Constructing Deep Learning Datasets to Reveal Climate Trends of Tropical Cyclone Intensity and Structure Extremes

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Introduction

Climate change is associated with shifts in tropical cyclone (TC) behavior, including poleward migration, heavier rainfall, and a growing proportion of major hurricanes. However, limited and inconsistent observational records have made it difficult to assess these trends confidently. To address this gap, we developed a deep learning (DL) model that transforms multichannel satellite imagery into 0–750 km wind profiles, creating an objective, homogenized global TC dataset (1981–2020). This dataset captures intensity, structure, and integrated kinetic energy (IKE) consistently. Our results indicate a ~13% rise in major TCs and a ~25% increase in extreme-IKE TCs (95th percentile) over four decades, revealing novel trends in TC structure extremes.

Objectives

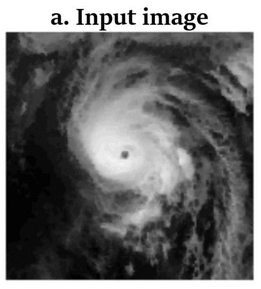
- Develop a DL approach to create a homogenized global TC wind profile dataset.
- Validate the dataset against independent satellite observations.
- Quantify long-term changes in TC intensity, structure, and integrated kinetic energy.

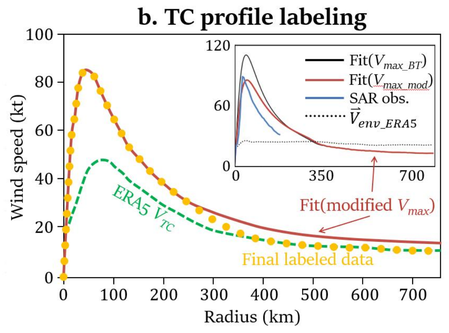
Data and Methods

■ Data Preprocessing

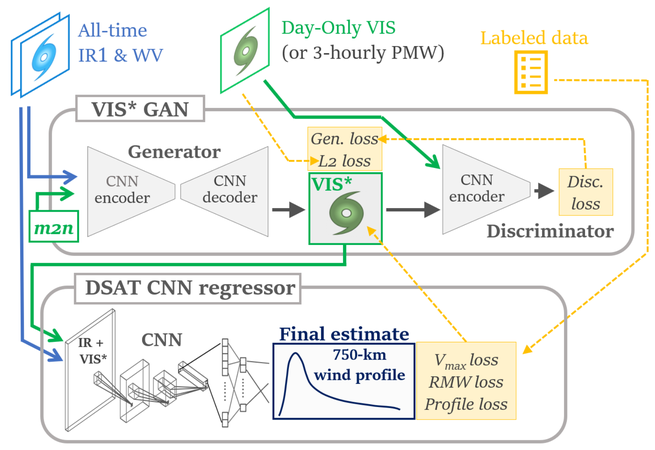
The DSAT model converts satellite images into TC radial wind profiles.

Labeled data are derived by combining best-track parameters, ERA5 reanalysis, and a parametric wind model.

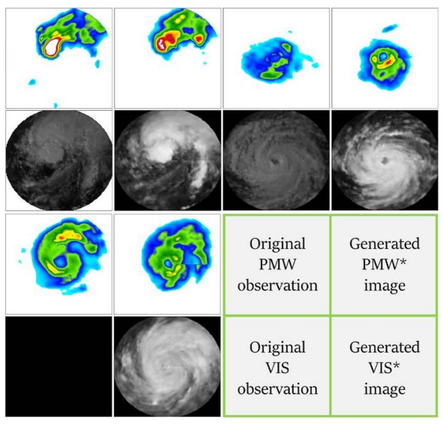




■ The Hybrid GAN-CNN DSAT model

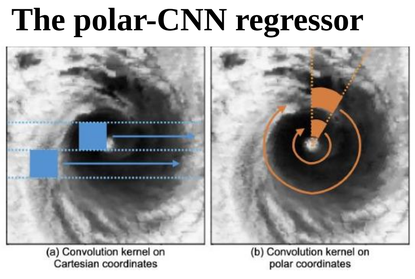


The GAN module



The hybrid GAN-CNN DSAT model includes a GAN module for generating mimic VIS* images based on the input IR and WV images, and a DSAT polar-CNN regressor that uses IR and VIS* images to estimate TC wind profiles within 750 km of the TC center.

