TROPICAL · RESEARCH PAPER

Global Climatology of Tropical Cyclone Power Dissipation

Sixty-six years of the JTWC+NHC+Neumann best track, confronted with the new homogeneous satellite record. What Emanuel (2005), Webster et al. (2005) and Kossin et al. (2020) claimed; what survives two more decades of data; and what an intensity trend is actually worth in dissipated energy.

Ryan Maue · climatlas · analysis generated 2026-09-18 · 108,737 best-track + 133,723 ADT-HURSAT fixes

Abstract. We construct a global climatology of tropical cyclone power dissipation from 108,737 six-hourly best-track fixes (JTWC + NHC + Neumann, 1960–2025) and confront it with the newly extended homogeneous satellite record, ADT-HURSAT v01 (133,723 fixes, 1978–2024). The 1991–2020 normal global PDI is $2.1×10^{12}$ m^3 s^{-2} — roughly 41 EJ of dissipated energy per year — of which the western North Pacific supplies 40.4%. Updating Emanuel (2005): the Atlantic doubling has *held* (×2.09 above its 1970s base in 2014–2023), the western Pacific rise has *reversed* (×1.12, with a significant -18%/decade decline since 1990), and global PDI has trended -8%/decade since 1990. Updating Webster et al. (2005): the Category 4–5 count doubling replicates (156→269) but the count has been flat for twenty years, and over 1979–1989 the homogeneous record puts the Cat 4–5 share at 35.8% against the best track's 23.0% — roughly half of the canonical rise is not shared by the homogeneous record, with observing-system evolution the leading (but, absent matched-sample attribution, not the only possible) explanation. Updating Kossin et al. (2020, as corrected): their +5%/decade [0.4, 11] reproduces on the new v01 record (era means matching the corrected 0.340 → 0.373) and survives seven added seasons at **+5.4%/decade** ($p = 0.003$) — the most robust global trend in the record. But priced through the measured dissipation exponent (PD ~ $V^{2.12}$, not V^3), that shift has raised per-fix dissipated energy by only +4.2% between 1979–1997 and 2005–2024, roughly half of what a cubic index implies. The strongest storms are getting stronger; the energy budget is moving far less than PDI says. A closing narrative traces the 2005–2026 argument milepost by milepost: the early technical objections were, on the specific checkable points, subsequently incorporated by the field — often by the original authors — while the core physical expectation survives at a fraction of its first-reported amplitude. What stands is smaller than the 2005 headlines and sturdier than the strongest doubts.

1 · THEORY

What power dissipation is, and the two substitutions everyone makes

A tropical cyclone extracts energy from the ocean and spends nearly all of it rubbing against the sea surface. The instantaneous spending is a power — an area integral of the cubed surface wind — and what a season dissipates is that power integrated over every storm's footprint and lifetime:

$$E = 2\pi \iint C_D \, \rho \, \left|V\right|^3 \, r \, dr \, dt$$

Emanuel (2005), eq. 1 — dissipated energy: drag coefficient, air density, and the cube of the surface wind, over radius and lifetime

Emanuel could not evaluate the area integral from historical data, so he substituted a point for the field —

$$PDI = \int V_{max}^3 \, dt$$

the power dissipation index: exact only if every storm's wind field is geometrically similar with a fixed area scale

— arguing, on the near-core profile similarity of Weatherford & Gray (1988) and Mallen et al. (2005) and the weak reported size–intensity correlation, that size varies mostly randomly, so ignoring it adds noise but little bias. The exact relation the approximation compresses is $E = \rho C_D PDI K$, where K is the V^3-weighted mean dissipation area — so the operative question is not whether storms differ in size (they do) but **whether K is stable enough, per season and per era, for the inference being made**. That question was probed rather than ignored in the two decades since: Sriver et al. (2008) compared satellite-integrated dissipation against PDI directly over 1998–2006 and found broad co-variation (with factor-scale calibration differences between sensors); Dean, Emanuel & Chavas (2009) and Chavas & Emanuel (2010) built the size climatologies the question needs; and modeling experiments cut both ways — Sun et al. (2017) and Xu et al. (2020) find size-aware dissipation responding *more* strongly than PDI under warming, not less. What no study had supplied is the fix-by-fix, all-basin measurement of K and its variability. The companion measurement on this site, from 43,086 fixes with agency-analysed wind fields, shows that the second assumption fails in a specific, systematic way: the effective dissipation area *falls* as $V^{-0.88}$ while storms intensify, so integrated dissipation follows **$V^{\approx 2.1}$, not V^3**, and grows about 4.6% per degree of latitude at fixed intensity. Size is not noise; it carries 41.8% of the interannual variance of global dissipation. Those two measured numbers — the exponent and the latitude slope — are the lens this paper reads the historical record through.

There is a second substitution, quieter than the first: taking the best track's V_{max} as a physical constant of the storm. It is an estimate, made by different agencies with different tools in different decades, and every claim about a PDI *trend* is a claim about the stability of that estimate. That is why this paper runs on two records instead of one.

2 · THE DATA

Two records of the same storms

The best track. 108,737 six-hourly tropical and subtropical fixes ≥34 kt from 5,734 storms, 1960–2025: NHC's HURDAT2 for the Atlantic and eastern/central Pacific, JTWC's fixes (via IBTrACS) for the western Pacific, Indian Ocean and southern hemisphere, and the Neumann and ds824 compilations filling the early southern hemisphere where JTWC has no record. This is the operational memory of every storm — and it embeds every change in how storms were observed: aircraft reconnaissance ending in the western Pacific in 1987, the Dvorak technique spreading through the 1970s–80s, scatterometry and microwave sounders arriving around 2000. No bias corrections are applied anywhere; this is the record as the agencies wrote it.

The satellite record. ADT-HURSAT version 01 (NCEI accession 0307249, released February 2026): the Advanced Dvorak Technique, one fixed algorithm (ADT 9.0), run over the homogenised 8-km, 3-hourly HURSAT-B1 geostationary infrared archive — 133,723 ocean fixes from 4,807 storms, 1978–2024. It extends by seven years the record behind Kossin et al. (2020). At any single fix it is the worse estimate: 8-km pixels blur small eyes and 3-hourly sampling clips intensity peaks. But it is the *same* worse estimate in 1980 and in 2024, which is precisely what a trend needs and the best track cannot offer.

The supporting layers. Four further datasets feed the deep sections. *Size:* the agency wind radii of the size layer (43,086 analysed fixes) and, for the pre-radii era, the Xu et al. (2024) ERA5 reconstruction — the ESSD global size dataset, 1959–2022, validated against the extended best track in the companion note (structure and interannual variability survive its drifting bias; trends do not). The younger reanalysis-size literature — Schenkel et al. (2017) against QuikSCAT, Thompson (2024) — corroborates that reanalyses carry credible *outer* size, which is the size that matters for the integrals here. *SST:* ERSSTv5, monthly, 1950–2026, for Emanuel's genesis boxes and the AMV index. *Indices:* ONI, the ERSST PDO, and AMV computed here. *Potential intensity:* this site's own MPI store — tcpyPI (Gilford 2021) on ERA5 at 0.25°, daily grids for August and September, 1996–2025.

> Where the two records agree, the shared signal is the strongest evidence the observational era can offer. Where they disagree, the disagreement itself is the finding — a specific, testable hypothesis about which record changed and why. Every claim below is put to that two-record test, and the language throughout distinguishes what is *shared*, what is *unshared*, and what remains a hypothesis.

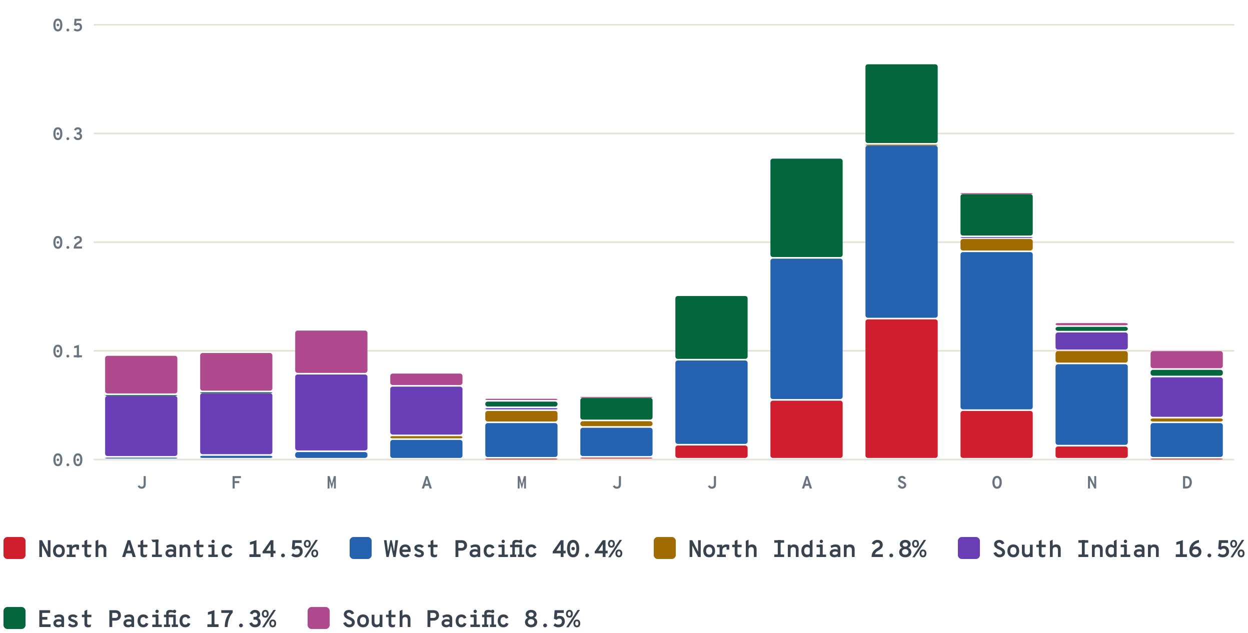
3 · THE CLIMATOLOGY

Where and when the planet dissipates its storm energy

Over the 1991–2020 normal period the globe accumulates a PDI of **2.1 $\times 10^{12}$ m^3 s^{-2}** in an average year. Converting the index to actual energy through the measured wind fields of the size layer, tropical cyclones dissipate roughly **41 exajoules per year** against the sea surface — around 1.3 TW as a year-round average, concentrated in a few dozen storms.

The seasonal cycle of power dissipation, by basin

Mean monthly PDI, 1991-2020 normals, 10^{12} m^3 s^{-2}. Stacked by basin.



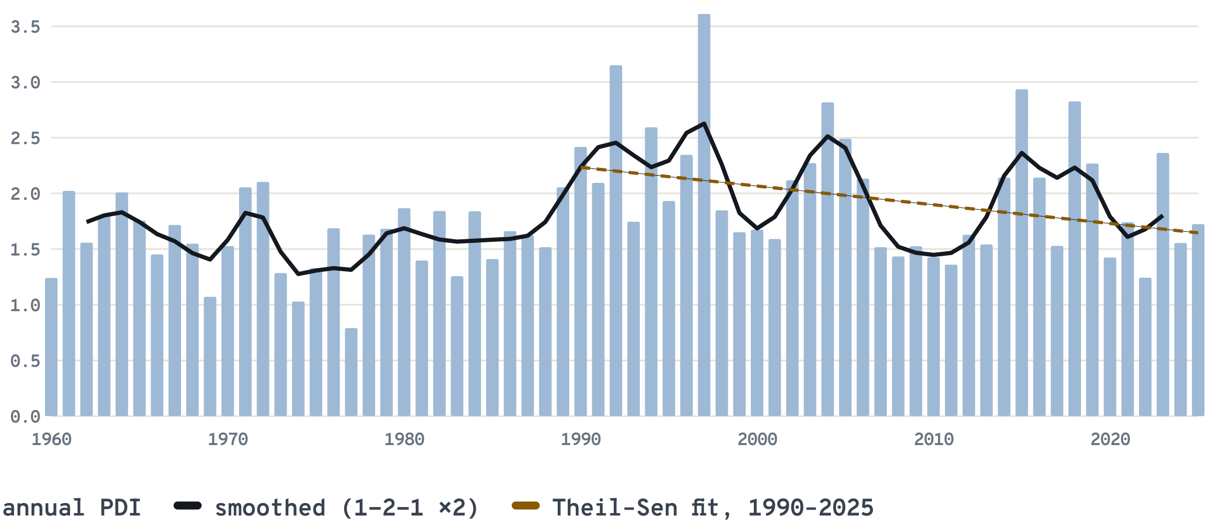
Two pulses: the northern-hemisphere peak in August–September and the smaller southern summer peak in January–March. The planet is never quiet — May is the only month that averages under 2% of the annual total.

