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ATTACHMENT 5 to the METEOROLOGY GROUP FACTUAL REPORT

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Appendix I from the National Oceanic and Atmospheric Administration's Service Assessment "The Historic South Carolina Floods of October 1-5, 2015."

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Appendix I: Hurricane Joaquin Analysis/Assessment

Model Performance for Hurricane Joaquin

The tropical depression that eventually became Hurricane Joaquin formed northeast of the Bahamas on September 28, 2015. During the next 3 days, it moved to the southwest, causing significant damage in the Bahamas before looping back to the northeast and continuing that track out to sea. During the first few days of Joaquin's life, most guidance suggested a threat to the U.S. East Coast; however, the European Center for Medium Range Forecasting (ECMWF) model predicted early on that the storm would not make landfall, while NCEP's Global Forecast System (GFS) was slower to capture the decreasing threat. The same was true for the Weather Research for Forecasting (WRF) model specifically tuned for hurricanes guidance (HWRF). The European Center Ensemble Prediction System (EPS) and the NCEP Global Ensemble Forecast System (GEFS) performed similarly to the deterministic runs. The GFS parallel (also called the GFSX) was slightly better than the operational GFS. This parallel model, which features several changes to the data assimilation, is scheduled for implementation as the next GFS model during spring of 2016.

Deterministic Models

Figures 1–9 show tracks for the GFS, ECWMF, and (when available) the parallel GFSX. **Figure 1** shows the 1200 UTC 28 September cycle, with both the GFS and ECMWF making landfall, but with the ECMWF targeting southern Virginia before making an odd loop that allowed for a second landfall farther north; the GFS was taking the storm into southern New England. Starting with the 0000 UTC 29 September cycles (**Figure 2**), the ECMWF correctly locked onto a track well offshore that posed no threat to the East Coast. The GFS did not show an actual landfall, but brought Joaquin perilously close to the Outer Banks of North Carolina. In both of these cycles, it was evident that the ECMWF correctly captured the initial south-southwest motion of Joaquin, accurately showing a threat to the Bahamas before a turn back to the northeast. The GFS immediately moved Joaquin to the north-northwest.

The 1200 UTC 29 September cycle (**Figure 3**) has the GFS, ECMWF, and GFSX all indicating no threat to the East Coast from Joaquin, although the three solutions were very different. The ECMWF correctly moved the storm south of 25 N initially, before turning it back to the northeast. The initial GFS movement was to the west before a turn to the north, followed by very slow movement before turning again to the east. The GFSX track ended up being more accurate than that of the GFS, but it was actually too far east, and like the GFS, initially moved the storm to the west instead of south.

A major change occurred with the 0000 UTC 30 September cycle (**Figure 4**). The ECWMF continued with its remarkably accurate track, but the GFS and GFSX had nearly identical tracks to the north with final curves into southern Virginia and remnants tracking into New England. The GFS and GFSX both finally had more of a southerly component in the initial motion, although still not moving Joaquin sufficiently southward. **Figure 5** shows that the GFS and GFSX did an even better job with the initial southward movement in the 1200 UTC 30

September cycle, but the GFS still brought the storm into the Carolina coast, while the GFSX showed landfall in the Delmarva Peninsula.

The 0000 UTC 1 October cycle (**Figure 6**) still saw the GFS and GFS turn Joaquin too far to the west after the initial southwest motion. The resulting turn was therefore more to the north, compared to the northeast turn by the ECMWF. The GFS simulation of Joaquin was possibly influenced by the large upper low over the southeast, and the model still made landfall, although dramatically farther north than previous cycles. The GFSX, however, did not show landfall, although its track was still too far to the west. The GFSX maintained a very similar track in the 1200 UTC 1 October cycle (**Figure 7**), but the GFS shifted well to the east and now joined the camp showing no landfall.

The 0000 UTC 2 October cycle (**Figure 8**) saw the GFS shift back to the west but still offshore, although indicating some impact in the Canadian Maritimes. The GFSX correctly curved Joaquin more to the east such that much of its later track matched that of the ECMWF. The 1200 UTC 2 October cycle (**Figure 9**) saw all three models keep Joaquin well offshore, with the GFSX slightly farther east than the GFS or ECMWF.

