# Forecasting Tropical Cyclones with Cascaded Diffusion Models

**Pritthijit Nath[1], Pancham Shukla[1], Shuai Wang[2] and César Quilodrán-Casas[3]**

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## Motivation

Climate change-induced extreme rainfall events pose significant challenges in various sectors, necessitating advanced solutions for management and planning. Machine learning, particularly diffusion models, stands out by providing accurate atmospheric modelling and efficient computational resource usage, revolutionizing weather forecasting and climate simulations.

Inspired by prior diffusion model applications in atmospheric modeling, this study aims to:

1. Develop a novel cascading diffusion model approach to predict tropical cyclones using ERA5 and IR 10.8µm satellite data.
2. Demonstrate single-step SSIM and PSNR performance above 0.5 and 20 dB respectively, and strong accuracy with rollout around 36 hours.
3. Construct an optimized model design for affordability on single GPUs.

## Data

### Data Acquisition

1. **Satellite Data:** Infrared (IR) 10.8µm data for 51 significant cyclones from six major basins, spanning January 2019 to March 2023.
2. **Atmospheric Data:** Hourly ERA5 reanalysis for four variables [u10, v10, tcc, tp] from cyclone formation to dissipation, via the Copernicus Climate Data Store.

### Data Processing

1. **Bounding Box Formulation:** Square bounding boxes defined for each of the 51 cyclones encompassing the entire hurricane trajectory, to enable cropping of IR images and ERA5 data.
2. **Metadata Creation:** High functional data structure, including region, name, coordinates, ERA5 filenames, and file count, facilitating easy data retrieval.
3. **Train Test Bifurcation:** Allocates 20% of the dataset for testing, using the remaining 80% for training, ensuring fair model evaluation.
4. **Dataloader Generation:** Custom dataloaders, based on metadata, streamline training with normalized and augmented data batches for model efficiency.

## Methodology

### Cascaded Structure

- Inspired by the Imagen paper [1], this study utilizes a cascaded setup with three U-Net based diffusion models, enhancing cyclone forecast efficiency through specialized tasks: base forecast generation, super-resolution, and precipitation modeling.

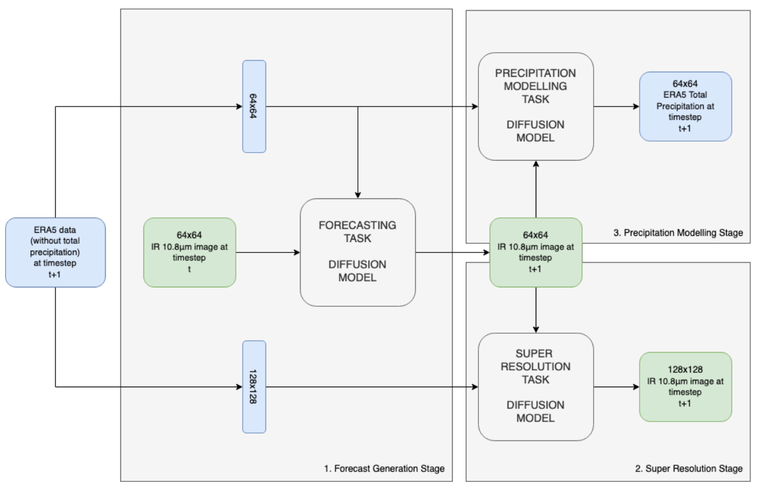


**Figure 1:** Illustration of the cascaded arrangement involving three task-specific diffusion models

- Each model incorporates classifier free guidance and dynamic thresholding for improved output, with data augmentation (rotate90, low-resolution noise injection) and post-processing (minimum filter for precipitation maps) further refining model performance.

### Evaluation Strategies

- Quantitative evaluation of the cascaded diffusion models utilizes MAE, PSNR, SSIM and FID scores for one-step performance assessment across epochs.
- Rollout analysis with SSIM measures the forecast's accuracy in an auto-regressive sequence over a cyclone's duration, using initial IR and forecasted ERA5 data.

## Results

1. Performance metrics highlight the diffusion models' superior forecasting abilities, with PSNR and SSIM values consistently exceeding 20dB and 0.5.
2. MAE values under 0.25 and FID scores below 1 for all models indicate high predictive accuracy.

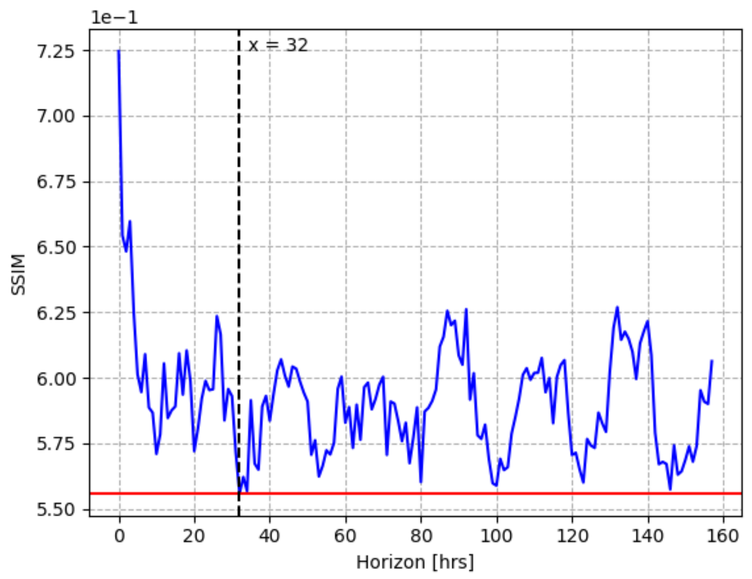


**Figure 3:** SSIM values over the entire cyclonic duration for Cyclone Mocha (North Indian Ocean)

3. SSIM analysis over cyclone durations shows a performance decline around the 36-hour mark, suggesting a reliable forecast horizon.
4. 36-hour "dip" indicates a limit to forecast reliability, achievable within 30 minutes on Nvidia A30/RTX 2080Ti GPUs.