BASIN	MEAN PDI	SHARE	PEAK	CV	R (ONI)
North Atlantic	0.30	14.5%	Sep	0.60	**−0.34**
West Pacific	0.83	40.4%	Sep	0.43	**+0.67**
North Indian	0.06	2.8%	Oct	0.90	—
South Indian	0.34	16.5%	Mar	0.37	−0.16
East Pacific	0.36	17.3%	Aug	0.66	**+0.40**
South Pacific	0.17	8.5%	Mar	0.65	**+0.38**
Global	**2.06**	**100%**	**Sep**	**—**	**+0.48**

The western North Pacific alone dissipates 40.4% of the global total — more than the Atlantic (14.5%) and eastern Pacific (17.3%) combined — and is also the steadiest (CV 0.43). The North Indian Ocean is the smallest (2.8%) and proportionally wildest (CV 0.90), with the double peak of the monsoon transitions rather than a single season. ENSO does not change how much the planet dissipates so much as *where*: El Niño years shift activity from the Atlantic (r = -0.34) into the two Pacific basins (r = +0.67 west, +0.40 east), and the global total correlates at r = +0.48 largely because the West Pacific is the biggest term.

Global annual power dissipation index, 1960–2025

Annual PDI over all six basins; heavy line is two passes of a 1–2–1 filter.



The smoothed series peaks in 1997 and bottoms in 2010 — the "historically low" global activity of Maue (2011), which the next decade only partially reversed.

Global power dissipation has **no significant long-term trend**: +2.5%/decade over 1960–2025 (p = 0.08), and **-8.3%/decade** since 1990 (p = 0.050). Interannual redistribution between basins, not a global drift, is the first-order story of this record.

4 · THE NEXUS

ACE, PDI, IKE and PD are one object with two knobs

The index families look like rival conventions. They are the same integral evaluated with different amounts of information, and the cleanest way to see it is the construction that runs from McTaggart-Cowan et al. (2007) through Maue et al. (2008), Maue (2010, ch. 7) and Fritz (2009): put an idealized **modified Rankine vortex** under the integrals. Wind rises linearly to V_{max} at the radius of maximum wind R_m, then decays outward as $(R_m/r)^x$ with $x \approx 0.5$:

$$V(r) = V_{max} \cdot (r/R_m) \quad [r \le R_m] \; ; \quad V_{max} \cdot (R_m/r)^x \quad [r > R_m]$$

the modified Rankine profile of Maue (2010) §7.4 and Fritz (2009); every index below is an integral of a power of this field

Substituting analytically and evaluating to the 34-kt radius gives every member of the family at once in closed form — for x = ½ the cubic integral is exactly $M_3 = 2\pi R34^2 u^3 (2 - (9/5)u/V_{max})$ with u = 34 kt — and the exponents below are numerical fits to those forms over realistic intensity ranges. Klotzbach et al. (2022) used the same modified-Rankine construction with observed radii to explain the tightness of the PD–IKE relationship; this table extends that argument across the family. Three scope notes before reading it: these are properties of *this profile family*, not of storms; the fixed-RMW column's supercubic growth includes an expanding integration domain (the truncation at R34 is physically essential — an r^−½ tail integrates to divergence); and a fit across *different* storms does not by itself establish that an *intensifying* storm follows the same path — the within-storm version is an open measurement.

DECAY X	IKE ~ V^A (R34 FIXED)	PD ~ V^A (R34 FIXED)	IKE ~ $R34^B$	PD ~ $R34^B$	PD ~ V^A (RMW FIXED)
0.4	0.10	0.23	2.0	2.0	5.23
0.5	**0.21**	**0.46**	**2.0**	**2.0**	**4.46**
0.6	0.33	0.70	2.0	2.0	4.03

Three lessons fall straight out of the algebra. **First**, at fixed footprint both integrals go as the **square of the outer radius**, exactly — which is why the empirical fits of the size layer return PD ~ $V^{1.23} R34^{1.9}$ (and the independent quadrant method $R34^{1.92}$): the R^2 is not an empirical accident, it is geometry. **Second**, at fixed footprint the integrals are nearly **flat in V_{max}** ($V^{0.2}$–$V^{0.5}$ for x near ½): once you know how big a storm is, its peak wind adds remarkably little energy information — the opposite of what a V^3 index assumes. **Third**, the last column is the self-similar limit PDI implicitly lives in: hold RMW fixed, let the profile carry V_{max} outward, and PD grows as V^{4-5} because the footprint balloons. Reality does neither extreme — observed R34 grows far slower with V than self-similarity demands, which is precisely the $A_D \sim V^{-0.88}$ contraction the size layer measures.

The nexus, in one sentence: ACE and PDI are the R34-blind members of a two-parameter family in which size enters squared and intensity enters weakly; IKE and PD are the size-aware members; and the family's internal disagreements are set by one number — the outer decay exponent x ≈ 0.5 of the Maue (2010)/Fritz (2009) modified Rankine vortex.

Empirically, the season-level family behaves exactly as the vortex algebra says it must — the point indices cluster, the field integrals cluster, and the two-parameter index $\Sigma\, V^2 R34^2$ sits between the camps, nearly interchangeable with full IKE:

	ACE	PDI	$\Sigma V^2 R34^2$	IKE	PD
ACE	1.00	**0.99**	0.92	0.86	0.87
PDI	**0.99**	1.00	0.92	0.82	0.84
$\Sigma V^2 R34^2$	0.92	0.92	1.00	**0.96**	**0.97**
IKE	0.86	0.82	**0.96**	1.00	**0.99**
PD	0.87	0.84	**0.97**	**0.99**	1.00

Season-level correlations, global 2002–2025 (log scale). ACE–PDI at r = 0.99 are operationally the same index; IKE–PD at r = 0.99 are the same integral; and the bridge index $\Sigma V^2 R34^2$ correlates 0.97 with full PD while needing nothing but the two numbers every agency already publishes. The practical content of twenty years of index debates reduces to one choice: with or without $R34^2$.

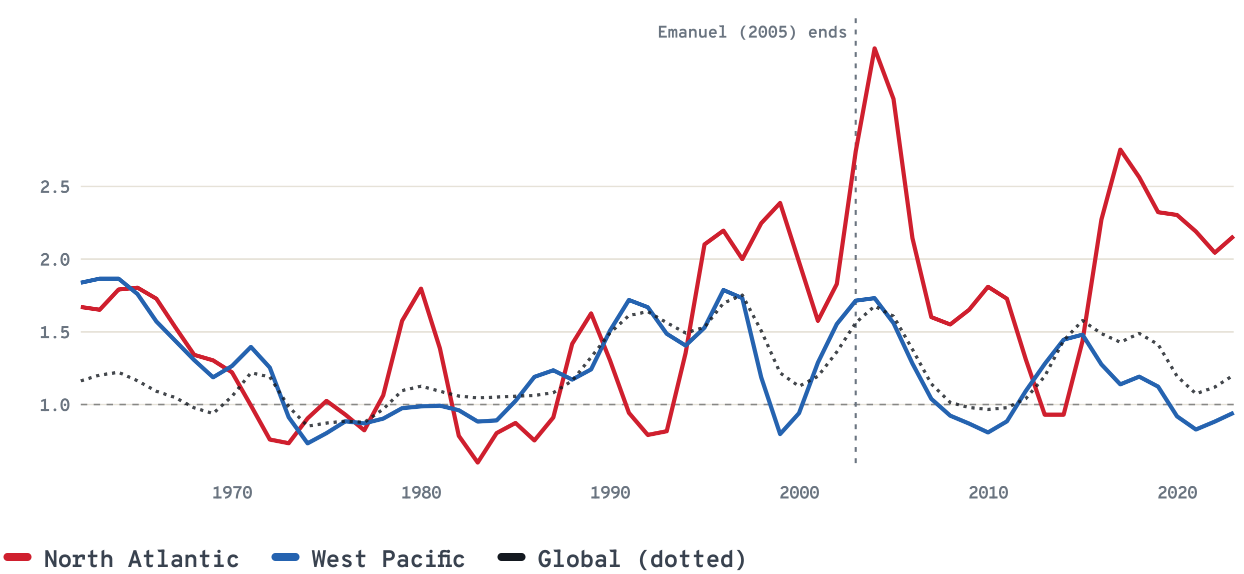
5 · EMANUEL (2005), RE-EVALUATED

The doubling that held, the one that didn't

Emanuel (2005) introduced PDI, smoothed it with two passes of a 1-2-1 filter, and reported that Atlantic power dissipation had *"more than doubled in the past 30 yr"*, western North Pacific dissipation had risen *"by about 75%"*, and their sum had *"nearly doubled"* — trends he tied to rising tropical sea surface temperature. The record then ended in 2003. It is now 2025, and the same filter over the same basins tells a more discriminating story:

Smoothed PDI, indexed to each series' 1970s mean

Two passes of the 1-2-1 filter (end-points dropped); each series ÷ its 1970–79 mean. Dashed rule at Emanuel's data edge, 2003.



SERIES	1970S MEAN	×, TO 1994-2003	×, TO 2014-2023	TREND 1990-2025	P
North Atlantic	0.16	×2.04	**×2.09**	+15.9%/dec	0.127
West Pacific	0.64	×1.39	**×1.12**	**−17.5%/dec**	0.018

SERIES	1970S MEAN	×, TO 1994-2003	×, TO 2014-2023	TREND 1990-2025	P
NATL + WPAC (Emanuel's sum)	0.80	×1.52	**×1.32**	−6.7%/dec	0.114
Global	1.50	×1.44	**×1.34**	**−8.3%/dec**	0.050

Emanuel's Atlantic doubling was real and has held: ×2.04 over his window, ×2.09 through 2014–2023 — and it needed none of his contested pre-1970 wind corrections, because it is measured against the 1970s themselves. **The western Pacific claim has not survived**: ×1.39 at his data edge, ×1.12 now, with a significant -18%/decade decline since 1990 ($p = 0.018$). His combined series stands at ×1.32 — closer to "up by a third" than to "nearly doubled".

The updated Atlantic series is also a lesson in what a 30-year window can and cannot say. The smoothed NATL PDI peaked at 0.55 in 2004 — the very seasons Emanuel was writing about — then collapsed to 0.15 by 2013, *below the 1970s trough* (0.16), before recovering in the late 2010s. A doubling, an un-doubling, and a re-doubling inside two decades is the signature of the Atlantic multidecadal variability Goldenberg et al. (2001) described, superposed on whatever slower trend exists; the 2005 paper caught the steepest face of one swing.

The deeper problem was scale, not arithmetic. Emanuel's two basins hold about 55% of global dissipation, and his global inference rested on their sum. The actual global series (Figure above) rose with his window, peaked in 1997, and has spent the two decades since his paper drifting down. Emanuel (2007) himself moved the argument from SST to potential intensity; the record since has mostly vindicated the caution of that revision over the boldness of the original.

The 1960s western Pacific is the least trustworthy decade on this page. The smoothed NWPAC series actually peaks in 1963 (1.20) — a decade of aircraft-reconnaissance typhoon winds widely believed too high, which Emanuel corrected downward and Landsea's comment contested in the opposite direction for the Atlantic. We apply no corrections in either basin, and draw no conclusion from any pre-1979 level that the satellite record cannot check.

