



Committee I.1: Environment



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Committee Mandate. Concern for descriptions of the ocean environment, especially with respect to wave, current and wind, in deep and shallow waters, and ice, as a basis for the determination of environmental loads for structural design. Attention shall be given to statistical description of these and other related phenomena relevant to the safe design and operation of ships and offshore structures. The committee is encouraged to cooperate with the corresponding ITTC committee.

Contributors

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1 Discussion

1.1 Official Discussion by D. Sc. Elzbieta M. Bitner-Gregersen, Norway

1.1.1 Introduction

Being the chairman of the Committee I.1 Environment in the period 2006–2015 it is my great pleasure to have been given the opportunity to serve as the official discussor of the report of the ISSC 2025 Committee I.1. The report covers a wide range of topics associated with descriptions of environmental conditions as specified in its mandate, that is, wind, waves, current and ice. It gives a comprehensive and impressive survey of recent developments since the previous ISSC report which is supported by 35 pages of relevant references. The highlight of the report is a benchmark study on extreme value analysis. The information included in the report is of interest to the marine industry as well as academia. During the ISSC 2025 term the Committee I.1 followed the findings of the corresponding ITTC committees.

The present report fulfils the mandate with good margin. I would like to congratulate the Committee's chairman and members for their success in achieving the task assigned to the ISSC 2025 Committee I.1.

I will permit myself a brief discussion of some topics, focusing on the subjects I am most familiar with. My comments will follow the sequence of the chapters in the Committee's report.

1.1.2 Remarks

The Committee's work is documented by a thoroughly written 119-page report. The report includes ten chapters discussed below, starting with an introduction and closing with conclusions. In addition, there are two appendixes: "Extreme value analysis benchmark" and "Publicly available environmental data sets".

I appreciate that although not mentioned in the mandate the Committee includes some aspects of environmental description that are important for renewable energy structures.

The report is generally well structured but there are some repetitions which are difficult to avoid in the present structure. I wonder why the chapter on field observations at sea is placed as one of the last, and not as the first chapter after introduction. Commonly we observe a phenomenon in nature, gather field observations, model it, and then validate a proposed model by field and laboratory data.

1.1.3 Introduction

Four focus areas have been selected for the report by the Committee: applying environmental descriptions to the design of ships and marine structures, statistical modelling, the impact of climate change on environmental descriptions and innovative technologies in the world of the ocean environment. These are rapidly evolving and critical topics.

The presented overview in Table 1, although non-exhaustive, highlighting the types of data and models required for design and operations of marine structures, illustrates clearly the need to translate academic findings for industry use.

I appreciate that the Committee recognizes the importance of collaboration of the marine industry and environmental community, and the significance environmental description has on design and marine operations. The Structural Reliability Analysis (SRA) has shown that the environmental description may contribute beyond 80% to the structural failure (e.g. (Bitner-Gregersen et al. 1992)). The collaboration of the marine industry with academia is also essential to push state-of-the-art knowledge about environmental description relevant for design and the safety of marine operations.

There is potential safety and economic advantage in utilizing the most recent knowledge about environmental description in design and operations of marine structures. To achieve acceptance, such description must be demonstrated to be robust and of adequate accuracy. As with most formal processes, updating codes and standards takes some time, and, consequently, updates may lag behind the state-of-the-art.

1.1.4 Large-Scale Metocean Climate Models

Chapter 3 gives a good review of the research findings on the past, present and future climate. The Committee underlines that projections of climate change remain to be affected by large uncertainties without discussing all of them in detail. One of them is sampling variability, the statistical uncertainty due to limited number of observations.

The projections of the past, present and future climate are based on ensemble simulations. The number of ensemble members of General Circulation Models (GCM) used to identify trends in metocean conditions arising from climate change will affect the results. This is not mentioned in the report. Bitner-Gregersen and (Bitner-Gregersen and Gramstad 2018) showed that differences between extreme significant wave height H_s calculated from different ensemble members can be larger than differences between projections given by different climate models. Therefore, to avoid getting biased results, dominated by natural climate variability, it is important to consider carefully the number of ensemble members used in investigations of potential impact of climate change on environmental conditions. Not all authors specify in their publications how many ensemble members are used when trends in metocean conditions caused by climate change are derived. Such information is important for comparison of results developed by different authors.

Despite the existing uncertainties associated with climate change projections the Norwegian Offshore Standard (NORSOK 2017), to be on the safe side in design, proposed an increase of extreme significant wave height and wind speed by 4% on q-probability values because of climate change. This could have been mentioned in the report.

1.1.5 Numerical Models at Engineering Scale

The survey presented shows progress made in the development of numerical models for the description of environmental phenomena. The Committee should get credit for Fig. 1, 2, 3 and 4 showing overviews of advances in wave, ice, current and wind model research, supported by references. The figures provide useful information for the marine industry as well as academic community.

I agree with the Committee that non-linear potential flow methods used for modelling of waves are faster but cannot be reliably applied to modelling of wave breaking and stability, while the techniques based on CFD (Computational Fluid Dynamics) have advances here. Therefore, coupling tools with different levels of fidelity seems to be a promising approach for assessment of wave impact. It is worth to mention that the marine industry has already started to use such approach in the last years, e.g. DNV (Bitner-Gregersen 2017).

I would like to direct the attention of the Committee to sampling variability which may affect significantly numerical simulations of phase-resolving wave models. Kurtosis being the third order effect represents an important characteristic of non-linearity of a sea state. The spatial kurtosis as a function of 1800s HOSM (Higher Order Spectral Method) simulations with the same seed for the PM ($\gamma = 1$) and JONSWAP spectrum with $\gamma = 2, 3.3$ and 6 for the Andrea unidirectional rogue-prone sea state is shown in Fig. 3. T_p in the figure denotes the spectral peak period while k_p the wave length associated with the spectral peak period.

The figure demonstrates that a single spatial 30-min realization of sea surface of a rogue-prone sea state may produce a higher kurtosis coefficient for the PM spectrum ($\gamma = 1$) than for the JONSWAP spectrum with $\gamma = 6, 3.3, 2$ due to inherent randomness of waves, what contrasts with the wave theory. The increased number of runs to 1000 plotted in Fig. 2 shows results which are consistent with the wave theory (Bitner-Gregersen et al. 2021). Therefore, the number of runs should carefully be considered, particularly when non-linear wave characteristics are investigated, which are more sensitive to sampling variability than linear ones.

As shown by Bitner-Gregersen et al. (2021) using numerical HOSM simulations having 20–30-min in-situ temporal or spatial wave records may prove challenging to determine the importance of non-linearity of surface elevation as the sampling variability may dominate over the non-linear effects.

The phased-averaged spectral wave models WAM, WW3 and SWAN, and the non-hydrostatic SWASH model remain the most used models, as correctly reported by the Committee. However, validation of these models with field observations is still ongoing. The Committee provides a nice review of these investigations, mentioning also the remaining problem. Too few measurements of significant wave height beyond 8–10 m exist making validation of spectral model extremes, being of interest for the marine industry, difficult. I hope that awareness of this situation, the application of new measuring techniques and the growing access to wave databases will contribute to solving this problem in the coming future.

