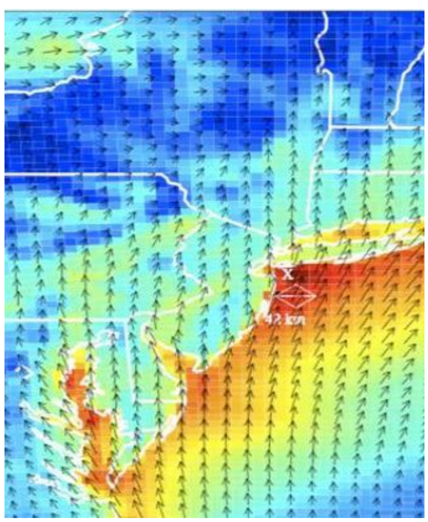
METOCEAN DATA NEEDS ASSESSMENT FOR U.S. OFFSHORE WIND ENERGY

Prepared for the US Department of Energy

Contract DE-EE0005372: *National Offshore Wind Energy Resource and Design Data Campaign—Analysis and Collaboration*.

January 2015



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ACKNOWLEDGMENTS

AWS Truepower would like to acknowledge the support and cooperation of the U.S. Department of Energy (DOE) in funding the associated research program (Contract No. DE-EE0005372) and reviewing this report. The authors would like to thank Philippe Beaucage, Katherine Rojowsky, Jeffery Freedman for their contributions to this report. Additionally, the authors would like to thank the following individuals for their cooperative efforts in reviewing and commenting during the development of this report: Andrew Clifton, Caroline Draxl, Frederick Driscoll, and Walt Musial of the National Renewable Energy Laboratory (NREL), Joel Cline and F. Jordan Dale of DOE, and Ioanna Karagali, Soren Larsen, and Anna Maria Sempreviva of the Technical University of Denmark (DTU).

Cover Page Photo Acknowledgement
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LIST OF ACRONYMS

A2e	Atmosphere to Electrons
ABS	American Bureau of Shipping
ADP	Acoustic Doppler Profiler
AMS	American Meteorological Society
API	American Petroleum Institute
AUV	Autonomous Underwater Vehicle
BOEM	Bureau of Ocean Energy Management
BOP	Balance of Plant
CALMET	California Meteorological Model
CFD	Computational Fluid Dynamics
CFSR	Climate Forecast System Reanalysis
CLASS	Comprehensive Large Array Data Stewardship System
CM	Centimeter
C-MAN	Coastal-Marine Automated Network
CTD	Conductivity-Temperature-Depth
CVA	Certified Verification Agent
DAWM	Deep Array Wake Model
DC	Direct Current
DNV	Det Norske Veritas
DOE	United States Department of Energy
DTU	Denmark Technical University
DWM	Dynamic Wake Meander
ECMWF	European Center for Medium-Range Weather Forecasts
EPC	Engineering, Procurement, Construction
ESRL	Earth System Research Laboratory
EV	Eddy Viscosity
FEED	Front End Engineering Design
FERC	Federal Energy Regulatory Commission
FFT	Fast Fourier Transform
G	Grams
GEV	Generalized Extreme Value
GHI	Global Horizontal Irradiance
GIS	Geographic Information System
GRERL	Great Lakes Environmental Research Laboratory
GPS	Global Positioning System
GW	Gigawatts
HAT	Highest Astronomical Tide
H_e	Extreme Wave Height
HF	High Frequency
HRD	Hurricane Research Division
H_s	Significant Wave Height
Hz	Hertz
IBL	Internal Boundary Layer
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
IEA	International Energy Agency
IEC	International Electrotechnical Commission

IOOC	Interagency Ocean Observation Committee
IOOS	Integrated Ocean Observing System
IWG-OP	Interagency Working Group on Ocean Partnerships
JMA	Japanese Meteorological Agency
JRA-55	Japanese 55-Year Reanalysis
KG	Kilogram
KM	Kilometer
LAT	Lowest Astronomical Tide
LAWF	Large Array Wind Farm
LES	Large Eddy Simulation
LIDAR	Light Detection and Ranging
M	Meters
MABL	Marine Atmospheric Boundary Layer
MADIS	Meteorological Assimilation Data Ingest System
MCP	Measure-Correlate-Predict
MERRA	Modern-Era Retrospective Analysis for Research and Applications
MHz	Megahertz
MSFD	Mixed Spectral Finite Difference
MW	Megawatts
NARR	North American Regional Reanalysis
NASA	National Aeronautical and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NDBC	National Data Buoy Center
NDVI	Normalized Difference Vegetation Index
NEPA	National Environmental Policy Act
NGDC	National Geophysical Data Center
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NOABL	Numerical Objective Analysis of Boundary Layer
NODC	National Oceanographic Data Center
NOS	National Ocean Services
NREL	National Renewable Energy Laboratory
NWP	Numerical Weather Prediction
NWS	National Weather Service
NWSTG	National Weather Service Telecommunication Gateway
NYSERDA	New York State Energy Research and Development Authority
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
OOI	Ocean Observatories Initiative
PBL	Planetary Boundary Layer
PC	Personal Computer
PODAAC	Physical Oceanography Distributed Active Archive Center
PORTS	Physical Oceanographic Real-Time System
POWWOW	Prediction of Waves, Wakes and Offshore Wind
RANS	Reynolds-Averaged Navier-Stokes Models
RASS	Radio Acoustic Sounding System

RFORE	Reference Facility for Offshore Renewable Energy
RMSE	Root Mean Square Error
S	Second
SCADA	Supervisory Control and Data Acquisition
SODAR	Sonic Detection and Ranging
SOWFA	Simulator for Offshore/Onshore Wind Farm Applications
SST	Sea Surface Temperature
SWAN	Simulating Waves Nearshore
TKE	Turbulent Kinetic Energy
UK	United Kingdom
UMOOS	University of Maine's Ocean Observing System
URANS	Unsteady Reynolds-Averaged Navier-Stokes
US	United States
USACE	United States Army Corps of Engineers
$V_{average}$	Annual Average Wind Speed at Hub Height
V_{e50}	Expected Extreme Wind Speed at Hub Height with 50-year Recurrence Period
V_{ref}	Extreme 10-Minute Average Wind Speed at Hub Height with 50-Year Recurrence Period
WAM	Wave Model
WAsP	Wind Atlas Analysis and Application Program
WEA	Wind Energy Area
WRF	Weather Research and Forecasting Model
WIND	Wind Integration National Dataset
WIS	Wave Information Studies
WMO	World Meteorological Organization
XBT	Expandable Bathythermograph

EXECUTIVE SUMMARY

A potential barrier to developing offshore wind energy in the United States is the general lack of accurate information in most offshore areas about the wind resource characteristics and external metocean design conditions at the heights and depths relevant to wind turbines and their associated structures and components. Knowledge of these conditions enables specification of the appropriate design basis for wind turbine structures and components so they can withstand the loads expected over a project's lifetime. Human safety, vessel navigation, and project construction and maintenance activities are equally tied to the metocean environment. Currently, metocean data is sparse in potential development areas and even when available, does not include the detail or quality required to make informed decisions. Therefore there is a critical need to improve the characterization of metocean conditions to facilitate future offshore wind energy development in the United States.

This report documents the vital role and importance of metocean information as it relates to the United States' emergent offshore wind energy industry. The objectives of this report are three-fold:

- To understand the multi-disciplinary, multi-stakeholder dependence on metocean-related information for offshore wind energy and identify knowledge gaps in our current understanding of metocean conditions in US waters;
- To address how these gaps can be resolved to facilitate the development of economical offshore wind energy; and
- To recommend a set of activities designed to improve the characterization of metocean conditions to facilitate future offshore wind energy development.

This report is a deliverable for a US Department of Energy (DOE) funded contract (DE-EE0005372) entitled *National Offshore Wind Energy Resource and Design Data Campaign—Analysis and Collaboration*. The project's goal is to supplement and facilitate multi-agency efforts to develop an enhanced, integrated national offshore wind energy data network.

Topics addressed in the report include:

- the primary uses and users of metocean data and the relevance to an offshore wind project's main lifecycle phases;
- the key atmospheric, water surface and sub-surface data parameters (e.g., winds, waves, currents, etc.) and derived statistics (e.g., wind shear, turbulence intensity, thermal stability, etc.) necessary to address data needs associated with the project phases;
- measurement instrumentation and approaches for metocean parameter characterization;
- the primary types of models used to simulate metocean conditions; and,
- recommendations for addressing metocean knowledge gaps.

These recommendations are presented in the form of a roadmap designed to be an impetus for developing a detailed action plan centered on the three categories of action items:

1. New Measurements
    - A. Initiate field campaigns near BOEM-designated wind resource areas
    - B. Develop and validate new metocean sensors and floating platform technologies
    - C. Foster innovative multi-site deployment scenarios
2. Analysis and Prediction Modeling
    - A. Improve wind/wave modeling and forecasting capabilities
    - B. Update wind maps and extreme event statistics
    - C. Advance plant wake and energy prediction modeling
3. Public-Private Synergy
    - A. Engage in stakeholder collaboration and outreach
    - B. Promote public-private data sharing and research
    - C. Foster best practices and standards for metocean characterization

The goal of the recommended activities is to reduce hurdles to progress toward accelerated offshore wind development in the United States. Sustained progress with measurements and modeling requires a commonly shared vision that seeks to reduce scientific and technical uncertainty, facilitate deployment, attract investment, and demonstrate viable operations while simultaneously ensuring environmental, health and safety stewardship. By providing clarity on metocean data needs and promoting an industry discourse on how to obtain data more quickly and efficiently, it is hoped that multiple stakeholders will contribute to, and likewise benefit from, an investment in metocean knowledge and awareness. The engagement of more stakeholders in the formative stages of this industry is likely to lead to faster progress on resolving metocean data gaps and shorter timelines for wind farm development. Greater certainty about environmental design conditions should also lead to lower project costs.

The time frame to carry out the roadmap is assumed to be a minimum period of 10 years. The critical path will be the development and deployment of offshore measurement systems. Once systems are commissioned, several years of data collection will be needed to enable the derivation of data products and achievement of modeling improvements.

1. INTRODUCTION

1.1 Background

Although offshore wind energy development began over two decades ago and has achieved over 7,500 megawatts (MW) of installed capacity worldwide by October 2014, this industry is only now emerging in the United States. According to the National Renewable Energy Laboratory (NREL), the country's offshore winds have a potential energy generating capacity that is four times greater than the existing land-based electric production capacity from all sources (Musial and Ram, 2010). Proposed and active offshore wind development is underway in several coastal states offshore of the Atlantic and Pacific Oceans, the Gulf of Mexico, and the Great Lakes. While no commercial offshore wind projects are anticipated to be commissioned before 2016, the US Department of Energy (DOE) estimates that 54 gigawatts (GW) of offshore wind capacity could be built in the United States by 2030 (Department of Energy, 2008).

A barrier to achieving or even approaching this 54GW target is the general lack of accurate information in most offshore areas about the resource characteristics and external design conditions at the heights and depths relevant to wind turbines and their associated structures. Although wind turbines are classified to meet specific ranges of environmental conditions that may be found in many regions of the world, these conditions may not encompass the weather extremes associated with strong hurricanes and intense Nor'easters that are relatively unique to the United States. Turbine foundations are tailored to site conditions and so these conditions need to be known before a foundation can be designed.

Temporally and spatially detailed information about particular atmospheric and oceanographic (including seabed) parameters are required to fully address and regulate the development, construction and operational aspects of offshore wind energy. The term "information" is generically used here to encompass the family and quality of knowledge gleaned from direct meteorological and oceanographic (i.e., metocean) observations, from derived values using various reconnaissance, modeling and data assimilation techniques, from the published literature and other marine disciplines (such as oil & gas industry), and from metadata. Integral to this characterization are attributes describing data quality, consistency, completeness, and areal and temporal coverage, among others. Without adequate qualification, information can have little value or even be misleading.

The user community for metocean data is large and diverse, despite the relative infancy of the United States' offshore wind industry. The community spans multiple sectors, project components, and project phases which range from conceptual assessments through a series of stages including development, construction and lifetime operations. Users can be found in the public and private sectors in such areas as regulation and certification, financing, manufacturing, insurance, transportation and transmission. Diversity is also found in the types of metocean information and data formats required by user groups given their disparate roles. Specific data requirements among groups are not yet widely known and will likely evolve as the industry expands and matures. A metocean data needs assessment will help facilitate the creation of strategies for new data collection and sharing initiatives by identifying existing gaps.

A framework by which tailored metocean data will be acquired and made available to multiple users in the future is also lacking. Marine data collection and analysis requires a significant investment in resources and time, and no strategy currently exists to acquire the data required to support future wind projects. The prevailing expectation in the United States is that private sector developers will carry out metocean assessments once they are granted development rights to designated lease blocks in federal waters. However, issues of data ownership and competition will likely restrict public access to the project-specific metocean information. To address this concern, another concept being considered by the DOE, individual states, and other organizations is the public investment in metocean campaigns that would provide data to a much wider audience of users. The establishment of best practices and standards for such campaigns would help ensure a minimum level of quality and consistency objectives are met wherever the data are taken.

1.2 Objective and Scope

This report documents the vital role and importance of metocean information as it relates to the emergent offshore wind energy industry in the United States. The objectives of this report are three-fold:

- To understand the multi-disciplinary, multi-stakeholder dependence on metocean-related information for offshore wind energy and identify knowledge gaps in our current understanding of metocean conditions in US waters;
- To address how these gaps can be resolved to facilitate the development of economical offshore wind energy;
- To recommend a set of activities designed to improve the characterization of metocean conditions to facilitate future offshore wind energy development.

This report is intended to be a resource to inform a broad array of stakeholders about the importance of advancing the knowledge of metocean issues, thereby facilitating the advancement of offshore wind energy in the United States. The offshore wind energy stakeholder community includes policy makers, energy companies, regulators, turbine manufacturers, investors, researchers, government entities, and many others. The ultimate goal is to encourage collaborative efforts among these stakeholders, with the aim of advancing the metocean science in ways that resolve barriers to, and reduce the costs of, domestic offshore wind energy.

In addition to being applicable to multiple stakeholders, this report's scope spans the entire life cycle of offshore wind projects, from pre-development feasibility and design studies to wind farm decommissioning. This breadth is inclusive of wind farm design requirements and standards conformance, wind resource and energy production assessments, wind farm construction and operations, and safety considerations. All known relevant metocean data parameters related to atmospheric and oceanic (including seabed) conditions are identified. Several of them are illustrated in Figure 1-1. These parameters can be obtained directly from measurements or derived from analysis and modeling techniques, both of which are described.

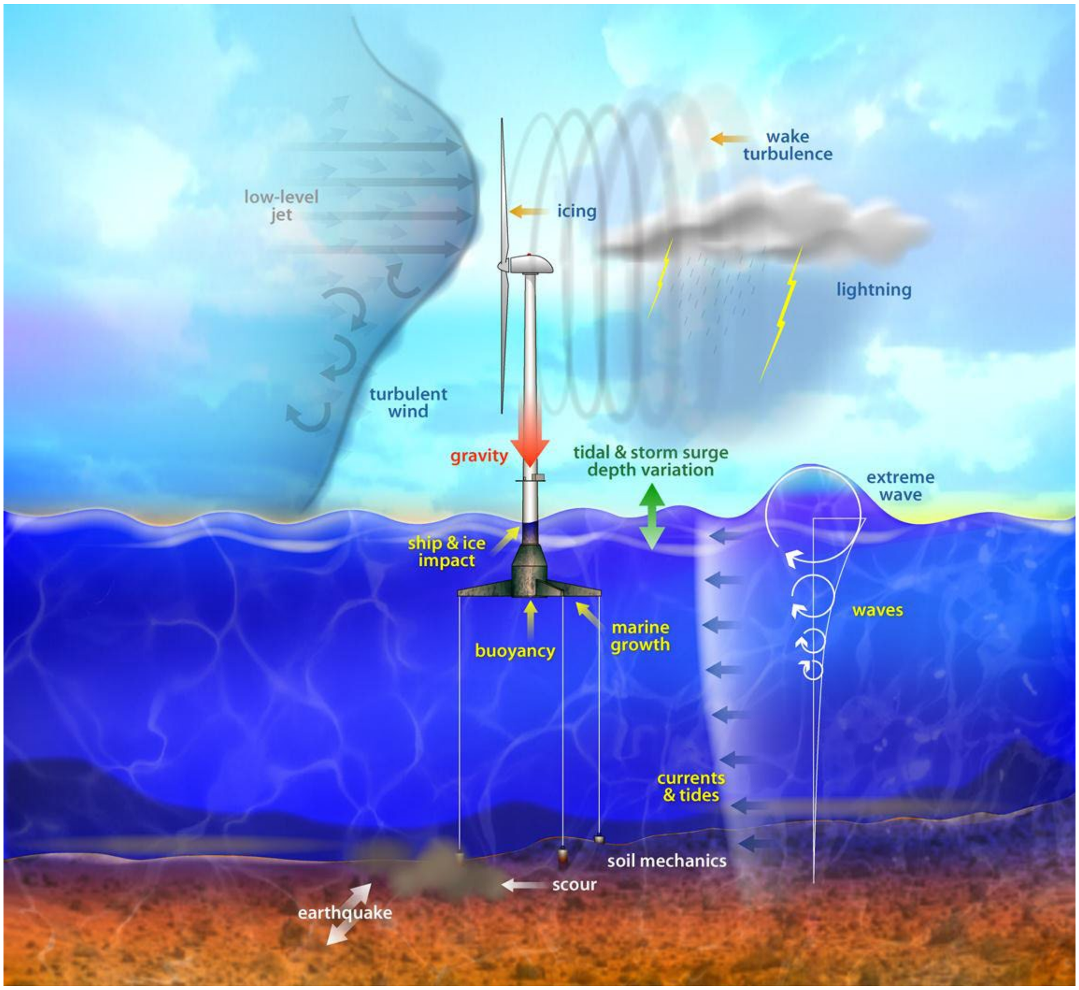

Figure 1.1 Illustration of Various Metocean Factors on a Floating Offshore Wind Turbine
(Source: National Renewable Energy Laboratory)

The goal of the activities recommended in this report is to reduce hurdles to progress toward accelerated offshore wind development in the United States. By providing clarity on metocean data needs and promoting an industry discourse on how to obtain data more quickly and efficiently, it is hoped that multiple stakeholders will contribute to, and likewise benefit from, an investment in metocean knowledge and awareness. The engagement of more stakeholders in the formative stages of this industry is likely to lead to faster progress on resolving metocean data gaps and shorter timelines for wind farm development. Greater certainty about environmental design conditions should also lead to lower project costs.

This report is a deliverable for a US Department of Energy (DOE) funded contract (DE-EE0005372) entitled *National Offshore Wind Energy Resource and Design Data Campaign—Analysis and Collaboration*. The objective of this project is to supplement and facilitate multi-agency efforts to develop an enhanced, integrated national offshore wind energy data network. Other publications produced by this project include:

- *Inventory of Met-Ocean Data Sources for the United States* (AWS Truepower, 2012): an inventory of relevant coastal and offshore metocean data sources and associated metadata for the United States, including the Great Lakes;
- *The Need for Expanded Meteorological and Oceanographic Data to Support Resource Characterization and Design Condition Definition for Offshore Wind Power Projects in the United States* (American Meteorological Society Offshore Wind Energy Committee, 2013): a high-level review of the offshore wind industry's needs for metocean information and recommended strategies for bridging important data gaps through multi-disciplinary engagement;
- *Assessment of Offshore Wind System Design, Safety, and Operation Standards* (National Renewable Energy Laboratory and AWS Truepower, 2014). Technical Report NREL/TP-5000-60573: a review and assessment of US and international standards that are related to the design and safety of offshore wind project components and activities such as manufacturing and construction.

These publications can be accessed at www.usmodcore.com. Also available at this site is a summary of a workshop—*Offshore Wind Energy Standards and Guidelines: Metocean-Sensitive Aspects of Design and Operations in the United States*—sponsored by DOE and the Department of Interior's Bureau of Ocean Energy Management (BOEM). The workshop, which took place in June 2014 in Arlington, VA, brought together a cross section of stakeholders in the offshore energy community to continue efforts on defining relevant metocean parameters, gap-filling activities, acceptable modeling approaches, and design standards.

This document represents the opinion of AWS Truepower, with valuable input provided by two project partners: the National Renewable Energy Laboratory (NREL) and the Technical University of Denmark (DTU).

1.3 Report Format

In addition to this introductory chapter, this report consists of five additional chapters plus an Appendix. Chapter 2 describes the primary uses and users of metocean data and the relevance to an offshore wind project's five main phases: pre-development, development, construction/commissioning, operations and decommissioning. Chapter 3 presents a summary of the key atmospheric, water surface and sub-surface data parameters and derived statistics necessary to address applications associated with the project phases. Chapter 4 provides an overview of measurement instrumentation and approaches for metocean parameter characterization. Chapter 5 reviews the primary types of models used to simulate metocean conditions, in particular winds, waves and currents. The final section—Chapter 6—describes an action plan for improving the characterization of metocean conditions in support of future offshore wind energy development.

The Appendix provides background material on the nature of the offshore wind environment. The material is tailored to readers who are relatively new to wind resource-related issues and interested in better understanding how offshore wind characteristics contrast with those over land. Covered topics include complex offshore wind flow regimes, mapped estimates of average wind speeds in the United States, wind shear, and others.

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2. METOCEAN INFORMATION USES, USERS, AND DATA APPLICATIONS

All phases of an offshore wind project are reliant on metocean information to enable sound planning and decision making among a broad range of users. As illustrated in Figure 2.1, the lifespan of a wind project can be grouped into five main phases: pre-development, development, construction & commissioning, operations, and decommissioning. The primary activities associated with each phase are described in this chapter.

Figure 2.1 Wind Project Phases

The metocean data user base is fairly large and diversified, and consists of public and private sector entities. Table 2.1 identifies eleven major user groups and the project phases for which metocean information is most relevant to them. Each user group is defined as follows:

- **Developer/Owner:** The legal entity or entities responsible for developing and operating a wind farm, including securing all applicable contractual agreements and leases and abiding by all applicable regulations.
- **Government/Regulators:** Ensure wind farm compliance with all regulatory requirements, including safety in operations, structural integrity, environmental compatibility and risks, and 'fair return' for national resources (BOEM) as well as electricity generation reliability (FERC). This includes abiding by National Environmental Policy Act (NEPA) terms and a host of other ocean regulations, which is required by all federal and state agencies. Regulators are responsible for stakeholder engagement and information sharing on a range of issues from wind resources to state revenue sharing.
- **Technical Consultants:** Firms retained by the developer/owner to conduct studies and provide services on their behalf related to wind farm facility design engineering, metocean studies, environmental/wildlife surveys, permitting, energy production assessment, and so on.
- **Original Equipment Manufacturers (OEMs)**: Producers of primary wind farm components such as turbines, foundations, electrical cables, substation, etc.
- **Investors/Lenders:** Providers of project equity and debt capital in amounts and terms determined in part by projected project performance and risks.
- **Engineering, Procurement, Construction (EPC) Providers:** Supplier of such services as detailed engineering design of the project, procurement of all necessary equipment and materials, and construction and commissioning of a functioning facility.
- **Certified Verification Agents (CVAs):** The organization conducting the formal design verification to ensure that the offshore wind project has been designed to withstand the maximum environmental and functional load conditions anticipated during the intended service life at the proposed location.
- **Insurers:** Provide policies and other instruments that spread or mitigate risks related to performance, technology reliability, and safety.

- **Grid Entities:** The utility (or utilities) and/or transmission system operator receiving the wind farm's output and responsible for the reliable and economic management of the regional electrical grid.
- **O&M Providers:** Responsible for executing all operations and maintenance activities for the wind farm.
- **Academia/Research:** The research institutions, government laboratories and universities who specialize in basic and applied research as well as technology transfer to the public and commercial sectors.

