



Impact of Storm Louis on two Spanish harbours: a multi-sensor approach

Pablo Lorente¹, Garbiñe Ayensa², Marta De Alfonso¹, Samuel Galán¹, Pilar Gil¹, Fernando Manzano¹, Anna Magdalena Matulka¹, Pedro Montero², Verónica Morales-Márquez¹, Begoña Pérez-Gómez¹,
5 Cristina Pérez-Íñigo¹, Susana Pérez-Rubio¹ and M. Isabel Ruiz¹

¹Puertos del Estado, Madrid, 28042, Spain

²INTECMAR (Instituto Tecnológico para o Control do Medio Mariño de Galicia), Vilagarcía de Arousa, 36611, Spain

Correspondence to: Pablo Lorente (plorente@puertos.es)

Abstract

10 Storm Louis struck south-western Europe between 22 and 26 February 2024, producing severe metocean conditions that led to significant disruptions in transportation networks, widespread power outages and one confirmed fatality. This high-impact event exemplified the growing threat that deep extratropical cyclones pose to European coastal infrastructure. The synoptic-scale characteristics of Storm Louis were examined using ERA5 reanalysis data, revealing a marked Azores High-Iceland Low dipole configuration, indicative of the canonical manifestation of the positive phase of the North Atlantic Oscillation. A
15 strong SW-NE pressure gradient gave rise to persistent and anomalously intense north-westerly winds over the northeastern Atlantic Ocean that induced significant waves heights above 8 m. The concurrent impact on two geographically distant Spanish ports – Langosteira in the northwestern Iberian (NWI) region and Tarragona in the northeastern Iberian (NEI) region – was evaluated using a multi-sensor observational framework that integrates *in situ* measurements from four buoys and two
20 tide gauges with remotely-sensed data provided by two High Frequency Radar (HFR) systems. In the NWI (NEI) area, multiple observed wind and wave parameters associated with Storm Louis exceeded the 99.9th (99th) climatological percentiles, based on a 11-year reference period spanning 2014-2024. Analysis of high-frequency sea level oscillations, recorded by tide-gauges at both ports during Storm Louis, revealed contrasting wave-induced agitation responses between Langosteira and Tarragona harbours, despite exceedance of their respective historical 99th percentile threshold. The former experienced a moderate but prolonged (33 h long) event peaking at 0.68 m with minimal storm surge influence, while the
25 latter underwent a shorter (16 h long), more intense peak of 1.77 m, also decoupled from storm surge. Over the 2014-2024 period, the relationship between offshore wave parameters and inner-harbour agitation was explored to isolate the open-ocean conditions most strongly associated with critical in-port sea states likely to compromise maritime operations. Results revealed significantly high linear correlations between offshore wave height conditions and harbour agitation ($R = 0.88$ for Langosteira, $R = 0.75$ for Tarragona). However, Tarragona harbour exhibited a more complex, bimodal directional response:
30 peak agitation events were predominantly associated with moderate offshore wave heights (< 3 m) propagating from the southernmost sector, underscoring the harbour's marked sensitivity to wave incidence angle and its role in amplifying internal hydrodynamic response. Finally, HFR wave data, validated against buoy observations, reliably captured storm-induced waves, highlighting their value for real-time extreme hazard assessment and climate-resilient port infrastructure.



1 Introduction

35 The genesis of deep extratropical cyclones over central Europe is governed by a complex interplay of synoptic-scale atmospheric and oceanic factors (Mohr et al., 2020). These systems commonly emerge when warm, moisture-laden air advected from the Mediterranean or North Atlantic converges with cold and dry continental air masses of Arctic or Siberian origin. The resulting sharp thermal and moisture gradients create atmospheric instability: as the warm air ascends and the colder air descends, a low-pressure centre forms, making the region susceptible to highly dynamic and rapidly evolving weather conditions. Such systems are often associated with intense windstorms, heavy precipitation, and, in some cases, catastrophic flooding, particularly during the winter season (Álvarez-Fanjul et al., 2022; Owen et al., 2021; Jacobeit et al., 2006; Wanner et al., 2004).

The socio-economic relevance of extreme extratropical cyclones has become increasingly prominent in recent decades, particularly in the context of anthropogenic climate change, which is projected to alter their frequency, intensity, and spatial distribution (Khodayar et al., 2025; Cao and Su, 2025; Kleespies et al., 2024; Konisky et al., 2015). These high-impact events have exposed the structural vulnerabilities of western Europe, highlighting the substantial risk posed to critical infrastructure, human assets, and regional economies (Leal Filho et al., 2024; Mateos et al., 2023; Forzieri et al., 2018). For instance, Storm Kyrill (17–19 January 2007) produced hurricane-force winds across large areas of Europe, resulting in 47 fatalities and generating the highest insured storm losses recorded in Europe to date (Kettle, 2023; Fink et al., 2009). Similarly, Storm Klaus (23–24 January 2009) caused 26 direct fatalities while impacting northern Iberia and southern France, with more than 715.000 insurance claims filed and total losses exceeding USD 6.0 billion, ranking it as the costliest weather-related disaster globally that year (Liberato et al., 2011; Aon Benfield, 2010). Storm Gloria (19-24 January 2020) caused several casualties and multi-million damages in susceptible coastal areas of Eastern Spain (Álvarez-Fanjul et al., 2022). More recently, Storm Ciara (8–9 February 2020) affected the British Isles, resulting in estimated insured losses of approximately GBP 200 million (Jardine et al., 2023). These events illustrate the mounting economic burden of windstorms under current climatic conditions and underscore the urgency of improved risk assessment, adaptation strategies, and early warning systems.

Severe sea states associated with extreme storm events can significantly disrupt port operations and damage coastal infrastructure, particularly in vulnerable locations such as deltas, low-lying areas, and erosion-prone shorelines (Lucio et al., 2024). Given their strategic role as logistic hubs within maritime transport networks, international supply chains and global trade, ports are critical economic assets (Verschuur et al., 2022). Consequently, storm-induced disruptions can result in substantial financial losses, not only from direct damages and operational delays but also from reputational impacts in an increasingly competitive global marketplace (Verschuur et al., 2023).

In recent years, extensive research has focused on assessing the vulnerability of port infrastructure to extreme weather, advancing climate risk analyses and formulating adaptation strategies within the Spanish port system (Fernández-Pérez et al., 2024; Portillo Juan et al., 2022; Izaguirre et al., 2021; Camus et al., 2019; Sánchez-Arcilla et al., 2016). At the global scale, a



comprehensive survey by Asariotis et al. (2017), encompassing port authorities in 29 countries across all world regions, reported that approximately 70% of respondents had experienced weather-related disruptions. These included impacts on operations (76%), delays (60%), and physical damage (45%). The most frequently cited climatic stressors - ranked in decreasing order - were strong winds, heavy precipitation, storm surges, fog, and wave penetration.

While high wind speeds can severely hinder crane operations and cargo handling efficiency within port terminals (Piñeres-Castillo et al., 2024), the operability of vessels is predominantly governed by the energy and directionality of incident offshore waves penetrating into the port basin, where they interact with complex bathymetry, harbour geometries, and structural elements (Romano-Moreno et al., 2022; Sierra et al., 2015). The resulting intra-harbour wave dynamics - commonly referred to as *wave agitation* - can significantly degrade operational efficiency and compromise safety margins. Excessive wave agitation amplifies vessel motions at berth, increasing the risk of mooring line failures and vessel-structure collisions, with potential damage to both ships and port infrastructure (Díaz-Hernández et al., 2021).

In this context, the precise monitoring and comprehensive understanding of extreme weather-related hazards are essential not only for the implementation of effective prevention strategies and the informed management of port operations, but also for strengthening the socio-ecological resilience of coastal communities (Linnenluecke et al., 2012). The present study focuses on the characterization of Storm Louis, which was associated with a deep low-pressure system (Fig. 1a) that traversed the North Atlantic, delivering severe weather conditions across large areas of western Europe between 22 and 26 February 2024. The storm was marked by intense rainfall and powerful winds (Fig. 1b), with sustained gusts exceeding $20 \text{ m}\cdot\text{s}^{-1}$ that caused widespread disruptions including transportation delays, power outages, and one fatality reported in France. From an oceanographic standpoint, the north-westerly winds accompanying the storm generated significant swell, with wave heights exceeding 8 meters (Fig. 1c), which severely impacted the Galician coastline (NW Iberia region) and, more specifically, Langosteira harbour (Fig. 1d and Fig. A1a). Additionally, harsh metocean conditions were also observed in NE Iberia: strong southeasterly winds (above $12 \text{ m}\cdot\text{s}^{-1}$, Fig. 1b) induced high waves that easily penetrated into Tarragona harbour due to its mouth orientation (Fig. 1e and Fig. A1b), handicapping port operations.

The signature of Storm Louis was investigated through a multi-sensor observational framework, integrating both *in situ* instruments - four directional wave buoys and two tide gauges - and a remote sensing technology - two High Frequency Radars (hereinafter, HFR) - to capture the storm's concurrent impact on two geographically distant Spanish harbours, located in the northwestern and northeastern Iberia areas, respectively (NWI and NEI, in Fig. 1a). This approach enabled a detailed assessment of the relationship between offshore wave characteristics and the resulting sea state within each harbour domain.

The analysis aimed to identify which open-ocean conditions are most likely to trigger hazardous port conditions, potentially disrupting maritime operations and compromising the cost-time efficiency of port logistics (Lorente et al., 2024; Romano-Moreno et al., 2022; Díaz-Hernández et al., 2021; Sierra et al., 2015).

