Asking “what-if” with an AI weather model

Maria J. Molina, University of Maryland, College Park

Collaborators:

Haoming Cai, **Sunny Sharma, Ayman Sayed, Dean Calhoun, Kyle J. C. Hall, Jhayron S. Pérez-Carrasquilla, Jonathan Starfeldt,** and Christopher A. Metzler



GRAND CHALLENGES GRANTS





U.S. DEPARTMENT of ENERGY



Genesis Mission





Overview

- Source of inspiration from an industry application
- How we have asked, **“What if?”** in the recent past
- Guided diffusion application to a weather emulator (and needed modifications)
- Demonstration of **“What if?”** with tropical cyclones

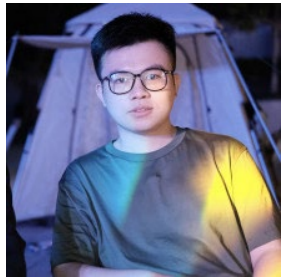
Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.

Overview

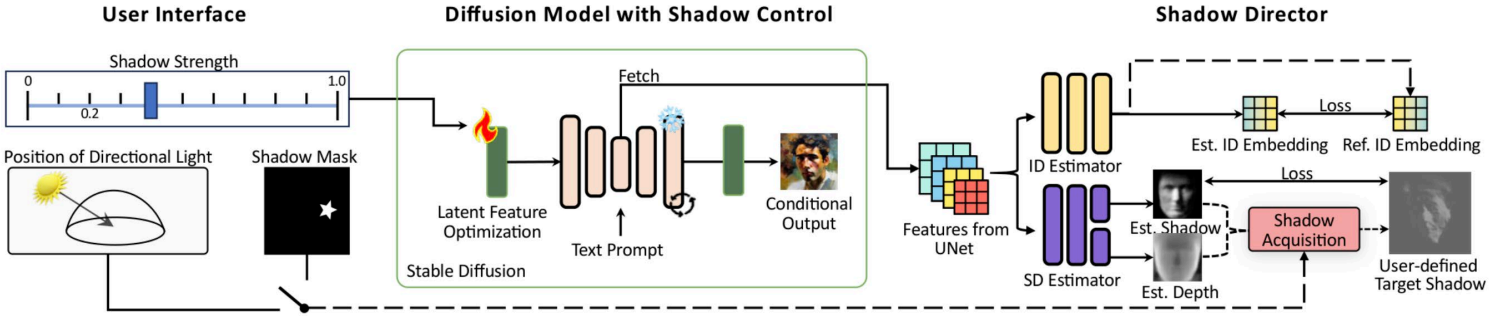
- Source of inspiration from an industry application
- How we have asked, **“What if?”** in the recent past
- Guided diffusion application to a weather emulator (and needed modifications)
- Demonstration of **“What if?”** with tropical cyclones

Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.

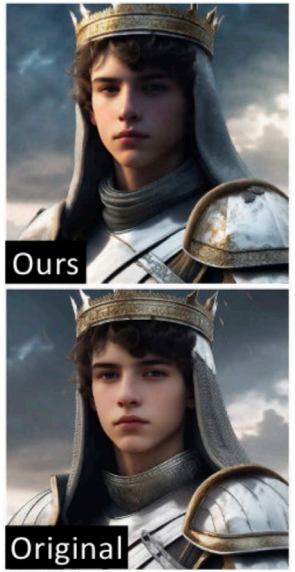
“…latent optimization through a compact network can effectively control attributes…”



Haoming Cai
CS PhD Student



Cai, H., et al. (2025)



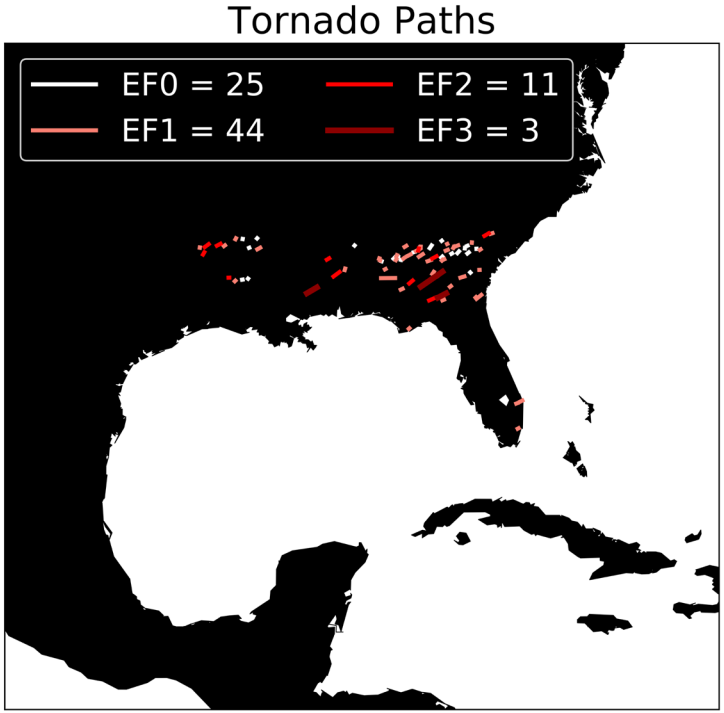
Luo, G., L. Dunlap, D. Huk Park, A. Holynski, and T. Darrell. Diffusion hyperfeatures: Searching through time and space for semantic correspondence. NeurIPS.
Luo, G., T. Darrell, O. Wang, D. B. Goldman, and A. Holynski. Readout guidance: Learning control from diffusion features. IEEE/CVF CVPR.
Cai, H., Huang, T.W., Gehlot, S., Feng, B.Y., Shah, S., Su, G.M., and Metzler, C., 2025. Parametric shadow control for portrait generation in text-to-image diffusion models. In *2025 IEEE/CVF ICCV.*