Table 1 summarizes the cycle at which various deterministic models first showed Joaquin not making landfall along the East Coast and then continued to not show a landfall in all subsequent runs. In addition to the GFS, GFSX, and ECMWF, times are given for the United Kingdom Meteorological Office Model (UKMET), the Japan Meteorological Agency Model (JMA), the Geophysical Fluid Dynamics Laboratory Model (GFDL), the Navy Global Environmental Model (NAVGEM), the Canadian Meteorological Center Global Model (CMC), and the North American Mesoscale Model (NAM).

HWRF

Figure 10 shows a composite of all HWRF tracks for Joaquin, every 6 hours, starting with 1800 UTC on 26 September and ending with the 1200 UTC cycle on 6 October, with the observed track in black. The first 19 cycles either made landfall or threatened the eastern U.S. coast. The 1200 UTC cycle on 1 October was the first cycle that did not show a U.S. landfall, although it still had the storm threatening the Canadian maritime region. Each cycle thereafter adjusted the track a little to the east.

Ensembles

This section assesses the performance of the GEFS and EPS with plots showing the ensemble mean (black line), individual members (white lines), and probabilities (color fill). Beginning with the 1200 UTC 29 September cycle (**Figure 11**), the ensemble means kept Joaquin offshore, but with many members indicating landfall. The 1200 UTC 30 September cycle (**Figure 12**) saw the EPS shift to showing a majority of members with a track out to sea, while the GEFS suggests high confidence in a North Carolina landfall. The 0000 UTC 1 October cycle (**Figure 13**) saw only a couple of EPS members with any landfall, while a majority of GEFS members had Joaquin striking the Outer Banks. The GEFS solutions were strongly bi-modals, with a large number of members showing landfall and a sizeable cluster showing a track well out to sea with nothing in between.

The 1200 UTC 1 October GEFS (**Figure 14**) made a large shift to the east, looking very much like the EPS (not shown but extremely similar), with only one member showing landfall. However, the 0000 UTC 2 October GEFS (**Figure 15**) again showed a significant number of members with landfall, although the larger cluster had a track well to the east. The 1200 UTC 2 October GEFS (not shown) finally saw all members keeping Joaquin well offshore.

Summary

All models during the development of Joaquin showed a significant threat of a major hurricane landfall along the East Coast. The ECMWF mode, however, quickly locked in on the idea that Joaquin would remain well offshore. The GFS, however, took two more days before showing that the threat did not exist. The GFSX parallel was 6 hours faster than the operational GFS in dismissing the East Coast threat. Like their deterministic systems, the EPS was significantly faster than the GEFS in dismissing a high threat of landfall. The GEFS solutions for many cycles showed a bi-modal distribution.

The ECMWF runs consistently and accurately captured the initial movement of Joaquin to the south-southwest, while the GFS had a very difficult time capturing the initial track. This resulted in less warning given to the Bahamas, where significant storm impacts occurred. It is not known whether successful simulation of the early part of the track was critical in accurately simulating the track of the storm after the turn to the north.

ECMWF	**00Z Sep 29**
GFSX	**00Z Oct 1**
UKMET	**00Z Oct 1**
GFS	**06Z Oct 1**
HWRF	**12Z Oct 1**
JMA	**12Z Oct 1**
GFDL	**18Z Oct 1**
NAVGEM	**06Z Oct 2**
CMC	**12Z Oct 2**
NAM	**18Z Oct 2**

Table 1: Lists of the first cycles for which various forecast models first indicated that Joaquin would not make landfall along the East Coast and kept the storm offshore in all subsequent cycles. Global models are in bold.

