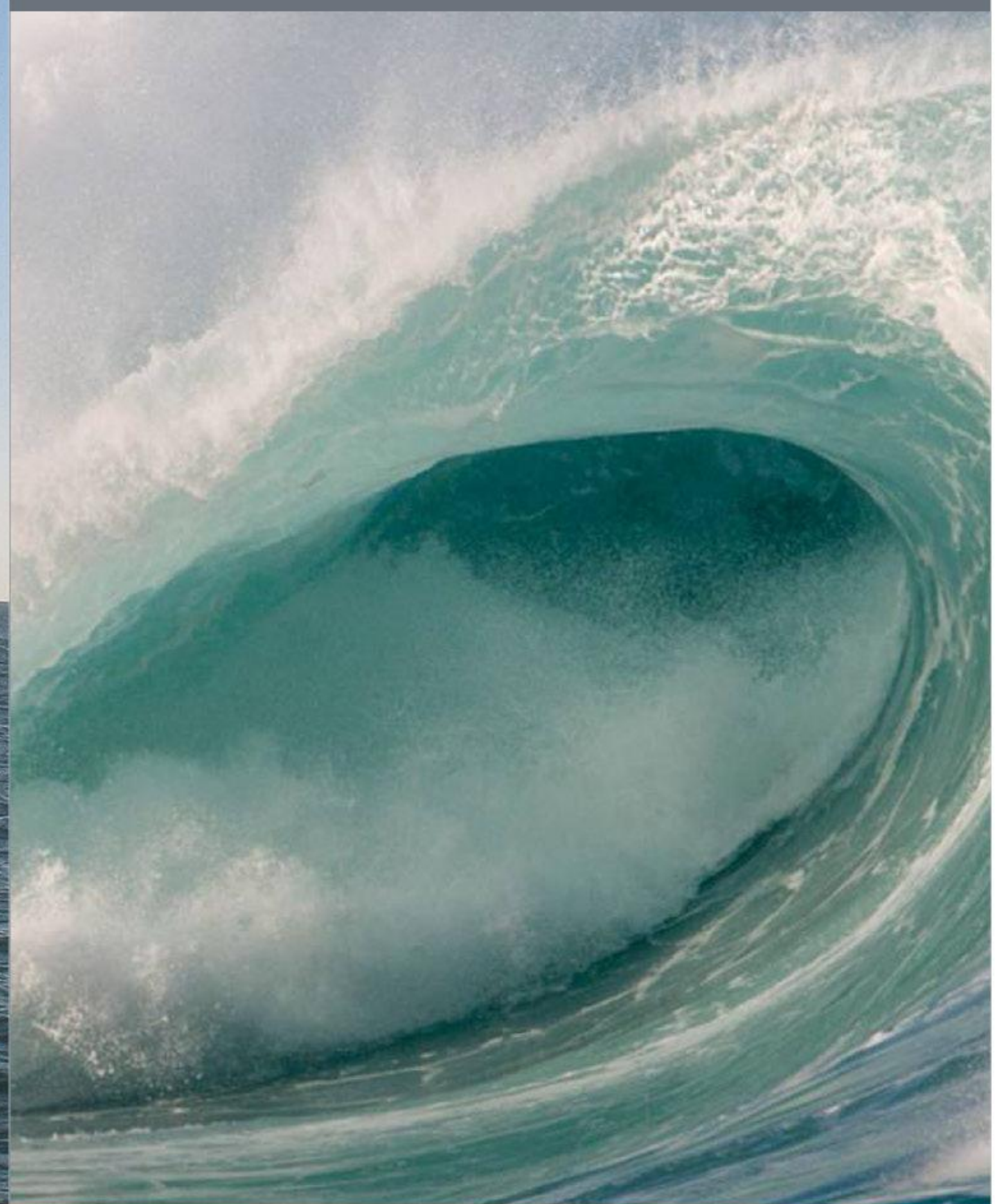
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

WIND AND WATER POWER PROGRAM

Offshore Resource Assessment and Design Conditions:

A Data Requirements and Gaps Analysis for Offshore Renewable Energy Systems

March 2012



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A Data Requirements and Gaps Analysis for Offshore Renewable Energy Systems

March 2012

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ENERGETICS

A Subsidiary of VSE Corporation

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ABOUT THIS DOCUMENT

This document is an aggregation of research, comments received at public information-gathering sessions, and contributions from experts. The most recent design standards were used to identify an initial set of information needed to appropriately design an offshore wind turbine. Additionally, the *Offshore Resource Assessment and Design Conditions Public Meeting* was held in June 2011 to gather input from industry, academia, and other government agencies regarding where information is currently lacking for offshore wind and marine and hydrokinetic (MHK) deployment. Finally, a team of experts across various sectors provided substantial input to help create this document and are acknowledged as contributing authors. The document has also been further supplemented with responses to DE-FOA-EE0000384 "DOE Offshore Wind Program – Input Requested for Demonstration Projects," a request for information posted by the U.S. Department of Energy (DOE) in June 2010.

The dual purposes of this document are (1) to provide an initial overview of the information required by a range of stakeholders to effectively deploy MHK and wind energy systems offshore and (2) to identify gaps in that required information. The data requirements and gaps are presented in the context of five broad application areas associated with development and operation of offshore renewable energy systems. This document is intended to inform the development of priorities and strategies for acquiring information to support the development of offshore renewable energy.

With the exception of the Introduction and summary chapters, the majority of this document is divided into sections based on specific applications of the information and data. The intent is to allow those interested in a particular application to quickly find that information without having to digest the content comprehensively. As such, if read in its entirety, this document contains many of the same themes and information gaps throughout. The overall gaps are summarized in the Gaps Summary section.

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LIST OF ACRONYMS

ACARS	Aircraft Communications Addressing and Reporting System
ADCP	Acoustic Doppler current profilers
API	American Petroleum Institute
AMOL	Atlantic Oceanographic and Meteorological laboratories
AWEA	American Wind Energy Association
CDIP	Coastal Data Information Program
CODAR	Coastal Ocean Dynamics Applications Radar (or Coastal RADAR)
DOE	U.S. Department of Energy
DODS	Distributed Oceanographic Data Systems (server)
EFDC	Environmental Fluid Dynamics Code
EPRI	Electric Power Research Institute
GFS	Global Forecast System
GPS	Global Positioning System
IEC	International Electrotechnical Commission
LIDAR	Light Detection and Ranging
MCP	Measure-Correlate-Predict
MHK	Marine and hydrokinetic
NAM	North American Mesoscale model
NCEP	National Centers for Environmental Prediction
NDBC	National Data Buoy Center
NESDIS	National Environmental Satellite Data and Information Service
NGDC	National Geophysical Data Center
NMREC	National Marine Renewable Energy Center
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanographic Data Center
NOMADS	NOAA Operational Model Archive Distribution System
NRL	Naval Research Laboratory
NWP	Numerical Weather Prediction
OCS	Outer Continental Shelf
POES	Polar Operational Environmental Satellite
RUC	Rapid Update Cycle
SAR	Synthetic-Aperture Radar

SCADA	Supervisory Control and Data Acquisition
SODAR	Sonic Detection and Ranging
SSM/I	Special Sensor Microwave/Imager
SST	Sea Surface Temperature
SWAN	Simulating WAves Nearshore
WMO-IOC-OSMC	World Meteorological Organization—Intergovernmental Oceanographic Commission Observing System Monitoring Center
WSR-88D	Weather Surveillance Radar, 1988, Doppler

INTRODUCTION

The offshore renewable energy industry requires accurate meteorological and oceanographic ("metocean") data for evaluating the energy potential, economic viability, and engineering requirements of offshore renewable energy projects. It is generally recognized that currently available metocean data, instrumentation, and models are not adequate to meet all of the stakeholder needs on a national scale. Conducting wind and wave resource assessments and establishing load design conditions requires both interagency collaboration as well as valuable input from experts in industry and academia. Under the Department of Energy and Department of Interior Memorandum of Understanding, the Resource Assessment and Design Condition initiative supports collaborative national efforts by adding to core atmospheric and marine science knowledge relevant to offshore energy development. Such efforts include a more thorough understanding and data collection of key metocean phenomena such as wind velocity and shear; low-level jets; ocean, tidal, and current velocities; wave characteristics; geotechnical data relating to surface and subsurface characteristics; seasonal and diurnal variations; and the interaction among these conditions. Figure 1 presents a graphical representation of some metocean phenomena that can impact offshore energy systems.

This document outlines the metocean observations currently available; those that are not available; and those that require additional temporal-spatial coverage, resolution, or processing for offshore energy in an effort to gather agreed-upon, needed observations.

A "**data requirement**" or "**information requirement**" is information that is essential for successful deployment of offshore wind and marine and hydrokinetic (MHK) plants. Data requirements can be defined either by established standards or known engineer needs. Data and information requirements include information gleaned from observations as well as estimated and modeled output.

A "**data gap**" or "**information gap**" as described in this document is data that is not currently available and will not become available as part of wind or MHK plant installation and operation. "Information gap" includes the missing ability to model or estimate what is needed. "Data gap" refers to a measurement that is currently missing.

Offshore Metocean Observations

Given the scarcity of measurement data in offshore regions (especially at wind turbine hub heights of 80+ m), model data are important for providing a preliminary analysis of the offshore wind resource distribution and estimates of power production. Furthermore, the model data can facilitate identification of candidate areas for measurements and more comprehensive assessments. It should be recognized that model errors may be greater in areas where strong gradients in the wind resource are evident or suspected.

The highest-quality and most useful in situ measurements for offshore wind energy projections are from heights of approximately 50 m or higher, using a tall tower or mast on a large platform. However, these data are sparse, because these types of measurement systems are expensive to install offshore. In some places, tall towers have been installed on coastal points or small islands that may provide reasonable data for estimating the wind resource characteristics in a nearby offshore area. Buoys with short masts (10 m or less) are less expensive and more abundant, but the low heights of these data make them unsuitable for accurate energy projections at heights of 80 m and above.

Remotely sensed measurements using, for example, Sonic Detection and Ranging (SODAR) and Light Detection and Ranging (LIDAR), are being evaluated for offshore applications and show promise to collect high-quality data at a significantly lower cost than tall towers installed offshore. Remote sensing devices can be installed on smaller platforms and buoys (although the buoy-based remote sensing systems are still under development and testing). Shore-based scanning LIDAR systems can measure winds offshore to distances of 15–20 km and are being evaluated for their accuracy and performance.

Satellite-borne systems, such as QuikScat and Special Sensor Microwave/Imager (SSM/I), can provide indirect measurements of near-surface (10 m) winds over large regions at approximately 25 km grid resolution. However, these data are not reliable within about 25 km of the shore or in shallow water areas. Moreover, the accuracy of these data varies by region and season and the availability of buoy data for calibration. As an alternative to the SSM/I and QuikScat, Synthetic Aperture Radar (SAR) offers higher resolution and the ability to take measurements closer to shore.

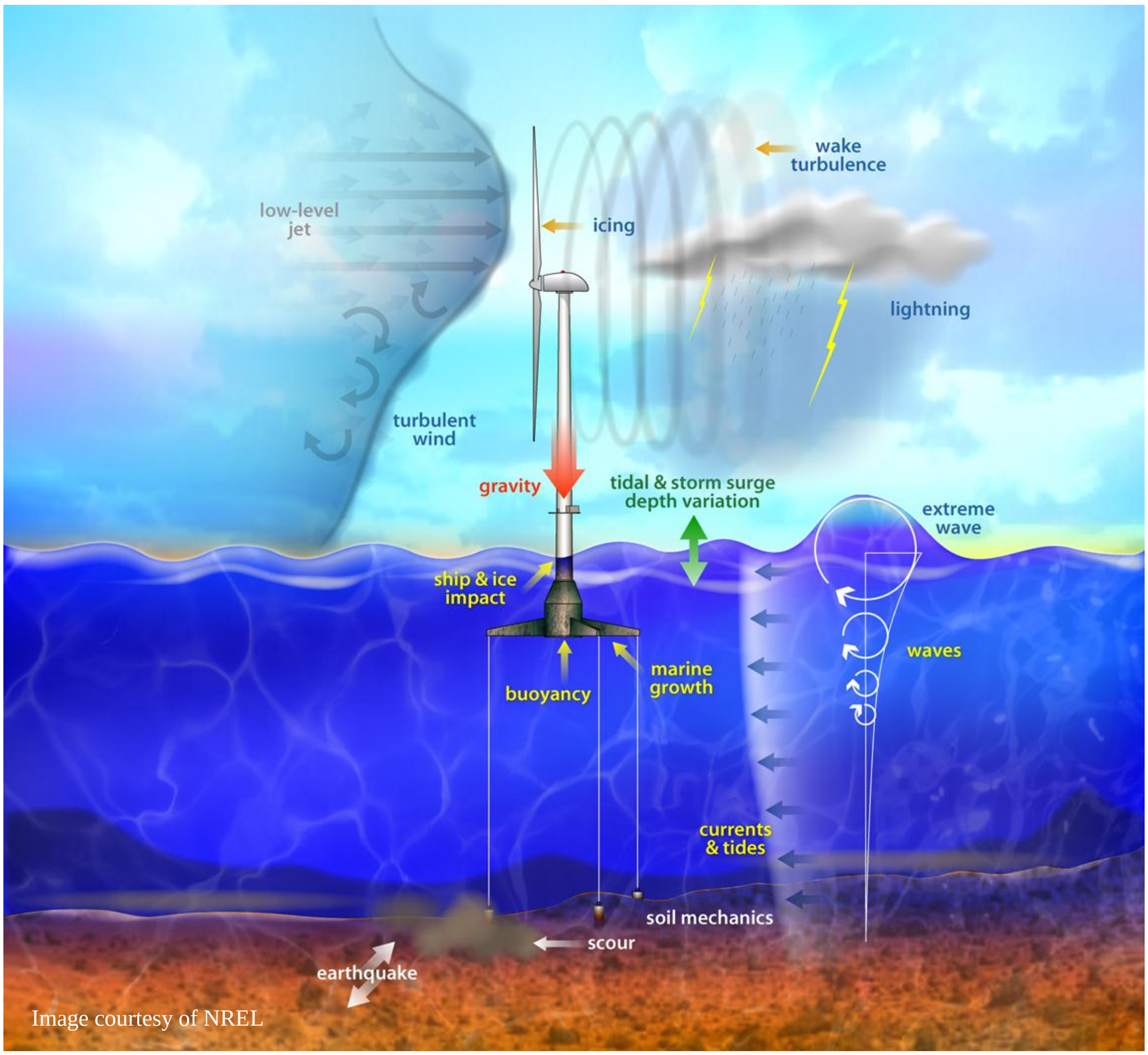

Figure 1. Phenomena for which measurement is needed to support the successful deployment of offshore wind and MHK devices.

DEFINING USERS AND APPLICATIONS

In order to safely and effectively deploy offshore renewable energy systems of the Outer Continental Shelf (OCS), a range of information is needed by various stakeholders. To understand what data is required, it is necessary to first identify the users of that data and understand the ways in which that data is transformed to information that can inform decisions. Table 1 summarizes the general user groups and their role in offshore renewable energy deployment.

Table 1. Examples of Typical Users of Information for Offshore Renewable Energy Systems

USERS	**Developers/Owners:** Evaluate a potential site on a wide range of criteria, including resource quality, ability to obtain permits, access to transmission, impact on and interactions with the surrounding environment, consistency with current land uses, and constructability.
	Facility Designers: Optimize facility and technology design based on site suitability, including resource potential. Construct site based on design requirements.
	Utilities: Ensure consistent flow of electricity to meet demand.
	Operations and Maintenance Services: Maintain facilities and adjust/modulate operations to ensure reliability and minimize lifecycle costs.
	Regulators: Ensure that facility complies with legal requirements, including safety in operations, structural integrity, environmental assessments, and a "fair return" on national resources (Bureau of Ocean Energy Management), as well as electricity generation reliability (Federal Energy Regulatory Commission).
	Financial Institutions: Provide financial backing for project investments based on information provided by developers.
	Warranty & Insurance Carriers: Guarantee operation and performance of an offshore energy project.

The level of detail required for metocean information depends on the application. Thus, specific data requirements are defined by their application. Table 2 summarizes these applications for offshore renewable energy systems.

