

Title: Early warning signals for Cyclone Alfred (2025): a moisture–convection co-burst precursor and an anomalous track in the 2024–25 Australian season

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Abstract: Storm genesis and rapid intensification depend on both **fuel** (precipitable water vapour, TQV) and **convective efficiency** (cooling at cloud tops, observed as depressed outgoing longwave radiation, LWTUP). Using MERRA-2 fields collocated to IBTrACS storm positions, we examine short-horizon “co-bursts” where TQV increases ahead of a storm while LWTUP simultaneously drops. We show that **Cyclone Alfred (2025)** exhibited **three distinct co-bursts within ~24 h**, a pattern not seen in any of the **other 31 storms** from the South Pacific and South Indian basins in 2024–25. Across the cohort, only **seven storms** produced a single co-burst; Alfred alone produced three, coincident with a pronounced track deviation toward the south-west and landfall much farther south than typical for the Coral Sea. We argue that co-bursts constitute an actionable early-warning cue and outline an operational rule. For within-storm diagnostics we use robust z-scores (median/MAD, clipped at ± 3) computed on each storm’s along-track series; for the historic SPI we use grid-point day-of-year baselines (2022–2025, 1° latitude $\times 1^\circ$ longitude).

Cyclone Alfred stood out from a total of 32 storms in the NOAA IBTrACS data collection for the SP and SI basins in the 2024-2025 season. It traversed an extremely unusual path, diverting south as far as the Queensland/New South Wales border, before crossing the coast. Around 3rd March, it sustained co-bursts of increased water vapour and decreased outgoing longwave radiation over a 24 hour period, the only storm to do so with concerted bursts in water vapour, accompanied by large drops in outgoing radiation. This was followed by large rises in pressure drops ahead and wind shear. This signal was extremely clear, as it was not found in another cyclone in the 2024-2025 season.

Background

Water vapor levels in the atmosphere have significantly increased in recent years. The most critical factor is the rise in global temperatures. As the air warms, it can hold more moisture - approximately 7% more for every 1°C increase in temperature.

As background moisture rises with a warming climate, the space–time alignment of water vapour supply and deep convection becomes increasingly decisive for storm behaviour. We observe that alignment by pairing a **fuel gradient** (ΔTQV 100 km ahead relative to the storm centre) with a **convection proxy** (negative ΔLWTUP ahead). When both spike together — a

co-burst — convection has “matched” the available fuel in the near field, a configuration we hypothesize can precipitate intensity spurts and even track anomalies.

We quantify surprising behaviour in terms of short-horizon intensity anomaly, in the case of Alfred, showing unusual tracking from standard route density by detecting co-bursts of both increased water vapour and decreased escaping longwave radiation within a short time frame. Spearman’s rho (ρ) correlation, used to assess the strength and direction of the association between these weather conditioning variables, was in the top 5% for Alfred - indicating an ‘ignition’ factor, which may have been sufficiently energetic to force Alfred onto a different track.

While seven of the season’s 32 cyclones exhibited a single co-burst of ≥ 2.5 standard deviations increase in convection ahead, with an accompanying ≥ 0.5 standard deviation in water vapour ahead, only Alfred showed this signal three times in a 24 hour period. The other cyclones showed this signal only once.

Key definitions

- **ΔTQV_ahead** : total column water vapour difference (“ahead minus here”) sampled ~ 100 km along the motion vector.
- **conv_ahead**: proxy for deep convection; we use $-\Delta OLR_ahead$ or $-(LW\uparrow_ahead - LW\uparrow_here)$. Higher values $\Rightarrow$ stronger convection.
- **Co-burst**: a time when conv_ahead crosses a z-threshold and ΔTQV_ahead is simultaneously elevated ($z \geq z_TQV$).
- **Near-zero-lag ρ** : Spearman correlation rho (ρ) scanned over ± 2 h; “ ρ_0 ” is the $|\rho|$ maximum within ± 2 h and its sign.
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- **Storm Propensity Index (SPI)** (historic, grid $1^\circ \times 1^\circ$, Day-of-Year (DOY) baseline 2022–2025): $z(TQV) \geq +3$, $z(LWTUP) \leq -3$ at $t-4$ days.
- **Storm Co-burst** (within-storm, robust z on the track series): $z(conv_ahead) \geq 2.5$ and $z(\Delta TQV_ahead) \geq 0.5$.

Metrics Used in the Study

ΔTQV_ahead (d_tqv_ahead) — “fuel gradient ahead”

- What it is: How much more (or less) precipitable water vapour sits 100 km ahead of the storm compared to the current storm position at the same time.
- Computed as: $d_tqv_ahead = tqv_ahead - tqv_here$ ($kg\ m^{-2}$).
- How to read it:
 - **Positive** → there's more fuel ahead (good for convection/precipitation).
 - **Negative** → the air ahead is drier than current location.

$conv_ahead$ — “convection proxy ahead”

- What it is: A simple, signed proxy for deep convection 100 km ahead using outgoing longwave radiation OLR (or LWTUP in NASA data). Lower OLR = colder cloud tops = stronger convection.
- How we compute: First $\Delta OLR_ahead = lwtup_ahead - lwtup_here$ ($W\ m^{-2}$). Then $conv_ahead = -\Delta OLR_ahead$.
- How to read it:
 - **Positive** → OLR drops ahead (colder tops), so more convection ahead
 - **Zero** → about the same.
 - **Negative** → less convection ahead.

$ready_light$ — “readiness dial”

- What it is: A standardized composite that says whether the column ahead is primed for convection right now. It blends fuel, a touch of lift, and reduced hostility.
- How we compute (per storm, z-scored within the storm's own time series):
 $ready_light = z(\Delta TQV_ahead) + 0.5 \cdot z(press_drop_ahead) - 0.5 \cdot z(shear_850_200)$
where
 - $press_drop_ahead$ is the positive version of the SLP slope ahead (lower pressure ahead $\Rightarrow$ positive), and
 - $shear_850_200$ is the vertical wind shear magnitude ($m\ s^{-1}$).
- How to read it:
 - **Big positive** → moist ahead, pressure tending lower ahead, shear tolerable → primed for a burst.
 - **Negative** → drier ahead and/or hostile shear → not primed.

Quick interpretation guide

- If $\Delta\text{TQV_ahead} \leftrightarrow \text{conv_ahead}$ peaks at lag ≈ 0 h, this is a snap-trigger regime: as soon as fuel appears ahead, convection responds now.
- If the peak is **leading**, fuel/ready leads convection by so many hours (preconditioning).
- If it's lagging, convection leads the water vapour, pressure drop and wind shear.

Methodology

MERRA-2 reanalyses (TQV, SLP, U/V at 850–250 hPa; LWTUP) and IBTrACS tracks data were accessed from NASA and NOAA respectively.

We use a standard pre-calculated z-score (how many standard deviations a data point is from the mean of a dataset) for increased water vapour **z(TQV)** and decreased radiation escaping at the top of the atmosphere **z(LWTUP)** where the divergence for each series is greater than 3 STD from the season/region wide standard deviations at a 1 degree latitude by 1 degree longitude grid. This is established as a Storm Propensity Index to identify probable early warning signals. See [Fractal and Early Warning Volatility Signals for Storms](#).

For each storm, at three hourly intervals by latitude and longitude, we derive weather and radiation metrics based on differences between water vapour, radiation, pressure and wind shear in the current location and ahead-of-track with a 100 km forward sample based on current trajectory.

Storm cards are generated both for **Alfred** and the other 31 cyclones.

