



1 **Metocean study for the planning of the FSRU terminal: a case study** 2 **at the Estonian coast of the Gulf of Finland**

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9 **Abstract.** Metocean analysis - applied meteorology and oceanography - is essential for the safe and efficient design and
10 operation of offshore installations. In the Baltic Sea, characterized by a complex coastline and fetch-limited wind-wave
11 dynamics, site-specific assessments are particularly important due to regional variability in extreme conditions. This study
12 delivers a comprehensive metocean characterization for the planned Floating Storage and Regasification Unit (FSRU)
13 terminal at the southern coast of the Gulf of Finland. Using data spanning 30 years from Copernicus Marine Service
14 products, satellite observations, and high-resolution numerical modeling (NEMO, SWAN), the study performed hindcasting,
15 hydrodynamic modeling, and extreme value analysis of wind, sea surface height, waves, and currents.

16 A dual approach—Peaks-Over-Threshold and Block Maxima Method—was used with Generalized Pareto and Extreme
17 Value Distributions to estimate extreme values corresponding to different return periods. For a 50-year return period, extreme
18 values were 23 m/s (wind), +1.5 m / −0.7 m (sea surface height), 4.1 m (significant wave height), and 0.37 m/s (surface
19 current speed). These thresholds define critical design parameters for the terminal's mooring and safety systems.

20 This study broadened the scope of extreme value analysis to include the entire Baltic Sea, highlighting critical maritime
21 infrastructure sites. The spatial distribution of extreme values corresponding to 50-year return period levels reveals strong
22 regional contrasts and high level uncertainties. This basin-wide perspective provides valuable input for harmonized safety
23 standards, infrastructure design, and coordinated maritime spatial planning across the Baltic region. For instance, the wind
24 speeds are high over the southern-western Baltic Sea up to 28±10 m/s while the highest extreme values of the significant
25 wave height of 10±5.5 m are found in the south-eastern Baltic Sea. These are the areas with existing/planned offshore wind
26 parks in the Baltic Sea.

27 **Short Summary.** The analysis identified the key extreme metocean conditions relevant to the design and operation of the
28 FSRU terminal at the Estonian coast of the Gulf of Finland. Using a combination of peaks-over-threshold and annual
29 maxima approaches, with fitting functions including the Generalized Pareto Distribution (GPD), exponential, Gumbel, and
30 Generalized Extreme Value (GEV) distributions, the study determined consistent and robust estimates of extreme values
31 corresponding to 50-year return period. These were found to be approximately 23 m/s for wind speed, +1.5 m and −0.7 m for



32 sea surface height maxima and minima, respectively, 4.1 m for significant wave height, and 0.37 m/s for surface current
33 speed. These extreme values provided critical thresholds for infrastructure design and operational safety margins in this
34 region of the Baltic Sea.

35 Furthermore, the study expanded its scope by extending the extreme value analysis to encompass the entire Baltic Sea basin,
36 using a harmonized methodology and long-term model datasets. This extension mapped the spatial variability of extreme
37 values of metocean characteristics with uncertainty estimates across major marine infrastructure locations, such as LNG
38 terminals and key port facilities (Fig. 4 and Fig. 1a). This basin-wide analysis enables consistent risk comparison across
39 regions, facilitates cross-border coordination in maritime infrastructure planning, and informs climate-resilient design
40 strategies tailored to the spatial variability of metocean extremes in the Baltic Sea.

41 1 Introduction

42 Meteorological and oceanographic (“metocean”) conditions critically influence the design, construction, and operation of
43 offshore energy infrastructure (Bitner-Gregersen, 2015; Robertson et al., 2021; Bailey and Freedman, 202). A comprehensive
44 metocean study is thus an essential prerequisite for any new offshore installation to ensure it can be built and operated safely,
45 efficiently, and with minimal environmental risk (Valamanesh et al., 2015; Ross et al., 2020; Cheynet et al., 2024). In the
46 case of a Floating Storage and Regasification Unit (FSRU) terminal – a floating liquefied natural gas import facility – the
47 stakes are especially high (Ho, 2008). FSRUs are moored vessels that are directly exposed to wind, wave, current, and sea
48 level extremes, so understanding the full spectrum of these conditions at a proposed site is fundamental to informed
49 decisions on structural design, mooring system requirements, and operational planning (Voogt et al., 2014; Mrozowski,
50 2024), such as safe cargo transfer windows (Allen et al., 2022). Skipping or underestimating this metocean assessment step
51 could lead to unsafe operating conditions, costly project delays, or even structural failures over the service life of the
52 terminal.

53 Beyond site-specific engineering concerns, the regional context of this study underscores the importance of robust metocean
54 data. Across Europe, recent geopolitical shifts have prompted urgent efforts to diversify natural gas supply and bolster
55 energy security – since early 2022, the EU has fast-tracked on the order of 30 new LNG import terminal projects in response
56 to the gas (Ostrowski, 2022; Rymut and Mihaylov, 2025). In the Baltic region, countries are rapidly developing LNG
57 infrastructure (including FSRU-based terminals) to reduce reliance on single pipeline routes and ensure reliable energy
58 supply (Slakaityte et al., 2022). Estonia’s planned FSRU near Paldiski, on the coast of the Gulf of Finland (Fig. 1), is a case
59 in point: the project was fast-tracked in 2022 as part of a broader strategy to improve the Baltic’s energy resilience. Given its
60 strategic role, it is imperative that this terminal be engineered to withstand the Gulf of Finland’s metocean extremes so that it
61 remains operational when most needed as a critical energy asset. This high strategic importance places additional emphasis
62 on getting the environmental design criteria right from the outset.



63 The Baltic Sea – and the Gulf of Finland in particular – presents unique metocean challenges that must be factored into
64 design. This shallow, semi-enclosed sea has an irregular, fragmented coastline and complex bathymetry that produce highly
65 localized wind, wave, and current patterns often harder to predict than those in the open ocean (Alenius et al., 1998;
66 Soomere, 2005; Westerlund et al., 2019; Pellikka et al., 2023). The Gulf of Finland, a long narrow sub-basin between Estonia
67 and Finland, further funnels winds and restricts water exchange, which can amplify wind-driven storm surges and seiche-like
68 oscillations and cause rapid, non-tidal sea level fluctuations (Medvedev and Kulikov, 2021; Barzandeh et al., 2025; Lorenz et
69 al., 2025). The gulf's enclosed fetch limits the development of long-period swells; storms instead generate short-period,
70 steep wind seas that – while lower in height than ocean swells – (Björkqvist et al., 2017; Kanarik et al., 2021; Björkqvist et
71 al., 2021) can induce vigorous motions and cyclic loads on a moored FSRU. In winter, parts of the Gulf freeze over with
72 seasonal sea ice, which dampens waves but introduces ice loading and operational constraints (Lu et al., 2024). These
73 combined factors – non-tidal water level extremes, steep short waves, complex coastal currents, and periodic ice cover –
74 create a demanding environment where high-resolution, site-specific metocean data and modeling are required to capture the
75 full range of conditions for design and operations.

76 To meet these challenges, the present study leverages state-of-the-art long-term datasets and numerical modeling tools to
77 characterize the metocean climate of the Paldiski site. Modern metocean analyses increasingly rely on multi-decadal
78 hindcasts and reanalyses to provide continuous, high-quality records of environmental parameters (Penalba et al., 2022;
79 D'Agostini et al., 2024). Here we utilize roughly 30 years of data (spanning from the early 1990s to the 2020s) from
80 open-access sources such as the Copernicus Marine Environment Monitoring Service (CMEMS) and ECMWF ERA5
81 Reanalysis, which offers specialized hindcast/reanalysis products for European regional seas. These include modeled time
82 series of Baltic Sea wind speeds, wave heights, sea level variations, and currents that have been consistently processed and
83 quality-controlled. Drawing on such extensive datasets ensures that both typical conditions and rare extremes are accounted
84 for, providing a robust statistical basis for estimating the design environmental criteria.

