Slower Intensity Decay of US Landfalling Tropical Cyclones and Its Implications on Predictive Model Skills

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Introduction and Research Questions

- **Motivation:** Tropical cyclones (TCs), known as hurricanes in North America, are powerful storms that pose significant risks, including strong winds, storm surge, extreme rainfall, and tornadoes.
- **Research gaps**: Inland TC decay timescales have increased since the mid-1990s. Traditional models like KD95 may no longer predict intensities accurately. Longer decay timescales Slower decay rates imply stronger inland storms, increasing risks. Improved models are needed for better forecasts and hazard mitigation.
- **Research questions:**
  1.How has the intensity decay of U.S. landfalling TCs changed from 1967–2023?
  2.How well do the exponential decay and KD95 models predict inland TC intensity across the U.S.?
- **Expected outcomes:** By examining long-term trends and evaluating prediction models, this work provides critical insights for improving TC hazard mitigation and refining intensity forecasting models.

Data and Methods

Tropical Cyclone Observations:

TC tracks for the North Atlantic were sourced from the HURDAT2 database (Landsea and Franklin, 2013). We analyzed 162 U.S. landfalling TCs from 1967–2023, focusing on reliable observations. Among these, 159 159 progressed inland beyond landfall, including 2 tropical depressions, 84 tropical storms, 36 weak hurricanes, and 37 major hurricanes (Fig. 1a).

Exponential Models for Post-Landfall TC Intensity:

The Kaplan and DeMaria (1995) decay model (KD95) was used to assess TC inland intensity decay. The model assumes exponential decay proportional to wind speed at landfall, expressed as:

$$V_t = V_0\, e^{-\alpha t}$$

Here, V_t and V_0 are wind speeds at time t (hours) after landfall and at landfall (t=0), respectively, and α is the decay constant. A refined model includes a background wind speed (V_b), reduction factor (R), and correction term (C) accounting for distance inland:

$$V_t = V_b + (R\, V_0 - V_b)\, e^{-\alpha t} - C$$

The decay constant (α=0.095 h^{-1}) was derived from U.S. TCs (1967–1993). Both models were evaluated using historical observations for their ability to simulate inland TC intensity decay.

Quantifying Temporal Trends in Decay:

Long-term trends in TC intensity decay were analyzed using decay timescales (τ), estimated for TCs meeting three criteria:

1.Wind speed at the first inland point (V_0) ≥ 64 kt.
2.At least four continuous inland points within 24 hours after landfall.
3.Decay timescales within two standard deviations of the long-term mean.

A final set of 50 TCs (1967–2023) was identified (Fig. 1b), enabling trend analysis using Theil–Sen regression and significance testing with the Mann–Kendall method.

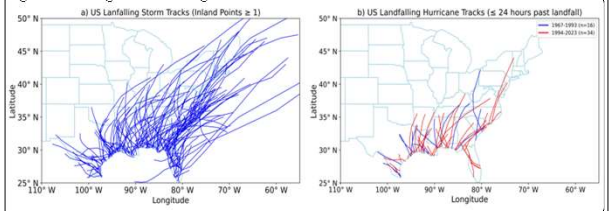


Fig. 1. (a) The tracks of 1967–2023 US landfalling TCs with at least one inland point following landfall, and (b) the tracks of 1967–2023 US landfalling hurricanes with at least four continuous inland points within the first 24 hours past landfall.

Fig. 2 illustrates how decay timescale (τ) of each TC is estimated by using Hurricane Camille (1969) and Carmen (1974) as examples. For their first five inland points (including the exact landfall point) after landfall, $\ln\left(\frac{V_t}{V_0}\right)$ is plotted against time after landfall, followed by the computation of a linear fit.

Here V_t and V_0 refer to the wind speeds at time t (hours) after landfall and at landfall (t=0), respectively. The slope of the linear fit indicates -1/ τ. As such, decay timescale (τ) is the negative inverse of the slope, and decay constant is the negative of the slope.

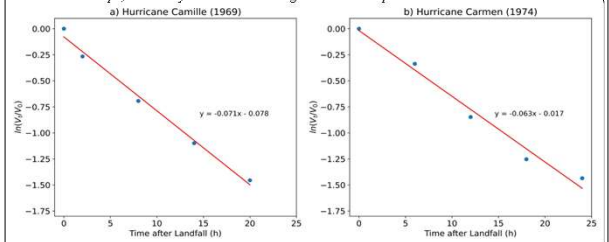


Fig. 2. The estimations of decay constant for Hurricane Camille (1969) and Carmen (1974). Y-axis shows $\ln\left(\frac{V_t}{V_0}\right)$ with indicating the wind speeds V_t and V_0 at time t (hours) after landfall and at landfall (t=0), respectively.

