ARF Preregistration Protocol (T1–T25)

Hypothesis & Design for a gated RI nowcast (PCI* + IR heating band + nocturnal OLR)

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0. Purpose & Scope

This preregistration fixes hypotheses, variables, datasets, model formulas, metrics, resampling, thresholds, robustness checks, and pass/fail criteria for evaluating the **Anthropocene Resonance Framework (ARF)** as a nowcast gate for tropical-cyclone Rapid Intensification (RI). Figures in the companion paper are illustrative/synthetic; no empirical claims are made there. This protocol governs the first real-data analysis.

1 Concept & Operational Definitions

Core idea. *Pre-resonant air volumes* modulate RI probability via three co-occurring signatures in the inflow: (1) high pre-charge state (PCI*), (2) an **IR heating band** at 850–600 hPa (IRB), and (3) a **nocturnal OLR minimum** (00–06 local time).

Indices and gates.

$$\mathrm{PCI}^\star = \mathrm{norm}_{[0,1]}(\mathrm{PCI}\cdot(1+\mathrm{PLF}_{\mathrm{total}})), \tag{1}$$

$$\mathrm{IRB} = \max_{p\in[850,600]\,\mathrm{hPa}} \left(\frac{\partial T}{\partial t}\right)_{\mathrm{rad}} \quad [\mathrm{K/d}]. \tag{2}$$

Inflow sector $\mathcal{S}_{\mathrm{inflow}}(t)$: ring segment with radial distance $r \in [100, 300]$ km upstream of motion, azimuth $[-60°, +60°]$ about the upwind direction, pressure $p \in [925, 700]$ hPa, with lead time $\Delta t \in [6, 18]$ h.

Primary gate (fixed a priori). Activate a 12–24 h RI *nowcast window* if and only if the following hold in $\mathcal{S}_{\mathrm{inflow}}$ at lead $\Delta t \in [6, 18]$ h:

G1 PCI$^\star \geq$ Q90 (quantile computed basin–season–year within-sample; see section 5 for leakage controls),

G2 IRB peak within 850–600 hPa (above a fixed **K/day** threshold θ_{IRB} pre-set below),

G3 nocturnal OLR minimum occurs (00–06 LT) relative to daily cycle in inflow.

2 Datasets, Period, Inclusion/Exclusion

Tracks & best tracks: IBTrACS (global), NHC/JTWC subsets as available.
Reanalysis: ERA5 (hourly or 3-hourly fields for radiation tendencies, OLR, winds, humidity; pressure levels).
Satellites (aerosols/trace): MODIS/VIIRS AOD, TROPOMI proxies; where vertical localization is uncertain, use diagnostic sensitivity (see robustness).

Period: 2002–2024 (inclusive) primary; 2025 for out-of-time *qualitative* case cards only (not for inference).
Inclusion: Tropical cyclones with at least 48 h of track and reliable intensity estimates.
Exclusion: High-latitude ET transitions at/after RI onset; missing ERA5/OLR coverage >30% in lead window; duplicate or conflicting best tracks.

3 Outcomes, Predictors, Controls

Outcome (binary): RI event within next 24 h per standard RI definition (e.g., $\geq$30 kt/24 h; locked a priori). Sensitivity to 25/24 h and 35/24 h in robustness.
Predictors (new): gate indicators $G1$, $G2$, $G3$; composites of PCI*, IRB, nocturnal OLR minima within inflow.
Controls (baseline): SST, OHC (where available), vertical wind shear (200–850 hPa), RH profiles, potential intensity (PI), storm translation speed.
Negative control domain: SAL masks (seasonal climatology) for ordering checks.

4 Preprocessing & Feature Extraction

- Temporal alignment: compute predictors at $\Delta t \in \{6, 9, 12, 15, 18\}$ h; RI outcome assessed over next 24 h from reference time t.
- Spatial reduction: mean/percentile summaries inside $\mathcal{S}_{\text{inflow}}(t)$; for IRB take layer-max of radiative heating tendency in 850–600 hPa.
- Normalization: basin–season (JAS/ASO etc.) min–max per *training fold only*; apply to test folds (no leakage).
- Fixed thresholds (pre-set): Q90 for PCI*; $\theta_{\text{IRB}} = 0.15\,\text{K/d}$ (sensitivity 0.10–0.20 in robustness); nocturnal window 00–06 LT.

5 Experimental Design, Splits & Resampling

Primary evaluation: Nested blocked CV with outer folds grouped by (basin, season-year). 5 outer folds; inner CV only for sanity (no threshold tuning; thresholds fixed as above).
Holdout strategy: Each outer fold holds out entire (basin, season-year) groups to prevent temporal/spatial leakage.
Uncertainty: Block bootstrap (by storm ID) with $N = 200$ resamples on *outer* test predictions to form 95% CIs.

6 Models & Statistical Tests

Baseline (B): logistic regression / gradient boosting using controls only.
Augmented (A): add gate indicators and interactions ($G1, G2, G3, G1{\cdot}G2{\cdot}G3$).
Metrics: AUC (DeLong test for AUC difference), Brier score, log loss, reliability (ECE), precision–recall AUC, Cox PH for ERC hazard subsection.
Significance & multiplicity: two-sided $\alpha = 0.05$; Benjamini–Hochberg FDR across families (skill family; fingerprint family; hazard family).

7 Primary Hypotheses & Tests (T1–T9)

T1 Added skill. $\Delta\text{AUC} = \text{AUC}(A) - \text{AUC}(B) \geq 0.05$ out-of-sample (pooled across folds), 95% CI excludes 0; DeLong $p < 0.05$.

