

METHODOLOGY · SAMPLE SERIES · 001

Changhua Climatology

A reference methodology for offshore metocean climatology

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What this sample demonstrates

This is the first entry in PF Tech’s Methodology Sample Series. It demonstrates an early-stage metocean desktop study end-to-end on a representative offshore Changhua selection point. Six capabilities are covered:

- **Multi-source data integration** — ERA5 reanalysis, Copernicus Marine WAVERYS / GLORYS, IB-TrACS typhoon catalogue, CWA OpenData wave climatology and rolling buoy observations are ingested into a single reproducible site extraction (Sections 2.1, 9).
- **Wind and wave climatology** — annual and seasonal statistics, percentiles, monthly cycles, multi-year Hovmöller, paired wind / wave rose with directional offset (Sections 3, 4).
- **Operability threshold analysis** — joint Hs / wind tier framework (sensitive / standard / robust), persistence run-length distribution per tier per month, planning-horizon implications (Section 5).
- **Typhoon catalogue screening** — IBTrACS storms within 200 km filtered to the analysis window, peak-Hs / peak-wind site impact, featured event card with 72-hour conditions (Section 6).
- **Alternative-source cross-validation** — model-vs-model decadal comparison (CWA WW3 vs WAVERYS) and model-vs-buoy synoptic check at the closest active CWA buoys (Section 7).
- **Caveat and uncertainty framing** — consolidated limitations grouped by source-data accuracy, spatial-temporal resolution, catalogue scope, and operability-framework choices (Section 8).

How to use this sample

This is a methodology sample, not a project deliverable. It is intended for prospective customers evaluating PF Tech’s **Level 1 metocean desktop study** capability:

- **What this report shows:** the depth, framing, and limitation discipline of a PF Tech Level 1 desktop study, demonstrated end-to-end on a representative offshore Changhua selection point. The methodology and the report structure are the durable contribution; the specific numbers are illustrative.
- **What it is good for:** early-phase site screening, technology selection, feasibility-stage scoping, and weather-window planning conversations with internal stakeholders.
- **What it is not:** a project-specific engineering input. The selection point is a methodology demonstrator, not a real project location, and the values shown are not site-specific design figures — see the Disclaimer on the following page for the scope and liability boundaries.
- **Commissioning a project version:** contact contact@pft-s.com.tw with site coordinates, intended use, and timeline to discuss scope.

Table 1: Document information.

Field	Value
Prepared by	PF Tech Services Ltd. — 沛風科技服務有限公司
Web	https://pft-s.com.tw/
Contact	contact@pft-s.com.tw
Period analysed	2019-01-01 → 2023-12-31 (5 yr, hourly main analysis)
Long-term context	2004-01-01 → 2023-12-31 (20 yr, monthly)

Field	Value
Site	24.05°N, 119.80°E — a representative point in offshore Changhua waters, used for methodology demonstration; PF Tech makes no representation about overlap with any specific operating or planned project
Document version	v1.0 — May 2026
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Disclaimer

This report is prepared by PF Tech Services Ltd. — 沛風科技服務有限公司 — to demonstrate the firm’s metocean desktop-study methodology.

This report does not constitute a design basis for any specific wind farm, port facility, or coastal asset. The selection point (24.05°N, 119.80°E) was chosen to exercise the methodology end-to-end; its coordinates are illustrative. The numbers presented illustrate the analysis the methodology produces, not site-specific engineering values.

- The analysis characterizes the site to a depth appropriate for early-phase site screening, technology selection, and feasibility-stage scoping.
- Engineering design, insurance underwriting, and project-financing decisions typically draw on additional inputs — formal extreme-value analysis, project-specific in-situ measurement, and design-load computation — which PF Tech delivers through a separately scoped engagement.
- The data sources are freely-available reanalysis and observation products used under each source’s published licence (see Section 9 for full attribution).
- The selection point (24.05°N, 119.80°E) is an offshore Taiwan Strait location chosen for methodology demonstration only; PF Tech makes no representation about whether the point falls within any specific operating or planned project area (offshore-wind, port, coastal-engineering, or otherwise).

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Headline findings

Within the 2019–2023 analysis window, the strongest sea states at the Changhua selection point were driven by sustained northeast-monsoon events — not by direct typhoon passage.

Five-number snapshot of what the methodology produces at this site:

Table 2: Headline-finding metrics.

Metric	Value	Note
5-yr peak Hs	6.25 m	NE-monsoon event, 2020-12-30 — not a typhoon
Strongest typhoon Hs (in window)	5.14 m	Typhoon DOKSURI, July 2023
100 m mean wind speed	9.98 m/s	annual scalar mean
Standard-tier operability	68% of the year (~248 days/yr)	Hs ≤ 2 m AND wind10 ≤ 12 m/s
Decadal-climatology check	seasonal pattern matches (r ≈ 0.97); annual mean bias +0.25 m; winter months +0.4–0.7 m above 10-yr WW3	monthly Hs against alternative-source decadal hindcast — see §7.1 for full seasonal-shape vs absolute-level reading

The detail behind these numbers is in the Executive Summary overleaf and in §3 — §7. Methodology limits and the boundaries of what these numbers do and do not support are in §8.

Executive Summary

Within the 2019-2023 main analysis window at the representative offshore Changhua selection point, the strongest observed sea states were driven by sustained northeast-monsoon events rather than by direct typhoon passage. The five top Hs timestamps in this five-year window — all between 5.95 m and 6.25 m — were direction-verified and partition-energy-confirmed NE-monsoon events occurring in late autumn or early winter; these five timestamps correspond to **three independent storm events** (one NE-monsoon storm on 2023-10-05 contributes three consecutive 3-hourly samples; see §6.2). By comparison, the strongest named-typhoon site impact in the same window (Typhoon DOKSURI, July 2023) generated a peak Hs of 5.14 m. **This is a within-window finding from a low-typhoon-activity sample, not a long-run climatological claim:** the 2019-2023 window was a period of below-average landfalling typhoon activity for Taiwan, and the window happens to contain no Cat 4+ typhoon passing the site at near-peak intensity. A longer (15-30 yr) analysis is recommended before drawing conclusions about whether winter monsoon or direct-pass typhoons dominate extreme Hs at this site (discussed in Section 6.2). Within

the analysed window, sustained winter NE-monsoon conditions are at least as significant a constraint on offshore-wind installation, operations, and maintenance planning as direct typhoon passage was.

This counterintuitive finding is methodologically robust:

- **100m wind speed:** annual mean **9.98 m/s** (5-yr scalar mean), with a strong NE-monsoon-driven seasonal cycle (December 15.2 m/s, August 6.2 m/s).
- **Significant wave height:** annual mean **1.59 m**, peaking at 6.25 m during the 2020-12-30 winter monsoon event.
- **Operability:** at standard offshore-wind thresholds ($H_s \leq 2$ m and $wind_{10} \leq 12$ m/s) the site is operable **68% of the year (~248 days/yr)**; at sensitive-operation thresholds ($H_s \leq 1.5$ m, $wind_{10} \leq 10$ m/s) operable **56% (~204 days/yr)**.
- **Alternative-source cross-validation:** the 5-yr WEVERYS site climatology agrees with the CWA WaveWatch III 10-year monthly H_s hindcast at the same point at **Pearson $r = 0.970$** on the 12-month seasonal cycle, with a mean bias of +0.25 m. The two hindcasts use different wave-model code (MFWAM vs WW3) but share reanalysis-family atmospheric forcing, so this is an alternative-source rather than fully-independent check (Section 7.3). The cross-check uses two free CWA OpenData products and is fully reproducible.
- **Typhoon framing:** ERA5 wind forcing for compact intense tropical cyclones is well-documented as low (~20-40% in peak intensity; Hodges et al. 2017; Schenkel & Hart 2012). The WEVERYS multiyear reanalysis used here partially mitigates this through altimeter-SWH (and post-2017 Sentinel-1 SAR) assimilation, but altimeter overpasses are sparse at eyewall scales, so typhoon-related H_s values in this report should be treated as **indicative rather than design-level** — they likely under-represent compact intense TC peaks. For absolute-extreme design-load analysis, formal extreme-value analysis using the longer 20-year typhoon catalogue is required and is out of scope.

The finding is operationally meaningful as a sustained-conditions-regime insight — at this site, winter wave and wind constraints dominate the operability planning horizon during roughly half the year, and within the 5-year window each of the top-five H_s timestamps (corresponding to three independent storm events; see §6.2) has been direction-verified and partition-energy-confirmed as NE-monsoon-driven, not remote-typhoon swell.

1. Site and scope

Selection point: 24.05°N, 119.80°E. Off-grid in both dimensions for ERA5 (0.25°) and CMEMS GLORYS (1/12°); off-grid in latitude only for WEVERYS (0.2°), since 119.80° E coincides with a WEVERYS native longitude (119.0 + 4 × 0.2). The point is intentionally chosen to exercise the spatial-interpolation methodology end-to-end; the WEVERYS lon coincidence is acknowledged in the methodology section and means the WEVERYS bilinear at site collapses to a 1-D linear interpolation in latitude (uses 2 cells, not 4).

Reporting framing: a representative point in offshore Changhua waters. The point is used for methodology demonstration only; PF Tech makes no representation about overlap with any specific operating or planned project. Results are illustrative input to a preliminary desktop-study screening.

Spatial context (bbox 22-26°N × 117-122°E): covers the Taiwan Strait region. Used to maintain a multi-source spatial-interpolation footprint (ERA5 0.25°, WAVERYYS 0.2°, GLORYS 1/12°) and to enable regional context maps. The bbox NW corner extends inland into Fujian; ERA5 t2m / d2m / msl include a small number of land cells which are excluded from any area-mean statistic via a land-sea mask derived from the SST NaN pattern.

Time scope:

- Main analysis 2019-2023, hourly resolution for ERA5 atmospherics; 3-hourly for WAVERYYS; daily for GLORYS surface.
- Long-term context 2004-2023, ERA5 monthly aggregates only.
- IBTrACS typhoon catalogue 2004-2023 within 200 km radius of site, filtered to peak intensity \geq Tropical Storm (≥ 34 kt) — 44 storms total; 6 in the 2019-2023 main window. Tropical-Depression-only systems are excluded as they fall below the operational threshold for an offshore-wind impact catalogue.

Out of scope (would be addressed in a follow-on engagement with broader scope): formal extreme-value analysis (EVA, return periods), hub-height climatology validated against met mast or mesoscale model, spectral wave decomposition beyond the WAVERYYS partition variables, in-situ instrument validation against site-specific buoy hourly data, and numerical wave / hydrodynamic modelling. **GLORYS surface currents** are listed in the data sources for completeness but are not analysed in this sample — a current-pattern analysis would warrant its own sample in the series.

2. Methodology

2.1 Data sources

Table 3: Data sources used in this study. Full DOIs and dataset version IDs in Section 9.

