GLOBAL EXTREME WEATHER AND CLIMATE CHANGE DASHBOARD

Methodology, Variables & Sources

How every trend on this dashboard is detected, corrected for chance, and sourced -- every headline variable's data provenance and reliable window, and the full literature it rests on.

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Methodology

The IPCC detection standard this dashboard applies throughout, the Benjamini-Hochberg multiple-comparisons correction across its 57 headline variables, each variable's reliable trend window and known coverage limits, a data-currency and per-continent coverage table, and a per-variable methodology note for every phenomenon tracked here -- in that order below. A downloadable PDF version bundles all of this with a full variable/source directory and bibliography.

Publicly available data, funded by taxpayers and governments around the world, makes this site possible. Open science serves everyone.

Detection and Attribution

This dashboard tracks detection only, following the IPCC framework the sibling US dashboard uses (Glossary, AR5/AR6/SR15, "Detection and Attribution"). The homepage defines both terms and the combined IPCC-likelihood-plus-magnitude "detected change" standard this site applies throughout.

Testing 57 variables at once: correcting for chance across the full set

Testing 57 variables independently at IPCC's flat 10% example threshold ($p<0.10$ in the Mann-Kendall test — see Detection and Attribution above) means chance alone produces some positive results even when no underlying change exists: a 10% per-test false-positive rate yields several "significant" results out of 57 tests by chance alone, regardless of anything real happening in the climate system. This site corrects for that directly rather than only disclosing it. Of the 57 headline variables, 42 carry enough data to test at all (the rest sit under the 30-year minimum record length, excluded before significance even enters the picture). Every chart, stat tile, and summary table on this site ranks those 42 p-values together and applies a Benjamini-Hochberg false-discovery-rate correction at IPCC's 10% standard: each result has to clear a bar that tightens the more other results test more strongly, rather than the same flat 10% cutoff no matter how many tests ran. A flat, uncorrected $p<0.10$ threshold alone would pass 23 of these 42 results; the corrected bar passes 20. This correction applies to each variable's own default view specifically — interactively adjusting a chart's time window or switching to a different selectable series reverts that one chart to the flat IPCC standard, since the correction's ranking only holds across the one fixed set of 42 headline results it was computed from, not an arbitrary exploration away from it. The magnitude-vs-variability check described above still applies on top of this, independently: a result has to clear both bars to count as a detected change here.

Many of these 57 variables also measure correlated aspects of the same underlying phenomenon (five different drought severity thresholds against the same precipitation record, for instance) rather than fully independent draws. Benjamini-Hochberg's false-discovery guarantee holds under independence or positive dependence between tests, which correlated variables like these satisfy -- worth stating plainly rather than assuming this complication away. The Every Variable page lists a still larger number of rows by additionally breaking out every selectable series (severity tier, region, metric) within each of these 57 variables, at the flat, uncorrected threshold -- those rows are alternative views of the same 57 corrected headline tests above, not additional independent trials to correct for separately.

3 results currently change outcome under this correction -- clearing IPCC's flat 10% example threshold on its own, but not the multiple-comparisons-adjusted bar:

- **Cold Extremes — Frost Days** (Extreme Cold) -- p=0.053, needed p<0.0500 at rank 21 of 42.
- **Flooding — River Discharge High-Flow Extent** (Flooding) -- p=0.070, needed p<0.0524 at rank 22 of 42.
- **Extratropical Cyclone Intensity — Minimum Pressure — Asia** (Winter Storms) -- p=0.083, needed p<0.0548 at rank 23 of 42.

The full ranked set, every headline variable's own p-value against the threshold it actually has to clear:

RANK	VARIABLE	PHENOMENON	P-VALUE	ADJUSTED THRESHOLD	RESULT
1	**Cold Extremes — TN10p (Cold Nights)**	Extreme Cold	0.000	p<0.0024	Clears adjusted bar
2	**Heat Waves — TXx (Annual Max Temperature)**	Extreme Heat	0.000	p<0.0048	Clears adjusted bar
3	**Flooding — River Discharge — South America**	Flooding	0.000	p<0.0071	Clears adjusted bar
4	**Heat Waves — Europe Magnitude Index (HWMId-style)**	Extreme Heat	0.000	p<0.0095	Clears adjusted bar
5	**Heat Waves — Europe Heat Wave Index**	Extreme Heat	0.000	p<0.0119	Clears adjusted bar
6	**Drought — Severe-or-Worse Land Area — Africa**	Drought	0.000	p<0.0143	Clears adjusted bar
7	**Heat Waves — Magnitude Index (HWMId-style)**	Extreme Heat	0.000	p<0.0167	Clears adjusted bar
8	**Cold Extremes — CSDI (Cold Spell Duration Index)**	Extreme Cold	0.000	p<0.0190	Clears adjusted bar
9	**Heat Waves — Global Heat Wave Index**	Extreme Heat	0.000	p<0.0214	Clears adjusted bar

RANK	VARIABLE	PHENOMENON	P-VALUE	ADJUSTED THRESHOLD	RESULT
10	**Convective Instability (CAPE)**	Severe Convective Storms	0.000	p<0.0238	Clears adjusted bar
11	**Heat Waves — TN90p (Warm Nights)**	Extreme Heat	0.000	p<0.0262	Clears adjusted bar
12	**Flooding — River Discharge — Africa**	Flooding	0.000	p<0.0286	Clears adjusted bar
13	**Widespread / High-CAPE Days**	Severe Convective Storms	0.000	p<0.0310	Clears adjusted bar
14	**Drought — Severe-or-Worse Land Area — South America**	Drought	0.001	p<0.0333	Clears adjusted bar
15	**Heat Waves — North America Heat Wave Index**	Extreme Heat	0.002	p<0.0357	Clears adjusted bar
16	**Heat Waves — WSDI (Warm Spell Duration Index)**	Extreme Heat	0.004	p<0.0381	Clears adjusted bar
17	**Drought — Global Severe-or-Worse Land Area**	Drought	0.017	p<0.0405	Clears adjusted bar
18	**Tropical Cyclones — Proportion of Hurricanes That Are Major**	Tropical Cyclones	0.030	p<0.0429	Clears adjusted bar
19	**Drought — Severe-or-Worse Land Area — Asia**	Drought	0.034	p<0.0452	Clears adjusted bar
20	**Tropical Cyclones — Frequency by Category**	Tropical Cyclones	0.035	p<0.0476	Clears adjusted bar
21	**Cold Extremes — Frost Days**	Extreme Cold	0.053	p<0.0500	Flips: clears flat 10%, not adjusted bar
22	**Flooding — River Discharge High-Flow Extent**	Flooding	0.070	p<0.0524	Flips: clears flat 10%, not adjusted bar
23	**Extratropical Cyclone Intensity — Minimum Pressure — Asia**	Winter Storms	0.083	p<0.0548	Flips: clears flat 10%, not adjusted bar
24	**Cold Extremes — TNn (Annual Min Temperature)**	Extreme Cold	0.103	p<0.0571	Does not clear either bar
25	**Tropical Cyclones — Accumulated Cyclone Energy (ACE) — Oceania**	Tropical Cyclones	0.118	p<0.0595	Does not clear either bar