I miss in Sect. 3.1.2 “Spectral models” a discussion about accuracy of wave spectra simulated by the spectral wave models. Some concern exists in wave community that the wave spectral models may provide spectra that are too broad compared to those

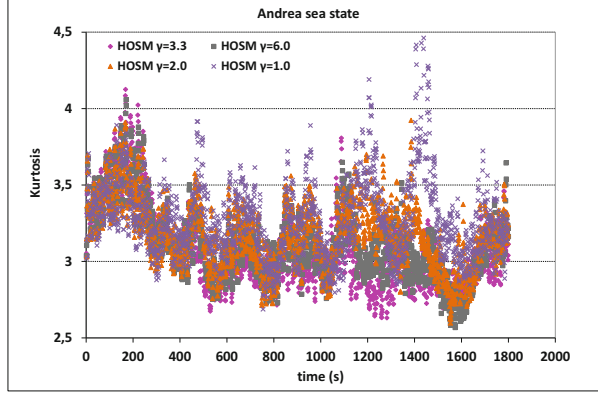


Fig. 1. Estimated spatial kurtosis as a function of simulation time. HOSM simulations for the selected seed; Andrea sea state $H_s = 9.2$ m and $T_p = 13.2$ s, $k_p H_s/2 = 0.11$; unidirectional waves. After (Bitner-Gregersen et al. 2021)

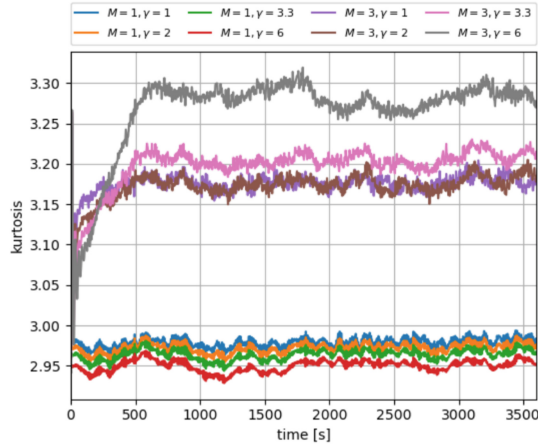


Fig. 2. Spatial kurtosis as a function of simulation time calculated as an average over 1000 repetitions of the 60-min simulation. HOSM and linear simulations; the Andrea rogue-prone sea state $H_s = 9.2$ m and $T_p = 13.2$ s, $k_p H_s/2 = 0.11$. M denotes the order of simulations, $M = 1$ referred to the linear simulations, $M = 3$ to the nonlinear third order HOSM simulations. After (Bitner-Gregersen et al. 2021).

derived from wave measurements (e.g. (Ardag and Resio 2019; Cavaleri et al. 2020)). Wave spectra represent an important input for phase-resolving wave models, laboratory experiments and design. Has not much progress been made since 2020?

Ice represents a hot topic in the debate of climate change, and ice conditions in the polar regions are of great interest to the marine industry, particularly the shipping industry, because of the Northern Sea Route and the Northwest Passage. Modelling of sea ice conditions in the Southern Ocean is gaining also increasing attention. Sea ice dynamics and ice interaction with other metocean phenomena are very complex phenomena and

modelling of them is challenging. The Committee should be congratulated on including a nice survey of the progress made in these fields and presenting it on a geophysical and engineering scale. The section is expected to get attention from many practitioners' readers.

Modelling current and wave-current interactions is important for many engineering applications but the topics are research demanding. Improvement of accuracy of such models has been going on for several years and as the Committee's review confirms this situation remains.

I was pleased to see that there have been improvements in simulations of typhoons which are very welcomed by the marine industry.

Wave-coupled phenomena (waves-wind-current) have been receiving increasing attention recently, and that is expected to continue. The Committee should be complimented on including in the review the (Janssen and Bidlot 2023) paper representing an important contribution to understanding wind-wave interactions and formation of extreme waves.

1.1.6 Data-Driven Models

The rapid expansion of artificial intelligence (AI) in recent years has significantly impacted many fields as well as environmental sciences. The contents of Chapter 4, reviewing atmospheric and oceanic applications of data-driven models, are very nicely prepared, giving good status of implementation of AI methodology in environmental description. I feel this Chapter is invaluable for many readers not only design/operation engineers of specified structures but also the ones in academia.

As pointed out by the Committee, this new research field brings interdisciplinary collaboration, as oceanographers and engineers work now closely with data scientists, mathematicians, statisticians, and software engineers, what I think is a positive development.

Implementation of AI in environmental sciences shows very promising results. The Committee lists common methodological mistakes made by a high number of research projects and scientific papers when applying AI. However, the shortcomings of the machine learning methodology are not emphasized. For example, the machine learning models are ocean location/region dependent. Thus, although the principles of the methodology will be valid, new simulations will be required for other ocean locations/regions, particularly if the environmental conditions are very different.

I would appreciate hearing the Committee's comments on the following questions:

1. The Committee documents that use of AI shows promising results for wind and wave forecasting. Further, it is written: "Surrogate models have the potential to completely replace numerical models with significantly lower computational costs." Physics-based spectral wave models used for forecasting and hindcasting are under continuous development. This refers also to other physics-based models. Should these developments be stopped?
2. Have developments of data-driven models reached so stage that they can be utilized, as a support, in the design process?

1.1.7 Laboratory Measurements and Observations

Chapter 5 includes a comprehensive and nice review of some new facilities that were opened during the Committee's term and the advances in experimental modelling of waves, ice, current, wind, and coupled wave-phenomena. This well written chapter contains, apart from valuable information about recent research findings, also the discussion of uncertainties associated with laboratory experiments. Particularly, experimental modelling of waves is thoroughly reviewed. In addition to statistical uncertainty, the epistemic uncertainties related to basin effects, scale effects, instrumentation and measure accuracy, determination generating of wave events, wave breaking and shallow-water wave generation are discussed.

I have not much to add to this chapter but have only two remarks. When investigating extreme and rogue waves the length of a basin is crucial. Depending on the initial condition, modulational instability can happen after 10–20 wavelengths. Further, numerous research has demonstrated theoretically, numerically, experimentally, and observationally that the gradual transition from Gaussian to non-Gaussian waves repeats after waves breaking. This phenomenon will not be observed in too short basins. Possible reduction of statistical uncertainty when doing laboratory experiments, should always be considered carefully.

1.1.8 Ocean Measurements and Observations

Observations at sea represent an integrated part of environmental description and are very important for validation of environmental models. Chapter 6 reviews advance in measurements at sea of waves, ice, current, wind, Argo fleet of drifting buoys and wave-coupled phenomena. The observations of the latter are important for better understanding of atmosphere-ocean interactions which modelling is much in focus at present and is expected to grow in the coming future.

In the Subject. 6.1.3 “In-situ measurements from platforms” the paper of Magnusson et al. (2021), showing an inter-comparison between three wave sensors: radar, laser, and a Waverider buoy, based on measurements made at the Ekofisk platform in the North Sea, could have been mentioning.

The assumption of stationarity of sea states on which most short-term environmental models are based on brings challenges when applying field observations for assessment of performance of ships and other marine structures at sea. For example, 20-min (17-min) duration of wave records, for which stationarity has commonly been adopted by wave community is often not valid for steep sea states, where stationarity can be applied to a shorter period only (e.g., (Bitner-Gregersen et al. 2021)). For this reason, an extension of duration of wave records, to reduce sampling variability, is often not possible. Therefore, numerical simulations and laboratory experiments represent a good support to field measurements.