Table 2. Applications of Information for Offshore Renewable Energy Systems

APPLICATIONS	**Facility Design**: Design offshore energy plants to maximum performance as a whole (turbine blades, power takeoffs, and other device components such as cabling), including accounting for interactions among individual devices (array effects).
	Energy Projections: Estimate future energy output from a deployment based on site criteria over the lifetime of the project.
	Technology Design and Validation: Design and validate energy-generating devices that can withstand physical loads while operating at optimum efficiency in the marine environment.
	Performance Monitoring: Once plants are in place, information will also be required to evaluate a plant's actual production and determine causes for changes in its performance.
	Operations Planning and Site Safety: Effectively schedule and execute construction, operation, and maintenance activities, including safe facility access and response to extreme events.
	Short-Term Forecasting: Initialize, constrain, and improve appropriate forecast models for predicting winds, waves, and currents hours to days in advance.

Table 3. Users and Applications Relative to Offshore Renewable Energy Deployment

Applications / Users	Short-Term Forecasting	Energy Projections	Technology Design and Validation	Facility Design	Operations Planning and Site Safety	Performance Monitoring
Project developers		X	X			
Facility designer			X	X		
Utilities	X	X				
Installation, operations and maintenance services					X	X
Regulators		X	X	X	X	X
Financial institution		X				
Warranty and insurance carriers			X	X		X

Tables 3 illustrates the breadth of the challenge in identifying useful information needed in decision making. As mentioned previously, the depth of this information varies based on the users' needs as well as the application.

For the purposes of this document, the observational and estimated metocean and geophysical information has been categorized into six condition types for ease of use (see Table 4).

Table 4. Categorized Metocean and Geophysical Conditions

Condition Type	Example of Condition
Typical wind conditions	Average wind velocity, direction, shear, turbulence intensity, and veer
Typical ocean conditions	Average wave height, period, tide, and current direction and speed
Atmospheric base-state conditions	Air temperature, density, visibility, relative humidity, air-sea temperature difference, and pressure
Marine subsurface conditions	Ocean depth and temperature, geotechnical characteristics, biofouling (marine growth), and sea floor scour
Extreme wind conditions	Extreme wind gusts and return periods
Extreme ocean conditions	Storm surge and significant/extreme wave height, current direction, and speed
Atypical environmental conditions	Phenomena such as sea ice, icing, hurricanes, and lightning

Table 5. Condition Types for Offshore Renewable Energy Deployment, by Application

Conditions / Application	Typical Wind Conditions	Typical Ocean Conditions	Atmospheric Base-State Conditions	Marine Subsurface Conditions	Extreme Wind Conditions	Extreme Ocean Conditions	Atypical Environmental Conditions
Forecasting	X	X			X	X	X
Energy projections	X	X	X		X	X	X
Technology design and validation	X		X		X		X
Facility design	X	X	X	X	X	X	X
Operations planning and site safety	X	X		X	X	X	X
Performance monitoring	X	X			X	X	X

Table 5 illustrates the breadth of information needed across the applications. Some, such as facility design, require a spectrum of information. Others, such as forecasting, are primarily concerned with general wind and wave, current, and tidal conditions and do not necessarily require all categories of information.

The Applications section of this document identifies the current needs, the existing information, and the data gaps relevant to each of the identified application areas. Information in this section was derived from input by a team of subject matter experts as well as information gathered from the “Offshore Resource Assessment and Design Conditions Public Meeting: Summary Report.” (EERE 2011) While numerous information needs and data gaps will be identified in the material that follows, it is important to highlight a gap that was repeatedly emphasized by participants in the public meeting and that spanned all applications: at present, there is no common access point or portal for the myriad of existing and anticipated information sources needed for the deployment of offshore renewable energy. Until this is rectified, it will not be possible to take full and cost-effective advantage of information resources.

The **Gaps Summary** provides a high-level review of the challenges within each application relevant to offshore wind and MHK deployment. A summary table for both wind and MHK technologies in this section summarizes where information is available for each application, what information is expected to be available as part of the offshore renewable energy systems installation, and where the gaps in information currently reside.

The Appendices contain three sections that add specific parameters and data sources to the information categories above. These documents are intended to be starting points and evolve as more information is gathered.

The International Electrotechnical Commission (IEC) standard 61400-3:2005, *Wind turbines - Part 3: Design requirements for offshore wind turbines* (IEC 2005a), contains standards that are ongoing and accepted by the European community for offshore wind turbine designs. Much of the information needed for the design of offshore wind plants is described in IEC 61400-3, although comparable standards have not been formally adopted for U.S. waters. **Appendix I** contains the relevant pieces of these existing IEC standards and attempts to translate these design conditions into necessary parameters (i.e., average wind speed, significant wave height). Similar design standards not yet available for MHK technologies are under development by Technical Committee 114 of the IEC.

Appendix II contains an initial analysis of the existing public data sources pertaining to offshore renewable energy systems and the specific parameters contained within that could be useful for users.

Appendix III contains a preliminary list of existing federal agencies that maintain data sources for purposes related to this document.

APPLICATIONS

I. Facility Design

For Wind Energy Technologies

The design of offshore wind plants begins with site selection, which not only must account for applicable regulations and potential use conflicts but also for the geotechnical and metocean environmental conditions. Geophysical and geotechnical information, such as bathymetry and sediment type, in combination with metocean data, is essential to successfully designing robust structures and foundations. Metocean information is essential for selecting turbines appropriate to the wind resource, for designing foundations to withstand turbine and wave loads (including those from extreme events), and for micrositing within the wind plant to account for dominant wind directions and wakes. In general, the information needed for design will be in the form of long-term means or frequency distributions of variables of interest.

Much of the information required for the design of offshore wind plants is described in IEC 61400-3, although comparable standards have not been formally adopted for U.S. waters. Where long-term observations are not available (which comprises most locations), the IEC standard accepts hindcasts or correlations between site-specific measurements and nearest stations with long-term records. Other applicable design standards[1] have been created and adopted by offshore oil and gas platforms. These existing standards may provide insight into the design of other offshore platforms and facility components beyond wind turbines and MHK devices (e.g., offshore substations).

Hub-Height Wind Speed

Turbines in offshore wind plants must be designed to withstand extreme wind events in the case of mechanical yaw error. This is commonly expressed in terms of the 1-year or 30-year return period for wind speed (Sharples 2009). Such statistical values require multiple years of wind speed time series to compute. There are currently no such long-term observations in U.S. offshore waters except at specific, isolated locations. Two basic options for estimating hub-height wind speed distributions are to use near-surface measurements from widely scattered buoys and other surface platforms and attempt to scale the measurements up to hub height. Currently, such methods lack extensive validation. As an alternative and second option, numerical weather prediction models can provide simulated time series, but these models still need to be validated offshore. With regard to hurricane risk, even long-term records may not be sufficient to assess 50- and 100-year return period winds, necessitating the use of stochastic modeling methods based on the existing Atlantic and Gulf of Mexico basin hurricane climatology.

Hub-Height Wind Direction

The distribution of wind direction, often expressed in combination with wind speed as a wind rose, is important input primarily for micrositing of turbines within a wind plant. The information is used by wind farm design tools to optimize locations of individual turbines with respect to spacing and wakes. As is the case for wind speed, there are no long-term hub-height measurements in U.S. waters from which wind roses can be constructed. Wind direction distributions can be obtained from the same numerical models

[1] Existing design standards for offshore oil and gas rigs are available at http://info.ogp.org.uk/standards/downloads/StandardsIssued.pdf and http://www.api.org/Publications/upload/2010_Catalog_web.pdf.

that provide wind speed distributions. These may be adequate for micrositing of turbines, because the output of wind plants is likely to be less sensitive to small errors in the distribution of wind direction than wind speed.

Hub-Height Shear and Natural Turbulence

For turbine selection and load estimation, it is also important to know the expected distribution of shear and natural (non-wake) turbulence. As turbine sizes have grown, this requirement has become more critical. Current sources of this information are surface measurements, which need to be scaled up to hub height, and numerical atmospheric models. Neither of these methods is adequate. Surface measurements are widely scattered. Moreover, the techniques for scaling wind from surface measurements generally involve either a power law approach or a logarithmic wind profile. These methods are commonly applied without regard to aerodynamic roughness of the sea surface, atmospheric thermodynamic stability, or the effect of rapidly changing atmospheric or oceanic conditions, leading to large errors in these approaches. There is no accurate method for scaling surface measurements to make accurate hub-height turbulence measurements. The situation is not much more encouraging with numerical models. Such models generate estimates both of wind shear and turbulence, but there is little evidence that validates their performance for hub-height shear and turbulence. Extreme wind shears and other supplemental data from hurricanes are available from archives of global positioning system (GPS) dropsonde wind profiles collected from the National Oceanic, Atmospheric, and National Oceanic and Atmospheric Administration (NOAA) and Air Force "Hurricane Hunter" aircraft since 1997.

Air Temperature and Atmospheric Surface Pressure

Air temperature is needed in conjunction with atmospheric pressure primarily to calculate the distribution of air density at prospective wind plant sites. Unlike dynamic variables, this information is well known both from surface measurements and from numerical models.

Lightning

Lightning is a common feature of offshore environments, and lightning protection systems should be routinely included in the design of renewable energy plants. Lightning detection networks extend well offshore; thus, frequencies of lightning events can be mapped for offshore waters. This information may have some utility in assessing lightning risk to a facility.

Ice Loading, Ice Accretion

Sea ice loading on structures is a significant design consideration in cold regions. A primary source for real-time sea ice information is the National Ice Center[2], which combines the resources of the U.S. Navy, U.S. Coast Guard, and NOAA to provide histories and forecasts of ice coverage in offshore waters, including the Great Lakes. Historical data are maintained at NOAA's National Snow and Ice Data Center[3].

Ice accretion affects blade aerodynamics for wind turbines and, in severe cases, could affect structural integrity of turbine components. Icing can result both from freezing precipitation and fog and from sea spray in subfreezing temperatures. Frequency and severity of icing conditions in particular locations can be estimated from operational experience and records of mariners and others. The likelihood of freezing sea spray can be estimated from simulations by weather forecast models of the combination of high winds and low temperatures over open water.

[2] Available at: http://www.natice.noaa.gov/
[3] Available at: http://www.nsidc.org

Significant Wave Height, Period, and Direction

Distributions of significant wave height and direction are important for determining structural loads on turbine installations. Such information is available from buoy observations collected by NOAA's National Buoy Data Center (NDBC)[4] and from hindcasts of models such as WAVEWATCH III. In addition, WAVEWATCH III also produces credible directional wave spectra (the joint frequency distribution of wave amplitude with direction). Recent improvements to WAVEWATCH III have extended its performance to shallow water regions.

Tidal Elevations

Tidal elevations for wind turbine structures are important primarily for designing access and for identifying the parts of structures that will need to be specially protected from sea water corrosion. Coverage and accuracy of tidal data is sufficient for wind development purposes. A primary source for tidal and other water-level information is NOAA's Center for Operational Oceanographic Products and Services[5] .

Currents

Information about ocean currents is important to assess structural loading, potential for scour of the sea bed, and for design of access to offshore structures. The IEC standard allows for the application of standard current profiles to surface current information to obtain subsurface currents. Site-based current profiles can also be readily obtained through the use of acoustic Doppler current profilers (ADCPs). The National Oceanographic Data Center (NODC)[6] acts as a central repository of many collections of ocean current information. Airborne eXpendable Current Profile current data are also available from selected Atlantic and Gulf of Mexico hurricanes from Hurricane Field Program campaigns executed by NOAA in partnership with the National Science Foundation, National Aeronautics and Space Administration, and the Office of Naval Research.

Salinity

Salinity information is important to inform design consideration for corrosion. In addition to straightforward direct measurements, the NODC also provides numerous compilations of ocean salinity data.

Water Temperature

Water temperature influences the corrosion potential of sea water and the activity of biofouling (marine growth), as well as icing potential. Short-term measurements can readily be made with numerous technologies, and the historical temperature information is archived and available from NODC. Water temperature profiles from hurricane events are available from archives of Airborne eXpendable BathyThermographs data collected during field programs.

Bathymetry

The topography of the seabed must be accounted for in the design of any offshore wind plant. This information is known in general and can be supplied in detail with site surveys as part of the design process.

[4] Available at: http://www.ndbc.noaa.gov/
[5] Available at: http://tidesandcurrents.noaa.gov/
[6] Available at: http://www.nodc.noaa.gov/General/current.html

Seabed Geology

Seabed geology, including sediment properties, is also part of critical information required for plant design, affecting both foundation choices and mitigation plans for seabed scour. Details of seabed geology for a prospective site can be obtained through surveys conducted in the planning process.

For MHK Technologies

IEC design standards for MHK plants are under development. However, information required for MHK device design and installation overlaps with that required for wind plants. The same phenomena that create loads and foundation stresses for wind plant structures also do so for MHK systems. Two differences between wind plant and MHK facility design information requirements are the effects that winds and currents have on these respective devices.

A few items worth noting for MHK devices are the existing Det Norske Veritas wave and tidal energy device certification standards,[7] which use 100-year wind and 10-year current, as well as wave, wind, and current direction, to determine mooring standards. Furthermore, Sandia National Laboratory is carrying out a 50- and 100-year extreme wave analysis using data from three NDBC/Coastal Data Information Program (CDIP) buoys from the coast of northwestern California. The results of this analysis were not complete at the time of this report.

Near-Surface Wind Velocity

The loading on a wind turbine largely arises from hub height winds impinging on the rotor, while MHK devices with a superstructure are mainly affected by near-surface winds. Observations or validated numerical simulations of these near-surface winds are needed just as they are needed for hub-height winds in wind energy applications. However, MHK applications have the advantage of not requiring extrapolation of wind speed measurements.

Currents

In the same way that wind shear and atmospheric turbulence are important design conditions for wind turbines, current shear and subsurface turbulence are especially important for MHK devices that extract energy from both tidal and open-ocean currents. As noted, technology exists to provide these measurements, but observations at any particular location are unlikely to be available.

[7] Available at http://exchange.dnv.com/Publishing/Codes/ToC_edition.asp.

Summary of Information Requirements for Facility Design

Entries in Table 6 marked "A" indicate that the information is generally available or should become available as part of a renewable energy plant's standard installation. "E" entries signify that data is expected to be available as part of the wind or MHK plant's installation, and entries noted as "G" are either not currently available or are of questionable accuracy.

Table 6. Facility Design Information Requirements and Gaps

Information	Availability	Comments
Near-surface wind speed (10-min average), wind direction	A	This information is used to drive wave models for MHK applications. In addition, surface winds can be scaled up to hub height, although validation of the methods and accuracy offshore is limited.
Long-term frequency distributions of wind speed (hub height)	G	Distributions are available from prognostic meteorological models, but validation of hub-height winds and turbulence from these models is limited offshore.
Shear (hub height), natural turbulence	G	Natural turbulence is characteristic of inflow rather than wakes.
Turbulence intensity (hub height)	G	This includes wake-modulated turbulence.
Air temperature	A	
Atmospheric pressure	A	
Lightning	A	Lightning detection networks currently cover significant offshore areas.
Ice loading, ice accretion	E	Ice loading, the stresses of sea ice on structures, is generally distinguished from ice accretion, the weather-related accumulation of ice.
Significant wave height, direction, period	A	
Joint wind, wave-height, wave direction	G	
Tidal elevation	A	
Current profile over water column	A	IEC standards indicate that surface current is sufficient for wind; however, during hurricanes, inertial oscillations may cause strong subsurface current shears in hurricane wakes.
Salinity	A	
Water temperature	A	
Bathymetry	A	
Seabed Scour	E	

II. Energy Projections and Performance Monitoring

For Wind Energy Technologies

The currently required variables are defined in IEC 61400-12-1:2005, *Wind turbines – Part 12-1: Power performance measurements of electricity-producing wind turbines* (IEC 2005b). The meteorological (met) mast must be properly sited, and not too close to wind turbines or major obstacles. The wind data must be collected at or close to the hub height of the wind turbines, which can be 80 –100 m above the water surface. The data must be free from wakes caused by the met mast and wind turbines. A data sampling rate of 1 hertz (Hz) or higher (speed and direction) must be used.

Installation of tall met towers in offshore areas is very expensive and, consequently, very few tall met towers currently exist offshore. Remote sensing systems such as SODAR and LIDAR provide profiles of wind measurements up to heights of 100 m or more above the surface and are being investigated as reliable and cost-effective replacements for tower measurements in offshore areas. These systems include vertical profilers installed on fixed or floating platforms and scanning profilers located on the shore or offshore platforms. Best practices for use of remote sensing measurements in wind resource assessments are currently under development by an International Energy Agency expert group, and updated guidelines for the use of remote sensing data in power performance measurements are being investigated by the IEC.