85 In addition to analyzing historical data, we apply high-resolution numerical models to downscale and resolve local metocean
86 conditions at the terminal site. A nested modeling approach is adopted: the regional Baltic wave model WAM (The Wamdi
87 Group, 1988) provides boundary conditions to a fine-resolution nearshore wave model SWAN (Simulating WAVes
88 Nearshore; Booij et al., 1999) configured with detailed coastal bathymetry, thereby simulating how offshore waves transform
89 as they propagate into the shallow gulf and around complex shoreline features. For hydrodynamics, we employ the NEMO
90 (Nucleus for European Modelling of the Ocean; Madec et al., 2017) framework and the GETM (General Estuarine Transport
91 Model; Burchard and Bolding, 2002) to reproduce local current patterns and sea level responses under various wind and
92 pressure scenarios. All these models have been calibrated for Baltic Sea conditions – accounting for factors like bottom
93 friction and seasonal ice coverage – and their performance tested in past Baltic applications. By combining broad-scale
94 reanalysis data with targeted local modeling, our study captures both large-scale climatic influences and fine-scale site
95 effects in the metocean conditions.



To quantify the design extremes, we perform statistical extreme value analysis on the assembled data. Both block-maxima and peaks-over-threshold techniques are employed, fitting Generalized Extreme Value (GEV) distributions and Generalized Pareto Distributions (GPD) respectively to the long-term time series. This yields estimated return levels for various return periods (e.g. 10-year, 50-year, 100-year events) for each key parameter: wind speed, significant wave height, extreme high and low sea levels, and surface current speed. For the 50-year return period, for instance, our analysis indicates roughly a 23 m/s extreme wind, a 4.1 m significant wave height, a +1.5 m storm surge high water (and −0.7 m extreme low water), and about a 0.37 m/s surface current. These metrics define the environmental design criteria for the FSRU – the loads and conditions that the terminal’s mooring system and operational limits must be built to withstand.

A crucial aspect of our approach is the integration and cross-validation of multiple data sources, aligning with best practices in modern metocean studies. We compare model outputs and hindcast data against available observations – including satellite measurements (for example, altimeter-derived sea levels and scatterometer winds) and in situ records from local buoys and tide gauges – to ensure the estimates are grounded in reality. This multi-source validation helps to quantify uncertainties and biases in the datasets, allowing us to correct or constrain the model predictions where necessary and improve confidence in the results. By fusing information from global reanalyses, regional models, remote sensing, and on-site measurements, the study minimizes the risk of relying on any single source. This data-driven, ensemble approach yields a more reliable metocean characterization that can be trusted for engineering design and risk assessment in a high-stakes project.

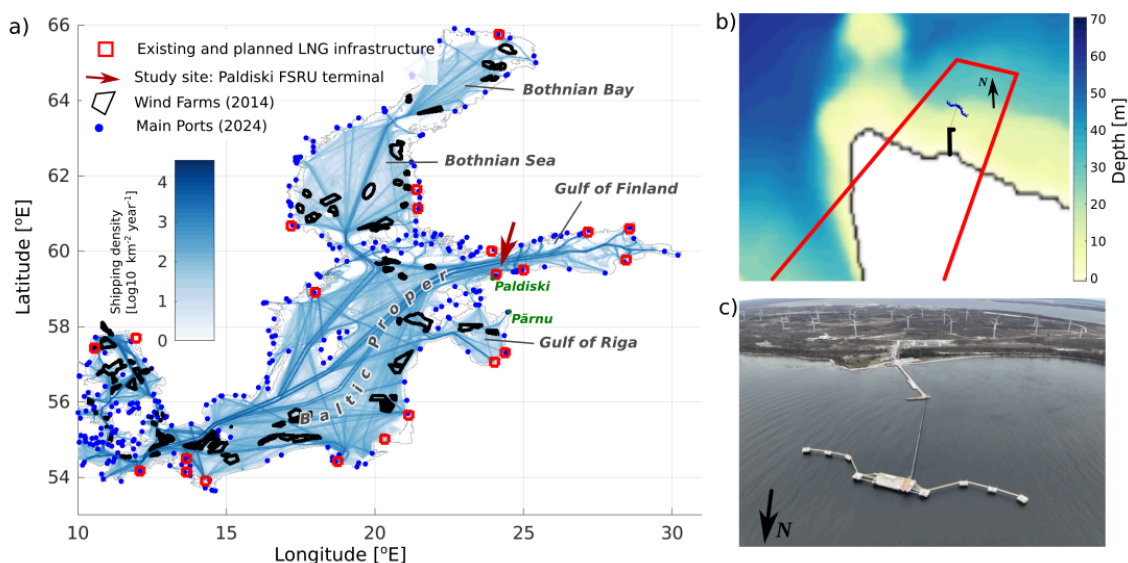


Figure 1. Map of the Baltic Sea showing locations of various human activities a). Existing and planned LNG infrastructure is redrawn from GIE (2019), GEM (2024); offshore wind farms from EMODnet (2024a); main ports from EMODnet (2024b); and vessel traffic density from EMODnet (2024c). Panels b) and c) highlight LNG terminals and the location of the FSRU mooring quay.



118 2 Data and methods

119 **Table 1:** Product Table

Product ref. no.	Product ID & type	Data access	Documentation
1	BALTICSEA_MULTIYEAR_PHY_003_011; Numerical models	EU Copernicus Marine Service Product (2025a);	Quality Information Document (QUID): Panteleit et al. 2025; Product User Manual (PUM): Ringgaard et al. 2024
2	BALTICSEA_REANALYSIS_WA_V_003_015; Numerical models	EU Copernicus Marine Service Product (2024a)	QUID: Kanarik et al., 2024 PUM: Lindgren et al., 2024
3	ERA5; Numerical models	Copernicus Climate Change Service (2023)	Product reference: Hersbach et al., 2023 Journal article: Hersbach et al., 2020
4	COSMO-REA6	DWD (2015)	Bollmeyer et al., 2015
5	BaltAn65+	*MSI	Luhamaa et al., 2011
6	NORA3	MET Norway (2021)	Solbrekke et al., 2021
7	WIND_GLO_PHY_L3_MY_012_005; Satellite observations	EU Copernicus Marine Service Product (2024b)	QUID: Driesenaar et al., 2024a PUM: Driesenaar et al., 2024b
8	WIND_BAL_PHY_HR_L3_MY_012_107; Satellite observations	EU Copernicus Marine Service Product (2025b)	QUID: Husson et al., 2025 PUM: CLS et al., 2025
9	Paldiski North Port (sea level)	*MSI	
10	SEALEVEL_EUR_PHY_L4_MY_008_068; Satellite observations	EU Copernicus Marine Service Product (2025c)	QUID: Ballarotta et al., 2025a PUM: Pujol, 2025a
11	SEALEVEL_EUR_PHY_L3_MY_008_061; Satellite observations	EU Copernicus Marine Service Product (2025d)	QUID: Ballarotta et al., 2025b PUM: Pujol, 2025b
12	NEMO-EST05	*MSI	Pärt et al., 2023, Barzandeh et al., 2025
13	GETM	*MSI	Maljutenko and Raudsepp, 2019
14	LainePoiss	*MSI	Alari et al., 2022
15	SWAN-EST05	*MSI	Pärt et al., 2023
16	Pakri coastal weather station (wind)	*MSI	Keevallik and Soomere, 2009

120 *MSI - data access upon request

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To support the metocean design basis for the proposed FSRU terminal near Paldiski, we employed a multi-source, multi-model approach combining observational datasets, global and regional reanalyses, and high-resolution numerical modeling. This section outlines the sources of environmental data and the methods used to derive local wind, sea level, wave, and current statistics, with particular focus on extreme value analysis. All results were cross-validated using independent datasets where available, including satellite observations and short-term in situ measurements. This multi-source approach ensures that return level estimates are robust and suitable for FSRU design criteria.

