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Weather-Related Navigational Hazard Exposure Along Alternative Shipping Routes in the Straits of Malacca, the South China Sea, and the Indian Ocean

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ABSTRACT

Weather-informed route selection is essential for improving navigational safety and operational decision-making, particularly in maritime regions exposed to variable wind and wave conditions. This study evaluates and compares forecast-based environmental hazard exposure along six alternative shipping routes across three major maritime regions: the Straits of Malacca, South China Sea, and Indian Ocean. Meteorological data were obtained from PredictWind and Windy.com over 18 weekly observation periods between July and October 2025, covering five sampling positions along each route. Descriptive statistical analysis, wave-height exceedance frequencies, weekly route comparisons, and threshold-sensitivity assessments were employed to identify spatial and temporal differences in forecast environmental conditions. The findings revealed substantial variations in wave and wind exposure among the alternative routes. The Indian Ocean Route C2 exhibited the highest recorded mean wave heights of 2.19 m and 2.55 m from PredictWind and Windy.com, respectively, compared with 0.84 m and 0.99 m for Route C1. Approximately 60% of valid C2 wave-height readings reached or exceeded the illustrative 2.0 m screening threshold, compared with 1.1%–3.3% for C1. Weekly comparisons consistently identified the same direction of mean wave-height differences between paired routes across both forecasting platforms. Additional threshold-sensitivity analysis reinforced the comparatively elevated wave exposure along Route C2. These findings demonstrate the importance of incorporating route-specific meteorological information into preliminary voyage planning and environmental hazard screening. However, the results represent sampled forecast conditions rather than verified sea states or quantified navigational risks. The study provides an evidence-based foundation for developing more comprehensive weather-routing decision-support frameworks that integrate vessel-specific operational limitations, environmental forecasting, and navigational safety considerations.

Keywords: weather routing; navigational hazard screening; wave exposure; route alternatives; maritime safety

1. Introduction

Weather-related voyage planning requires assessment of route length and environmental conditions together (Zis et al., 2020). A route that is shorter in distance may expose a vessel to larger waves or less favourable currents, whereas a longer route may incur different costs and constraints (Mannarini et al., 2016). Established

weather-routing research formulates this trade-off through route and speed decisions, with operational objectives that can include fuel use, safety, and arrival time (Lin & Fang, 2013; Zis et al., 2020). However, a favourable meteorological snapshot is not equivalent to a validated optimal ship passage (Marjanović, 2026). Accordingly, the present study does not treat any single forecast as a definitive basis for route selection; instead, it examines whether route-level differences in forecast wave and wind conditions are consistent enough to inform preliminary hazard screening, since weather routing approaches that integrate ship resistance under current, wave, and wind forcing have been shown to identify more fuel-efficient alternatives under adverse conditions (Kamis et al., 2026; Rahmi & Hermawan, 2025). Such findings suggest that route selection should be treated as a multi-criteria screening problem, in which forecast exposure along each candidate corridor is compared against vessel-specific operational limits rather than judged solely by distance or a single meteorological snapshot (Nishiyama et al., 2011).

Wave climate, wind regimes, and circulation differ among oceans and maritime approaches. Studies of maritime wind-wave environments indicate the importance of geographic variability in voyage exposure (Chiroșcă & Rusu, 2022), while multi-decadal analysis of the Indian Ocean emphasises basin-scale wave variability and seasonal forcing (Li et al., 2022). These regional differences make a single weather-screening description inadequate for every route (Casas-Prat et al., 2024). They also create a need to distinguish measurable environmental indicators from claims about navigational accident probability (Kumar et al., 2019).

Three corridor families provide the setting for the present comparison: alternative passages between Port Klang and Teluk Bayur in the Straits of Malacca; alternatives between Port Klang and Manila in the South China Sea; and nominal transoceanic alternatives between Port Klang and Tin Can Island, Nigeria, which include Indian Ocean segments and longer routes beyond that basin (Huang et al., 2021). The recorded route alternatives are denoted A1-A2, B1-B2, and C1-C2. Each is represented by five numbered forecast positions sampled weekly across July–October 2025.

The primary research question is: How do the recorded wind-wave conditions and exposure frequencies differ between paired alternative routes within each of the three corridor families? The objectives are (a) to summarise the forecast environmental profiles, (b) to compare descriptive exposure to higher wave-height readings, (c) to identify the influence of route and platform choice on interpretations, and (d) to define evidence-based limits for turning route-specific forecasts into operational decisions. This is an environmental hazard-screening exercise rather than a verified route optimisation or accident-risk model.

