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Analysis of Hurricane Track Forecast Accuracy During the 2018 Season

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Abstract

Hurricane track forecasting has become more accurate in recent years due to technological advances in modeling methods. However, due to the complex nature of the relationship between oceanic and atmospheric variables and hurricane tracks, noteworthy errors in track prediction, especially for predictions several days into the future, still remain. In this study, two different methods of forecasting hurricane tracks are compared. Using the four United States landfalling hurricanes of the 2018 season as a sample, the official forecast tracks published by the National Hurricane Center (NHC) and hypothetical tracks based purely on climatology were mapped simultaneously with the preliminary best track published by the NHC. The forecast tracks were generated by the NHC using a synthesis of various types of models, and the climatological tracks were generated using a weighted average of historical cyclone tracks. The results indicate that the official forecasts often performed better than the purely climatological tracks using the preliminary best track as a point of reference. These conclusions support the common understanding that climatological data alone are not sufficient for highly accurate hurricane track prediction, as current oceanic and atmospheric conditions must be incorporated into the models to reach higher levels of accuracy.

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.

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).

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.

2018 Hurricane Season

The 2018 Atlantic hurricane season concluded on 31 October and saw above average activity, with 15 named storms, including 8 hurricanes and 2 major hurricanes, and one tropical depression (NHC 2018a). The four cyclones (Alberto, Florence, Gordon, and Michael) that made landfall in the United States are the subject of this study.

Storm Reports

The following are summaries of the tropical cyclone reports published by the NHC upon the conclusion of the 2018 hurricane season.

Tropical Storm Alberto formed as a subtropical depression on 1200 UTC 25 May after the re-emergence of a low-pressure system characterized by an extensive wind field, asymmetric convection, and interaction with a mid- to upper-level low, that had originated from a disturbance moving eastward from the Gulf of Mexico. By 1800 UTC 26 May, the cyclone became a subtropical storm as deep convection developed, and the cyclone evolved into a tropical storm with an estimated peak intensity of 55 kt by 0000 UTC 28 May. The cyclone's winds weakened to about 40 kt before the system made landfall in the Florida Panhandle around

2100 UTC 28 May, and continued to weaken until reaching tropical depression status around 0000 UTC 29 near the Florida-Alabama border. The system remained a tropical depression with estimated maximum winds of 30 kt due to its continued deep convection and organized circulation as it moved northward through the midwestern United States. The system deteriorated into a remnant low by 0600 UTC 31 May near Saginaw, Michigan, and dissipated over southern Ontario later that day. Alberto produced heavy rainfall and flooding in western and central Cuba and the southern and central Appalachian mountains, leading to fatalities in Cuba, North Carolina, and Virginia (NHC 2018d).

Hurricane Florence developed into a tropical depression around 1800 UTC 31 August near the Cape Verde Islands from a convectively active tropical wave that moved off the west coast of Africa the day before. Within 12 hours the system strengthened to tropical storm intensity, but strengthened slowly over the next 48 hours as it moved steadily west-northwestward due to lower sea surface temperatures and cool, dry air incursions from the north. The system gradually increased to hurricane intensity, reaching an estimated maximum wind speed of 65 kt around 1200 UTC 4 September. Hurricane Florence experienced rapid intensification over the next 30 hours despite unfavorable environmental conditions, reaching Category 4 intensity with an estimated maximum wind speed of 115 kt by 1800 UTC 5 September over the central Atlantic Ocean. However, within 12 hours of reaching Category 4 intensity, the system experienced rapid weakening caused by strong southwesterly wind shear and weakened to tropical storm intensity by 0000 UTC 7 September at nearly the same rate as that by which it intensified. Despite severe disruption by the shear conditions, the inner-core wind field of the system remained undisturbed and Florence continued to re-strengthen as it followed its west-northwestward track, reaching hurricane intensity again by 1200 UTC 9

September. Pronounced outflow jets that had formed in the northwestern and southeastern quadrants of the hurricane allowed for a second rapid intensification, and Florence reached a peak intensity of 130 kt around 1800 UTC 11 September. As Florence continued to move west-northwestward, slowly approaching the North Carolina coast, it encountered areas of cold upwelling and began an eyewall replacement cycle, which, when coupled with the expansion of the hurricane's outer wind field, led Florence to weaken to Category 2 intensity by 1200 UTC 13 September. Florence continued to weaken as it slowly advanced toward the North Carolina coast and made landfall near Wrightsville Beach, North Carolina as a Category 1 hurricane around 1115 UTC 14 September.