2.1 Wind Data and Modeling

Surface wind conditions were assessed using a combination of in situ measurements, satellite observations, and reanalysis products. Long-term wind observations from the Paldiski meteorological station (59.39°N, 24.04°E) were used as a reference (product ref. no. 16). This record spans from 1993 to 2021, with 3-hourly resolution until 2003 and hourly resolution thereafter.

ERA5 reanalysis (Hersbach et al., 2020; product ref. no. 3), with 10 m wind data at 0.25° resolution, served as the primary dataset for wind climatology and was used to drive wave and hydrodynamic models. Alternative regional reanalyses—COSMO-REA6 (Bollmeyer et al., 2015; product ref. no. 4), BaltAn65+ (Luhamaa et al., 2011; product ref. no. 5), and NORA3 (Solbrekke et al., 2021; product ref. no. 6)—were evaluated but ultimately excluded due to systematic biases and inconsistencies when compared with coastal wind observations. COSMO-REA6 and BaltAn65+ consistently overestimated wind speeds during high wind events, with COSMO-REA6 also exhibiting unrealistic wind spikes. NORA3, despite its higher resolution, substantially underestimated high wind speeds. In contrast, ERA5 showed better agreement with in situ measurements throughout the year, justifying its selection as the primary wind dataset. A correction factor of 1.1 was applied to ERA5 wind speeds to better align with observed local maxima and represent offshore conditions.

Remote sensing data included ASCAT Level-3 scatterometer wind fields (MetOp A/B/C; 12.5 km resolution, 2007–present) (product ref. no. 7) and Sentinel-1 SAR Level-2 surface wind vectors (1 km resolution, 2017–present) (product ref. no. 8). Satellite wind data were extracted from open-sea locations approximately 15–20 km from the terminal site.

2.2 Sea Level Data and Modeling

Tide gauge measurements from the Paldiski North Port (59.34972°N, 24.0475°E) (product ref. no. 9) were used to evaluate sea level variability. Visual readings were available for 1993–2009, and hourly automated records for 2016–2021. Data gaps between 2010 and 2016 were supplemented by model output.

Satellite-derived sea surface height data included Level-3 along-track altimetry and gridded Level-4 products from multiple altimeter missions (Jason, Sentinel-3A, CryoSat-2, ENVISAT, etc.), obtained from the CMEMS database (product ref. no. 11 and 10).



Three model sources provided high-resolution sea level time series: 1) CMEMS Baltic Sea Physical Reanalysis (1 nmi resolution, 1993–2017) (product ref. no. 1), based on the NEMO-Nordic model; 2) NEMO-EST05 hindcast (product ref. no. 12); 3) GETM barotropic surge model (Maljutenko and Raudsepp, 2019; product ref. no. 13). All sea level heights were converted to the same vertical datum as the Paldiski gauge (normalized to its 1993–2009 mean water level of +0.21 m) so that model and observed datasets could be consistently compared.

2.3 Wave Data and Modeling

Wave statistics were derived from two primary hindcast sources: 1) CMEMS Wave Reanalysis (WAM Cycle 4.6.2; 1 nmi grid, 1993–2020) (product ref. no. 2); 2) SWAN-EST05 high-resolution model (0.5 nmi grid, 2000–2009) (product ref. no. 15). The CMEMS hindcast was calibrated using short-term wave buoy observations (LainePoiss buoy (Alari et al., 2022), May–June 2022) collected near the terminal site (59.399°N, 24.103°E) (product ref. no. 14). A comparison of the CMEMS hindcast (product ref. no. 2) to the short-term in situ measurements (product ref. no. 14) revealed that the model had a slight high bias in wave heights. The summer 2022 buoy data, although limited, indicated that CMEMS was over-predicting significant wave heights by roughly 15% in that period. A 15% correction was applied to significant wave heights and a 5% correction to wave periods to account for overestimations in CMEMS data. Satellite altimeter data (Level-3, 2002–2020) (product ref. no. 11) were also used to assess significant wave height distributions.

2.4 Current Data and Modeling

Daily mean surface current fields were obtained from: 1) CMEMS Baltic Sea Reanalysis (NEMO-Nordic, 1993–2017) (product ref. no. 1); 2) NEMO-EST05 high-resolution hindcast (product ref. no. 12), averaged to daily means for comparison. These models provide consistent estimates of surface currents, which are typically weak (<0.2 m/s), with occasional peaks during storms. No in situ current measurements were available for validation, increasing the reliance on model intercomparison.

2.5 Extreme Value Analysis (EVA)

To characterize metocean extremes, we applied statistical extreme value theory to the long-term time series. Two complementary methods were used: 1) Block Maxima Method, fitting Generalized Extreme Value (GEV) distributions to annual maxima; 2) Peaks Over Threshold (POT), fitting Generalized Pareto Distributions (GPD) to exceedances over a high threshold. Model fits were performed via Maximum Likelihood Estimation (MLE). Special cases, including the Gumbel (GEV with shape = 0) and Exponential (GPD with shape = 0) distributions, were used where justified by the data.

The return levels for 10, 20, 50, and 100-year periods were estimated for wind speed (product ref. no. 3, 16), significant wave height (product ref. no. 1, 15), sea level extremes (both high and low) (product ref. no. 1, 9, 12), and surface current



181 speed (product ref. no. 12) at the LNG site (Fig. 1). Selection of the final model and dataset for each parameter was based on
182 best fit, physical plausibility, and consistency across data sources.

183 2.6 Regional extreme value analysis

184 To extend the EVA regionally, we leverage comprehensive long-term datasets from the Copernicus Marine Service. The
185 hindcast data underpinning our analysis include the Baltic Sea Multi-Year Physics Reanalysis for sea levels and currents
186 (product ref. no. 1), and the Baltic Sea wave hindcast/reanalysis for wave heights (product ref. no. 2). These products provide
187 a ~30-year (1993–2023) homogeneous time series with daily temporal resolution (sea level and currents) and hourly (bulk
188 wave parameters) at spatial resolution of 1 nautical mile, which are crucial for stable extreme statistics. Wind forcing is taken
189 from the ERA5 global atmospheric reanalysis (hourly, ~31 km grid) (product ref. no. 3), whose 10-m wind speeds have been
190 rigorously validated and widely used for wave modeling in European seas (Hersbach et al., 2020). Recent evaluations
191 indicate that using ERA5 winds can improve the representation of Baltic wave extremes, even if some regional reanalyses
192 better capture the mean wave climate (Giudici et al., 2023).

193 Block Maxima Method, fitting Generalized Extreme Value (GEV) distributions to annual maxima was used for the EVA. To
194 estimate the uncertainties in EVA of wind speed, wave height, sea level, and currents—a bootstrap resampling method was
195 used. It is a non-parametric approach that involves resampling the original dataset (with replacement) many times and
196 refitting the extreme value model each time. This provides empirical distributions of return levels, from which confidence
197 intervals and bias estimates can be derived. Particularly useful when the sample size is small or when the distribution is
198 skewed. We used this method to estimate the ranges of return values. We used 180 iterations, with the 2.5th and 97.5th
199 percentiles as the lower and upper bounds of the results. That is, the 95% between them gives this "confidence" interval.

