80 The Track Deflection and Movement of Hurricane Florence 2018 Near and after Landfalling

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1. Introduction

Florence (2018) was classified as a strong Category 4 hurricane that made landfall near Wrightsville Beach, North Carolina as Category 1 (Stewart and Berg, 2019). The hurricane originated as a strong convective tropical wave, which was accompanied by a low-pressure system off the coast of Africa around August 30th. A tropical depression formed on August 31st, which strengthened to a tropical storm about 12 hours later. Florence became a 65-knot hurricane on September 4th and had a 30-mile diameter eye. The storm quickly regained strength due to rapid intensification after previously losing its strength. On the 14th the storm made landfall as a weak Category 1 with maximum winds of 90 mph. After landfall, Florence approached a frontal system that stalled the storm and produced heavy amounts of rain totaling 30 inches in some areas (Armstrong, 2018).

After stalling, the storm turned southward for a period of about 3 days, then curved back towards the northeast, forming an L-shaped track (Stewart and Berg, 2019; Yin et al., 2021), as shown in Fig. 1. Freshwater and saltwater flooding led to catastrophic events. Florence caused a record-breaking storm surge of eight to eleven feet and accounted for 53 fatalities (Paul et al. 2019). The storm ultimately produced $24.23 billion dollars of damage. Hurricane Florence is known for its unique L-shaped track and the storm stalling along the coast. This study focuses on the features of Florence's L-shaped track, the mechanisms of the track deflection, and the dynamic features that contribute to the storm steering.

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2. Methodology

In this study, we began with HWRF (Hurricane Weather Research and Forecast system) and WRF-ARW (Advanced Research WRF; denoted as WRF) modeling for the hurricane. In HWRF, we mainly varied the simulations starting times because the preset domain configurations and physics schemes were well tested for the best performance. In WRF, we varied the simulation starting times and chose various physics schemes. We then selected the best case from the HWRF simulations and the best case from the WRF simulations. The track and relative vorticity of these two cases were compared with those from the NHC best track and data from the ERA5 reanalysis model. We chose one simulation from each model for more detailed analysis. To examine the dynamics of track deflection and the storm's steering, we analyzed the sea level pressure, the geopotential height at different levels, the wind vectors, and the relative vorticity around the storm. In particular, we studied the shortwave ridge and high-pressure system during the storm's turning and passing.

2.1 *Description of Numerical Models*

Two atmospheric models were utilized to conduct this research: HWRF 4.0, and WRF-ARW 4.4. The HWRF model is a primitive-equation, non-hydrostatic, coupled atmosphere-ocean model with an atmospheric component that employs the Non-hydrostatic Mesoscale Model (NMM) dynamic core of the WRF model (WRF-NMM) (Biswas et al., 2018). HWRF focuses on improving track, intensity, rainfall, and other forecast predictions of hurricanes. HWRF simulations were set with three domains: one outer fixed domain with resolution 11km and 2 moving inner nested domains with resolutions 3.67km and 1.22km, respectively. The initialization data is the GFS (Global Forecasting

System) forecasting data. For all our cases we used the following specific physics schemes: Ferrier (new eta) for microphysics, NCEP Global Forecast System scheme for boundary layer model, and the old GFS simplified Arakawa-Schubert scheme for cumulus physics. The time step is 30 seconds. There were not many options of the physics schemes available in the HWRF package. We varied the starting time from September 11th through September 14th (Shumpert, 2022).

The Weather Research and Forecasting (WRF) Model is a three dimensional, non-hydrostatic, fully compressible model using topography vertical coordinates (Skamarock et al., 2019). The system is designed for a broad range of applications such as idealized simulations, forecasting, and data assimilation research. In this study, the WRF simulations were set as one single domain with resolution of 15km. Multiple simulations were conducted with various starting times and physics schemes. Time steps of 60 and 90 seconds were used in the simulations depending on the initialization time. The results from the simulations were compared with the NHC best track data. After some comparison, it was determined that the "tropical suite" of physics provided in the WRF package produced the best results. This tropical physics schemes set includes WSM 6-class graupel for microphysics, RRTMG scheme for longwave and shortwave radiation, Old MM5 for surface layer, Unified Noah for the land surface scheme, YSU for boundary layer, and A newer Tiedtke scheme for cumulus physics. This set of physics schemes was tested and performed well while also capturing the L shaped track better than other physics schemes used.