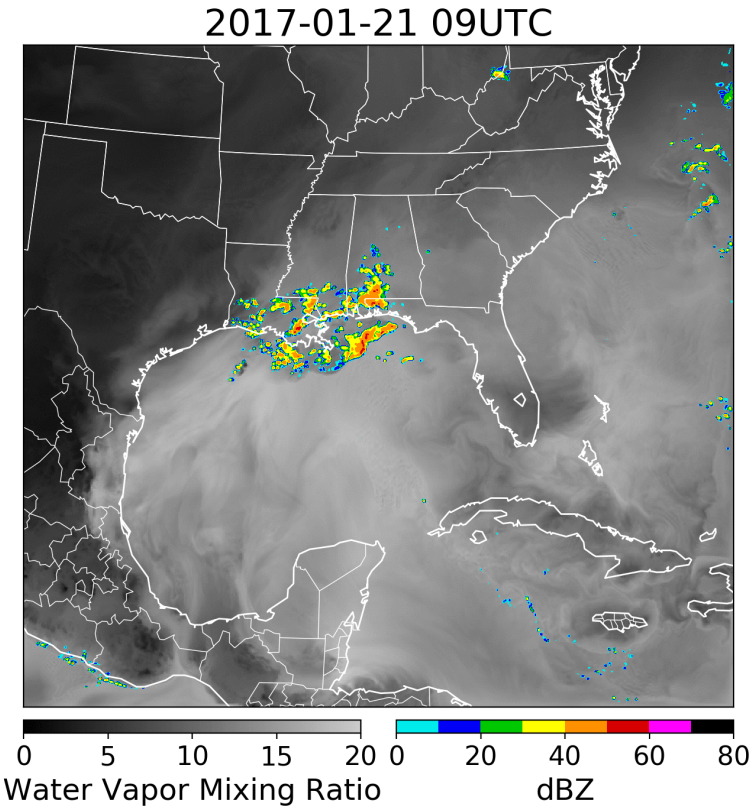
Overview

- Source of inspiration from an industry application
- How we have asked, **“What if?”** in the recent past
- Guided diffusion application to a weather emulator (and needed modifications)
- Demonstration of **“What if?”** with tropical cyclones

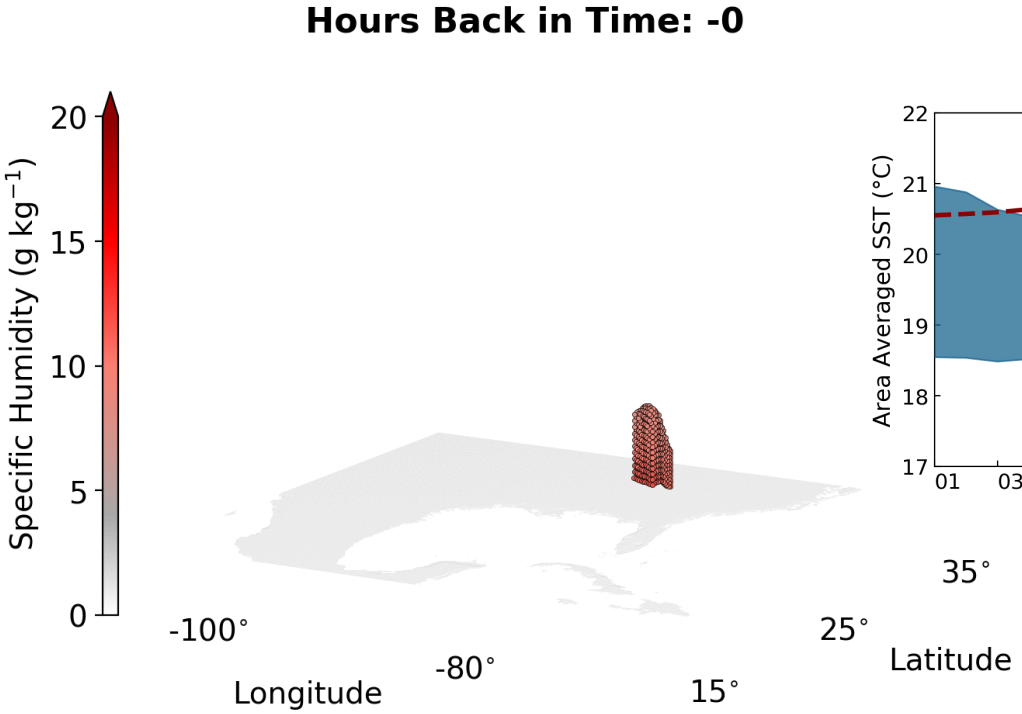
Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.