Accurate measurements are desired over the entire height of the turbine rotor disk and throughout the spatial domain of the wind power plant, including improved wind shear; wind veer; turbulence; and extreme wind speed observations, models, and predictions. Remote sensing technologies such as LIDAR and SODAR now make it possible to obtain measurements at heights spanning the diameter of the turbine rotor. These systems can also be used to assess the spatial variation of the wind flow within a wind farm or between different wind farms. Scanning LIDAR systems offer opportunities to map the detailed wind resource characteristics within large wind farms and around or between wind farms.

Accurate characterization of important boundary layer parameters is needed for improved modeling and understanding. In particular, atmospheric thermodynamic stability can have a large impact on the near-surface wind shear, but often the lower boundary layer is treated simply as being neutrally stratified. The effects of changing stability on the shape of the wind profile can be detected using vertically profiling remote sensing, such as SODAR and LIDAR. In contrast, detecting the changing temperature profile that causes different stability regimes requires other remote sensing devices, such as radiometers or Raman LIDARs. Remote sensing can be used to more fully understand the impact of the boundary layer on wind turbine and wind farm performance, and also for improved modeling of the lower atmospheric boundary layer for wind energy applications.

Wind Vectors

Wind vectors are typically measured using a cup anemometer (speed) and a wind vane (direction), which must meet required specifications and be mounted per required standards as defined in IEC 61400-12-1. The record length of observations must be sufficient to represent at least 1 year. For each 10-minute period, values of the mean, standard deviation, and maximum and minimum wind speeds should be recorded. The wind speed frequency distribution should be binned into 0.5 m/s bins centered on integer multiples of 0.5 m/s.

Wind Shear

The wind shear is generally estimated from measurements by applying a power law or neutral logarithmic profile of the wind to extend near-surface measurements to rotor altitudes. Log profiles take surface roughness into account, which has a dependence on wind speed and sea state. For many reasons, such as sea state, stability, and wind shears that result from coastal circulations, these estimates may deviate significantly from the actual wind. Some of the largest errors in energy production estimates are often attributed to errors in wind shear estimates (Rogers 2010).

Although existing standards for power performance measurements (IEC 61400-12-1) require only wind measurements at or near wind turbine hub heights, studies have shown that the wind shear profile over the rotor height can significantly affect the power performance. For example, if the hub-height wind speed is significantly less than the wind speed averaged over the entire rotor height, then wind power production would be underestimated, and vice versa. As wind turbine rotors increase in size, the potential for errors in power production estimates using only hub-height winds increases.

SODAR and LIDAR remote sensing systems are being used more frequently to measure winds at heights extending above the met masts and to provide more accurate estimates of wind shear at heights above the rotor height of wind turbines. Remote sensing systems have not yet been validated as replacements for met masts, but these systems can currently provide supplementary data for more accurate assessments of wind shear and resulting energy projections. Moreover, new power performance standards are under development that will include use of remote sensing measurements.

Turbulence

Turbulence intensity is the ratio of the wind speed standard deviation to the mean wind speed, typically measured over a 10-minute interval. Studies have shown that power performance is affected by turbulence intensity levels, but no guidelines have been established because results among the existing studies vary significantly, and there is considerable uncertainty about the affects of turbulence intensity on power production. Either turbulence or standard deviation at turbine cut-in and cut-out speeds can be used to generate the effective hysteresis algorithm. For example, “high-wind hysteresis” refers to the turbine’s control-system lag between shutting down in high wind speeds and starting up again. To prevent repeated startup and shutdown of the turbine when the winds are close to the shutdown threshold, hysteresis is used in the turbine control algorithm. Estimates of power production should consider losses due to hysteresis.

Wind Veer

Wind veer, or the change of wind direction with height, is not often measured or estimated over a wind turbine’s rotor height despite its potential significant effect on power production.

Wind Turbine Class

Wind turbine classes are described in IEC 61400-1:2005, *Wind turbines – Part 1: Design requirements* (IEC 2005c). The wind turbine classification offers a range of robustness clearly defined in terms of the annual average wind speed, the speed of extreme gusts that could occur over 50 years, and the turbulence intensity in the wind at specified wind speeds. This classification is used to determine which turbine is suitable for the wind conditions of a particular site. Therefore, the wind turbine class is a determinant of wind turbine power curves and energy projections.

The three wind turbine classes defined by the IEC standard correspond to high wind (Class I), medium wind (Class II), and low wind (Class III). In general, Class I wind turbines have the smallest rotors, and Class III turbines have the largest rotors for a given turbine capacity rating.

Extreme Wind Speed

The extreme wind speed is typically calculated based on a 50-year or 100-year recurrence period. This statistic is a determinant of wind class. In locations susceptible to hurricanes, 1–2 year data records are not sufficient to assess return period winds. Longer term records from reference stations may suffer from data gaps due to instrument damage or power outages during hurricane events. In such cases, supplemental stochastic modeling may be needed to determine design wind speeds.

Wake Effects

Wake and array effects on wind farm power production and performance depend on atmospheric conditions, wind turbine characteristics, and wind turbine spacing and layout. Factors such as atmospheric stability, wind speeds and directions, wind shear and veer, and turbulence influence the wakes and the resultant changes in power production.

Wake and array losses need to be more accurately determined in all types of offshore atmospheric conditions, leading to optimum layout of wind power plants. Careful analysis of wind turbine power output data can provide information on variations in power production for a wind farm and energy losses due to wake and array effects. However, details of the importance of certain wind characteristics (such as wind shear and turbulence) vary throughout large wind farms; impacts on individual turbines and overall wind farm performance are not known, because these types of comprehensive measurements are not currently available.

Wake and array effects are generally estimated by model simulations and validated with wind turbine production Supervisory Control and Data Acquisition (SCADA) data. Some observational data of wakes exist based on tower and/or remote sensing measurements, but these data are quite limited due to the difficulty in measuring over wind farm sites.

Measure-Correlate-Predict Requirements

Measure-correlate-predict (MCP) is a common method for predicting wind distribution and power production for wind turbine sites. The goal of this method is to estimate a long-term average over many years in order to smooth inter-annual variability.

For offshore areas, the body of reliable data that can be used for MCP is very limited. These data are primarily from buoy measurements near the surface and remote sensing data from satellite-borne systems, the National Centers for Environmental Prediction (NCEP) Re-analysis data can also be used. The satellite-derived wind estimates are affected by rain and sea state conditions and lower availability than direct measurements due to limited overflights (one or two per day).

Other State Variables

Air temperature and pressure measurements are necessary for accurate energy projection modeling. Observations should be taken at least once per minute, and 10-minute averages should be calculated. Air density is estimated from temperature and pressure measurements. When the temperature is high, humidity is required to more accurately calculate air density.

Accurate measurements are needed for all state variables over the entire height of the turbine rotor disk and throughout the spatial domain of the wind power plant. Vertical temperature profiles, sea surface temperatures, and currents are essential for research supporting energy projections in the marine environment.

Precipitation can affect energy production and should be accounted for by observations on heavy rain, snow, hail, or freezing rain. Similarly, observations on particles such as dust, salt, insects, and rime ice should be made because these particles can affect energy production by changed blade roughness. Advanced tools are needed to detect and monitor the occurrence of events, such as precipitation and atmospheric or environmental particles that detrimentally affect energy production.

Sources of Existing Measured and Modeled Data

Existing data are critical to making preliminary estimates of the wind resource and energy production for the development of wind power plants in offshore regions. These data can come from direct observations (such as in situ, remote, or satellite measurements) or from models or other methods, such as interpolation of model runs, that generate data in gridded form or for specific locations.

General Sources of Data for Energy Projections

Data obtained via direct observations generally come from devices floating on the surface and anchored to the bottom (buoys), affixed to the shore (on a dock), on fixed platforms (pilings and offshore towers), and ships. Direct observations provide verifiable data, usually of good quality. The disadvantage of direct observations is often inadequate spatial resolution.

Buoys provide observations at heights of normally a few meters and no more than 10 m above the sea surface. Because other met/ocean parameters are usually measured, it is also possible to perform boundary layer calculations using models of varying complexity.

Fixed platforms instrumented with masts provide high-quality data at various heights (usually in the range of 20–50 m), depending on the height of the platform and the measurement mast. In a few cases, taller towers have been installed.

Ships provide data but are not usually stationary. Sometimes, however, ships with fixed paths can provide long-term data (for example, the MV Oleander travels from New York to Bermuda biweekly).

Remote sensing data from satellite-borne systems provide data that can be used to estimate near-surface wind and wave conditions. These satellite-derived data have limited availability due to overpass frequency.

Ground-based or fixed remote sensing devices such as SODAR and LIDAR are being more frequently used and provide vertical profiles of measurement data to heights of 100 m and above.

Operational models are run several times a day at NCEP. The models include: the Global Forecast System (GFS), North American Mesoscale (NAM), and Rapid Update Cycle (RUC). The GFS, which has 40 km grid spacing, and NAM, which has 12 km grid spacing, are run four times per day (00, 06, 12, and 18 Coordinated Universal Time) out to day 14 and hour 84, respectively. The RUC, which has 13 km grid spacing, is run every hour out to either hour 12 or 24. The model data is archived at the NOAA Operational Model Archive Distribution System (NOMADS)[8]and includes the latest forecasts as well as archived model data since 2007. The North American Regional Reanalysis (Mesinger et al. 2006), which has 32 km grid spacing and covers North America and a large portion of the adjacent oceans, is also available from 1979 to present on NOMADS. NOMADS archives the global NCEP reanalysis at 2 degree resolution back to 1950 as well as the Climate Forecast System Reanalysis at 0.5 degree grid spacing back to 1979.

Mesoscale model data, which has a spatial resolutions of 5 km or finer and multiple nodes between the surface and 100 m, provide estimates of wind resource characteristics and power production potential for many offshore regions. For some regions, the resolution of the gridded model data is 200 m. In offshore wind mapping projects supported by the U.S. Department of Energy (DOE) and the National Renewable

[8] Available at: http://www.nomad3.ncep.noaa.gov/

Energy Laboratory, efforts were made to validate the model-derived data where possible with available measurement data.

Metadata

Metadata (or information about data) is important to properly interpret and process the data and to assess the quality and applicability of the data. Metadata usually includes the following types of information: the means of creation of the data, purpose of the data, time and date of creation, creator or author of data, placement on a computer network where data was created, and standards used.

When generating metadata, many more descriptors can be defined. Some of these will be fields describing the physical location of the data collection, while others will describe the instrumentation and equipment used to collect the data.

Metadata location fields and categories include the following:

- Physical location (latitude, longitude, and elevation)
- Site name and number
- Political region (county and state)
- Local environment description and photographs (topography, vegetation, and buildings or obstructions)

Instrumentation and equipment metadata and categories include the following:

- Data logger model and serial number
- Sensors (model, serial number, height, orientation or boom direction, and calibration information)
- Tower description (size, height, face width, and so on, lattice or tubular, guyed or non-guyed, face orientation, and tower commissioning report)
- Remote sensing data (type of instrument, model, and serial number)
- Data collection history (data outages, sensor changes, and unusual conditions such as severe weather)

Data set description metadata include the following:

- Starting and ending dates and times
- Data sampling interval
- Total number of records collected
- Data collection rate (0%–100%)
- Data format (ASCII text, database files, binary, and so on)
- Channel number for each sensor
- Name and contact of responsible person
- Quality control and data screening procedures that have been applied

Entries in Table 7 marked “A” indicate that the information is generally available or should become available as part of a renewable energy plant’s standard installation. “E” entries signify that data is expected to be available as part of the wind plant's installation, and entries noted as “G” are either not currently available or are of questionable accuracy.

Table 7. Energy Projections and Performance Monitoring Requirements and Gaps for Wind Technologies

Information	Availability	Comments
In-situ wind speed measurements (hub heights)	G	Such measurements would be available after a plant is installed, but not prior to, unless the resource assessment campaign involved installing offshore met towers
Estimated wind speed (hub height 10-min average)	E	Wind speed and direction can currently be estimated from weather forecast models but offshore hub-height validation is limited
Wind direction (hub-height 10-min average)	E	See comment above
Long-term frequency distributions of wind speed and direction (hub-height)	E	Inferences regarding the frequency distributions of wind at a particular site will be significantly aided by the resource assessments carried out prior to facility installation. Estimates of return periods for extreme events depend on the accuracy of these distributions.
Shear (hub-height)	G	Shear estimates will become available as part of a facility installation; however, current formulations are prone to systematic errors, so this is considered a gap
Vertical wind profiles	G	
Wind veer	G	
Wake and array effects	G	Following installation of a wind plant, SCADA data can be correlated with plant power output
Three-dimensional/detailed boundary layer wind field	G	
Turbulence intensity (hub-height)	G	
Precipitation type and amount	G	Advanced tools are needed to detect and monitor precipitation and other particles that can detrimentally affect energy production.
Humidity	E	
Air density	E	
Air temperature	A	
Atmospheric pressure	A	
Vertical temperature profiles	E	

For MHK Technologies

There are MHK technologies that target three distinct sources of energy: waves, tidal currents, and ocean currents. The most basic level of resource assessment involves estimating the theoretical resource, or the total energy contained in waves, tides, or ocean currents on an annual basis. Although past resource behavior may not indicate future performance, certain seasonal resource variations are predictable, and past inter-annual variations indicate the range of variability in wave and ocean current resources. The speed and direction of winds and surface currents display seasonal variations that affect the direction and strength of wave trains and ocean currents.

Modeling the theoretically available power in ocean currents is an open area of research. One framework for understanding this resource is applying what is known about intensified western boundary currents like the Florida Current to the work of Garrett and Cummins (2007), who describe the maximum power dissipated by tidal currents flowing through open channels. In this method, tidal power dissipated through open channel flow is proportional to the sum of the work done to drive the flow against friction and exit losses. It remains to be determined whether this is an appropriate model for open ocean currents because the friction forces acting on them are different, and they are in geostrophic balance with cross-channel elevation differences rather than being driven by an along-channel hydraulic head. Energy removal increases friction in current flow, which draws down the geostrophic pressure difference and generates lateral velocity. Unfortunately, energy budgets for ocean circulation that might be applied to this problem are not well understood (Wunsch and Ferrari 2004), and detailed regional budgets have not been established.

Inter-annual variations such as the El Niño/Southern Oscillation and secular trends due to rising global temperatures may have a long-term impact on MHK resources. At present, there are several projects sponsored by DOE in progress to provide resource assessments of the various MHK modes. DOE has also created three national centers for MHK research and development, each located in the vicinity of one or more of the modes. Wave energy tends to be strongest on the West Coast, and the centers in Hawaii and Oregon are advancing wave technologies. Tidal-current energy is strong in large embayments at higher latitudes, and the center in Washington is focusing on Puget Sound's resource. And the significant ocean-current energy resource in the United States is the Florida Current and its extension north to Cape Hatteras; the center in southeast Florida is working to advance development of related technologies.

State Variables

In addition to the current itself, parameters such as temperature, salinity, and sea surface height, among others, are incorporated into ocean models that are now being used to assess ocean current energy. The Naval Research Laboratory's (NRL) Global Digital Environmental Model (see Carnes 2009) archives temperature and salinity for sound-speed calculations. Additional resources include the NRL Navy Coastal Ocean Model [9]and the HYbrid Coordinate Ocean Model[10], a data-assimilative ocean circulation model providing hindcast and nowcast results for temperature, salinity, and sea surface height on a 1/12 or 1/25° grid scale. NOAA's NODC has a series of basin scale atlases that provide monthly climatological fields for temperature and salinity.

Wind Variables

Wind forcing is the dominant driver of wave dynamics. Wind vectors and upstream wind fields are required primarily for wave energy technologies. Wind measurements and hindcasts are used for prediction of waves and for estimating wave energy and direction.