2.2 *Data Collection*

Both HWRF and WRF simulations require the user to collect initialization and boundary data to be used for the simulations. The RDA (Research Data Archive) is a website where users can download data so that it can be interpreted in a way that the model can use it. For HWRF simulations we used NCEP GFS forecasting data with a resolution of 27.79 km (https://rda.ucar.edu/datasets/ds084.1/). The grid analysis produces forecast fields in different time steps with 3- and 12-hour intervals. For all our cases we downloaded the 3-hour intervals for the length of time we wanted to simulate.

For WRF simulations we utilized the ERA5 data (https://rda.ucar.edu/datasets/ds633.0/). This data set is an improved European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data of global climate that covers data from 1950 to near present. ERA5 has a resolution of 31 km with surface data and atmospheric data that is interpolated to 37 pressure levels. This data set contains multiple variables such as air temperature, humidity, convection, geopotential height, etc. Hourly data was collected for each initialization time and a data set for the month of September was used as well. A previous study was conducted on different ERA data sets and their impact on Florence's track and intensity. In this research, ERA5 performed better regarding track and intensity thus we decided to use this data set for our model initialization (Liu, 2020).

To compare our simulations with the actual track of the storm, we used the NHC best track data (https://www.nhc.noaa.gov/data/#hurdat). This website includes Best Track data that dates to 1851. It is important to visually observe the best track data when running simulations to properly assess the accuracy of our simulations results.

2.3 *Relative Vorticity Equation*

In this study, we calculated the vertical relative vorticity to study the relevant dynamics. In general, the vertical vorticity field is the vertical component of the curl of the velocity field. Vorticity describes the local spinning motion and the tendency of the flow to rotate. Relative vorticity is related to the counterclockwise circulation of a weather system due to the curve of the flow and wind shear. Mathematically, the vertical relative vorticity (ζ) is defined as $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$, where u and v are the latitudinal (x) and longitudinal (y) velocity components respectively. Numerically, ζ is approximated by taking the center difference of the v wind with respect to x and the center difference of u wind with respect to y. A positive vorticity value indicates counterclockwise (cyclonic) rotation, and a negative vorticity indicates clockwise (anti-cyclonic) rotation in the northern hemisphere. The relative vorticity's effect on track deflection is discussed more in depth in Sections 3.2 and 4.2.

3. Verification of WRF and HWRF Simulations

3.1 *Tracks*

HWRF simulations were conducted using various initialization times to determine proper spin up timing for an accurate simulation run, and the effect on the forecast track. The tracks of a few representative cases are reported in Fig. 2, including those initialized at 9/11/00Z in red, 9/12/00Z in blue, and 9/13/00Z in yellow with the NHC's best track in black. Overall, we concluded that the 9/13/00Z initialization produced the best HWRF track. It is noteworthy that the model run initialized at 12/00Z captures the northward turning of the Florence track better than the 13/00Z run, however, the earlier initialization time does not perform as well prior to landfall.

In WRF simulations, we varied the initialization time, from 9/10/00Z to 9/12/12Z, typically every 12 hours. We also simulated these times using different physics schemes. We conclude that the simulation initialized at 09/12/12Z using the tropical physics scheme produced a track that best matches the NHC best track. As shown in Fig. 3, the yellow track (9/12/12Z initialization) captures both the southward and northward turning very well.