2. Literature Review

2.1 Weather routing as a multi-objective problem

Traditional and contemporary approaches to weather routing consider a network of alternatives under changing wind, waves, and currents. The modified-isochrone approach of (Lin & Fang, 2013) combines environmental constraints with routing decisions, while (Gkerekos & Lazakis, 2020) link weather, ship performance, and a fuel-related objective. (Kytariolou & Themelis, 2022) explicitly include safety criteria. Reviews of ship weather routing emphasise that optimising route length, fuel consumption, voyage time, and navigational safety involves separate quantities and often conflicting choices (Zis et al., 2020).

For operationally meaningful route optimisation, the effect of a sea state depends on the vessel (Kytariolou & Themelis, 2022). Hull form, loading condition, heading relative to waves, speed, power margin, and motion limits can govern allowable conditions (Kytariolou & Themelis, 2022). A forecast wave height alone therefore cannot specify an acceptable ship speed or determine a casualty likelihood (Zhang & Li, 2017). This motivates an exploratory separation between forecast exposure and vessel-specific risk; the latter would require explicit seakeeping criteria, dynamic constraints, and technical vessel data (Kytariolou & Themelis, 2022).

2.2 Environmental exposure and regional wave variability

Chiroșcă & Rusu, (2022) demonstrate the usefulness of spatially resolved wind-wave statistics for maritime corridors. Indian Ocean wave research also describes seasonal variability driven by wind patterns and basin-scale oscillations, with wave behaviour differing by location (Li et al., 2022). The implication for the present comparison is limited but important: alternative routes should not be evaluated by geographic name alone. The relevant conditions are those encountered at specific positions and times, together with uncertainty in the forecast field (Mannarini et al., 2024; Nielsen, 2021).

The July–October observation period intersects, but does not represent in full, the seasonal meteorological cycle. It cannot establish an annual climatological norm, the frequency of all extreme events, or a future voyage's likely weather. Additionally, a route to Nigeria traverses more than the Indian Ocean; the selected "Indian Ocean" comparison is a broad corridor label rather than a geographically uniform sample.

2.3 Safety and environmental efficiency implications

International efforts to reduce ship greenhouse-gas emissions underscore the importance of voyage efficiency ("2023 IMO Strategy on Reduction of GHG Emissions from Ships," 2025). However, an emissions claim requires measured or modelled propulsion and fuel use, and a safety claim requires a relevant causal or risk framework (Poulsen et al., 2021; Yan et al., 2021). Weather routing may support these objectives, but the available dataset includes no vessel-specific performance curve, time-of-arrival calculations, bunkers consumed, casualty record, or operational safety outcomes (Tsai et al., 2021; Zis et al., 2020). Consequently, the present study contributes a descriptive baseline from which a future operational decision model could be developed, rather than quantifying those outcomes directly.

3. Methodology

3.1 Study corridors and alternatives

Six nominal alternatives were grouped into three route pairs. A1 and A2 run between Port Klang and Teluk Bayur and are labelled the Straits of Malacca family; B1 and B2 connect Port Klang and Manila across different South China Sea paths; C1 and C2 concern the voyage between Port Klang and Tin Can Island, Nigeria, through different long-distance corridors. Figures 1–3 show the original route sketches and their nominal geographic separation. These sketches establish an approximate comparative layout; they are not electronic navigational charts, surveyed traffic-separation routes, or evidence that all segments are legally or physically navigable under present restrictions.