As a secondary objective, the performance of both High Frequency Radar (HFR) systems in accurately monitoring extreme offshore wave conditions during Storm Louis was quantitatively assessed. While this land-based remote sensing technology has achieved global recognition for its capability to deliver reliable, near real-time, two-dimensional surface current maps



(Roarty et al., 2019; Rubio et al., 2017), its application for wave field characterization remains relatively limited within operational oceanography, with most studies confined to academic research settings (Morales-Márquez et al., 2024; López et al., 2019; Wyatt et al., 2005; Wyatt, 1986). To address this gap, a skill assessment was conducted by comparing HFR-derived wave parameters against *in situ* measurements from wave buoys located within the HFR coverage area. This evaluation aimed to enhance confidence in the use of HFR systems for monitoring extreme wave events, thereby supporting their integration into operational coastal hazard forecasting and maritime risk management frameworks (Basañez et al., 2019; Atan et al., 2015 and 2016).

This work is structured as follows: Section 2 outlines the observational and modelled data sources. Section 3 describes the methodology adopted. Results are presented and discussed in Section 4. Finally, principal conclusions are drawn in Section

5.

2 Data

All modelled and observational datasets employed in this study are summarized in Table 1 and Table 2 and are briefly described below. While some *in situ* instruments were deployed prior to 2014, the observational time series were standardised to the 2014–2024 period for consistency reasons, as the collection of directional wave data by Langosteira coastal buoy started on June 2013 (Table 3).

2.1 ERA5 reanalysis

ERA5, the fifth-generation reanalysis for the global climate and weather produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), provides high-resolution, consistent, and quality-controlled datasets extending back to 1940 (Product ref. No. 1 in Table 1). ERA5 offers hourly estimates of a wide range of atmospheric and oceanic variables, which are regridded, respectively, to a regular 0.25° and 0.5° horizontal grid. Synoptic-scale analyses of daily-averaged fields of sea level pressure (SLP), 10-meter wind speed (W10), significant wave height (SWH), and mean wave direction (MWD) were conducted over the North Atlantic domain (40°W–20°E, 20°N–70°N) to characterize the dominant metocean features during the peak phase of Storm Louis (Table 2, No. 1).

2.2 *In situ* buoys

Two deep-water and two coastal buoys, operated by Puertos del Estado, were utilized in this study (Fig. 1d-e, and Fig. A1). These *in situ* observational platforms provide quality-controlled, hourly-averaged measurements of a range of oceanographic parameters (Product ref. No. 2 in Table 1), including SWH, MWD, wave period at spectral peak (or peak wave period: PWP) and mean wave period -MWP- (Table 2, No. 2 and No. 3). Additionally, deep-water buoys also provide hourly-averaged estimations of atmospheric parameters (SLP and wind). Comprehensive technical specifications for each buoy are detailed in Table 3.



The quality control, defined by the Copernicus Marine Service *in situ* team (Copernicus Marine *In situ* Team, 2020), was based on a battery of automatic checks performed in real time to flag and subsequently filter inconsistent values: the spike test, stuck value check, or rate of change on time, among others.

2.3 Tide-gauges

- 135 Two radar tide gauges, manufactured by Miros and operated by Puertos del Estado as part of the REDMAR network (Pérez-Gómez et al., 2014), have been deployed at the mouth of Langosteira (Fig. 1d and Fig. A1a) and Tarragona (Fig. 1e and Fig. A1b) harbours since November 2012 and May 2011, respectively (Table 4). These sensors deliver quality-controlled sea level measurements at a sampling rate of 2 Hz (Product ref. No. 3, Table 1), facilitating the analysis of high-frequency oscillations such as meteotsunamis and infragravity waves (García-Valdecasas et al., 2021). Additionally, 20-minute
- 140 averaged estimates of port agitation - defined as port-scale oscillations induced by incoming wind waves with periods shorter than 30 s - were derived using an 8th-order Butterworth high-pass digital filter with a cut-off frequency of 1/30 Hz. The resulting agitation time series were subsampled to hourly intervals (Table 2, No. 3) for subsequent analysis:
- i) over the period 20-29 February 2024 to evaluate harbour response under extreme weather conditions. Complementarily, hourly storm surge estimates (i.e., meteorological residuals) were examined to assess their potential contribution on
 - 145 wave-induced agitation during Storm Louis.
 - ii) over the 11-year period spanning 2014-2024, to investigate the relationship between offshore energetic wave conditions and the sea state within both harbours, with a focus on the directional dependencies influencing wave penetration and the resulting agitation response.

2.4 High Frequency Radars (HFR)

- 150 Two 'direction-finding' SeaSonde HFR networks (Barrick, 1977), manufactured by CODAR Ocean Sensors, were employed in this study (Table 5). While the first one (composed by 5 sites) was deployed along the Northwestern Iberian Peninsula (HFR-NWI) in July 2010, the second one (formed by 3 sites) was installed in the Northeastern Iberian Peninsula (HFR-NEI) in December 2013. The geographical distribution of the radar stations is shown in Fig. 1d and Fig. 1e, respectively. Each network provides half-hourly wave observations (Product ref. No. 4, Table 1) - including SWH, centroid wave period
- 155 (CWP), and MWD - retrieved in near real time across multiple annular rings (circular concentric range arcs) extending radially from each onshore radar site (Fig. A2). For this study, HFR-derived wave measurements were subsampled to 60-minute intervals (Table 2, No. 4) to ensure temporal consistency across datasets, enabling not only the investigation of wave conditions during storm Louis but also a robust long-term skill assessment over the period 2014–2024.



3 Methodology

3.1 Characterization of Storm Louis

To elucidate the driving mechanisms underlying the development of Storm Louis, the prevailing atmospheric conditions were briefly examined at the synoptic scale, with particular emphasis on SLP and W10 fields. This analysis aimed to identify the large-scale barometric patterns, pressure gradients, and wind structures that contributed to the storm's intensification, thereby enabling a better understanding of the meteorological forcing responsible for the observed oceanographic impacts, especially within the affected harbour environments.

Recognizing the interconnected nature of hydrodynamic variables, an isolated analysis of individual extremes was deemed inadequate to capture the full spatial and temporal footprint of Storm Louis. Instead, a percentile-based statistical framework was employed to characterize the tail behaviour of key environmental variables, including W10, SWH, MWP and port agitation, among others. The 1st, 5th, 25th, 50th, 75th, 90th, 95th, 99th and P99.9th percentiles (P1, P5, P25, P50, P75, P90, P95, P99 and P99.9, hereinafter) were derived from an 11-year (2014-2024) observational dataset to contextualize storm Louis within its broader climatological distribution (Coles, 2001). These high-impact thresholds serve as operational benchmarks for impact-based analysis, facilitating the identification of critical exceedance frequencies relevant to risk assessment and port operational management. Notably, similar percentile-based thresholds have been previously proposed in the context of coastal storm characterization by Harley (2017), Morales-Márquez et al. (2020) and Fanti et al. (2023).

Hourly estimations of storm surge component (meteorological residuals) were analysed to assess their potential contribution to the pronounced increase in harbour agitation observed during storm Louis. This evaluation aimed to determine whether elevated water levels played a significant role in amplifying the port response under storm conditions. In this context, connected extremes are of particular concern for harbour operability. Their combined impacts can interact nonlinearly, resulting in synergistic effects that pose a greater threat to port infrastructure than isolated extreme events (Velpuri et al., 2023).

The long-term relationship between energetic offshore wave conditions (SWH, MWP and MWD) and port agitation was analysed to assess directional dependencies and harbour response under extreme forcing scenarios, as the direction of the most energetic incoming waves may be critical to harbour impacts. Scatterplots were thereby computed to infer the dependence between port agitation and offshore SWH data.

In addition, the monthly distribution of extreme hourly agitation events - defined as values exceeding the P90, P95, and P99 thresholds - was derived from the 11-year observational time series provided by Langosteira (NWI) and Tarragona (NEI) tide-gauges. This analysis aimed to identify potential seasonal patterns or preferential timing in the occurrence of high-agitation conditions, thereby providing insight into whether certain phases of the annual cycle are more prone to operational disruptions due to extreme metocean forcing.



190 3.2 HFR: fundamentals and data treatment

The HFR land-based remote sensing technology is based on measurements of the radiowave-backscattered signal from ocean surface gravity waves in the 3–30 MHz range of the electromagnetic spectrum (Crombie, 1955). CODAR SeaSonde “direction-finding” HFR systems measure the return signal continuously over all angles, exploiting the directional properties of a collocated three-element receive antenna system to infer the direction of the incoming signals (Barrick et al., 1977).

195 While fine-resolution maps of the surface circulation are obtained from the Doppler shift of the predominant first-order peaks in the sea-echo Doppler spectrum, wave parameters are deduced from the weaker and noisier second-order peaks. The second-order scattering-based methods significantly rely on the echo quality, which varies with sea state and radar frequency (Wyatt et al., 2005). The relative contribution of the second-order spectrum increases with both the radar frequency and the wave height. Since wave data are dependent upon the occurrence of both Bragg and larger surface gravity waves. There is a
 200 minimum threshold for sea states at a given radar frequency in which reliable wave parameters can be determined. Below such a sensitivity threshold, the lower-energy second-order spectrum is closer to the noise floor and more likely to be contaminated with spurious contributions that might result in wave height overestimation or limited temporal continuity in wave measurements (Lipa and Nyden, 2005). During extreme weather events, there is also a limiting factor for HFR accuracy as the wave height increases and exceeds the saturation limit defined (on an inverse proportion) by the radar
 205 transmit frequency. If the radar spectrum saturates, the first and second-order peaks merge and interpretation of the spectra becomes impossible with existing methods (Forney et al., 2015). It is worth mentioning that theoretical upper performance thresholds for each HFR system (Table 5), were not exceeded during storm Louis.