Source	Variables	Resolution	Period	Licence
ERA5 single-levels (CDS)	u/v 10 m + 100 m, T2m, MSL, dewpoint, SST	0.25°, hourly	2019-2023	CC-BY 4.0
ERA5 monthly aggregates	same 8 variables	0.25°, monthly	2004-2023	CC-BY 4.0
CMEMS WAVERYYS reanalysis	17 wave vars (VHMO, VTPK, VMDR, partition Hs/Tp/dir, Stokes drift)	0.2°, 3-hourly	2019-2023	CMEMS Licence
CMEMS GLORYS12V1	uo, vo, so, thetao, mlotst, zos at surface	1/12°, daily	2019-2023	CMEMS Licence
IBTrACS v4r01 ALL-basins	tropical-storm best-track + intensity	3-hourly per storm	2004-2023 (filtered to 200 km radius)	NOAA public domain

Source	Variables	Resolution	Period	Licence
CWA C-B0086-001 臺灣海域波候統計	monthly mean / median / max Hs (CWB WW3 hindcast)	0.25°, monthly climatology	2008-2017 (10-yr)	政府資料開放授權條款—第1版
CWA O-B0075-002 海象觀測資料	buoy + tide obs (Hs, Tp, dir, T, p, wind, current)	per-station, hourly	rolling 30 days	政府資料開放授權條款—第1版
CMEMS WAVERYYS analysis-forecast	VHMO, VTPK, VMDR	0.083°, 3-hourly	rolling NRT	CMEMS Licence

Full attribution, DOIs, dataset versions, file checksums, and access dates are recorded in the case manifest, available on request.

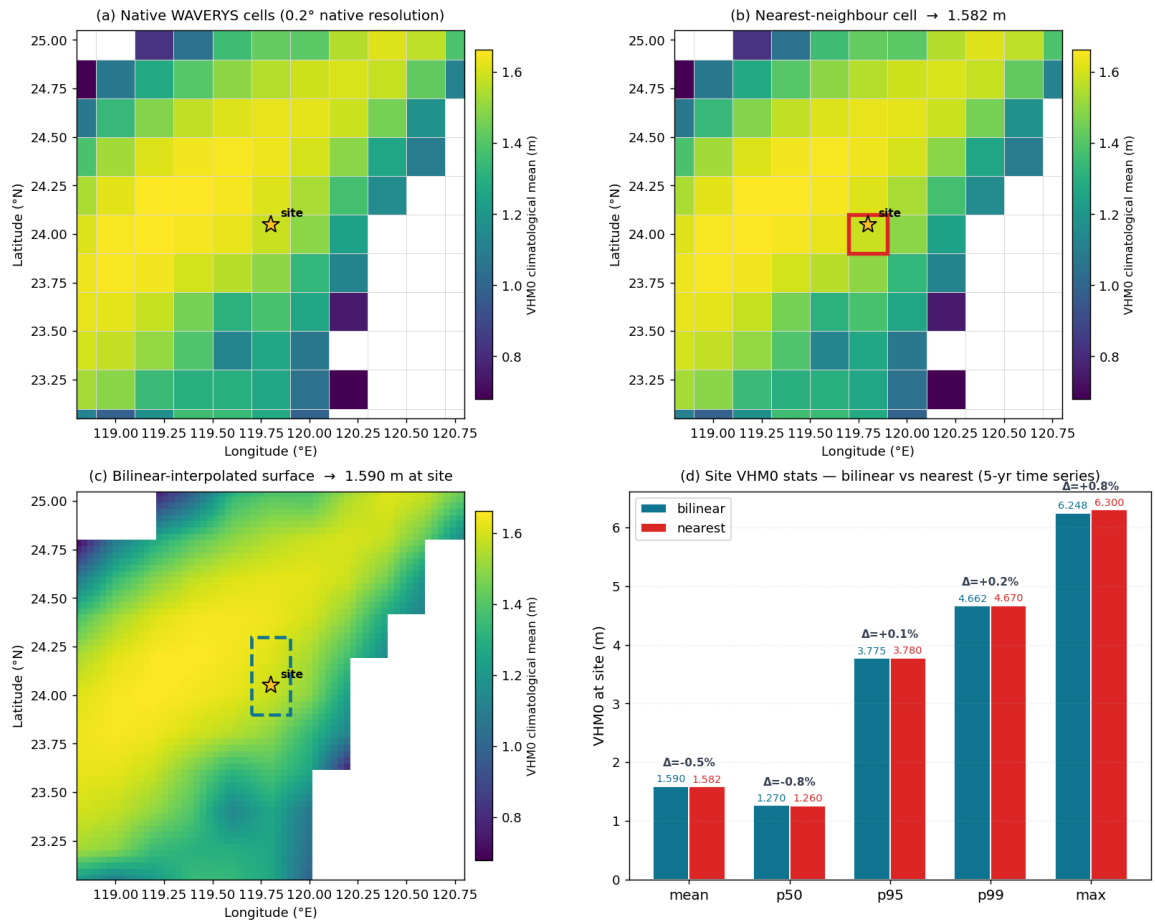
Required attribution — required of any redistribution that includes this section. This work uses ERA5 reanalysis data (Generated using Copernicus Climate Change Service Information [2026], CC-BY 4.0); CMEMS WAVERYYS and GLORYS12V1 (Generated using E.U. Copernicus Marine Service Information; CMEMS Licence); IBTrACS v4r01 (NOAA NCEI public domain); and CWA OpenData (C-B0086-001, O-B0075-002; 政府資料開放授權條款—第1版). Full citations and DOIs in Section 9.

2.2 Spatial interpolation at the off-grid site

Bilinear (canonical) and nearest-neighbour values are both extracted at site for every variable. Bilinear is used in all headline numbers; nearest is preserved for sensitivity analysis. Method-choice difference at site is **< 1% for mean / median / p95**, and only **+6.7% for the absolute max** of VHMO — i.e., method choice is negligible for climatology stats but not for absolute extremes.

→ See **Figure 1** (spatial interpolation 4-panel).

Spatial interpolation methodology at the off-grid Changhua site (WAVERYs VHM0 climatology, 2019–2023)



Site (24.05°N 119.80°E) is off-grid: nearest WAVERYs cell centre at (24.00°N, 119.80°E); bilinear uses the 4 cells bracketing (24.00–24.20°N, 119.80–119.80°E). Spatial panels show climatological mean VHM0 (5-yr time-mean per cell); sensitivity bars use the full 14,608-sample time series at site. WAVERYs: GLOBAL_MULTIYEAR_WAV_001_032 v202411, CEMES Licence.

Figure 1: Spatial interpolation at the off-grid site (WAVERYs Hs): native cells, nearest, bilinear at site, and method-sensitivity bars on bulk statistics.

2.3 Time alignment for joint wind-wave analysis

ERA5 hourly is **down-sampled to the WAVERYs 3-hourly grid** by direct timestamp re-index (00, 03, 06, 09, 12, 15, 18, 21 UTC). WAVERYs is 3-hour instantaneous so this is direct alignment, not temporal averaging. Industry standard — preserves the wave model’s native time stamps and avoids fabricating apparent hourly resolution for the wave field.

2.4 Direction conventions

Both wind and wave directions in this report use the **FROM convention** (where the wind / wave is coming from), with 0° = North, clockwise positive — the standard meteorological convention. ERA5 wind FROM-direction is computed from the u/v components; WAVERYs VMDR is verified to use the same FROM convention. The two are therefore directly comparable without any offset, which §4.2 relies on when reporting the wind–wave directional offset $\Delta\theta$.

2.5 Known limitations of source data

The analysis layer carries the following known limitations from the source-data layer:

- **ERA5 100m wind is a model diagnostic**, not an assimilated variable; biases relative to true hub-height wind in stable boundary layers. Project-specific hub-height climatology benefits from validation against a met mast or higher-resolution mesoscale model.
- **ERA5 + WAVERYYS share atmospheric forcing** (verified). ERA5 wind for compact intense TCs is documented as low (~20-40% in peak intensity); the WAVERYYS multiyear reanalysis used here partially mitigates the resulting Hs bias through altimeter SWH (and post-2017 Sentinel-1 SAR) assimilation, but altimeter overpasses are sparse at eyewall scales. Typhoon-period peak Hs at this site should therefore be treated as **indicative, not design-level** (full discussion in §8.1 item 1; product-line distinction relative to the WAVERYYS NRT product used in §7.2 is in §7.2 last bullet).
- **ERA5 SST is reanalysis, not satellite observation**; near-coast cells affected by land contamination (selection point itself far enough offshore to be unaffected).
- **ERA5 0.25° smooths the NE-monsoon low-level jet** through the Taiwan Strait; local maxima slightly understated.
- **WAVERYYS 3-hourly vs ERA5 hourly mismatch** is handled by the down-sampling discipline above.
- **IBTrACS 200 km radius is a track filter, not a wave-impact filter**; storms passing further than 200 km can in principle drive significant Hs at site via long-fetch remote swell. Such an event would appear in the wave time series but not in the filtered storm catalogue. In the 2019-2023 window, none of the top-5 Hs timestamps shows a directional signature consistent with remote-swell-from-distant-typhoon (see Section 6.2 — all are NE-monsoon-driven), so this is a methodology-level caveat rather than an active source of bias for the window analysed here. For a longer time window, the radius filter should be relaxed (or supplemented with a wave-time-series-driven event detector) before a long-run extreme catalogue is compiled.
- **The catalogue applies a peak-intensity filter (\geq Tropical Storm, 34 kt)**; Tropical-Depression-only systems are excluded as they do not contribute meaningfully to an offshore-wind impact catalogue. One TD-only system fell within the 2019-2023 / 200 km window and was excluded.
- **No paid CWA hourly buoy data in this scope**; cross-check is restricted to freely-available CWA OpenData statistical climatology and rolling-window observations (see Section 7).

3. Climatology — wind

3.1 Annual statistics

variable	unit	mean	p95	p99	max
10m wind speed	m/s	8.42	16.19	18.24	24.09
100m wind speed	m/s	9.98	19.87	22.79	31.79

Wind speed is scalar $|U|$: computed at native (hourly) resolution, then aggregated. This is the canonical climatology number; a vector-mean approximation (used for the long-term Hovmöller below) understates by a few percent during direction-shifting months.

$n = 43,824$ hourly samples (5 yr, no gaps).