In design, for long-term assessment of performance of marine structures at sea with durations of the order of their lifetimes it has been generally accepted that metocean climate variability can be discretized in stationary periods of 3 to 6 h. The use of the 3 to 6 h assumption of stationarity is seldom justified. This assumption should be considered

carefully when assessing marine structures' performance at sea, e.g. ships sailing with speed over 15 kn (Nielsen and Ikonomakis 2021).

1.1.9 Statistical Modelling

Chapter 7 presents recent developments in the theory and application of statistical modelling of environmental variables relevant for description of the ocean conditions. This well-prepared survey includes long- and short-term statistics, extreme value analysis, multivariate analysis, spatial-temporal analysis and non-stationary analysis.

In Sect. 7.1 the paper of Eisinger et al. (2016) could have been mentioning. (Eisinger et al. 2016) pioneered a method to make the best estimate of the environmental conditions experienced by operating vessels in their exact position using the Automatic Identification System (AIS) data and matching them with the ECMWF reanalysis data. 25-year return values of significant wave height were estimated by fitting a Weibull distribution to the available at that time three-year AIS-ECMWF sample.

It is written in the report, "For practical applications, Bitner-Gregersen *et al.* (1995) proposed a joint model using a 3-parameter Weibull distribution for H_s and a conditional lognormal distribution for wave period." Some clarification is necessary to this statement. The original Global Wave Statistics (GWS) data were not used because of two reasons. First, the joint model introduced some adjustment of inaccuracy of wave period. Secondly, in the GWS atlas the last wave height class is in the range 11–12 m, indicating that observations of wave height beyond 12 m were summed up by BMT (1986) in this class. The fitted distribution to the GWS wave heights and periods, necessary for applications in the Structural Reliability Analysis, provided higher wave heights being not consistent with the last 11–12 m class of the BMT Atlas (see (Bitner-Gregersen et al. 2013)). Therefore, the numerically generated scatter diagram from the joint wave height and wave period distribution was proposed. Note that the GWS data include bad weather avoidance as they were collected from ships in normal services.

In Sect. 7.2 "Long- and short-term statistics" and Sect. 7.3 "Extreme value analysis and extreme wave statistics" new fitting techniques for the probability distribution of H_s are mentioned, being a combination of two-three different distributions. Dividing wave data into blocks and fitting distributions separately to each block will usually result in a better fit than the one obtained by fitting a distribution to all data. However, a question arises whether there are any physical reasons for doing it, do the data in different blocks belong to different populations generated by different physical mechanisms? Some caution is advised when using such approaches to extrapolate beyond available data not to get unphysical results, e.g. extreme H_s which wind is not able to generate. I will mention in this connection the Norwegian Offshore Standard (NORSOK 2017) which requires that there must be enough room for the wave crest to pass beneath the platform deck to ensure that a 10000-year wave load does not endanger the structural integrity.

Figure 8 in Sect. 7.2 would benefit if the figure legend was included.

1.1.10 Extreme Events and Conditions

Three extreme phenomena have been selected by Committee I.1 for the survey in Chapter 8: rogue waves, extreme ice events and tropical cyclones. All represent actual topics receiving continuous attention in academia and the marine industry.

The practical definition of rogue waves adopted by DNV (2024) is due to Haver (2000), what could have been written in the report. I would like to mention two papers which may be of interest for Committee I.1. On November 30, 2018, a 20-min time series measured by the WaveRadar REX at Ekofisk recorded three consecutive waves with individual heights that all were more than twice the significant wave height (Magnusson et al. 2019). The last two of them were almost equally high with a factor 2.35 to the significant wave height of 4m. This triple rogue wave group was named the “Justine Three Sisters”. (Toffoli et al. 2024) reported direct observations of surface waves from a stereo camera system across the Southern Ocean in the Australian winter aboard the South African icebreaker S.A. Agulhas II. Using the collected data the authors documented that modulation instability exists in the ocean.

The survey of extreme ice events and climate change in polar regions includes information being of broad interest, particularly to the shipping industry.

The Committee I.1 prepared a nice survey of the recent developments in modelling tropical cyclones and their influence on ocean waves. Knowledge about these phenomena and the models describing them is crucial for design and disaster prevention.

1.1.11 Updated IACS Scatter Diagram

The Committee should be credited for including the updated IACS scatter diagram in Chapter 9 and for the discussion about some caution when using it outside the classification context. As correctly pointed out by the Committee I.1 it is essential to understand the underlying assumptions of the data and their implications for the entire design process.

1.1.12 Conclusions

Chapter 10 summarizes shortly the contents of all chapters. This is useful for the readers. Some recommendations for the topics to be considered by the next ISSC Committee I.1 are given also.

The summary documents clearly that the Committee I.1 has been successful with focusing on environmental descriptions relevant for the determination of environmental loads for design of ships and marine structures, while at the same time providing useful information about environmental descriptions for academia.

1.1.13 Appendix A: Extreme Value Analysis Benchmark

The Committee I.1 should be congratulated on carrying out the benchmark study on extreme value analysis. I agree with the Committee I.1 that methods and tools that are widely used by statisticians are not as well utilised as they could be in ocean engineering. Partly, because wind, waves, current and ice are investigated by researchers of different backgrounds, by oceanographers, applied mathematicians, statisticians, naval architects, hydro-engineers and data-scientists, having different levels of knowledge about statistics.

I think that adaptation of statistical methods and tools, not only in ocean engineering but also in ocean sciences, should be considered with some care as they should be anchored to physics of environmental phenomena.

In larger organizations not only a choice of extreme value models will impact the derived extreme values of metocean parameters but also who is carrying out such analysis. I think that for a selected data set the extreme value estimates should be compared with results from alternative methods. Then, in addition to the mean over all methods, also biases (systematic errors) between different methods can be obtained, representing useful information for a decision process.

1.1.14 Appendix B: Publicly Available Environmental Data Sets

The issue of met-ocean data ownership remained a general problem for several decades, what was pointed out by several previous ISSC I.1 committees. Some movement to solve this problem has been made, the access to several wave databases is available today, providing new opportunities for environmental modelling and design work. Among others, an initiative from the European Commission has contributed to it (<https://scihub.copernicus.eu/>).

The list prepared by the Committee I.1 of publicly available environmental data sets is very useful for the marine industry and academic community. I can add to the presented list the free and opened access weather, environment and climate data of the Norwegian Meteorological Institute (<https://data.met.no/>). See also the Frost API database including MET Norway's archive of quality controlled daily, monthly, and yearly measurements of temperature, precipitation, and wind data (<https://frost.met.no/index.html>).

1.2 Floor and Written Discussions

Xue-liang Wang: As we know the ship-based observation for wave is very important for ocean-going ships. However, now the ship-based observation method is usually X-band radar, but its data accuracy has half meter error range. It is not sufficient to real-time evaluation for wave loads and the corresponding structural responses, especially in key point of ship structure. So my question is whether the Environment Committee can give us some suggestions for new technologies for high accuracy observation of wave, for example, vision method etc.

Ekaterina Kim: The link to the Github open code for benchmarking does not have a license. In Github, a project with no license means that the code (by default) is under exclusive copyright (at least per Sept 23, 2025). While we can see the code we have no permission to use, modify or distribute it without the explicit permission of the creator. Is this your intention or were you unaware of this? Please add license.

Unknown Floor Discussor: The impact of offshore fracking for oil extraction, that is used more recently, on the environment can be very large in many ways. Did the committee discuss this impact in the report?