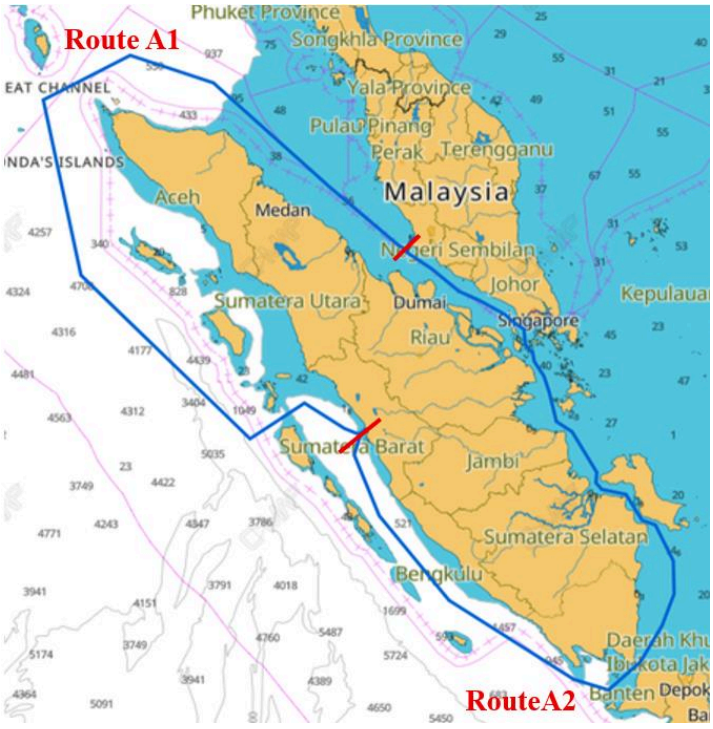


Figure 1. Nominal route alternatives A1 and A2, reproduced from the study's recorded route map.

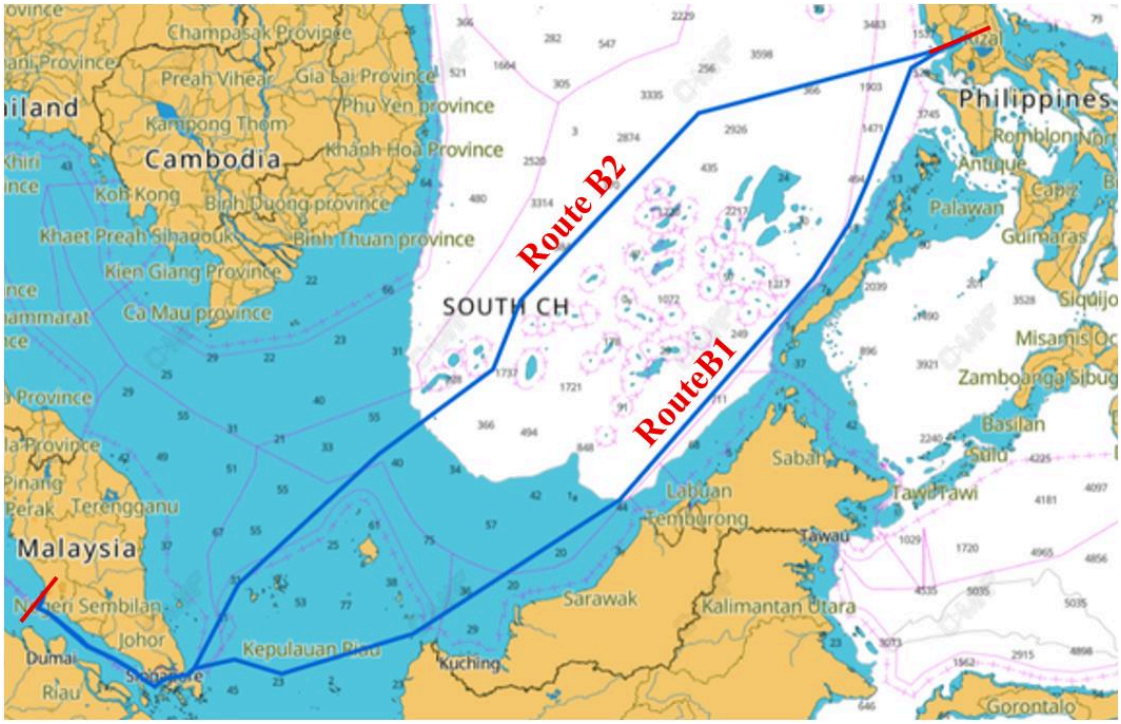


Figure 2. Nominal route alternatives B1 and B2, reproduced from the study's recorded route map.