RANK	VARIABLE	PHENOMENON	P-VALUE	ADJUSTED THRESHOLD	RESULT
26	**Flooding — River Discharge — Oceania**	Flooding	0.209	p<0.0619	Does not clear either bar
27	**Tropical Cyclones — Rapid Intensification**	Tropical Cyclones	0.212	p<0.0643	Does not clear either bar
28	**Tropical Cyclones — Accumulated Cyclone Energy (ACE) — North America**	Tropical Cyclones	0.231	p<0.0667	Does not clear either bar
29	**Drought — Severe-or-Worse Land Area — North America**	Drought	0.296	p<0.0690	Does not clear either bar
30	**Flooding — River Discharge — North America**	Flooding	0.303	p<0.0714	Does not clear either bar
31	**Tropical Cyclones — Accumulated Cyclone Energy (ACE) — Africa**	Tropical Cyclones	0.307	p<0.0738	Does not clear either bar
32	**Drought — Severe-or-Worse Land Area — Oceania**	Drought	0.314	p<0.0762	Does not clear either bar
33	**Tropical Cyclones — ACE per Storm**	Tropical Cyclones	0.354	p<0.0786	Does not clear either bar
34	**Tropical Cyclones — Accumulated Cyclone Energy (ACE) — Asia**	Tropical Cyclones	0.397	p<0.0810	Does not clear either bar
35	**Tornadoes (United States)**	Severe Convective Storms	0.435	p<0.0833	Does not clear either bar
36	**Extratropical Cyclone Intensity — Minimum Pressure**	Winter Storms	0.488	p<0.0857	Does not clear either bar
37	**Drought — Severe-or-Worse Land Area — Europe**	Drought	0.508	p<0.0881	Does not clear either bar
38	**Tropical Cyclones — Accumulated Cyclone Energy (ACE)**	Tropical Cyclones	0.580	p<0.0905	Does not clear either bar
39	**Extratropical Cyclone Intensity — Minimum Pressure — Europe**	Winter Storms	0.649	p<0.0929	Does not clear either bar

RANK	VARIABLE	PHENOMENON	P-VALUE	ADJUSTED THRESHOLD	RESULT
40	**Extratropical Cyclone Intensity — Minimum Pressure — North America**	Winter Storms	0.665	p<0.0952	Does not clear either bar
41	**Flooding — River Discharge — Asia**	Flooding	0.677	p<0.0976	Does not clear either bar
42	**Flooding — River Discharge — Europe**	Flooding	0.797	p<0.1000	Does not clear either bar
—	**Heat Waves — North America Magnitude Index (HWMId-style)**	Extreme Heat	—	—	Time series too short
—	**Wildfire — Burned Area (GWIS) — Africa**	Wildfire	—	—	Time series too short
—	**Wildfire — Burned Area (GWIS) — Asia**	Wildfire	—	—	Time series too short
—	**Wildfire — Burned Area (GWIS) — Europe**	Wildfire	—	—	Time series too short
—	**Wildfire — Burned Area (GWIS) — North America**	Wildfire	—	—	Time series too short
—	**Wildfire — Burned Area (GWIS) — Oceania**	Wildfire	—	—	Time series too short
—	**Wildfire — Burned Area (GWIS) — South America**	Wildfire	—	—	Time series too short
—	**Wildfire — Dry Matter Combusted (GFED5)**	Wildfire	—	—	Time series too short
—	**Wildfire — Dry Matter Combusted (GFED5) — Africa**	Wildfire	—	—	Time series too short
—	**Wildfire — Dry Matter Combusted (GFED5) — Asia**	Wildfire	—	—	Time series too short
—	**Wildfire — Dry Matter Combusted (GFED5) — Europe**	Wildfire	—	—	Time series too short
—	**Wildfire — Dry Matter Combusted (GFED5) — North America**	Wildfire	—	—	Time series too short
—	**Wildfire — Dry Matter Combusted (GFED5) — Oceania**	Wildfire	—	—	Time series too short

RANK	VARIABLE	PHENOMENON	P-VALUE	ADJUSTED THRESHOLD	RESULT
—	**Wildfire — Dry Matter Combusted (GFED5) — South America**	Wildfire	—	—	Time series too short
—	**Wildfire — Global Burned Area (GWIS)**	Wildfire	—	—	Time series too short

Reliable trend windows, and excluding the in-progress year

Every chart on this site shows only its reliable-trend-window data — years before a variable's network, model, or satellite record reaches meaningful global coverage drop out entirely, rather than sitting past a default so widening the window control could pull them back in. Each variable's reliable-start year rests on a specific basis: a station-count curve crossing a threshold, a documented satellite-era reanalysis-quality break, or an aircraft-reconnaissance-era record's beginning — see each variable's methodology note below for the evidence behind its start year. No chart shows the current, in-progress calendar year as a complete data point either: a partial season or year would otherwise appear as an artificially low final point, so every series ends at the most recently complete year.

Coverage limits — where this site falls short of literally global

Several variables cover less than the whole globe, or measure a related but different quantity from what the name suggests. Each variable page states its coverage limit; this list collects them in one place:

- **Extratropical cyclone intensity** covers the Northern Hemisphere winter season (October–March) only, despite the underlying TRACK catalog's "global climatology" title. The catalog also pre-filters for severity (64% of tracks already qualify as "bomb cyclones," against roughly 7% in an unfiltered climatology), so storm counts serve as description only, not as a trend metric, and this site does not trend them. Its per-continent breakdown covers North America, Europe, and Asia — 3 of the 6 continents the Northern-Hemisphere-winter catalog reaches; the catalog contains no data for Africa, South America, or Oceania.
- **Flooding** excludes 1979–1981 from both series: GloFAS's documented one-year model spin-up (Harrigan et al. 2020) leaves a residual bias in slow-draining basins, Africa especially, through the record's first three years. See Flooding.
- **Cold extremes** mirrors Heat Waves' scope: it builds only the overnight-low (TMIN) side (TNn, CSDI, TN10p, Frost Days), with no TX10p (cold days by daytime high) companion, matching Heat Waves' construction without a TX90p companion.

