# Metocean Characterization Recommended Practices for U.S. Offshore Wind Energy

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## Disclaimer

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# 1 GENERAL

## 1.1 Introduction

This document provides guidance to offshore wind energy developers and the Bureau of Ocean Energy Management (BOEM) on best practices to reliably collect, analyze, and use site-specific metocean data.

## 1.2 Objectives

The objectives of this guideline are to:

- Provide offshore wind energy stakeholders with comprehensive guidance on accepted and emerging metocean characterization techniques that deliver essential data parameters while meeting minimum quality standards and quantifying uncertainty.
- Elevate the industry's practices to a range of peer-reviewed metocean characterization methods.
- Provide guidance to renewable energy developers and BOEM on best practices to reliably collect, analyze, and use that site-specific data when developing Facility Design Reports and Construction and Operations Plans, as required in the Code of Federal Regulations, 30 CFR 585.700 and 585.600, respectively.

## 1.3 Scope and application

The scope of this guideline covers the data necessary to support proper design, installation, operation, and maintenance of offshore wind facilities located within United States (U.S.) waters on the federal Outer Continental Shelf (OCS). This includes environmental conditions associated with the following phenomena:

- Movement of water – levels and flows
- Wind conditions
- Sea states – waves
- Atmospheric parameters including temperature, precipitation, and other meteorological conditions
- Physical ocean parameters including temperature, salinity, and other conditions

This guideline covers metocean conditions that are relevant for all components of an offshore wind facility including the wind turbines and support structures, electrical service platforms, power cables, meteorological (met) towers, and any other associated infrastructure. The focus of this guideline is on characterization of metocean conditions to support assessment of the following:

- General metocean climate for purposes of fatigue assessment
- Extreme conditions
- Risk of weather preventing safe access to site and associated downtime

This document does not provide guidance for determination of environmental loads associated with the environmental conditions covered herein. Additionally, energy yield analysis is not considered in detail herein as this is considered a commercial concern and is not a primary focus for this guideline; however, the guidance provided in this document does consider the requirements for providing "bankable" wind resource data.

This document is not intended to provide guidance for metocean conditions characterization for offshore wind facilities in waters under state jurisdiction, including maritime submerged lands and freshwaters (e.g., the Great Lakes).

## 1.4 Alternative methods and procedures

Methods and procedures alternative to those described in this guideline may be used, provided they meet the overall objectives and are suitable for the application.

## 1.5 Structure of guideline

The guideline is organized as follows:

- Section 1 contains the objectives and scope of the guideline. It further provides definitions and abbreviations.
- Section 2 contains a summary of the requirements for metocean data throughout the offshore wind project lifecycle.
- Section 3 contains guidance for collection of metocean data.
- Section 4 contains guidance for numerical modeling and simulation of metocean data.
- Section 5 contains guidance for data analysis and interpretation.

## 1.6 References

In the process of developing this guideline, DNV GL reviewed numerous documents that present guidance on various aspects of metocean conditions characterization. These references are listed below.

### 1.6.1 Applicability

The following documents include provisions which, through specific reference in the text, constitute provisions of this guideline.

In case of conflict between requirements of this guideline and a referenced code, the requirements of the code with the latest revision date shall prevail.

### 1.6.2 Reference standards and other guidance documents

| Reference | Title |
|---|---|
| API 2INT-MET | API 2INT-MET: Interim Guidance on Hurricane Conditions in the Gulf of Mexico; May 2007<br>https://law.resource.org/pub/us/cfr/ibr/002/api.2int-met.2007.pdf |
| API RP 2MET | API Recommended Practice 2MET – Derivation of Metocean Design and Operating Conditions (modified version of ISO 19901-1:2005); November 2014<br>https://www.techstreet.com/api/standards/api-rp-2met?product_id=1886618 |
| API RP 2A-WSD | API Recommended Practice 2A-WSD: Planning, Designing, and Constructing Fixed Offshore Platforms—Working Stress Design, 22. Edition, Nov. 2014 |
| CTC819 | Carbon Trust Offshore Wind Accelerator roadmap for the commercial acceptance of floating LIDAR technology, November 2013<br>https://www.carbontrust.com/media/422195/ctc819-owa-roadmap-commercial-acceptance-floating-lidar-technologies.pdf |

| Reference | Title |
|---|---|
| CTC870 | Carbon Trust Offshore Wind Accelerator Recommended Practice for Floating LiDAR Systems, October 2016<br>https://www.carbontrust.com/media/673560/owa-floatinglidarrecommendedpractice-25oct2016-final.pdf |
| DNVGL-SE-0190 | Project certification of wind power plants<br>https://rules.dnvgl.com/docs/pdf/DNVGL/SE/2015-12/DNVGL-SE-0190.pdf |
| DNVGL-SE-0420 | Certification of meteorological masts<br>https://rules.dnvgl.com/docs/pdf/DNVGL/SE/2015-12/DNVGL-SE-0420.pdf |
| DNVGL-ST-N001 | Marine operations and marine warranty<br>https://rules.dnvgl.com/docs/pdf/dnvgl/st/2016-11/DNVGL-ST-N001.pdf |
| DNVGL-ST-0054 | Transport and installation of wind power plants<br>https://rules.dnvgl.com/docs/pdf/DNVGL/ST/2017-06/DNVGL-ST-0054.pdf |
| DNVGL-ST-0119 | Design of Floating Wind Turbine Structures<br>http://rules.dnvgl.com/docs/pdf/dnv/codes/docs/2013-06/os-j103.pdf |
| DNVGL-ST-0126 | Support structures for wind turbines<br>https://rules.dnvgl.com/docs/pdf/DNVGL/ST/2016-04/DNVGL-ST-0126.pdf |
| DNVGL-ST-0145 | Offshore substations<br>https://rules.dnvgl.com/docs/pdf/DNVGL/ST/2016-04/DNVGL-ST-0145.pdf |
| DNVGL-ST-0437 | Loads and site conditions for wind turbines<br>https://rules.dnvgl.com/docs/pdf/DNVGL/ST/2016-11/DNVGL-ST-0437.pdf |
| DNVGL-RP-0360 | Subsea power cables in shallow water<br>http://rules.dnvgl.com/docs/pdf/dnvgl/RP/2016-03/DNVGL-RP-0360.pdf |
| DNVGL-RP-C205 | Environmental conditions and environmental loads<br>http://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2017-08/RP-C205.pdf |
| IEC 61400-1 | Wind turbines – Part 1: Design requirements<br>https://webstore.iec.ch/publication/5427 |
| IEC 61400-3 | Wind Turbines – Part 3: Design requirements for offshore wind turbines<br>https://webstore.iec.ch/publication/5446 |
| IEC 61400-12-1 | Power performance measurements of electricity producing wind turbines<br>https://webstore.iec.ch/publication/60076 |
| ISO/IEC 17025 | General requirements for the competence of calibration and testing laboratories<br>https://www.iso.org/publication/PUB100424.html |
| ISO 19901-1 | Petroleum and natural gas industries -- Specific requirements for offshore structures -- Part 1: Metocean design and operating considerations<br>https://www.iso.org/standard/60183.html |
| TAP 670aa | Design Standards for Offshore Wind Farms, September 2011<br>https://www.bsee.gov/sites/bsee.gov/files/tap-technical-assessment-program/670aa.pdf |
| TAP 672 | Development of an Integrated Extreme Wind, Wave Current and Water Level Climatology to Support Standards-Based Design of Offshore Wind Projects, February 2014<br>https://www.bsee.gov/research-record/tap-672-development-integrated-extreme-wind-wave-current-and-water-level-climatology |
| TAP 724 | Development of Hazard Curves for WEAs off the Atlantic Seaboard, December 2015<br>https://www.boem.gov/724AA/ |
| WMO 1091 | Guidelines on Ensemble Prediction Systems and Forecasting, 2012<br>http://www.wmo.int/pages/prog/www/Documents/1091_en.pdf |
| WMO No. 8 | Guide to Meteorological Instruments and Methods of Observation: (CIMO guide)<br>https://library.wmo.int/pmb_ged/wmo_8_en-2012.pdf |
| MEASNET ESSWC | MEASNET Procedure: Evaluation of Site-Specific Wind Conditions. Version 2, April 2016 |

Note that IEC 61400-3 is currently being updated and the pending IEC 61400-3-1 “Design requirements for fixed offshore wind turbines” will include annexes focused on assessment of wind and wave conditions under tropical cyclone conditions as well as design rules for such conditions. When available, IEC 61400-3-1 should be considered for additional guidance within the framework of this document.

It is worth noting that IEC 61400-15 “Wind energy generation systems - Part 15: Assessment of site specific wind conditions for wind power stations” is currently in development and is planned to be published in 2019. The intention of IEC 61400-15 is to define a framework for assessment and reporting of the wind resource, energy yield and site suitability input conditions for both onshore and offshore wind facilities. This includes:

1. Definition, measurement, and prediction of the long-term meteorological and wind flow characteristics at the site
2. Integration of the long-term meteorological and wind flow characteristics with wind turbine and balance of plant characteristics to predict net energy yield
3. Characterizing environmental extremes and other relevant plant design drivers
4. Assessing the uncertainty associated with each of these steps
5. Addressing documentation and reporting requirements to help ensure the traceability of the assessment processes.

When available, IEC 61400-15 should be considered for additional guidance within the framework of this document.

Additionally, the American Wind Energy Association (AWEA) Offshore Wind Standards Subcommittee is in the process of establishing a set of guidance documents for offshore wind energy development in the US, including a Metocean Conditions Characterization Recommended Practice. The pending AWEA Metocean Conditions Characterization Recommended Practice is expected to build upon the guidance presented in this guideline and will also include areas that are out of scope for this guideline, including state waters and inland waterways. The AWEA Metocean Conditions Characterization Recommended Practice is expected to be published in 2019.

### 1.6.3 Other references

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## 1.7 Definitions

### 1.7.1 Verbal forms

| **Term** | **Definition** |
|---|---|
| shall | Verbal form used to indicate requirements strictly to be followed in order to conform to the document. |
| should | Verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required. |
| may | Verbal form used to indicate a course of action permissible within the limits of the document. |

### 1.7.2 Definitions

| **Term** | **Definition** |
|---|---|
| ambient turbulence | Turbulence with no offshore wind facility present, i.e., including no effect from turbines. |
| extreme external conditions | Extreme external conditions are events with a recurrence period of greater than 1 year. |
| facility | Term used in the context of wind farm projects to describe the project or object to be developed, manufactured, and maintained. In this document the term refers either to “wind turbines with support structures,” the “offshore substation with topside and support structure,” “power cables,” or “met towers.” |
| hindcast | Method of simulating historical (metocean) data for a region through numerical modelling. |
| metocean data | Term describing collectively the meteorological and oceanographic data relevant for offshore wind facilities. |
| normal external conditions | Normal external conditions are in general those events which have a probability of being exceeded once a year or more often. |
| omni-directional | Taking all wind/wave/current speed values in the dataset whatever the wind/wave/current direction. |
| wind shear | Vertical variation in mean wind speed. |

## 1.8 Abbreviations and symbols

### 1.8.1 Abbreviations and acronyms

| **Abbreviation** | **Meaning** |
|---|---|
| ADCP | Acoustic Doppler Current Profiler |
| AGL | Above Ground Level |

| **Abbreviation** | **Meaning** |
|---|---|
| AROME | Applications of Research to Operations at Mesoscale |
| ASL | Above mean Sea Level |
| BOEM | Bureau of Ocean Energy Management |
| BSEE | Bureau of Safety and Environmental Enforcement |
| CCI | Climate Change Initiative |
| CCMP | Cross-Calibrated Multi Platform |
| CDF | Cumulative Distribution Function |
| CFD | Computational Fluid Dynamics |
| CFR | Code of Federal Regulations |
| CFSR | Climate Forecast System Reanalysis |
| CI | Confidence Interval |
| CLC | CORINNE Land Cover database |
| CO-OPS | Center for Operational Oceanographic Products and Services |
| COP | Construction and Operation Plan |
| CNES | Centre National d'Etudes Spatiales |
| CTD | Conductivity Temperature Depth |
| CVA | Certified Verification Agent |
| DHQ | Mean Diurnal High Water Inequality: the difference in height of the two high waters of each tidal day for a mixed or semidiurnal tide |
| DLQ | Mean Diurnal Low Water Inequality: The difference in height of the two low waters of each tidal day for a mixed or semidiurnal tide |
| DOF | Degree of Freedom |
| DOI | U.S. Department of Interior |
| DTL | Diurnal Tide Level: the arithmetic mean of mean higher high water and mean lower low water |
| DUE | Data User Element |
| ECMWF | European Center for Medium range Weather Forecast |
| EOF | Empirical Orthogonal Function |
| ERA | ECMWF Reanalysis |
| ESA | European Space Agency |
| ESS | Extreme Sea State – used in IEC standards |
| ETC | Extra Tropical Cyclone |
| EWH | Extreme Wave Height |
| EWM | Extreme Wind speed Model |
| FDR | Facility Design Report |
| FLD | Floating Lidar |
| FLS | Fatigue Limite State |

| **Abbreviation** | **Meaning** |
|---|---|
| GEV | Generalized Extreme Value distribution |
| GMTED | Global Multi-resolution Terrain Elevation Data |
| GP | Generalized Pareto distribution |
| GPS | Global Positioning System |
| GT | Great Diurnal Range: the difference in height between mean higher high water and mean lower low water |
| HAT | Highest Astronomical Tide: the elevation of the highest astronomical predicted tide expected to occur at a specific tide station over 19 years |
| HF | High Frequency |
| HIRLAM | High Resolution Limited Area Model |
| HSE | Health Safety and environment |
| HSWL | Highest still water level |
| IEC | International Electrotechnical Commission |
| I-FORM | Inverse First Order Reliability Method |
| IOWAGA | Integrated Ocean Waves for Geophysical and other Applications |
| IPCC | Intergovernmental Panel on Climate Change |
| ISO | International Organization for Standardization |
| KF | Kalman Filter |
| LAT | Lowest Astronomical Tide: the elevation of the lowest astronomical predicted tide expected to occur at a specific tide station over 19 years |
| LIDAR | LIght Detection And Ranging |
| LSWL | Lowest Still Water Level |
| MCP | Measure Correlate Predict |
| MERRA | Modern Era Retrospective analysis for Research and Applications |
| MIC | Microbiologically Influenced Corrosion |
| MHHW | Mean Higher High Water: the average of the higher high water height of each tidal day observed over 19 years |
| MHW | Mean high Water: the average of all the high water heights observed over 19 years |
| MLLW | Mean Lower Low Water: the average of the lower low water height of each tidal day observed over 19 years. Reference for water levels. |
| MLW | Mean Low Water: the average of all the low water heights observed over 19 years |
| MN | Mean Range of Tide: the difference in height between mean high water and mean low water (Marnage) |
| MOS | Model Output Statistics |
| MSL | Mean Sea Level: the arithmetic mean of hourly heights overserved over 19 years |

| **Abbreviation** | **Meaning** |
|---|---|
| MTL | Mean Tide Level: the arithmetic mean of mean high water and mean low water |
| MWL | Mean Water Level |
| NASA | National Aeronautics and Space Administration |
| NCAR | National Center for Atmospheric Research |
| NCEI | National Centers for Environmental Information |
| NCEP | National center for Environmental Prediction |
| NEPA | National Environmental Protection Act |
| NOAA | National Oceanic and Atmospheric Administration |
| NSS | Normal Sea State – used in IEC standards |
| NTM | Normal Turbulent Model |
| OCS | Outer Continental Shelf |
| OGCM | Ocean General Circulation Model |
| OSU | Oregon State University |
| POT | Peak Over Threshold |
| PUV | Pressure and wave orbital velocity: zonal U and meridional V components |
| RCM | Rotor Current Meter |
| ROV | Remotely Operated Vehicle |
| RS | Remote Sensing |
| RWH | Reduced Wave Height |
| RWM | Reduced Wind-speed Model |
| SAP | Site Assessment Plan |
| SAR | Synthetic Aperture RADAR |
| SODAR | SOnic Detection And Ranging |
| SSS | Severe Sea State – used in IEC standards |
| SST | Sea Surface Temperature |
| TAP | Technology Assessment Program |
| TC | Tropical Cyclone |
| ULS | Ultimate Limit State |
| U.S. | United States |
| USGS | U.S. Geological Survey |
| VACM | Vector-Averaged Current Meter |
| VMCM | Vector-Measuring Current Meter |
| WRF | Weather Research and Forecasting model |

### 1.8.2 Symbols

| **Symbol** | **Meaning** |
|---|---|
| $\rho_{10min}$ | 10min averaged air density |
| $\Phi$ | Relative humidity |
| $\alpha$ | Constant in wave spectrum (Philipps, Hasselmann …) |
| $\alpha_w$ | Exponent in wind shear formulation |
| $\alpha_c$ | Exponent in current profile formulation |
| $\beta$ | Slope |
| $\gamma$ | Peak enhancement factor in JONSWAP spectrum |
| $\Gamma()$ | Gamma function |
| $\mu$ | Location parameter in a distribution function |
| $\sigma$ | Scale parameter in a distribution function |
| $\sigma_p$ | Width of peak parameter in JONSWAP spectrum |
| $\sigma_w$ | Wave spreading |
| $\sigma_U$ | standard deviation of 10-minute averaged wind speed |
| $\xi$ | Shape parameter in a distribution function |
| $\theta_{MWD}$ | Mean wave direction |
| $\Theta_{PWD}$ | Peak wave direction |
| $\omega$ | Wave pulsation |
| $\omega_p$ | Peak pulsation |
| $B_{10min}$ | Air pressure at hub height |
| $C$ | Wave phase speed |
| $C_g$ | Wave group speed |
| $D()$ | Angular Distribution Function |
| $d$, $h$ | Water depth |
| $f$ | frequency |
| $F()$ | 2D Wave spectrum (frequency, direction) |
| $F$ | Fetch length |
| $g$ | Gravity constant |
| $H$ | Individual wave height |
| $Cr$ | Individual wave crest height |
| $H_{m0}$ | Significant wave height, defined as $H_{m0}$ = 4sqrt(m0), where m0 is the zero moment (integral) of the wave spectrum |
| $H_S$ | Significant wave height, defined as the mean of the highest 1/3 of the wave heights in a sea state |
| $Ir$ | Iribarren Number |

| **Symbol** | **Meaning** |
|---|---|
| $k$ | Wave number |
| $L$ | Wave length |
| $P_c$ | Minimum pressure in the center of tropical cyclone |
| $P_n$ | Normal or ambient pressure |
| $P_w$ | Pressure vapor |
| $r$ | Radial distance (from center of tropical cyclone for example) |
| $R_{mw}$ | Radius of maximum sustained wind |
| $R_0$ | Gas constant of dry air |
| $R_w$ | Gas constant of water vapor |
| $S()$ | 1D wave spectrum (frequency or pulsation) |
| $S$ | Wave steepness |
| $s$ | Spreading coefficient in Cos 2s |
| $T_{10min}$ | 10min averaged air Temperature |
| $T$ | Individual wave period |
| $T_{m01}$ | Mean wave period from wave spectrum |
| $T_{m02}$ | Zero-up-crossing wave period from wave spectrum |
| $T_p$ | Peak wave period: inverse of frequency associated with the highest energy in wave spectrum |
| $T_Z$ | Zero-up-crossing wave period |
| u* | Friction velocity |
| $U_{10}$ | 10 min mean wind speed at 10m above mean sea level |
| $U(z)$ | 10 min mean wind speed at z height ASL |
| $U_{19,5}$ | 10 min mean wind speed at 19.5m above mean sea level (used in JONSWAP formulation) |
| $U_{c0}$ | Surface current velocity |
| $U_c(z)$ | Current velocity at z water depth |
| $V_{10m}$ | Wind speed at 10m ASL for tropical cyclone parametric model, varying with distance and direction |
| $V_{fm}$ | Forward cyclone speed |
| $V_p$ | Wind speed from parametric model, varying with distance |
| $Z$ | depth, varying from sea surface ($Z$=0) to sea bed ($Z$=-d) |
| $Z_0$ | Surface roughness parameter |

# 2 METOCEAN DATA NEEDS

This section describes the metocean parameters that are relevant for the various project lifecycle phases. For the purposes of this document, the offshore wind project lifecycle is broken down into five phases as shown in Figure 2-1.

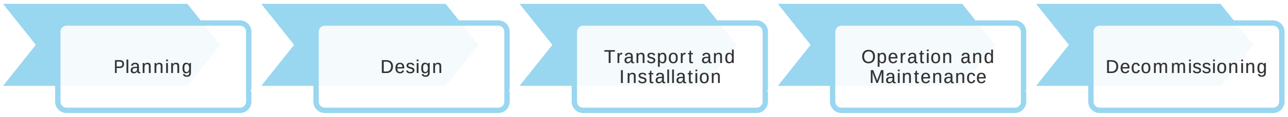


**Figure 2-1 Lifecycle phases of an offshore wind project**

Metocean data are required to describe conditions related to:

- Movement of water – levels and flows
- Wind conditions
- Sea states – waves
- Atmospheric parameters including temperature, precipitation, icing, and other meteorological conditions
- Physical ocean parameters including temperature, salinity, sea ice, and other conditions
- Joint conditions, such as wind and wave conditions.

Site conditions consist of all site-specific conditions that may influence the design of a wind turbine structure and other components of an offshore wind facility by governing their loading, capacity, or both. Additionally, site conditions include conditions that may influence marine operations associated with construction, operations and maintenance (O&M), and decommissioning. To ensure the appropriate level of safety and reliability, site specific conditions representative of the offshore wind facility site shall therefore be taken into account in the design. Site conditions cover virtually all environmental conditions on the site, including but not limited to meteorological conditions and marine conditions (together termed "metocean" conditions), soil conditions, seismicity, biology, and various human activities.

The metocean parameters required for each phase of the offshore wind project lifecycle are described in this section.

The metocean conditions are:

- Atmospheric conditions including wind speed, wind shear, and turbulence as well as weather conditions such as temperature, precipitation, density, and humidity
- Marine conditions including waves, sea currents, water level, sea ice, and marine growth.

These conditions may be mutually dependent. The aforementioned list of metocean conditions is not exhaustive. Relevant conditions include both measured parameters (e.g., wind speed) and derived parameters (e.g., shear, turbulence).

The metocean conditions at the offshore wind facility site should be established on the basis of measurements at the actual location or adjacent locations, and may be supplemented by hindcast data as well as theoretical models and recommendations given in various standards.

From a regulatory perspective, the requirements for offshore wind data are outlined at a high level in 30 CFR 585. Developers of offshore wind facilities in federal waters on the OCS are required to submit relevant information to support evaluation of the plans and designs for the facility. Typically, this includes a Site Assessment Plan (SAP), Construction and Operations Plan (COP) and Facility Design Report (FDR).

Per 30 CFR 585.611 and 585.627, a SAP or COP, respectively, shall include information regarding meteorological and oceanographic hazards to support BOEM's National Environmental Protection Act (NEPA) review process. The CFR does not provide any further guidance regarding what meteorological or oceanographic data should be submitted; however, BOEM guidance (https://www.boem.gov/COP-Guidelines/) indicates that the SAP or COP shall include a description of conditions that could destabilize planned activities or facilities.

For the FDR, 30 CFR 585.701 stipulates that a summary of the environmental data used in the design or analysis of the facility should be provided including information on:

1. Extreme weather
2. Seafloor conditions
3. Waves, wind, current, tides, temperature, snow and ice effects, marine growth, and water depth.

Note that seafloor conditions, including scour and bathymetry, are not covered in this document.

## 2.1 Planning

The planning phase includes the early stages of the project development process including initial site identification, conceptual design, site assessment, and permitting. Within the U.S. commercial leasing framework, this phase generally commences after a lease has been issued and includes the activities necessary to collect information to support design and planning for construction and operations. During the planning phase, the conceptual design is usually completed.

### 2.1.1 Overview of project requirements

During the planning stage, metocean data are required to support a range of activities including the following:

- Feasibility assessment
- Conceptual design
- Permitting
- Construction planning
- Operations and maintenance planning.

During the planning stage, developers of offshore wind facilities are required to submit specific planning documents that require metocean data, namely the SAP and COP. As indicated above, the SAP and COP shall include information regarding meteorological and oceanographic hazards. It is noted that the regulatory requirements for the SAP and COP are not specific, but BOEM has developed guidance documents to supplement the regulations.

In general, during the planning phase, site specific measurements may not be available, particularly during the early planning phase. As such, metocean data may be based on minimally verified modelled datasets, satellite measurements, and/or extrapolated from any nearby measurements that may be available. As development for a facility advances through the planning phase, a measurement campaign will typically be conducted to collect site specific metocean measurements.

Publicly available metocean datasets can be used to support the planning phase (and potentially later phases depending on the dataset). Examples of such datasets include the following:

- NREL Wind Prospector (maps.nrel.gov/wind-prospector/)
- MarineCadastre.gov
- Northeast Ocean Data (https://www.northeastoceandata.org/)
- Mid-Atlantic Ocean Data Portal (http://portal.midatlanticocean.org/)
- US Met-Ocean Data Center for Offshore Renewable Energy (http://www.usmodcore.com/)

### 2.1.2 Resource assessment and energy yield

At the planning stage, the following data need to be obtained for the extents of the site at hub height and throughout height of wind turbine, reflecting the expected spatial variability of the wind parameters:

- Wind speed statistics (minimum, mean, standard deviation, maximum) and distributions
- Wind directionality
- Wind profile, wind shear, turbulence.

In addition to the above wind parameters, density and temperature data are needed. Other atmospheric parameters such as precipitation and icing conditions can help inform resource and energy yield assessment.

At the planning stage this data can come from numerical models, with due attention paid to the quality of the modelled data, which should be calibrated and cross-checked against satellite data or other measured data available in the vicinity. The variability across the site can be estimated using modelled data points covering the full area of the facility with a resolution that is appropriate for the expected spatial variability of the site. Temporal variability on various time scales (e.g., 10 minute, diurnal, seasonal, annual, decadal) is also important to understand. The primary objective of a resource assessment campaign is to understand the long-term average wind resource conditions at hub height, and this is typically done by correlating relatively short-term measurement datasets (typically on-site) to longer term reference datasets (modeled or measured) to establish a relationship between the datasets. This relationship is then used to adjust the short-term measurements to come up with an estimate of the long-term conditions.

In addition, the following topics should be considered at the planning stage:

- Development of reliable power output curves
- Determination of wake effects and assessment of overall wind facility performance, including project losses
- Accuracy of existing data and planning for data collection/measurement campaign

- Identification of data gaps to be addressed.

With respect to project losses, a range of metocean parameters (in addition to wind conditions) is required to inform assessment of site specific project losses, for example:

- Waves and current conditions – necessary for assessing site accessibility
- Lighting frequency – required to assess lighting related losses
- Icing conditions – icing downtime and icing related performance degradation
- Precipitation (hail and rain, especially) – important for informing blade and other performance degradation losses
- Air temperature – required to quantify frequency and duration of high/low temperature losses.

In addition to performing an initial local resource assessment, the intention should be to understand as much as possible the wind resource across the site (including variability) and identify areas of uncertainty which may prove crucial for the accurate assessment of the power output and hence the project overall success. By the completion of the planning stage it is expected that a range of potential turbine options have been identified and basic layout will be completed as part of conceptual design. Uncertainty in the wind data, which may affect these choices, needs to be well understood and measures taken to reduce the uncertainty during the planning stage. Given the pace of technology development and the length of time between early planning and final turbine selection, initial resource assessment should consider existing turbine technology as well as emerging technology.

For detailed guidance on resource and energy yield assessment, MEASNET ESSWC should be consulted. Additionally, as noted above, the pending IEC 61400-15-1 will provide guidance on this topic.

### 2.1.3 Feasibility assessment and conceptual design

For feasibility assessment, it is necessary to gain an overall understanding of the metocean conditions across the area of interest and to identify any conditions or metocean phenomena that may pose a considerable risk to an offshore wind facility.

During this phase, primary concerns include the following:

- Adequacy of the wind resource
- Wave conditions
- Currents and water levels
- Extreme conditions including tropical cyclone conditions.

As noted in Section 2.1.2, the primary interest for wind resource assessment is the characterization of the long-term average conditions at hub height. For the balance of the other applications such as design, installation, and operational planning (and thus assessment of overall feasibility), consideration of extremes and transient events becomes important as well.

Other metocean conditions are generally secondary at this stage; however, conditions that may be unique or present considerable risk may need to be considered at this stage (e.g., presence of sea ice). Overall it is necessary to understand the key metocean conditions that will drive the design process that follows.

As a minimum, the following data should be obtained, which can come from a desk study using modelled data from hindcast or reanalysis databases validated against satellite measurements and any in-situ measurements available in the vicinity; the period covered by the data should be long enough to represent the different meteorological phenomena and their temporal variability. This preliminary data shall be refined at later stages of the project using additional site-specific information, for example using data arising from the metocean measurement campaign and site-specific numerical modelling. These data can be used to support development of conceptual designs which can be refined as development progresses and additional metocean data is collected. To the extent that other data are available at this stage (as described in Section 2.2), such data can be used to inform feasibility assessment and assess conceptual designs with greater confidence. Note that the objective and level of detail for a feasibility assessment may vary from project to project so the following should be considered as general guidance.

- Tropical/extratropical cyclone occurrence
    - Preliminary assessment of cyclone risk at a site including annual frequency of occurrence and variation on seasonal and annual basis
    - Average (10-min or 1-min wind speed) and maximum (3-sec gust) recorded strength
    - General trends and common tracks.
- Wind conditions
    - Preliminary estimate of extreme wind conditions including wind speed at 10 m asl and at hub height for various averaging periods (e.g., 1-hour, 10-min, 1-min and 3-sec gust) by direction and for appropriate return periods (e.g., 1, 10, 50 years), for normal and tropical cyclone conditions as appropriate. (Care shall be taken in extrapolation of extreme values for tropical cyclone prone areas as the synthesis of extreme value distributions for cyclone conditions is different than for normal conditions).
    - Estimate of average wind conditions for resource assessment (see Section 2.1.2).
- Wave conditions
    - Preliminary estimate of extreme wave conditions: 3-hour sea states including significant wave height and peak period by direction for appropriate return periods (e.g., 1, 10, 50 years), for normal and tropical cyclone conditions as appropriate.
    - Preliminary estimate of average wave conditions, including wave scatter diagrams of wave height versus peak period and by direction.
- Currents and water levels
    - Preliminary estimate of extreme current conditions: 1-hr mean current speed at surface and throughout water column by direction for appropriate return periods (e.g., 1, 10, 50 years), for normal and tropical cyclone conditions as appropriate.
    - Preliminary estimate of average current conditions, including scatter diagrams by direction.
    - Tidal levels, tidal ellipse.
    - Preliminary estimate of extreme water levels, including positive/negative surge and extreme crest elevation for normal and tropical cyclone conditions as appropriate.
- Other parameters – Overall atmospheric and oceanographic parameters are needed at this stage for preliminary design assessment and load calculations and for environmental impact assessment. Relevant parameters include the following:
    - Relative humidity
    - Air pressure
    - Density
    - Bathymetry, site survey
    - Sea ice, icebergs, ice floes

- Air and sea water temperature.

As indicated above, other parameters may be relevant to consider during the feasibility stage if such information is available.

### 2.1.4 Permitting and environmental impact analysis

As part of the permitting process, an assessment of potential environmental impacts would typically be conducted for a facility. The purpose of such an assessment is to identify any potential changes to baseline environmental conditions due to the planned facility and any associated impacts on sensitive receptors. In addition to other environmental data, metocean conditions data are necessary for this assessment. This typically includes general descriptions of the metocean conditions including the high frequency, low energy events (normal conditions) and the low frequency, high energy events (extreme conditions). This also includes assessment of various processes such as sediment transport which is based on models of physical processes and thus require a metocean database. At a minimum, this database should be consistent with the data used for conceptual design as described in Section 2.1.3. Additionally, metocean data should include information on tides, tidal streams and currents; weather, including visibility; and ice conditions to support assessment of navigational risks associated with an offshore wind facility, as outlined in NVIC 02-07.

## 2.2 Design

Metocean data are required to describe the metocean site conditions, which are part of the basis for the design of an offshore wind facility. These conditions include the ambient conditions as well as conditions that may be influenced by the wind turbines or other components of an offshore wind facility, for example wake effects. Such facility-influenced conditions are dependent on the layout of the turbines, and on the rotor-diameter of the wind turbines. These can only be determined at the stage in the design process when the facility layout and wind turbine type are known.

For representation of the metocean conditions for design purposes, a distinction is made between normal conditions and extreme conditions. Normal conditions are generally those that influence recurrent structural loading conditions which will occur more frequently than once per year during normal turbine operation, while extreme wind conditions represent rare external design conditions having a recurrence period longer than one year (for example, the recurrence period of 50 years is applied for turbine foundation design in DNVGL-ST-0437, a 100-year recurrence period is applied for offshore substation design in DNVGL-ST-0145, and additionally a 500-year recurrence period is applied for robustness check at sites with possible tropical cyclones per API RP 2A-WSD 22. Edition and IEC 61400-3-1 as well as accidental limit states in DNVGL-ST-0119). Normal conditions are primarily used as a basis for determining fatigue loads, and also extreme loads from extrapolation of normal operation loads. Extreme conditions are conditions that can lead to extreme loads on the components of an offshore wind facility including the wind turbine, the support structure, and the foundation.

### 2.2.1 Overview of project requirements

For the design of offshore wind facilities, site-specific metocean data shall be established containing information associated with the conditions listed below. The items above are detailed in the following sections and a more thorough overview of metocean site-specific parameters required for design is given in Section 2.2.9.

- Wind conditions
    - Normal wind conditions including omni-directional and directional wind speed distribution and shear
    - Ambient turbulence intensity and standard deviation including wake effects from neighboring turbines; the wake effects depend on the wind turbine layout and the rotor diameter and can only be estimated when this information is available in the design process
    - Extreme wind conditions including extreme wind speed, shear, extreme turbulence model, and extreme deterministic wind events such as extreme operating gust, extreme direction change. (As defined in the IEC system, the extreme deterministic wind events depend on the park layout and the rotor diameter and can only be estimated when the type of turbine has been decided. This information is available in the design process.)
- Marine conditions
    - Current speeds and directions for normal and extreme conditions
    - Water levels including tides, extreme water levels, and sea level change
    - Significant wave heights, maximum wave heights and crests, wave periods and directions for normal and extreme conditions
- The correlation of wind and wave statistics shall be established for normal and extreme conditions. Correlation of wind and waves shall also consider their respective directions. Correlation with water level and current statistics may be important at sites with high storm surge and/or current speed.
- Other metocean parameters, including:
    - Bathymetry and seabed changes which may influence the marine parameters and their variability over the offshore wind facility site
    - The vertical reference for the project
    - Wave breaking
    - Air temperature, air density, air humidity, lightning
    - Sea ice
    - Ice from precipitation/sea spray
    - Water density, water salinity, water temperatures
    - Marine growth.

In an offshore wind facility consisting of several wind turbines the metocean conditions and the water depth vary from turbine to turbine. If the metocean design conditions are determined for only one or a few locations (typically located at the facility’s corners), it should be ensured that the metocean parameters at these locations are conservative for design of the remaining turbine positions.

Additionally, consideration shall be given to metocean conditions for any cable routes associated with an offshore wind facility.

### 2.2.2 Wind conditions

Generally, in the short term (i.e., over a 10-minute period), stationary wind conditions with constant mean wind speed $U_{10}$ and constant mean standard deviation $\sigma_U$ are assumed to prevail. For design, the wind climate is therefore represented by the long-term 10-minute mean wind speed $U_{10}$ and the standard deviation $\sigma_U$ of the wind speed. Furthermore, various gust events are necessary for design, for example the extreme coherent gust with a time scale of 10.5 seconds for power production, the extreme operating gust with a time scale of 10.0 seconds for occurrence of fault during power production as well as for start-up and shut-down of the wind turbines, as defined in DNVGL-ST-0437 and IEC 61400-1, and extreme gusts with 3-second time scale for various recurrence periods, e.g., 50 years.

The 10-minute mean wind speed $U_{10}$ is a measure of the intensity of the wind and the standard deviation $\sigma_U$ is a measure of the variability of the wind speed about the mean. The variability of the wind speed is known as turbulence. The turbulence intensity is defined as $\sigma_U/U_{10}$. This is sometimes referred to as the ambient turbulence, i.e., the turbulence at the site without influence from neighboring turbines. The values of the turbulence intensity and standard deviation should be determined using appropriate statistical techniques applied to measured wind speed. Also, an offshore wind facility generates its own wind climate due to downstream wake effects, and the wind climate in the center of the facility may therefore be very different from the ambient wind climate. These effects are described further in section 5.1.

Wind speed data are height-dependent. Often, the wind speed measured at 10 m mean sea level (MSL) is used as a reference, or the hub height of the wind turbine if this is known. The vertical wind shear expresses the vertical variation in mean wind speed due to turbulent mixing, and depends for example on the atmospheric stability and terrain/surface roughness. Vertical wind profiles and shear are described further in Section 5.1.

When wind speed data are used for structural design, it is important to be aware of the reference temperature, in particular with a view to the operation philosophy adopted for the wind turbine design and the temperature assumptions made in this context.

#### 2.2.2.1 Wind data

Site-specific measured wind data over sufficiently long periods with minimal or no gaps should be applied. What is a sufficiently long period in this context depends on which kinds of wind parameters are sought-after. Representativeness of the data for interpretation of the sought-after wind parameters is the key issue, for example:

- For proper estimation of extreme values many years of data are needed, and generally the length of time covered by data should be long enough that the sought-after key figures can be captured and extracted; as an example, the DNV GL Standard DNVGL-ST-0437 states that the data period underlying extreme value estimates should preferably be 10 years or more.
- The mean value of the 10-minute mean wind speed is expected to exhibit variability from year to year such that several years of data are needed to properly estimate this parameter.

For other types of data shorter measurement periods may suffice; for example, wind shear and mean wind speed standard deviation conditioned on 10-minute mean wind speed (for turbulence).