Table 2.1. Metocean Data Users and Applicable Project Phases

	Offshore Wind Project Phase				
Data User Group	**Pre-development**	**Development**	**Construction & Commissioning**	**Operations**	**Decommis-sioning**
Developers/Owners	✓	✓	✓	✓	✓
Government/Regulators	✓	✓	✓	✓	✓
Technical Consultants	✓	✓	✓	✓	✓
OEMs		✓	✓	✓	
Investors/Lenders		✓	✓	✓	✓
EPCs		✓	✓	✓	✓
CVAs		✓	✓		
Insurers		✓	✓	✓	✓
Grid Entities		✓	✓	✓	
O&M Providers			✓	✓	
Academia/Research	✓	✓	✓	✓	✓

2.1 Pre-Development Phase

This phase is investigatory in nature and pertains to siting and feasibility studies that help determine whether a conceptual project is sufficiently viable to advance to the next planning step. Typical questions about viability pertain to: location options where a wind project could realistically be sited and permitted; achievable energy production potential and returns on investment; turbine/foundation technology suitability and constructability; and proximity to major ports and grid interconnection points, among others. This phase takes 1-2 years and relies primarily on historical metocean information (observations, model-based analysis products such as wind maps, etc.) as well as on environmental and demographic data (such as bathymetry and designated navigation lanes, for example). A key benefit of this phase is its ability to quickly identify and qualify areas of opportunity and conflict, and to focus subsequent pre-development efforts.

The siting landscape for offshore wind energy in federal waters has been changing in recent years with the designation of Wind Energy Areas (WEAs) on the Outer Continental Shelf by BOEM. The WEAs are defined by a multi-agency collaboration process to identify available areas that are attractive for offshore wind development while protecting important viewsheds, sensitive habitats and resources and minimizing space use conflicts with activities such as military operations, shipping and fishing. The Energy Policy Act of 2005 authorized BOEM to issue leases, easements and rights of way to allow for renewable energy development on the OCS. BOEM is working closely with over a dozen coastal states regarding offshore renewable energy development and is coordinating a number of federal-state task forces. By October 2014, commercial leases were announced or executed for offshore wind projects in Rhode Island, Massachusetts, Virginia, Delaware, and Maryland.

Pre-development studies have been conducted by or on behalf of project developers, government agencies (state and federal), and utilities. The goal of many publicly-funded studies is to provide decision makers—including developers, regulators, policy makers, and the public at large—with an assessment of the known development opportunities and challenges within a given geographic area, thereby advancing the public dialogue about the future potential for offshore wind energy. Studies have been commissioned in several East Coast and Great Lake states, including Delaware, Maryland, Massachusetts, New Jersey, New York, Ohio, Rhode Island, and Virginia. Studies conducted by NREL, under an interagency agreement with BOEM, have assessed the proposed delineation of leasing areas (i.e., WEAs) in four of these states. In essentially all cases, the studies have included a description of the metocean environment (e.g., winds, waves, bathymetry) that was derived from existing information. Although there is a relatively high degree of uncertainty associated with the accuracy of some metocean parameters (such as hub height wind speed), the approximations are usually sufficient to determine whether a wind energy project could be viable.

2.2 Development

This phase acquires metocean data to define a given site's resource and design conditions to develop a design basis to feed the engineered, permitting and financial activities. The metocean data is also essential for accurately estimating the long-term energy production from the planned wind farm. This step is measurement intensive, requiring a minimum of one-year to fully characterize conditions across the entire year, and preferably multiple years of high quality observations. Although standards do not yet exist to govern the design and execution of offshore wind assessments, best practices are usually adopted from experiences on land and from European offshore experience. Chapter 4 of this report focuses on these best practices as well as on relatively new measurement approaches. Mesoscale and microscale models (discussed in Chapter 5) are utilized in tandem with on-site and regional metocean observations to estimate long-term wind/wave conditions and energy production at every proposed turbine location while accounting for turbine wakes. Inter-annual production variability and the quantification of uncertainty are important analysis components of this phase (DNV KEMA, 2013).

The estimation of energy production from a proposed wind farm is determined by combining the specified operational characteristics of the facility with the relevant environmental conditions of the site. At the forefront of the energy estimation process is the characterization of the long-term hub-height wind resource and other meteorological conditions such as air density and turbulence intensity. Gross energy is predicted first by applying the relevant meteorological characteristics of the wind resource for the array of turbines to the applicable power and thrust curve specifications supplied by the turbine manufacturer. Once the gross energy estimate is obtained, expected production losses due to several factors are applied to obtain an estimate of the net energy output of the wind farm. The predominant loss factors are:

- turbine and plant availability, which is impacted by turbine, substation, and other outages and response times for restarts and maintenance, which are weather dependent.
- wake effects resulting from turbines within the wind farm and from other projects in the vicinity.
- electrical inefficiencies in all electrical components, including transformers and line losses. Power consumption for cold/extreme weather packages for turbines equipped with them are counted as losses.
- suboptimal turbine performance resulting from control setting issues, yaw misalignment, power curve deviation from the advertised curve, turbine shutdown and resets during high wind speeds, and other factors.
- environmental considerations including blade soiling and degradation, ice accumulation on blades, lightning, high/low temperature shutdown, and unfavorable sea states that can prevent or delay site access in response to maintenance needs.
- operational curtailment imposed by wildlife risk mitigation measures, transmission constraints, and prevention of excessive turbulence internal to the wind farm when the wind direction is parallel with strings of relatively closely-spaced turbines.

The magnitude of the individual energy losses are project and location specific. In general, encountered combined losses average between 15% and 25% for offshore wind projects. It is noteworthy that metocean conditions can impact losses and that an accurate metocean assessment will lead to more reliable wind farm production estimates.

The metocean campaign often informs and is conducted largely in parallel with other components of a project's development phase, which is expected to take five or more years to complete. These components include project design, permitting, biological and environmental surveys, turbine procurement, grid interconnection, construction, operations and maintenance, and project financing. The requirements for each component are as follows:

2.2.1 Project Design

The engineering specifications for all project components and subcomponents (turbines, blades, towers, foundations, substation, electrical cables, etc.) will be driven by the metocean statistics determined for the site. The choice of foundation type, for example, is largely dependent on the bathymetry, seabed conditions, and wind/wave conditions at a site. Historically turbine manufacturers have followed the IEC (International Electrotechnical Commission) 61400 design standards and associated subclasses which cover a broad spectrum of turbine design requirements, most of which apply to onshore projects.

Specific to offshore applications are IEC subclasses 61400-3 (for fixed bottom structures) and 61400-3-2 (for floating versions). Another dimension of project design—the layout and spacing of the turbine array—is largely determined by the joint wind speed-direction frequency distribution. The turbine array design is a key factor in the wake losses experienced by a wind farm.

2.2.2 Permitting Approvals

The regulatory process to obtain project approvals consists of formal review procedures involving federal and state agencies to determine (among other things) whether site-specific metocean considerations and their potential impacts on all aspects of project planning, implementation, and standards/guidelines conformance have been thoroughly and competently addressed. BOEM is the lead agency for proposed projects in federal waters, while lead agency status for proposed projects in state waters is determined by the individual states and the US Army Corps of Engineers (USACE).

2.2.3 Biological, Environmental and Other Surveys

Wildlife behavior responses to future wind farm construction activities and subsequent operations may be dependent on variable weather and sea states. The metocean measurement platform(s) may be capable of hosting wildlife monitoring equipment and should be considered for multi-purpose use.

2.2.4 Turbine Procurement

Site wind and weather conditions will determine which turbine models are compatible with the local operating environment. These conditions will be evaluated by both the turbine procurer and original equipment manufacturer (OEM) and may influence decisions related to certain turbine control settings, equipment enhancements (such as cold weather packages), and turbine warranty provisions. Commercial wind turbines are designed to meet type certification requirements which specify fatigue and extreme loads with regards to mean wind speed, site air density, turbulence intensity, wind speed distributions, shear profiles, and extreme wind events. The three IEC type classifications are class I, II and III, with a special S provision given turbines designed for standards outside of these three ranges. A new Class T is under consideration by the IEC to address tropical cyclone-prone regions, which exist in the United States but not in Europe where many IEC wind and weather categories were derived. The IEC class designations are shown in Table 2.2.

Table 2.2 Wind Turbine Classes and Basic Parameters
(Source: IEC, 2005)

Wind Turbine Classes	I	II	III	S
V_{ref} (10 min), (m/s @ hub height)	50	42.5	37.5	Values are specified by the designer
V_{e50} (3 sec), (m/s @ hub height)	70	59.5	52.5	
$V_{average}$ (10 min), (m/s @ hub height)	10	8.5	7.5	
A – turbulence intensity (%)	16			
B – turbulence intensity (%)	14			
C – turbulence intensity (%)	12			

Definitions
V_{ref}: extreme 10 min average wind speed with a recurrence period of 50 years at turbine hub height
V_{e50} : expected extreme wind speed (averaged over three seconds) with a recurrence period of 50 years at turbine hub height
$V_{average}$: annual average wind speed at hub height
A,B,C: Turbulence intensity classes

2.2.5 Grid Interconnection

When assessing the potential impact an offshore wind project will have on the grid, system operators must examine the capability of the system to serve the required load, with and without the addition of the wind project. To effectively assess the impact, system operations must have accurate information about variations in sub-hourly, hourly, monthly, and seasonal production. The ability of the system to respond to variations in load and production will determine the required upgrades and constraints placed on the project.

2.2.6 Engineering, Procurement, and Construction Contracting

The body of work entailing the detailed engineering design, equipment and materials procurement, and construction of a functioning project, is typically performed by an Engineering, Procurement and Construction (EPC) firm. Because they normally assume the risk for project schedule and budget, companies bidding for EPC contracts must account for the frequency and severity of challenging weather and sea state conditions when selecting appropriate construction-related vessels and lifting equipment as well as planning for associated logistics. This includes staging and scheduling transport from designated ports and on-site construction activities, which can be precluded for months at a time (typically winter in northern climates) due to the frequency of strong winds, high seas, or the formation of surface ice (particularly in the Great Lakes). A Front End Engineering Design, or FEED, is a basic engineering design used as the basis for bidding the EPC work.

2.2.7 Operations and Maintenance Agreement (O&M)

Bidders and providers of project O&M services must similarly account for challenging weather and sea state conditions when planning scheduled maintenance, ensuring crew safety, and assessing response times for unscheduled (or corrective) maintenance. Response time planning must also account for the distance between the harbor-based O&M facility and the project site.

2.2.8 Project Financing and Insurance

Metocean-related risk factors impact the equity and debt financing required to cover the capital and operating costs, and achieve the desired economic returns, of the wind project. Risk factors include probabilities of extreme wind and wave events, lightning, icing and significant deviation from expected annual energy production over the course of the investment period. Insurance products, including their cost and availability, are likewise linked to the degree of metocean-related risk.

2.3 Construction & Commissioning Phase

2.3.1 Scheduling and Cost Management

This phase involves one or more years of construction and transport work at sea and is constrained by permissive sea states and suitable weather windows. Foreknowledge of the approximate frequency and duration of favorable sea and weather conditions enables accurate construction scheduling and cost management. During construction much of the installation process must take place during periods of relatively calm weather with low winds and minimal wave heights. Short-term forecasting of offshore conditions is therefore a critical need during this phase. Reliable forecasts can help with contingency planning, recognizing that different operations have different weather sensitivities. For example, wind may have a greater effect on lifting operations than on subsea work. In mid- and northern latitude regions prone to stormy weather during the cold season, construction activities may be suspended altogether, thus requiring a multi-year construction schedule. Additional offshore observations will allow for improved forecasts for plant development scheduling.

2.3.2 Vessel Selection

Vessel selection and operation (including onboard lifting equipment) is dependent on such metocean factors as wave heights, wind speeds, water depth, and currents. Installation vessel types include cable laying vessels, jack-up barges/vessels that deploy legs into the seabed to lift the platform out of the water to provide improved stability for lifting operations, transport vessels, crane ships, accommodation vessels/platforms to house work crews, and purpose-built wind farm installation vessels. On-site metocean observations and operational wave and weather forecasts along the transit route from port are heavily relied upon by vessel captains and construction managers during construction and commissioning. Accurate forecasts can greatly reduce the capital intensive construction and worker safety risk of an offshore project.

2.3.3 Project Certification

Project certification is conducted by independent technical organizations (i.e., Certified Verification Agents, or CVAs) on behalf of project stakeholders and regulators to ensure that the site's metocean conditions are comprehensively evaluated and project design requirements are met.

2.3.4 Worker Safety

Worker safety is an integral part of construction, commissioning and operations, and is best achieved when metocean conditions are continuously monitored and complemented by short-term weather forecasts. Adverse metocean conditions can impact health and safety issues both by increasing the probability of injuries and errors and by increasing response and recovery times. The effects of metocean conditions on personnel include not only seasickness, fatigue, and cold, but also emergency response and casualty evacuation. In addition to cold temperatures, which can cause hypothermia, icy surfaces can prevent safe movement. Warm air temperatures can cause heat stress, whether as a consequence of working in hot enclosed spaces (such as turbine nacelles), or climbing an access ladder while wearing a survival suit. Rain, hail, snow and fog can all affect visibility, and lightning is a hazard to people exposed on structures. Construction activities may need to be terminated or postponed whenever worker safety is jeopardized.

2.4 Operations Phase

Offshore wind projects have a design life of at least 20 years. O&M activities rely on real-time observations as well as regional forecasts of waves, weather, and energy production. Site access by maintenance crews is governed by the availability of safe weather windows. Vessels used to support O&M activities include crew transfer vessels and multi-purpose vessels, which have equipment transfer and lifting capabilities. Wave heights are a significant concern as the majority of current service vessels have wave height restrictions of 1.5 m or less. This restriction severely limits the number of days that O&M crews can safely access a site.

Facility owner/operators compare projected with actual energy output based on the wind and weather conditions. Utilities and transmission system operators may request or require next-hour and next-day schedules of projected energy output, together with estimates of certainty or probability.

2.5 Decommissioning Phase

This phase, which is expected to be completed within 1-2 years depending on a project's size and location, has essentially the same sensitivities to metocean factors as the ones described in the construction and commissioning phase. Because some geophysical (seabed) conditions may have changed since the project was installed, a new survey may be needed prior to the onset of decommissioning work. A separate geophysical survey may be required post-decommissioning to verify that equipment removal and site restoration is consistent with the decommissioning plan.

References

DNV KEMA, 2013. Framework for the Categorization of Losses and Uncertainty for Wind Energy Assessments, 8 pp.

International Electrotechnical Commission, 2005. IEC 61400-1, Wind Turbines – Part 1: Design Requirements, Third edition 2005-08.

3. METOCEAN DATA PARAMETERS

3.1 Introduction

This chapter presents a summary of the key atmospheric, water surface, and sub-surface parameters (e.g., winds, waves, currents, etc.) and derived statistics needed for the various stages of offshore wind facility development, construction and operations. This chapter's goal is to help frame overall wind project data uses and to inform metocean monitoring program design.

3.2 Approach

The scope of metocean parameters relevant to the full life cycle of offshore wind development and operation is broad and defined by diverse stakeholders and analytical needs. As such, a representative cross-section of international standards and guidelines, turbine manufacturers' suitability forms, industry best practice documents, and previous offshore wind development work were consulted to build a matrix[1] of the key metocean data parameters from which most of the myriad unique task-specific analyses could be derived. This section provides an overview of metocean parameters necessary and relevant to the lifecycle of offshore wind project design and operation, but does not specify all of the myriad time scales, measurement and modeling approaches, analytical methods, end uses or uncertainties associated with each of the respective parameters.

Based upon the emergent state of the domestic offshore industry and the extensive analytical efforts required in project design, energy yield calculations and certification, this section will focus on parameters associated with these pre-construction tasks. The parameters commonly referenced in the source material were aggregated into three broad categories for consideration in this report: atmospheric, water and other. The following sections give narrative overviews and summary tables of the metocean data needs and uses within these categories.

3.3 Atmospheric Parameters

3.3.1 Atmospheric State and Meteorological Conditions

Knowledge of meteorological conditions is imperative throughout all phases of wind plant development, construction and operation. Relevant parameters are used for power production estimation, turbine selection, and plant design during pre-construction.

Various parameters influence the wind power production by affecting: 1) the actual amount of energy available, i.e., wind speed, air density and temperature, barometric pressure, atmospheric stability, and relative humidity; and 2) that which is harnessed due to operating constraints or efficiencies, i.e., icing, temperature, precipitation (through blade soiling), or lightning. The most important among these

[1] It is worth noting that many of the parameters presented in this chapter are common to multiple references, recommended practices, and applications; however, the means of measuring, calculating, and/or analyzing them can vary significantly. Design standards and guidelines provide procedures for certain parameters where consensus or industry best-practices are available. Among these references, however, differences exist in procedures and requirements, and many do not address all parameters equally.

parameters are wind conditions, which are addressed in the following section. Observation of the balance of these parameters used for power production estimates is required at multiple heights above the surface, with a priority on hub height and rotor swept area. In particular, vertical profile measurements used to derive thermal stability are needed to extend well above the rotor plane, as low level gradients in thermal stability are common in the coastal zone. These stability gradients affect vertical turbulent mixing and momentum transfer, thus impacting low-level wind speeds.

Turbine selection is influenced by various atmospheric state and meteorological conditions. Those parameters affecting power production also influence turbine selection through mechanical loading. Air chemistry or pollution, solar radiation, and precipitation influence equipment selection as these properties affect blade wear and composite fatigue.

Parameters sought for general site characterization include hurricane frequency and lightning occurrence, total solar radiation, and visibility. Statistics on hurricane frequency may affect computation of extreme wind statistics. Solar radiation – primarily global horizontal irradiance (GHI) – affects the power supply for ancillary equipment. Information on visibility is used in determining site access in both the construction and operational phases.

Table 3.1 presents a summary list of the meteorological parameters most commonly considered for offshore wind development and operation. Table 3.2 provides a more detailed, but not exhaustive, list of wind parameters commonly employed for offshore wind analyses.

3.3.2 Wind

The distribution of wind speed and direction, and their variation over short time scales, are a primary concern for offshore wind energy development and operation. These conditions characterize the potential energy available at a site, influence turbine selection, drive balance of plant design, and affect project construction and operational strategies. Measurements of wind speed and direction are preferred across the entire turbine operating height, with a priority on hub-height. Current industry practices employ a combination of direct and remote sensors to observe wind conditions.

If these observations are not at hub height, many analyses require that wind conditions be projected across the rotor plane and to hub height. This extrapolation of conditions observed below hub height is often conducted utilizing either a logarithmic wind profile assumption or the power law and a determined shear exponent. Alternatively, the wind shear profile and conditions across the rotor plane can be estimated by way of numerical weather prediction or other modeling approaches (see Chapter 5). In all cases, physical and climatic conditions affecting the wind variation with height need to be considered when projecting to hub height, including, but limited to: atmospheric stability, local terrain and surface roughness (for projects with land upstream), and wave and water surface conditions.

Various statistical methods are employed to evaluate and predict the wind conditions at a given site. Observed conditions at a site are often summarized with Weibull distribution functions, joint parameter frequency distributions (e.g. wind & energy direction frequency roses), and others. Long-term average conditions for a site (projected over a ten-year financing period or a full project lifespan) are commonly derived from limited-duration, dedicated measurement campaigns (typically two to five years, conducted on or near the project area) and long-term reference data sets by way of measure–correlate–

predict (MCP) climate adjustment methods. Other statistical techniques, such as the Method of Independent Storms, Gumbel Generalized Extreme Value (GEV), and Peak over Threshold, are also employed to estimate return periods, extreme values and to convert between measurement time scales.

Table 3.1 Atmospheric State and Meteorological Conditions

Category	Family	Parameter	Comments	Reference
Atmospheric State & Meteorological Conditions	Air Density	Air Density	Calculated for hub height from available measurements and an assumed lapse rate, or directly from hub height measurements. Affected by temperature, pressure, and humidity. Used to calculate power in the wind.	[2] [3] [4] [5] [7] [9]
		Air Density at Max Gust	Calculated for hub height from available measurements using an assumed lapse rate, or directly from hub height measurements concurrent with maximum gust.	[7]
	Barometric Pressure	Barometric Pressure	Used to determine air density, and to support site weather forecasting	
	Humidity	Specific and Relative Humidity	Both specific and relative humidity affect site characterization and design analyses. Relative humidity commonly utilized for air density and corrosion estimates. Vertical profile of specific humidity can be utilized to determine moisture impacts on stability, which has an effect on wind speed profile.	[2]
	Temperature	Temperature	Affects air density, and therefore power performance. Measurements are also used in planning, site safety, and corrosion estimates. Vertical profile of temperature can be used to estimate thermal stability. Normal, extreme operating, and survival temperature ranges are defined for a given turbine. Can be calculated for return periods.	[2] [4] [6] [7] [9]
		Thermal Stability	Calculated using temperature profile or flux measurements. Can also be approximated from turbulence intensity derived from anemometry, lidar or sodar. Stability classification methods include Richardson number, Monin-Obukhov length, Brunt-Väisälä frequency, and potential temperature gradients.	
	Hurricane Frequency	-	Track, intensity, and return periods of Category 1-5 hurricanes.	[4]
	Lightning	-	Observational climatology available from various surface-based or satellite-based monitoring systems (e.g., NASA, Vaisala).	[1] [7]
	Precipitation	Precipitation	Presence of precipitation and precipitation type are both useful. Rain, snow, hail, and icing frequency and/or amount. Supports data quality screening, affects corrosion estimates, and influences blade fouling/cleaning and structure fatigue.	[1] [4] [6]
		Hail Diameter	Used to estimate potential blade and/or nacelle damage from impacts. Methodology for derivation is not defined in current standards and OEM suitability requests.	[7]
		Hail Speed	Derived from hail diameter estimate using empirical equations. Methodology for derivation not defined in current standards and OEM suitability requests.	[7]
		Icing	Typically derived from air temperature, precipitation type, wind speed, wind direction, and relative humidity.	[2]

Category	Family	Parameter	Comments	Reference
	Solar Radiation	-	Surface measurements may be used to approximate blade deterioration rate, power supply for ancillary equipment, and also used in some stability classification methods.	[2]
	Visibility	-	Visibility characteristics may be used to support vessel and construction operations during turbine installation, and site access for O&M. It may also affect navigation marking requirements for the project.	[1] [2]
	Chemistry & Pollution	-	Presence, types and quantities of atmospheric chemically active substances or mechanically active particles. While there are no established guidelines for these parameters, IEC standards require that turbine manufacturers consider them for corrosion estimates.	[2]

Table 3.2 Wind Parameters

Category	Family	Parameter	Comments	Reference
Wind	Wind Speed	Wind Speed	One or more measurement height(s) of horizontal wind speed and wind speed standard deviation. Common averaging intervals are 1 minute, 10 minutes, and one hour. Typical gust averaging intervals are 2, 3 and 5 seconds. Common heights for analysis include 10 m, hub height, and elevations across the rotor span.	[1] [3] [4] [7] [8] [9]
		Wind Speed Distribution	Probability distribution function used to describe the distribution of wind speeds over an extended period of time.	[1] [7] [9]
		Wind Speed Standard Deviation	Standard deviation of horizontal wind speed. Used to calculate turbulence intensity. Standard deviation of vertical wind speed occasionally used to further characterize site turbulence characteristics. Used in quality control procedures.	
		Turbulence Intensity	Ratio of the wind speed standard deviation to the mean wind speed during the averaging period. Used for normal and extreme turbulence models. Can be defined as either ambient or effective (ambient plus wake-induced) turbulence intensity. Can be requested as a function of wind speed and/or wind direction. Can be empirically related to turbulent kinetic energy (TKE) when working with modeled and measured data.	[1] [7] [9]
		Wind Shear	Vertical profile calculated from measurements of horizontal wind speed at designated monitoring levels. Power law and logarithmic law are commonly used to extrapolate or interpolate speeds. Horizontal shear conditions are also calculated for some design cases.	[1] [7] [9]

Category	Family	Parameter	Comments	Reference
		Vertical Wind Speed	Large non-zero vertical wind speed gradients may be present due to land and sea breeze circulations, upstream topography, and unstable atmospheric conditions.	[1]
		Inclined Flow	Air flow angle relative to the water surface.	[1] [2] [7]
		Reference Wind Speed	Basic parameter for wind speed used for defining wind turbine classes. A turbine of a specific class is designed to withstand climates for which extreme 10-minute average hub height wind speed with a 50-year return period is less than or equal to the reference wind speed.	[1]
		Extreme Operating Gust	Used to define extreme operating gust speed for a given turbine design class. Can be considered for hurricane/non-hurricane conditions.	[1] [4] [7] [8] [9]
		Extreme Coherent Gust with Direction Change	Maximum 10-second concurrent 15 m/s wind speed increase and directional shift.	[1] [4] [9]
		Extreme Wind Shear	Extreme 12-second wind shear change, applied in both vertical and horizontal directions.	[1] [4]
	Wind Direction	Wind Direction	One or more measurement height(s) of horizontal wind direction and wind direction standard deviation.	[3]
		Wind Direction Distribution	Energy- and frequency-weighted wind rose.	[2] [7]
		Extreme Direction Change	Maximum 6-second wind directional shift.	[1] [4] [9]
		Wind Veer	Wind direction change with height over the rotor span or turbine operating height.	