The SST correlations, re-run on his own boxes

Emanuel's argument was not the trend alone; it was the correlation of smoothed PDI with smoothed SST in each basin's genesis region — $r^2 = 0.65$ (Atlantic, September 6–18°N 20–60°W), 0.63 (West Pacific, July–November 5–15°N 130–180°E), 0.69 (combined vs 30°S–30°N annual). Those boxes, that filter, ERSSTv5 through 2025, PDI uncorrected:

SERIES	EMANUEL R^2 (1949/30S-2003)	OURS, TO 2003	OURS, 1960-2025	2004-2025 ONLY	UNSMOOTHED
North Atlantic September MDR SST (6-18N, 20-60W)	0.65	0.45	**0.38**	0.01†	0.27
West Pacific Jul-Nov SST (5-15N, 130-180E)	0.63	0.13	**0.00†**	0.01†	0.03†
Global annual 30S-30N SST	0.69	0.41	**0.22**	0.20	0.08

The SST scaffolding has collapsed. On the same boxes and the same double-smoothed construction, the West Pacific correlation is gone entirely (r^2 = 0.00 on the full record, 0.01 since 2004); the Atlantic correlation survives historically (r^2 = 0.38) but explains **nothing since Emanuel's record ended** (r^2 = 0.01, p = 0.66); the combined-global version fell from 0.69 to 0.22. All three MDRs kept warming throughout (+0.14, +0.12, +0.12 °C/decade). Warmer water, indifferent PDI.

Fair differences from his construction, stated: our record starts in 1960 (his Atlantic figure reached back to 1930s SST and 1949 PDI), we apply none of his wind corrections, and smoothing inflates every r^2 through autocorrelation — his and ours alike, so the comparison is like-for-like and the direction of the change is what matters († = not significant at $p<0.05$). Credit where due: Emanuel's own 2007 revision already reported the West Pacific SST–PDI relationship collapsing to $r^2 \approx 0.01$ over 1983–2004 once his reanalysis-based corrections were applied — the extension here confirms and globalizes a weakening he identified first. The point is not that thermodynamics stopped operating; it is that **basin-mean SST was never the operative variable**, which is precisely why he moved the argument to potential intensity. Section 13 takes up that variable.

And the claim priced in actual dissipated energy

The Xu et al. (2024) ERA5 size reconstruction lets the Emanuel window be re-priced in area-integrated PD rather than the cubic point index. These are **reconstruction-dependent sensitivity estimates**, not independent measurements: the reconstruction's bias drifts (per the companion note's audit), a drifting multiplicative bias survives ratios as b_2/b_1, and the reconstruction is itself IBTrACS+ERA5 machine learning rather than observation. The 2014–23 column also mixes bases (observed radii carry the years past the reconstruction's 2022 end). Read the table as "what the claims look like if the reconstruction's era-to-era scale is roughly right":

SERIES	PDI ×, 1970S→94-03	PD ×, SAME	PDI ×, →2014-23	PD ×, SAME	PD TREND SINCE 1990
North Atlantic	×2.04	**×1.57**	×2.09	**×1.75**	+16.2%/dec (p=0.06)
West Pacific	×1.39	**×1.12**	×1.12	**×1.28**	−3.6%/dec (p=0.76)
Global	×1.44	**×1.24**	×1.34	**×1.33**	−2.2%/dec (p=0.62)

In dissipated energy the claims deflate again: the Atlantic's "more than doubled" is **×1.57** over Emanuel's own window (×1.75 through 2014–23), the West Pacific's +75% is ×1.12, and the global rise is ×1.24 — with no significant global PD trend since 1990 (-2.2%/decade, p = 0.62; radii-era basis). Under this reconstruction, the size term buffers the index — seasons of intense storms are seasons of compact storms, a compensation no point index can carry. Whether the buffering is as large as shown is exactly as trustworthy as the reconstruction's era-to-era scale, which is why these are sensitivity numbers, not a re-measurement of history.

6 · WEBSTER ET AL. (2005), UPDATED

The Category 4–5 doubling, split into storm and instrument

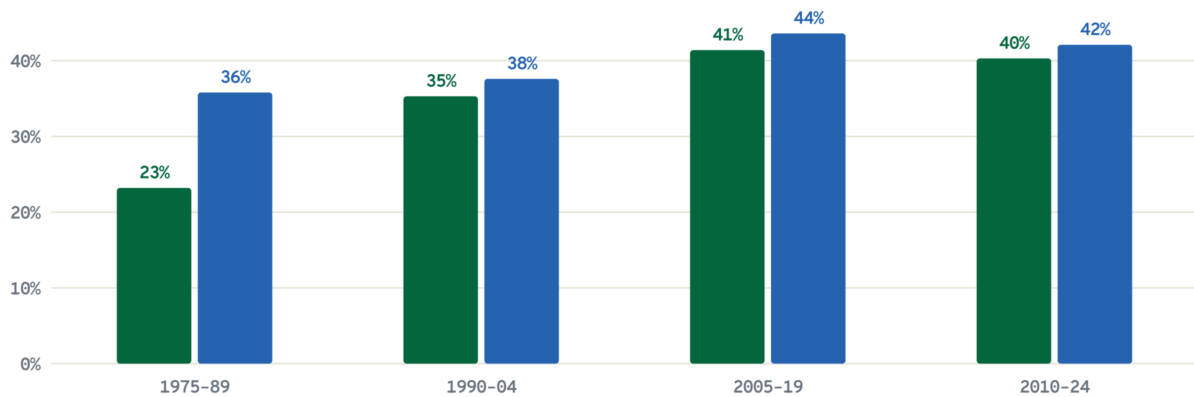
Webster, Holland, Curry & Chang (2005) counted 171 Category 4–5 storms globally in 1975–1989 and 269 in 1990–2004 — a near-doubling in number, and a rise from roughly 20% to 35% as a share of all hurricanes, with no trend in total storm counts. Klotzbach & Landsea (2015) revisited the claim ten years on and found the rise concentrated in the earliest, least reliable years. Both windows can now be extended a full generation, in both records:

RECORD · ERA	CAT 4-5	ALL HURRICANES	SHARE
Best track 1975–1989	156	671	23.2%

RECORD · ERA	CAT 4–5	ALL HURRICANES	SHARE
Best track 1990–2004	269	762	35.3%
Best track 2005–2019	287	693	41.4%
Best track 2010–2024	281	698	40.3%
ADT-HURSAT 1979–1989	159	444	35.8%
ADT-HURSAT 1990–2004	237	631	37.6%
ADT-HURSAT 2005–2019	268	614	43.6%
ADT-HURSAT 2010–2024	262	623	42.1%

Category 4–5 share of all hurricane-strength storms, by era

Lifetime-maximum intensity ≥114 kt as a share of LMI ≥64 kt (65 kt in ADT). ADT's first era begins in 1979.



> The count doubling replicates in the best track — 156 Cat 4–5 storms in 1975–1989, 269 in 1990–2004 (Webster reported 171 and 269) — but it has **not continued**: 287 in 2005–2019 and 281 in 2010–2024, on a flat trend since 1990 (0.0%/decade, p = 0.99). And over the same early era the homogeneous record already saw **35.8%** of hurricanes at Cat 4–5 where the best track saw 23% — **roughly half of the canonical rise is unshared with the homogeneous record**. Observing-system evolution is the leading hypothesis for the unshared half; settling it requires the storm-matched comparison the ledger begins.

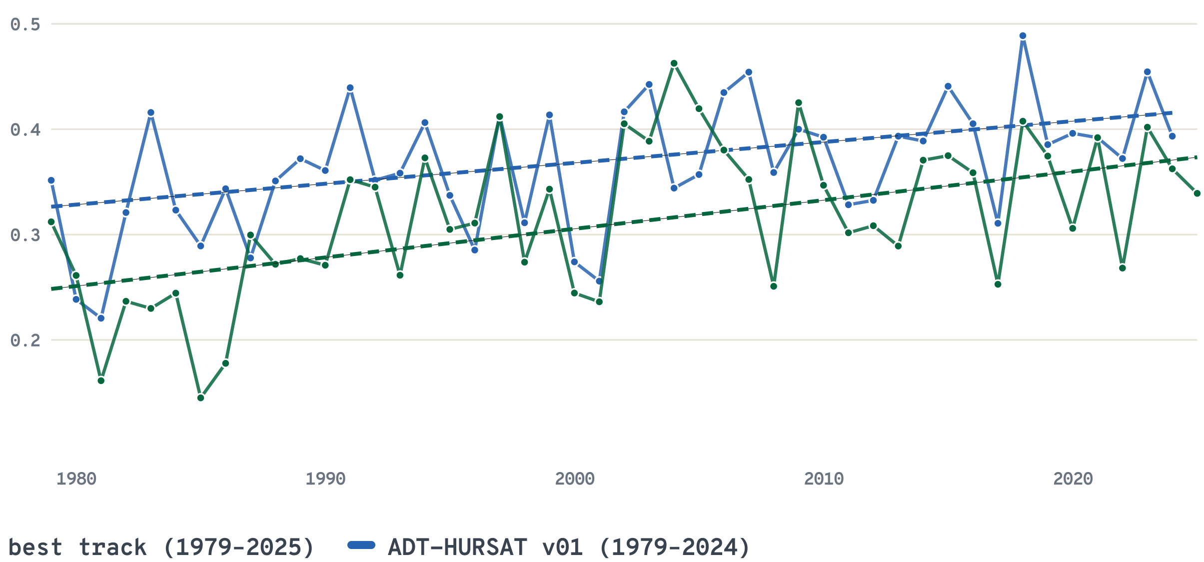
This is Klotzbach & Landsea's (2015) verdict, extended ten more years and given its mechanism by the satellite record: the ADT share rises only 35.8% → 43.6% across four decades, roughly a third of the best track's climb over the same span. What remains after homogenisation is real and consistent with the exceedance analysis below — but it is a shift of perhaps six points in the major share, not a doubling of the most dangerous storms. The western Pacific tells the same story at higher amplitude: Webster's 25% → 41% is, in our best track, 29.9% → 41.9% → 51.8% — and the west Pacific is precisely where aircraft reconnaissance ended in 1987 and the fleet's intensity estimates changed the most.

The exceedance trend, seven years on

Kossin, Knapp, Olander & Velden (2020) asked the cleanest version of the intensity question: among all hurricane-strength intensity estimates, what fraction are major (≥100 kt)? In ADT-HURSAT over 1979–2017 that exceedance probability rose about **+5% per decade** (95% CI [0.4, 11]), from 0.340 in 1979–1997 to 0.373 in 1998–2017, with the triad time-series trend at ~+6%/decade — the values of the *published correction* (PNAS, November 2020), which revised the widely-quoted original figures (+8%/decade [2, 15], 0.27 → 0.31) after a threshold error was found, without changing the conclusion. The February 2026 release of ADT-HURSAT v01 extends the homogeneous record through 2024 — seven more seasons, spanning both record-active and record-quiet years. Recomputed here on identical definitions:

P(major | hurricane-strength), annual, both records

Major fixes (≥100 kt) ÷ hurricane-strength fixes (≥65 kt), 6-hourly, calendar years.
Dashed: Theil-Sen fits over each record's full window.