200 3. Results and Discussion

201 3.1 Wind Speed

202 A comparison of reanalysis and observed wind data indicated that the ERA5 10-m wind speeds (product ref. no. 3) required
203 an increase of about 5% to match the highest winds recorded at the Pakri coastal weather station (product ref. no. 16). After
204 applying this correction factor, the distribution of ERA5 winds closely resembled open-sea conditions and aligned well with
205 satellite scatterometer (ASCAT) measurements (product ref. no. 7) over the overlapping period 2012–2021, while still
206 matching the high-end values recorded at Pakri (Fig. 2a,b). The Pakri station data, as expected for a land-based site, show a
207 higher frequency of low wind speeds due to sheltering when winds blow from land, but they also captured a few extreme
208 gusts that the coarser ASCAT sampling likely missed. Overall, the adjusted ERA5 dataset provides a representative wind
209 climate for the offshore terminal location, capturing both the predominance of moderate maritime winds and the magnitude
210 of rare storm peaks (Fig. 2a,b).



The fitted models describe the wind extremes well, including the highest recorded storm winds (Fig. 3a,b). The resulting 100-year return period wind speed – meaning the wind speed with a 1% annual probability of exceedance – is approximately 24 m/s at 10 m elevation. Lower return period estimates follow accordingly (e.g. about 23 m/s for a 50-year return period; see Table 2). This ~24 m/s extreme wind represents a critical design value for the FSRU terminal, defining the upper limit of wind loading that the mooring system and vessel must withstand.

3.2 Sea Level

Five different sea level datasets were evaluated to characterize water level variability at the site. These include two high-resolution hindcast model products (the CMEMS Baltic Sea reanalysis (product ref. no. 1) and the NEMO-EST05 model (product ref. no. 12), both at ~1 nmi grid resolution, the regional GETM model (product ref. no. 13), along with satellite altimetry (instantaneous along-track Level 3 and daily-averaged gridded Level 4 products) (product ref. no. 11 and 10), and the tide gauge observations at Paldiski (product ref. no. 9). Fig. 2c,d illustrates the probability distributions of sea level from these sources over their common period. The three continuous hindcasts (CMEMS, NEMO-EST05, and GETM), which provide hourly sea level time series for 1993–2017, show very similar distributions and are broadly in agreement with the statistical behavior of the Paldiski gauge record (which spans 1993–2009 with gaps). In contrast, the satellite-based records are either smoothed or sparse: the Level 4 product, with its daily averaging, smooths out short-lived peaks and thus underrepresents extreme high or low water events, whereas the instantaneous Level 3 altimeter data capture the full range of variability but contain relatively few data points near the study area. These differences in sampling density are reflected in the lengths of the distribution curves in Fig. 2c,d. When examining the upper and lower tails of the sea level distributions on a logarithmic scale (Fig. 2d), we find generally good agreement, but with some differences in extreme values across datasets. In the high-water (positive) tail, the CMEMS hindcast (product ref. no. 1) tends to predict slightly more frequent very high water levels than the NEMO-EST05 (product ref. no. 12) and GETM (product ref. no. 13) models. For instance, near the observed maximum sea levels, the CMEMS curve extends a bit further, suggesting a higher likelihood of extreme surge events in that dataset. The GETM and NEMO hindcasts yield somewhat lower extreme probabilities, but all three model-based datasets exhibit a similarly steep drop-off in the tail (Fig. 2 c,d), indicating they capture the rarity of extreme surges in the Gulf of Finland. In summary, while the lower-to-moderate sea level range is consistently represented across all sources, the CMEMS data provide a somewhat more conservative estimate of the highest water levels, making it a useful dataset for extreme analysis.

For extreme high sea levels, we focused on the model hindcasts for return period estimation, while using the Paldiski tide gauge data (product ref. no. 9) for context and validation. The annual maximum sea level in each year of the CMEMS (product ref. no. 1) and NEMO-EST05 (product ref. no. 12) series was extracted and fitted to GEV distributions. Both models yielded consistent results, with Gumbel-type fits adequately describing the upper tail (Fig. 3c,e). The CMEMS hindcast produced slightly higher estimates for a given return period, and we adopted those as a conservative choice for



design criteria. Notably, the largest storm surge on record in these series corresponds to the January 2005 cyclone “Gudrun,” which produced a water level of roughly +1.5 m at the site (Suursaar and Sooäär, 2007). In the CMEMS data, this event falls around the 100-year return level on the fitted curve, whereas in the NEMO-EST05 data it appears closer to a 50-year event based on extrapolation. Given historical knowledge that Gudrun was an exceptional Baltic Sea storm, we interpret it as approximately a 100-year event in this context. The extreme value analysis yields a 100-year return high water level of about +1.6 m relative to the local mean sea level (Fig. 3c). This value is taken as the extreme storm surge level for design purposes.

The annual minimum sea level from each year was used for the block-maxima analysis (since the lowest water level of each year represents the most extreme drop). This approach was chosen over a POT method because the very lowest value on record was a clear outlier that made threshold-based fitting unstable. The GEV fits to the annual minima from both the CMEMS (product ref. no. 1) and NEMO hindcasts (product ref. no. 12) suggest nearly identical low-water extremes. The estimated 100-year return period minimum sea level is approximately −0.8 m (i.e. 0.8 m below the mean sea level baseline). In practical terms, such an extreme low sea level, while infrequent, must be considered in FSRU design to ensure sufficient draught and flexible connections during extreme low-water events. The symmetry between the +1.6 m high and −0.8 m low centennial levels highlights the Gulf’s propensity for greater positive storm surges than negative seiches (since the basin’s geometry and prevailing winds favor high-water extremes (Medvedev and Kulikov, 2021).

3.3 Waves

To characterize the wave climate, we compared significant wave height data from multiple sources, emphasizing long-term model hindcasts as the basis for statistics. The primary datasets were the CMEMS Baltic Sea wave reanalysis (product ref. no. 2) and a high-resolution SWAN hindcast (product ref. no. 15). Available observations were limited to a short-term wave buoy deployment near the site in summer 2022 (product ref. no. 14) and a sparse set of satellite altimeter passes (Level-3 data, product ref. no. 11), which are insufficient to capture extreme wave conditions. As shown in Fig. 2g,h, the two hindcast models exhibit generally consistent wave height distributions. Both suggest that most of the time the significant wave height is relatively modest (<2 m) due to the fetch-limited nature of the gulf. There are, however, some differences in the frequency of moderate versus large waves: the SWAN hindcast (product ref. no. 15) predicts a slightly higher occurrence of moderate waves in the ~1–2.5 m range (perhaps owing to its finer resolution of nearshore wind and bathymetry effects), whereas the CMEMS reanalysis (product ref. no. 2) yields a greater number of the largest wave events (>2.5 m). This discrepancy likely arises because the CMEMS dataset covers a longer period including severe Baltic storms (e.g., the 2005 storm) that generated higher waves, while the SWAN simulation period does not include the absolute worst-case storm. Overall, both hindcasts identify a similar wave climate regime dominated by short-period wind seas, and they provide a sound basis for extreme wave analysis.