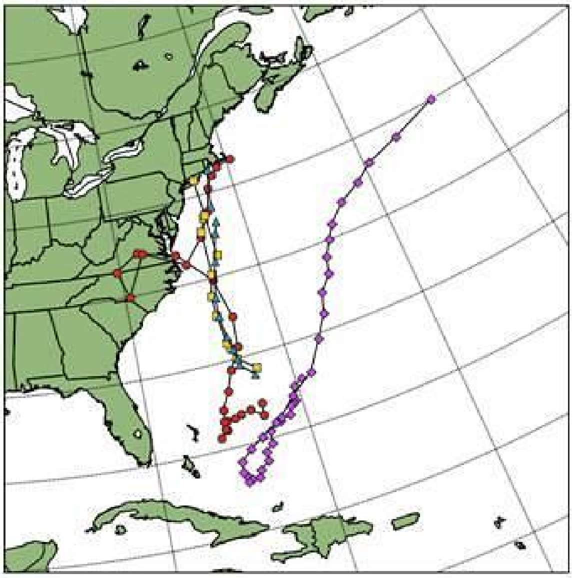

Figure 1: Tracks for the GFS (blue triangles), the ECMWF (red dots), the parallel GFSX (yellow squares), and the observed track (purple diamonds) for the 1200 UTC cycle 28 September 2015. The observed track is shown through 0300 UTC 7 October 2015.

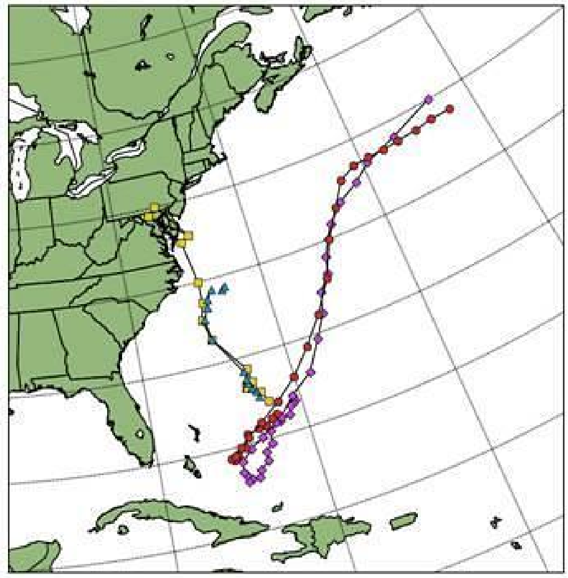

Figure 2: Same as in Figure 1, but for the addition of the 0000 UTC cycle 29 September.

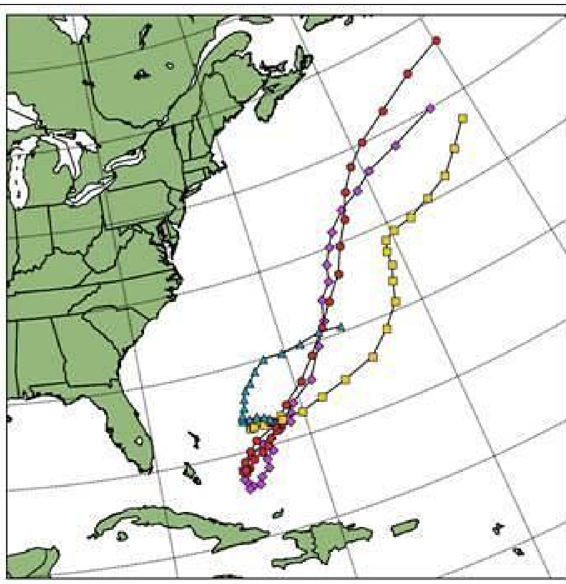

Figure 3: Same as in Figure 1, but for the addition of the 1200 UTC cycle 29 September.

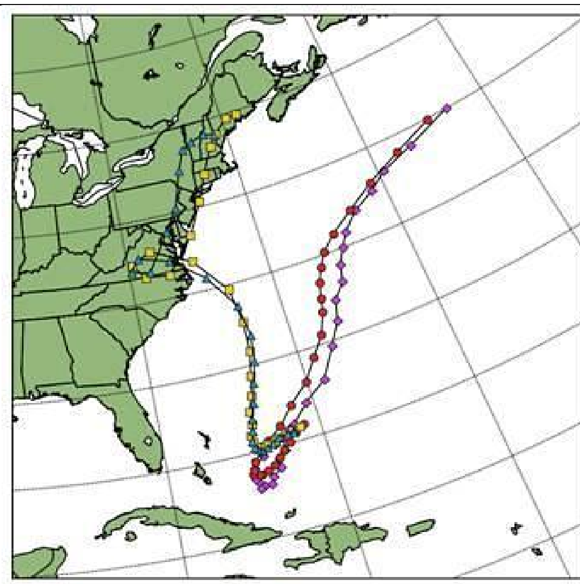

Figure 4: Same as in Figure 1, but for the addition of the 0000 UTC cycle 30 September.