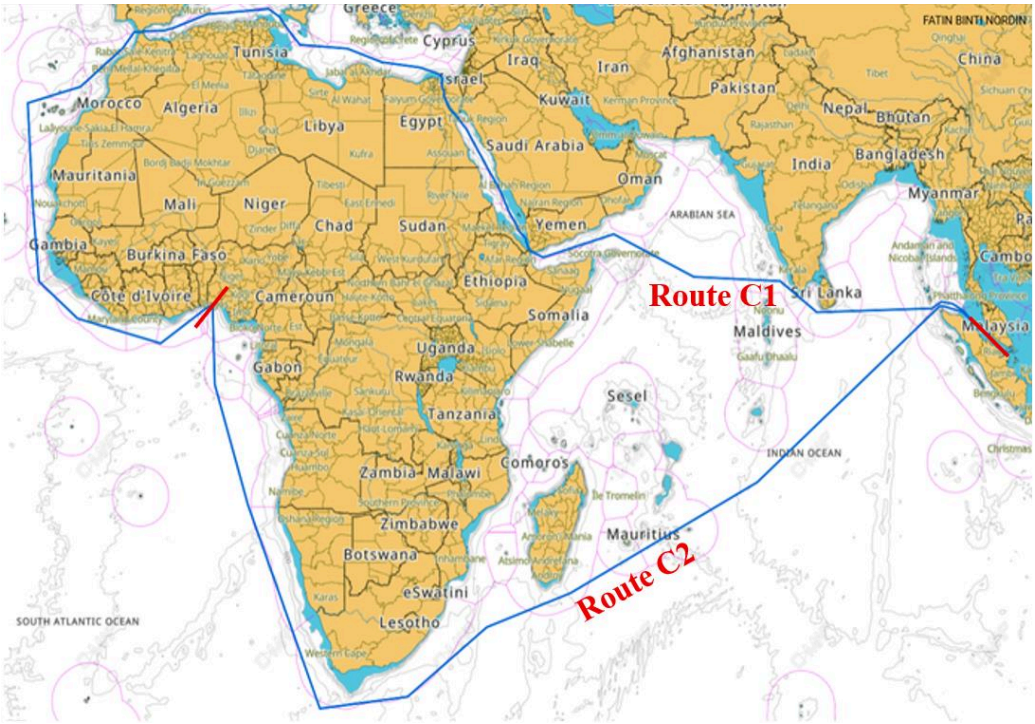


Figure 3. Nominal route alternatives C1 and C2, reproduced from the study's recorded route map.

3.2 Sampling, variables, and unit of comparison

Weather tables provided 18 approximately weekly observation dates from 2 July through 29 October 2025, with five observation positions for each route. Readings were recorded at about 10:00 and compared using both PredictWind and Windy.com. Main screening variables were reported wave height in metres and wind speed in knots; current speed, temperature, and qualitative weather-condition codes were used as supporting descriptors. Observation points were numbered 1–5, but a full set of georeferenced coordinates, route lengths, forecast lead times, and model product identifiers was not available.

The primary unit of analysis was a route–platform–week–position record, not an actual ship transit. Each route and platform yielded 90 expected observations per variable. For the wave field, the Windy.com C2 entry at position 1 on 9 July was malformed ("0.m") and excluded, leaving 89 valid C2 readings. A separate malformed

A2 wind record on 22 October caused one missing paired reading. Data were not interpolated or imputed. Observations from neighbouring waypoints and weeks were not assumed statistically independent.

3.3 Hazard exposure indicators

Per route and platform, arithmetic means and maximum reported values were computed for wave height and wind speed. A deliberately simple exposure screen counted positions with wave height ≥2.0 m and ≥4.0 m, and wind speed ≥25 knots. These are analyst-defined descriptive thresholds for comparing the archived numeric ranges, not vessel-specific safety limits, regulations, probability estimates, or evidence that any ship was endangered. Percentage exposure is 100 times the number of sampled readings exceeding the selected screen divided by valid readings for that route and platform.

Paired alternative-route comparison was descriptive. Because different alternatives cover different geographical paths, a "same point number" comparison is not interpreted as a colocated difference. No route exposure index was weighted by route length, vessel time spent in each segment, or expected crossing speed. The analysis therefore refrains from identifying a globally optimal route; rather, it identifies route segments and periods that warrant closer evaluation in a full voyage model.

4. Results

4.1 Route and region exposure profiles

Table 1. Mean and maximum recorded wave heights by alternative route.

Route	PW mean (m)		Windy mean (m)	Windy max (m)
A1	0.95	2.4	0.83	2.2
A2	0.82	1.9	0.70	1.7
B1	0.83	4.5	0.64	3.5
B2	1.14	6.0	0.90	4.8
C1	0.84	2.5	0.99	3.2
C2	2.19	7.0	2.55	9.5

Note. Per route and platform except Windy. These values are unweighted waypoint-date summaries, not entire-route exposure.

