Persistent Multi-Scale Consistency in Best-Track Intensity Evolution and Rapid Intensification in Atlantic Tropical Cyclones (1851–2024)

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Abstract

Rapid intensification (RI), commonly defined as an increase in maximum sustained wind speed of at least 30 kt within 24 h, remains one of the most challenging aspects of tropical cyclone forecasting.

This study evaluates whether persistent multi-scale consistency in best-track intensity evolution is statistically associated with RI occurrence across the full Atlantic historical record. A minimal, forward-only diagnostic is constructed from HURDAT2 using causal rolling means of maximum sustained wind speed at multiple timescales and a directional-agreement rule across scales. The method uses only current and prior best-track intensity values and is applied uniformly to 1,991 Atlantic tropical cyclones from 1851 to 2024.

Storms exhibiting longer durations of persistent multi-scale agreement form a small subset with substantially elevated RI occurrence. As persistence increases, RI probability rises from a basin-wide baseline of approximately 26% to about 60% for storms with at least 140 h of persistence and to about 67% for storms with at least 168–270 h of persistence.

The diagnostic is not interpreted as a direct measure of inner-core structure and is not proposed as an operational forecast tool. Instead, it provides a reproducible long-record statistical diagnostic derived solely from best-track data. The results indicate that prolonged multi-scale consistency identifies a subset of storms with substantially elevated RI likelihood and motivate further comparison with higher-resolution structural observations.

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1. Introduction

Rapid intensification (RI), typically defined as an increase in maximum sustained wind speed of at least 30 kt within 24 h, remains one of the most consequential and difficult-to-forecast aspects of tropical cyclone evolution (Kaplan and DeMaria 2003; Kaplan et al. 2010; DeMaria et al. 2021). Despite advances in statistical-dynamical guidance and environmental diagnostics, RI continues to exhibit substantial variability, with storms in similar large-scale environments often evolving differently.

Previous work has emphasized the role of environmental conditions such as vertical wind shear, sea surface temperature, and ocean heat content (Kaplan and DeMaria 2003; Kaplan et al. 2010). At the same time, a growing body of observational and modeling research highlights the importance of internal storm structure, including convective symmetry, vortex alignment, and inner-core evolution (Jiang 2012; Kieper and Jiang 2012; Rogers et al. 2015; Miyamoto and Nolan 2018; Shi et al. 2023). These results suggest that RI is influenced by both environmental forcing and evolving storm organization.

However, structurally informative observations are largely confined to the satellite and aircraft reconnaissance eras. In contrast, the Atlantic best-track dataset (HURDAT2) provides basin-wide coverage extending back to the mid-nineteenth century but contains limited direct information about storm structure (Landsea and Franklin 2013; Landsea et al. 2022; Vecchi and Knutson 2008, 2011).

This disparity motivates a simpler question: does the time evolution of best-track intensity contain a persistent statistical relationship associated with RI? Specifically, can a minimal, forward-only diagnostic derived solely from best-track intensity identify a subset of storms with systematically elevated RI likelihood?

The present study addresses this question using the full Atlantic record from 1851 to 2024. A persistence diagnostic is constructed using multi-scale smoothing and directional agreement applied to intensity evolution. The method is intentionally minimal and designed for consistent application across the full historical archive.

The objective is not to develop an operational prediction system or to directly diagnose inner-core structure. Instead, the study evaluates whether prolonged multi-scale consistency in intensity evolution identifies a statistically distinct subset of storms with elevated RI occurrence. If such a relationship exists, it would provide a long-record statistical perspective complementary to modern structural diagnostics.

A companion analysis applying identical construction to the Eastern Pacific basin is presented separately.

2. Data

This analysis uses the Atlantic hurricane database HURDAT2 (Landsea et al. 2022), which contains best-track information for 1,991 tropical cyclones spanning 1851–2024 at a 6-h advisory interval. For each storm and advisory time, the dataset provides storm position and maximum sustained wind speed (VMAX). In this study, VMAX is used to construct the persistence diagnostic and to define RI events.

Rapid intensification is defined as an increase in VMAX of at least 30 kt over 24 h, consistent with established operational and research conventions (Kaplan and DeMaria 2003; Kaplan et al. 2010; DeMaria et al. 2021).

