Supplemental Material

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A New Verification Approach? Using Coupled Natural–Human Models to Evaluate the Impact of Forecast Errors on Evacuations

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A new verification approach? Using coupled natural-human models to evaluate the impact of forecast errors on evacuations

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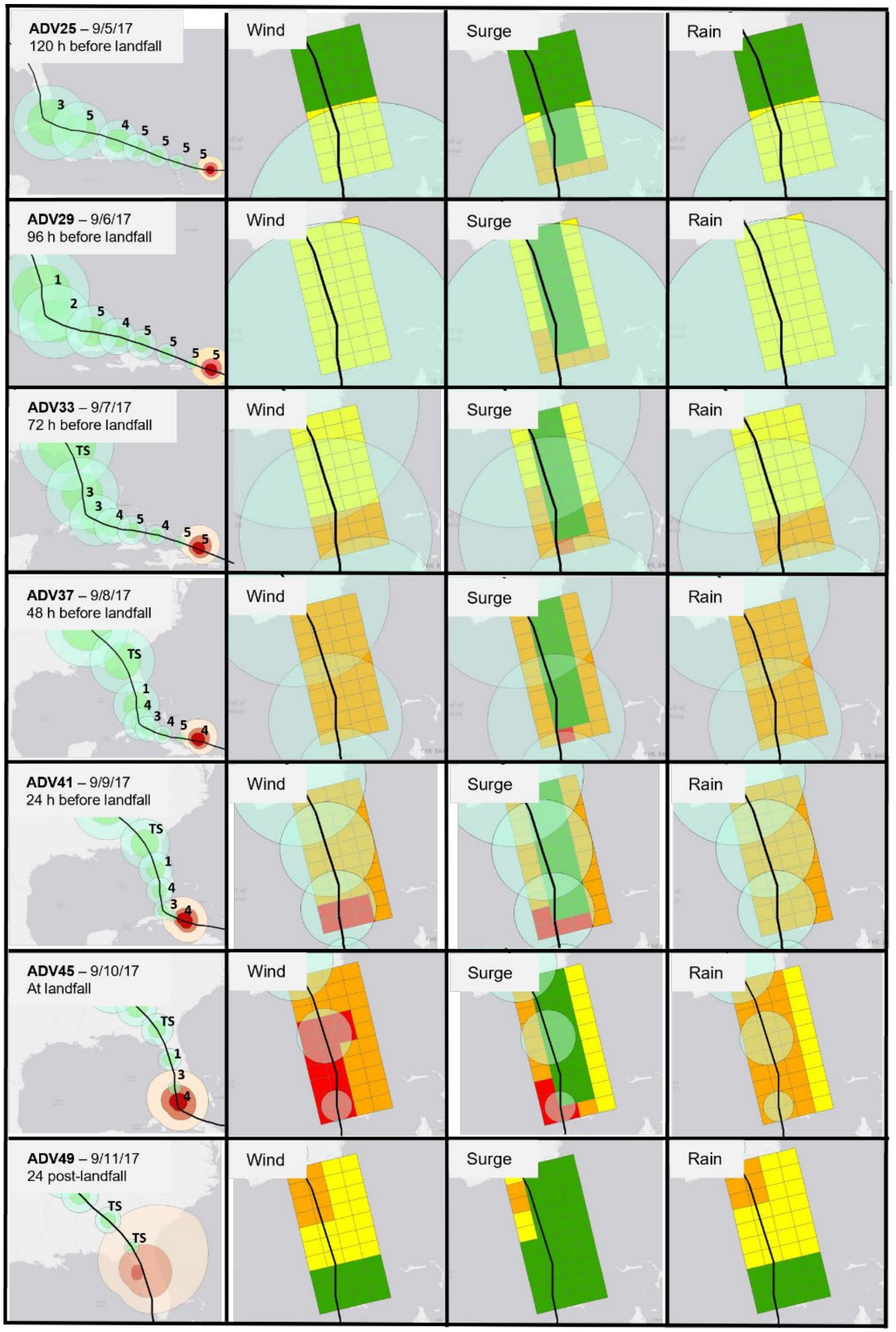
Cone of uncertainty in the Irma and Dorian (landfalling) Simulations

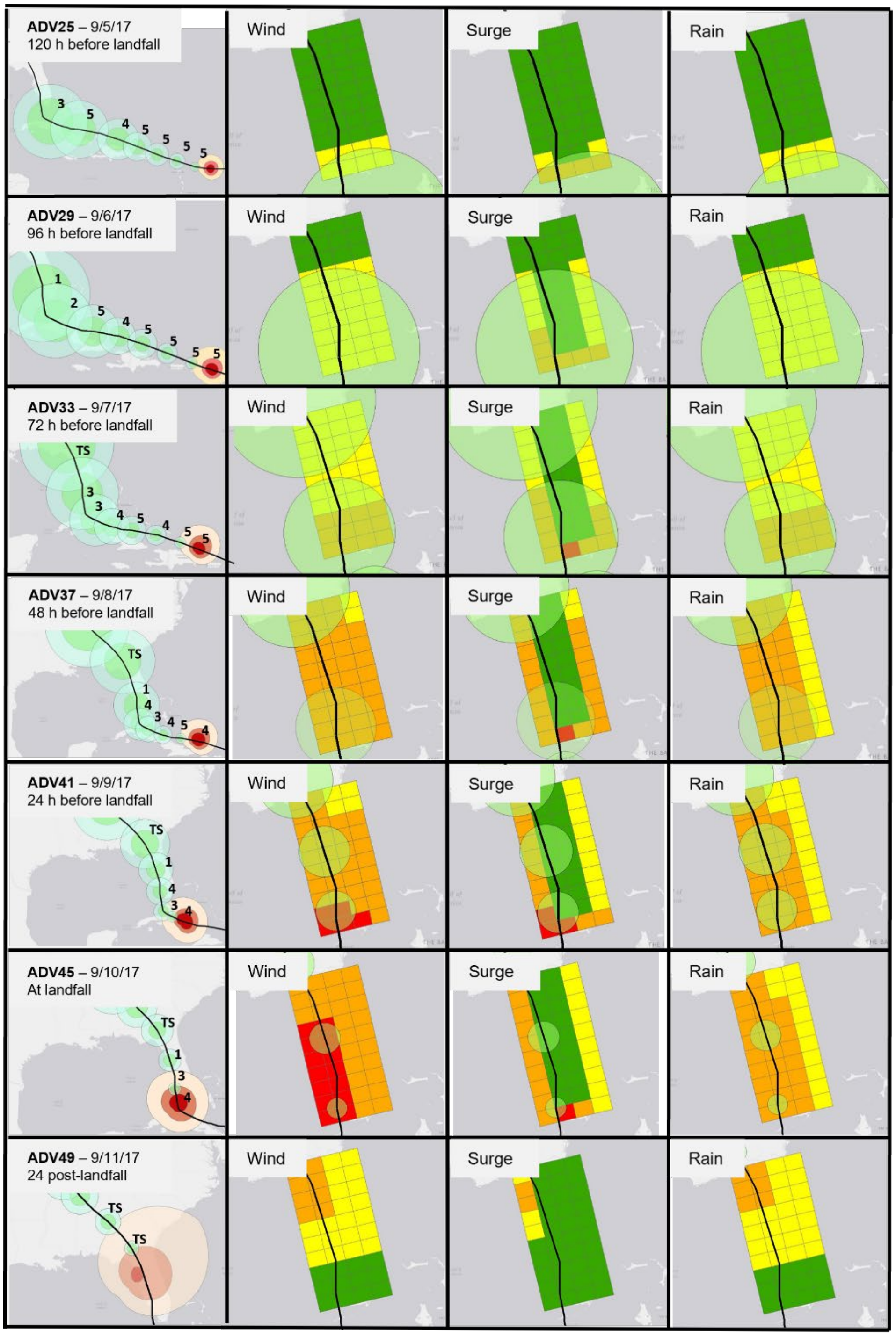
Forecast period (hours)	2/3 Probability Circles Atlantic Basin (nm)	
	2007	2022
12	39	26
24	69	39
36	99	52
48	124	67
72	179	100
96	252	142
120	326	200

Supplemental Table S1: Sizes of the circle radii used to draw the 2007 and 2022 cone of uncertainties. Values were taken from the 2/3 probability circles in the Atlantic Basin (nm) at different forecast periods (hours) provided on NHC's website for 2022 and 2007.