Unknown Author of a Written Question: Are there new probabilistic models for long-term wind and wave distributions? How were they implemented in design standards? For

example, for operations we need separate swell and wind-sea wave parameters. There needs to be a probabilistic model for such combination of wave parameters. Is there any new work on short-term (for example in seconds, minutes, hours and days) forecasting of wind and wave conditions? How were they used in practice?

2 Reply by Committee

2.1 Reply to Official Discusser

This section provides replies of the committee to the comments of the official discussor in Sect. 1.1. First of all we would like to thank the discussor for her thorough review and useful comments. Where necessary we repeated part of her comments below in bold with the addition ‘OD’ (official discussor), with our replies directly below them in normal font with the addition ‘CE’ (committee environment).

2.1.1 General Remarks

CE: We are happy to hear that the discussor appreciated the report and thinks it fulfils the mandate with good margin (as stated in Sect. 1.1.1). We reply to the additional remarks on the introduction below.

OD: The Committee’s work is documented by a thoroughly written 119-page report. The report includes ten chapters discussed below, starting with an introduction and closing with conclusions. In addition, there are two appendixes: “Extreme value analysis benchmark” and “Publicly available environmental data sets”.

I appreciate that although not mentioned in the mandate the Committee includes some aspects of environmental description that are important for renewable energy structures.

CE: Indeed, we think it is important to consider that ‘novel’ structures such as those utilised to harness renewable energy also require different information about the environment. They may for instance operate in different areas, water depths, wave and wind regimes, have larger or smaller dimensions than conventional maritime structures, have different lifetimes, or require more information about wind or current conditions than about wave conditions. These things should be properly supported by metocean studies.

OD: The report is generally well structured but there are some repetitions which are difficult to avoid in the present structure. I wonder why the chapter on field observations at sea is placed as one of the last, and not as the first chapter after introduction. Commonly we observe a phenomenon in nature, gather field observations, model it, and then validate a proposed model by field and laboratory data.

CE: This is a valid point. The structure we have now was more or less derived from the previous 2022 report, where we found it strange that the ocean and laboratory observations shared a chapter. We changed that, but indeed didn’t consider also moving the ocean observations chapter forward. This would be a good point to consider for the next committee.

2.1.2 Introduction

OD: *Four focus areas have been selected for the report by the Committee: applying environmental descriptions to the design of ships and marine structures, statistical modelling, the impact of climate change on environmental descriptions and innovative technologies in the world of the ocean environment. These are rapidly evolving and critical topics.*

The presented overview in Table 1, although non-exhaustive, highlighting the types of data and models require for design and operations of marine structures, illustrates clearly the need to translate academic findings for industry use.

I appreciate that the Committee recognizes the importance of collaboration of the marine industry and environmental community, and the significance environmental description has on design and marine operations. The Structural Reliability Analysis (SRA) has shown that the environmental description may contribute beyond 80% to the structural failure (e.g. (Bitner-Gregersen et al. 1992)). The collaboration of the marine industry with academia is also essential to push state-of-the-art knowledge about environmental description relevant for design and the safety of marine operations.

There is potential safety and economic advantage in utilizing the most recent knowledge about environmental description in design and operations of marine structures. To achieve acceptance, such description must be demonstrated to be robust and of adequate accuracy. As with most formal processes, updating codes and standards takes some time, and, consequently, updates may lag behind the state-of-the-art.

CE: We are glad to hear that the OD agrees that these are important topics for the maritime industry, and that the focus we put on practical applicability of the environmental knowledge in design and operation also came across. The mentioned percentage clearly illustrates this importance. The supporting publication dates from before our mandate period, otherwise it would have been a good addition. We agree that it is only to be expected that new findings in the academic world take some time to be translated to the industry and regulations. This is partly due to the need for proper interpretation and validation, but in some cases also to a lack of contact between the academic and corporate world. We hope to have provided a small contribution to this communication with the ISSC report.

2.1.3 Large-Scale Metocean Climate Models

OD: *Chapter 3 gives a good review of the research findings on the past, present and future climate. The Committee underlines that projections of climate change remain to be affected by large uncertainties without discussing all of them in detail. One of them is sampling variability, the statistical uncertainty due to limited number of observations.*

The projections of the past, present and future climate are based on ensemble simulations. The number of ensemble members of General Circulation Models (GCM) used to identify trends in metocean conditions arising from climate change will affect the results. This is not mentioned in the report. Bitner-Gregersen and (Bitner-Gregersen and Gramstad 2018) showed that differences between extreme significant wave height H_s calculated from different ensemble members can be larger than differences between

projections given by different climate models. Therefore, to avoid getting biased results, dominated by natural climate variability, it is important to consider carefully the number of ensemble members used in investigations of potential impact of climate change on environmental conditions. Not all authors specify in their publications how many ensemble members are used when trends in metocean conditions caused by climate change are derived. Such information is important for comparison of results developed by different authors.

CE: We agree with the Official Discussor regarding the importance of discussing the uncertainty associated to climate projections. One of the sources of uncertainty is indeed the statistical uncertainty due to limited number of observations, that influences how the number of ensemble members can affect the results obtained in trend analysis. However, the our knowledge, no good discussions about this have been published during the mandate of this committee (2022–2025). The reference from 2018 suggested by the OD would have been a good addition (that was not yet included in the earlier ISSC reports of 2018 or 2022), but it was also published before our mandate period.

OD: Despite the existing uncertainties associated with climate change projections the Norwegian Offshore Standard (NORSOK 2017), to be on the safe side in design, proposed an increase of extreme significant wave height and wind speed by 4% on q-probability values because of climate change. This could have been mentioning in the report.

CE: NORSOK Standard N-003 indeed emphasises the need for a proactive and adaptable approach to account for increasing extreme wave heights and wind speeds due to climate change and proposes an increase of extreme significant wave height and wind speed used for design. However, this standard was also published prior to our mandate period.

2.1.4 Numerical Models at Engineering Scale

OD: The survey presented shows progress made in the development of numerical models for the description of environmental phenomena. The Committee should get credit for Fig. 1, 2, 3 and 4 showing overviews of advances in wave, ice, current and wind model research, supported by references. The figures provide useful information for the marine industry as well as academic community.

CE: We extend our sincere gratitude for the thorough and insightful discussion of our report, which further enriches the discourse on numerical modeling advancements.

We deeply appreciate the recognition of Figs. 1–4 as valuable resources for the marine industry and academia. The references cited were carefully selected to highlight interdisciplinary progress in wave, ice, current, and wind modeling. These visuals were designed to show advances and innovations in environmental modeling.

OD: I agree with the Committee that non-linear potential flow methods used for modelling of waves are faster but cannot be reliably applied to modelling of wave breaking and stability, while the techniques based on CFD (Computational Fluid Dynamics) have advances here. Therefore, coupling tools with different levels of fidelity seems to be a promising approach for assessment of wave impact. It is worth to mention that

the marine industry has already started to use such approach in the last years, e.g. DNV (Bitner-Gregersen 2017).

CE: The OD's observation on the limitations of the non-linear potential flow methods' limitations used for modelling of waves aligns precisely with our findings. We fully agree that hybrid approaches (e.g., coupling potential flow with CFD) are promising, as evidenced by industry adoption (e.g., DNV's work). We also included some references on direct coupling methods in Sect. 3.1.1 (e.g., Pákozdi *et al.* (2022) and others mentioned there). A more in-depth discussion of multi-fidelity methods for extreme wave impacts is also included in Sect. 7.3 (extreme value analysis and extreme wave statistics).