- **Convective instability (CAPE)** uses a single 12Z UTC snapshot per day, not a full diurnal cycle — no single fixed UTC hour matches "local afternoon" everywhere at once, so the metric favors whichever longitudes sit near local afternoon at 12Z.
- **Wildfire** tracks two distinct metrics: GFED5 dry matter combusted (mass burned, by fire type) and GWIS burned area (hectares, MODIS-derived) — each a distinct physical quantity from the US dashboard's MTBS acres-burned metric, and from each other.
- **Tropical cyclones** reuses the companion global-tropical-cyclones.com site's global rollup directly rather than re-deriving it, and refreshes manually rather than on GWX's automated schedule.
- **Tornadoes** covers the United States only (reused directly from the sibling US dashboard) — no unified global tornado database exists beyond Europe's ESWD. The United States accounts for the large majority of the world's tornadoes (NOAA/NSSL's climatology puts the US share near 75%), so this site pairs US tornado counts with CAPE as the best available global proxy, rather than presenting CAPE as a stand-in for a tornado count.
- **A flat global mean can hide opposite regional signals** — this applies to every station-network or grid-based global variable on this site, not only one. Station and grid density varies: a global average weights a well-instrumented region like Europe or the US the same as a sparse one like Africa, South America, or the poles, so an increase in one continent can offset a decrease in another and net out to "no detected change" globally while opposite changes occur underneath. Where a per-continent breakdown exists (see Continents and the coverage table below), it offers a more complete read for this reason — check it before treating a global verdict as the whole picture.

Data currency — how current each variable runs, right now

Each variable page states its currency lag; this table collects them in one place, across all 13 GWX variables, checked directly against this build's data files.

VARIABLE	LATEST DATA	TYPICAL LAG
Drought (ERA5)	2026-07	About 1 month — ARCO-ERA5's near-real-time mirror.

VARIABLE	LATEST DATA	TYPICAL LAG
Convective instability (CAPE)	2026 (current)	About 1 month — the same ERA5 near-real-time source as Drought.
Tropical cyclones	2026 season	Reused from global-tropical-cyclones.com; refreshes manually, not on GWX's automated schedule.
Flooding (GloFAS)	2026-04	About 4 months — a documented GloFAS production lag, confirmed live.
Heat waves	2025	About 1 year — most non-US GHCN-Daily/GSN stations report roughly a year behind, worse than the US-only feed the sibling dashboard uses.
Cold extremes	2025	About 1 year — the same GHCN-Daily/GSN network and lag as Heat Waves.
Tornadoes (US-only)	2025	Standard annual — NCEI Storm Events' most recent complete year; 2026 remains partial and in progress, excluded per the rule above.
Wildfire — GFED5 (dry matter combusted)	2024	About 1.5–2 years — GFED5's summary-table regeneration cadence (files last regenerated 2025-10-07).

VARIABLE	LATEST DATA	TYPICAL LAG
Wildfire — GWIS (burned area)	2024	About 1.5–2 years — Our World in Data's GWIS mirror.
Extratropical cyclone intensity	2022	A fixed endpoint, not a lag that resolves with time — the TRACK/CEDA source catalog spans 1979–2022 with no newer years published, rather than running a currently updating feed behind.

Per-continent coverage

Drought, both wildfire variables, tropical cyclones (by ocean basin), flooding, and extratropical cyclone intensity (3 of 6 continents) run live per continent — see the nav's "Continents" dropdown for each landing page. Heat waves run live for Europe and North America (see below); the table below states the current status for every other variable.

VARIABLE	STATUS	BASIS
Drought	Live	Continent assignment runs per 5° grid cell via a point-in-polygon join against Natural Earth's 1:110m country boundaries — both the precipitation-only (SPI-style) and precipitation-minus-AED (SPEI-style) series, matching the global Drought page.
Wildfire (GFED5 DM)	Live	Sums GFED5's 14 "basis regions" (NHAF+SHAF for Africa, for example).
Wildfire (GWIS burned area)	Live	Our World in Data's GWIS mirror already breaks the data out by continent.

VARIABLE	STATUS	BASIS
Tropical cyclones	Live	Groups each continent by the ocean basin(s) that border it, not a landfall-based reclassification (Africa pairs with the South Indian Ocean; North America with the North Atlantic and Northeast Pacific). Live for 4 of 6 continents; Europe and South America have no bordering basin in this catalog.
Extratropical cyclone intensity	Live	Assigns a storm to a continent by proximity (within 500km of its Natural Earth landmass, since most fixes sit over open ocean) rather than a bounding box — live for North America, Europe, and Asia; the underlying Northern-Hemisphere-winter catalog contains no data for Africa, South America, or Oceania.
Heat waves / temperature extremes	2 of 6	GSN station density varies by continent (checked directly for all 6, 2026-08-18): Europe clears the global index's ~150-station bar (150+ by 1949); North America runs as a borderline case (peaks at 147, reliable window starts 2000); Asia (121), Africa (37), South America (33), and Oceania (56) all stay well under 100 at their historical peak, too sparse to support an index.

VARIABLE	STATUS	BASIS
Flooding	Live	GloFAS's pour-point network sits on the same 5° grid Drought uses — live for all 6 continents, both the percentile-based series and GloFAS's Alert/Warning/Severe return-period tiers.

Per-variable notes

Tropical Cyclones — ACE

Global (all-basin) Accumulated Cyclone Energy, from HURDAT2, IBTrACS, and real-time supplements. The reliable trend window starts in 1980, following Klotzbach & Landsea's published recommendation against pre-1980 data in global TC trend analyses. The 1980 cutoff addresses intensity-estimate accuracy, not basin coverage — raw storm counts already run stable well before 1980, but satellites through the 1970s carried only visible-light sensors, and the Dvorak technique reached global standardization only in the early 1980s. The companion global-tropical-cyclones.com site uses a 1966 start for the same underlying data, a difference in scope between the two sites' trend-reliability standards. An additional, lower-confidence "NATL+WPAC combined" series (selectable from this panel's Series dropdown, with a one-click time-period preset) extends back to 1945: both basins' aircraft-reconnaissance-era records begin then (NATL from 1944; NWPAC/JTWC's best-track record begins 1945), when combined NATL+NWPAC storm counts jump from 3–14/year pre-1944 to a stable 35–45+/year from 1945 on. These two basins track global activity closely: measured over the 1980–2025 global reliable window, NATL+WPAC combined account for about 52% of global ACE (WPAC alone about 37%, NATL alone about 15% — WPAC ranks as the single most active basin), about 45% of named-storm count, about 48% of hurricane and major-hurricane counts, and about 74% of Category 5 storms specifically (WPAC's warm pool produces most of the planet's strongest storms) — roughly half of global activity by every measure, and the majority of the most extreme events. The extended view carries caveats the 1980+ window avoids: NOAA's ongoing Atlantic Hurricane Reanalysis Project documents intensity biases even in the aircraft-recon era (Cat 1–2 systematically about 5kt high, the most intense storms undersampled), and WPAC's aircraft-fix record carries documented gaps (1952 missing entirely, 1955 limited).