After making landfall, Florence briefly turned west-southwest, which allowed the warm waters of the Gulf Stream to slightly inhibit the weakening process. Florence weakened to tropical storm intensity by 0000 UTC September just north of Myrtle Beach, South Carolina, and continued to weaken as it moved westward, eventually reaching tropical depression intensity near Florence, South Carolina, around 1800 UTC 16 September. The system began a northward track and became an extratropical system over West Virginia around 1200 UTC 17 September, and then turned northeastward, eventually dissipating over Massachusetts around 1200 UTC 18 September.

Though Hurricane Florence made landfall as only a Category 1 hurricane, its slow movement allowed for substantial rainfall and record flooding across much of southern North Carolina and northern South Carolina. The hurricane also produced 44 known tornadoes, including 1 EF-2 tornado, and caused catastrophic structural damage. Hurricane Florence was also responsible for 22 direct fatalities (NHC 2018b).

Tropical Storm Gordon formed as a tropical depression around 0600 UTC 3 September, about 92 mi southeast of Key Largo, Florida, after traveling across the Atlantic Ocean as a tropical wave that moved off the west coast of Africa on 26 August. Deep convection organized quickly after formation and the system made landfall near Tavernier in the Florida Keys around 1115 UTC 3 September as a tropical storm with an estimated maximum wind speed of 45 kt. Gordon made a second landfall later that day near Flamingo, Florida, around 1315 UTC. As the system moved into the Gulf of Mexico, the convective structure continued to develop, and Gordon strengthened to its peak intensity of 60 kt at 1800 UTC 4 September about 132 mi south-southeast of Pascagoula, Mississippi. Though the convective structure developed further before the system made landfall, the cyclone did not strengthen past tropical storm status before it made landfall in Pascagoula around 0315 UTC 5 September. Gordon weakened to a tropical depression by 1200 UTC the same day about 34 mi southeast of Jackson, Mississippi, and continued to weaken as it moved northwestward through Arkansas, where it dissipated by 0000 UTC 8 September. The remnant low merged with an extratropical low later that day, and the new system moved slowly over western Kentucky and the Ohio valley before dissipating after a few days. Gordon produced flooding rains both as a tropical storm and after merging with the extratropical low and caused moderate damage in the northern Gulf coast (NHC 2018e).

Hurricane Michael formed as a tropical depression around 0600 UTC 7 October about 150 mi south of Cozumel, Mexico, from a system that had evolved from the remnants of Tropical Storm Kirk merged with a disturbance that had formed over the central and western Caribbean Sea about 5 days earlier. Michael experienced rapid intensification as it moved north-northeastward over the Gulf of Mexico, reaching tropical storm intensity in just 6 hours and hurricane intensity by 1200 UTC 8 October. Though an upper-level trough caused moderate wind shear over the central Gulf of Mexico, its effect was overpowered by the diffluence caused by the trough as compensation for the shear and outflow into a second upper-level trough, intensifying Michael to a Category 2 hurricane with an estimated maximum wind speed of 85 kt by 1830 UTC 8 October, just west of Cabo del San Antonio, Cuba. Michael's rapid intensification slowed briefly, likely due to shear, a dry air incursion, or an area of colder SSTs, in the southeastern Gulf of Mexico, but resumed by 1200 UTC 9 October. Michael moved north-northeastward across the Gulf of Mexico, steadily intensifying, until making landfall as a Category 5 hurricane with an estimated maximum wind speed of 140 kt near Tyndall Air Force Base (AFB) in the Florida Panhandle around 1730 UTC 10 October. Michael weakened to a Category 3 hurricane by the time it moved into southwestern Georgia around 2130 UTC 10 October, and weakened to tropical storm intensity as it crossed into South Carolina around 1100 UTC 11 October. As Michael moved into North Carolina, extratropical transition began, and was complete by 0000 UTC 12 October. After moving through coastal Virginia and into the western Atlantic, Michael regained hurricane status briefly on 13 October, but soon weakened and dissipated west of Portugal on 15 October. Michael produced life-threatening floods, 16 known tornadoes, catastrophic agricultural and structural damage, and many fatalities in the United States and Cuba (NHC 2018c).

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.