Wave Variables

NCEP maintains a database of wave hindcast output from the global wind-wave model WAVEWATCH III (Tolman 2009). This model, which requires input ice and high-resolution 10 m wind fields, was recently rerun using a coupled reanalysis of atmospheric, oceanic, sea-ice, and land data from 1979 through 2010 (Saha et al. 2010). The resulting wave "reforecast" was used in DOE's U.S. wave resource assessment (EPRI 2011). The DOE assessment was based on 51-months (2005–2009) of WAVEWATCH III hindcast model output. The DOE study also included a comparison between the WAVEWATCH III hindcast results and measurements made by NDBC wave buoys over the same period of time. The final component of the study was an assessment of the 51-month period's representativeness

[9] Available at: http://www7320.nrlssc.navy.mil/global_ncom/pubs.html)
[10] Available at: http://hycom.org/

of the longer term (12.5-year) wave climate. This was done by comparing 52 months to 12.5 years of NDBC wave buoy measurements from 18 buoys. In particular, statistical comparisons were made between significant wave height, energy period, and wave energy flux derived from the spectral data recorded by the buoys over the shorter and longer periods. DOE followed up its resource assessment study with additional funding to NCEP for a 30-year WAVEWATCH III reanalysis that is now complete (Chawla et al. 2011). The WAVEWATCH III 30-year hindcast reanalysis will cover January 1, 1980, through December 31, 2009, and will include 1-hour (rather than 3-hour) intervals of coastal 4-minute resolution grids out to the 200 m depth contour off all U.S. coastlines. Full directional hindcasts have been requested for 50–100 additional NDBC measurement stations and "virtual stations" where it would be useful to archive the complete directional information. These full directional hindcasts will be resolved into 50 (rather than 25) frequency bins and 36 (rather than 24) directional bins. The GFS reanalysis wind fields driving the model will be more accurate, suggesting that these data also may be useful for offshore wind resource assessment and extreme event analysis.

The reanalysis will be the basis for additional work to identify the appropriate timescales for wave resource assessments and extreme event analyses. These parameters are needed to inform statistical distributions (which require a historical wave data set of at least 5 years), extreme event analyses (which require at least 20 years of historical data to extrapolate to a 100-year return event), and wave energy propagation models (which require detailed bathymetry for near-shore devices).

In predicting the performance of wave energy devices, further research is needed to understand the relationship between the devices' threshold and maximum operating conditions and the probability distributions of significant wave height versus energy period for a given wave field.

Wave climatologies that include wave directionality distributions as well as wave power density are helpful for developers interested in assessing the wave energy incident upon a linear buoy array or a directional wave energy converter.

Archiving not only sea-state parameter data (i.e., significant wave height, energy period, and so on), but also the complete directional spectra at more output locations than presently done would be beneficial for wave energy modelers. The existing operational practice is to display the parameters for only three partitions: the local wind-driven sea and the two highest swell trains. While this provides a relatively complete picture for the East Coast, Puerto Rico, and the Gulf of Mexico, it may under-represent the total wave energy on the West Coast, Gulf of Alaska, and Hawaii by a significant amount. Adding wave directionality instruments to more NDBC buoys in more energetic wave environments would also benefit wave energy developers. Currently, 52 (roughly half) of the NDBC buoys have wave directionality measurement capability, and many of these are located in the Gulf of Mexico, a region with a relatively low wave energy resource (EPRI 2011).

Current Vectors and Extreme Values

For wave energy projections, longer term (longer than 12 hours) wave, wind, and tidally induced current measurements are required as well as the extreme values. Marine currents can impact device performance, while the extreme values can be dominant drivers from a mooring and device design perspective. For tidal energy projections, at least one month of site-specific tidal current velocity distributions are required by developers. Measurements are typically taken using ADCPs that are either bottom-mounted or mounted on ships. For ocean current energy, the current velocities as functions of time and space and the derived velocity distributions are needed to downscale ocean current models and predictions. Coastal Ocean Dynamics Applications Radar (CODAR) systems can measure spatial variation in surface current velocities. Ocean current and turbulence profiles up to 200 m in depth are needed to validate remotely sensed surface currents.

Multiyear data sets of marine currents with broad geographical coverage would be useful and are at present unavailable from observations at spatial resolutions of interest. Most of the time, extreme values of currents are derived from short-term measurement data, which results in an unreliable extrapolation to extreme values.

Obtaining the ocean current velocity distributions requires long-term measurements, as modeling is difficult. There are several recent radar installations (CODAR and Wellen Radar)[11] that could yield good spatial coverage of near-coastal currents and could be used to develop reliable statistical distributions of surface current direction and velocity. At present, there is a limited amount of longer term data available. Most of the data is not in the public domain, and time histories are less than 2-years long. Longer term variability (such as seasonal and inter-annual variability) is not well understood. Spatial variability also needs to be quantified further, as the Gulf Stream meanders.

Tidal Elevations

Values of tidal elevations are required for tidal and current energy projections. These are readily available and quite reliable. The associated currents, however, have the same uncertainties in most cases as open-ocean currents.

Vertical Shear, Bottom Friction, Bathymetry, and Geometry

Vertical shear and bottom friction are needed for tidal energy projections. For near-shore devices, bathymetric characteristics and other geometric feature descriptions are needed to propagate wave energy resources to near-shore sites using shallow water wave transformation models.

Turbulence Intensity

Turbulence intensity is required for ocean current energy projections and is a critical design driver for any rotor device.

Entries in Table 8 marked “A” indicate that the information is generally available or should become available as part of a renewable energy plant’s standard installation. “E” entries signify that data is expected to be available as part of the MHK plant's installation, and entries noted as “G” are either not currently available or are of questionable accuracy.

[11] Available at: http://www.rsmas.miami.edu/groups/upper-ocean-dynamics/research/high-frequency-radar/gap-analysis/

Table 8. Energy Projections and Performance Monitoring Requirements and Gaps for MHK Technologies

Information	Wave Energy	Tidal Energy	Ocean Current Energy
Temperature	A	A	A
Salinity	A	A	A
Sea surface height	A	A	A
Wind vectors	A	-	-
Upstream wind fields	A	-	-
Wave climatologies (including wave directionality and wave power density)	G	-	-
Significant wave heights	A	-	-
Probability distributions of significant wave height versus energy period	G	-	-
Wave energy period	A	-	-
Wave energy flux	A	-	-
Current velocity distributions (multi-year data sets)	G	G	G
Marine current extreme values	G	-	-
Tidal elevations	-	A	A
Vertical current shear and bottom friction	-	E	-
Bathymetry, wetland distributions, and water absorption characteristics	-	A	-
Turbulence intensity	-	-	G

III. Technology Design and Validation

For Wind Energy Technologies

The currently required variables for offshore wind energy technology are specified in the IEC 61400-3 and some optional offshore requirements can be found in the American Petroleum Institute's (API) 2A-WSD Recommended Practices (API 2010). The major differences between these standards are the reference and return period specifications. The API uses a 1-hour reference period, while the IEC uses a 10-minute period. Extremes in the API are based on a 100-year return period, while the IEC uses 50-year and 1-year return periods. Often, quantities in the standards are specified based on measurements of annual average wind speeds, turbulence intensities, and wave heights and periods. These standards have evolved over many decades and are frequently based on measured extreme events. However, these extreme events may not be inclusive of all observable quantities offshore, and hence there is considerable room for improvement. In particular, applying these standards to areas susceptible to hurricanes requires updating based on field measurements and peer-reviewed publications.

Wind Measurements

All wind speed data should be based on a 10-minute sampling interval and include wind farm wake effects, where relevant. Wind speed measurements and statistics include the following:

- Annual average wind speed at hub height
- Annual average turbulence intensity (single component) at hub height
- Wind speed probability distribution (Weibull, Rayleigh, measured, and other)
- Wind direction distribution (wind rose)
- Wind shear vertical profile using the power law with an estimated exponent , or an exponent derived from measurements from multiple levels
- Wind veer across the rotor plane
- Wind gusts (3-second and 5-second return periods)

It is helpful to know the range of annual variability of the above measures as a function of atmospheric thermodynamic stability and other external conditions.

High-fidelity measurements across the rotor plane and tower of each turbine and covering at least one diameter upstream and downstream from the turbine, which ultimately could be 1 m spatial resolution and 20 Hz temporal resolution, would be very useful for technology design and validation. The measurements will likely be obtained through a combination of remote sensing and tower-based measurements in the future.

Larger scale wind measurements and vertical profile measurements up to or above the mixed layer of the atmospheric boundary layer would enhance understanding and prediction of mesoscale effects. These measurements would allow for more accurate quantification of the flow field around an entire wind farm. Understanding the spatial variation of wind vectors across arrays could inform wake interaction modeling and energy production forecasting. These types of measurements may be possible with the current generation of pulsed LIDARs.

The dominant turbulent length scale as a function of height and spatial coherence of the turbulence is needed to increase understanding of turbulent eddies, structures that have a significant impact on turbine loading. Site-specific turbulence energy levels on short timescales would be helpful in accomplishing this task.

Long-term changes in wind speed due to climate-induced variability may also have consequences for technology design, as well as energy production.

While the North Sea and other European locations can annually receive winds of Category 1 hurricanes, the U.S. coasts in the Mid Atlantic, Southeast, and Gulf of Mexico can experience major hurricanes much more destructive than European winter storms. In these areas, the extreme wind climate is dominated by hurricanes, so design standards specific to Europe or specific to oil and gas in the United States may not be relevant for offshore wind in the United States. In the United States, long-term records may be unavailable or too compromised by exposure and sensor survivability issues to be able to assess return period wind speeds, necessitating the use of stochastic methods similar to those used by the insurance industry (e.g., Powell et al. 2005). Power law wind shear profiles are not applicable in extreme hurricane winds. Wind shear depends on marine roughness, which in turn depends on wind speed and sea state. Roughness models that assume linear increases with wind speed are not applicable in extreme winds over 28 m s^{-1}. In addition, hurricanes contain persistent low-level jet features that will affect turbine loading. Turbulence models may also need revision to account for different vertical and horizontal coherence and turbulence intensity properties associated with coherent fine-scale wind features and persistent low-level jets. Better measurements of such features will provide data needed for improved models. NOAA's Hurricane Research Division archive of GPS dropwindsondes, Doppler radar, and hurricane wind field analyses, together with onshore flow hurricane wind tower data sets from the Florida Coastal Monitoring Program (University of Florida) and Texas Tech University are applicable to improved specification of extreme hurricane events.

Finally, wind measurements should be combined with other variables (such as wave measurements) in order to more fully understand loading and the occurrence of coherent structures such as atmospheric Kelvin-Helmholtz waves and low-level jets in the offshore environment.

Extreme Wind Events

Most methods for assessing extreme events are prescribed in the IEC, as observations from which related probability distributions may be developed are generally not available. Specific data requirements include the following:

- Wind speed: 1-year and 50-year return period extremes
- Wind shear: 50-year extreme for wind shear power law exponent (both vertical and horizontal shear)
- Extreme wind direction change for 1- and 50-year recurrence periods (30-second duration)
- Extreme 50-year wind speed gust (5-second duration)
- Extreme combined wind speed gust and direction change
- Combined 50-year extreme wind speed and sea state (1-hour duration)

Long-term (multi-year), continuous, high-frequency wind speed measurements at various locations are needed to fully validate predictions of extreme wind events. Additionally, site-specific extreme event measurements and improved estimates are needed.

Wake Impacts

The impacts of mean wind loss, turbulence increases, and vertical momentum fluxes influence technology design. For example, wind farms will lose 10%–20% their energy production from wake losses, and a better physical understanding of wakes from measurement may enable control systems designed to minimize these losses. Similarly, better measurements of wake turbulence may lead to better maintenance scheduling for turbines within wind farms that currently experience higher operations and maintenance costs due to larger fatigue loads resulting from elevated turbulence from wakes. These measurements can be obtained by a combination of data collected at the tower, remotely sensed data, and turbine SCADA data. Turbine SCADA data is also needed to assess wind farm impacts relative to estimates of conditions made prior to wind farm installation for all variables (for example, the API recommends a blockage factor to effectively reduce the current speed).The following information is specifically needed to assess wake impacts:

- Reduction in mean wind speed
- Increase in turbulence intensity

State Variables

Atmospheric and oceanic stability can have a large impact on wake behavior, which in turn greatly impacts the power production within wind farms and also the structural fatigue damage on each individual wind turbine. Understanding stability will also help determine the probability of occurrence for certain atmospheric conditions, such as low-level jets and Kelvin-Helmholtz waves. Stability estimates require state variable measurements for both air and sea. Data should be collected at hub height with a 10-minute reference period. Required state variables include the following:

- Temperature measurements
- Vertical temperature profile
- Sea surface temperature
- Humidity
- Surface barometric pressure

Water temperature measurements are not currently addressed within IEC standards.

Waves

Wave data should be based on a 3-hour reference period. Required wave variables include the following:

- Significant wave height (Hs)
- Peak spectral period (Tp)
- Wave direction
- Wind and wave joint distribution (Hs, Tp, and wind speed), including directionality
- Relationship between wave height and effective surface roughness for impact on wind

High-fidelity measurements, which ultimately could be 1 m spatial resolution and 20 Hz within 100 m of each wind turbine in the wind farm, would be ideal. These space and time resolutions are commensurate with the scales that will excite the natural frequencies of currently sized turbines. However, as turbine sizes continue to increase, natural frequencies will decrease and characteristic length scales will increase, allowing for a less stringent requirement for observational resolution. It is more difficult to measure wave speed, height, and period than it is to measure wind speed.

The data record should also be as long as 50 years to be able to obtain good probabilities of extreme events. Given the limited wave measurement history at most locations, extreme event probabilities will continue to be derived from hindcasts.

Wind farms may also influence wave states; inner turbines within the wind farm may see modified wave states due to damped winds inside the wind farm. Understanding the correlation between wind, wave, and current variables (e.g., speed, direction, and so on) will shed light on the modification of wave states within wind farms.

Extreme Wave Events

Similarly to extreme wind variables, many of the extreme marine variables are prescribed based on measurements of the local significant wave height and spectral period. Furthermore, the development of standards requires the joint probability of combinations of events. Near the surface, ocean wave activity can superimpose an oscillating flow onto the operating rotor. This in turn acts like “turbulence” on the rotor and can have implications on rotor design and fatigue issues. Current IEC standards allow for “reduced” extreme winds considering wind and wave events to be independent. For locations susceptible to hurricanes, extreme winds and waves may be highly correlated within the same event.

Required extreme wave event variables include the following:

- 1-year and 50-year return period significant wave height
- 1-year and 50-year return period range of peak wave periods
- Individual extreme wave height for 1- and 50-year recurrence periods
- Range of associated wave periods for 1- and 50-year recurrence periods
- Extreme crest height with a recurrence period of 50 years
- Breaking waves (currently estimated from bathymetry)

Marine Variables

Required marine variables include the following:

- Surface and subsurface current speed (0–20 m below surface)
- Tide: highest and lowest astronomical tide
- Ice: calculate impact on turbine loads – static and dynamic
- Biofouling (marine growth): influence on structure mass, geometry, and surface texture
- Seabed movement and scour
- Extreme events:
    - 1-year and 50-year subsurface current speeds
    - 50-year maximum water level range – from tidal variation or storm surge
- Bathymetric variability
- Salinity

How and where breaking waves are located is largely dependent on the local water depth and bathymetric variation, variables which may be impacted by installation of turbines. Measurements taken before and after wind farm installations would be crucial to understanding breaking waves and the implications for technology design.

Other Variables

There are no detailed specifications for the following quantities in the IEC standard, but the turbine manufacturers are required by the IEC standard to take these variables into consideration for their turbine design:

- Solar radiation
- Rain, hail, snow, and ice
- Chemically active substances
- Mechanically active particles
- Salinity causing corrosion
- Lightning/electromagnetic charge measurements
- Seismicity/earthquakes
- Water density
- Icing characterization:
    - Cover probability
    - Thickness
    - Composition

    - Floe speed
- Water salinity and/or salinity of local atmosphere
- Proximity to land
- Detailed terrain/vegetation measurements within 100 km of wind farm
- Avian and aquatic life surveys
- Environmental impacts or mitigation strategies
- Noise propagation factors:
    - Wind speed
    - Turbulence
    - Humidity
    - Atmospheric stability

Entries in Table 9 marked "A" indicate that the information is generally available or should become available as part of a renewable energy plant's standard installation. "E" entries signify that data is expected to be available as part of the wind plant's installation, and entries noted as "G" are either not currently available or are of questionable accuracy.

