

Overall recommendation: Minor revision

This is a well-executed, scientifically robust paper that successfully links real-time multi-platform monitoring with climate-resilient port operations. With modest editorial refinements and expanded contextual discussion it will represent an exemplary contribution to State of the Planet 2025.

We sincerely thank the anonymous Reviewer 2 for the detailed review and the thoughtful questions aimed at fostering discussion. Below, we provide a thorough point-by-point response, with the aim of improving the manuscript and ensuring its suitability for final publication.

General comments

This manuscript provides a robust and timely analysis of Storm Louis (February 2024) and its impact on two Spanish ports: Langosteira (NW Iberia) and Tarragona (NE Iberia), through a multi-platform observing system that combines in situ moored buoys and tide gauge data with High-Frequency Radar (HFR) land-based remote sensing. The study is scientifically rigorous, well structured, and operationally relevant, offering valuable insights into harbour agitation dynamics under extreme conditions. Its novelty lies in the real-time, multi-platform assessment of a deep extratropical cyclone affecting two contrasting coastal regions, supported by strong offshore-in-port statistical relationships and a meaningful validation of HFR-derived wave parameters.

The methods are clearly described and reproducible, and the results are well supported by high-quality figures and tables. The discussion effectively contrasts the responses of Langosteira and Tarragona and highlights the influence of geometry, exposure, and wave directionality on port vulnerability. The percentile-based contextualisation is appropriate for the available 11-year record, though the authors should clarify that this does not constitute a full climatological baseline.

Following Reviewer 2's suggestion, we acknowledge that the 2014–2024 period does not constitute a full climatological baseline, as the World Meteorological Organization guidelines require time series of at least 30 years. Accordingly, the term "*climatological percentiles*" has been replaced throughout the manuscript with the more accurate expression "*historical percentiles based on the available 11-year observational record*".

The comparison of HFR performance between regions is insightful and would benefit from additional clarification regarding network specifications, retrieval methods, and local factors affecting skill.

We thank Reviewer 2 for this insightful comment. In response, we have expanded the discussion to provide additional clarification on the comparison of HFR performance between regions, including key aspects related to network specifications, retrieval methodologies, and local environmental factors influencing skill. These additions aim to better contextualize the observed differences and strengthen the interpretation of the results.

A minor but important recommendation is to revise the title by replacing "multi-sensor" with "multi-platform," as this terminology is broader, more accurate, and aligned with current operational oceanography and observing-system frameworks.

As we fully agree with this suggestion, the term "multi-sensor" has been replaced by "multi-platform" throughout the entire manuscript, including the title.

Contextualisation is strong and well referenced, with opportunities to incorporate additional key literature on observing systems, HFR wave estimation, and climate-related port adaptation.

We thank Reviewer 2 for this positive assessment. Most of the suggested references have now been incorporated into the manuscript and added to the reference list, particularly those related to observing systems, HFR-based wave estimation, and climate-related port adaptation, thereby further strengthening the contextualisation of the study.

Minor editorial refinements, including condensing the introduction, harmonising terminology, improving reference formatting, and clarifying technical details in Section 4.3, will further enhance clarity and coherence.

We thank Reviewer 2 for these helpful recommendations. The manuscript has been carefully revised to streamline the introductory section, ensure consistent use of terminology, improve the presentation of references, and further clarify the technical discussion.

Specific comments

Novelty and contribution (Score: 1- Excellent)

The manuscript offers several high-value contributions:

- A real-time, multi-platform assessment of a deep extratropical cyclone and its contrasting impact on two ports under the same synoptic forcing.
- New insights into harbour agitation dynamics, supported by long-term offshore–in-port statistical relationships.
- A meaningful validation of HFR-derived wave parameters during an extreme storm.
- A cross-regional comparison (Atlantic vs. Mediterranean) effectively illustrating how geometry, exposure, and wave directionality modulate port vulnerability.
- A complementary perspective to long-term climate-adaptation literature (e.g., Sierra et al., 2023; Portillo Juan et al., 2022), reinforcing the need for port-level resilience assessments.
- Suggestions for improvement:
 - a) Add a short paragraph in the discussion explicitly positioning the study in the broader context of climate-resilient port management framework, and multi-hazard early warning systems (e.g., link to SDG 13 and 14, or EU Mission Ocean).