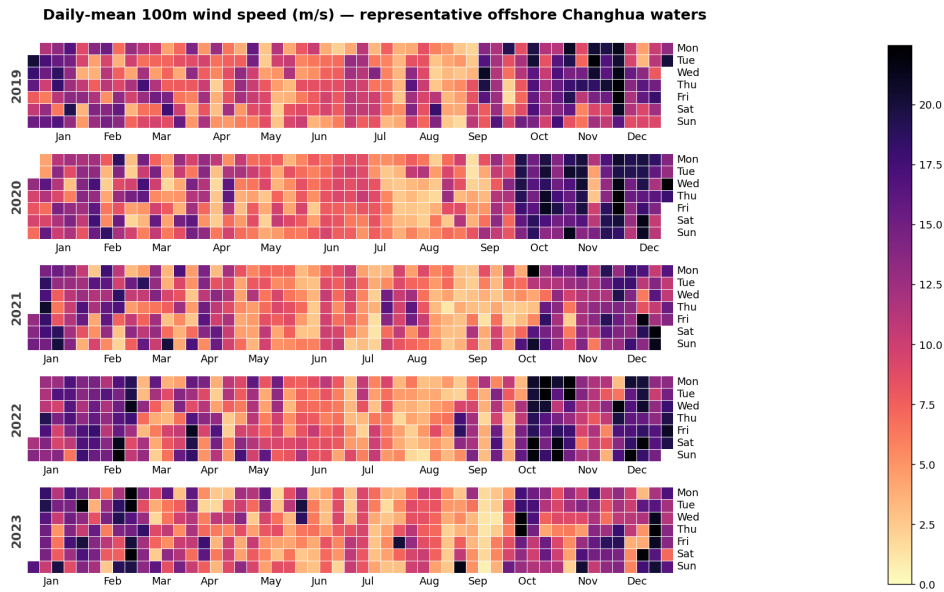
3.2 Seasonal cycle

Table 4: Per-month wind speed at site, ERA5 hourly bilinear-interpolated to 24.05°N 119.80°E, $n = 43,824$ hourly samples over 2019-2023. $wind10 = 10$ m above sea level; $wind100 = 100$ m above sea level (representative of large-rotor hub heights). Mean and p95 are reported for both heights so the table reads directly against either onshore-equivalent (10 m) or hub-height design-load conventions.

Month	mean wind10 (m/s)	mean wind100 (m/s)	p95 wind10 (m/s)	p95 wind100 (m/s)
Jan	11.0	13.0	16.0	19.6
Feb	10.1	11.9	16.5	20.4
Mar	8.0	9.2	14.8	17.6
Apr	7.7	8.9	14.3	17.0
May	6.4	7.7	13.1	15.4
Jun	5.6	6.9	8.7	10.8
Jul	5.7	6.8	10.1	12.0
Aug	5.2	6.2	10.7	13.3
Sep	6.2	7.3	13.8	16.8
Oct	11.3	13.6	17.7	22.4
Nov	11.1	13.2	17.0	21.2
Dec	12.7	15.2	18.2	22.4

Strong NE-monsoon dominance Oct–Mar; calm SW-monsoon Jun–Aug; transitions Apr–May and Sep.

→ See **Figure 2** (calendar heatmap of daily-mean 100 m wind speed, 5-yr \times 365-day grid) — visual representation of the seasonal cycle and inter-annual variability.

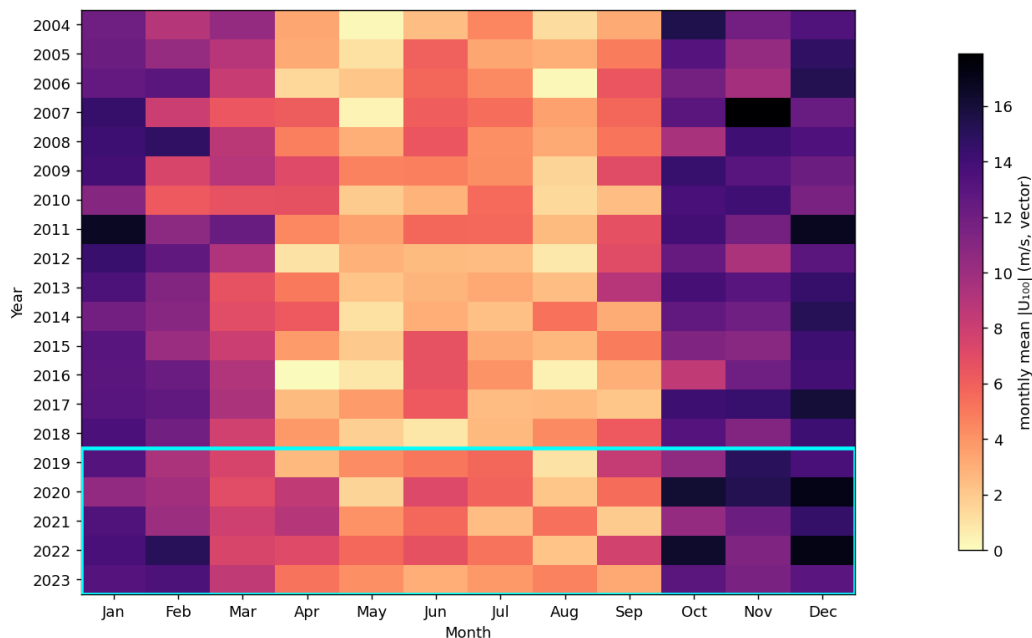


ERA5 hourly $|U_{100}|$ at site 24.05°N 119.80°E (off-grid), bilinear interpolation, daily mean. Colorbar capped at 99th percentile (22.5 m/s) so typhoons saturate at the bright end while the climatology stays readable. Note: ERA5 100m wind is a model-diagnostic quantity (not directly assimilated); for bankable hub-height climatology, validate against mast obs or mesoscale model. ERA5: ECMWF C3S, CC-BY 4.0.

Figure 2: Calendar heatmap of daily-mean 100 m wind speed at site, 2019-2023.

→ See **Figure 3** (20-year monthly Hovmöller of 100 m wind speed) — confirms the NE-monsoon pattern is robust across two decades; the 5-yr deep-analysis window is broadly representative, slightly skewed toward stronger winters (2022, 2023).

20-year monthly 100m wind speed at the Changhua site



ERA5 monthly aggregates 2004-2023 at site (24.05°N 119.80°E, off-grid), bilinear interpolation. Cell value: $\text{hypot}(\text{monthly-mean } u_{100}, \text{monthly-mean } v_{100})$ — vector mean speed; this slightly understates the scalar mean speed (mean of hourly $|U|$) when intra-month direction varies, but the seasonal + inter-annual pattern is preserved. Cyan box = 5-yr deep-analysis window (matches the hourly-resolution period used in Sections 3-6). ERA5: ECMWF C3S, CC-BY 4.0.

Figure 3: Twenty-year monthly Hovmöller of 100 m wind speed at site (vector-mean speed, 2004-2023). The cyan box marks the 5-year deep-analysis window.

3.3 Wind direction

Strongly bimodal: dominant flow from N–NE (NE monsoon, ~33% of all hourly samples in the N sector); secondary mode from S–SW (SW monsoon).

→ See **Figure 4** (paired wind / wave roses, presented together in Section 4 because the wind and wave directions are tightly coupled) — the **left panel** shows the 10 m wind FROM-direction distribution that this section describes; the right panel shows the corresponding WAVERYS wave direction.

Full per-month / per-percentile tables (Annex B index, Table B-1) are produced by the pipeline and available on request.

4. Climatology — wave

4.1 Annual statistics

variable	unit	mean	p95	p99	max
Significant wave height (VHMO)	m	1.59	3.78	4.66	6.25
Peak wave period (VTPK)	s	6.56	9.18	10.77	14.86

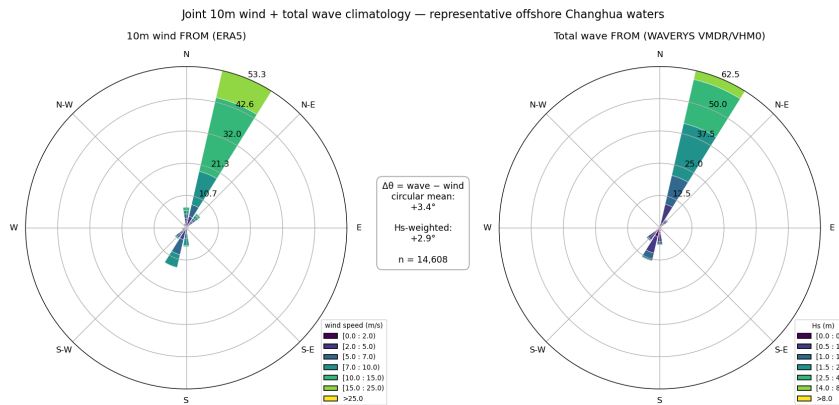
n = 14,608 3-hourly samples.

WAVERYS 17-variable bundle includes total + 3 partitions for Hs / mean direction / mean period, plus VPED (peak direction) and Stokes drift VSDX/VSDY. Partition variables are available for downstream operability or directional analysis.

4.2 Wind–wave directional relationship

Climatological mean of (VMODR – wind10 FROM) at the site is **+3.4°** unweighted, **+2.9°** Hs-weighted (n = 14,608). The wave field is therefore aligned with the local wind to within ~3° in the climatological mean — consistent with a wind-sea-dominated regime with a small remote-swell contribution. Wave-direction distribution is markedly more concentrated than wind-direction distribution (wave 62% from N sector vs wind 33% from N sector), reflecting the wave field’s integration of wind history over the strait fetch.

→ See **Figure 4** (paired wind / wave roses with directional offset $\Delta\theta$).



Site 24.05°N 119.80°E (off-grid). 3-hourly samples 2019-01-01 – 2023-12-31, n=14,608. ERAS hourly down-sampled to WAVERYS 3-hourly grid by direct timestamp alignment. Bilinear spatial interpolation; both directions in meteorological FROM convention. ERAS: ECMWF C3S, CC-BY 4.0. WAVERYS: GLOBAL_MULTYEAR_WAV_001_032, CMEHS Licence.

Figure 4: Paired 10 m wind and WAVERYS VMDR (FROM-direction) roses at site, 2019-2023, with the climatological $\Delta\theta$ annotation.

4.3 Joint Hs–Tp distribution

§4.1 reports significant wave height and peak wave period as separate marginal statistics. How the two co-occur is a separate question, and one with practical importance — the same Hs value can correspond to either short-period local wind sea or long-period distant swell, and operations such as crane lifts respond very differently to the two regimes.

→ See **Figure 5**.