For the Straits of Malacca alternatives, the reported mean waves were 0.95 m and 0.83 m (PredictWind, Windy.com) for A1, compared with 0.82 m and 0.70 m for A2. In the South China Sea, B2 had higher mean values than B1 in both platforms (1.14 vs 0.83 m in PredictWind and 0.90 vs 0.64 m in Windy.com). The Indian Ocean difference was larger: C2 averaged 2.19 m and 2.55 m against 0.84 m and 0.99 m for C1. These figures describe the particular archived waypoint values and do not establish route-wide safe passage or seasonal climatology.

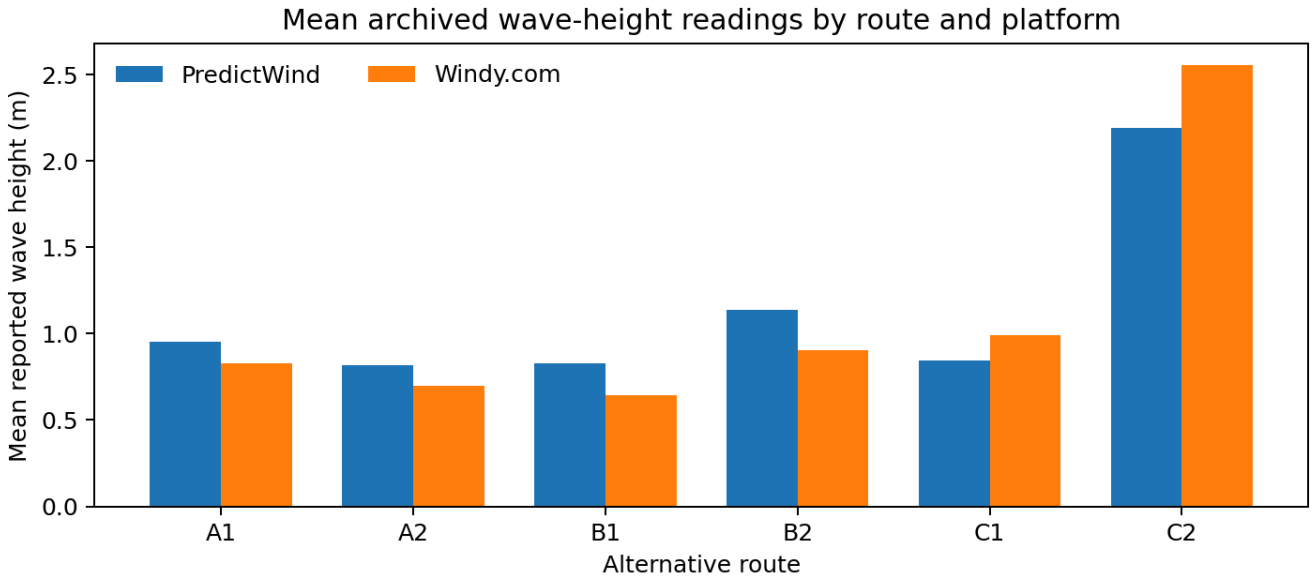


Figure 4. Mean recorded wave height for six alternatives using each weather platform.

4.2 Exposure at illustrative wave-height thresholds

Table 2. Counts and proportions at illustrative wave-height screening levels.

Route	, (%)	, n	Windy ≥2 m, (%)	Windy ≥4 m, n
A1		0		0
A2		0		0
B1		1		0
B2		2		1
C1		0		0
C2		9		15

Note. Thresholds are descriptive screens, not vessel-specific safety limits. Missing “0.m” was excluded, not interpreted as zero.

C2 had the highest fraction of sampled wave-height readings meeting the 2.0-m screen in PredictWind and in Windy.com. C1 recorded and , respectively. At the 4.0-m screen, C2 contained nine PredictWind entries and fifteen Windy.com entries, with maxima of 7.0 and 9.5 m. The fact that two sources display the same general route contrast does not independently verify the extremes, because their weather-model provenance and forecast lead times were not documented.