For a more detailed analysis of the track, we plotted the 9/12/12Z case track at different layers in the atmosphere. In addition to the surface, in Fig. 4 we plotted the track figures at specific layers (850mb = red, 700mb = blue, and 500mb = green) to see how dynamics at these layers affected the shape of the track. Note that the 850mb track is similar to the surface track, but the 850mb track swings more westward as the storm begins the northward turning. In upper layers, such as higher than 500mb, the green track does not turn as much southward as on the other layers, and it made the landfall further to the north than observed at the surface. Thus, we concluded that the surface track would be the best to use.

3.2 *Relative Vorticity*

To determine which model simulation case (HWRF or WRF) to use for the analysis, we examined the relative vorticity at the 850mb layer using the best HWRF simulation and the best WRF simulation. Figure 5 shows the relative vorticity (in shading), geopotential height (in contours), and wind (in vectors), at some typical times. We compared our simulations results with the ERA5 reanalysis data before and after the southward turn, with the typical times shown in Fig. 5.

Negative values of relative vorticity are shaded in blues and positive in green, orange, and reds. The WRF result is on the left, the ERA5 data is in the middle, and the HWRF result is on the right. The WRF figures show large areas of strong negative relative vorticity near the storm and around areas of high pressure and ridges. In comparison, the HWRF figures show weaker areas of negative relative vorticity and there are larger areas of positive vorticity. The shortwave ridge in the HWRF figures is also not as intense and organized as that in the WRF case. The positive relative vorticity near the center of the storm in the HWRF figure is also not as strong as those in the WRF figure. The dynamics represented in the WRF simulation are closer to those in ERA5 than those obtained using HWRF.

4. Results and Discussions

4.1 *Shortwave Ridge and High-Pressure System*

Our focus on track deflection for Florence revolves around a shortwave ridge and the high-pressure system that is located at the northwest of Florence as it made its dissent on land. A hurricane is defined as a rotating low-pressure weather system. In general, when a hurricane meets a high-pressure system, it can disrupt the hurricane's cyclonic flow as high-pressure systems move anticyclonically. To avoid flow disruption and dissipation a hurricane may move around a high pressure making sure not to encounter that anticyclonic flow. High pressure systems create a blockade that a hurricane will ultimately avoid so to maintain its organization (Lin et al., 2016). A shortwave ridge is defined as an embedded kink in a ridge system that moves faster than the longwave system. In the case of Florence, such a system created a strong blockage that kept the storm from moving in the normal north/northwest direction.

Figure 6 shows the sea level pressure and geopotential height at different levels before and after the southward and northward turnings of Florence. A common phenomenon can be seen at each layer: a strong shortwave ridge and high-pressure system are present before and after the southward turning. As the storm began to turn back to the north/northeast, the shortwave ridge loses its intensity, and the high-pressure system starts to recede to the northeast. A combination of these factors gives Florence the room, after its southward descent, to turn northward and track to the northeast as it dissipates.

At the 700mb layer a strong high pressure system surrounds Florence as it makes landfall and turns southward. Comparing it to the lower levels, we also see a more organized and intense shortwave ridge system that maintains organization longer than layers higher in the atmosphere. At 500 mb, we observe that the shortwave ridge and high-pressure system isn't as intense. This is comparable to the 500mb green track, as that track doesn't curve as far to the south or as much to the west during the same times as lower-level tracks do. It is still notable to mention that although dynamic features aren't as strong at 500mb, the same trend exists. Overall, a shortwave ridge and intense high pressure are causing a blocking effect that led to Florence's track deflection.

4.2 *Relative Vorticity*

Troughs and ridges are associated with relative vorticity due to the difference in horizontal wind speed. Troughs produce negative relative vorticity as the flow is anticyclonic, ridges are associated with positive relative vorticity due to its cyclonic wind flow. Like a high-pressure system, negative relative vorticity also spins anticyclonically, which creates a blocking mechanism causing the storm to move around to avoid disruption. As mentioned above, the relative vorticity figures at 850mb were used for the verification of the HWRF and WRF simulations. We also plotted these figures at 700mb and 500mb levels for further analysis in Fig. 7.