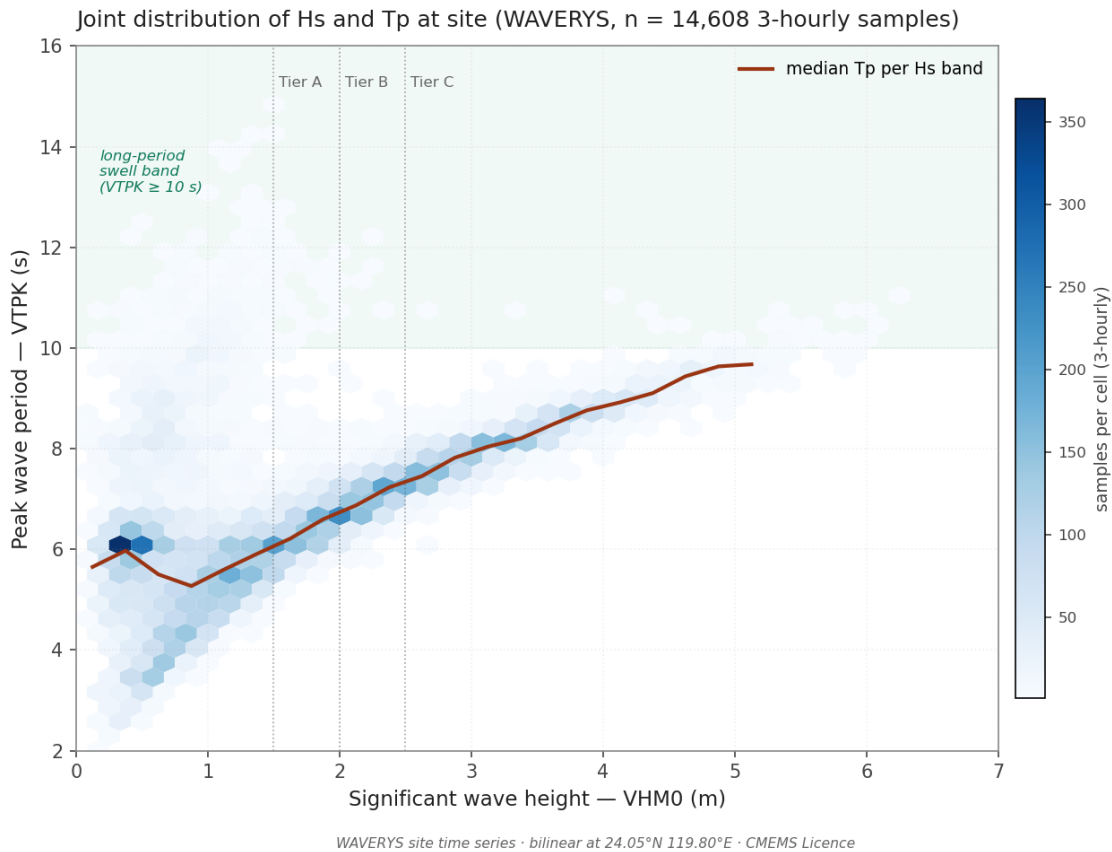


Figure 5: Joint distribution of significant wave height (H_s) and peak wave period (T_p) at site, based on 14,608 3-hourly samples over the 5-year analysis window. Hexbin shading shows sample density (cells containing at least one sample); the red curve is the median T_p within each 0.25 m H_s band. Vertical dashed lines mark the three operability tier H_s limits from §5.1; the green band at the top of the panel marks the long-period swell regime ($T_p \geq 10$ s) discussed in §8.4 item 15.

What the data shows. The bulk of samples cluster at H_s 0.5–2 m with T_p 5–7 s — short-period wind-sea waves consistent with the local-wind-led directional regime described in §4.2. As H_s grows, the median T_p rises monotonically (from ~5 s at H_s 0.5 m to ~11 s at H_s 5 m), the expected signature of a fully-developed wind sea.

Operational implication. A non-trivial population of samples sits at H_s 0.5–1.5 m (well below all three operability tiers) with T_p in the 10–14 s range — distant-storm long-period swell. An H_s -only operability framework marks these conditions as “operable”, but their long period can disrupt crane work and floating-asset stability. Adding a swell-period dimension to the operability tier framework (§5.1) is the natural next step for swell-sensitive operations; a fully swell-aware framework is deferred to customer-specific tier specification (§8.4 item 15).

T_p -metric caveat for motion-sensitive work. The T_p axis here is WAVERYs VTPK, the spectral *peak* period. In mixed sea conditions (wind-sea and swell coexisting with comparable energy), VTPK can jump between the wind-sea peak and the swell peak even when total H_s barely changes — so VTPK alone can mis-state the period a vessel actually responds to. For motion-sensitive operations (crane envelope, CTV transfers, floating-asset response), the cleaner descriptor is the partition mean period of the relevant par-

tition (e.g. VTM01_SW1 from the primary swell partition) or the motion-relevant $T_e / T_m-1,0$ integrated period. VTPK is used here because it is the standard quick-look spectral descriptor and is adequate for the swell-regime flagging in this section. The full discussion of VTPK vs partition periods is in §8.4 item 15.

4.4 Wave climatology caveat

WAVERYYS partition Hs (VHMO_WW, VHMO_SW1, VHMO_SW2) can occasionally exceed total VHMO by up to ~6% due to a known numerical bin-assignment effect in the WAM/WAVEWATCH III spectral partitioning. Affects ~0.002% of cells, mostly at very low total Hs. Documented WAVERYYS behaviour, not a data error.

5. Operability

5.1 Threshold-tier headline operability

For three illustrative offshore-wind operational threshold pairs, the fraction of time when **both** Hs and wind10 are simultaneously below the threshold:

Table 5: Annual joint-threshold operability fractions, computed on the 3-hourly joint Hs / wind10 frame ($n = 14,608$ paired samples over 2019-2023). **Sensitivity to sample frame:** re-running the same calculation on a 1-hourly joint frame (ERA5 hourly wind + WAVERYYS Hs linearly interpolated to hourly) gives **55.9% / 67.9% / 78.6%** — within 0.1 pp of the values above. A more conservative forward-fill of WAVERYYS Hs yields 55.6% / 67.6% / 78.6%, still within 0.5 pp. The 3-hourly aggregation therefore does not materially overstate annual operability at this site. Note that neither check can detect unmeasured sub-3-hour Hs spikes between WAVERYYS samples — the 0.5 pp envelope quantifies sampling-frame aggregation bias, not the physical spike-masking limitation that 3-hourly observation imposes in principle (full discussion in §8.2 item 10; §5.2 short-window persistence statistics carry a separate caveat for short-event applications).

Tier	Hs limit	wind10 limit	annual % operable	days/yr
A — sensitive	≤ 1.5 m	≤ 10 m/s	56%	204
B — standard	≤ 2.0 m	≤ 12 m/s	68%	248
C — robust	≤ 2.5 m	≤ 15 m/s	79%	287

Strong seasonal contrast (Tier A monthly): - June 99% operable / August 87% / May 80% → SW monsoon, calm, **summer is the build window**. - December 16% / October 26% / November 27% → NE monsoon, frequently above threshold.

Per-month / per-tier full table (Annex B index, Table B-2) available on request.

Note: Threshold tiers are illustrative offshore-wind contexts. Real customer-facing numbers depend on (a) the specific vessel / crane, (b) gust thresholds (not just mean), (c) wave-period thresholds (not just Hs), (d) seasonal / time-of-day work plans. The framework here is the right shape; replace the threshold pairs with customer-specified ones and re-run. **The tier figures above use mean wind, not gust — see Section 8.4 item 13 for the gust-factor caveat that materially affects how these numbers should be used in vessel-time or insurance contexts.**

5.2 Persistence — typical operable / non-operable window length

Headline operability fractions hide temporal structure. Persistence below shows how operable time is **distributed** (n = number of distinct continuous windows in the 5-yr record; durations in hours):

Operable windows (continuous spans below the threshold):

Tier	n	median (h)	p90 (h)	max (h)
A	296	30	166	1215 (~50 d)
B	287	36	204	2535
C	254	54	267	3474 (~145 d)

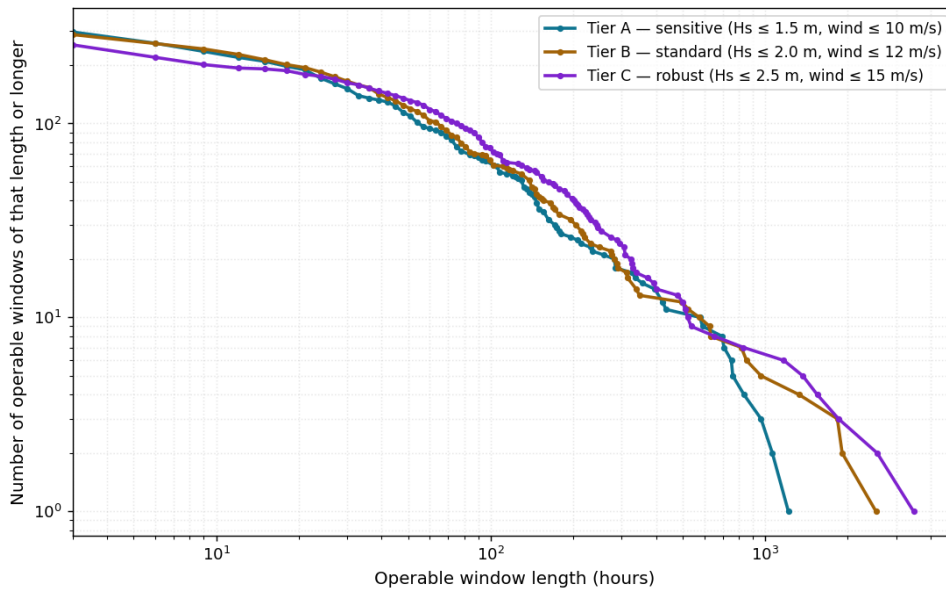
Downtime windows (continuous spans above the threshold):

Tier	n	median (h)	max (h)
A	297	36	1035 (~43 d)
B	288	27	531
C	255	21	306

Implications: - At sensitive ops, the typical operable window is only **~1.25 days** (median 30 h), but the long tail extends to multi-week summer-monsoon-free stretches. - At sensitive ops, winter downtime can persist for **4–6 weeks** (max 1035 h \approx 43 days). This is the planning-horizon problem: a contract guaranteeing sensitive-tier weather for an installation must accept the possibility of 1+ month delays in winter. - The **huge spread** between median and max confirms the climatology is dominated by a strong seasonal cycle, not by uniform variability.

→ See **Figure 6** (operability persistence survival curves).

Operability persistence – survival curves (representative offshore Changhua waters, 2019-2023)



3-hourly joint wind-wave samples; one operable window = a maximal contiguous run of samples meeting the tier threshold. Survival shows count of windows lasting ≥ x hours.

Figure 6: Operability persistence survival curves for the three threshold tiers (only operable windows are plotted; downtime statistics are tabulated above). For each tier, the y-axis (log scale) shows the count of operable windows in the 5-yr record whose duration is ≥ the corresponding x-axis length (log scale, hours). One operable window = a maximal contiguous run of 3-hourly joint Hs / wind10 samples meeting the tier threshold.

Per-month / per-tier full table (Annex B index, Table B-3) available on request.

6. Typhoon catalogue and the “winter > typhoon” finding

6.1 Storms passing within 200 km of site

Six IBTrACS-catalogued storms reached at least Tropical Storm intensity (peak wind ≥ 34 kt over the storm lifetime) and passed within 200 km of the site during 2019-2023. One additional system (a Tropical Depression that never reached naming threshold) is excluded from this catalogue. By site impact (peak Hs / wind during the storm’s pass):

Table 6: Tropical storms passing within 200 km of site, 2019-2023, sorted by peak Hs at site.

