Research Statement

Introduction – In the mainland US, the hurricane-forecast-evacuation system is uncertain, dynamic, and complex. As such, there is a need to integrate its many physical-social elements into a single computational framework where its complexities can be examined and understood. With this in mind, [redacted] et al. (2021) (hereafter HRM21) designed a coupled natural-human, ABM framework for exploring the systems' dynamics, including the dynamical prediction of forecast impacts on evacuations. Called FLEE (Forecasting Laboratory for Exploring the Evacuation-system), the model includes representations of the following subsystems: the natural hazard (hurricane), the human system (information flow, evacuation decisions), the built environment (road infrastructure), and connections between systems (forecast information, evacuation orders, traffic). FLEE simulates key aspects of these subsystems at a high level to provide a first-order analysis of the system's behaviors across many real and hypothetical forecast-population-infrastructure scenarios (see scientific basis, key assumptions in HRM21).

FLEE builds on previous work using models for studying evacuation communication (e.g., [redacted] et al. 2017), evacuation decision-making (e.g., [redacted] et al. 2013; [redacted] et al. 2018), and evacuation traffic (e.g., [redacted] et al. 2014), and links these components together in a computationally feasible framework for the first time. Decisions about what to include in FLEE were influenced by empirical knowledge of evacuation gained through surveys and interviews of decision-makers in past hurricanes (e.g., [redacted] et al. 2016; [redacted] et al. 2019). In HRM21, FLEE was validated against empirical data (e.g., overserved evacuation rates and traffic intensity across different areas impacted) during two real hurricanes, Irma and Dorian, adding confidence the model captures the important features for a first-order analysis of the system.

Building on HRM21, our team conducted several more studies using FLEE. First, [redacted] et al. (2022) (hereafter HMR22), explored how FLEE's evacuations change with different forecast scenarios impacting Florida (Irma, Dorian) and how that compares across different evacuation management strategies, policies, and population characteristics. Second, Harris et al. (2023) (hereafter HRM23), began to explore how changes in Irma's forecast accuracy might have impacted evacuations e.g., by creating track and rapid onset scenarios representative of average errors today and in the past and assessing their impact on evacuations. However, as seen in Table 1, FLEE had limitations in its assumptions, resolution, and computational speeds that prevented HRM23 from fully exploring how small changes in forecast accuracy impacts evacuations, limiting the project's scope. Nevertheless, these proof-of-concept and convergent studies ([redacted] et al. 2022) demonstrate the potential of using coupled models for (1) exploring the hurricane-forecast-evacuation system dynamics, (2) bridging social-physical spaces in atmospheric science, and (3) developing societally relevant verification approaches for the weather enterprise that complement traditional metrics of forecast accuracy.

Project Goals – Building on HRM23, the proposed project is to redesign FLEE – including improving its resolution and computational speeds – so FLEE can better explore how small changes in forecast accuracy (in track, intensity, forward speed) impact evacuations. As part of this, experiments will be run for old (Irma, Dorian) and new (Ian) hurricane scenarios. New guiding research questions of interest are: **RQ1 –** Which forecast elements are most important to accurately predict for these storms and does this vary with different measures of evacuation success? **RQ2 –** Are there diminishing returns in forecast accuracy with respect to evacuations and how does that compare with physical limits of predictability of tropical systems? **RQ3 –** How do answers 1–2 vary across future projected population-infrastructure-climate scenarios?

Table 1 – Proposed updates to FLEE

Issue	Intended Update	Purpose	Approach
Each simulation requires 3-5 days of real-time to run on a PC	Improve the code's efficiency and/or put on Cheyenne	Run more simulations and experiments	CISL is willing to collaborate and has provided suggestions to start
Virtual world is a 10 x 4 depiction of Florida (each cell is 69 x 69 km)	Increase the number of grid points to 100 x 40 or something greater	Better capture responses to small changes in forecast	Conduct sensitivity experiments to identify ideal resolution needed
Evacuation success only measured by evacuation rates and traffic intensity across impacted areas	Also simulate economic measures of evacuation (cost-benefit) and power outages	Provides new ways of measuring "evacuation success"	Codify this process based on empirical literature provided by an economist ([redacted]
FLEE has 4 forecast risk categories (red-orange-yellow-green) for wind, rain, and surge	Increase the number of forecast risk categories from 4 to 10 for all hazards	Allows FLEE to capture impacts of subtle forecast errors on evacuation	Create more possible risk categories in the lookup tables (process described in HRM21)
FLEE validated w/ empirical evacuation data from Irma and Dorian only	In addition, validate FLEE against new empirical evacuation data from Hurricane Ian (2022)	Adds confidence in ability to answer RQ 1-3 and explores a new case	Use [redacted] (MMM) novel longitudinal public survey data set; [redacted] (MMM) cell phone data for Ian's evacuation rates

Methodology – The first step in the proposed project is to implement the model updates suggested in Table 1 to create FLEE 2.0. These updates are motivated by limitations observed in HRM23 and will better position FLEE to effectively answer RQ1–3. Once complete, evacuations in FLEE 2.0 will be compared to empirical data on evacuations during Irma and Dorian (available data/verification method shown in HMR22). In addition, FLEE 2.0's simulated evacuations during Ian will be compared against new empirical data on Ian's evacuation rates and timing (e.g., [redacted] longitudinal public survey data set). By validating and calibrating the model with the old and new empirical data, FLEE will be optimized for experimentation.