HFR directional wave spectrum and derived parameters (SWH, CWP and MWD) can be determined from the weaker second-order sea-echo Doppler spectrum by adopting two main approaches: full integral inversion or fitting with a model of
 210 ocean wave spectrum (Lipa and Nyden, 2005). A variety of inverse techniques have been developed over the last decades (Barrick, 1977; Hisaki, 2006). The wave parameters used in this study, based on 30 min averaged backscatter data, were obtained directly by the CODAR radar proprietary software, which performs a least square fitting technique between the second-order radar spectrum and a Pierson-Moskowitz with cardioid directional function model. Specifically, SeaSonde HFR systems measure a wave period that represents the centroid of the model being fitted to the second-order Doppler
 215 spectrum (Lipa and Nyden, 2005), hence hereafter referred to as the centroid wave period (CWP).

HFR wave data were collected in near real-time, assuming the homogeneity over the whole of each range cell (RC). Specifically, each site composing HFR-NWI system has 5 individual RCs (5.1 km wide), which extended radially from an origin at the onshore radar site to a distance 25.5 km offshore (Fig. A2a). Each site from HFR-NEI presents 7 RCs (1.66 km wide) which extended radially from an origin at the onshore radar site to a distance 11.62 km offshore (Fig. A2b). While the
 220 returned signal might be too weak for the outermost RCs, shallow water effects can become significant for innermost RCs, impacting also on radar sea-echo (Lipa et al. 2008). Therefore, we selected the intermediate RC that recorded the highest percentage of valid data, based on the same quality control procedures previously applied to the *in situ* wave observations.



Accordingly, RC3 from Villano site (HFR-NWI) and RC4 from Alfacada site (HFR-NEI) were selected for comparison with *in situ* wave observations from Villano-Sisargas and Tarragona buoys, respectively, in order to evaluate HFR accuracy to capture extreme offshore wave conditions (Fig. A2). The selected sites were those closest to their corresponding deep-water buoys and/or exhibited the highest wave data availability throughout the lifecycle of Storm Louis.

Finally, the statistical metrics used in the present study to compare two data sets included the mean, the standard deviation – σ –, the root mean squared error - RMSE - and the Pearson correlation coefficient - R - (Emery and Thompson, 2001).

4 Results

4.1 Analysis of storm Louis

The large-scale synoptic conditions associated with Storm Louis were characterized using ERA5 reanalysis data for SLP, W10 and SWH (Fig. 1a-c). The prevailing SLP pattern featured a classic dipole structure, consisting of a persistent subtropical high over the southwestern North Atlantic and a deep low centred over northeastern Europe (Fig. 1a). This configuration, commonly referred to as the Azores High–Icelandic Low dipole, is a key expression of the North Atlantic Oscillation, a dominant mode of atmospheric variability modulating storm tracks and weather extremes across the North Atlantic sector (Hurrell and Deser, 2009). During the peak phase of the storm (23 February 2024), the pressure gradient exceeded $1.7 \text{ Pa} \cdot \text{km}^{-1}$ and was oriented along a southwest–northeast axis, promoting sustained north-westerly winds with velocities surpassing $18 \text{ m} \cdot \text{s}^{-1}$ over the northeastern Atlantic (Fig. 1b). These intense winds generated high-energy swell systems with SWH exceeding 8 m (Fig. 1c).

In particular, the NWI study area (Fig. 1d) and Langosteira harbour (Fig. A1a) experienced substantial wave impact and atmospheric pressure anomalies. The Villano-Sisargas deep-water buoy recorded a cumulative SLP drop of 33 hPa between 20–25 February, reaching a minimum of 1000 hPa (Fig. 2a), a value slightly below the P5 threshold derived from the 2014–2024 climatology (Fig. 2b). Concurrently, peak offshore wind speeds reached $17.57 \text{ m} \cdot \text{s}^{-1}$, exceeding the local P99.9 percentile (Fig. 2c). Langosteira coastal buoy detected extremely energetic sea states from the northwest (Fig. 1d), with a peak SWH of 8.44 m and a peak MWP of 13.7 s recorded on 24 February (Fig. 2a). Notably, the P99.9 threshold of SWH (8.04 m) was occasionally exceeded during two non-consecutive hours, while the observed MWP fairly surpassed the P99.9 level (12.0 s), nearly matching the all-time maximum value of 13.9 s recorded during the 2014–2024 reference period (Fig. 2d).

Severe oceanographic conditions were also observed in the NEI study area (Fig. 1e). Near Tarragona Harbour (Fig. A1b), the deep-water buoy recorded a SLP minimum of 999 hPa (Fig. 2e), approaching the P1 threshold for the region (Fig. 2f). Offshore wind speeds peaked at $14.29 \text{ m} \cdot \text{s}^{-1}$, exceeding the local P99 (Fig. 2g). The Tarragona coastal buoy recorded high waves coming from the southernmost sector (Fig. 1e), with SWH and MWP peaking at 1.67 m and 6.04 s, respectively,



during the early hours of 26 February (Fig. 2e). These values were close to or marginally above the P99 thresholds for the corresponding wave parameters (Fig. 2h).

255 4.2 Sea state within two harbours

Hourly time series of the storm surge component (meteorological residuals) and port wave agitation, measured during the full lifecycle of storm Louis at Langosteira (NWI area) and Tarragona (NEI area) tide-gauges, are presented in Fig. 3a and Fig. 3b, respectively. While both sites experienced high wave agitation above historical P99 thresholds, the intensity and temporal structure of these events differed substantially. Langosteira tide-gauge displayed a moderate but prolonged agitation episode, reaching a peak of 0.68 m on 24 February afternoon (Fig. 3a). The P99 threshold for the 2014–2024 period (set to 0.52 m) was slightly surpassed for 33 non-consecutive hours. The storm surge component remained relatively subdued throughout the event, with fluctuations mostly below 0.50 m, and no clear peak coinciding with the maximum agitation. By contrast, Tarragona tide-gauge captured an intense and short-lived event, peaking at 1.77 m on early 26 February 2024 (Fig. 3b). The local P99 threshold for the 2014–2024 period (set to 1.20 m) was far exceeded for 16 consecutive hours. The storm surge signal at Tarragona tide-gauge remained modest, with magnitudes generally under 0.3 m, exhibiting minimal correlation with the agitation peak, consistent with a wave-driven dynamic.

Hourly scatter plot analyses conducted over the 11-year study period (2014–2024) revealed a strong statistical correlation between offshore wave conditions and internal harbour agitation across both study sites (Fig. 3c–f). Linear regression analysis of the SWH against harbour agitation yielded significantly high correlation coefficients, specifically $R=0.88$ for Langosteira harbour and $R=0.75$ for Tarragona harbour. In the case of Langosteira harbour (Fig. 3c–d), a total of 743 hourly records exceeded the P99 agitation threshold (0.52 m). Of these, the 100% were associated with MWP above 6 s and incident wave directions within the prevailing sector 295° – 360° (clockwise from true north). By contrast, the scatter plot for Tarragona harbour exhibited a more complex, bimodal directional response (Fig. 3e–f). Despite the highest offshore SWH (>3 m) and MWP (>7 s) values being observed from wave directions between 90° and 120° , these did not correspond to peak agitation events within the port basin. Instead, agitation events exceeding 2 m were predominantly driven by moderate offshore wave heights (~ 2 – 3 m), associated with MWP values in the range 5–7 s, penetrating from the southernmost sector (150° – 210°). This indicates a pronounced sensitivity of the harbour's internal hydrodynamics to wave approach angles, likely modulated by local bathymetric features and structural configurations at the port entrance.

In addition, the monthly distribution of extreme wave-induced agitation was assessed areas over an 11-year period (2014–2024), as shown in Fig. 3g–h. A pronounced seasonal signal was evident in Langosteira harbour, with peak exceedance frequencies occurring during the boreal winter months (Fig. 3g). Specifically, January through March exhibit the most severe agitation conditions: cumulative exceedance percentages over the 3-month period reached approximately 57%, 61%, and 68% of total hours above the P90, P95, and P99 thresholds, respectively. As the annual cycle advances, a marked decline in exceedance frequency is observed, reaching near-negligible levels between June and August. This attenuation coincides with the seasonal minimum in offshore wave energy flux. From September onwards, there is a gradual resurgence in the



frequency of agitation exceedance, with a secondary peak observed in October through December. This bimodal distribution suggests that, in addition to the primary forcing by winter storm activity, transitional swell events and associated synoptic-scale disturbances during the late autumn months contribute substantially to Langosteira harbour agitation.

By contrast, the monthly distribution at Tarragona harbour revealed a more evenly spread regime for the extreme agitation (Fig. 3h). High exceedance percentages were evident during the first four months of the year, particularly in March, where the percentages across all thresholds approached 16–17%. Unlike Langosteira harbour, where agitation was heavily concentrated in January and February, Tarragona harbour exhibited a more gradual onset and decay of agitation activity during the winter-to-spring transition. From June to September, the proportion of hourly agitation exceeding any threshold fell below 5%, marking a seasonal minimum consistent with the calm summer wave climate typical of the western Mediterranean Sea. A second rise in extreme agitation was observed in the final quarter of the year. November and December, in particular, exhibited a high proportion of hours exceeding the P99 threshold, reaching nearly 15%. These outcomes underscore Tarragona harbour's sensitivity to storm events, particularly those originating from southern or southeastern sectors, which are known to be energetically effective in exciting agitation in this specific port geometry.