Results

Change in TC Intensity Decay Timescale

- From 1967 to 2023, inland TC decay timescales increased by 1.6 hours per decade (p = 0.048), rising from 18 to 27.1 hours—a 50.6% increase(Fig. 3a).
- Event-level analysis shows significantly longer decay timescales post-1993 (p = 0.026), with 14.7% exceeding 40 hours compared to none pre-1994 (Fig. 3b).

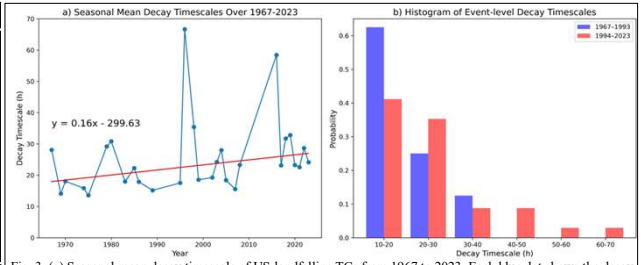


Fig. 3. (a) Seasonal mean decay timescale of US landfalling TCs from 1967 to 2023. Each blue dot shows the decay timescale averaged over all TCs in the same season, and the red line shows the linear fit using the Thei-Sen regression. (b) Distribution of decay timescales estimated from individual landfalling TCs over 1967–1993 (blue bar) and 1994–2023 (red bar), respectively.

Evaluating TC Intensity Models

The spatial distributions of wind speed errors from the two prediction models.

- The hindcast model tends to produce minimal or slightly positive errors, with 89% of the errors falling within the range of -5 kt to 15 kt.
- In contrast, the KD95 model frequently yields negative errors, with the range of -5 kt to -25 kt accounting for 45.5% of the errors.
- For both models, the positive and negative errors appear to be fairly evenly distributed across the region.

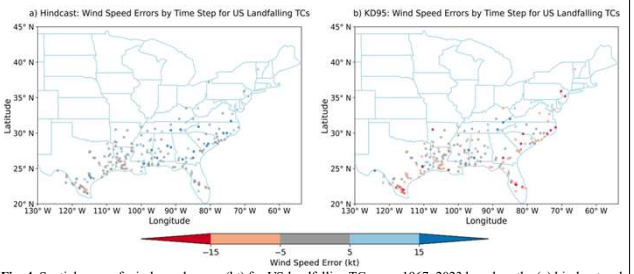


Fig. 4. Spatial maps of wind speed errors (kt) for US landfalling TCs over 1967–2023 based on the (a) hindcast and (b) KD95 models, respectively. Each dot indicates one time step of inland TCs. There were 41 and 9 TCs making landfall along the Gulf Coast and Atlantic Coast, respectively.

- Both KD95 and Hindcast models produce small TC wind speed errors, but the Hindcast model performs better.
- Average wind speed errors are 3.6 kt (Hindcast) and -3.5 kt (KD95), with 95% confidence intervals of [2.8 kt, 4.5 kt] and [-4.7 kt, -2.3 kt], respectively.
- The Hindcast model shows narrower error distributions, with 65% of errors within -5 to 5 kt, compared to 38.5% for KD95, indicating greater reliability.

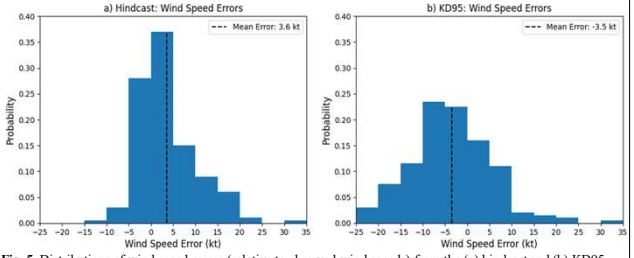


Fig. 5. Distributions of wind speed errors (relative to observed wind speeds) from the (a) hindcast and (b) KD95 models, respectively.