The chosen measurement period should include all load-relevant aspects. These are, in particular:

- Seasonal and diurnal effects
- Thermal effects.

Various means of measuring techniques are described in Section 3.2, and methods for filling data-gaps and correlating short-term data with an appropriate long-term data source to achieve a synthesized long-term data series are given in Section 5.1.

When no site-specific wind data are available and data from adjacent locations are to be capitalized on instead, proper transformation of such other data shall be performed to account for possible differences due to, for example, proximity of land. This may for example be done by applying hindcast data or information from hindcast databases.

Hindcast of wind data are generally considered to be too smoothed by the numerical interpretation to be applicable as the sole source for wind assessment, but may be used for correlation of wind and waves, to extend measured time series, or to interpolate to places where measured data have not been collected. If hindcast is used, the hindcast model shall be validated against measured data to ensure that the hindcast results comply with available measured data. Hindcasts are described in more detail in Section 4.

For the purposes of assessment of ambient turbulence, if measurements of mean wind speed standard deviation conditioned on 10-minute mean wind speed are not available, measurements from similar sites may be utilized. It is important that the sites have similar characteristics relating to parameters important for turbulence, for example regarding distance to land, as turbulence over land is higher than turbulence over sea, and wave climate, as this affects the surface roughness.

Simultaneous observations of metocean data (wind, waves, current, water level) may be obtained to establish correlations. Correlation between wind and waves is of special importance for design of offshore wind turbines and is described in Section 2.2.4.

#### 2.2.2.2 Normal wind conditions

The normal wind conditions are specified in terms of an air density, a long-term distribution of the 10-minute mean wind speed, a wind shear in terms of a gradient in the mean wind speed with respect to height above the sea surface, and turbulence.

For determination of the normal wind conditions, values of the following parameters at the wind turbine site should be estimated:

- The long-term 10-minute average wind speed at hub height; monthly, all-year and omni-directional, directional
- Wind speed distribution (e.g., Weibull, Rayleigh, measured, other); omni-directional and directional
- Wind speed vertical profile
- Wind shear
- Ambient turbulence intensity and standard deviation as a function of average wind speed.
- Turbulence including wake effects from neighboring turbines; the wake effects can only be estimated when the type of turbine has been decided in the design process
- Air density.

These items are described in more detail in Section 5.1.

An appropriate interval of wind speed bin and wind direction sectors used in the above should be chosen. As an example, 2 m/s or less for wind speed bins and 30° or less for wind direction sectors is consistent with DNVGL-ST-0437 and IEC 61400-3.

All parameters, except air density, should be available as functions of wind direction, given as 10-minute averages.

Care should be taken when interpreting and manipulating observed data that may be developed through means other than the averaging of continuous high frequency observations over the reporting period (e.g., 10 min or hourly). For example:

- Modeled time series data with a 10 minute or hourly time stamp may in fact only be a single sample of data over that time step, rather than an average
- Some NOAA buoys and land station measurements reported hourly represent an average or gust within 2 minutes or 8 minutes of observations over the hour reporting interval (http://www.ndbc.noaa.gov/measdes.shtml).

### 2.2.2.3 Extreme wind conditions

The extreme wind conditions are specified in terms of an air density in conjunction with prescribed wind events. The extreme wind conditions include wind shear events, as well as peak wind speeds due to storms, extreme turbulence, and rapid extreme changes in wind speed and direction (gusts).

For determination of the extreme wind events, values of the following parameters at the wind turbine site should be estimated:

- Extreme 10-minute average wind speed at hub height with specified recurrence periods, for example 1-year, 50-year, 100-year, 500-year, 1000-year return periods
- Extreme 3-second average wind speed (gust) at hub height with specified recurrence periods
- Extreme wind shear
- Extreme deterministic wind events such as extreme gust events (in the IEC and DNVGL system the gust events to include in the design is defined as the extreme operating gust and the extreme coherent gust with time scales of 10.5 and 10.0 seconds, respectively) and extreme direction change events. The extreme deterministic wind events depend on the park layout and the rotor diameter and can only be estimated when the type of turbine has been decided. Regarding floating systems the gust period has to be adjusted in accordance with the systems dynamics, see DNVGL-ST-0119. This information is available in the design process.)
- Extreme turbulence intensity
- Air density.

The unconditional values of wind speeds for specified return periods may be determined from analysis of appropriate measurements and/or hindcast data for the offshore wind turbine site. Methods for calculating the extreme unconditional wind speeds are described in section 5.6. Extreme wind shear and extreme turbulence intensity are described in more detail in Section 5.1.

Where site-specific extreme average wind speeds are available only for averaging periods longer than 10 minutes, conversion factors shall be used to estimate the extreme 10-minute wind speed; see Section 5.1.

Methods for determining the extreme deterministic wind events (including gusts and direction change) can be found in DNVGL-ST-0437 and IEC 61400-1.

## 2.2.3 Marine conditions

This section describes marine conditions including waves, currents, and water levels. For other marine conditions see Section 2.2.6.

### 2.2.3.1 Waves

Waves are irregular in shape, vary in height, length, and speed of propagation, and may approach an offshore wind turbine from one or more directions simultaneously. Generally, over a 1-hour or 3-hour period, stationary wave conditions with constant $H_S$ and constant $T_P$ (defined below) are assumed to prevail. These short-term stationary wave conditions are denoted a “sea state,” and may be represented by a wave spectrum (i.e., the power spectral density function of the sea elevation process). The wave spectrum represents the sea state as the superposition of many small individual frequency components, each of which is a periodic wave with its own amplitude, frequency, and direction of propagation; the components have random phase relationships to each other. The wave spectrum expresses how the energy of the sea elevation is distributed between various frequencies and is a function of site specific wave height $H_S$, peak period $T_P$, and mean wave direction $\theta_{MWD}$ or the peak wave direction $\theta_{PWD}$ as defined in the bullets below:

- The wave height $H$ of a wave cycle is the difference between the highest crest and the deepest trough between two successive zero-upcrossings of the sea elevation process. The arbitrary wave height $H$ under stationary 1- or 3-hour conditions in the short term follows a probability distribution which is a function of the significant wave height $H_S$.
- The significant wave height $H_S$ is defined as
    - as $H_{m0}$ decided from the wave spectrum: $H_{m0} = 4\ (m_0)^{(1/2)}$, where $m_0$ is the zero moment of the wave spectrum, and $H_{m0}$ is thereby defined as four times the standard deviation of the sea elevation process
    - or the mean of the highest 1/3 of the waves in the sea state.

  The significant wave height is a measure of the intensity of the wave climate as well as of the variability in the arbitrary wave heights.
- The wave crest height $C_R$ is the height of the highest crest between two successive zero-upcrossings of the sea elevation process. The arbitrary wave crest height $C_R$ under stationary 1- or 3-hour conditions in the short term follows a probability distribution which is a function of the significant wave height $H_S$.
- The wave period is defined as the time between two successive zero-upcrossings of the sea elevation process. The arbitrary wave period $T$ under stationary 1- or 3-hour conditions in the short term follows a probability distribution, which is a function of $H_S$, $T_P$ (defined below), and $H$.
- The peak period $T_P$ is related to the mean zero-crossing period $T_Z$ of the sea elevation process.
- The mean wave direction $\theta_{MWD}$ is the averaged direction of the waves, and the peak wave direction $\theta_{PWD}$ is the direction of the peak waves; both can be used for characterizing the wave direction, as long as either $\theta_{MWD}$ or $\theta_{PWD}$ is consistently used, and not mixed.

The long-term distributions of $H_S$ and $T_P$ should preferably be based on statistical data for the same reference period for the waves as the reference period that is used for the determination of loads. If a different reference period than 1 or 3 hours is used for the determination of loads, the wave data may be converted by application of appropriate adjustment factors.

Wave spectra are described in more detail in Section 5.2.

In some applications, periodic or regular waves can be used as an abstraction of a real sea for design purposes. A deterministic design wave shall be specified by its height $H$, period $T$ and direction $\theta$.

The wave parameters are highly dependent on location and may vary considerably over an offshore wind facility site, as sea bed formations such as sand waves and sand bars alter the wave field. These effects are described in further detail in Section 5.3.2.

#### 2.2.3.2 Current

Sea currents shall be assessed taking account of components associated with tidal, storm surge, wind generated, and wave induced surf currents, where these are relevant to the wind turbine site. In addition to their impact on the loading of the support structure of an offshore wind turbine, currents affect the location and orientation of boat landings and fenders and may create seabed scouring.

Although sea currents may, in principle, vary in space and time, they are generally considered as a horizontally uniform flow field of constant velocity and direction, varying only as a function of depth. The following components of sea current velocity shall be taken into account when relevant:

- Sub-surface currents generated by tides, storm surge, and atmospheric pressure variations, etc.
- Wind generated, near surface currents
- Near shore, wave induced surf currents running parallel to the coast: In the case where an offshore wind turbine is to be sited near a coastal breaking wave zone, consideration shall be given to the surf currents generated by the shear forces of the breaking waves; see Section 5.3.

The total current velocity is the vector sum of these components.

Wave induced water particle velocities and current velocities shall be added vectorially.

The influence of sea currents on the relationship between wave length and wave period is generally small and may therefore be neglected.

The influence of sea currents on the hydrodynamic fatigue loading of an offshore wind turbine may be insignificant in cases where the total current velocity is small compared to the wave induced water particle velocity below the wave crest and where vibrations of the support structure are unlikely to occur due to vortex shedding or moving ice floes.

The variation of the current with the water depth shall be considered when relevant. This is done by applying an appropriate current speed profile, either decided by measurements or from literature.

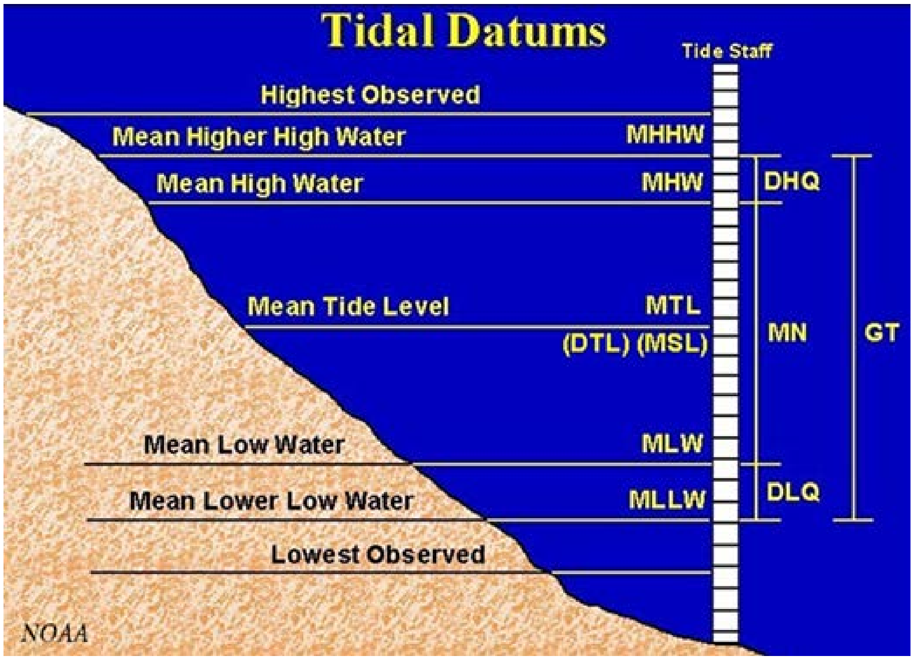
The current components are described in more detail in Section 5.3.

#### 2.2.3.3 Water levels

For the calculation of the hydrodynamic loading of an offshore wind turbine, the variation in water level (if significant) at the site shall be taken into account.

The water level consists of a mean water level in conjunction with tidal water and a wind- and pressure-induced storm surge. The tidal range is defined as the range between the highest astronomical tide (HAT) or Highest Observed and the lowest astronomical tide (LAT) or Lowest Observed, as shown in Figure 2-2 below, which presents tidal datums as defined by NOAA's Center for Operational Oceanographic Products and Services (CO-OPS).

Note the reference level in U.S. waters to provide any water level is the Mean Lower Low Water (MLLW).



***Source: NOAA***

**Figure 2-2 Definition of tidal levels**

The mean and fluctuation in water level at the facility site shall be assessed in order to determine the following parameters relative to MLLW:

- MSL
- HAT and LAT
- Highest still water level (HSWL) including extreme positive storm surge and tide level (HAT or MHHW)
- Lowest still water level (LSWL) including extreme negative storm surge and tide level (LAT or MLLW).

These parameters shall be determined from the site-specific metocean data. Accurate estimates of storm surge require a long data set. Long-term measurements or hindcasts available from a nearby location may be used together with correlation techniques to derive the site-specific storm surge characteristics.

Water level and wind are correlated, because the water level has a wind-generated component. The correlation between water level data and wind data shall be accounted for in design when relevant.

Note that the reference datum for modeled data, e.g., atmospheric data from a mesoscale model (e.g., MSL), may be different than the reference used for on-site observations or for engineering purposes (e.g., MLLW, LAT). Care should be taken to reconcile the definition of hub height conditions to accommodate the different datums.

#### 2.2.3.4 Marine data

Site-specific measured marine data over sufficiently long periods with minimal or no gaps should be applied. What is a sufficiently long period in this context depends on which kinds of marine parameters are sought-after. Representativeness of the data for interpretation of the sought-after marine parameters is the key issue, for example:

- For proper estimation of extreme values many years of data are needed, and generally the length of time covered by data should be long enough that the sought-after key figures can be captured and extracted; as an example, DNVGL-ST-0437 states that the data period underlying extreme value estimates should preferably be 10 years or more.
- The wave height is expected to exhibit variability from year to year such that several years of data are needed to properly estimate this parameter, and waves associated with large storm events should also be captured.

The chosen measurement period shall include all load-relevant aspects. These are, in particular:

- Seasonal and diurnal effects
- Thermal effects.

Other effects on the representativeness of data are, for example:

- Flow stratification: A depth averaged value may not be representative for the load calculations
- In areas where the wave field consists of multiple components, for example waves generated by the local wind (wind-sea) and by far-field wind (swell waves), a separation of spectral wave components in wind-sea and swell components may be necessary to correctly capture the wave period for fatigue loads, where it is important to correctly represent waves with periods close to the first eigen-period of the structure. See for example Section 5.2.2.2 and 5.2.4.

Various means of measuring techniques are described in Section 3.2. Methods for filling data-gaps and correlating short-term data with an appropriate long-term data source to achieve a synthesized long-term data series are given in Section 5.1 for wind, and applies for marine parameters too.

When no site-specific marine data are available and data from adjacent locations are to be capitalized on instead, proper transformation of such other data shall be performed to account for possible differences due to, for example, sea bed morphology. This may for example be done by applying hindcast data.

Site-specific hindcast of marine data may be used for marine assessment if only limited measurements are available, or to extend measured time series, or to interpolate to places where measured data have not been collected. If hindcast is used, the hindcast model shall be validated and if necessary calibrated against measured data to ensure that the hindcast results comply with available measured data. When calibrating the hindcast model, parameters such as bed friction and wind-wave interaction parameters are chosen so that the results compare as closely as possible with measurements. The measurement period used for calibration shall not also be used for validation. Hindcasts are described in more detail in Section 4.

Simultaneous observations of metocean data (wind, waves, current, water level) may be obtained to establish correlations. Correlation between wind and waves is of special importance for design of offshore wind turbines and is described in Section 2.2.4.

Time series of measurements/hindcast data may be of particular importance, in order to characterize wave heights, periods, and wave spectra at shallow water sites.

### 2.2.3.5 Normal marine conditions

Normal marine conditions (sometimes referred to as the Normal Sea State (NSS) model, in for example DNVGL-ST-0437 and IEC 61400-3) are characterized by:

- A significant wave height, a peak period, and a wave direction, associated with a concurrent mean wind speed. The significant wave height of the normal sea state is defined as the expected value of the significant wave height conditioned on the concurrent 10-minute mean wind speed.
- The appropriate site-specific sea current associated with normal wave conditions. The site-specific sea current associated with normal wave conditions may not be aligned with the main wave direction. However, for load calculations, it is generally acceptable to assume that the sub-surface currents are aligned with the wave direction.
- The normal water level range, often assumed equal to the variation in water level with a recurrence period of one year. In the absence of site-specific data to characterize the long-term probability distribution of water levels, the normal water level range may be assumed to be equal to the variation between HAT and LAT.

The NSS should at least be given by all-year omni-directional values, but also monthly and all-year directional and omni-directional values may be given.

### 2.2.3.6 Extreme marine conditions

Extreme wave conditions are often referred to as the Extreme Sea State (ESS) model, in for example the DNVGL-ST-0437 and IEC 61400-3. The ESS are characterized by:

- A significant wave height, a peak period, maximum wave height, corresponding maximum wave crest level and a wave direction, for specific return periods, for example 1-year, 50-year, 100-year, 500-year, 1000-year, return periods. The return periods to apply for design are specified in the standards applied for design of the specific offshore wind facility. The range of associated wave periods to each of these individual maximum wave heights shall be considered. Design calculations shall be based on values of the associated wave period which result in the highest loads or load effects in the structure.
- The appropriate site-specific sea current with recurrence periods specified as above. In general, it may be acceptable to assume that the sub-surface currents are aligned with the wave direction.
- The extreme water level range for the recurrence periods as specified above. Load calculations shall be undertaken based on the water levels which result in the highest loads acting on an offshore wind turbine.

The unconditional values of the marine parameters for specified return periods may be determined from analysis of appropriate measurements and/or hindcast data for the offshore wind turbine site. Methods for calculating the extreme unconditional marine parameters are described in Section 5.6.

For load calculation, the joint wave height, water level, current conditions for specified return periods may also be applied. These can be determined from analysis of appropriate measurements and/or hindcast data for the offshore wind turbine site, for example from the environmental contour method, or the IFORM method – see Section 5.6.

### 2.2.4 Wind and wave correlation

Wave climate and wind climate are often correlated, because waves are usually wind-generated. The correlation between wave data and wind data shall be accounted for in design. Consideration of mean wind and wave directions shall be made. The distributions of wind and wave directions (multi-directional) may, in some cases, have an important influence on the loads acting on the support structure. The importance of this influence will depend on the nature of the wind and wave directionality and the extent to which the support structure is axis-symmetric. Wind and wave directionality have significant impact on floating structures behaviour and shall, thus, be considered in the analysis.

Within a period of stationary wind and wave climates (10 minutes), the short-term wind speeds and wave heights can be assumed independent and uncorrelated.

Extreme waves may not always come from the same direction as extreme winds. This may in particular be so when the fetch in the direction of the extreme winds is short. Extreme wind and wave direction misalignment is also common when extremes may be driven by storm with a cyclonic nature that may have significant wind direction changes over a short time scales (e.g., minutes to hours).

#### 2.2.4.1 Wind and wave data for correlation

Simultaneous observations of wave and wind data in terms of simultaneous values of $H_S$ and $U_{10}$ shall be obtained and directionality of wind and waves shall be simultaneously recorded.

Various means of measuring techniques are described in Section 3.2.

#### 2.2.4.2 Normal joint wind-wave conditions

The significant wave height, peak spectral period and direction for each normal sea state shall be selected, together with the associated mean wind speed, based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site.

Representation of wind-wave correlation is described further in Section 5.5.1.

#### 2.2.4.3 Extreme joint wind-wave conditions

The extreme event of conditional wind and waves with a 50-year recurrence period is often referred to as the Severe Sea State (SSS) model, (DNVGL-ST-437 and IEC 61400-3). These sea states are used in combination with normal wind conditions for calculation of the ultimate loading of an offshore wind turbine during power production, by associating a severe sea state with each mean wind speed in the range corresponding to power production.

The SSS is characterized by:

- A significant wave height, a peak period, an individual maximum wave height and associated range of wave periods, and a wave direction. It is associated with a concurrent mean wind speed. The significant wave height of the severe sea state is defined by extrapolation of appropriate site-specific metocean data such that the load effect from the combination of the significant wave height and the 10-minute mean wind speed $U_{10}$ has a return period of 50 years.

- A sea current appropriate for normal conditions.
- A water level appropriate for normal conditions.

Methods for calculation of the extreme conditional wave heights and wind speeds are described in Section 5.6.2.

## 2.2.5 Extreme tropical cyclone design conditions

The extreme tropical cyclone design conditions are defined as the extreme design criteria of metocean data under tropical cyclone conditions. Indeed, tropical cyclones are specific meteorological phenomena with their own physics, seasonality, and impacts. That is why their design criteria are generally dissociated from “non-cyclone” or “normal” conditions.

### 2.2.5.1 Wind

The extreme values of wind speed under tropical cyclone conditions are based on the 1-minute mean wind speed at 10m above mean sea level. By order of preference, measurements or wind modelling or theoretical shear profile adapted to the cyclone conditions shall be used to estimate the wind at hub height (or any other heights required for the design wind turbine).

Gust factors shall be estimated from a relation or spectra formulation, with the estimated 1-minute extreme wind speed (TAP 670aa).

The monthly extreme value analysis shall assess the seasonal variability in terms of severity and also in terms of directionality if prevailing tracks occur and change during the year.

Finally, the methodology to assess the directionality shall be chosen by considering characteristics of the location of the facility, especially the presence of islands and coast.

Values of the following parameters at the wind turbine site should be estimated:

- The extreme 10-minute average wind speed at hub height with specified recurrence periods (for example 50-year, 100-year, 500-year, and 1,000-year return periods)
- The extreme 3-second average wind speed (gust) at hub height with specified recurrence periods
- Extreme wind shear
- Extreme turbulence intensity at hub height
- Air density at hub height.

The assessment of seasonal and directional variabilities is recommended by using appropriate data and methodology.

### 2.2.5.2 Wave

The extreme waves under tropical cyclone conditions are highly correlated to wind but may be affected by local characteristics of the project location, even more than wind parameters, considering bathymetry and fetch influences.

Values of the following parameters at the offshore wind facility site should be estimated:

- Extreme values of $H_S$ and associated $T_P$ with specified recurrence periods (for example 50-year, 100-year, 500-year, and 1,000-year return periods)
- Individual wave height and associated period with specified recurrence periods
- Extreme crest height
- Directional wave spectra properties (appropriate formulations and associated parameters).

### 2.2.5.3 Current and water levels

Site specific studies shall estimate the extreme current over the water column under cyclonic conditions. The tropical cyclone-generated current may temporarily be the dominant component of the total current; consequently, it is important to estimate its influence on the site.

In addition, the tropical cyclone storm surge may be particularly large during this type of extreme event, because of strong wind and low pressure occurring during tropical cyclones.

Values of the following parameters at site should be estimated for tropical cyclone conditions:

- Extreme values of total current with specified recurrence periods (for example 50-year, 100-year, 500-year, 1000-year return periods) in surface and different water depths
- Shape of the extreme current profile (at least current speed, recommended for both horizontal components)
- Extreme values of storm surges.

## 2.2.6 Other metocean parameters

Other relevant metocean parameters are, for example, air and sea temperatures, air and sea density, air humidity, lightning, and the items listed below, which are described further in this section.

- Bathymetry and seabed changes (global scour) including vertical reference level for the project
- Wave breaking
- Sea ice
- Ice from precipitation/sea spray
- Marine growth
- Air temperature
- Humidity
- Air density
- Solar radiation
- Rain, hail, snow and ice
- Chemically active substances
- Mechanically active particles
- Water salinity causing corrosion
- Lightning
- Water density
- Water temperature

### 2.2.6.1 Bathymetry and seabed changes (global scour) including vertical reference

For design, the vertical reference level shall be decided and referred to in a consistent manner. The vertical reference level for a site is often a regional or national reference level.

For design of offshore structures, up-to-date information of the bathymetry at the site and the surrounding area is of key importance. This information is obtained through surveys, preferably of a high spatial resolution over the offshore wind site. The horizontal and vertical accuracy of applied surveys shall be included in the design.

Furthermore, the stability of the seabed shall be assessed. It shall be determined whether the bathymetry at the site is stable or if it changes during the lifetime of the offshore wind asset.

Based on observations, sea floor variations can usually be characterized as a combination of the following:

- Local scour characterized by steep sided scour pits around structural elements such as piles and pile groups. This is not described further in the present Guideline.
- Global scour characterized by shallow scoured basins of large extent around a structure, possibly caused by overall structure effects, multiple structure interaction, or wave-soil structure interaction. This is not described further in the present Guideline.
- Overall seabed movement of sand waves, ridges and shoals which would occur in the absence of a structure. Such movements can result in the lowering or rising of the sea floor.

Seabed movement can influence the intensity of the marine parameters and the variation of these over the site, as well as the geotechnical design.

### 2.2.6.2 Wave breaking

Wave breaking may take place because of shoaling and limited water depth, or due to surface steepness of the waves. The influence of breaking waves shall be assessed during the design of an offshore wind turbine.

Breaking waves are generally classified as spilling, plunging, or surging; the first two types being relevant to sites suitable for offshore wind turbines. The water depth, sea floor slope, and wave period determine whether the breaker is spilling or plunging. This is described in more detail in Section 5.2.

### 2.2.6.3 Sea ice

At some locations, loading of the support structure of an offshore wind turbine due to sea ice can be critical. The ice loads may be associated with static loading from a fast ice cover, or dynamic loading caused by wind and current induced motion of ice floes. Moving ice floes impacting the support structure over a considerable period may result in significant fatigue loading.

The influence of sea ice shall be assessed during the design of the support structure of an offshore wind turbine that will be installed at a site where sea ice is expected to occur. An assessment will require detailed information concerning the properties of the sea ice at the offshore wind turbine site. The designer shall describe in the design documentation the sea ice properties assumed. The following parameters shall be determined from statistical data from an ice atlas or similar document:

- Ice thickness with a specified return period; as an example, a 50-year recurrence period
- Ice crushing and bending strength
- Risk of current or wind induced ice floe
- Risk of forces induced by fluctuating water level
- Frequency of ice concentration.

Based on the sea ice risk and data collected, additional data may have to be considered. These are in general:

- ice bulk salinity
- ice brine volume
- ice porosity
- ice temperature
- ice density
- ice strength
- ice flow velocity

Additionally, formation of ice ridges may need to be considered based on the available data and the risk associated with such formations.

#### 2.2.6.4 Ice from precipitation/sea spray

For the design of offshore wind turbines, loads caused by ice accretion from sea spray, snow, rain, and air humidity shall be considered where relevant. The thickness and density of ice and snow accretion and its dependence on height above sea level shall be assessed, based on applicable recommendations, local experience, and existing measurements.

#### 2.2.6.5 Marine growth

Marine growth may be considerable at some locations and shall be factored into the design of the support structure. Marine growth influences the mass, the geometry, and the surface texture of the support structure of an offshore wind turbine. Consequently, marine growth may influence hydrodynamic loads, dynamic response, accessibility, and corrosion rate of the structure.

Marine growth is broadly divided into “hard” (generally animals such as mussels and barnacles) and “soft” (seaweeds and kelps), where hard growth is generally thinner but rougher than soft growth. Marine organisms generally colonize a structure soon after installation but the growth rate tapers off after a few years.

The nature and thickness of marine growth depends on the structural member’s position relative to the sea level, orientation relative to dominant current, age and maintenance strategy; but also on other site conditions such as salinity, oxygen content, pH value, current, and temperature.

The corrosion environment is normally modified by marine growth in the upper submerged zone and the lower part of the splash zone of the support structure. Depending on the type of marine growth and other local conditions, the net effect may be either to enhance or retard corrosion attack. Enhancement of corrosion processes by marine growth (e.g., through corrosive metabolites) is commonly referred to as Microbiologically Influenced Corrosion (MIC). Marine growth may further interfere with systems for corrosion control, including coatings/linings and cathodic protection.

The thickness of marine growth and its dependence on depth below sea level shall be assessed, based on applicable recommendations, local experience, and existing measurements. Site-specific studies may be necessary to establish the nature, likely thickness, and depth dependence of marine growth (information regarding marine growth is available for some areas (North Sea, Persian Gulf, West African coast, Gulf of Mexico, coast of California, East coast of Canada; refer to ISO 19901-1).

Due to the uncertainties involved in assumptions regarding marine growth, a strategy for inspection and possible removal of marine growth should be planned as part of the support structure design. The frequency, inspection method and growth removal criteria shall be based on the impact of marine growth on the structural reliability of an offshore wind turbine, and the extent of experience with marine growth under the specific conditions prevailing at the site.

### 2.2.7 Climate change considerations

Because the life span of structures is increasing (due to materials, better design methodology, etc.), several tens of years can occur between feasibility assessment for a project and decommissioning at the end of the facility's life. It is assumed as a long enough period to be subjected to climate change influence.

Consequently, this impact may appear in different ways including, but not limited to, the following:

- Sea level rise
- Changes in frequency and severity of tropical cyclones or other extreme events
- Long-term wind resource variation
- Influence on air/sea temperature.

The impact of climate change on design parameters is a complex issue that requires specialized knowledge and large computing resources. However, an extensive body of knowledge exists, and review of current literature, especially the Intergovernmental Panel on Climate Change (IPCC) reports, should be conducted as a minimum to inform any assessment. Note that the design lifetimes for some key project components may not be aligned, and therefore, the effects of climate variation may need to be applied over different time scales for a facility.

### 2.2.8 Further considerations

As offshore wind facilities inevitably move into deeper water, the relative significance of various metocean parameters may change. For example, a floating wind turbine requires a mooring system and floating substructure, often with deep draft as in the case of a spar. Consequently, the current profile is a main parameter for this kind of turbine and the overall sea-state conditions need to be described with a lot more detail (compared to a fixed-foundations project) to enable design of the floater and mooring system. The SSS needs also to be reliably described, especially for the fatigue analysis of the mooring lines.

### 2.2.9 Summary, the metocean data

The site-specific metocean data shall include information on all metocean parameters relevant for design.

In an offshore wind facility consisting of several wind turbines the metocean conditions and the water depth varies from turbine to turbine, and it may be beneficial for design to derive metocean data for several locations. If the metocean design conditions are only determined for one or a few locations, it should be ensured that the metocean parameters at these locations are conservative for design of the remaining turbine positions.

The site-specific metocean data may be established from site-specific measurements supported, where appropriate, by numerical simulations (hindcasts). If site-specific measurements are used, the results should generally be correlated with data from a nearby location for which long-term measurements exist, unless the results can otherwise be shown to be conservative. The monitoring period for the site-specific measurements should be sufficient to ensure reliable statistics for the individual parameters. The joint probability distribution of the long-term site-specific measurements for these parameters is generally not required when correlation with suitable long-term data from a nearby location is undertaken or when numerical tools can be reliably applied for transposing the long-term data to the wind turbine site.

Time series measurements may be needed to characterize wave heights, periods, and wave spectra at shallow water sites.

When assessing the quality and quantity of data, special attention should be given to the adequacy of the data with respect to extrapolation to very infrequent events.

Specifically, the following information should be given:

- Vertical reference level
- Hub-height, not known until type of turbine has been decided
- Annual average wind speed (at hub height or another reference height)
- Wind speed distribution (Weibull, Rayleigh, measured, other) omni-directional and directional (wind-rose) (at hub height or another reference height)
- Normal wind shear and wind profile
- Turbulence intensity and standard deviation (for normal conditions this includes influence of wakes from other turbines at the site or near-by sites; the wake effects depend on the facility layout and rotor diameter and can only be decided when this information is available)
- Extreme wind speeds (10-minute and 3-second averages) for specified recurrence periods [m/s] (at hub-height or another reference height)
- Extreme wind shear and wind profile
- Extreme turbulence intensity and standard deviation (this shall include maximum wake effects, which can only be decided when the rotor diameter is known)
- Tidal variation and/or storm surge (specified recurrence period) [m]
- HAT [m relative to vertical reference level]
- LAT [m relative to vertical reference level]
- HSWL (specified recurrence period) [m relative to vertical reference level]
- LSWL (specified recurrence period) [m relative to vertical reference level]
- Significant wave height for specified recurrence periods [m]
- Peak periods for specified recurrence periods [s]
- Individual extreme wave height for specified recurrence periods [m]
- Range of associated wave periods for specified recurrence periods [s]
- Extreme crest height for specified recurrence periods [m relative to vertical reference level]
- Extreme sea surface current for specified recurrence periods [m/s]
- Wind and wave joint distribution ($H_s, T_p, U_{\text{ref-level}}$) including directionality
- Wave spectrum and parameters
- Breaking wave possibility and type model and parameters
- Sea ice conditions
- Local and global scour or sum of both (maximum allowed) [m]
- Sea floor level variation (maximum allowed) [m]
- Marine growth profile and thickness [mm]
- Normal and extreme air temperature ranges [°C]
- Normal and extreme sea temperature ranges [°C]

- Air density [kg/m$^3$]
- Air humidity [%]
- Water density [kg/m$^3$]
- Salinity [g/m$^3$]
- Solar radiation [W/m$^2$]
- Rain, hail

## 2.3 Transport and installation

### 2.3.1 Overview of project requirements

For the installation phase, metocean data are required to support construction planning, real-time monitoring, and forecasting during construction. As part of the regulatory review and approval process for an offshore wind facility, the installation phase needs to be described in the Fabrication and Installation Report submitted to BOEM. Understanding of metocean conditions is required for all offshore activities during the construction phase including the following:

- Vessel selection
- Loadout of components for transportation to the project site
- Transportation of components to the project site
- Positioning of construction vessels
- Jacking operations
- Crane operations
- Piling, drilling, seabed levelling, and placement of scour protection
- Diving/remotely operated vehicle (ROV) operations
- Cable laying and burial
- Personnel transfers
- Commissioning and testing.

For many of these activities, limiting metocean conditions place restrictions on the operating windows for each activity.

- Limiting conditions:
    - Wind
    - Sea state
    - Currents
    - Water level
    - Visibility
- Weather windows
- Medium and long-range forecasts for assessing favorability of conditions for start of installation activities.
- Risks:
    - Waiting on weather/demurrage
    - Operating in unsafe conditions – harm to equipment and/or workers

    - Wasted time/transport if conditions aren't right

- Safe operating limits will be pre-determined and written into construction contracts/charters
- Need wind speed information at maximum crane heights
- Metocean requirements for installation are primarily driven by safety concerns
- Construction and Operations Plans require developers to describe safety, prevention, and pollution control features or practices that will be used.

It is important to:

- Explain overall project requirements: type, time, and extent of data. Explain purpose and overall logic, and link with simultaneous engineering needs of the project. Refer to next sections for modeling (forecast).
- Have data to support all installation operations: loading, transport or tow, vessel selection, drilling/piling or seabed levelling, crane operations, diving operations including ROV, cable laying, personnel transfers.

The DNVGL-ST-0054 provides further guidance on transport and installation of wind power plants.

## 2.3.2 Installation planning

### 2.3.2.1 Downtime analysis

When operability conditions are identified (such as thresholds on wave and/or wind and/or current, and duration of operations), it is recommended to perform downtime or weather window analysis, by applying these conditions on long calibrated hindcast or measurements time series of the required metocean parameters.

This analysis should estimate the percentage of time during which operations are possible.

### 2.3.2.2 Seasonal variability at site

The previous analysis should be performed at least monthly to define the best period and associated probability. Knowledge of the seasonal variability is an important decision-making tool for the installation planning. It may assist in reducing waiting time due to unfavorable conditions or even result in the engagement of a new vessel/procedure to allow more weather window occurrences.

## 2.3.3 Installation execution

Weather forecasting service is required for the duration of the offshore installation operations. For the execution of installation operations, arrangements should be made for receiving weather forecasts at regular intervals before, and during, the marine operations. Such weather forecasts should be from recognized sources and be project specific. Weather forecast procedures should consider the nature and duration of the planned operation.

A combined approach linking real-time monitoring and forecast can increase the efficiency of the installation phase, by providing reliable information; this is especially necessary for operations with limiting conditions.

### 2.3.3.1 Real-time monitoring

The role of the real-time monitoring is multiple. First, the measurements of local conditions allow the reliability of weather forecasting to be estimated. Then, by using appropriate equipment, it is possible to assess the local individual wave conditions with high temporal frequency, when forecasting providing future sea state conditions every 1, 3, or even 6 hours. Finally, by applying appropriate methodology, it may possible to predict wave, and pitch, roll, and heave but in very short term (micro-forecast). As an example, Figure 2-3 shows a wave field obtained from radar, showing a potential wave with about 10.2 m height approaching the structure from back side (after heading direction).

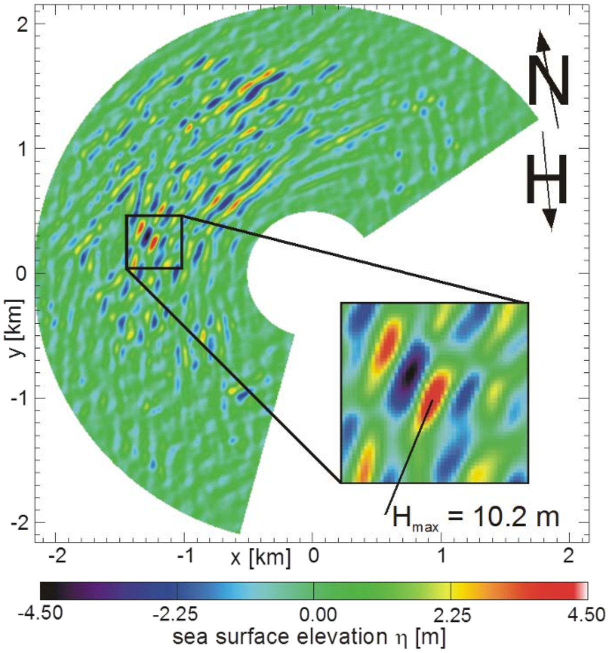


**Figure 2-3 Wave field from WaMoS post processing**

To support real-time monitoring, metocean conditions should be continuously measured and recorded, as a minimum including wind, wave, water level, and current conditions, all of which influence vessel positioning and loading on structures. Interpretation of the real-time records of metocean parameters to support micro-forecasting during operations requires software tools and experienced users.