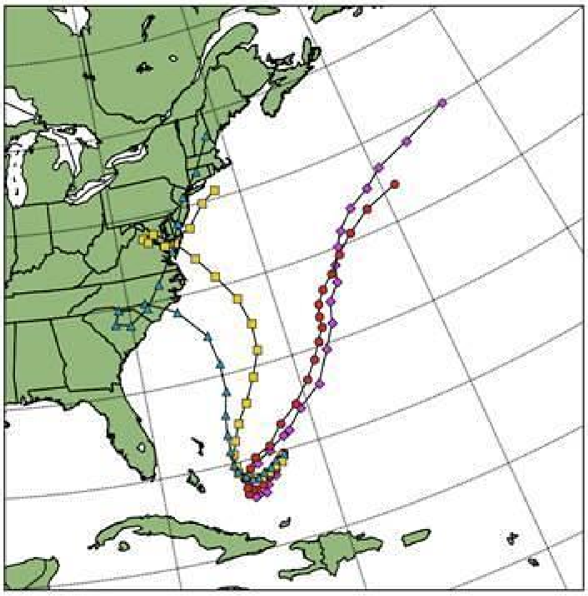

Figure 5: Same as in Figure 1, but for the addition of the 1200 UTC cycle 30 September.

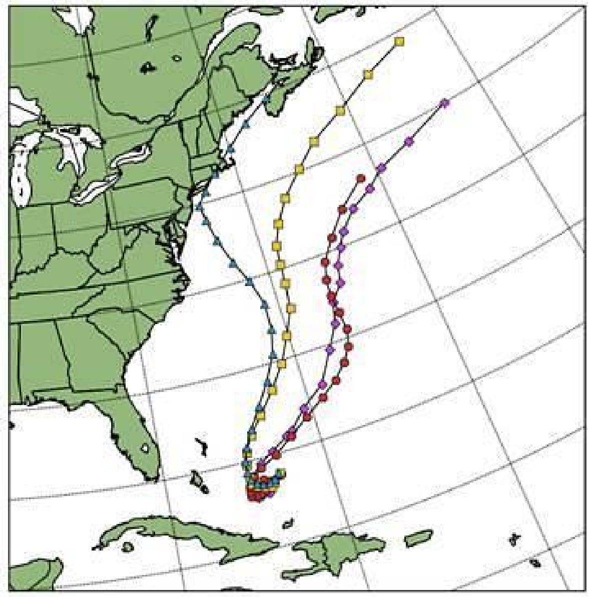

Figure 6: Same as in Figure 1, but for the addition of the 0000 UTC cycle 1 October.

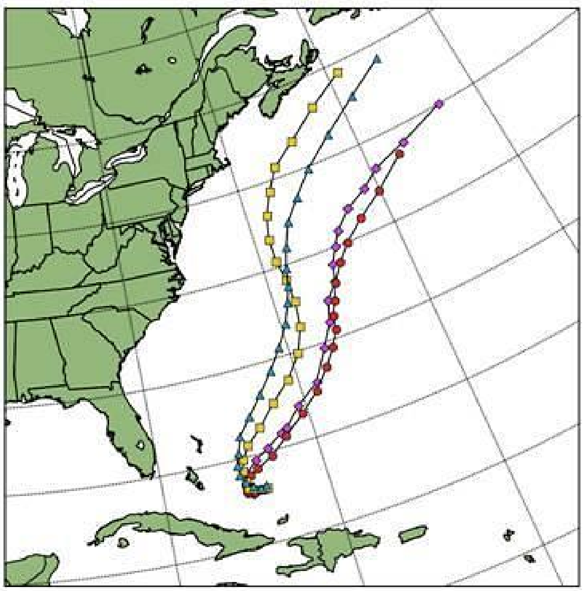

Figure 7: Same as in Figure 1, but for addition of the 1200 UTC cycle 1 October.