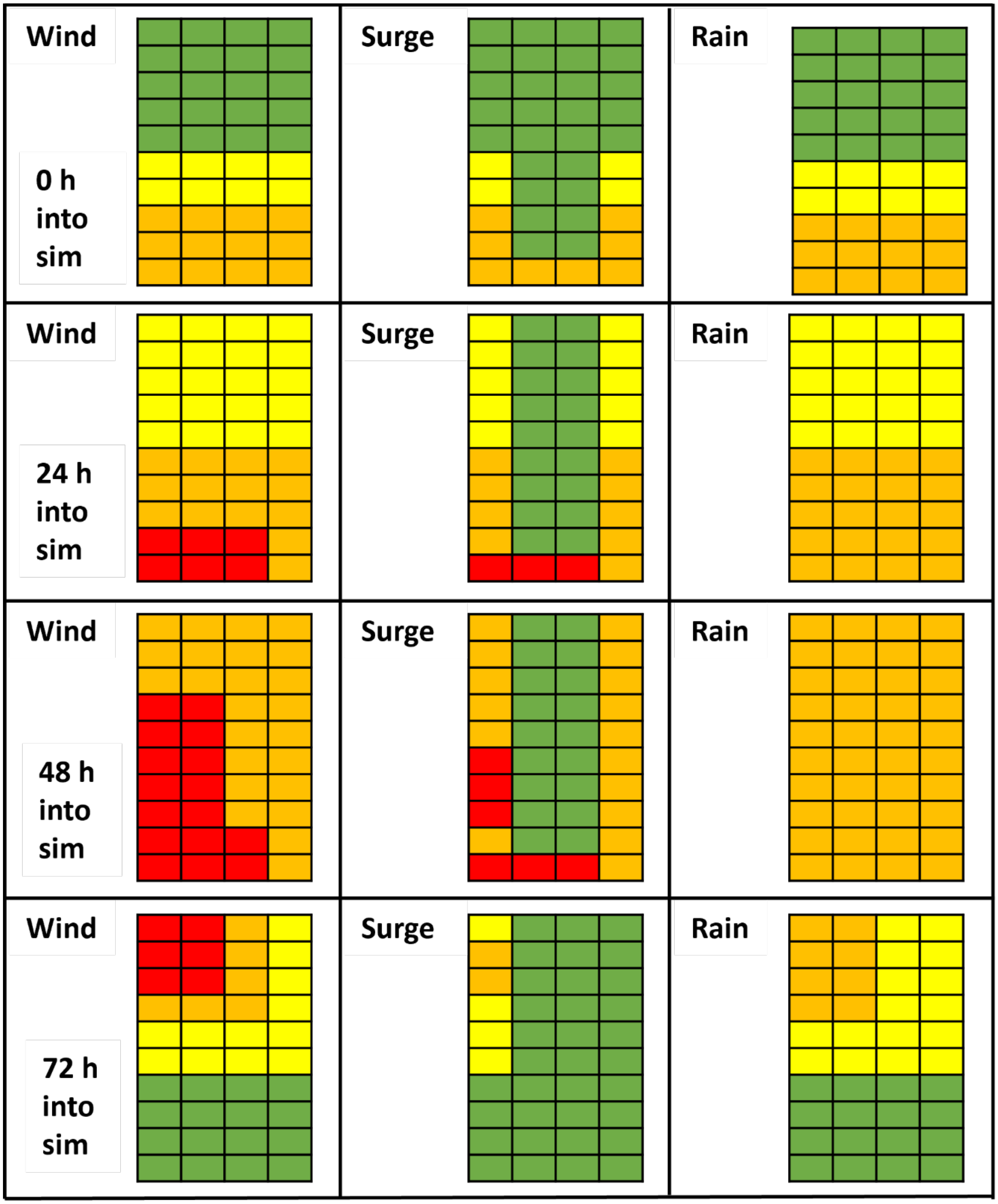
Irma Simulations – Supplementary Information



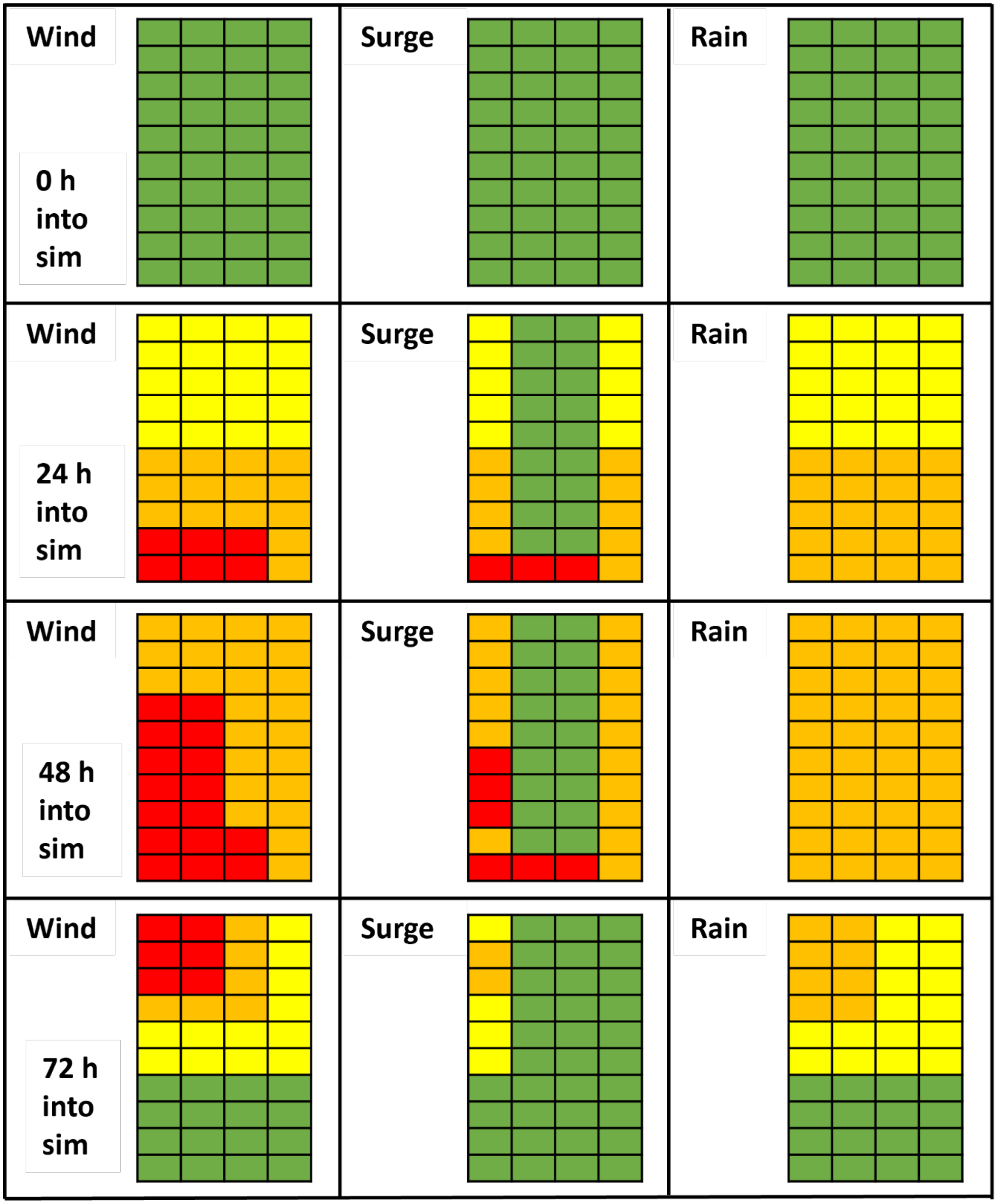
Supplementary Figure S1: Irma best track forecasts with the 2007 Cone of Uncertainty and corresponding estimates of wind, surge, and rain risks as the storm approaches and travels through the Florida-like, model grid. "Forecasts" are shown at 24 hour intervals, but update every 6 hours in the model simulations (not shown). Left column: Irma's NHC best track (black center line), observed storm intensity on the Saffir-Simpson scale (TS/numbers), circles used to draw the 2007 (blue) and 2022 (green) cone of uncertainties, and current wind radii at 34 (white), 50 (pink), and 64+ (red) knot intervals. Right three columns: The light-system threats for wind, surge, and rain are shown on the model grid for equivalent times in the simulation, with the best track (center black line) and circles used to draw the 2007 cone of uncertainty (blue circles) included for reference.