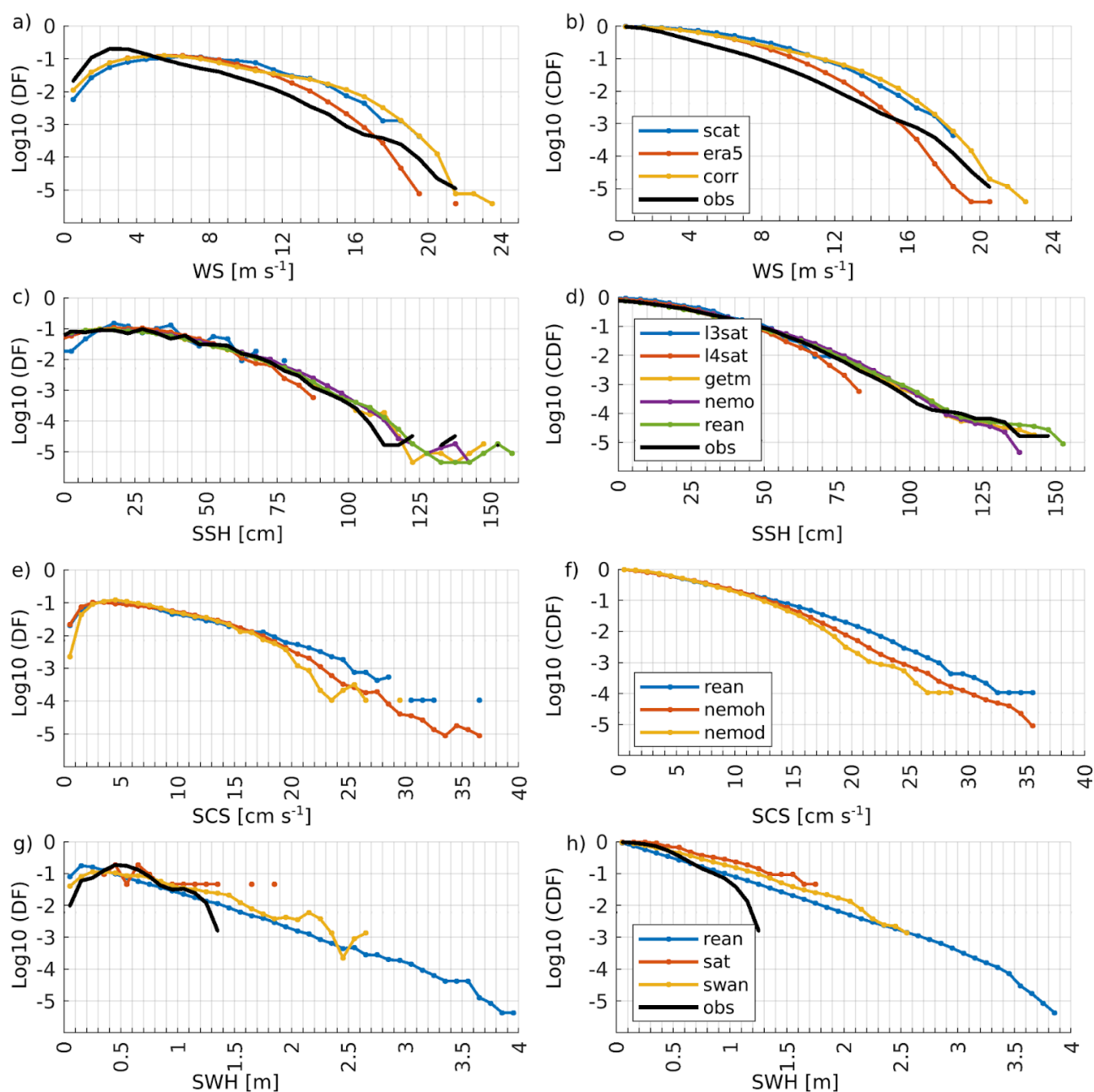


Despite the different spatial resolution and time span of the two wave models, their extreme value statistics turned out to be in strong agreement. GEV fits to the annual maxima from CMEMS (product ref. no. 2) and SWAN-EST05 (product ref. no. 13) each followed a Gumbel distribution quite closely, and the GPD fits to peaks over threshold (with an exponential tail) likewise captured the upper-end behavior of both datasets (Fig. 3j,k; Fig. A1j,k). For example, the statistically estimated 100-year return significant wave height is on the order of 4.2 m based on these fits. The CMEMS (product ref. no. 2) annual-maxima series did exhibit a slightly heavier tail (deviating from a straight Gumbel line at the very top end), but overall the differences between the two hindcasts and the two analysis methods were minor – a reassuring consistency that indicates the wave extreme estimates are robust.

3.4 Currents

Observations of surface currents in the Gulf of Finland are sparse, so we relied on hydrodynamic model data to assess current speed statistics. Two model sources were considered: the NEMO-EST05 high-resolution Baltic Sea circulation hindcast (1993–2017) (product ref. no. 12) and the surface current product from the CMEMS reanalysis (daily outputs over a similar period) (product ref. no. 1). To enable a direct comparison, the NEMO-EST05 1-hour data were averaged into daily means to match the temporal resolution of CMEMS. The resulting distributions of surface current speed from the two models are plotted in Fig. 2e,f on a logarithmic scale. Both datasets indicate that currents at the proposed terminal location are generally weak. Typical surface flow speeds are on the order of a few centimeters per second, and even the upper quantiles remain modest (on the order of 0.1–0.2 m/s). The two hindcasts agree well on this overall magnitude: their probability density curves overlap closely through most of the range. Both models paint a consistent picture of a low-energy surface circulation regime at the site, driven primarily by wind and seiche events in the semi-enclosed gulf.

For extreme current speeds, we extracted the annual maximum surface current from the NEMO-EST05 hindcast (considering the top 1 m layer average) (product ref. no. 12) and performed extreme value fitting. The NEMO-based extreme value curves suggest that 100-year return period surface currents are on the order of 0.4 m/s. The GEV fit for the annual maxima had a positive shape parameter (indicating an upward-curving tail in Fig. 3k), while the exponential-tail POT fit captured the few highest current events well (Fig. A1k); both methods yielded similar 100-year estimates around 0.37–0.40 m/s. It should be noted that these values come with larger uncertainty bands compared to the other parameters, mainly due to the lack of long-term current measurements for validation and the inherent variability in modeling coastal currents. We interpret ~0.4 m/s as a reasonable upper-bound estimate for the site's surface current under present climate conditions. Although this extreme current speed is relatively low in comparison to open-ocean currents, in combination with high winds and waves it could still contribute to the total environmental force on the moored FSRU.



302

303 **Figure 2.** Log scale density distribution functions (DF) (left column) and cumulative distribution function (CDF) (right
304 column) of wind speed (WS) (a,b) (product ref. no. 7, 3, 16), sea surface height (SSH) (c,d) (product ref. no. 11,10, 13, 12, 1,
305 9), sea surface current speed (SCS) (e,f) (product ref. no. 1, 12) and significant wave height (SWH) (g,h) (product ref. no. 2,
306 11, 14, 15) of various data sources at the location of the Terminal. Time series cover the 2012-2021 period.

