INSTITUTE OF MARINE Engineering, Science & Technology

Metocean Procedures Guide for Offshore Renewables

Produced and Compiled by
Offshore Renewables Special Interest Group

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Contributors (to this version) are:

Zoe Roberts	Corio Generation
Robert Mawdsley	Nadara
Mark Calverley	Blue Ocean Consulting
Gus Jeans	Oceanalysis
Edward Steele	UK Met Office
Alastair Stagg	Independent

Reviewers:

Jon Upton	Shell
Alice Goward Brown	Wood

Contents

1 Introduction

This edition of the IMarEST Metocean Procedures Guide for Offshore Renewables addresses the global nature of the offshore renewables (OR) energy market. It is intended to assist OR projects in the accurate characterisation of the metocean environment and hence optimise design and cost. At the end of 2022 64.3 GW of offshore wind capacity had been installed globally and a further 380 GW is expected to be added by 2032 according to the Global Wind Energy Council. As such, whilst relevant to all OR technologies, offshore wind projects remain the current focus of this guide.

Metocean is a technical engineering discipline that addresses meteorological and physical oceanographic matters. It originated in the oil and gas sector in the late 1970s and is equally applicable to the OR sector. Metocean is primarily concerned with quantifying weather and sea conditions and the physical aspects of the water column. The impact of metocean conditions on structures and operations can then be accurately assessed.

There is considerable scope within the metocean component to drive cost savings throughout the OR project lifecycle. Investment in metocean at an early stage of the project will result in significant cost savings in later phases. Changes in metocean criteria during the project lifecycle can introduce large engineering variations, programme delay and impact future turbine availability, resulting in both increased capital and operational expenditure or lost revenue. Reducing uncertainty (and hence risk) in engineering design loads and understanding the impact of metocean conditions on construction schedules and operations and maintenance (O&M) strategy is key to minimising project spend.

The value of metocean data and information is often underestimated, for example:

- The cost of supporting structures is highly dependent on the metocean forces they experience. Optimisation of the structural design can be achieved through reducing the uncertainty in the metocean design basis. For example, as multiple support structures are required within an offshore wind farm, any costs associated with over-conservative design is multiplied by the number of turbines, leading to significant increases.
- Understanding the impact of metocean conditions on transport and installation operations will help inform scheduling of metocean critical operations. Unforeseen downtime resulting from poor site characterisation can quickly escalate costs, lead to protracted claims resolution processes and, in the worst case, extend the time between investment and revenue generation. As new vessels enter the industry to meet the demand, understanding the metocean conditions will help design both vessels and infrastructure to ensure they offer efficient capability. High quality metocean information will help transport and installation contractors refine cost and provide quantifiable estimates of potential weather downtime costs.
- Identifying an appropriate O&M strategy, optimising weather windows to support maintenance scheduling and conducting early intervention when metocean impacts on structural integrity occur can have significant positive influence on operational expenditure.

Early engagement of metocean expertise and front-end loading of the required metocean activities is one of the key steps in reducing overall project risk and mitigating future cost variation within the project budget.

This guide outlines the metocean activities required to support all phases of an OR project, through development and construction to ongoing O&M. It is intended as a tool for all those involved in OR, including project managers, structural engineers, surveyors, and logistics personnel, based within OR companies or support organisations and contractors.

As metocean is specifically concerned with physical oceanography, it does not address chemical, biological or environmental considerations. However, there is overlap between metocean and environmental requirements, so collaboration between the two disciplines should be considered, where appropriate, to enable cost savings.

Metocean in the context of this document excludes estimation of the energy resource that can be extracted from the atmosphere or ocean. However, both resource assessment and metocean engineering ultimately rely on the same types of data and similar analysis methods. It is recommended that both engineering and resource assessments are derived from the same data sources and that both disciplines are carefully aligned throughout the engineering process. Utilising the same numerical wind model as inputs to metocean and wind analyses and conducting coordinated wind and metocean surveys are advised. It is common that measurement of wind resource is undertaken in conjunction with metocean measurement.

Whilst this document relies heavily upon experience gained from offshore wind developments on fixed structures, the majority is also applicable to other technologies, including floating wind, wave and tidal. Procedures may be applied globally taking into account local conditions and engineering standards.

This guide applies to the OR site area, cable routes, maintenance base(s) and access routes throughout the lifetime of a project, from early development through to decommissioning. This guide may also be used to support Environmental Impact Assessment (EIA) during the consenting process. The majority of the associated metocean activities take place during the development and pre-construction stages of the project, however continued data acquisition during O&M can add significant value.

It must be emphasised that this is a generic guide illustrating typical approaches to be adopted. The implementation of the metocean strategy may vary from the approach suggested here, as individual projects may have different ways of defining stages within their governance process. However, the principles will be the same.

The Version 3 2024 update includes:

1. Reduced regional focus, improved global relevance.
2. Review and update of all sections.
3. Addition of Section 5.5 Requirements for Floating Offshore Wind.
4. Addition of Section 6 MARINE WEATHER FORECASTING.
5. Addition of Section 7 CLIMATE CHANGE.

A concise list of applicable standards (Section 2.4) and a glossary of terms **(Appendix 1)** are included in this guide.

Photo credit: Vattenfall

2 Metocean Considerations

All offshore activities are affected by prevailing metocean conditions. There is a requirement for metocean information and support at all stages of a project, and throughout its operation after installation through to decommissioning. Because many metocean requirements are dependent on one another, for example, reliable statistics need quality long-term datasets, it makes sense to view and conduct metocean activities in a coordinated and integrated way.

2.1 Metocean function

Metocean (and its subdisciplines of analysis, measurement, and forecasting) should be fully represented within a given project and preferably embedded within an OR project developer. The presence of such a function should be included on organisational charts. Consideration should be given as to how the metocean function integrates with other site conditions disciplines such as Wind and Geoscience, and with project engineering packages. A specific role (or roles) managing and executing the metocean function and its interfaces should be appointed. This can be filled by in-house appointments or external consultants.

2.2 An Integrated Approach

There are three key elements to consider with respect to an integrated metocean approach:

1. Data Collection
   Metocean data are acquired (or purchased if such data already exists), either on-site, and/or by running numerical models.
2. Data Management
   Measured or numerical data is quality controlled and stored to provide ready access and search capability or offered as data services in a digital environment.
3. Data Analysis
   Stored and real-time data is analysed to produce key information that will be used in project work packages or to support live operations.

Issues to consider include:

1. The metocean process is iterative in nature, allowing for the evolution of data and data products to support the different stages of the project.
2. Ensuring data collection starts early in the project lifecycle, enabling measured data to be collected over a sufficient length of time. This should include consideration of the duration of the procurement process, lead time of equipment from contract award and consenting/permitting timelines.
3. Selecting technically competent metocean personnel or contractors to:
   a. Perform on-site measurement.
   b. Undertake metocean modelling.
   c. Independently quality control the data.
   d. Conduct data analysis studies.
   e. Provide weather forecasts.
4. Encouraging metocean contractors to work together where appropriate to maximise data returns, ensure data quality and improve forecasts.
5. Enabling good communication between providers and end-users of metocean information, and the timely and appropriate dissemination of resulting data and information. Early dialogue between design engineers and metocean practitioners is fundamental to ensuring requirements are fully understood.

2.3 Contractors

Metocean activities can be broadly classified into five categories with respect to services offered by metocean contractors:

1. On-site measurement.
2. Numerical hindcast modelling.
3. Numerical ocean and atmosphere forecasting.
4. Satellite observations.
5. Data analysis and desktop studies.

Some contractors offer a comprehensive service covering all categories whereas others occupy specific niches. Many companies offer online metocean databases and analysis services. It is important to ensure that, in choosing contractors, due account is taken of their relevant competency, experience, reputation, health and safety record and quality assurance system.

As part of the contracting process, it is imperative to have a clearly defined, fit-for-purpose scope of work. This should be developed by the metocean function in conjunction with the project team. Further discussion regarding the scope of work for observational and modelling campaigns can be found in **Appendix 2** and **3** respectively.

2.4 Relevant International Standards

A wide range of documents with metocean guidance for OR has been produced by many interested parties, including this one. The concise review in this section is focussed on the latest international standards developed for the offshore wind industry. Similar standards for wave and tidal energy are emerging as the industry moves to commercial scale. The primary international standards for offshore wind, wave and tidal energy are produced by the International Electrotechnical Commission (IEC), with a selection most relevant to metocean conditions given below. These make extensive reference to the primary metocean standard from the International Organization for Standardization (ISO), also included below.

The ISO references within IEC recognise the origin of metocean industry standards from oil and gas. The ISO key reference below is presently undergoing further revision, with the entire series of related ISO standards being extended to include low carbon energy. Liaison between IEC and ISO is underway to encourage collaboration, coordination, and consistency. New developments in this area will be a continuous feature of the urgent energy transition and further rapid global growth of offshore wind energy. Some of the less developed offshore renewable energies should soon benefit from similar growth if catastrophic climate change is to be averted.

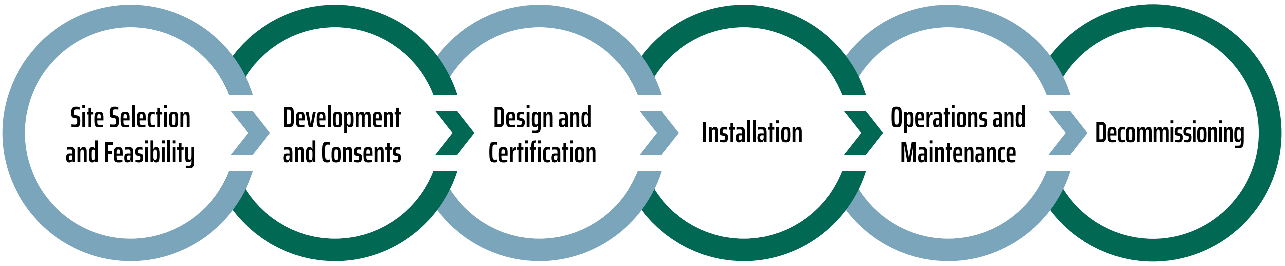
Despite comprehensive cross referencing between the IEC and ISO standards, some differences still exist, mainly in relation to how wind is quantified. This is predominantly due to wind being the energy resource in addition to another environmental load. The different resource assessment and metocean perspectives can be a challenge to the efficiency of some developments, and the two disciplines require careful alignment throughout the duration of the project lifecycle.

Ultimately, a suitably experienced metocean practitioner must ensure appropriate data and methods are used to quantify the key metocean processes of critical engineering impact. Additional requirements of any relevant certification or classification bodies also need to be considered, such as ABS, BV, ClassNK, DNV, LR or TUV Nord. Reliable results may not always be produced by simply following one guideline, especially if it is out of date or not relevant to the region or application.