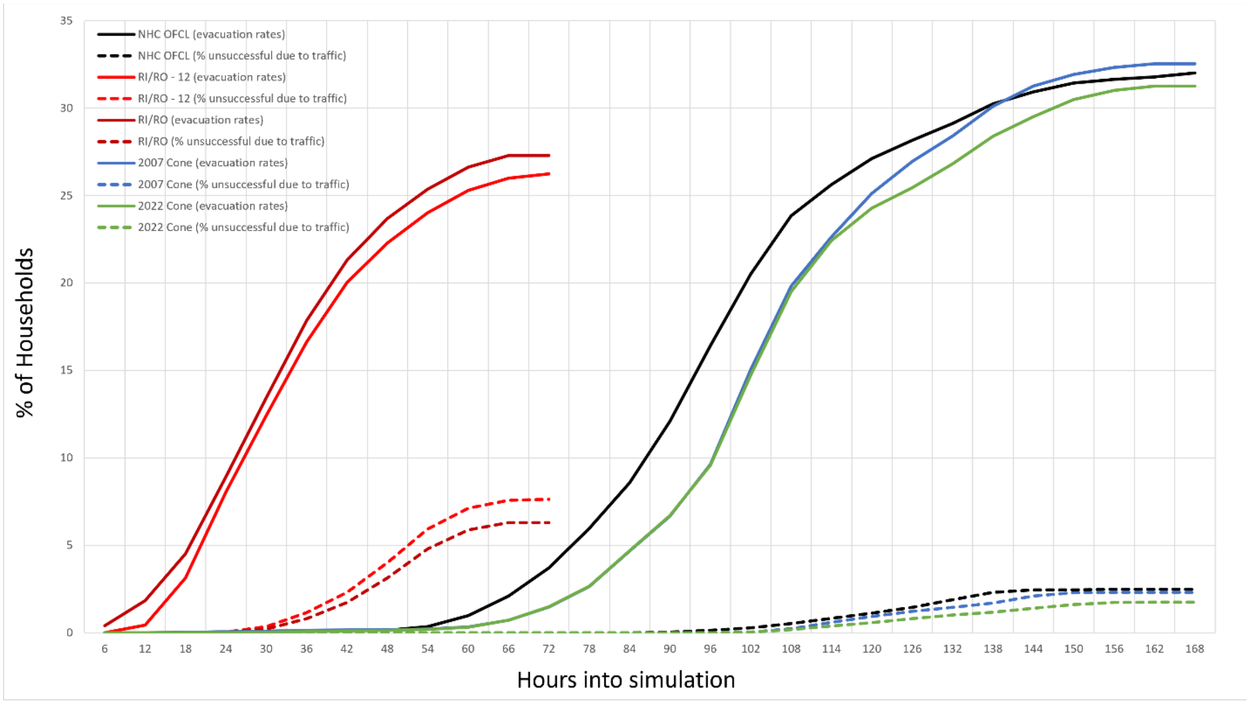
Supplementary Figure S2: Irma best track forecasts with the 2022 Cone of Uncertainty and corresponding estimates of wind, surge, and rain risks. "Forecasts" are shown at 24 hour intervals, but update every 6 hours in the model simulations (not shown). Left column: Irma's best track (black center line), observed storm intensity on the Saffir-Simpson scale (TS/numbers), circles used to draw the 2007 (blue) and 2022 (green) cone of uncertainties, and current wind radii at 34 (white), 50 (pink), and 64+ (red) knot intervals. Right three columns: The light-system threats for wind, surge, and rain are shown on the model grid for equivalent times in the simulation, with the best track (center black line) and circles used to draw the 2022 cone of uncertainty (green circles) included for reference.



Supplemental Figure S3: Irma's NHC OFCL with RI/RO forecasts. Here we shorten the forecast timeline of the NHC OFCL forecasts shown in Figure 1 from 168 hours to 84 hours, by using every other advisory (only the 00 and 12 UTC advisories), while only 6 hours of time elapses in the simulation. Forecasts are shown every 24 hours but update every 6 hours (not shown). The peak magnitudes of risk (wind, surge, rain) for each grid cell are the same as Irma; however, the timelines are condensed, effectively creating large and intertwined forward speed, intensity, and track errors meant to emulate the effects of rapid onset/intensity cases.