## References

[1] Ho J, Saharia C, Chan W, Fleet DJ, Norouzi M, Salimans T. Cascaded Diffusion Models for High Fidelity Image Generation. Journal of Machine Learning Research. 2022;23(47):1–33. Available from: http://jmlr.org/papers/v23/21-0635.html.

**Affiliations**
[1] Department of Computing, Imperial College London
[2] Department of Geography and Spatial Sciences, University of Delaware
[3] Department of Earth Science and Engineering, Imperial College London

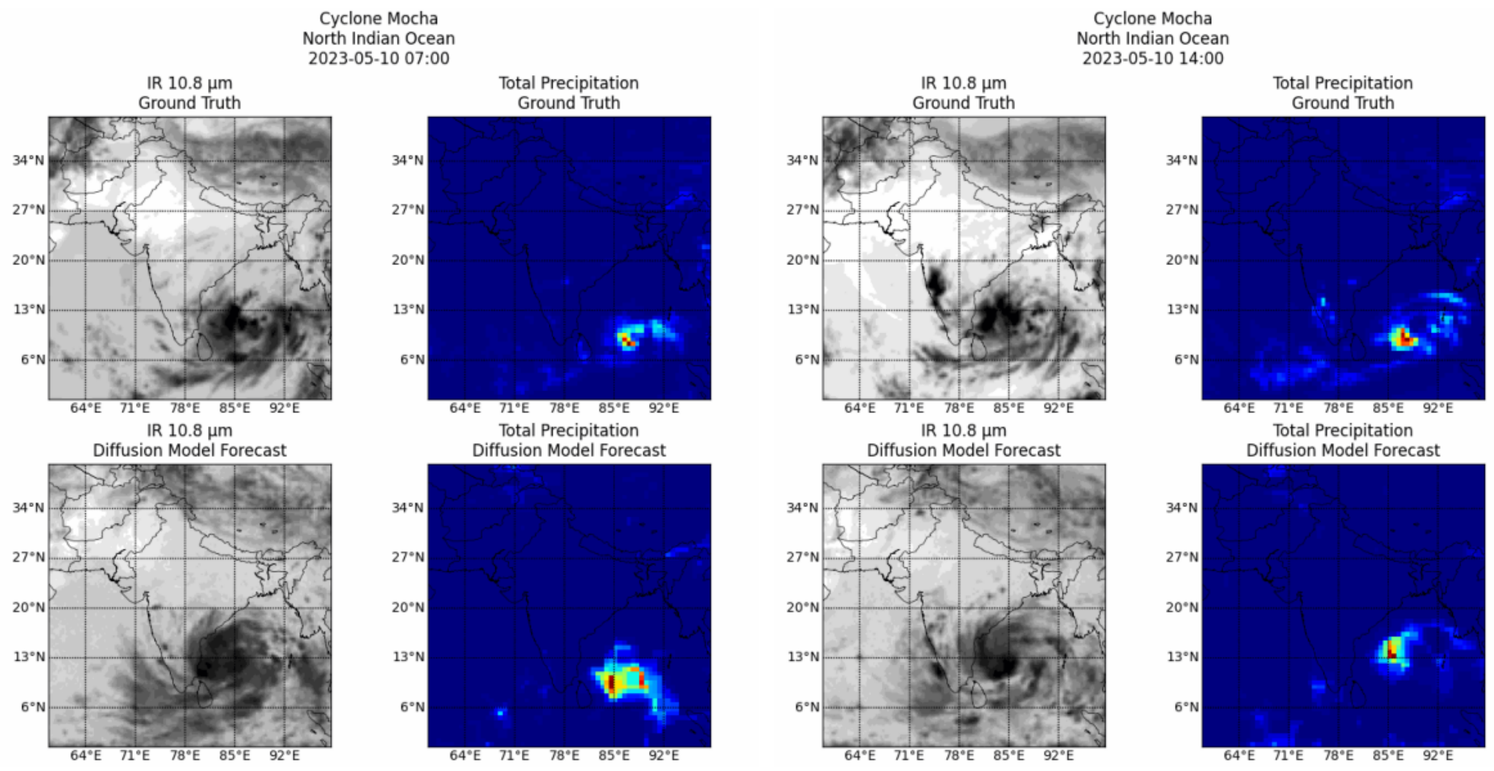


**Figure 2:** Forecast at 31h (left) and 38h (right) of Cyclone Mocha over the North Indian Ocean on 10th May 2023. The upper rows resemble the ground truth IR 10.8µm satellite image and total precipitation while the lower rows show the forecast generated at that particular timestep.