HURDAT2 is not temporally homogeneous across the full record. Earlier portions of the dataset are subject to greater uncertainty in storm detection and intensity estimation, particularly prior to the satellite era (Landsea and Franklin 2013; Vecchi and Knutson 2008, 2011; Vecchi et al. 2021). These limitations are considered in interpretation but are not explicitly corrected in the present analysis. The goal is to evaluate whether a simple within-storm persistence property is associated with RI across the archive despite these known constraints.

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3. Methods

3.1. Persistence diagnostic

Let (V(t)) denote maximum sustained wind speed at 6-h intervals. To characterize intensity evolution across multiple temporal scales, three causal rolling means are computed:

[
V_3(t), \quad V_5(t), \quad V_9(t)
]

where each rolling mean is calculated using only the current and preceding observations.

For each smoothed series, a one-step tendency is defined as:

[
D_s(t) = V_s(t) - V_s(t-1), \quad s \in {3,5,9}.
]

Directional agreement is evaluated across three window pairs: ((3,5)), ((5,9)), and ((3,9)). For each pair, define:

$$
A_{ij}(t) =
\begin{cases}
1, & \text{if } \mathrm{sign}(D_i(t)) = \mathrm{sign}(D_j(t)) \\
0, & \text{otherwise}.
\end{cases}
$$

The multi-scale agreement score is:

$$
PL(t) = \frac{1}{3} \sum A_{ij}(t),
$$

which ranges from 0 to 1 and measures directional consistency across temporal scales.

3.2. Activation rule and persistence

A time step is classified as active when:

- $PL(t) \ge 0.67$, and
- the condition persists for at least two consecutive advisories.

This requirement ensures that activation reflects sustained rather than transient agreement.

For each storm, persistence is defined as:

$$
\text{Persistence} = N_{\text{active}} \times 6 \text{ h},
$$

where N_{active} is the number of active time steps. Persistence therefore represents the total duration of sustained multi-scale agreement in intensity evolution.

All statistics are computed at the storm level to avoid temporal dependence within individual storm time series.

3.3. Interpretation

The persistence diagnostic is intended as a minimal proxy for sustained multi-scale consistency in best-track intensity evolution. It is not a direct measurement of inner-core structure and does not incorporate environmental predictors. Its purpose is to determine whether prolonged multi-

scale agreement in intensity tendency identifies a statistically distinct subset of storms within the historical record. The use of multi-scale smoothing and directional agreement is conceptually consistent with prior applications of scale-dependent coherence in geophysical time series (Torrence and Compo 1998; Grinsted et al. 2004; Ng and Chan 2012).

3.4. Comparison metric: single-scale persistence

To assess whether the multi-scale persistence diagnostic adds information beyond simpler persistence measures, a single-scale comparison metric was also constructed. This comparison metric uses only the 5-step causal rolling mean of VMAX, with activity defined when the one-step tendency remains positive for at least two consecutive advisories. Storm-level persistence is then defined as the total duration of active time steps, using the same 6-h accumulation rule applied to the multi-scale diagnostic. This comparison is intended to isolate the contribution of cross-scale agreement relative to a simpler single-scale persistence measure.

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4. Results

Across the Atlantic dataset (1851–2024; 1,991 storms), 525 storms satisfy the rapid intensification (RI) definition, corresponding to a basin-wide RI probability of approximately 26.4%.

Storms stratified by persistence duration exhibit a clear and largely monotonic increase in RI probability (Fig. 1). For storms with persistence of at least 72 h, the RI probability increases to approximately 49.6% (n = 659). At higher persistence thresholds, the enrichment continues: 60.1% for ≥140 h (n = 228), 66.4% for ≥168 h (n = 146), and 66.7% for ≥270 h (n = 24). These values correspond to a roughly 2.3–2.5× increase relative to the basin baseline (26.4%).