Along-track environment features

- $\Delta\text{TQV_ahead} = \text{TQV_ahead} - \text{TQV_here}$ (kg m^{-2}) — “fuel gradient”.
- $\text{conv_ahead} = -\Delta\text{LWTUP_ahead} = -(\text{LWTUP_ahead} - \text{LWTUP_here})$ (W m^{-2}).
- $\text{press_drop_ahead} = -\partial\text{SLP}/\partial s$ along track (**hPa per 100 km**). We compute the along-track SLP slope (hPa/km) and multiply by 100 for reporting.
- $\text{shear_850_200} = |V(200 \text{ hPa}) - V(850 \text{ hPa})|$ (m s^{-1})

Z-scores in figures are dimensionless.

Normalization

For within-storm diagnostics we use **robust z-scores** (median/MAD, clipped at ± 3) to reduce leverage from outliers. For the historic, grid-based **Storm Propensity Index (SPI)** used in prior work, indices were computed on $1^\circ \times 1^\circ$ lat/lon grids over **2022–2025** with a day-of-year baseline; $\text{SPI} > 0$ required **z(TQV) $\geq +3$** and **z(LWTUP) ≤ -3** at **t-4 days** relative to storms.

Cyclone Alfred

Cyclone Alfred charted a rarely seen path towards the southern coast of Australia, particularly impacting the Brisbane area. Typically, cyclones formed in the Coral Sea either drift towards the northeast or dissipate offshore. Alfred's trajectory was notably unpredictable, as forecasts initially suggested it would remain well offshore or affect central Queensland. Most Australian cyclones follow a path further north or remain well offshore. Instead, it took a sharper turn westward, with an exceptionally slow movement, making it unpredictable in comparison with cyclones in this region.

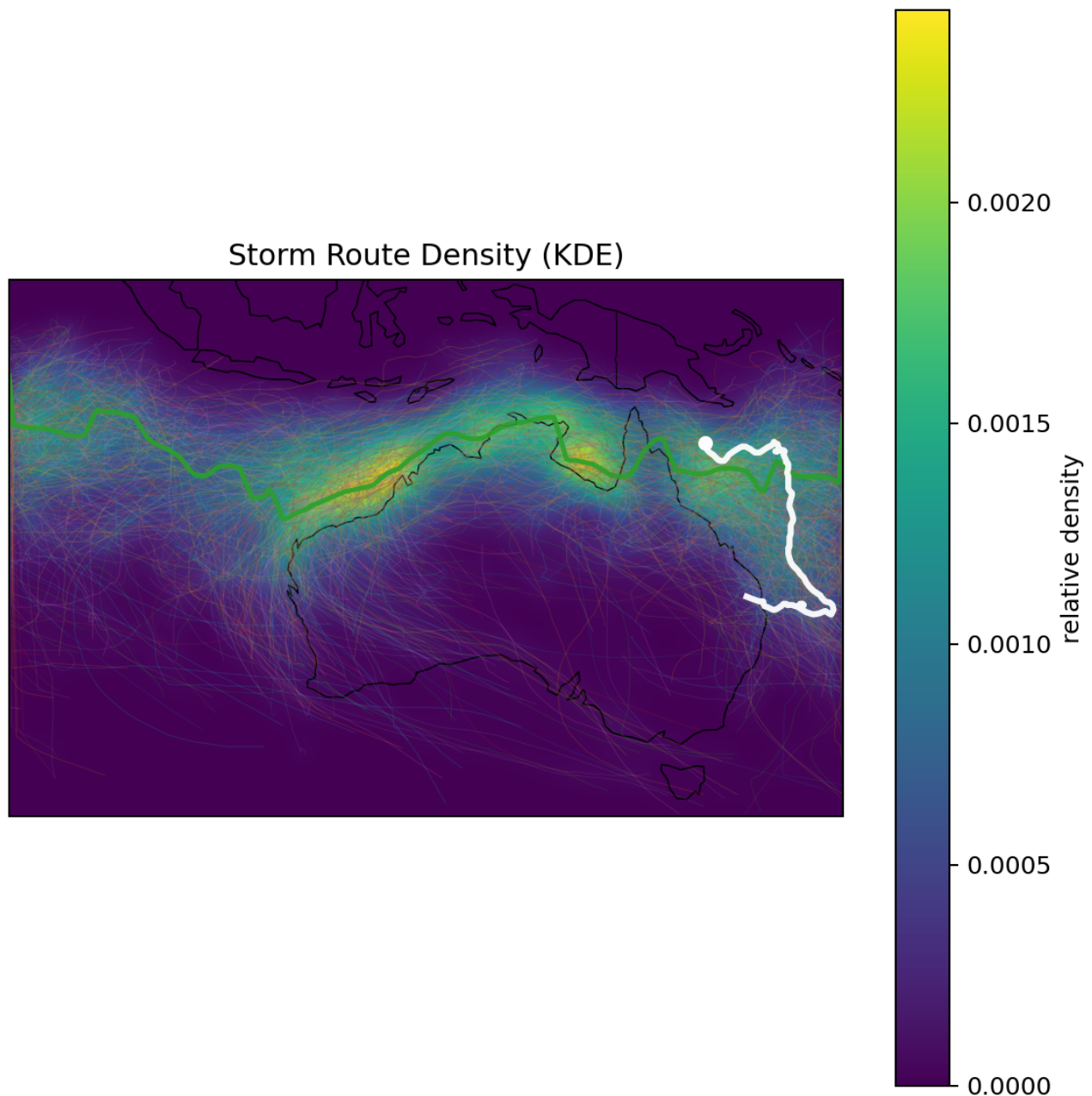


Figure — *Cyclone Alfred's 2025 trajectory, showing the relative route background density from IBTrACS data.*

The unusual turn westward towards the coast coincided with bursts of both increased precipitable water vapour and decreased outgoing longwave radiation, which indicates increased convection and more energy being utilised by the storm. The thresholds defined in this study were radiation delta decrease greater than 2.5 standard deviations and water vapour delta increase greater than 0.5 standard deviations with the current trajectory 100 kms ahead.

The following figures provide graphical representation of cyclone Alfred tracking.

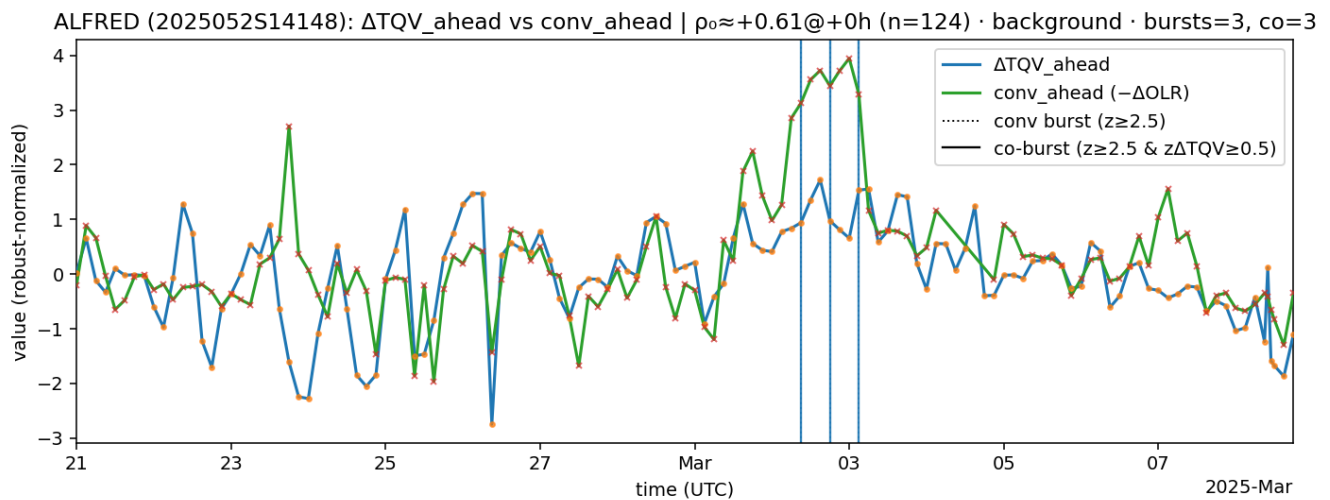


Figure A — ΔTQV_ahead vs $conv_ahead$ for Alfred (21-2-2025 - 08-3-2025 UTC). Blue: ΔTQV_ahead (z), green: $conv_ahead$ (z). Vertical lines mark co-bursts ($z \geq 2.5$).