We thank the reviewer for this helpful suggestion. In response, Section 5 has been expanded with a brief paragraph that highlights the relevance of this study for climate-adaptive port planning and risk-informed maritime operations, including connections to sustainable development goals and relevant EU initiatives.

“Beyond the event-scale analysis, this study contributes to the broader framework of climate-resilient port management by illustrating how compound metocean hazards and associated wave agitation may compromise critical harbour operations. The impacts observed at Langosteira and Tarragona harbours underscore the need for integrated multi-hazard early warning systems to support anticipatory decision-making and robust, evidence-based assessments of harbour operability. Such approaches align with the objectives of the EU Mission “Ocean and Waters” which promotes the enhancement of

long-term infrastructure resilience and the translation of scientific knowledge into operational tools for sustainable ocean governance under a changing climate (EU Mission Ocean and Waters website, 2025)."

- b) Explicitly note AEMET's classification of Storm Louis as a high-impact storm (winds $>140 \text{ km h}^{-1}$, waves $>8 \text{ m}$), underlining its relevance as a test case.

We thank the reviewer for this suggestion. The Introduction has been updated to highlight the significance of Storm Louis, noting that the Spanish Meteorological Agency officially classified it as a high-impact event, with locally measured wind gusts exceeding $140 \text{ km}\cdot\text{h}^{-1}$ and extreme sea states:

"In Spain, the event was officially classified by the State Meteorological Agency (AEMET) as a high-impact storm, reflecting wind gusts locally exceeding $140 \text{ km}\cdot\text{h}^{-1}$ and the generation of extreme sea states (AEMET website, 2025)."

Scientific approach and methods (Score: 1- Excellent)

- Methods are clearly described and reproducible, with tables summarizing datasets (ERA5, HFR, REDMAR, and in-situ buoys) and their temporal coverage (Tables 1–5) with strong statistical analysis.
- The percentile-based approach for contextualizing extremes and capturing the spatio-temporal footprint of Storm Louis is appropriate for characterizing the event within the available 11-year record, although it should be noted that this period does not constitute a full climatological baseline.
- The analysis of long-term relationships between significant wave height, mean wave period, and mean wave direction with port agitation, supported by directionally resolved scatterplots, offers a valuable quantification of harbour sensitivity under energetic offshore conditions.
- HFR–buoy comparison is statistically rigorous (correlation, RMSE, regression slopes) and consistent with existing literature
- Suggestion for improvement:

Briefly discuss uncertainties related to (i) the distance between HFR range cells and their comparison buoys (e.g., 22–47 km; Fig. A2), and (ii) local bathymetric influences on wave transformation, which are relevant for future HFR calibration, etc. These elements are relevant for future calibration and are consistent with existing HFR literature.

We thank the reviewer for this helpful observation. The revised manuscript now includes a brief discussion of the sources of uncertainty affecting the HFR–buoy comparison, focusing on the effects of spatial separation between observation points and on site-specific seabed characteristics that influence wave evolution. These considerations are framed in terms of their relevance for interpreting the results and for informing future HFR calibration efforts, thereby placing the regional skill differences in a broader methodological context.

Results and discussion (Score: 2- Good)

- Results are detailed and supported by clear figures (e.g., Fig. 1–4, and three additional ones in Annexes).
- The contrasting wave-induced agitation responses between Langosteira and Tarragona are well substantiated by geometry and exposure.
- The manuscript effectively quantifies high correlations between offshore wave height and in-port agitation ($R = 0.88$ for Langosteira, $R = 0.75$ for Tarragona).
- The manuscript analyzes Tarragona's marked sensitivity to wave incidence angle and its role in amplifying internal hydrodynamic response.
- The seasonal analysis (Fig. 3g–h) operational relevance for long-term risk management.
- Suggestions for improvement:
 - a) Suggestion to expand the discussion on operational thresholds (e.g., downtime limits for mooring and cargo handling) to better link with the port operability metrics proposed by Sierra et al. (2023).