3.4 Water Parameters

Water parameters influence many aspects of offshore wind project design, development and operation. For example, water conditions play large roles in the design and certification of certain turbine components (e.g. towers), foundations and floating platforms, and balance of plant components. Many of the offshore wind design standards and guidelines provide specific direction on the analysis of water and joint atmosphere-water conditions. While wind and related meteorological conditions are the primary concerns in many offshore wind activities and analyses, water (and joint wind-water) conditions can be more significant design-drivers in than atmospheric characteristics alone. Representation of these parameters is normally based on on-site or regional observations and through modeling and hindcast studies

The family of water parameters includes the water's physical state(s) and properties (such as density and salinity), and oceanographic characteristics such as waves, currents and water level. Estimates of storm surge and sea/lake ice properties are water surface properties. All other oceanographic parameters presented in this section are relevant throughout the depth of the water column. As referenced earlier, "oceanographic" shall refer to water characteristics in both marine and fresh water bodies. Any distinctions in parameters or properties required for these two different environments will be specifically identified.

3.4.1 Water State Properties

The physical state and properties of the water column, specifically characteristics such as temperature, salinity, density, and ice loading, are important inputs to structural loading calculations, corrosion estimations, site access, construction planning and execution, current, wave and (to a lesser extent) wind characteristics. Knowledge of these properties is important throughout the development and design phases, as well as for operations and maintenance.

The parameters affecting the density of sea water, such as salinity and temperature, also affect the structural loading due to the water and/or wave action flow. Salinity in oceanic coastal and offshore waters generally ranges between 32 and 38 g kg^{-1} (NASA, 2013), although local values can range much higher or lower in shallow, protected waters depending upon evaporation and inputs of fresh water (through riverine sources or meltwater from glaciers and ice sheets). In addition, the presence of sea/lake ice and its physical properties can greatly affect air-sea interactions and structural loading in cold climates. For example, ice cover may significantly modify the wave state, which can also affect the surface layer wind profile.

Corrosion potential may be estimated from observation of water chemistry or pollution, and salinity. Water conductivity measurements are frequently used to estimate water salinity, given known or assumed proportions of dissolved salts. Water temperature also affects corrosion rates, in addition to influencing structural loading characteristics through marine growth[2].

[2] Refers to the colonization on marine structures by marine organisms.

Estimates of storm surge and sea/lake ice properties are ocean surface observations. For all other parameters listed here, observations throughout the depth of the water column are essential for accurately gauging conditions at development sites.

3.4.2 Wave Heights

Wind-generated waves[3] are surface waves that usually result from the wind blowing over a stretch of water (fetch). Wind waves range in size from small ripples to tens of meters in height. The wave height is the difference between the elevation of a crest (the top of the wave) and a neighboring trough (see Figure 3.1). The wavelength is the length between crests of two successive waves. A swell consists of wind-generated waves that are not generally affected by the local wind. Additionally, a swell is typically generated from a distant source (such as a storm), or some time ago. The frequency is the number of waves or swells passing a point per unit time, while the period is the time interval between the arrival of consecutive crests at a stationary point (the inverse of the frequency).

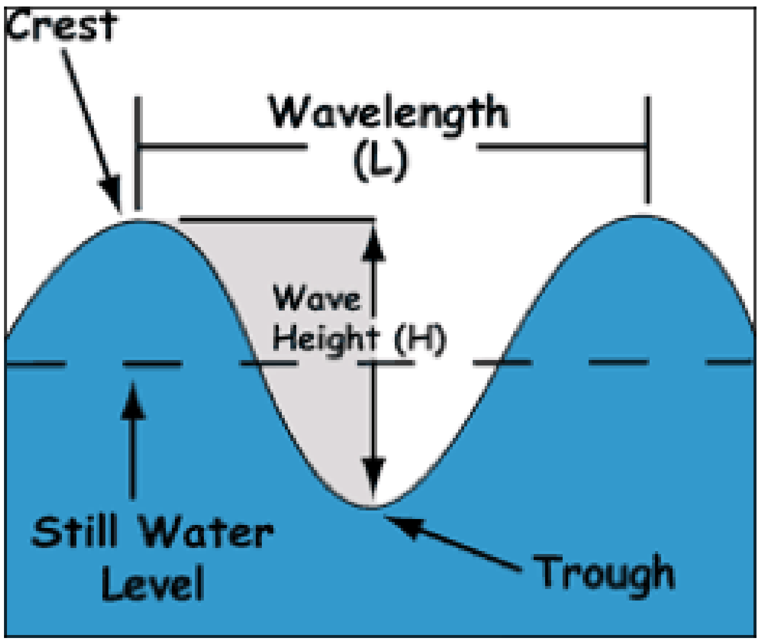

Figure 3.1. Schematic of a Typical Ocean Wave

Wave reports from buoys and other observation platforms typically represent a mix of wave and swell heights (that is, the observations do not differentiate between a more locally induced wave and a long traveling swell). Although only significant wave height (H_s) observations (defined as four times the square root of the first moment of the wave spectrum; see below) are usually available, individual wave heights can be described using a Rayleigh Distribution (Longuet-Higgins 1952), which, for its cumulative probability form, is given as

$$F(x) = 1 - exp\left[-\frac{x^2}{2}\right], \quad 0 \leq x \leq \infty$$

[3] As distinguished from other force-generated waves such as from earthquakes and landslides.

For example, given that H_s = 10 m, then

- 1 wave in 10 will be larger than 10.7 m
- 1 wave in 100 will be larger than 15.1 m
- 1 wave in 1000 will be larger than 18.6 m

This allows for calculation or estimates of the extreme wave height (H_e). Wave heights can be measured or inferred from a number of different sensor types. In-situ and remote wave height sensors are discussed in Section 4.

As mentioned previously, the wave and swell state can also have a measureable effect on the wind profile by the exchange of momentum at the air-sea interface. For example, waves/swells following or opposing the prevailing wind measurably alter the surface roughness and drag coefficients in the lowest tens of meters of the marine atmospheric boundary layer (MABL). The potential impacts of the sea state on hub height/rotor plane winds is currently under investigation, as more observational studies are needed to ascertain effects under the spectrum of air-sea states and high wind conditions.

3.4.3 Wave Spectra

Wave measurements are usually not directly measured by sensors on buoys. Instead, on-board accelerometers or inclinometers measure the heave acceleration or the vertical displacement of the buoy hull during the wave acquisition time period. A Fast Fourier Transform (FFT) is applied to the data by the processor on board the buoy to transform the data from the temporal domain into the frequency domain. The spectral approach indicates what frequencies have significant energy content, as well as the direction wave energy is moving at each frequency. A wave spectrum can readily be plotted in a frequency vs. energy density graph (see Figure 3.2), which can provide important information about a wave sample and the corresponding ocean conditions. The general shape of the plot can reveal a great deal: whether seas or swell predominate, the number of distinct swells present, etc. For example, the National Climatic Data Center (NCDC) typically calculates and archives the spectral wave energy (m^2 /Hz) for frequency bins from 0.03 Hz to 0.40 Hz. In Figure 3.2, several years of frequency spectra are averaged at buoy 44025 and Coastal-Marine Automated Network (C-MAN) station ALSN6 (60 km south and Islip, New York and 15 km southeast of New York City). Other key information derived from wave spectra include dominant wave and swell periods and wave roses, which, as in Figure 3.3, for buoy 44009 (about 50 km southeast of Cape May NJ), provide directional information regarding favored sectors for approaching waves and swells. This information, as with winds, can be broken down by total wave frequency and wave energy (Figure 3.2).

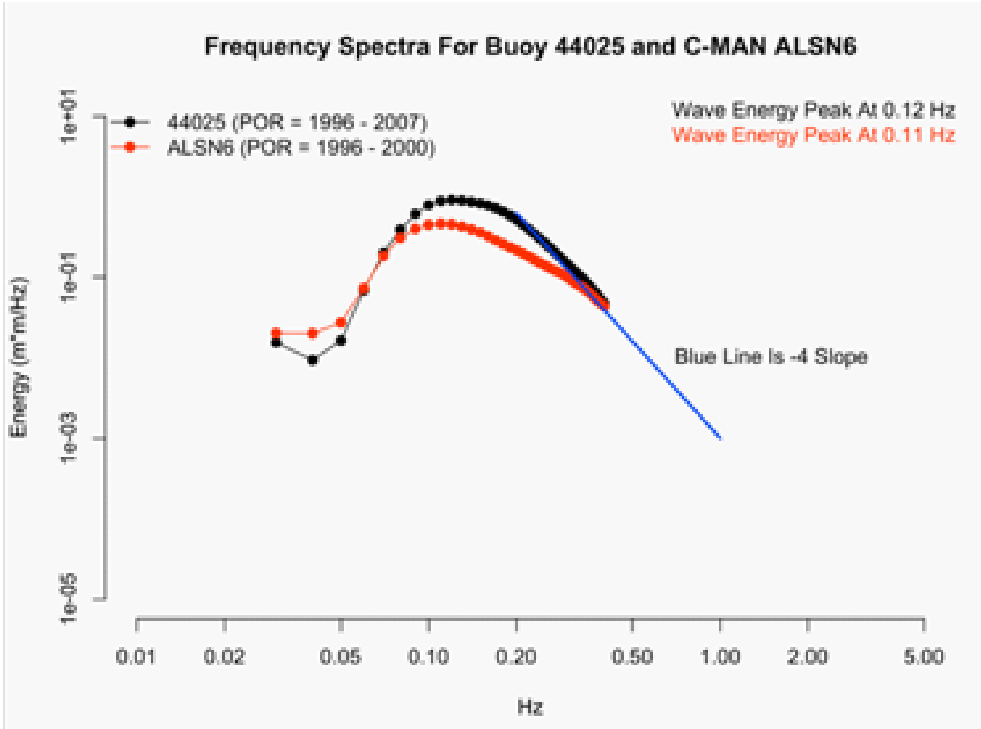

Figure 3.2. Frequency Spectra Examples. Spectra for buoy 44025 (black) and C-MAN station ALSN6 (red). Plotted on log-log axes where the blue line represents the -4 slope as suggested by Toba (1973).

From Figure 3.2, the spectral wave energy peaks for 44025 and ALSN6 are at 0.12 and 0.11 Hz, or wave periods of 8.33 and 9.09 seconds, corresponding to moderate short-period swells that often traverse the offshore waters of the east coast of the United States. The higher energy peak at buoy 44025 reflects its location further offshore where higher waves and swells are more common. Note also that the wave spectra at each station decays (that is, the waves tend to lose their energy at these frequencies) at roughly the -4 slope as suggested by Toba (1973).

From the wave spectra, first-order information regarding frequencies of wave height and wave direction and other wave statistics are derived. Combined with wind information discussed in section 3.3.2, additional analysis regarding the air-sea-current interface and how it affects turbine and foundation design (such as resonant frequencies and damping values) can be performed.

3.4.4 Wave Statistics

Wave conditions at a site are described according to short-term, long-term, and extreme value statistics. Short-term wave statistics are given by the wave spectrum. These short-term statistics are derived from observations of significant wave height, wave period, and wave direction. Extreme value statistics may be calculated using observed parameter measurements together with empirical formulas, or by fitting observations to distribution models and projecting return times based on the observed frequency of events over a given reference period. Typically 50- and 100-yr return periods are used in extreme waves analysis. Care must be taken in choosing which generalized extreme value method to use, as wave height distributions do not necessarily follow the popular Gumbel distribution (see section 3.4.2) and large differences in return period heights can result from the combination of a limited period of record and choice of extremes statistical tool.

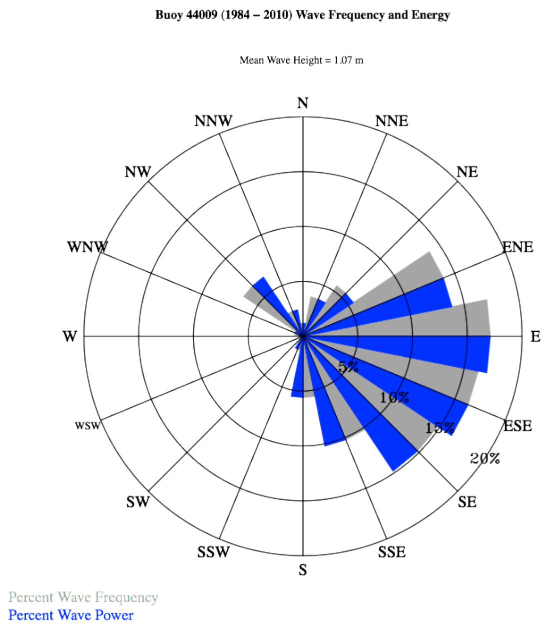

Figure 3.3. Wave Rose Example. For buoy 44009 for the period 1984 - 2010. Grey shading represents total wave frequency; blue shading shows frequency by wave energy.

3.4.5 Ocean Currents

Ocean currents are defined as "a movement of ocean water characterized by regularity, either of a cyclic nature or, more commonly, as a continuous stream flowing along a definable path" (American Meteorological Society, 2014). The forces causing ocean currents come primarily from the wind and unequal heating and cooling of ocean waters. Typically, the speed of surface currents is about 2% of the speed of the wind causing them (e.g. a 10 m/s wind would produce a 20 cm/s surface current). For the water column (from ocean surface to the sea bottom), the deflective force of the earth's rotation (the Coriolis force) causes a change in direction of currents with depth (the Ekman spiral). However, in more shallow waters, these deflective forces are diminished, although they can produce coastal upwelling (Ekman transport) of deeper, colder water given winds blowing parallel to the shore.

There are five primary mechanisms responsible for the ocean currents. These are:

- Large-scale currents such as the Gulf Stream.
- Wind-generated near-surface currents. These currents may reinforce or oppose the general flow of the larger-scale currents.
- A swell and surf generated longshore current. For example, a predominant southeast swell generates a net east to west current. This current can reverse with westerly winds and swell from the southwest.

- Swell and surf-generated rip currents, which counteract the net transport of water toward the shore. Rip currents form narrow zones of low waves and rapid (up to 3 m/s) seaward flow that extend several hundred meters to a kilometer offshore.
- Tidal Currents. These currents are usually important only in the vicinity of the inlet channels. Flow is along the axis of the channels in and out of the inlets, roughly perpendicular to the coastline.

The first two mechanisms are of primary interest, as they are the principal current components in the open waters within and around where offshore wind projects will be built and also determine the current profile from the ocean surface down to the sea floor. Sea floor topography and these sub-surface and bottom currents will determine the magnitude of sediment transport, scouring, and forces impinging upon wind turbine foundation structures and vessels working in the project area.

Although IEC design standards allow for application of standard current profiles to surface current measurements for obtaining site-specific profiles, sites where local currents may deviate significantly from these standard profiles may require observations throughout the water column. Local deviations may occur in shallow water areas with significant wave-induced current stretching or compression, or in areas with high thermal or salinity gradients.

3.4.6 Other Oceanographic Parameters

Waves, currents, and water properties represent largest families of priority oceanographic parameters; however, several other variables are also important to offshore wind development and operation. Among the other relevant parameters are water level, marine growth, and bottom surface characteristics.

The water level range consists of an astronomical tidal fluctuation and any additional storm surge. These parameters are essential to foundation and piling design, as well as to navigation. The tidal datum is a local vertical reference elevation used to measure water levels based on tidal fluctuation. Notation of the reference datum is particularly important, as engineering design and preliminary wind development tasks may not use the same datum as a default. For example, wind maps are commonly referenced from mean sea level (MSL) and foundation designs often reference mean lower low water (MLLW). Storm surge consists of a wind-driven and small pressure driven component that increases water level heights. The juxtaposition of tidal range with storm surge levels gives the maximum range of water levels expected at a site.

Characterization of marine growth–referring to the colonization of organisms on structures by underwater organisms – is required for the design and maintenance of any sub-subsurface components in an offshore wind farm. The type(s) of organisms, the rate(s) of growth, the percentage coverage and the thickness by depth are all used to support sub-surface loading calculations and maintenance program design.

Table 3.3 lists relevant water state and properties while Table 3.4 describes several oceanographic parameters.

Table 3.3 Water State and Properties

Category	Family	Parameter	Comments	Reference
Water State and Properties	Chemistry & Pollution	-	Observations of active chemical substances (e.g. dissolved salts such as Sodium, Chloride, Potassium, and Magnesium) and oxygen levels. Affects corrosion estimates, paint and anode design for turbine and electric service platform foundations. Contaminant transport models available to measure dispersion from source pollutants.	[2]
	Conductivity	-	A measure of an electrolyte's (here, seawater) ability to conduct electricity. Affects corrosion estimates, paint and anode design for turbine and electric service platform foundations.	[2]
	Density	-	The mass of water per cubic volume. Calculated at the surface and within water column as necessary given temperature and salinity (or conductivity) measurements. Affects wave loads calculations. Used for depth-varying current modeling. Sea water densities generally vary between 1.020 to 1.029 kg/m^3 .	[2] [4] [6]
	Salinity	-	Amount of dissolved salts per kg of water. One near-surface measurement at a minimum, two or more preferred, to calculate profile. Satellite measurements available but only for the sea surface. Used for depth-varying current modeling, as well as corrosion calculations.	
	Marine Growth	-	Refers to the colonization of organisms on structures. Marine growth profile in terms of rate, percentage coverage and thickness by depth to be used to support sub-surface loading calculation.	[2] [4] [6] [9]
	Ice	-	Generally the thickness of sea or lake ice or accretion on structures from spray or wave deposits. Such data provides basis for a statistical representation of ice characteristics, including crushing and bending strengths, pack ice concentration, and freezing spray. Mechanical properties of sea ice and lake ice can differ greatly. Affects turbine foundation and balance of plant (BOP) design, as well as energy yield calculations.	[2] [4] [6]
	Temperature	Water	Surface and water column: one monitoring depth at a minimum, two or more preferred, to calculate vertical stability profile. Underwater temperature utilized in 3-dimensions for depth-varying hydrodynamic current profile modeling. Also affects corrosion estimates. Supports site forecasting, stability, conductivity, and density calculations.	[2] [4] [6] [9]
		Seabed	Utilized in foundation design and BOP; estimates.	[4] [6]

Table 3.4 Oceanographic Parameters

Category	Family	Parameter	Comments	Reference
Oceanography	Wave	Wave Direction	The direction from which waves are coming. Used as input to joint wind and wave directionality tables. Important for resonant frequencies and damping values.	[2] [9]
		Wave Height	Defined as the difference between the elevations of a crest (the top of the wave) and a neighboring trough (the minimum height between waves (see Figure 3.1). Common design criteria include: normal wave height (expected value of significant wave height for a given mean wind speed), significant wave height (H_{sig}), and extreme wave height (H_{ext}) using e.g. a Rayleigh distribution--see section **Error! Reference source not found.**. Return periods (50-yr and 100-yr) should be calculated for H_{sig} and H_{ext}.	[2] [4] [6] [9]
		Significant Wave Height	Statistical measure of wave height, defined as four times the standard deviation (or four times the square root of the first moment of the wave spectrum), of sea surface elevation. If wave frequencies are narrow, this is approximately equal to the mean height of the highest one-third of all waves.	[2]
		Dominant Wave Period	The temporal wave period with maximum wave energy. Can be expressed in terms of the range of peak periods for various return periods and range of peak periods by significant wave height.	[2] [4]
		Directional Spectrum	Wave energy as a function of direction. Consists of H_{sig} and the dominant wave period.	[4]
		Frequency Spectrum	The wave energy in the frequency domain.	[2] [4]
		Mean Wave Speed	Various wave propagation theories are used to describe water particle kinematics based on wave amplitude, wave period, and water depth i.e., linear or higher-order wave theories.	[4]
		Wave Model	A stochastic wave model is necessary to resolve the superposition of many frequency components with independent amplitude and directions of propagation. Several models/theories of shallow water hydrodynamics and breaking waves exist.	[2]
	Current	Current	A movement of ocean water characterized by regularity, either of a cyclic nature or, more commonly, as a continuous stream flowing along a definable path. Speed and direction profiles are typically measured at multiple depths.	[2] [4] [6] [8] [9]

Category	Family	Parameter	Comments	Reference
Oceanography	Water Level	Still Water Level	Hourly (or more frequent) measurements of water levels compared with a station's Datum, a fixed base elevation at a tide station to which all water level measurements are referred. Water level ranges are used to define mean sea level, mean low water, mean high water, normal (1-year return period), extreme (50-year), and survival (>50-year) water levels.	[2] [4] [6] [8]
		Storm Surge	The abnormal rise in water level, over and above the regular astronomical tide, caused by a severe storm such as a tropical cyclone or a cold season extra-tropical system.	[2] [9]
		Tidal Datums	Markers of tidal variation such as highest astronomical tide (HAT) and lowest astronomical tide (LAT).	[2]

3.5 Additional Parameters

Many additional parameters, as well as the combination of those parameters, are relevant to metocean characterization. Additional parameters include geophysical and geotechnical descriptors. While an in-depth treatment of geophysical and geotechnical parameters is beyond the scope of this study, several can affect other metocean design conditions. In particular, the bottom surface characteristics– bathymetry, soil type, and scour conditions – influence adjacent water conditions (e.g., currents, waves, breaking wave frequency, etc.) and directly influence project design. Seismic conditions are more rigorously treated during geotechnical and foundation design processes, but are still identified as a notable parameter in several of the standards cited.

Design load cases (both ultimate loading and fatigue loading) in several of the standards, as well as the turbine vendor-specific design basis documents, mandate joint analyses between various atmospheric and water conditions. While numerous combinations of wind-wind, wind-water, and water-water parameter analyses are required, some of the most common are presented in Table 3.5. Joint parameter comparisons can be the driving conditions in key design processes, including turbine suitability determination, foundation and tower design, and potentially turbine back-up power requirements (in the event of a loss of grid power or substation).