The proposed experimental design is similar to HRM23 where, based on the official NHC forecasts, several hypothetical scenarios with characteristic forecast errors are introduced. For example, in HRM23, hypothetical tracks were introduced to the left and right of NHC's official track forecasts for Irma by distances equaling 2001 and 2021 average errors at different lead times. By comparing FLEE's evacuations using these hypothetical scenarios to those using the official NHC forecasts, HRM23 began to assess the impact of forecast errors on evacuation rates and traffic intensity across different areas impacted by the storms.

Using FLEE 2.0, this analysis will be repeated for track, intensity (new relative to HRM23), and forward speed (new relative to HRM23) errors based on average amounts in 2001 and 2021. Since FLEE 2.0 will be better positioned to capture smaller changes in the forecast (and its impact on evacuations), additional experiments will be conducted at 5-year increments (e.g., based on average forecast errors in 2001, 2006, 2011, 2016, 2021). The analysis will be repeated for Irma, Dorian, and Ian (new relative to HRM23). Follow-up experiments may be conducted to better understand how forecast errors propagate throughout the different subsystems.

Addressing RQ1 – The relative importance of track, intensity, and forward speed errors on evacuations will be compared across the three forecast scenarios (Irma, Dorian, Ian). As part of this, measures of evacuation success used in HRM23 – such as evacuation rates and traffic intensity in different areas – will be compared with new economic and power outage measures of success. *Addressing RQ2* – Using the same experiments, diminishing returns in forecast accuracy will be identified by finding where evacuation outcomes are least sensitive to changes in forecast elements, lead times, and scenarios. Conversations with MMM scientists will contextualize the work with the general predictability of tropical systems. *Addressing RQ3* – In addition to repeating the experiments for different hurricane scenarios (Irma, Dorian, Ian), simulations will be repeated with Florida projected population in 2040 – and under scenarios where evacuation management strategies are implemented – to see if answers to RQ1–2 change with more people on the roads. Time permitting, it would be interesting to begin exploring how evacuations change as hurricanes change under future warming scenarios ([redacted] has mentioned using data from downscaled CESM2 LENS landfalling TC simulations). In total, this results in 180 planned simulations (more can be added, depending on FLEE 2.0's run time after improvements are made).

Research Timeline – Model updates for FLEE 2.0 will be finished by Fall 2023, a conservative estimate based on discussions with CISL. Model validation against new Ian datasets will be complete by Winter 2023. Proposed experiments will be done by Fall 2024 with 1-2 manuscripts published by Spring 2025.

Why NCAR for the project? One reason is that ABMs provide a natural "bridge" between social, physical, and computational spaces. If given the privilege of working with NCAR scientists that have relevant expertise on all sides, the proposed project can connect NCAR's scientists, laboratories, and disciplines. For example, [redacted] (MMM) and [redacted] (UWM) are willing to provide guidance on ABMs; [redacted] and [redacted] (MMM) can help effectively incorporate social science data into the model; [redacted] and [redacted] (CISL) are willing to provide computational support to improve FLEE 2.0's runtime; [redacted] (RAL) brings valuable knowledge of vulnerable populations and GIS; [redacted] and others at MMM offer understanding of tropical systems and their physical limits of predictability which contextualizes the work; [redacted] (MMM) can help connect the research with questions of interest for private insurance industry, including climate change impacts on evacuations. Lastly, there may be opportunities to connect ABMs with ongoing projects of interest at RAL (e.g., WRF-FIRE, Hurricane Calculator, TCGP, MDSS, to name a few).

References (1) [redacted] (2022). Advancing interdisciplinary, actionable, and convergent research in the atmospheric and related sciences: Findings and recommendations from a project at the National Center for Atmospheric Research. **(2)** [redacted] RE. 2021: An agent-based modeling framework for examining the dynamics of the hurricane-forecast-evacuation system. *Int. J. Disaster Risk Reduct.* **(3)** [redacted] and others, 2017: Hazardous weather prediction and communication in the modern information environment. *Bul. Amer. Met Soc*, 98, 2653–2674. **(4)** [redacted] 2013: Simulating the effects of social networks on a population's hurricane evacuation participation. *J. Geogr. Syst.*, 15, 193–209. **(5)** [redacted] and coauthors, 2018: An integrated scenario ensemble-based framework for hurricane evacuation modeling: Part 1—decision support system. *Risk Anal.*, 40, 97–116. **(6)** [redacted] 2014: An agent-based modeling system for travel demand simulation for hurricane evacuation. *Transp. Res. Part C.*, 42, 44–59. **(7)** [redacted] 2016: Who leaves and who stays? A review and statistical meta-analysis of hurricane evacuation studies. *Environ. Behav.*, 48, 991–1029. **(8)** [redacted], 2019*: Large-Scale Evacuation: The Analysis, Modeling, and Management of Emergency Relocation from Hazardous Area: 1st Edition*. Taylor & Francis. **(9)** [redacted], 2022: What Improves Evacuations? Exploring the hurricane-forecast-evacuation system dynamics using an agent-based framework. *Nat. Haz. Rev.* Manuscript in review. **(10)** Harris, A. R, P.J. [redacted], 2023: A new verification approach? Using coupled natural-human models to evaluate forecast impact on evacuations *Bul. Amer. Met Soc.* Manuscript in review.