Tropical Cyclones — Category Frequency, ACE per Storm, % Major, Rapid Intensification

Category frequency and ACE-per-storm reuse GTC's per-storm peak-intensity-tier and lifetime-ACE table directly — category frequency counts each storm's exact peak tier, not the cumulative "Cat 3+ or stronger" counts the ACE panel's levels show; Cat 1 and Cat 2 share one band (both fall in the 64–95kt "H" range, GTC's HURDAT2/IBTrACS convention). % major measures the major-hurricane share of hurricanes specifically, not of all named storms. Rapid intensification (a 30kt-orgreater increase in maximum wind within 24 hours, the standard NHC definition) runs from GTC's 6-hourly best-track fixes, comparing each fix only against the same storm's fix exactly 24 hours earlier, so a storm's first day, or any fix following a data gap, correctly registers no RI event. Hurricane Otis (2023) recorded a computed 24-hour wind increase of 90kt (55kt to 145kt) under this method, matching its documented record as one of the fastest tropical cyclone intensifications observed. All four metrics share the 1980 reliable window (Klotzbach & Landsea) and the manual-refresh schedule described above.

ACE-per-storm shows no detected change (Mann-Kendall p=0.35, nominally decreasing, 18% of the 90% historical range) over the same 1980–2025 window where % Major Hurricanes shows a detected change (p=0.030, +2.1 points/decade, 34% of the 90% range) — the two panels answer different questions rather than disagreeing. Comparing 1980–2002 to 2003–2025, Cat 1–3 storm counts have declined (Cat 1–2 hurricanes, for example, 25.8→21.1/season) while Cat 4–5 counts have risen (10.9→12.9 and 3.7→6.0/season). % major captures that compositional shift directly; ACE-per-storm averages across all named storms, most of them weak systems, so the ACE lost from fewer moderate hurricanes roughly offsets the ACE gained from the rarer, more extreme ones. Over the 1980–2025 global window, every one of the 5 category-frequency levels above individually clears detection (p between 0.03 and 0.0004 across NS/H/MH/IH/C5; magnitude 35–56% of the 90% historical range).

Both panels also carry NATL+WPAC-only levels (reliable back to 1945, versus 1980 for global), run over both the matching 1980–2025 window and the full 1945–2025 extended window, with mixed results that bear on how confidently the %major finding in particular should be read: NS and MH hold up as detected changes at every window length checked. H's decline and %major's increase do not survive the full 1945–2025 window — both flip to not-detected (%major's magnitude falls from 34% of the 90% range over 1980–2025 alone to 6% over the full record). IH's global-level increase never clears detection in this 2-basin subset at any window length, which places that increase in the basins NATL+WPAC excludes. C5's increase survives but weakens over the longer window (p=0.008 narrows to p=0.08, at the significance edge this site applies). None of this overturns the global 1980–2025 findings — the pre-1980 portion of the extended record carries documented intensity biases (see the ACE panel above), which could mask a recent trend as easily as reveal that one lacks durability — but the %major finding in particular remains open, not fully settled.

Heat Waves

GHCN-Daily's GCOS Surface Network (GSN, about 991 stations across 164 countries), the global analog of the US HCN network. Station-relative detection (a trailing 4-day mean temperature above each station's 90th-percentile-of-record threshold) makes this well-posed globally across every hemisphere and season, the same principle global-mean-temperature-anomaly products use. The reliable trend window starts in 1949 (station count crosses the same ~300-station bar the US network's 1895 window used, later here since WMO international cooperation only began in 1950). 2024 and 2023 rank as the two highest years in the 2006–2025 window, matching the established finding that 2024 and 2023 rank as the two hottest years on record globally (NASA GISS, NOAA, Copernicus, and Berkeley Earth all agree). GSN's international reporting lag runs materially worse than the US-only feed the sibling dashboard uses — most non-US stations report roughly a year behind, visible in this variable's falling station count over its most recent 1–2 years. The qualifying station count drops by roughly a third between 2018 and 2019 (from about 400–480 down to about 270–330) and stays down through 2025, a permanent contraction in the network's post-2018 completeness rather than ordinary year-to-year reporting lag; the pattern matches a systemic change in how a batch of international station reports flow into GHCN-Daily. A separate Europe-only index applies the same method to GSN stations within Europe (Russia included, per Natural Earth's continent boundaries), the one continent with a GSN network dense enough (150+ stations by 1949) to support its index.

Three companion metrics extend the headline index. The **magnitude index**(HWMId-style, Russo et al. 2014/2015) scores each qualifying station's most severe heat wave of the year by summing every day's magnitude — (a day's 4-day mean temperature minus the station's 25th-percentile annual maximum) divided by (the 90th-percentile minus the 25th-percentile annual maximum, the index's detection threshold) — both anchors drawn from the same station-relative annual-max distribution the event-count index uses, a simplification of Russo et al.'s original construction, which uses a separate calendar-day threshold and a 25th/75th-percentile scale. 2010 ranks as the single highest year in the record (1.78, more than 4 times the 1949–2025 mean), matching the documented 2010 Russian heat wave, Russia's worst on record; that same year ranks outside the top 5 on the bare event-count index (0.43), illustrating the distinction between one severe event and many mild ones this metric captures. **TXx** (IPCC AR6/ETCCDI standard) reports the single hottest daily high temperature observed each year at each qualifying station, averaged across stations, with no percentile threshold or base period. 2024 posts the highest TXx of the displayed window (35.6°C), matching 2024's status as the hottest year on record globally.**WSDI** (ETCCDI/CLIMDEX, Zhang et al. 2005) counts days in a run of 6 or more consecutive days above a station's fixed-base-period (1961–1990) 90th percentile.**TN90p** (ETCCDI/CLIMDEX) reports the percentage of days with an overnight low above the same fixed-base-period 90th percentile — NCA5 flags nighttime-low warming as a distinct, high-confidence signal, not a restatement of TXx. TXx, WSDI, and TN90p all share the 1949 reliable trend window.

Convective Instability (CAPE)

ARCO-ERA5, the same global reanalysis store the US dashboard's CAPE variable uses. The reliable trend window starts in 1979, marking ERA5's documented post-TOVS-satellite reanalysis-quality improvement. A single 12Z UTC snapshot per day stands in for a full diurnal cycle — no single fixed UTC hour matches "local afternoon" everywhere at once, and correcting for that would cost roughly 24 times more to assemble, the same cost as pulling all 24 hours. The day-count metrics (widespread and high-CAPE days) use the 90th percentile of the record's distribution, computed fresh each run, rather than a fixed absolute threshold: the US dashboard's fixed thresholds (10% of CONUS at moderate CAPE; 2500 J/kg for extreme) produce no signal at global scale, since global %-area-moderate never approaches 10% (the planet runs mostly ocean, desert, or polar at any instant) while global max CAPE exceeds 2500 J/kg on nearly every day (a thunderstorm occurs somewhere in the tropics on most days). Both metrics instead use percentile-relative thresholds, the same approach the Heat Waves variable uses. "Widespread instability days" counts days in the top decile of global %-area-at-moderate-CAPE; "high-CAPE days" counts days in the top decile of the single most unstable grid cell on Earth that day.