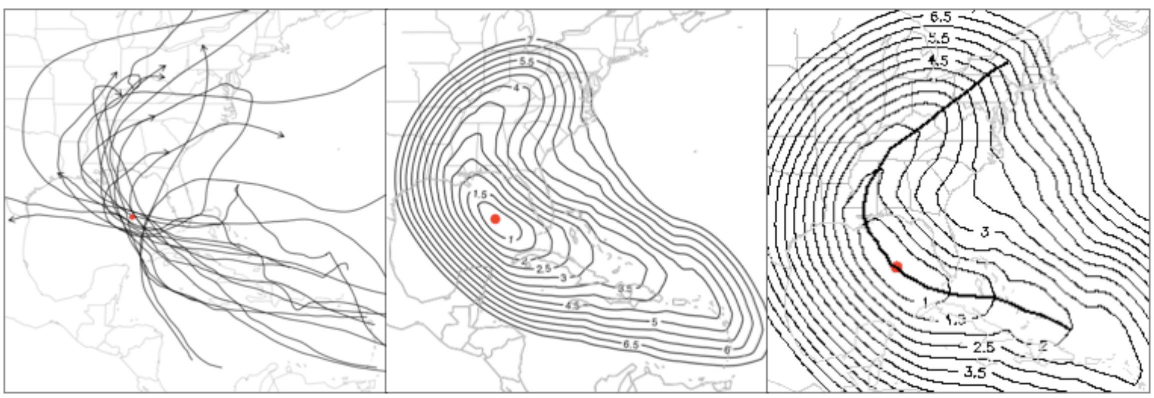


Figure 1. The first panel shows the historical tracks selected using the search criteria for Hurricane Michael, one day before landfall. The second panel shows the contour of weighted average distance, and the third shows the "average track" generated using the contour.

Limitations

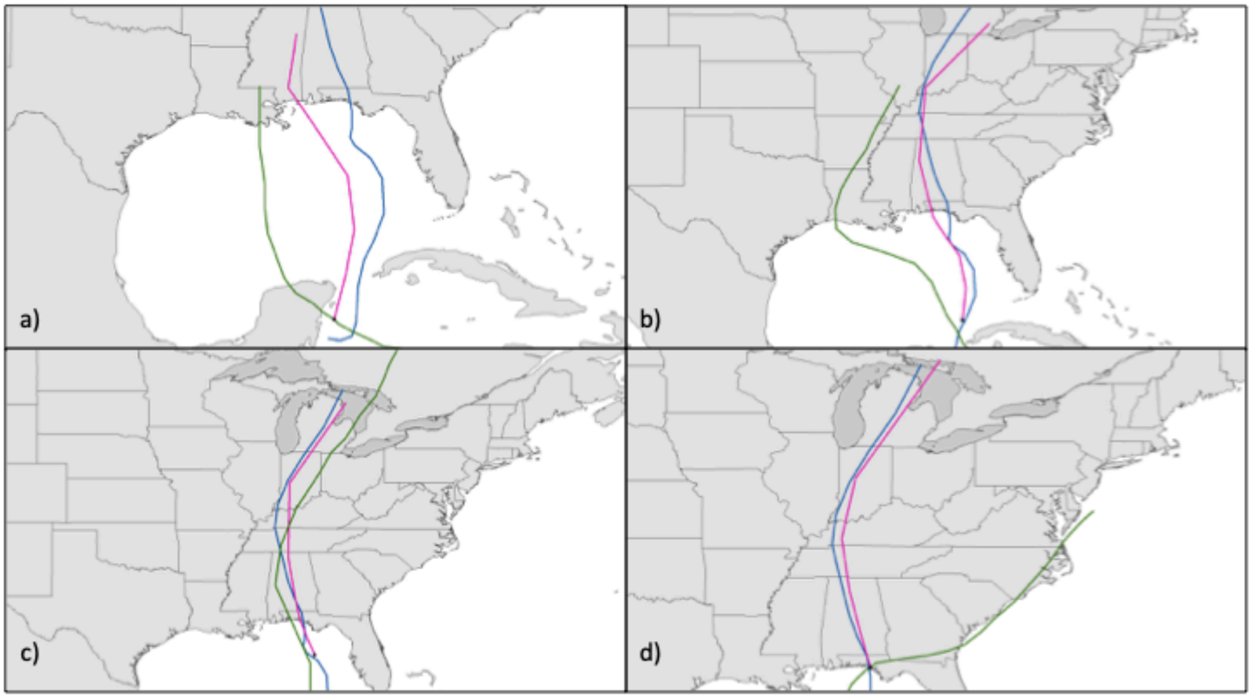
One limitation arose in select cases where a historical track passed through the exact coordinate of the 2018 cyclone center location, resulting in a divide-by-zero error in the code. To resolve this issue, the latitude of the coordinate was shifted by a negligible value of 0.01, which ensured the impossibility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