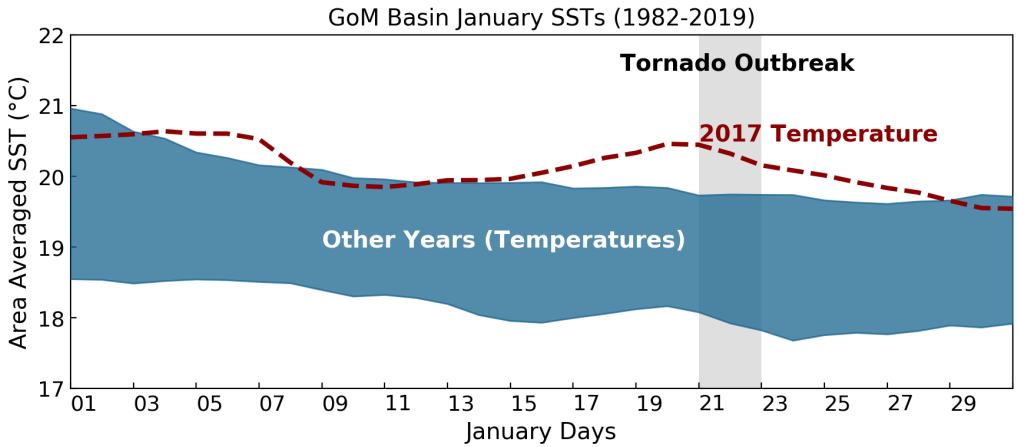
21-23 January 2017 Tornado Outbreak





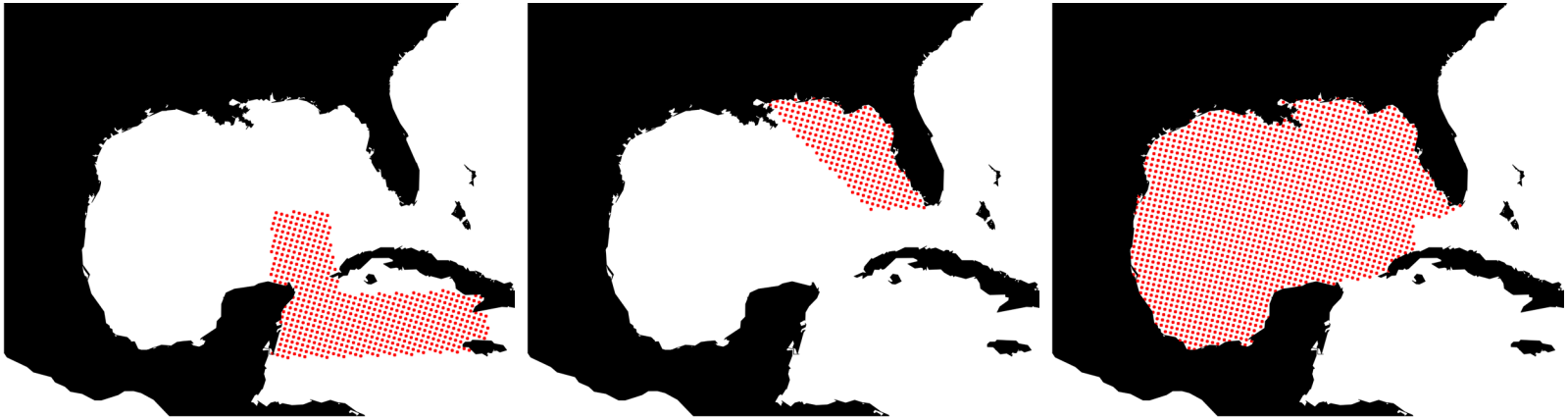
Molina, M. J., J. T. Allen, and A. F. Prein (2020). Moisture Attribution and Sensitivity Analysis of a Winter Tornado Outbreak. Weather and Forecasting.





Molina, M. J., J. T. Allen, and A. F. Prein (2020). Moisture Attribution and Sensitivity Analysis of a Winter Tornado Outbreak. Weather and Forecasting.

SSTs perturbed by -2°C, -1°C, +1°C, and +2°C across three regions.



Molina, M. J., J. T. Allen, and A. F. Prein (2020). Moisture Attribution and Sensitivity Analysis of a Winter Tornado Outbreak. Weather and Forecasting.

Challenges with “physics-based” sensitivity tests

- Recreating the event itself (as a control) is not trivial.
- Formulated perturbations may not be physically realistic.
- Nonlinearities may confound the event response.
- Results depend on the chosen model, parameters, and physics.
- Computationally expensive for a sufficient ensemble size.

Molina, M. J., J. T. Allen, and A. F. Prein (2020). Moisture Attribution and Sensitivity Analysis of a Winter Tornado Outbreak. Weather and Forecasting.

Overview

- Source of inspiration from an industry application
- How we have asked, **“What if?”** in the recent past
- Guided diffusion application to a weather emulator (and needed modifications)
- Demonstration of **“What if?”** with tropical cyclones

Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.

- We generate a large ensemble of possible forecasts using GenCast.
- **“What if?”** scenarios can be sampled from the respective forecast distribution (or beyond).