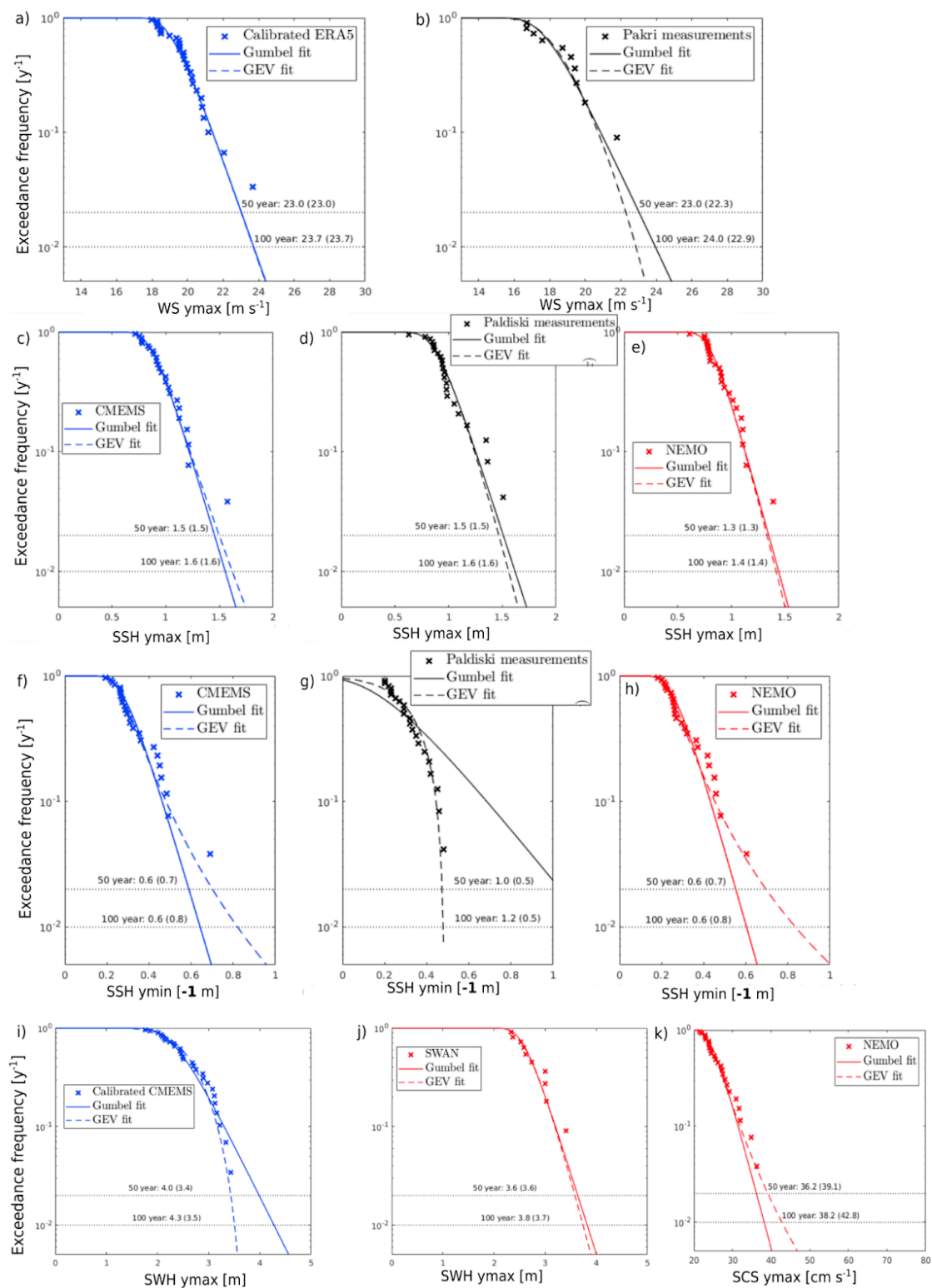




Figure 3. Generalized Extreme Value (GEV) and Gumbel distributions fitted to annual maxima and minima of key oceanographic variables: wind speed (WS y_{max}, panels a–b) (product ref. no. 3(a), 16(b)), sea surface height maxima (SSH y_{max}, panels c–e) (product ref. no. 1(c), 9(d), 12(e)), sea surface height minima (SSH y_{min}, panels f–h) (product ref. no. 1(f), 9(g), 12(h)), significant wave height maxima (SWH y_{max}, panels i–j) (product ref. no. 1(i), 15(j)), and surface current speed maxima (SCS y_{max}, panel k) (product ref. no. 12(k)). For SSH minima, positive values indicate sea levels below zero. Horizontal lines denote the 50- and 100-year return periods, with corresponding return levels shown (GEV estimates indicated in brackets).

Table 2. An overview of the return levels for the environmental variables for return periods of 10, 20, 50 and 100 years at LNG site.

	10 y	20 y	50 y	100 y
Wind speed (m/s)	21	22	23	24
Sea surface height (m)	+1.3	+1.4	+1.5	+1.6
Sea surface minima (m)	-0.5	-0.6	-0.7	-0.8
Significant wave height (m)	3.5	3.7	4.1	4.3
Surface current (cm/s)	33	35	37	39

3.5. Extension of the Extreme value analysis to the whole Baltic Sea

In this section, we broaden the extreme value analysis beyond the local Gulf of Finland site to the wider Baltic Sea, incorporating state-of-the-art methods and regional data sets. We have calculated extreme values of metocean variables corresponding to the return period of 50-years (Fig. 4).

The wind speed values are higher over the sea area than over the land (Fig. 4a). This is because of the absence of orographic restrictions over the sea area. Over the sea, extreme wind speeds show a north-south and coastal-offshore variability. The wind speeds are high and confidence intervals are wide over the southern-western Baltic Sea (Fig. 4a,b), which indicates that the range of extreme wind speed could reach 38 m/s (28±10 m/s). The most severe Baltic windstorms, often following a track across the open sea, have produced 10-minute mean wind speeds above 30 m/s over water (Björkqvist et al., 2020). For example, the January 2019 storm’s peak winds reached 32.5 m/s over the Baltic Proper, driving the extreme waves (Björkqvist et al., 2020). A significant wave height of 8.1 m was measured in the northern Baltic – the highest on record – with hindcasts suggesting waves up to 9 m in the Bothnian Sea (Björkqvist et al., 2020). Over analysis shows high extreme value of the wave height and wave period over the eastern Baltic Proper (Fig. 4c-f). Especially in the south-eastern Baltic Sea, significant wave height and wave period could reach the values of 15 m (10±5.5 m) and 11 s (9±2 s), respectively.



332 Sea surface current speeds are high at the coastal sea, where locally, the extreme values could reach 1 m/s (Fig. 4g).