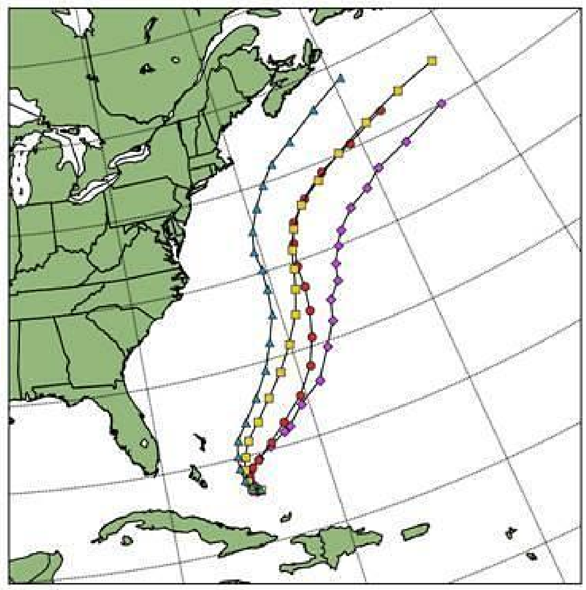

Figure 8: Same as in Figure 1, but for the addition of the 0000 UTC cycle 2 October.

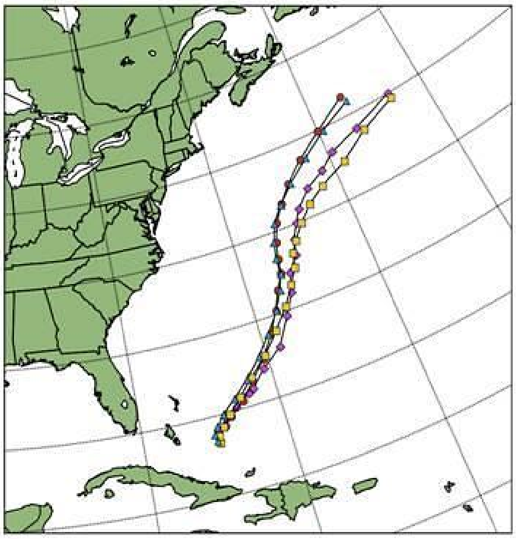

Figure 9: Same as in Figure 1, but for the addition of the 1200 UTC cycle 2 October.

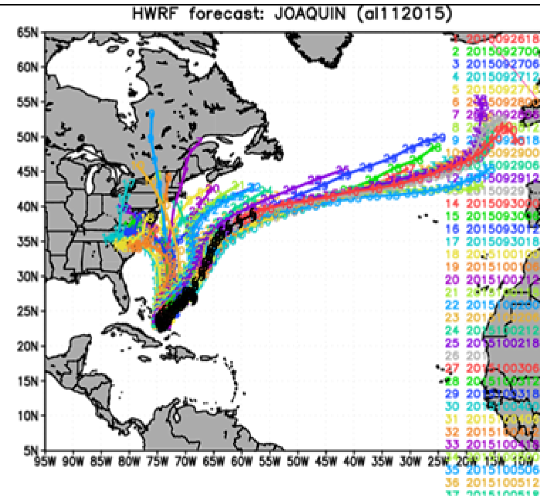

Figure 10: Composite of tracks for all HWRF runs between 1800 UTC 26 September and 1200 UTC 6 October.