DOCUMENT	REFERENCE
IEC 61400-3-1:2019	International Electrotechnical Commission (2019). International Standard, Wind energy generation systems - Part 3-1: Design requirements for fixed offshore wind turbines.
IEC TS 61400-3-2:2019	International Electrotechnical Commission (2019). Technical Specification, Wind energy generation systems - Part 3-2: Design requirements for floating offshore wind turbines
IEC 61400-50-1:2022	International Electrotechnical Commission (2022). International Standard, Wind energy generation systems - Part 50-1: Wind measurement - Application of meteorological mast, nacelle and spinner mounted instruments
IEC 61400-50-2:2022	International Electrotechnical Commission (2022). International Standard, Wind energy generation systems - Part 50-2: Wind measurement - Application of ground-mounted remote sensing technology
IEC 61400-50-3:2022	International Electrotechnical Commission (2022). International Standard, Wind energy generation systems - Part 50-3: Use of nacelle-mounted lidars for wind measurements
IEC TS 61400-50-4 ED1	International Electrotechnical Commission (2023), Proposed Technical Specification, Wind energy generation systems - Part 50-4: Use of floating lidars for wind measurements
IEC 61400-15-1 ED1	International Electrotechnical Commission (2023). Proposed International Standard, Wind energy generation systems - Part 15-1: Site suitability input conditions for wind power plants
IEC TS 62600-2:2019	International Electrotechnical Commission (2019). Technical Specification, Marine energy - Wave, tidal and other water current converters - Part 2: Marine energy systems - Design requirements
IEC TS 62600-101:2015	International Electrotechnical Commission (2015). Technical Specification, Marine energy - Wave, tidal and other water current converters - Part 101: Wave energy resource assessment and characterization
IEC TS 62600-201:2015	International Electrotechnical Commission (2015). Technical Specification, Marine energy - Wave, tidal and other water current converters - Part 201: Tidal energy resource assessment and characterization
ISO 19901-1:2015	International Organization for Standardization (2015). International Standard, Petroleum and natural gas industries - Specific requirements for offshore structures - Part 1: Metocean design and operating considerations. Second edition.

3 Metocean Through Project Lifecycle

Metocean plays a key role in all aspects of the OR project lifecycle:



Typically, an OR project will be broken down into smaller components (or work packages), each requiring specialist metocean inputs. The metocean process is iterative, improving in accuracy and quality at every phase of the project lifecycle, with prior metocean information being added to, or superseded, as the project progresses.

Due to the importance of metocean input in all aspects of the project lifecycle, it is recommended that any metocean expertise be embedded within, or directly available to, a project development team and close relationships developed with work package requirements throughout every phase. A strategy, to be adopted to ensure that metocean decisions, requirements and products appropriate to an OR project are delivered throughout its lifecycle, is provided in Section 3.7.

It should be noted that the metocean process may be entwined with energy resource assessment. It is, therefore, necessary to consider requirements in each phase from the resource perspective, as well as that of engineering.

3.1 Site Selection and Feasibility

Within this phase, it is necessary to understand the regional metocean conditions, (examined further in Section 4). Identifying key regional metocean processes forms part of the due diligence process which seeks to provide preliminary information for concept selection, and to identify any conditions that preclude an economically viable technical solution for engineering design, transport and installation or operation and maintenance.

It is pertinent to conduct a literature review, identify any available data sources in the region, and to summarise the information obtained in a short briefing note. This may warrant engagement of metocean expertise specific to the region. The amount of work that is required at this phase depends on the lease award process. In some European countries, much of this work is carried out by the awarding authority.

A briefing note would typically include:

- General description of the proposed site.
- Summary of available data sources and data gap analysis.
- Identification of potential hazards.
- Estimates of wind, wave, current and water level conditions.
- Recommendations for the intended metocean strategy, along with resourcing, budget estimates and programming.

The briefing note should quantify the conditions to enable selection of the preliminary concept and if relevant identify conditions that may impact the technical feasibility and economic viability of a potential project. If a specific risk is identified, it may require further investigation at an early stage of the project.

3.2 Development and Consents

Early in the development and consents phase, definition of the preliminary metocean dataset to support the project design envelope is required, fulfilling the requirements of the project for the purposes of consenting and concept design. The available data will be dependent on the maturity of the regional market. In mature markets regional models are likely to be regionally well validated due to a significant number of measurements, which may also be available. Online metocean databases based upon regional metocean models may be utilised, but it is critical to understand whether metocean processes are appropriately represented and the potential level of uncertainty in the data. In less mature, or frontier regions, data may be scarce and this introduces greater uncertainty.

The preliminary metocean dataset provides a best estimate of metocean conditions based on available measured data or coarse, uncalibrated, unvalidated model data if insufficient measured data is available, obtained for little or no cost.

Preliminary data and analyses will generally include:

- Conservative, quantified description of conditions at a representative location or locations (also considering coverage of the export cable corridor).
- Quantification of potential hazards and assessment of associated risk.
- Concurrent time series of wind, wave, current and water level
- Derivation of operational, extreme, and weather downtime statistics and preliminary loads cases.

Preliminary metocean data and analyses will also contribute to other aspects of the project, such as definition of the environmental baseline and impact studies regarding foundation impact on metocean regime, scour, and sediment dispersion due to piling, seabed preparation or cable burial.

Requirements for this dataset will be project specific as a combined consequence of site conditions, project definition, project team and the methodologies used for preliminary design. It is therefore recommended that the detailed content of the preliminary engineering data and analyses be defined in coordination with the project team and should address the certifying authority's requirements.

At this early stage in the project the metocean criteria should be conservative, so that the impacts become less onerous as more reliable data become available. This can lead to conflict between resource assessment and engineering over the interpretation of 'onerous' and this must be carefully managed.

It is within this phase that an appropriate on-site measurement campaign (see **Appendix 2**) should be initiated, balancing scale and cost, to enable:

1. Definition of the environmental baseline.
2. Validation of future numerical modelling.
3. Development of a certifiable detailed design basis.

The timescales of the measured dataset required for consent applications and design purposes may differ, with observational datasets usually required to cover a minimum of 1-year to capture seasonal variability for numerical model calibration and validation. It is worthwhile considering the deployment of a continuous long-term on-site measurement campaign throughout the development and design phases and onwards into construction and O+M. It is important to consider synergy and coordination with other aspects of the project, such as EIA and resource assessment. This will ensure cost-saving, promote consistent approaches, and maximise the value of integrated observational campaigns.

Towards the end of the development and consents phase, execution of well-validated, detailed metocean modelling (see **Appendix 3**) should be underway, using industry best practice techniques and utilising all available observational data. Forcing of numerical metocean models with bespoke downscaled wind models which will also be used as input to the wind resource aspect should be considered, improving alignment between the two disciplines.

3.3 Design and Certification

By the time of transition into the design phase, a suitably reliable metocean dataset (representing all key processes) should be finalised, based upon the combined outcomes of detailed numerical modelling and site-specific data acquisition. This dataset will inform the engineering design basis, which will be used consistently across the project for engineering design and operational planning.

To ensure it meets their needs, requirements for the final metocean dataset should be agreed in advance with stakeholders. The full dataset will comprise a high quality, accurate account of metocean conditions from detailed hindcast modelling validated against on-site measurements, taking account of spatial variability, including:

- Quantified description of conditions at several locations depending on spatial variability, including the export cable corridor.
- Associated long time series.
- Presentation of validation methodology and results.
- Statistical analyses, including operational extremes, fatigue and weather downtime.
- Additional specialist analyses as required by project teams.

Typical statistical analyses undertaken and presented within a metocean study (often called marine site characterisation) are described further in Section 5. Note that many data users are moving towards the direct use of time series data, reducing the need to produce detailed statistics. This is already true for operability and will become true for design as engineering tools adapt to harness the computing power available via cloud services, and automation is developed.

The full dataset and analyses will be required as soon as is practicably possible within the design phase and will form the basis of engineering design and installation planning. Risks and any potential shortcomings should be identified, and outcomes presented in summary form to the relevant stakeholders, ensuring they are fully understood. It is vital to ensure that project teams are made aware of newly available data and analyses and their associated uncertainties, and that use of previously supplied preliminary data and information ceases, to reduce risk and prevent inaccuracy being carried into the design phase. Use of version control within engineering document systems readily addresses reports, but data can be more challenging.

It is recommended that the final metocean modelling study is certified as soon as is practicably possible to ensure a smooth design process. Depending on the available timescales, the final design basis and final metocean study may be certified concurrently. When seeking certification, the structure of the design basis should follow that of the standard against which it is being certified. Attention should be paid to the required nomenclature to avoid confusion.

3.4 Installation

Prior to an installation campaign, it is necessary for Developers and their contractors to have a clear idea of the range and likelihood of weather downtime for all locations affecting construction and installation, including ports, wet storage and vessel routes. This will enable negotiation of contractual terms and allocation of appropriate cost and programme contingency. Risks related to weather downtime may be shared by both parties, or assigned to one party depending on the preferences of those concerned.

The risk of weather downtime must be calculated by analysis and/or simulation of the proposed installation schedule using the best available metocean data (for example, the final metocean dataset once available). Developers should enable a fair bidding process by ensuring that a consistent approach to weather downtime risk estimation is adopted by bidders. This should include the use of the same metocean dataset (supplied by the Developer), and a consistent method of analysing weather downtime. Indeed, the fairest method of assessing bids may be for contractors to supply their proposed working schedules and day and downtime rates, and for the Developer to calculate the price of each contractor independently.

In the lead up to the installation phase of the project, it is necessary to procure weather and ocean forecasting services for the duration of the offshore installation activities. This should be undertaken in conjunction with real-time monitoring, which may be an extension of the previous metocean measurement campaign. A real-time monitoring approach combined with improved forecasting and modelling capability from assimilation of measurements is of paramount importance in ensuring the safety of teams working offshore. It is also likely to increase installation efficiency by providing marine personnel with reliable information from which they can make decisions, minimising downtime due to adverse weather and reducing the risk of compensation claims from contractors.

Prior to installation, the Marine Warranty Surveyor and the Developer and/or Contractor will agree the metocean limits or response limits and their applicable durations for the intended operations. Appropriate standards regarding marine operations should be consulted. Further conservatism will be applied when deriving operational limits, to account for the level of accuracy possible when assessing the actual weather conditions under which an operation will take place. The level of additional conservatism can be reduced by using real-time measurements, considering more than one forecast, or by having a dedicated weather forecaster supporting. Additional conservatism may result from human decision making if the forecast is not trusted by the parties involved. It is therefore recommended that 24/7 access to an experienced weather forecaster is arranged, possibly remotely, and used unreservedly during installation. It may also be useful to obtain forecasting services during the period of the metocean measurements to allow the reliability of forecasts to be assessed, and potentially improved prior to installation activities.

3.5 Operations and Maintenance

The O&M phase of a project has similar requirements to that of the installation phase, that is, provision of weather forecasting and real-time data for work planning and execution. In addition, operations will also require large scale monitoring, including the continuation of metocean measurements. This enables performance to be analysed and supports further understanding of the impact of localised events, enabling revision and adaptation of the O&M strategy as necessary. Furthermore, metocean measurement and modelling requirements should be agreed with asset management stakeholders to complement structural monitoring campaigns and understand structural performance. The latter includes all elements of the structure including depth of pile burial, and scouring events that may impact the structural integrity of the pile.