Analyzing the figures in Fig. 7, we see a strong area of negative relative vorticity (blue) present to the northeast of the storm at both levels, before and after the southward turn. This contributes to the southward deflection of the storm: Florence turned southward to avoid the direct impinging which may cause the storm's destruction. After the storm continued in its southward deflection for almost two days, we see those previously large areas of negative relative vorticity lessen and shift easternly allowing Florence to track north/northeastward.

At the 700mb level in Fig. 7, we see strong areas of negative relative vorticity, whereas the 500mb level shows larger areas of positive relative vorticity than that of negative relative vorticity. Larger areas of positive relative vorticity can be seen during the northward turning that also align with the direction of the track. Positive relative vorticity is a more favorable condition that does not contribute to the organizational destruction of hurricanes.

4.3 *Translation Speed of Florence*

It is important to study Florence's translation speed as it made landfall, i.e., the storm's stalling. When a storm stalls after making landfall it allows tremendous rain, storm surge, and heavy winds to affect an area for a longer duration of time (Callaghan, 2020). To make it more visually comprehensive, in Fig. 8 we plotted the storm's speed from the WRF case (blue line) and the NHC track data (orange line). The speed values are estimated as the ratio of difference in the storm's center locations (latitude and longitude) over the time difference. We plotted a 6-day period plotting 6-hour intervals from 9/12/12Z to 9/18/12Z to analyze Florence's speed. When comparing our case to the NHC track data we see just how slowly Florence moved. For about a 3-day period Florence does not move faster than 10 mph. Some of the lowest speeds can be walked and run faster by humans. Our WRF-ARW simulation case even shows no movement during 9/16/00Z. This slow-moving tenure is attributed to most of the damage and deaths incurred by Florence.

5. Conclusion

In conclusion, we obtained our best results from our WRF simulation and were able to analyze those results to discuss track deflection. Based on our simulated results and analysis, we can conclude that there was a strong shortwave ridge and high-pressure system present during Florence's landfall that attributed to its track deflection. The high-pressure system and shortwave ridge created a blocking effect causing the storm to slow down and turn southward. A strong blockage of negative relative vorticity appeared to the northwest of the storm, causing it to also turn southward. About a day after landfall, the shortwave ridge lost its intensity and the high-pressure system to the northeast allowed Florence to track back northeast as it dissipated. Overall, we can say that multiple dynamics were at play to cause Florence to deflect to the south after landfalling, and back to the northeast as it dissipated.

6. Acknowledgments

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8. Appendix: Figures

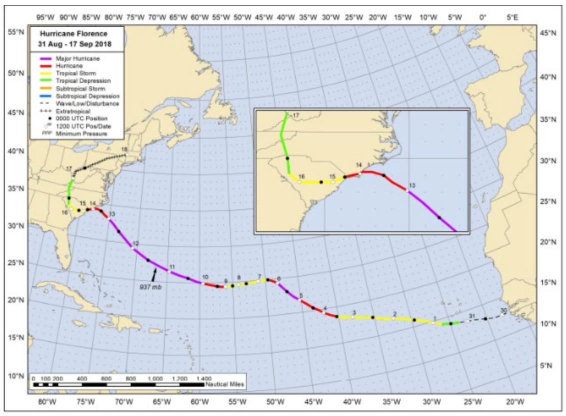

Figure 1. NOAA track figure shows L-shaped track in (zoomed in)

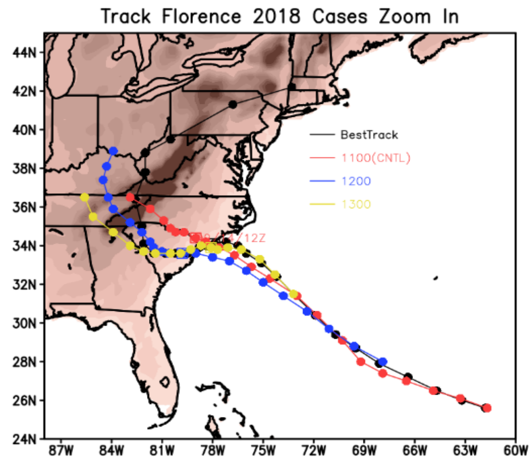

Figure 2. HWRF track figure 11/00Z (red), 12/00Z (blue), 13/00Z (yellow)