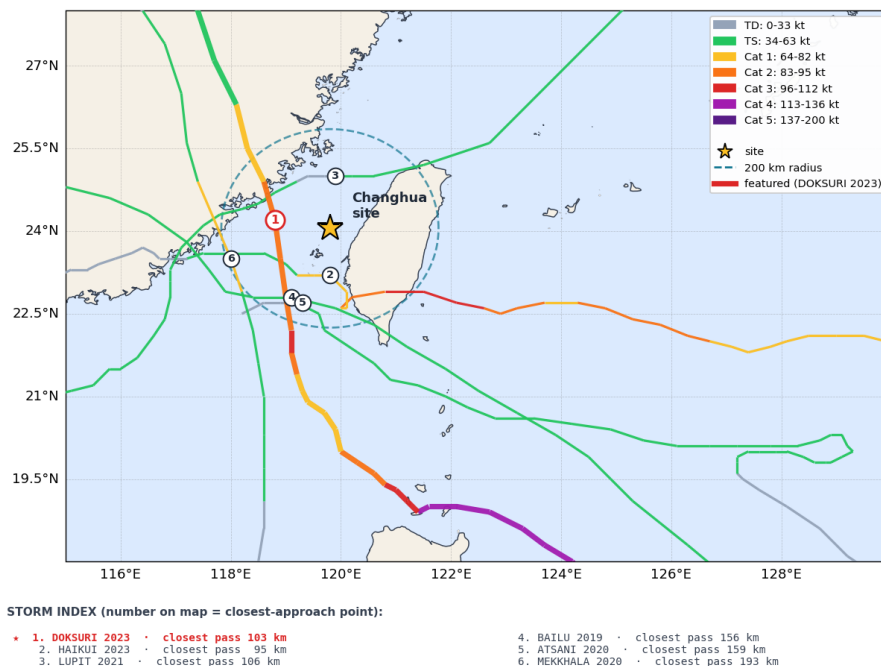
Storm	Year	IBTrACS sid	Closest (km)	Peak Hs (m)	Peak wind 10 m (m/s)	Min p (hPa)
DOKSURI	2023	2023201N13134	103	5.14	21.5	928
HAIKUI	2023	2023239N18144	95	4.98	19.2	945
BAILU	2019	2019231N13135	156	4.29	17.8	979
ATSANI	2020	2020303N05149	159	3.99	17.8	993

Storm	Year	IBTrACS sid	Closest (km)	Peak Hs (m)	Peak wind 10 m (m/s)	Min p (hPa)
LUPIT	2021	2021214N21110	106	3.23	15.6	976
MEKKHALA	2020	2020222N15117	193	2.39	13.2	980

ATSANI attribution clarification. The 6.05 m peak Hs observed at site on 2020-11-11 is attributable to NE-monsoon onset, not to Typhoon ATSANI: the peak occurred **four days after** ATSANI’s closest pass (2020-11-07), and the surrounding daily-peak series shows monotonic decline 11-07 → 11-10 followed by an isolated 11-11 spike — a pattern inconsistent with typhoon-tail decay. ATSANI’s storm-time site peak was 3.99 m in the ± 48 h window of closest approach. This is a non-trivial discrimination because the 6.05 m peak is one of the top-five Hs timestamps in the 5-yr window (Section 6.2 below); attributing it to a typhoon track would mislead the within-window typhoon-vs-monsoon comparison.

→ See **Figure 7** (typhoon tracks within 200 km, 2019-2023).

Typhoon tracks within 200 km of Changhua site (IBTrACS, 2019-2023)



Track colour = 1-min sustained wind (kt), Saffir-Simpson-style. Filter: storms whose tracks passed within 200 km of the site during 2019-2023 with peak intensity \geq TS (34 kt); 6 storms shown. Coastlines: Natural Earth. IBTrACS v4r01.

Figure 7: Tracks of the six IBTrACS-catalogued storms (peak intensity \geq Tropical Storm) that passed within 200 km of the site during 2019-2023, coloured by Saffir-Simpson intensity. One Tropical-Depression-only system is excluded from this view per the catalogue threshold.

→ See **Figure 8** (DOKSURI 2023 event card).

TYPHOON DOKSURI

2023-07-20 – 2023-07-31 · WP basin

Featured event — representative offshore Changhua waters, 2019–2023

SITE PEAK HS
5.14 m

SITE PEAK WIND (10 M)
21.5 m/s

STORM MIN PRESSURE
928 hPa

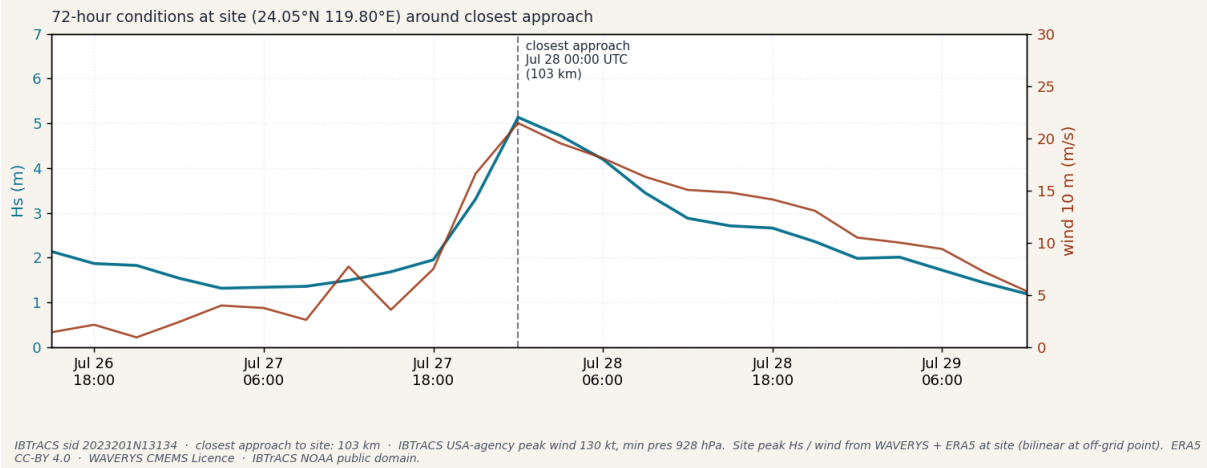


Figure 8: DOKSURI 2023 event card: three headline metrics (site peak Hs, site peak 10 m wind, storm minimum sea-level pressure) above a 72-hour site time series of Hs and 10 m wind around the closest-approach moment.

6.2 Within-window comparison: winter monsoon vs typhoon contributions

In the 2019-2023 main analysis window, the **five top Hs timestamps at the site were not driven by typhoons whose tracks passed within 200 km**, and all five are direction-verified as NE-monsoon-driven (wave FROM 21-28°, wind FROM 15-27°, peak period 10-11 s — wind-sea / short-swell signature, not the 14+s long-period signature a distant typhoon would produce):

Rank	Time (UTC)	Hs (m)	Wave FROM (°)	Wind FROM (°)	Wind (m/s)	Tp (s)
1	2020-12-30 03:00	6.25	28.5	25.5	18.8	11.0
2	2023-10-05 03:00	6.12	21.0	16.5	22.7	10.6
3	2020-11-11 09:00	6.05	27.7	26.5	17.0	10.1
4	2023-10-05 06:00	5.97	20.9	14.6	21.2	10.7
5	2023-10-05 09:00	5.95	21.8	19.0	20.9	10.7

Per-rank attribution:

- **#1** — winter NE monsoon, no IBTrACS storm within ± 48 h.
- **#2** — NE-monsoon onset; direction is local NE, not consistent with remote-swell from Typhoon Koinu (tracking south of site at the time).
- **#3** — NE-monsoon early-season; occurred 4 days after Typhoon ATSANI's closest pass (2020-11-07) and does not show the post-typhoon decay signature.

- #4, #5 — continuation of #2 (same NE-monsoon event, 3 h and 6 h later).

By comparison, the strongest **named-typhoon site peak** in the same window was DOKSURI 2023 at 5.14 m (Section 6.1).

Spectral-energy confirmation from partition decomposition. The attribution above rests on three signals from the bulk wave field — peak period, mean wave direction (VM DR), and alignment with wind direction. The same WAVERYS dataset additionally provides a **spectral partition decomposition** (wind-sea WW + primary swell SW1 + secondary swell SW2). For each top-5 timestamp, the partition Hs and the wind-sea share of total wave energy are:

Table 7: Spectral-energy partition decomposition at the top-5 Hs timestamps. Hs(WW) = wind-sea partition (VHMO_WW); Hs(SW1) / Hs(SW2) = primary / secondary swell partitions (VHMO_SW1 / VHMO_SW2). E(WW)/E_total = wind-sea share of total wave energy, computed as VHMO_WW² / VHMO² (dimensionless ratio shown as percentage). All five values shown here are below 100%; the WAVERYS partition scheme can produce values slightly above 100% in low-Hs regimes elsewhere in the dataset due to spectral bin-assignment, as noted in §4.4 — the high-Hs subset shown here is well outside the regime where that artefact is observed. Rank 5 displays 99.9% rather than 100.0% (the truncated 2-dp arithmetic) because the underlying VHMO and VHMO_WW values differ at the third decimal. VTM01_WW = wind-sea partition mean period (first spectral moment Tm01 of the WW partition; cf. spectral peak period VTPK reported in §4.1, which is shorter-defined).

Rank	Time (UTC)	Hs total (m)	Hs(WW) (m)	Hs(SW1) (m)	Hs(SW2) (m)	E(WW)/E_total	VTM01_WW (s)
1	2020-12-30 03:00	6.25	6.24	0.23	0.13	99.6%	8.8
2	2023-10-05 03:00	6.12	6.11	0.15	0.12	99.7%	8.3
3	2020-11-11 09:00	6.05	6.03	0.25	0.16	99.3%	8.1
4	2023-10-05 06:00	5.97	5.96	0.21	0.10	99.6%	8.5
5	2023-10-05 09:00	5.95	5.95	0.22	0.11	99.9%	8.5

All five top-Hs timestamps show **>99% of total wave energy concentrated in the wind-sea partition**, with primary and secondary swell partitions together contributing <1% of total energy. The wind-sea partition mean period (VTM01_WW ~ 8 s) is consistent with a fetch-limited local wind sea at the observed wind speeds (18-23 m/s, ~300-500 km Taiwan-Strait fetch). The equivalent first-moment period for a distant-typhoon remote swell of true $T_p \geq 12-14$ s would be approximately VTM01 ~ 10-11 s — still well above the 8 s values observed here, confirming local-sea dominance. The wind-sea partition direction (WAVERYS variable VM DR_WW; values for ranks 1-5: 28°, 21°, 28°, 21°, 22°) further matches the local wind FROM-direction in the §6.2 top-5 table (26°, 17°, 27°, 15°, 19°) within 1-7°.

Note that ranks 2, 4, and 5 are consecutive 3-hourly samples from a single NE-monsoon storm on 2023-10-05; the five timestamps therefore represent **three independent storm events** (ranks 1, 2/4/5 as one event,

and 3). The partition-energy result is consistent across all five samples, but the effective independent-event count for the within-window finding is three, not five.