Impacts of changing Decay Timescale on TC Intensity Prediction:

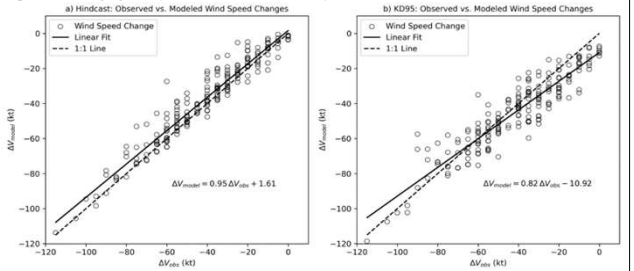


Fig. 6. Scatterplots of observed and modeled wind speed changes (denoted as Δvobs and ΔVmodel) within the first 24 hours past landfall. The changes are relative to observed wind speeds at landfall (V0). Modeled wind speeds are derived from the (a) hindcast and (b) KD95 models, respectively.

- The hindcast model closely matches observed post-landfall wind speed changes (slope: 0.95, R^2: 0.93), outperforming the KD95 model (slope: 0.82, R^2: 0.85), demonstrating its superior accuracy (Fig. 6).
- The hindcast model maintains high accuracy across both periods (1967–1993 and 1994–2023), with slopes near 1 and $R^2 > 0.91$ (Fig. 8a).
- The KD95 model performs better for 1994–2023, with an improved slope (0.86), R^2 (0.87), and reduced RMSE (9.2 kt vs. 11 kt for 1967–1993; Fig. 8b)

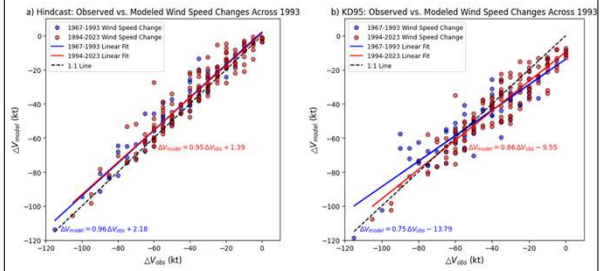


Fig. 7. As in Fig. 6 but dividing into two periods (a) 1967–1993 and (b) 1994–2023.

- The hindcast model outperforms the KD95 model, with a lower seasonal mean RMSE (6.3 kt vs. 9.2 kt; Fig. 8a-b).
- Both models show slight, non-significant RMSE decreases from 1967 to 2023, linked to observed wind speed trends.
- Observed landfall wind speeds decreased significantly by 6.2 kt/decade ($p < 0.01$; Fig. 8c), driven by three high-intensity storms (≥110 kt) from 1967–1970.
- Post-landfall wind speeds within 24 hours showed no significant change (-0.4 kt/decade; p = 0.72; Fig. 8d).
- From 1983–2023, landfall wind speeds decreased by 1.8 kt/decade, while post-landfall speeds increased by 1.9 kt/decade, reflecting slower intensity decay and longer decay timescales.

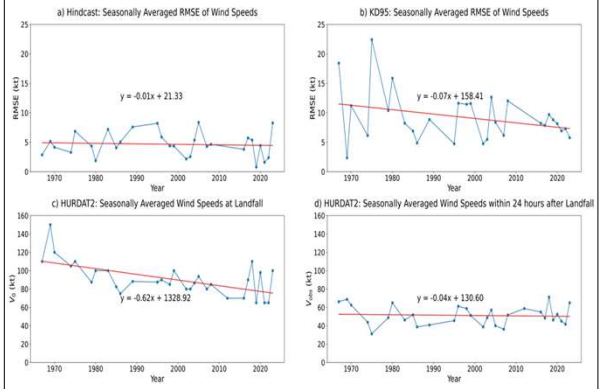


Fig. 8. Seasonally averaged root mean square errors (RMSE) of wind speeds from the (a) hindcast and (b) KD95 models, respectively. (c-d) Seasonally averaged wind speeds at landfall (V0) and within the first 24 hours past landfall (Vobs) in the HURDAT2 dataset.

Conclusions

- The decay timescale of inland TCs increased significantly by 1.6 h/decade from 1967 to 2023, with a pronounced rise after 1994. Longer decay timescales result in slower intensity loss and higher inland TC intensity.
- Both models effectively predict inland TC wind speeds over time and space. The hindcast model shows better accuracy with smaller wind speed error ranges.
- Despite the increasing decay timescale, both models remain effective for predicting inland TC wind speeds.

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