The ability to correlate structural performance to actual metocean conditions helps to improve engineering models; the safety factors applied in the engineering process; the management of risk of catastrophic failure during the asset's life; and the asset's End of Life expectancy based on actual fatigue experienced, enabling possible lifetime extension. Cost benefits will likely arise from such an approach, particularly as offshore wind moves into regions impacted by tropical storms.

3.6 Decommissioning

The metocean requirements during decommissioning are very similar to those during installation. These include provision of hindcast data for programme planning, and weather forecasting with real-time data for work planning and execution.

Photo credit: Fugro

3.7 Strategy Overview

A recommended metocean strategy is summarised in a Gantt chart shown in Figure 1. Activities have been categorised at a high level: on-site data collection, numerical modelling, and desktop studies. Emphasis within the strategy has been placed upon the production of a high-quality database of metocean data in time series format, from which subsequent metocean analyses may be conducted. Consultation with project teams throughout each phase is necessary to ensure that analyses conducted fulfil the specific needs of the project.

Figure 1: Gantt chart describing the metocean strategy in terms of key deliverables and required activities throughout the project lifecycle.

DELIVERABLE	ACTIVITIES	SITE SELECTION AND FEASIBILITY	DEVELOPMENT AND CONSENTS	DESIGN	INSTALLATION	OPERATION AND MAINTENANCE	DECOMMISSIONING
Metocean briefing note	Literature review[D]	■					
	Data collation from free sources and gap analysis[D]	■					
	Resourcing, budget and programme requirements[PM]	■					
Preliminary engineering dataset and analyses	Purchase of data[D]		■				
	Modelling[M] (calibrated/validated with publicly available data where possible)		■				
	Data analysis[D]		■	■			
	Environmental impact analysis [DMS]		■				
Full engineering dataset and analyses	*In-situ* measurement[S]		■	■			
	Fully calibrated/ validated modelling[M]			■			
	Data analysis[D]			■	■	■	■
Other	Weather forecast modelling[M]				■	■	■
	Real-time *in-situ* measurement[S]				■	■	■
	O&M strategy optimisation and condition monitoring[DMS]					■	
	End of life assessment[DMS]					■	

D Data analysis and desktop studies, including satellite observations
M Numerical hindcast and forecast modelling
PM Project management
S On-site measurement

4 Metocean Data

The required level of accuracy, and therefore cost, of metocean data evolves with the project. Public data are often available and can be used to provide a preliminary characterisation of metocean conditions in a region. At the early stage, inherent uncertainties and limitations of the data should be acknowledged, and the potential implications understood and interpreted if relevant. As the project progresses and the design is refined, more accurate data and information are required. This reduces uncertainty in the design basis. As outlined in Section 3, early stage metocean criteria should be conservative, so that the consequences of any change are minimised during later stages.

4.1 Data Sources

There are 3 fundamental sources of metocean data, obtained by:

1. On-site measurement.
2. Numerical modelling.
3. Satellite observations.

These are subject to analysis to produce a range of statistics and information suitable for engineering applications. Within the context of metocean data gathering, a fourth effective type of metocean data may be added:

4. Statistics from pre-existing proprietary reports or publications.

A suitable metocean database usually includes all aspects listed above. Some of these data can be obtained from public domain sources, industry and academic data sharing initiatives, or collaboration with other operators with interests in the region. However, an offshore development usually requires, and directly benefits from, a dedicated site-specific data collection effort. On-site measurement provides reliable quantification of conditions at a specific site during the instrumentation deployment period but are usually of too short a duration for reliable quantification of long-term trends, normal statistics, and extreme value analysis.

Numerical models provide the required long-term (inter-annual) context but require validation and calibration using on-site measurement or satellite observations. Numerical models and satellite observations both provide valuable spatial coverage, well beyond a limited set of on-site measurement sites but have limitations in terms of temporal and spatial resolution. As such, a good metocean database is the result of careful combination of data sources and data management (see Section 4.3).

4.2 Key Metocean Processes

Selected data sources must represent the key metocean processes that impact the development site. These processes vary considerably from region to region.

Examples of key metocean processes affecting extreme and operating conditions:

- Winds forced by atmospheric disturbances.
- Wind-sea waves generated by the local near surface wind field.
- Swell waves generated by the remote near surface wind field.
- Tidal currents and water level driven by predictable astronomical forcing.
- Surge currents and water level driven by less predictable atmospheric disturbances.
- Tropical revolving storms, such as hurricanes, cyclones and typhoons.
- Monsoons.
- Squalls.

The spatial and temporal resolution of selected datasets must be sufficient to resolve the dominant metocean processes. Typically, time intervals between 3 hours and 10 minutes will generally suffice. However, more frequent sampling is required to capture the small scale, rapidly varying processes that dominate in other regions (for example, turbulence, solitons and squalls). Such events are not well represented in large-scale numerical model datasets. In regions where high impact events such as tropical revolving storms occur, analysis of spatial data such as storm tracks are required to inform numerical modelling.

Where effects of climate change on site conditions are understood, they should be incorporated into the metocean analysis, for example, the poleward migration of tropical cyclones, or changes in sea-ice cover – see Section 7 for further detail.

Although OR projects need site-specific (and possibly technology-specific) information, a general understanding of the broader metocean processes in a region is also useful.

4.3 Data Management

Metocean data is a valuable resource which needs to be carefully managed. Its value can be increased through the application of FAIR data principles. The FAIR data acronym is used to describe the following attributes:

- Findable – the data should be accompanied by rich metadata to allow them to be searchable. The metadata should be persistent.
- Accessible - a standardised communications protocol allows the data to be accessed with appropriate authorisation procedures.
- Interoperable data use a formal, accessible, shared and broadly applicable language for knowledge representation.
- Reusable Data are released with a clear and accessible data usage licence and provenance.

Although a commercial organisation may not wish to share all their data, the FAIR principles are equally valid within an organisation.

The ability to find data to support analysis and development of information or products is essential if the data are to be fully exploited. Company structures often preclude sharing knowledge of data generation, which creates the potential to duplicate effort across the phases of the project lifecycle or even across stakeholder disciplines. Applying the findable principle will likely offer significant cost savings, once the initial effort to set up a data management system has been completed.

The level of quality control applied to data should be included in the metadata to permit assessment of its reliability for a particular purpose. Reports relating to the deployment of the instruments, instrument calibration, for example, should be considered as part of the data process and digitalisation of this information enables a robust audit trail regarding the quality of the data. This information will save significant time when data are used by different stakeholders.

The meteorological and oceanographic communities have undertaken significant work to create common parameter naming and metadata standards. Common parameter naming is important to ensure data users understand the parameter being utilized and to enable discovery. Data suppliers often use different naming conventions which can lead to confusion; therefore, it is recommended to adopt a naming convention. The most utilized convention is Climate and Forecasting **(CF Conventions)** which also offers metadata standards for NetCDF files (frequently used for modelling outputs). Similarly, the SeaDataNet and MarineXML Vocabulary Content Governance Group **(SeaVoX)** initiative has developed vocabularies for the marine environment, which seek to satisfy the requirements of the standard ISO19115-1:2014 Geographic information - Metadata. Adopting these vocabularies will significantly increase the interoperability of data. The IEA Task 43 Wind Energy Digitalisation initiative **(IEA)** developed a data model to unlock the full value of wind energy through digitalisation. The data model was developed initially with a land focus but has gradually been extended to the use of Floating LiDAR Systems and is also considering metocean data.

How data are stored will be dependent on the resources of an OR project development company, and its degree of digitalisation. Many companies are looking to move away from flat file storage to ensure that data is visible to users to maximize the value that may be derived from the data. The size of metocean datasets can be relatively small, but they are increasing rapidly with changing technology. Metocean data also has a strong temporal element, which is often not considered in wider geoscience datasets held by project developers. Some may choose to undertake this internally whilst for others it may be appropriate to outsource to suitably skilled contractors. Consideration should also be given to other types of data that the stakeholders may be accessing to determine whether the metocean data can leverage existing digitalisation within an organization.

Stakeholders may require the data in various formats for use in their applications, as such the company will need to determine how to enable data users to interact with the data. An application programming interface would allow access in single or multiple formats directly by another software application however a database administrator could also deliver data requirements. The availability of database and associated software from cloud providers offers relatively low-cost solutions as software code requirements are reduced. Cloud providers are focussed on enabling better use of data through the development of applications and machine learning to derive and exploit information.

4.4 Data Sharing

In addition to the value metocean data offers to individual companies, contributing data to the wider community provides benefits in terms of improved understanding of the marine environment, and other broader societal benefits. To enable this, several marine data management schemes are offered at national, regional and global scales.

The Global Ocean Observing System **(GOOS)** is an Intergovernmental Oceanographic Commission **(IOC)** programme developing a global ocean observing system that delivers information needed for sustainable development, safety, wellbeing and prosperity. OR developers are encouraged to contribute to local or regional GOOS initiatives. These connect directly to the Copernicus Marine Environment Monitoring Service **(CMEMS)** which provides access to both global on-site data and model data, enabling global collaboration and cooperation. CMEMS provides regular and systematic core reference information on the state of the physical oceans and regional seas. The observations and forecasts produced by the service support all marine applications. Similarly, the International Council for the Exploration of the Sea **(ICES)** is a global collaborative effort with a well-established data centre managing large marine environmental datasets. On a European level, the European Marine Observation and Data Network **(EMODnet)** provides an excellent example of distributed data sharing for a diverse range of ocean users.

The Netherlands Enterprise Agency **(RVO)** provides a global role model in strategic metocean data collection and sharing for offshore wind energy. They publish detailed site data and characterisation studies across the Dutch sector at an early stage in wind farm development. These adopt the Creative Commons 4.0 CC-BY-SA license, which allows free usage and publication of new results with appropriate acknowledgement.

In the United Kingdom, The Crown Estate's Marine Data Exchange **(MDE)** and Offshore Wind Evidence and Knowledge Hub **(OWEKH)** provide a digital platform for offshore wind projects to share survey data and information including the guidance and best practice documentation.

Metocean specialists should be able to provide guidance on appropriate global and regional data management schemes.

5 Metocean Analyses

The type of analyses undertaken in the process of an OR project will generally incorporate assessment of operational climate, extreme climate and weather downtime using statistical techniques, and preparation of inputs for structural design load calculations, either by the Developer or by an external consultant.

5.1 Operational Climate

The operational climate is a statistical description of the normal metocean conditions experienced at the site. It is these conditions which drive fatigue and govern day-to-day operations. Typically, the operational metocean climate is described using scatter or bivariate tables of metocean parameters (see Figure 2), and rose plots (see Figure 3). The information should consider the end user application and regional metocean conditions to ensure it addresses the likely needs. This may include, but is not limited to, the following:

- Significant wave height by month
- Significant wave height vs. wave direction
- Significant wave height vs. mean wave period
- Significant wave height vs. peak wave period
- Significant wave height vs. wind speed
- Significant wave height vs. wind direction
- Wind speed by month at various elevations
- Wind speed vs. wind direction at various elevations
- Wave spectra for vessel response analysis and fatigue analysis in foundation design
- Total surface current speed vs. current direction
- Total depth averaged current speed vs. depth averaged current direction
- Nearbed current speed vs. current direction
- Vertical current profile and current shear
- Tidal water levels.