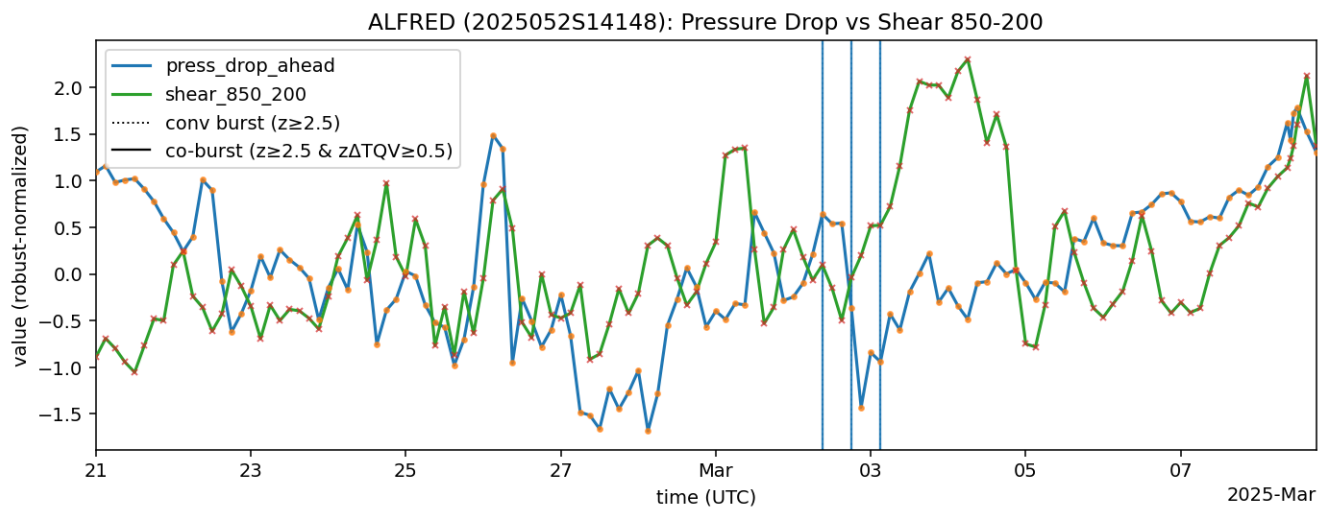


Figure B — Pressure-drop-ahead (z) vs shear_850–200 (z). Note the shear increase following the co-burst window.

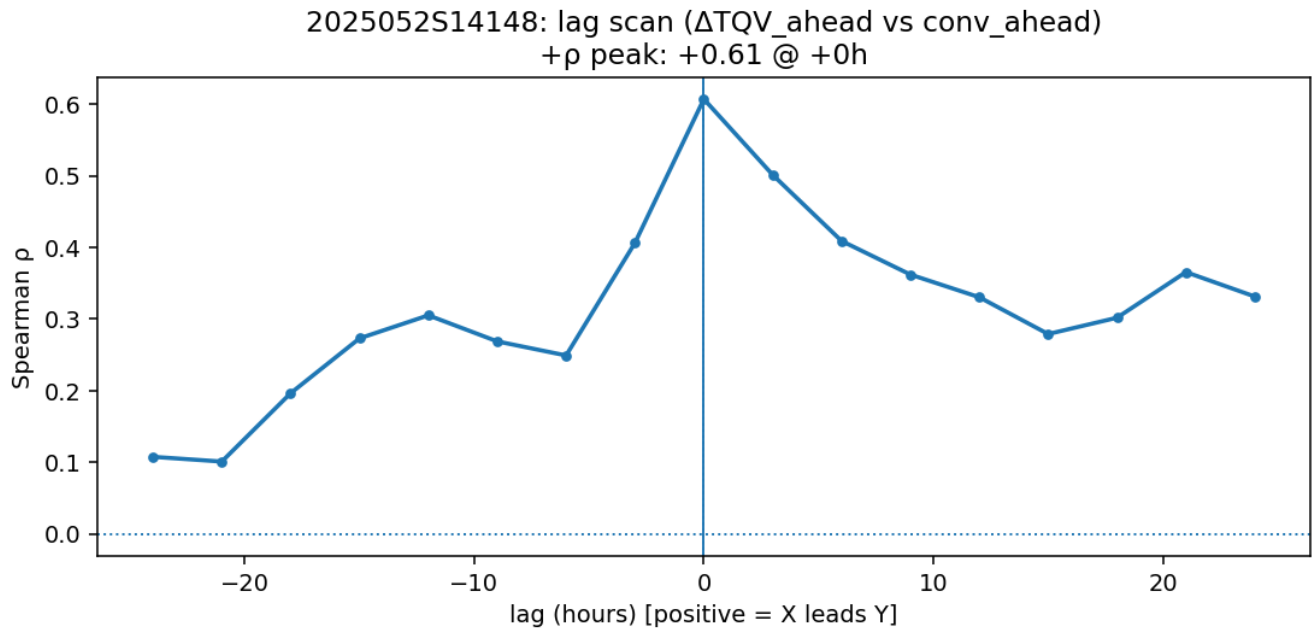


Figure C — *Lag scan: $\Delta TQV_ahead \rightarrow conv_ahead$* . Spearman ρ across $-24 \dots +24$ h. Note the peak $\rho \approx 0$. A peak near $\rho \approx 0$ is consistent with a ‘snap’ regime where convection responds almost immediately to fuel changes; (we avoid causal claims given small- n).