We appreciate this valuable suggestion. However, we believe that a detailed discussion of operational thresholds, such as downtime limits for mooring and cargo handling, would require a dedicated analysis beyond the scope of the present manuscript and is therefore more appropriately addressed in a complementary study.

On the other hand, in the absence of official reports of operational disruptions due to extreme agitation, the recorded agitation at the port entrance should be considered within the tolerance ranges for routine activities within the port basin, consistent with the port's historical operational experience under similar wind and wave conditions. It should also be noted that harbour-specific thresholds are highly berth-dependent and often account for factors such as vessel size, mooring arrangements, operational schedules and type of activity performed.

To our knowledge, the operational thresholds typically used by Port of Tarragona's decision makers are primarily related to wind and overtopping, particularly when exceptionally strong winds and waves originate from the climatologically predominant NE sector, as observed during the record-breaking Storm Gloria (January 2020).

- b) Briefly compare Storm Louis with notable historical storms such as Storm Gloria (2020) to contextualise its magnitude.

We thank the reviewer for this valuable suggestion. While a direct comparison with well-documented events such as Storm Gloria (2020) could be informative, we consider that the magnitude of Storm Louis is more consistently and objectively contextualised through the percentile-based analysis presented in Fig. 2 (panels b–d for the NWI region and panels f–h for the NEI region). Given that Storm Louis and Storm Gloria were associated with markedly different synoptic-scale atmospheric configurations, a direct event-to-event comparison could be misleading. We therefore opted for a general contextualisation based on long-term percentiles, which provides a robust and homogeneous framework for assessing the extremeness of the event across regions.

- c) Section 4.3: This section is strong but would benefit from additional clarity:
 - i) Note that an 11-year dataset is not a climatological baseline (WMO requires ≥ 30 years). I would suggest referring instead to "historical percentiles based on the available 11-year record."

As we totally agree with this suggestion, the following clarification has been added not only to Section 3.1 ('Methodology') but also to the abstract:

"[...] multiple observed wind and wave parameters associated with Storm Louis exceeded the 99.9th (99th) historical percentiles, based on the available 11-year observational record period spanning 2014-2024".

- ii) Use the official names of the HFR networks: HFR-Galicia and HFR-DeltaEbro, and list specific sites and frequencies.

Official names of the HFR networks have been used along the entire manuscript, including Tables, Figures and Annexes.

- iii) Specify HFR direction of arrival (e.g. direction-finding) and CODAR software version, given its influence on wave algorithms.

While the method of arrival has been specified in Table 5, the CODAR software version has been detailed in section 3.2.: *"The wave parameters used in this study, based on 30 min averaged backscatter data, were obtained directly by the CODAR radar proprietary software: the SeaSonde Radial Suite Software Release 7 (R7). This wave processing tool..."*

- iv) Clarify reasons for lower HFR skill in the NEI region (e.g. reduced coverage, geometry, bathymetry, lower energy levels, and CWP sensitivity to SNR).

We have expanded the discussion to briefly identify the main factors contributing to the reduced HFR performance in the NEI region, including spatial mismatch with the buoy, radar geometric limitations, bathymetric complexity, and storm-related variability in wave energy and sea-state structure. This clarification helps to interpret the observed regional differences in HFR skill.

- v) Confirm that the analysed range cells are in sufficiently deep water to avoid shallow-water artefacts.