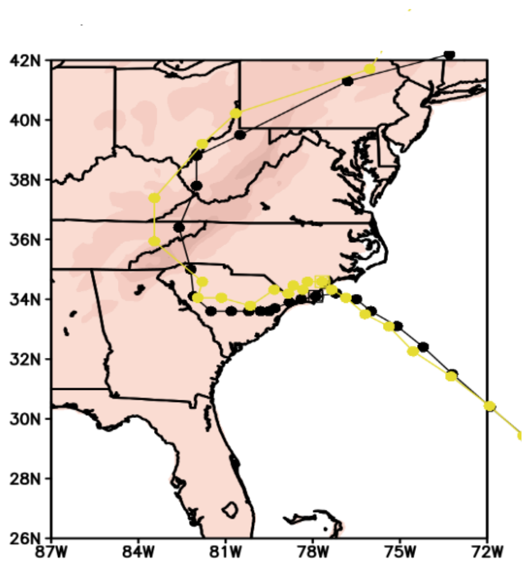

Figure 3. WRF-ARW Track 9/12/12Z (yellow) and NHC Best track data (black)

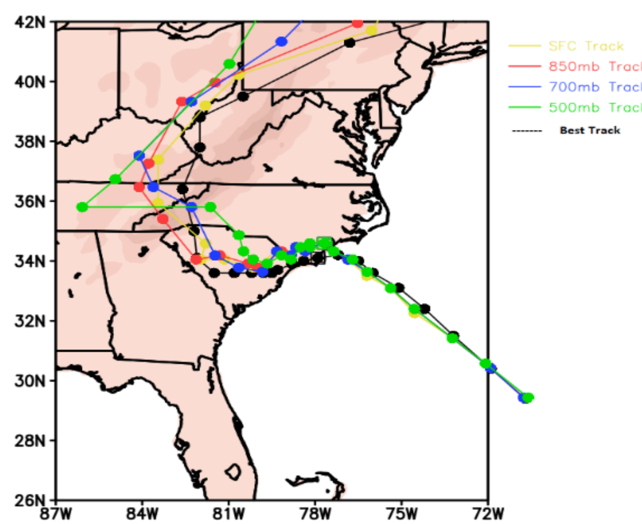

Figure 4. WRF-ARW track at different layers

Different dynamics at different layers affect the shape of the track

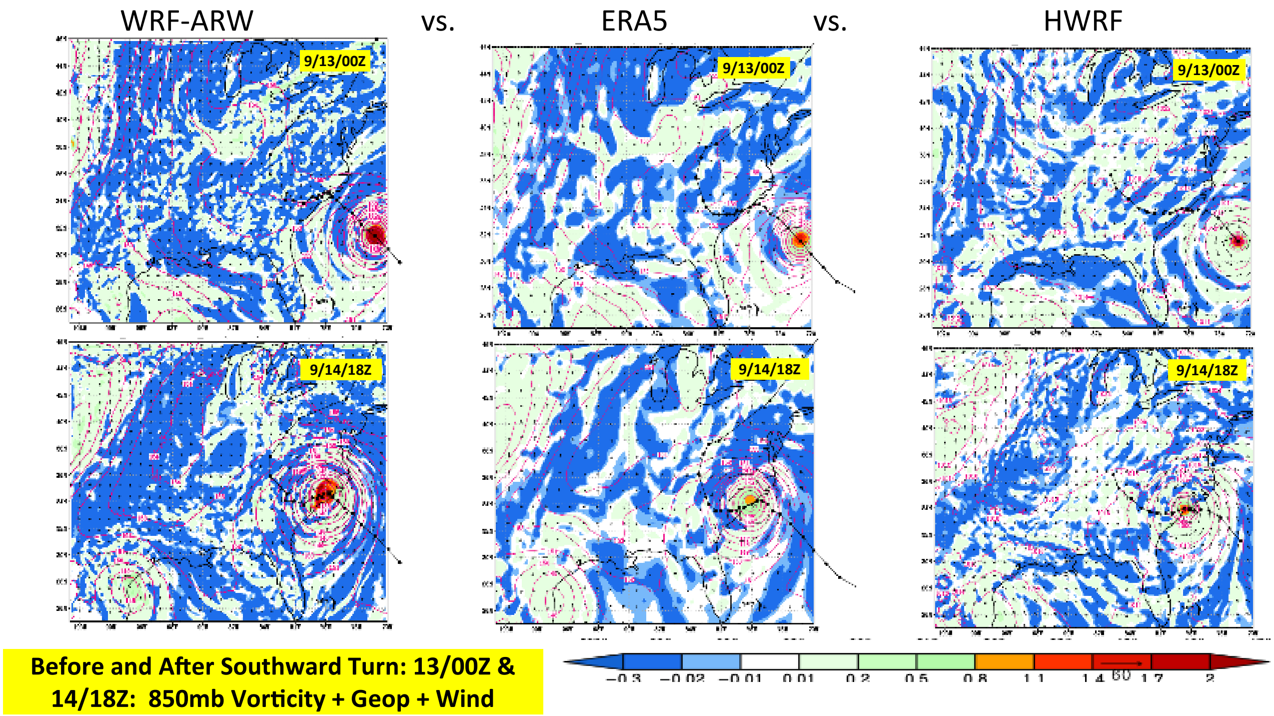

Figure 5. Verification of WRF Simulation

Relative Vorticity (shade), Geopotential Height (contour), Wind (vector)

Compared with the observation (ERA5) data analysis, the WRF-ARW simulation result represents the similar dynamics better than the HWRF simulation result