Table 9. Technology Design and Validation Requirements and Gaps for Wind Technologies

Information	Availability	Comments
Long-term frequency distributions of wind speed and direction (hub-height)	G	
Shear (hub-height)	G	Shear estimates will become available as part of a facility installation; however, current formulations are prone to systematic errors, so this is considered a gap
Vertical wind profiles	G	
Wind veer	G	
Three-dimensional/detailed boundary layer wind field	G	
Turbulence intensity (hub-height)	G	
Significant wave height, direction, wave period	A	
Tidal variation	A	
Currents	A	
Biofouling (marine growth)	A	
Joint distributions of wind speed with wave heights	G	
Breaking waves	E	
Surface and subsurface currents	E	
Precipitation type and amount	G	
Humidity	A	
Air density	A	
Atmospheric pressure	A	
Air temperature	A	
Vertical temperature profiles	G	
Salinity	A	
Water temperature	A	

Information	Availability	Comments
Bathymetry	A	
Seabed Geology	E	
Seabed scour	E	

For MHK Technologies

The variables that are different between MHK and offshore wind energy devices are subsurface temperature, salinity, and current measurements, and a greater focus on bottom scour impacts. Underwater current measurements must include mean quantities, turbulence, and extremes in shear, speed, and direction, quantities somewhat analogous to wind variables required for wind technology design and validation. There are currently no standard requirements for such MHK devices.

MHK technologies should be designed to withstand a certain level of extreme events such as hurricanes; however, further research is needed to understand these design requirements. Turbulence intensity is a key determinant of structural loads and device performance.

Information on the strength, duration, and frequency of such events will help device engineers tailor their designs to expected operating conditions and project developers assess weather-related risks associated with deploying devices at specific sites. Important parameters include the extreme values and frequency distributions of wind speed, wave height, wave period, and subsurface current speeds.

The efficiency of large-scale device deployments will depend on the geometry in which devices are arrayed. As with wind turbine wakes, MHK array design has a significant impact on device energy capture efficiencies and hydrodynamic impacts that have near- and far-field environmental effects. For a given number of in-stream turbines, the exact arrangement that maximizes energy extraction and minimizes impacts on downstream flow is highly dependent on the site-specific channel geometry and flow characteristics.

A DOE-funded Environmental Fluid Dynamics Code (EFDC)-based model developed at Sandia National Laboratory addresses array optimization by simulating changes in the turbulent kinetic energy and turbulent kinetic energy dissipation rates caused by placing different turbine arrays into flow through a channel. Real systems can be modeled to optimize turbine placement for energy extraction and predict environmental impacts before devices are actually deployed. The model's ability to simulate turbine arrays in the Mississippi River is currently being tested and tuned using data collected at a turbine deployment site in the river.

The hydrodynamic effects of wave energy converters are more difficult to model, but a second effort is underway at Sandia to couple EFDC to Simulating WAves Nearshore (SWAN), a near-shore wave model, and to simulate the impact of wave energy converter arrays on wave and flow fields. Sandia is currently assessing the shallow wave climate of the northern California Coast using a validated SWAN model of Monterey Bay and a circulation model of Santa Cruz Bight (as well as the buoy data). Frequency tables of the significant wave height versus peak period will be used to optimize device design and operations. The Northwest National Marine Renewable Energy Center is currently testing wave point absorber array effects in its wave tank facilities at Oregon State University.

From a resource assessment standpoint, a specific set of design parameters and modeling methods are needed in order to estimate what portion of the theoretical resource can actually be captured by a specific technology. Known as the technical resource, assessing this quantity will require models of array effects and other “back effects,” device efficiency data, and cut-in and cut-out parameters. DOE's water power program is filling this need through its reference model effort, which will provide numerical estimates of baseline performance data for six generic MHK device designs (the first three reference models are a wave energy point absorber and two in-stream turbines).

Entries in Table 10 marked “A” indicate that the information is generally available or should become available as part of a renewable energy plant’s standard installation. “E” entries signify that data is expected to be available as part of the MHK plant's installation, and entries noted as “G” are either not currently available or are of questionable accuracy.

Table 10. Technology Design and Validation Requirements and Gaps for MHK Technologies

Information	Availability	Comments
Wind speed (near surface, 10-min average)	A	
Wind direction (near surface 10-min average)	A	
Significant wave height	A	
Significant wave direction	A	
Significant wave period	A	
Tidal variation	A	
Mean current speed	A	
Current velocity distributions (multi-year data sets)	G	This is a gap particularly for subsurface currents
Extreme current velocities	G	
Wave climatologies	G	
Dominant wave period	A	
Current shear (long-term observations)	G	
Subsurface turbulence (long-term observations)	G	
Turbulence intensity	G	Campaign measurements of ocean turbulence have frequently been made, but these are generally episodic rather than characteristic of a particular location
Wake affects	G	
Surface scour	E	
Biofouling (marine growth)	A	
Joint wind, wave height, wave direction distributions	G	
Two-dimensional wave spectrum	G	
Salinity	A	
Water temperature	A	
Vertical current profile	G	
Seabed geology	E	
Seabed scour	E	

IV. Operations Planning and Site Safety

For Wind Energy Technologies

The term "operations" encompasses both the routine activities of wind power generation as well as scheduled or unscheduled maintenance. Over the scope of operations, safety is paramount. While standards for safety are undergoing development for the wind industry (Sharples 2009), there is a long history of best practices developed for work on oil rigs and other marine platforms that are applicable.

For wind power generation, the primary information needed for planning are the wind and associated power forecasts. These are required for the day-ahead and real-time power forecasts that must be provided to independent system operators. In addition to these conventional forecasts, very short-term forecasts, which are essentially extrapolations from remote sensing systems such as LIDAR, present a developing opportunity for adaptive operation of individual turbines to increase turbine and wind plant efficiency. In addition, the presence or potential presence of icing conditions may indicate curtailment of operations.

For extreme events such as hurricanes, accurate track and wind field forecasting are needed to plan for system downtime and post-event damage assessment, or to evacuate installation or maintenance teams.

For maintenance planning, both forecasts and historical information are needed. Historical information in the form of statistical distributions provides an indication of the best weather conditions that can be expected to occur on required maintenance intervals. Thus, procedures can be developed to routinely and safely work in those conditions. In addition, forecasts identify specific windows of opportunity for maintenance procedures.

There are a variety of aspects of the environment that affect the safety of operations. For working at heights, wind is a primary issue. Icing is also an issue for working on exposed surfaces as well as being a physical hazard for workers if accreted ice is dislodged from the turbine. For worker exposure, temperature, humidity, and lightning potential are additional factors. Sea state determines the ability to safely access individual turbines for maintenance.

For MHK Technologies

Once MHK deployments and maintenance become routine, the accuracy and timely delivery (within minutes) of weather and sea state observations will be important. Analogous to wind energy, MHK will need to be scheduled for delivery to the grid. Thus, forecasting of waves, tides, and currents is important for MHK operations. Safety in operations requires much the same information for MHK as for wind.

Specific Information Needs and Gaps for Both Wind and MHK Plants

Near-Surface Wind Speed

Near-surface wind speed, typically available from buoys, has several applications for safety and operations planning for renewable energy plant installations. Real-time values (e.g., current reading or most recent 10-min average) allow adapting to conditions to ensure safe access to towers and other platforms from vessels and to ensure worker safety in exposed locations. Metocean buoys are widely separated, and it is likely that the nearest existing buoy will be many tens of kilometers from any particular renewable energy plant. However, for real-time data at the location of a wind plant, it is cost-effective to deploy a metocean buoy, and the current quality of information from this source is adequate for these purposes.

Forecasts to 24 hour or longer are important for scheduling management and operating activities. General forecasts of surface winds are routinely provided offshore out to 7 days by the National Weather Service. There is more uncertainty in this information, however, primarily owing to the almost complete absence of upper-air data to initialize the weather forecast models offshore. Finally, the general absence of validation data for specific locations means that there may be systematic errors caused by coastal effects on winds that remain undetected.

The long-term frequency distribution of surface wind speed, or of joint wind speed and wave height, is useful as a context for planning operations. The distribution allows inferences about the likelihood that conditions will be better (or worse) than current or near-term-forecast conditions for executing operational activities. Because of the lack of observations offshore, these distributions must be largely developed from multiyear runs of weather forecast models, and thus there is significant uncertainty in these distributions for many areas.

Seasonal forecasts can be obtained from the Climate Forecast System, which is a climate prediction model that runs the NCEP, or a similar numerical weather prediction models. Such forecasts provide a broad indication of how the winds for an upcoming season are likely to deviate from the long-term mean in a particular area and provide supplemental information to the frequency distribution.

Near-Surface Wind Direction

Measurements of real-time near-surface wind direction are useful for guiding operations where wind direction is a significant consideration for safe vessel operation. As in the case of wind speed, metocean buoys can currently provide adequate measurements for such purposes.

Precision and accuracy in near-term forecasts of wind direction are generally less critical for operations than wind speed. Current forecast models likely provide adequate information for operational and safety purposes.

Hub-Height Wind Speed

Real-time measurements of hub-height wind speed are conventionally available from nacelle-mounted anemometers. These measurements are degraded in accuracy by flow distortion around the structure of the turbine itself, although they are generally corrected in terrestrial operation using meteorological masts or other reference data. Offshore, there is little reference data available. However, for real-time safety needs, their accuracy is adequate.

A key additional use for real-time, hub-height wind speed (together with wind direction), is to adjust the configuration of individual turbines for optimum and safe operation as wind speed and direction change. The in situ anemometers mounted on the nacelle are used for this purpose; significant improvements may be achieved if true inflow measurements of wind and turbulence from devices such as nacelle-mounted, forward-looking LIDARs become available.

Near-term forecasts of wind speed, and ultimately power production, are an essential input for wind plant operational planning. Currently, forecasts of hub-height winds in the offshore environment have had limited validation, and these forecasts are necessary for plant energy commitments; nevertheless these forecasts are necessary for wind energy plant commitments.

Seasonal forecasts of hub-height winds may be useful for hedging resources, but this would need to be done within the broad uncertainties described for the surface wind speeds.

Hub-height wind speed has no direct impact on MHK operations.

Hub-Height Wind Direction

In real time, knowledge of hub-height wind direction is needed to determine the appropriate yaw for each turbine. Nacelle measurements are generally adequate for this purpose, flow distortion effects notwithstanding. Forecasts of direction may also be useful for scheduling if there is a significant wind directional dependence of overall plant efficiency.

Air Temperature

Real-time air temperature is needed for safety to assess the thermal exposure risks for workers and the possibility of structural icing in cold weather. Because of the possibility of strong vertical temperature gradients in dynamic weather conditions, temperature information is needed both at the surface and at turbine hub height.

Day-ahead temperature forecasts are also needed for scheduling, because large but realistic changes in temperature can change air density by more than 5% with a corresponding change in power output for the same wind speed.

Atmospheric temperature is routinely accurately measured and sufficiently accurately forecasted such that useful values should be expected to be available to offshore wind plants.

Surface Barometric Pressure

Atmospheric surface pressure is needed in addition to temperature in order to compute air density. In dynamic weather conditions, atmospheric pressure changes should cause less than a 3% change in air density over a 24-hr period. Barometric pressure is routinely measured and forecasted with adequate accuracy for renewable energy applications.

Precipitation (Including Type)

Real-time precipitation information is needed to assess evolving safety hazards associated with slippery surfaces and, in cold temperatures, with ice accretion on turbine blades and towers. The likely most useful sources of this information are coastal NOAA weather radars. With a scanning range of several hundred kilometers, these systems cover the outer continental shelf to provide detailed areal maps of significant precipitation events, including whether the precipitation is frozen.

Near-term forecasts of precipitation are produced by the same numerical weather prediction models that are used to forecast wind and are similarly subject to errors arising from errors in the model initialization fields. The forecast accuracy needed to account for safety in operational planning, however, is likely less than the wind accuracy required for scheduling.

Lightning

Lightning detection is primarily related to safety in operations. Real-time maps of the location of lightning activity are routinely available, notably from Vaisala’s National Lightning Detection Network. Lightning detection is valid for marine as well as terrestrial locations.

Near-term forecasting of lightning is a consequence of forecasts of convection from numerical weather prediction models, and this information is currently available for use in operations planning.

Visibility

Visibility is largely unrelated to scheduling, but it is significant for safe operations. Real-time visibility measurements are available from routinely available instrumentation. Ceiling and visibility forecasting has significant uncertainties and remains an area of active research associated in particular with the airline industry.

Ice Loading

Ice loading is an issue for operations for all offshore renewable energy types in regions where significant ice thicknesses develop in wintertime operations. Ice loading on structures remains an active area of research. In the presence of ice loads, operations must be modified according to the best understanding of potential failure modes of the renewable energy systems.

Significant Wave Height

Significant wave height and direction are needed for safe access to structures and for power scheduling for MHK plants. At present, this information is readily measured from buoys in real time and is well forecast by models such as WAVEWATCH III.

Joint Wind, Wave-Height, and Wave-Direction Distributions

The historical distributions of wind speeds, wave heights, and wave directions have been individually developed for many locations. However, the joint observation of these quantities to assess how they might occur together is much rarer. For example, it is helpful for planning purposes to know what kind of sea state is likely to occur with a particular wind forecast in a particular location.

Tidal Variation

For safe access to structures, tidal forecasts are routinely available.

Currents

Currents, both tidal and non-tidal, can be readily monitored in real time with devices such as acoustic Doppler current profilers. Near-term current forecasts are available from a variety of sources ranging from the National Weather Service's Ocean Prediction Center to private sources that use satellite altimeter data and other information in proprietary models.

Salinity and Water Temperature

Salinity and water temperature are needed to determine water density as an input for power scheduling for MHK devices.

Summary of Information Requirements for Operations Planning and Site Safety

Tables 11 through 13 summarize specific information needed for operations planning, adaptive operations and site safety. Entries marked “A” indicate that the information is generally available or should become available as part of a renewable energy plant’s standard installation. “E” entries signify that data is expected to be available as part of the wind or MHK plant's installation. Entries noted as “G” are either not currently available or are of questionable accuracy.

Table 11. Operations Planning Information Requirements and Gaps

Information	Real-Time	Near-Term to Day-Ahead	Seasonal Forecast	Frequency Distribution
Near-surface wind speed (10-min average)	—	A	G	G
Near-surface wind direction (10-min average)	—	A	—	—
Hub-height wind speed (10 min)	—	G	G	—
Hub-height wind direction (10 min)	—	A	—	—
Air temperature	—	A	—	—
Atmospheric pressure	—	A	—	—
Precipitation (including type)	—	A	—	—
Lightning	—	G	—	—
Visibility	—	E	—	G
Ice loading	E	A	A	—
Significant wave height, direction	—	A	—	A*
Joint wind, wave-height, wave-direction	—	E	—	G
Tidal variation	—	A	A	A
Currents	E	G	G	G*
Salinity	E	—	—	A*
Water temperature	—	A	—	—

* Indicates that long-term mean values should be sufficient for planning operations.

Table 12. Adaptive Operations Information Requirements and Gaps

Information	Real-Time	Near-Term to Day-Ahead	Seasonal Forecast	Frequency Distribution
Near-surface wind speed (10-min average)	E	—	—	—
Near-surface wind direction (10-min average)	E	—	—	—
Hub-height wind speed (10 min)	E	E	—	—
Hub-height wind direction (10 min)	E	E**	—	—
Air temperature	E	—	—	—
Atmospheric pressure	E	—	—	—
Precipitation (including type)	E	—	—	—
Significant wave height, direction	E	—	—	—
Currents	E	—	—	—
Salinity	E	—	—	—
Water temperature	E	—	—	—

**Near-term” refers to the transit time of approaching wind changes that may be detected by forward-facing LIDARs.

Table 13. Site Safety Information Requirements and Gaps

Information	Real-Time	Near-Term to Day-Ahead	Seasonal Forecast	Frequency Distribution
Near-surface wind speed (10-min average)	E	A***	—	—
Near-surface wind direction (10-min average)	E	A	—	—
Hub-height wind speed (10 min)	E	E	—	—
Hub-height wind direction (10 min)	E	E	—	—
Air Temperature	E	A	—	—
Precipitation (including type)	E	A	—	—
Lightning	E	E	—	—
Visibility	E	A	—	—
Ice loading	E	A	—	—
Significant wave height, direction	E	A	—	—
Currents	E	—	—	—
Water temperature	E	—	—	—

*** The difference between E in column 1 and A in column 2 is that column 1 (real-time data) depends on measurements at the plant to ensure the most accuracy. Much of the information in column 2 is available from current NOAA forecasts with an accuracy that will allow the avoidance of near-term and potentially dangerous situations, such as rapidly increasing winds or wave fields.