RECORD · WINDOW	P(MAJOR) TREND	P	YRS	
Kossin et al. (2020), as corrected	+5%/dec	—	39	95% CI [+0.4, +11]; triad trend ~+6%/dec
ADT v01 · 1979–2017 (their window)	**+5.7%/dec**	0.0268	39	replication
ADT v01 · 1979–2024	**+5.4%/dec**	0.0028	46	**the update**
ADT v01 · 1979–2024, no 30–100°E	**+5.4%/dec**	0.0135	46	sensitivity
Best track · 1979–2017	**+10.9%/dec**	0.0022	39	
Best track · 1979–2025	**+8.6%/dec**	0.0007	47	
Best track · 1990–2025	+2.3%/dec	0.4295	36	post-recon era

The corrected Kossin et al. result replicates, and survives the seven-year extension. On v01 over their own window: +5.7%/decade with era means 0.351 → 0.377 — landing almost exactly on the corrected published values (+5%/decade [0.4, 11]; 0.340 → 0.373). Extended to 2024: **+5.4%/decade** ($p = 0.0028$), with P(major) stepping to 0.4 in 2005–2024. This is an independent reproduction of their finding on the updated dataset — the most robust global trend anywhere in this paper, and it belongs to them.

The best track tells the same story louder: +10.9%/decade over 1979–2017 — nearly double the satellite rate. The gap is the instrument again: scatterometry, SFMR, and microwave sounders taught agencies to find peak winds that infrared silhouettes miss, inflating recent maxima relative to the 1980s. Start the clock in 1990, after the deepest of those transitions, and the best-track trend collapses to +2.3%/decade ($p = 0.43$) — indistinguishable from zero — while the homogeneous record keeps rising. The two records measure different mixtures of storm and observing-system change; the working hypothesis consistent with both is a real shift near the satellite rate (~5%/decade) plus an operational component concentrated in the pre-1990 era — a hypothesis the matched-sample tests of the storm ledger were built to probe.

Sensitivity: excluding every fix between 30–100°E (the sector affected by the 1998 Meteosat view-angle discontinuity that Kossin screened by satellite) leaves the update at +5.4%/decade ($p = 0.013$). Within the post-1998 era alone the trend has the same slope (+5.3%/decade) but 27 years is not yet enough to establish it independently ($p = 0.24$). Whether the record is better read as a continuous trend or a late-1990s step is settled formally in Section 8: the linear model beats the step on BIC.

Levels are not comparable across ADT versions; trends are. Our v01 record (ADT 9.0 on HURSAT v07b) carries P(major) near 0.351–0.4, above the ~0.27–0.31 of Kossin's ADT 8.2.1 run — algorithm recalibration moves the whole curve. Every comparison here is therefore a comparison of slopes, computed identically (Theil–Sen on annual proportions, ocean fixes, 6-hourly). The ADT's own caveats stand: 8-km pixels underestimate small-eye majors, and that bias, if eye sizes are shrinking, works *against* the trend it shows.

8 · THE STRESS TEST

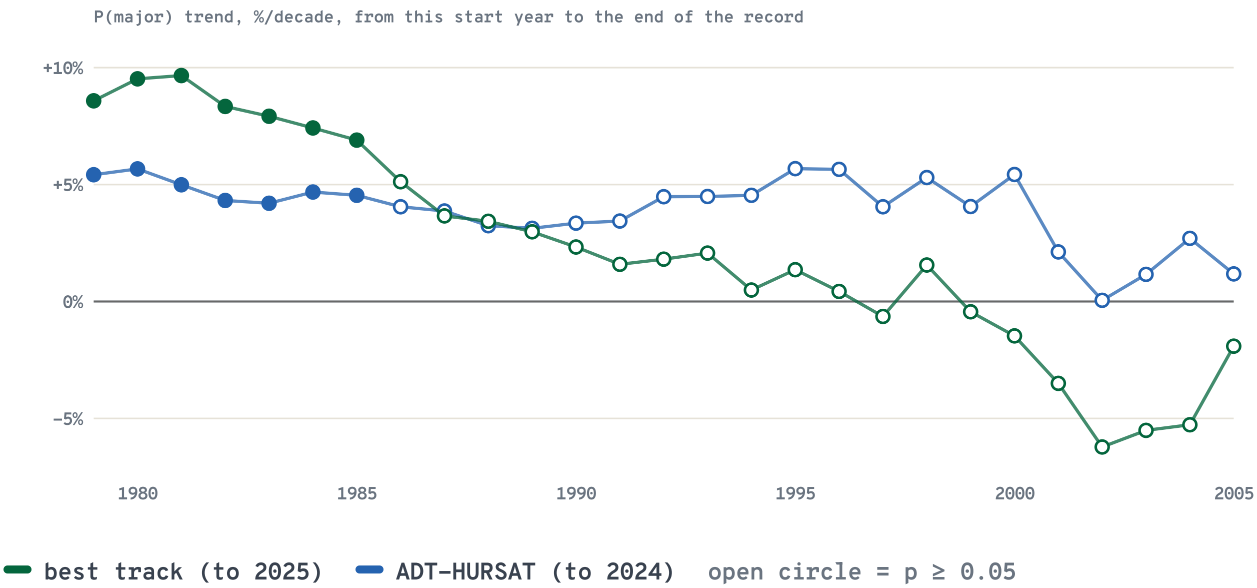
"Stronger storms are getting stronger," interrogated five ways

The exceedance trend of Section 7 is the strongest global signal in the record, so it gets the adversarial treatment: every way the claim could be an artifact of window, threshold, basin mix, or metric definition, tested in both records. (The storm-by-storm decomposition of these aggregates — which individual Cat 4–5 storms the record missed, which it overcalled, and per-decade count bands — is the Storm Ledger, a standing page built from this paper's data.)

1 · Does the trend depend on where you start the clock?

The exceedance trend as a function of start year

Theil-Sen slope of annual P(major | hurricane fix), each start year through the record's end. Filled: $p < 0.05$.

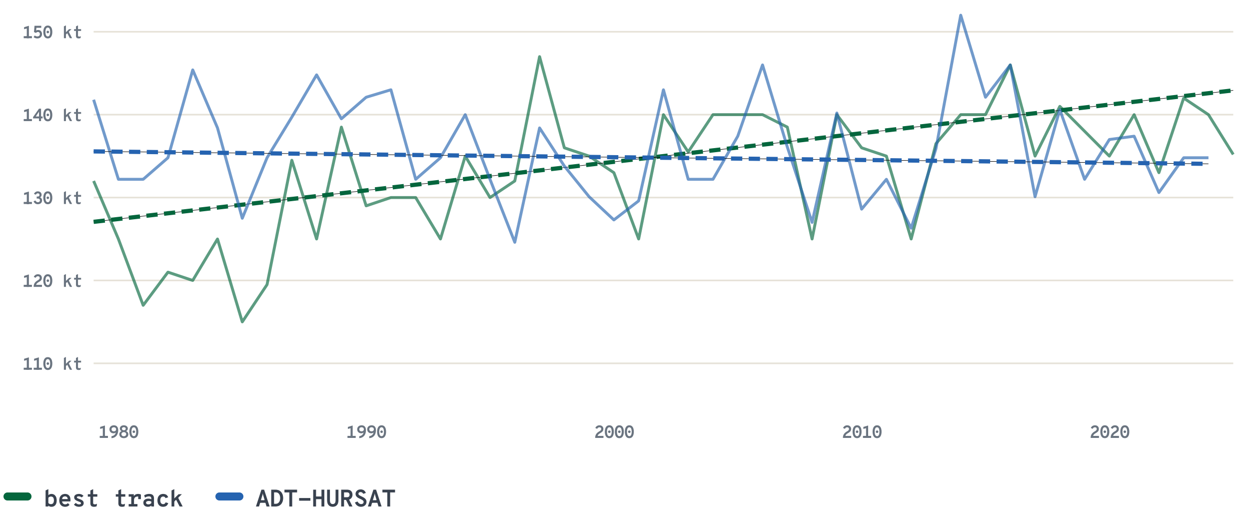


The two records fail in opposite, diagnostic ways. The best-track slope itself collapses as the start year advances past the deep observing-system transitions — +8.58%/decade from 1979 to **+1.59%/decade from 1991** and ~0 from the late 1990s: its trend is a property of the era mix. The ADT slope holds near +4–6%/decade at every start year and only its *significance* erodes as the sample shortens. That contrast — slope decay versus power decay — is the signature expected when one record's trend depends on its era mix and the other's does not. It is strong evidence, not proof: a change concentrated in the early era would look similar. What it establishes firmly is that the best-track trend cannot be quoted without its start year.

2 ·Are the strongest storms peaking higher, or are there just more majors?

Annual 90th-percentile lifetime-maximum intensity

p90 of LMI among hurricane-strength storms, both records, with Theil-Sen fits from 1979.



> **The top of the distribution is not rising in the homogeneous record.** p90 LMI trends: best track **+2.6%/decade** (p = 0.0000) against ADT **-0.2%/decade** (p = 0.59), 1979 onward; the medians are flat in both. The "strongest storms are getting stronger" phrasing, read as *peak intensities rising*, exists only in the operational record.

What, then, carries the exceedance trend of Section 7? It obeys an exact identity — P(major fix | hurricane fix) = (major storms ÷ hurricane storms) × (days-at-major per major ÷ days-at-hurricane per hurricane) — so its trend decomposes, term by term, in both records:

RECORD (%/DECADE OF LN)	P(MAJOR FIX) TREND	= COMPOSITION	+ DURATION AT MAJOR	− DURATION AT HURRICANE	SUM
ADT-HURSAT, 1981–2024	+5.1	+3.0	**+5.0**	−1.9	+6.1
Best track, 1979–2025	+8.7	+2.9	**+1.4**	+3.6	+8.0

In the homogeneous record the verdict is clean: **about half the exceedance trend is major storms holding major intensity longer** (+5.0%/decade of the +5.1; the level trend in days-at-major is significant at p = 0.032), about a third is composition (+3.0, not significant alone), and longer hurricane-stage lifetimes partially offset it. The best track agrees on composition but manufactures its excess (+8.7 vs the satellite's +5.1) in its *denominator*: booked hurricane-days per hurricane are shrinking (-3.6%/decade) — a bookkeeping change, not a storm change.

The sharpest two-record contrast on this page: time spent *within 10 kt of the storm's own peak*. In ADT it rises **+7.1%/decade** ($p < 10^{-4}$) — storms genuinely plateau at the top longer. In the best track it **falls -8.8%/decade** ($p < 10^{-4}$) — because the modern fleet books ever sharper, briefer peak spikes (a scatterometer pass, an SFMR run) that the storm's own history never sustains. One instrument sees the plateau lengthen; the other sees the spike sharpen; both are consistent with the same physical storm. The lengthening plateau is the reading consistent with a fixed instrument; the sharpening spike is the reading consistent with an improving one; the observing-system simulation experiments proposed in the methods are how the two get separated for good.

3 ·Which basins carry it?

BASIN	BEST TRACK, %/DEC	ADT–HURSAT, %/DEC	VERDICT
North Atlantic	+15.8*	+12.6*	agree — real (and AMV-timed)
East Pacific	+6.7	+4.3	agree — weak
West Pacific	+9.7*	+2.4	disagree — best-track artifact (recon ended 1987)
North Indian	–	–	too few hurricane fixes for annual proportions
South Indian	+13.1*	+11.2*	agree — but the 30–100°E satellite seam runs through it
South Pacific	+13.8*	−4.4	disagree — best-track artifact

P(major │ hurricane fix) trends, 1979–2025 (best track) and 1979–2024 (ADT); * = p<0.05. The global agreement of Section 7 is carried by the Atlantic and the South Indian Ocean; the two Pacific-wide disagreements are exactly the basins where JTWC's observing base changed most. Kossin's corrected Atlantic figure (+38%/decade epoch change, 1979–2017) compares with +12.6%/decade here — a different estimator (annual Theil–Sen vs epoch ratio) over a window seven seasons longer, both firmly positive.

4 ·Trend or step?

Trend, not step. Kossin et al. flagged the 1998 satellite-era discontinuity as the record's weak point, and our first reading of the era means (0.35 → 0.38 → 0.40) suggested a step. Formally compared on the annual series: linear trend BIC -263.8 (R^2 = 0.233), step-at-1998 BIC -257.8 (R^2 = 0.126); adding a step to the trend improves nothing (BIC -260.7, and the fitted step turns slightly negative). The homogeneous record prefers a continuous drift — the strongest version of the exceedance result, not the weakest.