The polar-CNN regressor



Three-stage training strategy and performance evaluations

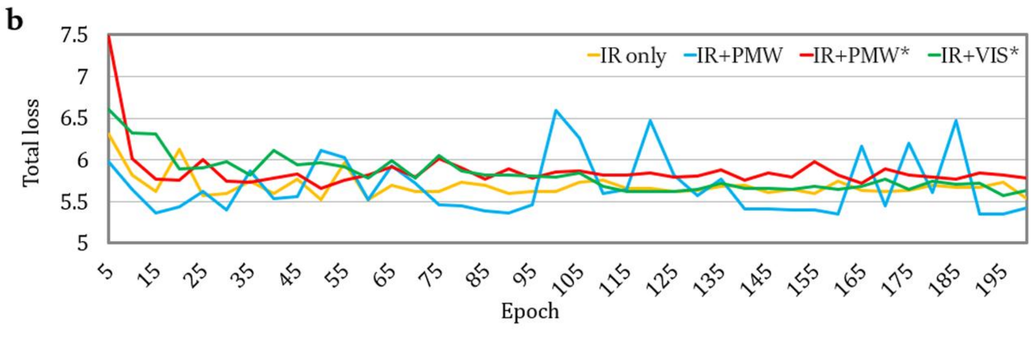
a

1. **Pretrain CNN regressor**
   - Use IR+VIS (or IR+PMW) to pretrain regressor.
   - Date from 2004–2014; only good VIS are used.

2. **Train VIS* (PMW*) generator**
   - Input IR+WV to generate VIS*, with VIS as the target.
   - Input IR+VIS* to the regressor to get regressor loss (l_{regr}).

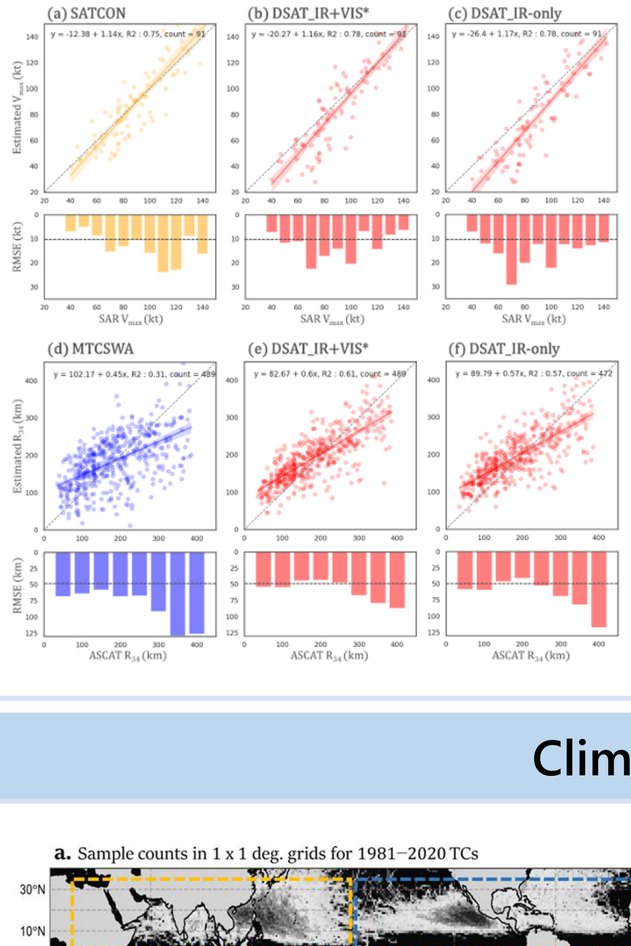
3. **Finetune CNN regressor**
   - Use the generated VIS* and original IR to estimate TC structure.
   - All date from 2004–2014.

b

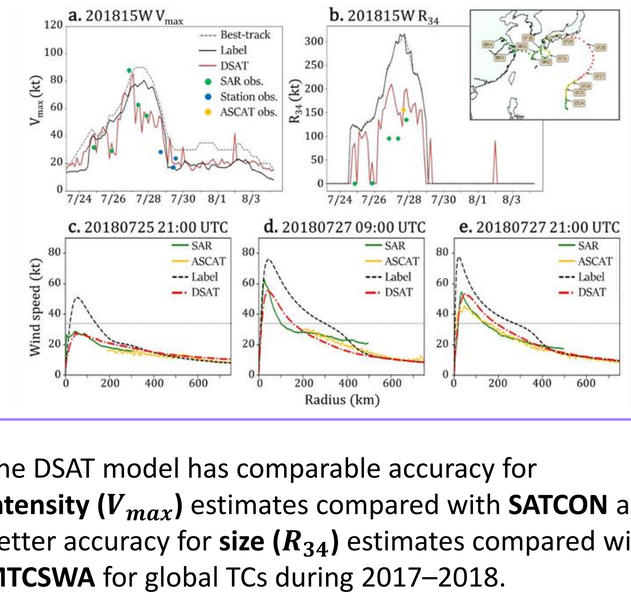


Verification

We use independent ASCAT and SAR observations to evaluate DSAT performance.