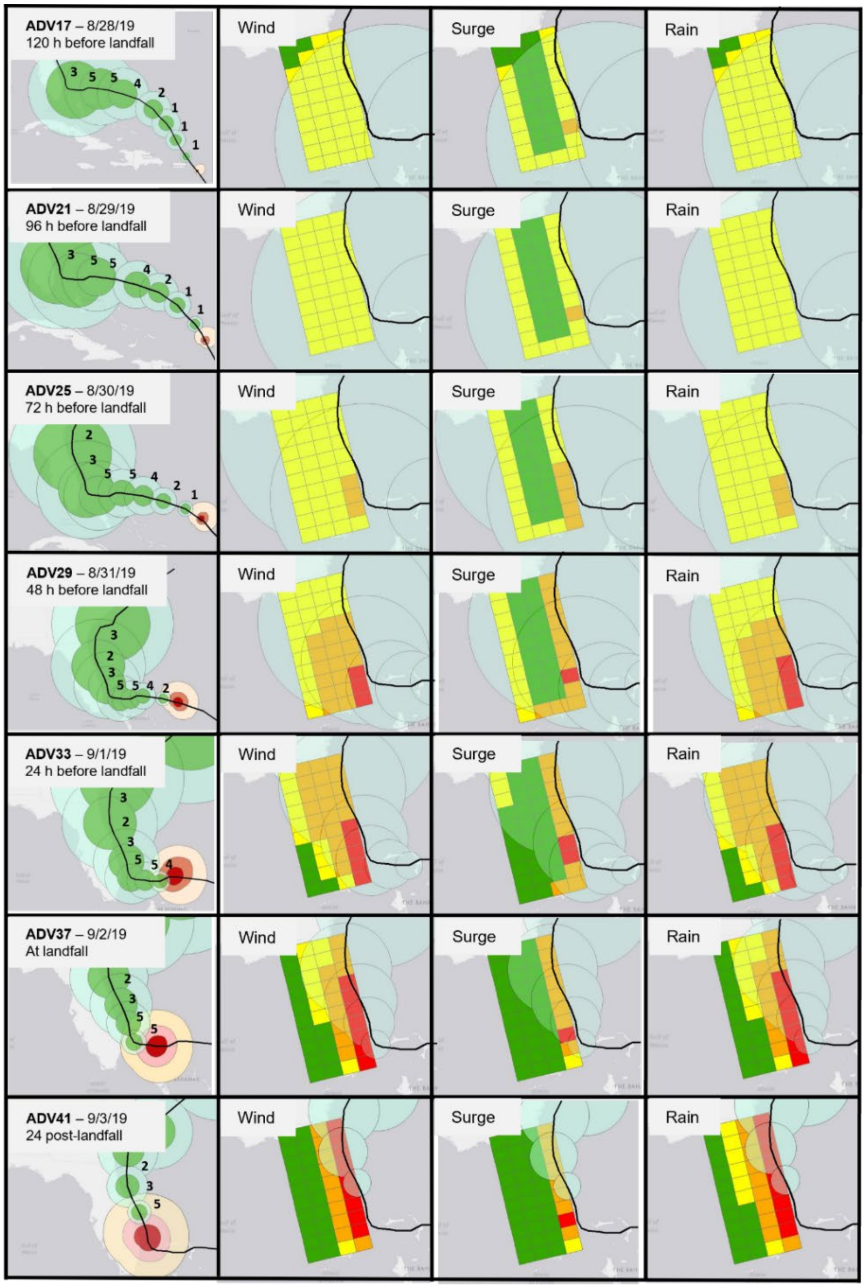


Supplemental Figure S4: Irma's NHC OFCL with RI/RO – 12 hours forecasts. Here we shorten the forecast timeline of the OFCL NHC forecasts shown in Figure 1 from 168 hours to 72 hours, by using every other advisory (only the 00 and 12 UTC advisories), while only 6 hours of time elapses in the simulation. Forecasts are shown every 24 hours but update every 6 hours (not shown). The peak magnitudes of risk (wind, surge, rain) for each grid cell are the same as Irma; however, the timelines are condensed, effectively creating large and intertwined forward speed, intensity, and track errors meant to emulate the effects of rapid onset/intensity cases.

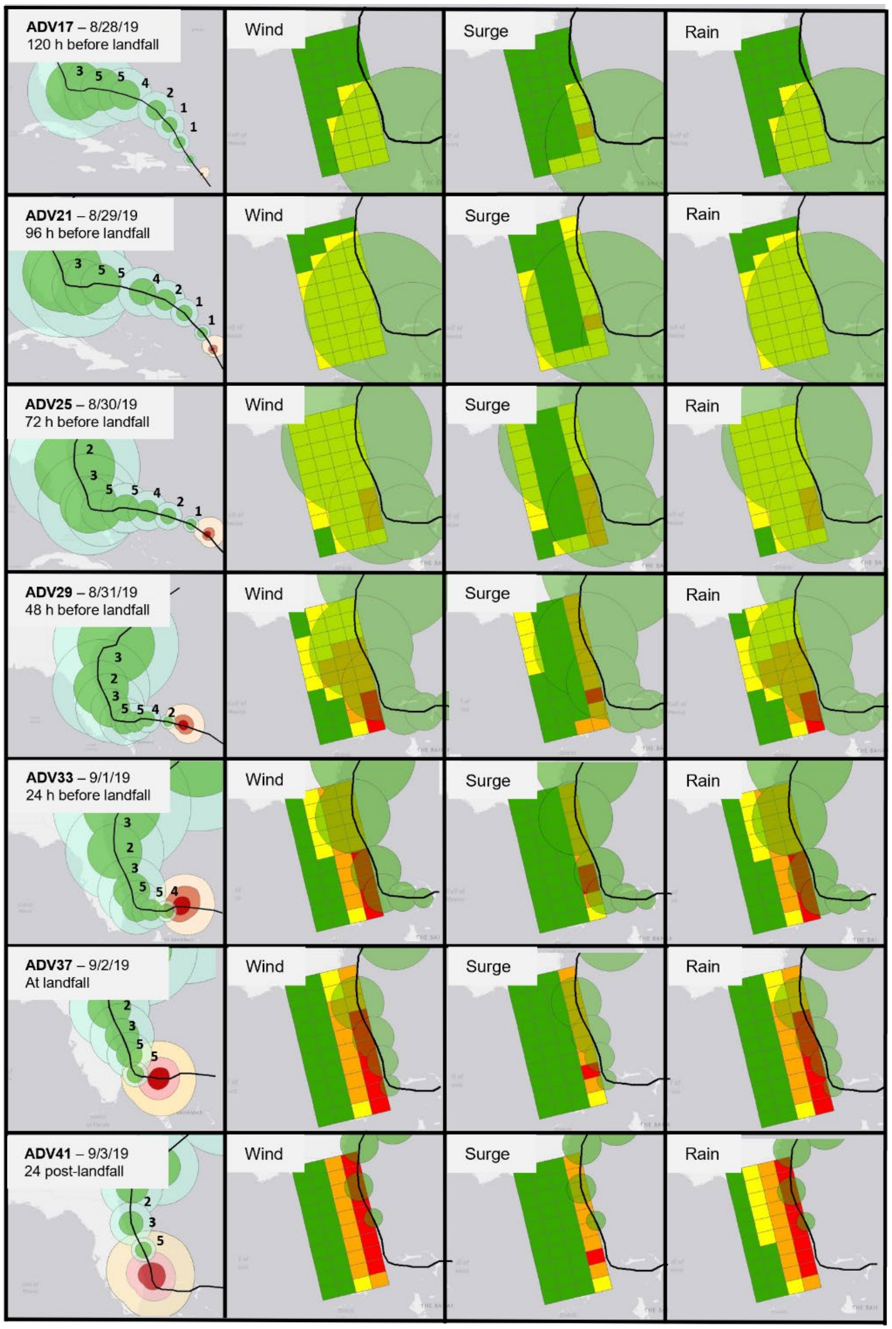


Supplemental Figure S5: Evacuation rates over time for Irma's experiments. The temporal effects of the experiments on evacuation rates (solid lines) and % who unsuccessfully evacuated due to traffic (dashed lines), averaged across grid cells, throughout the simulations. The NHC OFCL is expressed (black lines), as are NHC OFCL with RI/RO (dark red lines), NHC OFCL with RI/RO – 12 hours (light red lines), 2007 cone of uncertainty case with the best track (blue lines), and the 2022 cone of uncertainty case with the best track (green lines).