4.3 Remote wave monitoring with two HFR systems

A quantitative skill assessment of HFR-derived wave estimates during Storm Louis was performed. In the NWI region, time series from the Villano site and the Villano-Sisargas deep-water buoy exhibited strong visual agreement throughout the extreme event (Fig. 4a). The correlation coefficient for SWH is high ($R = 0.92$), with a RMSE of 0.96 m, indicating a high degree of coherence. Both sensors captured the initial wave growth from 21 February, the primary energy peak between 24–25 February, and a secondary crest around 26–27 February. Villano site slightly overestimated SWH maxima relative to the buoy, particularly during the storm's mature phase, although both records converge during the storm's decay stage. The concurrent wave period time series in NWI area showed moderate agreement ($R=0.66$, Fig. 4b), with the HFR-derived CWP and buoy PWP estimates both resolving the rise to values above 14 s during the 21–22 February surge, a brief drop around 23 February, and a sustained 13–15 s regime during the storm's main phase. The HFR data tend to smooth out high-frequency fluctuations, leading to an underestimation (~ 1 s) of the maximum buoy-reported wave periods (16–17 s), and an overestimation during the waning stage of the storm. It is worth mentioning that SeaSonde HFR systems measure a wave period (CWP) that represents the centroid of the model being fitted to the second-order Doppler spectrum (Lipa and Nyden, 2005). Thus, HFR centroid periods dropped always between PWP and MWP collected at Villano-Sisargas buoy. This fact is relevant to properly interpret the skill metrics obtained from comparison, which was conducted against PWP.

By contrast, wave field dynamics in the NEI sector exhibited lower overall energy levels. Both the Alfacada site and the Tarragona deep-water buoy recorded relatively calm conditions until 23 February, followed by a marked intensification and a first peak on 26 February. After a rapid decline, a new peak reaching 2.6 m was observed on 28 February (Fig. 4c). Agreement is weaker in this region, with a correlation coefficient of 0.60 and an RMSE of 0.51 m. Wave period estimates in the NEI region (Fig. 4d) demonstrated poorer agreement ($R = 0.34$ and $RMSE = 1.55$ s). The buoy data exhibited



pronounced high-frequency variability, with wave periods ranging from 3 to 10 s. However, the HFR-derived CWP was smoother, capturing the dominant 5–8 s wave band during 24–26 February but underrepresenting both short-period (<4 s) and long-period (>9 s) oscillations by up to 2 s.

Overall, the results confirm that HFR systems effectively capture the general evolution and magnitude of extreme storm-induced wave fields, with consistently higher skill in estimating SWH than wave period. Performance is notably better in the NWI region, where wave energy levels were higher and radar coverage more extensive. These findings underscore both the potential and limitations of HFR technology for real-time wave monitoring under severe weather conditions, particularly in high-energy offshore environments.

Additionally, a comprehensive long-term validation of HFR-derived wave parameters provided by Villano site was conducted using *in situ* measurements from Villano-Sisargas deep-water buoy over an 11-year concurrent period (2014–2024). The scatter analysis of SWH (Fig. A3a) demonstrated strong agreement between the two sensors, with a significantly high correlation coefficient ($R = 0.87$), a moderately low RMSE of 0.82 m, and a best-fit regression slope near unity (1.02). The negligible intercept (-0.01 m) and close clustering along the 1:1 reference line further confirms the HFR system's ability to capture both the magnitude and variability of SWH over extended timescales. By contrast, the comparison of wave periods (Fig. A3b) yielded a moderate, yet statistically significant, correlation coefficient ($R = 0.71$) accompanied by a higher RMSE of 1.61 s. The best-fit slope of 0.61 and intercept of 4.25 s indicate a systematic divergence between the HFR-derived CWP and the buoy-derived PWP. Specifically, the HFR tends to underestimate high-period events while overestimating lower-period regimes, reflecting inherent methodological differences in how each system resolves wave spectral characteristics. For MWD (Fig. A3c), the scatter distribution is more dispersed, with a reduced slope (0.52), intercept of 135.28° and RMSE of 33.97° . Despite a moderate correlation ($R = 0.66$), the observed bias and compression of the directional range suggest limitations in the angular resolution of the HFR system, particularly at longer ranges where reduced Bragg scattering coherence may degrade directional accuracy. These outcomes, which are in accordance with previous statistical results reported in the literature (Atan et al., 2015; Long et al., 2011), collectively demonstrate that the Villano site provides robust long-term estimates of SWH, moderately reliable wave period data, and qualitatively accurate but less precise wave direction estimates. The performance differences across parameters reflect known limitations of HFR systems in estimating wave direction and longer-period waves, especially under complex sea states or reduced HFR return conditions. It is also worth mentioning that the considerable distance between the deep-water buoy positions and the selected RCs - 22.52 km for HFR-NWI (Fig. A2a) and 47.39 km for HFR-NEI (Fig. A2b) - represents a potential source of discrepancy that may influence the computed skill metrics.

5 Conclusions

The projected rise in both the frequency and intensity of extreme extratropical cyclones presents a growing threat to the resilience of European coastal infrastructure (Little et al., 2023). These powerful storm systems can generate severe



metocean conditions, including high winds, heavy precipitation, and dynamic sea-level fluctuations. Among the most vulnerable components of coastal infrastructure are ports, which serve as critical hubs in the global maritime transport network and are essential to international trade and economic stability (Verschuur et al., 2022). As mean sea levels continue to rise due to climate change, the impact of storm surges and extreme wave events is expected to intensify. In particular, wave-induced port agitation poses a significant operational hazard, as energetic wave conditions can severely disrupt internal basin dynamics, impair docking maneuvers, and reduce overall port efficiency even in the absence of structural damage. Such phenomena can lead to both temporary and, in some cases, permanent inundation of port facilities, disrupting operations, damaging equipment and structures, and incurring significant economic costs (Verschuur et al., 2023). The combined effect of these hazards underscores the urgent need for adaptive measures and resilient design in coastal and port infrastructure planning.

This study investigates the meteorological and oceanographic features of Storm Louis, a high-impact deep low-pressure system that affected large areas of Western Europe during 22–26 February 2024. This extreme metocean event was characterized by a pronounced Azores High–Icelandic Low dipole pattern, a canonical manifestation of the positive phase of the North Atlantic Oscillation, which imposed an intensified southwest–northeast pressure gradient exceeding $1.7 \text{ Pa}\cdot\text{km}^{-1}$. This synoptic configuration facilitated persistent and anomalously strong north-westerly wind over the northeastern Atlantic Ocean (with peaks above $17.57 \text{ m}\cdot\text{s}^{-1}$), generating high-energy wave systems (with SWH and MWP values exceeding 8 m and 13 s, respectively) that significantly impacted the western European coastline.

Two Spanish harbours – Langosteira in NWI region and Tarragona in the NEI region - were used as case studies to examine the storm's impact. A multi-sensor observational analysis, combining *in situ* observations from four buoys and two tide gauges with remotely sensed data from two HFR systems, was performed to evaluate the relationship between open-ocean wave parameters and the wave-induced agitation within the harbour domain. In the NWI (NEI) area, multiple observed wind and wave parameters associated with Storm Louis exceeded the 99.9th (99th) climatological percentiles, based on a 11-year reference period spanning 2014–2024.

The analysis of high frequency sea level oscillations during Storm Louis revealed differences in harbour agitation between Langosteira and Tarragona tide-gauges, despite both exceeding their respective historical P99 thresholds. Langosteira experienced a moderate but prolonged event peaking at 0.68 m, with minimal storm surge influence, while Tarragona underwent a shorter, more intense peak of 1.77 m, also decoupled from storm surge. This heterogeneity in storm response between both harbours may be attributable to i) differences in mouth orientation relative to the predominant incident wave direction; and ii) the contrasting exposure levels of the tide-gauge locations. Specifically, the Tarragona tide gauge is situated in an exposed position at the harbour entrance, at the seaward terminus of the main breakwater (Fig. A1b), which makes it more susceptible to incoming wave energy. By contrast, the Langosteira tide gauge is located in a more protected position, behind a secondary breakwater (Fig. A1a), resulting in significantly lower agitation levels during the same storm event. This outcome highlights the critical functional role of secondary defensive structures—such as inner or secondary breakwaters—in mitigating wave-induced agitation. Long-term data (2014–2024) showed strong correlations between



385 offshore wave height conditions and harbour agitation ($R = 0.88$ for Langosteira, $R = 0.75$ for Tarragona), though Tarragona port exhibited a more complex, directionally sensitive response. Peak agitation events were predominantly associated with moderate offshore wave heights (below 3 m) propagating from the southernmost sector, underscoring the harbour's marked sensitivity to wave incidence angle and its role in amplifying internal hydrodynamic response.

Seasonally, agitation in Langosteira harbour was sharply concentrated in winter, especially January–March, with negligible summer activity, whereas Tarragona port displayed a more evenly distributed pattern with notable secondary peaks in late autumn, particularly December. Furthermore, the threshold values defining P90, P95, and especially P99 are significantly higher in Tarragona, indicating that Tarragona port experiences generally higher agitation magnitudes than Langosteira port. This analysis of agitation exceedance over time emphasizes the importance of integrating seasonal variability into port management practices and engineering design frameworks, ensuring that they reflect the fluctuating intensity of metocean forcing throughout the year. The dataset serves as a key resource for quantifying exposure to wave agitation and underpins evidence-based evaluations of harbour operability and long-term infrastructure resilience.