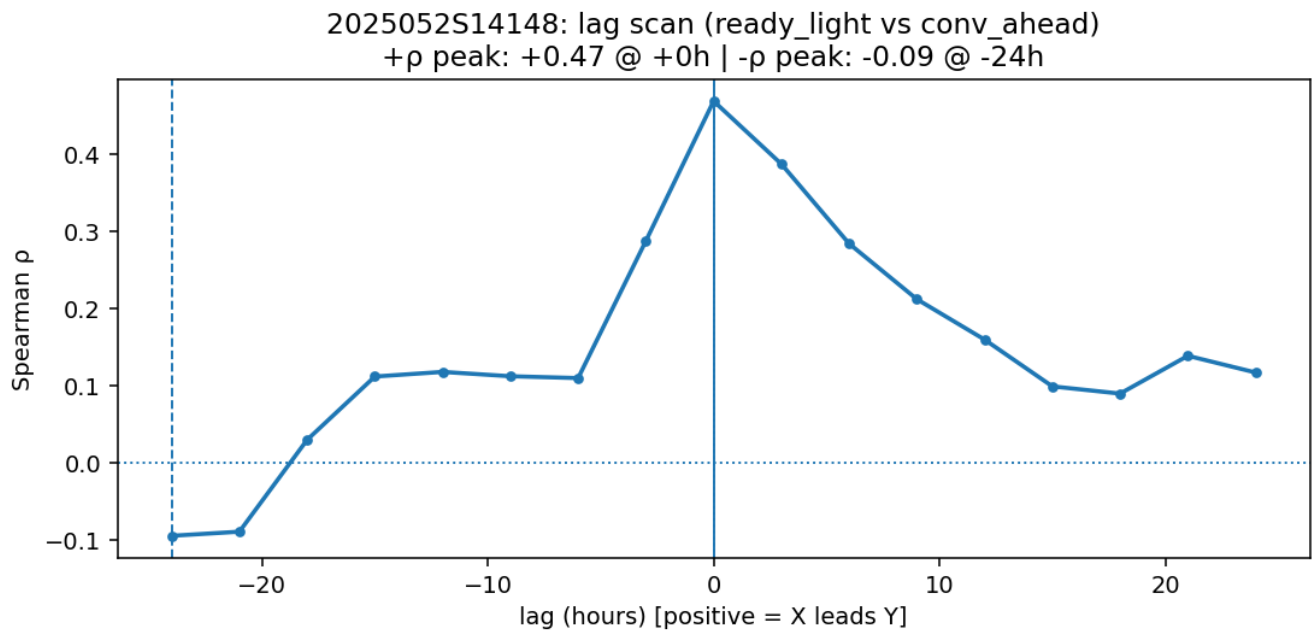


Figure D — *Lag scan: $ready_light \rightarrow conv_ahead$* . Peak $\rho \approx 0$.

Cohort comparison

Of **32 storms** in the season sample, **seven** exhibited a **single** co-burst; **only Alfred** showed **three** distinct co-bursts in a day. This makes Alfred the clear outlier in short-horizon intensity priming and aligns with its **track anomaly** toward the south-west and landfall far south of typical Coral Sea trajectories. See [storm cards for all cyclones](#). Alfred also exhibited a clear synchronicity of water vapour and radiation bursts (lag 0), while not unique, was relatively rare amongst all cyclones. Possible interpretation is that with no other avenue of release, the sudden energy burst shifted the storm's vortex, and affected the storm's path.

Discussion

Mechanism. Co-bursts are moments when fuel and convective efficiency line up in the immediate path of the storm. In Alfred, repeated alignment likely produced an **impulse of diabatic heating** and vortex stretching sufficient to alter the steering depth and nudge the track into an otherwise low-density corridor. The subsequent rise in shear and weakening of pressure support matches the observed decay in convective signal.

Operational cue. A simple rule is effective in practice:

- **Flag** when $z(\text{conv_ahead}) \geq 2.5$ and $z(\Delta\text{TQV_ahead}) \geq 0.5$ at least **twice in 24 h**;
- **Elevate** if the **+p lag peak** > 0.3 with a **lead** $\geq +12$ h (preconditioning present).

Sensitivity and limitations

- **Thresholds.** 2.5/0.5 is conservative; 2.0/0.3 increases recall but adds false positives.
- **Baselines.** Within-storm robust z's stabilize diagnostics; the historic SPI uses a **multi-year DOY baseline** on 1° grids to be “apples to apples” by geography, which is preferable for long-term comparisons.
- **Sampling.** “Ahead” is fixed at **100 km**; other distances (50–150 km) give similar patterns but shift amplitudes.
- **Data.** Reanalyses are not truth; convective extremes can be smoothed. Small-n cohort ($n=32$) limits inference on rates, but the Alfred outlier remains.
- **Attribution.** We discuss **consistency**, not causality; background circulation shifts late-2024 may be relevant but are outside scope.

Storm Season Timeframe: These results cover the South Pacific and South Indian basins in the 2024–2025 cyclone season (IBTrACS), n=32 storms.

Findings and Recommendations

Cyclone Alfred’s three moisture–convection **co-bursts** within a day, paired with lag evidence of **moisture leading convection**, identify a compact early-warning signature that preceded a rare **track deviation**. Across 32 storms in 2024–25, this pattern is **unique to Alfred**, suggesting that short, high-amplitude alignment of fuel and convective efficiency can both **amplify intensity** and **perturb tracks**. The proposed rule is simple enough for operations and robust to baseline choices.

Application of this methodology to storms globally would be useful to determine whether this is universal or peculiar to Australian cyclones.

In storm systems, moisture is a critical component. Particle advection helps meteorologists understand how moisture is transported into and within storms, influencing precipitation patterns. Tracking Moisture Transport and how moisture from the surrounding environment is drawn into the storm, where convection processes may lead to rapid rainfall and severe weather, may increase understanding of storm path behaviour.

In future, a numerical finite-time Lyapunov exponent (**FTLE**) approach may provide a dynamical instability proxy, A next step may be to track particle-advection using $FTLE \approx (1/\Delta t) \cdot \ln \sigma_{\max}(\partial\Phi/\partial x)$.

In addition tracking aerosol particle density could also be useful for fine tuning of storm forecasting. See Proposed Further Analysis section *ibid*.

Explanatory Notes

We thank collaborators in prior SPI work and acknowledge the NASA GMAO MERRA-2 team and the IBTrACS project.

Data and code availability

IBTrACS storm tracks and NASA MERRA-2 reanalyses were used. Derived along-track features (parquet) and plotting scripts are available upon request; figures in this manuscript are reproducible from those artefacts. Data collections and plots for this study are available [here](#). This includes:

Figures generated by storm card generation python; filenames: _A_dtqv_vs_conv_norm.png, _B_press_vs_shear.png, _C_lags_dtqv_conv.png, _D_lags_ready_conv.png

Acronyms

References

NASA MERRA-2 Data Source Information

<https://gmao.gsfc.nasa.gov/pubs/docs/Collow1253.pdf>

UK Met Office Past Weather Events

<https://www.metoffice.gov.uk/weather/learn-about/past-uk-weather-events>

Trac-Car OpenAI Fractal Analysis of Net Radiative Flux

<https://trac-car.com/Fractal%20Analysis%20of%20Net%20Radiative%20Flux.pdf>

Nolds Lyapunov Analysis Documentation

https://nolds.readthedocs.io/_/downloads/en/0.5.2/pdf/

NASA MERRA-2 <https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/>

Fractal and Volatility Early Warning Signals for Storms: Murray, Nya Alison

<https://zenodo.org/records/15774831>

Terminology

Term	Clarification
NASA MERRA-2 Data	The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) provides data beginning in 1980. It was introduced to replace the original MERRA dataset because of the advances made in the assimilation system that enable assimilation of modern hyperspectral radiance and microwave observations, along with GPS-Radio Occultation datasets.
IBTrACS	International Best Track Archive for Climate Stewardship . It is a global database that contains historical tropical cyclone track and intensity information, primarily used for climate research and analysis.