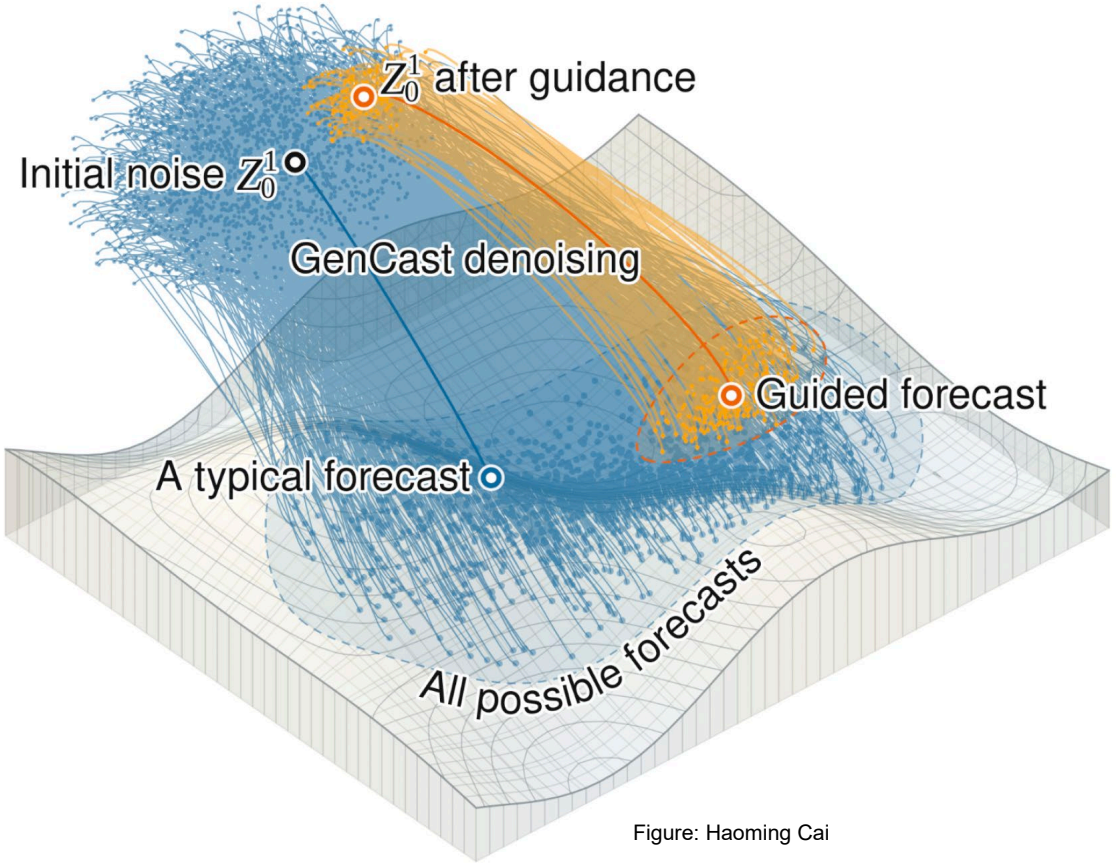


Figure: Haoming Cai

Price, I., et al., 2025. Probabilistic weather forecasting with machine learning. Nature, 637(8044), pp.84-90.

Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.

- Readout learns to predict TC probability from the GenCast latent representation.
- GenCast employs 20 denoising steps.
- We apply readout guidance at **denoising step zero.**

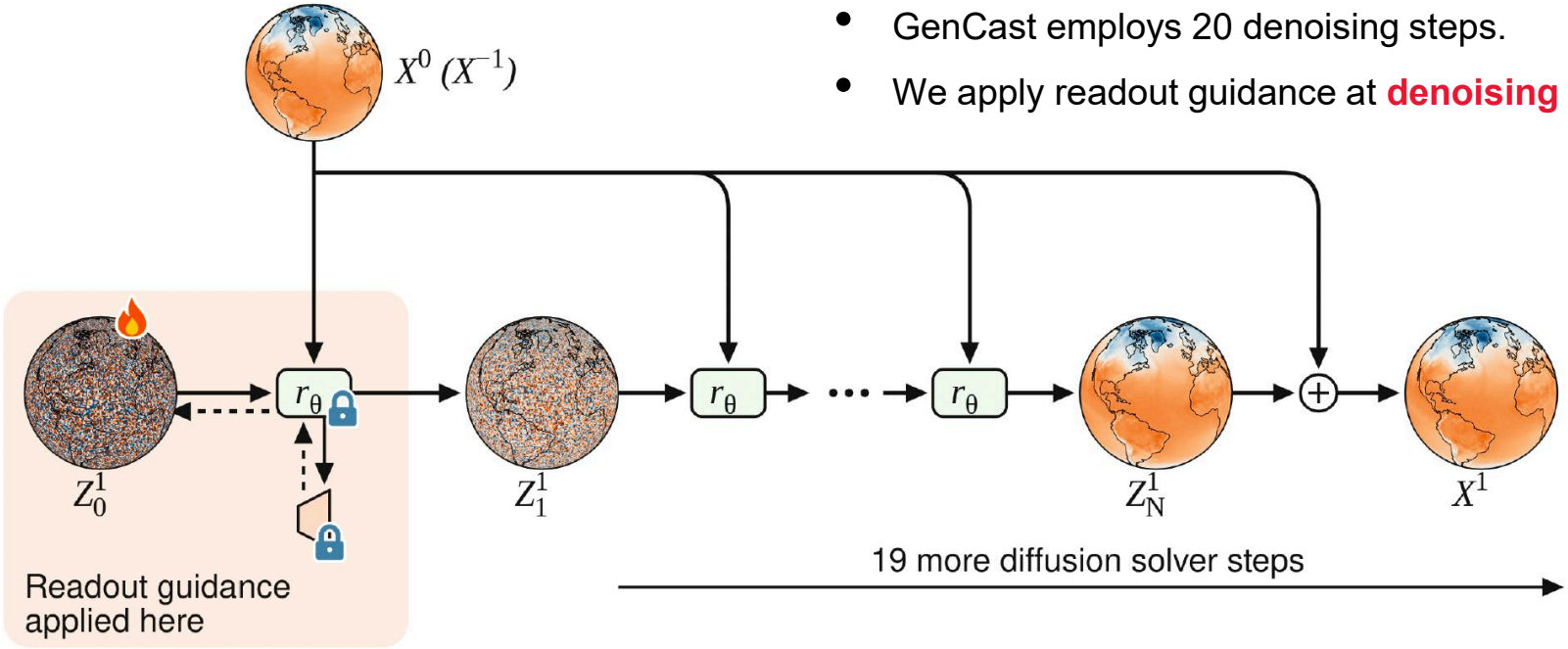


Figure: Haoming Cai

Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.