In addition, the capacity of HFR technology to capture extreme wave conditions was evaluated through direct comparison with *in situ* buoy measurements. Results suggest that HFR systems are capable of reliably characterizing storm-induced offshore wave fields, supporting their broader adoption in operational monitoring frameworks. Complementarily, a long-term (2014–2024) validation of HFR-derived wave parameters from Villano site against *in situ* data from Villano-Sisargas deep-water buoy revealed a strong agreement for SWH ($R = 0.87$), a moderate concordance for CWP ($R = 0.71$) but revealed systematic biases due to methodological differences. MWD showed greater dispersion and reduced accuracy ($R = 0.66$), reflecting well-known HFR limitations such as radio frequency interference under low-wave conditions. The considerable distance between the deep-water buoy locations and the selected RCs (shown in Fig. 2A) should also be acknowledged, as it may influence the accuracy and interpretation of the derived skill metrics. The sensitivity of wave parameter estimates to the aforementioned low-frequency noise could be mitigated through the implementation of a multi-frequency HFR system. By alternating the transmit frequency from 5 MHz to 13 MHz during low to moderate sea states - typically occurring in NWI during late spring and summer - measurement performance across a broad range of SWH may be substantially improved (Wyatt and Green 2009).

410 In summary, the present study underscores the importance of integrated observational platforms for real-time extreme hazard assessment and highlights the critical need to develop climate-resilient port infrastructure capable of withstanding intensifying ocean–atmosphere extremes.

Data availability

The model and observation products used in this study from both the Copernicus Marine Service and other sources are listed in Table 1.



Author contributions

PL, GA, PM, SG, CPI, MA, VMM, PG, FM, AMM, BPG, SPR and MIR conducted the pilot study through fruitful discussions in the framework of working team meetings. PL: designed the experiment, analysed the data, created the figures, and prepared a first version of the draft with inputs from all co-authors. MA, SM and CPI: conducted a bibliographic
420 revision of extreme metocean events previously occurred in the study areas. PG, AMM and MIR: prepared the ERA5 dataset. FM: extracted time series from Puertos del Estado internal database and prepared diverse *in situ* sensors datasets. BPG: proposed the agitation study in both ports and analysed the corresponding tide-gauge records. SPR: analysed the atmospheric driving mechanisms during the event. MIR: applied a quality control for historical time series of wave parameters from coastal buoys. PM and GA prepared datasets from Villano radar site, while VMM did so for the Alfacada
425 radar site. Finally, all authors participated in successive iterations, the drafting and revision of the manuscript.

Competing interests

The contact author has declared that none of the authors has any competing interests. Disclaimer. Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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Tables

Product ref. No.	Product ID & type	Data access	Documentation
1	ERA5 global reanalysis, numerical models	Hersbach et al. (2023)	Copernicus Climate Change Service, Climate Data Store, (2023): ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI: 10.24381/cds.adbb2d47 (last access: 21 July 2025)
2	INSITU_IBI_PHYBGCWAV_DI SCRETE_MYNRT_013_033, <i>in</i> <i>situ</i> observations	EU Copernicus Marine Service Product (2024)	PUM: <i>In situ</i> TAC partners (2024) QUID: Wehde et al. (2024)
3	2 Hz data, high frequency sea level oscillations and agitation parameters from tide gauges, <i>in</i> <i>situ</i> observations	Puertos del Estado website: https://portus.puertos.es , last access: 21 July 2025. Puertos del Estado website: https://portuscopia.puertos.es /Catalog, last access: 21 July	García-Valdecasas et al. (2021) Product description: https://bancodatos.puertos.es/BD/informe s/INT_3.pdf , last access: 21 July 2025.



		2025.	
4	30-minute wave estimations provided by High Frequency radars, remote observations	Puertos del Estado website: https://portus.puertos.es , last access: 21 July 2025. Puertos del Estado website: https://portuscopia.puertos.es/Catalog , last access: 21 July 2025.	Product description: https://bancodatos.puertos.es/BD/informes/INT_6.pdf , last access: 21 July 2025.

Table 1.. Products from the Copernicus Marine Service and other complementary datasets used in this study, including the Product User Manual (PUM) and Quality Information Document (QUID). For complementary datasets, the link to the product description, data access and scientific references are provided. Last access for all web pages cited in this table: 1 May 2025.

Source (Product ref. No.)	Type	Location (coverage)	Variable (unit)	Temporal resolution	Time span used	Spatial resolution
Numerical Model (1)	ERA5 reanalysis	Regional domain (40°W - 20°E 20°N - 70°N)	SLP (Pa)	Daily	February 2024	0.25°
			W10 (m·s ⁻¹)			0.25°
			SWH (m)			0.5°
			MWD (°)			0.5°
			SWH (m)			
			MWP (s)			



<i>In situ</i> sensor (2)	Buoy	Coastal locations	PWP (s)	Hourly	2014-2024	Point-wise location
			MWD (°)			
<i>In situ</i> sensor (3)	Buoy	Deep-water locations	SWH (m)	Hourly	2014-2024	Point-wise location
			MWP (s)			
			PWP (s)			
			MWD (°)			
			SLP (Pa)			
			W10 ($\text{m}\cdot\text{s}^{-1}$)			
<i>In situ</i> sensor (4)	Tide gauge	Port location	Sea level (m)	Hourly	2014-2024	Point-wise location
			Agitation (m)			
Remote sensor (5)	HFR	Coastal and deep- water locations	SWH (m)	Hourly	2014-2024	Concentric arcs: 5.1 km wide for HFR-NWI, 1.66 km wide for HFR-NEI
			CWP (s)			
			MWD (°)			

Table 2. Complementary information about the data sources used in this study. The temporal resolution column corresponds to the processed datasets employed in the analysis and do not reflect the native resolution of the original, raw data.



Buoy	Villano-Sisargas	Langosteira	Tarragona	Tarragona
Study area	1 (NWI)	1 (NWI)	2 (NEI)	2 (NEI)
Type of buoy	Deep-water	Coastal	Deep-water	Coastal
Type of sensor	SeaWatch	WatchMate	SeaWatch	Triaxys
Longitude	9.21°W	8.56°W	1.47°E	1.19°W
Latitude	43.50°N	43.35°N	40.69°N	41.07°N
Depth	386 m	60 m	688 m	15 m
First deployment	May 1998	June 2013	August 2004	November 1992
Parameters	directional waves temperature salinity currents wind atmospheric pressure	directional waves temperature	directional waves temperature salinity currents wind atmospheric pressure	directional waves temperature

600 Table 3. Technical description of the four *in situ* buoys used in the present study.

Tide-gauge	Langosteira	Tarragona
Type (manufacturer)	Radar (MIROS)	Radar (MIROS)
First deployment	November 2012	May 2011
Owned by	A Coruña port authority	Tarragona port authority
Operated and maintained by	Puertos del Estado	Puertos del Estado
Longitude	8.53°W	1.21°W
Latitude	43.35°N	41.08°N
Location	At the end of the breakwater, protected by an inner breakwater	At the end of the breakwater, non- protected by an inner breakwater
Parameters	Sea level, agitation and infragravity waved	Sea level, agitation and infragravity waved
Frequency of sampling	2 Hz	2 Hz



Table 4. Technical description of the two tide-gauges used in the present study.

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HFR networks	HFR-NWI	HFR-NEI
Type of radar	CODAR SeaSonde	CODAR SeaSonde
Number of sites (name: from north to south)	5 (Prior, Villano, Finisterre, Silleiro and Leça de Palmeira)	3 (Salou, Alfacada and Vinaroz)
First deployment	July 2010	December 2013
Operated by	Puertos del Estado Intecmar Portuguese Hydrographic Institute	Puertos del Estado Magrama Acuamed
Frequency (MHz)	4.86	13.5
Bandwidth (KHz)	29.41	90.67
Time resolution of wave data	30 minutes	30 minutes
Site selected in this work	Villano	Alfacada
Number of range cells	5	7
Range cell selected	4	3
Saturation (upper) limit (m)	21.41	7.07

Table 5. Technical description of the two High Frequency Radar (HFR) systems used in the present study.