V. Forecasting

For Wind Energy Technologies

The ability to forecast (or hindcast) meteorological conditions relevant to wind energy using numerical weather prediction models is implicit in current design and operation standards. However, standards are not specified for the models themselves or for the information required to establish their boundary and initial conditions. This is partly a result of remaining uncertainty in the representation of physical processes that act on shorter periods and over smaller distances than are resolved by these models. It is also because observations to initialize these models are largely lacking over the ocean. Because the ability to forecast underpins much of the work of resource assessment and the establishment of design conditions offshore, this section focuses on the information needs for the forecasting process itself. More than for other applications, filling many of the information gaps to enable successful forecasting will require new research and development.

Complexity of Offshore Meteorology

Forecasting winds and turbulence for offshore wind turbines is challenging because of the many complex meteorological phenomena that exist in the coastal zone. These phenomena are driven by the sharp changes in temperature, humidity, and roughness between land and water at the coastal boundary, and (for many locations) by near-coastal topography as well. These phenomena include complex flows such as sea and land breeze circulations, low-level wind jets, winter cold-air outbreaks, and coastal fronts.

Thermally driven circulations such as the land and sea breeze are influenced by the Earth's rotation and the preexisting large-scale flow, leading to variable times of onset and peak circulation. Land and sea-breeze circulations have a jet-like maximum wind level above which speeds decrease with height, and they can be topped by a return flow layer. Summer thunderstorms can form on their boundaries, with outflows that can spawn additional convection or provide high cloud cover that can effectively eliminate the thermal forcing and stop the sea-breeze circulation. Areas off the west coast have relatively cold water offshore that creates a marine layer with fog and thick stratus clouds that can complicate the wind forecast depending on the background weather pattern, coastal terrain, and inland desert heating.

Coastal-zone thermal and humidity contrasts also provide the forcing associated with the genesis of marine winter cyclones that rapidly amplify over warmer water. Prefrontal southerly flows in the winter and spring are associated with stable flows, low-level jets, and large wind shears, while post-frontal cold-air outbreaks are known to occur with strong air-sea contrasts (cold air over warm water), enhanced turbulent vertical mixing, and instability. Offshore flow in the summer months also results in stably stratified shallow internal boundary layers, characterized by large shears in the turbine layer, with little known about their vertical structure or their offshore extent.

Tropical cyclones bring distinct risks to the Atlantic and Gulf of Mexico coasts, but little is known about hurricane wind exceedance probabilities because long term records suffer when anemometers fail or are affected by exposure problems. Stochastic risk models (e.g., Powell et al. 2005) rely on statistical properties of the observed tropical cyclone activity in a particular area and are applicable for constructing return period wind maps. Turbulent wind shear and direction change properties as a function of height. The aerodynamic roughness of the sea surface depends on wave conditions, and this roughness affects air-sea momentum exchange and the vertical profile of wind. Roughness tends to increase with wind speed until it levels off and decreases as winds pass hurricane speeds, but most studies have been based on deep water observations. Offshore wind turbines will be placed in regions with shallow water and shoaling waves, with little known about how stress and roughness vary with wind speed. The impact of nonequilibrium surface ocean waves that are traveling orthogonal to or in the opposite direction to the near surface winds is poorly understood, yet their potential to alter the near-surface wind speed profile is significant.

Finally, coastal topography can act as a barrier, especially to stably stratify marine air, forcing eddies, gap winds, and waves in the atmosphere that can lead to high spatial variability of turbine-height wind speeds and turbulence.

Thus, a wide variety of flow conditions with a significant range of space and time scales must be properly characterized in Numerical Weather Prediction (NWP) models to accurately forecast offshore turbine height winds.

Forecasting Challenge: Accurately Capturing the Complexity

Forecasting for the coastal zone is also complicated by the variable nature of the ocean, including sea surface temperatures (SSTs), near-surface currents, and the full spectrum of surface waves. For shorter-term forecasts, the influence of the ocean may be adequately captured by a static initial ocean state (especially for SSTs), but at longer ranges it may be necessary to run fully coupled atmosphere-ocean-wave models that can capture changes to the ocean state over the forecasted timeframe.

Forecasting of winds in the coastal zone may be limited by the inability of presently used model parameterizations to represent all of the important sub-grid-scale processes that occur. Examples include not only air-sea interaction, but also turbulent mixing, boundary-layer fog/cloud dynamics, and the dynamics of shallow internal boundary layers in offshore flow.

Forecasting for the coastal zone will also require much higher resolution models than those that are presently operational and perhaps even higher resolution than prototype NWP models presently run in a developmental stage. For example, many wind turbines are likely to be placed within 10 kilometers of the coast, and yet winds can vary by a significant amount over this short distance due to the sea breeze and other coastal meteorological phenomena. To fully characterize this small spatial scale variability to the accuracies required for wind energy will likely require models with sub-kilometer horizontal resolution and very high vertical resolution as well. In addition, forecast models may be required to properly account for the effects of large arrays of turbines in multiple closely spaced wind farms in order to properly forecast wakes that can persist for long distances in the stably stratified, low-turbulence marine boundary layer.

In addition to these forecasting challenges that are specific to the coastal zone, other challenges exist that NWP developers are faced with for all environments. In particular, significant progress in improving and implementing advanced data assimilation techniques could greatly improve offshore wind forecasts. In addition, a better use of ensembles and probabilistic techniques could also improve these forecasts. Finally, a better understanding of model errors, and methods to apply corrections for these errors, perhaps through reforecast techniques, could especially improve the forecast skill of relatively rare (or extreme) meteorological events.

Forecasting Challenge: Lack of Observations

Forecasting the complex phenomena that exist in the coastal zone is complicated by the relative lack of observational data (compared to overland locations) that can be used to initialize forecast models through data assimilation. For example, land-based observational systems that play key roles in the initialization of NWP models but that do not exist over the ocean include the following: surface weather stations, balloon-based sounding systems, scanning Doppler radar (e.g., Weather Surveillance Radar, 1988, Doppler [WSR-88D] radars), wind profiling radars, and low-level Aircraft Communications Addressing and Reporting System (ACARS) soundings from commercial aircraft ascents/descents at airports. There are some satellite-derived measurements that can only be taken over the ocean (e.g., surface wind speed from satellite passive microwave, synthetic aperture radar, and scatterometer instruments), but on balance, many fewer and less accurate observations are available over the ocean than over land.

In addition to the need to initialize forecast models, there is also a need to validate them. Just as initialization data are largely absent over the ocean, validation data—particularly at rotor heights—is also essentially nonexistent. Buoys provide some wind information at the surface, but they cannot provide confirmation that models produce accurate winds and turbulence forecasts tens to hundreds of meters above the surface. Similarly, satellite data provides a means to estimate the spatial distribution surface winds over the ocean, but these observations carry significant uncertainty of their own.

Information Needs for Offshore Meteorological Forecasting

For information needs for offshore meteorological forecasting, the gaps outnumber the information that is currently available. While current models produce forecasts offshore, they are weakly initialized in the offshore region and largely unvalidated in their predictions of hub-height meteorology. Moreover, there are known, unsolved problems with the representation of unresolved physical processes in these models. Gaps are described by category below.

Initialization

Ideally, forecast models are initialized with accurate, three-dimensional data fields that cover the model domain. This requires, in particular, accurate information above the surface. As noted above, many of the measurements systems used for this purpose over land, such and wind profiling radars and radiosondes, cannot be readily deployed on a long-term basis over water. Some volumetric scanning systems, such as WSR-88D Doppler weather radars, provide wind measurements above the surface, but their range from shore-based installations does not cover the entire offshore area for which forecasts are needed. Information about temperatures and surface winds (from sea surface roughness) is available from satellites. In general, there are no technologies that can cost-effectively provide the initialization required by forecast models offshore, and what the appropriate suite of technologies should be remains to be determined. Thus **initialization fields** in general for forecast models **represent a significant information gap** for the deployment of wind plants offshore.

Validation

At present, there are no facilities that can validate forecasts of winds and turbulence at turbine rotor heights in U.S. offshore waters. Without this information, it is not possible to quantify the performance of forecast models. Thus, the **absence of accurate meteorological observations at rotor heights** constitutes a serious information gap with respect to forecasting for wind energy.

Physical Processes

Because of the complexity of the atmosphere and its interaction with the sea surface in the coastal environment, it is very likely that forecasting winds accurately will require improvements to the models' representations of physical processes. This particularly affects the choice of space and time resolution and the corresponding algorithms to produce calculations of winds and turbulence in the lowest few hundred meters of the atmosphere. The degree to which current forecasts are in error due to physics errors in the models is not known, largely because of the lack of validation data noted above. Without knowing the current magnitude of the errors, it is also difficult to assess how much the models might be improved. Thus, lack of knowledge of the **optimum representation of physical processes** for forecast models applied offshore is a significant gap.

For MHK Technologies

Resource prediction is distinctly different for wave, tidal stream, and ocean current energy, the three major energy resources. Wave forecasting is relatively advanced because it has been used in a number of other applications, but its use in predicting wave energy generation is nascent and as yet not fully tested. A recent study during summer months found that the existing forecast capabilities of NOAA's WAVEWATCH III model was fully adequate out to 48 hours for providing needed wave energy forecasts when tested on the coasts of Washington and Oregon (Bedard 2008). Tidal elevations are fully predictable years in advance, but the relationship between the tides and tidal current speeds that actually determine in-stream energy generation is not well understood. Detailed hydrodynamic models have been developed for use in certain regions such as Puget Sound that are rich in tidal energy (Yang and Khangaonkar 2010), but this remains a basic research problem, and tidal current speeds are at present measured at specific sites rather than forecast. Assessing the energy in large-scale current systems using surface current measurements is also an area of active research. While many of the most powerful ocean current systems reside far offshore, beyond the practical reach of MHK deployments, the Florida Current, the southern segment of the Gulf Stream, passes within 15 miles of the Florida shoreline.

Information needs are categorically different for wave energy prediction and for other forms of energy. For wave forecasts, the primary inputs needed are winds and surface currents over a broad area of the ocean. The recent evaluation of WAVEWATCH III suggests that these inputs are well-enough known for fully useful forecasts (Bedard 2008). Thus, there **do not appear to currently be significant gaps with respect to wave energy prediction**.

In contrast, the prediction of **tidal and open-ocean subsurface currents** is still a matter of research and development. Thus, for these energy sources, the **information gap is fundamental knowledge of physical processes** needed to develop accurate models for prediction. More actual measurements of tidal and ocean currents are needed to improve and refine the models that we have. The gaps in physics mostly involve the back-effects of large-scale developments on the resource.

Summary of Information Requirements for Forecasting

Entries in Table 14 marked "A" indicate that the information is generally available or should become available as part of a renewable energy plant's standard installation. "E" entries signify that data is expected to be available as part of the wind or MHK plant's installation, and entries noted as "G" are either not currently available or are of questionable accuracy.

Table 14. Summary of Gaps for Forecasting

Information	Availability	Comments
Initialization fields	G	These fields are vector winds, temperature, and other variables that define the starting value of forecast models at each calculation node. They require measurements of the atmosphere at many points in the vertical and horizontal dimensions in order to be accurate. Such measurements do not currently exist over the ocean.
Validation observations at rotor heights	G	Models of necessity contain approximations to actual atmospheric processes and are subject to varying error under various atmospheric conditions and locations. The range of these errors can only be defined by comparison with observations at calculations points of interest. Long-term validation measurements do not exist in U.S. offshore waters.
Best approximations to physical processes	G	Forecast models are generally not oriented to maximum accuracy in near-surface winds. To do this, more knowledge is essential to best represent the physical processes controlling winds at turbine heights.
Wave energy forecasts, deep water	A	WAVEWATCH III is generally regarded as currently providing sufficiently accurate forecasts.
Wave energy forecasts, shoaling zone	G	Current models, such as the Simulating WAves Nearshore (SWAN) model, do not satisfactorily forecast wave energy where bathymetry exerts a controlling influence on wave dimensions and breaking.
Forecasts of tidal and open-ocean subsurface currents	G	A lack of fundamental physical knowledge limits the accuracy of today's current models, which makes them insufficient for MHK purposes.

VI. Gaps Summary

Understanding the breadth and depth of information necessary for effective offshore renewable energy system deployment is no easy task. However, many pieces of information from existing ocean observational networks and atmospheric models used for land-based wind farms are already available. Moreover, experts in offshore renewable energy project siting as well as atmospheric and oceanic scientists have provided key input to this document, which will be used as a springboard to further identify gaps and existing, needed information.

When determining the design of an offshore renewable energy facility, information necessary will be in the form of long-term means or frequency distributions of variables of interest. Furthermore, information about sediment type and bathymetry help define appropriate foundations for offshore wind plants. Some areas of improvement include understanding coupled wind and wave interactions and their impacts on devices, most notably wind turbine foundations, over their anticipated lifespan as well as wake effects for device spacing purposes.

In estimating energy from either a potential wind or MHK project, a developer needs to know the information most relevant to energy capture, such as the average wind speed or wave, current, and tidal frequencies. Additionally, an estimate of energy loss or system downtime from extreme events is needed to accurately describe the long-term revenue stream from a plant. Areas of concern or lack of information include the frequency of extreme events and their potential impacts on energy production, energy loss due to wake effects, and an understanding of precipitation and other particles and their impact on energy production.

For those that design the technology, having sufficient models that reflect accurate marine conditions can provide a platform for improving designs and ultimately system efficiency. For wind energy technologies, IEC 61400-3 provides a guide for how these technologies may withstand these offshore conditions; however, there are significant areas that will require improvement as the marine conditions are better understood, especially for relevance to areas with tropical cyclone risk. For technologies, no standards currently exist, because these technologies are in the early stages of maturation. For both, the potential risk and impacts of extreme events (such as icing, hurricanes, and lightning) on devices are clear areas of improvement.

Weather conditions are most important during the construction and operation and maintenance phases of the project. For operations planning and site safety purposes, most of the current atmospheric and oceanic conditions are readily available; however, being able to predict windows of opportunity for device repair and maintenance can be the biggest challenge.

Forecasting meteorological conditions relevant to wind energy offshore is improving for land-based wind farms; however, the extensive observational networks needed for establishing boundary and initial conditions for models in the offshore environment is significantly lacking. Furthermore, research to understand mesoscale and microscale phenomena in this environment is needed to improve forecasting models. For MHK devices, further fundamental knowledge of physical processes of tidal and open-ocean subsurface currents is needed.

In conclusion, the areas of lacking information needed for effective deployment of offshore renewable energy technologies crosscut these applications, and progress in further defining parameters in one area will likely result in progress in other application areas. As noted in the introduction, a common access point to the disparate information sources that exist or may become available is a critical need to ensure the full usefulness of that information. Such a system does not currently exist.

Tables 15 and 16 summarize some of the key pieces of information, including where information is currently available or where information is expected to become available based on siting and other activities needed for offshore renewable energy development. A gap is indicated where there is no information currently available and there is no expected information to become available. The tables also note some of the existing potential data sources of for currently available information. For further information about some of the existing data sources and associated data, see **Appendix II.** For a preliminary list of existing federal agencies that can supply data for purposes related to this document, see **Appendix III**.

