intensity prediction is of the utmost importance when considering possible ways to preemptively mitigate hurricane damage.

1.1 Forecast models

The National Hurricane Center (NHC) uses numerous global and regional dynamical models, statistical models, and ensembles and consensus aids to forecast hurricane characteristics such as track, intensity, and wind radii (NHC 2017). Dynamical models use high-speed computing to solve equations that describe atmospheric motion, whereas statistical models consider historical relationships between storm behavior and storm characteristics such as location and date (NHC 2017). Ensemble models are composed by combining forecasts from multiple models of all types (NHC 2017). Hurricane trajectory models determine a probable track according to the prevailing atmospheric flow determined by a separate dynamical model, and represent the forecast track as most likely path as the “average track” of the forecasts from individual models in an ensemble (NHC 2017).

Many statistical models input hurricane climatology information, such as cyclone position, motion, and intensity to determine a potential cyclone track (HRD 2014). However, due to the dependence of a cyclone track on variability in current oceanic and atmospheric conditions, purely statistical models based solely on climatology are considered “no skill” predictors because they do not consider present conditions and are likely inaccurate (HRD 2014).

1.2 North Atlantic Hurricane Climatology and Modeling

Large-scale patterns in hurricane movement observed in long-term hurricane variability are dictated to an extent by global teleconnections such as the North Atlantic Oscillation, the Atlantic Multidecadal Oscillation, and the El-Niño Southern Oscillation, which fluctuate between a set of prescribed values over a given time (Ellis et al. 2016). These oscillations play roles in determining regional atmospheric and oceanic conditions (e.g. upper-level wind shear, atmospheric currents, sea surface temperatures, etc.) at a given time and location. These factors are used to predict likely seasonal hurricane track patterns for an upcoming season. The track of an individual tropical cyclone, however, is better determined by factors associated with regional and local climate variability, such as genesis location, cyclone intensity, duration, and frequency (Kossin et al. 2010).

Kossin et al. (2010) divide North Atlantic hurricane tracks into clusters using a technique described in Gaffney et al. (2007) that highlights intrabasin variability in hurricane climatology and emphasizes connections of hurricane variability to climatic variability. Using this objective method of separation, North Atlantic tropical cyclones demonstrate quantifiable intrabasin differences in track variability, which indicate the ineffectiveness of considering Atlantic tropical cyclone tracks as a whole when attempting to evaluate the climatic influence on cyclone track (Kossin et al. 2010). For instance, cyclones that originate in the Gulf of Mexico and Western Caribbean Sea tend to develop at higher latitudes than other cyclones and follow a pronounced northward track, whereas cyclones that originate near the west coast of Africa tend to form at lower latitudes and follow a near westward track while slowly drifting northward before recurving northeast (Kossin et al. 2010). From a point of genesis, a cyclone's track may be inferred, though all cyclone tracks are modified by small-scale fluctuations in synoptic conditions that guide a cyclone's intensity and direction of movement (Ellis et al. 2016). These factors complicate climate modeling methods used to predict hurricane tracks, as models must incorporate systematic variability in both regional atmospheric circulation and thermodynamic state (Kossin et al. 2010). However, Ellis et al. (2016) observe that more intense tropical cyclones are more likely to follow an expected track and make landfall at their maximum intensity, which helps increase the efficiency of models that input climatological data to generate forecast tracks.

Recent technological advances have made great strides in reducing error in hurricane track forecasts, though the total elimination of any error in forecasting is impossible. This study aims to visualize the error in hurricane forecast methods using the four United States landfalling cyclones of the 2018 hurricane season as a sample. The official forecast tracks produced by the NHC and a hypothetical forecast track using a purely statistical forecast method were mapped against the preliminary best track data for qualitative analysis to determine how actual hurricane tracks differed from forecast tracks and describe the effectiveness of purely climatological models.

2. Data and Methods

Considering the significant human impact of landfalling tropical cyclones, the four hurricanes of the 2018 season that made landfall in the United States (Alberto, Florence, Gordon, and Michael) were chosen for this study. For each cyclone, four significant moments during the lifespan and the corresponding storm center locations were chosen for forecast track analysis. These include the cyclone center locations at the time of the first forecast discussion issued by the NHC and consecutive (24-hour interval) forecast discussions from two days before landfall to landfall. The first discussion was chosen due to the high uncertainty in potential track for hurricanes at that point, and the locations relative to landfall were chosen due to the high human impact of landfalling hurricanes.