Figures

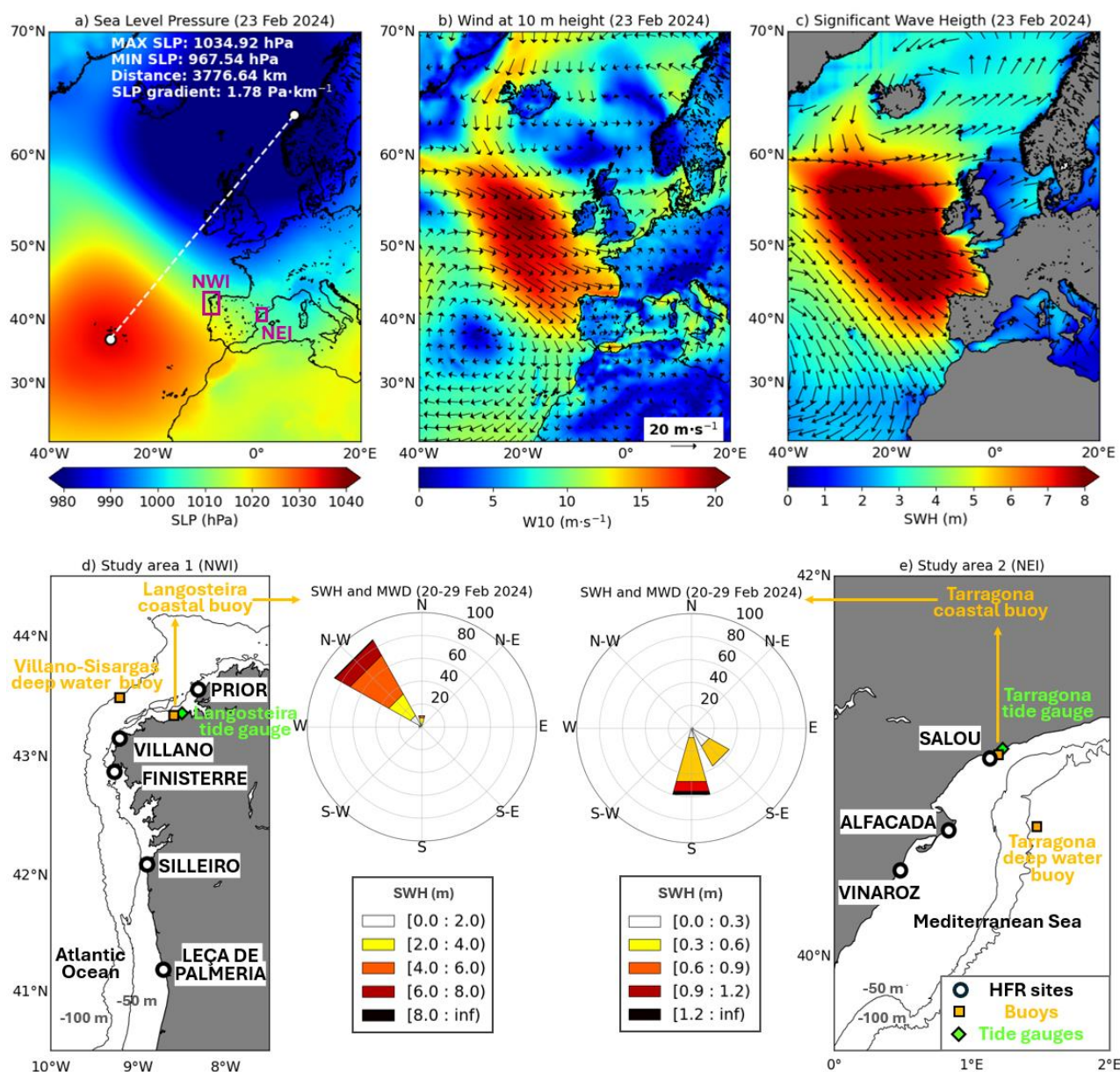


Figure 1. (a-c) Synoptic-scale meteocean conditions during storm Louis as derived from ERA5 -product ref. no. 1 (Table 1)-: daily maps of sea level pressure (SLP), wind at 10 m height (W10) and significant wave height (SWH) for 23 February 2024 (peak intensity of Storm Louis); (d-e) Study areas: northwestern Iberia (NWI) and northeastern Iberia (NEI) regions, respectively. The location of each ocean sensor -product ref. no. 2, 3 and 4 (Table 1)- employed in this work is depicted. Orange squares, green diamonds and white dots denote the location of moored buoys, tide



gauges and High-Frequency radar (HFR) sites, respectively. Isobath depths are labelled every 50 m. Wave roses
illustrate the mean incoming wave direction (MWD) and SWH during 10-day period (20-29 February 2024) -product
ref. no. 2 (Table 1).

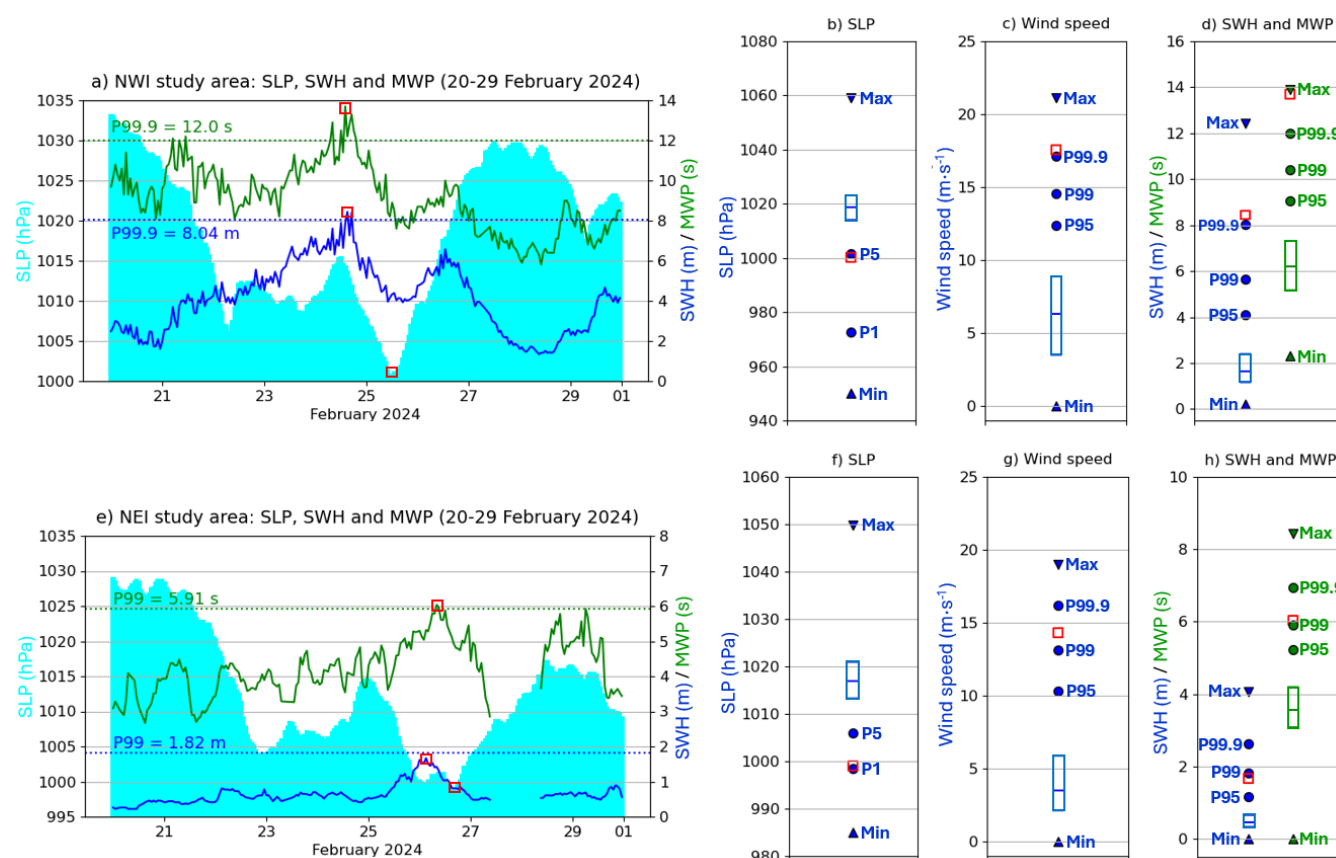
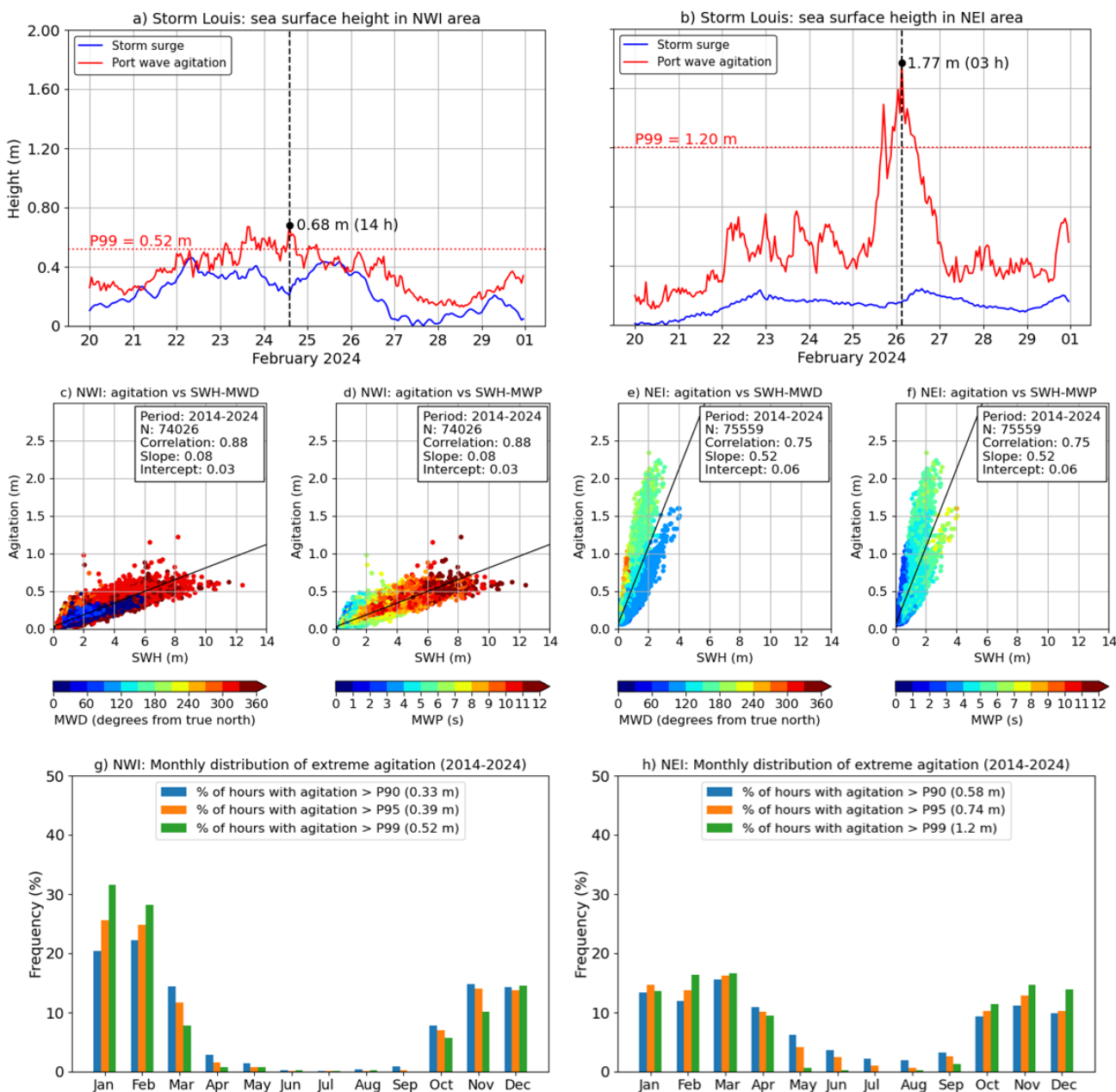