OD: I would like to direct the attention of the Committee to sampling variability which may affect significantly numerical simulations of phase-resolving wave models. Kurtosis being the third order effect represents an important characteristic of non-linearity of a sea state. The spatial kurtosis as a function of 1800s HOSM (Higher Order Spectral Method) simulations with the same seed for the PM ($\gamma = 1$) and JONSWAP spectrum with $\gamma = 2, 3.3$ and 6 for the Andrea unidirectional rogue-prone sea state is shown in Fig. 1. T_p in the figure denotes the spectral peak period while k_p the wave length associated with the spectral peak period.

*The figure demonstrates that a single spatial 30-min realization of sea surface of a rogue-prone sea state may produce a higher kurtosis coefficient for the PM spectrum ($\gamma = 1$) than for the JONSWAP spectrum with $\gamma = 6, 3.3, 2$ due to inherent randomness of waves, what contrasts with the wave theory. The increased number of runs to 1000 plotted in Fig. 2 shows results which are consistent with the wave theory (Bitner-Gregersen *et al.* 2021). Therefore, the number of runs should carefully be considered, particularly when non-linear wave characteristics are investigated, which are more sensitive to sampling variability than linear ones.*

*As shown by Bitner-Gregersen *et al.* (2021) using numerical HOSM simulations having 20–30-min in-situ temporal or spatial wave records may prove challenging to determine the importance of non-linearity of surface elevation as the sampling variability may dominate over the non-linear effects.*

CE: We agree that the sampling variability's impact on phase-resolving models should be well noted. The example of spatial kurtosis in rogue waves (Fig. 1) and the need for sufficient simulation runs (e.g., 1000 runs per (Bitner-Gregersen *et al.* 2021)) are critical insights. The observation on the critical role of kurtosis as a third-order non-linearity indicator is particularly valuable. The comparative analysis between PM and JONSWAP spectra in Fig. 1 effectively demonstrates how inherent wave randomness can produce counter-theoretical kurtosis results. The reference to Bitner-Gregersen *et al.* (2021)'s 1000-run benchmark (Fig. 2) provides essential empirical evidence supporting the necessity of sufficient simulation repetitions, especially when investigating non-linear wave characteristics that exhibit higher sensitivity to sampling variability than linear parameters.

OD: The phased-averaged spectral wave models WAM, WW3 and SWAN, and the non-hydrostatic SWASH model remain the most used models, as correctly reported by the Committee. However, validation of these models with field observations is still ongoing. The Committee provides a nice review of these investigations, mentioning

also the remaining problem. Too few measurements of significant wave height beyond 8–10 m exist making validation of spectral model extremes, being of interest for the marine industry, difficult. I hope that awareness of this situation, the application of new measuring techniques and the growing access to wave databases will contribute to solving this problem in the coming future.

CE: The ongoing challenges in validating spectral models (WAM, WW3, SWAN, SWASH) for extreme waves ($>8\text{--}10\text{ m}$) are acknowledged. Although some recent studies (e.g., (Hauteclouque et al. 2023; Kodaira et al. 2023; Sasmal et al. 2021)) on the validation of different numerical models by buoy and altimeter measured data for extreme waves ($>8\text{--}10\text{ m}$) in the North Atlantic are already discussed in Sect. 7.1, we share the hope that emerging measurement technologies and expanded databases will mitigate this gap.

OD: I miss in Sect. 3.1.2 “Spectral models” a discussion about accuracy of wave spectra simulated by the spectral wave models. Some concern exists in wave community that the wave spectral models may provide spectra that are too broad compared to those derived from wave measurements (e.g. (Ardag and Resio 2019; Cavaleri et al. 2020)). Wave spectra represent an important input for phase-resolving wave models, laboratory experiments and design. Has not much progress been made since 2020?

CE: We appreciate the call to address spectral broadening concerns (Ardag and Resio 2019; Cavaleri et al. 2020), as wave spectra represent an important input for phase-resolving wave models, laboratory experiments and design. Advances have been made (e.g., machine learning-enhanced spectral tuning) recently. For example, (Jonathan et al. 2024) deals with an assessment of trimodal wave spectral parameters using three machine learning (ML methods for an offshore site in the Norwegian Sea, and found that the Extra trees method has the best performance and is very accurate for predicting spectral parameters of three wave systems, (Martzikos et al. 2025) investigates the prediction of sea surface elevation spectra from pressure measurements using frequency-specific artificial neural networks (ANNs) and found that incorporating spectral features of pressure signals into ANN architectures provides a robust and efficient framework for sea surface spectra prediction. These references have been included in the final report.

OD: Ice represents a hot topic in the debate of climate change, and ice conditions in the polar regions are of great interest to the marine industry, particularly the shipping industry, because of the Northern Sea Route and the Northwest Passage. Modelling of sea ice conditions in the Southern Ocean is gaining also increasing attention. Sea ice dynamics and ice interaction with other metocean phenomena are very complex phenomena and modelling of them is challenging. The Committee should be congratulated on including a nice survey of the progress made in these fields and presenting it on a geophysical and engineering scale. The section is expected to get attention from many practitioners’ readers.

Modelling current and wave-current interactions is important for many engineering applications but the topics are research demanding. Improvement of accuracy of such models has been going on for several years and as the Committee’s review confirms this situation remains.

I was pleased to see that there have been improvements in simulations of typhoons which are very welcomed by the marine industry.

CE: The positive feedback on the polar ice dynamics review is encouraging. We also note the complexity of wave-current interactions and typhoon modeling, areas where incremental progress remains vital.

OD: Wave-coupled phenomena (waves-wind-current) have been receiving increasing attention recently, and that is expected to continue. The Committee should be complimented on including in the review the (Janssen and Bidlot 2023) paper representing an important contribution to understanding wind-wave interactions and formation of extreme waves.

CE: The growing significance of wave-wind-current interactions in marine research is accurately noted, and we share the enthusiasm for this emerging interdisciplinary field. We agree that the research of Janssen and Bidlot (2023) on wind-wave interactions provide crucial theoretical foundations for understanding the formation mechanisms of extreme waves, and this study will be duly incorporated into our review.

The expertise and discussion have highlighted nuances that deepen the report's relevance. We welcome further dialogue on these topics and will integrate these perspectives into ongoing work.

2.1.5 Data-Driven Models

OD: The rapid expansion of artificial intelligence (AI) in recent years has significantly impacted many fields as well as environmental sciences. The contents of Chapter 4, reviewing atmospheric and oceanic applications of data-driven models, are very nicely prepared, giving good status of implementation of AI methodology in environmental description. I feel this Chapter is invaluable for many readers not only design/operation engineers of specified structures but also the ones in academia.

As pointed out by the Committee, this new research field brings interdisciplinary collaboration, as oceanographers and engineers work now closely with data scientists, mathematicians, statisticians, and software engineers, what I think is a positive development.

CE: We thank the discussor for this positive evaluation. We agree that interdisciplinary work often leads to surprising and interesting outcomes.

OD: Implementation of AI in environmental sciences shows very promising results. The Committee lists common methodological mistakes made by a high number of research projects and scientific papers when applying AI. However, the shortcomings of the machine learning methodology are not emphasized. For example, the machine learning models are ocean location/region dependent. Thus, although the principles of the methodology will be valid, new simulations will be required for other ocean locations/regions, particularly if the environmental conditions are very different.