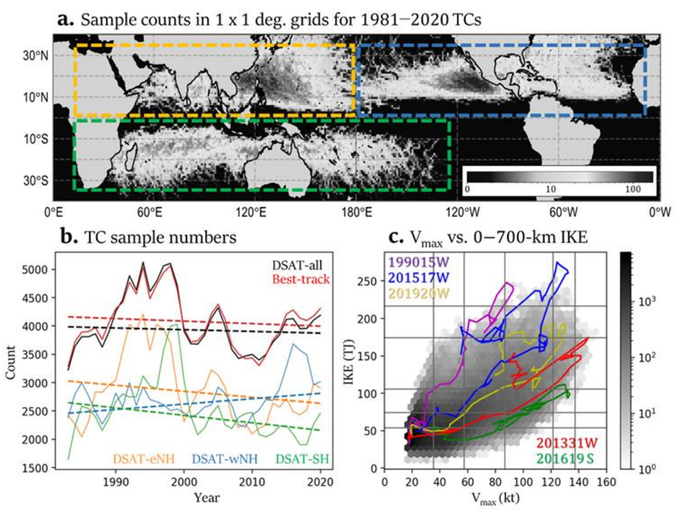


A case study of DSAT performance for Typhoon Jondari (201815W)



The DSAT model has comparable accuracy for **intensity (V_{max})** estimates compared with **SATCON** and better accuracy for **size (R_{34})** estimates compared with **MTCSWA** for global TCs during 2017–2018.

Climate trend

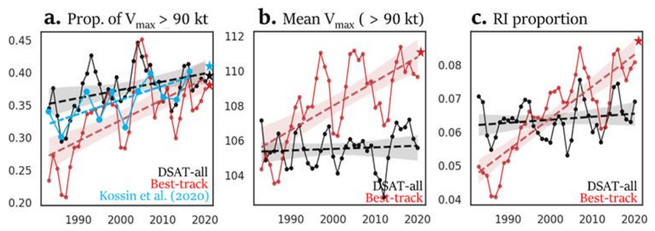


40-year (1981–2020) global TC wind profiles reconstructed using the DSAT model. TC parameters, such as V_{max} and IKE, can be directly calculated with the reconstructed wind profiles.

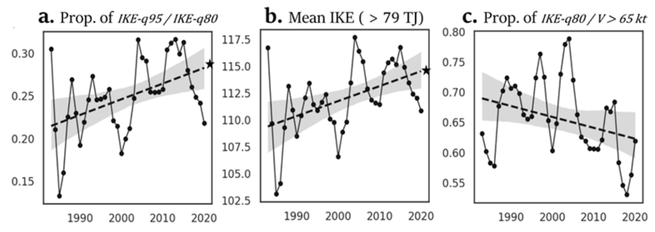
Three-yearly averaged annual TC sample numbers from 1981–1983 to 2017–2020 show no significant trends during this period.

V_{max} and IKEs are loosely correlated (R^2 = 0.4)

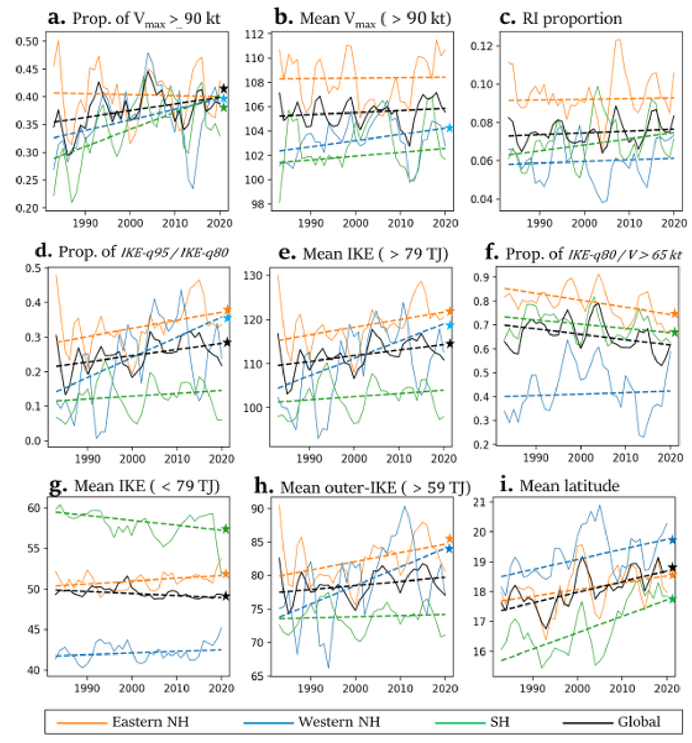
TC intensity trend



TC IKE trend



Basin variabilities of DSAT TC climate trends



Conclusions and Future direction

This study applies a deep learning approach to reconstruct global tropical cyclone (TC) wind profiles from 1981 to 2020, creating a homogenized dataset to investigate TC intensity and structure trends under a changing climate.

Our results indicate:

- A ~13% increase in the fraction of major TCs over the past four decades.
- A ~25% rise in the fraction of extreme TCs in terms of integrated kinetic energy (IKE), reflecting stronger overall storm circulations.
- A growing divergence in the TC population: TCs with very high IKE are becoming more common, while weaker TCs show little sign of intensification.

These findings underscore that climate change may not only increase storm intensity for a subset of TCs, but also expand their overall wind structure and energy. This new dataset can help refine climate model validation and deepen our understanding of TCs in a warming world.