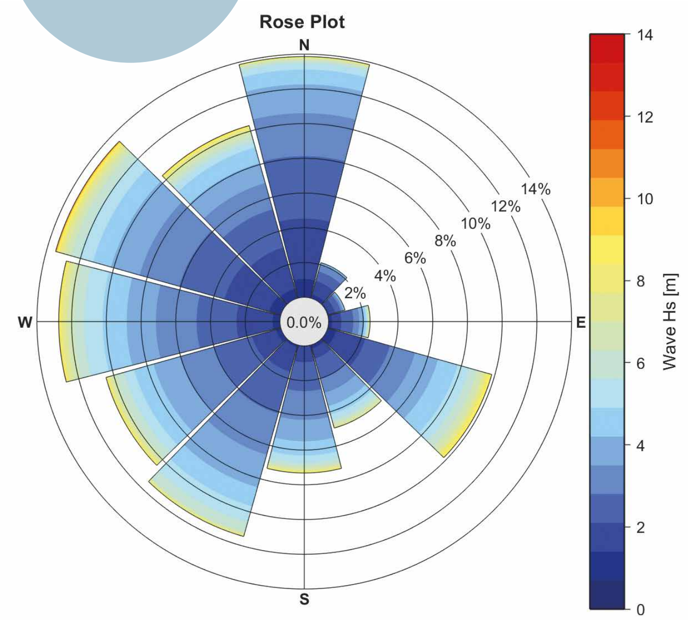
Consideration of the total significant wave height is frequently insufficient where distinct sea and swell components exist. The sea and swell will provide different responses in vessels and structures and will need to be considered.

Figure 2: Joint frequency table depicting percentage occurrence of significant wave height versus peak wave period (courtesy of MetOceanWorks Toolbox)

Joint Frequency Table

Wave Hs [m] \ Wave Tp [s]	0.00 to 1.00	1.00 to 2.00	2.00 to 3.00	3.00 to 4.00	4.00 to 5.00	5.00 to 6.00	6.00 to 7.00	7.00 to 8.00	8.00 to 9.00	9.00 to 10.00	10.00 to 11.00	11.00 to 12.00	12.00 to 13.00	13.00 to 14.00	14.00 to 15.00	15.00 to 16.00	16.00 to 17.00	17.00 to 18.00	18.00 to 19.00	19.00 to 20.00	Total
Total				0.02	1.38	5.44	12.86	17.78	17.45	14.07	11.12	8.41	5.47	3.04	1.71	0.61	0.54	0.09	<0.01	<0.01	100.00
13.30 to 14.00																					
12.60 to 13.30																					
11.90 to 12.60																<0.01					<0.01
11.20 to 11.90															<0.01	0.01					0.01
10.50 to 11.20															0.01	<0.01					0.02
9.80 to 10.50														0.01	<0.01						0.02
9.10 to 9.80												<0.01	0.06	0.04	<0.01						0.11
8.40 to 9.10												0.05	0.06	0.03	<0.01						0.14
7.70 to 8.40												0.12	0.07	0.03	<0.01						0.23
7.00 to 7.70											0.08	0.27	0.18	0.05	0.03						0.61
6.30 to 7.00										<0.01	0.65	0.29	0.18	0.11	0.03						1.26
5.60 to 6.30										0.23	1.23	0.29	0.07	0.08	0.03						1.92
4.90 to 5.60									0.05	1.53	1.46	0.37	0.09	0.09	0.05						3.64
4.20 to 4.90								0.04	1.14	3.06	0.95	0.34	0.21	0.22	0.07	<0.01					6.06
3.50 to 4.20							<0.01	0.72	4.49	3.04	0.97	0.40	0.49	0.34	0.19	0.02	0.03				10.70
2.80 to 3.50							0.31	5.69	5.41	2.13	0.67	0.96	1.34	0.55	0.24		<0.01				17.31
2.10 to 2.80						0.17	4.74	6.96	3.49	1.84	1.65	2.32	1.37	0.55	0.15	0.06	0.08		<0.01	<0.01	23.39
1.40 to 2.10					0.14	3.00	5.90	3.81	1.97	1.31	2.51	2.04	0.60	0.37	0.26	0.21	0.27	0.06			22.44
0.70 to 1.40				0.02	1.08	2.25	1.91	0.57	0.83	0.89	0.91	0.87	0.59	0.51	0.59	0.29	0.16	0.03			11.49
0.00 to 0.70					0.16	0.02			0.05	0.03	0.05	0.09	0.16	0.07	0.02						0.65

Figure 3: Example rose plot (courtesy of MetOceanWorks Toolbox)



Generally, data will be presented as a percentage frequency of occurrence for all or part of the dataset. Number of records or frequency of occurrence scaled to parts per hundred thousand or average number of waves per year may also be presented.

Directional sectors will typically be a maximum of 30 degrees, centred on North. Often, tables and roses will be presented for annual, seasonal or monthly partitions of the data, by directional sector, or by intensity bin. This allows consideration of the directional aspects of the metocean regime on operations.

In the earlier phases of the project, the operational climate may be summarised in less detail. However, as the project progresses, and particularly in approach to final design, the full suite of operational climate descriptions will be required, including consideration of parameter relationships by intensity bins and directionality. It is typical for information to be presented in more than one way, for example, significant wave height direction vs. wind direction by wind and wave intensity bins.

5.2 Extreme Climate

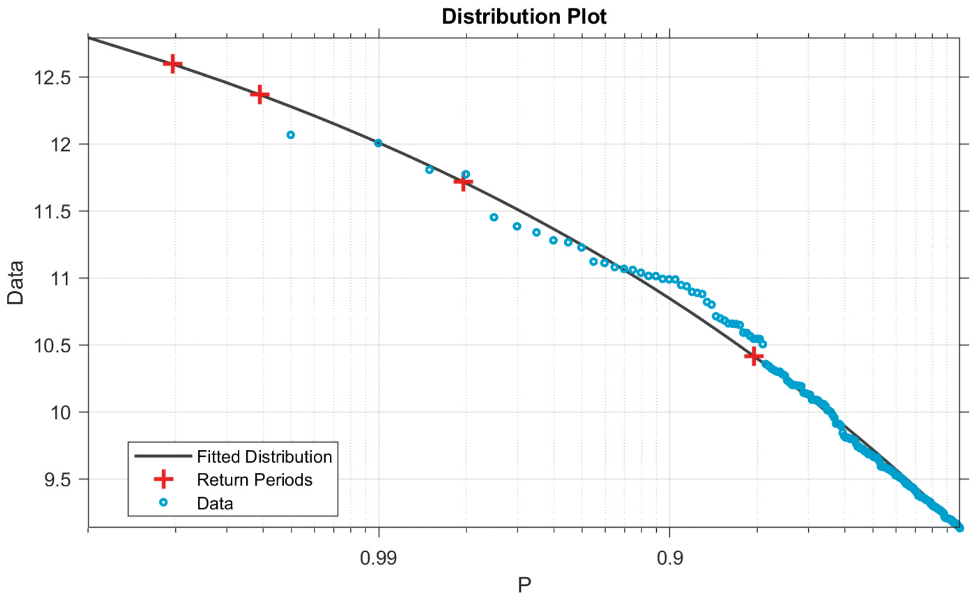
The extreme climate is a statistical description of the abnormal metocean conditions experienced at the site.

Estimates of metocean parameters for a selection of return periods are derived from statistical methods of extreme value analysis (see Figure 4). Confidence intervals applied to the extreme values will help the user to understand the level of uncertainty associated with them. To account for inter-annual variability, it is fundamental that time series of data to be analysed are both long enough (>30 years) and have the temporal resolution to capture peaks. Extreme value analysis should, where possible, consider the joint probability of occurrence of two variables, to reduce the conservatism inherent in combining parameters assumed to be independent of one another, which is often the case. As such, it is highly recommended that extreme value analysis is conducted by persons possessing demonstrable competence. Extreme value analysis (EVA) theory is complex and evolving. More recent approaches seek to better characterise the uncertainty through the application of Bayesian statistics and definition of epistemic uncertainty. The assumption of stationarity, which underpins traditional EVA, likely no longer holds true due to climate change, and new non-stationary EVA methods are under consideration. For some applications, the metocean data are used as inputs to engineering models, and the extreme value analysis is performed on the engineering response.

The outcomes of extreme value analysis may include, but are not limited to, the 1, 10, 50, 100, 1000 and 10000 year return period of relevant metocean parameters, omni-directional and for each directional sector, all year and by month. Directional sectors should be 30 degrees or lower. Consideration should be given to the presence of wave breaking, which may limit wave growth for selected sites.

In areas experiencing tropical revolving storms, careful analysis of such conditions must be undertaken, taking in account the variable temporal and spatial nature of these systems. Such analysis may comprise parametric/probabilistic synthetic storms or use of mesoscale numerical datasets from third parties.

Signal Selection	
Dataset	SWAN 57.160°N, 001.891°E (90.1985m)
Signal	Wave Hs
Column	1
Extreme Value Calculation	
Extr. Val. Method	Fitted Distribution
Data Downselection	
Method	Number of Peaks
Number of Peaks	200
Selected Data To Fit	
Number of Points	200
Number Per Year	5.1289
Number Per Year Source	Auto
Distribution Fitting	
Distribution	Generalized Pareto
Method	Max Prod of Spacings
Fitted Distribution	
Distribution	Generalized Pareto
Location	9.1266
Scale	0.90205
Shape	-0.17006



Return Period	Probability	Extreme Value
1	0.8050245266	10.41
10	0.9805024527	11.72
50	0.9961004905	12.37
100	0.9980502453	12.60

Figure 4: Example extreme value analysis for significant wave height (courtesy of MetOceanWorks Toolbox)

5.3 Weather Windows and Adverse Weather Downtime

Weather window persistence statistics (for example, Figure 5) may be required by any work package resulting in offshore works, including survey, civil and structural engineering, turbine engineering and cable package.

Persistence statistics may be requested as part of a metocean study, however, specific combinations of operational limits for particular or combined series of operations are difficult to pre-empt early in the project lifecycle. It is therefore recommended that more complex assessments of operability are conducted in close partnership with logistics and construction planning teams.

Dedicated studies with regards to persistence may also be contracted once the operational limits and weather window durations are fully understood. Alternatively, simulation of the installation programme against time series may be conducted by a competent practitioner to build up probability distributions regarding the likely time taken to complete the installation sequence.

5.4 Input to Design Loads Cases

In fixed offshore wind, numerous loads cases are conducted according to the key standards (Section 2.4). Most loads cases will incorporate descriptions of the combined hydrodynamic and aerodynamic conditions impacting upon the structure with varying severity referred to as reference sea states and reference wave heights, for example:

- Normal Sea State
  Characterised by a significant wave height, a peak period and a wave direction and associated with a concurrent mean wind speed, such that the significant wave height is the expected value for the associated wind speed.
- Severe Sea State
  Characterised by a significant wave height, a peak period and a wave direction and associated with a concurrent mean wind speed,

Figure 5: Percentage probability of the condition significant wave height (Hs) <1.5m existing for varying weather window durations.