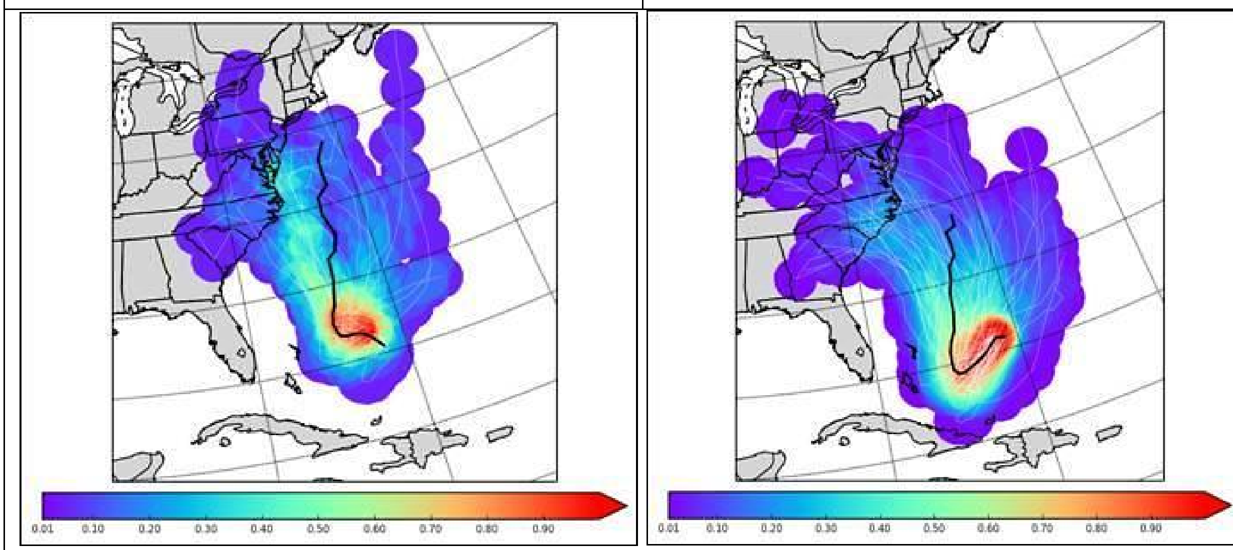

Figure 11: Ensemble forecasts showing mean (solid black line), individual members (thin white lines), and probabilities (color fill) from the 1200 UTC 29 September 2015 cycles of GEFS (left) and EPS (right).

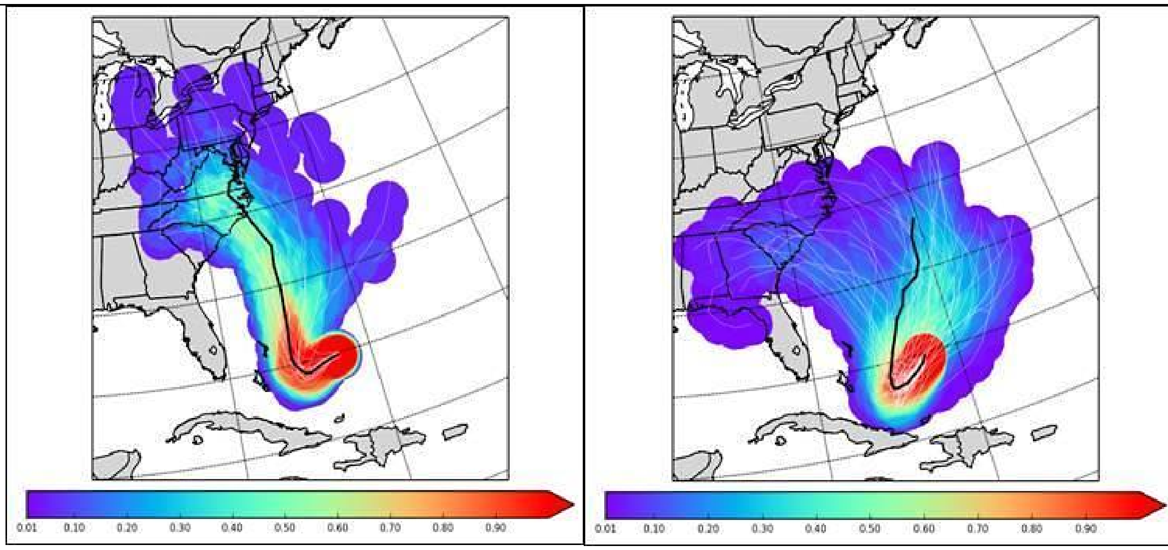

Figure 12: Same as in Figure 11, but for the addition of the 1200 UTC cycle 30 September.