### 2.3.3.2 Forecast

Forecasts during the installation phase are used in making decision scheme (launch, delay, or stop operations) by providing long-term weather prediction (at least five days). Even if error in forecasting is unavoidable, the trend of weather conditions (increasing of sea state intensity for example) is well captured in general; by crossing the trend forecast with real-time monitoring, the decision to stop operation to anticipate bad weather impact could be done with a high confidence level.

In addition, it is possible to validate and check the reliability of forecast by comparing predictions with observed data of the previous days and using statistical estimators. Observations may be used to define locally the initial conditions of the forecast system. Observations may be used to define locally the initial conditions of the forecast system.

Section 2.7 Weather Forecasts of DNVGL-ST-N001 provides detailed guidance on obtaining and using weather forecasts for marine operations.

## 2.4 Operation and maintenance

### 2.4.1 Overview of project requirement

The operation and maintenance phase requires similar types of data to the transport and installation phase. It is assumed that during operation there will be a real-time monitoring program. The data arising from the monitoring during the operational phase shall provide the information needed to analyze the performance of the offshore wind facility and to analyze specific meteorological or oceanographic events (leading to damage or failure for example). The additional measurements will increase the knowledge of the local conditions and revision of Metocean data should be performed to confirm or revise criteria and fatigue life estimations.

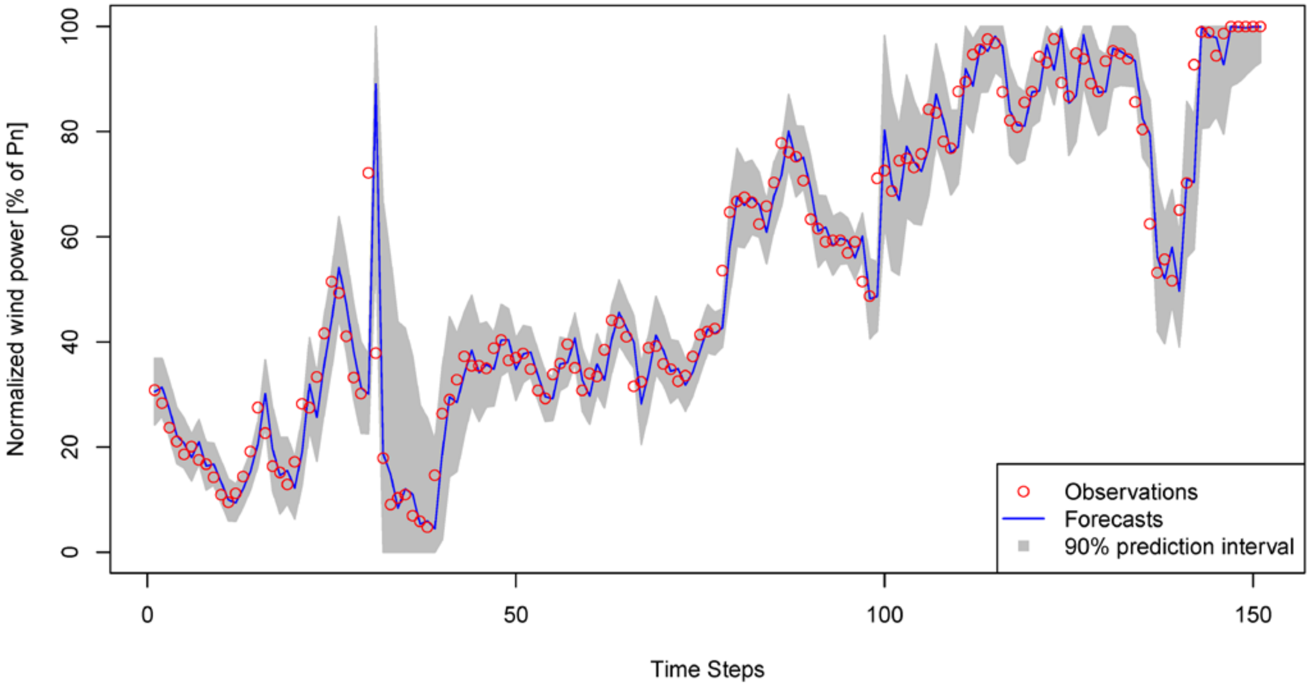
Periodic monitoring and scheduled maintenance of wind turbines, substation, power cables, and control station shall be planned by considering the duration and environmental limitations of each task, and weather windows available. Downtime / weather window analyses are consequently required to identify the best periods for planning maintenance from a metocean point of view. However, maintenance tasks will only be executed upon receipt of a favorable weather forecast for the entire duration of the task.

DNVGL-SE-0190 provides further guidance on the requirements for operations, maintenance, and in-service monitoring related to offshore wind facilities.

### 2.4.2 Real time monitoring and forecasting

As in the installation phase, monitoring and weather forecast services are required for the safety of environment, equipment, and people during maintenance (planning and operation).

The forecast and monitoring are also essential to estimate the potential power that the wind facility will provide in the following day. The use of weather forecast, actual measured metocean parameters, and power production shall enable prediction of the electricity availability / production from the wind facility. The use of probabilistic approaches for the different inputs (weather ensemble forecast) shall allow for estimation of uncertainty. Figure 2-4 shows an example of normalized wind power forecasts and observed power; the observed minima and maximum are always in the 90% prediction interval.



Source: Trombe (2012)

**Figure 2-4 Normalized wind power forecasts and observed power**

In areas within tropical cyclone basins, receiving tropical cyclone warnings is necessary, to be obtained from the relevant government agency and updated every 3 to 6 hours.

For scheduling of maintenance operations involving personnel working on turbines at height, expected lightning occurrence shall be considered and lightning forecast obtained as necessary.

Power production forecasting is relevant at time scales beyond day-ahead (e.g., hour ahead, 6 hour ahead), and on higher frequencies for ramp events. It is worth noting this for both O&M planning purposes, as well as grid interconnection requirements, or other planning related to potential grid curtailment (if applicable).

## 2.5 Decommissioning

The decommissioning phase will occur several decades after the beginning of the project and the design criteria phase. The decommissioning operations may last several months so, the program of the phase has to be scheduled by considering the monthly variability, with hindcast and/or measurements, in downtime study. Several years of measurements and recent hindcast databases (with improvements of physics, parametrization, and process formulations) may be available, leading to more reliable data than at the beginning of the project.

For the decommissioning operations, the real-time monitoring and forecasting are again required to proceed in safe conditions.

The subject of decommissioning and deconstruction of the wind power plant is addressed in Section 6 of DNVGL-SE-0190.

In case of an interest in extending the in-service lifetime of the facility beyond the original design lifetime, Section 5 of DNVGL-SE-0190 may be considered.

Repowering of wind power plants is addressed in Section 7 of DNVGL-SE-0190.

# 3 DATA COLLECTION – MEASUREMENTS

## 3.1 Considerations for a successful measurement campaign

### 3.1.1 Defining scope of measurement campaign

The scope of a measurement campaign is driven by data requirements, budgets, schedules, and contractual deadlines. Project or measurement uncertainties are often lowered with improved spatial coverage across the project area and longer measurement duration. However, the ideal measurement campaign is often not realized due to budget and time constraints. Therefore, there is a balance between the ideal case and tolerable project uncertainties.

The scope of a measurement campaign should first consider project boundary and any measurement restrictions, such as conservation zones, shipping routes, and fishing areas. Setting this out first will provide guidance on the project scale and the overall measurement campaign requirements. The second consideration is to outline the schedule. It is important as on-site metocean measurements, such as wind and waves, should be completed over at least one year, to capture seasonal variations, but preferably for two or more years. Finally, it is essential to design a measurement campaign that considers the suitability of the instruments and the overall goals for the campaign. These aspects are presented in the rest of Section 3.

### 3.1.2 Selection of instrumentation

Sections 3.2 through 3.6 provide information and guidance on selecting the various metocean instrumentation. At a high-level, instrumentation and data acquisition systems should be robust enough to withstand the harsh metocean climate, be suitable for its intended purpose, provide high-quality data with good data recovery rates, and operate autonomously. The data acquisition system should also be able to store all recorded data between service visits and may be operated and accessed remotely with capabilities to send data to a secure location. The data logging and storage capabilities should be sufficient to avoid any loss of data in the event that planned service visits are not possible due to access problems.

### 3.1.3 Spatial and temporal requirements

Spatial coverage for a measurement campaign depends on size of site, complexity of the oceanography and wind conditions at the site, and the availability and quality of information at or near the site.

From a temporal perspective, the minimum duration of a measurement campaign should not be less than one year to cover seasonal variability, but should preferably cover at least two full years to support assessment of inter-annual variability. A longer-term continuous campaign is preferred that provides continuity from development through construction and operations.

The spatial and temporal coverage should be determined based on consultation with an experienced metocean expert.

The measurement campaigns should be aligned to ensure simultaneous wind, wave, and current measurements. The measurement campaign timeline should consider planning requirements, any necessary permitting, and set-up and validation periods (such as required for a floating lidar unit). Additionally, the quality and recovery of the data are important considerations and the duration of the campaign should be determined based on data quality and recovery metrics, on monthly and annual scales.

### 3.1.4 Instrumentation deployment and recovery

During instrument deployment and recovery, the following shall be considered:

- Schedule should account for any permitting requirements and necessary consultations with stakeholders (i.e., fishing and vessel traffic)
- All measurement campaigns should consider time required for validation, calibration, and/or commissioning of equipment.
- Weather conditions and potential limitations associated with certain times of year (i.e., harsh winter conditions; extreme wind gusts outside sensor measurement range of approximately >70 m/s)
- Accessibility of the site for maintenance and inspection
- Appropriate actions should be taken to notify mariners and properly mark any devices deployed
- Health, Safety & Environment (HSE) considerations given work offshore
- Storage and retrieval of data
- Decommissioning requirements.

### 3.1.5 Instrumentation operations and maintenance

Instrumentation should be able to capture the full range of metocean conditions at the site with good data recovery. Often metocean measurements will be made with more than one data acquisition system. It is important that the clocks are synchronized so all metocean measurements can be combined into a single database for analysis.

It is best practice to have a routine maintenance schedule for platforms and instruments. Although the frequency of inspections or maintenance will vary for equipment and structures, trips should be consolidated where possible to minimize HSE risks and costs. At minimum, inspections and maintenances should follow manufacturer recommendations. Also, instrumentation should be replaced before the calibration dates expire.

A maintenance record should be kept for all measurement systems associated with a measurement campaign and should include:

- Inspection date and time
- Condition of equipment and structures before and after site inspection and maintenances
- Date and time of any repairs or replacements.

It is also recommended that photos of the equipment and structures are used as part of the maintenance documentation. Additional documentation requirements are provided in Section 3.8.3. Such documentation is critical for data interpretation and assessing uncertainty.

# 3.2 Wind

## 3.2.1 Wind measuring instruments

### 3.2.1.1 Anemometers

Cup anemometer

The mechanical cup anemometer is the industry standard for measuring the wind speed at potential wind facility developments and to define wind turbine power curves. Wind speeds should be sampled at 1 Hz and 10-minute records of average, maximum, minimum, and standard deviation should be stored. Wind gusts should also be recorded and shall be defined by a 3-second maximum wind speed [IEC 61400-1:2005, MEASNET “Site Evaluation of site specific wind conditions” (ESSWC)]. The cup anemometers should be calibrated at a MEASNET-accredited facility before being installed. For the campaign to be IEC compliant, the primary and control anemometers shall also be calibrated in the same measurement campaign.

The wind speeds measured by cup anemometers are influenced by turbulence, air temperature, air density, and the mean inflow inclination angle. Cup anemometers are vulnerable to various sources of uncertainty that may affect the accuracy of wind speed measurements. Known impediments include: tower/boom wake effects, cup rotor dynamic over speeding and bearing friction, calibration uncertainty, vertical turbulence effects, and vertical flow effects.

While these impediments can introduce material error in the estimation of the true mean wind speed they are also quite well understood and often easily mitigated or corrected. Data coverage for cup anemometers is generally high and greater than remote sensing (RS) devices. Data coverage is limited by ice accumulation on the cups and/or shaft, and precipitation. Cup anemometers should be replaced biannually as their calibration expires after two years. Additionally, cup anemometers may need to be replaced due to bearing wear or physical damage from extreme wind conditions or during periods of heavy icing.

Prop anemometer

A cup or sonic anemometer should be used to measure horizontal wind speeds as a propeller (prop) anemometer measures both the horizontal (u) and transverse (v) wind speeds. For this reason the IEC 61400-12-1:2017 states that a cup or sonic anemometer shall be used to measure horizontal wind speeds. It is noted that some existing measurement stations utilize prop anemometers to measure horizontal wind speeds, and there will be an elevated uncertainty in the measurement. Care should be taken when interpreting measurements and calculations such as wind shear from prop horizontal wind speed measurements.

A vertical facing prop anemometer maybe used to measure the vertical (w) wind speed component. This can be used as input in wind inflow angle or atmospheric stability calculations. Wind measurements are generally sampled at 1 Hz and 10-minute records of average, maximum, minimum, and standard deviation are stored. Data coverage is limited by ice accumulation on the cups and/or shaft. The propellers on these anemometers are fragile and may break in high winds.

Sonic anemometer

Sonic anemometers are either 2-dimentional and measure horizontal wind speed or 3-dimensional and measure the horizontal, transverse, and vertical (u, v, and w) components of the wind speed. A sonic anemometer may also have the capability to measure wind direction and temperature. For wind resource assessment, measurements are generally sampled at 1 Hz and 10-minutes records of average, maximum, minimum, and standard deviation are stored. Sonic anemometers should be calibrated at a MEASNET-accredited facility for directional sensitivity before being installed. Depending on the model, an advantage of a sonic anemometer is that it may allow for the calculation of atmospheric stability and it is not subject to dynamic overspeed or bearing friction. These sensors are fragile and care should be taken during transportation and installation. Sonic anemometers require continuous power that can be met with an autonomous solar panel and battery bank system. Data coverage is limited by ice accumulation and precipitation.

#### 3.2.1.2 Wind vanes

The mechanical wind vanes are used in conjunction with cup anemometers to measure wind direction. Wind directions are generally sampled at 1 Hz and 10-minutes records of average, maximum, minimum, and standard deviation are stored.

Data coverage for wind vanes is generally high and data coverage is limited by ice accumulation. It should be noted that over time the wind vane components, such as the potentiometer fail and need replacement every few years.

#### 3.2.1.3 Sodars

Sonic detection and ranging (sodar) systems have an established history in the atmospheric science research domain dating back several decades. These devices are designed to emit acoustic pulses at some known and stable frequencies. Typically, the atmosphere is probed with a series of three “beams” of sound to collect information that can be used to determine the horizontal, transverse, and vertical (u, v, and w) components of the wind. After an acoustic pulse is emitted, the signal is scattered by turbulent refractive index changes that are present in the local atmosphere. This interaction causes a small proportion of the emitted acoustic signal to be backscattered and returned to the sodar system for subsequent detection and analysis. The acoustic return signal arrives at a frequency that has been shifted from the originally emitted frequency. The degree to which the emitted frequency is shifted (the Doppler shift) is directly proportional to the radial wind speed (the wind speed component along the beam). Through a series of geometric and signal processing calculations, the radial wind speeds are converted to the horizontal and vertical wind speeds samples. Depending on the sodar model, a single wind speed measurement occurs approximately every 3 seconds. These are averaged over a 10-minute period. Depending on the sodar model a 10-minute average, maximum and standard deviation wind speed is recorded, a 10-minute average with turbulence intensity is recorded, or only a 10-minute average wind speed is recorded. It should also be noted that data availability within the 10-minute period is often less than 100% and data are rejected when the reliability or availability in the sample becomes too low. Limitations on the use of sodar measurements are provided in section 3.2.1.6.

In addition to manufacturer calibrations, a sodar device shall be validated before deployment at a stand-alone offshore location. Sodar devices are relatively easy to operate and maintain because they often have low power requirements that can be met with a simple solar panel and battery bank arrangement, which permits unattended use in remote offshore areas. The relatively inexpensive initial acquisition cost of a sodar system is another powerful advantage of this technology that is largely comprised of simple, readily available components. Sodars typically probe the atmosphere at heights up to approximately 110–120 meters AGL with adequate data recovery. However, the acoustic signal that is transmitted by sodar systems can be influenced by echo interactions, precipitation, and loud noises that may introduce measurement bias or limit data availability. Data coverage maybe also limited under stable or neutral atmospheric conditions, extreme changes in temperature with height, high winds, precipitation, and fog. Sodar operations are further limited offshore as many systems are not designed for continuous operation in a marine environment (particularly close to the water surface or splash zone). Additionally, sodar devices generally have relatively large space requirements compared to lidars, which can create challenges for offshore deployments.

#### 3.2.1.4 Lidars

Vertical lidar

A light detection and ranging (lidar) system is in many ways is similar to a sodar system. The fundamental difference between these systems is that a lidar device probes the atmosphere with a highly coherent laser (light) beam rather than acoustic pulses. Lidar devices may transmit light at a known frequency in either a pulsed or continuous wave approach. In either case, the transmitted signal is reflected by atmospheric particulates that scatter the incident light in all directions. Some of the reflected light is subsequently detected by the lidar system and analyzed to determine the mean frequency of the return signal and the Doppler shift. Lidars may use samples gathered from three to five separate beam directions or may scan in a continuous pattern, for example in a circle, collecting a series of samples around the circle. Lidar systems then transform the samples of radial wind speeds into average horizontal and vertical wind speeds over a given averaging period. Depending on the lidar configuration, wind speeds are sampled every 1 second or 3 seconds and averaged over a 10-minute period. In general, lidars record a 10-minute average, maximum, minimum and standard deviations wind speed. It should also be noted that data availability within the 10-minute period is often less than 100% and data are rejected when the availability in the sample becomes too low. Limitations on the use of lidar measurements are provided in section 3.2.1.6.

In addition to manufacturer calibrations, a lidar device shall be validated before deployment at a stand-alone offshore location. Lidar technology is appealing because the transmitted laser signal is not subject to influence by echo interactions or loud noise. Typically, lidar data availability is quite good and light to moderate precipitation events do not significantly affect measurement accuracy. It is typical for lidar devices to probe the atmosphere at heights up to approximately 150–170 meters AGL with suitable data recovery. Lidar device data coverage maybe limited under stable or neutral atmospheric conditions, fog, or heavy precipitation. While laser-based remote sensing systems offer many useful advantages, they are known to be fragile, expensive, and they may have relatively onerous power requirements for remote operation. Note that as wind turbine technology evolves with larger turbines being developed, the ability of lidar to reliably measure wind conditions at or above hub height may be limited, however lidar technology and the application thereof continues to evolve so these effects are expected to be mitigated.

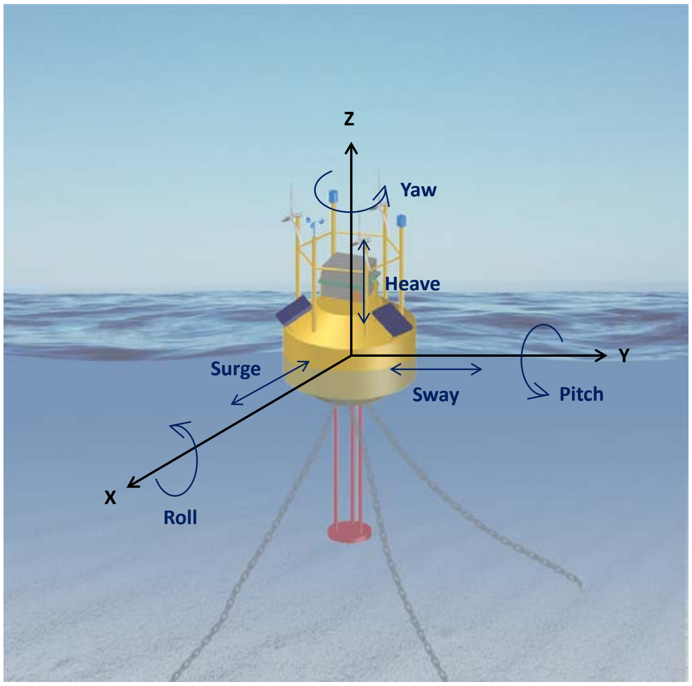
Scanning lidar

In general, scanning lidars operate under the same principles as vertical lidars, but face horizontally to measure the wind speeds several kilometers across a site at several scanning heights above the sea. The scanning range depends on the lidar model, configuration and site specific conditions. A scanning lidar maybe located onshore or offshore. Onshore scanning lidar measurements should only be considered when the project area is within the scanning range of the lidar device; however, there may be situations for which the project area of interest is outside the scanning range but the measurements provide useful qualitative information on the spatial variability of the wind resource near the project area. Scanning lidars are highly configurable as users can define the scanning locations and heights. The probing volume is much larger than a vertical facing lidar as the distance measured is significantly farther from the lidar lens. Thus, the measured wind speed in non-benign wind conditions may be representative of an area mean rather than the reference point. Therefore, the absolute mean wind speeds at a reference point, such as a turbine location, from the scanning lidar are more uncertain as compared to those observed at a measurement location.

Scanning lidars should be validated either during or before deployment. Scanning lidars are appealing as they measure data for many locations above sea over a relatively short window of time. Generally, scanning lidar devices probe the atmosphere at distances of several kilometers at heights of interest with suitable data recovery.

Floating lidar

Floating lidar devices (FLDs) are lidars that are installed on a floating platform (typically a buoy or vessel-shaped platform) and a motion compensation system. The motion of the buoy can be described as six degrees of freedom (DOF) as shown in Figure 3-1. The measurement of DOF is used to correct the lidar measurement to be equivalent to a mast height measurement at sea level.



Source: Fraunhofer IWES modified

**Figure 3-1 The six degrees of freedom of a floating lidar**

FLD have the same advantages and disadvantages as a vertical or scanning lidar, but face the additional challenge of measuring wind conditions under dynamic conditions associated with the movement of the ocean. In some instances, this leads to a teething period after the initial installation to obtain valid data. Therefore, it is recommended that additional time and budget is incorporated into the measurement campaign to allow for this set-up period (if required). FLDs are economical as they do not require a fixed platform. There are several commercially available FLD models that can produce wind data within an acceptable level of accuracy.

A FLD may be employed as a supplemental measurement to a meteorological mast, or as a primary measurement and substitute to anemometer measurements. The use of a FLD will be largely driven by the maturity of the system as defined by the “OWA roadmap for the commercial acceptance of floating LIDAR technology” (CTC819), and summarized in Table 3-1. Only FLDs that have reached a “Commercial” maturity stage, such as Scenarios E, F, and G in Table 3-1 below, should be used without undergoing a validation period with a trusted reference measurement system. However, for the most certain approach, it is recommended that a validation period is undertaken as described in CTC819 and the “Offshore Wind Accelerator Recommended Practice for Floating LiDAR Systems” (CTC870).

**Table 3-1 Summary of roadmap and FLD Maturity**

(from Carbon Trust Offshore Wind Accelerator roadmap for the commercial acceptance of floating lidar technology)

| Prerequisites (type validation) | | Campaign Requirements | | Indicative Measurement Uncertainty |
|---|---|---|---|---|
| | | **Possible Applications** | **Limitations** | |
| **Baseline** | • LIDAR type considered as "proven technology" in onshore wind industry. | **Scenario A**<br>Fixed met mast supplemented by one or more FLD deployments | • FLD data used only in a relative sense to support wind flow modelling used to estimate horizontal and vertical variation in wind resource across site. | N / A (uncertainty assessment driven by primary met mast measurements) |
| **Pre-commercial** | • As above, plus:<br>• Pilot validation trial for FLD type completed successfully including independent scrutiny and confirmation of Acceptance Criteria. | **Scenario B**<br>Single FLD deployment | • 2-Phase FLD Unit Validation required.<br>• Metocean conditions during campaign shall be demonstrated to be within the Unit Validation and Type Validation.<br>• Independent wind data source (regional measurements or modelling) and / or high level of industry experience of wind resource in region required to cross-check results. | 4-7% |
| | | **Scenario C**<br>Multiple FLD deployments | | |
| | | **Scenario D**<br>Fixed met mast supplemented by one or more FLD deployments | • 2-Phase FLD Unit Validation required.<br>• Phase 2 can be carried out on target site. | N / A<br>(uncertainty assessment driven by primary met mast measurements) |
| **Commercial** | • As above, plus:<br>• Good operational experience and accuracy achieved across a number of pre-commercial deployments.<br>• Residual environmental sensitivities well understood and documented. | **Scenario E**<br>Single FLD deployment | • Scenario B and C Limitations recommended for lowest uncertainty, although not essential. | 2-4% |
| | | **Scenario F**<br>Multiple FLD deployments | | |
| | | **Scenario G**<br>Fixed met mast supplemented by one or more FLD deployments | • 2-Phase FLD Unit Validation recommended for lowest uncertainty, but not essential. Phase 2 can be carried out on target site. | |

#### 3.2.1.5 Radar

Doppler radars can be used to measure three-dimensional wind speeds and direction for several kilometers across a wind facility. These devices are designed to emit radio or electromagnetic signals, and basic principles are akin to sodar technology. The size of the radar units varies and, depending on the model, maybe located onshore near the wind facility, on fixed marine platform, or can be placed on a floating platform such as a buoy. The use of radar in offshore wind is relatively new and the application of this technology for offshore wind is still in the research phase of development.

#### 3.2.1.6 Comparison of wind instruments applications

The preferred primary wind speed measurement is from a hub-height MEASNET-calibrated cup anemometer [IEC 61400-12-1, MEASNET ESSWC]. Therefore, it is preferred that wind speed measurements from the lower blade tip to at least hub height are made with cup anemometers.

A good quality sonic anemometer will have high quality wind measurements. The wind speed can be used as redundant or control wind speed measurement to a cup anemometer. It should be noted, however, that slight differences in wind speeds between a cup anemometer and sonic anemometer exist as cup anemometers are a scalar point measurement and sonic anemometers are essentially a vector point measurement. Thus, is it not recommended to directly splice cup anemometer data with redundant sonic anemometer data to gap fill missing periods. Rather data maybe synthesized by Measure-Correlate-Predict (MCP) or other appropriate methods.

Accurate wind speeds may also be obtained from a RS device. An advantage of a sodar or lidar is that it can measure wind speed, direction, and vertical wind speeds across the rotor at multiple heights. However, the application of the wind speed measurements is more limited than with a cup anemometer due to the way they measure wind speed. This is in part because RS devices measure a volume of air that produces inherently different wind speeds compared to conventional anemometry, the magnitude of which is dependent on the homogeneity of the sample area. Thus, caution should be applied when using remote sensing devices to measure extreme wind speeds. Also, data coverage at high wind speeds can be poor from a RS device and maximal wind speeds may not be recorded. Many commercial sodars are unable to measure 3-second gusts. Therefore, caution should also be applied when utilizing RS technology to perform extreme gust analyses to inform wind turbine site suitability and design. Note that application of RS technology is still evolving and, thus, additional guidance is expected to emerge and current best practices should be assessed prior to conducting a campaign with RS technology.

Cup and sonic anemometers are recommended to derive turbulence intensity, which characterizes the variability of the local wind regime to gain an understanding of the loads one might expect a wind turbine to experience if it were to be constructed near the point of data collection. Given the low turbulence intensity levels offshore, resulting turbine wake losses calculated can be sensitive to changes in input turbulence intensity profile, therefore mast wakes on anemometry can significantly impact turbulence modelling and only mast wake free wind speeds should be used. This can be avoided by installing redundant anemometers on a mast and orienting anemometers to minimize influence of the mast on measurements.

It is currently not recommended to directly interpret turbulence parameters that are recorded with remote sensing devices until more is understood about the consistency, accuracy, and meaning of such measurements with respect to associated turbine loads. This is because the average wind flow across a large volume of the atmosphere is somewhat less variable than that at a particular point in the atmosphere. This trait, as well as others, contributes to a significant disagreement in turbulence measurements that are reported by remote sensing devices as compared to anemometry.

Wind directions on a mast can be used from a wind vane, sonic anemometer, or RS devices. Typically, when cup anemometers are used a wind vane or sonic anemometer will be used.

Vertical wind speeds can be measured by a sonic anemometer, vertical propeller anemometer, or RS device. An advantage of a prop anemometer over a sonic anemometer is that it is relatively inexpensive and does not require power. However, the propellers on these anemometers are fragile and may break in high winds. A great advantage of a lidar or sodar is that it can measure vertical wind speeds across the rotor at several heights. All of these sensors are sensitive to off-level measurements and proper installation is important to obtain accurate vertical wind speed measurements.

All wind measurement equipment is susceptible to bird perching and fouling. This can be a significant O&M and measurement problem as it will interfere a with obtaining reliable wind speeds measurements and can damage equipment. Remote sensing devices are particularly susceptible as perching locations are often at the site of measurement, thus impeding the ability to obtain wind data. Bird deterrents such as spikes or lasers may be necessary to minimize impacts from perching and fouling.

Table 3-2 provides an overview of site suitability for each type of wind measurement.

**Table 3-2 Overview of site suitability**

| **Measurement Device** | **Requires Platform** | **Relative Cost** | **Maintenance labor** | **Application** | **Limitations** |
|---|---|---|---|---|---|
| Anemometry | Yes | High | High | All phases of wind facility | Installation and maintenance cost is high |
| Sodar | Yes | Medium | Low | Preconstruction energy assessment | Sensitive to acoustic noise and echoes from platform; relatively large space requirements; typically not designed for marine operations |
| Vertical lidar | Optional | Medium to low | Low | All phases of wind facility | Some floating lidars models have not achieved commercial acceptance per the OWA roadmap |
| Scanning lidars | Optional<br>(generally Yes) | Medium to low | Low | Preconstruction and operational assessments | Higher uncertainty than vertical lidar. Often used qualitatively in wind measurement campaigns. |
| Radar | Optional | High to medium | Low | Commercial use to date are for operational assessments | Mostly in R&D phase |

## 3.2.2 Met-masts and fixed platforms vs floating solutions

### 3.2.2.1 Tall masts

Given the variability of the atmosphere from the sea surface to hub height, all wind, temperature, pressure, and humidity measurements should be completed at or near hub height, if possible, as well as at lower heights. As mentioned previously, installing redundant equipment can reduce unexpected maintenance trips, and increases measurement certainty. A simple met-mast should include the following:

- 2x anemometers at hub height
- 2x vanes at or near hub height
- 2x temperature sensors near or at hub height
- 2x barometric pressure sensors near or at hub height
- Optional near or at hub height measurement of relative humidity
- Optional near or at hub height measurement of vertical wind speed
- 2x anemometers at mid-blade
- 2x anemometers at blade tip
- Optional 2x wind vanes at blade tip for veer calculations.

Regardless of the mast height, number of booms, or sensors, the configuration should meet the requirements outlined in Annex G of IEC 61400-12 Ed. 2 and MEASNET ESSWC document for met-mast equipment. Following these best practices will minimize mast wakes and mounting errors.

The preferred method of measuring a wind resource includes a met mast as the industry standard is to measure wind speeds with cup anemometers. A tall mast also allows key climate measurements (i.e., temperature and pressure) to be made at or near hub height. A strategically placed hub height mast can be used throughout the project’s life cycle (preconstruction energy assessments, construction, power performance test, and operation). However, tall masts are expensive to install and maintain relative to RS devices.

DNVGL-SE-0420 specifies requirements for certification of meteorological masts and provides guidance to developers, owners, designers, and contractors for design, manufacturing, transportation/installation, commissioning, and in-service phases.

### 3.2.2.2 Fixed platforms

A fixed platform can house a tall met-mast, an RS device, or both. An advantage of a platform is that it is stable and wave actions cannot bias measurements. Additionally, all metocean measurement equipment can be installed on and around the platform. The platform requires the following:

- A boat landing or helicopter access
- Power supply for lighting and equipment
- Annual maintenance and inspection.

Fixed platforms are relatively expensive.

### 3.2.2.3 Floaters

Floaters are often used in short measurement campaigns beside a fixed platform or alone within the project area. The location of a floater should be selected to provide the most representative assessment of site conditions across the project area. If multiple floaters are deployed (or a single floater at multiple locations for successive time periods) the locations may also be selected to bracket the range of conditions expected across the site. Floaters are typically used to support lidars and may include a short mast measuring temperature, pressure, and other atmospheric parameters. As recommended earlier, redundancy in the wind measurements is important to reduce uncertainty and potentially increase data coverage. With respect to floaters, deploying two different lidar units (and potentially two different lidar models) on a single platform can provide redundancy and help to reduce uncertainty. This redundancy is most critical when the floater is not situated near a tall met-mast or other suitable reference. It should be noted that because floaters are often much smaller than fixed platforms, the number of metocean sensors installed is often limited.

All floaters shall contain an autonomous power supply to power both the instrumentation, data acquisition system and lighting. An advantage of floaters is that they are portable and can be moved from one location to the next with relative ease. They are also substantially less expensive to install and maintain relative to a fixed platform.

A disadvantage of floaters is that they often do not incorporate or are incapable of measuring temperature and pressure at hub height, which are important for characterizing the site conditions and calculating site air densities.

#### 3.2.2.4 Comparison

The following presents a high-level comparison of the key differences between fixed platforms and floaters:

- Fixed platforms can house all metocean measurements throughout the entire life cycle of a wind facility from development to decommissioning.
- Fixed-platform measurements do not need to be corrected for motion.
- Fixed platforms can measure wind, temperature, pressure, etc. at hub height; whereas, floaters often lack the ability of measuring non-wind measurement at hub height.
- Fixed platforms are expensive to install, maintain, and decommission.
- Fixed platforms generally are more challenging to permit relative to floaters.
- Floaters are less expensive than fixed platforms and are portable.
- Floaters typically utilize lidars and, as discussed in Section 3.2.1.6, are not recommended to evaluate extreme wind speeds or turbulence intensity.

### 3.2.3 Recommendations for wind instrument selection

When selecting instrumentation for an offshore wind measurement campaign it essential that the equipment is robust enough to withstand the climatic conditions, can operate under the anticipated wind and temperature ranges of the site, and is suitable for the intended purpose. The instrumentation suite utilized shall achieve the goals of a wind resource assessment and fulfill requirements of industry standards and best practices [IEC 61400-12-1, MEASNET ESSWC].

Offshore preconstruction wind resource and energy yield assessment will ideally be based on measured data from a hub height met-mast in a location that represents the majority of wind turbine locations. Remote sensing devices can then be used to help reduce the spatial wind flow uncertainties across the project. However, many offshore wind measurement campaigns cannot tolerate this expense and often only FLDs are used. This latter scenario typically will result in greater uncertainty in the preconstruction wind resource and energy yield assessment than the former.

An offshore wind measurement campaign at minimum should include measurements of horizontal wind speed and wind direction from blade tip to at least hub height, 3-second maximum wind gust at hub height, and measurements of temperature and pressure at ideally hub height. It also is desirable to have hub height measurements of relative humidity for air density calculations and vertical wind speed to evaluate inflow angles. This is because wind shear profile can be complex during jets and high wave activity, etc. These measurements can be achieved with either a tall mast or in part with a short mast in combination with a remote sensing device.

It is best practice to build redundancy in wind speed measurements; however, given the remoteness of an offshore project it is beneficial to build in redundancy for all wind and site condition measurements. Redundancy reduces measurement uncertainty, and if a sensor breaks, another measurement is available. Although redundancy increases upfront cost for a measurement system, the benefits of maximizing data coverage and reducing unplanned maintenance trips makes redundancy of all measurements worth considering.

Note that heated anemometers and vanes may be useful in environments subject to high levels of icing. A variety of heated sensors are available from multiple vendors with different designs and performance. Heated sensors may perform significantly different from non-heated sensors and, thus, it is common practice to rely on heated sensors as secondary instruments to detect and quantify icing events and rely on standard equipment for wind speed and direction monitoring. Heated sensors also have higher power requirements than standard sensors and this should be considered for determination of the overall power budget.

The number of measurement locations across a project will be defined by the wind project area, and proximity to the shoreline. For example, for near-shore facility, the met mast or RS device should be installed within 2 km of future turbine locations. This can be relaxed for far offshore facilities as the spatial variation across a wind project area is greatly reduced relative to a near-shore location.

Scanning lidar and radar can be used to help evaluate operational wind facility wakes and wind production across the site. This can be beneficial when evaluating wind facility operations.

Measurements of wind conditions (and other meteorological data) should be performed in accordance with IEC 61400-12-1 and should follow MEASNET ESSWC procedures. In situations where other measurements are used that are not performed in accordance with IEC 61400-12-1 and MEASNET ESSWC (e.g. in case of historical measurements by NOAA or other organizations), the quality of such measurements shall be considered in the analysis and interpretation of such data.

## 3.3 Waves

### 3.3.1 Wave measuring instruments

#### 3.3.1.1 In-situ direct measurements

Wave staff

The simplest and oldest of wave measuring instruments is the wave staff, which generally consists of one or two wires vertically attached to a fixed structure, with a current running through. The staff should span from below the expected minimum water level and penetrate the sea surface to above the maximum expected water level. Various types exist, such as resistance type, capacitance type, Baylor, or transmission line type, measuring the elevation either by measuring the change in resistance, or capacitance, or transmission through the wire(s). Extensive experience exists in using and calibrating these instruments, as they have been widely used on oil and gas platforms in the Gulf of Mexico and elsewhere. They are found to be robust, relatively immune to fouling, and not particularly affected by spray. They are appropriate to use on slender structures, placed so that they are exposed to the primary direction of the incident waves, in order to avoid measurement contamination by wave-structure interaction effects. Wave staffs consist of a single point surface elevation measurement and do not provide any directional information.

Wave-following buoy

The most commonly used instrument when directional wave information is needed is a wave buoy, typically instrumented with an accelerometer and a direction sensor, and possibly tilt sensors depending on the type. Wave buoys have varying diameters, typically around 1-2 m, and a soft mooring system designed to allow them to follow the waves and respond in heave, pitch, and roll. The buoy motions are measured and transformed into wave motion using a transfer function. For accurate measurements, the motions need to be either measured directly in an earth-fixed coordinate system (e.g., by placing instrumentation on a vertically stabilized platform, such as a gyroscope or a gimbaled system), or use advanced signal processing methodologies to convert measurements from a buoy-fixed coordinate system to an earth-fixed one. In recent years, systems that measure wave motion based on a global positioning system (GPS) have also been developed. Systems also exist which include an acoustic current meter or similar, to obtain surface current measurements as well.