Table 3.5 Additional Parameters

Category	Family	Parameter	Comments	Reference
Soil	Sea Floor Variations	Bathymetry	Local and regional bathymetry / bottom topography can affect a number of water parameters, including wave heights and breaking wave frequency. This is an important input for wave and ocean / lake modeling, as well as foundation design and cable routing	
		Soil Type	Affects project siting, turbine and BOP micrositing, cable route and installation method, scour, seabed movement, foundation type (and design), installation methods and vessels, and other parameters.	
		Seabed Movement	Stability of seabed, including probability of slope failure, slides, cavity failure, erosion, etc, as well as settlement and soil liquefaction must be taken into account for foundation design and cable placement and protections. This includes the movement of sand waves, ridges and shoals which would occur in the absence of a structure.	[2] [4]
		Scour	Either local (steep sided, around structural elements) or global (shallow basins, large extent around structures due to single structure, multiple structures, and/or wave-soil-structure interaction). This affects foundation design and cable installation / protection	[2] [4] [9]
Seismic	-	Earthquake	Where applicable, seismic loading will depend on ground acceleration and response spectrum requirements as defined in local codes or by means of a site-specific evaluation.	[1] [9]
		Tsunami	Where applicable, hydrodynamic loads from waves resulting from sub-sea earthquakes (tsunamis) may be considered.	[2] [9]
Joint Probability Distributions	-	Wind Direction - Wave Direction	Used for fatigue loading under combined wind and wave conditions. Important for resonant frequencies and damping values.	[2] [7] [9]
		Wind Direction - Wind Speed	Used to summarize temporal frequency, mean/standard deviation/maximum TI, mean wind shear.	[2] [7] [9]
		Significant Wave Height - Peak Spectral Period - Wave Direction	Used to represent the normal, severe, and extreme sea states. Can include wind directionality.	[2] [6] [7]
		Wind-generated Current - Wind Speed	Used to represent the normal and extreme current models.	[4] [6]
		Wave Height - Wind Speed	Used to represent the severe wave height, estimates of surface roughness, and modification of the wind profile.	[2] [4]

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4. PARAMETER CHARACTERIZATION: OBSERVATIONAL APPROACHES

4.1 Introduction

Observational approaches to metocean parameter characterization have a long history of development and application worldwide. Directly and remotely observed data often form the foundation for many analyses related to offshore project wind design, deployment and operation. Local and regional observations–including historical data sets–support a variety of offshore wind applications and also serve to initiate, tune and validate other analytical techniques.

Design, deployment and operation of dedicated observational stations (or broader networks) – typically considered the highest confidence approach to site-specific metocean assessment – can require significant investments of time and money for offshore wind projects. As such, understanding the characteristics and quality of existing observations, as well as the tools and techniques available for new measurements, is essential to cost-effective metocean assessment. New or existing measurements should also be considered in context with contemporary modeling and analytical methods, as these tools are often integrated with observations to enhance and expand their spatial and temporal representativeness.

This chapter presents observational approaches for metocean parameter characterization. It covers the most common instrumentation currently in place and available for measuring primary offshore wind parameters. It also describes the various platforms for these observations, and introduces concepts related to integrating observations with modeling and analytical approaches.

This chapter considers two categories of instrumentation for metocean site characterization: direct and remote measurement sensors. Direct sensors typically provide point measurements of one or two variables, and require multiple instrumentation heights (or depths) to develop profiles of relevant parameters. Direct measurement sensor families are comprised of many of the instruments historically employed in offshore wind, including cup anemometers, wind direction vanes, and air/sea temperature sensors. Remote sensing instruments employ a variety of techniques to provide volumetric or area measurements of numerous atmospheric and oceanic parameters. The offshore wind industry is increasingly relying upon several types of sensors in this category to support project development and operations. The instruments discussed below are grouped according to observation category or measurement principle.

Direct and remote sensors commonly operate as integrated parts of purpose-designed measurement stations or platforms, e.g., a tall tower on a bottom-fixed offshore platform, a metocean buoy, or a coastal measurement station. The characteristics of these integrated stations are often as important to the resulting observational data sets as the sensors they support. The station or platform configuration will influence the types and numbers of sensors deployed, the temporal and spatial coverage of the observations, and often the uncertainty of the resultant measurements. Power supply, data logging and storage, remote communication and other ancillary operational characteristics of a platform further affect the data recovery and data quality of its instrumentation suite. Platform and station configurations relevant to existing metocean data sets and offshore wind measurement are introduced and discussed in the sections below.

Finally, this chapter identifies attributes of observational data sets that influence their application to various offshore wind-related tasks. High-level characteristics such as period of record, time scales of measurement and averaging, spatial and temporal applicability, data recovery and uncertainty are important to consider for all metocean sensor types, platforms and applications. These characteristics affect the observations' utility and confidence when applied to specific data needs, and are relevant to their integration with other site assessment tools, such as numerical models. Relevant national and international guidelines that affect or inform metocean observations, station configuration or data use, are also discussed here.

4.2 Instrumentation

This section identifies the primary instrument types that are typically used to create metocean data sets, as well as those available and commonly employed for offshore wind-specific metocean measurement applications. The sensors are organized by environment–atmospheric and oceanic–and by direct or remote measurement configuration. The information presented herein is not intended to reflect an exhaustive list of current and historical instruments; rather, it is a survey of the most common instrument types in 2014 for measuring important metocean parameters for offshore wind.

4.2.1 Atmospheric: Direct Measurement Sensors

Anemometers and Wind Vanes

Anemometers and vanes are the historical standards for wind speed (anemometers) and wind direction (vanes) measurements. Mechanical wind sensors are available in a variety of configurations to measure one, two or three components of the wind – cup anemometers, propeller-vane anemometers, and 3D propeller anemometers, respectively. Sensor quality and performance characteristics–such as accuracy, stability of performance over time, robustness, etc.–vary by brand and model, and are often matched against measurement requirements and budget.

Mechanical Anemometers: Both cup- and propeller-type anemometers convert the rotational speed of the rotor/propeller assembly into an electrical signal that is proportional to wind speed. The frequency or magnitude of that signal can then be converted to a wind speed value through a sensor-specific transfer function. International methods for sensor classification (Risø, 2006), calibration procedures (MEASNET, 2009), and mounting and uncertainty calculations (IEC, 2005) have been developed to support the use of mechanical cup anemometers in wind energy applications. Sensors intended for deployment and operation on buoys or other near-surface systems may follow other standards or best practices.

Sonic Anemometers: Similar in dimension, mounting, and integration to traditional mechanical wind instruments, ultrasonic anemometers measure the frequency shifts of ultrasonic pulses emitted across a small measurement volume to determine wind speeds along two or three axes. While common in many meteorological and ocean measurement payloads, there are no specific guidelines for use of sonic anemometers in the context of supporting offshore wind energy.

Wind Vanes: The aerodynamic characteristics of a mechanical direction sensor cause the vane to face into the prevailing wind direction. The orientation of the wind vane relative to an internal reference is converted to an electrical signal, commonly through a potentiometer. This signal is then converted to a direction value using a sensor-specific transfer function and offset. Measurement standards are not typically as rigorous for wind direction sensors; basic performance specifications (Brower, 2012) for sensors employed for terrestrial wind energy projects are generally applicable offshore.

Air Temperature Sensors

Standard Sensors: Ambient air temperature sensors are typically composed of three parts: the transducer, an interface device, and a radiation shield. The transducer contains a material (usually nickel or platinum) exhibiting a known relationship between resistance and temperature. Thermistors, resistance thermal detectors (RTDs), and temperature-sensitive semiconductors are common element types. The resistance value is measured by the data logger (or interface device), which then calculates the air temperature based on the known relationship. The temperature transducer is housed within a radiation shield to prevent it from being warmed by sunlight.

Delta-Temperature Sensors: The parameter ΔT (pronounced delta-tee) is the difference in air temperature between two heights and is a measure of atmospheric stability or buoyancy. Meeting guidelines for ΔT accuracy (EPA, 2000) requires the use of at least two identical temperature sensing subsystems calibrated and matched by the manufacturer, as well as specific mounting techniques and sensor ventilation. The need for vertical separation between ΔT sensors almost always necessitates deployment on an offshore or coastal tall tower.

Relative Humidity

Relative humidity data can improve the accuracy of air density estimates, as well as inform other design inputs for offshore wind projects; it also supports icing calculations in cold climates. Ambient relative humidity is measured with a capacitive sensor and conveyed to the data logger typically as an analog voltage measurement. Relative humidity sensors are commonly integrated with standard and high-precision air temperature sensors. Accuracy requirements are not standardized for this sensor in the context of offshore wind energy applications, so basic specifications from terrestrial applications are valid.

Barometric Pressure

Several barometric pressure sensors, or barometers, are commercially available. Most models use a piezoelectric transducer to generate an analog direct current (DC) voltage signal and require excitation from the data logger. Accuracy requirements are not standardized for this sensor in the context of offshore wind energy applications, so basic specifications from terrestrial applications are valid.

4.2.2 Atmospheric: Remote Measurement Sensors

Wind Parameters

Light Detection and Ranging (lidar): Lidar most commonly operates by emitting a laser light signal (either as pulses or a continuous wave) which is partially scattered back in the direction of the emitter by suspended aerosol particles. In Doppler wind lidar the light scattered from these particles is shifted in frequency in proportion to their speed (and the speed of the wind). This frequency shift is used to derive the radial wind speed along the laser path. Multiple laser measurements are taken at prescribed angles to resolve the three-dimensional (3D) wind velocity components at various reporting elevations above the system. Some systems use the strength of the backscatter at different radial distances to estimate the bulk flow vectors. The operational characteristics, number of measurement ranges, the depth of the observed layer, and even the shape of the measurement volume vary greatly by lidar model type.

Three distinct types of lidar are currently employed in offshore wind energy. Profiling lidars measure the wind along one dimension, usually vertically, similar to measurements taken from a tower. These lidars typically measure wind speeds from 20 to 300 m above the device, and can be mounted on the ground (for coastal deployment), on a fixed offshore platform, or on a floating offshore platform. Three-dimensional scanning lidars have the capacity to rotate the laser beam about two axes, which allows the device to measure wind speed at nearly any point within a hemispherical volume. This scanning technology is typically designed to obtain an array of wind speeds over a large area, with some units having a line-of-sight range of several kilometers. These too can be deployed onshore or offshore. Nacelle-mounted lidars are systems specially designed to support the measurement of inflow and outflow conditions from a turbine. All three lidar types require external electrical power, typically ranging from about 50 to 400 watts, continuous.

Lidar is increasingly common as both a supplementary and primary wind measurement tool for offshore wind projects. While there are no specific guidelines for offshore lidar use, available best practices for remote sensing use in simple terrain (IEC 15, 2013) are generally applicable to lidar placed on stable offshore platforms. Guidelines for profiling lidar classification (IEA, 2013) and validation (IEA Task 32, 2013) are currently under development.

Sonic Detection and Ranging (sodar): Sodar operates by emitting acoustic pulses (audible chirps or beeps) upward into the atmosphere and listening for the backscattered echoes. The scattering is caused by turbulent eddies (small-scale fluctuations in air density) carried along by the wind. The motion of these eddies causes a Doppler frequency shift. As with lidar, the beam is usually at a slight angle to vertical, and so the line of sight velocity can be converted into an estimate of the horizontal and vertical velocities. The timing of return echoes establishes the height at which the scattering occurred. Most sodar devices measure the wind profile from 30 m up to about 200 m above ground in increments of 5 m to 20 m.

Power consumption for sodars typically ranges between about 20 and 100 watts. Though less common and more challenging to operate offshore than lidar, sodar has nonetheless been successfully deployed and operated as part of offshore wind measurement campaigns. The major challenges in operating sodar offshore include the noisy environment, the size of the equipment, and fouling of the transmitter/receiver array by bird dropping and snow.

Though less common and more challenging to operate offshore than lidar, sodar has nonetheless been successfully deployed and operated as part of offshore wind measurement campaigns. While many of the same monitoring practices apply to both lidar and sodar, the differences in the two technologies do warrant consideration in campaign design and data analysis.

Temperature Parameters

Radiometer: Radiometric instruments measure the amount of electromagnetic energy emitted from objects. They can be used on a variety of platforms, including surface, aircraft, or satellite mounting. The choice of platform is dependent upon the intended observation. These instruments are used in measuring atmospheric temperature and humidity profiles, solar radiation estimates, and other meteorological parameters. Temperature profiling radiometers are the configuration most commonly utilized in wind energy-related applications, and activities are underway to develop marinized sensors to better perform in the metocean environment.

Radio acoustic sounding system (RASS): Measurement of atmospheric virtual temperature profiles using RASS is based on the Doppler frequency shift of radar echoes. A RASS is typically deployed in conjunction with a wind profiler (commonly sodar or lidar) for detailed analyses of the atmospheric boundary layer. These data can support the derivation of atmospheric temperature and stability profiles, as well as forecasts of weather conditions for a site. While not commonly deployed offshore due to the costs associated with operations and maintenance, this instrument provides a useful alternative for collecting temperature profiles through the boundary layer.

4.2.3 Oceanic: Direct Measurement Sensors

Water Level

Two main types of direct water level gauges exist for wave and tidal measurements: electric level and pressure gauges. Electric level gauges are mounted on submerged moorings near the water surface and provide non-directional measurements of water level heights. Pressure gauges are typically bottom mounted, and if organized in an array, provide both water level heights and wave direction measurements.

Surface Current

Two families of measurement technologies are available to characterize currents. In situ flow meters mounted on fixed or moored, floating platforms measure water velocities at discrete depths at a fixed location, similar to anemometers measuring wind speed. Gliders, drifting buoys and other mobile measurement platforms provide current measurements over an area and/or path of travel at one or more depths, depending upon configuration.

Water Temperature and Salinity

Surface water temperature and temperature profiles are commonly observed using direct measurement probes e.g., CTD (conductivity-temperature-depth) or XBT (expendable bathythermograph) instruments. Conductivity measurements are used to derive the salinity of the water and, with temperature and pressure data, support density calculations. These probes can be mounted on a variety of platforms, both land-based (coastal stations) and offshore.

Wave Conditions

Two primary types of direct wave measurement systems are available, both typically deployed in wave-riding buoys. The first-- non-directional wave buoys-- use accelerometers or inclinometers to measure the heave acceleration or the vertical displacement of the hull during a measurement period. The second type-- directional wave buoy-- measures hull azimuth, pitch, and roll, in addition to buoy heave acceleration. Various sensor packages and methods exist for measuring directional wave data. Figure 4.1 shows a directional wave buoy deployment.

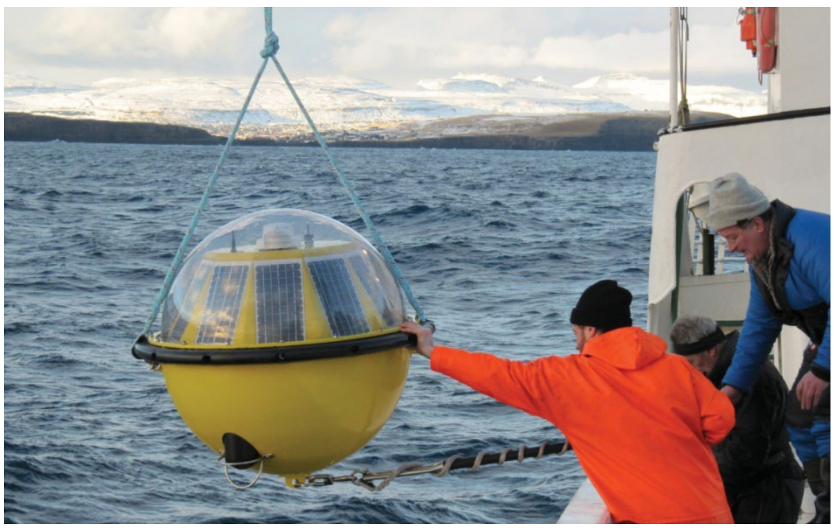

Figure 4.1 Directional Wave Buoy
(Source: AXYS, 2012)

4.2.4 Oceanic: Remote Measurement Sensors

Waves, Currents, and Surface Winds

Acoustic Doppler Profiler: Similar to sodar, this system employs measured Doppler shifts in emitted sonic pulses to calculate water current velocities over a depth range. When mounted to the sea or lake floor, the sensor may be used to measure both current profiles and directional surface wave information (i.e., wave height and direction). Acoustic doppler profilers can be mounted individually, but are commonly deployed with surface buoys or other offshore platforms to support power and communication needs. Figure 4.2 shows an example of an acoustic doppler profiler.

Figure 4.2 Acoustic Doppler Profiler
(Source: NOAA, 2006)

Radar: High Frequency (HF) radar maps sea surface velocity vectors and wave properties by measuring the Doppler shift of HF radio waves (3-50 MHz) reflected back to the emitting source by ocean surface waves. These sensors are commonly deployed as part of land-based coastal stations (or networks) and have effective ranges of several hundred meters (200-500), or several kilometers (3-12), depending upon model and configuration. Related systems, such as radar altimeters and Synthetic Aperature Radar (SAR) – operate at frequencies in the gigahertz range and are deployed on satellite observation platforms (see following section) to assess sea level, wave heights and wind surface wind speeds over open water.

Scatterometers: This family of sensors, primarily deployed on space-based platforms (satellites), actively transmits electromagnetic pulses – typically in the microwave spectrum – and measures the backscattered signal from the ocean surface. Depending upon the sensor design, scatterometers can measure or estimate sea surface temperatures, sea ice concentrations, and other relevant metocean parameters, including surface wind speeds and directions.

Radiometers: Space-borne radiometers, typically measuring in the infrared and/or microwave spectra, are employed to characterize a number of oceanographic parameters, including sea surface salinity and temperature, near-surface wind speed, and sea ice properties.

4.3 Measurement Platforms

Various platforms exist from which single- and multi-parameter metocean observations can be made. The use or configuration of specific measurement platforms is driven by the type(s) of parameter being observed (i.e., atmosphere or ocean), the measurement principle (i.e., direct or remotely sensed), and the desired monitoring heights and/or depths. This section presents the platforms relevant to offshore wind-related measurements, including satellites, bottom-fixed offshore platforms, surface buoys, and land-based stations.

Land-Based Stations

Land-based monitoring stations can have utility for offshore wind energy applications. Direct observations of coastal atmospheric and ocean conditions, such as those provided by shoreline meteorological masts, tide and water temperature sensors, and related instruments, can be valuable for characterizing near-shore environments, for specific metocean phenomena (e.g., sea breezes), and for integration with models and larger networks. The value, accuracy and representativeness of many coastal measurements can decrease with increasing distance from shore. Use of these data sets can be valuable for long-term reference or near-shore applications, but can carry significant uncertainty in analyses further from shore.

Land-based remote sensing systems, such as volume scanning lidar and various radar systems, can provide observations (or derivations) of metocean parameters further offshore. Coastal radar systems can measure surface current parameters and wavefield characteristics at distances from several hundred meters to over 10 km. Volume scanning lidar systems have line-of-sight wind measurement ranges of between several hundred meters and over 10 km, depending on model and configuration. While both of these sensor systems have been in use for many years, their application to offshore wind analyses in the United States is relatively new. As such, care must be taken when considering use of their respective data sets.

Surface Buoy

A wide array of instrumentation may be mounted on a surface buoy. This platform type is one of the historical standards for in-situ ocean and surface meteorological monitoring. It is deployed in a variety of physical sizes and configurations, from small (approximately 1 m diameter) wave buoys to 12 m discus buoys with extensive monitoring payloads. Developments in remote sensing technology, platform design and data analysis have enhanced the sensor options for buoys and the suite of parameters they can monitor.

Surface buoys can be divided into two broad categories, moored and drifting. Drifting buoys are used for ocean current measurement through the use of GPS tracking, and commonly host additional instrumentation for metocean parameters such as salinity and water temperature, surface winds, air temperature and pressure. Moored buoys also measure these conditions, as well as wave parameters, subsurface current and temperature profiles, and other metocean variables at fixed locations. Figure 4.3 shows an example of a traditional moored buoy.

The integration of remote sensing instruments, lidar in particular, on buoys has expanded their potential value for offshore wind monitoring. The motion characteristics of the buoy platforms and the measurement characteristics of the lidars employed in these systems can vary significantly, as can the balance of the system configurations. Several entities, including consultancies (DNV, 2014), non-profits (Carbon Trust, 2013), and the IEA (IEA, 2013), are developing roadmaps and guidelines for the use of buoy-based lidar in offshore wind applications, but the library of long-term performance data is still small for these systems. Efforts are underway to develop and integrate additional instruments for buoys to enhance their value for offshore wind, including radiometers and biological monitoring systems.

Figure 4.4 shows an example of a buoy-based lidar system in use for offshore wind resource and metocean data collection.

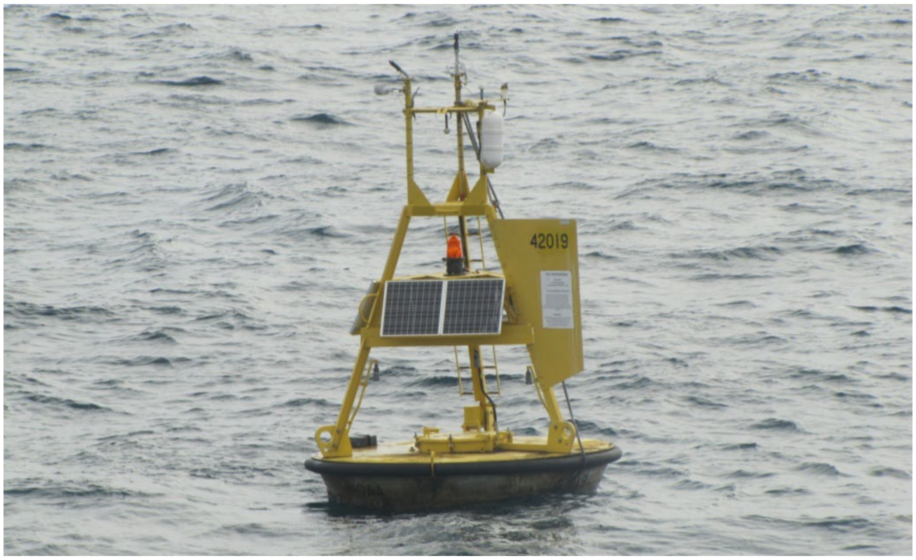

Figure 4.3 National Data Buoy Center (NDBC) 3-Meter Discus Buoy.
(Source: NOAA, 2012)

Figure 4.4 Buoy-Based Lidar System.
(Source: AXYS, 2014)

Bottom Fixed Platform

Bottom-fixed offshore platforms can be employed in a variety of physical configurations to host direct and remote sensing instrumentation for atmospheric and oceanic monitoring purposes. This platform type is generally characterized by a rigid substructure and foundation directly anchored to the sea or lake bed with one or more fixed monitoring elevations above the surface. It is a stable and robust approach to collecting offshore observations, often providing a basis for high-confidence, long-term measurement of numerous metocean parameters. However, the benefits come at the expense of high installation and operational costs. The application of this platform type is commonly restricted to relatively shallow waters (less than 60 m), as greater depths make the platforms cost-prohibitive.

For offshore wind applications, this platform type provides an attractive option for metocean measurements. The design of the structure can allow for the deployment of a tall monitoring tower (100 m above mean sea level, or higher), thereby facilitating the direct, high-confidence observation of atmospheric conditions up to and above wind turbine hub heights. This approach, which replicates the historical standard for terrestrial and offshore wind measurement, is used as a benchmark against which other offshore monitoring platforms and approaches are compared (or validated). Figure 4.5 shows an example of a meteorological tower mounted on a bottom-fixed platform.

Figure 4.5 Offshore Meteorological Tower: Cape Wind
(Source: AWS Truepower)

Beyond the deployment of a tall tower (or as a supplement to one), the stability and available physical space afforded by offshore platforms also facilitates the use of diverse metocean instrument types. The space and power requirements of multiple remote sensors, such as lidars and radiometers, can be satisfied to characterize atmospheric parameters across a turbine's full operating height. Observations of ocean parameters can be accommodated with the deployment of sensors on the platform, its substructure, and in the vicinity using the platform to support power and communication requirements. Bottom-fixed platforms also provide relatively unique measurement opportunities in some environments, such as the direct observation of marine growth and corrosion characteristics on foundations, year-round atmospheric and surface measurements in severe icing environments (e.g., the Great Lakes), and the capability to host other observations relevant to offshore wind such as marine mammal and avian monitoring systems. Examples of bottom-fixed platforms that are used for wind energy applications included the FINO I, II, and III platforms in the North and Baltic Seas, the UK Offshore Catapult's Anemometry hub near Blyth in the UK, and the Cape Wind tower in Massachusetts (Figure 4.5). Aside from the Cape Wind tower, other limited-duration metocean campaigns have been conducted on existing bottom-fixed offshore structures in the United States. Figure 4.6 illustrates monitoring equipment deployed in South Carolina and New York in support of offshore wind energy research.