5 ·Threshold sensitivity

Threshold and metric sensitivity. Move the major threshold from 100 to 96 kt and the ADT trend moves from +5.4 to +4.6%/decade (both p<0.01) — insensitive. Storm-level rather than fix-level: +3.6%/decade (p = 0.13) — weaker, as the duration decomposition above explains. Every version of the claim survives in sign; only the fix-level, 100-kt, 1979-anchored version is individually significant — and that is the version Kossin et al. published. It was, in retrospect, the strongest defensible framing of a real but modest signal.

6 ·Is it the storms, or the tracks?

Assemble what moves and what does not. **Per-storm behavior is flat**: p90 peaks flat (above), the share of storms with an RI episode flat (Section 11), utilization of the thermodynamic ceiling flat-to-declining (Section 13). **What moves is exposure**: the latitude of lifetime-maximum intensity drifts poleward (+0.24°/decade since 1982, p = 0.039); hurricane genesis drifts weakly poleward (+0.16°/decade, p = 0.14) and West Pacific genesis westward (-1.2°/decade, p = 0.09); and the potential intensity *sampled by storms along their tracks* rises (+0.93 m s^{-1}/decade, p = 0.038, Section 13) while the fixed-box ceiling stays flat — the storm population is spending more of its life in higher-ceiling air.

The residual signal is a change in track character, not in storm character. Individual storms are not peaking higher, not converting more of their allowance, and not more likely to intensify rapidly once counted per storm. What has changed is where storm lifetimes are spent — poleward, westward (WNP), and in higher-PI environments, for longer near peak. That is the signature of the *large-scale steering and genesis environment* — the part of the system general circulation changes can actually reach — while storm-scale behavior remains, on this evidence, statistically indistinguishable from a stationary draw. The climate question and the storm question are different questions, and the record answers them differently.

Two checks keep this honest. First, the same storm-level lens applied to Kossin's (2018) celebrated −10% global *slowdown* of translation speed finds nothing: storm-median speed is flat over 1966–2025 (-0.1%/decade, $p = 0.77$) and *rises* +1.8%/decade since 1990 ($p = 0.008$) — the slowdown lives in the pre-satellite era mix, as its critics (Moon et al., Lanzante 2019) argued. Not every track-character claim survives the storm-level test; the ones above do. Second, the duration channel could in principle be storms *choosing* to linger via slower decay rather than tracks delivering longer exposure — the ledger's family analysis says both are entangled (the growing RI-major family is also the long-lived family). The majors paper now takes this question to the storm scale — the ignition analysis there finds RI onset occurring ~8 m s^{-1} above each storm's own mean ceiling in 90% of cases, a stationary environment-timed rule whose *supply*, not whose behavior, is what the era has changed.

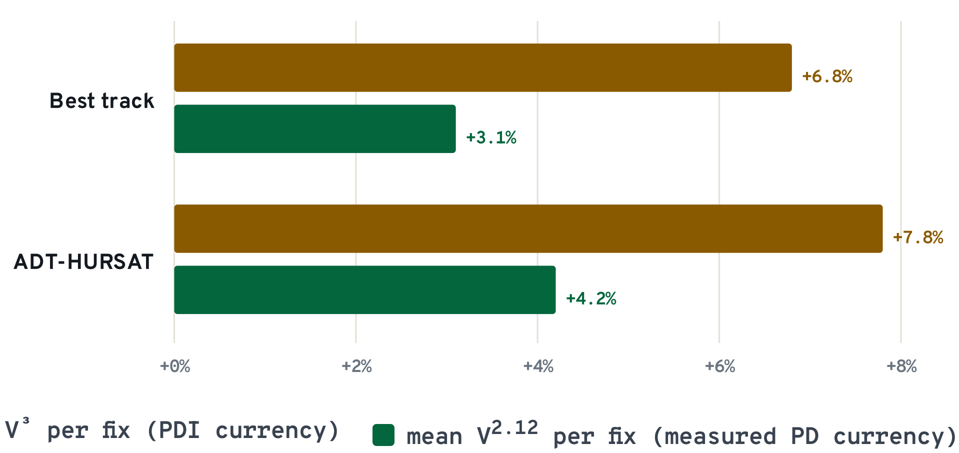
9 · THE CONNECTION

What an intensity trend is worth in energy — a conditional sensitivity experiment

Here the two halves of this research program meet, with the label stated up front: what follows applies a *modern, cross-sectional* relationship (dissipation area falling as $V^{-0.88}$ across the 2002–2025 population, latitude and basin controlled) to historical wind distributions. That is a conditional sensitivity experiment — "if the modern structure–intensity relationship transfers, then..." — not an observed historical energy change; the mixture of sizes, latitudes and lifecycle stages behind the modern exponent need not be the historical mixture, and the regression's construction (A_D contains V^3 in its denominator) shares errors with its regressor, both audited in the companion note. With that scope:

The same distribution shift, priced in two currencies

Change in per-fix mean, 1979–1997 → 2005–2024, fixes ≥34 kt. Same wind distributions, two exponents.



Between 1979-1997 and 2005-2024 the shift toward higher intensities raised the mean per-fix V^3 by **+7.8%** (ADT; +6.8% best track). Priced with the measured exponent — dissipation ~ $V^{2.12}$, because the dissipation area contracts as storms intensify — the same shift is worth **+4.2%** (+3.1%). **A cubic index roughly doubles the apparent energy consequence of the observed intensification** (overstatement ×1.88 ADT, ×2.18 best track) — *conditional on the modern exponent transferring*.

The size layer adds a term the intensity record cannot see at all. The median latitude of lifetime-maximum intensity has migrated poleward at +0.24°/decade since 1982 ($p = 0.039$; Kossin et al. 2014 found +0.53°/decade in the earlier satellite record) — and at the measured +4.6% of dissipation area per degree, that drift alone adds roughly +1.1%/decade to dissipated energy with *no change in any storm's peak wind*. Over the full 66-year best track the migration vanishes (-0.04°/decade, $p = 0.56$) — another signal that lives in the satellite era and dissolves into the inhomogeneous decades before it.

Assemble the pieces and the accounting closes. The homogeneous record shows a real, modest migration of intensity into the major categories (+5%/decade in exceedance), worth about +4.2% in per-fix energy over four decades; a poleward drift worth perhaps +1%/decade through the size–latitude channel; no trend in global frequency; and a measured global dissipation series whose interannual variance is dominated by storm *size* (41.8% of it) — a term uncorrelated with ENSO, unmeasured before 1990, and needing ~98 years of record for trend detection. That is why global PDI can trend -8%/decade since 1990 while the strongest storms strengthen: the two facts are not in tension, they are about different moments of a distribution whose energy-bearing width nobody was measuring.

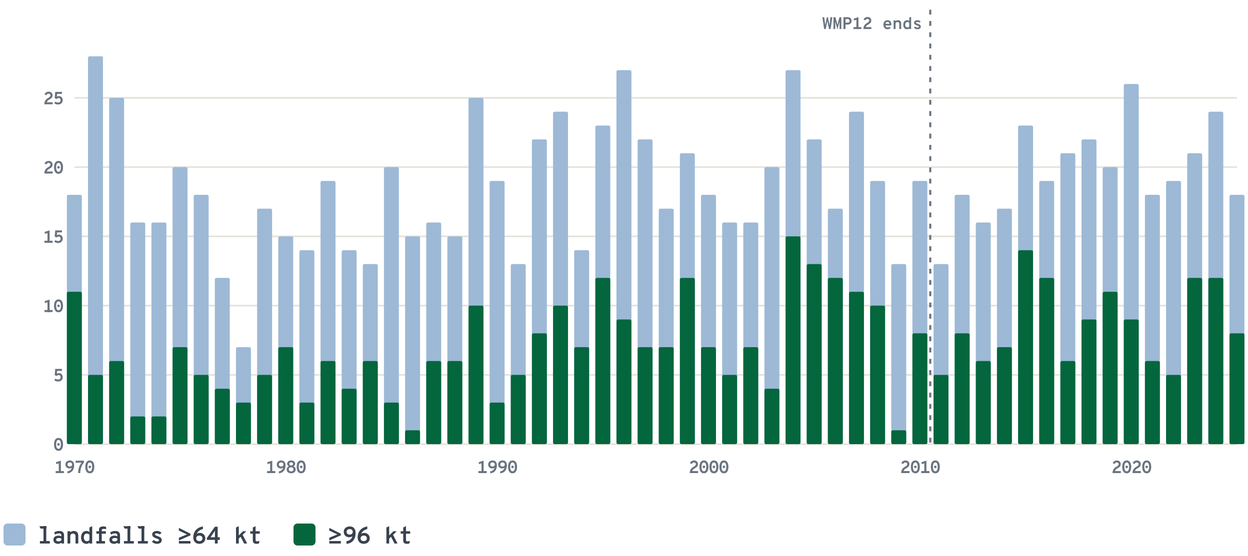
10 · LANDFALLS

Weinkle, Maue & Pielke (2012), extended fifteen seasons

What ultimately matters is what reaches a coast. Weinkle et al. (2012) built the global landfall record 1970–2010 — about 15 hurricane-strength landfalls a year, about 5 of them Category 3+, and no trend in either — and it became the observational backbone of the normalized-damage literature. The same method (NHC-glossary landfall against a land mask, quarter-degree position buffer, landfall intensity from the landfall fix and the fix before it), applied to the merged best track and extended through 2025. The complete record — both definitions, the landfall map, and the fix-by-fix reproduction of the 2012 method against its published Table 2 — is a standing page at /tropical/landfalls/; this section carries the verdicts.

Global hurricane-strength landfalls per season, 1970–2025

Storms making landfall at ≥64 kt (bars) and at ≥96 kt (dark). Weinkle et al.'s record ended at the dashed rule.



ERA	HURRICANE LANDFALLS/YR	MAJOR (≥96 KT)/YR	MAJOR SHARE
1970–1989	17.1	5.1	29.7%
1990–2009	19.7	8.2	41.9%
2010–2025	19.6	8.6	43.9%

Weinkle et al.'s null holds where their record was strong and breaks where it was weak. Hurricane-strength landfalls: 18.4/yr over their window, trend +3.8%/decade (p = 0.07) through 2025 — still no significant change, fifteen seasons later. *Major* landfalls: +12.6%/decade from 1970 (p = 0.0005) — but **+4.2%/decade from 1990** (p = 0.44). The landfall record inherits the same era problem as the basin record: the "more major hits" signal lives in the 1970s–80s baseline, where landfall *occurrence* is solid but landfall *intensity* carries every bias Sections 6–8 document over open water.

The geography is stable in every dimension tested. Mean latitude of hurricane landfalls: 0.00°/decade (p = 0.99) — the poleward migration of lifetime-maximum intensity has, so far, **not moved where storms hit land**, consistent with Knutson et al.'s (2010+) point that LMI location and landfall location are governed by different dynamics (steering and coastline geometry, not genesis thermodynamics). The share of the world's hurricanes that make landfall at hurricane strength holds near 40% (+3.3%/decade, p = 0.07). Per basin, only the North Atlantic shows a landfall-count trend (+10.3%/decade, p = 0.03) — the AMV recovery of Section 12 arriving at the coast.

Size at the coast. The size layer adds what no landfall count can carry: how much wind field arrives. Landfalling storms' final hurricane-strength fix has a median R34 of 97.5 n mi against 113.8 n mi for the same storms over open water — storms typically arrive at the coast *below* their peak size — and the annual median shows no trend over the radii era (-6.2%/decade, p = 0.13, 2002–2025, n = 534 storms). The integrated-energy exposure of coastlines is, on this record, governed by the same interannual lottery as everything else in this paper — not by a trend.