Figure 2. a) Hourly time series of SLP (from Villano-Sisargas buoy: cyan bars), SWH (from Langosteira buoy: blue
line) and MWP (from Langosteira buoy: green line) -product ref. no. 2 in Table 1- during Storm Louis in the NWI
area. The P99.9 thresholds are indicated by dotted blue and green lines, respectively. Read squares represent peaks of
SWH and MWP and minimum value of SLP; b-d) Retrospective analysis for the 2014-2024 period: minimum value of
SLP and peaks of wind speed (from Villano-Sisargas buoy) during Storm Louis along with peaks of SWH and MWP
(from Langosteira buoy) are indicated with red squares. In each box, the central mark is P50, the edges of the box are
the P25 and P75 thresholds; e) Hourly time series of SLP (from Tarragona deep-water buoy), SWH (from Tarragona
coastal buoy) and MWP (from Tarragona coastal buoy) -product ref. no. 2 in Table 1- during Storm Louis in the NEI
area; f-h) Retrospective analysis for the 2014-2024 period: minimum value of SLP and peaks of wind speed (from
Tarragona deep-water buoy) during Storm Louis along with peaks of SWH and MWP (from Tarragona coastal
buoy) are indicated with red squares.



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635 **Figure 3.** Hourly time series of storm surge (meteorological residual) and port wave agitation (product ref. no. 3 in Table 1) recorded during Storm Louis (20–29 February 2024) by (a) Langosteira and (b) Tarragona tide-gauges (Fig.



1A). The 99th percentile (P99) thresholds for agitation are indicated by dashed red lines. Scatter plots relating port agitation (product ref. no. 3 in Table 1) to coastal wave conditions (product ref. no. 2 in Table 1) during the 2014-2024 period for: Langosteira (c-d) and b) Tarragona harbour (e-f). Hourly data from Langosteira coastal buoy and
640 Langosteira tide-gauge were used for Langosteira harbour (NWI area), while hourly observations from Tarragona coastal buoy and Tarragona tide-gauge were employed for Tarragona harbour (NEI area). Statistical metrics are adhered in the white boxes. Monthly distribution of extreme port agitation (product ref. no. 3 in Table 1) events from 2014 to 2024, expressed as the percentage of hours exceeding the 90th (P90), 95th (P95) and 99th (P99) percentiles in (g) Langosteira and (h) Tarragona harbours.

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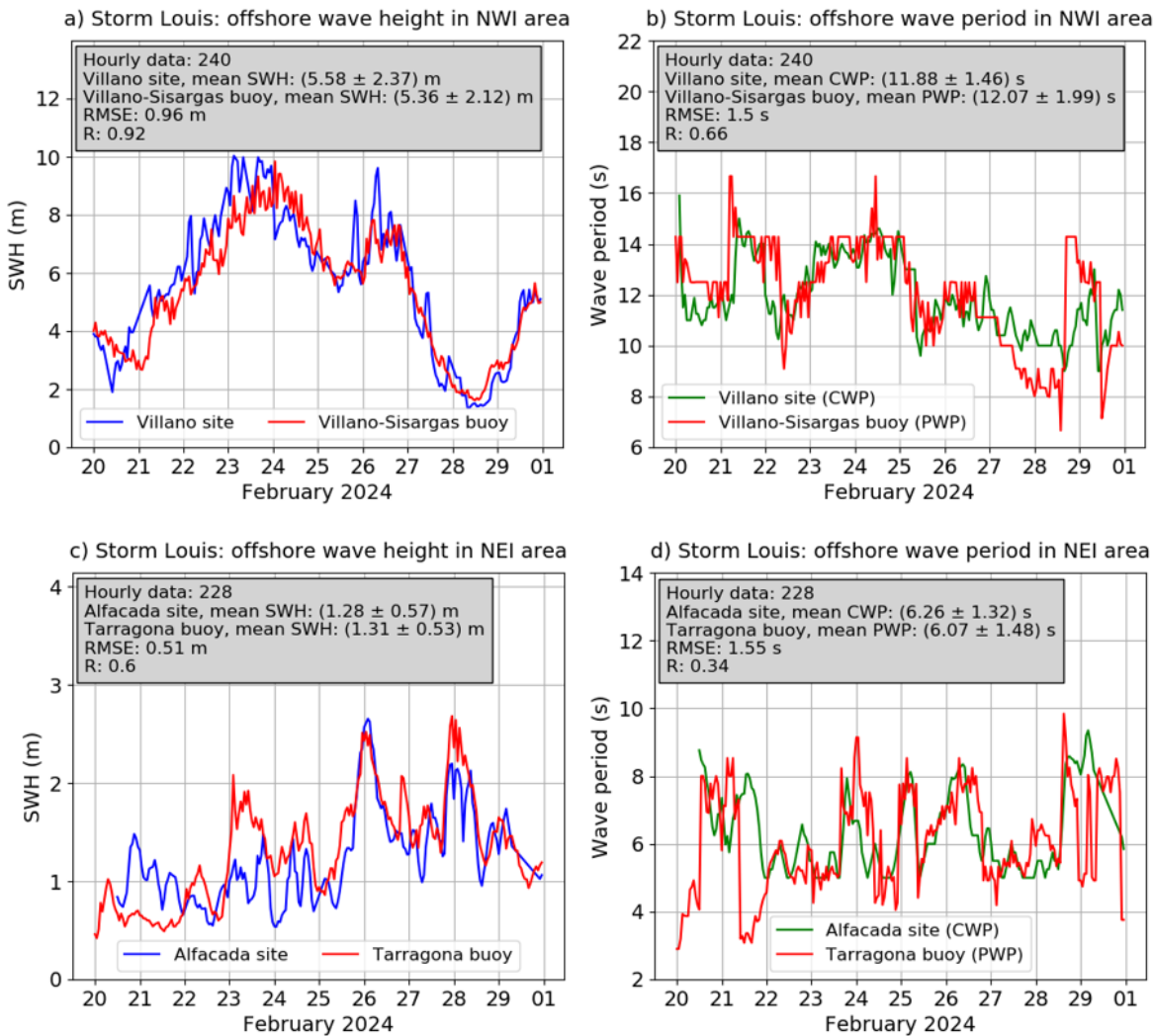


Figure 4. Comparison of hourly estimations of offshore significant wave height (SWH, left panels) and centroid/peak wave period (CWP/PWP, right panels) provided by High-Frequency radar (HFR) sites (product ref. no. 4 in Table 1) against *in situ* buoy observations (product ref. no. 2 in Table 1) during Storm Louis, in the northwestern Iberia (NWI; top panels) and northeastern Iberia (NEI; bottom panels) areas. Hourly data from Villano-Sisargas deep-water buoy and Villano site were used for NWI area, while hourly observations from Tarragona deep-water buoy and Alfacada site were employed for NEI area. Statistical metrics are adhered in the grey boxes.