We thank the reviewer for this comment. Shallow-water effects are known to influence radar sea echo by enhancing second-order spectral energy relative to first-order components and by reducing the wave-height saturation limit as water depth decreases (Lipa et al., 2008). For the HFR-Galicia network (4.46 MHz), such effects become relevant at depths shallower than approximately 35 m. The selected range cell (RC3) is located at about 150 m depth (as can be qualitatively inferred from Annex 2a), which comfortably satisfies the deep-water assumption and ensures that nonlinear shallow-water contamination is negligible.

For the HFR-DeltaEbro system operating at 13.5 MHz, shallow-water effects are expected to occur at much smaller depths due to the shorter radar wavelength. The selected range cell (RC4) is located at approximately 50 m depth (as derived from Annex 2b), which is well above the threshold for shallow-water contamination at this frequency, confirming the suitability of the wave dataset for subsequent analysis.

The panels in Annex 2 have been accordingly updated.

Cite additional HFR wave-estimation studies (Tian et al., 2017; Lipa et al., 2018).

We thank the reviewer for this suggestion. The manuscript has been updated to include the studies by Tian et al. (2017) and Lipa et al. (2018), which have also been added to the reference list.

Emphasize that NWI vs. NEI differences are consistent with Saviano et al. (2022), who describe similar skill contrasts under varying energy and bathymetric conditions.

A paragraph has been added to note that the differences between the NWI and NEI regions are consistent with Saviano et al. (2022), who reported comparable HFR–buoy skill contrasts under varying wave energy and bathymetric conditions. This addition situates our Storm Louis results within the existing literature.

Structure, clarity and presentation (Score: 1- Excellent)

- The manuscript follows a clear and coherent structure, progressing logically
- English language quality is excellent, with minor redundancies.
- Figures, tables, and annexes are well designed and informative as well as professionally prepared and properly referenced.
- Suggestions for improvement: condense the introduction (pp. 2–4), reducing the number of historical storm examples and emphasising the novelty of the multi-platform approach.

We thank the reviewer for this recommendation. The Introduction has been streamlined by removing the mention of the Storm Ciara event and its associated reference (Jardine et al., 2023), thereby placing greater emphasis on the originality of the multi-platform approach.

References and contextualization (Score: 1- Excellent)

The reference list is extensive (over 70 entries), up-to-date, and integrates both global and regional literature.

a) Suggested additions and improvements:

- Tintoré et al. (2019): importance of sustained/integrated observing systems.

Cited and added to the reference list, along with Davidson et al. (2019).

- Lorente et al. (2021): HFR wave field review.

Cited and added to the reference list.

- Sierra et al. (2023) and Portillo Juan et al. (2022): climate change impacts and port adaptation.

Cited and added to the reference list.

- Toledo et al. (2024): storm surge processes and atmospheric forcing

Not cited to maintain a focused reference list and avoid excessive length.

- De Alfonso et al. (2021): for storm statistics in the Spanish Mediterranean.

Not cited to maintain a focused reference list and avoid excessive length.

- Saviano et al., (2022): HFR performance under varying sea-state and bathymetric conditions.

Cited and added to the reference list.

b) Formatting suggestions: to bring the reference list fully in line with the journal's formal requirements.

- Ensure all authors follow the “Surname, Initials” format (e.g., change forms like “J. Goggins, M. Hartnett” to “Goggins, J., Hartnett, M.”) and use “and” consistently instead of “&”.

Done!

- Standardise journal names and apply the required order (journal – volume – pages – DOI – year). Some entries may need harmonisation and DOI inclusion (e.g., Morales-Márquez et al., 2020, Harley (2017)).

Done!

- Cite reports/datasets (e.g., Aon-Benfield; Copernicus/CMEMS manuals) with full institutional details, URLs, and DOIs where available.

Done!

- For discussion papers or preprints, use the final published version when possible, or include the correct preprint DOI per journal guidelines.

Done!

Figures/tables and supplementary material (Score: 1- Excellent)

- Tables 1–5 and Figures 1–4 are informative and well-integrated.
- The annexes (A1–A3) add clarity to the site configurations and validation procedures, enhancing reproducibility.