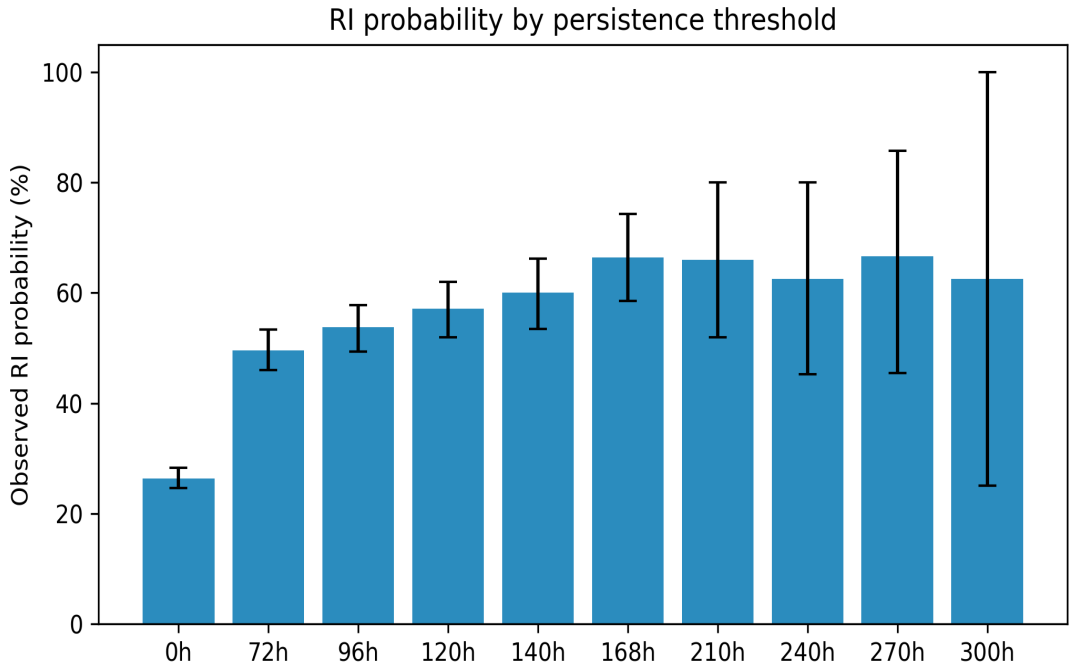

Fig. 1. RI probability as a function of persistence duration threshold. Error bars indicate bootstrap confidence intervals. Sample sizes decrease with increasing threshold, leading to wider uncertainty beyond ~168 h. Sample sizes decrease from n = 1991 at 0 h to n = 24 at 270 h and n = 8 at 300 h.

Stratification by observational era shows that the persistence–RI relationship is preserved across multiple historical regimes (Fig. 3), with similar monotonic structure evident in pre-1944, mid-century, and modern subsets. Differences in absolute RI probability across eras are consistent with known observational and intensity estimation differences, but the underlying relationship remains intact.