Condition	Duration (h)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Average
Hs<1.5	3	47%	57%	64%	78%	83%	84%	85%	81%	70%	61%	52%	45%	**67%**
Hs<1.5	6	46%	55%	61%	74%	79%	81%	82%	77%	67%	58%	51%	45%	**65%**
Hs<1.5	12	42%	52%	59%	74%	79%	79%	80%	76%	66%	56%	47%	39%	**62%**
Hs<1.5	24	35%	44%	52%	67%	72%	74%	76%	70%	58%	48%	39%	31%	**56%**
Hs<1.5	48	26%	33%	42%	56%	62%	63%	66%	59%	47%	37%	30%	22%	**45%**
Hs<1.5	72	20%	26%	35%	47%	54%	54%	59%	50%	39%	29%	24%	16%	**38%**

such that the combined wave height and wind speed has a return period of 50 years.

- Extreme Sea State
  Characterised by a significant wave height, a peak period and a wave direction, wherein the significant wave height has a specified return period of 1 and 50 years.

The derivation of these sea state scenarios requires detailed knowledge of structural design to ensure that the most appropriate combinations of parameters are applied (for example, taking into account the eigen-frequency sensitivity of the structure). Such derivations should be conducted by specialist practitioners and may not be within the capability of the metocean contractor.

As noted in the introduction, this procedures guide is heavily focused on offshore wind developments involving a fixed structure, due to relative technical maturity. Many of the general principles will also apply to floating wind, wave and tidal, however, some specific details will differ. The project team should be consulted at an early stage to correctly scope the metocean requirements for wave, tidal and floating wind developments, in conjunction with the available guidance and standards.

For floating wind energy and wave energy, a major difference from a metocean perspective will be the characterisation of metocean conditions required to quantify impact upon a floating structure, which reacts dynamically to its environment. For example, it is necessary to characterise details of the full directional wave spectra. A major challenge is designing for platform motion with corresponding motion of the wind turbine blades, or electrical power take-off in the case of wave energy.

With regard to tidal energy, one major difference will be the need to characterise ocean turbulence. This is analogous to the need to characterise atmospheric turbulence for wind turbine engineering, but may bring specific new challenges to the data collection strategy. Potential tidal energy development sites are situated in regions of strong tidal flow, which are often highly turbulent.

5.5 Requirements for Floating Offshore Wind

Floating offshore wind (FOW) becomes an option in water depths greater than 60 m, opening new geographical regions to offshore wind. Locations further from shore and in countries surrounded by deeper water introduce new challenges from a metocean perspective.

For any new area of opportunity, a thorough risk assessment of regional metocean characteristics must be conducted. Tropical revolving storms, stratified water columns, internal waves and tsunamis are all phenomena that are more common in regions being proposed for FOW. Many more exist and a metocean specialist can provide a thorough risk assessment for a particular region.

For each specific project, the construction and installation, and possibly maintenance, of the infrastructure may be spread over many different locations. Assembly takes place onshore or in dock. Metocean conditions in port should be assessed, including onshore wind speed and direction, wave conditions in port (including long-period waves) and wave and current at the port entrance. Once assembled floaters are towed either to a wet storage area or to site, meaning that tow route analysis is required. Tow-to-shore is currently required for maintenance.

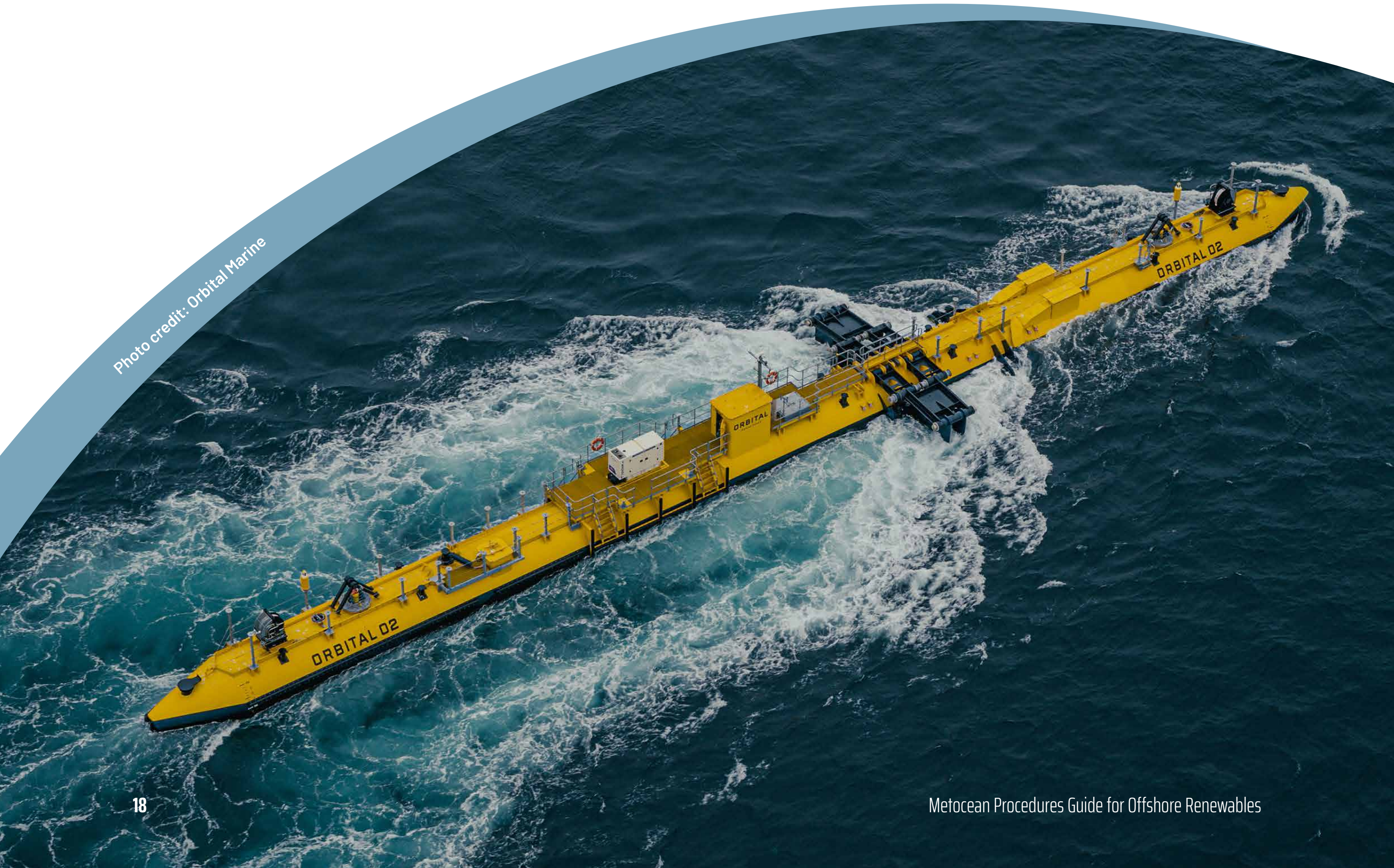
The importance of tow-route analysis increases with the length of the tow and the variability of the metocean conditions along the route. Tow routes for FOW could be over long distances because of the distance offshore and restricted port availability. Wet storage of the floaters after assembly, alleviates some pressure on port space but means that the metocean conditions need to be assessed at the wet storage location. These locations will be more sheltered from wind and waves than the offshore wind farm, but the station keeping and fatigue during this brief period will depend on the overall metocean regime and requires assessment. To provide metocean conditions for all locations used for construction and maintenance, the metocean study should cover a wider area and once locations are defined for each activity, an assessment commensurate with the activities at each site should be conducted.

In addition to the greater geographical spread, the importance of metocean conditions through the entire water column increases, because the water depth and amount of infrastructure in the water column increases. Current solutions for FOW have the floating foundation, dynamic cables, and mooring lines through the water column, while on the seabed, anchors hold the system in place. These all have new dynamics in comparison to fixed bottom. These dynamics are affected by variation in salinity and temperature through the water column, and these parameters all vary more in deeper water. Stratified water columns introduce variability, over depth and time, to the density of the water and the forces acting on the infrastructure.

Metocean requirements for the anchors used for station keeping increases the importance of understanding seabed currents, which in fixed-bottom OWF were primarily used in cable design or seabed mobility studies. Recent problems with cables and cable protection systems have highlighted the importance of accurate characterisation of currents at the seabed, including wave induced currents. In deeper water, current measurements from seabed mounted frames and deep-water moorings are recommended since instruments installed in surface buoys cannot measure the bottom 10% or more of the water column.

While the parameters that are measured remain essentially the same, the relative importance of them will vary. As mentioned above, currents and temperatures through the water column become more important, as the variability in those parameters increases with deeper water. Wave induced motion on vessels and structures, becomes important for the assessment of seasickness, especially for technicians in the turbine nacelle or for the relative motion of a vessel next to the floating foundation. Each vessel or foundation type will respond differently to the metocean conditions, and therefore accurate characterisation of the wave spectra across the full range of periods is necessary. Directional data and misalignment between wind, wave and currents, is critical in the design of the foundation, and the design and layout of the dynamic cables and mooring lines. Marine growth is an often-overlooked parameter in fixed bottom offshore wind, but marine growth will alter the buoyancy of infrastructure and increase drag, change the resonant frequency, and damage cables and mooring lines. Cleaning strategies will be defined on the expected rate of growth, which in current standards is defined only for a few broad areas.

Floating offshore wind is a new industry, but there is much to be learned from fixed-bottom offshore wind and the oil and gas industry. The metocean community will be required to work closely with FOW developers to address the need for new technological solutions.



6 Marine Weather Forecasting

Marine weather forecasts are essential for supporting safe, efficient, and successful operations, accurately characterising the predicted (rather than climatological) metocean conditions expected to be encountered during the planned installation and operation period; allowing the 'workability' associated with approaching weather systems to be assessed relative to the limits of the activities being undertaken.

There are two main types of marine weather forecasts: deterministic and ensemble. Further details are given in Sections 6.1 and 6.2 respectively. Typically, a mixture of the two types may be used.

During construction and operations/maintenance, an OR project will require short-range forecasts for the site, with lead times of up to about 5-7 days ahead, issued up to 4 times per day (i.e. every 6 hours). Other locations, for example, load-out ports, wet storage area and vessel routes may also be needed. The ability to add or remove forecast locations ad-hoc is desirable as, often during long installation periods, plans change. A supporting 24/7 on-call meteorologist may also be of additional benefit. Medium-range forecasts, with lead times of up to 15-days ahead, enable planning on longer timescales. Tidal water levels and current speeds may be provided in addition to standard weather forecast information.

A lightning outlook or thunderstorm forecast is advised, including an alert service should a high risk of lightning develop. Alerts should be provided as soon as possible to enable safeguarding of offshore personnel. Equipping personnel with lightning detection systems should also be considered.