LEGEND	
Gap Type	
A	Data is available at the appropriate scale
E	Data is expected to be available as part of the wind or MHK plant's installation
G	Data is not available nor will it become available as part of wind or MHK plant's installation
-	Not currently essential for this application

Application Type	
FD	Facility Design
EP	Energy Projections
TDV	Technology Design and Validation
OP/SS	Operations Planning and Site Safety
FX	Forecasting

Table 15. Summary of Gaps for All Applications under Wind Energy Technologies

Information Type (Wind)	Gap Type					Notes	Data Source
	FD	EP	TDV	OP/SS	FX		(Organization-Database)
Wind							
Wind speed (near surface, 10-min average)	-	-	-	A/E/G	A	**OP/SS** A: Near-term for planning and site safety; E: Real-time for site safety; G: Seasonal forecasts for planning	NDBC - DODS, WMO-IOC-OSMC, NESDIS - WindSAT
Wind direction (near surface 10-min average)	-	-	-	A	A		NDBC - DODS, WMO-IOC-OSMC, NESDIS - WindSAT
Long-term frequency distributions of wind speed(near surface)	-	-	-	G	-		
In-situ wind speed measurements (hub height)	-	G	-	E/G	E	**EP:** A gap unless the resource assessment campaign installs an offshore met tower to hub height at the site. **OP/SS** E: Real-time and near-term for adaptive and site safety; G: Near-term and Seasonal for planning	

Information Type (Wind)	Gap Type					Notes	Data Source
	FD	EP	TDV	OP/SS	FX		(Organization-Database)
Estimated wind speed (hub-height 10-min average)	G	E	-	G	-	Wind speed and direction can currently be estimated from weather forecast models, but offshore hub-height validation is limited. OP/SS: G is for lack of validated day-ahead to seasonal forecasts.	
Wind direction (hub-height 10-min average)	G	E	-	A	E	See comment above.	
Long-term frequency distributions of wind speed and direction (hub height)	G	E	G	-	-	Inferences regarding the frequency distributions of wind at a particular site will be significantly aided by the resource assessments carried out prior to facility installation. Estimates of return periods for extreme events depend on the accuracy of these distributions.	
Shear (hub-height)	G	G	G	-	-	Shear estimates will become available as part of a facility installation; however, current formulations are prone to systematic errors, so this is considered a gap.	
Vertical wind profiles	-	G	G	-	G	**FX:** Long-term wind profiling measurements do not cover the entire offshore area in which forecasts are needed	
Wind veer	-	G	G	-	G		
Wake and array effects	G	G	-	-	-	**EP:** Following installation of a wind plant, SCADA data can be correlated with plant power output	
Three-dimensional/detailed boundary layer wind field	-	G	G	-	G		
Turbulence intensity (hub height)	G	G	G	-	-		
High fidelity (1m spatial res., 20 Hz temporal res.) measurements across rotor plane	-	-	G	-	-	These are needed to evaluate probabilities of short-duration gusts as well as turbulence intensity.	
Initialization fields	-	-	-	-	G		
Meteorological measurements (hub height)	-	-	-	-	E		

Information Type (Wind)	Gap Type					Notes	Data Source
	FD	EP	TDV	OP/SS	FX		(Organization-Database)
Optimum representation of physical processes	-	-	-	-	G		
Water							
Significant wave height, direction, wave period	A	-	A	A/E	-	**OP/SS** A: Near-term for planning and site safety; E: Real-time for adaptive operations and site safety	NDBC - DODS,WMO-OC-OSMC
Tidal variation	A	-	A	A	-		NDBC - DODS,WMO-IOC-OSMC
Currents	A	-	A	E/G	E	**FD:**IEC standards indicate that surface current is sufficient for wind energy technologies **OP/SS** E: Real-time for planning, adaptive operations, and site safety; G: Near-term, seasonal, and frequency distribution for planning	NDBC - DODS
Biofouling (marine growth)	-	-	A	-	-		NDBC-DODS
Coupled Wind/Wave							
Joint distributions of wind speed with wave heights, directions and periods	G	-	G	E/G	-	**OP/SS** E: Near-term for planning; G: frequency distribution for planning	
Breaking waves	-	-	E	-	-		
Surface and subsurface currents	E		E				
State							
Precipitation type and amount	-	G	G	A/E	-	**EP:** Advanced tools are needed to detect and monitor precipitation and other particles that can detrimentally affect energy production, **TD**: Precipitation information is not available with the specificity that would be useful for design at particular locations. **OP/SS** A: Near-term for planning and site safety; E: Real-time for adaptive and site safety	NDBC-DODS, NESDIS-WindSAT, NESDIS-SSM/I, NESDIS-POES
Humidity	-	E	A	-	E		

Information Type (Wind)	Gap Type					Notes	Data Source
	FD	EP	TDV	OP/SS	FX		(Organization-Database)
Air density	-	E	A	-	-		
Salinity	A	-	A	A/E	-	**OP/SS** A: Frequency distribution - Long-term mean values sufficient for planning; E: Real-time for planning, adaptive, and site safety	NDBC-DODS, WMO-IOC-OSMC
Air temperature	A	A	A	A/E	A	**OP/SS** A: Near-term for planning and site safety; E: Real-time for planning, adaptive, and site safety. FX: Air temperature is available, but not densely enough to generate accurate details in model initialization fields.	NESDIS-WindSAT
Atmospheric pressure	A	A	A	A/E	A	**OP/SS** A: Near-term for planning and site safety; E: Real-time for planning, adaptive, and site safety	NDBC-DODS,WMO-IOC-OSMC,
Water temperature	A	-	A	A/E	A	**OP/SS** A: Near-term for planning and site safety; E: Real-time for adaptive, and site safety	NDBC-DODS
Vertical temperature profiles	-	E	G	-	G	**FX**: This is a gap given the density needed to create high-fidelity model initialization fields.	
Visibility	-	-	-	A/E/G	-	**OP/SS** A: Near-term for site safety; E: Real-time for adaptive and site safety, near-term for planning; G: Frequency distribution for planning	NDBC-DODS
Geophysical/Geotechnical							
Bathymetry	A	-	A	-	-		NOAA-NGDC
Seabed geology	-	-	E	-	-		
Seabed scour	E	-	E	-	-		
Atypical							
Hurricane	E	E	E	E	-	There is currently information on the probability of an extreme event occurring at a specific location, however impacts from such events on these technologies is relatively unknown.	
Lightning	E	-	E	E	-	See comment above	Vaisala's National Lightning Detection Network, NESDIS-WindSAT

Information Type (Wind)	Gap Type					Notes	Data Source
	FD	EP	TDV	OP/SS	FX		(Organization-Database)
Ice loading, ice accretion	E	E	E	A/E	-	**FD:** While ice loading information is not currently compiled for specific sites, currently available databases should allow for such estimates. **OP/SS** A: Near-term and seasonal for planning; E: Real-time for planning and site safety	NESDIS-ASCAT, NESDIS-WindSAT, NOAA - National Ice Center
Seismicity/earthquakes	-	-	-	-	-	Not addressed in text above but an important consideration	NOAA-NGDC
Tsunami	-	-	-	-	-	See comment above	NOAA-NGDC

Table 16. Summary of Gaps for All Applications under MHK Technologies

Information Type (MHK)	Gap Type					Comment	Data Source
	FD	EP	TDV	OP/SS	FX		(Organization-Database)
Wind							
Wind speed (near surface, 10-min average)	A	A	A	A	A		NDBC - DODS, WMO-IOC-OSMC, NESDIS - WindSAT
Wind direction (near surface 10-min average)	A	A	A	A	A		NDBC - DODS, WMO-IOC-OSMC, NESDIS - WindSAT
Water							
Significant wave height	A	A	A	A	-	**OP/SS:** Frequency distributions are needed	NDBC - DODS,WMO-IOC-OSMC
Significant wave direction	A	A	A	A	-	**OP/SS:** Frequency distributions are needed	NDBC - DODS,WMO-IOC-OSMC
Significant wave period	A	A	A	-	-	**OP/SS:** Frequency distributions are needed	NDBC - DODS
Tidal variation	A	A	A	A	A		NDBC - DODS,WMO-IOC-OSMC
Mean current speed	A	A	A	A	-		NDBC - DODS
Current velocity distributions (multi-year data sets)	-	G	G	-	G	This is a gap particularly for subsurface currents.	
Open-ocean subsurface currents	-	-	-	-	G		
Extreme current velocities	-	G	G	-	-		
Wave climatologies	-	G	G	-	-		
Dominant wave period	-	A	A	-	-		NDBC - DODS
Current shear (long-term observations)	-	G	G	-	-		
Subsurface turbulence (long-term observations)	-	G	G	-	-		
Turbulence intensity	-	G	G	-	-	Campaign measurements of ocean turbulence have frequently been made, but these are generally episodic rather than characteristic of a particular location.	

Information Type (MHK)	Gap Type					Comment	Data Source
	FD	EP	TDV	OP/SS	FX		(Organization-Database)
Wake affects	-	G	G	-	-		
Surface scour	E	E	E	-	-		
Biofouling (marine growth)	-	-	A	-	-		NDBC-DODS
Coupled Wind/Wave							
Joint wind, wave height, wave direction distributions	G	-	G	G	-	**OP/SS:** Frequency distributions are needed	
Two-dimensional wave spectrum	G	-	G	-	-	**OP/SS:** Frequency distributions are needed	
State							
Precipitation type and amount	-	-	-	E	-		NDBC-DODS, NESDIS-WindSAT, NESDIS-SSM/I, NESDIS-POES
Salinity	A	A	A	A	-		NDBC-DODS, WMO-IOC-OSMC
Air temperature	-	-	-	A	-		NESDIS-WindSAT
Water temperature	A	E	A	A	A		NDBC-DODS
Vertical temperature stratification	-	E	-	-	E	**FX:** Vertical temperature structure may be difficult to obtain over broad areas.	
Visibility	-	-	-	A	-		NDBC-DODS
Vertical current profile	E	G	G	E	G		
Geophysical/Geotechnical							
Bathymetry	A	A	A	A	-		NOAA-NGDC
Seabed geology	-	-	E	-	-		
Seabed scour	E	-	E	-	-		

Information Type (MHK)	Gap Type					Comment	Data Source
	FD	EP	TDV	OP/SS	FX		(Organization-Database)
Atypical							
Hurricane	E	E	E	E	-	There is currently information on the probability of an extreme event occurring at a specific location, however impacts from such events on these technologies is relatively unknown.	
Lightning	E	-	E	E	-	See comment above	Vaisala's National Lightning Detection Network, NESDIS-WindSAT
Ice loading	E	E	E	E		See comment above	NESDIS-ASCAT, NOAA-National Ice Center
Seismicity/earthquakes	-	-	-	-	-	Not addressed in text above but an important consideration	NOAA-NGDC
Tsunami	-	-	-	-	-	See comment above	NOAA-NGDC

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APPENDIX

I. Design Conditions and Parameters

Below is a table categorizing specific design conditions (from IEC 61400-3:2005, *Wind turbines – Part 3: Design requirements for offshore wind turbines*) into general conditions. An initial list of observational or modeling parameters needed to inform the design condition is provided. The list below is an initial attempt to align parameters with design conditions appropriate for offshore renewable energy deployment; however, more observational and modeling parameters are needed to fulfill the design requirements. Furthermore, there may be other design conditions not identified here that are applicable.

Table I-1. Design Conditions and Parameters

Condition	Design Condition	Parameter
Typical Wind Conditions	Turbulence intensity as a function of mean wind speed used for the Normal Turbulence Model and Extreme Turbulence Model	Average wind speed
		Need to define other observational parameters for model
	Annual average wind speed (at hub height) [m/s]	Average wind speed
	Average inclined flow [º]	Wind flow inclination angle
	Wind speed distribution (Weibull, Rayleigh, measured, other)	Average wind speed
	Normal wind shear model and parameters	Average wind speed
	Turbulence model and parameters	*Need to define observational parameters for model*
	Wind direction distribution (wind rose)	Wind direction
Extreme Wind Conditions	Hub height extreme wind speeds *V*e1 and *V*e50 [m/s]	Maximum wind speed
	Extreme gust model and parameters for 1/50/100-year recurrence periods	Maximum wind speed
		Other parameters observations used in modeling
	Extreme direction change model and parameters for 1/50/100-year recurrence periods	*Need to define observational parameters for model*
	Extreme coherent gust model and parameters	Maximum wind speed
		Need to define observational parameters for model
	Extreme coherent gust with direction change model and parameters	Maximum wind speed
		Need to define observational parameters for model
	Extreme wind shear model and parameters	Extreme wind speeds (50- and 100-year return period)
		Need to define observational parameters for model
Typical Ocean	Highest astronomical tide [m]	*Maximum sea level height*

Condition	Design Condition	Parameter
Conditions	Lowest astronomical tide [m]	*Minimum sea level height*
	Highest still water level [m]	*Maximum still water height*
	Lowest still water level [m]	*Minimum still water height*
	Significant wave height for 1-, 50-,100-year recurrence periods [m]	Average wave height
	Range of peak periods for 1-, 50-, 100-year recurrence periods [s]	Max and minimum wave periods
	Wind and wave joint distribution (Hs,Tp,V) including directionality	
	Wave spectrum and parameters	Wave height
		Wave period
		Wave direction
	Deterministic wave model and parameters	*Need to define observational parameters for model*
	Breaking wave model and parameters	*Need to define observational parameters for model*
		Current velocity
		Current direction
		Current depth
Atypical Ocean Conditions	Individual extreme wave height for 1-, 50-. 100-year recurrence periods [m]	Maximum wave height
	Range of associated wave periods for 1-, 50-, 100-year recurrence periods [s]	Average wave period
	Extreme crest height with a recurrence period of 50 and 100 years [m]	*Maximum wave height*
	Extreme sea surface current for 1-, 50-, 100-year recurrence periods [m/s]	Maximum current velocity
	Tidal variation and/or storm surge (50- and 100-year recurrence period) [m]	*Need to define observational parameters for model*
Atypical Environmental Conditions	Extreme air temperature ranges [°C]	Air temperature
	Extreme sea temperature ranges [°C]	Ocean temperature
	Sea ice conditions	*Need to determine parameters that determine these conditions*
	Rain, hail, snow, and icing	Precipitation
		Temperature, air density, humidity
	Hurricane models	
	Earthquake model and parameters (description)	*Need to define observational parameters for model*
	Lightning protection system	
Atmospheric Base State	Air density [kg/m^3]	Atmospheric pressure
		Air temperature

Condition	Design Condition	Parameter
Conditions	Solar radiation [W/m^2]	Solar radiation
	Atmospheric pressure	
	Normal air temperature	
	Humidity %	Humidity
	Chemically active substances	
	Mechanically active particles	
Marine Subsurface Conditions	Local and global scour or sum of both (maximum allowed) [m]	*Need to determine parameters that determine these conditions*
		Geotechnical characteristics *(more information needed)*
	Sea floor level variation (maximum allowed) [m]	Ocean depth
	Normal sea temperature ranges	
	Water density [kg/m^3]	Water temperature
		Water salinity
	Salinity [g/m^3]	Water salinity
	Marine growth profile and thickness [mm]	
Other Conditions	Maximum water level variation [m]	Sea level height
	Permitted atmospheric temperature [°C]	Air temperature
	Maximum wind speed for maintenance [m/s]	Maximum wind speed
	Displacement of transport vessel [metric tons]	

II. Existing Data Sources

Table II-1 outlines existing data sources for parameters required for resource assessment and design conditions parameters. This is an initial search for data sets and databases that contain observational or modeling parameters required for design conditions taken from IEC 61400-3:2005, *Wind turbines – Part 3: Design requirements for offshore wind turbines*. When collecting data sources, only national and global efforts from government agencies were considered; this inventory of existing data sources does not include regional or local efforts, or research programs through universities or industry. This inventory is not comprehensive. Rather, it provides an initial framework for continued research into existing data sources.

Notes:

- Wind speeds are listed as "Typical Wind Conditions" regardless of whether maximum wind speeds can be calculated from them (i.e., as "Extreme Wind Conditions").
- Some information could not be found to fully detail each data set.
- One significant gap in this data search is the height at which wind measurements are taken, which is frequently not stated explicitly.