Wildfire

Global Fire Emissions Database (GFED5), dry-matter-combusted totals by fire type, via its pre-aggregated summary tables. Coverage runs 1997–2024, the full available record. GFED5's authors state that 1997–2000 uses coarser ATSR/VIRS-scaled estimates rather than the MODIS burned-area retrieval every year from 2001 on uses, and describe 1997–2000 as "not on par with data from the MODIS era"; the reliable trend window accordingly starts in 2001. Canada's boreal-forest DM for 2023 stands as the record in the series, 2.5 times the next-highest year, matching Canada's documented 2023 wildfire season. **A second metric** — GWIS burned area (hectares, MODIS MCD64A1-derived), via Our World in Data's public mirror of the JRC's GWIS dataset — covers 2002–2024. Africa averages about 67% of the global burned-area total, matching known savanna-fire dominance, and the global total declined about 18% from 2002–2012 to 2013–2024, matching Andela et al. 2017's documented decline in global burned area.

Extratropical Cyclone Intensity

CEDA/TRACK catalog (Gray, Volonte, Martínez-Alvarado, Harvey 2024), ERA5-driven — the same source and algorithm the US dashboard's Northeast-focused ETC intensity variable uses, here computed over each storm's whole track rather than a US-coast bounding box, an extension the already Northern-Hemisphere-wide underlying catalog supports directly. The reliable trend window starts in 1979. The single lowest minimum-pressure storm in the 1979–2022 record (genesis 1993-01-10, minimum MSLP 914.87 hPa) matches the Braer Storm, both in date and pressure, against the widely cited (about 914–916 hPa) historical record of that event. A per-continent breakdown covers North America, Europe, and Asia. Since most ETC fixes sit over open ocean rather than land, a strict landfall test would miss nearly every storm — this site instead assigns a storm to a continent when its track comes within 500km of that continent's Natural Earth landmass, and a storm can count toward more than one continent (one North Atlantic storm affecting both eastern North America and western Europe in sequence, for example). The Braer Storm reproduces in Europe's continent-filtered subset at effectively the same pressure.

Drought

A live index built directly from ARCO-ERA5 precipitation, in place of SPEIbase (the standard global-gridded-SPEI source), which has published no release since July 2024, breaking its roughly annual release cadence. Each 5°-coarsened land grid cell's 3-month trailing precipitation runs percentile-ranked against that cell's same-calendar-month history, never against an absolute precipitation normal, and classifies into USDM-equivalent D0–D4 categories, the same convention the US dashboard's drought variable uses. The reliable trend window spans the full 1979–2026 record. At the precipitation-only D2+ level, 2021 ranks as the single highest year in the record (the Horn of Africa's worst drought in 40 years began that year, alongside a severe western North America megadrought), with 2011 second (the Horn of Africa famine, the historic Texas/Southern Plains drought). **A second, AED-inclusive companion series** subtracts atmospheric evaporative demand (AED, estimated via the FAO-56 Hargreaves method from ERA5 temperature, a simplification of the source paper's full Penman-Monteith calculation) from precipitation before ranking, extending through the present the central finding of Vicente-Serrano et al. 2022 ("Global drought trends and future projections," *Phil. Trans. R. Soc. A* 380: 20210285): precipitation-only ("SPI-style") metrics show little or no significant historical global trend, while AED-inclusive metrics reveal regional drying that precipitation alone misses, as AED has risen with warming (+0.93 points precipitation-only versus +3.35 points AED-inclusive, comparing 1980–2002 to 2003–2025). Gebrechorkos et al. 2025 (*Nature*), co-authored by Vicente-Serrano, finds AED has increased drought severity by about 40% globally, a newer and independent source for the same mechanism. This site replicates the paper's historical-trend finding only, not its future-projection component. See the Library.

Cold Extremes

The structural counterpart to Heat Waves: four standard ETCCDI/CLIMDEX cold-side indices (TNn, CSDI, TN10p, Frost Days) built from the same GHCN-Daily GSN network and station data, using the same pooled-percentile-window and spell-duration-run logic as TXx/WSDI/TN90p, generalized to the cold side. Frost Days carries no percentile or base-period logic — an absolute TMIN<0°C count. The reliable trend window starts in 1949, matching Heat Waves' station-count threshold. San Antonio's station record shows TNn of −12.7°C and CSDI of 7 days in 2021 (against 0 CSDI days in each neighboring year), matching the documented February 2021 Winter Storm Uri cold wave (NWS-recorded low of −12.8°C).

Flooding

GloFAS (Global Flood Awareness System), ERA5-forced LISFLOOD reanalysis, subsampled to 1,074 "pour point" cells (the highest-upstream-area grid cell in each of the same 5° blocks Drought uses) — river discharge runs as a channelized quantity, so this site applies the standard gridded-hydrology "pour point" technique rather than Drought's block-mean approach. Two distinct series run alongside each other: an invented-here 90th-percentile-of-its-history "high flow" metric (continuous, about 10% of days qualify at any cell by construction), and GloFAS's published 2/5/20-year return-period discharge thresholds, classified into the same Alert/Warning/Severe tiers GloFAS's operational forecasting system uses (cumulative — a Severe day also counts as Warning and Alert). Both series exclude 1979–1981: GloFAS-ERA5's documented one-year model spin-up (Harrigan et al. 2020) leaves a longer residual bias in at least one region — Africa's pour-point cells averaged about 56% above their 1985–2025 baseline discharge in 1979, elevated fairly uniformly across all 12 months and fading only gradually through 1980–1981, consistent with a slow-draining-groundwater spin-up artifact rather than an actual flood event (other continents' 1979 values show no comparable anomaly). A single cutoff, `FLOOD_INDEX_RELIABLE_START_YEAR = 1982`, applies to every region and both series. Each region's highest-flood months line up with documented events: 1998 (El Niño East Africa and Yangtze River floods), 1982–83 (one of the 20th century's strongest El Niños, catastrophic South American flooding), 1988 (the Khartoum/Sudan flood), 2010 (the Pakistan floods) and 2010–11 (La Niña Queensland floods), 2019 (US Midwest flooding), and 2022–2024 (eastern Australia, Greece/Balkans, and West/Central Africa flood events). See `docs/FLOODING_METHODOLOGY.md` for the full construction.