T2 IR fingerprint lead. IRB peaks 6–18 h before RI onset more often than chance; circular–linear alignment with nocturnal OLR minimum; Rayleigh test $p < 0.05$.

T3 Diurnal superiority. Night (00–06 LT) gate performance (AUC, TPR@FPR=0.1) exceeds day by ≥ 0.03; paired bootstrap $p < 0.05$.

T4 ERC hazard. Post-ERC re-intensification hazard higher under persistent AOD_{IR} (50–150 km inflow); Cox HR > 1 with 95% CI excluding 1 after controls.

T5 Negative control ordering (SAL). $\Delta\text{AUC}_{\text{BC/VOC}} > \Delta\text{AUC}_{\text{clean}} > \Delta\text{AUC}_{\text{SAL}}$; pairwise differences > 0 with BH-adjusted $p < 0.05$.

T6 Monotone ablation. PCI $\rightarrow$ PCI* increases skill monotonically across PLF quantiles (Q25,Q50,Q75,Q90); Jonckheere–Terpstra trend $p < 0.05$.

T7 Lag–threshold ridge. Heatmap of ΔAUC vs. threshold (Q70–Q95) and lead (6–18 h) has maximum near (Q90,12–15 h); pre-specified ROI test.

T8 Robust to shear/SST. Conditioned on strong baseline predictors (PI, shear), gates retain positive coefficients or additive gain; nested model LRT $p < 0.05$.

T9 Out-of-basin generalization. Train on basins A,B; test on held-out basin C retains $\Delta\text{AUC}\geq$ 0.03 with 95% CI excluding 0.

8 Extended Hypotheses (T10–T25) — pre-specified

T10 COVID natural experiment. 2019 vs 2020 pre–post in flight corridors: reduction in gate activations proportional to traffic decline; difference-in-differences on matched routes.

T11 PLF mixed-phase fingerprint. Regime-dependent γ improves fit for PCI*–RI link vs. no-γ variant; AIC/BIC and ΔAUC gains.

T12 Warm-rain delay. Autoconversion proxy shifts consistent with higher PCI*; mixed-effects slope > 0, $p < 0.05$.

T13 Electric diagnostics. Lightning density / electric field proxies correlate with gate activations; Kendall $\tau > 0$, $p < 0.05$.

T14 Casecard timing. On selected 2025 cases (qualitative), PCI* $\geq$Q90, IRB peak, OLR min align within ± 6 h of the schematic sequence.

T15 Ocean coupling cap. Added shortwave heating (column) obeys $\leq 5\%$ cap in coupled sensitivity runs; stability preserved.

T16 Alternative thresholds. Q85 and Q95 retain positive ΔAUC with smaller magnitude; monotone around Q90.

T17 Window sensitivity. 00–03 vs 03–06 LT: earlier subwindow not worse than later by more than 0.02 AUC.

T18 Outcome robustness. Using RI $=\geq 35$ kt/24 h preserves sign of ΔAUC and key fingerprints.

T19 Seasonality. Peaks occur in known aerosol seasons; cross-correlogram significant at 0 lag with BH control.

T20 Translation speed. Gate benefits not solely due to storm motion; partial correlation of IRB with RI controlling for speed remains > 0.

T21 Regional SAL check. In SAL-dominated months, gates rarely activate (specificity > 0.9).

T22 AOD vertical sensitivity. Using alternative vertical assumptions does not flip conclusions; sign preserved in 80% of sensitivity draws.

T23 Reanalysis bias check. ERA5 heating-rate diagnostics vs satellite-derived proxies: correlation > 0.5 in inflow composites.

T24 Compute reproducibility. Rerun with different seeds/bootstraps: CI overlap $> 70\%$ across repeats.

9 Pass/Fail & Decision Rules

Primary pass: (i) T1 passes (ΔAUC≥ 0.05, CI excludes 0) *and* (ii) at least one fingerprint test among T2–T4 passes *and* (iii) T5 negative-control ordering holds.
Fail: T1 fails *and* no fingerprint passes (T2–T4). Mixed outcomes trigger **inconclusive** status.

10 Robustness, QC, and Missing Data

- Missingness: require $\geq 70\%$ coverage per predictor in lead window; otherwise drop that (storm,time) instance.
- QC: Winsorize extreme heating rates at 99th percentile per fold; confirm results with and without winsorization.
- Multiple testing: BH FDR per family; families are (Skill), (Fingerprint), (Hazard/Diurnal), (Robustness).

11 Computation & Reproducibility

Environment: Python/R stack (versions recorded), deterministic seeds.
Code availability: hooks and configs per Zenodo paper doi:10.5281/zenodo.17235213; repository link to be added on release.
Artifacts: Save fold-wise predictions, ROC data, bootstrap indices, and YAML config snapshots for audit.

12 Planned Figures/Tables (Generated by this Study)

ROC curves (B vs A), reliability diagram, ΔAUC heatmap (threshold vs lead), diurnal alignment plot, Cox hazard forest plot, negative-control bar chart, ablation trend plot, gate activation timelines for casecards.

13 Deviations Policy

Any deviation from this preregistration (thresholds, splits, metrics) will be (i) labeled as *exploratory* and (ii) documented with rationale and timestamps in an OSF update; inferential claims will rely on preregistered analyses only.

14 Ethics, Conflicts, Provenance

No human subjects. No competing interests declared. Human–AI collaboration used for synthesis; the AI is a tool, not an author.

15 Licensing & Sharing

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End of preregistration.