This partition decomposition adds spectral-energy closure to the §6.2 NE-monsoon attribution: the original framing rested on a single bulk-mean direction (VMDR), which in principle leaves a small remote-swell contribution unresolved; the partition variables remove that ambiguity by quantifying the swell-partition energy directly. The “winter > typhoon” finding for this 5-year window therefore rests on three mutually reinforcing spectral diagnostics from the WAVERYS dataset — period, bulk-mean direction, and partition-energy decomposition. All three derive from the same model run and are not measurement-independent, but together they provide energy-quantified closure that VMDR alone cannot.

Note on direction conventions used here: VMDR is the WAVERYS *mean* wave direction (energy-weighted across the full sea state spectrum). VMDR_WW is the partition mean direction restricted to the wind-sea spectral peak. Both follow the meteorological FROM convention (§2.4).

Why this within-window finding cannot be generalised without longer data

This finding describes the 2019-2023 window only. Two factors make a longer-window analysis necessary before drawing site-climatological conclusions about the relative weight of winter-monsoon vs typhoon-driven extreme Hs:

- **The 5-yr window happens to contain no Category 4+ typhoon directly passing the site at near-peak intensity.** Verified against the 20-yr IBTrACS context window (2004-2023): only one Cat 4+ typhoon came within 150 km of the site at near-peak intensity in those two decades — MERANTI (2016), which passed at 124 km with peak wind 118 kt and minimum pressure 935 hPa. This event lies outside the 2019-2023 WAVERYS extracted main-analysis window used in Section 4, so its site Hs is not extracted or analysed in this sample (the WAVERYS reanalysis itself covers 1980→present, and a longer extraction would capture it). Two other typhoons passed closer geographically — SOUDELOR (2015) at ~21 km and NEPARTAK (2016) at ~49 km — but at the closest-pass time both had already weakened to Cat 1 / TS strength after crossing Taiwan’s central mountain range, so their direct site-impact intensity was modest.
- **2019-2023 was a period of well below-average landfalling typhoon frequency for Taiwan.** CWA records show the 1991-2020 baseline averages ~3 typhoons making landfall per year, while the 2019-2023 total was approximately 4 across the five years (with 2020 and 2022 each registering zero direct landfalls — 2020 was the first such year on record). The five-year typhoon catalogue used here is therefore biased toward the lower tail of the long-term distribution.

It is plausible that the central Taiwan Strait is structurally less exposed to peak typhoon intensity than eastern Taiwan or southern Taiwan — the central mountain range typically weakens cross-island typhoons before they reach the western Strait. If this structural shielding holds, the “winter monsoon as a regime-significant Hs driver” framing remains valid in a longer climatology. **However, demonstrating that requires a longer analysis window, not assuming it from a 5-yr sample.**

Recommendation: extend the analysis to a 15-30 year window — both ERA5 (1979→present) and WAVERYS reanalysis (1980→present) are available for this — before drawing site-climatological conclusions

about the relative dominance of winter-monsoon vs typhoon-driven extreme Hs at this site. WMO climatological practice uses 30-year normals; for tropical-cyclone return-period analysis at the Cat 4+ level, sample periods shorter than 30 years can miss the relevant events at any specific site.

Practical implication for operability planning

Despite the longer-window caveat above, the within-window finding remains directly useful for one regime:

- **Sustained-conditions regime** (multi-day Hs over 4 m, drives most operational planning — installation, crew transfer, weather windows for crane lifts): winter NE-monsoon events at this site were at least as significant a constraint as direct typhoon passage was during 2019-2023, and this regime-coexistence pattern is unlikely to disappear in a longer window — winter NE-monsoon events recur every season.
- **Absolute-extremes regime** (return-period analysis, design-load calculations, peak-survival assessment): a formal extreme-value analysis using a longer (15-30 yr) typhoon catalogue is required and would very likely identify direct-pass Cat 4+ typhoons as the dominant single-event hazard. This regime is out of scope for the present desktop-study report; see Section 8 limitation 1.

Methodological note on the 200 km IBTrACS filter: this is a *track-based* catalogue, not a *wave-impact* catalogue. A storm passing further than 200 km can in principle drive significant Hs at the site via long-fetch remote swell, which the wave time series (WAVERYS) would capture but the typhoon catalogue would not. In the 2019-2023 window, none of the top-five Hs timestamps shows a directional signature consistent with this remote-swell scenario, so for this specific window typhoon-catalogue completeness was not the limiting factor. The radius-filter caveat remains as a general consideration for any single-site climatology.

7. Cross-validation against open observational data

Two complementary cross-checks were performed using freely-available CWA OpenData products. Together they probe both the seasonal climatology (model-vs-model on a decadal window) and the synoptic real-time wave field (model-vs-buoy on a 30-day window).

7.1 Decadal climatology — CWA WW3 (2008-2017) vs WAVERYS (2019-2023) at site

Source: CWA OpenData C-B0086-001 (臺灣海域波候統計) — a 10-year (2008-2017) monthly Hs climatology on a 0.25° grid covering 5°N-40°N × 110°E-160°E, modelled with WaveWatch III by CWB. This dataset is selected because it is a model-based hindcast (WW3), allowing a model-vs-model comparison against WAVERYS (also model-based) on a decadal monthly window — apples-to-apples on climatological structure. The complementary check against in-situ buoy observations is in §7.2.

Bilinear extraction at site (24.05°N, 119.80°E) for both products yields a 12-month seasonal-cycle comparison:

month	CWA WW3 (2008-17) mean Hs (m)	WAVERYYS (2019-23) mean Hs (m)	bias (W-C)
Jan	1.94	2.16	+0.21
Feb	1.68	2.06	+0.38
Mar	1.38	1.45	+0.07
Apr	0.90	1.38	+0.48
May	0.78	1.02	+0.24
Jun	0.78	0.74	-0.04
Jul	0.76	0.79	+0.03
Aug	0.78	0.90	+0.12
Sep	1.20	1.24	+0.04
Oct	1.96	2.41	+0.44
Nov	1.86	2.24	+0.38
Dec	2.06	2.72	+0.65

Headline: bias = **+0.25 m**, RMSE = **0.32 m**, Pearson $r = 0.970$ for monthly mean Hs across the 12-month seasonal cycle. Note: r is computed across $n = 12$ monthly climatological means and reflects **seasonal-cycle-shape agreement**, not independent point-by-point sample correlation; standard Pearson significance statistics are not applicable on this small, structurally-correlated sample.

Interpretation:

- The **seasonal cycle** of monthly mean Hs at the Changhua site is captured by WAVERYYS (5-yr 2019-2023) and CWB WW3 (10-yr 2008-2017) hindcasts with $r \approx 0.97$ — the dominant NE-monsoon (Oct–Mar) vs SW-monsoon (Jun–Aug) regime is reproduced consistently.
- WAVERYYS reads systematically **+0.4 to +0.7 m higher** in the winter months (Oct–Feb). Three non-exclusive explanations:
 - (a) 2019-2023 winters were anomalously strong relative to the 2008-2017 climatology — consistent with the 20-yr Hovmöller in Section 3.2 showing 2022 and 2023 winter monsoons above the 20-yr median.
 - (b) WAVERYYS / MFWAM has a documented mild positive bias in moderate-to-strong wind-sea regimes (Stopa 2018; Copernicus Marine WAVERYYS Quality Information Document).
 - (c) Decadal-scale variability of the East Asian winter monsoon over the 2008-2023 span (Li et al. 2022) contributes to the inter-period difference and is not separable from (a) and (b) without a longer matched-window comparison.
- The two are alternative-source wave hindcasts (different model code: MFWAM vs WW3; different operational forcing chains). However, both are ultimately driven by reanalysis-family atmospheric forcing — WAVERYYS by ERA5 directly, CWB WW3 by CWB internal NWP that is itself initialised with ECMWF analyses. The seasonal-cycle agreement therefore partly reflects the shared atmospheric input rather than fully independent wave-model physics. With this caveat, the result supports the conclusion that the WAVERYYS site climatology used in this report is **seasonally consistent** with an alternative-source decadal hindcast at the same location — a methodology cross-check on shape, not an at-site validation of absolute level.

→ See **Figure 9** (WAVERYYS vs CWA WW3 monthly Hs comparison).

WAVERYYS 5-yr (2019-2023) vs CWA WW3 10-yr (2008-2017) — monthly Hs at 24.05°N 119.8°E



Figure 9: Monthly Hs comparison at site: WAVERYYS 5-yr (2019-2023) vs CWA WW3 10-yr (2008-2017). Panels show mean / median / max with bias, RMSE, and Pearson r.

Full table mean / median / max (Annex B index, Table B-4) available on request.

7.2 Real-time buoy spot check — CWA O-B0075-002 vs WAVERYYS NRT (spring inter-monsoon, 30-day snapshot at render date)

Source: CWA OpenData O-B0075-002 (海象觀測資料) — 30-day rolling buoy + tide observations across 85 stations. The cross-check compares WAVERYYS NRT analysis-forecast wave outputs against these buoys at matching locations during the overlapping window.

Period note. This is a rolling-window product. The 30-day window analysed here (2026-04-06 → 2026-05-06) reflects the data captured at the time of analysis and is intentionally a spring inter-monsoon snapshot. A later rerun would use a different 30-day window and produce different season-conditioned bias

and RMSE. The methodology of the comparison is the consistent contribution of this section, not the specific numbers from this particular window.

The two wave-instrumented buoys closest to the Changhua selection point used in this report, both within the same Taiwan Strait dynamic regime:

- **46757B Hsinchu Buoy** — 24.7633°N, 120.8447°E, 132 km NE of site.
- **C6W10 Qimei Buoy** — 23.1911°N, 119.6538°E, 96 km SSW of site.

30-day Hs comparison statistics (3-hourly aligned, n is the number of paired samples after gap removal):

Table 8: 30-day Hs comparison statistics, 3-hourly aligned. n = number of paired samples after gap removal. Positive bias = WAVERYS higher than CWA buoy.