For each of these points, two different forecast tracks were compared to the actual track of the cyclone according to the preliminary database. The climatological track was created using a method described in Scheitlin (2010), which employs an hourly-interpolated version of the HURDAT ("best track") database. The data, now updated and referred to as HURDAT 2, are available for 1851–2017 from the NHC Data Archive, and instructions for performing the hourly interpolations are described in Elsner and Jagger (2013). A search was run for historical cyclones that passed within a radius of 200 nautical miles of the given point and a minimum intensity threshold equal to the intensity of the cyclone (maximum sustained wind speed in knots) at the given point (Table 1). Each search returned a maximum of 100 tracks that were compiled into a contour illustrating the weighted average distance in degrees latitude of the historical tracks to the selected point. The weights were based on the track's distance to the point, with the closest track being the closest weight. From this contour a single climatological "average track" was digitized manually (Figure 1) following the shortest average distance. The official forecast track data were obtained from the NHC GIS Archive – Tropical Cyclone Advisory Forecast, and the preliminary best track data were obtained from the NHC GIS Archive – Tropical Storm Best Track. The three tracks were plotted simultaneously and qualitatively analyzed.

Cyclone	Point	Latitude	Longitude	Intensity (kt)	Analogs
Alberto	first	19.7	-86.8	35	100
Alberto	2 days before	23.3	-85.1	35	100
Alberto	1 day before	28.0	-85.2	45	100
Alberto	landfall	15.0	30.3	40	100
Florence	first	12.9	-18.4	25	53
Florence	2 days before	29.8	-71.3	115	14
Florence	1 day before	33.4	-75.5	90	66
Florence	landfall	34.0	-78.0	70	100
Gordon	first	22.7	-77.3	25	100
Gordon	2 days before	23.4	-78.7	25	100
Gordon	1 day before	26.9	-84.3	50	100
Gordon	landfall	30.3	-88.4	60	100
Michael	first	18.0	-86.6	25	100
Michael	2 days before	22.2	-85.2	70	100
Michael	1 day before	26.0	-86.4	105	30
Michael	landfall	30.9	-85.1	110	8

Table 1. Search criteria and results for storm analysis.

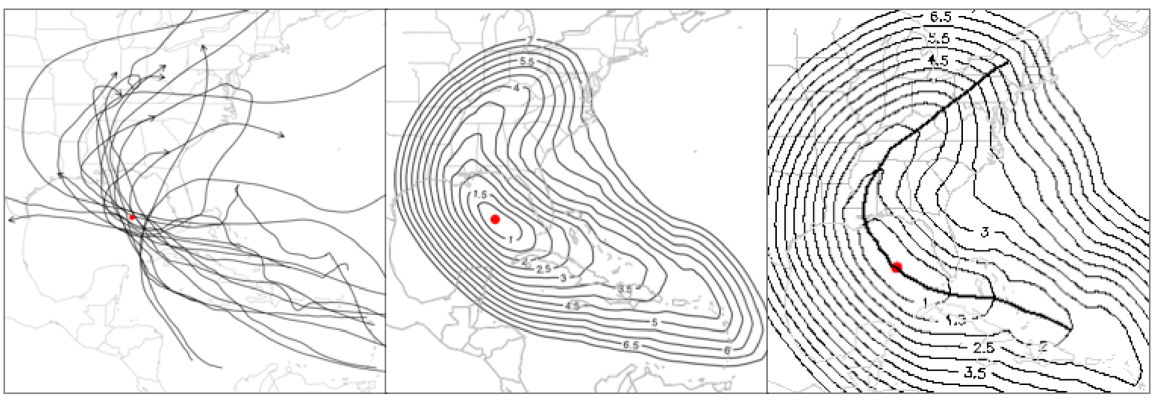


Figure 1. The first panel shows the historical tracks selected using the search criteria for Hurricane Michael, one day before landfall. The second panel shows the contour of weighted average distance, and the third shows the "average track" generated using the contour.