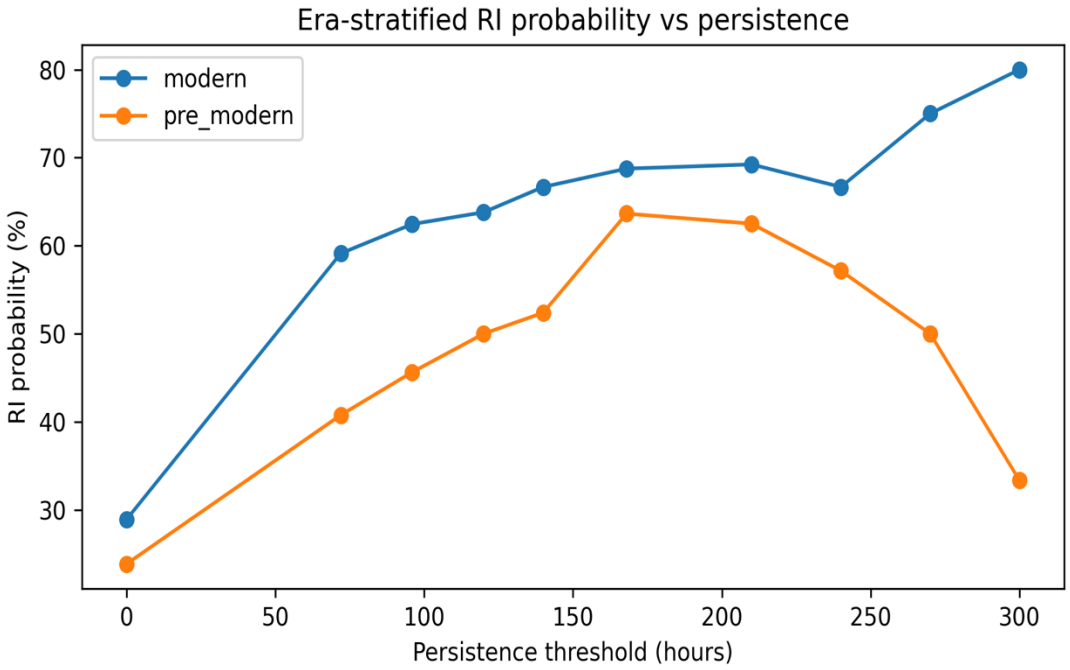

Fig. 3. RI probability as a function of persistence duration stratified by observational era (pre-modern vs modern). Both subsets exhibit similar monotonic enrichment, indicating that the persistence–RI relationship is not dependent on the observing system.

Bootstrap confidence intervals indicate that the enrichment remains statistically distinct from the baseline across thresholds up to at least 168 h (e.g., 0.534–0.662 at 140 h; 0.585–0.744 at 168 h). At higher thresholds, confidence intervals widen due to decreasing sample size, but point estimates remain elevated.

The persistence diagnostic therefore identifies a conditionally enriched subset rather than providing broad detection of all RI events. The observed pattern is best interpreted as evidence that prolonged multi-scale consistency in intensity evolution is associated with a distinct class of storm behavior within the historical record.

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5. Robustness and Sensitivity Analyses

5.1. Bootstrap uncertainty

Uncertainty in the persistence–RI relationship was evaluated using storm-level bootstrap resampling. Across all persistence thresholds, bootstrap confidence intervals remain well above

the basin baseline, indicating that the observed enrichment is not driven by sampling variability. While uncertainty increases in the highest-persistence cohorts due to small sample size, the central tendency of the relationship remains stable.

5.2. Permutation null test

To assess whether the observed enrichment could arise from random association between persistence and RI, a permutation null test was conducted in which RI labels were randomly reassigned across storms. Under this null hypothesis, the persistence–RI relationship collapses, and the probability of observing enrichment comparable to the empirical result is low ($p < 0.01$ across thresholds).

This indicates that the observed monotonic increase in RI probability with persistence duration is not consistent with random assignment and reflects a structured relationship within the dataset.

5.3. Block-shuffle null

A more stringent null was constructed by applying block-wise temporal shuffling within storms, which disrupts temporal multi-scale consistency in intensity evolution while preserving marginal intensity distributions and coarse storm structure.

Under this null, partial overlap with the observed statistical relationship is present at some thresholds, indicating that aspects of the persistence–RI relationship are embedded in the temporal evolution of intensity itself. This result supports the interpretation that persistence captures meaningful properties of intensity evolution rather than representing a fully independent structural association.

5.4. Sensitivity to parameter choices

The persistence–RI relationship was evaluated under multiple parameter configurations, including alternate smoothing windows and stricter activation rules. Across these configurations, the monotonic enrichment pattern is preserved, and effect sizes remain similar to the baseline configuration.

This indicates that the result is not dependent on a specific parameter choice and is robust to reasonable variations in construction.

5.5. Observational era stratification

The dataset was partitioned into pre-modern and modern observational eras. In both subsets, the persistence–RI relationship is preserved. RI probability increases from approximately 24% to approximately 63% in the pre-modern subset and from approximately 29% to approximately 69% in the modern subset at comparable persistence thresholds.

The persistence–RI relationship remains consistent across all three observational eras (Fig. 4), with similar monotonic structure despite differences in absolute probability levels.