TQV, Δ TQV	total precipitable water vapor kg m ⁻² , change in TQV
LWTUP, Δ LWTUP	upwelling longwave flux at toa W m ⁻² , change in LWTUP
OLR	Outgoing longwave radiation (another term for LWTUP)
Z-Score (median, MAD)	Z-score is a statistical measure that describes how far away a data point is from the mean (average) of a dataset, expressed in terms of standard deviations. However, when using the Median Absolute Deviation (MAD) method, the calculation is adjusted to provide a more robust measure, especially in datasets that may contain outliers.
Spearman correlation	Spearman's rho is a non-parametric measure of rank correlation that assesses the strength and direction of the association between two ranked variables.
press_drop_ahead	Pressure drop ahead calculated as the difference between the current location and 100 km along the motion vector.
KDE	Kernel Density Estimation (KDE) in relation to route density is a non-parametric statistical technique used to estimate the probability density function of a random variable, allowing for the visualization of the density of routes or points of interest on a map.
U850, V850, U250, V250	eastward wind at 850 hPa,northward wind at 850 hPa,eastward wind at 250 hPa,northward wind at 250 hPa, used to calculate wind shear.
Convection	Storm convection is the process by which warm, moist air rises in a storm system, leading to cloud formation and precipitation as it cools and condenses at higher altitudes.
Co-burst	In this context, a dramatic change in both water vapour (increase) and outgoing longwave radiation (decrease)
SPI	Storm Propensity Index
FTLE	Finite-time Lyapunov exponents (FTLE). Applied to storm particle convection measures the rate of stretching of particles in a turbulent

	flow, indicating how quickly and in what manner particles are dispersed within the storm system over a specified time interval.
Okubo-Weiss analysis	Okubo-Weiss analysis in a storm context examines the balance between vorticity (rotation) and strain (deformation) in a fluid flow, helping to identify areas of potential cyclonic or anticyclonic rotation within storm systems. This analysis aids in understanding storm dynamics, stability, and the development of features like mesocyclones, allowing meteorologists to better predict storm behavior and intensity.
Satellite AOD	Aerosol Optical Depth (AOD) measured by satellites quantifies the extent to which aerosols absorb and scatter sunlight in the atmosphere, providing insights into aerosol concentration, distribution, and their impact on climate and air quality. This data is crucial for understanding the role of aerosols in atmospheric processes, including their influence on weather patterns and radiative forcing.

Storm Propensity Index Trigger Table by Storm 2022 - 2025

To quantify pre-storm anomaly, a **Storm Propensity Index (SPI)** was defined using the following criteria:

- For each spatial bin and date, if:
 - TQV index (4 days later) $\geq +3.0$, and
 - LWTUP index (4 days later) ≤ -3.0 ,
- Then, SPI is triggered:

$$SPI = 0.5 \times (|TQV_{lead}| + |LWTUP_{lead}|)$$

$$\{SPI\} = 0.5 \times (|TQV_{lead}| + |LWTUP_{lead}|)$$
- Otherwise, SPI = 0.

This metric aims to detect **simultaneous excess moisture and energy trapping**, which are hypothesized to precede convective instability and storm genesis.

SPI uses $z(TQV) \geq +3$ and $z(LWTUP) \leq -3$ evaluated **at t-4 days**; the table lists the **start** of the 14-day pre-genesis window over which we count SPI>0 days.

Storm Name	14 Day Lead Date	Date	Storm Region	No of Days Storm Precursor Triggered over 14 Days Prior to Storm
ADRIAN	2023-06-13	2023-06-27	East Pacific	12
AERE	2022-06-15	2022-06-29	West Pacific	7
AGATHA	2022-05-13	2022-05-27	North Atlantic (FL)	6
ALBERTO	2024-06-03	2024-06-17	North Atlantic (FL)	9
ALETTA	2024-06-19	2024-07-03	East Pacific	7
ALEX	2022-05-19	2022-06-02	North Atlantic (FL)	8
ALFRED	2025-02-07	2025-02-21	South Pacific	13
ALVARO	2023-12-18	2024-01-01	South Indian Ocean	10
AMPIL	2024-07-28	2024-08-11	West Pacific	12
ANA	2022-01-06	2022-01-20	South Indian Ocean	14
ANCHA	2024-09-17	2024-10-01	South Indian Ocean	11
ANGGREK	2023-12-29	2024-01-12	South Indian Ocean	12
ANIKA	2022-02-09	2022-02-23	South Pacific	12
ARLENE	2023-05-17	2023-05-31	North Atlantic (FL)	11
ASANI	2022-04-21	2022-05-05	North Indian Ocean	11
ASHLEY	2022-09-11	2022-09-25	South Indian Ocean	13
ASNA	2024-08-16	2024-08-30	North Indian Ocean	12
BALITA	2022-09-19	2022-10-03	South Indian Ocean	13
BANYAN	2022-10-14	2022-10-28	West Pacific	10
BARIJAT	2024-09-20	2024-10-04	West Pacific	12
BATSIRAI	2022-01-10	2022-01-24	South Indian Ocean	15
BEATRIZ	2023-06-15	2023-06-29	North Atlantic (FL)	13

BEBINCA	2024-08-26	2024-09-09	West Pacific	9
BELAL	2023-12-29	2024-01-12	South Indian Ocean	12
BERYL	2024-06-14	2024-06-28	Far East Atlantic	9
BHEKI	2024-10-31	2024-11-14	South Indian Ocean	13
BIANCA	2025-02-05	2025-02-19	South Pacific	13
BILLY	2022-02-26	2022-03-12	South Indian Ocean	10
BIPARJOY	2023-05-22	2023-06-05	North Indian Ocean	12
BLAS	2022-05-31	2022-06-14	East Pacific	12
BOLAVEN	2023-09-22	2023-10-06	West Pacific	9
BONNIE	2022-06-13	2022-06-27	Far East Atlantic	9
BRET	2023-06-05	2023-06-19	Far East Atlantic	7
BUD	2024-07-10	2024-07-24	East Pacific	7
CALVIN	2023-06-26	2023-07-10	North Atlantic (FL)	14
CANDICE	2024-01-11	2024-01-25	South Indian Ocean	12
CARLOTTA	2024-07-17	2024-07-31	East Pacific	11
CELIA	2022-06-02	2022-06-16	North Atlantic (FL)	12
CHABA	2022-06-14	2022-06-28	West Pacific	8
CHARLOTTE	2022-03-03	2022-03-17	South Pacific	8
CHENESO	2022-12-30	2023-01-13	South Indian Ocean	10
CHIDO	2024-11-25	2024-12-09	South Indian Ocean	15
CHRIS	2024-06-16	2024-06-30	North Atlantic (FL)	7
CIMARON	2024-09-09	2024-09-23	West Pacific	12
CINDY	2023-06-08	2023-06-22	Far East Atlantic	9
CLIFF	2022-01-19	2022-02-02	South Indian Ocean	11

CODY	2021-12-24	2022-01-07	Western South Pacific	7
COLIN	2022-06-17	2022-07-01	North Atlantic (FL)	7
COURTNEY	2025-03-08	2025-03-22	South Pacific	13
DAMREY	2023-08-07	2023-08-21	West Pacific	15
DANA	2024-10-09	2024-10-23	North Indian Ocean	10
DANIEL	2024-07-20	2024-08-03	East Pacific	11
DANIELLE	2022-08-17	2022-08-31	Mid-Atlantic Drift	13
DARBY	2022-06-25	2022-07-09	East Pacific	6
DARIAN	2022-11-28	2022-12-12	South Indian Ocean	10
DEBBY	2024-07-19	2024-08-02	North Atlantic (FL)	12
DIANNE	2025-03-12	2025-03-26	South Pacific	13
DIKELEDI	2024-12-26	2025-01-09	South Indian Ocean	10
DINGANI	2023-01-17	2023-01-31	South Indian Ocean	13
DJOUNGOU	2024-02-01	2024-02-15	South Indian Ocean	11
DOKSURI	2023-07-06	2023-07-20	West Pacific	12
DON	2023-06-27	2023-07-11	Mid-Atlantic Drift	14
DORA	2023-07-17	2023-07-31	East Pacific	11
DOVI	2022-01-24	2022-02-07	Western South Pacific	11
DUMAKO	2022-01-28	2022-02-11	South Indian Ocean	11
EARL	2022-08-19	2022-09-02	Far East Atlantic	11
ELEANOR	2024-02-05	2024-02-19	South Indian Ocean	11
ELLIE	2022-12-07	2022-12-21	South Pacific	11
ELVIS	2025-01-15	2025-01-29	South Indian Ocean	12
EMILIA	2024-07-21	2024-08-04	East Pacific	11