Wave buoys have been the norm in oceanographic measurements when high-quality directional spectral information is needed. Typically, these systems have a battery life ranging from a few months to a few years, and can transmit data in real time using various communications options. However, these systems are expensive, they are at high risk of damage or total loss due to environmental conditions or shipping, and have been known to underestimate or miss extreme crests either due to limitations of the mooring system or because they “skirt” the highest crests. Simpler systems with only heave sensors are available, if directional information is not needed.

### 3.3.1.2 In-situ indirect measurements

Pressure sensor

Pressure sensors can be installed below water surface either on the seabed or on a submerged buoy not significantly affected by waves and used to obtain wave data although with some limitations in deeper water environments. Since the pressure profile attenuates more rapidly for high-frequency (HF) waves, these sensors have depth limitations and may not provide a realistic spectrum because in deeper water HF wave amplitudes are underestimated. Linear wave theory shall typically be assumed to convert pressure into wave surface elevation. A single pressure sensor can only provide point measurements. However, if combined with a current meter or an acoustic Doppler velocimeter measuring two horizontal velocity components directional wave information can be derived (P-U-V method). P-U-V systems are routinely used for coastal engineering applications in shallow waters.

Acoustic Doppler Current Profilers

In more recent years, ADCP systems have been used as directional wave measurement systems. ADCPs are widely used for other measurement applications (see Section 3.4.1), and in the last decade have gained increasing popularity as wave measuring instruments since they are much more cost-effective than a directional wave-rider buoy. ADCPs emit acoustic signals in beams focused at different water depths, and using the Doppler shift, measure wave orbital velocities at different bins throughout the water column. An in-built pressure sensor assists with measuring wave surface elevation. They are typically bottom-mounted on the seabed and facing upward, although they can also be mounted on a fixed structure (subsurface) and face horizontally. As with a P-U-V system, accurately measuring HF wave components is challenging, but results are more robust since measurements exist at a multitude of water depths. As with the pressure-sensor, linear wave theory is assumed to transform the orbital velocities into wave elevation.

### 3.3.1.3 Remote Sensing

Microwave Radar

A wide variety of different radar systems exist and have been developed for wave measurements. The most common operate in the microwave radio-frequency band, and use a continuous wave frequency modulated or pulsed signal in the GHz range. These systems can generally be separated into two categories, downward-facing and forward-facing radars.

Downward-facing systems are typically mounted on fixed structures above the highest expected total water level (extreme wave crest and tidal excursion), with a clear downward view of the sea surface. They make direct measurements based on reflections off the water surface, using a fixed narrow beam (beam width on the order of 10 degrees), and hence measure only surface elevation without directional information. Directional information can be obtained by mounting three vertical radars in an appropriate configuration and signal processing the results. Downward-facing radars have been used extensively on fixed platforms, and are known to generally perform well, although interference or shielding from the platform may be an issue.

Forward-facing radars operate at low-grazing angles to scan entire sectors ahead of the instrument, usually using x-band marine navigation radar. The wave environment is deduced from Bragg scattering; therefore, these systems do not work if surface ripples (Bragg waves) are not present. They are classified as an indirect measurement method, since there is no direct relation between the wave amplitude and the amplitude of the backscatter modulation. Unlike the downward-facing radar, they can be easily used to obtain directional wave spectra. They are most often mounted on floating vessels, in which case a motion compensation unit may be used to remove the effects of the vessel motion. As measurements are made at a distance from the instrument, they are practically unaffected by the presence of the platform or vessel.

Laser

Although less common, it is possible to use pulsed infrared laser to measure wave height at a point. Like downward-facing radar systems, lasers are mounted looking vertically downward on fixed structures and an array of at least three instruments is needed to obtain directional information. These systems are operationally more problematic because they can be seriously affected by fog and it is uncertain what they measure in the case of sea spray.

HF Radar

Significant advances have been made in the last decades in developing HF radar systems (functioning in the HF band of 3-30 MHz) to enable long-distance current measurements. These systems are installed in arrays along the coastline, and can have a measuring range of up to a few hundred kilometers depending on the transmission. They are also based on Bragg scattering and the Doppler-frequency shift of the return signal, therefore require a minimum threshold of sea-state conditions in order to work. They are primarily focused and optimized for current measurements, and wave data are the result of a second-order scattering mechanism, therefore are more difficult to obtain with high accuracy. However, it is likely that they will be used increasingly in the future for wave measurements as well, if present shortcomings, relating to the signal to noise ratio and behavior in shallow water and in extreme sea-states, are sufficiently addressed. Currently arrays of HF radars such as the CODAR SeaSonde are installed across U.S. coastlines, as part of the Global HF radar network.

### 3.3.2 Comparison of solutions

The types of instruments described in the previous section all have benefits and limitations. If directional wave data is required then the options are either an array of lasers or downward looking radars, a low grazing angle radar, a subsurface P-U-V system, an ADCP or a wave rider buoy.

In the context of a wind facility development, arrays of lasers or downward looking radars are the least convenient option since they require a fixed structure with a large surface area to be mounted on. If a fixed structure, such as a met-mast, is already part of a wind facility development, a forward-facing radar (for example Miros) can be installed, consisting of rangefinder and an x-band marine radar as input. This may not offer significant economic benefit compared to employing a wave rider buoy, although these systems require significantly less maintenance. They are typically calibrated only once by the manufacturer before installation, and remain in constant operation throughout the duration of the measurement campaign, even throughout the lifetime of the wind facility. The data return is generally high, and the data accuracy satisfactory although less than a wave rider buoy.

A P-U-V system can be used in the range of water depths of wind facility developments in shallower waters (15-30 m), but this system is less appropriate for wind facilities in deeper waters (>30m). A P-U-V system is relatively inexpensive and easy to install, usually equipped with a release mechanism which when activated releases the instruments to the surface for recovery. Inherent assumptions of linear wave theory result in reduced accuracy of spectral information in extreme sea states, whilst they are known to underestimate HF spectral content and a correction generally needs to be applied to the spectrum when postprocessing the data.

A wave rider buoy is still considered to provide the most accurate directional wave spectral information, despite the high costs of purchase and maintenance. If a good quality well calibrated instrument is selected, antifouling paint is used, an appropriate mooring system is installed, and the wave buoy is retrieved for maintenance every 1 to 2 years, the data return can be as high as 99% and the quality better than any of the other systems, although they are at risk from shipping or fishing activities. In locations with strong currents a wave rider buoy may not be appropriate and alternative solutions need to be found.

The most recent alternative to a wave rider buoy is the ADCP, which may in the future combine some of the benefits of the P-U-V system with the accuracy of the wave rider buoy. It can either be seabed mounted, much like a P-U-V system, or subsurface mounted on a fixed structure. Since these devices have been used to measure currents for many decades, the technology of the instrument itself is well-established and they are robust with a very high data return, although measurement inaccuracies may arise in the bins close to the seabed and close to the free surface. They also have difficulty measuring in the presence of bubbles at the surface, which can be a major shortcoming in severe sea states. Much research has been done in comparing the directional wave results of ADCP against traditional instrument types. When equipped with a pressure sensor, and thanks to measurements made at multiple layers, the instrument can provide multiple estimates of wave height, and check for consistency within itself leading to higher accuracy data. It has also been observed that the greater number of degrees of freedom of measurement result in sharper directional spectra and more complex multi-directional distributions can be measured compared to the wave rider. Table 3-3 presents an overview of the site suitability of wave measuring instruments.

**Table 3-3 Overview of site suitability of wave measuring instruments**

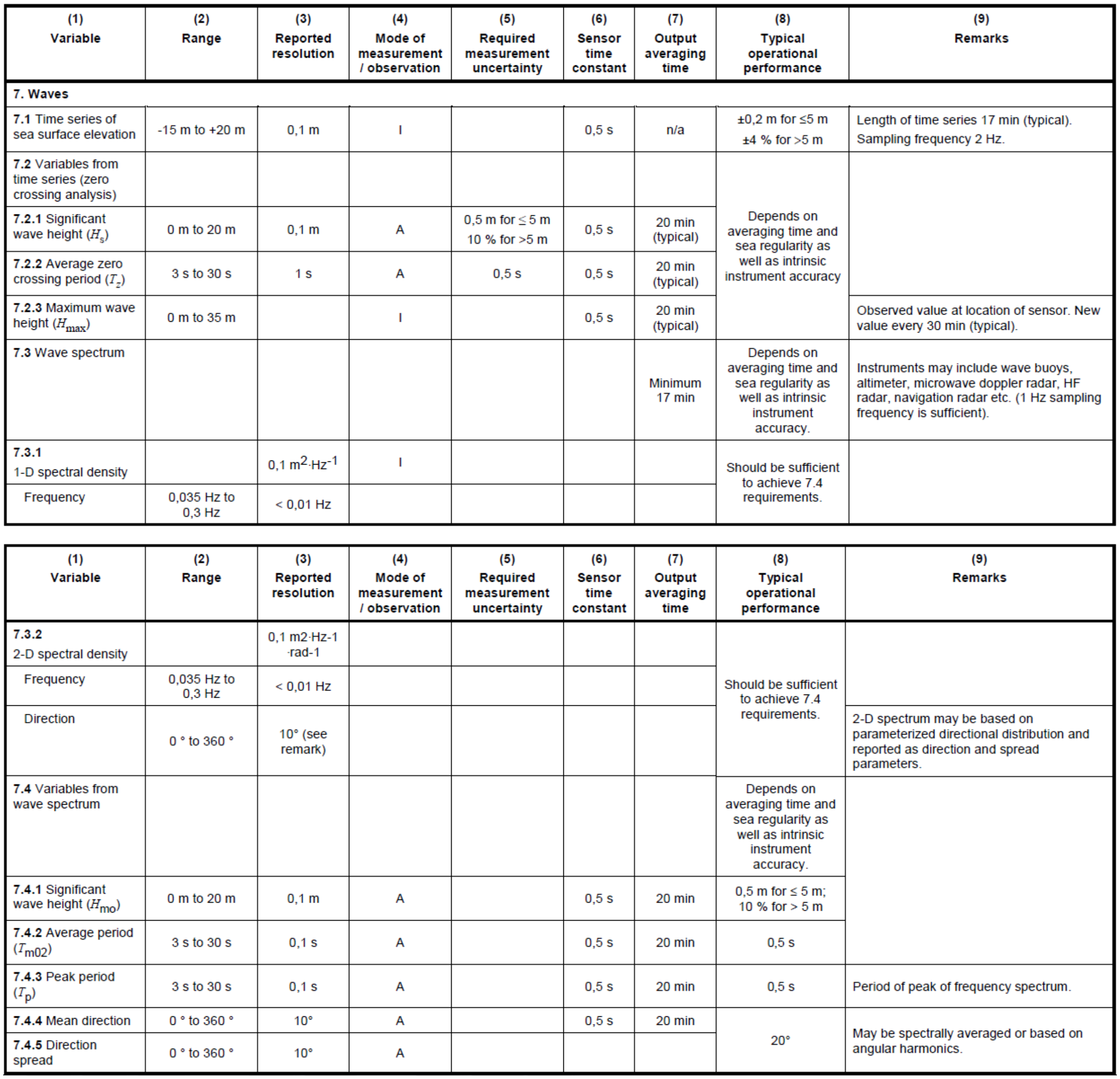
| Measurement device | Requires platform | Cost | Maintenance labor | Application | Limitations |
|---|---|---|---|---|---|
| Wave staff | Yes | Very Low | Low | Preliminary assessment | Only non-directional measurements; interference of the structure |
| Wave-rider buoy | No | High | High | All phases of facility lifecycle | May not capture extreme crests; at risk from marine traffic; cannot be used in areas of very high current. |
| Pressure sensor | No | Low | Medium | All phases of facility lifecycle | For directional measurements, current meter or similar is needed; shallow water only. |
| ADCP | No | Medium | Medium | All phases of facility lifecycle | Less experience with wave measurements from the instrument; accuracy under verification. |
| Downward-facing Radar | Yes | Medium | Low | All phases of facility lifecycle | Array needed for directional measurements requiring platform with large surface area. |
| Forward-facing radar | Yes | Medium -High | Low | All phases of facility lifecycle | Less accurate than wave buoy; only works if Bragg waves present. |
| Laser | Yes | Medium | Low | All phases of facility lifecycle | Array needed for directional measurements requiring platform with large surface area. Does not work in fog, issues with wave spray. |
| HF Radar | No | Medium -High | Low | Preliminary assessment | Wave measurements still in research phase. |

### 3.3.1 Recommendations for wave instrument selection

The most appropriate measurement instrument for collection of wave data will vary depending on the site (water depth, wave climate, proximity to shore, shipping traffic, or fishing activity) and the purpose of the wave data.

Other than the differences highlighted in Table 3-3 above, if good quality equipment is selected, well calibrated, and appropriately installed and maintained, all the above systems can provide acceptable data for facility design and development. The requirements for data collection are set out in ISO 19901-1:2015 (Annex A.11, Table A.8, in turn based on Annex 1.B, pp 19-24, Chapter 1, of WMO-No. 8:2008) and the wave section presented here as Table 3-4. This table presents the required measurement range, resolution, and operational performance to result in suitable data for each type of wave information.

**Table 3-4 Recommended instrument accuracy and operational performance - waves**



| (1) Variable | (2) Range | (3) Reported resolution | (4) Mode of measurement / observation | (5) Required measurement uncertainty | (6) Sensor time constant | (7) Output averaging time | (8) Typical operational performance | (9) Remarks |
|---|---|---|---|---|---|---|---|---|
| **7. Waves** | | | | | | | | |
| **7.1** Time series of sea surface elevation | -15 m to +20 m | 0,1 m | I | | 0,5 s | n/a | ±0,2 m for ≤5 m<br>±4 % for >5 m | Length of time series 17 min (typical).<br>Sampling frequency 2 Hz. |
| **7.2** Variables from time series (zero crossing analysis) | | | | | | | Depends on averaging time and sea regularity as well as intrinsic instrument accuracy | |
| **7.2.1** Significant wave height ($H_s$) | 0 m to 20 m | 0,1 m | A | 0,5 m for ≤ 5 m<br>10 % for >5 m | 0,5 s | 20 min (typical) | | |
| **7.2.2** Average zero crossing period ($T_z$) | 3 s to 30 s | 1 s | A | 0,5 s | 0,5 s | 20 min (typical) | | |
| **7.2.3** Maximum wave height ($H_{max}$) | 0 m to 35 m | | I | | 0,5 s | 20 min (typical) | | Observed value at location of sensor. New value every 30 min (typical). |
| **7.3** Wave spectrum | | | | | | Minimum 17 min | Depends on averaging time and sea regularity as well as intrinsic instrument accuracy. | Instruments may include wave buoys, altimeter, microwave doppler radar, HF radar, navigation radar etc. (1 Hz sampling frequency is sufficient). |
| **7.3.1** 1-D spectral density | | 0,1 $m^2 \cdot Hz^{-1}$ | I | | | | Should be sufficient to achieve 7.4 requirements. | |
| Frequency | 0,035 Hz to 0,3 Hz | < 0,01 Hz | | | | | | |
| **7.3.2** 2-D spectral density | | 0,1 m2·Hz-1 ·rad-1 | | | | | Should be sufficient to achieve 7.4 requirements. | |
| Frequency | 0,035 Hz to 0,3 Hz | < 0,01 Hz | | | | | | |
| Direction | 0 ° to 360 ° | 10° (see remark) | | | | | | 2-D spectrum may be based on parameterized directional distribution and reported as direction and spread parameters. |
| **7.4** Variables from wave spectrum | | | | | | | Depends on averaging time and sea regularity as well as intrinsic instrument accuracy. | |
| **7.4.1** Significant wave height ($H_{mo}$) | 0 m to 20 m | 0,1 m | A | | 0,5 s | 20 min | 0,5 m for ≤ 5 m;<br>10 % for > 5 m | |
| **7.4.2** Average period ($T_{m02}$) | 3 s to 30 s | 0,1 s | A | | 0,5 s | 20 min | 0,5 s | |
| **7.4.3** Peak period ($T_p$) | 3 s to 30 s | 0,1 s | A | | 0,5 s | 20 min | 0,5 s | Period of peak of frequency spectrum. |
| **7.4.4** Mean direction | 0 ° to 360 ° | 10° | A | | 0,5 s | 20 min | 20° | May be spectrally averaged or based on angular harmonics. |
| **7.4.5** Direction spread | 0 ° to 360 ° | 10° | A | | | | | |

All the instruments discussed above, with the exception of the wave staff, can provide wave spectra and hence the variables derived from the spectra. In the context of an offshore facility development on fixed foundations, this is sufficient information. Commercial systems are available in each of the above categories which fulfill the requirements set out in Table 3-3, and it is up to the user to ensure that the specific instrument selected is appropriate. The wave staff and the wave buoy are the only instruments that can reliably provide a time-history of sea-surface elevation, and hence the variables derived from it. For future wind facility developments on floating foundations, obtaining high-accuracy wave measurements is far more important, and a real-time history of sea-surface elevation can greatly assist with the design activities relating to the floating foundations.

For a successful measurement campaign redundancy in instrumentation is required. As a minimum two instruments measuring simultaneously should be deployed, ideally of a different type (e.g., a wave-rider buoy and an ADCP). If water depths across the site vary significantly (more than 10-15 m) and if the bathymetry is complex, additional instruments should be used to capture site variability.

## 3.4 Currents

Ocean currents can be measured either in a Eulerian frame of reference (measurements taken at a fixed location) or a Lagrangian frame of reference (measurements taken by following individual velocity particles). Lagrangian measurements, taken using drifting buoys or “drifters,” may be very informative when studying large scale ocean processes but are not appropriate for the development of metocean criteria in the context of the design of an offshore wind facility. Therefore, only Eulerian measurements are discussed here.

### 3.4.1 Current measuring instruments

#### 3.4.1.1 In-situ measurements

In-situ measurements can be made either with mechanical, acoustic, or electromagnetic devices.

Mechanical current meters

Mechanical current meters employ a propeller or rotor to make direct measurements of current speed. The propeller sensors can be used on their own with a vane (together with compass) to measure current direction. An example is the rotor current meter (RCM) which measures speed and direction directly, or the vector-averaged current meter (VACM), which uses the speed and direction measurements from the rotor and vane to compute and average the horizontal and vertical components of the velocity. Alternatively, the propeller sensors can be used in bi-axial or tri-axial configurations to measure directly two or three vector components of the current flow without the need for a vane. An example of this is the vector-measuring current meter (VMCM). Mechanical current meters make point measurements of the flow at the instrument location.

Acoustic current meters

Acoustic current meters can either be based on the Doppler shift principle or on acoustic travel time. Acoustic travel time current meters emit acoustic pulses and measure the difference in travel time of the pulses. Different types exist, emitting two pulses in opposite directions, or one pulse following another in one direction, or emitting continuous signals in opposite directions. All these types make point measurements of the flow at the instrument location.

Bottom-mounted ADCP can measure current speed and direction throughout the water column at equal intervals, by transmitting HF sound and measuring the Doppler shift of the return signal. They have a range of up to 1000 m water depth depending on the settings, and unlike mechanical sensors they can measure small scale currents. These instruments are now also being used to measure wave height and direction (see Section 3.3.1.2).

Electromagnetic current meters

Electromagnetic current meters measure the electromagnetic field changes induced by ocean currents flowing through a magnetic field, and as such are an indirect method of measurement. These instruments measure speed and direction, using Faraday’s law of induction. They are robust instruments in the marine environment, with low maintenance and no fouling due to the absence of any protruding or moving components. They are also unaffected by bubbles, therefore can be used in the splash zone. However, their high energy consumption means there has been limited uptake in oceanographic applications so far. Electromagnetic current meters make point measurements of the flow at the instrument location.

#### 3.4.1.2 Remote sensing

Many of the remote sensing techniques used to measure waves (see Section 3.3.1.3) are also appropriate for measuring surface current. HF radar was principally developed for surface current, and is better suited to this application. Some of the commercially available wave radars also provide surface current measurements together with the wave measurements. These solutions are generally based on the scattering of surface Bragg waves and can only provide surface current with no information on the rest of the water column.

### 3.4.2 Comparison of solutions

Mechanical current meters are the oldest type of current measuring device. They have been in use since the 1960s and are simple, inexpensive, and easy to maintain and use. However, the moving parts mean that they are very prone to marine fouling, are known to stall at speeds lower than approximately 2 cm/s, and may undergo damage at high-current speeds. In addition, the rotor/vane systems may respond excessively in oscillatory flow and are influenced by the dynamic response of the instrument. By being placed in the flow, they inevitably cause obstruction and hydrodynamic interference which may affect the measurements. The bi- or tri-axial propeller configurations such as the VMCM perform better than the rotor and vane types, especially when measuring horizontal flow in the near-surface region, since they are not as affected by the presence of waves, and this technology is still used in some practical applications.

Mechanical current meters are being fast superseded by acoustic solutions, primarily the ADCP. An ADCP can provide measurements throughout the water column using a single instrument, and the same technology can be used also for simultaneous wave measurements. They are robust, and the length of deployment is limited only by battery life, which can span up to a few years depending on the setup. Remote sensing techniques can provide reliable measurements and benefit from using the same instrument for wave and current, but can only provide surface current measurements.

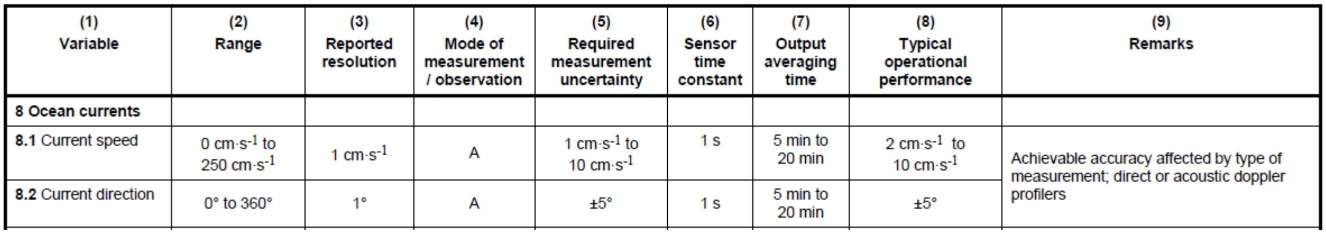
### 3.4.3 Recommendations for current instrument selection

Following ISO 19901-1:2015 recommendations, ocean currents should be measured at fixed depths (or bins), and include at least three depths in shallow waters: near-surface, mid-depth, and near-bottom. This requirement can either be satisfied with a number of single-point measuring devices on a mooring system, or a profiler such as an ADCP.

For future floating wind facility applications, where measurements in deeper waters will be required, the following depths should be considered in addition to near-surface and near-bottom: 50 m, 100 m, 150 m, 200 m, 300 m, and every 200 m thereafter to 3 m above the seabed (ISO 19901-1:2015). In deeper waters, the most economical solution may prove to be an ADCP, which can measure at a large number of levels. Since the ADCP has difficulty measuring in the boundaries (close to seabed and at the free surface), if a detailed high quality current profile is needed for the mooring system or floating turbine foundation design, the ADCP can be supplemented with additional single-point measuring instruments.

The mean speed and direction of ocean currents should be recorded at least once per hour for a duration of at least 10-20 minutes, or more often if possible. The recommended instrument accuracy and operational performance from ISO 19901-1:2015 are given in Table 3-5.

**Table 3-5 Recommended instrument accuracy and operational performance - current**



| (1) Variable | (2) Range | (3) Reported resolution | (4) Mode of measurement / observation | (5) Required measurement uncertainty | (6) Sensor time constant | (7) Output averaging time | (8) Typical operational performance | (9) Remarks |
|---|---|---|---|---|---|---|---|---|
| **8 Ocean currents** | | | | | | | | |
| **8.1** Current speed | 0 cm·s$^{-1}$ to 250 cm·s$^{-1}$ | 1 cm·s$^{-1}$ | A | 1 cm·s$^{-1}$ to 10 cm·s$^{-1}$ | 1 s | 5 min to 20 min | 2 cm·s$^{-1}$ to 10 cm·s$^{-1}$ | Achievable accuracy affected by type of measurement; direct or acoustic doppler profilers |
| **8.2** Current direction | 0° to 360° | 1° | A | ±5° | 1 s | 5 min to 20 min | ±5° | |

## 3.5 Water levels

Water levels at the site should be measured with a tidal gauge, which may be an acoustic, pressure, or radar system. All these systems can provide real-time information. Pressure gauges can be placed on the seabed or on a mooring system whilst acoustic and radar systems require a fixed platform. Regardless of the chosen system, it should be adequately calibrated and checked, for example using a tidal staff placed on a fixed platform and used as visual reference. Many current and/or wave measuring systems such as the ADCP and the P-U-V system already include pressure gauges which can also provide tidal level data. Therefore, a separate measurement system for tidal levels is often not required.

Water levels offshore should be measured with a resolution and instrument accuracy of ±1 cm. The output averaging time should be 10 minutes, and the sampling frequency at least 1 Hz.

## 3.6 Other parameters

### 3.6.1 Atmospheric parameters

#### 3.6.1.1 Air density, air temperature, air pressure, humidity

Air density shall be derived from measurement of air temperature, air pressure, and relative humidity. As an alternative to the humidity measurement, an assumed value of 50% relative humidity may be used if humidity is not measured. The air density shall be calculated according to Equation (3-1):

$$\rho_{10\text{min}} = \frac{1}{T_{10\text{min}}}\left(\frac{B_{10\text{min}}}{R_0} - \Phi P_{\text{w}}\left(\frac{1}{R_0} - \frac{1}{R_{\text{w}}}\right)\right) \qquad \textbf{(3-1)}$$

where

$\rho_{10\text{min}}$ is the derived 10 min averaged air density;

$T_{10\text{min}}$ is the measured absolute air temperature averaged over 10 min [K];

$B_{10\text{min}}$ is the air pressure corrected to hub height averaged over 10 min [Pa];

$R_0$ is the gas constant of dry air 287.05 [J/kgK];

$\Phi$ is the relative humidity (range 0 % to 100 %);

$R_{\text{w}}$ is the gas constant of water vapor 461.5 [J/kgK];

$P_{\text{w}}$ is the vapor pressure equal to $0{,}0000205 \cdot \exp(0.0631846 \cdot T_{10\text{min}})$ [Pa]. Vapor pressure $P_{\text{w}}$ depends on mean air temperature over 10 min.

The air temperature and humidity sensor shall be mounted within the upper 10 m of the measurement mast or at least at 10 m height. For the determination of atmospheric stability, it is recommended to measure the air temperature with the necessary accuracy at least at two different heights with adequate spacing.

Air pressure measurements shall be always corrected to the appropriate hub height according to ISO 2533.

The measurement period should cover at least 12 complete months in order to appropriately assess seasonal variations. Adequate shielding is mandatory to minimize biases and uncertainties due to solar radiation.

Extrapolation of temperature, air pressure, and humidity should be performed, provided that appropriate long-term data are available in order to derive the long-term mean values of air temperature, air pressure and humidity for the site.

Air temperature, air pressure, humidity, and precipitation may be sampled at a slower rate than 1 Hz, but at least once per minute.

The data acquisition system shall store either sampled data or statistics of data sets as follows:

- Mean value
- Standard deviation
- Maximum value
- Minimum value

Selected data sets shall be based on 10-minute periods derived from contiguous measured data.

For more details refer to IEC 61400-12-1 and MEASNET ESSWC.

### 3.6.1.2 Precipitation

Precipitation (rain, sleet, or snow) is typically measured as part of the data collection campaign for the site of interest. Precipitation sensors (such as rain gauges or similar) will typically be mounted on the met mast if used as part of the meteorological monitoring of the site, or on other nearby structures as applicable. Details on instrument accuracy and calibration are found in WMO-No. 8, Parts I and III.

### 3.6.1.3 Ice loading and accretion

There are several possibilities to detect ice, including ice detectors for atmospheric icing, ice detectors for instrumental icing, visual observation, or similar. Ice accretion occurs at temperatures below, or around zero.

Ice accretion on support and mounting structures can have a significant effect on the flow conditions for the anemometer. It is essential that such situations are avoided. A thorough assessment or monitoring of the conditions is required. It is recommended to use sufficiently heated structures near the instruments to prevent ice accretion.

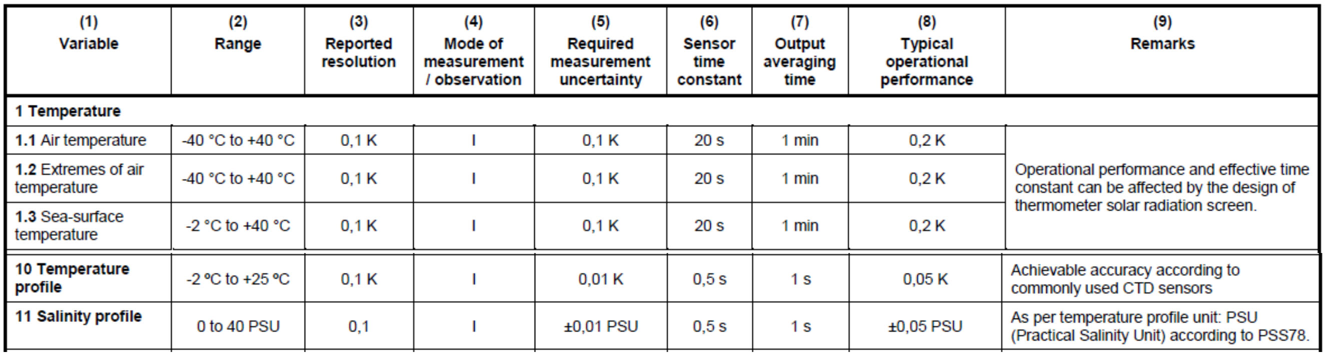
## 3.6.2 Other oceanographic parameters

### 3.6.2.1 Sea-water temperature, density, and salinity

Sea-water temperature, density, and salinity are usually obtained from a CTD (conductivity-temperature-depth) device. Temperature is directly measured, whilst salinity is related to the measurement of conductivity, and both are used to obtain the water density. If a CTD is used, the data should be stored at least for every 50kPa increase in pressure.

The requirements for data collection are set out in ISO 19901-1:2015 (Annex A.11, Table A.8, in turn based on Annex 1.B, pp 19-24, Chapter 1, of WMO-No. 8:2008) and extracts relevant to sea-water temperature and salinity are presented here as Table 3-6.

**Table 3-6 Recommended instrument accuracy and operational performance - various**



| (1) Variable | (2) Range | (3) Reported resolution | (4) Mode of measurement / observation | (5) Required measurement uncertainty | (6) Sensor time constant | (7) Output averaging time | (8) Typical operational performance | (9) Remarks |
|---|---|---|---|---|---|---|---|---|
| **1 Temperature** | | | | | | | | |
| **1.1** Air temperature | -40 °C to +40 °C | 0,1 K | I | 0,1 K | 20 s | 1 min | 0,2 K | Operational performance and effective time constant can be affected by the design of thermometer solar radiation screen. |
| **1.2** Extremes of air temperature | -40 °C to +40 °C | 0,1 K | I | 0,1 K | 20 s | 1 min | 0,2 K | |
| **1.3** Sea-surface temperature | -2 °C to +40 °C | 0,1 K | I | 0,1 K | 20 s | 1 min | 0,2 K | |
| **10 Temperature profile** | -2 ºC to +25 ºC | 0,1 K | I | 0,01 K | 0,5 s | 1 s | 0,05 K | Achievable accuracy according to commonly used CTD sensors |
| **11 Salinity profile** | 0 to 40 PSU | 0,1 | I | ±0,01 PSU | 0,5 s | 1 s | ±0,05 PSU | As per temperature profile unit: PSU (Practical Salinity Unit) according to PSS78. |

#### 3.6.2.2 Marine growth

The thickness of marine growth depends on the position of the structural component relative to the sea level, the orientation of the component relative to the sea level and relative to the dominant current, the age of the component, and the maintenance strategy for the component. The thickness of marine growth is difficult to determine by measurements unless some structures are installed in the area of interest for several years. As an alternative, if no data are available, the following marine growth profiles may be used:

- Offshore central and southern California, marine growth thicknesses of 200 mm are common.
- In the Gulf of Mexico, the marine growth thickness may be taken as 38 mm between LAT +3 m and 50 m depth, unless site-specific data and studies indicate otherwise.

Unless more accurate data are available, the density of the marine growth may be set equal to 1325 kg/m$^3$.

#### 3.6.2.3 Icebergs, sea ice, and floes

Sea ice data can be found from observation, measurements, and historical data, collected in ice charts. As for wind and metocean data, appropriate institutes can deliver such sea ice data:

- National Ice Center, USA (NATICE), http://www.natice.noaa.gov/
- National Snow and Ice Data Center, USA (NSIDC), http://nsidc.org
- NOAA Atlas, AN Electronic Atlas of Great Lakes Ice Cover, http://www.glerl.noaa.gov/data/ice/atlas/
- Canadian Ice Service, https://www.ec.gc.ca/glaces-ice/.

## 3.7 Satellite measurements

Satellite measurements of atmospheric and oceanographic conditions on the Earth have routinely been made since the 1980s. Various missions such as ERS-1, ERS-2, ENVISAT, Topex/Poseidon, Jason-1, Jason-2, GEOSAT and GEOSAT Follow-On (GFO), and QuikSCAT have been undertaken in the last three decades, providing a vast quantity of data covering worldwide locations.

### 3.7.1 Types of data available

Depending on the mission, wave, wind, and water level data are generally available. Significant wave height is typically provided by radar altimeter, whilst synthetic aperture radar (SAR) can also provide some directional information. Wind speed is usually obtained either from microwave radiometer, or microwave scatterometer, both instruments showing typically good agreement with each other. Satellite measurements can also readily provide sea-surface temperature.

Although the raw satellite data are usually made publicly available, these data sets are difficult to interpret and use unless by an expert in the field. However, various government-funded organizations or private agencies regularly produce calibrated, checked, consistent datasets which can be used directly by a metocean analyst.

For example, the GlobWave Project is an initiative funded by the European Space Agency (ESA) through the Date User Element (DUE) program and subsidized by the Centre National d’Études Spatiales (CNES). The main goals of the project are: (1) to develop and maintain a GlobWave web portal providing a single point of reference for satellite wave data and its associated calibration and validation information and (2) to provide a uniform, harmonized, quality controlled, multi-sensor set of satellite wave data and ancillary information in a common format, with a consistent characterization of errors and bias. The raw-data satellite measurements were calibrated and quality-controlled before being made available.

In addition, various datasets exist which are a mix of numerically modelled and satellite data, such as the Cross-Calibrated Multi-Platform (CCMP) gridded surface vector winds, produced using satellite wind measurements from radiometer and scatterometer together with a background model wind field from the ECMWF ERA Interim reanalysis model.

The National Oceanic and Atmospheric Administration (NOAA) Office of Satellite and Product Operations has a number of operational products available and surface wind datasets from ongoing missions.

### 3.7.2 Relevance and applicability

Satellite measurements per se cannot provide detailed enough data for development of a site. However, they have important uses particularly in the early stages of a project where generic information about a site is needed to assess suitability and no site-specific data are yet available from a measurement campaign. Satellite measurements over an area can be used to give initial estimates of wind and wave climate, assess bias of hindcast datasets in the general area of the wind facility, and calibrate numerical models. For these purposes, only a high-quality database, checked for accuracy against in-situ measurements and having undergone strict quality control by the provider, should be used.

### 3.7.3 Outlook

The remote sensing techniques used in satellite measurements are constantly being refined and it is highly likely that the quality, reliability, and the extent of the datasets will increase considerably in the near future, making this a data source of increasing importance in the definition of metocean criteria.

## 3.8 Quality control and data management

### 3.8.1 Quality control techniques

Data quality control includes the assessment of the communication and operation of data acquisition systems, power supplies, and measured data. These should be regularly reviewed to help ensure high quality data. Data reviews should include:

- Visual inspection of the data to ensure it lies within the sensor measurement range and expected range for the climate and time of year. The visual inspection is used to identify erroneous spikes, dropouts, or nonsensical trends in the data. At minimum, visual inspection should include:
    - Time series and scatter plots of data from redundant sensors
    - Time series and scatter plots of data at different elevations
    - Time series and scatter plots of data between measurement locations (if available)
    - Time series review of data from power systems, such as battery voltage, to ensure adequate power is being supplied
- Correlation tests
- Examination of data coverage of the number valid of records within the averaging periods and the availability of the entire data record over time. Poor data coverage is an indication of either a

systematic sensor or recording error, or the inability of the sensor to operate at the climatic conditions at the site.

- Check that the data acquisition system is not omitting or duplicating timestamps
- Identify and exclude sensors failures or periods of erroneous data
- Test for trends and inconsistencies (e.g., sensor drift)

The above evaluation should be used to inform what maintenances need to occur and if the schedule needs to be altered. Once the above assessments are completed and erroneous data are removed from the dataset, the overall quality or uncertainty of the measurements can be evaluated.

Where redundant sensors are available, data may be gap-filled using appropriate techniques, such as MCP procedures. The appropriateness of using gap filled data should be assessed before being included in the final dataset. The uncertainty of gap-filling data shall be included in the overall project measurement uncertainty.

### 3.8.2 Storage and access

The data acquisition system should be able to store all recorded data between site inspections. It should also have the ability to be remotely operated or accessed to modify programming, synchronize the clock, or download data. It is strongly recommended that data be autonomously sent by the device to a secure location daily.

### 3.8.3 Metadata

Proper documentation is a vital part of a measurement campaign. Poor documentation can lead to increased overall measurement uncertainties and is easily avoided. Documentation shall include commissioning reports, inspection and maintenance logs, and decommissioning reports. Reporting requirements are provided in Annex A of MEASNET ESSWC and summarized in Table 3-7.