It is recommended that any site-specific forecast makes use of available real-time on-site measurements, for example via data assimilation or, particularly, via data post-processing of the raw model output to further increase accuracy.

Similarly, any forecast should undergo verification (see Section 6.3), as forecast models may be more or less accurate for given locations. Forecast performance should be carefully monitored and feedback provided to the supplier.

During construction, adherence to Marine Warranty Survey requirements is necessary. The combination of reliable forecasts (including a second independent weather forecast), supported by dedicated forecasters and live-data, can act to minimise the conservatism (alpha-factor) required by a Marine Warranty Surveyor when planning and executing offshore construction work.

6.1 Deterministic forecasts

Traditionally, weather forecasts are based on deterministic (or single) predictions, which offer a best estimate of the parameter of interest and are useful for supporting decisions on timescales of up to about 5-7 days ahead. Such data are generated by numerical modelling, the selection and suitability of which is dependent on the configuration of the system and the processes resolved. Subsequent adjustments are applied in forecast post-processing to further tailor and bias correct the raw model outputs for the location of interest, utilising observations where available. Typical products usually consist of a series of tables and graphs summarising the relevant metocean parameters. In addition, a general weather, visibility, temperature, and cloud cover overview is often presented.

In OR applications, with people working at height in relatively exposed locations, it is also critical to consider risk of lightning. Regional-scale numerical modelling can be used to give an indication of high-risk areas where convection is likely to occur, however it is acknowledged that beyond this there is often a reliance on post-processing techniques and particularly meteorologist interpretation guided by real-time observations from ground and/or satellite-based sensors (appreciating the respective benefits and limitations of each).

6.2 Ensemble forecasts

The highly nonlinear nature of the atmosphere and ocean imposes a limit on how far ahead any parameter can be predicted, with errors increasingly common beyond a few days to a week ahead. However, this uncertainty varies day-by-day, depending on the given weather situation. Ensemble prediction systems can be used to quantify this uncertainty dynamically, by running multiple forecasts with varying initial states and/or model parameterisations. This complete set of forecasts is referred to as an ensemble, and the individual forecasts within it as ensemble members. Ensemble systems are constructed such that results from each member will be equally likely, and therefore the proportion of ensemble members that forecast an event will be representative of the likelihood (or probability) of it occurring.

Existing ensemble forecast systems typically contain between 36 to 51 ensemble members and are suitable for extending planning decisions to more complex cases, such as identification of long weather windows on timescales up to (and beyond) 15 days ahead.

6.3 Forecast verification

Forecast verification may be established by comparing the prediction against a corresponding observation of what occurred, or another equivalent source of 'truth'. This comparison should offer some information about the nature of any forecast errors, with the purpose of monitoring forecast quality, improving forecast quality, and/or comparing the quality of different forecast providers/systems. See **Forecast Verification** for a useful overview.

It is often appropriate to consider a variety of metrics that measure consistency, quality, and value to fully characterise performance, although the specific attributes of accuracy and skill are the most common areas of focus. It is important to note that quality is not the same as value. For example, isolated regional thunderstorms may be observed in the vicinity, but not in the exact locations predicted by the model. Such forecasts will have a poor quality according to standard verification methods but may have high value to a meteorologist issuing warnings to offshore renewables operators.

Verification results are more trustworthy when the quantity and quality of the observed data is high, especially in cases of rare events, large environmental variability and when making forecast comparisons. Observations used as 'truth' also contain their own uncertainty in the form of analysis, measurement, representation, or sampling errors/biases, although such errors are typically smaller than the expected forecast errors.

7 Climate Change

The Climate Change 2023: Synthesis Report - Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change **(IPCC AR6)** states that human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global mean surface temperature reaching 1.1°C above the 1850-1900 mean in 2011-2020. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. Human-caused climate change is already affecting many weather and climate extremes in every region across the globe.

The impact of future climate change on the marine environment is a complex problem associated with high uncertainty. The science supporting assessment of climate change on the marine environment is evolving rapidly. For OR projects it is necessary to consider climate change impact from both a resource and engineering perspective, so that OR projects can mitigate the risks associated.

It is expected that all metocean parameters will change because of increasing global temperatures, however the amount of change will vary across regions, and changes may be more or less significant for varying OR technologies. Rising global temperatures lead to increased storminess and hence higher wind speeds, wave heights and current speeds, along with sea level rise. These changes will impact tidal regimes, sediment mobility, and seawater properties.

Storm events may become more frequent in some regions, and less so in others. Wind energy produced during localised storm events is often unexploitable and increased storminess may in fact lead to more frequent curtailment or shutdown. Estimations of future wave power resource need to consider bathymetric changes, as increased bottom friction reduces nearshore wave power. Tidal sites that are currently viable for high energy exploitation may become less profitable over the next century. The opposite could also be true, sites which are currently not viable may find themselves becoming future tidal stream hotspots.

For offshore wind, increased or changed patterns of coastal erosion, sand wave propagation and sandbank movement may cause significant issues for cable landings, cable burial/exposure and free spanning. Ensuring safety and longevity of installed infrastructure will require more steel, as extreme and fatigue loading from wind, wave and current increases. More frequent storm damage because of wave run up and slamming may be expected, coinciding with reduced weather windows for construction and operation. In regions where high impact events such as tropical revolving storms occur, frequency may increase, and storm tracks may extend further. Sea level rise may compromise infrastructure, affecting access, causing flooding and inundation. Extreme heat and cold poses a risk to those working offshore to construct and maintain infrastructure.

The impact of climate change on metocean parameters should be addressed in future detailed metocean studies, and subsequently in the design and engineering of future OR projects, to safeguard the infrastructure that, fundamentally, serves to tackle the issue of climate change.

APPENDIX

1 Glossary

A1.1 General

Adverse weather downtime
Periods when offshore operations must be suspended due to adverse weather conditions, due to the exceedance of operational limits.

Analyses
Statistical analysis of selected datasets to produce information or products, for example, design criteria or weather downtime.

Data
Individual measurements or model outputs at discrete timesteps, for example, hourly.

Dataset (or time series)
A record of parameters at discrete timesteps for a given time period, for example, 2 years of observational wave data or 40 years of hindcast wave data. This time series of data is the basis for all statistical analyses.

Design criteria
A statement of the worst-case (or extreme) metocean conditions that a structure or vessel must be designed to withstand, including information on the cyclic loading which drives fatigue damage to the structure.

Extremes
The metocean conditions associated with specific low probabilities of exceedance in any year. Usually expressed in terms of return periods and derived from statistical extreme value analysis, often taking into account the interdependence between variables.

Fatigue
The progressive and localized structural damage that occurs when a material is subjected to cyclic loading. i.e. the weakening of material that occurs when a material is subjected to repeated loading and unloading.

Forecast
Prediction of future metocean conditions. Deterministic forecasts may be model driven (direct output from a numerical model), or forecaster driven (output from a numerical model informed by skilled forecasters using a variety of guidance data such as on-site or satellite measurements). Ensemble forecasts utilize a range of initial conditions or physical perturbations to generate a number of possible outcomes, permitting a probabilistic forecast to be generated. Due to the chaotic nature of atmospheric and oceanographic conditions, forecasts are generally constrained to a 7–10-day period ahead. Seasonal forecasts are sometimes used but offer relatively poor reliability. The reliability of the forecast is dependent on the forecast horizon and synoptic situation.

Hindcast
Numerical modelling of a historical period. Hindcast techniques allow a numerical wave, current or wind model to be verified against available observations, thereby improving accuracy and reliability, and allowing the production of long-term time series of data.

On-site measurement
Measurement or observation of real metocean conditions at a specific location.

Loads
The forces, deformations, or accelerations applied to a structure or its components, resulting in stresses, deformations, and displacements in structures. Excess load or overloading may cause structural failure.

Metadata
Data or information that provides information about other data. Metadata may be descriptive, structural, administrative, reference and/or statistical.

Metocean
A technical engineering discipline that addresses

meteorological and physical oceanographic matters, originating from the oil and gas sector in the late1970's and equally applicable to the offshore renewables sector.

Metocean processes
All-encompassing term for the physical processes governing the metocean regime that vary from region to region, such as tides, ocean circulation or atmospheric phenomena.

Mid-latitude storm
Synoptic scale low pressure weather systems occurring at mid-latitudes.

Numerical modelling
Computer simulation of the known dynamics of the real world.

Operational limits
The metocean conditions up to which an activity can be performed, for example, significant wave height < 1.5m.

Return period
The duration (in years) within which an extreme value is expected to be equalled or exceeded once, for example, once in 1, 10, 50 or 100 years.

Satellite Observation
Data derived from satellite missions supporting metocean sensors including altimetry (water level, wind speed and wave height), Synthetic Aperture Radar imagery (wave periods), visible and infrared imagery (sea surface temperature, ocean colour, etc), microwave radiometers (salinity) and reflectometers (wave/wind).

Scour
The removal of sediment such as sand and silt from around an object (resulting in a local depression), due to an increase of flow velocity around that object.

Solitons
Nonlinear wave motions in the water column causing potentially high impact short duration current events.

Spatial resolution
The spacing of model grid points or observations, for example, 1m, 100m, 3km or 1 degree.

Squall
A sudden sharp increase in wind speed resulting from localised events such as thunderstorms.

Temporal resolution
The frequency of measurements or model output in time, for example, 1 second, 1 minute, 10 minutes or 1 hour.

Tropical revolving storms
Hurricanes, tropical cyclones and typhoons.

Turbulence
Disturbed, semi-random motion of air or water particles, occurring where flow interacts with a structure.

Weather window
The minimum time period within an operational limit required to perform a given installation or maintenance activity, for example, significant wave height <1.5 m for a weather window of 6 hours.

A1.2 Wind

Wind speed and direction
The sustained wind speed over a given period at a given height above the sea surface (typically 10 metres) and associated direction, usually expressed as follows:

- **1 hour mean –** mean wind speed measured over 1 hour
- **10 minute mean –** mean wind speed measured over 10 minutes
- **1 minute mean –** mean wind speed measured over 1 minute
- **3 second gust –** maximum three second average wind speed measured within the associated mean wind speed averaging period (e.g. the 10min average wind speed was 7.5ms^{-1} with an associated 3s gust of 8.2ms^{-1}).

A1.3 Wave

Bi-modal (or multi-modal) sea
A Sea State in which the Wave Spectrum is comprised of two (or more) independent wave systems. These are relatively common and of interest for both engineering and operations. Work in multi-modal seas can require separate estimates of wave parameters for each component.

Directional spreading
A measure of the breadth of the wave spectrum with direction.

Frequency spreading
A measure of the breadth of the wave spectrum with frequency.

Maximum individual wave height
The highest individual wave crest to trough excursion in a wave sample.

Mean zero-crossing period
The average period between successive (up or down) crossings of waves in a sea state.

Peak period
The period corresponding to the frequency where the spectral density (see below) reaches its maximum.

Sea (or wind-sea)
Component of the sea state related to locally generated wind.