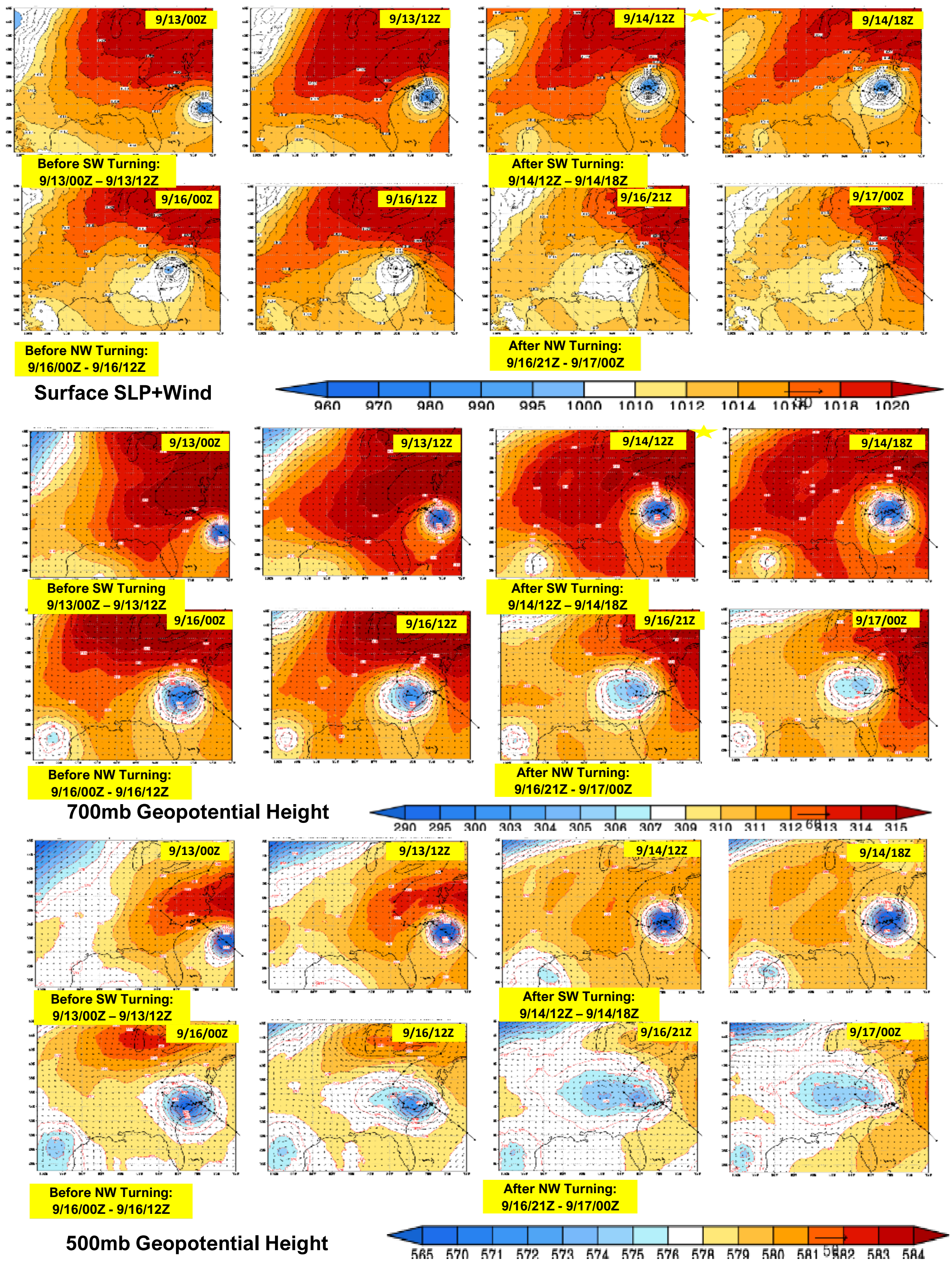

Figure 6. Shortwave ridge and High Pressure, Geopotential Height (shade, contour) Wind(vector)

Before and after the SW turning, an intense shortwave ridge and high-pressure system caused a blocking effect. The shortwave ridge and high-pressure system receded after the NW turning, allowing Florence to track back Northeastward.