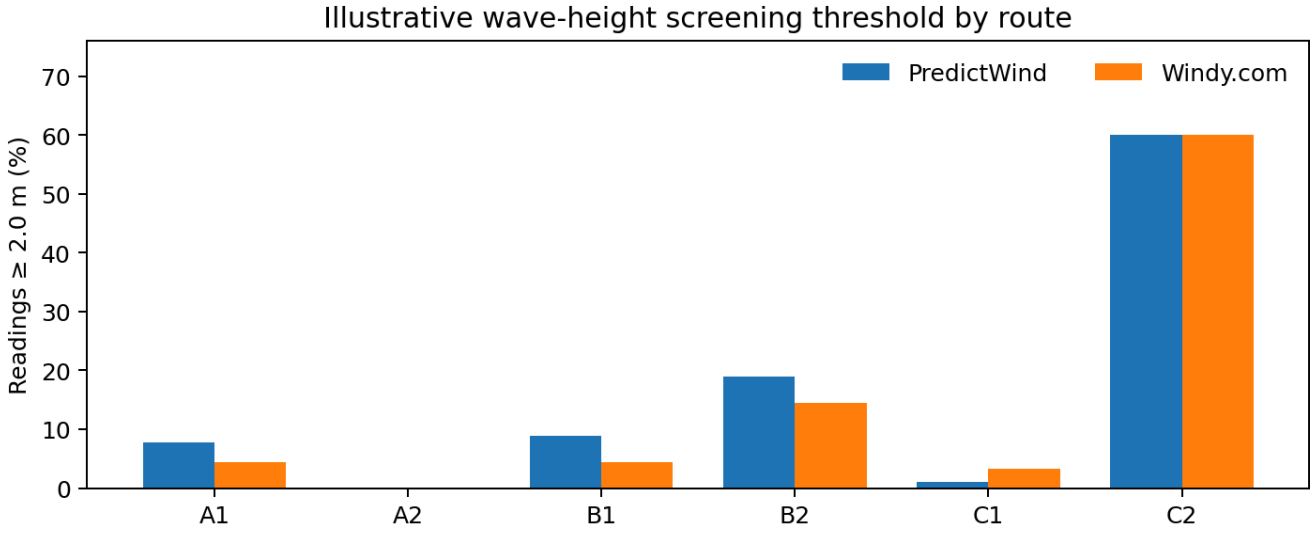


Figure 5. Percentage of sampled wave-height readings at or above the illustrative 2.0-m screen.

4.3 Wind conditions and categorical weather indicators

Table 3. Reported wind-speed levels and illustrative elevated-wind counts.

Route	PW mean			Windy mean	Windy	Windy ≥25 kn
A1	9.3	20	0	8.0	18	0
A2	9.6	18	0	8.2	15	0
B1	11.1	40	2	9.0	32	2
B2	12.9	45	7	10.4	36	2
C1	9.0	22	0	10.7	28	1
C2	14.3	40	7	16.4	48	11

Note. All wind values are knots. The ≥25-knot screen is an analyst-defined comparison threshold, not an operational limit.

The highest average wind readings appeared in C2 (14.26 knots for PredictWind and 16.40 knots for Windy.com), whereas B2 also recorded episodes of stronger winds. At the 25-knot wind screen, C2 produced seven PredictWind and eleven Windy.com observations; B2 produced seven and two, respectively. The two applications also differed in qualitative descriptions of rain and thunderstorms. Such categorical differences caution against treating a single weather-condition label as an objective route-risk score.

4.4 Sensitivity to platform and aggregation

Relative route comparisons for wave height had broadly consistent direction within the paired corridor families. A2 was lower than A1 in route-level average wave readings under both applications, B2 was higher than B1, and C2 was higher than C1. However, agreement about average ranking is not evidence of a universally preferable route, because the five positions are unweighted, the analysis omits route lengths and vessel speeds, and individual storms may be highly localised. The quantitative contrast is most informative as a flag for focused voyage-specific verification rather than as an instruction to divert.

5. Discussion

5.1 Interpreting exposure rather than probability

Environmental screening statistics are not equivalent to accident likelihood or vessel survivability. A recorded wave height of 4 m can have different operational consequences depending on encounter angle, period, length, draft, stability, and speed. Conversely, even smaller waves may be consequential in confined waters or

particular vessel-response conditions. The literature on weather routing explicitly links environmental inputs with vessel dynamics, weather constraints, and optimisation objectives (Kytariolou & Themelis, 2022; Lin & Fang, 2013). None of the present statistics includes a motion-response model or validates ship-handling safety.