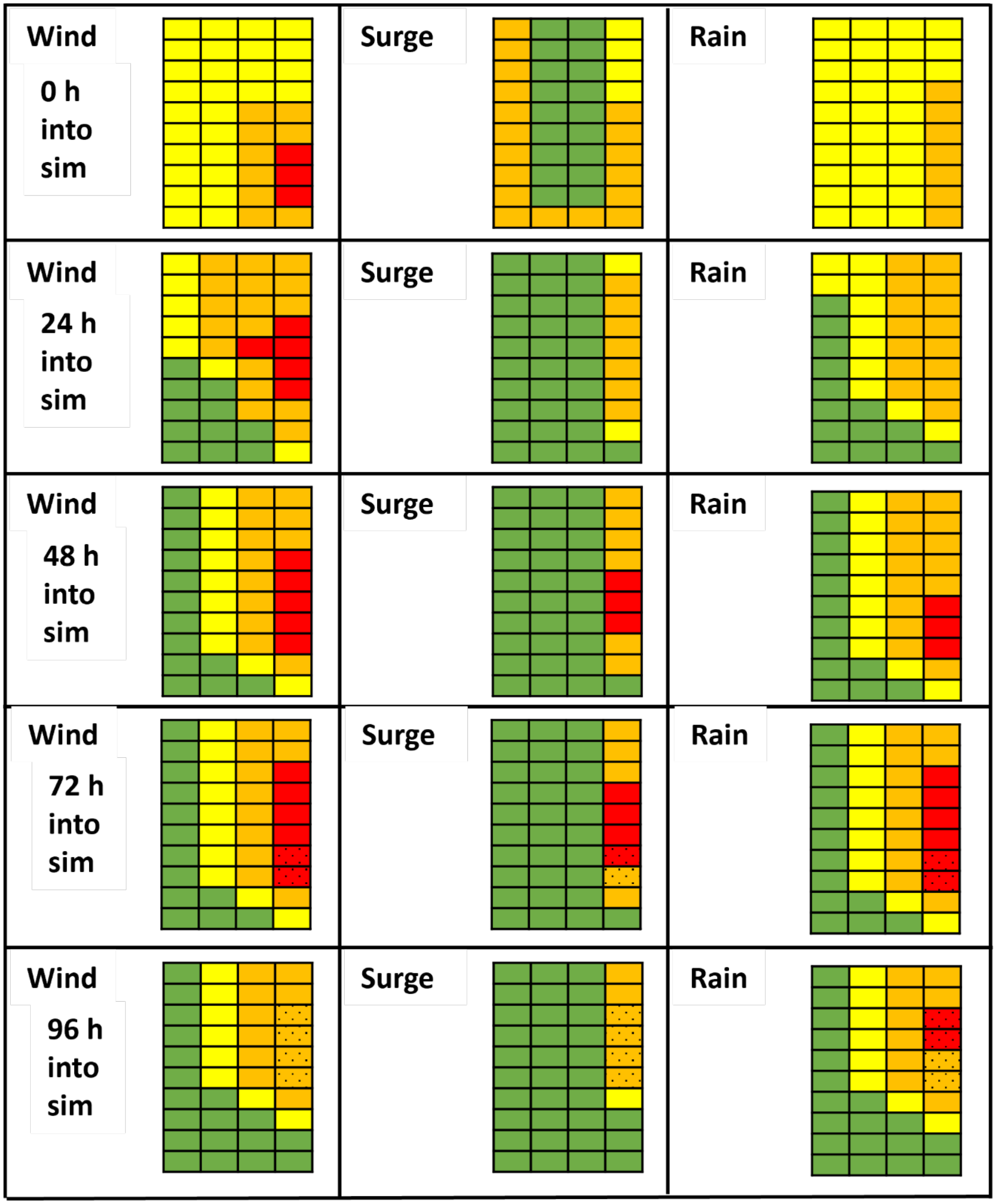
Dorian (landfalling) Simulations – Supplementary Information



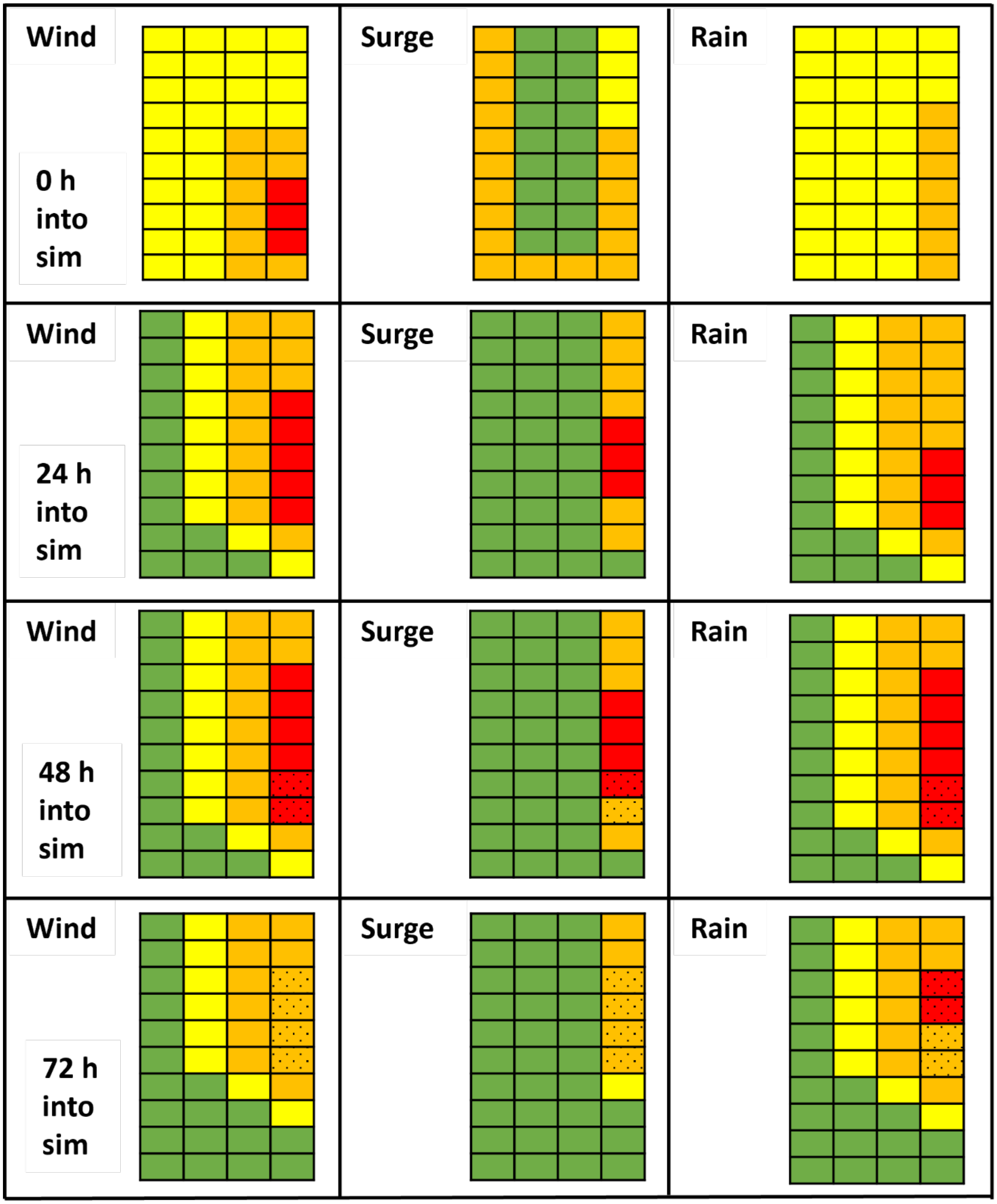
Supplementary Figure S6: Dorian NHC best track forecasts (shifted) with the 2007 Cone of Uncertainty and corresponding FLEE estimates of wind, surge, and rain risks. We note that the light system forecasts for ADV33-41 have been shifted westward from Dorian's OFCL forecasts by 70 km to create a hypothetical scenario where Dorian makes landfall along the east coast. "Forecasts" are shown at 24 hour intervals, but update every 6 hours in the model simulations (not shown). Left column: Dorian's shifted best track (black center line), observed storm intensity on the Saffir-Simpson scale (TS/numbers), circles used to draw the 2007 (blue) and 2022 (green) cone of uncertainties, and current wind radii at 34 (white), 50 (pink), and 64+ (red) knot intervals. Right three columns: The light-system threats for wind, surge, and rain are shown on the model grid for equivalent times in the simulation, with the best track (center black line) and circles used to draw the 2007 cone of uncertainty (blue circles) included for reference.