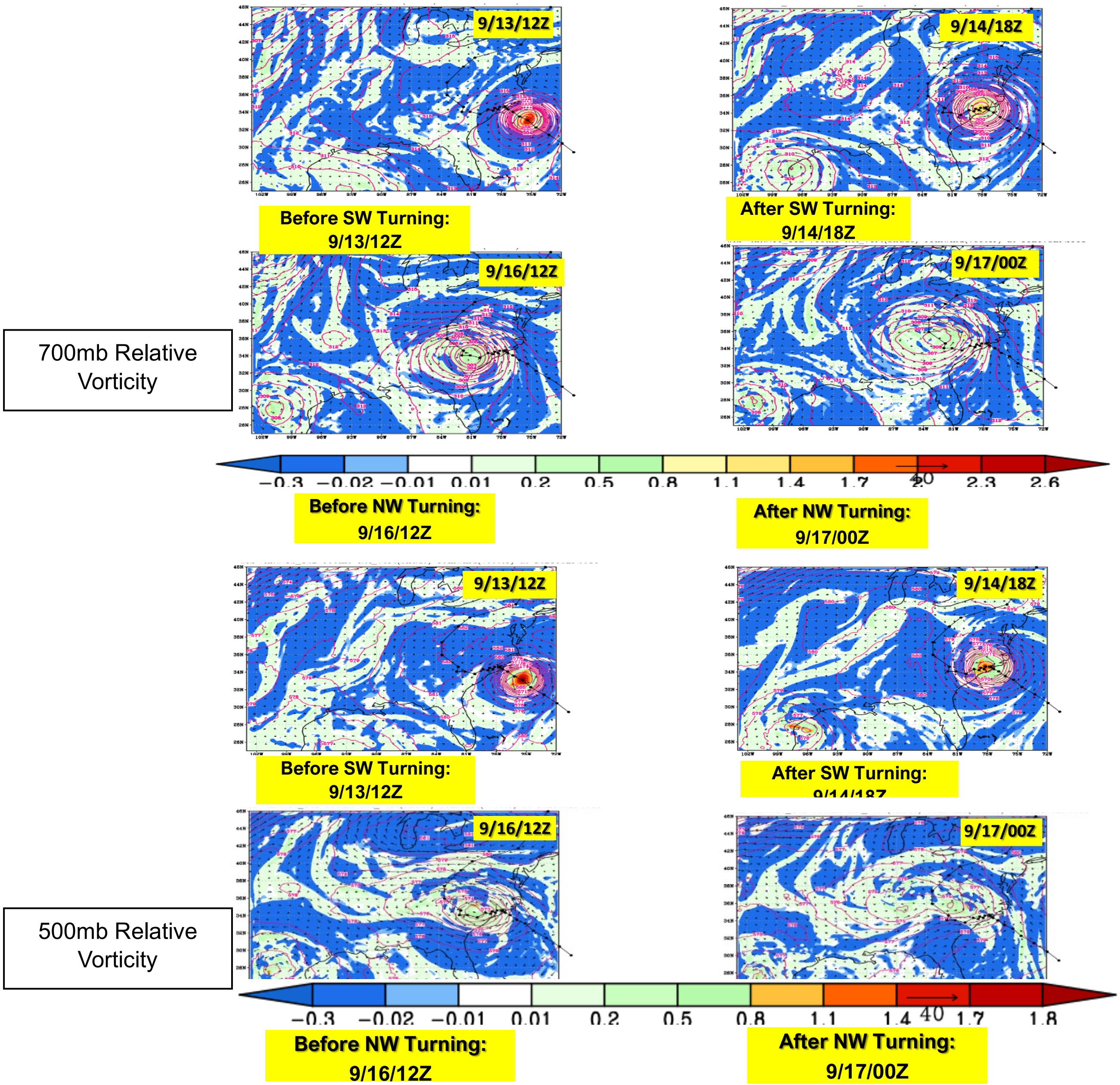

Figure 7. Relative Vorticity (shade), Geopotential Height (contour), Wind (vector)

700mb level shows a strong negative relative vorticity north of the storm.