Tornadoes (United States) & Severe Convective Storms

Tornado counts reuse the sibling US Extreme Weather Dashboard's pipeline directly, sourced from the NCEI Storm Events Database (reconstructed tornado tracks). The reliable trend window starts where NEXRAD-era radar and spotter coverage began detecting far more weak tornadoes than earlier decades could — an observing-network change rather than a climate signal in the counts before then. The United States records the large majority of the world's known tornadoes: NOAA/NSSL's international tornado climatology puts the US share near 75% of the global total (Canada adds about 5% more, so North America accounts for about 80%), a consequence of the Great Plains and Midwest's combination of moist Gulf air, dry continental air, and jet-stream shear. This concentration is why the Tornadoes page pairs US tornado counts with global CAPE as a proxy for severe-thunderstorm-favorable conditions, rather than presenting CAPE alone as a tornado count. See Convective Instability (CAPE) above for that variable's construction.

Loss Normalization

Not a live GWX pipeline like the variables above — a curated literature page (built on Pielke 2020's full 53-study normalization review) plus two separately sourced pie charts covering economic losses and loss of life, 1980–2025. Economic-by-phenomenon comes directly from EM-DAT's published dollar totals; economic-by-continent required reconstructing dollar figures from a %-of-GDP series (World Bank nominal GDP, current US$), since no ready-made continent-level dollar total exists — summing the reconstruction back up by phenomenon reproduces EM-DAT's totals within 1–3%. Loss-of-life comes from a separate source (the economic paper makes no fatality claims): North America accounts for over half of economic losses but under 4% of the weather-related death toll over the same window, while Africa and Asia together account for about 74% of deaths, each dominated by a different cause (African drought, Asian tropical cyclones).

Full per-variable technical detail (data sources, cost estimates, validation checks) lives in each variable's methodology document in this project's source repository (`docs/*_METHODOLOGY.md`).

Appendix A: Variable & Data Source Directory

Every headline variable on this site (22 global variables plus 35 continent-scoped tiles, 57 total), its data source, unit, and reliable trend window.

VARIABLE	PHENOMENON	SOURCE	UNIT	WINDOW
Drought — Global Severe-or-Worse Land Area	Drought	ARCO-ERA5 (ECMWF ERA5 reanalysis, Google Cloud mirror) Monthly	% of land cells	1979–2026
Drought — Severe-or-Worse Land Area — Africa	Drought	ARCO-ERA5 (ECMWF ERA5 reanalysis, Google Cloud mirror) Monthly	% of land cells	1979–2026
Drought — Severe-or-Worse Land Area — Asia	Drought	ARCO-ERA5 (ECMWF ERA5 reanalysis, Google Cloud mirror) Monthly	% of land cells	1979–2026
Drought — Severe-or-Worse Land Area — Europe	Drought	ARCO-ERA5 (ECMWF ERA5 reanalysis, Google Cloud mirror) Monthly	% of land cells	1979–2026
Drought — Severe-or-Worse Land Area — North America	Drought	ARCO-ERA5 (ECMWF ERA5 reanalysis, Google Cloud mirror) Monthly	% of land cells	1979–2026
Drought — Severe-or-Worse Land Area — Oceania	Drought	ARCO-ERA5 (ECMWF ERA5 reanalysis, Google Cloud mirror) Monthly	% of land cells	1979–2026
Drought — Severe-or-Worse Land Area — South America	Drought	ARCO-ERA5 (ECMWF ERA5 reanalysis, Google Cloud mirror) Monthly	% of land cells	1979–2026
Cold Extremes — CSDI (Cold Spell Duration Index)	Extreme Cold	NOAA GHCN-Daily, GCOS Surface Network (GSN) stations Annual	days per year	1949–2025
Cold Extremes — Frost Days	Extreme Cold	NOAA GHCN-Daily, GCOS Surface Network (GSN) stations Annual	days per year	1949–2025
Cold Extremes — TN10p (Cold Nights)	Extreme Cold	NOAA GHCN-Daily, GCOS Surface Network (GSN) stations Annual	% of valid days	1949–2025
Cold Extremes — TNn (Annual Min Temperature)	Extreme Cold	NOAA GHCN-Daily, GCOS Surface Network (GSN) stations Annual	°C (annual min daily low)	1949–2025
Heat Waves — Europe Heat Wave Index	Extreme Heat	NOAA GHCN-Daily, GCOS Surface Network (GSN) stations, Europe subset Annual	events per station per year	1949–2025

VARIABLE	PHENOMENON	SOURCE	UNIT	WINDOW
Heat Waves — Europe Magnitude Index (HWMId-style)	Extreme Heat	NOAA GHCN-Daily, GCOS Surface Network (GSN) stations, Europe subset Annual	magnitude index (dimensionless)	1949–2025
Heat Waves — Global Heat Wave Index	Extreme Heat	NOAA GHCN-Daily, GCOS Surface Network (GSN) stations Annual	events per station per year	1949–2025
Heat Waves — Magnitude Index (HWMId-style)	Extreme Heat	NOAA GHCN-Daily, GCOS Surface Network (GSN) stations Annual	magnitude index (dimensionless)	1949–2025
Heat Waves — North America Heat Wave Index	Extreme Heat	NOAA NCEI nClimGrid-Daily (homogenized), via the sibling US Extreme Weather Dashboard Annual	days per year	1951–2025
Heat Waves — North America Magnitude Index (HWMId-style)	Extreme Heat	NOAA GHCN-Daily, GCOS Surface Network (GSN) stations, North America subset Annual	magnitude index (dimensionless)	2000–2025
Heat Waves — TN90p (Warm Nights)	Extreme Heat	NOAA GHCN-Daily, GCOS Surface Network (GSN) stations Annual	% of valid days	1949–2025
Heat Waves — TXx (Annual Max Temperature)	Extreme Heat	NOAA GHCN-Daily, GCOS Surface Network (GSN) stations Annual	°C (annual max daily high)	1949–2025
Heat Waves — WSDI (Warm Spell Duration Index)	Extreme Heat	NOAA GHCN-Daily, GCOS Surface Network (GSN) stations Annual	days per year	1949–2025
Flooding — River Discharge — Africa	Flooding	GloFAS (Global Flood Awareness System), Copernicus Early Warning Data Store Monthly	% of pour-point cells	1982–2026
Flooding — River Discharge — Asia	Flooding	GloFAS (Global Flood Awareness System), Copernicus Early Warning Data Store Monthly	% of pour-point cells	1982–2026
Flooding — River Discharge — Europe	Flooding	GloFAS (Global Flood Awareness System), Copernicus Early Warning Data Store Monthly	% of pour-point cells	1982–2026
Flooding — River Discharge — North America	Flooding	GloFAS (Global Flood Awareness System), Copernicus Early Warning Data Store Monthly	% of pour-point cells	1982–2026
Flooding — River Discharge — Oceania	Flooding	GloFAS (Global Flood Awareness System), Copernicus Early Warning Data Store Monthly	% of pour-point cells	1982–2026