Sea state
Condition of the sea during a period of time in which its statistics remain approximately stationary. In a statistical sense the sea state does not change markedly within the period. The time period during which this condition exists is often assumed to be 3 hours, although it depends on the particular weather situation at any given time.

Significant wave height
A measure of wave energy, defined either as the mean wave height of the third largest crest to trough wave heights ($H_{1/3}$) or four times the square root of the zeroth-order moment of the wave spectrum (H_{m0}).

Swell
Component of the sea state in which waves generated by wind remote from the site have travelled to the site, rather than being locally generated.

Wave crest elevation
The elevation of an individual wave crest above the still water level.

Wave direction
The direction from which a wave propagates.

Wave spectrum
The wave spectrum or spectral density describes how the variance of the sea surface elevation is distributed over frequency and propagation direction, from which all wave parameters may be estimated.

A1.4 Current

Residual current
Residual currents are caused by a variety of physical mechanisms and comprise a large range of natural frequencies and magnitudes in different parts of the world. The residual current is the part of the total current that is not constituted from harmonic tidal components.

Tidal current
Tidal current is the part of the total current related to the astronomical forcing alone. As a result, tidal currents are predictable, with accuracy increased by analysis of the total current against increased numbers of harmonic constituents.

Total current
The combination of tidal and residual currents makes up the total current which is the resulting (primarily) horizontal flow of water experienced.

A1.5 Water Levels

Amphidromic point
A location where the tidal range is zero.

Chart datum (CD)
The level of water that charted depths displayed on a nautical chart are measured from. A chart datum is generally a tidal datum, typically mean sea level or lowest astronomical tide.

Extreme water level (EWL)
An engineering abstraction calculated by combining extreme wave crest elevation, tide and surge. EWL is important in determining interface levels above LAT or MSL for offshore structures. Other factors such as water depth uncertainty and seabed subsidence should be considered when determining interface heights.

Ordnance Datum (OD)
A vertical datum used by an ordnance survey as the basis for deriving altitudes on maps.

Still water level (SWL)
An engineering abstraction calculated by adding the effects of tides and storm surge to the water depth, but excluding variations due to waves. It can be above or below mean sea level.

Surge
The change in Still Water Level (either positive or negative) that is due to meteorological (rather than tidal) forcing.

Tidal levels
A range of different levels related to the various daily, monthly, annual and decadal astronomical cycles. Semi-diurnal tides are described as:

- HAT – the highest level of tide which occurs once every 18.6 years
- MHWS – mean high water springs
- MHWN – mean high water neaps
- MSL – mean sea level
- MLWN – mean low water neaps
- MLWS – mean low water springs
- LAT – the lowest level of tide which occurs once every 18.6 years

Sites where diurnal tides dominate may alternatively use:

- MHHW – mean high high water
- MLHW – mean low high water
- MHLW – mean high low water
- MLLW – mean low low water

Note that some regions also experience seasonal variations in water level.

Tidal range
Either the vertical difference between a high tide and the succeeding low tide, or HAT and LAT.

Water depth
In offshore engineering, taken to be the vertical distance between the sea floor and a designated datum, typically LAT or MSL

A1.6 Units and Convention

- Units are expressed using the Standard International (SI) convention:
  - Distance (wave height, surface elevation and water depth) in metres
  - Time (wave periods) in seconds
  - Velocity (wind or current speed) in metres per second
- Wave and wind direction is expressed as 'coming from' in nautical degrees, i.e. degrees relative to true north positive clockwise.
- Current direction if expressed as 'going to' in nautical degrees, i.e. degrees relative to true north positive clockwise.

APPENDIX 2 On-Site Data Collection

The start of any metocean data collection is determined on a project-specific basis but will generally be initiated at the beginning of the development and consent phase, with consultation between the project teams. When deciding on the commencement of a measurement campaign, consideration should be given to the entire project programme, taking into account the desire for long-term on-site measurements.

A2.1 Scope of Works

A long-term metocean measurement campaign is encouraged, covering the development and design phase of the project, and maintained throughout construction and O&M phases to support forecasting and operations with real-time data.

The following aspects should be considered with respect to a data collection programme:

- Data collection must be initiated early enough to collect sufficient data (at least 1-2 years for development needs, preferably longer to ensure validation of design criteria, depending on availability of other data).
- Benefits of real-time access to data for monitoring and quality control purposes.
- Potential for collaborative data collection efforts, for example, in conjunction with resource, using multi-use measurement platforms such as floating laboratories and onshore technologies such as dual scanning LiDAR.
- Data quality control frequency, for example, monthly or quarterly or as and when data becomes available.
- Data archiving options, for example, in-house or with a contractor.
- Continuation of data collection into the operational phase of any development to provide information for maintenance activities, to improve and/or verify forecasts and future statistical analyses, and to support maintenance activities.
- Site specific data available to forecast services will likely improve and enable the verification of forecasts, which allows for inclusion of performance criteria to maximise commercial benefit.
- Extension of data collection into the operational phase will provide valuable data for understanding structural performance. The fatigue life of the structures can be verified using the actual loading rather than the loading derived from hindcast data.
- Detailed knowledge of the metocean conditions driving scour events will help mitigation measures to be engineered, and the potential risk of failure to be evaluated.
- New techniques using machine learning will enable better understanding of the structural integrity and scour behaviour, which may allow reduced inspection programmes. Training data sets will be required to enable exploration and effectiveness of such techniques.
- Use of a weather forecast service to assist with deployment and recovery phases.

The metocean measurement campaign should comprise, as a minimum, measurement of wave, water level, water currents and weather conditions, unless long-term on-site data are already available at the site. It is usually cost-effective to simultaneously collect wind resource and environmental monitoring data, for example:

- Bird, bat and subsea noise sensors.
- Seabed samples, water samples and a time series of suspended sediment concentrations to support impact studies.
- Outline assessment of biofouling and marine growth potential.
- Current profiling transects using a vessel mounted Acoustic Doppler Current Profiler (ADCP), particularly where sandbanks and mobile sandwaves are present and may result in complex current fields and spatial variation across the site.

It may be prescient for a Developer to buy and maintain their own measurement equipment for use throughout the project lifecycle, which can be relocated around site once the project moves into construction and O&M phases. The cost of maintaining equipment internally must be weighed against the cost of a comprehensive service and the reliability gained from using an experienced contractor. Alternatively, equipment can be hired which may provide better value for short-term campaigns.

The number of locations where measurements should be made will depend on the size of the site in question, the length of the cable corridor, the complexity of the oceanography in the region, and the existence and availability of prior metocean measurement data. Consideration should be given to the need for redundancy in the equipment deployed. In addition to measurements at the sea-surface and seabed, measurements at mid-depths may be required. Potential contractors will be able to provide recommendations as to the optimum campaign design, therefore the Developer is encouraged to discuss in depth with potential contractors their requirements and eventual intentions for the use of observed data.

A2.2 Schedule

It is pertinent to consider the scheduling of a metocean data collection campaign to ensure the best opportunity for gathering information on extreme events, however, deployment of metocean equipment mid-winter is ill-advised. Developers should initiate procurement of contracted services in good time to ensure deployment by, for example, the end of summer for 1-year campaigns, taking into consideration the likelihood of vessel schedules having been set well in advance. Lead-times for the contracting and deployment of metocean equipment will vary from company to company, and Developers should initiate contracting in a timely manner to allow for the full tendering process, acquisition of necessary licenses and future availability of potential contractors.

The possibility for alignment with other measurement campaigns (for example, those requiring installation of meteorological masts or fixed or floating LiDAR) within the project is advised. Where possible, it is recommended that metocean data is collected alongside other measurement campaigns, in order that the full dynamics of a site can be captured concurrently. However, factors such as lead time and cost of concurrent deployment must also be allowed for.

A2.3 Data and Equipment Loss

Consideration must be given to the level of data loss deemed acceptable by the developer. Data loss can be mitigated by real-time transmission of data, or by redundancy of equipment in the measurement strategy.

It should be noted that the deployment of metocean equipment may require licensing from relevant national bodies and is likely to include, for example, the issue of a Notice to Mariners. In some locations, it may be necessary to request an addition to navigational charts and, for busy shipping areas, the use of higher-grade guard buoys should be considered. Additionally, in areas of intense fishing activity, it may be beneficial to contract a local Fisheries Liaison Organisation to assist in the engagement of the industry and distribution of information.

Assessing the risk to third parties of installed equipment is extremely important. In addition, assessing the risk to the equipment from shipping and other activities such as trawling, is key to the execution of a successful measurement campaign. Analysis of shipping risk and the presence of unexploded ordnance should be undertaken. Metocean measurement campaigns often experience issues such as collisions with vessels and mooring or technology failure, so it is important to ensure that any contract incorporates appropriately shared risk management and emergency response in order to rectify issues and minimise loss of data.

A2.4 Data Specification

It is recommended that raw, as well as processed data, be obtained from the contractor. A metocean measurement campaign will generally result in large amounts of raw data. It is necessary to plan how and where data will be stored and archived, how it will be accessed, and to ensure adequate quality control methodologies. Refer to Section 4.3 for further information.

A2.5 Health, Safety and Environment (HSE)

During the planning of a metocean measurement campaign, a detailed, site-specific method statement should be developed, and a risk assessment performed. It is recommended that the relevant Health, Safety and Environment (HSE) guidelines be consulted, including the Developer's Employer's Requirements and local procedural documentation (of relevance on Construction and Operational sites). A full documentation pack detailing the Project Execution Plan, HSE plan, Emergency Response Plan and accompanying Risk Assessments and Method Statements, compliant with client and regulatory HSE requirements, should be submitted for review and approval prior to the commencement of any offshore works. Personnel to be used in offshore operations must possess the correct experience and certification (for example, offshore survival training and medical). Vessels and other equipment (such as cranes) should be third party certified to ensure their suitability for the task and compliance with requirements.

Given the nature of metocean measurements, weather is a key variable which will affect data collection procedures. It is important to have awareness of the weather windows required for safe operations. In general, it is recommended that, when possible, moorings are deployed at neap slack water and in low wind conditions. Monitoring of the weather forecast will be required to identify a suitable window in which to conduct deployments or retrieval of equipment, with the vessel master having the final say in commencement of the works from a vessel handling and deck safety perspective.

A2.6 Measurement Campaign Specification Sheet

When designing a metocean measurement campaign, several elements need to be defined within the Scope of Works. To aid in the definition of an appropriate campaign and assist in deliberations with potential contractors, an example Measurement Campaign Specification Sheet is provided in Figure 6. The sheet should be modified to reflect the specific project requirements in any given case.

Figure 6:
Measurement Campaign Specification Sheet

OFFSHORE WIND FARM PROJECT: WIND AND METOCEAN SURVEY SPECIFICATION

Outline scope

Offshore Wind Farm Project (2.2GW) requires the collection of wind and metocean data to inform design engineering and resource assessment, T&I and O&M strategy. The proposed survey will comprise 2x Floating LiDAR Systems equipped with metocean sensors, 1x wavebuoy and 2x seabed frames within the site, and 2x seabed frames within the export cable corridor and nearshore landfall. Additional or alternative measurement options may be suggested. The offshore survey will be complemented by onshore scanning lidar.