3. Limitations

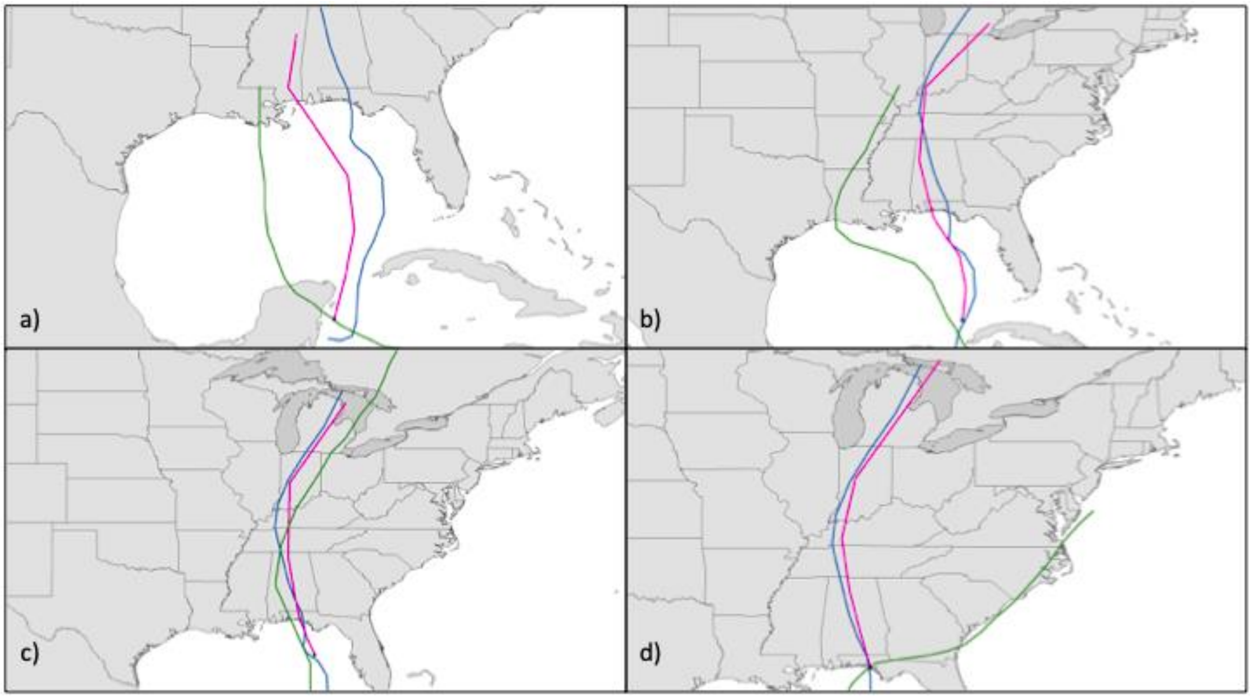
One limitation arose in select cases where a historical track passed through the exact coordinate of the 2018 cyclone center location, resulting in a divide-by-zero error in the code. To resolve this issue, the latitude of the coordinate was shifted by a negligible value of 0.01, which ensured the impossibility of such an error due to the rounding of the historical best track coordinate data to one decimal place.

Another limitation is the use of preliminary best track data. Occasionally there were discrepancies in the coordinates of the 5-day forecast initial storm locations, causing the mapped forecast track to not align properly with the mapped preliminary best track. In other cases, the preliminary best track did not include the storm center locations after the storm made landfall and subsequently weakened to tropical depression intensity. In these cases, primarily the locations closer to landfall, the mapped preliminary best tracks were exceeded by both the forecast and weighted average tracks. While it is reasonable to assume the official forecast track is an appropriate stand-in for the preliminary best track due to the observable, consistent accuracy of the forecasts, the lack of the actual track data with which to compare the weighted average track diminishes the soundness of those conclusions.