EMILY	2023-08-04	2023-08-18	Far East Atlantic	13
EMNATI	2022-01-22	2022-02-05	South Indian Ocean	11
ENALA	2023-02-04	2023-02-18	South Indian Ocean	12
ERNESTO	2024-07-28	2024-08-11	Far East Atlantic	12
ERROL	2025-03-26	2025-04-09	South Pacific	12
ESTELLE	2022-07-01	2022-07-15	North Atlantic (FL)	9
EUGENE	2023-07-21	2023-08-04	East Pacific	11
EVA	2022-02-12	2022-02-26	Western South Pacific	13
EWINIAR	2024-05-09	2024-05-23	West Pacific	12
FABIEN	2023-04-28	2023-05-12	South Indian Ocean	14
FABIO	2024-07-22	2024-08-05	East Pacific	12
FAIDA	2025-01-14	2025-01-28	South Indian Ocean	12
FENGAL	2024-11-15	2024-11-29	North Indian Ocean	15
FERNANDA	2023-07-29	2023-08-12	East Pacific	13
FEZILE	2022-02-01	2022-02-15	South Indian Ocean	13
FILI	2022-03-20	2022-04-03	Western South Pacific	13
FILIPO	2024-02-25	2024-03-10	South Pacific	12
FIONA	2022-08-31	2022-09-14	Far East Atlantic	12
FRANCINE	2024-08-25	2024-09-08	North Atlantic (FL)	9
FRANK	2022-07-11	2022-07-25	North Atlantic (FL)	8
FRANKLIN	2023-08-05	2023-08-19	North Atlantic (FL)	14
FREDDY	2023-01-21	2023-02-04	South Pacific	13
GABRIELLE	2023-01-22	2023-02-05	Western South Pacific	12
GAEMI	2024-07-05	2024-07-19	West Pacific	9

GAMANE	2024-03-12	2024-03-26	South Indian Ocean	13
GARANCE	2025-02-11	2025-02-25	South Indian Ocean	13
GASTON	2022-09-05	2022-09-19	Mid-Atlantic Drift	13
GEORGETTE	2022-07-13	2022-07-27	East Pacific	8
GERT	2023-08-05	2023-08-19	Far East Atlantic	14
GILMA	2024-08-04	2024-08-18	East Pacific	12
GINA	2022-05-02	2022-05-16	Western South Pacific	11
GOMBE	2022-02-20	2022-03-06	South Indian Ocean	13
GORDON	2024-08-28	2024-09-11	Far East Atlantic	8
GREG	2023-07-31	2023-08-14	East Pacific	13
GUCHOL	2023-05-21	2023-06-04	West Pacific	13
HAIKUI	2023-08-13	2023-08-27	West Pacific	12
HAITANG	2022-09-27	2022-10-11	West Pacific	10
HAITANG	2022-09-30	2022-10-14	West Pacific	12
HALE	2022-12-21	2023-01-04	South Pacific	9
HALIMA	2022-03-06	2022-03-20	South Indian Ocean	9
HAMOON	2023-10-06	2023-10-20	North Indian Ocean	9
HAROLD	2023-08-07	2023-08-21	North Atlantic (FL)	15
HECTOR	2024-08-08	2024-08-22	East Pacific	13
HELENE	2024-09-09	2024-09-23	North Atlantic (FL)	12
HERMAN	2023-03-13	2023-03-27	South Indian Ocean	10
HERMINE	2022-09-09	2022-09-23	Far East Atlantic	13
HIDAYA	2024-04-17	2024-05-01	South Indian Ocean	10
HILARY	2023-08-02	2023-08-16	East Pacific	13

HINNAMNOR	2022-08-13	2022-08-27	West Pacific	13
HONDE	2025-02-11	2025-02-25	South Pacific	13
HONE	2024-08-05	2024-08-19	East Pacific	13
HOWARD	2022-07-23	2022-08-06	East Pacific	13
IALY	2024-05-02	2024-05-16	South Indian Ocean	8
IAN	2022-09-08	2022-09-22	North Atlantic (FL)	13
IDALIA	2023-08-12	2023-08-26	North Atlantic (FL)	13
ILEANA	2024-08-28	2024-09-11	East Pacific	8
ILSA	2023-03-22	2023-04-05	South Pacific	12
IRENE	2023-01-01	2023-01-15	Australian Cyclones	9
IRWIN	2023-08-12	2023-08-26	East Pacific	13
ISAAC	2024-09-10	2024-09-24	Mid-Atlantic Drift	12
ISSA	2022-03-29	2022-04-12	Unclassified	14
IVETTE	2022-07-29	2022-08-12	East Pacific	9
IVONE	2025-02-22	2025-03-08	South Indian Ocean	13
JASMINE	2022-04-06	2022-04-20	South Indian Ocean	15
JASPER	2023-11-18	2023-12-02	Western South Pacific	10
JAVIER	2022-08-17	2022-08-31	East Pacific	13
JEBI	2024-09-11	2024-09-25	West Pacific	12
JELAWAT	2023-11-30	2023-12-14	Western North Pacific	9
JOHN	2024-09-08	2024-09-22	North Atlantic (FL)	11
JONGDARI	2024-08-04	2024-08-18	West Pacific	12
JOSE	2023-08-15	2023-08-29	Mid-Atlantic Drift	12
JOVA	2023-08-21	2023-09-04	East Pacific	11

JOYCE	2024-09-13	2024-09-27	Far East Atlantic	12
JUDE	2025-02-22	2025-03-08	South Indian Ocean	13
JUDY	2023-02-10	2023-02-24	Western South Pacific	15
JULIA	2022-09-22	2022-10-06	North Atlantic (FL)	12
KARIM	2022-04-21	2022-05-05	South Indian Ocean	11
KARL	2022-09-27	2022-10-11	North Atlantic (FL)	10
KATIA	2023-08-16	2023-08-30	Far East Atlantic	12
KAY	2022-08-21	2022-09-04	East Pacific	12
KENNETH	2023-09-04	2023-09-18	East Pacific	12
KEVIN	2023-02-13	2023-02-27	South Pacific	15
KHANUN	2023-07-12	2023-07-26	West Pacific	10
KIRK	2024-09-15	2024-09-29	Far East Atlantic	12
KIROGI	2023-08-15	2023-08-29	West Pacific	12
KIRRILY	2024-01-03	2024-01-17	Australian Cyclones	12
KOINU	2023-09-13	2023-09-27	West Pacific	11
KONG-REY	2024-10-10	2024-10-24	West Pacific	11
KRATHON	2024-09-12	2024-09-26	West Pacific	13
KRISTY	2024-10-07	2024-10-21	North Atlantic (FL)	9
KULAP	2022-09-11	2022-09-25	West Pacific	13
LAN	2023-07-23	2023-08-06	West Pacific	10
LANE	2024-10-18	2024-11-01	East Pacific	8
LEE	2023-08-22	2023-09-05	Far East Atlantic	11
LEEPI	2024-08-18	2024-09-01	West Pacific	12
LESLIE	2024-09-17	2024-10-01	Far East Atlantic	11