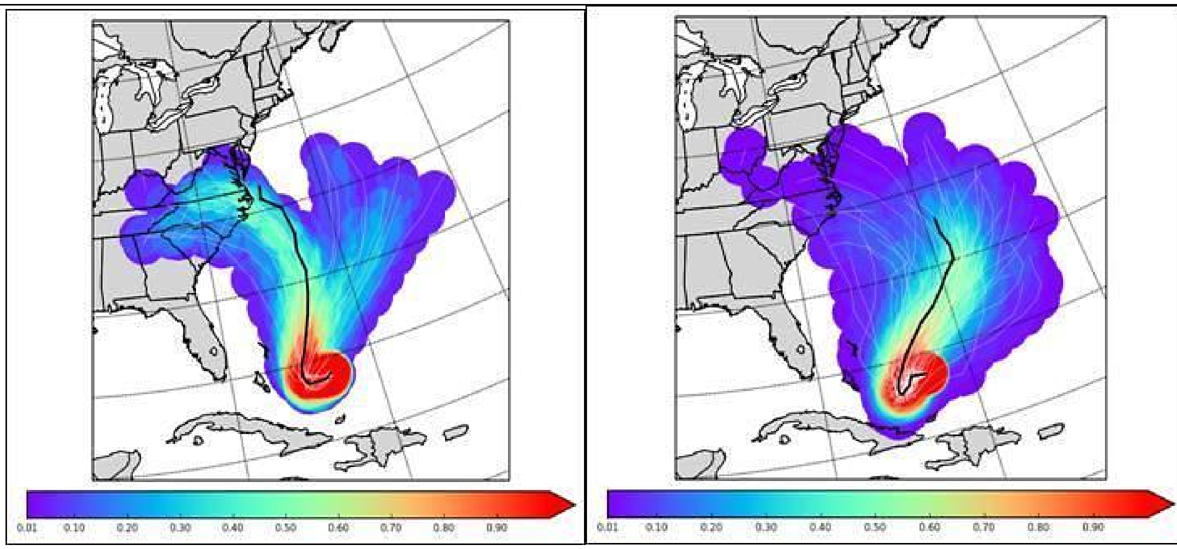

Figure 13: Same as in Figure 11, but for the addition of the 0000 UTC cycle 1 October.

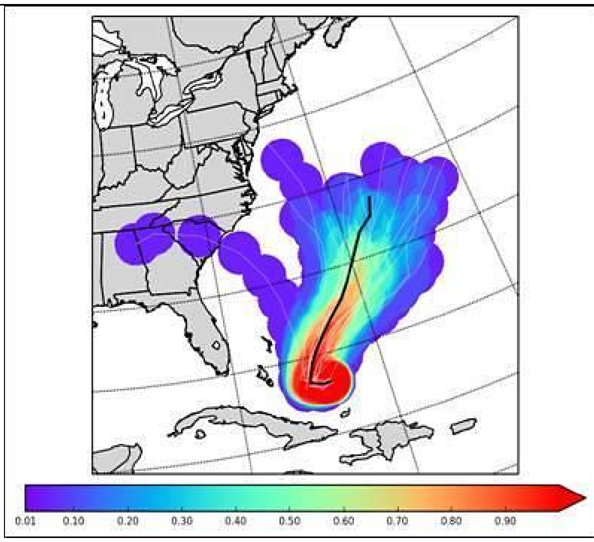

Figure 14: Same as in Figure 11, but for the addition of the 1200 UTC cycle 1 October, and only the GEFS is shown.

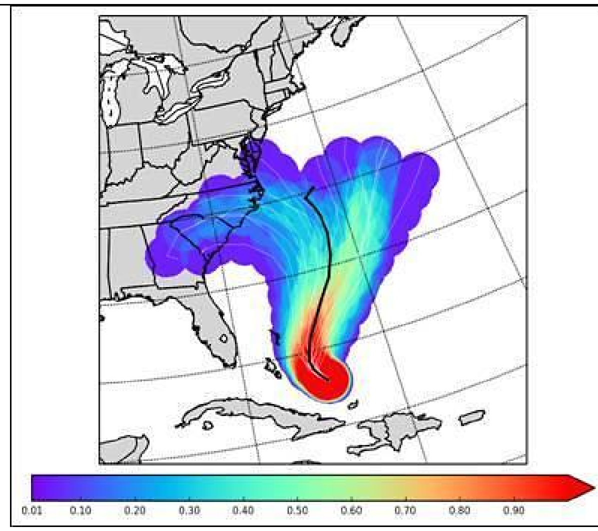

Figure 15: Same as in Figure 11, but for the addition of the 0000 UTC cycle 2 October, and only the GEFS is shown.