**Table 3-7 Required documentation for a measurement campaign**

| **No.** | **Report contents** | **Details to include** |
|---|---|---|
| 1 | Location | • Coordinates, coordinate system and accuracy of position<br>• Photo documentation of position and bearing, surroundings<br>• Magnetic declination |
| 2 | Measurement equipment | • Type and dimensions<br>• Specify the height and orientation<br>• Photograph of installed and replaced equipment (if possible)<br>• Serial number(s)<br>• Calibration report(s)<br>• Distance to obstacles such as nearby turbines, platforms or masts (if applicable)<br>• Power supply and/or heating (if applicable) |

| No. | Report contents | Details to include |
|---|---|---|
| 3 | Measurement data | • Start and end dates of calibration factors or offsets applied<br>• Sampling rate and averaging periods |
| 3 | Measurement history | • Date and time of installation/maintenance/decommissioning<br>• Changes to equipment, datalogger programs or firmware (include date and time)<br>• Log of observed equipment failures, power supply problems, significant icing events etc. Start and end dates of these events should be noted in the log.<br>• Equipment location changes (if applicable) |
| 4 | Other documentation | • Validation report for remote sensing devices |

## 3.9 Reporting requirements

The Report for a Metocean Study involving collection of metocean data through in-situ measurements should as a minimum (in addition to any data results reported) contain:

- Specification of the requirements set out at the beginning of the metocean measurement campaign.
- Choice of instrument selection to fulfill the requirements, including explanation of the choice and comparison with other options available.
- Details of the instrumentation, including as a minimum the provider, key data facts of each instrument, calibration, expected performance.
- Instrumentation deployment report, including details and photos of the vessel and operation.
- Maintenance record of the instrumentation as appropriate.
- Instrumentation recovery report, including details and photos of the vessel and operation and any observed failures or damage to the instrument.
- Measured dataset details, including data return achieved and overall success of data collection campaign.
- Any post-processing or quality control procedures undertaken after data collection.
- Any other information not mentioned above relevant to the end-user of the datasets.

# 4 NUMERICAL MODELLING

Numerical modeling can be very useful for helping to understand and define site conditions in metocean studies. Measurement campaigns are expensive and time consuming, and they only sample a very small area (typically a few points, or even a single point) and for a relatively short period (often a year or less). An increasingly common practice is to augment the measurements with numerical simulations that are used to fill in the data gaps in a measurement campaign, extrapolate/interpolate between and away from the measurements, and/or to extend the measurement information back in time over a multi-year period.

Over the past 30 years, major advances have been made in numerical models of the atmosphere and ocean, and with their ever-increasing accuracy, these models have become the mainstay in both the onshore and offshore wind industries. Some of the most widely used models have been rigorously tested and validated for many applications and regions around the world, and so their performance and characteristics are well understood. Key advantages of numerical model output are that it is can be available on a regularly spaced grid over the area of interest, it can provide output at high temporal frequency, and the simulations can extend over a several-year period (some spanning back 10-20 years), which allows representation of the full spectrum of atmosphere-ocean conditions in and around the site. However, the models shall be calibrated and compared with measurements to verify/justify choice of parametrizations, grid scale and/or domain sizes.

Characterizing site conditions requires the accurate prediction of atmospheric and oceanic processes across a spectrum of spatial and temporal scales, and proper representation of atmosphere-ocean interactions. A key interaction is the transfer of energy between the wind blowing over the ocean surface and the ocean's upper layer. This necessitates accurate prediction of near-surface winds and air temperature, ocean currents, and surface waves. Typically, separate specialized models are used to simulate the atmosphere and the ocean surface, and thus the output from these specialized models shall be “coupled” to fully represent the salient atmosphere-ocean interactions. Often the flow of outputs is in one direction: the atmospheric model is run first to provide the near surface meteorological conditions (wind is the primary forcing mechanism for ocean surface waves), which feed into ocean surface models to characterize the surface sea state and currents, including wave spectra and transport.

Modelling past conditions is crucial for design by simulating long periods of environmental data; however, the main benefit of weather, wave and hydrodynamic models, is the capability to predict conditions with high accuracy for marine operations, helping in decision making for safety of persons and equipment.

There are two main approaches to perform forecasting:

- Deterministic forecast – a single prediction for a future period
- Probabilistic or ensemble forecast – multiple predictions for a future period.

The deterministic forecast requires one run (simulation) of weather and/or wave and/or current for the future period, and consequently very high resolution (spatial and temporal) can be imposed for this simulation; ensemble forecast requires multiple runs (20 are done in NCEP, 50 in ECMWF) for the same future period. The main argument to prefer ensemble forecast is that a deterministic forecast is not in agreement with a scientific method, which should consider and try to estimation of uncertainties when they exist. In forecasting, uncertainties are identified in the assessment of the initial conditions of the atmosphere/ocean and in the modelling of its evolution. An ensemble forecast takes into account uncertainty of initial conditions and physical processes. Hence, the ensemble products combine different runs (forecasts of the same period), each one being based on slightly different initial conditions or using different parametrizations or configurations of the prediction model.

The ability to forecast sudden and dangerous events or to forecast periods where favorable weather conditions stay beyond a given threshold (allowing safe operations) is critical for optimizing operational schedules and minimizing exposure to hazardous conditions. At present, a deterministic forecast is not considered sufficient to reach these objectives, because no information on uncertainty is available. The ensemble forecast, on the other hand, allows for improved quality of the forecast by integrating the errors at each stage of the process: in the estimation of the initial conditions, in the parametrization of sub-grid phenomena and implemented physics.

By these means, prediction bulletins can provide information on accuracy level, the most probable forecast, and the probability of these results. For this reason, this approach is recommended in the WMO 1091 guideline (2012).

Significant advances have also been made in the science of tropical cyclone track simulation. One of the biggest challenges for tropical cyclone modeling is creating a model that can accurately depict different scales associated with different main processes: the large-scale environmental flow of the atmosphere, that is largely responsible for steering the tropical cyclone, and the finer scale details of the core region, that determine the intensity of the tropical cyclone. Consequently, tropical cyclone modeling requires large informatic resources and computing power; that is why parametric wind models (or profiles) are often used in engineering, which use numerous observed past tracks to generate the wind fields.

The following sections describe these models in more detail, as well as best practices for application of these models.

## 4.1 Type of numerical models

### 4.1.1 Atmospheric models

Because the emphasis is on site-specific conditions, and the regions of interest are geographically limited (a site has well defined limits) local area atmospheric models are typically used—commonly the “mesoscale” numerical weather prediction model. In the language of atmospheric science, mesoscale (middle scale) generally refers to atmospheric phenomena which operate on length scales ranging from 1 km to a few hundred km, and time scales of a few minutes to a few days. Arguably the world’s most used and rigorously validated mesoscale model is the Weather Research and Forecasting (WRF) model, an open source community model officially supported by the National Center for Atmospheric Research (NCAR). WRF has specialty capabilities for wind energy resource assessment, weather prediction, tropical cyclones, regional climate, and dynamical downscaling of atmospheric reanalysis (sometimes termed “hindcasting”). WRF is one of the key operational models employed by the U.S. National Centers for Environmental Prediction (NCEP). WRF is also widely used within the wind and maritime industries, in large part due to extensive validation for most regions and environments in the world (including the coastal regions), and these validations have been widely published in thousands of papers in many scholarly peer-reviewed scientific and technical journals. Other mesoscale models that have been used for wind energy applications include the Skiron regional atmospheric system, developed at the University of Athens, Greece, the Unified Model developed and maintained by the UK Met Office, the Netherland Weather Service HIRLAM (High Resolution Limited Area Model), and the Météo-France AROME model (Applications of Research to Operations at Mesoscale).

Mesoscale models represent the myriad of physical processes that drive atmospheric motions including clouds, rainfall, solar radiation, turbulent exchanges, exchanges of heat and moisture with the earth's surface, surface hydrology and runoff, and interactions with terrain and coastlines. The models can be used in forecast mode to predict the future weather conditions from an hour ahead to several days ahead. Another common use is to run mesoscale models in "dynamical downscaling" mode to produce a "reanalysis" (hindcast). Mesoscale "reanalyses" are reconstructions of historical weather conditions and yield (typically) hourly data on a regular grid covering the area of interest. They provide the best possible estimate of the atmosphere in three spatial dimensions and the time dimension. Atmospheric state variables most important for metocean studies include near-surface wind speed and wind direction. These data are used as input to ocean surface wave models to simulate wave generation, wave movement, wave shoaling, refraction, energy transfer between waves, and wave dissipation (described in more detail in next section).

There now exist a number of turn-key community and commercial models, which are very easy to set up and run, and their use has become widespread across numerous industries and disciplines. The increased recognition of the value and utility of numerical simulations has spurred many commercial firms to offer modeling data and services. However, it is important to note that the quality and rigor of the modeling varies greatly. This is due to the growing fraction of model users who lack formal training in numerical prediction and, in some cases, they are not atmospheric/oceanic scientists. A challenge is that many model users tend to lack an appreciation of the sensitivity of model solutions to the many seemingly arbitrary decisions that are made when configuring a model for a particular application. Fortunately, there are well-established best practices which have been codified in the following publications:

> *Numerical Weather and Climate Prediction,* by Thomas Tomkins Warner, 2011, Cambridge University Press, 550 pp. ISBN: 9780521513890.

And the article summarizing the best practices from that book:

> *Quality Assurance in Atmospheric Modeling*, by Thomas T. Warner, Bulletin of the American Meteorological Society, 2011, pp. 1601-1610. https://doi.org/10.1175/BAMS-D-11-00054.1.

Although the aforementioned references can be reviewed for comprehensive guidance, the following points represent the most relevant best practices for application of atmospheric models for metocean studies.

Use a well-documented and validated mesoscale atmospheric model.

As noted earlier, a number of atmospheric models have been used for wind energy applications. Some of these (particularly WRF) are considered mainstream, and they are thoroughly documented in the open peer-reviewed literature and industry/scientific conference proceedings. The use of poorly validated and/or unpublished models should be avoided. Suppliers of mesoscale atmospheric modeling services and data should explain in detail the model used, information about how their modeling system has been validated, and quantitative (and preferably published) results of their validations.

Use high quality input data sets.

The quality of any atmospheric modeling system critically depends on the input data. The highest resolution and most up-to-date inputs should be used, including the large-scale atmospheric reanalysis, sea-surface temperatures, sea ice (if relevant), surface terrain elevation, vegetative canopy (aerodynamic roughness length), soil temperature, and soil moisture. These latter four inputs are required for accurate representation of the shoreline.

At the time of this writing, the two most widely used large-scale atmospheric reanalysis datasets are MERRA-2 and ERA-Interim. MERRA-2 (Modern-Era Retrospective analysis for Research and Applications, Version 2) is produced by the U.S. National Aeronautics and Space Administration (NASA), and is available on a ~50 km global grid from 1980 to present. ERA-Interim (European Centre for Medium Range Weather Forecasting Reanalysis) is also available on a global grid at ~75 km resolution, and spans the period from 1979 to present. ERA5, the successor to ERA-Interim is planned for full release in 2018, and will be available on a global ~31 km grid. These atmospheric reanalysis datasets are widely considered the best available, they are thoroughly documented, and they have been rigorously validated.

WRF includes up-to-date global 500 m resolution terrain elevation and surface land cover datasets, but other public datasets are available, such as the U.S. Geological Survey (USGS) Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010), the European Space Agency (ESA) global land cover map (GlobCover Version 2), and the ESA CORINE Land Cover (CLC) database. Global sea-surface temperature (SST) data are freely available from the U.S. National Centers for Environmental Information (NCEI), as well as the Copernicus Marine Environment Monitoring Service (e.g., OSTIA: Operational Sea Surface Temperature and Ice Analysis). These SST datasets span back to 2006 and earlier, and provide daily mean values.

The NASA Land Data Assimilation Systems project provides routinely updated global 3-hourly and daily soil temperature and soil moisture data spanning the 1979-present period. The advantage of the NASA repository is that the soil data are available on the four most commonly used land surface model grids, and these data can be directly ingested by WRF and several other mesoscale models. The European Space Agency Climate Change Initiative (CCI) Open Data Portal also provides global soil moisture parameters.

<u>Use the highest possible spatial and temporal resolution.</u>

Since many offshore wind sites are located within a coastal zone, land-sea breezes are a common occurrence. This necessitates the use of more vertical computational layers within the lowest 1-2 km of the surface to resolve these shallow thermally-driven wind flows, as well as a finer horizontal grid increment to properly resolve the coastline and land-sea interface. As a general rule, a 1-3 km horizontal grid increment should be used, as is common practice within the wind industry, and is based upon a large number of independent validation studies. Also, mesoscale atmospheric processes are short lived—from a few minutes to a few hours—and often exhibit a distinct diurnal cycle. For these reasons, output from mesoscale models should be provided with high temporal frequency, preferably with hourly or finer outputs (e.g., 10 minutes). Suppliers should clearly specify the spatial and temporal resolution used for the modeling.

A cautionary note: Some suppliers will claim that their models provide outputs down to 100-200 m resolution. Mesoscale model computations at this scale are prohibitively expensive and time consuming. Thus, spatial resolutions finer than about 1 km are almost always obtained using some kind of post-processing algorithm. Typically, this involves a statistical regression and/or a “microscale model,” that omit important physical processes such as land-sea breezes, turbulent exchanges, and heat and moisture fluxes with the ocean surface and/or representation of the physics. While such fine-grained simulations may appear to yield more accurate and detailed results, they are often no more accurate than mesoscale simulations with horizontal grid increments of 1-3 km resolution. Be sure to ask suppliers to provide published validations that clearly demonstrate how output from their very-fine-grained models are superior to that from mesoscale model simulations.

Use a long simulation period to capture the full spectrum of weather and climate conditions.

Comprehensive metocean studies require the characterization of the full spectrum of weather and climate impacts at a site. Thus, the mesoscale atmospheric simulations should span a historical period of at least a decade, and preferably 20-30 years. This is particularly important for capturing the rare, but significant weather events. Most global reanalysis datasets are available from 1980-present, which permits the detailed reconstruction of historical weather over the region of interest. The result typically is an hourly time series of the relevant weather variables on a regular grid in three spatial dimensions, providing information at the measurement sites, but also filling in the gaps between and away from the instrument locations.

Ensure the modeling team has the requisite expertise and experience.

There now exist a number of community and commercial turn-key atmospheric and ocean modeling systems. While it has become relatively easy to set up and run a model, it is not easy to run a model properly. Models are complex and sophisticated tools, but they are not complete and true representations of the atmosphere-ocean system. Thus, it is imperative that their shortcomings are well understood by the user. An even greater challenge is that an increasing number of model users have no background in atmospheric or oceanic science, and they have no formal training in numerical prediction. This means that they are less likely to recognize when a modeling solution looks physically unreasonable, because of basic model deficiencies, or improper model settings and inputs. To compound the issue, time and commercial pressures sometimes prevent users from carefully applying the models—even experienced users are subject to such constraints.

Ideally, a skilled model user will have a university degree in atmospheric or oceanic science, and formal training in numerical prediction. They should have at least 3-5 years of practical experience running models for a variety or research and/or commercial applications. Expertise can be demonstrated through formal publication of their work in peer-reviewed journals or conference proceedings.

### 4.1.2 Wave models

Wave propagation models or sea state simulation models may be split into two main categories:

1. Wave spectral model: It represents sea states as an energy spectral density, from which it is possible to estimate the main physical parameters (significant wave height, peak period, etc.). It is adapted for large areas (ocean and coast domains).
2. Phase-resolving model: It represents the sea states as the sum of several individual waves. It is adapted for small area which requires highly detailed representation of the sea state (coastal and port domains).

The main difference between models in each category comes from the processes which can be taken into account and their parametrization, and the level of simplification in equations.

#### 4.1.2.1 Wave spectral model

Wave spectral models can be used to simulate sea state with variable spatial resolution in the model domain, allowing for modeling of wave conditions in offshore and coastal areas. The processes implemented in wave spectral models allow consideration of driving forces both for deep waters and shallow waters. In deep waters, wind generation, quadruplet wave-wave interactions (transfer of wave energy to the high frequency part of wave spectrum (young wind-sea), and white capping are dominant; whereas in shallow waters, bottom friction, refraction, shoaling and triad wave-wave triplet interaction (in very shallow water, as shallow water permits near-resonance of three wave components) are the main processes.

The size of the domain often leads to choosing a coarse computational grid of several tens of kilometers in deep water, and refining the computational grid to few tens of meters by approaching the coast with several embedded domains or with one unstructured grid.

The models require input data for key forcing parameters including wind, ice concentration, current, and water level, as well as wave boundary conditions. Typically, these forcing inputs vary in time and space and accurate hindcast of these parameters, particularly wind conditions, is critical for wave prediction. The bathymetry shall also be incorporated in the input fields; the resolution of bathymetry is probably the most important because it leads the level of details of the main processes acting during wave propagation in shallow water. For deep water sites, the benefit of high resolution wave modelling may be limited, but may still add value by considering impacts of spatial variability of wind and current fields (this requires high resolution inputs) and land/island mask effects, for example.

Wave spectral models are third generation models, meaning that the two-dimensional wave spectrum is allowed to evolve freely under the influences of the physical processes, with no constraints on the spectral shape. WAVEWATCH 3, SWAN, and Mike 21 are well documented models and intensively used in marine engineering; they can run on several processors, under Windows or Linux stations. All the main processes are implemented with different parametrizations (they differ in function of the model).

Free-of-charge hindcast databases based on spectral wave model output already exist and can be used in the early phases of development of offshore wind facilities:

- NOAA database is based on WAVEWATCH 3 wave model, using Climate Forecast System Reanalysis (CFSR) wind forcing. For each output point, the model provides 3-hourly time series including: significant wave height, peak period, wave direction, wind speed, and wind direction, for a period of 31 years (from 01 January 1979 to 31 December 2009). Several domains, with different resolutions, are available: Global (30 min), U.S. coast (4 min or 10 min), North Sea (4 min or 10 min), North-West Indian Ocean (10 min) and Mediterranean Sea (10 min).
- Integrated Ocean Waves for Geophysical and other Applications (IOWAGA) database also based on WAVEWATCH 3 model, using CFSR or ECMWF wind forcing and different physical parametrization than NOAA. IOWAGA produced hindcast databases for several domains: the whole world up to 80°N (GLOBAL) at 0.5° resolution and higher resolution zooms in specific areas: Mediterranean (0.1°), Black Sea, Western Caribbean, East Pacific, Hawaii and Tuamotus, New Caledonia and Vanuatu, Iroise Sea. An unstructured grid database is also available in Bay of Biscaye with few hundreds of meters close to the coast.

Commercial databases are also available from metocean companies, for example with added parameters such as sea state components and with use of current and water level as input to their models.

For detailed design criteria estimations, the wave model should:

- Have spatial resolution of less than 5 km
- Use reliable wind forcing, for example from mesoscale modelling
- Take into account water level variation
- If large eddies or velocities are expected in the area, also take current into account.

In addition, wave measurements are necessary to calibrate the model and/or correct the output times series at the location of interest.

#### 4.1.2.2 Phase resolving model

Phase resolving models are used on small areas such as ports or wind farm domains only, where the evolution of sea surface in time and space is required for more detailed studies – for example for analysis of short and long period wave disturbance in ports and harbors and coastal areas. The phase resolving models are computationally demanding; they can represent the wave field change over a short distance of about one wave length, and consequently they require fine bathymetry and high-resolution computational grid.

The general approach in the phase resolving models is based on equations of potential motion with a free boundary, and therefore the phase is resolved in this type of model, whereby the evolution of sea surface in time and space is modeled.

Some of these models are:

- The so-called “mild-slope,” using approximations of velocity potential equation
- The Boussinesq equation, which allows for extending the validity domain and solving the refraction, diffraction, shoaling, and nonlinear interactions between wave and harmonic generation. Additionally, wave reflection and transmission can also be assessed with appropriate boundary conditions.

### 4.1.3 Ocean models

Ocean models aim to study the motion of fluid by simulating the flow of water and its corresponding change in properties (temperature and salinity). The basis of computational hydrodynamic models is the Navier-Stokes equations. These equations are derived from Newton’s laws of motion and describe the action of force applied to the fluid; that is, the resulting changes in flow. The Navier Stokes equations are essentially 3-dimensional (3D) equations, i.e., the governing parameters (such as the fluid velocity and pressure) varies with the depth-coordinate and area coordinates; however, solving the 3D equations are computationally expensive, and therefore often the 2-dimensional (2D) version of the Navier Stokes equations are solved instead, for example by expressing the depth dependency with a depth-averaged parameter. Furthermore, for hydrodynamic modelling, the Navier-Stokes equations are simplified by the specific properties of the ocean leading to the shallow water equations, because the scale of features in the horizontal is much greater than in the vertical.

The main processes are the wind forcing, the tide, and thermodynamics/stratification.

The wind is taken into account through the surface stress and associated drag coefficient. The formulation or value of this coefficient can be chosen in most of the models; this can be used in the calibration phase, like the bed resistance (Chézy or Manning number).

The basic equations of tidal dynamics have been understood for more than two centuries since Pierre-Simon Laplace developed the dynamic theory of tides in 1775. However, there are some difficulties even for 2D barotropic tidal modelling, which simulates flow in depth averaged domain: accurate open boundary conditions and bottom topography, parameterizations of dissipation in the tidal equations, and influence of the ocean stratification on the barotropic tides, which may be difficult to account for without full 3D modelling of baroclinic tidal currents. Using altimetry data from satellite observation has allowed improvement in the performance of global tidal models. The outputs of this type of model are the elevation of the surface and 2D depth average current.

Examples of tidal models include:

- FES2014 (Finite Element Solution), which can provide elevation and tidal current on a regular grid 1/16 degree resolution
- Tidal models from Oregon State University (OSU), for example the TPXO (TOPEX/Poseidon inverse model solution) with the OTIS (OSU Tidal Inversion Software) can provide tidal information in different domains from 1/12 to 1/60 degree resolution.

Ocean general circulation models (OGCMs) use in general the wind and the thermodynamic forcing to generate 3D current-, temperature-, and salinity- fields and 2D surface height. The thermodynamic processes are influenced by evaporation, sensible and latent heats, and precipitation. The presence of river discharge is also essential and sea-ice conditions modify the fluxes, both by blocking air-sea material exchanges and through freezing and melting. The OGCMs are mainly used in climate studies: Ocean surface temperatures show substantial decadal variability in the regional spatial patterns of atmospheric "teleconnection" modes such as the North Atlantic Oscillation or El Nino Southern Oscillation.

Examples of OCGMs which can be used by engineers to build a global or regional database include: ROMS, HYCOM, NEMO, Mike Suite (DHI). These models can be used in different configurations: only 2D tide modelling or full 3D simulation with atmospheric, ice, and river discharge forcing. Depending on the location of the offshore wind farm project, the configuration has to be adapted; for example, conducting a mooring analysis for a floating turbine requires the detailed assessment of the current profile therefore may require 3D modelling.

Of relevance to this document, the OCGM models can also provide non-tidal current and surge in the first phase of a wind facility:

- Hycom Reanalysis database, available on the globe with 0.08 degree horizontal resolution and 32 vertical levels between 1993 and 2012.
- MERCATOR analysis: based on the NEMO model, it is also available on the globe with 0.08 horizontal resolution and 50 vertical levels, between 2007 and 2016.
- National Oceanographic Data Center allows access to current meter or ADCP data, which may be close to the region of interest and useful for comparison with model data.

## 4.2 Numerical modelling at the site

### 4.2.1 Wind modelling

The main objective of wind modelling at the scale of the wind facility site, is the assessment of the spatial variability of the wind field and turbulence intensity; indeed, the wake effect of the different wind turbines leads to large perturbation in the wind flow and consequently to the loss of production, as illustrated in Figure 4-1.

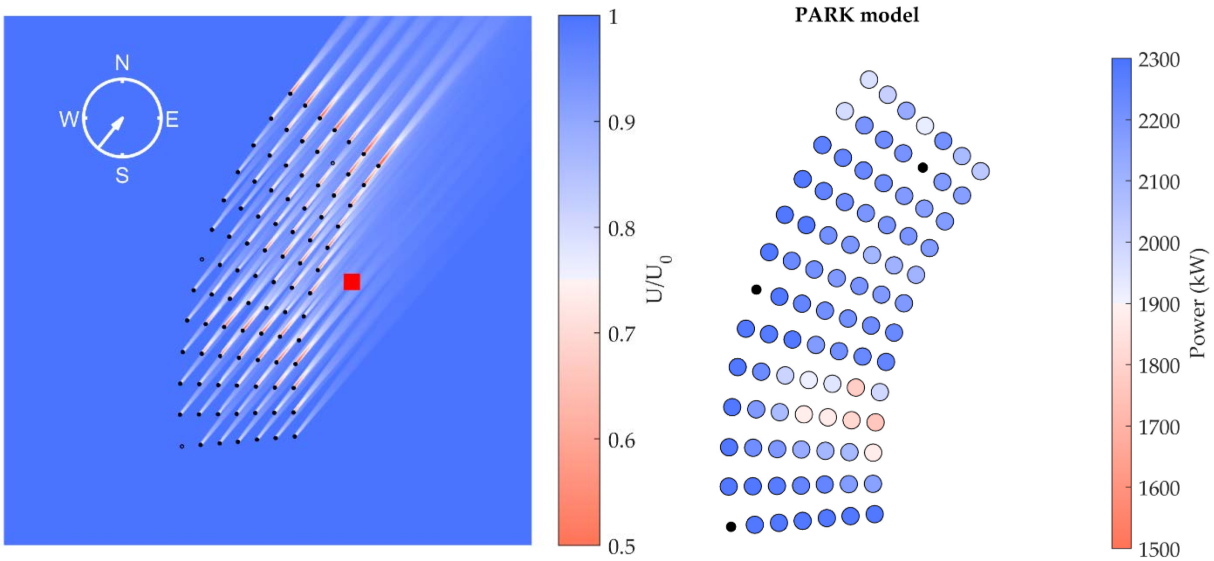


**Figure 4-1 Wind farm wake from Hasager (2017)**

Because of the very high resolution of simulation, which is required to represent the processes across the wind facility, mesoscale and Computational Fluid Dynamics (CFD) models are the most powerful tools.

The CFD modelling allows for a very high-detailed resolution of the flow around one wind turbine. The resolution may be decreased to allow for the computation of conditions for the entire wind facility in reasonable computing time. However, these estimations are performed for specific values of wind speed and direction.

The increase in computational power allows the use of mesoscale model, whose main aim is to simulate regional weather conditions with a spatial resolution about few kilometers, with a higher spatial resolution of about one hundred meters and parametrize the wind farm and wind turbines interactions as other sub-grid processes: the both require more informatic resources in terms of memory, time computing and storage. The advantage of this approach is the use of realistic meteorological conditions for initial and boundary conditions; in addition, it is also possible to assess the impact of the wind facility on weather conditions in the region by analyzing the parent domains; to reach high spatial resolution, it is necessary to apply downscaling method with several embedded areas: parent domain is the area which contains the domain of interest. The wind farm domain may require three or four parent domains to reach high spatial resolution at wind farm from low resolution forcing fields on the first domain (for example, from 25km resolution for the first domain, decreasing to 5km, then 1km, and finally 200m).

Because of computing time to reach the high spatial resolution, it is generally not feasible to create a long hindcast database (more than 10 years) to derive design criteria; but the very high resolution modelling approach is extremely useful to test types of turbines, wind facility configurations, and local wake and interaction effects within the facility.

### 4.2.2 HydroDynamic (HD) current and water level modelling

The choice between 2D and 3D model depends on several factors. For example, in shallow waters wind and tidal current are often sufficient to keep the water column well-mixed (i.e., sufficiently homogeneous in salinity and temperature). In such cases and when the description of depth-averaged current is sufficient for the engineering, 2D model may be used. If detailed analysis of current profile is required or if the wind facility location is expected in waters with stratification, a 3D model should be used.

For most fixed offshore facilities where the “ocean loads” are wave driven it is sufficient to setup a detailed 2D HD model. The boundary conditions for the local 2D model may be taken from a 2D or a 3D regional/ global HD model. It is important that the boundaries are placed where flow is as uniform as possible. It is important that the global/local HD model that is used as boundary conditions for the local HD model is well calibrated and is verified by nearby measurements.

In most cases where a 2D model is sufficient, the flow is best described by specifying the water level (calculated by regional/ global) HD model. By doing this the in-out outflow then becomes a result of the simulation.

In areas with bed forms such as sand dunes or banks, the resolution of the HD model shall be sufficiently detailed to describe the local variations.

Hydrodynamic models generally work with similar schemes and require inputs, boundary conditions, and choice in parametrization. The main features are:

- Input
    - Computational mesh and bathymetry
    - Simulation length and time step
    - Boundary conditions (fluxes, water levels, or combinations)
- Calibration factors for 2D HD model
    - Bed resistance (including effect increase due to the possible waves, and bed forms not resolved in the model
    - Momentum dispersion models
    - Wind friction factors
- Boundary conditions
    - Closed
    - Water level
    - Discharge

- Driving forces
    - Wind speed and direction
    - Tide
    - Wave radiation (possible gradients in wave heights, and wave direction may create local water level changes, that may drive a current, for example a long shore current driven by oblique waves moving toward the coast).

Several models are intensively used in industries for the hydrodynamic simulations in ocean: Mike 21, MARS, ROMS, Delft suite.

### 4.2.3 Wave modelling

In a wave hindcast model the sea state is described as a spectrum; the sea surface is decomposed into waves of varying frequencies using the principle of superposition. The spectral wave energy is separated by direction of propagation. The sea state evolves according to physical equations – based on a spectral representation of the conservation of wave action, which include:

- Wave propagation/advection
- Refraction (by bathymetry and currents)
- Shoaling
- A source function which allows for wave energy to be augmented or diminished. The source function for fixed offshore wind farms has at least four terms:
    - Wind forcing
    - Nonlinear transfer
    - Dissipation by white-capping
    - Bottom friction.

The winds that drive the wave model are typically provided from a separate atmospheric model from an operational weather forecasting center.

Offshore facilities are affected by local generated waves as well as by waves generated far from the facility. It is important that both types of waves are simulated correctly. Often a local high-resolution hindcast model is setup around the facility, using time varying wave boundary conditions from a courser regional or a global wave model.

The seabed bathymetry and the numerical resolution within the local hindcast model shall be sufficiently detailed to correctly describe the local ocean conditions. Wave propagation and processes interact with and are influenced by with bathymetry. Sand bars and large gradients shall be correctly represented in input of the model to assess their impact on wave fields.

The measured seabed bathymetry often has a much finer resolution than the grid to be used in a hindcast model. In such cases the ocean hindcast bathymetry can be interpolated directly from the measured bathymetry data. If local seabed variations may influence the ocean conditions within the wind farm, the grid resolution in the hindcast model shall be sufficiently fine to capture these variations, otherwise alternative conservative choices shall be made; for example, if few grid points are in the wind facility area, design criteria shall be derived at the most severe location.

In areas with strong current, the current may influence the waves, and should be included also in the wave hindcast model. In areas with large tidal variations, or shallow water sites, the water level variations should be included in the hindcast model.

#### 4.2.3.1 Morphologically active area

For wind facilities located in bathymetrically dynamic areas, for example in areas with sand dunes, a Morphodynamic Desk Study shall be completed determining possible long-term seabed variations. The study should be based on long-term extrapolation of measured bathymetries. The long-term extrapolation can among others be based on:

- Historical bathymetrical measurements
- Uncertainties in bathymetrical measurements
- The actual metocean conditions in the wind farm area (including long-term fluctuations)
- The sediment properties
- The geophysical properties in area.

### 4.2.4 Model calibration

It is well known that numerical simulations are subject to some unavoidable errors and uncertainties, including the input datasets, the lateral boundary conditions, the numerical approximations used in the dynamical core of the model, and the imperfect representation of the complex physical processes that strongly drive the atmospheric and ocean motions. Many calibration techniques have been developed to compensate for these errors, and typically yield increases in accuracy equivalent to many years of improvements to the basic model, and with relatively little increase in the computational time and expense. Calibration involves applying statistical methods to correct and/or further refine the output from numerical models. It is important to note that these “post processing” techniques only reduce the systematic error (e.g., the model consistently overpredicts the wind speed magnitude). Random errors, such as errors in timing or position of meteorological features will remain in the solution, and cannot be removed statistically. However, the systematic error often accounts for a significant fraction of the total error—especially near the earth’s surface—and so removing these errors is very beneficial. Also, systematic errors near the earth’s surface are relatively stable over days, weeks, or longer, thus statistical methods are very effective at compensating for these deficiencies.

A statistical correction scheme should have the following characteristics. First, it should be robust and applicable to any type of terrain or ocean surface conditions. Second, it should be effective in regions of sparse data, yet also able to take advantage of higher data densities when they are available. Third, it should be viable in regions where long-term measurement records do not exist. Finally, it should be able to deal effectively with weather regime changes, when a model’s systematic errors may abruptly change. The sections below outline the most well-established approaches for performing atmospheric model calibration.

Running mean bias correction

A running mean bias correction operates by quantifying the difference between the average measurement and the average model prediction within a sliding time window. This difference represents a “bias correction factor” that is applied to the model solution at a given time and location. For example, the running mean wind speed bias is computed over the most recent 7-day period, and this bias is used to adjust the “raw” model prediction for the present day. It is important to define the optimal time window over which to compute the bias correction factors. A longer window tends to yield a more statistically stable correction factor, but it is unable to respond to weather regime changes. Very short time windows yield noisy and unreliable correction factors, which, if applied, actually degrade the model prediction. A number of studies have demonstrated that an averaging period of 7-15 days works well in most circumstances.

### Model Output Statistics (MOS)

MOS involves exploiting statistical correlations between a model and the measurements. All MOS approaches are based on multiple regression, with predictors in the regression equations coming from either the model output or measurements (or both) at a given location. Separate regression equations are required for each model variable, for each time of day, and for each measurement location. This results in a large number of equations. Additionally, MOS equations are highly model-specific, so if a new model or an updated version of the existing model becomes available, a new set of MOS equations shall be developed. For the regressions to be robust, a long archive of model predictions and measurements is generally required—typically at least two years—although “updatable” MOS systems have been developed which do not require such long records.

### Kalman filter

The Kalman filter (KF) is an algorithm designed to estimate a signal from noisy data. Since its introduction in the early 1960s, the basic algorithm has been adapted for a very large number of applications and disciplines. The KF has also been widely used as a bias correction method during post processing of atmospheric model predictions. In this application, KF correction uses an adaptive algorithm to estimate the model bias using recent measurements and model predictions, while fully accounting for time variations of the model error at specific locations. Again, bias is defined as the difference between the average measurement and the average model prediction. The KF bias estimate is then used to correct the raw model prediction for the present day. Unlike other calibration approaches which require a long training period and a “fixed” set of equations (e.g., MOS), the KF adapts during each iteration, rapidly and effectively responding to changing weather regimes, changing seasons, and even if an entirely new model is introduced. KF bias correction techniques are straight forward to implement, and require minimal computational resources. They are statistically robust, meaning that they work well in most circumstances and provide reliable improvements to the model prediction.

### Analog methods

Analog techniques have a rich history in the atmospheric sciences and many other technical disciplines. Over the past decade, analog methods have been adapted for calibrating atmospheric model simulations. The idea is to look for patterns in past model predictions that are similar to the current prediction (termed *analogs*). By examining the measurements of selected weather variables and/or features following those predictions, we can estimate the expected errors and compensate for them in the current prediction. The underlying assumption is that if “close” matches for the current model prediction can be found within the historical archive of predictions from the same model, their errors are likely be similar. The analog pattern matching step involves a “localized” (in space and time) search across relevant physical variables and the spatial and/or temporal patterns of those variables. In order to find good matches, only those variables known to be correlated to the variable to be corrected are used, and they may be weighted according to their level of correlation. Once the set of analogs has been identified, a “correction factor” can be constructed from the weighted mean of their errors, or alternatively, a linear combination of the actual measurements at the locations and times of the best analogs. This technique has been shown to be highly effective at reducing systematic error in atmospheric model predictions across a wide range of variables and applications. Emphasis has been placed on correcting near-surface wind speed and wind direction predictions.

It is important to note that the above techniques apply at measurement locations only. It is not straightforward to infer systematic errors at any arbitrary location between and away from the measurement sites. Near-surface errors are strongly a function of terrain elevation, ocean surface characteristics (e.g., sea surface temperature gradients, and/or ice cover), vegetative cover, soil characteristics, etc. It is possible to "map" the errors at the measurement locations to the entire computational grid. Simpler approaches include objective analysis procedures such as a Cressman weighting scheme, or applying the correction factors from the measurement sites with similar land-use and/or terrain elevation at neighboring grid points. More sophisticated approaches include successive correction methods, statistical interpolation, and variation approaches. Owing to their computational expense and complexity, these "gridded bias correction" techniques are typically not practically feasible in a commercial setting.

### 4.2.5 Model correction

Even after calibration of the model, systemic error may still exist; or during the preliminary phase of a project, when no mesoscale modelling is required, existing global database may not have enough resolution to represent the influence of local bathymetry and/or coast configuration.

In that case, it is possible to apply correction factors to avoid large overestimation or underestimation.

The correction factor is estimated by using quality checked measurements and model data on the same period allowing direct estimation of the performances of the simulation and of the correction through bias, root mean square error, coefficient correlation, or scatter index. A regression on the scatter plot or Quantile-Quantile plot allows us to catch the trend of the error. When the seasonal (e.g., Monsoon circulation) and/or directional variabilities (refraction in the entrance of a bay) are large, it is recommended to estimate the correction factors by month and/or by directional sector.

Table 4-1 and Figure 4-2 illustrate the correction of an offshore model grid point (outside a bay) with buoy data at the future location of a wind turbine inside a bay. The refraction is a main process in the wave propagation, leading more or less attenuation of sea state energy in function of the wave incidence.