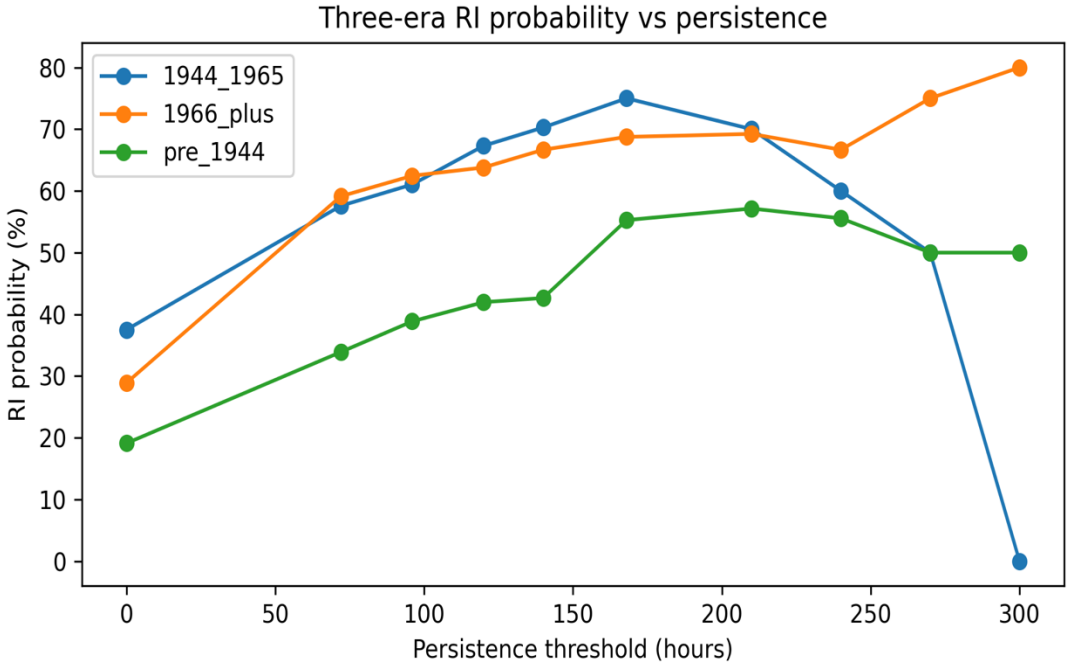

Fig. 4. RI probability as a function of persistence duration across three observational eras. All subsets exhibit similar monotonic structure, with differences in magnitude consistent with known observational and intensity estimation differences. The preservation of the relationship across eras indicates that the persistence–RI association is robust to historical inhomogeneities in the best-track record. Estimates at the highest thresholds are based on small sample sizes and should be interpreted cautiously.

5.6. Duration normalization

To evaluate whether persistence simply reflects storm duration, a duration-normalized persistence metric was analyzed. The persistence–RI relationship remains monotonic under normalization, indicating that persistence captures additional information beyond storm lifetime.

5.7. Pre-event persistence

Persistence computed prior to RI onset is rare at high thresholds and associated with small sample sizes. While estimates are therefore uncertain, the presence of elevated persistence prior to RI onset suggests that sustained temporal multi-scale consistency can precede intensification events. These results should be interpreted cautiously.

5.8. Logistic regression analysis

Logistic regression models were constructed to evaluate whether persistence provides independent explanatory information beyond storm duration.

In a univariate model, persistence exhibits a positive and statistically significant coefficient ($\beta \approx 0.015\ h^{-1}$; odds ratio ≈ 1.015 per hour). When storm duration is included as a covariate, the persistence coefficient remains unchanged, while the duration coefficient collapses toward zero.

This indicates that the persistence–RI relationship is not reducible to storm lifetime and that persistence provides independent explanatory statistical association beyond storm duration.

5.9. Comparison with a single-scale persistence metric

To evaluate whether the observed relationship depends on the multi-scale construction, a comparison was performed using a single-scale persistence metric.

The single-scale comparator also exhibits increasing RI probability with persistence duration, indicating that persistence in intensity evolution itself contains meaningful association. However, the multi-scale diagnostic yields systematically stronger and more stable enrichment across thresholds. For example, RI probability increases to approximately 66% at ≥168 h for the multi-scale diagnostic, compared to approximately 56% for the single-scale comparator.