CE: This depends on the machine learning model and architecture. Widely-used methods such as multilayer perceptron and LSTM indeed are dependent to the locations and

data there have been trained. However, there are recent physics-informed neural networks and similar methods that model the physics and not the multivariate and temporal dependences alone. Moreover, one can also use the same traditional neural networks to model certain components inside numerical models, which also make it associated with the physics and not the time-series and variables of specific locations. In these cases, it is possible to extrapolate to any location. Weather models such as FourCastNet or GraphCast, for example, can be implemented in any sub-region or domain of interest.

I would appreciate hearing the committee's comments on the following questions:

- *The Committee documents that use of AI shows promising results for wind and wave forecasting. Further, it is written: "Surrogate models have the potential to completely replace numerical models with significantly lower computational costs." Physics-based spectral wave models used for forecasting and hindcasting are under continuous development. This refers also to other physics-based models. Should these developments be stopped?*
- *Have developments of data-driven models reached so stage that they can be utilized, as a support, in the design process?*

CE: Unfortunately we did not have the opportunity to discuss this interesting more 'philosophical' question with the full committee. This is therefore the ~~personal~~ combined reply of the author of the chapter and the committee chair to both questions. While indeed AI makes rapid advances and can do more than most of us expected a few years ago, we think that these developments make it even more important for humans to keep their physical 'intuition' up to date. This is and will remain an important barrier and check for wrong or improbable outcomes. This can only be done by continuously working on the physics-based models. Traditional physics-based models should also not be abandoned, as they have evolved over decades and many components provide highly accurate results. For example, in wave models, the propagation and input source terms yield excellent performance with relatively low computational cost. On the other hand, dissipation and non-linear interactions remain partially understood, often degrade the results, and are associated with high computational costs. New AI algorithms could be used to replace these specific components of physics-based models or to incorporate the well-understood parts of the physics into broader AI architectures. ‡ We also strongly believe in the capabilities of hybrid and multi-fidelity surrogate models, which use the strong points of both machine learning and physics-based models. So in short, my answer to the first question would be 'no' at the moment (although this may of course change at some point in the future, we do not rule out the possibility that AI could one day replace the entire system, from the atmosphere to the ocean, across various time and spatial scales). With regard to the second question, my answer would be 'yes'. As of now, data-driven models can certainly support the design process, but they cannot fully replace certain components, whether in terms of physics, statistical foundations, or the expertise of experienced analysts. There are quite a few studies that demonstrate the capabilities of hybrid models to introduce more strongly non-linear physics (such as non-linear wave propagation, wave breaking, wave impact loads on structures, propeller ventilation in waves, extreme value prediction of rare events, etc.) in earlier stages of the design, whereas right now this is not possible to do until a later design stage. These

methods are not fully mature, but in the present stage they could already benefit the design process when there are still some checks with conventional high-fidelity methods in the final design stages (e.g., by means of experiments of CFD)—in my opinion. However, it is important to remember that, as the name suggests, data-driven models depend heavily on measurements, which is a major challenge in itself. The technology required for data collection, as well as the post-processing, still relies significantly on traditional methods and the careful judgment of trained professionals—aspects that, for now, cannot be fully replaced by automation or AI.

2.1.6 Laboratory Measurements and Observations

OD: *Chapter 5 includes a comprehensive and nice review of some new facilities that were opened during the Committee's term and the advances in experimental modelling of waves, ice, current, wind, and coupled wave-phenomena. This well written chapter contains, apart from valuable information about recent research findings, also the discussion of uncertainties associated with laboratory experiments. Particularly, experimental modelling of waves is thoroughly reviewed. In addition to statistical uncertainty, the epistemic uncertainties related to basin effects, scale effects, instrumentation and measure accuracy, determination generating of wave events, wave breaking and shallow-water wave generation are discussed.*

CE: We thank the discussor for these remarks. We tried our best to find relations between the different studies and between the different sources of uncertainty in laboratory modelling. We are glad that this is appreciated by the discussor.

OD: *I have not much to add to this chapter but have only two remarks. When investigating extreme and rogue waves the length of a basin is crucial. Depending on the initial condition, modulational instability can happen after 10–20 wavelengths. Further, numerous research has demonstrated theoretically, numerically, experimentally, and observationally that the gradual transition from Gaussian to non-Gaussian waves repeats after waves breaking. This phenomenon will not be observed in too short basins. Possible reduction of statistical uncertainty when doing laboratory experiments, should always be considered carefully.*

CE: We agree with the discussor that the length of the basin plays an important role in the (uncertainties of) the resulting extreme waves. The length of the basin does not only determine the fetch length available for the development of non-linear wave effects such as modulational instability and wave breaking, but a longer basin also decreases the influence of wavemaker side effects, increases the space for a large beach to dampen reflections etc. This is e.g., recognised by the referenced publications of Canard *et al.* (2022, 2024) in the report.

2.1.7 Ocean Measurements and Observations

OD: *Observations at sea represent an integrated part of environmental description and are very important for validation of environmental models. Chapter 6 reviews advance in measurements at sea of waves, ice, current, wind, Argo fleet of drifting buoys and wave-coupled phenomena. The observations of the latter are important for*

better understanding of atmosphere-ocean interactions which modelling is much in focus at present and is expected to grow in the coming future.

In the Subsect. 6.1.3 “In-situ measurements from platforms” the paper of Magnusson et al. (2021), showing an inter-comparison between three wave sensors: radar, laser, and a Waverider buoy, based on measurements made at the Ekofisk platform in the North Sea, could have been mentioned.

CE: We thank the discussor for this reference; it was added to the final report.

OD: The assumption of stationarity of sea states on which most short-term environmental models are based on brings challenges when applying field observations for assessment of performance of ships and other marine structures at sea. For example, 20-min (17-min) duration of wave records, for which stationarity has commonly been adopted by wave community is often not valid for steep sea states, where stationarity can be applied to a shorter period only (e.g., (Bitner-Gregersen et al. 2021)). For this reason, an extension of duration of wave records, to reduce sampling variability, is often not possible. Therefore, numerical simulations and laboratory experiments represent a good support to field measurements.

In design, for long-term assessment of performance of marine structures at sea with durations of the order of their lifetimes it has been generally accepted that metocean climate variability can be discretized in stationary periods of 3 to 6 h. The use of the 3 to 6 h assumption of stationarity is seldom justified. This assumption should be considered carefully when assessing marine structures’ performance at sea, e.g. ships sailing with speed over 15 kn (Nielsen and Ikonomakis 2021).

CE: These are valid comments. In the context of a different study the committee chair happened to be looking for a reference to show that this assumption is not always valid for ships with forward speed, so she’s very thankful for the Nielsen & Ikonomakis reference. We’ve added a short discussion about this in the final report, in the introduction of Sect. 6.1.

2.1.8 Statistical Modelling

OD: Chapter 7 presents recent developments in the theory and application of statistical modelling of environmental variables relevant for description of the ocean conditions. This well-prepared survey includes long- and short-term statistics, extreme value analysis, multivariate analysis, spatial-temporal analysis and non-stationary analysis.

CE: Thanks for this positive summary of this chapter.