**Table 4-1 Influence of correction on error estimators and main statistics**

| **Hs (m)** | **RMSE** | **Correlation coefficient** | **Mean** | **Q90%** | **Q95%** | **Maximum** |
|---|---|---|---|---|---|---|
| Model (IOWAGA) | 0.71 | 0.71 | 0.66 | 1.45 | 2.0 | 5.0 |
| Model – corrected | 0.15 | 0.71 | 0.19 | 0.44 | 0.61 | 1.5 |
| Model – corrected by sectors | 0.11 | 0.84 | 0.20 | 0.45 | 0.61 | 1.8 |
| *Measurements* | | | *0.20* | *0.47* | *0.63* | *1.7* |

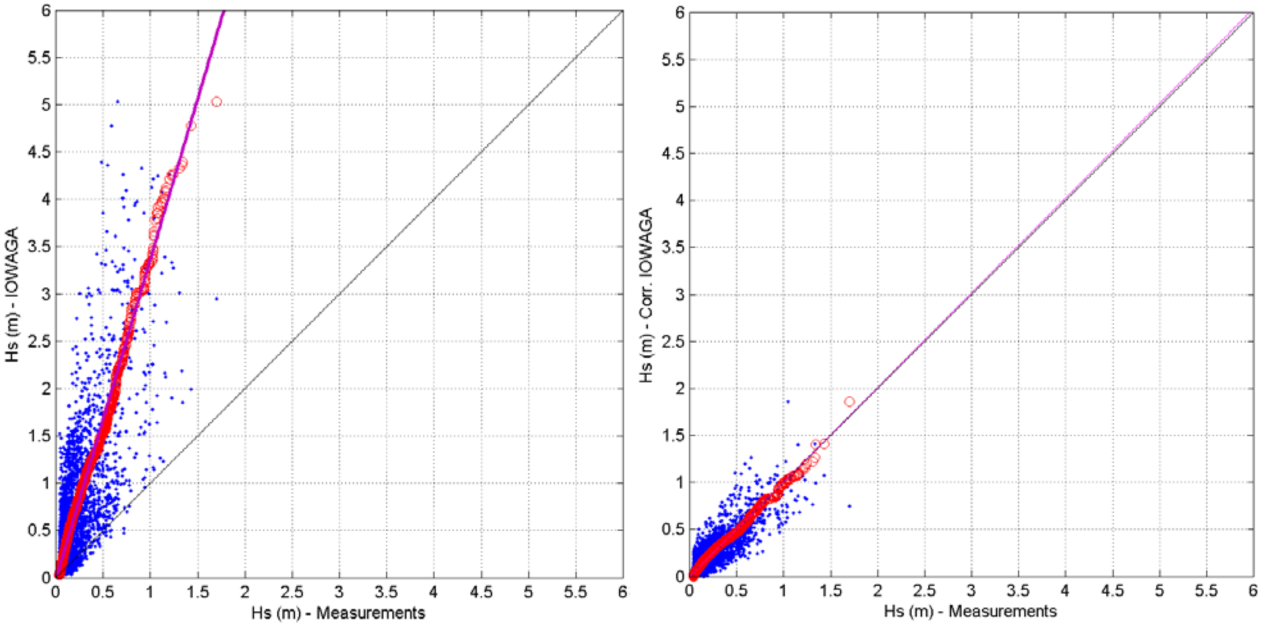


**Figure 4-2 Influence of correction on scatter plot**

## 4.3 Tropical cyclone and extra-tropical cyclone conditions

A tropical cyclone is a fast-rotating low-pressure system with strong winds and a spiral arrangement of convective cells that produce heavy rain. Depending on its location and strength, a tropical cyclone is referred to by names such as hurricane, typhoon, tropical storm, cyclonic storm, tropical depression, and simply cyclone. Tropical cyclones typically form over large bodies of relatively warm water. They derive their energy through the evaporation of water from the ocean surface, which ultimately re-condenses into clouds and rain when moist air rises and cools to saturation.

The strong rotating winds of a tropical cyclone are a result of the conservation of angular momentum imparted by the Earth's rotation as air flows inward toward the axis of rotation. As a result, they rarely form within 5° of the equator. Tropical refers to the geographical origin of these systems, which form almost exclusively over tropical seas. Cyclone refers to their cyclonic nature, with wind blowing counter clockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. The opposite direction of circulation is due to the Coriolis effect. In addition to strong winds and rain, tropical cyclones are capable of generating high waves, and damaging storm surge and currents. They typically weaken rapidly over land where they are cut off from their primary energy source.

Extratropical cyclones also contribute to the transfer of energy from the tropics to the poles. These types of cyclones are large-scale (synoptic) low-pressure weather systems, occurring in the middle latitudes. Extratropical cyclones are baroclinic phenomena, because they are generated by large horizontal temperature and dew point gradients along frontal zones; fronts between different air masses provide the energy for extratropical cyclone, whereas the energy for tropical cyclones comes from the sea (surface temperature and moisture).

There are, on average, 200 winter storms in the Northern Hemisphere per year. Hurricane-force extratropical cyclones are most likely to form in the northern Atlantic and northern Pacific oceans in the months of December and January. Extratropical cyclones are generally driven by deep westerly circulation of mid-latitudes; changes in direction are mainly due to interaction with other low-pressure systems, troughs, ridges, or with anticyclones. Extratropical cyclones can bring mild weather with a little rain and surface winds of 15–30 km/h or they can be cold and dangerous with torrential rain and winds exceeding 119 km/h; it depends on the severity and maturity of the system.

In the future, some studies highlight an expected increase of the number of intense cyclones over specific regions (the Northeast Atlantic and British Isles, and in the North Pacific) associated with a poleward shift of storm tracks. However, there is no scientific consensus mainly because of the methodology to define and select the storms.

### 4.3.1 Parametric models

Hurricane wind field modeling has been the subject of considerable research over many years. Since neither hindcast model data nor satellite data can adequately capture the extremes of wind and wave caused by the passing of a tropical cyclone, it is necessary to employ parametric wind models to obtain an estimate of the cyclonic wind field at each time step in the storm track and at the location of interest.

Most parametric models require as input the maximum wind speed, $V_{max}$, the radius-to-maximum-winds, $R_{mws}$, the cyclone forward speed and direction, as well as the cyclone track. In addition, some models require the minimum pressure, $P_C$, and the ambient pressure, $P_n$. With the exception of the ambient pressure and the radius-to-maximum-winds, which are not often reported for historic cyclones, the remaining parameters can be easily obtained or estimated from databases in the public domain.

Several formulations were proposed by different authors: Cooper (1988), Holland (2010), Willoughby (2006).

In addition to the parametric wind, correction may be applied in order to represent forward motion influence and its asymmetry on generated wind field. In the Northern Hemisphere, cyclonic winds circulate counter-clockwise; the wind field is asymmetric so that winds are typically stronger to the right of a cyclone's track and lower to the left due to the contribution of the cyclone movement. Harper et al. (2001) proposes the following general relationship:

$$V_{10m}(r,\theta) = k_m * V_p(r) + \delta_{fm} * V_{fm} * \cos(\theta_{max} - \theta) \qquad \textbf{(4-1)}$$

The proportion of the added forward cyclone speed $V_{fm}$ can be adjusted using the correction factor $\delta_{fm}$. The maximum intensity is added along an assumed line of maximum winds defined by the angle $\theta_{max}$ measured relative to the cyclone movement direction; in the Southern Hemisphere, is commonly taken as 115° (corresponding to the rear left quadrant) but values around 65° (front left quadrant) are also employed in more recent studies (opposite values shall be selected in the Northern Hemisphere).

The wind inflow angle shall also be introduced in the previous parametric model, which assumes a circular wind flow pattern, which does not represent the observed surface wind directions. Friction effects cause the inflow of the wind toward the center of the cyclone. The inflow angle $\beta$ is about 25° but decreasing toward the center of the storm.

Sobey et al. (1977) proposes the following formulations:

$$\begin{aligned} &\beta = 10 * \frac{r}{R_{mw}} && \text{for } 0 \le r < R_{mw} \\ &\beta = 10 + 75 * \left(\frac{r}{R_{mw}} - 1\right) && \text{for } R_{mw} \le r < 1.2 * R_{mw} \\ &\beta = 25 && \text{for } r \ge 1.2 * R_{mw} \end{aligned} \tag{4-2}$$

Phadke et al. (2003) revises the values as follows:

$$\begin{aligned} &\beta = 10 * \left(1 + \frac{r}{R_{mw}}\right) && \text{for } 0 \le r < R_{mw} \\ &\beta = 20 + 25 * \left(\frac{r}{R_{mw}} - 1\right) && \text{for } R_{mw} \le r < 1.2 * R_{mw} \\ &\beta = 25 && \text{for } r \ge 1.2 * R_{mw} \end{aligned} \tag{4-3}$$

Figure 4-3 below shows an example of wind speed field from parametric field.

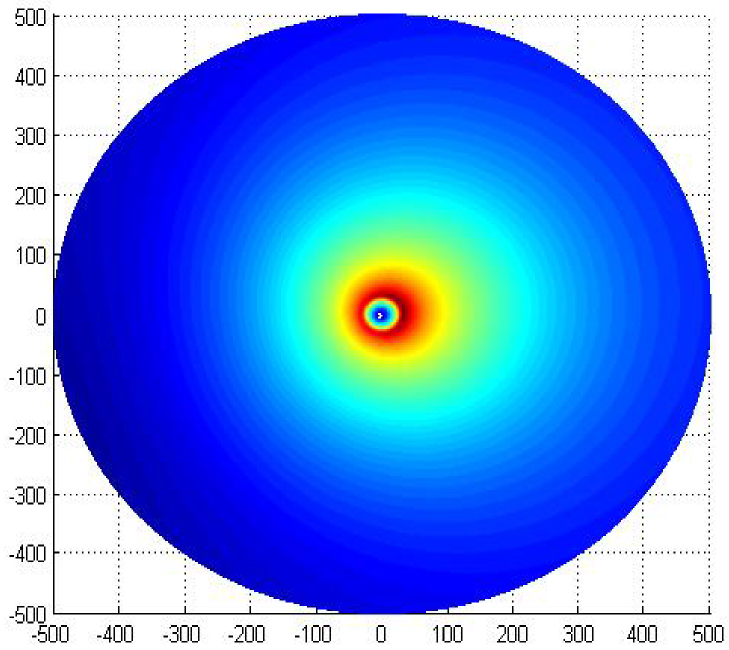


**Figure 4-3 Example of wind speed field from parametric field (in house Mike 21)**

### 4.3.2 Mesoscale modelling

Mesoscale modelling may be performed to represent wind fields under tropical cyclone conditions. Even though the computational time becomes dramatically large in comparison with employing a parametric profile, the advantage is in resolution of the physics of the atmospheric conditions and the interactions with the “normal” conditions close to the area of cyclone influence.

Because of the large convective phenomenon and particular physics of the tropical cyclone, the mesoscale model has to be tuned with a suitable parametrization which may differ from the one used to build a hindcast (simulate past weather) or to perform forecast in the area of interest. For example, the level of tropopause may be lower, influence of surface sea temperature shall be considered, etc.

### 4.3.3 Tropical cyclone waves

Cooper formulated in 1988 (OTC 5738) the 25% rule; for a given 1-minute cyclonic wind speed, the corresponding significant wave height can be approximated by:

$H_s = {}^{U}/_{k}$ where $k$ is a factor with a mean value of 4.0 (**4-4**)

API Interim guidelines present results for the four different regions in the Gulf of Mexico which show that the factor k varies from 3.7 to 4.2 for water depth equal or greater than 1000 m. This factor is then increased with decreasing water depths. For 300 m water depth, it varies from 3.8 to 4.4, and for 30 m water depth, from 5.0 to 6.0.

In the same, time Young developed a parametric model to get the maximum significant wave height and its associated peak period.

It is also possible and recommended to perform wave modelling to estimate sea state conditions in cyclone conditions; since, the above parametric models do not consider local influence of the bathymetry and topography (coast, island) and of their spatial variability. Figure 4-4 shows wave fields during Hurricane Katrina.

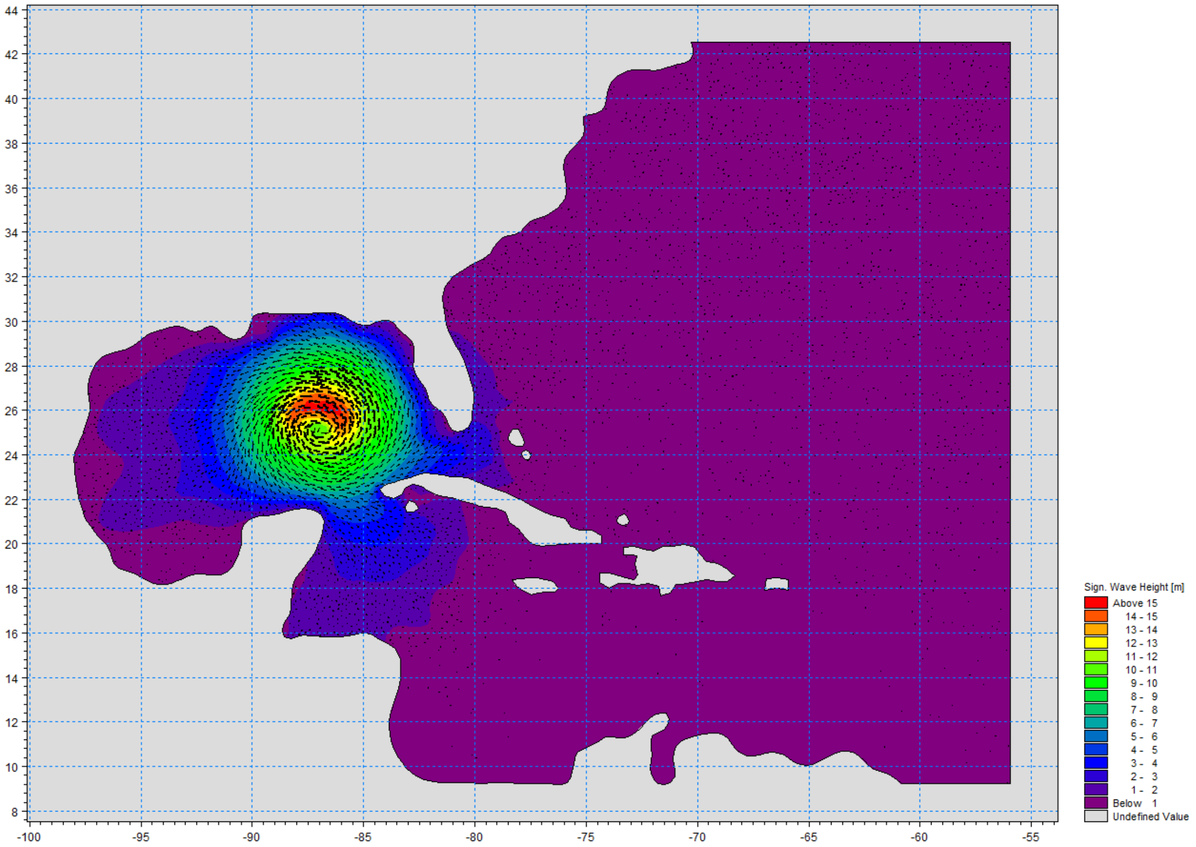


**Figure 4-4 Wave fields during Hurricane Katrina (in house Mike 21)**

### 4.3.4 Synthetic storms and Monte Carlo simulations

Due to the random and infrequent nature of tropical cyclones, it is generally difficult to obtain sufficient data for a given location for generating reliable long-term statistics. However, methods have been developed in recent years for generating synthetic storms which can provide the necessary data to support robust statistical analysis. There are multiple techniques possible, generally based on Monte Carlo techniques to generate random parameters for the synthetic storms, while applying physical limits to the random choices. Randomness can typically be included in the tropical cyclone track, maximum wind and/or minimum pressure, and radius to maximum winds, thus creating very large databases of possible tropical cyclones in a basin. Care shall be taken to ensure statistical independence of the results as much as possible through rigorous application of suitable Monte Carlo techniques, and in the selection of appropriate distributions and limits for the parameters being varied. Since many of these techniques can be applied also in the interpretation/analysis of tropical cyclone data, more information is given in Section 5.7.

## 4.4 Reporting requirements

In addition to any data results reported, a report for a metocean study involving numerical modelling should as a minimum contain the following (if relevant):

- Details of the model used, including an explanation of the physics included and any simplifying assumptions made
- Details of the model setup, including a grid sensitivity study and explanation of the choices of area covered and fineness of mesh, with a discussion on computational time and requirements
- Discussion on and demonstration of appropriateness of seabed bathymetry as applicable
- Details of the boundary conditions and data used as model input, including details of larger scale model and nesting techniques as appropriate
- If relevant, demonstration that a regional hindcast model can be used as input for the local model
- Details of the measured wind and ocean data used for calibration or verification of the local model
- Sensitivity studies of model calibration parameters
- A description of the preformed calibration/verification of local models

# 5 DATA ANALYSIS – INTERPRETATION

This section highlights on the methodology to derive the metocean criteria described in Section 2 and introduce different physical processes behind the data.

## 5.1 Wind

Examples of methodology to derive the wind design criteria for non-tropical cyclone conditions as described in Section 2.2.2 are given in the following sections.

The wind speed distribution is significant for wind turbine design because it determines the frequency of occurrence of individual load conditions for the normal design situations. Examples of wind speed distributions are given in Section 5.1.1.

Wind speed and direction varies in time and space. Within long durations, there will be shorter durations with higher wind speeds (gusts). Therefore, wind speeds shall be referred together with the associated averaging period and reference level. As described in Section 2.2.2.1, stationary wind conditions with constant mean wind speed $U_{10}$ and constant mean standard deviation $\sigma_U$ are generally assumed to prevail over a 10-minute period. The wind climate for design is therefore represented by the 10-minute mean wind speed $U_{10}$ and the standard deviation $\sigma_U$ of the wind speed, at a specified reference height. Often, the mean 10-minute wind speed measured at 10 m MSL is used as a reference, or the hub height of the wind turbine if this is known. Conversion between averaging period and vertical levels are described in Section 5.1.2 and 5.1.3.

The natural variability of the wind speed about the mean wind speed $U_{10}$ in a 10-minute period is known as turbulence and is characterized by the standard deviation $\sigma_U$. Turbulence is described in Section 5.1.5.

As described in Section 2.2.2.1, the various wind parameters required for design should preferably be determined based on site-specific wind measurements, possibly supplemented by hindcast data. When no site-specific wind data are available, or only short term site specific data are available, data from adjacent locations are to be capitalized on instead. In this case, proper transformation of such other data shall be performed to account for possible differences due to, for example, proximity of land. This may for example be done by applying hindcast data or information from hindcast databases. This is described in Section 5.1.4.

For details, reference is made to relevant standards, for example DNVGL-ST-0437, IEC 61400-1, IEC 61400-3, and API RP 2A-WSD 22nd Edition 2014.

### 5.1.1 Wind speed distribution and roses

The arbitrary 10-minute mean wind speed $U_{10}$ in a given height over reference sea level can often be described by a Weibull distribution $F_{U_{10}}(u)$:

$$F_{U_{10}}(u) = 1 - \exp\left(-\left(\frac{u}{A}\right)^k\right) \qquad \textbf{(5-1)}$$

In which A is the scale parameter and $k$ is the shape parameter, which can be decided based on fitting the distribution to data. A and k are height-dependent.

The long-term probability distributions for the wind climate parameters $U_{10}$ and $\sigma_U$ that are interpreted from available data can be represented in terms of generic distributions or in terms of scatter diagrams:

- A typical generic long-term distribution representation consists of a Weibull distribution for the 10-minute mean wind speed $U_{10}$ as given above, in conjunction with a lognormal or Weibull distribution of $\sigma_U$ conditional on $U_{10}$ (reference is made to for example IEC 61400-1).
- A scatter diagram provides the frequency of occurrence of given pairs ($U_{10}$, $\sigma_U$) in a given discretization of the ($U_{10}$, $\sigma_U$) space.

The long-term wind distributions can be given per wind speed direction if this information is available.

The frequency of the wind in each specified direction and associated wind speed can then be represented by a wind rose, as shown in Figure 5-1.

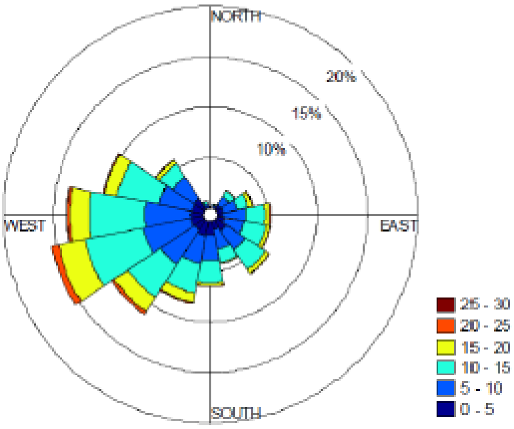


**Figure 5-1 Joint distribution of wind speed and direction or wind rose**

### 5.1.2 Wind speed averaging period

The long-term probability distribution of mean wind speed at a certain reference height may be assumed to be independent of averaging period for periods in the range between 10 minutes and 3 hours.

This is not the case for extreme wind speeds. In general, the longer the averaging period, the smaller the associated extreme wind speed, as the more frequent lower wind speeds are included in the averages.

The long-term distributions of $U_{10}$ and $\sigma_U$ for extreme average wind speeds should preferably be based on statistical data for the same averaging period for the wind speed as the averaging period, which is used for the determination of loads. For the extreme wind speeds, where site-specific extreme average wind speeds are available only for averaging periods longer than 10 minutes, conversion factors shall be used to estimate the extreme 10-minute wind speed. The conversion factors given in Table 5-1 are from IEC 61400-3 and give the ratio between the extreme wind speed for a given averaging period and the extreme 10-minute average wind speed.

**Table 5-1 Example extreme wind speed conversion factors of different averaging periods (from IEC 61400-3)**

| **Averaging period** | 10 min | 1 hour | 3 hours |
|---|---|---|---|
| **Correction factor relative to extreme 10-min average wind speed** | 1.00 | 0.95 | 0.90 |

### 5.1.3 Vertical wind profile, wind shear

The wind speed profile is required to convert the mean wind speed from one reference height to another. The wind profile expresses the mean wind speed with a given average period as a function of height above the reference water level.

Wind speed profiles may vary regionally, for example due to wind climate, and therefore different recommended wind speed profiles are found in different standards. In the following, examples of two wind profiles are given:

In the IEC 61400-1 the vertical wind profile for the 10-minute wind speed is given by the power law:

$$U(z) = U(z_{ref}) \cdot \left(\frac{z}{z_{ref}}\right)^{\alpha_w} \qquad \textbf{(5-2)}$$

expressing that the 10-minute wind speed at a reference level $z_{ref}$, $U(z_{ref})$, increases exponentially with height above the reference height $z_{ref}$ with the wind shear exponent $\alpha_w$.

The wind shear coefficient $\alpha_w$ expresses the vertical mixing due to turbulence and depends on for example the surface roughness (of terrain or sea surface) and atmospheric stability, and may therefore vary seasonally and from day to night (in general, stable conditions prevail when the surface is cooled and turbulent mixing is suppressed, while unstable conditions prevail when the surface is heated and vertical turbulent mixing is increased), as well as regionally due to terrain roughness. The wind shear exponent may be decided based on measurements of wind speed in various heights, with a period down to one or two years (to capture seasonal variations). To estimate the extreme shear, analyses are performed for high wind speeds only. However, since it is difficult to estimate or measure the wind speed vertical shear over an operating turbine rotor, $\alpha_w$ is compiled for normal and extreme offshore wind conditions in iEC 61400-3, and specified as 0.14 for normal wind conditions and 0.11 for extreme wind conditions, for load calculations.

In API RP 2A-WSD 22nd Edition 2014 and the DNVGL-RP-C205 the offshore mean wind speed for averaging periods equal or below 1 hour is given by the Fröya Profile:

$$U(z,t) = U(z)\left[1 - 0.41 I_u ln\frac{t}{t_0}\right] \qquad \textbf{(5-3)}$$

where, the mean wind speed U(z) with averaging period $t<t_0$ and $t_0=1$ hour, at level z is given by

$$U(z) = U_0\left[1 + Cln\frac{z}{z_{ref}}\right] \qquad \textbf{(5-4)}$$

in which $U_0$ is the reference 1-hour wind speed at reference level $z_{ref}$, a C is given by

$$C = 5.73 \cdot 10^{-2}\sqrt{1 - k_1 U_0} \tag{5-5}$$

and the turbulence intensity $I_o$ at reference level $z_{ref}$ is given by

$$I_0 = 0.06(1 + k_2 U_0)\left(\frac{z}{z_{ref}}\right)^{-0.22} \tag{5-6}$$

The reference level $z_{ref}$ is 10 m in SI units, with $k_1$=0.15 and $k_2$=0.043; and the reference level $z_{ref}$ is 32.8 ft in USC units, with $k_1$=0.0457 and $k_2$=0.0131.

According to DNVGL-RP-C205, this vertical mean wind speed profile is applicable for extreme wind speed with recurrence in excess of approximately 50 years, where the mean wind speed has the same return period as $U_0$.

### 5.1.4 Examples of wind-data correlations and corrections

If a sufficiently long data period for the wind speed is not available for the site, or data from adjacent sites are to be capitalized on, a synoptic long-term wind speed data series can be obtained from the available data by correlation with other long-term wind speed data sets, for example data from a meteorological station at another location or with hindcast data (which should include the long-term average diurnal, seasonal and inter-annual variation that is specific for the site).

The correlation can for example be performed by applying a Measure-Correlate-Predict (MCP) method, which exists in various more-or-less complicated versions, and is often built-in in wind analysis tools.

A simple version is the linear regression MCP, where the measured short-term wind data at the site and simultaneous long-term data are recorded and a straight line is fitted to the data by least square technique to relate the short-term wind speeds of proposed wind farm site and concurrent wind speed in the long-term wind speed data series. The coefficients' slope and intercept are determined through linear regression. The long-term data are then corrected with the obtained slope and intercept to create a long-term wind speed data series with the characteristics of the short-term wind speed data at the site.

For measurements covering shorter periods, to be used for example for estimation of turbulence and shear, it is important to avoid seasonal bias due to data gaps and data not covering a full integer of years. This kind of data correction may for example be done with the Mean-of-Monthly-Means method, which is a method of weighting data points by how often they occur in a month of the year, for example by:

- Ascribing to each measurement data point an integer n ϵ [1,12], given by the month the data point is recorded in
- For each data point with the same integer value (i.e., the same month n), ascribe a weight, which will be used to weight the data point. This weight equals the maximum number of data points that are possible in the month n divided by the actual number of data points.

### 5.1.5 Turbulence

The natural variability of the wind speed about the mean wind speed $U_{10}$ in a 10-minute period is known as turbulence and is characterized by the standard deviation $\sigma_U$. For given value of $U_{10}$, the standard deviation $\sigma_U$ of the wind speed exhibits a natural variability from one 10-minute period to another.

The turbulence intensity is defined as the ratio $\sigma_U/U_{10}$. This is sometimes referred to as the ambient turbulence, i.e., the turbulence at the site without influence from neighboring turbines.

It is notable that turbulence intensity decreases with height.

The value of the turbulence intensity and standard deviation shall be determined using appropriate statistical techniques applied to measured data. Where topographical (shoreline) or other local effects may influence the turbulence intensity, these effects shall be represented in the data. The characteristics of the anemometer, sampling rate, and averaging time used to obtain measured data shall be taken into account when evaluating the turbulence intensity.

#### 5.1.5.1 Wake effects: effective turbulence and maximum center wake

A wind facility generates its own wind climate due to downstream wake effects, and the wind climate in the center of the wind facility may therefore be very different from the ambient wind climate. The layout of the wind facility has an impact on the wind at the individual wind turbines. Wake effects within a wind facility will generally imply a considerably increased turbulence relative to ambient turbulence, reflected in an increased standard deviation $\sigma_U$ of the wind speed. This effect may be significant even when the spacing between the wind turbines in the wind farm is as large as 8 to 10 rotor diameters. Wake effects fade out more slowly and over longer distances offshore than they do over land.

Wake induced turbulence within a wind facility is important for the fatigue loads in offshore wind turbine structures.

The wake effect can for example be estimated by the method described in the IEC 61400-1 standard and summarized below:

The turbulence in a wind facility with turbines in operation is affected by:

- The ambient turbulence (i.e., turbulence without influence of wind turbines)
- The operating turbine induced turbulence (in the IEC system this turbulence is denoted “the maximum center wake turbulence”) that depends on:
    - The spacing of the turbines (farm layout)
    - The rotor diameter
    - How much the wind is slowed down over the rotor plane as expressed by the thrust-curve of the turbine

For each turbine in the planned wind facility, the IEC 61400-1 method combines the ambient turbulence with the maximum center wake turbulence caused by wakes from the surrounding turbines, based on specifications of when a turbine is considered to be in wake. With the total overall turbulence in the farm being different depending on wind direction, the IEC method furthermore includes a weighting that yields an effective (Ieff) turbulence that, without considering direction, yields the same fatigue as would arise from a calculation of sector wise fatigue. This is done by including the structural fatigue damage expressed by the SN-curve slope “m”-fatigue parameter, which depends on the material for the support structure (as the fatigue is dependent on the SN-curve slope “m” and on the stress cycles).

#### 5.1.5.2 Extreme turbulence

The extreme turbulence with no effect from the neighboring wind turbines can be derived by extreme value analysis (see Section 6.5) on the long-term distribution for $\sigma_U$ conditioned on wind speed.

Caution should be exercised when fitting a distribution model to data for the standard deviation $\sigma_U$. Often, the lognormal distribution provides a good fit to data for $\sigma_U$ conditioned on $U_{10}$ (as mentioned in section 5.1.1) but use of a normal distribution, a Weibull distribution, or a Frechet distribution is also seen. The choice of the distribution model may depend on the application, i.e., whether a good fit to data is required to the entire distribution or only in the body or the upper tail of the distribution.

If no site-specific data are available, expressions for the extreme $\sigma_U$ can be found in some standards, for example in IEC 61400-1.

In a wind facility, the maximum center wake may be larger than the extreme turbulence with no effect from the neighboring wind turbines. In this case, the maximum center wake turbulence shall be applied.

## 5.2 Waves

This section provides general information on waves and their evolution in function of the domain of propagation: ocean, continental sea, coastal and harbor. The processes contributing to wave evolution, including generation, propagation and dissipation, are cited in Table 5-2; all processes that have a dominant and significant influence on waves shall be considered in the physics modelling for any offshore project.

Then the spectral representation of sea states is detailed, because of its importance in design of offshore structure, load studies, and mooring analysis. The spectral approach allows to sum-up in a wave spectrum of a sea state, the chaotic aspect of the sea, because of the different frequencies and directions of waves, due to irregular and turbulent nature of wind forcing.

After those paragraphs on sea state, a section is dedicated to individual waves; indeed, a sea state is often defined as the average wave field on 3-hours period. Consequently, during one sea state, several thousand of waves occurred. The section links both aspects and time scale, by introducing, wave measurements analysis (if high resolution measurements are available) and theoretical distributions.

Finally, a last paragraph present the long-term statistics, which are necessary to describe and understand the wave conditions in the location of interest.

### 5.2.1 General

Waves are undulatory phenomena that perturbate the sea surface; they are generated by wind friction at the interface between atmosphere and sea locally, and propagate over long distance by being transformed by different types of processes (Table 5-2).

In deep water, the transformations are due to the adding of energy from wind, the dissipation with white capping and viscosity effect, and transfer of energy to short frequencies (structuration of waves leading to swell formation).

In shallow water, several phenomena modify the wave propagation, like bottom friction, refraction, and complex processes leading to energy transfer to high and/or low frequencies. The propagation finally ends with wave breaking and dissipation of energy.

Wave is a term associated with the individual event defined by a trough and a crest. The sea state is more appropriate to describe the wave's field, using synthetic parameters, like significant wave height, peak period, etc.

**Table 5-2 Summary of main wave transformation processes and their applicability**

| **Process** | **Ocean domain (infinite depth deep water)** | **Continental sea (finite depth intermediate water)** | **Coastal domain (shallow water)** | **Harbor domain** |
|---|---|---|---|---|
| Wind growth | 🟥 | 🟥 | 🟩 | ⬜ |
| White capping | 🟥 | 🟥 | 🟩 | ⬜ |
| Quadruplets | 🟥 | 🟥 | 🟩 | ⬜ |
| Current refraction | 🟩 | 🟨 | 🟨 | ⬜ |
| Bottom friction | ⬜ | 🟥 | 🟨 | ⬜ |
| Bottom refraction | ⬜ | 🟨 | 🟥 | 🟨 |
| Shoaling | ⬜ | 🟩 | 🟥 | 🟩 |
| Wave breaking | ⬜ | 🟩 | 🟥 | ⬜ |
| Triplets | ⬜ | ⬜ | 🟨 | 🟨 |
| Diffraction | ⬜ | ⬜ | 🟩 | 🟥 |

| ⬜ **Negligible** | 🟩 **Weak influence** | 🟨 **Significant** | 🟥 **Dominant** |
|---|---|---|---|

## 5.2.2 Spectral representation of sea state

Wave spectrum is the basis of sea-state propagation modelling and the synthetic parameters like significant wave height or peak period are derived from it. The spectral representation highlights on the repartition of energy in frequency and in direction; this information is crucial for design, load studies, and fatigue analysis.

### 5.2.2.1 Principle

Spectral description of the sea state represents the wave field as the sum of several individual regular waves with different frequencies, periods, amplitudes, and/or directions, giving the chaotic aspect of the sea, as illustrated in Figure 5-2.

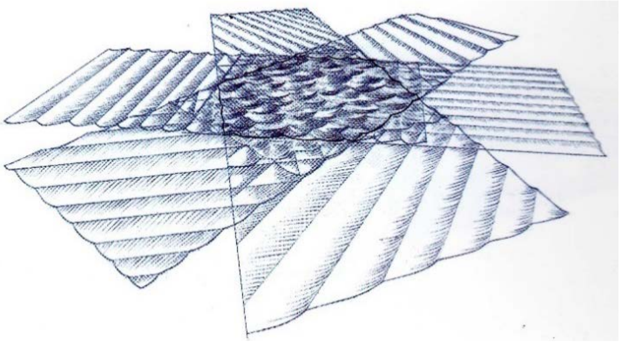


**Figure 5-2 Illustration of the sum of several individual regular waves**

The Fourier analysis determines the spectrum of the sea state, defined as the energy distribution per frequency and per direction. The wave spectrum presents less variation in time and space than the wave field; by definition, it represents the state of the sea on 3-hours period generally. This simplified representation of the wave environment is useful for wave propagation modelling.

From the directional wave spectrum $F(f,\theta)$, several synthetic parameters can be derived, associated with a physical representation:

Significant wave height, $H_s = H_{m0} = 4\sqrt{m_0}$, with $m_0 = \int_0^\infty F(f)\,df$ **(5-7)**

Peak wave period, $T_p = 1 / f_p$, with fp the peak frequency (frequency associated with the maximum of energy) **(5-8)**

Mean wave period, $T_z = T_{m02} = \sqrt{\frac{m_0}{m_2}}$ **(5-9)**

Mean wave direction, $\theta_{MWD} = \arctan(b/a)$ with

$$a = \int_0^{2\pi}\int_0^{+\infty} \cos(\theta) * F(f,\theta)\, d f\ d\theta$$ and

$$b = \int_0^{2\pi}\int_0^{+\infty} \sin(\theta) * F(f,\theta)\, d f\ d\theta$$ **(5-10)**

Wave spreading, $\sigma_w = \sqrt{2\left(1-\sqrt{a^2+b^2}\right)}$ **(5-11)**

When a sea state is composed of several components (distinct peaks of energy in a wave spectrum), post processing of wave spectrum time series shall be performed to define and analyze components. Such post processing shall be based on splitting and fitting with a theoretical spectrum of the original wave spectrum, in order to define each component and estimate their parameters. If this additional post processing is not performed, the parameters are estimated with all components and may not represent properly the wave climate in the location of interest, especially when components occur from different incidences and/or are associated with different frequencies.

### 5.2.2.2 Wave spectrum formulation

This section introduces the main theoretical spectra used in design. The directional repartition function is also presented, which allows to represent the energy incidence and spreading. The choice of the spectrum is done by comparisons with spectra derived from measurements or from hindcast data.

It is especially necessary/useful for floating structures to study motion of structure, wave loads, fatigue, forces and interactions with mooring systems; the knowledge of the local distribution of energy in frequency and in direction will allow suitable and reliable design.

The following paragraphs introduce several formulations to describe wave spectrum. It is recommended to choose the formulation by comparisons with local spectra from measurements or modelling.

Pierson Moskowitz

This spectrum model was proposed by Pierson and Moskowitz in 1964 after analyzing measurements in the North Atlantic. Fully developed seas were considered to define it; consequently, it is only adapted for this type of sea.

$$S(\omega) = \frac{\alpha * g^2}{\omega^5} \exp\left(-\beta * \left(\frac{\omega_0}{\omega}\right)^4\right)$$

where $\alpha$ = 8.1*10-3 (Philipps constant),

$\beta$ = 0.74, and, **(5-12)**

$\omega_0 = \frac{g}{U_{19.5}}$ (ratio between gravity and wind speed at 19.5m above sea level – height of anemometer on ships)

International institutions recommend different expression. ISSC (International Ship and offshore Structures Congress) recommends:

- In Equation 5-12, replace $\alpha * g^2$ with $\frac{173 * Hs^2}{T_{m01}^4}$, where $T_{m01} = m_0/m_1$, and replace $\beta * \omega_0^4$ with $\frac{691}{T_{m01}^4}$.

U.S. Navy recommend:

- In Equation 5-12, replace $\alpha^* g^2$ with $\frac{483.5 * Hs^2}{T_p{}^4}$, and replace $\beta * \omega_0^4$ with $\frac{1944.5}{T_p{}^4}$.

JONSWAP spectrum

The JONSWAP wave spectrum model was defined by Hasselmann in 1973, after analyzing storm measurements in North Sea during the JOint North Sea WAve Project. It is consequently adapted for limited fetch area.

$$S(\omega) = \frac{\alpha * g^2}{\omega^5} \exp\left( -\frac{5}{4} * \left( \frac{\omega_p}{\omega} \right)^4 \right) * \gamma^{\exp\left( -\frac{(\omega - \omega_p)^2}{2 * \sigma_p * \omega_p^2} \right)} \tag{5-13}$$

Different values for parameters are proposed in Table 5-3.