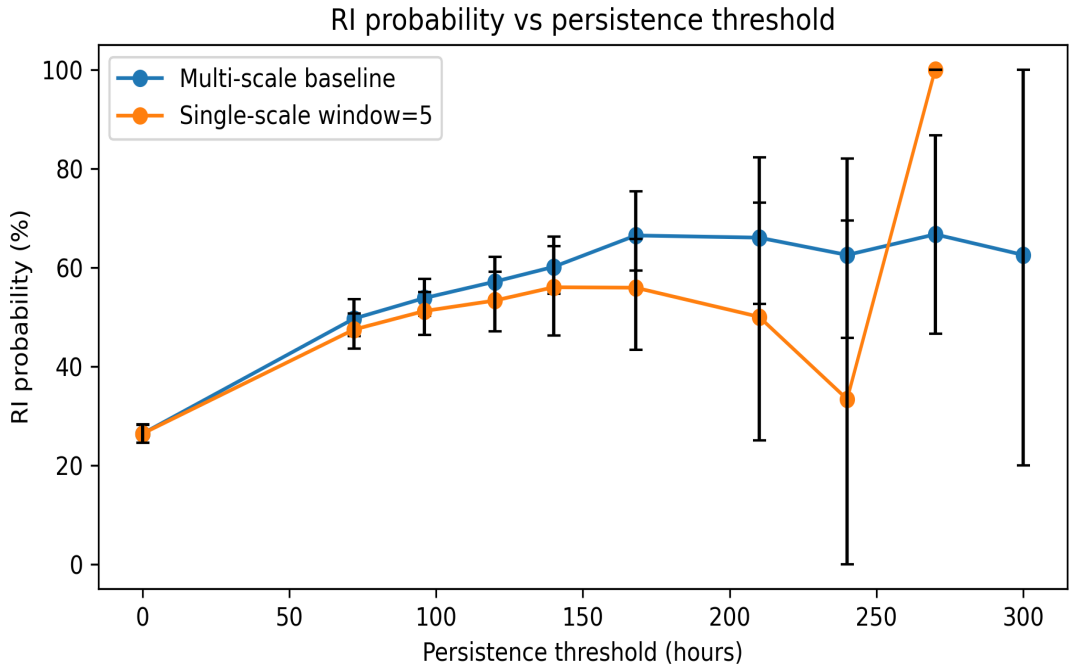

Fig. 2. Comparison of multi-scale persistence diagnostic and single-scale persistence metric. While both exhibit increasing RI probability with persistence, the multi-scale diagnostic produces stronger and more stable enrichment across thresholds, particularly at intermediate durations (72–168 h).

At higher persistence thresholds, the single-scale comparator becomes unstable due to small sample sizes, with sharp fluctuations in estimated RI probability. In contrast, the multi-scale diagnostic maintains a more consistent upper-tail behavior, indicating improved discrimination of persistent storm evolution.

Logistic regression results further support this distinction. While single-scale persistence is positively associated with RI occurrence, its effect weakens when controlling for storm duration. In contrast, the multi-scale persistence metric retains a stronger and more stable relationship with RI under duration control, indicating that it captures additional structure beyond simple storm longevity.

These results indicate that persistence in intensity evolution contains meaningful information, but that requiring directional agreement across multiple temporal scales sharpens the identification of storms with elevated RI likelihood. This isolates the contribution of cross-scale agreement while holding persistence definition constant.

6. Discussion

The principal result of this study is that prolonged multi-scale consistency in best-track intensity evolution is associated with a conditionally enriched subset of storms exhibiting elevated RI occurrence across the Atlantic historical record. This relationship is supported by monotonic enrichment across persistence thresholds, robustness to parameter variation, and independence from storm duration in regression analysis.

Comparison with a single-scale persistence metric indicates that persistence in intensity evolution itself contains meaningful association, but that requiring directional agreement across multiple temporal scales yields stronger and more stable separation of high-RI subsets. In particular, the multi-scale diagnostic produces consistently higher RI probabilities across intermediate thresholds (72–168 h) and maintains more stable behavior in the upper tail, where the single-scale comparator becomes sensitive to small sample sizes. This suggests that cross-scale agreement provides additional structure beyond persistence at a single smoothing scale.