4. Results

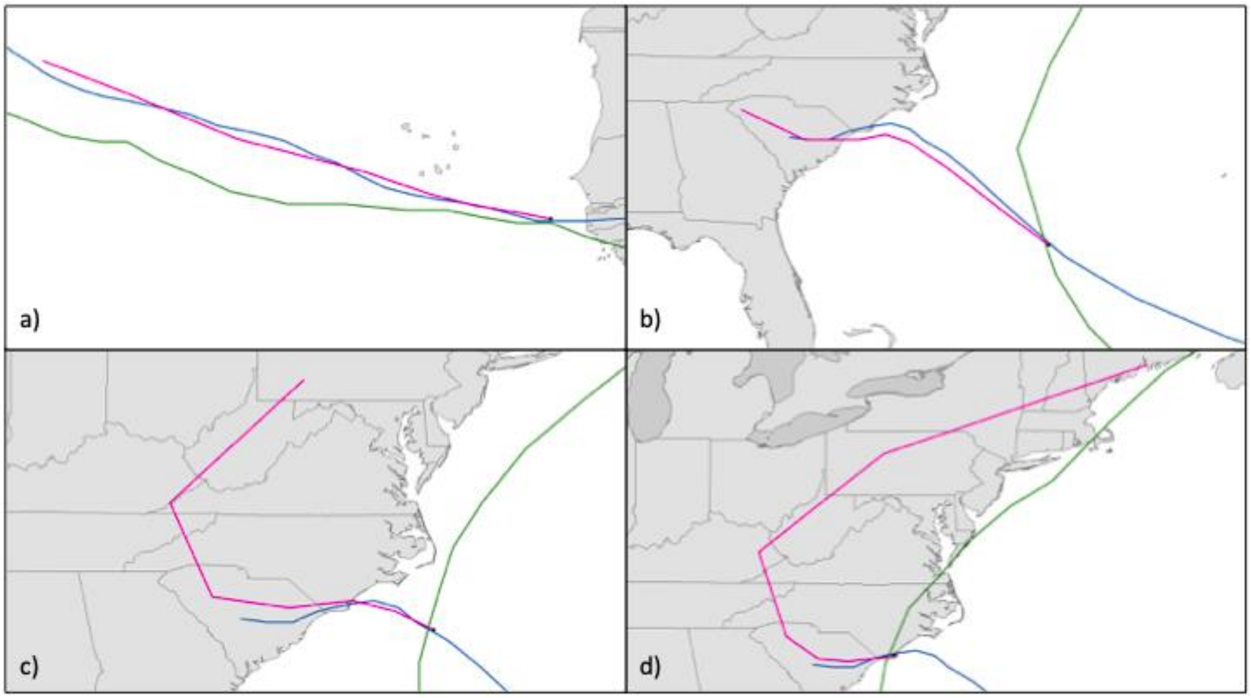
Local hurricane impacts can vary greatly depending on individual cyclone characteristics such as the hurricane center location, the extent of the cyclone's rain bands, the cyclone's wind profile, etc. For this reason, any forecast or weighted average track that is estimated to fall around 50 miles from the preliminary best track data is considered moderately accurate, and any forecast or weighted average track that falls over 50 miles from the preliminary best track is considered inaccurate. The landfall position predicted by each of these forecast tracks is used as a point of comparison. These conclusions are subjective and based on qualitative observation.

Figure 2. Results for Tropical Storm Alberto, including official forecast tracks (pink), weighted average tracks (green), and preliminary best tracks (blue) at (a) the time of the first forecast discussion published, (b) two days before landfall, (c) one day before landfall, and (d) landfall.