Figure 4.6 US Metocean Monitoring Deployments on Existing Platforms: Sodar deployment on a US Coast Guard Platform in South Carolina[4] (left), and Portions of the metocean monitoring package installed on the (now decommissioned) Ambrose Light Station in NY Harbor (right).
Source: Second Wind, 2014 (left), and AWS Truepower (right)

Satellite

The satellite platform is used for remote observation or derivation of near-surface ocean winds (often represented at 10 m elevation) and various ocean surface conditions such as currents, tides, sea surface temperature and sea ice properties. Remote sensor types employed on satellite platforms include visible, infrared and microwave radiometers, radar altimeters, synthetic aperture radar, and various types of scatterometers. Satellite observations provide a wide sampling of metocean conditions in the spatial domain, often being the only source of observations far offshore. These observations can be valuable as inputs to numerical weather prediction and ocean models, as well as initial indications of

[4] Deployment carried out by Savannah River National Lab, Clemson University Restoration Institute and Partners

conditions distant from other monitoring stations. However, the utility of satellite data sets can be constrained in some offshore applications due to limited or discontinuous temporal coverage at a particular location, the spatial resolution of the satellite imagery, and the presence of land within a particular imagery cell or block.

Other Measurement Platforms

A diverse spectrum of other platforms exists for the observation of metocean parameters. Many of them have specialized uses or have only had limited application for offshore wind. The following paragraphs identify other platforms types that may provide useful observations.

Floating platforms of various configurations–including spar buoys, tension leg platforms and semi-submersibles–are available for metocean observations. In the context of offshore wind, floating platforms of these types are being considered and tested as alternatives to dedicated bottom-fixed platforms and buoys. The goals of these floating platforms are to provide greater stability and payload capacity compared to surface buoys, and to be more cost-effective deployments at water depths over 60 m compared to a bottom-founded platform (Idermar, 2014; Natural Power, 2010, AWS Truepower, 2014). Only a small number of these platform types have been deployed for offshore wind applications, and the configurations have varied. Platforms have hosted a tall meteorological tower (Idermar, Spain), profiling lidars (e.g. Searoc and Babcock & Brown's tensioned spar buoys), and related metocean instruments.

Aircraft are employed for offshore measurements during specific phenomena, such as sea breeze events, hurricanes (NOAA, US Air Force Reserve), and other conditions of interest. While the temporal coverage of these data sets is commonly short, the observations collected during the measurement runs can be quite relevant and valuable to offshore wind. As atmospheric measurement platforms, aircraft can be equipped with expendable instrumentation packages (e.g., dropsondes that characterize numerous parameters over their drop area) or multi-use sensors (e.g., wind speed, air temperature, pressure and related sensors) to collect data along the flight path. Remote sensing packages to observe sea surface temperature, wave conditions, surface winds, and other metocean parameters can also be deployed on aircraft.

Autonomous or remotely controlled vehicle platforms are available for both atmospheric and ocean condition observations. Autonomous underwater vehicles (AUV's) and gliders have been used in independent studies of the offshore environment, and in conjunction with fixed project deployments. These vehicles are capable of housing sonar units to map the seafloor, as well as other instrumentation to generate transects of water column properties, e.g., temperature, salinity, dissolved oxygen. Remotely controlled model aircraft or drones can be equipped with wind speed and other atmospheric sensors.

4.4 Data Attributes

The value of observational data sets related to offshore wind applications varies greatly by instrument type and platform type. The specific attributes of the data collected further influence the relevance and confidence assigned to these observations. While "attributes" of observational data can be broadly defined, three general categories can be useful in identifying characteristics that influence the use of the observations on their own, as well as their integration with modeling and other analyses. These categories are: temporal characteristics, spatial characteristics and operational characteristics.

This section identifies and discusses key data attributes within each of these categories. Characteristics that strongly affect observations' uncertainty or applicability to offshore wind are highlighted. Data attributes that are considered priorities when designing integrated measurement, modeling, and analytical campaigns are also identified.

4.4.1 Temporal Attributes

The temporal attributes of a data set include the sampling rate, the duration of the sampling, and the downsampling (averaging) period.

The temporal characteristics of observational data are important at short (order 1 second) and long (annual and decadal) time scales. Intermediate timescales–diurnal, monthly, seasonal–are also relevant when analyzing individual metocean parameters or phenomena. For specific measurements, the key attributes are the sampling frequency (or period) and averaging period. A data set's period of record, defined as the dates and duration of available observations, influences its value and application to many metocean analyses. The relevance of each of the attributes is discussed here in the context of common offshore wind applications.

Sampling periods for metocean instruments are influenced by the parameter being measured, the instrument configuration, and the intended data application. Using wind speed as an example, the sampling period of mechanical anemometers is typically 0.5 to 2 seconds for most applications that will use 10-minute or longer time periods. These applications include wind resource assessment, forecasting, and related analyses; relevant guidance documents recommend a minimum wind speed measurement frequency of every 1 second, or 1 hertz (IEC, 2005; MEASNET, 2009). Sampling at that time scale is sufficient to define most common statistics, including standard wind gusts. However, for specialized applications relating to turbine design, structural loading, or component performance analyses, higher frequency variations in wind speeds become important and the sampling frequency may be increased to 10 Hz or more.

Many metocean sensors and systems have user-selectable sampling frequencies and measurement durations. This capability allows the user to balance statistical needs for the observations with the system's power budget and data storage capacity. For example, higher sampling frequencies can yield more robust characterization of the measured parameters (e.g., more points to calculate standard deviations) but can result in higher power draws, while lower sampling frequencies can have lower power and data storage requirements at the expense of some measurement rigor. For data applications where employing and recording high-frequency observations are required for parameter characterization (either meteorological or oceanic), sensor selection, data recording, and platform configuration parameters (including power, communication, and data storage) merit special attention. For example, several cup anemometer models common to the wind industry cannot reliably collect data at frequencies greater than one hertz due to their signal generation configurations; also, many sensors have a response time of several seconds to changes in the external conditions. In some cases where a system's sampling frequency is not compatible with required analyses, e.g., gusts, or turbulence intensity characterization, analytical methods may be available to convert between time scales. This topic is addressed further, below.

The averaging interval is the time period over which individual samples are combined to generate observations and statistics. Many analyses and data applications require observations to be averaged or processed at specific time scales greater than the sampling period. These times scales for averaging and analysis can vary significantly based upon the application and measurement type; some of the most common are listed below.

- **3 and 5 second**: Time scales used to define wind gusts by standards organizations (IEC, 2009; ABS, 2013) and NOAA (NOAA, 2014) typically calculated as the maximum of 3-, or 5-second rolling average of samples during a reporting period;
- **1 minute**: Time scale commonly referenced by NOAA for maximum sustained wind speeds, employed in defining (Hurricane Research Division, 2014) high wind events such as gales, tropical cyclones and hurricanes;
- **10 minute**: International standard time interval for defining mean wind speeds (IEC, 2005; World Meteorological Organization, 2008) and interval over which most other wind statistics and standard meteorological parameters are calculated;
- **1 hour**: Typical averaging and reporting interval for many metocean measurements; typical interval for model output.
- **3 hour, 6 hour, and 24 hour**: Averaging periods employed for analyzing wave conditions (DNV, 2013), intercomparison of disparate data sets, or conducting analyses (e.g., MCP).

For many observational parameters, the averaging time period is commonly the same as a system's reporting or recording interval. As an example, a standard 10-minute wind data record includes statistics (mean, maximum, minimum, standard deviation, etc.) calculated on 600 one-hertz samples collected continuously over the 10-minute averaging period. For ocean and surface meteorology parameters (such as those collected on buoys), the averaging and reporting periods are often not the same. As an example, a one-hour wind data record from a buoy may include statistics calculated from 480 one-hertz samples collected continuously over the first eight minutes of the hour. Understanding these differences in data attributes is essential when interpreting atmospheric and ocean measurements together.

Metocean analyses for offshore wind applications can require values of specific parameters at time scales where they may not be available; wind gusts are a common example. This circumstance, as well as the combined analysis of multiple parameters such as the calculation of certain joint wind and wave conditions, can require comparison of data sets with notably different temporal characteristics. Where possible, conversion of one averaging or reporting period to another is based upon the site-specific conditions. In some cases, however, conversion factors or other approaches are required to reconcile (or at least compare) observations with different temporal characteristics. Methods have been developed by a number of entities involved in various aspects of metocean analysis to help address these issues. The World Meteorological Organization (WMO) developed guidelines for the conversion between various wind averaging periods and maximum speed estimates in tropical cyclone conditions (Harper, et al., 2010). Offshore design standards and guidelines, including those from the wind, oil and gas industries, address various aspects this topic, and RISØ (now the Technical University of Denmark, Wind Energy Department) proposed methods for the transformation of both wind and wave time scales (Tarp-Johansen and Frandsen, 2004).

An observational data set's period of record is one of its defining characteristics and strongly influences its applicability to many offshore wind analyses. The assessment of a data set's period of record is driven by the particular application. Preconstruction analyses–e.g., wind resource assessment and design condition characterization–require that at least one continuous year of key metocean observations are available for a project area to cover seasonal variations at the site. Additional years, preferably three or more, help reduce the uncertainty associated with many of the calculations and help mitigate any data recovery issues. Considering a data set as a long-term reference to adjust site-specific observations to long-term trends typically requires a continuous period of record of at least ten years, with 15 or more years being preferable depending on location, reference data set characteristics and the analyses being conducted. Assessment of inputs for offshore wind turbine and platform design requires long-term regional observational data (periods of record extending multiple decades) to be integrated with site measurements and statistical and modeling methods to develop 10, 50, 100, and 500 year return periods for extreme conditions. Multi-decadal reference data sets, known as reanalysis, are discussed in Chapter 5.

4.4.2 Spatial Attributes

The spatial characteristics of observational data are closely linked to their value in various offshore wind applications. The relative scarcity of measurements offshore and the growing dimensions of offshore wind turbines–both in hub height and rotor diameter–drive the importance of observations' horizontal and vertical spatial characteristics. Since most metocean data parameters are collected as points or profiles, the specific location and siting characteristics of the measurement station(s), and the resulting data sets, also influence their applicability.

The applicability and representativeness of a data set to a specific project area is strongly affected by the distance separating them. Geographic variation of many average metocean parameters is small in the offshore environment compared to over land, particularly at sites that are more than a few kilometers from shore. However, the scarcity of existing offshore data still results in many candidate wind farm sites being tens of kilometers or more from the nearest monitoring site. While distant data sets may be applicable for long-term correlations, defining site-specific conditions with high confidence requires dedicated measurements within or adjacent to the project area. The growing sizes of proposed offshore wind projects, and the large regions of ocean identified as Wind Energy Areas by the BOEM, may necessitate multiple metocean measurement points to fully characterize them.

In addition to distance from an area of interest, numerous siting attributes require review when designing a measurement campaign or analyzing the values of existing data. Consideration of the following several questions can help illustrate the influence of siting and other spatial characteristics:

- Is the location of the measurements useful in the context of expected prevailing wind and wave conditions?
- Are the water depths and currents representative of the area of interest?
- Are terrain or obstruction features, including the coast lines, islands, or existing wind farms, affecting the metocean data set and the project area differently?

- If a monitoring station is located within the interior of a project area, will the value of its data be compromised after the turbines are installed and operating?
- Based upon the conditions expected in the region and the size of the area of interest, how many observational data points will be necessary?

The characteristics of a metocean data set in the vertical dimension are some of the most relevant. While ocean surface measurements are important to offshore wind applications, information through the water column and up into the atmospheric boundary are also essential. Ocean current, temperature and salinity profiles are necessary for project foundation and platform design, as well as for installation techniques and collection system design. Extrapolation techniques (Jeans and Feld, 2001) and ocean modeling tools (Rutgers Ocean Modeling Group, 2014) exist to calculate average and extreme current profiles; however, observational data still add significant value to design input calculations.

Offshore wind speed profile observations up to and beyond turbine hub height are among the most important parameter sets for offshore wind, and are nearly non-existent in the United States. As such, much effort has been expended on developing and refining techniques to translate lower-elevations observations to hub height (and across the rotor plane) under a variety of atmospheric and ocean conditions. Various exponential and power law methods are defined by international standards and guidelines (see Figure A.1 in the Appendix), while numerical weather prediction and other flow models are becoming increasingly relied upon as well. The uncertainty resulting from extrapolating the lower elevation data sets is strongly influenced by the monitoring height(s) of the station and the target analysis elevation (i.e., hub height). Higher monitoring elevations, greater vertical resolution in the measurements, and closer proximity to the target elevation all serve to increase confidence in the conditions calculated at hub height.

4.4.3 Operational Attributes

Operational attributes are things related to the operation of the metocean data sets, and they are often taken for granted. However, these attributes can significantly impact the value and confidence associated with the observations or any resulting analyses. For example, a well-instrumented, well-sited monitoring station's data can become essentially useless if it is poorly configured, inadequately documented, or incorrectly operated and maintained. Given the complexity and costs of offshore monitoring, particularly over extended periods, it is not a trivial task to document and maintain these attributes at a consistently high standard. Procedures and best practices are available to help preserve high quality operations, and it is important for any observational data users to scrutinize the operational attributes of the measurements they are using.

Similar to siting characteristics, a station's physical configuration–including instrument locations, orientations, mounting hardware and technique–needs to be considered in the context of exposure and the intended data uses. International standards for wind resource assessment and site characterization are under development by the IEC (IEC, 2013) and are expected to provide guidance on offshore measurement station configuration. In the meantime, guidance on direct and remote sensing configuration can be applied from terrestrial wind energy monitoring guidelines, including but not limited to the following:

- The New York State Energy Research and Development Authority Wind Resource Assessment Handbook (NYSERDA, 2010);
- MEASNET's Evaluation of Site-Specific Wind Conditions (MEASNET, 2009);
- IEA's Recommended Practices for Vertically-Profiling Remote Sensing (IEA, 2013); and
- Annex G of IEC 61400-12-1, Power Performance Measurements of Electricity Producing Wind Turbines (IEC, 2005).

Guidance on the configuration of ocean surface and subsurface measurements can be derived from WMO's guide to moored buoys (WMO, 1996), the NDBC (NDBC, 2014), and related documentation from the Integrated Ocean Observing System (IOOS, 2014) community (for example, the University of Maine's Ocean Observing System buoy configurations; UMOOS, 2014).

Station operations and maintenance start with pragmatic and thoughtful system configuration. Understanding instrument operational characteristics, such as useful lifetime, stability of performance with time, maintenance requirements, response to environmental conditions, and others, helps inform operational plans and schedules. Building redundancy and robustness into a configuration, particularly around high-priority instruments, helps mitigate unplanned maintenance requirements and data gaps. Inadequate operations and maintenance of a station, including both the instrumentation suite and the platform itself, can lead to degradation of data quality, data gaps, and ultimately increased uncertainty associated with the resulting period of record.

Documentation and the development of accurate metadata help ensure that an observational data set is well described and interpreted correctly. The absence of documentation results in great uncertainty around history and quality of a measured dataset. Documentation of the station configuration and data output at commissioning establishes a baseline understanding for the site. Subsequent documentation of operations activities, such as changes to instrumentation, configuration, or data output, as well as data processing procedures, is essential to maintain an accurate assessment of the resulting period of record.

4.5 Data Sources

The primary source for historical and ongoing US offshore measurement and modeling data is NOAA, particularly the National Data Buoy Center (NDBC). Buoys and C-Man stations are the most common source of historical metocean data. Figure 4.7, Figure 4.8, Figure 4.9, and Figure 4.10 depict the location and wind measurement heights for these types of measurement stations for the Atlantic Coast, Great Lakes, Gulf of Mexico, and Pacific Coast regions, respectively. Similar data sources can also be found in the Integrated Ocean Observing System (IOOS), other networks deployed in coastal, inner and outer shelves and offshore regions, and satellite platforms. Modeled data sets include atmospheric parameters, waves, and surface and sub-surface currents and are primarily based upon hindcasting and reanalysis techniques to build long-term gridded data sets. These compilations are available through a variety of government and research-oriented sources, most of which are available online. A comprehensive list of all available data sources is beyond the scope of this report; however a sample summary of sources is listed in Table 4.1. Links to many freely-available long-term measured and modeled data sets are identified. Many of these sources are 'data clearinghouses' or central locations where data are organized and stored for distribution to interested users. In many cases these clearinghouses may contain a number of different types of data for a specific agency or geographic location. A more comprehensive description of relevant observed and modeled metocean data can be found in a separate report prepared for DOE by AWS Truepower titled *Inventory of Met-Ocean Data Sources for the United States* (AWS Truepower, 2012), which is available at www.usmodcore.com.

Table 4.1 Sources and Types of Metocean Data for Offshore Wind Energy

Source	Data Type	Availability
NOAA's Multipurpose Marine Cadastre	Atmosphere, oceanographic modeling; research	http://www.csc.noaa.gov/digitalcoast/tools/mmc
NOAA Coastal and Marine Spatial Planning	GIS	http://www.msp.noaa.gov/data-tools/index.html
NOAA Digital Coast, Coastal Services Center	GIS	http://www.csc.noaa.gov/digitalcoast/
NOAA Earth System Research Laboratory (ESRL)	Atmosphere, oceanographic modeling; research	http://www.esrl.noaa.gov/
NOAA Meteorological Assimilation Data Ingest System (MADIS)	Atmosphere, oceanographic observation archive	http://www-sdd.fsl.noaa.gov/MADIS/index.html
NOAA Great Lakes Environmental Research Laboratory (GLERL)	Atmospheric, limnological, and geological	http://www.glerl.noaa.gov/
International Comprehensive Ocean-Atmosphere Data Set (ICOADS)	Observed and modeled atmospheric and oceanographic historical data	http://icoads.noaa.gov/index.shtml
NOAA Environmental Modeling Center - Ocean Prediction Center and Marine Modeling and Analysis Branch Products	Analysis and model real-time and archived forecasts of atmosphere and ocean waves and currents.	http://www.opc.ncep.noaa.gov/ http://polar.ncep.noaa.gov/mmab/products.shtml
NOAA National Climatic Data Center (NCDC)	Comprehensive archive of atmospheric and oceanic observational and model data	http://www.ncdc.noaa.gov/oa/ncdc.html
NOAA National Data Buoy Center (NDBC)	Atmosphere, oceanographic observation real-time and archived data	http://www.ndbc.noaa.gov/
NOAA National Geophysical Data Center (NGDC)	Geophysical data describing the earth, marine, and solar-terrestrial environments	http://www.ngdc.noaa.gov/ngdc.html

Source	Data Type	Availability
National Oceanographic Data Center (NODC)	In-situ and remotely sensed (including satellite) physical, chemical, and biological oceanographic data from coastal and deep ocean areas	http://www.nodc.noaa.gov/
NOAA NOS Data Explorer, National Ocean Service (NOS)	Including but not limited to bathymetry, coastal maps, environmental sensitivity index maps, aerial photographs, etc.	http://oceanservice.noaa.gov/dataexplorer/
NOAA NWS Telecommunication Gateway (NWSTG)	Storehouse of all nationally-generated forecast products and globally received observational data	http://www.nws.noaa.gov/tg/index.html
NOAA Physical Oceanographic Real-Time System (PORTS®)	Disseminates observations and predictions of water levels, currents, salinity, and meteorological parameters (e.g., winds, atmospheric pressure, air and water temperatures)	http://tidesandcurrents.noaa.gov/ports.html
U.S. Army Corps of Engineers Wave Information Studies (WIS)	Hourly, long-term (20+ years) wave climatology's along all US coastlines, including the Great Lakes and US island territories	http://wis.usace.army.mil
NOAA Comprehensive Large Array-Data Stewardship System (CLASS)	Satellite	http://www.class.ngdc.noaa.gov/saa/products/welcome
ECMWF ERA-Interim	Reanalysis	http://www.ecmwf.int/research/era/do/get/era-interim
NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA)	Reanalysis	http://gmao.gsfc.nasa.gov/merra/
NASA Physical Oceanography Distributed Active Archive Center (PODAAC)	Satellite and Moored Buoy	http://podaac.jpl.nasa.gov/
NOAA Climate Forecast System	Reanalysis	http://cfs.ncep.noaa.gov/

Source	Data Type	Availability
NOAA NCEP North American Regional Reanalysis: NARR	Reanalysis	http://www.esrl.noaa.gov/psd/data/gridded/data.narr.html
Wind Integration National Dataset (WIND) toolkit	7-year long reanalysis dataset of wind energy relevant parameters, as well as wind power and wind power forecasts	http://www.nrel.gov/docs/fy14osti/60669.pdf