The persistence–RI relationship is preserved across observational eras, with similar monotonic behavior evident in pre-1944, mid-century, and modern subsets. Differences in absolute RI probability across eras are consistent with known changes in observational coverage and intensity estimation, but the underlying relationship remains intact. This indicates that the statistical relationship is not an artifact of the observing system and reflects a persistent property of storm evolution captured in the best-track record.

These findings are consistent with prior observational and modeling studies linking RI to evolving storm organization, including convective symmetry, precipitation structure, and vortex alignment (Jiang 2012; Rogers et al. 2015; Miyamoto and Nolan 2018; Shi et al. 2023). The present analysis does not resolve these processes directly, but demonstrates that a simple diagnostic derived from intensity evolution alone is associated with systematically different RI likelihood.

The persistence diagnostic differs fundamentally from the RI definition itself. RI is defined by a fixed magnitude threshold over a specified time interval (Kaplan and DeMaria 2003), whereas the persistence metric reflects sustained directional agreement across multiple temporal scales. The presence of high-persistence storms that do not undergo RI indicates that the diagnostic captures a broader property of storm evolution rather than a direct transformation of intensity change.

Attenuation under block shuffling indicates dependence on temporal ordering, consistent with the diagnostic capturing structured evolution rather than marginal intensity properties alone. This is consistent with the interpretation that persistence reflects sustained multi-scale consistency in intensity evolution, rather than a fully independent structural variable.

The persistence diagnostic presented here is derived entirely from best-track intensity evolution and therefore is not independent of the underlying intensity signal used to define rapid intensification (RI). However, it differs fundamentally from magnitude-based RI definitions in

that it does not depend on threshold exceedance over a fixed time interval, but instead reflects sustained directional consistency across multiple temporal scales. The comparison with a single-scale persistence metric further indicates that persistence alone does not fully account for the observed relationship; requiring agreement across temporal scales yields stronger and more stable enrichment of RI probability. The persistence diagnostic should therefore be interpreted as identifying a statistical regime within storm evolution rather than as a direct proxy for physical structure or a predictive model of intensification.

At the same time, uncertainties in the historical best-track record, particularly prior to the satellite era, may influence both persistence estimates and RI classification. The preservation of the persistence–RI relationship across observational eras indicates that the signal is not solely an artifact of changing observing systems, but the results should nevertheless be interpreted as a long-record statistical association rather than a direct measurement of underlying physical processes.

Taken together, these results indicate that persistent multi-scale consistency in intensity evolution identifies a statistically distinct subset of storms with elevated RI likelihood, using only best-track data and without reliance on environmental predictors or satellite-era structural diagnostics.

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7. Limitations

Several limitations should be noted:

- The highest-persistence subsets contain relatively few storms, limiting statistical precision.
- The diagnostic is derived solely from best-track intensity and does not directly measure physical storm structure.
- The analysis is observational and does not establish causality.
- HURDAT2 contains known inhomogeneities across observing eras.
- While multiple robustness analyses are included, additional work could further evaluate alternative definitions, basin extensions, and physical interpretation.

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8. Conclusion

A forward-only persistence diagnostic derived from best-track intensity evolution identifies a small subset of Atlantic tropical cyclones with substantially elevated RI occurrence over 1851–2024. This relationship is robust to bootstrap resampling, null testing, parameter variation, and observational-era stratification and is not explained by storm duration alone.

The results demonstrate that persistent multi-scale consistency in intensity evolution is a measurable and statistically stable property of storms in the historical record. This provides a foundation for future work linking long-record intensity-based diagnostics with higher-resolution structural observations.

Replication under identical construction in an independent basin further supports the interpretation that this relationship reflects a general property of tropical cyclone intensity evolution rather than a basin-specific artifact.

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9. Data Availability

The Atlantic hurricane database (HURDAT2) used in this study is publicly available from the National Hurricane Center (https://www.nhc.noaa.gov/data/). Code and derived data supporting the persistence diagnostic are archived at Zenodo (DOI: https://doi.org/10.5281/zenodo.19273323). The repository includes a minimal, reproducible implementation of the diagnostic and example datasets sufficient to reproduce the analysis from HURDAT2.

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