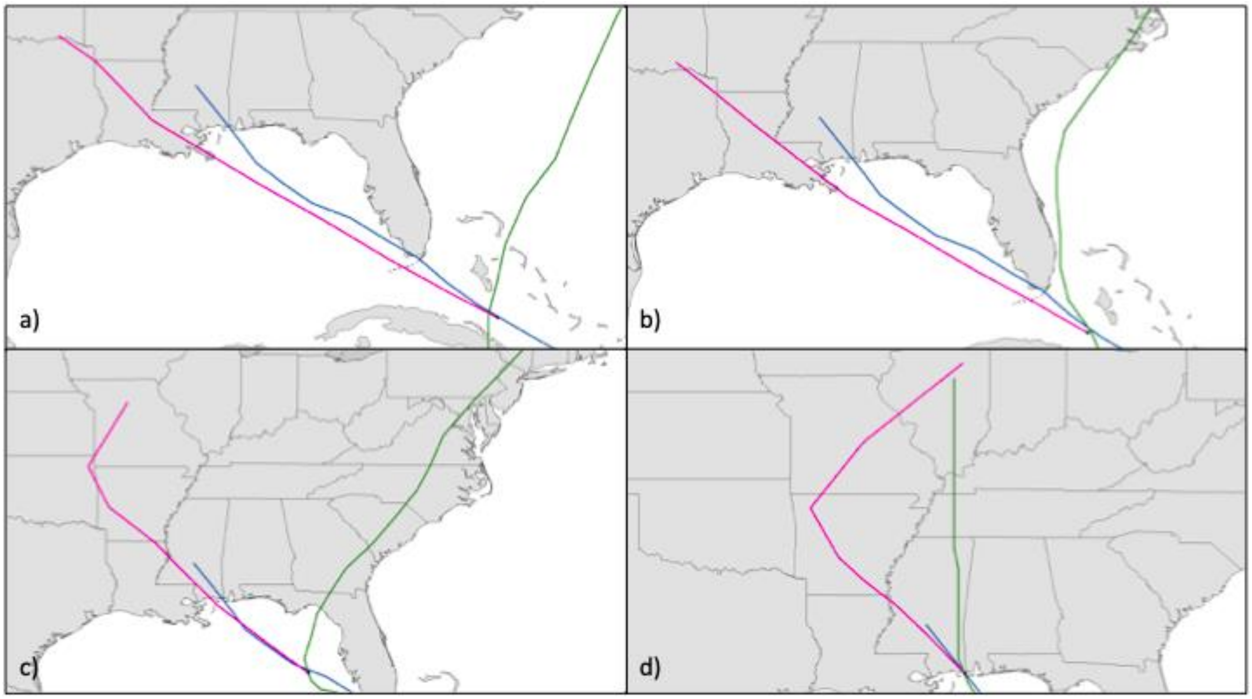
Results for Tropical Storm Alberto are shown in Figure 2. At the time of the first forecast discussion published, neither the official forecast nor the weighted average track performs well. The official forecast predicts landfall in Mississippi, the weighted average predicts landfall in Louisiana, and neither is remotely close to the actual landfall in Florida. Two days before landfall, the weighted average still predicts landfall in Louisiana, and though the official forecast has moved into Florida, the distance between the expected and actual landfall is still observably inaccurate. One day before landfall, the official forecast is observed to be highly accurate for the first time intervals, but the weighted average, though it predicts landfall in Florida, is still far enough away from the actual track to be considered inaccurate. At landfall, the official forecast is still highly accurate, but the weighted average has diverged completely from the actual track.

Figure 3. As in Figure 2, for Hurricane Florence.