**Table 5-3 Examples of parameter formulation for JONSWAP**

| Parameter | Definition | Author | Coefficient |
|---|---|---|---|
| $\alpha$ | Constant | Philipps | $\alpha = 8.1 * 10^{-3}$ |
| | | Hasselmann | $\alpha = 0.076 * \left( \frac{g * F}{U_{10}^2} \right)^{-0.22}$ |
| | | Sarpkaya | $\alpha = 0.066 * \left( \frac{g * F}{U_{19.5}^2} \right)^{-0.22}$ |
| $\omega_p$ | Peak Pulsation | Hasselmann | $\omega_p = 7 * \pi * \frac{g}{U_{10}} * \left( \frac{gF}{U_{10}^2} \right)^{-0.33}$ |
| | | Sarpkaya | $\omega_p = 5.68 * \pi * \left( \frac{gF}{U_{19.5}^2} \right)^{-0.33}$ |
| $\gamma$ | Peak Enhancement Factor | | $\gamma = 5 \quad strong\ peak$<br>$\gamma = 3.3$ standard<br>$\gamma = 1 \quad Pierson - Moskowitz$ |
| $\sigma_p$ | Width of peak | | $\sigma_p = 0.07 \quad for\ \omega \le \omega_p$<br>$\sigma_p = 0.09 \quad for\ \omega > \omega_p$ |
| F | Fetch | | |
| $U_{10}$ | Wind speed at 10 m | | |
| $U_{19.5}$ | Wind speed 19.5 m | | |

Fetch and wind speed are considered in this spectrum formulation; the peak enhancement factor (gamma) has a default value of 3.3 for North Sea but it should be changed to adapt the shape of spectrum and a better representation of high and/or low frequencies to local conditions; because of long travelling of swell across Pacific, the non-linear interactions affect the shape of wave spectrum leading to high gamma value for the swell component (above 5).

TMA spectrum

The Texel Marsen Arsloe (TMA) spectrum is an extension of the JONSWAP spectrum to take into account the nonlinear effects (e.g., energy transfer, bottom friction) during propagation toward shallow water. TMA spectra allows for representation of sea states in limited fetch area and in finite depth. It was defined using numerous observations between 6 and 42 m (outside the wave breaking zone):

- Near Texel in North Sea
- During Marsen project in North Sea
- During Arsloe project at Duck in North Carolina

$S(\omega) = S_{JONSWAP}(\omega) * \phi(\omega_h)$ with $\phi(\omega_h) = \dfrac{k_h^{-3} \dfrac{\partial k_h}{\partial \omega}}{k_\infty^{-3} \dfrac{\partial k_\infty}{\partial \omega}}$ and $k_h$ is **(5-14)**

the wavenumber at the depth h.

K and ω are related by the dispersion relation. Considering the equation $\omega^2 = gk\tanh(kh)$, it leads to

$$\phi = \tanh^2(kh) \cdot \left(1 + \frac{2kh}{\sinh(2kh)}\right). \qquad \textbf{(5-15)}$$

Ochi-Hubble spectrum

Many sea sates are composed of several components leading to several peaks in wave spectrum; most of the time a swell and a wind sea occur at the same time.

To represent sea states with both peaks, Ochi-Hubble proposed the following formulation with six parameters, three for each component: significant wave height *Hs*, shape parameter *λ,* and peak pulsation $\omega_p$.

$$S(\omega) = \frac{1}{4} * \sum_{j=1}^{2} \frac{\left(\dfrac{4*\lambda_j+1}{4} * \omega_{pj}^4\right)^{\lambda_j}}{\Gamma(\lambda_j)} * \frac{Hs_j^2}{\omega^{4*\lambda_j+1}} * \exp\left(-\left(\frac{4*\lambda_j+1}{4}\right) * \left(\frac{\omega_{pj}}{\omega}\right)^4\right) \qquad \textbf{(5-16)}$$

The shape parameter can vary to fit to measurements; without reference, the following values are used:

$\lambda_1 = 2.72$ and $\lambda_2 = 0.5547 * e^{-0.027*Hs}$ **(5-17)**

Angular distribution function

The previous formulations allow representation of the density function of sea state in function of the energy and the frequency S(f) or pulsation S(ω) (1D model). However, no information on direction is available; an angular distribution function shall be introduced to assess the directionality of sea state; the 2D spectrum is defined as:

$$S(f,\theta) = S(f) * D(f,\theta) \tag{5-18}$$

In a sea state, waves propagate in a sector between -π and π from a main propagation direction $\theta_0$. Longuet-Higgins proposed in 1963 the following formulation:

$$D(f,\theta) = \frac{1}{2\sqrt{\pi}} * \frac{\Gamma(s+1)}{\Gamma(s+1/2)} * \cos^{2s}\left(\frac{\theta-\theta_0}{2}\right) \tag{5-19}$$

with Γ gamma function and s, spreading coefficient, decreasing when direction spreading increases

The analysis of the local directional wave spectra allows to estimate s parameter and derive appropriate values.

Figure 5-3 shows a directional distribution in function of s coefficient and relation between s and directional spreading. Other formulations exist but are less used, such as Poisson, normal and wrapped normal.

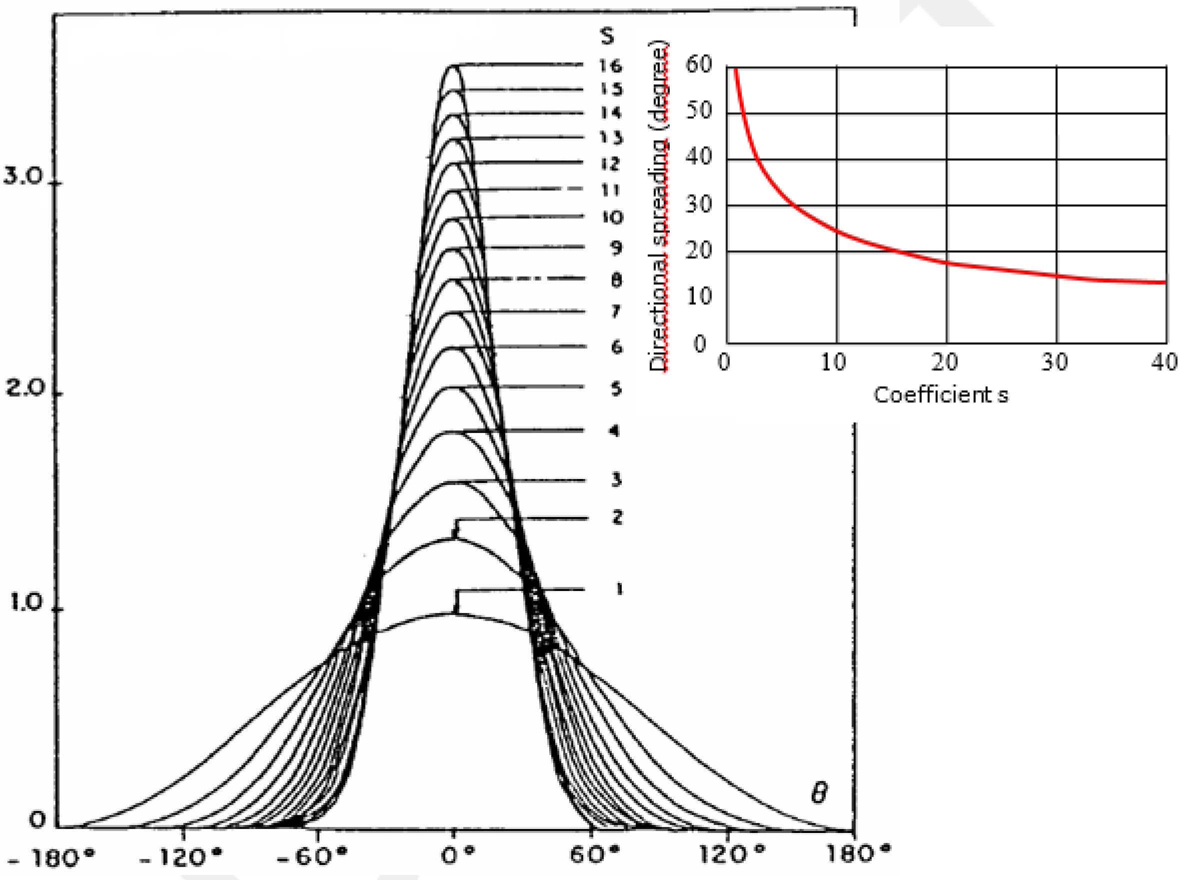


**Figure 5-3 Directional distribution in function of s coefficient and relation between s and directional spreading (red curve)**

### 5.2.2.3 Multi-modal spectrum

Because of complex bathymetry and non-linear phenomena, the wave spectrum may have several components, modes, or peaks; for example, two swells with different main incidences and or peaks of frequency and one local wind sea.

It is recommended to characterize each component with a theoretical spectrum, associated shape parameter and directional spreading, for operational conditions and for extreme conditions, as illustrated in Figure 5-4; indeed, the extreme conditions may be characterized by only one component in the wave spectrum, when mild conditions experience several components in the same time.

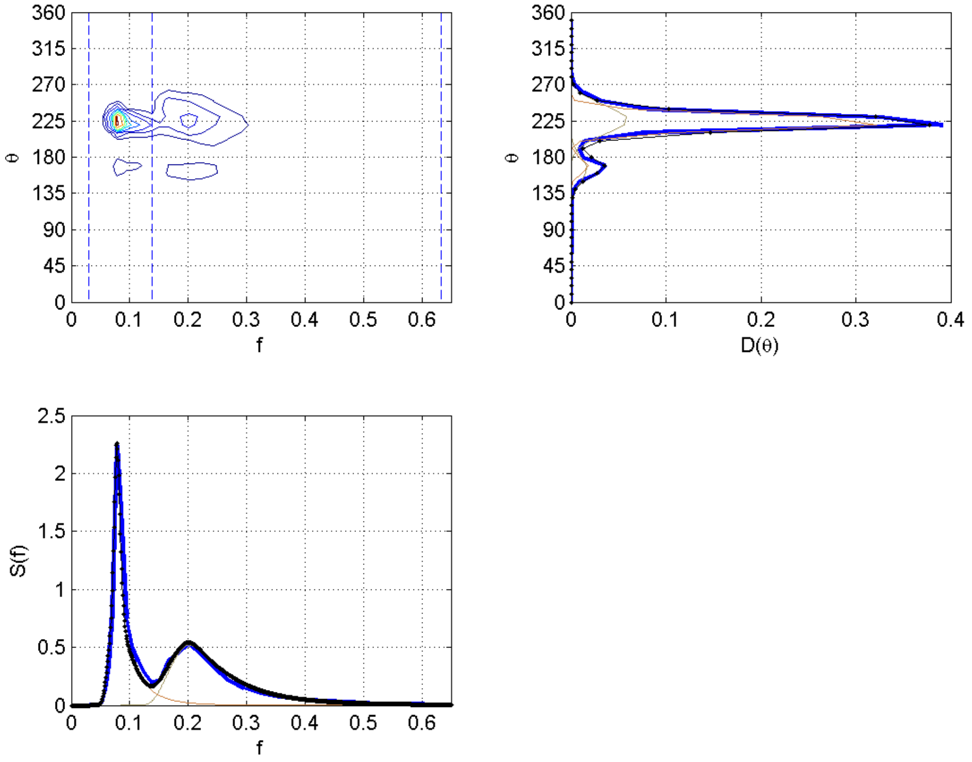


**Figure 5-4 Direction-Frequency wave spectrum (top left), direction distribution (top right) and frequency spectrum (bottom left)**

The original spectrum leads to blue lines in frequency spectrum; each component is modelled by a JONSWAP (with different gamma factor) and the sum of both gives the dark dots.

JONSWAP spectrum may be a first choice to define wave spectrum; a main advantage is the possibility to define peak enhancement to better describe wave spectrum by comparison with measurements. A second advantage consists in the opportunity to add “several individual” JONSWAP to represent each component of multi-modal spectrum.

## 5.2.3 Short term wave statistics

This section provides more information on individual wave, which may be considered as a link between sea state and the thousands of individual waves that compose this sea state.

The concrete goals are to define maximum individual wave height and wave crest for design of structure and provide tables for fatigue analysis. Those objectives can be reached with a direct analysis of measurements (sea elevation at high resolution, 1Hz or more) or by applying theoretical distributions.

### 5.2.3.1 Wave measurements analysis

The wave analysis derives each individual wave from a time series of sea elevation measurements. There are different methods to get the individual wave from observed dataset:

- Zero-up-crossing or zero-down-crossing methods – both methods consider two consecutive passages through level 0 by increasing (zero-up) or by decreasing (zero-down) to define one wave. The height and period then are estimated (Figure 5-5).
- Rain flow methodology – this method derives the cycles inside a time series without considering a threshold. It allows to take into account local minima and maxima as described by Gomez et al (2012).

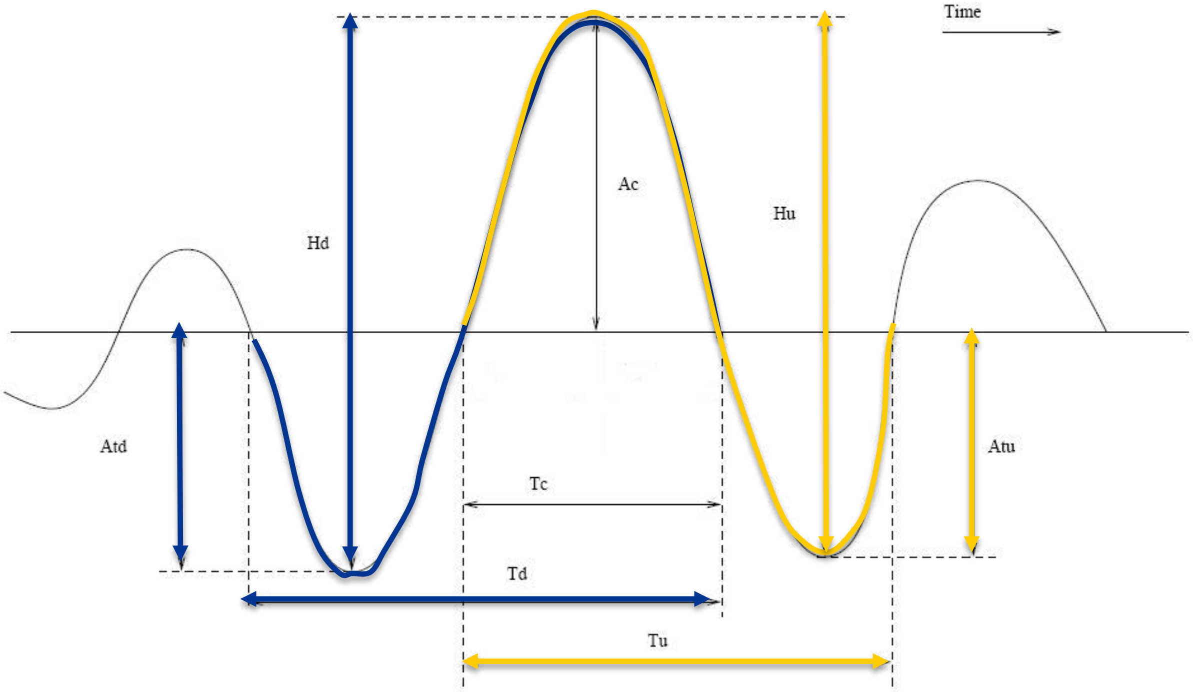


**Figure 5-5 Methods zero-up-crossing (orange) and zero-down-crossing (blue)**

From the measurements and the individual wave heights H and periods T, it is possible to derive the statistical distributions for these parameters; the distribution of wave height is close to a Rayleigh distribution in the linear theory. When no measurements are available, the sea elevation can be simulated using a theoretical wave spectrum.

The sum of a large number of independent sine waves should lead to a Gaussian distribution. However, the observations highlight that there are more high waves than predicted by the Gaussian law because of non-linear processes. The next section introduces height and crest distribution formulations which try to consider this influence, using water depth for example.

### 5.2.3.2 Statistical distributions of wave height and crest

The use and quality of the distribution models are crucial in ocean and coastal engineering. The main aim is to get a suitable representation of the extreme wave which may damage structures. Limitations of the models come from assumptions, like sine waves for Rayleigh law; the distributions may also be derived from measurements and are consequently only suitable locally.

The Rayleigh law follows the Weibull distribution with two parameters: 0.707 for scale parameter and 2 for shape parameter; it remains the basis of other models, authors proposing their own values for the parameters; Haring proposed another distribution formulation. In the following formulations, x is the ratio between H (individual wave height) and Hs (significant wave height, fixed value):

Rayleigh: $F(x) = 1 - \exp(-(\frac{x}{\alpha})^{\beta})$ with, α=0.707 and β=2.000

Forristall: $F(x) = 1 - \exp(-(\frac{x}{\alpha})^{\beta})$ with, α=0.681 and β=2.126

Nolte and Hsu: $F(x) = 1 - \exp(-(\frac{x}{\alpha})^{\beta})$ with, α=0.682 and β=2.138

Krogstadt: $F(x) = 1 - \exp(-(\frac{x}{\alpha})^{\beta})$ with, α=0.679 and β=2.130

Haring: $F(x) = 1 - \exp(-2 * x^2 * (0.968 + 0.176 * x))$

Others' distributions describe the crest probability and some laws introduce the water depth to represent the non-linear effect and get higher occurrence for highest values (Figure 5-6). Like individual wave height, Rayleigh and Forristall proposed Weibull law to describe the crest distribution in function of Hs, but with different scale and shape parameters values; other authors proposed also other laws. In the following formulations, *x* is the ratio between $C_r$ (crest height) and $H_s$ (significant wave height, fixed value):

Rayleigh: $F(x) = 1 - \exp(-(\frac{x}{\alpha})^{\beta})$ with, α= $\frac{1}{\sqrt{8}}$ and β=2

Forristall: $F(x) = 1 - \exp(-(\frac{x}{\alpha})^{\beta})$ with, α= $\frac{1}{\sqrt{8}} - 0.2892 * S + 0.1060 * Ur$ and

β=2-2.1597*S+0.0968*Ur$^2$, S= $\frac{2\pi}{g} * \frac{Hs}{T_m^2}$, Ur= $\frac{Hs}{k^2 * d^3}$, water depth: d, wave number: k

Haring and Heideman: $F(x) = 1 - \exp(-8 * x^2 * (1 - 2.49 * \frac{Hs}{d} x + 4.37 * (\frac{Hs}{d} x)^2))$

Rayleigh-Stokes: $F(x) = 1 - \exp(-8 * \frac{(\sqrt{1 + 2 * k * Hs * x} - 1)^2}{k * Hs^2})$

Forristall distributions appear most of the time suitable to model distributions of wave height and crest; they are intensively used in offshore industry. When measurements are available, here individual wave height and crest height measurements, comparisons between distributions from the measurements and theoretical Forristall distributions are recommended. Indeed, large differences between both may highlight local processes affecting wave field and choice model distributions of wave and crest shall be changed or adapted.

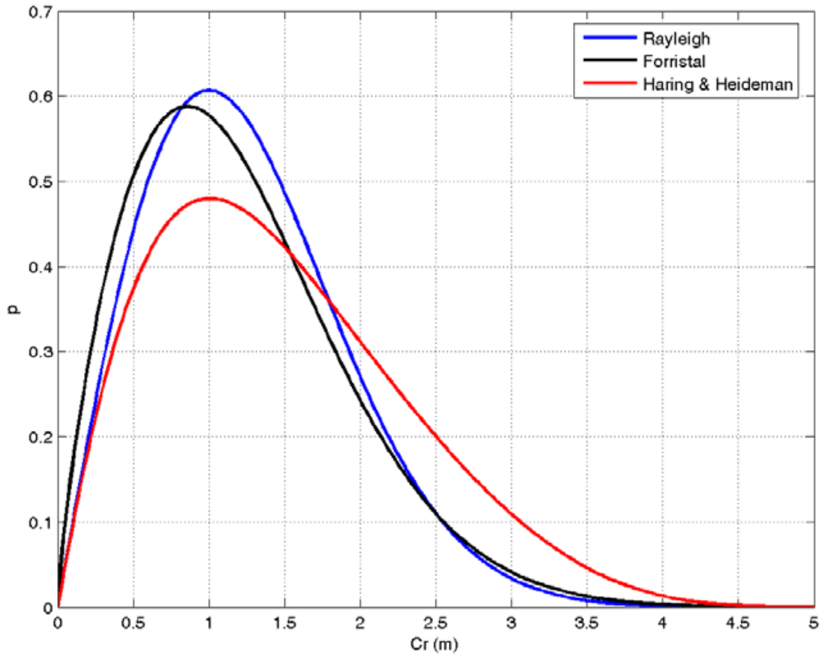


**Figure 5-6 Crest height (Cr) distribution for Hs=4.0m and water depth of 10m**

In the past, Longuet-Higgins (1962) and Breitschneider (1969) defined distribution models for individual wave period T. However, with experience, it is more realistic to simulate times series of sea elevation and apply wave analysis (5.2.3.1) to get the wave period distribution and fit a model.

When in-situ data or simulated data are available, the normal and log-normal laws provide a reliable representation of wave period distribution.

### 5.2.4 Long-term wave statistics

The description of long-term wave conditions requires the analysis of long time series, lasting several years. The hindcast databases are useful because they simulate sea states over large areas and long periods.

The analysis shall provide statistics of main parameters, which shall include as a minimum: significant wave height, peak period, and mean or peak wave direction (Figure 5-7). The statistics consist of all-year and monthly minimum, mean and maximum, histograms and joint distributions. When there are enough years of data, it is also possible to analyze the inter-annual variability and link it to major climate pattern.

Finally, when several components occur in the sea states, the above statistics shall be provided for total sea and each component (at least one swell and one wind sea).

Extreme waves are also necessary to assess the potential severity of the area; it is recommended to perform the extreme value analysis per directional sector, as a minimum. Best practices for extreme estimations are given in Section 5.6.

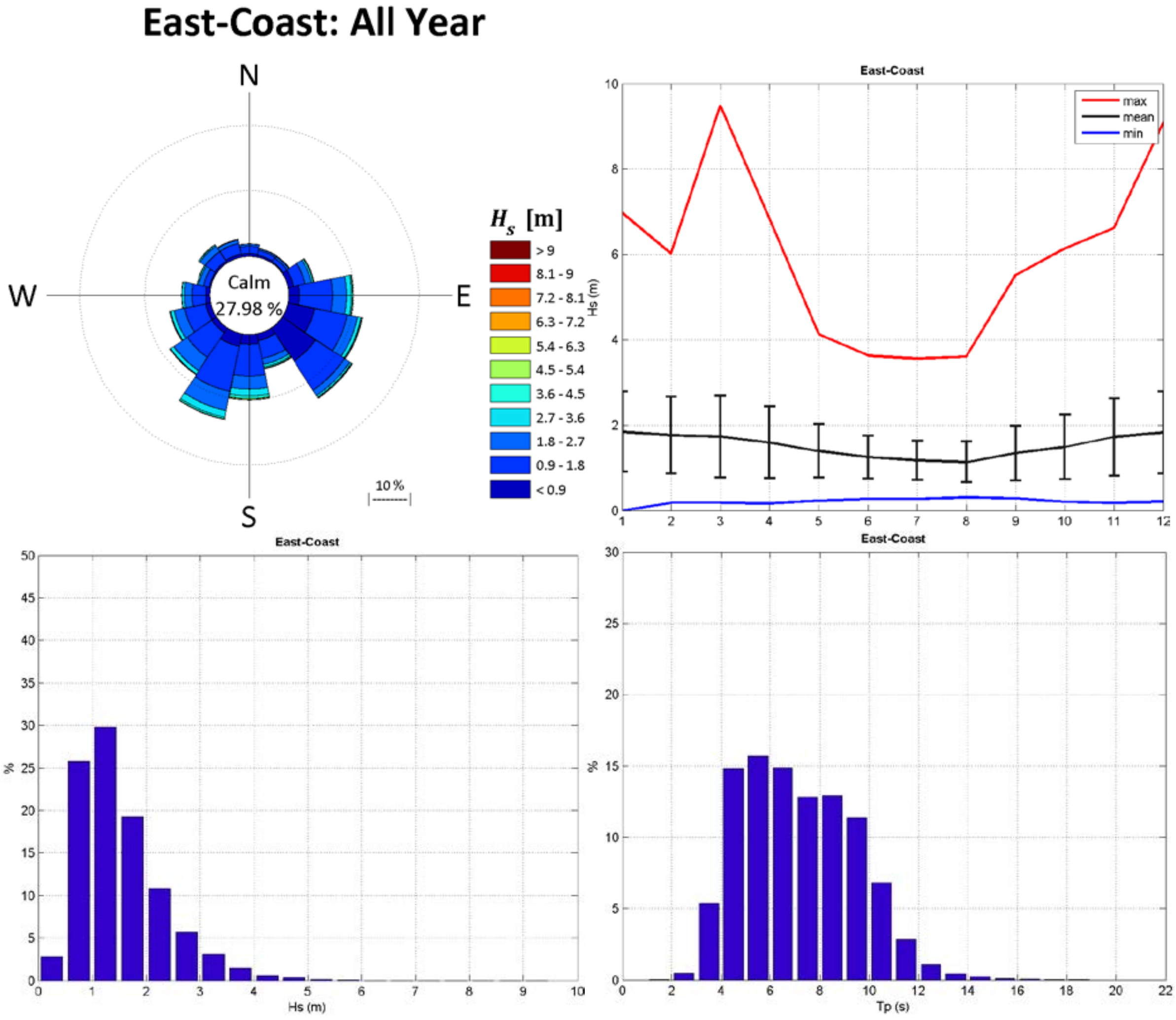


**Figure 5-7 Long-term statistics from NOAA-WaveWatch 3 – Offshore Atlantic**

## 5.3 Current

Oceanic current is the movement of water from one location to another; this movement is generally measured in meters per second or in knots (1 knot = 1.85 kilometers per hour or 1.15 miles per hour). The motion of water has three main components:

- Tidal currents
- Wind driven currents
- Thermohaline circulation.

Within the context of requirements for offshore wind facilities, only tidal and wind driven components typically need to be analysed to derive extreme values and detailed statistics for design and operations. However, depending on the location of interest, influence of certain components may be negligible and it may be appropriate to focus the analysis on a primary component, like tide if the facility is located within a bay or other enclosed area subject to strong tidal currents.

Currents have impact on the environmental actions and effect on the structure, but can also have adverse influence during operations.

## 5.3.1 Components of current

### 5.3.1.1 Tidal currents

Tidal currents result from astronomical forcing and occur in conjunction with the rise and fall of sea level due to tide. In the nearshore locations, the vertical motion of the tides implies an inflow of water, which moves horizontally, creating currents; the water movement toward the land and away from the sea leads to “flood,” and the opposite motion is called “ebb.” Figure 5-8 shows the evolution of tidal currents throughout the tidal cycle.

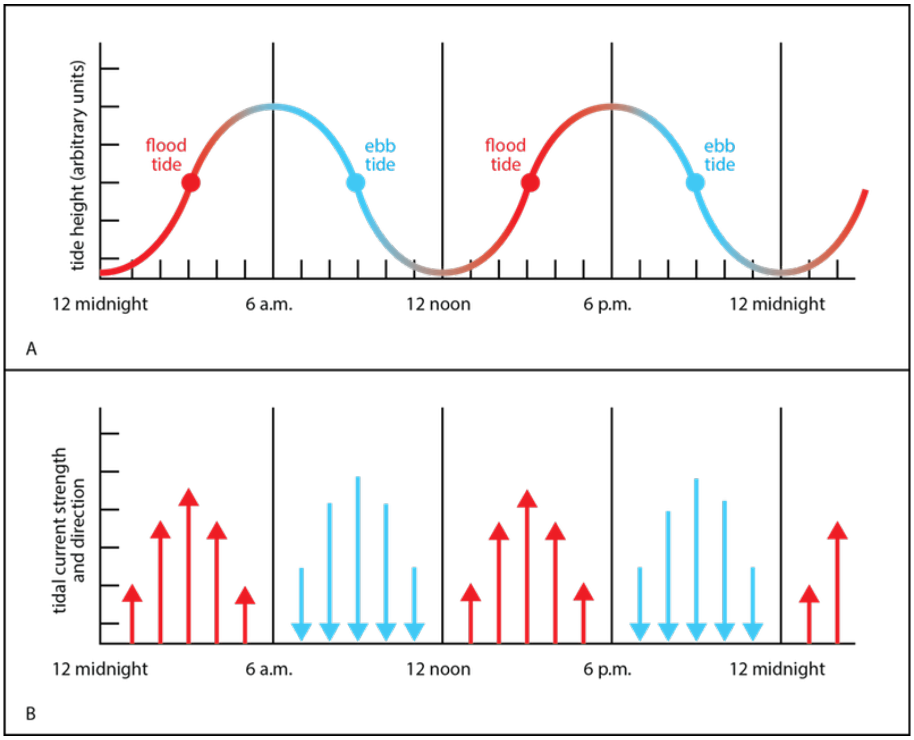


**Figure 5-8 Tidal current evolution as a function of sea level variation**

Where the direction of flow is not restricted by any barriers (rock, bathymetric gradients), the tidal current is rotary; that is, it flows continuously, with the direction changing through all points of the compass during the tidal period.

The intensity of tides and associated currents is influenced by the astronomical phases, the shape of bays or estuaries, and local bathymetry. Funnel-shaped bays in particular can dramatically increase tidal current magnitude.

### 5.3.1.2 Wind driven current

Wind-generated currents are caused by the direct action of the wind shear stress on the surface of the water. The wind-generated currents are normally located in the upper layer of the water body. DNVGL-ST-0437 limits the influence of wind generated currents to the first 50 m, whereas IEC61400-3 limits this influence to the first 20 m. For a conservative approach, 50 m should be used for the depth of influence. The transfer of energy from wind leads to surface current velocity about 2-3% of the wind speed. The extreme wind driven surface current may be derived by applying the 2-3% factor to the extreme wind speed, or by performing hydrodynamic simulations. With a single modelling simulation, considering tide in input and atmospheric forcing, it is possible to split tide and non-tidal current signals, and then analyse them separately, by deriving statistics, distributions and extreme values. The benefit of the simulation is the representation of the interaction between tide and atmospheric forcing in the model.

### 5.3.1.3 Ocean circulation

Depending on the location of interest, the ocean circulation may become significant and need be considered in the analysis of current measurements or when performing hydrodynamic modelling. Indeed, U.S. waters experience several currents that may extend their influence nearshore, like California Current and Alaska Current.

## 5.3.2 Current profile

From an engineering point of view, load induced by current is a main consideration in offshore and coastal design. Understanding of the dependence between current at different depths of the water column is crucial to estimate extreme loads and for fatigue analysis.

The current profile may be simple in a shallow water and tide dominant conditions, uniform along the water column, or more complex with reverse current occurring; this usually occurs in deep waters, where opposite currents may exist at different layers, or in areas with complex bathymetry.

It is recommended to analyze in-situ observations or calibrated model data to define the characteristics of the current profile.

### 5.3.2.1 Theoretical profiles

When no information is available and remaining in an offshore wind farm project context, current profile, or variation of current velocity with depth, is assumed to be the sum of tidal and wind driven current:

$$U(z) = U_{tide}(z) + U_{wind}(z) \quad \textbf{(5-20)}$$

The following formulations are recommended in main standard documents:

$$U_{tide}(z) = U_{tide}o * \left(\frac{z+d}{d}\right)^{\alpha_c} \quad \textbf{(5-21)}$$

where,
$U_{tide}(z)$ is the tidal current velocity at depth z (between -d and 0)
$U_{tide}o$ is the surface tidal current velocity
d is the water depth
$\alpha_c$ is the exponent (typically 1/7)

$$U_{wind}(z) = U_{wind}o * \left(\frac{z+d0}{d0}\right) \quad \textbf{(5-22)}$$

where,
$U_{wind}(z)$ is the wind driven current velocity at depth z (between -d0 and 0)
$U_{wind}0$ is the surface wind driven current velocity
d0 is the water depth

### 5.3.2.2 Empirical orthogonal function method

When local data are available, the current velocity and direction are measured over a relative long period (several months) at several water depths, leading to a large amount of information. Furthermore, large current at one depth may be associated with particular current conditions at other depths; for example, strong currents are often associated with a vertical propagation of the flow.

Statistical techniques can be used to reduce the quantity of data/observations by keeping the information on the amplitude and variability of dataset. The principal components analysis procedure (Jolliffe 2002), also referred to as empirical orthogonal function (EOF, Bjornsson et al 1997, Medoume et al 2008), can be used to convert a set of observations of possibly correlated variables (here current at each depth) into a set of values of linearly uncorrelated variables called principal components or eigen vectors. This transformation is defined in such a way that the first principal component has the largest possible variance (that is, accounts for as much of the variability in the data as possible), and each succeeding component in turn has the highest variance possible under the constraint that it is orthogonal to the preceding components. The resulting vectors are an uncorrelated orthogonal basis set.

Then extreme values analysis of the original profiles can be performed by considering the most informative principal components.

### 5.3.2.3 Clustering analysis

Cluster analysis is a statistical method to group objects based on their characteristics; in a geometrical representation, the objects in a group (cluster) are close together, while the distance between clusters is larger. It differs from the EOF, for which grouping is based on patterns of variation.

The clustering analysis is not a specific algorithm but a general approach; based on distance, methods of cluster may differ with the definition of the used distance (Euclidean, Chebychev); for example, clusters may be based on distance connectivity, or using statistical distribution.

The best-known clustering algorithm is the K-means method: the method defines k centroids, one for each cluster, and associates each object to the nearest centroid. It uses an iterative algorithm that finds the local minimum of the sum of object-to-centroid Euclidean distances, summed over all k clusters.

## 5.4 Water level

The water depth at any offshore location consists of a stationary component and a time-varying component. The variations are due to astronomical tide, wind, and atmospheric pressure. Wind and variations in atmospheric pressure create storm surges, positive or negative. Other variations in water depth can be due to long-term climatic changes or episodic events like tsunamis.

The range of water depths at a particular site is important for the design of structures as it affects several parameters, including:

- Environmental actions on the structure

- Elevations of boat landings, fenders, and cellar deck on bottom-founded structures
- Mooring forces for taut or vertically moored floating structures

The water level consists of a mean water level in conjunction with tidal water and a wind- and pressure-induced storm surge. The tidal range is defined as the range between the HAT and the LAT, see Figure 2-3. The mean sea level (MSL) is defined as the average of HAT and LAT.

Both negative and positive storm surges should be considered in the design, particularly for those minimum support structures, such as monopiles and tripods. The negative storm surge increases the hub height wind speed and thus the aerodynamic loads; but this effect becomes negligible with modern turbine and its hub height exceeding 100 m. A negative storm surge also increases the likelihood of wave breaking, hence slamming. The wave theory employed in the design should reflect the effect of water depth.

The best estimates of the water depth and of the fluctuations in water level (HAT, LAT, extreme surge elevation, and extreme total still water level) are derived from site-specific measurements with an offshore tide gauge measuring pressure from the sea floor. If the tidal signal is dominant, adequate estimates of the tidal range at a given site can be obtained from one month of measured data. However, accurate estimates of “extreme” tides, including HAT and LAT, require at least one complete year of high-quality data from one location.

A method of analyzing water level data requires:

- Conversion of pressure measurements to equivalent depths, using density/temperature/atmospheric pressure corrections
- Harmonic tidal analysis, giving values of all significant tidal constituents and the mean water level
- Prediction of tides over 19 years (to account for the 18.6-year precession of the lunar nodes) and extraction of HAT and LAT
- Subtraction of predicted tides from measured levels, giving time series of storm surge elevations
- Separate statistical analyses of the tidal and storm surge elevations, and combination of the frequency distribution of tidal and surge elevations to give the required probabilities of total still water level.

When tide gauge measurements have not been made and water depth has been determined by local soundings, corrections should be made for the state of the tide by reference to published tide tables, cotidal charts or the nearest available tide gauge.

### 5.4.1 Harmonic analysis – Tide

Tidal variations are the result of the gravitational and rotational interaction between the sun, moon, and earth and are regular and largely predictable; they are bounded by the HAT and the LAT at the site.

The variations in elevation of the daily astronomical tides determine the elevations of boat landings, fenders, splash-zone treatment, and the upper limits of marine growth for bottom-founded structures.

As illustrated in Figure 5-9, tides are classified into three common types:

- A semidiurnal tidal cycle is characterized by two high tides daily of about equal heights occurring about 12 hours and 25 minutes apart. The east coast of the United States usually experiences semidiurnal tides.

- In a mixed tidal cycle, the tides also occur twice daily, but the two high tides and two low tides are unequal in height. Mixed tides occur on the west coast of the continental United States and in Alaska and Hawaii.
- A diurnal tidal cycle is characterized by a single high tide every 24 hours and 50 minutes. Diurnal tides typically occur in partially enclosed basins, such as the Gulf of Mexico.