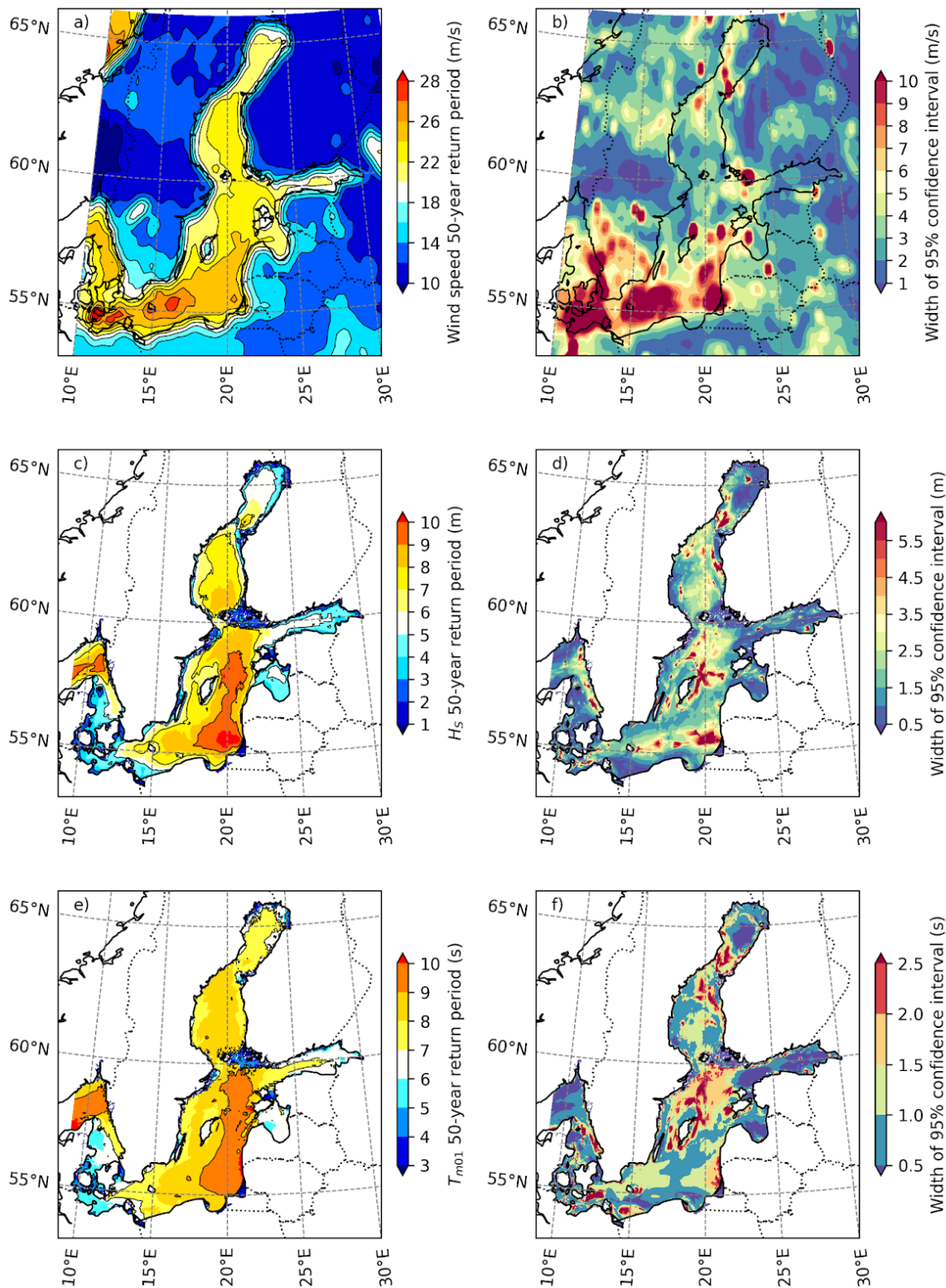
333 Simultaneously, the uncertainties of these extreme values are almost 2 m/s (Fig. 4h).

334 Storm surge (sea level) extremes display particularly strong spatial variability due to the Baltic's complex geometry and
335 bathymetry. Extreme sea levels in the Baltic Sea are driven by wind-driven surge, atmospheric pressure, and seiche
336 oscillations. The highest surges occur when strong winds align with the basin's long axis and push water into narrow bays or
337 gulfs. Maximum sea level anomalies are expected in the eastern Gulf of Finland and the Gulf of Riga (Fig. 4i). There, the
338 extreme sea level corresponding to the 50-year return period could be as high as 1.3 m. At the end of the Gulf of Finland,
339 uncertainties of the extreme value estimate are also high, reaching up to 1.3 m (Fig. 4j). In the Gulf of Riga the uncertainties
340 remain below 0.8 m (Fig. 4j). In the Gulf of Riga, the town of Pärnu has suffered two record surges: 2.53 m in 1967 and 2.75
341 m in January 2005 (Lorenz et al., 2025; Suursaar and Sooäär, 2007) – the latter being one of the highest reliably measured
342 sea levels in the entire Baltic during the last century.

343 Meanwhile, minimum sea levels were found to be around -0.7 m for a 50-year return period at the site of the LNG terminal
344 (Table 2). The Baltic Sea wide estimates provide minimum sea levels down to -0.4 m (Fig. 4k) with maximum uncertainty
345 of up to 0.3 m (Fig. 4l) corresponding to a return period of 50-years. The discrepancy could be related to the fact that hourly
346 sea level values were used at the LNG while daily values for the whole Baltic Sea. We note that uncertainty in these return
347 level estimates is considerable, owing to the relatively short observational records (30–60 years) and natural variability. We
348 like to note that extreme values of high sea level are significantly higher than low sea levels relative to zero sea level.

349 Metocean criteria derived from local and Baltic-wide EVA feed directly into the engineering specifications for mooring
350 systems, platform freeboards, breakwater heights, and operational limits. For example, the calculated extreme significant
351 wave height guides the required height of mooring dolphins and fenders to avoid collision or overtopping in a storm. The
352 extreme wind speed and current inform the loads on the FSRU's mooring lines and the tension capacity needed to keep it in
353 place during a gale. Even extreme low water levels (e.g. -0.7 m in our 50-year estimate) are important, as they determine the
354 minimum under-keel clearance and the design of intake/outlet systems for the FSRU.

355 Finally, the broader strategic relevance of extreme value studies in the Baltic Sea must be underscored. The Baltic region is
356 characterized by sensitive environmental conditions and heavily used sea routes (Fig. 1a) (for commerce and increasingly for
357 energy transport). Geopolitical factors – such as shifting trade patterns, military considerations, and transnational energy
358 projects – mean that infrastructure robustness is part of national resilience. For example, the disruption of one LNG terminal
359 by an extreme storm could have ripple effects on multiple countries' energy supply. Therefore, a regional perspective on
360 metocean extremes, as provided by our Baltic-wide EVA extension, is valuable for coordinated contingency planning.