LESTER	2022-09-01	2022-09-15	North Atlantic (FL)	11
LIDIA	2023-09-19	2023-10-03	East Pacific	11
LINCOLN	2024-01-31	2024-02-14	South Pacific	11
LISA	2022-10-16	2022-10-30	North Atlantic (FL)	9
LOLA	2023-10-05	2023-10-19	Western South Pacific	8
MA-ON	2022-08-06	2022-08-20	West Pacific	10
MADELINE	2022-08-28	2022-09-11	East Pacific	13
MAL	2023-10-29	2023-11-12	Western South Pacific	12
MALAKAS	2022-03-23	2022-04-06	Western North Pacific	13
MALIKSI	2024-05-16	2024-05-30	West Pacific	13
MAN-YI	2024-10-24	2024-11-07	Western North Pacific	11
MANDOUS	2022-11-20	2022-12-04	North Indian Ocean	10
MARGOT	2023-08-24	2023-09-07	Far East Atlantic	11
MARIA	2024-07-22	2024-08-05	West Pacific	12
MARTIN	2022-10-16	2022-10-30	North Atlantic (FL)	9
MAWAR	2023-05-04	2023-05-18	West Pacific	15
MAX	2023-09-24	2023-10-08	North Atlantic (FL)	8
MEARI	2022-07-25	2022-08-08	West Pacific	11
MEGAN	2024-02-28	2024-03-13	South Pacific	13
MEGI	2022-03-25	2022-04-08	West Pacific	14
MERBOK	2022-08-27	2022-09-10	West Pacific	13
MICHAUNG	2023-11-16	2023-11-30	North Indian Ocean	9
MIDHILI	2023-10-30	2023-11-13	North Indian Ocean	13
MILTON	2024-09-20	2024-10-04	North Atlantic (FL)	12

MOCHA	2023-04-24	2023-05-08	North Indian Ocean	10
MUIFA	2022-08-20	2022-09-03	West Pacific	11
MULAN	2022-07-25	2022-08-08	West Pacific	11
NADINE	2024-10-04	2024-10-18	North Atlantic (FL)	9
NALGAE	2022-10-12	2022-10-26	West Pacific	12
NANMADOL	2022-08-28	2022-09-11	West Pacific	13
NAT	2024-01-22	2024-02-05	Western South Pacific	9
NESAT	2022-09-28	2022-10-12	West Pacific	11
NEVILLE	2024-02-22	2024-03-07	South Indian Ocean	9
NEWTON	2022-09-07	2022-09-21	East Pacific	13
NICOLE	2022-10-23	2022-11-06	North Atlantic (FL)	4
NIGEL	2023-09-01	2023-09-15	Far East Atlantic	11
NORMA	2023-10-03	2023-10-17	East Pacific	7
NORU	2022-09-07	2022-09-21	West Pacific	13
OLGA	2024-03-21	2024-04-04	South Pacific	12
OPHELIA	2023-09-07	2023-09-21	North Atlantic (FL)	12
ORLENE	2022-09-14	2022-09-28	East Pacific	11
OSAI	2024-01-23	2024-02-06	Western South Pacific	9
OSCAR	2024-10-05	2024-10-19	North Atlantic (FL)	9
OTIS	2023-10-07	2023-10-21	North Atlantic (FL)	8
PABUK	2024-12-07	2024-12-21	West Pacific	9
PAINE	2022-09-19	2022-10-03	East Pacific	13
PAKHAR	2022-11-24	2022-12-08	West Pacific	12
PATTY	2024-10-17	2024-10-31	Mid-Atlantic Drift	8

PAUL	2024-03-26	2024-04-09	Australian Cyclones	11
PHILIPPE	2023-09-09	2023-09-23	Far East Atlantic	12
PILAR	2023-10-14	2023-10-28	North Atlantic (FL)	12
PITA	2024-12-28	2025-01-11	Western South Pacific	10
PRAPIROON	2024-07-05	2024-07-19	West Pacific	9
PULASAN	2024-09-01	2024-09-15	West Pacific	10
RAE	2025-02-08	2025-02-22	Western South Pacific	13
RAFAEL	2024-10-20	2024-11-03	North Atlantic (FL)	9
RAMON	2023-11-07	2023-11-21	East Pacific	10
REMAL	2024-05-11	2024-05-25	North Indian Ocean	13
RINA	2023-09-14	2023-09-28	Far East Atlantic	11
ROBYN	2024-11-09	2024-11-23	South Indian Ocean	14
ROKE	2022-09-12	2022-09-26	West Pacific	13
ROSLYN	2022-10-06	2022-10-20	East Pacific	12
SANBA	2023-10-01	2023-10-15	West Pacific	7
SANVU	2023-04-04	2023-04-18	Western North Pacific	10
SAOLA	2023-08-08	2023-08-22	West Pacific	15
SARA	2024-10-30	2024-11-13	North Atlantic (FL)	12
SEAN	2023-09-26	2023-10-10	Far East Atlantic	9
SEAN	2025-01-03	2025-01-17	South Pacific	13
SERU	2025-02-10	2025-02-24	Western South Pacific	13
SHANSHAN	2024-08-06	2024-08-20	West Pacific	13
SITRANG	2022-10-07	2022-10-21	North Indian Ocean	13
SON-TINH	2024-07-27	2024-08-10	West Pacific	12

SONCA	2022-09-28	2022-10-12	West Pacific	11
SONGDA	2022-07-12	2022-07-26	West Pacific	8
SOULIK	2024-09-01	2024-09-15	West Pacific	10
TALAS	2022-09-05	2022-09-19	West Pacific	13
TALIAH	2025-01-17	2025-01-31	South Pacific	12
TALIM	2023-06-29	2023-07-13	West Pacific	14
TAM	2025-03-31	2025-04-14	Western South Pacific	15
TAMMY	2023-10-04	2023-10-18	Far East Atlantic	7
TEJ	2023-10-05	2023-10-19	North Indian Ocean	8
TIFFANY	2021-12-25	2022-01-08	South Pacific	8
TOKAGE	2022-08-07	2022-08-21	West Pacific	10
TORAJI	2024-10-25	2024-11-08	West Pacific	11
TRAMI	2024-10-04	2024-10-18	West Pacific	9
TRASES	2022-07-15	2022-07-29	West Pacific	10
UNNAMED1	2023-07-06	2023-07-20	East Pacific	12
UNNAMED10	2022-07-26	2022-08-09	North Indian Ocean	11
UNNAMED11	2022-07-28	2022-08-11	North Indian Ocean	9
UNNAMED12	2022-07-31	2022-08-14	North Indian Ocean	9
UNNAMED13	2022-08-03	2022-08-17	North Indian Ocean	10
UNNAMED14	2022-08-28	2022-09-11	North Indian Ocean	13
UNNAMED15	2022-11-06	2022-11-20	North Indian Ocean	10
UNNAMED16	2022-11-28	2022-12-12	North Indian Ocean	10
UNNAMED17	2022-12-08	2022-12-22	North Indian Ocean	11
UNNAMED18	2023-01-16	2023-01-30	North Indian Ocean	12