Suggestions for improvement:

- Table 1: Include DOIs for datasets where applicable.

Only the ERA5 product has a specific DOI and was already provided.

- Table 2: Add definitions of all EOV acronyms in the caption to improve readability → done!
- Tables 3 and 4: Several parameters repeat information already provided in Table 2 for buoys and tide gauges. Either remove redundancies or ensure full consistency between the variables listed across the tables. → done!
- Table 5:
 - Use official HFR network names (HFR-Galicia / HFR-DeltaEbro) → done!
 - Replace “systems” with “networks” → done!
 - Verify site frequencies (HFR-Galicia includes 4.463 MHz and 13.5 MHz sites) → done!
 - Include the HFR direction of arrival method (e.g. direction-finding) → done!
- Figure 1d and e: Add a bounding box or visual marker to clearly highlight the Langosteira and Tarragona Harbour areas, respectively → done!

- Figure 4 - caption: Please indicate in the caption that the y-axis scales differ between the Langosteira and Tarragona panels, so that readers can correctly interpret and compare the magnitudes of offshore wave height and period → [done!](#)

Technical corrections (throughout manuscript)

- Page 1, line 14: include “low pressure dipole” and “intense north-westerly maritime-polar winds”.

We have added to the abstract:

“[...] revealing a marked Azores High-Iceland Low pressure dipole configuration”

“A strong SW-NE pressure gradient gave rise to persistent and anomalously intense north-westerly maritime-polar winds over the northeastern Atlantic Ocean and the Iberian Peninsula that induced significant waves heights above 8 m.”

- Page 1, line 16: clarify location (“over the northeastern Atlantic Ocean and the Iberian Peninsula”) and specify wave heights (“6–8 m, locally exceeding 8 m in Galician and Cantabrian coasts and wind gusts above 140 kmh⁻¹ in exposed mountainous and coastal areas”).

[Done!](#)

- Page 2, line 44: Remove “which is projected” for conciseness.

[Done!](#)

- Page 3-4, Introduction: Condense background on historical storms; emphasize Louis-specific context and novelty.

[Done!](#)

- Page 3, line 92: Replace with “...two High Frequency Radar Networks”

[Done!](#)

- Page 3, line 98: Use “networks” instead of “systems”.

[Done!](#)

- Page 5, line 134: Replace “Additionally” with “Complementarily”

[Done!](#)

- Page 5, line 134: Consider moving Table 3 to Supplementary Material if length reduction is needed.

[We thank the reviewer for this suggestion. As no reduction in manuscript length is necessary, Table 3 has been retained in its current location.](#)

- Page 5, line 152: Use the official names of the HFR networks registered in the European HFR Node: HFR-Galicia (FIST, SILL, LPRO, PRIO, VILA) and HFR-DeltaEbro (ALFA, SALO, VINA).

[We thank the reviewer for this recommendation. The official names of all HFR sites have been applied consistently throughout the manuscript, including in Tables, Figures, and Annexes.](#)

- Page 7, line 203: Consider adding recent HFR wave-estimation references (e.g., Tian et al., 2017; Lipa et al., 2018) to complement Lipa and Nyden (2005).

Both works have been cited in the manuscript and added to the reference list.

- Page 7, lines 220-224: Verify and confirm whether the range cells are located in sufficiently deep water to avoid shallow-water nonlinear ‘contamination’.

We thank the reviewer for this comment. Shallow-water effects are known to influence radar sea echo by enhancing second-order spectral energy relative to first-order components and by reducing the wave-height saturation limit as water depth decreases (Lipa et al., 2008). For the HFR-Galicia network (4.46 MHz), such effects become relevant at depths shallower than approximately 35 m. The selected range cell (RC3) is located at about 150 m depth (as can be qualitatively inferred from Annex 2a), which comfortably satisfies the deep-water assumption and ensures that nonlinear shallow-water contamination is negligible.