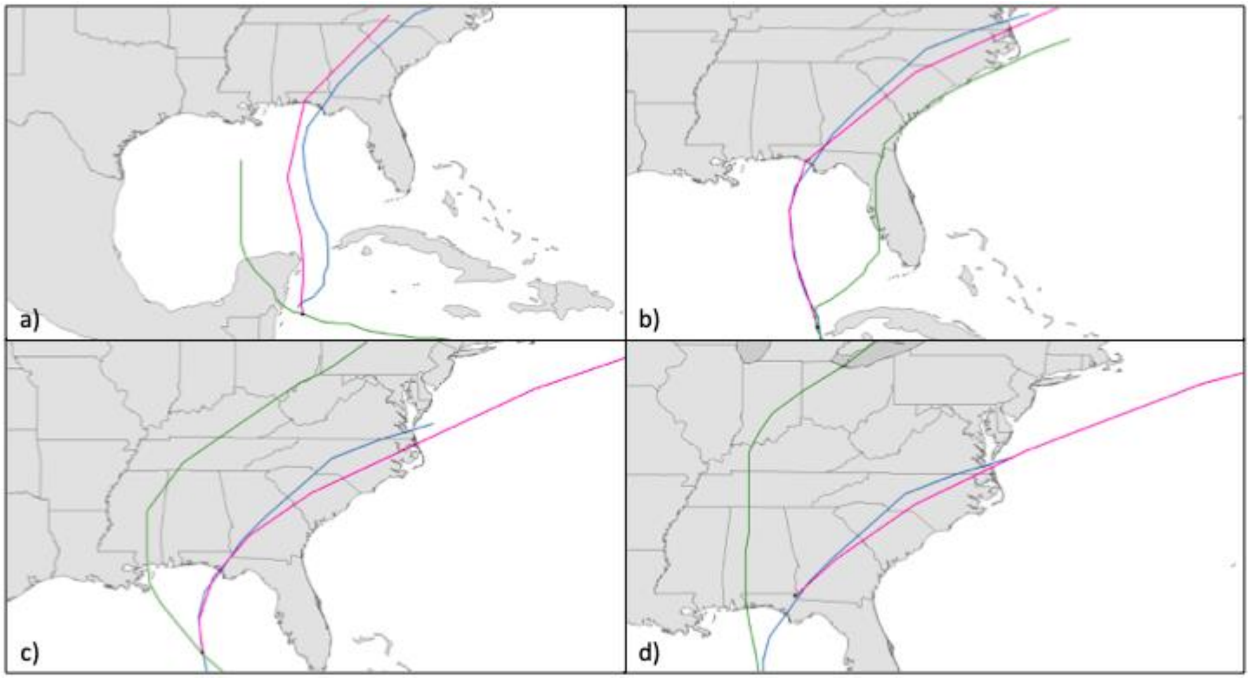
Results for Hurricane Florence are shown in Figure 3. At the time of the first official forecast discussion, the official forecast performed well, but the weighted average, though following the same direction as the preliminary best track, diverges enough to be considered inaccurate. Though the cyclone was tracking over open ocean at the time, this conclusion comes from the implications this discrepancy between forecast and actual tracks would have if the cyclone were tracking over land. Two days before landfall, the official forecast performs moderately well, although the difference in predicted and actual landfall is worth noting. One day before landfall, the official forecast performs extremely well in predicting the landfall location, though it diverges slightly from the preliminary best track after landfall. At landfall, the preliminary best track is not long enough for conclusive observation. The weighted average tracks do not perform well at all in the days leading up to landfall and including landfall, as the tracks diverge from the preliminary best track at nearly perpendicular angles in all three cases.

Figure 4. As in Figure 2, for Tropical Storm Gordon.



Results for Tropical Storm Gordon are shown in Figure 4. At the time of the first forecast discussion as well as two days before landfall, the official forecast track, though following the same direction as the preliminary best track, does not perform well. In both cases, the official forecast predicts landfall in Louisiana, and neither is close to the actual landfall at the Alabama-Mississippi border. At these times, the weighted average tracks do not perform well either, diverging greatly from the preliminary best track. One day before landfall, the official forecast has noticeably improved, though the distance between the predicted landfall and the actual landfall is still enough to be considered inaccurate. At this time, the weighted average track performs even worse, still diverging and placing the predicted landfall in the Florida Panhandle. At landfall, the preliminary best track is not long enough for conclusive observation, though it worth noting that the weighted average diverges from the official forecast, which roughly follows the track of the remnants of the cyclone.

Figure 5. As in Figure 2, for Hurricane Michael.



Results for Hurricane Michael are shown in Figure 5. At the time of the first forecast discussion, the official forecast correctly predicts the landfall location in the Florida Panhandle, but the distance between the expected and actual landfall is still observably inaccurate. The weighted average track is not long enough to make a valid predicted landfall position, but the track is observably inaccurate compared to the preliminary best track. Two days before landfall, the official forecast performs reasonably well, but the weighted average, despite ultimately following the direction of the preliminary best track, diverges initially, predicting landfall on the Florida peninsula instead of the Panhandle. One day before landfall, the official forecast performs extremely well, but the weighted average diverges in the other direction, incorrectly placing the predicted landfall in Mississippi. At landfall, the official track still performs moderately well, though it diverges slightly from the preliminary best track as the system moves into North Carolina. This is worth noting because Michael remained at tropical storm intensity even after moving into South Carolina, and the local effects of such an intense system would still be significant. The weighted average at this time does not perform well, placing the landfall location correctly in the Florida Panhandle but still a large distance from the actual landfall and then diverging from the preliminary best track.