VARIABLE	PHENOMENON	SOURCE	UNIT	WINDOW
Flooding — River Discharge — South America	Flooding	GloFAS (Global Flood Awareness System), Copernicus Early Warning Data Store Monthly	% of pour-point cells	1982–2026
Flooding — River Discharge High-Flow Extent	Flooding	GloFAS (Global Flood Awareness System), Copernicus Early Warning Data Store Monthly	% of pour-point cells	1982–2026
Convective Instability (CAPE)	Severe Convective Storms	ARCO-ERA5 (ECMWF ERA5 reanalysis, Google Cloud mirror) Annual	J/kg, global 12Z mean	1979–2025
Tornadoes (United States)	Severe Convective Storms	NCEI Storm Events Database (reconstructed tornado tracks) Annual	tornadoes per year	1980–2025
Widespread / High-CAPE Days	Severe Convective Storms	ARCO-ERA5 (ECMWF ERA5 reanalysis, Google Cloud mirror) Annual	days per year	1979–2025
Tropical Cyclones — Accumulated Cyclone Energy (ACE)	Tropical Cyclones	global-tropical-cyclones.com (HURDAT2 + IBTrACS + real-time) Annual	ACE units (10^4 kt²)	1980–2025
Tropical Cyclones — Accumulated Cyclone Energy (ACE) — Africa	Tropical Cyclones	global-tropical-cyclones.com (HURDAT2 + IBTrACS + real-time) Annual	ACE units (10^4 kt²)	1980–2025
Tropical Cyclones — Accumulated Cyclone Energy (ACE) — Asia	Tropical Cyclones	global-tropical-cyclones.com (HURDAT2 + IBTrACS + real-time) Annual	ACE units (10^4 kt²)	1980–2025
Tropical Cyclones — Accumulated Cyclone Energy (ACE) — North America	Tropical Cyclones	global-tropical-cyclones.com (HURDAT2 + IBTrACS + real-time) Annual	ACE units (10^4 kt²)	1980–2025
Tropical Cyclones — Accumulated Cyclone Energy (ACE) — Oceania	Tropical Cyclones	global-tropical-cyclones.com (HURDAT2 + IBTrACS + real-time) Annual	ACE units (10^4 kt²)	1980–2025
Tropical Cyclones — ACE per Storm	Tropical Cyclones	global-tropical-cyclones.com (HURDAT2 + IBTrACS + real-time) Annual	ACE units (10^4 kt²) per storm	1980–2025
Tropical Cyclones — Frequency by Category	Tropical Cyclones	global-tropical-cyclones.com (HURDAT2 + IBTrACS + real-time) Annual	storms per season	1980–2025
Tropical Cyclones — Proportion of Hurricanes That Are Major	Tropical Cyclones	global-tropical-cyclones.com (HURDAT2 + IBTrACS + real-time) Annual	% of hurricanes	1980–2025

VARIABLE	PHENOMENON	SOURCE	UNIT	WINDOW
Tropical Cyclones — Rapid Intensification	Tropical Cyclones	global-tropical-cyclones.com (HURDAT2 + IBTrACS + real-time) Annual	% of named storms	1980–2025
Wildfire — Burned Area (GWIS) — Africa	Wildfire	Global Wildfire Information System (GWIS/JRC), via Our World in Data Annual	hectares	2002–2024
Wildfire — Burned Area (GWIS) — Asia	Wildfire	Global Wildfire Information System (GWIS/JRC), via Our World in Data Annual	hectares	2002–2024
Wildfire — Burned Area (GWIS) — Europe	Wildfire	Global Wildfire Information System (GWIS/JRC), via Our World in Data Annual	hectares	2002–2024
Wildfire — Burned Area (GWIS) — North America	Wildfire	Global Wildfire Information System (GWIS/JRC), via Our World in Data Annual	hectares	2002–2024
Wildfire — Burned Area (GWIS) — Oceania	Wildfire	Global Wildfire Information System (GWIS/JRC), via Our World in Data Annual	hectares	2002–2024
Wildfire — Burned Area (GWIS) — South America	Wildfire	Global Wildfire Information System (GWIS/JRC), via Our World in Data Annual	hectares	2002–2024
Wildfire — Dry Matter Combusted (GFED5)	Wildfire	Global Fire Emissions Database (GFED5) Annual	1e12 g/year (DM)	2001–2024
Wildfire — Dry Matter Combusted (GFED5) — Africa	Wildfire	Global Fire Emissions Database (GFED5) Annual	1e12 g/year (DM)	2001–2024
Wildfire — Dry Matter Combusted (GFED5) — Asia	Wildfire	Global Fire Emissions Database (GFED5) Annual	1e12 g/year (DM)	2001–2024
Wildfire — Dry Matter Combusted (GFED5) — Europe	Wildfire	Global Fire Emissions Database (GFED5) Annual	1e12 g/year (DM)	2001–2024
Wildfire — Dry Matter Combusted (GFED5) — North America	Wildfire	Global Fire Emissions Database (GFED5) Annual	1e12 g/year (DM)	2001–2024
Wildfire — Dry Matter Combusted (GFED5) — Oceania	Wildfire	Global Fire Emissions Database (GFED5) Annual	1e12 g/year (DM)	2001–2024

VARIABLE	PHENOMENON	SOURCE	UNIT	WINDOW
Wildfire — Dry Matter Combusted (GFED5) — South America	Wildfire	Global Fire Emissions Database (GFED5) Annual	1e12 g/year (DM)	2001–2024
Wildfire — Global Burned Area (GWIS)	Wildfire	Global Wildfire Information System (GWIS/JRC), via Our World in Data Annual	hectares	2002–2024
Extratropical Cyclone Intensity — Minimum Pressure	Winter Storms	CEDA / TRACK catalog (Gray, Volonte, Martinez-Alvarado, Harvey 2024) Annual	hPa (lower = more intense)	1980–2021
Extratropical Cyclone Intensity — Minimum Pressure — Asia	Winter Storms	CEDA / TRACK catalog (Gray, Volonte, Martinez-Alvarado, Harvey 2024) Annual	hPa (lower = more intense)	1980–2021
Extratropical Cyclone Intensity — Minimum Pressure — Europe	Winter Storms	CEDA / TRACK catalog (Gray, Volonte, Martinez-Alvarado, Harvey 2024) Annual	hPa (lower = more intense)	1980–2021
Extratropical Cyclone Intensity — Minimum Pressure — North America	Winter Storms	CEDA / TRACK catalog (Gray, Volonte, Martinez-Alvarado, Harvey 2024) Annual	hPa (lower = more intense)	1980–2021

Appendix B: Full Bibliography

The complete citation list backing the GWX dashboard's methods and findings, grouped by topic — identical to the Library page.

Tropical Cyclones

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- Barichivich, J., Gloor, E., Peylin, P., Brienen, R.J.W., Schöngart, J., Espinoza, J.C., Pattnayak, K.C. (2018). Recent intensification of Amazon flooding extremes driven by strengthened Walker circulation. *Science Advances, 4(9), eaat8785*. Basis for the South America continent-page flooding note: a fivefold increase in severe Amazon floods at Manaus since the early 2000s.