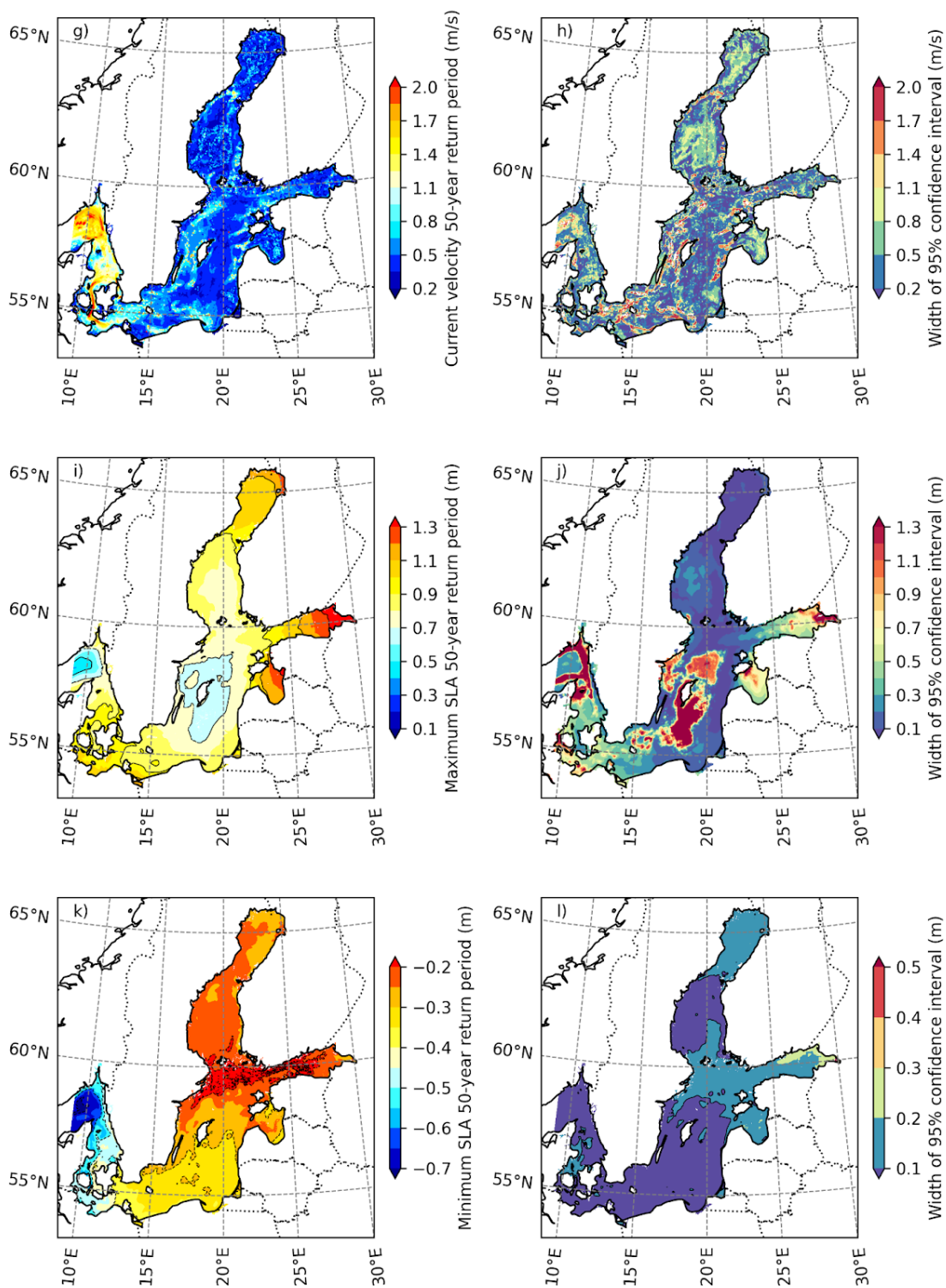




Figure 4. Extreme values corresponding to the return period of 50-years (left panels) and the uncertainties of their estimates (right panels). Wind speed (a, b), significant wave height (c, d) and peak period (e, f), current velocity (g, h), and maximum (i, j) and minimum (k, l) sea level anomaly.

Conclusions

This metocean study supports infrastructure resilience and safety planning for the FSRU terminal in the Gulf of Finland, identifying key extreme thresholds for design and operations. By incorporating both localized and basin-wide perspectives, the research not only informs the Estonian site but also contributes to broader strategic planning across the Baltic Sea. The extension of the extreme value analysis across the entire Baltic Sea, with a focus on critical infrastructure locations (Fig. 1a), is a key innovation. It enables comparative risk assessment, fosters harmonized engineering standards, and supports transnational decision-making for energy security and maritime infrastructure resilience. Regional variability - ranging from highly exposed offshore sites to sheltered gulfs - demonstrates the importance of spatially detailed metocean data. Such an integrated approach, combining Copernicus Marine Service products, advanced modeling, and observational validation, sets a methodological benchmark for future infrastructure planning under changing climate and marine conditions.

Data Availability

This study is based on public databases and the references are listed in Table 1.

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Special issue statement

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Competing Interests



392 The authors declare that they have no conflict of interest.

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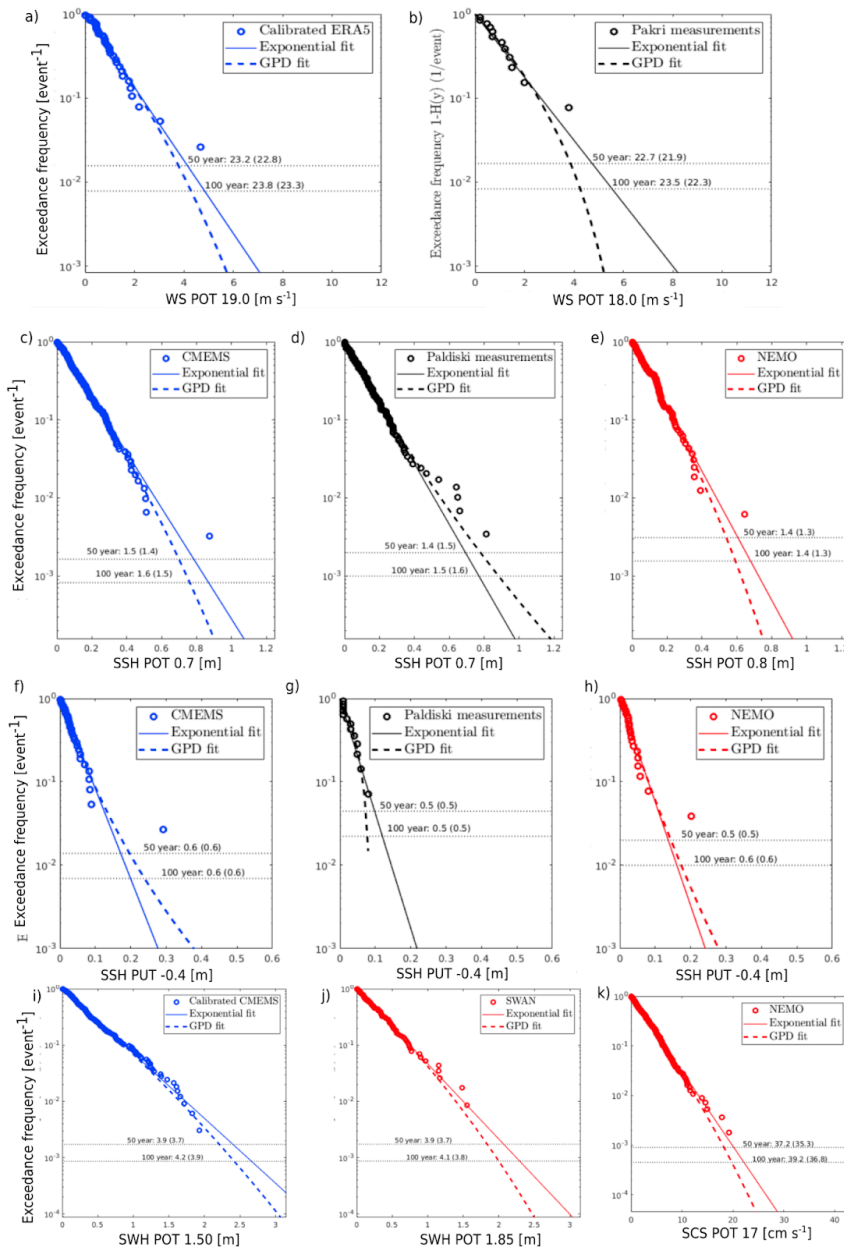
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583 Appendixes



584

585 **Figure A1.** Generalized Pareto Distribution (GPD) and Exponential distribution fits to peaks over/under thresholds
586 (POT/PUT) for selected oceanographic variables: wind speed (WS ymax, panels a–b) (product ref. no. 3(a), 16(b)), sea
587 surface height maxima (SSH ymax, panels c–e) (product ref. no. 1(c), 9(d), 12(e)), sea surface height minima (SSH ymin,
588 panels f–h) (product ref. no. 1(f), 9(g), 12(h)), significant wave height maxima (SWH ymax, panels i–j) (product ref. no.
589 1(i), 15(j)), and surface current speed maxima (SCS ymax, panel k) (product ref. no. 12(k)). For SSH minima, positive



590 values represent depressions below the threshold (i.e., negative sea level excursions). Horizontal lines indicate the 50- and
591 100-year return periods, with corresponding return levels shown (GPD estimates indicated in brackets).