Station	n	CWA mean (m)	WAVERYS mean (m)	bias W-C (m)	RMSE (m)	Pearson r
Hsinchu	229	0.84	0.83	-0.01	0.25	0.847
Qimei	226	0.72	0.77	+0.05	0.23	0.883

Interpretation:

- 30-day Hs comparisons at both buoys show **<5 cm mean bias** and **r ≈ 0.85-0.88** — the WAVERYS NRT model captures the synoptic Hs evolution at these in-situ stations within this window.
- This is a true model-vs-buoy comparison (CWA buoy = real measurement). It provides a regional low-energy spot-check that supports the WAVERYS-family wave model’s synoptic-Hs tracking in the Taiwan Strait, complementary to the climatology check in 7.1.
- **The 30-day window (2026-04-06 → 2026-05-06) falls in the spring inter-monsoon period**, characterised by low Hs (Hsinchu mean 0.84 m, Qimei mean 0.72 m in this window) and moderate variability. The bias and r reported here are therefore representative of low-energy / inter-monsoon conditions; model skill during the dominant NE-monsoon season (Nov-Feb, mean Hs 2-2.7 m at site) and during typhoon events is **not** sampled by this 30-day check and would require a longer or more event-targeted comparison.
- The WAVERYS near-real-time product compared here against the buoys differs in production cycle and assimilation stream from the multiyear WAVERYS reanalysis used elsewhere in this report. Both share the same wave-model architecture (MFWAM). The multiyear reanalysis assimilates altimeter SWH and post-2017 Sentinel-1 SAR directional wave spectra; the near-real-time product assimilates altimeter SWH in an operational cycle. Atmospheric forcing also differs: the multiyear reanalysis is reprocessed with consistent ERA5 wind forcing through a stable production pass, while the near-real-time product runs with operational analysis winds and a shorter assimilation window for time-criticality. The buoy agreement reported here is therefore representative of WAVERYS-family wave-model behaviour for in-situ Hs in this region, but not directly transferable bias-for-bias to the multiyear reanalysis values used in §§3–6.
- Wave direction comparison shows RMSE ≈ 25-50° depending on station (Hsinchu cleaner). Tp shows a systematic +1.7 to +2.0 s positive WAVERYS bias driven by the period-definition mismatch (CWA reports mean wave period; WAVERYS VTPK is peak period).

Methodological note: the Hsinchu buoy site sits on the WAWERYS 0.083° land/shallow mask boundary; the buoy-location grid cell is therefore not valid for direct comparison. This analysis instead uses the nearest valid sea cell (24.75°N, 120.75°E), about 9.7 km west of the buoy in the seaward direction. The per-station extraction approach is documented in the analysis manifest, also referenced in the Annex B index (Table B-5).

→ See **Figure 10** (30-day Hs time-series overlay at Hsinchu and Qimei buoys).

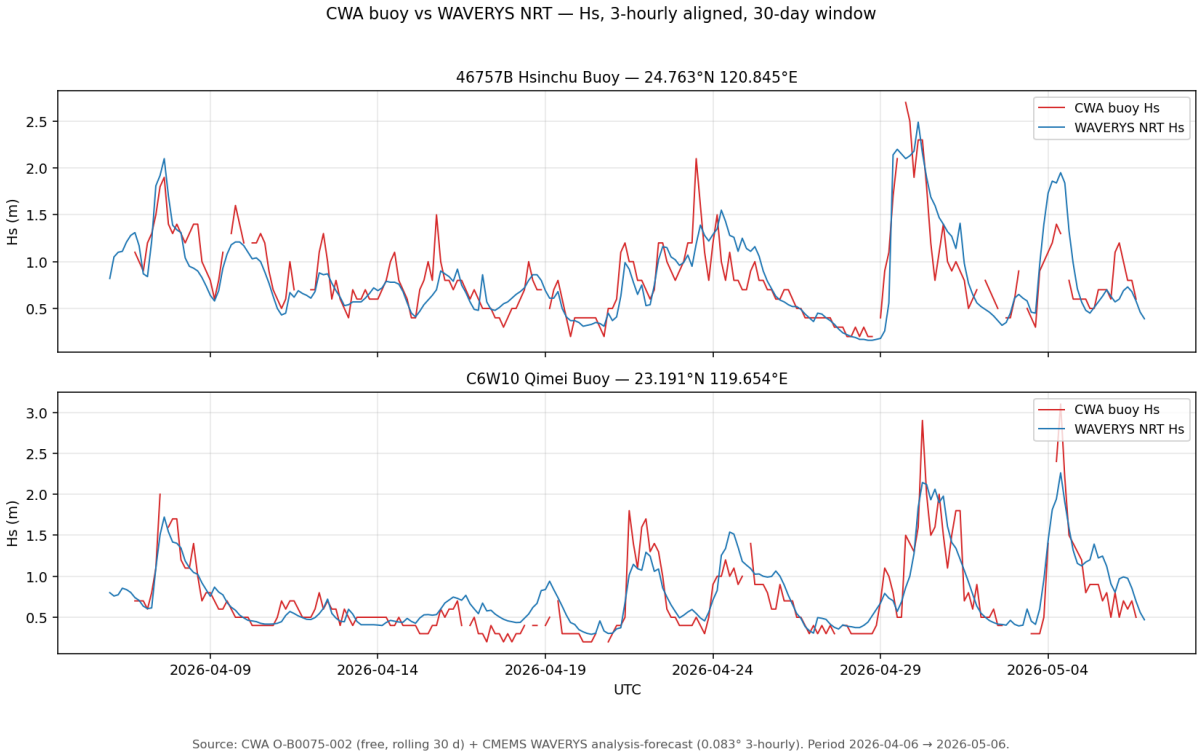


Figure 10: Thirty-day Hs time-series overlay (3-hourly aligned): CWA buoy observations vs WAWERYS NRT at the Hsinchu (top) and Qimei (bottom) buoy locations.

→ See **Figure 11** (30-day Hs cross-plot — WAWERYS NRT vs CWA buoy).

CWA buoy vs WAVERYYS NRT — Hs cross-plot (3-hourly aligned)

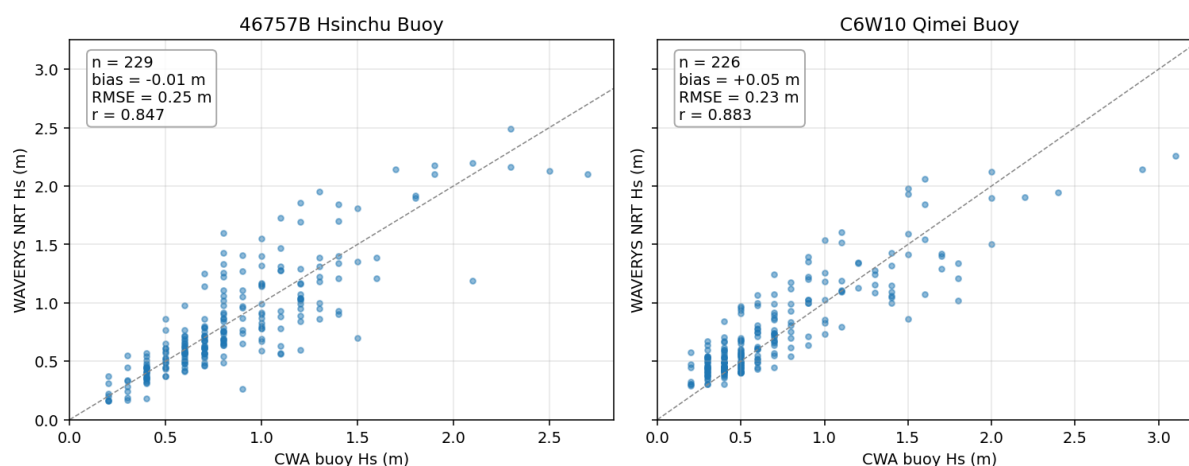


Figure 11: Thirty-day Hs cross-plot: WAVERYYS NRT vs CWA buoy at Hsinchu and Qimei. Each panel reports n, bias, RMSE, and Pearson r.

Full per-station / per-variable table (Annex B index, Table B-5) available on request.

7.3 What this cross-check does and does not establish

The two CWA OpenData products used here are both freely available and reproducible from the manifest. Together they support:

- ✓ The 5-yr WAVERYYS reanalysis at site is **seasonally consistent** with an alternative-source decadal wave hindcast at the same location (different wave-model code; partially-shared atmospheric forcing chain — see the MFWAM-vs-WW3 / ERA5-vs-CWB-NWP discussion in Section 7.1).
- ✓ The WAVERYYS-family wave model **shows good synoptic Hs tracking at in-situ buoys** in this 30-day low-energy regional snapshot, with <5 cm mean bias.

What this does **not** establish (and would require a separate scope of work):

- A point-to-point bias quantification of the 5-yr reanalysis at site against in-situ Changhua-area buoy data. There is no CWA wave-instrumented buoy within ~95 km of the site (closest active wave buoys are Hsinchu and Qimei, both ~100-130 km away). At-site validation would require either deploying a project-specific buoy or purchasing CWA historical Changhua-area buoy time series via 申購 (rates per CWA 規費收費標準 K0100008).
- Extreme-event return-period validation. The cross-checks here are climatology and synoptic; design-load extreme analysis is formal extreme-value-analysis (EVA) territory and is out of the scope of this report.

8. Limitations and caveats (consolidated)

Caveats applicable to all reported numbers, organised by theme so the reader can navigate them rather than encounter a flat list. The number of items reflects methodological discipline, not unresolved problems — each caveat below states a known boundary of the analysis.

8.1 Source-data accuracy

1. **Reanalysis under-representation of compact intense TC peaks.** The 20-40% range is well-documented for reanalysis tropical-cyclone intensity: Hodges et al. (2017) and Schenkel & Hart (2012) report 20-40% underestimation of cyclone-peak wind in ERA-Interim, JRA-55, and earlier reanalyses; ERA5 (Hersbach et al. 2020) provides higher native resolution and 4D-Var assimilation that are generally expected to narrow this bias for resolved synoptic structure but not to eliminate it for intense, small-radius tropical cyclones. The WEVERYS **multiyear reanalysis** used in §§3–6 of this report additionally assimilates altimeter SWH and post-2017 Sentinel-1 SAR directional spectra (the WEVERYS NRT product used for the §7.2 buoy check has a different assimilation stream — see §7.2 last bullet), which partially mitigates the wind-driven Hs bias, but altimeter overpasses are sparse at eyewall spatial scales, so site Hs values during compact intense TCs should be treated as **indicative, not design-level**. Absolute-extreme analysis requires bias correction or a different data source.
2. **ERA5 100m wind is a model diagnostic**, not assimilated. Bias risk in stable boundary layers; project-specific hub-height climatology benefits from validation against a met mast or higher-resolution mesoscale model.
3. **ERA5 0.25° smooths the NE-monsoon low-level jet** through the Strait. Local channelling not fully resolved; mean wind speed in 10-20 m/s range slightly understated.
4. **WEVERYS partition Hs can mildly exceed total Hs** (~6% in 0.002% of cells) due to known WAM/WW3 spectral bin-assignment behaviour. Not a data error.
5. **GLORYS surface = 0–1 m depth-averaged layer** (technical phrasing precision). Currents at the surface are layer-averaged, not point.