OD: In Sect. 7.1 the paper of Eisinger et al. (2016) could have been mentioning. (Eisinger et al. 2016) pioneered a method to make the best estimate of the environmental conditions experienced by operating vessels in their exact position using the Automatic Identification System (AIS) data and matching them with the ECMWF reanalysis data. 25-year return values of significant wave height were estimated by fitting a Weibull distribution to the available at that time three-year AIS-ECMWF sample.

CE: Thanks for drawing our attention to this paper, which we believe are relevant. However, the main scope of the current review is literature that has been published after September 2022 (after the previous ISSC-2022) and this paper has also already been well reviewed by some referenced papers (e.g. Miratsu et al. (2022)) included in Sect. 7.1 of the committee report. We have therefore not included this paper in the present committee Report.

OD: *It is written in the report, “For practical applications, Bitner-Gregersen et al. (1995) proposed a joint model using a 3-parameter Weibull distribution for H_s and a conditional lognormal distribution for wave period.” Some clarification is necessary to this statement. The original Global Wave Statistics (GWS) data were not used because of two reasons. First, the joint model introduced some adjustment of inaccuracy of wave period. Secondly, in the GWS atlas the last wave height class is in the range 11–12 m, indicating that observations of wave height beyond 12 m were summed up by BMT (1986) in this class. The fitted distribution to the GWS wave heights and periods, necessary for applications in the Structural Reliability Analysis, provided higher wave heights being not consistent with the last 11–12 m class of the BMT Atlas (see (Bitner-Gregersen et al. 2013)). Therefore, the numerically generated scatter diagram from the joint wave height and wave period distribution was proposed. Note that the GWS data include bad weather avoidance as they were collected from ships in normal services.*

CE: We thank the official discussor for providing some clarification regarding the reasons to fit the joint model proposed by the official discussor et al. to the original Global Wave Statistics (GWS) data. These reasons are detailed in the book (Bitner-Gregersen et al. 2013) and have been well reviewed and discussed in a previous report (ISSC-2015) of this Committee. It is believed that this is already well-recognized within academia/marine industry, and it was not deemed necessary to explain this further in the present Report of this Committee. Notwithstanding, we believe this clarification is useful in the official written discussion of the report.

OD: *In Sect. 7.2 “Long- and short-term statistics” and Sect. 7.3 “Extreme value analysis and extreme wave statistics” new fitting techniques for the probability distribution of H_s are mentioned, being a combination of two-three different distributions. Dividing wave data into blocks and fitting distributions separately to each block will usually result in a better fit than the one obtained by fitting a distribution to all data. However, a question arises whether there are any physical reasons for doing it, do the data in different blocks belong to different populations generated by different physical mechanisms? Some caution is advised when using such approaches to extrapolate beyond available data not to get unphysical results, e.g. extreme H_s which wind is not able to generate. I will mention in this connection the Norwegian Offshore Standard (NORSOK 2017) which requires that there must be enough room for the wave crest to pass beneath the platform deck to ensure that a 10000-year wave load does not endanger the structural integrity.*

CE: Thanks for this comment. There can be different reasons to fit separate distribution models to different subsets of the data. One of those reasons can be the effect of covariates. For example, waves during summer months may be different from waves during winter months, and it may be sensible to fit separate distributions to summer- and winter data.

Likewise, waves from certain directions may be very different from waves from other directions, e.g. due to predominant wind directions, varying fetch etc., so it might be advisable to fit separate distributions to data corresponding to different sectors of wave or wind direction. An alternative to several distributions for various sub-populations of the data is to fit non-stationary distribution models, where covariates are introduced to account for dependencies with e.g. direction and season. This is also discussed in the report.

Sometimes, one may also use a hybrid distribution model and fit a specific distribution to the extreme values above a certain threshold (the tail of the distribution), and another distribution below the threshold (the body of the distribution). It does not mean that the tail of the distribution necessarily belongs to a different distribution than the body of the distribution. However, since there will be much more data available near the mode of the distribution, fitting a parametric model to data may capture central behavior of the data very well (mean, median, standard deviation), but may fail to accurately capture tail behavior. Hence, by fitting a particular model to the tail, one may give more attention to this part of the distribution and possibly improve how the model extrapolates. Extreme value theory suggests reasonable distribution models that are asymptotically correct, given certain conditions. However, extreme value analysis in practice remains a challenging task, and it is not obvious how well asymptotic models perform in the sub-asymptotic range.

So, yes, in some cases data from different sub-populations may be generated by different physical mechanisms and in those cases, it may be a good idea to fit separate distributions to various subpopulations of the data. Moreover, in some situations it might be a good idea to fit separate models to specific parts of the distribution (e.g. the upper tail). It is believed that this needs to be carefully considered on a case-by-case basis, and it is difficult to provide generic recommendations. We agree with the official discussor that great caution is advised, and that one should pay particular attention when extrapolating beyond the support of the data to avoid non-physical results. As the discussor points out, this is particularly important when one wants to estimate extremes associated with very long return periods such as the 10 000-year extremes prescribed by the NORSOK standard.

OD: Fig. 8 in Sect. 7.2 would benefit if the figure legend was included.

CE: Thanks for this comment. In principle, we agree, but we feel that including a legend would need to be accompanied by an explanation in the text which we believe to be outside the scope of this report. We prefer to keep this figure as an illustration only. The various lines in this plot represent different parametric models fitted to crest height data (Forristall, Rayleigh and several variants of the Tayfun-Fedeale distribution), and we believe that a description of all these is outside the scope of this report. However, the interested reader may find more details about these distribution and similar plots in Vanem et al. (2024) (This paper was published after the committee report was delivered and is therefore not referred to in the report).

2.1.9 Extreme Events and Conditions

OD: *Three extreme phenomena have been selected by Committee I.1 for the survey in Chapter 8: rogue waves, extreme ice events and tropical cyclones. All represent actual topics receiving continuous attention in academia and the marine industry.*

The practical definition of rogue waves adopted by DNV (2024) is due to Haver (2000), what could have been written in the report.

CE: We thank the discussor for this clarification; it was added to the final report.

OD: *I would like to mention two papers which may be of interest for Committee I.1. On November 30, 2018, a 20-min time series measured by the WaveRadar REX at Ekofisk recorded three consecutive waves with individual heights that all were more than twice the significant wave height (Magnusson et al. 2019). The last two of them were almost equally high with a factor 2.35 to the significant wave height of 4m. This triple rogue wave group was named the “Justine Three Sisters”. (Toffoli et al. 2024) reported direct observations of surface waves from a stereo camera system across the Southern Ocean in the Australian winter aboard the South African icebreaker S.A. Agulhas II. Using the collected data the authors documented that modulation instability exists in the ocean.*

CE: We thank the discussor for these references, which are very relevant publications. The paper from 2019 is from before our mandate period, but we’ve added the study of Toffoli et al. (2024) to the final report.

OD: *the survey of extreme ice events and climate change in polar regions includes information being of broad interest, particularly to the shipping industry.*

The Committee I.1 prepared a nice survey of the recent developments in modelling tropical cyclones and their influence on ocean waves. Knowledge about these phenomena and the models describing them is crucial for design and disaster prevention.

CE: We thank the OD for the recognition that these are active fields of study, which are important for the maritime industry.