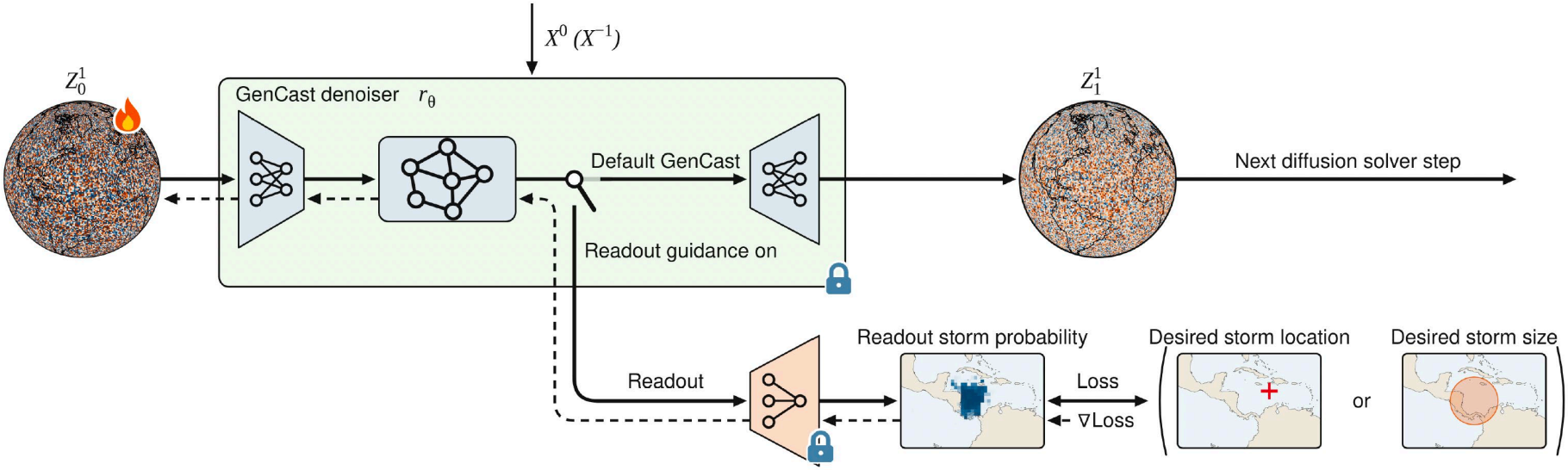
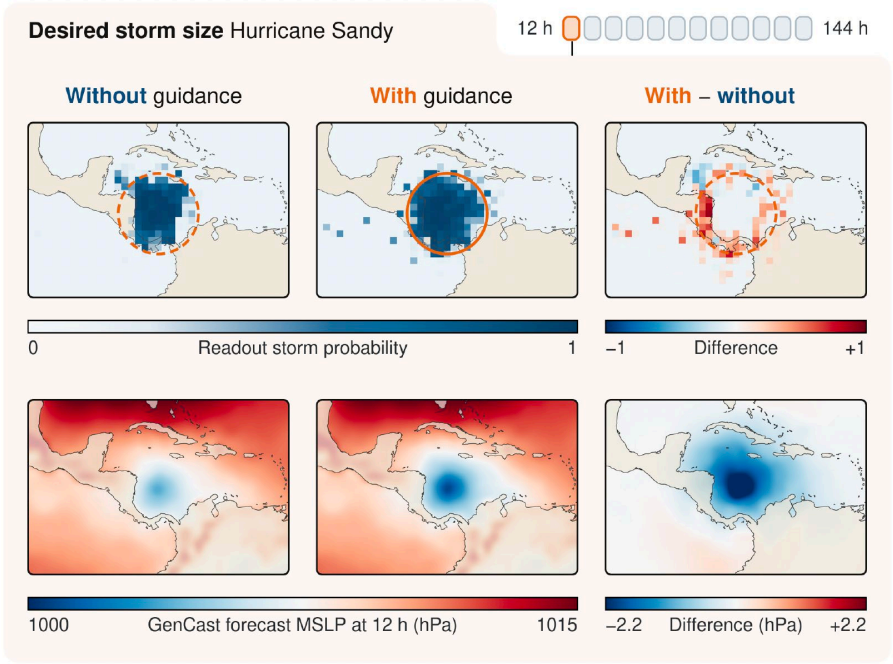
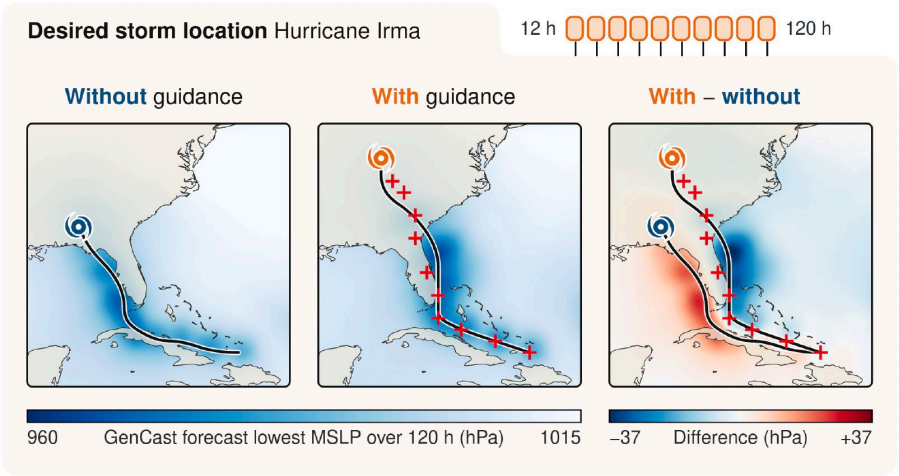


Figure: Haoming Cai

- We apply a guidance loss function that **targets a specific TC property.**
- Benefits: no longer need to manually prescribe sensitivity perturbations, changes apply across the full state (all variables), target the desired change outright, and it is less computationally expensive.

Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.