Deployment duration

The equipment spread will deployed for a minimum of 12 concurrent months, summer-summer, commencing Aug 2025.

Deployment locations

The following locations are suggested, based on requirements for wind resource assessment and expected variations in the metocean regime across the site. Locations will be finalised in conjunction with the contractor, considering data and equipment risk.

NAME	LATITUDE (°N)	LONGITUDE (°W)
FLS 1	48.8235	14.1885
FLS 2	48.9164	14.0046
Wavebuoy	48.9456	14.1524
Seabed Frame 1	48.9231	14.1989
Seabed Frame 2	48.7511	14.1556
Seabed Frame 3	48.5262	14.0420
Seabed Frame 4	48.5568	14.2012

Parameters and sampling requirements (depths, intervals, frequency

The FLS shall measure: horizontal 10-minute average wind speed and direction; vertical wind speed; turbulence intensity (motion compensated where possible); LiDAR status flags (except surface); LiDAR Carrier-to-Noise Ratio; LiDAR Availability; extreme 3s gust; horizontal 10-minute average wind speed and direction from an additional device e.g. anemometer at <10mMSL; and a range of meteorological parameters. The Contractor shall propose a minimum of 10 collection heights to be agreed with the Project.

From a range of metocean devices (including FLS) the survey shall measure: directional sea states including extreme wave heights, a range of peak periods and full directional wave spectra; current speed and direction at a minimum of ten levels within the water column including single point current measurement at the near-surface and near-bed; water level or depth; temperature and salinity at the sea surface; temperature, salinity and pressure at the seabed; and GPS location.

Sampling rates, heights/depths and bin sizes will be agreed in conjunction with the Contractor. Measurements should be made at suitable intervals accounting for accuracy, data quality and battery life. Where sensors at one location allow for measurement of the same parameter, that parameter shall be collected across sensors to enable cross-validation. Where additional measurements are available by default from selected sensors, they should also be obtained.

Servicing interval and methodology

Equipment shall be serviced according to the suppliers recommended servicing intervals, or once every 6 months.

Reporting requirements

Operational reports (deployment, servicing, and recovery). Emergency response reports as required.

Monthly data reports detailing data availability and demonstrating verification between devices, summary statistics and graphical representation.

Final data report including full data availability and discussion of the dataset achieved, summary statistics and graphical representation.

Data Delivery

Data and metadata will be provided in accordance with the MEDIN Data Guidelines for Physical Oceanography and Metocean (MEDIN). Real time data will be accessible via online portal. Raw and processed data will be uploaded monthly to the Projects' secure data server. All high frequency and other raw data will be provided following maintenance events and final recovery. Final deliverables will include full consolidation of processed data into a single file per sensor.

APPENDIX

3 Modelling

The data collection campaign often provides data at a limited number of points, for a limited duration. In order to extrapolate these results to a wider area, for a duration long enough to be used in design (preferably 20-40 years), or for a scenario different from the present conditions (that is, with additional structures present in the water), a modelling exercise is required.

Wind, wave, current, water level and sediment conditions are generally modelled using dedicated numerical hindcast models. Because these parameters are so critical to the design of the project, it is cost efficient to invest in a comprehensive modelling study. Such studies can be carried out internally or externally; however, any modelling that also feeds into the Environmental Impact Assessment (EIA) may be better accepted if carried out externally, by a consultant well known to the regulator. In some countries, the choice of a local consultant may also contribute to the acceptability of the study by the regulator/stakeholders.

A3.1 Inputs

Figure 7 summarises the inputs required for the modelling of wave, wind, current, water level and sediment. The resolution of bathymetry data should be consistent with the model resolution, which should be chosen to appropriately represent the physical processes to be modelled.

A3.2 Methodology

When reviewing proposed methodologies, attention should be given to:

1. *Accuracy*. The more accurate the model, the more costly. For example, in the early stage of development, it may be sufficient to have a qualitative model.

2. *Numerical model(s)*. Modelling of the key parameters usually requires the use of dedicated wave, wind, and hydrodynamic models. It is necessary to ensure the model(s) appropriately represent the physics of the site. To capture the complexities of the region, coupled modelling may be required. For EIA purposes, it is important to ascertain that the model would be accepted by the regulator. The choice of numerical model may be dictated by the stage of the project lifecycle. For example, during site selection, depth-averaged models are sufficient for tidal stream site selection, however during the design phase a 3-D model is necessary for the vertical profile of the site to be captured. Forcing of numerical wave and hydrodynamic models with bespoke downscaled wind models which will also be used as input to the wind resource aspect should be considered, improving alignment between the two disciplines.

Figure 7: Inputs required by a modelling study.

	WAVE	WIND	CURRENT	WATER LEVEL	SEDIMENT	USUAL PROVIDER
Bathymetry data	✓		✓	✓	✓	Client
Boundary conditions	✓	✓	✓	✓		Contractor
Sediment distribution					✓	Client
Atmospheric forcing	✓		✓	✓		Contractor
Calibration data	✓	✓	✓	✓	✓	Client
Physics modules	✓	✓	✓	✓	✓	Contractor

Photo credit: Fugro

3. *Calibration.* Model calibration should be undertaken to ensure an accurate outcome. Typically, this is done by running the model(s) under various setups for short periods and comparing their results with observations, to tune the model setup for the location before initiating the full model run. Note, however, that in some instances, models may be inadvertently calibrated against data that has been assimilated.

4. *Validation.* The model results should be extensively validated, and the validation exercise documented in detail within the final deliverable. Typical presentations include plots of modelled versus measured data alongside statistical comparative measures, for example correlation coefficient, root-mean-square-error, and scatter index. Again, it is important to ensure models are not inadvertently validated against data that has been assimilated.

5. *Resolution.* The model resolution, both spatial and temporal, should be sufficient to appropriately represent the physics of the site.

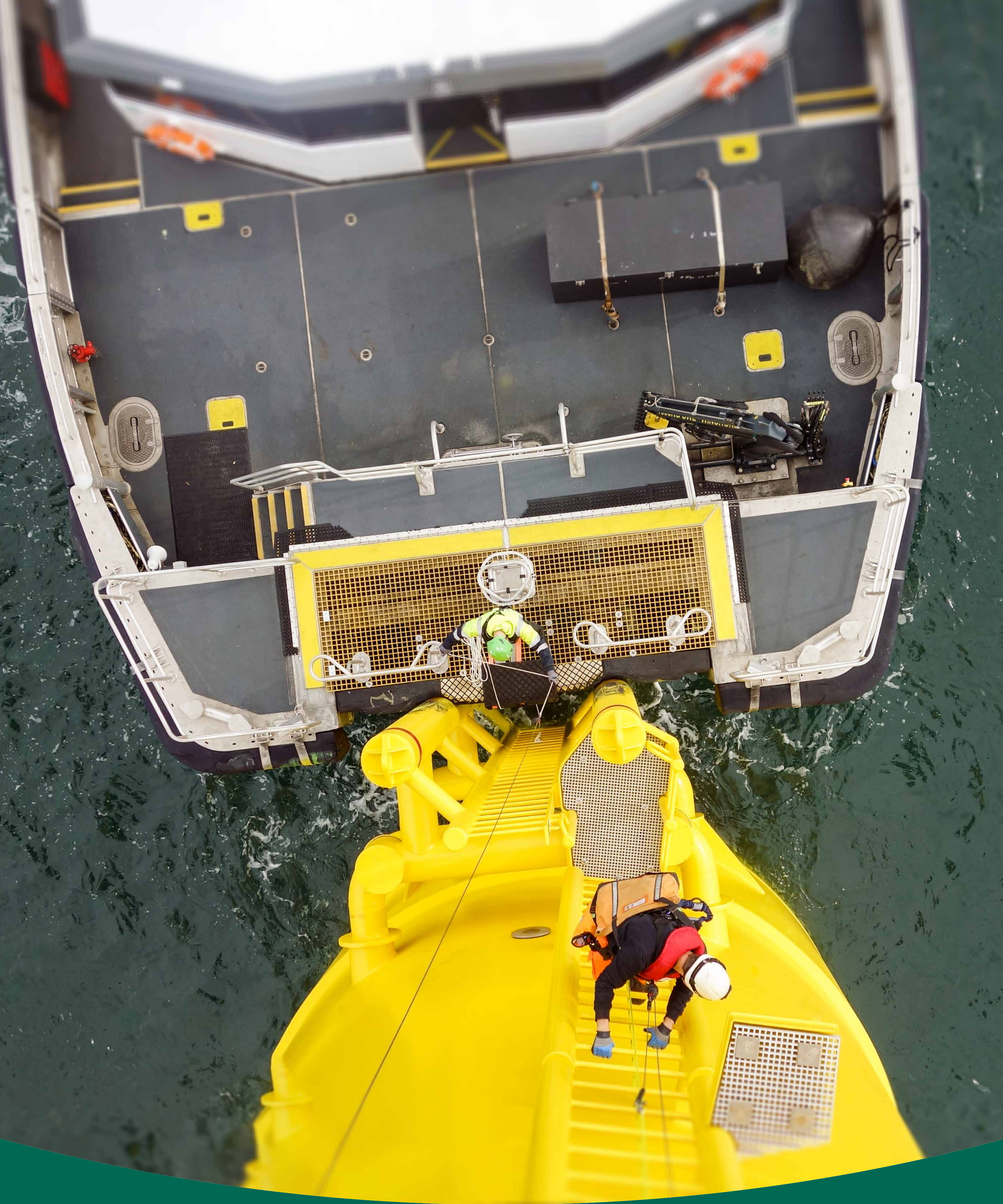
A3.3 Deliverables

Two key deliverables are expected from the modelling:

1. A comprehensive, long-term data set of wind, wave, current and water level. Early in the development of the project, these may be based on uncalibrated models and used for preliminary design; however, the models should be thoroughly calibrated and validated against on-site site measurements prior to detailed design or resource assessment.

2. An estimate of the impact of the project on wind, wave, current and sediment regimes during construction and operations. If the impacts on these parameters can be argued to be negligible based upon present knowledge and theoretical considerations, they may not need to be modelled.

Traditionally, time series at a number of points are provided as part of the deliverables, along with analyses based on these time series (see Section 5), and a calibration and validation report demonstrating the accuracy of the data. However, the data may be available to the modellers at all points in the model domain, in which case it may be cost-efficient to request the complete data set. Many modelling consultancies can provide the full dataset in the form of a database, accessed via online cloud services. The delivery method should consider the digitalisation path being adopted by the Developer, and how the data are made available to those using it directly and via software packages. Many cloud providers now offer solutions that readily deal directly with numerical model outputs such as NetCDF files or GRIB files.



International HQ: 1 Birdcage Walk , London SW1H 9JJ • United Kingdom • **Tel:** +44 (0) 20 7382 2600 • **Email:** info@imarest.org
Asia-Pacific Office: 298 Tiong Bahru Road, #05-01 Central Plaza, Singapore 168730 • **Tel:** +65 6472 0096

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