- Do, H.X., Westra, S., Leonard, M. (2017). A global-scale investigation of trends in annual maximum streamflow. *Journal of Hydrology, 552, 28–43*. Basis for the Asia continent-page flooding note: Asia's average streamflow gauge record length (~17 years) is too short for a defensible long-term trend claim -- a data-coverage gap, not an absence of interest.

Loss Normalization

- Pielke Jr., R. (2020). Economic 'normalisation' of disaster losses 1998–2020: a literature review and assessment. *Environmental Hazards*. Source of the full Table 1 (53 weather/climate-related normalization studies) on the Loss Normalization page.
- Pielke Jr., R. (2019). Tracking progress on the economic costs of disasters under the indicators of the sustainable development goals. *Environmental Hazards, 18(1), 1–6*. Finds weather/climate disaster losses declined as a share of global GDP from 1990, even as absolute losses rose -- the indicator the Loss Normalization page's top chart extends through 2025.
- Mohleji, S., Pielke Jr., R. (2014). Reconciliation of trends in global and regional economic losses from weather events: 1980–2008. *Natural Hazards Review, 15(4), 04014009*. Source of the Loss Normalization page's economic-loss-by-phenomenon-and-continent pie charts (extended through 2025 with fresher EM-DAT data, replacing the paper's rate-of-increase framing).
- Centre for Research on the Epidemiology of Disasters (CRED), UCLouvain (2026). EM-DAT: The International Disaster Database. *emdat.be*. Source (via Our World in Data's public mirror) of the Loss Normalization page's economic-loss and fatality data, and the Flooding/Wildfire economic-context figures on this dashboard.
- Zhang, J., Trück, S., Truong, C., Pitt, D. (2023). Time trends in losses from major tornadoes in the United States. *Weather and Climate Extremes, 41, 100579*. Added to the Loss Normalization page's study table: a significant national decline in normalized US tornado losses, 1954-2018.
- Willoughby, H.E., Hernandez, J.I., Pinnock, A. (2024). Trends in U.S. Atlantic tropical cyclone damage, 1900–2022. *Journal of Applied Meteorology and Climatology, 63(12), 1499–1510*. Uses the ICAT Damage Estimator dataset (flagged in the study table's ICAT/BDD column); reports a detected increase in normalized US Atlantic hurricane damage. See Pielke (2025) below and this same author team's 2025 reply.

- Muller, J., Mooney, K., Bowen, S.G., Klotzbach, P.J., Martin, T., Philp, T.J., Bhatt, D., Dixon, R.S., Girimurugan, S.B. (2025). Normalized hurricane damage in the United States: 1900–2022. *Bulletin of the American Meteorological Society, 106(1), E51–E67*. Also uses the ICAT/combined dataset; finds no detected trend in normalized US hurricane damage over the full record.

- Pielke Jr., R. (2025). Do not use the ICAT hurricane loss "dataset": An opportunity for course correction in climate science. *Journal of Applied Meteorology and Climatology, 64(4)*. A direct critique of the ICAT Damage Estimator dataset's reliability as a basis for trend detection, aimed at Willoughby et al. (2024) and Muller et al. (2025) above -- see Willoughby et al.'s (2025) direct reply.

- Willoughby, H.E., Hernandez, J.I., Pinnock, A. (2025). Reply to Pielke (2025). *Journal of Applied Meteorology and Climatology, 64(4)*. Direct reply to the critique above; revises the authors' 2024 trend finding down to a weaker, not-statistically-significant 0.6%/year result.

- Paprotny, D., Tilloy, A., Treu, S., Buch, A., Vousdoukas, M.I., Feyen, L., Kreibich, H., Merz, B., Frieler, K., Mengel, M. (2025). Attribution of flood impacts shows strong benefits of adaptation in Europe since 1950. *Science Advances, 11, eadt7068*. Added to the study table: a detected decrease in normalized European flood losses, attributed to adaptation.

- Paprotny, D., Terefenko, P., Śledziowski, J. (2024). HANZE v2.1: An improved database of flood impacts in Europe from 1870 to 2020. *Earth System Science Data, 16, 5145–5170*. The underlying European flood-impact database Paprotny et al. (2025) above draws on; this paper finds reporting completeness, not a trend, dominates the raw 1870-2020 record's apparent pattern.

- Vessey, A.F., Baker, A.J., Marcellin-Honore, V., Michelin, J. (2026). Combining hazard, exposure and vulnerability data to predict historical United States hurricane losses. *Natural Hazards and Earth System Sciences, 26, 2133–2150*. Primarily a loss-prediction methodology paper; an upward fit in US hurricane losses (1979-2024) appears incidentally, not as a tested detection claim.

- Botzen, W.J.W., Estrada, F., Tol, R.S.J. (2021). Methodological issues in natural disaster loss normalisation studies. *Environmental Hazards, 20(2), 112–115*. A methods-focused commentary on normalization studies generally, added to the study table as a methods row (no empirical detection/attribution result).

Statistical Methodology

- Mann, H.B. (1945). Nonparametric tests against trend. *Econometrica, 13(3), 245–259*. The Mann-Kendall trend test itself -- the significance test lib/trend.ts applies to every variable on this site.
- Sen, P.K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association, 63(324), 1379–1389*. Sen's slope estimator -- the trend-magnitude (per-decade rate) figure shown on every chart's assessment text.
- Weatherhead, E.C., Reinsel, G.C., Tiao, G.C., Meng, X.-L., Choi, D., Cheang, W.-K., Keller, T., DeLuisi, J., Wuebbles, D.J., Kerr, J.B., Miller, A.J., Oltmans, S.J., Frederick, J.E. (1998). Factors affecting the detection of trends: Statistical considerations and applications to environmental data. *Journal of Geophysical Research, 103(D14), 17149–17161*. The standard formula this site uses to estimate how many years of record a trend of a given magnitude and noise level needs to be reliably detected -- shown as a caveat on non-detected results where it's binding, especially on noisier continent-scale series.
- Hamed, K.H., Rao, A.R. (1998). A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology, 204(1-4), 182–196*. Basis for the lag-1-autocorrelation effective-sample-size correction in lib/trend.ts -- a simplification of this paper's full multi-lag method, a GWX-specific enhancement not yet on the US dashboard.
- Benjamini, Y., Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society, Series B, 57(1), 289–300*. The false-discovery-rate correction lib/bhCorrection.ts applies across the headline variables tracked here -- see the Methodology page's multiple-comparisons section.
- Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences. *2nd edition, Routledge*. Reference point (Cohen's d ≈ 0.2/0.5/0.8 for small/medium/large effect) informing the magnitude-vs-natural-variability detection tier used here.

IPCC Assessment Reports

- IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*. The Sixth Assessment Report itself -- the comparison point for the Detection & Attribution page.