Figures: Haoming Cai

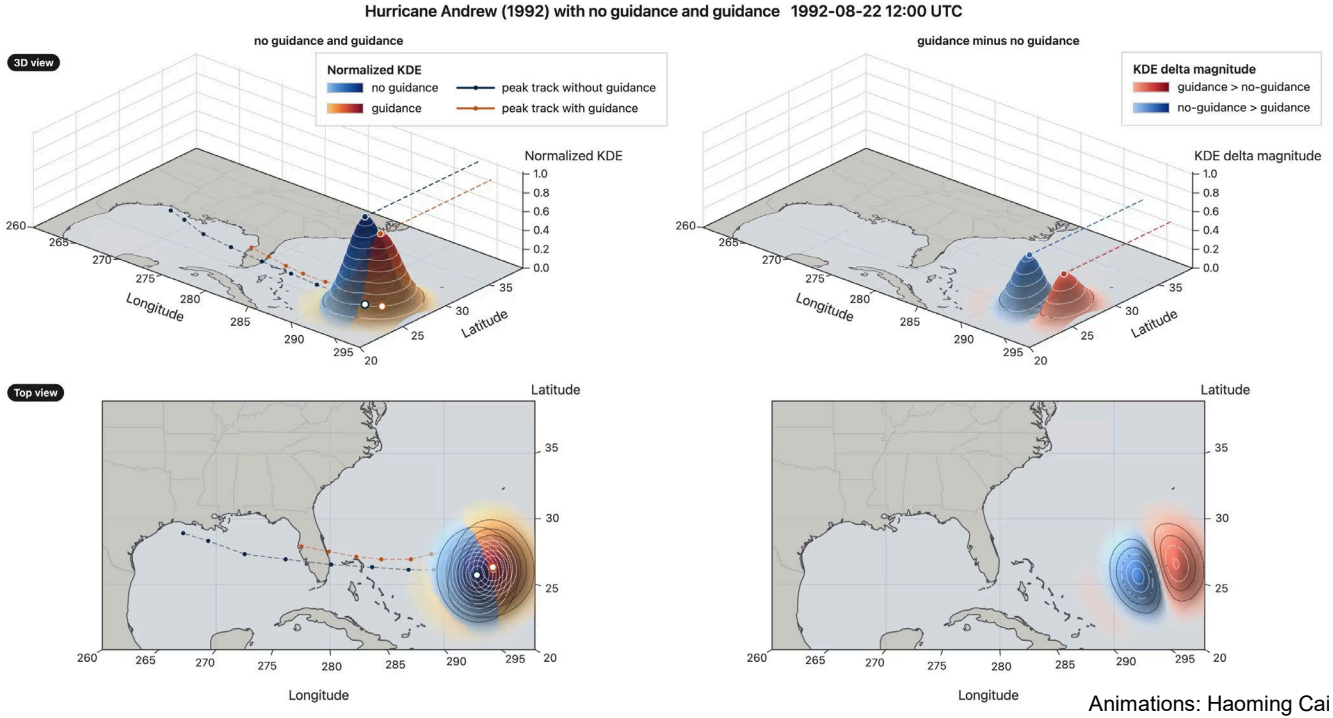
Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.

Overview

- Source of inspiration from an industry application
- How we have asked, **“What if?”** in the recent past
- Guided diffusion application to a weather emulator (and needed modifications)
- Demonstration of **“What if?”** with tropical cyclones

Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.

If Andrew (1992) had started with a larger, model-resolved outer circulation, would GenCast have produced a slower track resembling the NHC forecast?



- At < 24 hours, our steering estimate mostly failed to explain the change in storm motion.
- At 24+ hours, the slowdown was accompanied by weaker steering and a smaller residual.

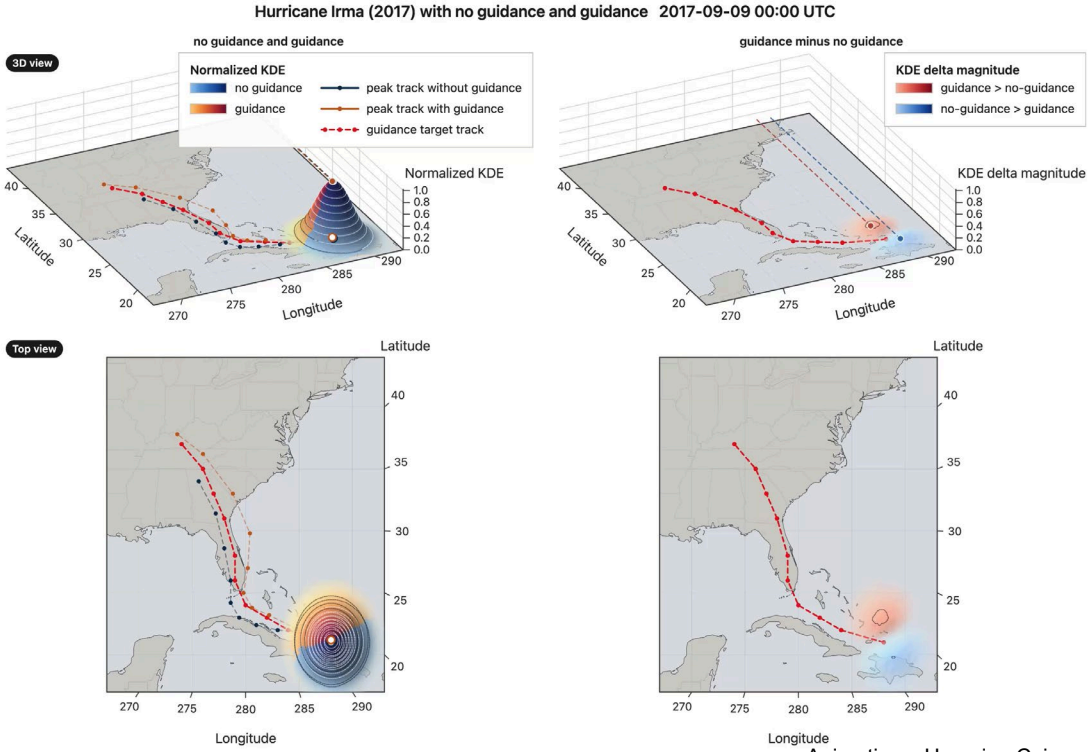
Animations: Haoming Cai

Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.

What conditions would be associated with a forecast that retained Irma's (2017) earlier projected landfall near Miami?

- Steering (annulus-averaged) influence on Irma's accelerated motion increased during later lead times.
- Guidance-based changes to Irma's track led to unguided changes in Maria's track and strength.