2.1.10 Updated IACS Scatter Diagram

OD: *The Committee should be credited for including the updated IACS scatter diagram in Chapter 9 and for the discussion about some caution when using it outside the classification context. As correctly pointed out by the Committee I.1 it is essential to understand the underlying assumptions of the data and their implications for the entire design process.*

CE: We appreciate this support. We think it is very important to consider the new scatter diagram only in combination with the underlying assumptions, in order to avoid over- or under-engineering of new designs.

2.1.11 Conclusions

OD: *Chapter 10 summarizes shortly the contents of all chapters. This is useful for the readers. Some recommendations for the topics to be considered by the next ISSC Committee I.1 are given also.*

The summary documents clearly that the Committee I.1 has been successful with focusing on environmental descriptions relevant for the determination of environmental loads for design of ships and marine structures, while at the same time providing useful information about environmental descriptions for academia.

CE: Thanks for these kind words. We are glad to hear that the focus areas we determined at the start are also visible and appreciated in the resulting report.

2.1.12 Appendix A: Extreme Value Analysis Benchmark

OD: The Committee I.1 should be congratulated on carrying out the benchmark study on extreme value analysis. I agree with the Committee I.1 that methods and tools that are widely used by statisticians are not as well utilised as they could be in ocean engineering. Partly, because wind, waves, current and ice are investigated by researchers of different backgrounds, by oceanographers, applied mathematicians, statisticians, naval architects, hydro-engineers and data-scientists, having different levels of knowledge about statistics.

I think that adaptation of statistical methods and tools, not only in ocean engineering but also in ocean sciences, should be considered with some care as they should be anchored to physics of environmental phenomena.

In larger organizations not only a choice of extreme value models will impact the derived extreme values of metocean parameters but also who is carrying out such analysis. I think that for a selected data set the extreme value estimates should be compared with results from alternative methods. Then, in addition to the mean over all methods, also biases (systematic errors) between different methods can be obtained, representing useful information for a decision process.

CE: This is a very valid comment. We totally agree that not only the tool but also the user, method, choices made for e.g., thresholds, POT versus BM, fitted theoretical distribution, fitting method, selected return periods and quantiles etc. are extremely important for the outcomes. We originally envisaged a two-stage benchmark: first comparing different tools with exactly the same input, then comparing different approaches of different users. However, within our mandate period we only managed to execute the first study. We warmly encourage the next Environment committee to add the second part of such a benchmark.

2.1.13 Appendix B: Publicly Available Environmental Data Sets

OD: The issue of met-ocean data ownership remained a general problem for several decades, what was pointed out by several previous ISSC I.1 committees. Some movement to solve this problem has been made, the access to several wave databases is available today, providing new opportunities for environmental modelling and design work. Among others, an initiative from the European Commission has contributed to it (<https://scihub.copernicus.eu/>).

The list prepared by the Committee I.1 of publicly available environmental data sets is very useful for the marine industry and academic community. I can add to the presented list the free and opened access weather, environment and climate data of

the Norwegian Meteorological Institute (<https://data.met.no/>). See also the *Frost API database including MET Norway's archive of quality controlled daily, monthly, and yearly measurements of temperature, precipitation, and wind data* (<https://frost.met.no/index.html>).

CE: We thank the OD for her useful additions to our list of data sources!

2.2 Reply to Floor and Written Discussion

Reply to Xue-liang Wang: The committee agrees that accurate, real-time observation of waves is very valuable for assessing wave loads and structural responses on ocean-going ships. This is also acknowledged in Table 1 of the report (which provides examples of environmental input for design and operation of maritime structures). Section 6.1.4 of the report discusses the progress in real-time wave prediction using on-board radar measurements. While X-band radar remains the most widely used system, its accuracy limitations are well recognised. Focusing on this, some additions to the discussion in Sect. 6.1.4 can be made, also including some work that is more recent than the end of the mandate period. There are some studies that use ship motion measurements and the known ship response functions to calibrate the wave elevation from the X-band radar observations (e.g., (Lee et al. 2025)). Older work also fuses stereo-imaging with X-band radar wave data (e.g., (Benetazzo et al. 2018)), but no relevant updates in the mandate period were found. Several emerging technologies can substantially improve ship-based wave measurement. Stereo and high-frame-rate vision methods can in theory deliver high-resolution, near-real-time surface elevation fields, especially when combined with machine-learning techniques. One example is (Jebari et al. 2025), who developed a system using dual cameras and stereo disparity estimation with a deep learning model to reconstruct spatial wave fields from moving vessels in simulations, with good accuracy and generalization. However, this method was only validated against simulated data that was visualised with render software Blender, its validity for real ocean application has not yet been tested. Another example is (Zhao et al. 2025), who applied machine-learning methods to extract accurate real-time significant wave height information from X-band radar measurements. (Greenberg and Ben-Moshe 2023) present a real-time method for detecting and tracking ocean waves around small autonomous ships, based on stereo vision sensors. The method was tested during field experiments with a yacht on the Mediterranean Sea, and with a small motorboat in a wave flume. However, they write that it was shown that the method “outperforms human visual ability both in terms of wave detection and wave relative height classification according to their amplitude (e.g., ‘small’, ‘medium’, or ‘high’ waves)”; a more thorough validation of wave elevation is still lacking. An open dataset of stereo imaging of the sea surface elevation in different areas (Black, Adriatic, Yellow and Iriose Seas) is provided by Guimarães et al. (2020).

Reply to Ekaterina Kim: This was not our intention, and we will add an open license to the Github page.

Reply to Unknown Floor Discussor: This is an good question that highlights a point addressed in Sect. 1.2 of our report: “*A note on the influence of marine structures on the environment*”. The environmental effects of marine and offshore structures, such as

their impact on biodiversity and marine life, are receiving increasing attention within the industry, and the committee fully supports this focus. We must remain aware of the consequences of our activities, including the effects of large structures on marine habitats and biodiversity, wind turbines on birds, sonar on marine mammals, ship propellers on sea life, and the risk of pollution. As noted by the floor discussor, similar concerns apply to offshore fracking, which can contaminate marine waters, disrupt ecosystems, and increase the risk of spills, seismic activity, and greenhouse gas emissions. While we recognise the importance of these issues, our current mandate addresses the *effects of the ocean environment on ships and offshore structures*, not the reverse. This topic therefore lies outside the scope of the present report. However, it may be valuable to consider establishing a future ISSC committee focused specifically on the environmental impacts of maritime activities, involving experts in e.g., marine ecology and biodiversity.

Reply to Unknown Author of a Written Question: This question consists of several sub-questions, which can be divided into two main categories: probabilistic modelling of wind-wave distributions, and short-term wind and wave forecasting. Starting with the second category, for the short-term wave forecasting we would like to refer to Sect. 6.1.4 of the report, and the answer to the floor question of Xue-liang Wang above. With regard to the question about probabilistic modelling of wind-wave distributions and their implementation in design standards, we can say the following. Yes, there are several new probabilistic models for long-term conditions, which are discussed in Sect. 7 of the report. Examples are the SPAR model, non-stationary models where e.g., direction and season can be included as covariates, and mixture models. We have also reported some progress on environmental contour approaches, which are also relevant to this topic. Details of each of these models can be found in the report. We do not have an overall view of all current design standards related to long-term wind and wave distributions. We did report specifically on the update of the IACS wave scatter diagram and the related implications for design in Sect. 9. However, this does not account for joint wind-wave distributions, and is only one (important) example of a design standard. It could be a suggestion for a next committee to add a dedicated review of updates to design standards related to environmental modelling to the report.

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