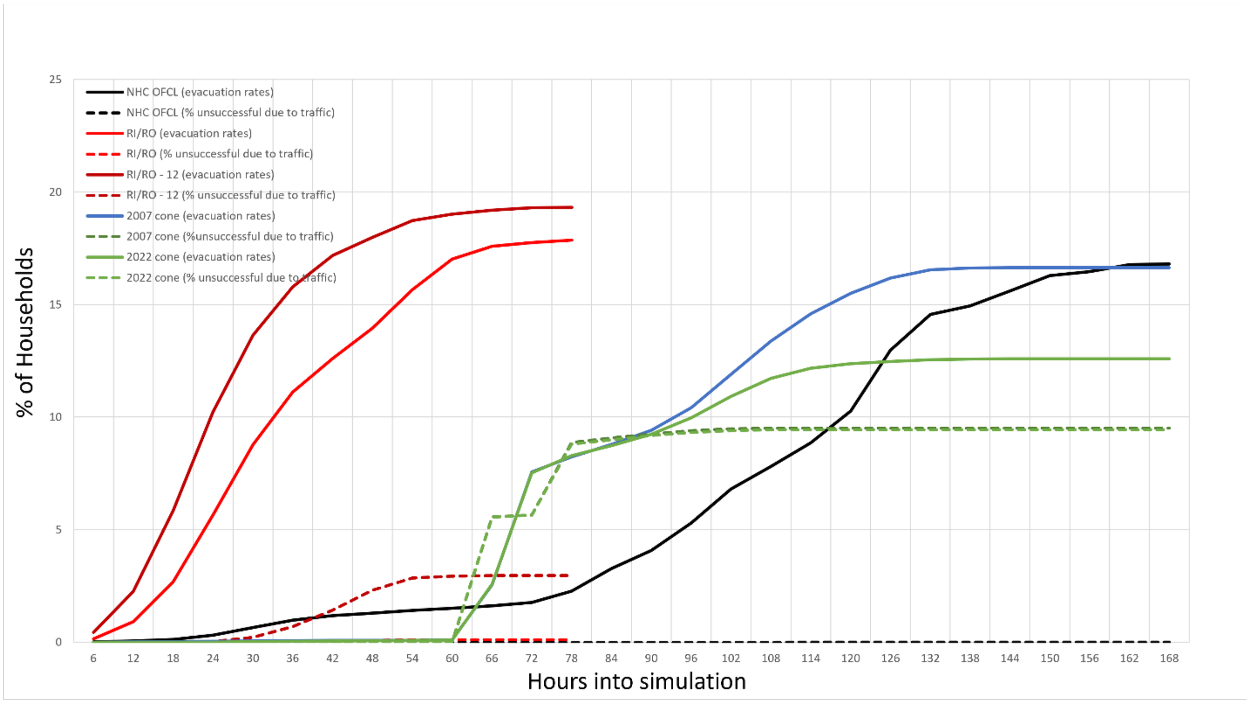
Supplementary Figure S7: Dorian NHC best track forecasts (shifted) with the 2022 Cone of Uncertainty and corresponding FLEE estimates of wind, surge, and rain risks. We note that the light system forecasts for ADV33-41 have been shifted westward by 70 km to create a hypothetical scenario where Dorian makes landfall along the east coast. "Forecasts" are shown at 24 hour intervals, but update every 6 hours in the model simulations (not shown). Left column: Dorian's shifted best track (black center line), observed storm intensity on the Saffir-Simpson scale (TS/numbers), circles used to draw the 2007 (blue) and 2022 (green) cone of uncertainties, and current wind radii at 34 (white), 50 (pink), and 64+ (red) knot intervals. Right three columns: The light-system threats for wind, surge, and rain are shown on the model grid for equivalent times in the simulation, with the best track (center black line) and circles used to draw the 2022 cone of uncertainty (blue circles) included for reference.



Supplemental Figure S8: Dorian NHC OFCL (shifted) with RI/RO forecasts. Here we shorten the forecast timeline of the OFCL NHC Dorian landfalling forecasts from 168 hours to 84 hours, by using every other advisory (only the 00 and 12 UTC advisories), while only 6 hours of time elapses in the simulation. Forecasts are shown every 24 hours but updated every 6 hours (not shown). The peak magnitudes of risk (wind, surge, rain) for each grid cell are the same as Dorian LF; however, the timelines are condensed, effectively creating large and intertwined forward speed, intensity, and track errors meant to emulate the effects of rapid onset/intensity cases. We note that the light system forecasts for ADV33-41 have been shifted westward by 70 km to create a hypothetical scenario where Dorian makes landfall along the east coast.



Supplemental Figure S9: Dorian NHC OFCL (shifted) with RI/RO – 12 hours forecasts. Here we shorten the forecast timeline of the OFCL NHC Dorian landfalling forecasts shown in Figure 1 from 168 hours to 72 hours, by using every other advisory (only the 00 and 12 UTC advisories), while only 6 hours of time elapses in the simulation. Forecasts are shown every 24 hours but updated every 6 hours (not shown). The peak magnitudes of risk (wind, surge, rain) for each grid cell are the same as Dorian-LF; however, the timelines are condensed, effectively creating large and intertwined forward speed, intensity, and track errors meant to emulate the effects of rapid onset/intensity cases. We note that the light system forecasts for ADV33-41 have been shifted westward by 70 km to create a hypothetical scenario where Dorian makes landfall along the east coast.