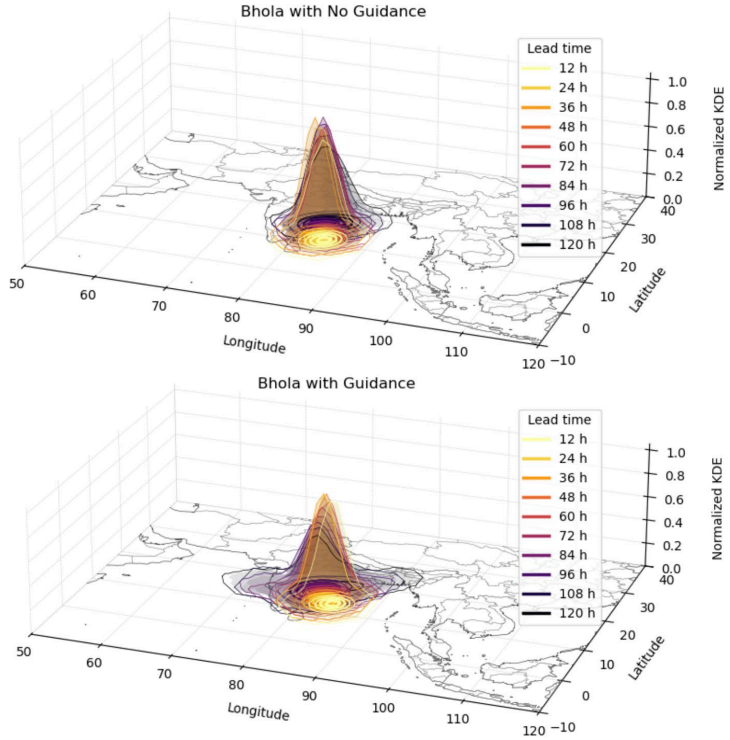




Animations: Haoming Cai

Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.

If Cyclone Bhola (1970) had started with a larger, model-resolved outer circulation, would GenCast spread better resemble the observed track?

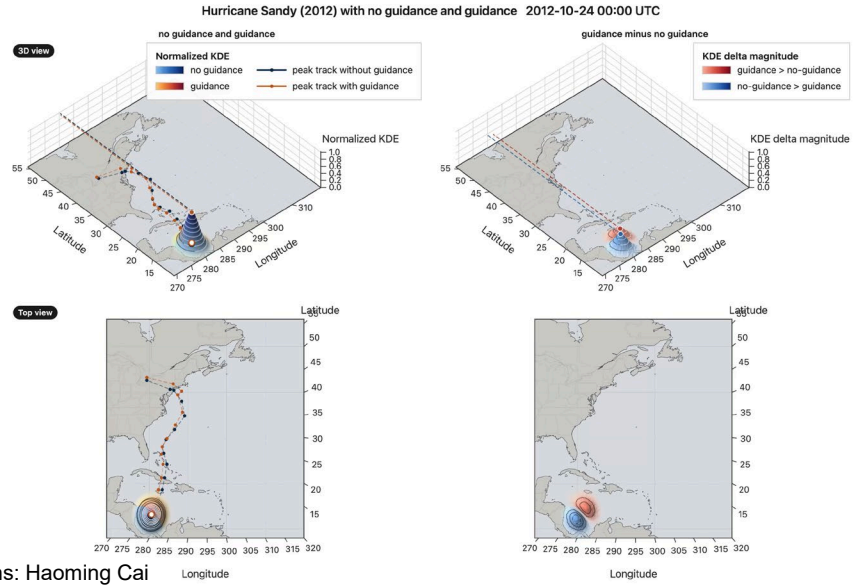


- Increasing Bhola's model-resolved outer circulation produces a GenCast-guided forecast envelope that expands to encompass its eventual landfall location, but also expands in the opposite direction.
- Bhola falls outside GenCast's training period.

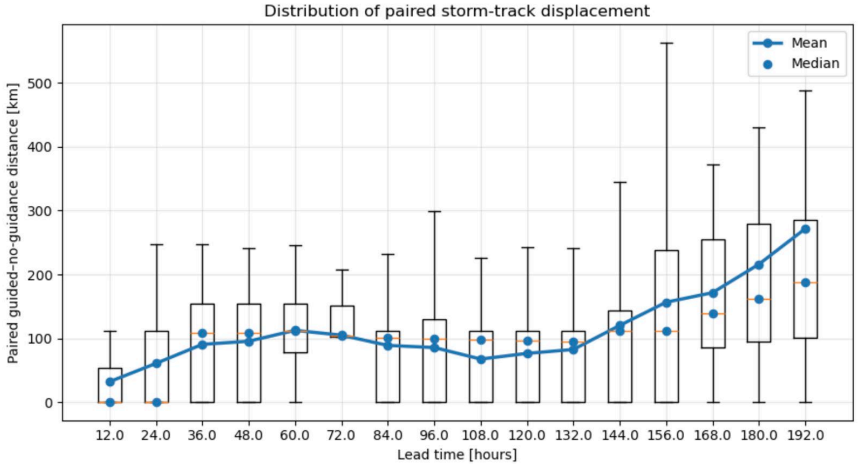
Frank, N.L. and Husain, S.A., 1971. The deadliest tropical cyclone in history?. Bulletin of the American Meteorological Society, 52(6), pp.438-445.

Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.

If GenCast's Sandy (2012) had started with a larger, model-resolved outer circulation, would it be more "Euro" or "American" model-like?