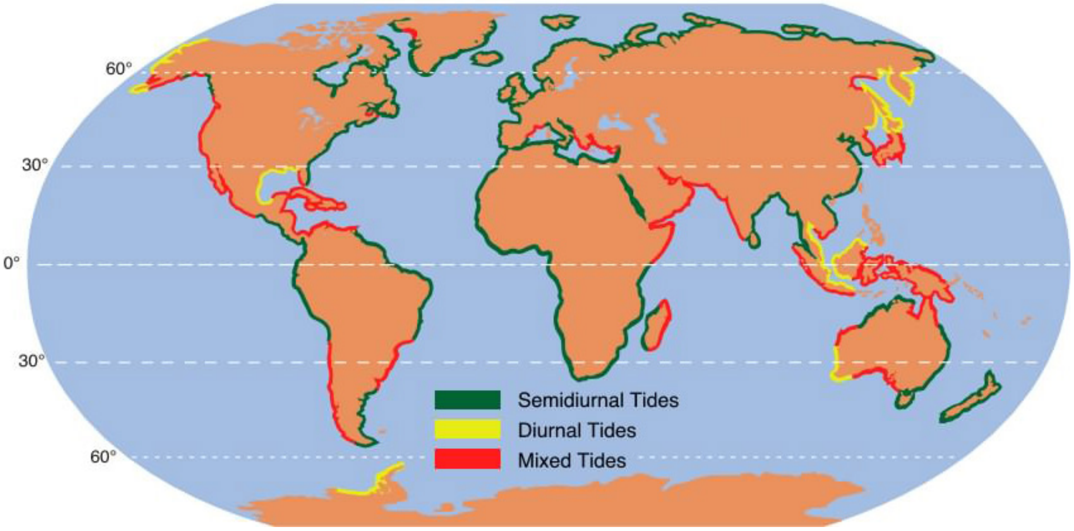


**Figure 5-9 Types of tide per region**

The characteristics of tides can be derived by a harmonic analysis; it is a branch of mathematics concerned with the representation of functions or signals as the superposition of basic waves (Fourier Series). The analysis decomposes any periodic signal as the sum of simple sine waves and describe this system with the amplitude, frequency, and phases of the oscillatory components.

In a study of tide, these characteristics of the tidal signal are unique and associated with the location of interest, because of bathymetry influence. it is necessary to acquire samples of water depth as a function of time at the location of interest at closely enough spaced intervals to see each oscillation and over a long enough duration that multiple oscillatory periods are likely included. Knowing the properties of the main constituents, it is possible to simulate 19-year long time series of sea elevation and derive the tidal levels.

## 5.4.2 Filtering method

The filtering method allows to remove the tidal signal in the sea level (water depth) time series, hence keeping the meteorological induced influence. Filtering methods and associated coefficients are shown in Table 5-4. Several filters exist; all are based on weighted factors at time steps; they differ by the number of time step to consider and value factor. The most known were proposed by Doodson (1921), Munk (1966), Godin (1972), or Demerliac (1974).

$$\tilde{N}(t_0,M) = \sum_{k=-n}^{n} a_k \cdot h(t_0 + k \cdot \Delta) \qquad (5\text{-}23)$$

With $M=2*n+1$, Δ time step, $a_k$ the below coefficients.

**Table 5-4 Filtering methods and associated coefficients**

| k | Average of 25 values $25*a_k$ | Doodson $30*a_k$ | Munk $10^7*a_k$ | Godin $14400*a_k$ | Demerliac $24576*a_k$ |
|---:|---:|---:|---:|---:|---:|
| 0 | 1 | 0 | 395287 | 444 | 768 |
| 1 | 1 | 2 | 386839 | 443 | 766 |
| 2 | 1 | 1 | 370094 | 440 | 762 |
| 3 | 1 | 1 | 354118 | 435 | 752 |
| 4 | 1 | 2 | 338603 | 428 | 738 |
| 5 | 1 | 0 | 325633 | 419 | 726 |
| 6 | 1 | 1 | 314959 | 408 | 704 |
| 7 | 1 | 1 | 300054 | 395 | 678 |
| 8 | 1 | 0 | 278167 | 380 | 658 |
| 9 | 1 | 2 | 251492 | 363 | 624 |
| 10 | 1 | 0 | 234033 | 344 | 586 |
| 11 | 1 | 1 | 219260 | 323 | 558 |
| 12 | 1 | 1 | 208050 | 300 | 512 |
| 13 |  | 0 | 195518 | 276 | 465 |
| 14 |  | 1 | 180727 | 253 | 435 |
| 15 |  | 0 | 165525 | 231 | 392 |
| 16 |  | 0 | 146225 | 210 | 351 |
| 17 |  | 1 | 122665 | 190 | 325 |
| 18 |  | 0 | 101603 | 171 | 288 |
| 19 |  | 1 | 85349 | 153 | 253 |
| 20 |  |  | 72261 | 136 | 231 |
| 21 |  |  | 60772 | 120 | 200 |
| 22 |  |  | 47028 | 105 | 171 |
| 23 |  |  | 30073 | 91 | 153 |
| 24 |  |  | 13307 | 78 | 128 |
| 25 |  |  |  | 66 | 105 |
| 26 |  |  |  | 55 | 91 |
| 27 |  |  |  | 45 | 72 |
| 28 |  |  |  | 36 | 55 |
| 29 |  |  |  | 28 | 45 |
| 30 |  |  |  | 21 | 32 |
| 31 |  |  |  | 15 | 21 |
| 32 |  |  |  | 10 | 15 |
| 33 |  |  |  | 6 | 8 |

| **k** | **Average of 25 values 25*a$_k$** | **Doodson 30*a$_k$** | **Munk 10^7*a$_k$** | **Godin 14400*a$_k$** | **Demerliac 24576*a$_k$** |
|---|---|---|---|---|---|
| 34 | | | | 3 | 3 |
| 35 | | | | 1 | 1 |

### 5.4.3 Surge

A storm surge is an abnormally high sea level produced by severe atmospheric conditions, lasting for a period ranging from a few minutes to a few days. Storm surges are particularly associated with deep atmospheric low pressure systems (either Tropical Cyclones, TC, or Extra-Tropical Cyclones, ETC), which have associated high winds which drive water onto the shore. However smaller-scale storms can also induce storm surges.

## 5.5 Joint conditions

Offshore turbines may be placed in areas with low correlation between wind, waves, and current, for example:

a) When exposed to wind and waves from various directions (for example, when the wind is mainly coming from land and waves are coming from offshore)

b) In areas where the prevailing current direction is different from the wave direction (for example, areas dominated by a strong long-shore current where the waves are coming from offshore)

Offshore wind turbines shall be designed for the combined ULS (Ultimate Limit State, defined for various recurrence periods) loads from waves, current, and wind. It is thus allowed to include, if documented, the joint probabilities between parameters so that combined ULS loads, (including possible dynamic effect), will have the required return period (see Section 5.6.2 for extreme joint correlations).

For the FLS (Fatigue Limit State) design it is important that input for load simulations reflects the actual structure and site conditions.

### 5.5.1 Wind and wave correlation and misalignment

For FLS design load calculations the joint probability can be determined from long time hindcast simulations and/or long-term measurements of at least the wind speed, wind direction, wave height, wave period, and wave direction. As the number of independent variables is high (at least five) it is not possible to make a general procedure on how this should be done.

However, often the site-specific wind and wave climate can be described by only three free parameters (wind speed, wind direction, and wave direction), and by considering the wave height and wave period dependent on the three free parameters:

- By taking wave height as a function of the wind speed and wind direction
- By taking the wave period be as function of the wave height and the wave direction

- By a 12x12 wind – wave directions 30 degrees scatter diagram: For each 30 degrees wind-direction, a scatter diagram of wave height as function of wind speed for each of the 12 30-degree wave-directions are made, resulting in 12x12 scatter diagrams

When setting up the actual input (the wind speed, the wind direction, the wave height, the wave period, the wave direction, etc.) for load simulations, not only the site conditions but also the dynamic response of the substructure and turbine shall be considered. As an example, for dynamic sensitive low damped monopiles or floating structures, sea-states with peak wave periods close to the natural period introduce larger loads than sea-states with long period swell waves. For such cases, the loads will be underestimated if the wave period is taken as a simple mean.

## 5.6 Extreme conditions

Extreme conditions are rare events generating peak values of single Metocean parameter conditions (extreme wave) or joint conditions (extreme wind and associated wave) that shall be considered in any design of an offshore structure. For design purposes, the conditions shall be derived per directional sectors, as a minimum. It is recommended to estimate them on a monthly basis to assess the seasonal variability.

### 5.6.1 Extreme value analysis

Statistical extreme value theory is a field of statistics dealing with extreme values, i.e., large deviations from the median of probability distributions. Even using long period databases, the design of structures requires return periods exceeding the period covered by the modelled data, which leads to extrapolation methods by using theoretical distributions. The theory assesses the type of theses extreme distributions.

Two main approaches exist for practical extreme value applications. The first method relies on deriving block maxima or minima series, the second method relies on extracting peak values above or below a certain threshold from a continuous record. A third approach the so-called r-largest order statistics represents a compromise between the block maxima and peak over threshold approach.

#### 5.6.1.1 Block maxima

If the database is sufficiently long, the block maxima methodology uses sample of annual maxima (in that case, the maxima is estimating on one year period); the empirical distribution of the annual maximum can be obtained directly from the time series. Generally, it is better to consider a smaller block size (e.g., a month) that remains sufficiently large to respect independence between maximum values in metocean parameters.

After the estimation of the empirical distribution, it is necessary to fit an extreme distribution to the empirical in order to extrapolate to very high levels (or return periods) and to estimate the associated extreme values. The statistical theory of extremes says that the maximum of n independent identically distributed random variables, as n is high, is a random variable with a distribution of only three types which have a unified under the GEV (Generalized Extreme Value Distribution) formulation.

$$G(y) = exp\left(-\left[1+\xi\left(\frac{y-\mu}{\sigma}\right)\right]^{-1/\xi}\right)\ if\ \xi \neq 0$$
$$G(y) = exp\left(-exp\left(-\frac{y-\mu}{\sigma}\right)\right)\ if\ \xi = 0 \qquad \textbf{(5-24)}$$

μ is the location parameter

σ is the scale parameter

ξ is the shape parameter

GEV has three types, depending on the shape parameter:

- If ξ=0, the type is a Gumbel distribution
- If ξ>0, the type is a Frechet distribution
- If ξ<0, the type is a Weibull distribution

### 5.6.1.2 Peak over threshold

The Peak Over Threshold (POT) method involves extracting samples from the time series which are sufficiently separated in time to be considered as independent storm maxima. In contrast to block maxima methods these are not the maximum values over a particular period (i.e., the monthly or annual maxima). Instead the samples are chosen based on their exceedance of a set threshold. An asymptotic result of the theory of extremes states the conditional distribution of a random variable, for high threshold, tends only to three types, unified in the GP (Generalized Pareto) distribution.

$$G(y) = 1 - \left[1 + \xi\left(\frac{y-u}{\sigma}\right)\right]^{-\frac{1}{\xi}} ;with\ \sigma > 0, y > u\ and\ 1 + \xi\left(\frac{y-u}{\sigma}\right) > 0 \qquad \textbf{(5-25)}$$

The shape parameter leads again the type of distribution:

- If ξ=0, the type is a Exponential distribution
- If ξ>0, the type is a Pareto distribution
- If ξ<0, the type is a Beta distribution

It is clear there are here two difficulties. First, a good construction of the storm sample (techniques of optimized declustering), secondly the good choice of the threshold *u* which shall be high enough, but not too high to permit a good fit of the GP distribution.

The selection of this threshold is, however, not trivial and is potentially difficult for the non-expert to apply effectively. There are two possibilities for that:

- Find a stability zone in the plot of the mean residual life (mean of *X-u* for *X>u* and *u* varying from 0 to max of *X*)
- Find a stability zone in plots of parameters of fitted GPD for increasing thresholds.

### 5.6.1.3 r-largest order extreme

Instead of considering only the maximum in a block, the r largest observations are used to estimate the empirical distribution. If independence between observations is verified, the distribution is associated with the GEV formulation.

### 5.6.1.4 Fit method

When the formulation is identified, the parameters of the extreme distribution shall be estimated to allow the calculation of the extreme values. The parameters are estimated to get the best representation of the empirical distribution. This is obtained by maximum likelihood estimation, method of moments, or simply the minimization of root mean square error.

#### 5.6.1.5 Uncertainty with bootstrap

The bootstrap, a technique for determining the accuracy of statistics has become increasingly popular since the early 1990s in many areas of environmental sciences. It relies on computer simulations and ranks among resampling techniques that can provide estimates of uncertainty of distribution parameters and quantiles in the frequency analysis in circumstances in which confidence intervals (CIs) cannot be obtained or are difficult to obtain analytically.

There are two main methods used in bootstrap technique:

- Nonparametric bootstrap method: Resampling with replacement from the given sample (time series, maxima on block size or peak values) and calculating the required statistic (extreme values) from many repeated samples.
- Parametric bootstrap method: Randomly generated samples from the distribution fitted to the data.

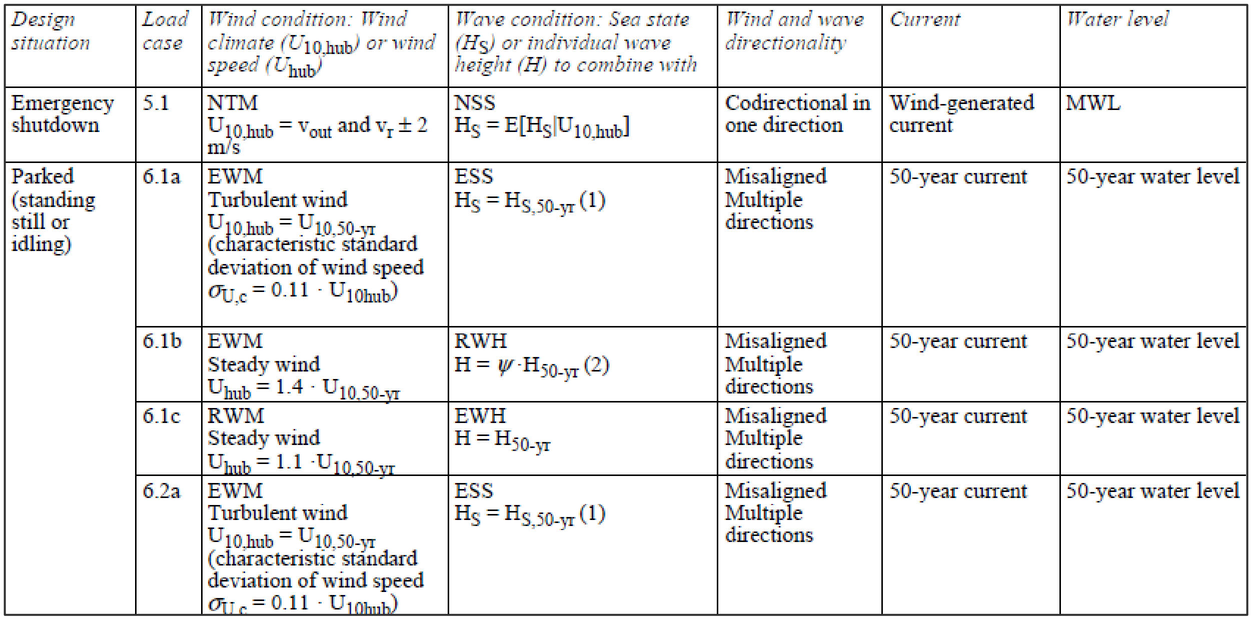
The second version of the bootstrap is preferred if a suitable model for the examined sample is known and if the data samples are relatively short and the tail behavior is particularly important (Davison and Hinkley, 1997).

### 5.6.2 Extreme joint conditions

The examination of multivariate extreme statistics is more complex. If, for example, waves, wind, and current intervene simultaneously in extreme loadings, the definition of a centennial condition is not possible, only a condition which induces a centennial response has a meaning.

The crudest approach is to associate 100-year wave, wind, and current return values. Of course, this is generally over-conservative as the different phenomena are not strongly correlated. The simplest way to deal with this is to associate different return values to define the n-year conditions, e.g., 100-year Hs associated with 20-year Wind speed associated with 10-year Current speed. The choice of the set of return periods is based on experience and is depending of the design criteria.

**Table 5-5 Examples of joint conditions for several design load cases (from DNV OS-J101)**



| *Design situation* | *Load case* | *Wind condition: Wind climate ($U_{10,hub}$) or wind speed ($U_{hub}$)* | *Wave condition: Sea state ($H_S$) or individual wave height (H) to combine with* | *Wind and wave directionality* | *Current* | *Water level* |
|---|---|---|---|---|---|---|
| Emergency shutdown | 5.1 | NTM<br>$U_{10,hub} = v_{out}$ and $v_r \pm 2$ m/s | NSS<br>$H_S = E[H_S \mid U_{10,hub}]$ | Codirectional in one direction | Wind-generated current | MWL |
| Parked (standing still or idling) | 6.1a | EWM<br>Turbulent wind<br>$U_{10,hub} = U_{10,50\text{-}yr}$<br>(characteristic standard deviation of wind speed $\sigma_{U,c} = 0.11 \cdot U_{10hub}$) | ESS<br>$H_S = H_{S,50\text{-}yr}$ (1) | Misaligned<br>Multiple directions | 50-year current | 50-year water level |
| | 6.1b | EWM<br>Steady wind<br>$U_{hub} = 1.4 \cdot U_{10,50\text{-}yr}$ | RWH<br>$H = \psi \cdot H_{50\text{-}yr}$ (2) | Misaligned<br>Multiple directions | 50-year current | 50-year water level |
| | 6.1c | RWM<br>Steady wind<br>$U_{hub} = 1.1 \cdot U_{10,50\text{-}yr}$ | EWH<br>$H = H_{50\text{-}yr}$ | Misaligned<br>Multiple directions | 50-year current | 50-year water level |
| | 6.2a | EWM<br>Turbulent wind<br>$U_{10,hub} = U_{10,50\text{-}yr}$<br>(characteristic standard deviation of wind speed $\sigma_{U,c} = 0.11 \cdot U_{10hub}$) | ESS<br>$H_S = H_{S,50\text{-}yr}$ (1) | Misaligned<br>Multiple directions | 50-year current | 50-year water level |

### 5.6.2.1 Associated extreme values

A simple way to estimate associated extreme values is to derive regression from scatter table. It is assumed that the extreme conditions follow the same trend existing between parameters, at least for the highest values of the main parameter. For example, in Figure 5-10, the correlation between wind speed and significant wave height is very weak, by considering the entire dataset; however, it increases by considering wind speed above 10 m/s. Figure 5-11 introduces a case with high dependency between both parameters.

In general, dependency between wind speed (also peak period) and significant wave height is large, when the wave climate is dominated by wind sea; it occurs mainly in closed or semi-closed basins. In other locations, the total sea may be a mix of swell and wind-sea leading to the loss of the dependency; it may be interesting to analyze each sea state components instead of the total sea.

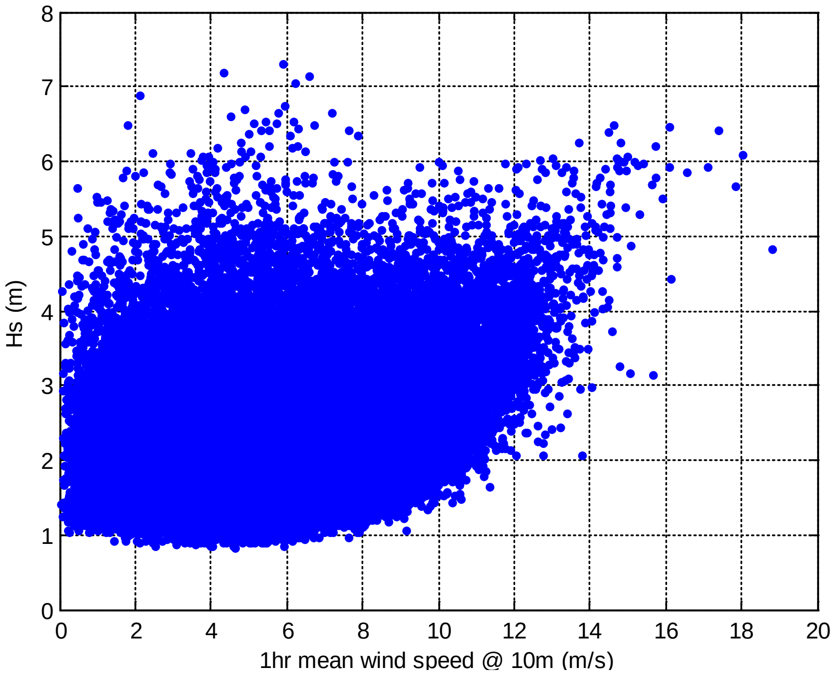


**Figure 5-10 Example of wind speed - Hs scatter table with weak correlation**

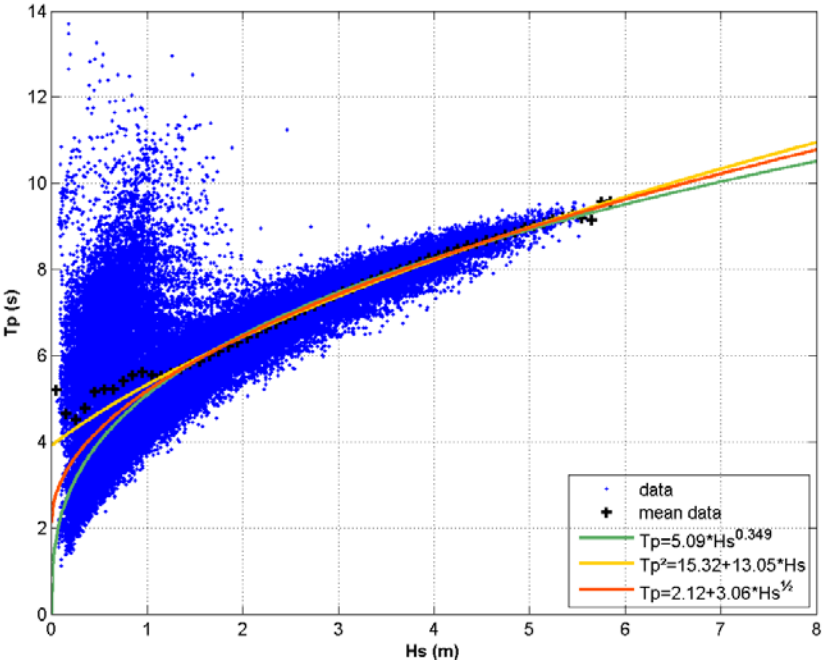


**Figure 5-11 Example of Hs-Tp scatter table and regression formulations allowing to derive the associated peak period to the extreme values of Hs**

### 5.6.2.2 Contours IFORM

To provide an advanced statistical and metocean answer to the issue of multi-parameter extremes, a suggested approach is to apply the Inverse-First Order Reliability Method (I-FORM). The method transforms the multivariate distribution of environmental parameters (e.g., Hm0, Tp, Wind speed) from the physical space to the standard Gaussian space, thus allowing by inverse transform to calculate a n-year contour in the physical space along which the n-year response will occur (in fact the maximum response on the contour).

In practical terms, any point of a n-year I-FORM contour is likely to induce a system response with a probability of exceedance of once every n years. It is important to note that the knowledge of the structure itself is not needed to build a contour valid for any type of system response.

The main advantage of the method is to deduce the extreme environmental contours between variables which are dependent (Figure 5-12) or independent.

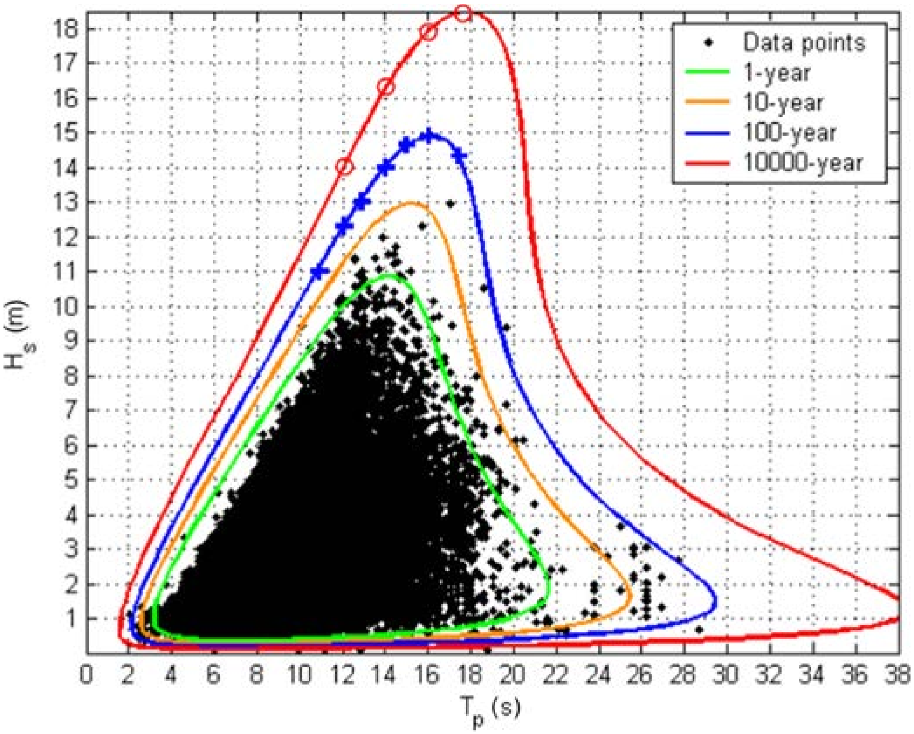


**Figure 5-12 Example of extreme contours Hs-Tp for several return periods**

## 5.7 Tropical cyclone conditions

This section presents methods to define the data set on which extreme value analysis should be applied to estimate extreme wind speed under tropical cyclone conditions: by directly using parametric profile formulations or by previously anticipating the variability in track with grid pooling, track shifting, or synthetic storm methods.

### 5.7.1 Parametric wind formulations

Even if tropical cyclones are large spatial storm, the radius of maximum wind speed is limited. Consequently, when extreme values in cyclone conditions are estimated for a location, all events occurring in a basin are not used. It is usual to analyze storms passing in the 3-5 degree radius around the location of interest.

The wind speed values are estimated locally at each time step from the track information for each cyclone using parametric model. The maximum of each tropical cyclone is kept, which ensures the independency of the observations to estimate the empirical distribution. Then an extreme value analysis is performed by fitting the distribution with model laws. It may be necessary to apply Peaks over Threshold (POT) technique with varying thresholds to identify the cyclones which impact the location of interest. The extreme values can be calculated in terms of the numbers of storms per year, which can be converted to return period in years, by using the average occurrence of (analyzed) storms per year.

This type of extreme value analysis described above is based on historical tracks for a limited number of events. It may be difficult to estimate extreme values for this kind of meteorological phenomenon using this analysis, especially when considering a region with few tropical cyclone occurrences. In addition, it is not reasonable to expect that extreme tropical cyclones in the next few centuries will have the same tracks as historical tropical cyclones. The track variability has to be considered and forms the basis of spatial smoothing techniques which were developed. Commonly used methods include simple spatial smoothing of site specific estimates, track shifting, and grid point pooling.

### 5.7.2 Grid point pooling

Grid point pooling methodology is used to estimate cyclone conditions by taking into account track variability; indeed, if one tropical cyclone affects a specific location, a future tropical cyclone with similar severity may affect a neighboring location. Based on this assumption, the extreme condition can be anticipated and estimated by considering the past track.

Two main conditions shall be fulfilled to apply correctly (from a statistical point of view) the methodology:

- The sites which are selected in the pool shall be part of a homogeneous region, in terms of water depth, fetch limitation, and orientation of major storm track.
- The sites shall also be spaced far enough (75 km) to reduce statistical dependency.

In deep water, it is usual to consider a “five-points cross” centered on the site (one point at the position of interest, one point taken northward, one point southward, one point chosen eastward, and one point westward) to get the influence of southern-northern and eastern-western tracking cyclones near the location of interest. It is possible to select more points but with a distance less than 300 km.

### 5.7.3 Track shifting

The methodology has the same aim as grid pooling, to assess the variability of tropical cyclone tracks to better estimate severe conditions. However, instead of the variability with several sites for a single track of one cyclone, it considers variability within one site for several tracks of one cyclone.

The characteristics of the cyclone remain the same, except for the longitude and the latitude; it leads, however, to a different wind speed (locally) because of the change in distance with the eye and the change in Coriolis parameter which influences the wind field.

Consequently, the change in wind field leads also to change in wave fields.

### 5.7.4 Synthetic storms

As with both previous methodologies, the idea is to compensate for the shortness of the data series. For example, Vickery et al. (2000) used statistical properties of historical tracks and intensities to generate a large number (thousand) of synthetic storms (Monte Carlo simulation) in the North Atlantic basin Figure 5-13. Six-hour changes in direction, translation speed, and intensity along each track were modeled as linear functions of previous values of those quantities as well as position and sea surface temperature.

The main limitation of the approach is the assumption that the intensity evolution is independent of the particular track taken by the storm.

A similar approach in the track generation technique was described by Emanuel (2006); this approach differs, however, from statistical models that only consider observed tropical cyclone properties, by also using modelling (axisymmetric balance model coupled to an equally simple one-dimensional ocean model), and consequently, understanding of the involved physical mechanisms to better estimate the intensity. The synthetic track generation remains based on Monte Carlo methods using Markov chain (probability of a variable at a time step is dependent of the value at the previous time step).

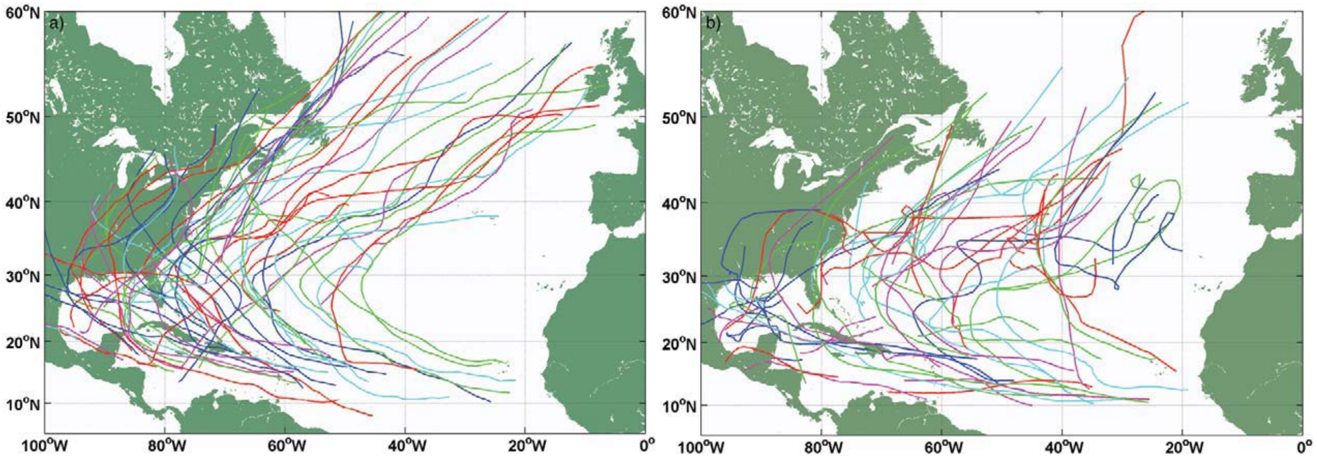


**Figure 5-13 Historical tracks (left) and synthetic tracks (right) on a similar period**

This methodology was also used in the TAP 672 in order to estimate extreme wind speed and significant wave height under cyclone conditions, for the U.S. Atlantic coast.

### 5.7.5 Summary

The section summarizes the advantages of the different techniques used to estimate reliable extreme values in cyclone conditions; it should be noted that a parametric wind model may be used directly or be part of the track shifting or grid pooling methods. In the same way, results of mesoscale modelling can be directly used at the location of interest or by applying the grid pooling approach to consider the variability in tropical cyclone tracks. The methodologies, which were described in the previous paragraphs, are recommended for design phase; for a first assessment of metocean conditions, Technology Assessment and Research Project 672 for Atlantic coast and API BULLETIN 2INT-MET for Gulf of Mexico provide information for main parameters: wind, wave, current, and water level.

The reliability of the extreme conditions is related to the quality of representation of tropical cyclone wind fields and the number of events available to estimate long return periods.

The assessment of sea states requires wave modelling, a fetch limitation approach being not appropriate to represent correctly local topographic and bathymetric influences.

Because of the low number of severe tropical cyclones, the variability of track storm is a main issue; grid pooling allows to consider neighboring sites which may have experienced more severe conditions than the location of interest. The application of the method is simple, by using output of wave/wind modelling; there are, however, precautions to take in order to select grid points.

The track shifting is another approach to consider the variability of track, by artificially shifting past tracks and so generating new tracks. It leads to locally major change in wind fields (especially maximum wind location) and consequently, a new wave simulation has to be performed for each new track. A conservative approach consists in keeping the artificial track which lead to the most severe conditions for each analyzed cyclone.

Finally, the synthetic storm method, based on Monte Carlo simulations, allows to dramatically increase the number of tropical cyclones, up to 1,000 or more. It is not feasible to perform wave modelling for each synthetic tropical cyclone; it may be possible to only simulate wave conditions for a reduced set of storms, chosen in function of the proximity to the location of interest or in function of the local wind generated by the cyclones.

## 5.8 Downtime analysis – waiting on weather

This type of analysis is used to estimate the workability in the location of interest for operations. The equipment used during operations will define the operability limitations. These boundaries mainly consist of thresholds for significant wave height and/or wind speed, but other parameters may be relevant as well, depending on the operation. It is also possible to refine them with peak period if necessary.

### 5.8.1 Frequency of conditions

As an initial assessment, the frequency of certain conditions may be analyzed, typically presented as the percentage of time during which a parameter (i.e., the significant wave height) is higher or lower than thresholds (as shown in Table 5-6); note that this percentage includes all occurrences. This approach provides a general view of the magnitude of the assessed conditions.

**Table 5-6 percentage of time with Hs lower than thresholds (example)**

| % | Hs<1.00 | Hs<1.25 | Hs<1.50 | Hs<1.75 | Hs<2.00 |
|---|---|---|---|---|---|

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Jan | 45.1 | 83.9 | 97.4 | 99.3 | 100.0 |
| Feb | 36.7 | 83.4 | 96.2 | 98.9 | 100.0 |
| Mar | 19.1 | 61.1 | 90.2 | 97.9 | 99.6 |
| Apr | 6.4 | 40.9 | 73.2 | 89.0 | 95.8 |
| May | 4.5 | 26.1 | 57.9 | 80.1 | 90.8 |
| Jun | 6.0 | 24.7 | 52.5 | 78.0 | 90.6 |
| Jul | 8.4 | 29.0 | 54.2 | 73.0 | 84.3 |
| Aug | 5.8 | 23.0 | 49.6 | 68.9 | 82.3 |
| Sep | 13.5 | 40.2 | 67.1 | 82.1 | 91.8 |
| Oct | 17.1 | 56.2 | 79.0 | 91.1 | 97.3 |
| Nov | 22.7 | 63.6 | 84.0 | 93.2 | 98.1 |
| Dec | 36.5 | 81.0 | 95.2 | 99.1 | 99.8 |

### 5.8.2 Probability of weather windows

The previous section highlights the percentage of time during which the conditions are fulfilled; however, there is no information on the duration of the favorable periods or “events” which fulfill the limits.

Operations can last several hours and the estimation of probability to encounter a favorable period lasting at least *D*-hours (where *D* is the desired duration of the favourable period or window) may be crucial for operators (See Table 5-7). This probability can be given per month to assess the seasonality in function of the limitations. In this example, the probability to experience 48 hours with favorable conditions is about 22% in November and 71% in April.

**Table 5-7 Probability to experience favorable conditions for windows of at least *D*-hours (example)**

| **Duration (hrs)** | **6** | **9** | **12** | **24** | **48** |
|---|---|---|---|---|---|
| Jan | 63.7 | 59.7 | 56.5 | 45.6 | 29.8 |
| Feb | 67.9 | 62.5 | 59.8 | 53.9 | 35.7 |
| Mar | 74.2 | 70.2 | 66.1 | 52.8 | 40.7 |
| Apr | 86.7 | 85.0 | 83.8 | 78.8 | 71.3 |
| May | 83.9 | 81.7 | 79.6 | 71.6 | 57.1 |
| Jun | 90.2 | 88.8 | 87.1 | 82.5 | 74.2 |
| Jul | 88.9 | 87.3 | 85.7 | 79.2 | 69.0 |
| Aug | 85.1 | 82.9 | 80.8 | 72.4 | 56.5 |

| **Duration (hrs)** | **6** | **9** | **12** | **24** | **48** |
|---|---|---|---|---|---|
| Sep | 69.2 | 65.8 | 63.8 | 58.8 | 50.4 |
| Oct | 62.5 | 58.5 | 54.0 | 40.7 | 25.8 |
| Nov | 49.2 | 45.8 | 42.9 | 32.9 | 21.7 |
| Dec | 56.0 | 50.8 | 48.8 | 42.3 | 29.0 |

### 5.8.3 Event statistics

This section deals with the methodology to get more details on the characteristics of the favorable (or unfavorable) events (or occurrences). It consists in identifying in the time series of parameters the time steps fulfilling the conditions; then it is possible to derive main characteristics, for example:

- Monthly mean duration with fulfilled operability conditions (sum of all occurrences during the month divided by the number of years)
- Mean number of occurrence per month and per year
- Duration statistics: minimum, maximum and quantiles (10%, 30%, 50%, 70% and 90%) duration of the occurrences.

## 5.9 Reporting requirements

Test reports shall be prepared by accredited testing laboratories and meet the requirements of ISO 17025 and relevant standards for the specific testing.

A Metocean Study report containing the results of metocean data analysis and interpretation should as a minimum include:

- Description of the data used, clearly identifying the sources (whether from in-situ measurements, numerical modelling, satellite, etc.), the data provider, the quality control and checks undertaken.
- A qualitative and quantitative assessment of the datasets including as a minimum length, resolution in time and space, data gaps, quality flags, and overall confidence in the data.
- When multiple datasets are used to arrive at design criteria, results should clearly state which dataset has been used for which analysis, and any adjustments/uplift/calibration being made.
- Details of analysis methods, clearly stating any assumptions made and any shortcomings of the methods used which may affect the accuracy of the results.
- Where statistical fits and extrapolations to extreme return periods are undertaken, results should clearly state details of the distributions used and goodness of fit parameters (or equivalent assessment of quality of data fit).
- Metocean design criteria being reported should clearly include their units of measure, averaging intervals, height or depth of reported value, and the relevant season or direction as applicable. An overall statement on the suitability and applicability of the reported metocean values (post-analysis) for application to a wind facility project, including any refinements that may need to be made in the future to increase confidence.

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