Supplemental Figure S10: Evacuation rates over time for Dorian LF's experiments. We note that, in all these experiments, the storm's track and corresponding forecasts have been shifted westward by 70 km to create a hypothetical scenario where Dorian makes landfall along the east coast. The temporal effects of the experiments on evacuation rates (solid lines) and percent of unsuccessful evacuations due to traffic (dashed lines), averaged across grid cells, throughout the simulations. The NHC OFCL (shifted) simulation with the shifted track is expressed (black lines), as are NHC OFCL (shifted) with RI/RO (light red lines), NHC OFCL (shifted) with RI/RO – 12 hours (dark red lines), NHC Best Track (shifted) with 2007 Cone of Uncertainty (blue lines), and the NHC Best Track (shifted) with 2022 Cone of Uncertainty (green lines).

Supplemental Methods and Results for Hurricane Dorian (landfalling) simulations

Experimental Design

In this hypothetical forecast scenario, Dorian's later forecasts (ADV33–41) are intentionally shifted west of the original track by 70 km using ArcGIS tools so the storm impacts eastern Florida. This westward shift is done for both the NHC OFCL forecast track used in the RI/RO experiments (Table 1, experiments 6-8) and the NHC Best Track used in the 2007 and 2022 Cone of Uncertainty experiments (Table 1, experiments 9-10). This hypothetical case is new relative to those in HRM21 and HMR22 and demonstrates the power of using the models to explore many different impactful scenarios.

NHC OFCL

NHC OFCL light system forecasts are shown at 24 hour intervals for the hypothetical version of Dorian (Figure S11). Forecasts place the entirety of Florida under threat initially, with the most likely outcome as a landfalling major hurricane somewhere along Florida's east coast. Because of the forecasts, simulated evacuation orders were issued along FLEE's east coast (Figure S12a–b; red cells). The exception is Miami-Ft. Lauderdale, which avoided evacuation orders, matching what was observed (Roache 2019). In the actual Dorian case, the storm remains nearly stationary over the Bahamas for many hours, before accelerating northward and missing Florida's east coast. However, in this hypothetical case, we shift forecasts westward by one grid cell (70 km) in ADV33-41 to create a scenario where Dorian's hurricane-force winds impact Florida's east coast as the storm accelerates northward (e.g., see Figure S11a–b; dotted cells).

Looking at evacuations given the OFCL NHC Dorian (landfalling) forecasts, FLEE's evacuation rates were significantly lower with Dorian (landfalling) (16.8%) than Irma (32.0%), which is 2.4 million less evacuees (Table S2a–b). Due to fewer evacuees – and the evacuation being spread over a longer time – fewer people give up due to traffic (0.0%) with Dorian (landfalling) than Irma (2.5%). These outcomes seem reasonable, given that both the forecasts and the storm itself influence a smaller portion of the model in Dorian (landfalling) compared to Irma.

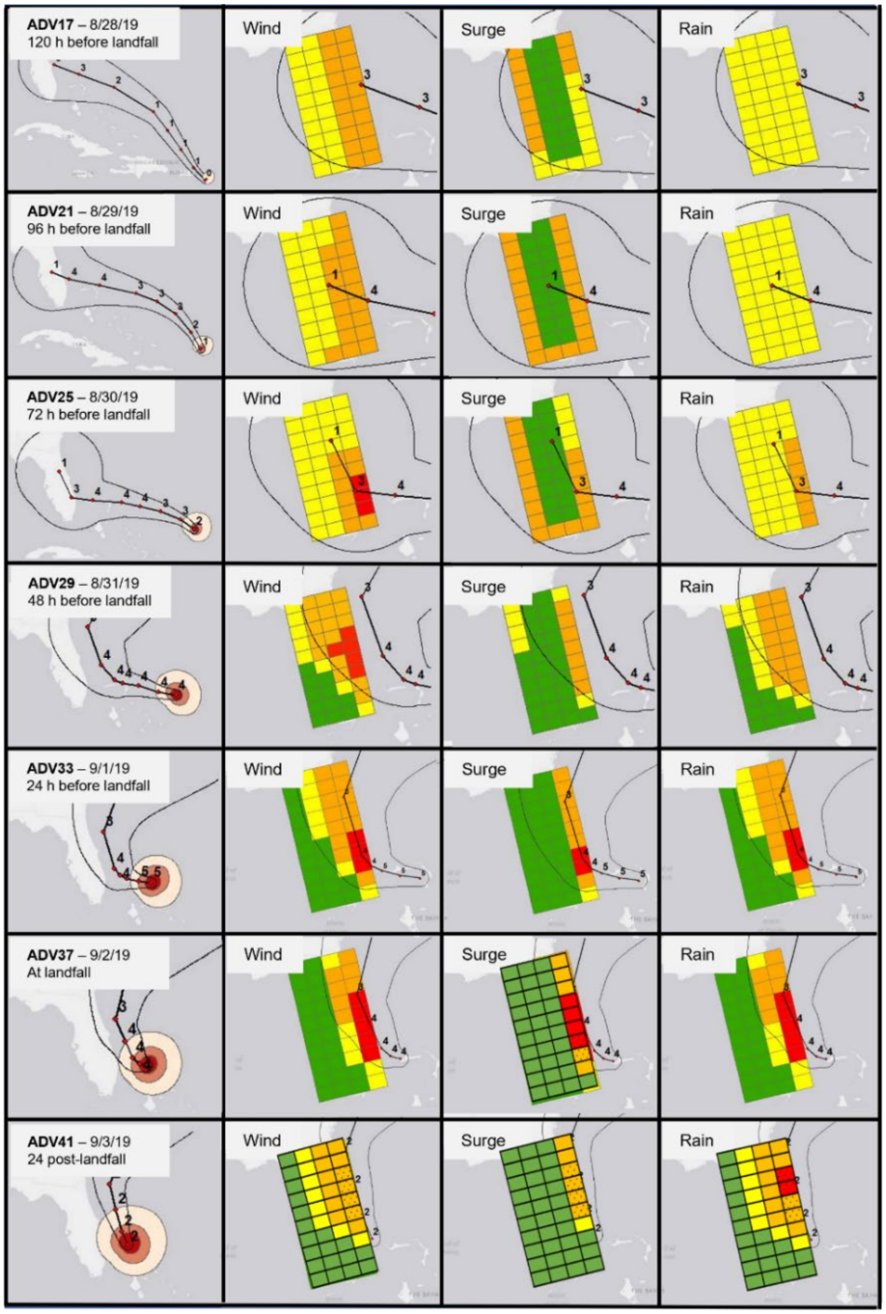


Figure S11: **NHC OFCL (shifted) forecasts for Hurricane Dorian (2019) (landfalling) and corresponding FLEE estimates of wind, surge, and rain risks.** We note that the light system forecasts for ADV33-41 have been shifted westward by 70 km to create a hypothetical scenario where Dorian makes landfall along the east coast. Forecasts are shown at 24 hour intervals, but update every 6 hours in the model simulations (not shown). Left column: Evolving, OFCL NHC forecast track (black center line) that is shifted west, storm intensity on the Saffir-Simpson scale (TS/numbers), the 2019 cone of uncertainty (edges are outer black lines), and current wind radii at 34 (white), 50 (pink), and 64+ (red) knot intervals. Right three columns: The light-system threats for wind, surge, and rain are shown for equivalent times in the simulation, with the forecast track (center black line) and the 2019 cone of uncertainty (outer black lines) included for reference.