UNNAMED19	2023-05-25	2023-06-08	North Indian Ocean	10
UNNAMED2	2023-09-01	2023-09-15	East Pacific	11
UNNAMED20	2023-07-16	2023-07-30	North Indian Ocean	11
UNNAMED21	2023-09-16	2023-09-30	North Indian Ocean	12
UNNAMED22	2022-02-09	2022-02-23	South Indian Ocean	12
UNNAMED23	2022-02-13	2022-02-27	South Indian Ocean	13
UNNAMED24	2022-03-16	2022-03-30	South Indian Ocean	12
UNNAMED25	2022-04-09	2022-04-23	South Indian Ocean	15
UNNAMED26	2022-04-11	2022-04-25	South Indian Ocean	15
UNNAMED27	2022-07-13	2022-07-27	South Indian Ocean	8
UNNAMED28	2022-10-18	2022-11-01	South Indian Ocean	7
UNNAMED29	2023-02-08	2023-02-22	South Pacific	15
UNNAMED3	2023-09-09	2023-09-23	East Pacific	12
UNNAMED30	2024-01-17	2024-01-31	South Indian Ocean	10
UNNAMED31	2024-05-05	2024-05-19	South Indian Ocean	11
UNNAMED32	2024-12-10	2024-12-24	South Indian Ocean	7
UNNAMED33	2024-12-25	2025-01-08	South Indian Ocean	10
UNNAMED34	2025-03-03	2025-03-17	South Indian Ocean	13
UNNAMED35	2022-01-15	2022-01-29	South Pacific	14
UNNAMED36	2023-01-05	2023-01-19	Australian Cyclones	11
UNNAMED37	2024-01-17	2024-01-31	Australian Cyclones	10
UNNAMED38	2024-02-01	2024-02-15	Western South Pacific	11
UNNAMED39	2024-12-15	2024-12-29	Western South Pacific	9
UNNAMED4	2024-09-16	2024-09-30	North Atlantic (FL)	12

UNNAMED40	2025-01-19	2025-02-02	Western South Pacific	12
UNNAMED41	2025-01-28	2025-02-11	Western South Pacific	14
UNNAMED42	2025-04-02	2025-04-16	South Pacific	14
UNNAMED44	2022-03-15	2022-03-29	West Pacific	13
UNNAMED45	2022-07-20	2022-08-03	West Pacific	12
UNNAMED46	2022-08-15	2022-08-29	West Pacific	13
UNNAMED47	2022-09-30	2022-10-14	West Pacific	12
UNNAMED48	2022-10-05	2022-10-19	West Pacific	12
UNNAMED49	2023-03-28	2023-04-11	West Pacific	11
UNNAMED5	2024-10-19	2024-11-02	East Pacific	9
UNNAMED50	2023-09-09	2023-09-23	West Pacific	12
UNNAMED51	2023-10-26	2023-11-09	West Pacific	12
UNNAMED52	2024-06-29	2024-07-13	West Pacific	7
UNNAMED53	2024-09-06	2024-09-20	West Pacific	9
UNNAMED54	2022-08-05	2022-08-19	North Atlantic (FL)	11
UNNAMED55	2022-09-12	2022-09-26	Far East Atlantic	13
UNNAMED56	2022-09-20	2022-10-04	Far East Atlantic	13
UNNAMED57	2023-01-01	2023-01-15	Unclassified	9
UNNAMED58	2023-10-09	2023-10-23	North Atlantic (FL)	10
UNNAMED59	2023-11-02	2023-11-16	North Atlantic (FL)	13
UNNAMED6	2022-02-17	2022-03-03	North Indian Ocean	14
UNNAMED60	2024-09-01	2024-09-15	North Atlantic (FL)	10
UNNAMED7	2022-03-06	2022-03-20	North Indian Ocean	9
UNNAMED8	2022-05-06	2022-05-20	North Indian Ocean	9

UNNAMED9	2022-07-02	2022-07-16	North Indian Ocean	8
USAGI	2024-10-26	2024-11-09	West Pacific	12
VERNON	2022-02-09	2022-02-23	South Indian Ocean	12
VINCE	2025-01-17	2025-01-31	South Indian Ocean	12
WUKONG	2024-07-28	2024-08-11	West Pacific	12
YAGI	2024-08-17	2024-08-31	West Pacific	12
YAMANEKO	2022-10-28	2022-11-11	Western North Pacific	6
YINXING	2024-10-19	2024-11-02	West Pacific	9
YUN-YEUNG	2023-08-21	2023-09-04	West Pacific	11
ZELIA	2025-01-25	2025-02-08	South Pacific	14

Proposed Further Analysis

Finite Time Lyapunov Exponents (FTLE)

Why FTLE here?

The co-burst story is Eulerian (values at/beside the track). FTLE gives the complementary **Lagrangian geometry**: where the flow is strongly stretching (repelling LCS, forward-time FTLE) or converging (attracting LCS, backward-time FTLE). These ridges are the “transport scaffolding” that channels moisture and can pre-organize convection.

Next Steps

Use finite-time Lyapunov exponents (FTLE) computed from low-level winds to reveal transient transport barriers that focus moisture into Alfred’s pathway. Co-bursts tend to occur near backward-time FTLE ridges (attracting LCS), consistent with rapid moisture convergence prior to intense convection.

- **Velocity field:** MERRA-2 U/V at **850 hPa** (or 850–500 steering mean already computed).

- **Domain/resolution:** AU basin, 0.5° grid (coarser is fine for the paper); resample hourly.
- **Integration horizon (T):** 24–48 h. Use **forward-time** for repelling, **backward-time** for attracting structures (the latter is often more aligned with convergence/co-bursts).
- **Integrator:** RK4 with 1 h step; clamp domain; assume spherical metric (or locally flat with latitude scaling).
- **FTLE formula:** $\lambda_{\max}$ from the Cauchy–Green tensor of the flow map; $\text{FTLE} = (1/|T|) \cdot \ln \sqrt{\lambda_{\max}}$.
- **What to show:** 2–3 snapshots (T=36 h) with Alfred track overlain; mark co-burst timestamps; a short table: “fraction of co-bursts within X km of FTLE ridges.”

If resources are constrained a useful surrogate may be

- **Okubo–Weiss (OW)** on the same grid:

$$W = s_n^2 + s_s^2 - \omega^2$$

$$W = s_n^2 + s_s^2 - \omega^2$$
 Strain-dominated filaments ($W > 0$) often approximate FTLE ridges at far lower cost.

Verify that OW filaments collocate with FTLE ridges for sampled dates; use FTLE in the Extended Data and OW in the main text for real-time feasibility.”

Adding aerosols

Aerosols modulate cloud microphysics (CCN) and can both pre-load (accumulate in convergence zones) and then **crash** during deep convection (wet scavenging). Two pragmatic paths:

A) Reanalysis (no gaps, easy to automate)

- MERRA-2 AER (tavg1_2d_aer_Nx): pull AOD@550 (often TOTEXTTAU) and, if optionally, species AOD (DUEXTTAU, SSEXTTAU, BCEXTTAU, SO4EXTTAU, OCEXTTAU) and surface PM2.5 (PM25_RH35_GCC or variant—check actual var names).
- Add to the along-track extractor exactly as for TQV/LWTUP:
 - aod_total_here, aod_total_ahead, and d_aod_ahead = ahead - here

- z-normalize and scan co-bursts with conv_ahead (there may be a positive z(AOD) preceding, then a sharp negative dip at or after bursts).

B) Satellite AOD (MODIS/VIIRS/MAIAC)

- Higher spatial detail but cloud gaps; best for precision. .

Steps to integrate with existing storm cards/readiness

- Extend ensure_columns() to parse AOD; add a panel “AEROSOLS vs conv”.
- Optionally extend the readiness light: readiness += +0.3*z(AOD_ahead) before convection starts; once deep convection triggers, expect rapid z(AOD) drop (note that sign flip might require a two-regime logic or use $|\Delta AOD|$).
- Add a small lag-scan (AOD vs conv) as for ΔTQV .