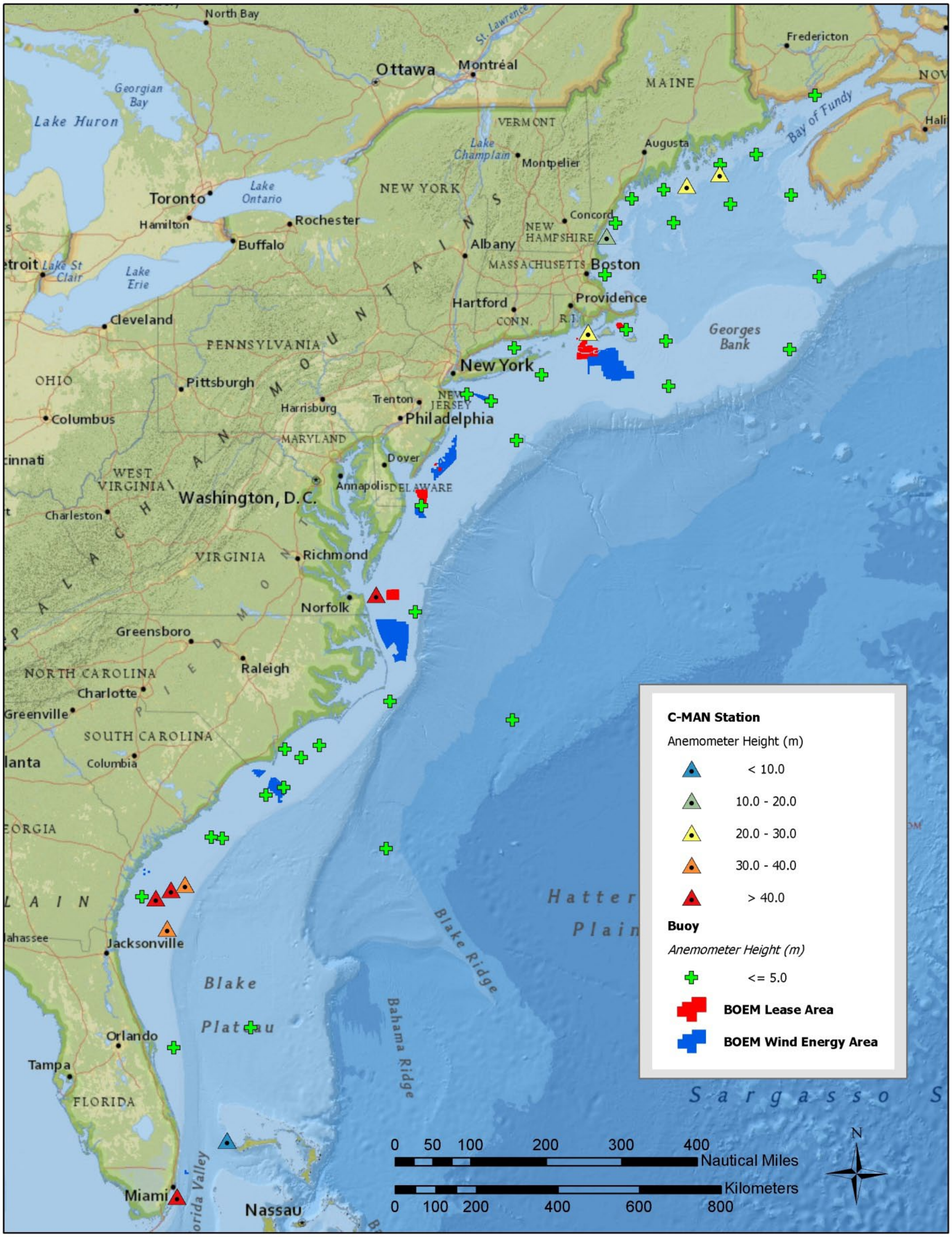

Figure 4.7 Atlantic Offshore Measurement Assets

Figure 4.8. Great Lakes Offshore Measurement Assets

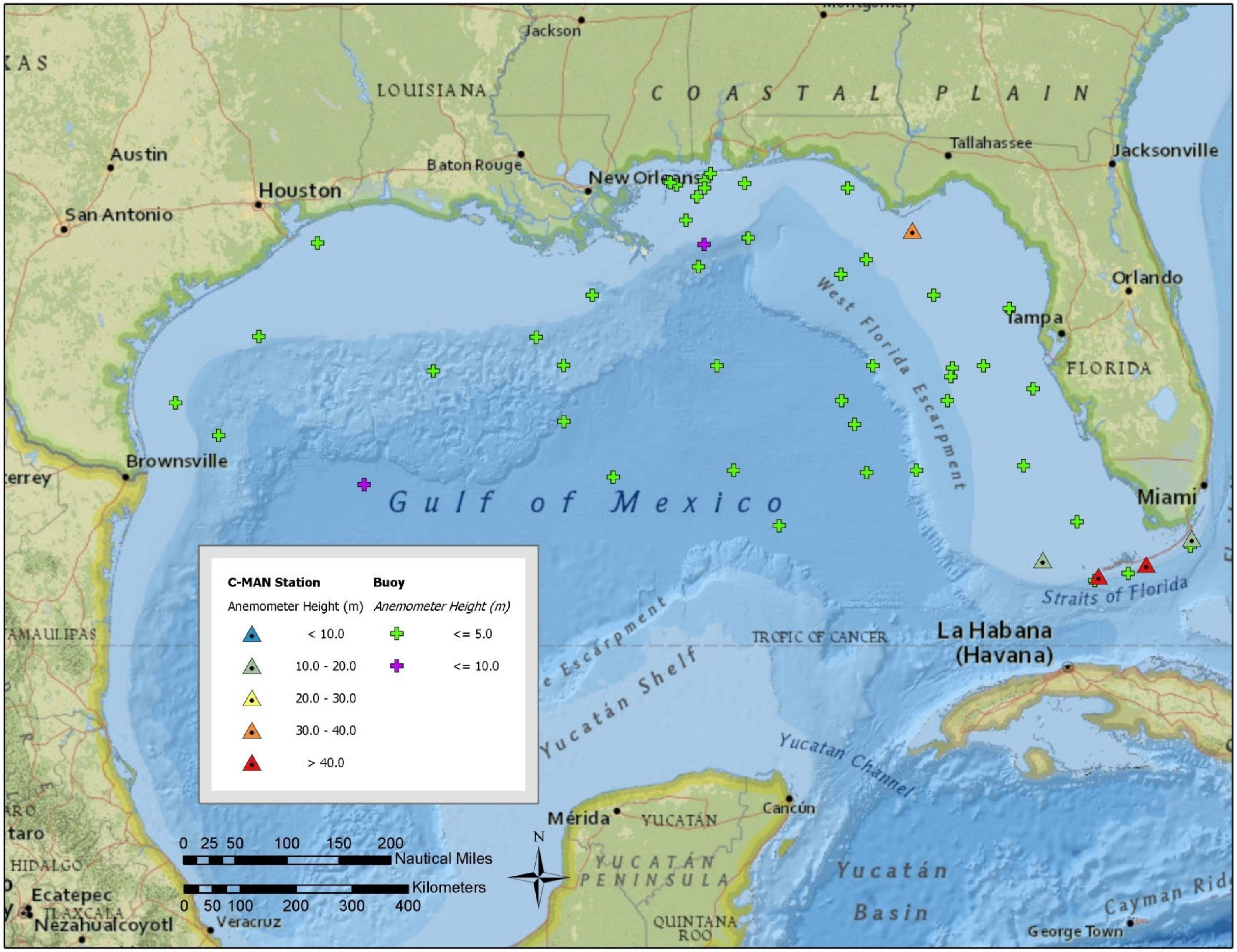

Figure 4.9 Gulf of Mexico Offshore Measurement Assets

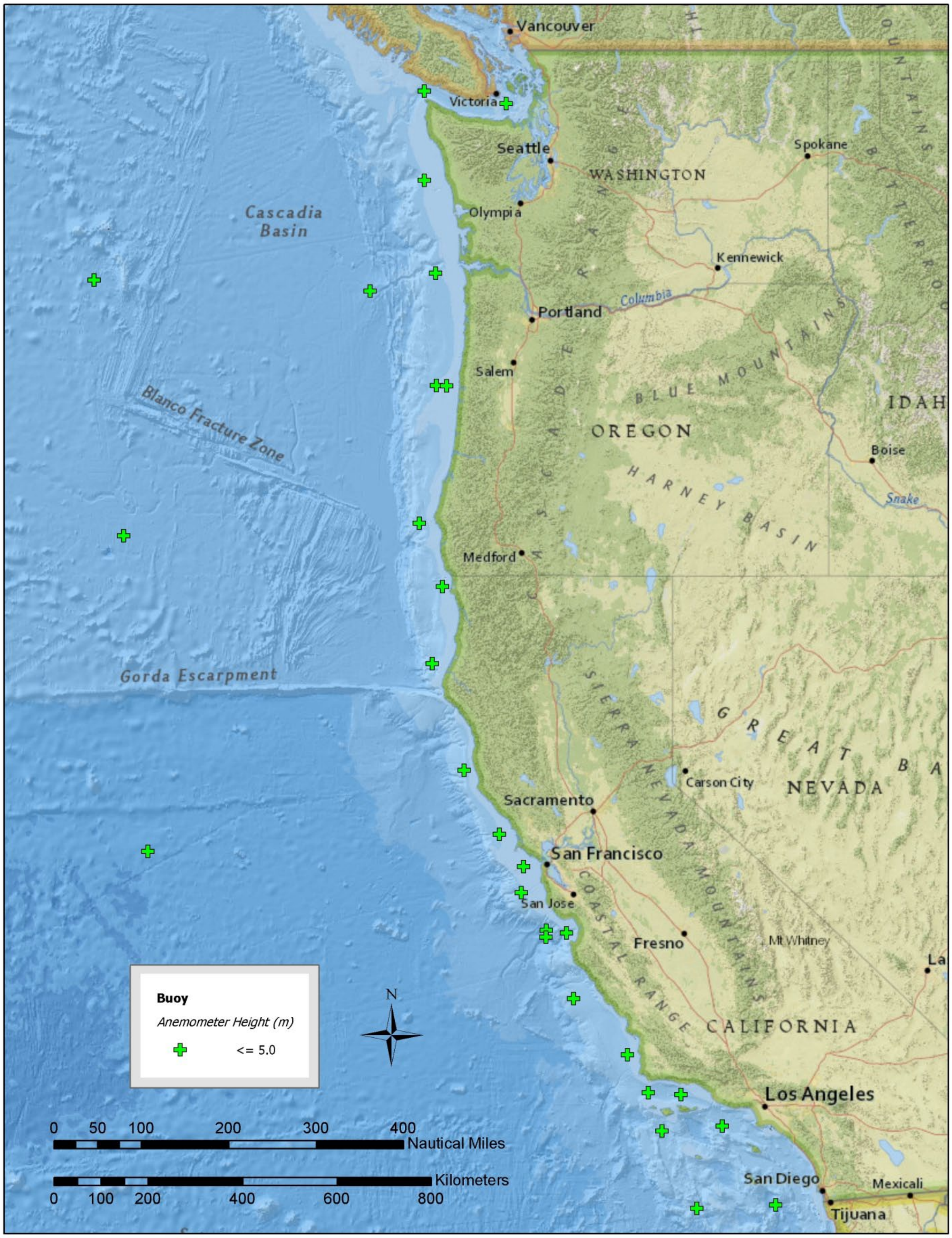

Figure 4.10 Pacific Offshore Measurement Assets

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5. PARAMETER CHARACTERIZATION: MODELING APPROACHES

5.1 Introduction

Numerical modeling is the most popular tool for addressing knowledge gaps in understanding metocean phenomena when and where measurements are lacking. In recent decades the steady increase in computing power has allowed numerical models to become more effective than physical or statistical models for analysis and forecasting purposes. Given the scarcity of observations, especially in offshore environments, numerical models are needed to interpolate and extrapolate those observations in both time and space. Model performance is strongly dependent on the quantity and quality of available metocean observations, which means that accurate characterization is dependent on both measurements and modeling. This chapter will review the primary types of models used to simulate metocean conditions (winds, waves, currents, etc.), with an emphasis on the atmospheric modeling of winds, which drive the operation of wind turbines but are also a primary driving factor in the generation of waves and currents. Trending in model advancements, as well as remaining gaps, are also discussed in the context of metocean uncertainty mitigation and the benefits of reducing the overall cost of offshore wind energy.

Meteorological phenomena occur over a wide range of time and space scales. Figure 5.1 gives an example of atmospheric processes ranging from seconds to weeks, and from meters to thousands of kilometers. The four space scales—microscale, mesoscale, synoptic, and global—refer to the horizontal dimension of atmospheric motions, which range from short-lived microscale phenomena, such as turbulent eddies and wind gusts, to much longer lasting global long waves and trade winds. All these scales of atmospheric motion interact with each other as well as with the land, the oceans (and other water bodies), and sea ice.

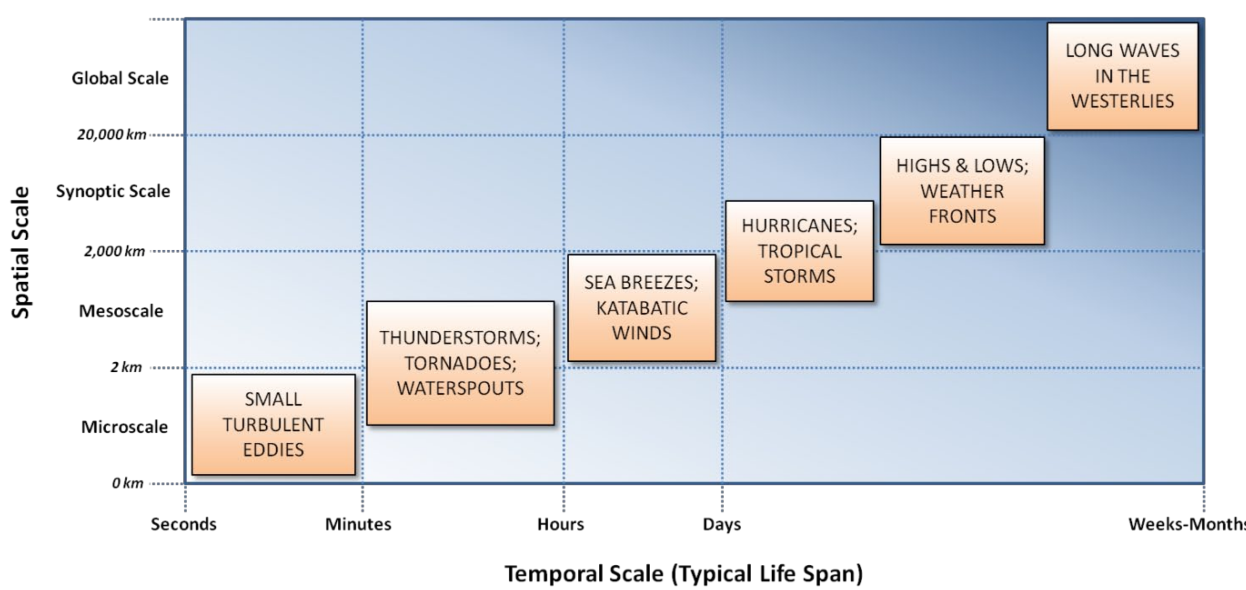

Figure 5.1 Time and Size Scales of Atmospheric Motion

In atmospheric sciences, numerical models are built around the equations of fluid dynamics, namely the Navier-Stokes equations, with varying degrees of complexity (or non-linearity). The equations may include conservation of mass, momentum, energy, and moisture, as well as an equation of state for air based on the ideal gas law. Numerical weather prediction models (NWP) and large-eddy simulations (LES) solve all of these equations. Due to computational runtime, cost, or other constraints, some (simpler) models solve only a subset of the equations. Although the atmosphere is always evolving and various weather variables are changing in intensity, not all numerical models are able to step forward in time. Prognostic models are ones that simulate the evolution of atmospheric conditions over time, while diagnostic models simulate steady-state conditions.

As explained in the following sections, models of different types operate at different time and space scales, depending on the application. For example, climate models predict long-term changes in atmospheric properties (such as mean temperature, precipitation, and winds) over large portions of the globe (i.e. at the synoptic and global scales). NWP models simulate short-term changes within smaller regions (i.e., the mesoscale and synoptic scale). LES models are applied to microscale processes. Since all models work with a finite data set, they represent the environment with a three-dimensional grid, as illustrated in Figure 5.2. Most atmospheric models incorporate multiple vertical layers, some extending up to several kilometers in altitude. Typically, large grids have a coarser resolution than small grids, so the selection of grid spacing and domain size in a modeling exercise is critical when attempting to represent the flow phenomena of interest.

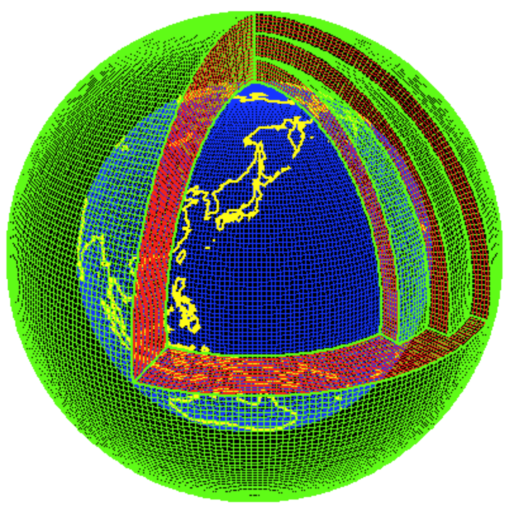

Figure 5.2 Three-Dimensional Global Grid with Several Vertical Layers Used by Most Numerical Models.
(Source: http://www.jma.go.jp/jma/jma-eng/jma-center/nwp/grid.jpg)

Physical processes such as turbulence or cumulus clouds that are too small to be explicitly resolved by a model within its grid scale need to be approximated using some sort of parameterization scheme. Physical features such as mountains, islands or irregular coastlines that are smaller than the model's grid resolution will generally be ignored. A standard strategy to capture small features or small-scale processes with a numerical model is to run a finer-resolution grid nested inside a coarser-resolution grid.

Typically, the latter covers a much larger region than the finer-resolution grid (similar to a box inside a box). Grid nesting is used to downscale coarse resolution information to a finer resolution grid while ensuring proper energy transfers in the atmosphere.

The remaining sections of this chapter address the roles played by different atmospheric, wave and ocean models in the definition of metocean conditions for offshore wind energy applications. First, NWP models are described, particularly in the simulation of mesoscale flow features at grid resolutions as fine as 1-10 km. This scale is consistent with the size of modern wind farms. Microscale models, which simulate flow fields at much finer resolutions (i.e., at the scale of individual turbines and blades), are discussed next. This is followed by a description of different approaches to modeling the turbulent wakes produced by wind turbines and their impacts on the performance of downstream turbines. Lastly, popular wave models are discussed, together with advancing approaches to the coupling of atmosphere and ocean models.

5.2 Numerical Weather Prediction (NWP) Models

NWP models have been developed primarily for weather forecasting purposes over different time horizons ranging from hours to days (Ahrens, 2003). These models heavily rely on observations of initial surface and atmospheric conditions, which include surface weather stations, buoys, ships, radiosondes (weather balloons), radars, aircraft, and satellites (visible, infrared and microwave bands). Much of the improvement in weather forecasting accuracy in recent decades has been attributed to the increase in computing power and improved data assimilation methods (Kalnay, 2003). Data assimilation is the process of combining different sources of observational data into a NWP model to produce a best estimate, or "analysis", of the state of the atmosphere at a given time (typically every 1 to 6 hours). A schematic representation of the inputs and outputs of a mesoscale NWP model is shown in Figure 5.3.

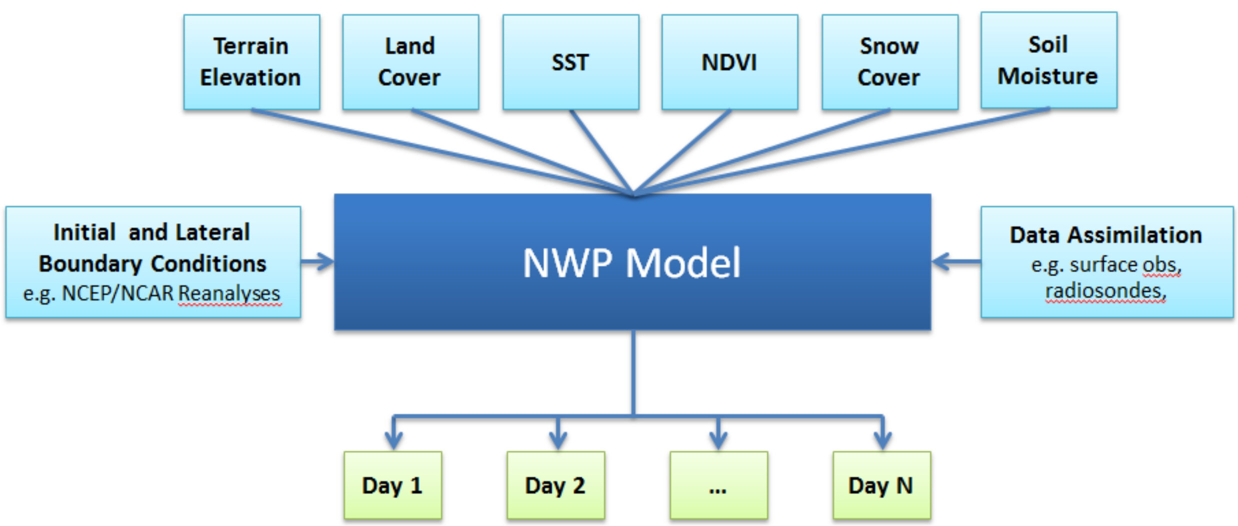

Figure 5.3 Diagram of NWP Modeling Process. SST and NDVI refer to sea surface temperature and normalized difference vegetation index.
(Source: adapted from Beaucage et al., 2013).

Mesoscale models take into account subgrid scale effects and physics parameterizations for solar radiation, land surface-atmosphere interaction, the planetary boundary layer (PBL), turbulence, cloud convection, and cloud microphysics (Stensrud, 2007). Since they incorporate the dimensions of both energy and time, NWP models are capable of simulating such phenomena as thermally driven mesoscale circulations (e.g., sea breezes, thunderstorms) and atmospheric stability, or buoyancy. In the world of mesoscale modeling – as in the real world – the wind is never in equilibrium with the surface because of the constant exchange of energy. This exchange occurs through solar radiation, radiative cooling, evaporation and precipitation, the cascade of turbulent kinetic energy down to the smallest scales and dissipation into heat, and even sound waves.

Mesoscale NWP models are well-equipped for simulating wind flows accurately in offshore environments. Several research studies have demonstrated their ability to represent many of the complex wind phenomena found in offshore environments: mountain and island blocking, gap flows, coastal barrier jets, internal boundary layer growth, stability transitions, mesoscale circulations, and so on (e.g., Colle and Novak, 2010; Freedman et al., 2010; Steele et al., 2013; Skyllingstad et al., 2001; Gilliam et al., 2004). NWP models are imperfect, however, and are prone to phase errors in time and space (Mass et al., 2001). The root mean square error (RMSE) of wind speed data from NWP models is typically around 2 to 3 m/s in offshore regions and the coefficient of determination (R^2) is usually high (Jimenez et al., 2007; Berge et al., 2011; Beaucage et al., 2007, Dvorak et al., 2010). In addition to wind speed components at several heights, NWP models can output almost any atmospheric variable.

One drawback of mesoscale models is their large computing power requirements to run at the scales necessary for the assessment of wind farms. For this reason, NWP models are typically run on small clusters or supercomputers with a Linux operating system, not on a stand-alone PC with Windows operating system. The typical model resolution for most mesoscale simulations is on the order of a few kilometers, i.e., near the interface between the microscale and mesoscale. Since this scale does not provide a very detailed picture of wind conditions within a large wind farm, coupling with a microscale model is often done to obtain the desired detail. It has been demonstrated that a coupled mesoscale NWP and microscale model shows improvement over a mesoscale model alone (Frank et al., 2001). Examples of coupled mesoscale and microscale models include AWS Truepower's MesoMap (Brower, 1999) and SiteWind systems, Risø National Laboratory's KAMM-WAsP system (Frank et al., 2001), and Environment Canada's AnemoScope system (Yu et al, 2006). Research studies on land suggest that such methods are more accurate than microscale wind flow models alone, especially where mesoscale effects play a significant role (Beaucage et al., 2013; Poulos and Kumar, 2013).

In addition to forecasting weather conditions, NWP models are useful in predicting atmospheric conditions for historical periods, i.e. looking backwards in time. This practice is sometimes referred to as "hindcasting" and has the capability of assessing regional wind conditions from existing long-term datasets before launching new measurements at an offshore site of interest. A number of mesoscale gridded datasets are now available on a global basis from various sources spanning several decades. Referred to as "reanalysis", these datasets have been compiled using a fixed data assimilation approach and NWP model with the primary goal of removing potential biases or artificial trends resulting from the gradual changes in modeling approaches, observation types and regional data collection concentrations over the decades (Kistler et al., 2001). For example, from the 1940s into the 1970s, weather observations were primary derived from fixed surface weather stations, buoys, weather balloons, ships, and aircraft. Beginning in the 1970s, satellite-based observations of cloud-tracked winds and other parameters began, and since then significant increases in the number of satellites and types of onboard sensors have made satellites the dominant environmental data gatherer across the globe. Even among the non-satellite types of measurement systems, over time there have been large changes in the density and number of surface and upper air observations, improvements in the quality of the data collected, and the introduction of new data recording and sensing technologies and the retirement of old ones. Reanalysis datasets, therefore, provide the most consistent records of atmospheric conditions over long periods of time.

The first reanalysis dataset was created by Kalnay et al. (1996) and is known as the National Center for Environmental Predictions/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1. It covers the period from 1948 to present at a spatial resolution of 1.87° (approximately 205 km). Since then, several national meteorological agencies and national research laboratories including the European Center for Medium-Range Weather Forecasts (ECMWF), NCEP, National Aeronautics and Space Administration (NASA) and the Japanese Meteorological Agency (JMA), have issued their own reanalysis products. These state-of-the-art reanalysis projects include the ERA-Interim, Climate Forecast System Reanalysis (CFSR), Modern-Era Retrospective analysis for Research and Applications (MERRA) and Japanese 55-year Reanalysis (JRA-55). They are based on advanced data assimilation schemes and NWP models and have been generating data at a finer spatial resolution of 0.5° to 0.75° (55 or 83 km) than the NCEP/NCAR Reanalysis 1. Reanalysis data are typically available on a 6-hour interval, however there are two exceptions: the MERRA and CFSR, which are available hourly for some surface fields and limited pressure levels.

The relatively coarse grid resolution of reanalysis data (50 km or so) can capture offshore wind flows well if the site of interest is located far enough from the coast (or islands) such that the model grid cell doesn't include any land portion. However, nested, higher resolution grids can be modeled to simulate near-shore wind circulations. Reanalysis datasets are also valuable for correlating short-term time series measurements collected on offshore platforms with long-term climatological records. Even though the mean bias between reanalysis and meteorological mast data can be substantial, the value of reanalysis data relies mostly in their correlation to onsite measurements, which are not impacted by a bias. Several studies (Brower et al., 2013; Lileo and Petrik, 2011; Decker et al., 2012; Stoelinga et al., 2012) show that the latest generation reanalysis datasets—for instance ERA-Interim, CFSR and MERRA—have superior accuracy in term of their correlation to mast data.

5.3 Microscale models

In order of increasing complexity, microscale wind flow models fall into three broad categories: mass-conserving, Jackson-Hunt type (or linear Navier-Stokes formulation) and computational fluid dynamics (or non-linear Navier-Stokes formulation).