5.2 Comparisons within the corridor pairs

The two Malacca alternatives exhibited comparatively low sample means, but the A1 maximum of 2.4 m in PredictWind illustrates that lower average exposure does not rule out individual higher readings. A2 had lower average wave readings, yet differences in navigable channel constraints, shallow water, traffic separation, and currents are outside the present model. In the South China Sea, B2 registered a higher wave mean and more screened wave readings than B1; a passage decision would also require verified routing geometry, operational restrictions, and vessel-specific controls. These issues preclude a claim that one route is categorically safest.

The largest within-pair contrast occurred between C1 and C2, consistent with the dependence of marine environments on geographical path and forcing. Indian Ocean wave variability has documented seasonal and basin-scale structure (Li et al., 2022), which supports the need for location-specific analysis but does not validate any particular 2025 platform value. C2's 9.5-m maximum should be treated as a reported model output requiring confirmation rather than an observed sea state. The destination route also extends beyond the Indian Ocean, and route maps require professional passage-planning verification before use.

5.3 Translating a screening profile into voyage planning

A practical two-stage decision process would first identify and inspect high-exposure points and dates, then evaluate feasible alternative tracks using updated forecasts, charted constraints, vessel response, and fuel and time implications. This resembles the separation between environmental data and optimisation calculations in studies by (Gkerekos & Lazakis, 2020; Zis et al., 2020). Where the platform readings disagree, a prudent navigator would review the original weather-model runs and independent forecasts rather than simply selecting the lower figure.

Potential fuel savings and emissions reductions remain plausible motivations for rigorous weather routing, consistent with maritime emissions objectives ("2023 IMO Strategy on Reduction of GHG Emissions from Ships," 2025). However, no time-history speed profile, shaft power, resistance model, fuel-use measurement, or distance-weighted routing solution is available in the study. It would be scientifically unsound to report achieved fuel savings, a quantified safety improvement, or optimal routing efficiency based on the environmental screens alone.

5.4 Uncertainty, data-quality concerns, and research priorities

The dataset has limitations in spatial representativeness and traceability. Five observations per nominal route do not represent the entire waterway, and a single weekly reading cannot resolve rapidly changing storms. The relevant platform model, issue and valid times, and whether temperatures represent sea-surface temperature were not confirmed. Some temperature entries on the extended Indian Ocean route vary sharply across adjacent stations and platforms; these should be validated before making physical claims about thermal gradients or engine-cooling implications. One malformed wave entry and one malformed wind entry were excluded; no value was inferred.

Future work should reconstruct the route geometries from authoritative navigational information, retain coordinates and forecast metadata, independently validate significant wave height and wind outputs, and sample at intervals compatible with vessel ETA and forecast lead time. A vessel-specific model could then combine route length, wave encounter conditions, speed loss, emissions, and credible safety constraints. Prospective validation using actual voyage records would be required before assessing whether the route-screening framework reduces operational risk (Kytariolou & Themelis, 2022; Zis et al., 2020).

6. Conclusion

The analysis of 18 weekly weather archives identified heterogeneous environmental exposure across six alternative shipping routes. The most pronounced contrast appeared within the nominal Indian Ocean route family: reported C2 mean wave height was 2.19–2.55 m across the two platforms, versus 0.84–0.99 m for C1, and approximately 60% of C2 wave-height entries met the descriptive ≥2.0-m screening level. The South China

Sea B2 route also showed higher average wave readings than B1, while A2 was lower than A1 in the Straits of Malacca comparison. These are comparisons of sampled forecast values, not validated wave observations or ship-specific navigation risks.

The principal contribution is a transparent screening framework that separates recorded environmental exposure from decisions requiring vessel particulars, passage geometry, temporal forecasting, and independent verification. Additional route-specific modelling and operational data are essential before claims about safety, optimal route selection, voyage duration, emissions, or fuel economy can be justified.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used ChatGPT to assist with language refinement, grammatical correction, and improvements to the clarity and readability of the text. The authors subsequently reviewed, edited, and verified the content to ensure its accuracy, originality, and scientific integrity. The authors take full responsibility for the content of the published article.

Conflict of Interest

The authors declare that they have no known financial or non-financial conflicts of interest that could have influenced the research, analysis, interpretation, or publication of this manuscript.

Author Contributions

Data availability.

The dataset comprises dated, route-specific meteorological readings recorded at five positions for each of six route alternatives. The analysis tables report the derived comparisons. The available study records do not contain complete georeferenced positions, platform model identifiers, or archived forecast lead times.

Ethics statement.

The investigation uses secondary environmental data and involves no recruited human participants or human-subject intervention.

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