Animations: Haoming Cai

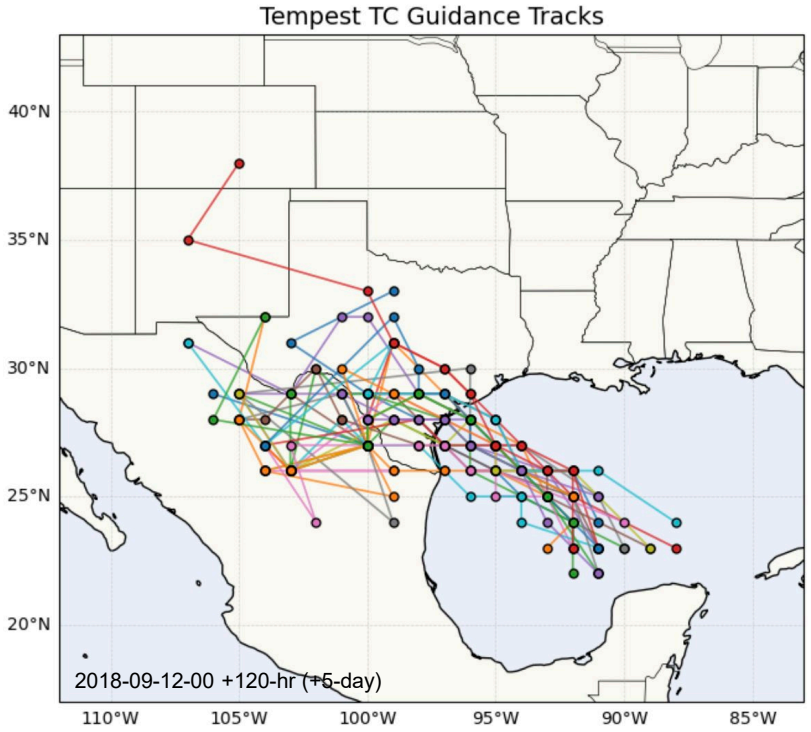


- More Euro-like!
- Interestingly, differences between unguided and guided ensembles do not increase monotonically with lead time.

Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.

Would a TC have developed if a disturbance was present?

- Favorable grid cells in ERA5 had SST >26.5°C, 200--850-hPa wind shear <12.5 m s^{-1}, 700-hPa RH >55%, and 850-hPa relative vorticity >1x10^{-5} s^{-1}.
- Unfavorable grid cells satisfied at most one favorable criterion and at least two of the following: SST < 26.5 °C, wind shear > 20 m s^{-1}, RH < 45%, and relative vorticity < 0.5 × 10 s^{-1} .

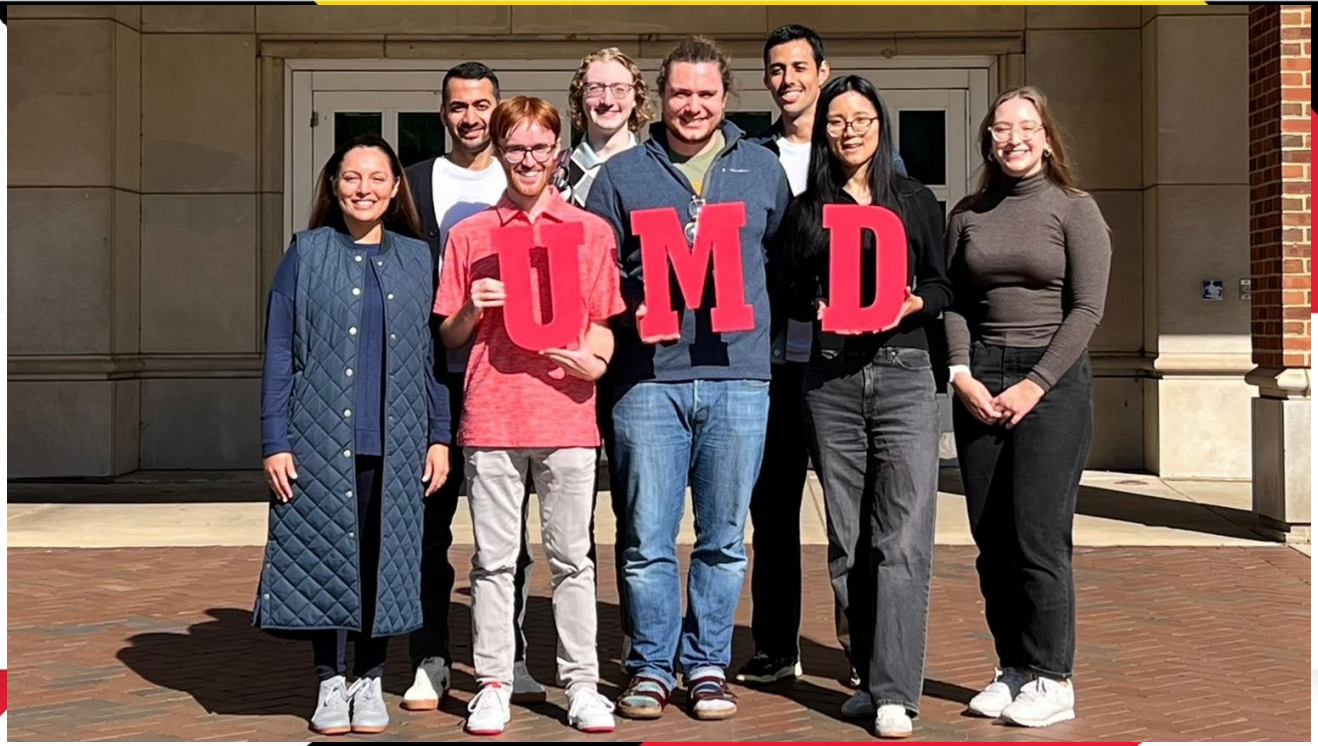


Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.

Lots to explore and challenges ahead…

- Guidance can encounter issues when multiple storms are in close proximity, e.g., Typhoon Meranti (2016).
- How does guidance differ between in-sample and out-of-sample cases?
- Diffusion can be computationally less expensive than physics-based models (on CPUs), but still more expensive compared to stochastic generators.
- Orchestrating the full workflow, from guidance to TC tracking to data analysis, can be complex and time-consuming; an opportunity for agentic AI?

Cai, H., S. Sharma, A. Sayed, D. Calhoun, K. J. C. Hall, J. S. Pérez-Carrasquilla, J. Starfeldt, C. A. Metzler, and **M. J. Molina** (In Prep). What If? Guided Diffusion as a Tool for Scientific Inquiry into Tropical Cyclones.



UNIVERSITY OF MARYLAND

GRAND CHALLENGES GRANTS

NSF

U.S. DEPARTMENT of ENERGY

Genesis Mission

National Defense Science and Engineering Graduate Fellowship Program

UMD PARETO group

mariajmolina.github.io