Mass-Conserving Model

The first generation of wind flow models (like NOABL [Phillips, 1979]) developed in the 1970s and 1980s were mass-conserving types, so called because they solve just one of the physical equations that govern mass conservation. When applied to the atmosphere, the principle of mass conservation implies that wind forced over higher terrain must accelerate so that the same volume of air passes through the region in a given time. As a result, mass-conserving models predict stronger winds on hill and ridge tops and weaker winds in valleys. They cannot handle thermally-driven wind patterns, such as sea breezes, mountain-valley circulations, and flow separations on the lee side of mountains.

Most mass-conserving models like WindMap (Brower, 1999) and CALMET (Scire, 2000) are designed to depart by the smallest possible amount from an initial wind field estimate derived from observations and/or a mesoscale model output. This characteristic sets this model type somewhat apart from other numerical models, in that the solution improves directly as the initial estimate improves. It also means that mass-consistent models are also able to take advantage of data from additional meteorological towers in a natural way, by modifying the initial estimate. Mass-conserving models are generally not used as stand-alone models and are often coupled to a mesoscale NWP model. This coupled approach has been adopted to develop validated national and regional wind maps for the United States (Schwartz et al., 2010). Maps with a spatial resolution of 200 m and heights of 60 to 100 m were jointly created by NREL and AWS Truepower with this mesoscale-microscale modeling technique and adjusted to reduce errors through a bias-correction procedure involving data from well over 1000 measurement masts (Elliott et al., 2010; AWS Truepower, 2012). Figure 5.3 is a representation of the wind resources (smoothed to a 2 km resolution) estimated at a 100-m height for all 50 states as well as offshore resources up to 90 kilometers from shore.

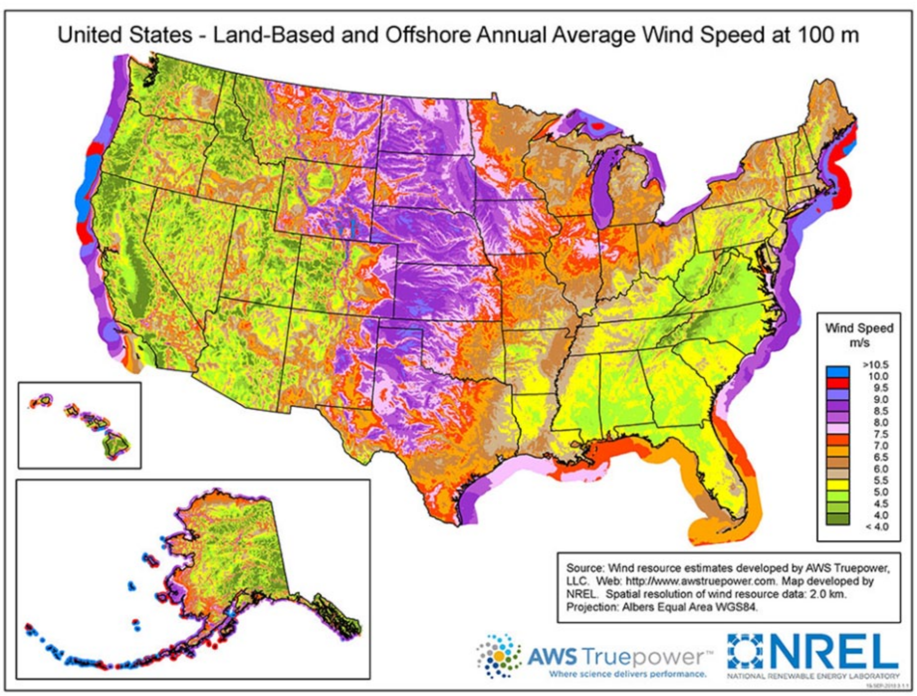

Figure 5.3 Annual Average U.S. Wind Speed at 100 m above the Surface, Land-Based and Offshore

Linear Flow Models

Linear wind flow models like the Wind Atlas Analysis and Application Program (WAsP; Troen and Petersen, 1989; Troen, 1990), MS3DJH/MsMicro (Taylor et al., 1983), the Mixed Spectral Finite Difference model (MSFD; Beljaars et al., 1987), and Raptor (Ayotte and Taylor, 1995) are based on the theory of Jackson and Hunt (1975). They go beyond mass conservation to include momentum conservation by solving a linearized form of the Navier-Stokes equations under several assumptions: steady-state flow, linear advection, and first-order turbulence closure. Jackson-Hunt models do not take into account any horizontal temperature gradients or flow acceleration. The most important simplification in the Jackson-Hunt theory is that the terrain causes a small perturbation to an otherwise constant background wind. Jackson-Hunt wind flow models came into wide use in the 1980s when the computing resource was very limited. Compared to NWP models, linear wind flow models require a smaller set of input data as they rely solely on onsite wind measurements, terrain elevation and surface roughness maps. They have been and still are widely used to predict the spatial variation of the average wind speed, directional frequency distribution (wind rose), wind shear, and other boundary layer characteristics. In coastal areas where the wind is not significantly affected by the adjacent terrain, thermally driven flows or other dynamic and nonlinear phenomena, it is advised to rely on more advanced wind flow models such as coupled mesoscale and microscale models or large eddy simulations.

Computational Fluid Dynamics (CFD)/Reynolds-Averaged Navier-Stokes (RANS) Models

Reynolds-averaged Navier-Stokes models (referred to as RANS) are emerging as an alternative to Jackson-Hunt models for wind energy applications as personal computers have grown more powerful. They were designed originally to model turbulent fluid flows for airplane bodies, jet engines, vehicles, and the like. Several CFD/RANS models are being used in the wind energy industry: Fluent, CFX, Star-CCM+, OpenFOAM, Meteodyn WT, WindSim, Ventos, etc. The critical difference between CFD/RANS and Jackson-Hunt models is that the former solve the non-linear Navier-Stokes momentum equations, but none of them include the full conservation of energy equation. The RANS models assume steady-state flows, so they tend to run faster on a standard personal computer than a mesoscale NWP model but slower than mass-conserving or Jackson-Hunt models. This in turn allows CFD/RANS models to simulate the influences of roughness changes and obstacles directly. CFD/RANS models are designed to reproduce mechanical production of turbulence (such as flow separation), but they are not designed to take into account circulations (such as sea breezes) due to temperature gradients. In the real world, both the mechanical and buoyancy effects of the atmosphere drive the turbulent motions. To overcome a limitation of CFD/RANS, modelers can rely on an unsteady RANS (URANS) version to capture flow accelerations that would otherwise not be simulated given the steady-state assumptions in RANS models. An alternative to adding a time integration capability within a RANS model to simulate unsteady flows is to conduct Large-Eddy Simulations.

Large-Eddy Simulations (LES)

LES have their origin in meteorology and weather prediction (Deardorff, 1972 and 1974; Smagorinsky, 1963; Lilly, 1967; Moeng and Wyngaard, 1984) and are a promising alternative to RANS models. LES explicitly resolve the energy-containing eddies—those larger than the grid spacing—while simulating the effects of smaller turbulent eddies through a subgrid scale parameterization scheme. LES can include the full suite of physics parameterization schemes: radiation, microphysics, land surface-atmosphere interaction, turbulence, etc. LES models are based on the raw equations of motion, i.e., unsteady, non-linear Navier-Stokes equations. The LES approach is in contrast to RANS and NWP models where the equations of motion are averaged with the turbulence effects appearing only in the turbulence closure parameterization. Another fundamental difference between LES and RANS models is that LES solve the conservation of energy equation, which allows LES to fully capture the wind circulations forced by thermal gradients, which is an important driver of offshore wind flows. Unfortunately, it is not possible to resolve explicitly all scales of atmospheric motions within the boundary layer with the currently available computational resources (Pope, 2000). LES are designed to run at very fine spatial resolutions using a grid spacing in the 1 to 100 m range.

LES models are mainly used as a research tool since the necessary computing power is huge. They have been popular in analyzing flows in idealized conditions with convective, neutral and stable boundary layers. The validity of LES depends crucially on the quality of the chosen subgrid scale turbulence scheme because of limited grid resolution and thermal stratification effects. Although LES of convective boundary layers have been studied successfully for two or three decades, only recently has LES been applied to stable boundary layers (e.g., Nieuwstadt et al., 1991; Andren et al., 1994; Mason, 1994; Beare and MacVean, 2004; Basu and Porté-Agel, 2006; Huang and Bou-Zeid, 2013; Churchfield et al., 2014; Aitken et al., 2014). LES using idealized conditions have been performed to study the atmospheric marine boundary layer. For instance, Sullivan et al. (2008) simulated the impact of fast-running swells generated by distant storms on the turbulent wind flow (Figure 5.4). LES have been rarely used to determine the offshore wind resource due to their computational expense and the fact that NWP and microscale models tend to perform relatively well when dealing with the average wind speeds across a large area. However, there is a growing interest for LES to capture the unsteady and non-linear turbine-induced wakes as well as their two-way interactions with the boundary layer (Jimenez et al., 2007; Calaf et al., 2010; Churchfield et al., 2012).

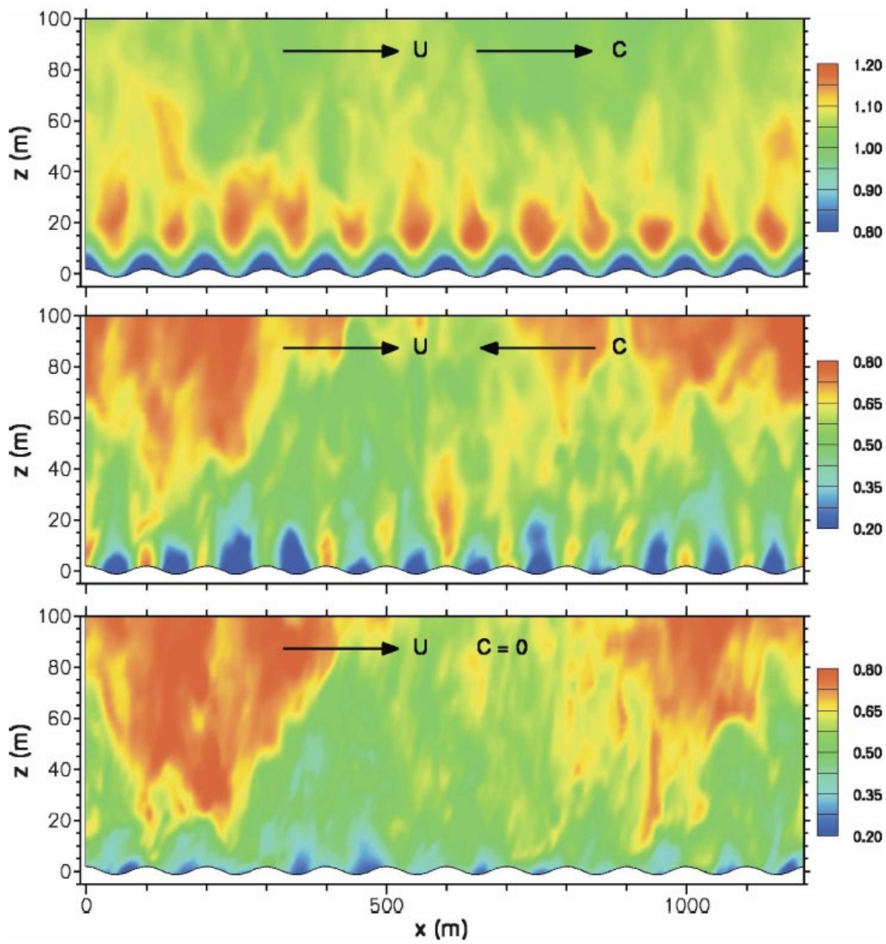

Figure 5.4 Contours of the u Component of the Horizontal Wind Field for Cases with Moving and Stationary Surface Waves. The non-dimensional field shown is u/Ug, where u is the wind speed and Ug the geostrophic wind. (top) Wind following waves; (middle) wind opposing waves; and (bottom) stationary bumps. For each case the geostrophic wind (*Ug*, *Vg*) = (5.0) m/s and the wave slope *ak* = 0.1 where the wave amplitude *a* = 1.6 m. In the top and middle panels the wave phase speed *c* = 12.5 m/s. (Source: Sullivan et al., 2008).

5.4 Modeling of Turbine-Induced Wakes

While the foregoing discussions about models have focused on the representation of ambient atmospheric conditions at different space and time scales, another modeling problem is the understanding of distortions within these conditions when wind turbines are added to the modeling domain. These distortions are commonly referred to as wakes, which are comprised of turbulent eddies shed by the turbines' blades, nacelle and tower. As turbulence sources and momentum sinks, upwind turbines within an array reduce the energy output and increase the structural fatigue of downwind turbines. Energy production losses in large wind farms due to the compounding effects of wakes caused by multiple turbine rows can exceed 15-20% if not properly arranged. The importance of turbine-induced wakes for offshore wind projects is not limited to wake losses due to individual turbines; the entire wind farm can impact neighboring wind farms (Nygaard, 2014). This latter effect is sometimes called wind farm shadowing. The next few paragraphs discuss different approaches used to model turbine wakes and their impacts on wind farm performance. These approaches include engineering/hybrid models, CFD/RANS models, NWP and LES models.

For over 20 years, wake-effect predictions have been based on a handful of engineering computer models, most importantly Park (Katic et al., 1986; Jensen, 1983) and Eddy Viscosity (EV) (Ainslie, 1988). The Park model implements a simple formula for the size of the wake deficit and its expansion downstream with a single adjustable parameter, the wake decay constant. The EV model solves an axisymmetric form of the Navier Stokes equations; it therefore qualifies as a simple RANS model. With the construction of offshore wind projects of significant size, it has become apparent that the standard Park and EV models tend to underestimate wake losses in offshore arrays (Brower and Robinson, 2009; Schlez and Neubert, 2009; Barthelmie et al., 2010). This may be in part because the models assume that wind turbines have no effect on the planetary boundary layer (PBL) other than the wakes they directly generate. As a consequence, new codes have been developed to account for two-way PBL-wake interactions such as the deep-array wake model (DAWM) in Openwind (Brower and Robinson, 2009) and Large Array Wind Farm (LAWF) model in WindFarmer (Schlez and Neubert, 2009). The DAWM is based on the surface-drag-induced internal boundary layer approach which modifies the wind speed profile within the PBL with increasing distance downstream of the front of a turbine array. The EV or Park model is retained for estimating direct wake effects, thus the term hybrid model. The LAWF model (Johnson et al, 2009) is an extension of standard wake models whereby each turbine is treated as a disturbance analogous to a roughness element that influences the free stream flow, resulting in a growth of the internal boundary layer. Both approaches are commonly used today and have demonstrated significant improvement over the original models (Beaucage et al., 2012; Brower and Robinson, 2009). However, they are limited in their ability to capture the detailed characteristics of the wakes. Another relatively new type of engineering model capable of predicting the turbine-induced wakes is the dynamic wake meander (DWM) model, which is a more detailed model of the flow field behind the upstream turbine (Larsen et al., 2012). This method applies a meandering process within an aeroelastic code in order to simulate the incoming flow field at downstream turbines and calculate both energy production and loading. It is an area of active research and development.

Stand-alone CFD models based on the RANS equations are equipped to simulate turbulent flows without the simplifying assumptions of the EV model. Nevertheless they have their own weaknesses. Most RANS models are run in steady-state mode and without a complete prognostic equation for temperature (i.e., conservation of energy). Therefore, they are typically limited in capturing the time-varying thermal structure of the boundary layer, which may substantially alter the results. Wharton and Lundquist (2012) have shown that atmospheric stability can have a strong impact on the power curve of tall wind turbines, i.e., up to a 20% difference in power output between stable and convective regimes during the spring and summer seasons. In addition, the turbulence closure commonly used in RANS software has been shown experimentally to be problematic for flows containing large adverse pressure gradients (Bardina et al., 1997), such as the gradient generated by the thrust force of a turbine. Several researchers are attempting to overcome the issues of the turbulence model by modifying the parameters and/or adding source and sink terms in the turbulent kinetic energy (TKE) and dissipation equations; the Fuga model is one of them. It was developed by Ott et al. (2011) and bears some similarities to WAsP, including a mixed spectral solver using pre-calculated look-up tables. Fuga is a linearized RANS model that inserts an actuator disk (an idealized model of a wind turbine rotor's effect on the airflow) to simulate the wakes. Another relatively new commercial RANS model is WindModeller based on Ansys CFX (Montavon et al, 2011). It is a RANS model with a turbulence closure and an actuator disk. Fuga and WindModeller have been found to perform better than the standard Park model at multiple offshore sites when the direction sectors are narrow (Garza et al., 2011). However, they give comparable results to the Park model when the wind direction bin size exceeds 10 degrees.

LES models have recently been used to study single and multiple turbine-induced wakes (Wu and Porté-Agel, 2011; Calaf et al., 2010; Churchfield et al., 2012; Troldborg et al., 2014; Mirocha et al., 2014). For single turbine-induced wakes, LES models with a wind turbine parameterization using an actuator disk and/or actuator line model can compare favorably to wind tunnel measurements even in the challenging near-wake region as shown in Figure 5.5 (Wu and Porté-Agel, 2011). Using the OpenFOAM software, Stovall et al. (2012) showed that the power deficit ratios for LES and RANS simulations are within 2-4% and 15-43% of experimental data, respectively. The advantage of unsteady simulations and full conservation of energy equation in LES come with a cost: the runtime for LES simulations is approximately 60 times longer than that for RANS simulations in OpenFOAM (Stovall et al., 2012). Nevertheless, LES codes are a promising approach to simulating wakes if a high performance computing system is available. Both the open-source Simulator for Offshore/Onshore Wind Farm Applications (SOWFA) from NREL (Churchfield et al., 2012) and the LES implemented in the WRF model (Mirocha et al., 2014), offer opportunities for the academic and industry sectors to collaborate and develop the next generation of turbine-induced wake models.

Wind farm parameterizations have also been developed for mesoscale NWP models (Adams and Keith 2007, Fitch et al. 2012). Instead of treating wind farms as a "forest" of wind turbines, the rotor plane of wind turbines is modeled by a porous disk which removes momentum (i.e. actuator disk theory). The grid spacing of mesoscale NWP models (> 1 km) is too coarse to resolve each individual wind turbine, but these wind farm parameterizations have been used for assessing the impacts of wind farms on regional climate (Keith et al., 2004; Baidya et al., 2004; Sta Maria and Jacobson, 2009).

Another benefit to advancing turbine wake models and improving their fidelity is to enable turbine and wind farm control systems to optimize operations using wake-related intelligence. For example, under some weather conditions it is possible to enhance overall wind farm output by manipulating (yawing) the orientation of upwind turbines so that their wakes are steered to mitigate negative impacts on downstream turbines. This capability is especially feasible with real-time monitoring of boundary layer conditions (winds, stability, turbulence) at a wind farm.

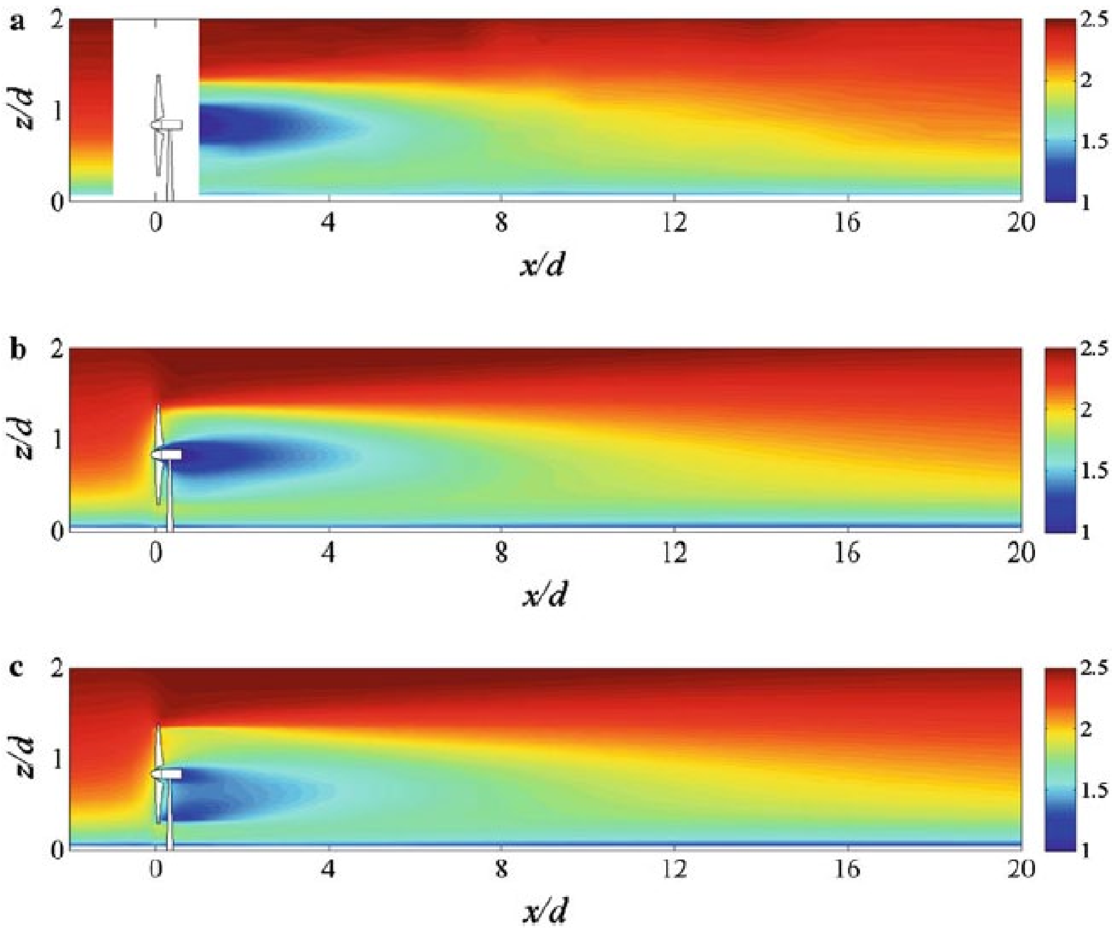

Figure 5.5 Cross-Section of the Time-Averaged Streamwise Velocity in the Vertical Plane Perpendicular to the Turbine: a) wind-tunnel measurements, b) actuator disk model with rotation, c) actuator disk model without rotation. The distances are normalized with the rotor disk "d" (Source: Wu and Porté-Agel, 2011).

Although many new wake models have been introduced in the last decade or so, the amount of publicly available operational turbine data remains limited. The SCADA (supervisory control and data acquisition) data at operational US wind farms are proprietary to wind farm owners/operators. Through collaboration with the owners/operators, some researchers can gain access to the SCADA data. However, most wake models developed recently have relied on a sample of processed turbine data (not SCADA data) at a few offshore European wind farms. A dataset available through the Prediction of Waves, Wakes and Offshore Wind (POW'WOW) project (Barthelmie et al., 2010) includes processed turbine data from two Danish offshore wind farms: Horns Rev 1 and Nysted. Improvements in wake modeling can only go as far as the measurements available to gain an understanding of wind turbine behaviors in different atmospheric conditions and wind farm layouts. Hence, it is recommended that more SCADA data from operating wind farms, together with onsite meteorological observations, become available to researchers to facilitate the further advancement of wake models.

5.5 Wave Models and Coupled Atmosphere-Ocean Models

Several wave modeling approaches are available for developing wave climatologies through hindcasting and for producing operational forecasts from hours to days in advance. For example, the U.S. Army Corps of Engineers (USACE) Wave Information Studies (WIS) project generates hourly, long-term (20+ years) wind and wave climatologies along all US coastlines, including the Great Lakes and island territories. The wavefield climatologies synthesize observations, hindcasts and storm event archives. The WIS database consists of hindcasted wave and wind information for a densely-spaced (approximately 50 - 100 km) linear series of "virtual wave gauges" in water depths of 15-20 m and for a less-dense series in deeper water (100 m or more). Three wave models are used in the WIS effort: WISWAVE, WAVEWATCH-III, and WAM (Wave Model). Unlike a forecast, a wave hindcast predicts past wave conditions using a computer model and observed wind fields. By using value-added wind fields, which combine ground and satellite wind observations, hindcasted wave information is generally of higher accuracy than forecast wave conditions and is often representative of observed wave conditions.