Counting conventions. Our detector implements Weinkle et al.'s method but keeps every landfall above a 50 km^2 island threshold, where they hand-curated a landmass whitelist; our level therefore runs higher (18.4/yr vs their ~15) with the Lesser Antilles and similar islands included. Collapsing to their one-landfall-per-storm convention changes the level, not the trends (hu +3.7%/dec p = 0.07; mh from 1990 +4.3%/dec p = 0.41). Levels are convention; trends are the result.

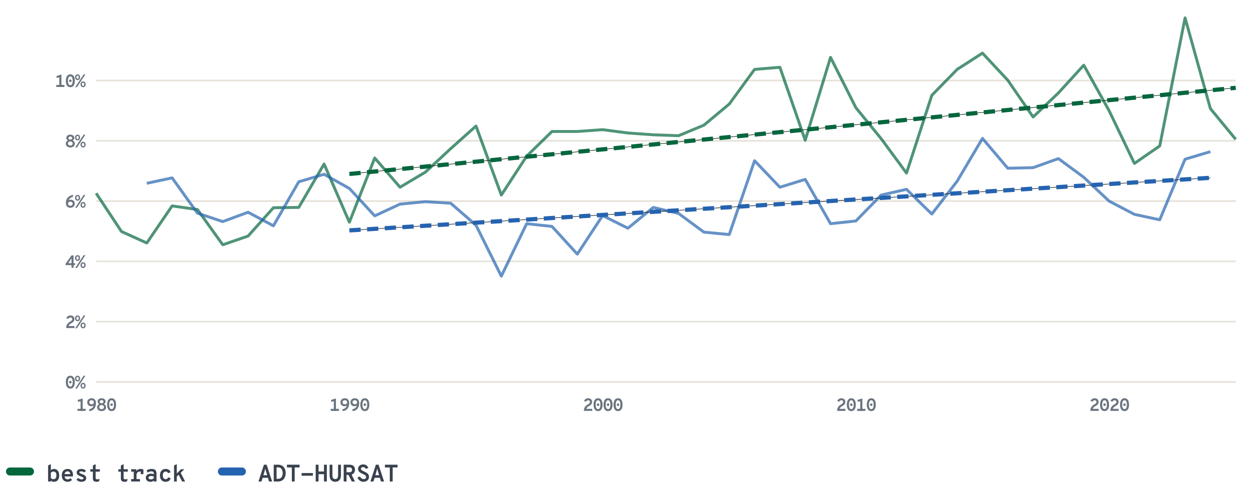
11 · RAPID INTENSIFICATION

The change that survives both records — and what size has to do with it

Bhatia et al. (2019) found rising 24-hour intensification rates in the high quantiles of both the best track and ADT-HURSAT over 1982–2009, and it has since become the strongest-credentialed of the change claims. Recomputed on both of this paper's records, through 2025, with RI defined as ≥30 kt in 24 h:

Share of 6-hourly fixes beginning a ≥30-kt/24-h intensification

Fixes with a ≥30-kt intensification over the following 24 h, as a share of all 6-hourly fixes ≥30 kt. Dashed: Theil-Sen fits from 1990.



Rapid intensification is the change both records agree on. Since 1990 the share of fix-time entering RI has risen **+9.5%/decade** in the best track (p = 0.0014) and **+8.6%/decade** in ADT-HURSAT (p = 0.0034) — the same signal, in two instruments that disagree about nearly everything else, in the era where the best track is at its most trustworthy. Bhatia et al. (2019) survives its audit with room to spare.

The anatomy is subtler than the headline. The share of *storms* experiencing at least one RI episode is flat in both records since 1990 (+1.4%/dec bt, -0.3%/dec adt, both p > 0.5): the same storms RI, they RI *more* — more episodes and longer episodes per storm, which is the same duration fingerprint as the exceedance decomposition of Section 8, seen from below. The extreme tail is where the instruments part company again: p99 of 24-h changes rises +6.3%/decade in the best track but only +1.9%/decade (p = 0.08) in ADT — the "record-shattering intensification" genre rests disproportionately on the record whose ability to catch extreme 24-h jumps (recon, SFMR, microwave) is itself what improved.

Size selects for rapid intensification

INTENSITY BAND	SMALLEST QUARTILE	Q2	Q3	LARGEST QUARTILE	N
34-63 kt	11.0% R34 33.8	11.1% R34 55	10.0% R34 75	7.4% R34 110	18,912
64-95 kt	16.7% R34 65	16.5% R34 90	12.8% R34 115	7.4% R34 155	10,606

Compact storms rapidly intensify at more than twice the rate of large ones. At hurricane intensity (64–95 kt), the smallest size quartile enters RI from 16.7% of fixes against 7.4% for the largest — P(RI) falls monotonically with R34 in both intensity bands, and RI-onset storms run 10% smaller than intensifying-but-not-RI storms at the same intensity.

This is the size layer's third structural law (after $A_D \sim V^{-0.88}$ and the +4.6%/°lat growth), and it closes a loop: a world with more RI is, other things equal, a world whose intense storms are *selected for compactness* — which deepens the size–intensity anticovariance that already carries −21% of the interannual dissipation variance, and pushes the real energy exponent still further below the cubic index. More RI means more majors and less energy per major than PDI accounting assumes. The mechanism also runs in the causal direction Carrasco et al. (2014) documented operationally: small inner-core storms spin up faster; and it makes the RI trend and the duration-at-major trend two faces of one change.

12 · THE MODES

ENSO, PDO, AMV — and the Maue (2011) minimum, fifteen years on

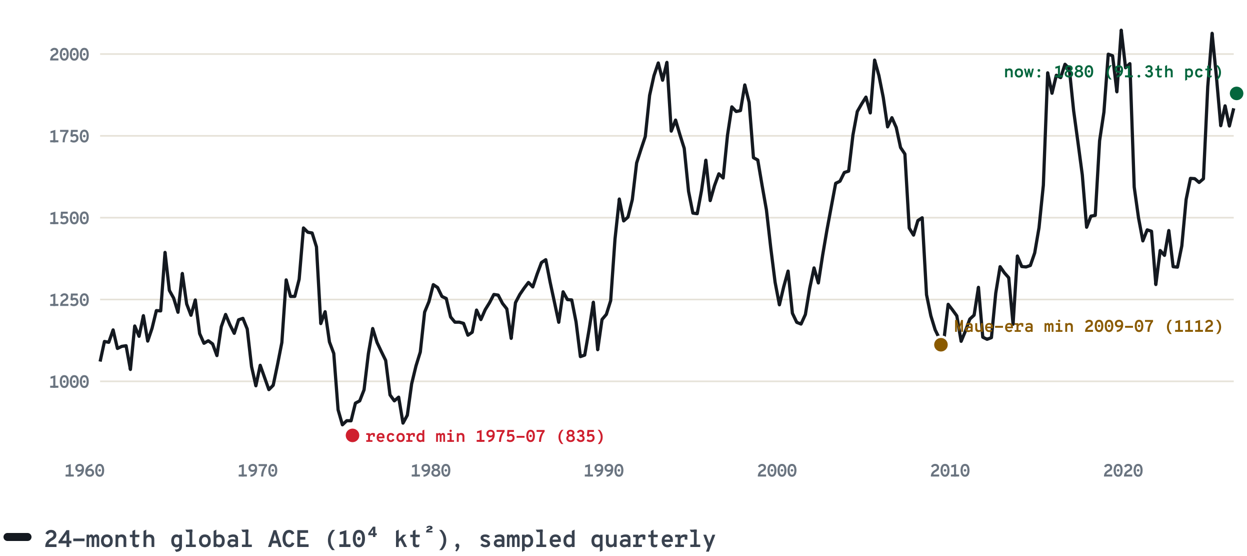
Interannual-to-decadal variability is the dominant term in this record, and it has an address. Correlating each basin's PDI (1966–2025) against the three canonical indices — ONI (ASO), the PDO (ASO), and the Atlantic Multidecadal Variability index computed here from ERSSTv5 (North Atlantic 0–60°N minus the 60°S–60°N global mean):

SERIES (1966-2025)	ONI (ASO)	PDO (ASO)	AMV
Global PDI	**+0.48**	**+0.33**	−0.14
NH PDI	**+0.54**	**+0.36**	−0.14
SH PDI	+0.15	+0.11	−0.10
NATL PDI	**−0.34**	**−0.32**	**+0.63**
NWPAC PDI	**+0.67**	**+0.46**	**−0.33**
NEPAC PDI	**+0.40**	**+0.35**	**−0.34**

Three regimes, one planet. The Pacific basins answer to ENSO (NWPAC r = +0.67); the Atlantic answers to the AMV (r = +0.63, r^2 = 0.40) and *anti*-correlates with ENSO; the PDO adds nothing ENSO hasn't already said (its NWPAC r = +0.46 is ENSO covariance wearing a decadal coat). The southern hemisphere answers to none of them at PDI scale — and the companion note showed ENSO cannot touch the size term anywhere. Every "trend" debate of Sections 5–8 plays out on top of this machinery: the AMV alone moves the Atlantic between halves and doubles of its mean on a 30–40 year period, which is the entire lesson of the Emanuel window.

24-month running global ACE, 1959–2026

Trailing 24-month sum of global ACE, reconstruction-filled series (calendar attribution). Marked: the record minimum, the Maue (2011) minimum, and today.



Maue (2011), inverted by the following decade. The 24-month global ACE that fell to 1112 in 2009-07 — the 13th percentile of the 1959–2026 record, the collapse that paper documented — stands today at **1880, the 91th percentile**. Global activity swung from near record-low to top-decile inside fifteen years with no net trend across the record (Section 3). Both the 2011 paper's observation and its implicit lesson — that integrated global activity is dominated by variability, not drift — have aged well; anyone who read the 2008–2011 minimum as a new normal made Emanuel's window mistake with the sign reversed.

The mechanism of the minimum is the modes table in motion: 2007–2011 stacked back-to-back La Niñas onto a deeply negative PDO phase, gutting the two Pacific terms that carry >55% of global dissipation, while the AMV-warm Atlantic — the one active basin — holds only 14.5% of the global budget and could not compensate. The record low of 1975-07 (835) sits in the mid-1970s cold-PDO trough for the same reason. When the Pacific hemicycle turned after 2013, global ACE followed. None of this needed a secular cause going down, and none of the recovery needs one coming up.

13 · FROM SST TO POTENTIAL INTENSITY

The thermodynamic speed limit, measured instead of proxied

Section 5 showed the SST correlations that carried the 2005 argument have largely dissolved. That is not evidence against thermodynamic control; it is evidence that SST was always the wrong variable — a proxy for **potential intensity** (Emanuel 1986; Bister & Emanuel 2002), which depends on the difference between the sea surface and the whole tropospheric column, and which Emanuel (2007) himself moved to after the SST framing came under fire. PI is computed here rather than proxied: the tcpyPI algorithm (Gilford 2021) run on ERA5 at 0.25°, daily, for the two peak northern months, 1996–2025 — this site's own MPI store.