For the HFR-DeltaEbro system operating at 13.5 MHz, shallow-water effects are expected to occur at much smaller depths due to the shorter radar wavelength. The selected range cell (RC4) is located at approximately 50 m depth (as derived from Annex 2b), which is well above the threshold for shallow-water contamination at this frequency, confirming the suitability of the wave dataset for subsequent analysis.

- Page 8, line 211: Consider adding Wyatt (1990) to strengthen the citation.

The suggested work has been cited and added to the reference list.

- Page 8, line 212: Specify the CODAR software version, as retrieval algorithms differ across releases and reproducibility depends on it.

This information has been specified in section 3.2.: “*The wave parameters used in this study, based on 30 min averaged backscatter data, were obtained directly by the CODAR radar proprietary software: the SeaSonde Radial Suite Software Release 7 (R7).*”

- Page 8, line 232: Include SLP values for high and low (as shown in Figure 1)

This information has been added to Section 4.1.: “*... a persistent subtropical high (~1035 hPa) over the southwestern North Atlantic and a deep low (~968 hPa) centred over northeastern Europe (Fig. 1a)*”.

- Page 9, line 280: Include reference to (Fig. 3c and e, respectively)

Included!

- Page 10, lines 322-326: Expand briefly on the physical/technical reasons for lower HFR skill in the NEI region (e.g., greater distance from buoy, geometric constraints, bathymetric complexity, lower sea-state energy during parts of the storm, and mixed-sea states that affect period retrieval).

We appreciate the reviewer’s insightful comment. Accordingly, we have expanded the discussion to clarify the factors likely responsible for the reduced HFR performance in the NEI region. The revised manuscript now emphasizes the influence of the spatial offset between the radar footprint and the buoy location, limitations related to the radar geometry, and the increased bathymetric heterogeneity of the area. In addition, we discuss how storm-phase variations in wave energy and the occurrence of complex sea-state conditions may contribute to uncertainties in wave period estimation. This added explanation helps to contextualize the observed regional differences in HFR skill.

- Terminology corrections (throughout manuscript)
 - Use “metocean” consistently.

Done!

- Replace “multi-sensor” by “multi-platform”.

Done!

- Replace “buoys” by “moored buoys” (as in Figure caption A2).

Done!

- Replace “HFR systems” by “HFR networks” (for HFR-Galicia and HFR-DeltaEbro)

Done!

- Ensure Villano HFR site and Alfacada HFR site are consistently named.

Done!

- Page 11, line 343: Confirm whether the HFR coverage in each region is sufficiently wide and unobstructed to ensure stable directional solutions.

We thank the reviewer for this comment. In both study regions, the HFR installations provide wide and unobstructed coverage, ensuring stable and reliable directional solutions. In the case of HFR-Galicia network, all HFR sites are installed at lighthouse locations, which offer elevated, exposed positions with clear line-of-sight over the ocean and minimal physical obstructions. In the HFR-DeltaEbro network, the HFR sites are deployed within a protected natural area, where infrastructure is limited and the surrounding environment is well preserved, resulting in minimal electromagnetic or physical interference. These site characteristics ensure favourable geometric configurations and stable directional performance for wave retrieval in both regions.

To clarify this point, a paragraph has been added to Section 2.4

- Page 13, line 397- 405: Consider adding a brief synthesis noting that the comparison between HFR-derived and buoy-observed wave parameters during Storm Louis aligns with the performance patterns reported by Saviano et al. (2022).

We thank the reviewer for this valuable suggestion. In response, we have added a new paragraph in the revised manuscript highlighting that the differences observed between the NWI and NEI regions are consistent with the findings of Saviano et al. (2022). In particular, we note that the skill contrast between HFR-derived and buoy-observed wave parameters under Storm Louis reflects similar performance patterns reported under varying wave energy and bathymetric conditions. This synthesis has been incorporated to better contextualize our results within the existing literature.