5. Discussion

Disregarding the two cases in which the official forecast track could not be compared to the preliminary best track, the forecast tracks overall were highly accurate in 6 of the 14 total cases, moderately accurate in 4 of the cases, and inaccurate in 4 of the cases. However, disregarding the one case in which the weighted average track could not be compared to the preliminary best track, the weighted average tracks were highly accurate in none of the 15 total cases, moderately accurate in 2 of the cases, and inaccurate in 13 of the cases. These conclusions reflect the common understanding that purely statistical models serve as “no skill” predictors due to their inability to incorporate current meteorological data.

The official forecasts from the early points in the cyclone lifespan (at the time of the first discussion and two days before landfall) were seemingly less accurate for the two tropical storms, and more accurate for the two hurricanes, supporting the observation of Ellis et al. (2016) that more intense cyclones are more likely to follow an expected track. The official forecasts performed moderately to very well for all four cyclones at the two later points in the lifespan, though both cases in which the official forecast was disregarded were the last point in the lifespan (landfall). This reflects the natural tendency of forecast error to increase with the projection of the forecast into the future.

There were no observable patterns in the accuracy of the weighted average tracks. The two cases in which the weighted average track performed moderately well were for Alberto at one day before landfall and Florence at the time of the first forecast discussion. Hurricane

Florence is a special case in the North Atlantic hurricane climatology, as tropical cyclones that form near the Cape Verde Islands tend to either recurve while tracking across the Atlantic Ocean without making landfall in the United States or track westward into the Gulf of Mexico before recurving, making landfall on the Gulf Coast. This trend is observed in Kossin et al. (2010), who demonstrated that the cyclones in clusters 3 and 4, which included nearly all of the “Cape Verde hurricanes,” made landfall more often in the Caribbean Sea and the Gulf Coast than on the eastern coast of the United States. Therefore, it is reasonable that the weighted average forecast tracks for Hurricane Florence were highly inaccurate, as Florence was frequently location in positions where no previous storms had ever been and subsequently made landfall in the United States.

6. Conclusion

Hurricane track forecasting is inherently complicated, as an individual cyclone’s track is determined by many characteristics that each influence the cyclone’s motion in different and sometimes contradictory ways. That being said, technological advances have greatly improved hurricane track forecasting in recent years, though long-term (i.e. greater than 48-hour) forecasting is still an area for improvement, as uncertainty is still high in forecasts valid at those intervals. Forecasting based purely on climatological data at a single given point has shown consistently inaccurate predictions; however, using more information (e.g. multiple past locations) improves the skill of such a technique.

For future research, the weighted average tracks could be improved by using search criteria that includes multiple locations at once (e.g. a search for historical cyclones that passed within 200-nautical-mile radii of multiple points). This selects historical tracks of cyclones even more similar to the present cyclone and is a better simulation of statistical models still in use. A test of this method using all four points and the lowest intensity for Michael as search criteria resulted in a weighted average track nearly identical to the preliminary best track.

The future of hurricane track prediction is somewhat uncertain. Though errors in hurricane track forecasting have decreased by an estimated two thirds within the last few decades, a study by Landsea and Cangialosi (2018) that fit regressions to the track error data found that more recent (i.e., within the last 5 to 10 years) trends have started to level off. This "flattening" trend indicates a loss of momentum in the forward progress in error reduction and raises questions about the limit of predictability in hurricane track forecasting. The slowdown has not been observed in a time period long enough for conclusive statistical significance testing, but the observation suggests that further improvements to track forecasting may occur at a slower pace than in the last few decades (Landsea and Cangialosi 2018).

It is also worth noting that while models have seen technological advances, the models must account for variations in several climatic variables that are currently seeing unprecedented changes as well due to the changing climate. As the reaction of these conditions (upper ocean dynamics, atmospheric circulation, etc.) to climate change is still uncertain, future models will need to account for this uncertainty in their predictions (Emanuel 2017). This, coupled with the increasing vulnerability of coastal populations to hurricane impacts, highlights the importance of improving model forecast accuracy.

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