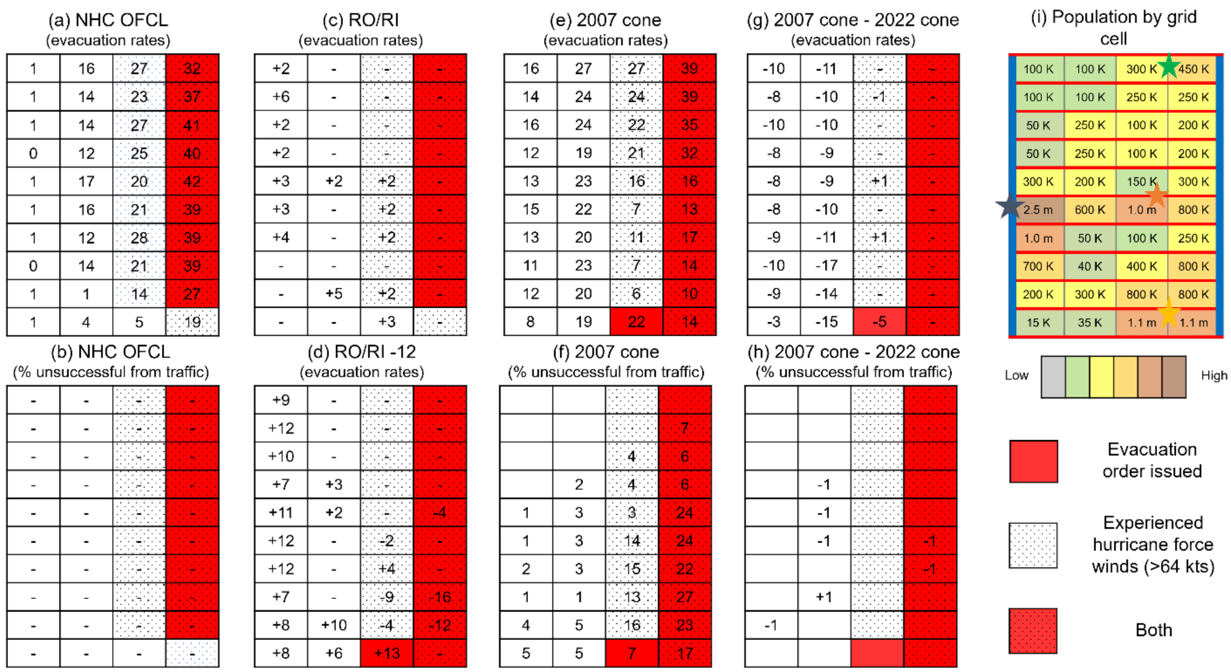


Figure S12: Dorian (landfalling)'s evacuation rates across grid cells, including (a) evacuation rates and (b) percent of evacuees who were unsuccessful due to traffic, both for the NHC OFCL forecast. Evacuation rates are presented for the NHC OFCL with (c) RI/RO and (d) RI/RO – 12 hour cases, with values expressed as the departure from the (a) NHC OFCL evacuation rates. Evacuation rates and the percentage of evacuees who were unsuccessful due to traffic are presented for the Best Track with 2007 Cone of Uncertainty scenario (e–f). The difference between the 2007 and 2022 Cone of Uncertainty cases with Best Track is then presented, both for evacuation rates (g) and the percentage of unsuccessful evacuations due to traffic (h). Also shown in (a)-(h) are grid cells that experienced hurricane force winds (dotted cells) and evacuation orders (red cells). To provide a frame of reference for interpreting the simulations, (i) shows the population by grid cell along with the approximate location of several major cities on the model grid: Miami-Ft. Lauderdale (yellow star), Tampa Bay-St. Petersburg (blue star), Jacksonville (green star), and Orlando (orange star).

Dorian-LF Experiments	(a) Evacuation rates	(b) Evacuated	(c) Coastal >64 knot zone	(d) Inland >64 knot zone	(e) Coastal < 64 knot zone	(f) Inland < 64 knot zone	(g) % Unsuccessful evacuation due to traffic	(h) Unsuccessful evacuation due to traffic
NHC OFCL	16.8	2.84 m	33.0	21.1	2.0	13.3	0.0	32
NHC OFCL with RI/RO	18.3	3.09 m	33.2	22.0	4.9	14.6	0.1	17 K
NHC OFCL with RI/RO -12 h	19.3	3.26 m	28.2	18.4	13.6	15.4	3.0	486 K
Best Track with 2007 Cone	16.6	2.78m	18.8	11.9	15.5	22.5	9.5	1.56m
Best Track with 2022 Cone	12.6	2.06m	18.7	12.0	7.9	11.9	9.4	1.55m

Table S2: Dorian (landfalling)'s evacuation behaviors averaged across all grid cells for the different experiments. In addition to evacuation rates and total numbers evacuated, evacuation rates are broken down into impact zones (coastal vs. inland, and areas experiencing vs. not experiencing hurricane force winds of 64+ kts) and the percentage and numbers of evacuees who attempted to evacuate but were unsuccessful due to excessive traffic.

Impact of Poorly Forecast RI/RO

Regarding the NHC OFCL with RI/RO experiments where forward speed and intensity errors are significant (RQ1), evacuation rates and traffic increased everywhere relative to NHC OFCL (Table S2). This is surprising, as there is less time to evacuate everyone safely, and is opposite to Irma's results. Upon closer examination, the increase in evacuation rates occurs primarily across western Florida (Figure S12c–d) where the shorter timeline forced evacuation decisions early when forecasts were uncertain for these areas. In this sense, the RI/RO forecasts resulted in arguably negative outcomes for these areas relative to NHC OFCL.

When comparing the two RI/RO experiments, cases with larger forward speed and intensity errors (RI/RO – 12 hours) resulted in worse evacuation rates and more traffic, suggesting an extra 12 hours of forecast lead time can improve evacuations in these scenarios. For example, in addition to increasing unnecessary evacuations across western Florida (Figure S12c–d), the RI/RO – 12 scenario decreases evacuation rates along the most impacted areas along the east coast. Backing up this idea, evacuation rates in the coastal and inland > 64 knot zones decrease by 5.0% and 3.6% respectively between the two cases (Table S2c–d), while evacuation rates across the coastal and inland < 64 knot zones increased by 8.7% and 0.8% (Table S2e–f),

When considering these results alongside the Irma case, this is the first study (to our knowledge) to begin quantifying the impact of these errors on evacuation outcomes (RQ1), and to suggest that reducing these errors should translate to improved evacuations.

Impact of Reduced Track Errors

In this section, we change from OFCL to Best Track as the simulated forecast, and modify NHC's Cone of Uncertainty to sizes representative of track errors today (2022) and in the past (2007) and examine their impact on FLEE's evacuations (RQ2). The forecasts corresponding to these experiments are provided in Figures S6–7. While both the 2007 and 2022 cones with the best track place western Florida under risk initially, the 2022 cone is quicker to remove many unimpacted areas from risk as we get closer to landfall. This difference is reflected in evacuation rates across both cases (Figure S12g), where the 2022 cone reduced evacuation rates by 3-15% across the western half of the grid relative to the 2007 cone. Backing up this idea, evacuation rates in the coastal and inland < 64 knot zones decrease by 7.6% and 10.6% respectively (Table S2e–f), while evacuation rates remained the same across impacted areas (Table S2c–d). These results agree with the Irma experiments, and thus provide additional evidence that reduced forecast track errors over the 2007–2022 year period resulted in improved evacuation outcomes (RQ2).