Annex

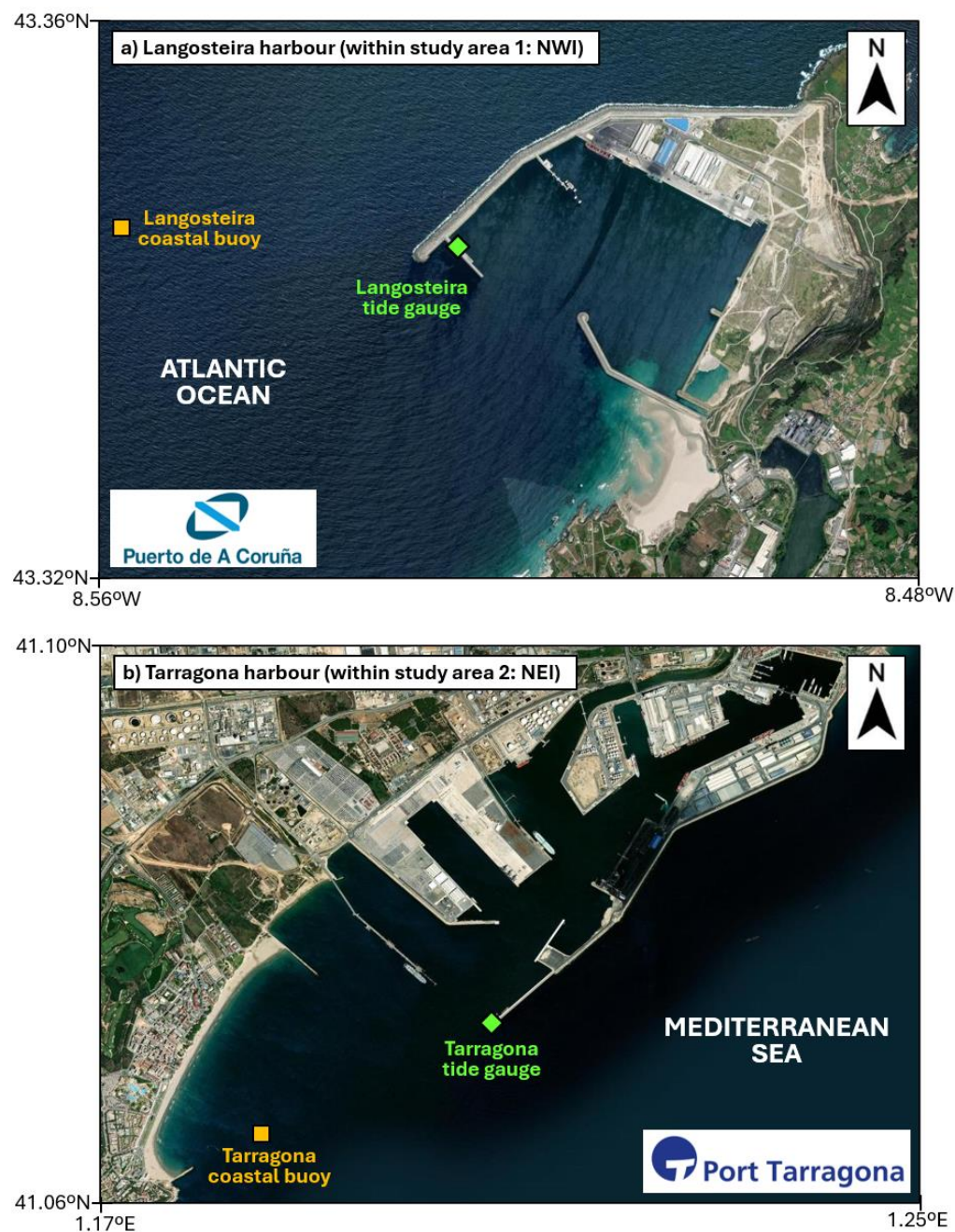
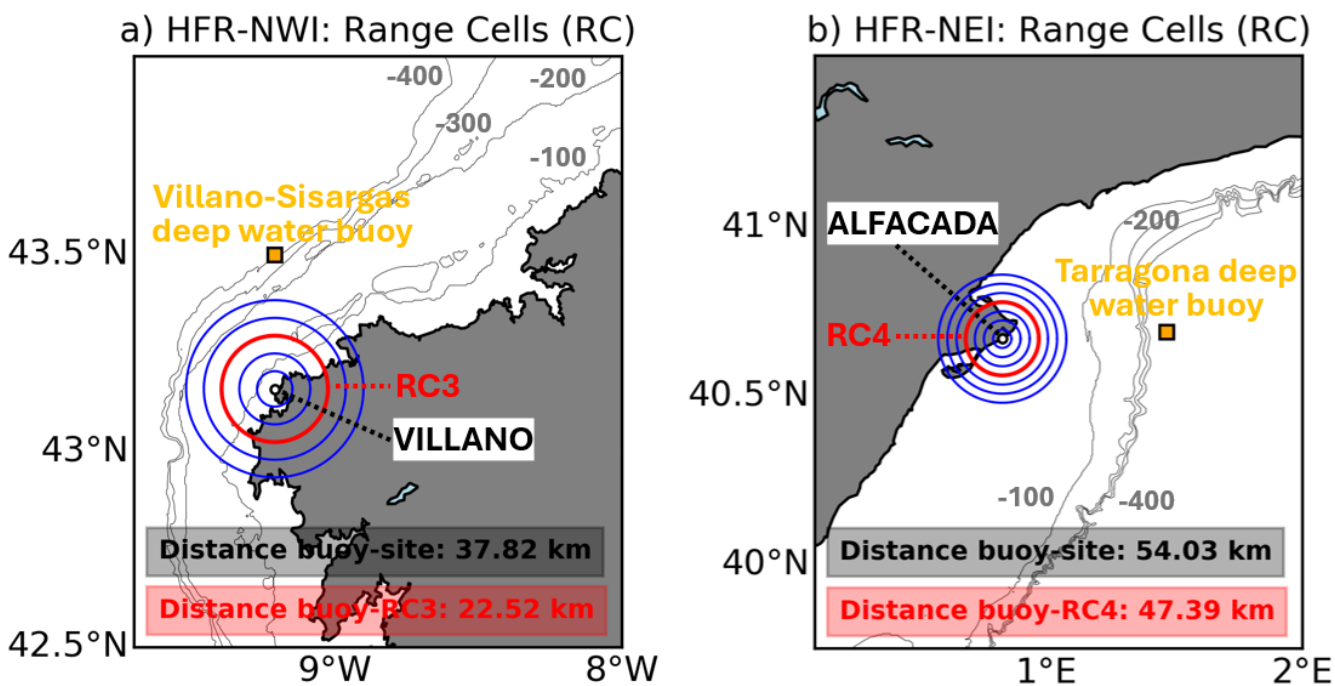


Figure A1. Aerial snapshot showing the geometry of two Spanish harbours: (a) Langosteira harbour (which belongs to A Coruña port authority), located in the northwestern Iberia (NWI) area and (b) Tarragona harbour, situated in



the northeastern Iberia (NEI) area. Orange squares and green diamonds denote the location of coastal buoys and tide gauges, respectively. Map by © ArcGIS.

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Figure A2. Spatial distribution of the concentric range cells (RC) extending radially from the onshore origin at (a) the Villano site (HFR-NWI system) and (b) the Alfacada site (HFR-NEI system). Wave data derived from HFR - product ref. no. 4 in Table 1- for the selected RC (highlighted in red) were compared with *in situ* measurements (product ref. no. 2 in Table 1) from moored buoys (indicated by orange squares). Isobath depths are labelled every 100 m. Distances between buoys, their respective sites and selected RCs are shown in the lower boxes.

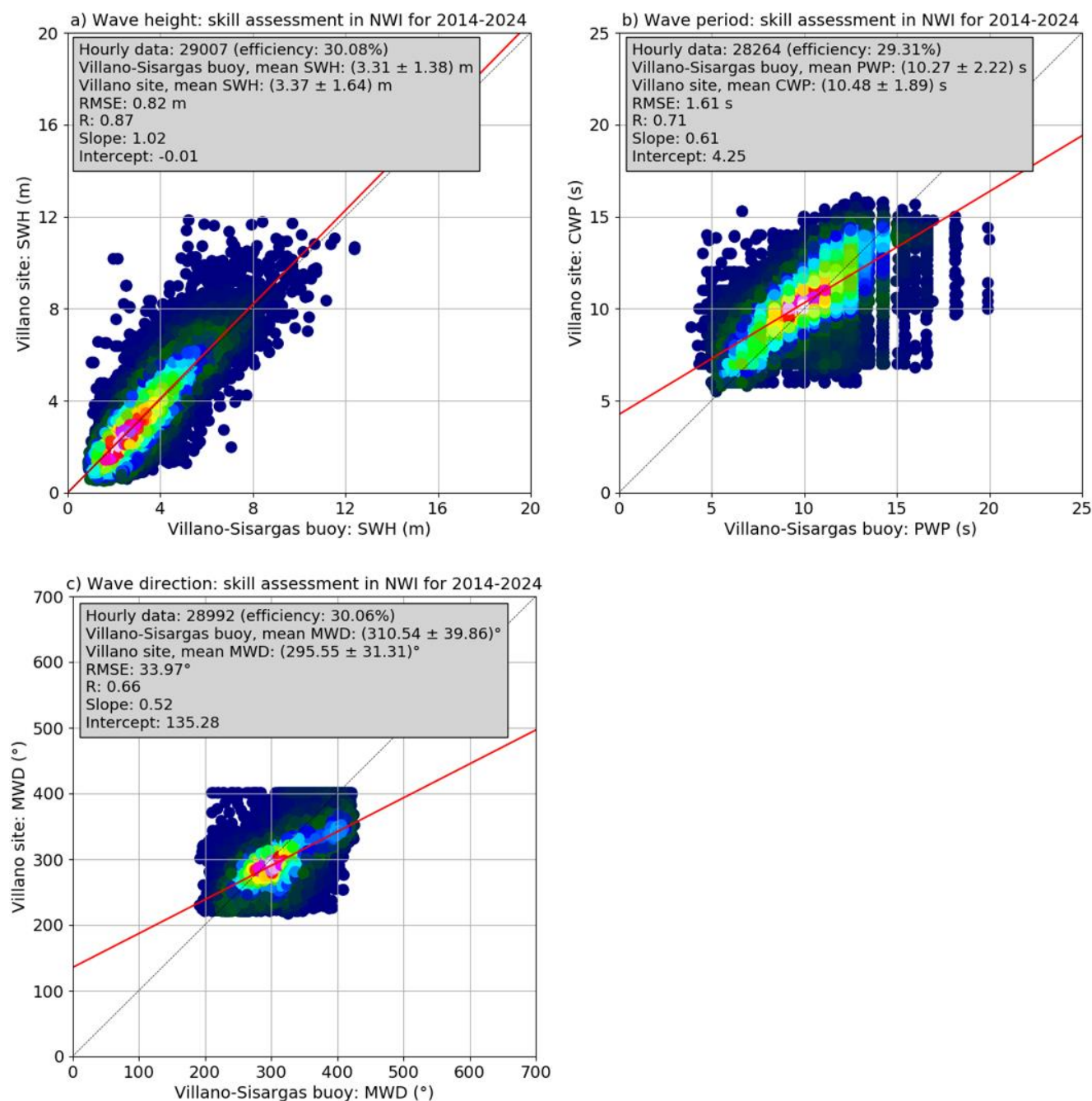


Figure A3. Long-term skill assessment of Villano site wave data at range cell 3 (RC3) -product ref. no. 4 in Table 1- against *in situ* observations provided by Villano-Sisargas deep-water buoy -product ref. no. 2 in Table 1- for the concurrent 11-year period (2014-2024): best linear fit (solid red line) of scatter plot between hourly observations of a) significant wave height (SWH), b) period (centroid and peak wave period -CWP and PWP, respectively-) and c) mean



wave direction (MWD), where angles less than 60° were adjusted by adding 360° to improve visibility and facilitate linear regression. The dotted black line represents the result of perfect agreement with slope 1.0 and intercept 0.

680 Statistical metrics are presented in the grey box.