Larger areas of positive relative vorticity can be seen at 500mb level

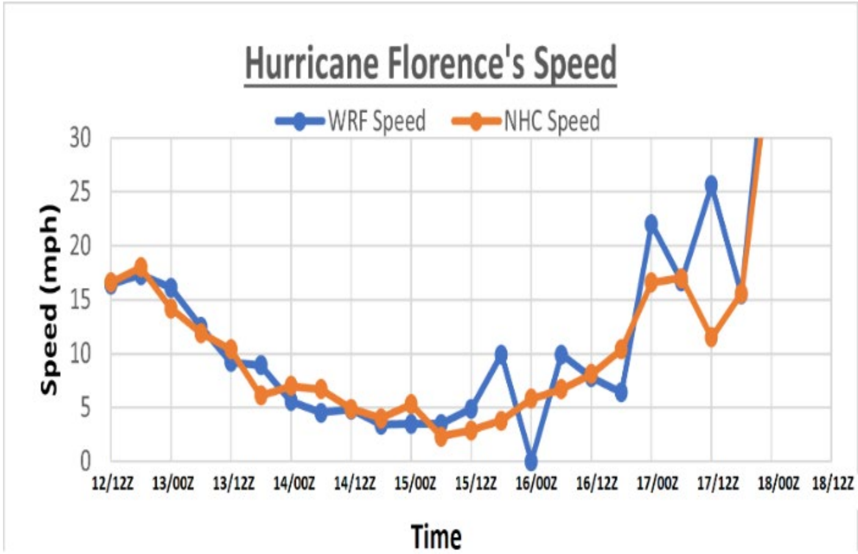

Figure 8. Florence speed

Figure shows during certain times a person can walk/run faster than Florence was moving