Results

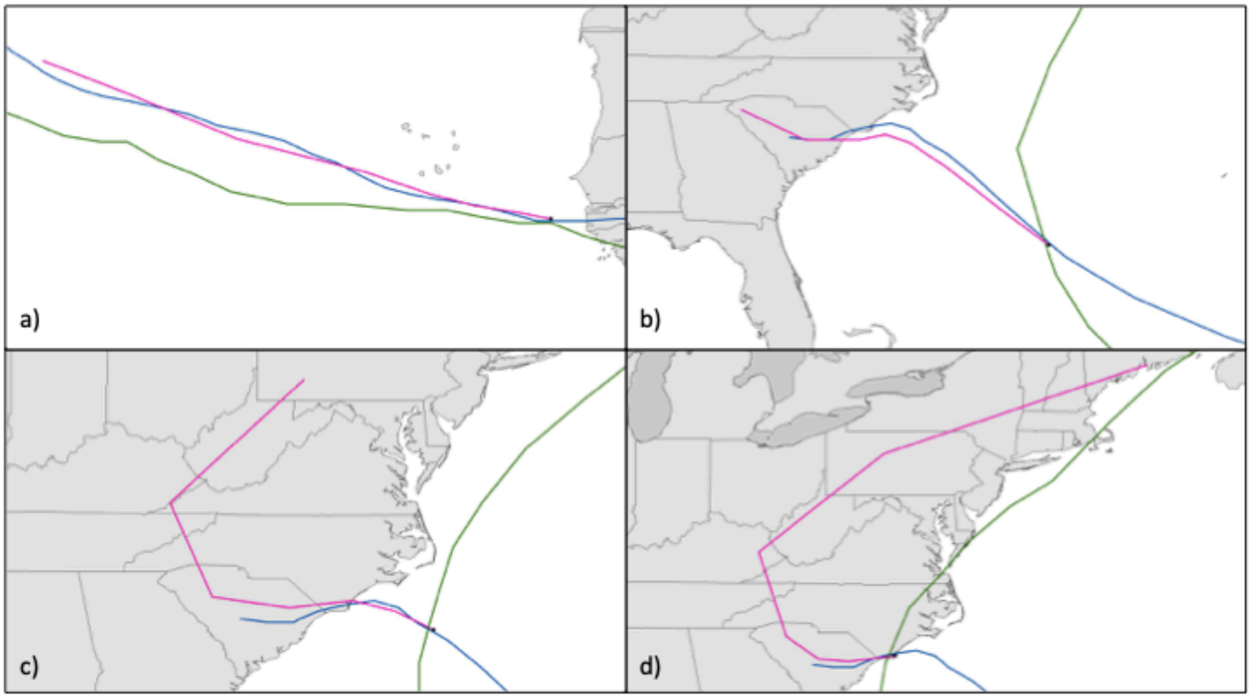
Local hurricane impacts can vary greatly depending on individual cyclone characteristics such as the hurricane center location, the extent of the cyclone's rain bands, the cyclone's wind profile, etc. For this reason, any forecast or weighted average track that is estimated to fall around 50 miles from 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.



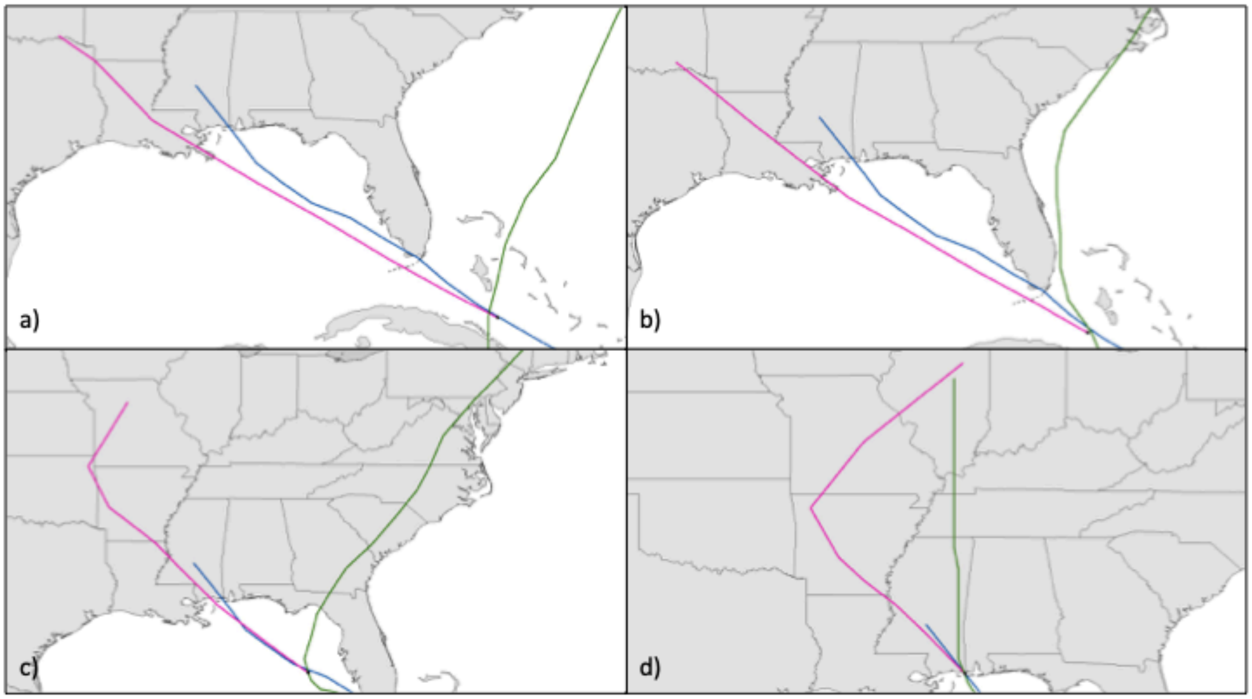
Results for Tropical Storm Alberto are shown in Figure 2. At the time of the first forecast discussion published, neither the official forecast nor the weighted average track performs well. The official forecast predicts landfall in Mississippi, the weighted average predicts landfall in Louisiana, and 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.