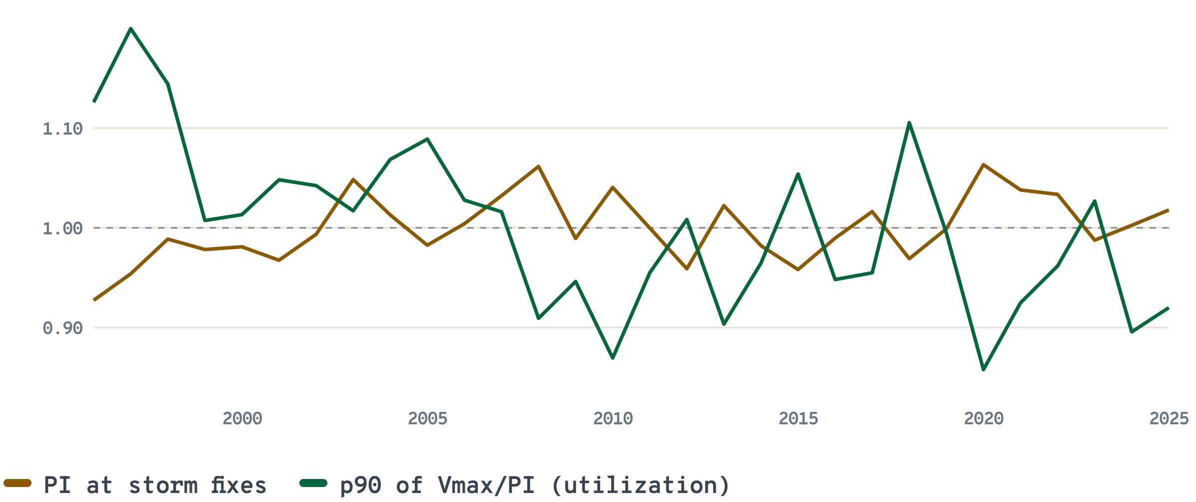
BOX · MONTH	MEAN PI, M S^{-1}	TREND, M S^{-1}/DEC	P
Atlantic MDR ·September	75.9	+0.35	0.284
Atlantic MDR ·August	72.0	−0.34	0.571
West Pacific MDR ·September	82.4	+0.64	0.074
West Pacific MDR ·August	80.8	**+1.20**	0.005
East Pacific MDR ·September	70.5	+0.19	0.750
NH tropics 0–30°N ·September	69.8	+0.28	0.372
Tropics 30°S–30°N ·September	55.7	−0.18	0.501

On the measurable window, the ceiling has barely moved. September tropics-mean PI trends -0.18 m s^{-1}/decade ($p = 0.50$) over 1996–2025 and the Atlantic MDR +0.35 ($p = 0.28$) — statistically flat. The significant movers are local: the West Pacific MDR in August (+1.20 m s^{-1}/decade, $p = 0.005$) and the areal share of tropical ocean with PI ≥ 70 m s^{-1} in August (+0.8 points/decade, $p = 0.009$). The published ~+0.5–1 m s^{-1}/decade estimates (annual means, 1980–2020 windows) sit inside our confidence intervals — but a 30-year peak-season window cannot independently confirm them. The ceiling story is, on this record, as window-dependent as every other trend in this paper; that is itself the finding.

Sampling PI at every August–September northern-hemisphere fix ($n = 20{,}349$, cells with PI ≥ 20 m s^{-1}) turns the ceiling into a per-storm diagnostic. Storms achieve a median 51% of their local thermodynamic allowance and the 99th percentile reaches 1.6 — storms do exceed point-PI on occasion, a known feature of comparing a balance-theory bound against best-track maxima. Two opposing trends share the window: **the PI storms encounter rose** (+0.93 m s^{-1}/decade, $p = 0.038$) even as the fixed boxes stayed flat — the storm population increasingly samples high-ceiling environments through track and timing — while **p90 utilization declined** (-5.8%/decade, $p = 0.0013$), from ~1.15 to ~0.95: achieved intensity has not kept pace with the allowance the storms themselves experience.

September potential intensity and how much of it storms use

Aug-Sep NH fixes, 1996-2025: environmental PI sampled at each best-track fix, and the p90 of Vmax/PI. Each series ÷ its own mean.



Read jointly — supply flat in the mean, sampling of supply rising, use of supply easing — the peak-month PI record does *not* support a simple "thermodynamic forcing is visibly driving intensification" narrative over 1996–2025, any more than the SST correlations of Section 5 do. What it supports is the framework: PI is measurable at 0.25° daily, it varies where and when storms are, and the modest real signals of Sections 7 and 11 must be prosecuted against it rather than against basin-mean SST. Emanuel's 2007 move from SST to potential intensity was the right move; the data to finish the argument now exist, and on their first thirty years they counsel the same patience as everything else in this paper.

> **Scope.** This PI record covers the two peak northern months at 0.25° daily over 30 years — it cannot speak to the southern hemisphere's season or to 1979–1995, and a 30-year trend on a field with ENSO-scale variance carries intervals wide enough to contain the published positive estimates: "statistically flat" here means "indistinguishable from zero *and* from +1 m s^{-1}/decade", which is a statement about power, not stability. The at-fix sampling is same-day and storm-centered, so it can include the storm's own modified environment (cold wake most importantly); pre-storm or annulus sampling is the required refinement before utilization trends are read physically, and utilization can also absorb reanalysis-era evolution. The store is append-only and the backfill scripts exist; extending September to 1979 is a solved problem awaiting machine time. Constants: tcpyPI with C_K/C_D = 0.9, dissipative heating on, following Gilford (2021).

14 · THE RECORD OF THE ARGUMENT

2005–2026: claims, corrections, and what stands

The two founding papers entered the most receptive news environment in the history of the field. Emanuel's letter was submitted in January 2005 and published on 4 August; Hurricane Katrina made landfall twenty-five days later. Webster, Holland, Curry and Chang appeared in *Science* on 16 September, between Katrina and Rita, with Wilma still to come. "Doubling" and "destructiveness" became the public shorthand for what tropical cyclone data showed, and they have never fully left the discourse.

The pushback was immediate — and it was technical, not rhetorical. Landsea's *Nature* comment identified two specific defects: the smoothed series retained unsmoothed end-points, so that *"about one-third of the increase in Atlantic PDI in Emanuel's graph for the past ten years is incorrect owing to inappropriate plotting of the data"*; and the pre-1970 Atlantic bias-removal reached −12.2 m s^{-1} on the strongest storms, far beyond the 2.5–5 m s^{-1} the underlying pressure–wind inconsistency justified. Pielke showed normalized US hurricane damage carried no trend, so either the index was mismeasuring destructiveness or the trend was not real. Chan (2006) read the western Pacific rise as one phase of a documented multidecadal oscillation. Landsea, Harper, Hoarau & Knaff (2006) argued that operational intensity estimates outside the Atlantic could not support trend analysis at all. Gray said the same, less diplomatically.

Emanuel's reply conceded both technical points — *"I neglected to drop the end-points"*; *"I accept his revision to my analysis"* — while maintaining the conclusion, and by 2007 had rebuilt the argument on potential intensity rather than SST: a quiet retreat from the boldest 2005 framing. The more consequential response was institutional: the homogenization program the critics' argument demanded was actually built, by Kossin, Knapp, Olander and Velden — mainstream scientists, not skeptics — and its first product (Kossin et al. 2007) found exactly what Landsea, Harper, Hoarau and Knaff had predicted: outside the North Atlantic, the best-track trends largely evaporated in homogeneous data. Kossin et al. (2013) repeated the verdict at higher resolution. Then the atmosphere weighed in: global accumulated energy collapsed to multi-decade lows by 2010 (Maue 2011 — the minimum year of the smoothed global series in Section 3), the western Pacific kept falling, and Webster's Category 4–5 count stopped rising the year after his paper. Klotzbach & Landsea (2015) made the accounting explicit; Kossin et al. (2020) — a model of careful framing next to 2005 — salvaged what was real as a modest exceedance trend with honest error bars.

YEAR	CLAIM OR OBJECTION	VERDICT, 2026 (THIS PAPER)
2005	Emanuel: Atlantic PDI "more than doubled"	Held — ×2.09 in 2014–23; but it un-doubled to below the 1970s trough in 2013 on the way

YEAR	CLAIM OR OBJECTION	VERDICT, 2026 (THIS PAPER)
2005	Emanuel: West Pacific PDI up ~75%	Reversed — ×1.12 now; -18%/decade since 1990 (p = 0.018)
2005	Emanuel: combined series "nearly doubled", read globally	×1.32 now; global PDI -8%/decade since 1990
2005	Webster et al.: Cat 4–5 storms nearly doubled	Count replicates (156→269) then flat for 20 yrs; ~half the rise is unshared by the homogeneous record (1979–89 share: ADT 35.8% vs best track 23%)
2005	Landsea: retained end-points exaggerate the upswing	Conceded by Emanuel within months; the filter is applied correctly throughout this paper
2005	Landsea: pre-1970 wind corrections over-reach	Conceded by Emanuel; no correction is needed for any claim made here
2005	Pielke: normalized damage shows no trend	Still none (Weinkle et al. 2018) — and consistent with the V^2.12 energy accounting of Section 9
2006	Chan: the WNP rise is multidecadal variability	The WNP series has since given the rise back
2006	Landsea–Harper–Hoarau–Knaff: non-Atlantic best tracks cannot carry trends	Confirmed by the homogenization program itself: exceedance +11%/dec (best track) vs +5.7%/dec (ADT), same window
2007–13	Kossin et al.: homogeneous record deflates non-Atlantic trends	Replicated and extended here on v01
2011	Maue: global activity at historical lows	The smoothed global series bottoms in 2010
2012	Weinkle–Maue–Pielke: no trend in global hurricane landfalls	Holds through 2025: +3.8%/dec (p = 0.07); major-landfall rise is pre-1990-loaded like everything else (Section 10)
2015	Klotzbach–Landsea: Webster's rise mostly pre-1990 and artificial	Confirmed, extended ten more years, and given its mechanism (Section 6)
2018	Kossin: global −10% slowdown of translation speed	Absent at storm level: flat 1966–2025 (p = 0.77), +1.8%/dec since 1990 — the era mix again, as Moon et al. and Lanzante argued
2019	Bhatia et al.: intensification rates rising in both records	Confirmed and extended: RI share +9%/dec (bt) and +9%/dec (ADT) since 1990 — the rare change claim that passes the two-record test (Section 11)
2020	Kossin et al.: exceedance +5%/dec [0.4, 11] (as corrected, Nov 2020)	Reproduced here on v01 (era means match the corrected values) and extended 7 seasons at +5.4%/dec (p = 0.003) — the durable core of the whole argument

Twenty years on. Of the 2005 headline claims: the Atlantic rise held (as one phase of a multidecadal swing), the West Pacific rise did not persist, and the Category 4–5 rise stands at roughly half its original amplitude with the remainder unshared by the homogeneous record. Of the early technical objections: each was subsequently addressed — several by the original authors and the homogenization program the field built in response. What survives everything is a modest, corrected, independently reproduced composition shift: smaller than the 2005 headlines, sturdier than the strongest doubts.

The methodological lessons, stated without hindsight's advantages. First passes at hard records always contain errors, and several of the 2005-era choices shared a common structural sensitivity that later work exposed: smoothing conventions whose end-point handling mattered most exactly where the claim lived; historical bias corrections applied in one era without a symmetric assessment of the modern fleet's evolving ability to find peak winds (an effect the two-record comparison of Section 7 now sizes at roughly half of the operational trend); trend windows that opened at the trough of a known multidecadal oscillation; regional sums captioned globally; and a cubic point index carrying the word "destructiveness" that the measured $V^{2.12}$ structure does not support. Each choice was defensible in isolation and each was subsequently revised — by the original authors, by their critics, or by both. The transferable lessons are procedural: state smoothing and window conventions where the conclusion depends on them; correct symmetrically or not at all; treat any trend through an observing-system transition as provisional; and publish claims and their audits in the same venue, so revision costs no one a headline.

Read as a whole, the record is one of a field correcting itself — unevenly, but genuinely, and from both directions. The technical objections of 2005–2006 were largely incorporated: Emanuel accepted the end-point and correction revisions within months and rebuilt his argument on sounder footing in 2007; the homogenization program that the critics' argument demanded was built by the original community, and it is what converted "doubling of the most dangerous storms" into a defensible "+5% per decade in the major share, CI [0.4, 11]" — a number this paper independently reproduces. Equally, the core physical intuition of the 2005 papers — that a warming ocean should leave a fingerprint on the intensity distribution — is what the corrected, extended, homogeneous record now supports, at a fraction of the originally headlined amplitude. The early cautions were, on the specific checkable points, well taken; the early physical instinct was, at reduced scale, also right. Both halves of the 2005 exchange contributed pieces of what now stands, and the milepost table above is best read as that joint construction — not as a scoreboard of winners.