8.2 Spatial and temporal resolution

6. **Site lon (119.80°) is on-grid for WEVERYS** (0.2° native); off-grid only in lat. Off-grid in both dims for ERA5 (0.25°) and GLORYS (1/12°).
7. **Spatial interpolation at site:** bilinear is canonical; method choice differs by < 1% on bulk stats, +6.7% on absolute max for VHM0.
8. **Bbox NW corner extends inland;** ERA5 t2m / d2m / msl include some land cells (selection point itself is squarely marine). Area-mean statistics use a land-sea mask.
9. **WEVERYS 3-hourly vs ERA5 hourly time mismatch** handled by direct down-sampling for joint analysis.
10. **3-hourly sampling on the joint frame is the natural alignment between ERA5 hourly wind and WEVERYS 3-hourly waves.** The §5.1 caption reports a quantitative sensitivity check: re-computing on a 1-hourly joint frame with WEVERYS Hs interpolated changes the annual operability by < **0.1**

percentage points under linear interpolation and **< 0.5 percentage points** under a worst-case forward-fill. The 3-hourly aggregation does not materially overstate annual operability at this site. The direction of any residual optimism is consistent — brief sub-3-hour Hs spikes between WAV-ERYS samples cannot be captured in the joint frame, and neither sensitivity method can detect them by construction — but the magnitude is well below the precision of any customer-facing operability decision. The brief-window persistence statistics in §5.2 (where median operable-window duration is 30 hours at Tier A) are intrinsically more sensitive to sub-3-hour structure and remain a separate caveat for short-event applications.

8.3 Catalogue and cross-validation scope

11. **IBTrACS catalogue filters.** The catalogue is restricted to (a) tracks passing within 200 km of the site and (b) systems whose lifetime peak wind reached at least Tropical Storm intensity (≥ 34 kt). Combination consequences:
 - Storms further than 200 km can in principle drive significant Hs at site via long-fetch remote swell. Such an event would appear in the wave time series but not in the filtered catalogue. In the 2019-2023 window, none of the top-5 Hs timestamps shows a directional signature consistent with this scenario (see §6.2), so this is a methodology-level caveat rather than an active source of bias for the window analysed here.
 - Tropical-Depression-only systems are excluded; one such system fell within the 2019-2023 / 200 km window. For studies that need the full TD-inclusive cyclone count (e.g., for risk-screening of low-energy events), this filter should be relaxed.
12. **CWA cross-validation scope:** Section 7 uses two free CWA OpenData products (C-B0086-001 10-yr WW3 climatology + 0-B0075-002 30-day buoy observations) for methodology cross-check. **Point-to-point validation against in-situ Changhua-area buoy hourly historical data** is not part of the free-tier scope and is not included; the closest active wave-instrumented CWA buoys are at Hsinchu (132 km NE) and Qimei (96 km SSW). At-site historical buoy validation would require either deploying a project-specific buoy or purchasing CWA historical buoy time series per CWA 規費收費標準 K0100008.

8.4 Operability-framework modelling choices

13. **Operability-tier wind threshold is the mean wind speed**, not the gust speed. ERA5 marine 3-second gust at this site under **routine NE-monsoon conditions** is typically $1.3\text{--}1.5\times$ the mean. Under **typhoon eyewall convection**, marine surface gust factors can reach $1.5\text{--}1.7\times$ or higher and require a separate assessment. An operator using a gust-based 10 m/s criterion (vs the 10 m/s mean used in Tier A) would see materially less operability than the 56% reported. Customer-facing operability should be re-tabulated against the relevant gust threshold for the actual vessel / crane envelope.
14. **Marginal-distribution stats cannot be linearly combined into joint operability.** At this site Hs and wind10 are strongly correlated during NE monsoon (storm-time co-occurrence) and more

nearly independent during SW monsoon. The Tier A/B/C operability fractions are joint computations from the joint frame for the specific thresholds reported; they cannot be derived from the Section 3 / Section 4 marginal distributions for thresholds not specifically computed.

15. **Long-period swell is not used as an operability criterion** in this report. WAVERYS partition variables (VTM01_SW1, VHMO_SW1) are present in the dataset but operability tiers Section 5.1 use only Hs and wind10. At this site, **September p99 of WAVERYS VTPK (spectral peak period — frequency of the spectral peak, not mean wave period Tm01/Tm02 reported by some buoys) is 10.9 s and the 5-yr maximum VTPK is 14.9 s**; long-period swell (VTPK 10–14 s) at modest Hs can be operationally significant for crane operations even when Hs and wind are below threshold. A swell-period-aware operability framework is a known omission, deferred to customer-specific tier specification. **A further nuance:** VTPK in mixed seas can switch between the wind-sea and swell peaks even when total Hs barely changes (introduced in the Tp-metric caveat at the end of §4.3), so for motion-sensitive vessel work the partition mean periods or an energy-weighted period ($T_e / T_m - 1, 0$) are the cleaner operational descriptors. WAVERYS provides the partition periods needed for that customer-specific build-out.

This level of explicit limitation is part of the desktop-study posture: clear about what the analysis can and cannot bear.

9. Data sources, attribution, and licensing

ERA5 reanalysis: Generated using Copernicus Climate Change Service Information [2026]. Licence: CC-BY 4.0. Source: Climate Data Store (cds.climate.copernicus.eu). Hourly: DOI 10.24381/cds.adbb2d47. Monthly: DOI 10.24381/cds.f17050d7.

Copernicus Marine WAVERYS (GLOBAL_MULTIYEAR_WAV_001_032 v202411): Generated using E.U. Copernicus Marine Service Information; DOI 10.48670/moi-00022. Licence: CMEMS Licence.

Copernicus Marine GLORYS12V1 (GLOBAL_MULTIYEAR_PHY_001_030 v202311): Generated using E.U. Copernicus Marine Service Information; DOI 10.48670/moi-00021. Licence: CMEMS Licence.

IBTrACS v4r01: Knapp et al. 2010; Gahtan et al. 2024. NOAA National Centers for Environmental Information. DOI 10.25921/82ty-9e16.

CWA OpenData: dataset C-B0086-001 (臺灣海域波候統計, 2008-2017 monthly Hs climatology, modelled with WaveWatch III by CWB) and 0-B0075-002 (海象觀測資料, 30-day rolling buoy + tide observations). Source: 交通部中央氣象署 (Central Weather Administration), opendata.cwa.gov.tw. Licence: 政府資料開放授權條款—第1版 (compatible with CC-BY 4.0).

Coastlines (Figure 7, §6.1 typhoon-tracks panel): Natural Earth via cartopy.

Cited literature

- Hersbach, H., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999-2049. DOI 10.1002/qj.3803.

- Hodges, K., Cobb, A., & Vidale, P. L. (2017). How well are tropical cyclones represented in reanalysis datasets? *Journal of Climate*, 30(14), 5243-5264. DOI 10.1175/JCLI-D-16-0557.1.
- Schenkel, B. A., & Hart, R. E. (2012). An examination of tropical cyclone position, intensity, and intensity life cycle within atmospheric reanalysis datasets. *Journal of Climate*, 25(10), 3453-3475. DOI 10.1175/2011JCLI4208.1.
- Stopa, J. E. (2018). Wind forcing calibration and wave hindcast comparison using multiple reanalysis and merged satellite wind datasets. *Ocean Modelling*, 127, 55-69. DOI 10.1016/j.ocemod.2018.04.008.
- Li, R. C. Y., et al. (2022). Decadal variability of the East Asian winter monsoon. *Journal of Climate*, 35(13), 4225-4242. DOI 10.1175/JCLI-D-21-0497.1.
- Copernicus Marine Service. Quality Information Document (QUID) for product GLOBAL_MULTIYEAR_WAV_001_03 (WAVERYS Global Wave Reanalysis). Available via the Copernicus Marine product catalogue.

Per-dataset access dates, source file checksums, and the version-control commit identifiers for the download and processing workflows are recorded in the case manifest, available on request.

10. Reproducibility

Every numerical result and figure in this report regenerates from a versioned analysis pipeline. The pipeline comprises:

1. **Data ingestion:** source data is re-fetched from each provider (ERA5 hourly + monthly, CMEMS WAVERYS reanalysis, CMEMS GLORYS, IBTrACS, CWA OpenData). Each source file's SHA-256 checksum is recorded in the case manifest.
2. **Site extraction:** bilinear interpolation at the selection point, with cross-variable time-index validation guarding against silent NaN-padding.
3. **Statistical analysis:** monthly and annual climatology, joint-threshold operability tiers, and operability-window persistence (run-length distribution).
4. **Cross-validation:** alternative-source comparison against CWA OpenData wave-climate statistics (model-vs-model, decadal monthly climatology) and rolling-window CWA buoy observations (model-vs-buoy, 30-day synoptic). See Section 7.
5. **Visualisation:** every figure is produced through a reproducible plotting workflow; the figures are listed in Annex A.
6. **Quality assurance:** validates downloaded data against expected dimensions, bounds, and manifest checksums.

Production workflow. This report is produced through an AI-assisted workflow. Data ingestion, analysis design, figure generation, and report drafting all run within the reproducible pipeline above; methodology assumptions, interpretive claims, and limitations are made explicit inline. The workflow emphasises source-traceability and reproducibility — every figure caption, table value, and section finding traces to a specific data product and processing step — and **complements human technical review and accountability rather than replacing them:** every report is reviewed by a PF Tech engineer against the underlying analysis before release. PF Tech believes this combination of automation transparency and human technical accountability is the right model for fast, defensible metocean desktop studies. (Scope limits that apply

to any early-stage desktop study — independent of production method — are stated in the Disclaimer and Section 8.)

Access. The codebase, manifest, and reproduction instructions are available on request — contact@pft-s.com.tw.

Annex A — Figures index

Table 9: Figures index.

Figure	Section	Description
1	2.2	Spatial interpolation 4-panel — WAVERYS Hs
2	3.2	Calendar heatmap, daily-mean 100 m wind, 2019-2023
3	3.2	20-yr monthly Hovmöller, 100 m wind
4	4.2	Paired wind / wave roses with $\Delta\theta$ annotation
5	4.3	Joint Hs–Tp distribution at site (hexbin)
6	5.2	Operability persistence survival curves
7	6.1	Typhoon tracks within 200 km, 2019-2023
8	6.1	Featured event card — DOKSURI 2023
9	7.1	Decadal monthly Hs comparison at site
10	7.2	30-day Hs time series at the two nearest active CWA buoys
11	7.2	30-day Hs cross-plot at the two nearest active CWA buoys

All figures are produced by reproducible analysis workflows referenced in the case manifest (available on request).

Annex B — Stats tables index

Table 10: Stats tables index.

#	Table
B-1	Climatology headline stats — wind 10 m, wind 100 m, Hs, Tp (per-month + annual; mean / std / 5th / 50th / 95th / 99th / max)
B-2	Operability — joint Hs / wind10 thresholds (3 tiers): annual fraction, days per year, monthly breakdown
B-3	Operability persistence — run-length distribution per tier per month (median, p90, max for operable + downtime)

#	Table
B-4	CWA WW3 10-yr vs WAVERYS 5-yr climatology cross-check at site (mean / median / max Hs per month)
B-5	CWA buoy 30-day vs WAVERYS NRT spot check (per-station Hs / Tp / direction; per-station extraction-method note)

This is an **index of supporting statistical tables** generated by the analysis pipeline. The body of this report cites them by ID (e.g. “Table B-2”) for traceability; the full tables themselves are not embedded in the public methodology sample. Each table is available on request as part of a scoped engagement, or in CSV / Parquet form alongside a full project deliverable.