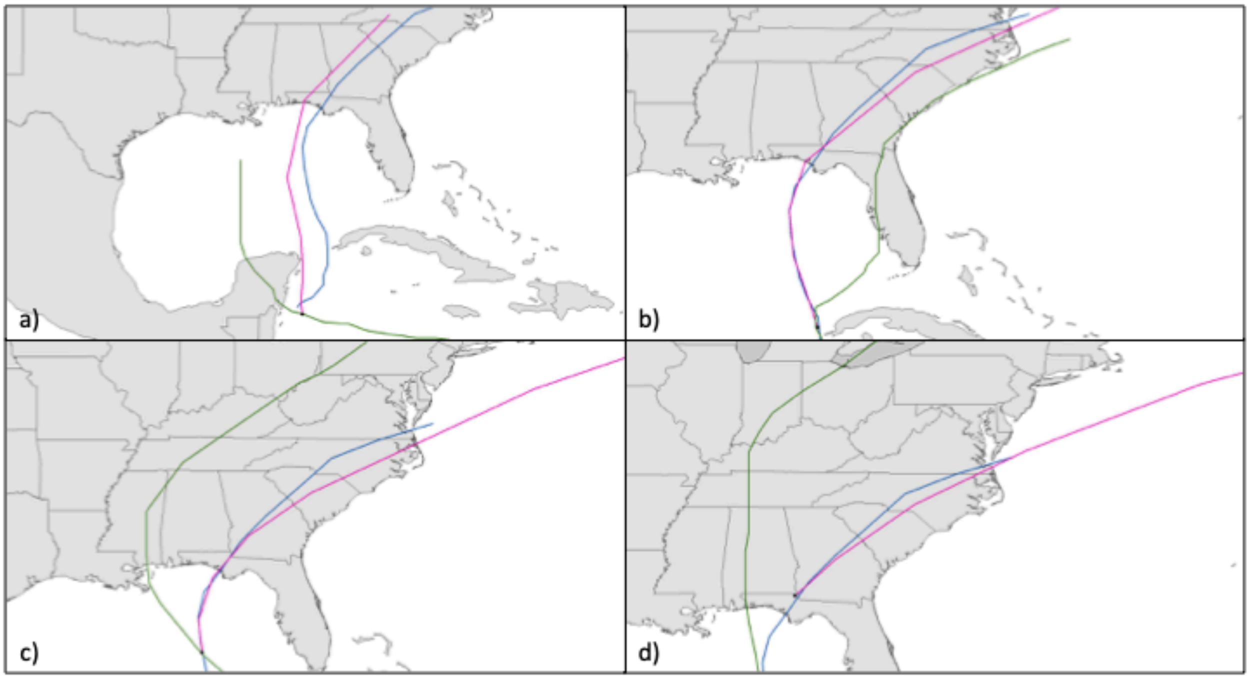
Results for Hurricane Florence are shown in Figure 3. At the time of the first official forecast discussion, the official forecast performed well, but the weighted average, though following the same direction as the preliminary best track, diverges enough to be considered inaccurate. Though the cyclone 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.

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.

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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