15 · IMPLICATIONS

What follows, for science, risk and the public argument

1. **Detection standard.** No global tropical cyclone trend should be asserted from the best track alone. The operational record's exceedance trend runs nearly double the homogeneous record's over the same window; best-track-only trends are upper bounds, and attribution or projection studies calibrated to them inherit the fleet's inflation.

2. **Window discipline.** A 30-year window on a system with multidecadal modes is a trend trap: the Atlantic doubled, un-doubled and re-doubled inside two decades. Claims should be stated against the full record and the known oscillations, not from a trough to a peak.

3. **Energy accounting.** "Destructiveness" claims priced in V^3 overstate the energy consequence of the observed intensification by roughly a factor of two. The persistent null in normalized damages is not a paradox needing explanation; it is what the $V^{2.12}$ physics, flat frequency, and a ~+4.2% per-fix energy shift actually predict, before any societal signal is even sought.

4. **What is real still matters.** The homogeneous record's +5%/decade shift of the intensity distribution toward major status, and the poleward drift of peak intensity, are genuine risk signals: more of the hazard arriving at Category 3+ and at higher latitudes moves building codes, surge exposure and insurance pricing even with global totals flat. Skepticism of the 2005 claims is not a license to dismiss these.

5. **Metric reform.** PDI should be retired from energy and destructiveness arguments. ACE sits nearer the measured exponent by accident; a size-aware index ($\Sigma\ V^2 R34^2$, or IKE where radii exist) tracks actual dissipation far better, and the agencies already publish the needed radii.

6. **Monitoring priority.** The energy budget is governed by storm size — unmeasured before 1990, 41.8% of interannual variance, ~98 years from trend detectability at present noise. An ADT-HURSAT-style homogeneous *structure* reconstruction is the highest-value observational project in this field.

7. **Landfall risk is a composition story, not a frequency story.** What hits land has not changed in number, latitude, or arrival size on any defensible window; what has changed is the same composition-and-duration shift as over open water, at half the best-track amplitude. Coastal risk models driven by landfall-count trends are fitting noise; those driven by exposure growth are fitting the signal.

8. **Rapid intensification is the forecast problem and the verified change.** The one storm-behavior change both instruments confirm is also the one that erodes warning time — and it preferentially occurs in compact storms, whose damage footprint the cubic index overprices and whose surge footprint is small. RI research and size-resolved risk metrics are the same agenda.

9. **Every trend claim needs a modes audit.** The AMV explains 40% of Atlantic PDI variance on a 30–40 year period; ENSO explains 45% of the West Pacific's interannually. Any window shorter than a mode's period will manufacture trends of either

sign on demand — 2005's upswing and 2011's collapse were the same lesson taught in opposite directions.

10. **Potential intensity should replace SST in every public-facing claim.** The SST correlations that carried the 2005 argument are empirically dead; the PI framework is alive, measurable at 0.25° daily, and separates the ceiling (slow, currently near-flat on measurable peak-season windows) from utilization (dynamic, variable, dominant — and not rising). The right public sentence is not "warmer water, stronger storms"; it is "a speed limit that has barely moved, that storms sit at half of, and that they are not using any more fully than before".

11. **The communication debt.** For twenty years the public heard the 2005 version — doubling, destructiveness, unprecedented. The corrected version, a modest and real compositional shift inside a flat energy budget, never ran at front-page volume. The debt compounds: each season's extremes are read against the inflated baseline, and the field's credibility pays the interest. The remedy is the practice of this paper: publish the claims and their audits in the same place, priced in the same units.

16 · CONCLUSIONS

What sixty-six years and two instruments support

1. **The climatology.** Earth dissipates ≈41 EJ/yr of storm energy (2.1×10^{12} m^3 s^{-2} of PDI): 40.4% in the West Pacific, two hemispheric pulses, May the only quiet month. ENSO redistributes it between basins far more than it changes the total.

2. **Emanuel (2005), twenty years on.** The Atlantic doubling held (×2.09); the West Pacific rise reversed (×1.12, −18%/decade since 1990); the combined "near-doubling" is now ×1.32; global PDI has no significant 66-year trend and has declined since 1990. The 2005 result was a basin-scale multidecadal swing read at its steepest point as a global trend.

3. **Webster et al. (2005), split.** The Cat 4–5 count doubling replicates and then stops: flat since 1990. The homogeneous record assigns roughly half of the 1980s→2000s rise to observing systems. What survives is a ~6-point rise in the major share — real, and consistent with the exceedance trend.

4. **Kossin et al. (2020), reproduced and extended.** The corrected result (+5%/decade [0.4, 11]) replicates on the new v01 record and stands at +5.4%/decade with seven more seasons ($p = 0.003$), robust to the Indian-Ocean sensitivity test. This — not any PDI series — is the defensible core of the "storms are strengthening" literature, and it is its original authors' result.

5. **The exchange rate.** Dissipation follows $V^{2.12}$, not V^3. The observed intensity shift is worth about half as much energy as cubic accounting implies, and the poleward size channel adds energy no intensity metric can register. Trend claims priced in PDI overstate the energy change and miss a term of comparable size.

6. **The frontier is width, not height.** The best-measured moment of the intensity distribution (its top) moves modestly; the energy budget is governed by a moment (storm area) measured only since 1990–2002. Extending the homogeneous size record — an ADT-HURSAT for structure — would do more for the dissipation question than any further refinement of V_{max}.

7. **The nexus is one object.** ACE, PDI, IKE and PD are a single Rankine-family integral read with different information: size enters squared, intensity weakly (V^0.2–0.5 at fixed footprint). ACE–PDI correlate at 0.99 and IKE–PD at 0.99; $\Sigma V^2 R34^2$ bridges the camps at $r = 0.97$ with only public data. The index wars were about one term: $R34^2$.

8. **Landfalls have not changed.** Counts, latitude, arrival size, and the landfalling share of global hurricanes are all trendless on defensible windows through 2025; the apparent major-landfall rise since 1970 is loaded into the pre-1990 intensity baseline. Weinkle, Maue & Pielke (2012) extends unbroken.

9. **Rapid intensification is the real behavioral change, and it selects for small.** +9%/decade in both records since 1990, flat share of storms affected — the same storms RI more and hold peak longer. P(RI) falls monotonically with size; more RI deepens the compactness of the intense population and widens the PDI–energy gap.

10. **The ceiling is not doing what the narrative needs.** Peak-month ERA5 potential intensity is statistically flat over 1996–2025 in the tropics-wide mean and the Atlantic MDR; the PI storms encounter rises (track and timing), and their utilization

of it eases. SST, the proxy that launched the field's loudest decade, no longer correlates with the activity it was said to control — and its replacement counsels patience, not alarm.

11. **The record of the argument.** The specific technical objections of 2005–2006 — the end-points, the corrections, the instruments, the damage record, the multidecadal framing — were subsequently addressed, several by the original authors and the field's own homogenization program; the core physical expectation survives at reduced amplitude. The residue of the audit — a ~5%/decade exceedance shift, corrected, reproduced, extended — is real, and it is a fraction of what two decades of "destructiveness" headlines conveyed. The lesson is procedural, not personal: publish claims and audits together.

METHOD & CAVEATS

Definitions, choices, and what could be wrong

Best track. 108,737 fixes / 5,734 storms, 1960–2025: HURDAT2 (NATL, NEPAC incl. CP), IBTrACS USA/JTWC fixes (NWPAC, NIO, SIO, SPAC), Neumann and ds824 filling the pre-JTWC southern hemisphere. Six-hourly synoptic times only; tropical/subtropical statuses only; ≥34 kt. No wind corrections of any kind. Northern basins use calendar-year seasons; southern basins July–June labelled by the ending year; Kossin-style annual proportions use calendar years in both hemispheres.

ADT-HURSAT. 133,723 fixes / 4,807 storms from the 4,852 per-storm v01 netCDF files: ocean fixes (Land flag), valid WindSpeed, the 3-hourly record subsampled to 6-hourly synoptic slots (±1 h), de-duplicated per slot. 1978 is partial and excluded from trends. We do not reproduce Kossin's per-satellite 60°E screen; the 30–100°E exclusion above bounds its possible effect.

Definitions. PDI = $\Sigma V^3 \Delta t$ over fixes ≥34 kt (10^{12} m^3 s^{-2}); ACE = $\Sigma V^2 \times 10^{-4}$; major = ≥100 kt at the fix, Cat 4–5 = LMI ≥114 kt (ADT winds are quantized by the Dvorak CI–wind table in ~2.4-kt steps, not 5-kt bins — 96- and 100-kt thresholds select genuinely different fix sets); P(major) = major fixes ÷ hurricane-strength fixes per calendar year. Trends are Theil–Sen slopes with Mann–Kendall p-values; smoothing is two passes of Emanuel's 1-2-1 filter with end-points dropped (the Landsea correction). Energy conversions use the measured PD/PDI relationship of the companion note (ρ = 1 kg m^{-3}, C_D = 10^{-3}).

Known weaknesses, in the open. Early southern-hemisphere winds mix agency practices and averaging periods; the 1960s NWPAC carries the reconnaissance-era high bias; JTWC winds are 1-minute while some source agencies analyse 10-minute (the merged record uses the USA estimate throughout, so the mix is stable in time within each basin after ~1985). ADT's 8-km pixels underestimate small-eyed intensity and its 3-hourly cadence clips peaks; both are stable in time, which is the property used. The best-track/ADT global PDI ratio runs 1.271→1.13 (early→late 15-yr means) with an insignificant drift (-0.22%/decade, p = 0.84), the correlation of their annual logs is r = 0.60 — same storms, different rulers, no runaway divergence.

The deep layer. SST boxes are Emanuel's own, from ERSSTv5 monthlies; the AMV is North Atlantic (0–60°N, 80°W–0°) minus the 60°S–60°N mean, annual; the PDO is the ERSST index, ASO-mean. Landfalls follow the Weinkle et al. (2012) method as implemented in this site's best-track pipeline (NHC-glossary center-crossing against a ≥50 km^2 land mask, 0.25° position buffer, landfall wind = max of the landfall fix and the fix before); both every-landfall and collapsed-per-storm conventions are reported. RI is a ≥30-kt rise over 24 h from any 6-hourly fix ≥30 kt; ADT-HURSAT's Rule-8 time-averaging damps its 24-h changes, so RI levels differ between records by construction and trends are the comparison. The size–RI table uses agency radii only. Potential intensity is tcpyPI (Gilford 2021; C_K/C_D = 0.9, dissipative heating on) over ERA5 0.25° daily fields for August and September 1996–2025, area-weighted over ocean cells; utilization samples the 3×3-cell PI around each NH best-track fix on the same day. The Rankine nexus integrals are evaluated numerically to the 34-kt radius with $x \in \{0.4, 0.5, 0.6\}$.

Alternative size records. The pre-radii size axis uses the Xu et al. (2024) ESSD reconstruction (1959–2022), whose fitness was audited fix-by-fix in the companion note: structure and interannual variability survive, trends do not, and it is used here only for window ratios. The reanalysis-size literature (Schenkel et al. 2017 vs QuikSCAT; Thompson 2024) supports outer size as the recoverable quantity; no other global size dataset yet reaches the pre-satellite era.

Reproduction. `python -m pipeline.pd_climatology` regenerates `data/pd_climatology.json` — every number and figure on this page — from the merged best-track parquet and the ADT-HURSAT netCDF archive; `python -m` `pipeline.pd_research` regenerates the companion size-layer numbers this paper imports; `python -m pipeline.pd_deep` regenerates the deep layer (Sections 4–5, 8, 10–13), and `pipeline.pi_extract` (in the zarr venv) rebuilds the potential-intensity series from the MPI store.

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climatlas ·Tropical — a Ryan Maue project. Every number on this page is computed by `pipeline/pd_climatology.py` from the merged JTWC+NHC+Neumann best track and the per-storm ADT-HURSAT v01 netCDF files, plus the wind-field measurements of the companion note. Live season ·Size & energy ·PD & IKE note ·Maue (2010).