Table II-1. Detailed Inventory of Data Sources Found, Arranged by Variable and Condition

Condition	Variable	Database	Service	Notes	Resolution	Type of Msmt	Method/ Instrument	Link
Typical wind conditions	Directional ambiguity	(ASCAT)	National Environmental Satellite Data and Information Center(NESDIS)			Satellite		
Typical wind conditions	Experimental COASTAL wind vectors	ASCAT	NESDIS	pre-operational	25 km	Satellite		
Typical wind conditions	Global ambiguity	QuikSCAT / SeaWinds	NESDIS	Discontinued: 1999–2010	3 km	Satellite	Scatterometer	
Typical wind conditions	Global ambiguity	WindSAT	NESDIS	Launched in 2004	25 km	Satellite	Polarimetric microwave radiometer	http://www.nrl.navy.mil/WindSat/index.php
Typical wind conditions	New GMF testing wind vectors	ASCAT	NESDIS		50 km, 25 km	Satellite		
Typical wind conditions	NRT testing wind vectors	ASCAT	NESDIS			Satellite		
Typical wind conditions	Surface current vectors	National Data Buoy Center (NDBC)	National Oceanic and Atmospheric Administration (NOAA)		6 km, 2 km, 1 km, 500 m	Coastal to 300 km offshore	High-frequency radar	Download from website
Typical wind conditions	Surface winds	(POES)	NESDIS		8 km, 3–12 h	Satellite	DMSP Special Sensor Microwave Imager imagery	File transfer protocol (FTP) site–text, MDFile
Typical wind conditions	Ultra-high resolution winds (gom)	ASCAT	NESDIS			Satellite		
Typical wind conditions	Wind direction	(OSMC)	World Meteorological Organization - Intergovernmental Oceanographic Commission (WMO-IOC)	WMO-IOC (looking at data since 2008)	Varies	In situ	Drifting buoys, ships, moored buoys, shore and bottom station	Geographic display application on website

Condition	Variable	Database	Service	Notes	Resolution	Type of Msmt	Method/ Instrument	Link
Typical wind conditions	Wind direction and speed	DODS	NDBC	NOAA > (NWS) > NDBC > Distributed Oceanographic Data Systems (DODS)			Continuous winds data set	http://dods.ndbc.noaa.gov/thredds/catalog/data/catalog.html
Typical wind conditions	Wind direction and speed	DODS	NDBC	NOAA > NWS > NDBC > DODS			Standard meteorological data set	http://dods.ndbc.noaa.gov/thredds/catalog/data/catalog.html
Typical wind conditions	Wind speed	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	Varies	In situ	Drifting buoys, ships, moored buoys, shore and bottom station	Geographic display application on website
Typical wind conditions	Wind speed and direction	ASCAT	NESDIS		25 km, 12.5 km	Satellite	Scatterometer on Eumetsat's MetOp satellite	http://www.knmi.nl/scatterometer/ascat_ear_25_prod/ascat_app.cgi#description
Typical wind conditions	Wind speeds	Special Sensor Microwave /Imager (SSM/I)	NESDIS		25 km at 19.5 m height	Satellite		
Typical wind conditions	Wind speeds	Shared Processing Products	NESDIS			Satellite	DMSP plus POES, ingested by NOAA	
Typical wind conditions	Wind speeds	OSTM	NESDIS		300 m	Satellite	Altimetry	FTP site
Typical Wind Conditions	Wind vectors	QuikSCAT /SeaWinds	NESDIS	Discontinued: 1999–2009	25 km, 12.5 km	Satellite	Scatterometer	http://manati.orbit.nesdis.noaa.gov/products/QuikSCAT.php
Typical wind conditions	Wind vectors	WindSAT	NESDIS	Launched in 2003	25 km	Satellite	Polarimetric microwave radiometer	http://www.nrl.navy.mil/WindSat/index.php
Typical wind conditions	Wind vectors	ERS-2	NESDIS		25 km	Satellite		
Extreme wind conditions	Gust direction and speed gust time	DODS	NDBC	NOAA > NWS > NDBC > DODS			Peak winds	http://dods.ndbc.noaa.gov/thredds/catalog/data/catalog.html

Condition	Variable	Database	Service	Notes	Resolution	Type of Msmt	Method/ Instrument	Link
Extreme wind conditions	Gust speed	DODS	NDBC	NOAA > NWS > NDBC > DODS			Standard meteorological data set	http://dods.ndbc.noaa.gov/thredds/catalog/data/catalog.html
Typical ocean conditions	Meteorological residual tidal elevation	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	Varies	In situ	None	Geographic display application on website
Typical ocean conditions	Tidal elevation WRT local chart datum	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	Varies	In situ	Shore and bottom stations	Geographic display application on website
Typical ocean conditions	Water direction and speed	DODS	NDBC	NOAA > NWS > NDBC > DODS		In situ	Acoustic Doppler current profilers (ADCP) and MMS ADCP data set	http://dods.ndbc.noaa.gov/thredds/catalog/data/catalog.html
Typical ocean conditions	Water direction and speed	DODS	NDBC	NOAA > NWS > NDBC > DODS			Marsh-mcbirney current measurements data set	http://dods.ndbc.noaa.gov/thredds/catalog/data/catalog.html
Typical ocean conditions	Water level	DODS	NDBC	NOAA > NWS > NDBC > DODS			Water level	http://dods.ndbc.noaa.gov/thredds/catalog/data/catalog.html
Typical ocean conditions	Wave density and direction	DODS	NDBC	NOAA > NWS > NDBC > Distributed Oceanographic Data Systems DODS			Spectral wave density and direction	http://dods.ndbc.noaa.gov/thredds/catalog/data/catalog.html
Typical ocean conditions	Wave height	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	Varies	In situ	Ships (limited), moored buoys, shore and bottom station	Geographic display application on website
Typical ocean conditions	Wave height, dominant wave period, average wave period, mean wave direction, water level	DODS	NDBC	NOAA > NWS > NDBC > DODS			Standard meteorological data set	http://dods.ndbc.noaa.gov/thredds/catalog/data/catalog.html

Condition	Variable	Database	Service	Notes	Resolution	Type of Msmt	Method/ Instrument	Link
Atypical ocean conditions	Sea surface height—for tsunami prediction	DODS	National Geophysical Data Center (NGDC)	dart 1 2003–2008, dart 2 2008-–present	15 s, transmitted differently for standard and event cases	Calculated	Dart– system of anchored bottom pressure recorders	
Atypical environmental conditions	Ice	QuikSCAT /SeaWinds	NESDIS	Discontinued: 1999–2012		Satellite	Scatterometer	
Atypical environmental conditions	Ice	ASCAT	NESDIS			Satellite		
Atypical environmental conditions	Rain	WindSAT	NESDIS	Launched in 2006	25 km	Satellite	Polarimetric microwave radiometer	http://www.nrl.navy.mil/WindSat/index.php
Atypical environmental conditions	Rain	SSM/I	NESDIS			Satellite		
Atypical environmental conditions	Rain rate	POES	NESDIS		8 km, 3-–12 h	Satellite	DMSP SSM/IS imagery	FTP site–text, MDFile
Atypical environmental conditions	Rain rate	POES	NESDIS		8 km, 3–12 h	Satellite	(AMSU) microwave imagery	FTP site–text, MDFile
Atypical environmental conditions	Rain rate	Shared Processing Products	NESDIS			Satellite	DMSP plus POES, ingested by NOAA	
Atypical environmental conditions	Significant earthquakes	NGDC	NGDC	NGDC (NOAA)		Various		http://maps.ngdc.noaa.gov/viewers/hazards/?layers=4
Atypical environmental conditions	Significant volcanoes	NGDC	NGDC	NGDC (NOAA)		Various		http://maps.ngdc.noaa.gov/viewers/hazards/?layers=5
Atypical environmental conditions	Storm	QuikSCAT /SeaWinds	NESDIS	Discontinued: 1999-–2011	25 km for wind retrievals	Satellite	Scatterometer	
Atypical environmental conditions	Storm	ASCAT	NESDIS			Satellite		

Condition	Variable	Database	Service	Notes	Resolution	Type of Msmt	Method/ Instrument	Link
Atypical environmental conditions	Storm	WindSAT	NESDIS	Launched in 2005	25 km	Satellite	Polarimetric microwave radiometer	http://www.nrl.navy.mil/WindSat/index.php
Atypical environmental conditions	Tsunami events	NGDC	NGDC	NOAA	15 s, transmitted differently for standard and event cases	Various	Eyewitness, bottom pressure recorders, tide gauge, deep ocean gauge, post tsunami survey, saiche or atmospheric wave pressure	http://www.ngdc.noaa.gov/nndc/struts/results?&t=102597&s=1&d=1
Atmospheric base-state conditions	85 Ghz radiance	POES	NESDIS		8 km, 3–12 h	Satellite	DMSP SSM/IS imagery	FTP site–text, MDFile
Atmospheric base-state conditions	89 Ghz radiance	POES	NESDIS		8 km, 3–12 h	Satellite	AMSU microwave imagery	FTP site–text, MDFile
Atmospheric base-state conditions	Air pressure air temperature dew point temperature	DODS	NDBC	NOAA > NWS > NDBC > DOD			Standard meteorological data set	http://dods.ndbc.noaa.gov/thredds/catalog/data/catalog.html
Atmospheric base-state conditions	Air temperature	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	varies	In situ	Drifting buoys (limited), ships, moored buoys, shore and bottom station	Geographic display application on website
Atmospheric base-state conditions	Cloud fraction by altitude	Multiangle Imaging Spectro-Radiometer (MISR)	Atmospheric Science Data Center (ASDC)	ASDC	1.1 km, 250 m, daily, monthly, quarterly, or yearly	Satellite	MISR	"How to" obtain MISR information and data
Atmospheric base-state conditions	Cloud motion vector	MISR	ASDC	ASDC	1.1 km, 250 m, daily, monthly, quarterly, or yearly	Satellite	MISR	"How to" obtain MISR information and data
Atmospheric base-state conditions	Cloud vapor	WindSAT	NESDIS	Launched in 2007	25 km	Satellite	Polarimetric microwave radiometer	http://www.nrl.navy.mil/WindSat/index.php

Condition	Variable	Database	Service	Notes	Resolution	Type of Msmt	Method/ Instrument	Link
Atmospheric base-state conditions	Clouds	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	Varies	In situ	Drifting buoys, ships, moored buoys	Geographic display application on website
Atmospheric base-state conditions	Precipitable water	POES	NESDIS		8 km, 3-–12 h	Satellite	DMSP SSM/IS imagery	FTP site– text, MDFile
Atmospheric base-state conditions	Precipitable water	POES	NESDIS		8 km, 3-–12 h	Satellite	AMSU microwave imagery	FTP site– text, MDFile
Atmospheric base-state conditions	Precipitation	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	varies	In situ	Ships (limited)	Geographic display application on website
Atmospheric base-state conditions	Radiance	MISR	ASDC	ASDC	1.1 km, 250 m, daily, monthly, quarterly, or yearly	Satellite	MISR	"How to" obtain MISR information and data
Atmospheric base-state conditions	Water vapor	WindSAT	NESDIS	Launched in 2008	25 km	Satellite	Polarimetric microwave radiometer	http://www.nrl.navy.mil/WindSat/index.php
Atmospheric base-state conditions	Water vapor	SSM/I	NESDIS			Satellite		
Atmospheric base-state conditions	Water vapor	(GOES)	NESDIS		1–8 km, 30 min–6 h	Satellite	IR3	FTP site– text, MDFile
Atmospheric base-state conditions	Water vapor	Shared processing products	NESDIS			Satellite	DMSP plus POES, ingested by NOAA	
Marine subsurface conditions	Fugacity of CO^2 in seawater	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	Varies	In situ	None	Geographic display application on website
Marine subsurface conditions	Salinity	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	Varies	In situ	Ships, moored buoys, shore and bottom station, argo floats and gliders	Geographic display application on website

Condition	Variable	Database	Service	Notes	Resolution	Type of Msmt	Method/ Instrument	Link
Marine subsurface conditions	Sea level pressure	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	Varies	In situ	Drifting buoys (limited), ships, moored buoys, shore and bottom station	Geographic display application on website
Marine subsurface conditions	Sea surface salinity	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	Varies	In situ	Ships (2008)	Geographic display application on website
Marine subsurface conditions	Sea surface temperature	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	Varies	In situ	Drifting buoys (limited), ships, moored Buoys Shore and Bottom Station	Geographic display application on website
Marine subsurface conditions	Sea surface temperature	DODS	NDBC	NOAA > NWS > NDBC > DODS			Standard meteorological data set	http://dods.ndbc.noaa.gov/thredds/catalog/data/catalog.html
Marine subsurface conditions	Sea surface temperature	WindSAT	NESDIS	Launched in 2003	25 km	Satellite	Polarimetric microwave radiometer	http://www.nrl.navy.mil/WindSat/index.php
Marine subsurface conditions	Seafloor pressure	DODS	NGDC	dart 1 2003–2008, dart 2 2008-–present	15 s, transmitted differently for standard and event cases	In situ	Dart–system of anchored bottom pressure recorders	The high-resolution, edited **BPR Data**, along with accompanying metadata, can be downloaded, viewed, and plotted
Marine subsurface conditions	Seafloor temperature	DODS	NGDC	dart 1 2003–2008, dart 2 2008-–present	15 s, transmitted differently for standard and event cases	In situ	Dart–system of anchored bottom pressure recorders	http://www.ngdc.noaa.gov/hazard/DARTData.shtml
Marine subsurface conditions	Temperature profile	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	Varies	In situ	Drifting buoys (limited), ships, moored buoys, dhore and bottom station , argo floats and gliders	Geographic display application on website

Condition	Variable	Database	Service	Notes	Resolution	Type of Msmt	Method/ Instrument	Link
Marine subsurface conditions	Water column height	OSMC	WMO-IOC	WMO-IOC (looking at data since 2008)	Varies	In situ	Moored buoys (limited)	Geographic display application on website
Marine subsurface conditions	Water temperature, conductivity, salinity, O^2 saturation, dissolved oxygen, chlorophyll, concentration, turbidity, water ph water eh	DODS	NDBC	NOAA > NWS > NDBC > DODS			Oceanographic data set	http://dods.ndbc.noaa.gov/thredds/catalog/data/catalog.html
Other conditions	Visibility	DODS	NDBC	NOAA > NWS > NDBC > DODS			Standard meteorological data set	http://dods.ndbc.noaa.gov/thredds/catalog/data/catalog.html
		GOES	NESDIS		1–8 km, 30 min–6 h	Satellite	Visible	FTP site–text, MDFile
		GOES	NESDIS		1–8 km, 30 min–6 h	Satellite	Shortwave (IR2)	FTP site–text, MDFile

III. Agencies and Organizations That Can Supply Data

Department of Energy

National Renewable Energy Laboratory (NREL): http://www.nrel.gov/

- Offshore Wind Resource Maps: http://www.windpoweringamerica.gov/windmaps/offshore.asp

National Marine Renewable Energy Centers (NMREC)

- Hawaii NMREC (HiNMREC): http://hinmrec.hnei.hawaii.edu/
- Northwest NMREC (NNMREC): http://depts.washington.edu/nnmrec/
- Southeast NMREC (SNMREC): http://snmrec.fau.edu/?p=pilot

National Oceanic and Atmospheric Administration (NOAA)

National Data Buoy Center: http://www.ndbc.noaa.gov

- Moored buoys: http://www.ndbc.noaa.gov/mooredbuoy.shtml
- C-MAN Stations: http://www.ndbc.noaa.gov/cman.php

National Ocean Service: http://www.nos.noaa.gov

National Weather Service: http://www.nws.noaa.gov

National Hurricane Center: http://www.nhc.noaa.gov

Atlantic Oceanographic and Meteorological laboratories (AOML): http://www.aoml.noaa.gov/

AOML Hurricane Research Division: http://www.aoml.noaa.gov/hrd

Voluntary Observing Ship Program (VOS): http://www.vos.noaa.gov/

NOAA Coastal Services, Digital Coast Data sets: http://www.csc.noaa.gov/digitalcoast/

- Offshore Renewable Energy: http://www.csc.noaa.gov/digitalcoast/energy/index.html
- Regional and State specific data: http://www.csc.noaa.gov/digitalcoast/data/state.html

National Geophysical Data Center: http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html

National Water Level Observation Network (NWLON): http://tidesandcurrents.noaa.gov/nwlon.html

Satellite Scatterometer: http://manati.orbit.nesdis.noaa.gov/datasets/ASCATData.php/

National Ice Center: http://www.natice.noaa.gov/

National Snow and Ice Data Center: http://www.nsidc.org

National Oceanographic Data Center: http://www.nodc.noaa.gov/General/current.html)

National Ocean Service Hydrographic Database: http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html

NOAA Operational Model Archive Distribution System (NOMADS): http://www.nomad3.ncep.noaa.gov/

National Centers for Environmental Prediction: http://www.ncep.noaa.gov/

Bureau of Energy Management and NOAA

Multipurpose Marine Cadastre: http://www.marinecadastre.gov/default.aspx

National Aeronautics and Space Administration (NASA)

Satellite Scatterometer:

- http://podaac-www.jpl.nasa.gov/OceanWind
- http://winds.jpl.nasa.gov/

Department of Defense, U.S. Navy

Navy Coastal Ocean Model (NCOM): http://www7320.nrlssc.navy.mil/global_ncom/pubs.html

Integrated Ocean Observing System (IOOS)

IOOS: http://www.ioos.gov/partners/national.html

Regional networks (MARACOOS, GCOOS, etc.): http://www.ioos.gov/partners/regional.html

Other Sources

Vaisala's National Lightning Detection Network (NLDN): http://www.vaisala.com/en/products/thunderstormandlightningdetectionsystems/Pages/NLDN.aspx

U.S. Offshore Wind Collaborative (USOWC): http://www.usowc.org/index.html

- Information and links to offshore wind projects, studies, and data

Other Satellite Scatterometer:

- http://www.remss.com/
- Maps at http://cioss.coas.oregonstate.edu/scow/

International Comprehensive Ocean-Atmosphere Data Set (ICOADS): http://icoads.noaa.gov/index.shtml

- Surface marine data from ships, buoys, and other platform types summarized by 1 deg x 1 deg grid cells since 1960

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