The popular WAVEWATCH-III model (version 4.18 was released in March 2014), which is free and open source, is widely used to generate operational wave forecasts and is run four times a day (00Z, 06Z, 12Z, and 18Z) by NOAA/NWS/NCEP. Each run starts with 9-, 6- and 3-hour hindcasts and produces forecasts of every 3 hours from the initial time out to 180 hours (84 hours for the Great Lakes). WAVEWATCH-III is evolving from a wave model into a wave modeling framework, which allows for easy development of additional physical and numerical approaches to wave modeling. The SWAN (Simulating Waves Nearshore) model, which was developed by the Delft University of Technology (The Netherlands), downscales coarse-resolution ocean conditions and is a third generation wave model designed to solve shallow water parameterizations such as refraction, shoaling, and diffraction. SWAN allows for direct coupling with either WAM or WAVEWATCH-III and is run after the larger-scale models are run and boundary files have been generated. NCEP currently supports several coupled SWAN model runs for several near-shore regions of the United States.

Wave models are forced by wind fields generated by a NWP model. Wave model outputs typically consist of significant wave heights, directions, frequencies, peak and mean wave period, as well as wind speed and direction. The accuracy of wave predictions is highly dependent on the accuracy of the wind field (speed and direction) and on the quality of the model itself. Inaccurately defined winds can cause non-linearly larger wave prediction errors. For example, a 10% error in the assessment of surface wind speed can cause a 10-20% error in the significant wave height (Hs) and an even larger error in wave energy (Komen et al., 1994). Wave predictions can also be hampered by the long distance propagation of waves and swells from outside the modeling domain.

Traditional wave models are an example of one-way coupled models whereby the atmospheric model provides low-level wind fields to drive the wave model, but there is no information transmitted from the wave model to the atmospheric model. As a result, the atmospheric model must estimate the surface roughness length over the ocean as a simple function of local wind speed. In two-way coupling, the wave model provides information on the local wave heights and wavelength so that roughness length for atmospheric modeling can be computed directly from the wave information. For example, Sullivan et al. (2010, 2014) couple a turbulence-resolving LES of the lower atmosphere to a 3-dimensional time-dependent surface wave field. Hanley et al. (2010) produced a global climatology of wind-wave interactions, which are defined in two regimes: wind-driven waves and wave-driven winds. Wind-driven waves occur most frequently in the midlatitudes (Chen et al., 2002). Wave-driven winds are prevalent in the tropics where wind speeds are generally light and swell can propagate from distant storms at higher latitudes. The swell transfers momentum into the lower atmosphere, impacting near-surface winds (Smedman et al., 1999).

While coupling wind and wave modeling is important, coupling to oceanic models may be even more important since the thermal influences of the ocean on the atmosphere (specifically the impacts of currents, winds and precipitation on sea surface temperature) play a critical role in the response of the marine atmospheric boundary layer. The main benefit of coupling atmospheric, wave and ocean models is balancing the fluxes of heat and momentum at the water surface. Without coupling, closed models tend to develop solutions in unrealistically diverging ways. Coupled wave-ocean-atmosphere models incorporate physics-based parameterizations that can significantly improve simulations and forecasts of wind, waves and currents—including hurricane tracks and intensity—in coastal regimes where air-land-sea contrasts drive mesoscale circulations (Lee and Chen, 2012). In cases where new observations are to be sited with an explicit goal of improving model predictability, modeling techniques are now available that can reveal the measurements types and locations that are most influential in producing a forecast of sufficient accuracy over a given area.

5.6 Conclusion

Models are effective and essential tools when analyzing data fields, simulating important ocean and atmospheric processes, and forecasting changes in metocean conditions over different time scales. They are also essential to critical decision-making and other activities associated with every phase of a wind farm's life. Improved modeling capabilities are needed to accurately interpolate and extrapolate information—both temporally and spatially—from a finite number of observation stations. Enhancing both the number of strategically-sited measurements and the quality and types of observations will dramatically advance model performance by more accurately defining initial state and boundary conditions and by providing validation data. In a study of field data from offshore northern New England (Marquis et al., 2014), NOAA recommends a specific strategy to combine new targeted measurements and modeling to gain much-needed insights into the regional nature of winds affecting future offshore wind turbines. Modeling improvements also mean better representations of important dynamic offshore processes. These include complex land-sea-air interactions that influence sea breeze circulations, low-level jets, thermal profiles, and other marine boundary layer phenomena that directly impact wind farm performance, long-term reliability, and economic viability.

While there is an array of atmospheric and wave modeling tools available, more focus is needed on processes that couple the turbulent atmospheric and oceanic boundary layers across the interface through the exchange of momentum, mass, and heat. Separate atmospheric and wave models are closed systems that rely on simplified boundary conditions, which can lead to inaccurate solutions. Coupled ocean-atmosphere models incorporate physics-based parameterizations that can significantly improve simulations and forecasts of wind, waves and currents—including hurricane tracks and intensity—in coastal regimes where air-land-sea contrasts drive mesoscale circulations.

There is a growing number of commercial and research wind turbine wake models but validation datasets from operating offshore wind farms remain limited. Further, those datasets collected by private entities are not typically shared. Because turbine wakes can be a significant cause of power production losses, especially in large arrays, ongoing model advances are desired to optimize wind farm performance through improved layouts and turbine control strategies, and through reduced fatigue loads on turbine structures.

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6. RECOMMENDATIONS FOR IMPROVING THE CHARACTERIZATION OF METOCEAN CONDITIONS IN THE UNITED STATES

6.1 Introduction

Metocean data are integral to defining the external operating conditions and the expected energy yield of offshore wind projects in locales where they may be sited. These conditions encompass the atmosphere and water column, as well as the sea bed (see Chapter 3). Knowledge of these conditions enables the design of appropriate structures and components to withstand the loading factors expected over a project's lifetime. Human safety, vessel navigation, project construction and maintenance activities are equally tied to the metocean environment. Project financing and economic viability are also strongly affected by the definition of long-term wind resource characteristics and operating conditions informed by onsite and regional metocean conditions.

In the United States, offshore wind projects are being developed or considered off the Atlantic and Pacific coasts, the Gulf of Mexico, and the Great Lakes. However, domestic observational metocean data is sparsely collected and relies heavily on surface weather buoys that do not probe hub height wind conditions. Significant portions of the oceans and Great Lakes contain no year-round observational data at all and rely on model-derived approximations to estimate metocean conditions, greatly inhibiting the predictability of extreme storms to US waters. This state of affairs results in a high degree of uncertainty when attempting to define the resource and design environment in most offshore areas. This in turn imposes severe limitations on current abilities to reduce the cost and risks associated with offshore wind energy until the situation is remedied. Therefore there is a critical need to improve the characterization of metocean conditions to facilitate future offshore wind energy development in the United States.

This chapter recommends a set of activities to address this critical need. These recommended activities are relevant to the interests of multiple stakeholders and are grouped into three categories: new measurements, analysis and prediction modeling, and public-private synergy. Each category is more fully described below. These activities are also incorporated into a proposed roadmapping exercise, which is presented in the final section. Roadmapping is the use of a framework to create a big-picture of a complex subject and to define strategic actions.

6.2 Recommended Activities

6.2.1 New Measurements

1. Definition of Data Parameters, Applications and Users

Given sufficient time, data needs can be resolved by the initiation of new measurements at a multitude of locations, followed by a multi-year data collection program. The prohibitive cost and impracticality of this approach, however, demands a targeted and pragmatic solution. A first step in the planning process for new measurements is the identification of important data parameters and products, which are defined by their intended applications and users. A distilled list of relevant metocean data parameters is provided in Table 6.1. Parameters that are measured directly are distinguished from those that are derived from the measurements. Most data applications will pertain either to defining the hydrodynamic and atmospheric loading conditions on structures according to established standards and best practices, or to predicting project capital and operating costs as well as annual energy production. Primary data users are project developers (private and utility sectors), original equipment manufacturers, marine design engineers, regulators, financiers, and the research community. Required parameters, their applications, and the available measurement and modeling technologies will likely expand over time, so it is imperative to remain abreast of offshore wind industry development and new data needs.

Table 6.1 Relevant Metocean Data Parameters for Offshore Wind Energy Applications

Wind and Other Meteorological		Oceanographic, Water State & Other	
Direct Measurements	**Derived Parameters**	**Direct Measurements**	**Derived Parameters**
• Horizontal Wind Speed @ Multiple Heights • Wind Direction @ Multiple Heights • Vertical Wind Speed • Inclined (off axis) Flow • Barometric Pressure • Relative Humidity • Temperature • Lightning • Precipitation • Solar Radiation • Visibility	• Wind Speed Distribution & Standard Deviation • Turbulence Intensity • Turbulent Kinetic Energy • Wind Shear • Extreme Operating Gust • Extreme Coherent Gust with Direction Change • Wind Direction Distribution (wind rose) • Wind Veer • Wind Density • Thermal Stability • Hurricane Category Frequencies	• Wave Height • Dominant Wave Period • Mean Wave Speed • Wave Direction & Directional Spectrum • Current @ Multiple Depths • Still Water Level • Tidal Datum • Seabed Movement • Temperature • Salinity • Conductivity • Ice Thickness (and other qualities) • Bathymetry • Soil Type • Scour	• Significant Wave Height • Frequency Spectrum • Storm Surge • Water Density • Seismic & Tsunami Risk

2. Strategic Siting

Another planning step is to target measurement locations in areas where wind energy development is expected in the foreseeable future. Many areas are already known from announced project proposals, including three pilot projects recently awarded support from the DOE, and from awarded or pending Wind Energy Areas, which are managed by BOEM. Currently, the majority of areas are located adjacent to the coastline of the eastern United States stretching from Maine to Georgia. Other areas include offshore sections of Oregon, Ohio (in the Great Lakes), and Texas. The goal of siting is to locate new measurements where they will be geographically representative and provide high value to intended users.

Two types of siting strategies are likely to predominate: one led by a project developer and the other by a government agency. In the first case, new measurements are likely to focus within or immediately adjacent to a proposed project area. This placement will ensure maximum applicability of the collected data to the project and will minimize reliance on distant measurement points to derive site-specific estimates. In the second case, a government entity seeking information about metocean conditions as part of marine spatial planning and/or to support regional research activities is likely to take a different siting path. Here, the goal is to find a convenient measurement location that experiences metocean conditions that are regionally representative. Hence, there can be numerous candidate monitoring sites to choose from.

Existing platforms within these areas are natural candidates for measurements because they can potentially be retrofitted at a lower cost than installing a completely new platform. Such "platforms of opportunity" are relatively sparse and are dominated by decades-old structures. Some have not been actively used or maintained for several years, may contain hazardous materials, lack reliable power sources for observation equipment, or are at heights too low to measure within turbine rotor swept areas. Many have been used (and continue to be used in some cases) to support government-sponsored metocean measurements. Examples of these platforms include: the remaining "Texas Tower" light stations (Chesapeake Light off of Virginia, Diamond Shoals east of the Outer Banks of North Carolina, and Frying Pan Shoals east of southern North Carolina); US Navy towers used for flight training exercises (e.g., off the Georgia coast); near-shore Coastal-Marine Automated Network (C-MAN) stations (e.g., Buzzards Bay, MA; Stannard Rock, MI); and oil rigs (primarily in the Gulf of Mexico and off the California coast). Their future use for metocean monitoring would be an important step in regionally characterizing metocean climatologies, validating models, and in serving as long-term regional benchmarks (or references) to compare and correlate with data from new measurement campaigns.

3. Sensor and Platform Technology Development

Accomplishing the task of collecting the desired data parameters depends on the availability of appropriate and affordable sensors and platforms. Sensors need to be robust and proven to reliably operate in the harsh marine environment. Suitable platforms that physically support the sensors and house the data collection, communications, and power systems are necessary, too. Fixed-bottom meteorological towers are a tried and true approach to platform design. A tall tower—one that extends on the order of 100 m in height above mean water level—has the advantage of enabling direct measurements of wind, temperature and other variables at the heights of interest (including hub height) using marine-hardy, commercially-available sensors. However, fixed tower costs are relatively high ($8-$15 million or more, depending on water depth, wave and seabed environment). Timing is a factor too; it can take two or more years to design, permit, construct and commission an offshore meteorological tower. This approach may be perfectly feasible for a long-term application that is intended to continue after the site assessment phase to support wind plant operations, or to support a regional research initiative. For site assessment purposes alone, a tower may be overkill and result in unnecessary delay.

The emerging availability of surface-based remote sensing technologies—including profiling, scanning and floating versions of lidar systems—have shown promise as lower-cost and bankable alternatives to tower-based measurement programs. Relatively stable buoy platforms to support surface-based remote wind and temperature sensing systems are becoming more available and show similar promise. These floating platforms have the expected added advantage of shorter deployment cycles and multi-site mobility. Accelerated development and validation of new lidar and platform technologies are needed to speed up deployment cycles and earn industry acceptance as alternative approaches. Initial roadmaps (Flowers et al, 2013; Carbon Trust, 2013) for advancing the application and bankability of floating lidar have been published in several international forums, and the International Energy Agency (IEA) is currently drafting recommendations for the use and validation of lidar in offshore applications (IEA, 2013). Further, the IEC is expected to include the use of remote sensing in the development of standards for wind resource assessment (IEC, 2013). Side-by-side field testing at a fixed instrumented offshore structure—be it new or pre-existing, as discussed in the prior recommendation—is one of the key approaches to facilitating use and acceptance of these technologies.

4. Deployment Scenarios

The DOE has the opportunity to influence the future of domestic offshore metocean characterization by fostering a national framework that leads to the initiation of one or more field campaigns, including the establishment of an offshore scientific reference facility. A proposed reference facility for offshore renewable energy (RFORE) would be a major contribution in that the facility's objectives include: (a) continuous collection of core metocean parameters that would become publically available; (b) deployment and testing of innovative measurement technologies, including profiling/scanning lidar; (c) research that addresses key scientific questions and uncertainties of concern to the offshore wind industry at large; and (d) access to the facility by industry constituents who desire to invest in complementary measurement, research and testing activities. The Chesapeake Light Tower has been considered for this facility, and if developed, would constitute the very first facility dedicated to metocean characterization and research for offshore wind energy applications in the United States. If Chesapeake Light is unable to proceed, an alternative facility should be pursued so that the aforementioned objectives can be addressed.

Through co-funding, technical support and other initiatives, the DOE can also influence offshore measurement campaigns initiated by others (e.g., developers, state agencies, utilities, universities). This influence can take many forms, including the setting of minimum requirements for measurement program design and quality assurance, establishing common protocols for data formatting, handling, storage and accessibility, and facilitating data transmission, collection and distribution. Additional ideas about instituting best practices or standards for metocean measurement, and about data sharing mechanisms, are presented in the section on Public-Private Synergy. It would also be advantageous to leverage the three pending DOE offshore demonstration projects in New Jersey, Oregon and Virginia (announced in May 2014) for publicly-available metocean data collection.

Another dimension to deployment, be it government or developer led, is the concept of multi-site installations in a hierarchical fashion. This concept entails the installation of a limited number of high intensity (i.e., high cost) measurement stations within a target region together with a greater number (or density) of relatively low intensity (i.e., fewer sensors), complementary measurement stations. An example of this strategy would be the installation of a fixed, tall meteorological tower (including a wave/current/water temperature profiling package) positioned within a proposed development region, plus the surrounding deployment of multiple floating lidar systems and conventional weather/wave buoys throughout the region. This parent-child concept to multi-station measurements can be cost-effective and achieve good regional coverage while also taking advantage of platform location mobility.

6.2.2 Analysis and Prediction Modeling

1. Improved Modeling and Forecasting Capabilities

There are several phenomena that define the mean, variable and extreme metocean environment relevant to the development and operation of offshore wind projects. A better understanding of these features and their predictability will require advancements in observational and modeling tools, building on the past development of increasingly robust three-dimensional atmospheric and oceanographic simulation capabilities. The goal is to accurately observe and predict the complex interaction and forces of wind, waves and other metocean parameters. In addition to more observations, there is a need for improved modeling capabilities to accurately interpolate and extrapolate information—both temporally and spatially—from a finite number of stations and remote-sensing platforms (including ground-based and satellite systems) while representing important dynamic offshore processes. These processes include complex land-sea-air interactions that play a vital role in sea breeze circulations, low-level jets, thermal profiles and stability, and other marine boundary layer phenomena. These interactions can result in sharp gradients in metocean conditions across the coastal zone, thus challenging both the optimal siting of wind projects as well as accurately forecasting energy production in hour-ahead and day-ahead markets.

Improved models will play a critical role in both resource characterization and operational forecasting. More focus is needed on processes that couple the turbulent atmospheric and oceanic boundary layers across the interface through the exchange of momentum, mass, and heat. Separate atmospheric and wave models are closed systems that rely on simplified boundary conditions, which lead to inaccurate solutions. Coupled ocean-atmosphere models incorporate physics-based parameterizations that can significantly improve simulations and forecasts of wind, waves and currents—including hurricane tracks and intensity—in coastal regimes where air-land-sea contrasts drive mesoscale circulations. In cases where new observations are to be sited with an explicit goal of improving model predictability, modeling techniques are available that can reveal the measurements types and locations that are most influential in producing a forecast of sufficient accuracy over a given area.

2. Updated Wind Maps and Extreme Event Statistics

Existing maps of the offshore wind resource contain high degrees of uncertainty due to the lack of validation data at hub height. As new observations are taken and modeling improvements are achieved, updated maps should be produced. The maps and their underlying datasets should contain mean, distribution, and extreme statistics for wind speed and direction, wind power density, and a host of other relevant parameters. Comparable maps for the wave and current environment are also needed.

Design criteria for offshore structures, as established by the IEC, API and other organizations, include 50- and 100-year return periods for extreme wind and wave events. Due to the lack of long-term measurements in US waters, existing probability statistics for extreme conditions also contain a high degree of uncertainty. Furthermore, as evidenced by the variety of severe weather events in recent years, climatological statistics for extreme event probabilities derived solely from historical records may need to be revised in light of climate change. More reliable statistics for extreme event probabilities, derived from the combination of new observations and modeling approaches, will reduce the need for large uncertainty margins in system design as well as lessen investment risk and costs.

3. Plant Wake and Energy Prediction Models

The understanding of wake impacts on turbine fatigue loads and energy production is more challenging for offshore projects because they are generally larger in scale than their land-based counterparts. Surface roughness and atmospheric stability regimes are significantly different too. Due to their relative simplicity, current commercial wake modeling tools cannot accurately simulate wake development, propagation and dissipation behavior for large arrays, resulting in undesirably high levels of prediction uncertainty. More sophisticated models designed to address some of these uncertainties are under development, or are as yet too computationally intensive for commercial optimization applications. It is recommended that wake modeling improvements be pursued to better optimize turbine layouts and mitigate wake-induced impacts and uncertainties on project performance and reliability. Wake modeling advancement will enable higher energy yielding projects and lower operations and maintenance costs.

6.2.3 Public-Private Synergy

1. Collaboration and Outreach

Synergy can be defined as the interaction or cooperation of two or more organizations to produce a combined impact (or benefit) greater than the sum of their separate impacts. While the US offshore wind industry progresses through its current formative stages, the need to improve metocean data quality, coverage and access remains unchanged. Continued progress on this front will help overcome the siting, design, cost and operational challenges of this emerging domestic industry. Moving steadily forward requires a commonly shared vision that seeks to reduce scientific and technical uncertainty, accelerate deployment, attract investment, and demonstrate viable operations while simultaneously ensuring environmental, health and safety stewardship. Concerted collaboration and outreach are integral to this vision to ensure an open exchange and sharing of information and ideas among stakeholders.

A way to ensure that these objectives are met in a proactive way over the foreseeable future is to establish a funded, formal collaboration and outreach initiative having a clear mission and family of goals. These goals should include effective outreach activities involving industry participation (such as workshops, publications and other communications), a web-based information clearinghouse, and an organized process to identify and prioritize issues of concern to stakeholders. The stakeholder community should represent the public and private sectors comprising the greater offshore wind industry, including developers, regulators, equipment and service providers, researchers, financiers, and utilities, among others. The community should be international in scope because of the existing geography of stakeholders, and also because the lessons learned from the European offshore wind experience can inform US activities. To date, some key stakeholders in the United States—developers, in particular—are not yet focused on metocean issues while they first pursue rights to lease block options as well as promising signals in regional energy markets. Hence, the collaborative and outreach initiative should ramp up appropriately as the offshore wind industry gains momentum.

It is important to recognize the existence of, and collaborate with, other federal ocean data initiatives. These include the National Oceanographic Data Center (NODC), the National Science Foundation's Ocean Observatories Initiative (OOI), the Interagency Working Group on Ocean Partnerships (IWG-OP), and others. In 2013, the Interagency Ocean Observation Committee (IOOC) published a report on the IOOS Summit (held November 13-16 in Herndon, VA), which produced a strategy for developing a stronger national ocean observing system over the next decade (US IOOS, 2013). This strategy recognizes the data needs of the offshore wind industry. A white paper written by AWS Truepower as part of its DOE-supported work was submitted to IOOC to help inform the strategy making process (Bailey et al, 2013).

2. Private-Public Data Sharing and Research

Most commercial offshore project development is expected to be financed in large part by the private sector, which implies that metocean data collection will be privately held as well. Given the critical importance of observational data to advancing the greater industry's understanding of the offshore environment, there would be tremendous value in finding ways for privately-held data to be shared, either partially or in full, with the research community and other stakeholders. In some cases, it may be desirable for such data sharing to be done in near real time to support forecasting research and operations. Precedents for data sharing already exist. For example, the Meteorological Assimilation Data Ingest System (MADIS, established by the National Weather Service) processes and disseminates observations from thousands of non-government meteorological measurement stations. Established guidelines designate how contributed data is handled, including a category for proprietary data authorized for use for government purposes but not for outside distribution. Given the success of the MADIS program and its use of restricted data licensing, a similar program policy and architecture should be considered for offshore wind data sharing.

Several offshore wind developers have expressed interest in principle on metocean data sharing for the public good. Others have advanced this concept further in collaborative efforts with public universities or outreach with their measurement campaigns. Engagement of the DOE and other Federal agencies with the private sector by way of outreach, structured collaboration efforts, and cost sharing is expected to be productive in establishing a precedent of public-private data sharing.

3. Best Practices and Standards for Metocean Characterization

There is no international standard for offshore wind resource assessment and ocean characterization. The pending IEC standard (61400-15) for wind resource assessment and site characterization is anticipated to include content on offshore conditions. However, the creation of this document was just recently approved and the exact content – particularly with respect to offshore site assessment – has yet to be formalized. While these standards are anticipated to add value to the global wind industry, the uncertainty around their development schedule and offshore-related content limit their anticipated near-term impact on the US offshore market.

Development of US-centric recommended practices in collaboration with key sectors—industry, the research and regulatory communities, and the finance and insurance communities—will help ensure that future monitoring approaches are broadly accepted and utilized. Further, such an approach will ensure that metocean conditions relevant to the US industry, such as hurricanes and Great Lakes ice, will be addressed with adequate detail and weight. While not necessarily standards—which often imply legal or commercial obligation for adherence—a "best practices" framework could address typical (meteorological tower) and novel (floating lidar) metocean monitoring and validation approaches and would provide a common, accepted starting point for future monitoring deployments. A consensus-based best practices framework is likely to take considerably less time and effort to complete than a standards setting approach, but it may have shorter-term value for the industry. Best practices often precede standards because experience with the former is used to inform the latter.

6.2.4 A National Needs-Based Science and Technology Roadmap

The foregoing recommendations can be compiled into a roadmap, or action plan, to summarize the overall mission and key planning elements. In this case, the mission is to improve metocean characterization to adequately define external design and operating conditions for offshore wind projects in the United States. Table 6.2 outlines the principal roadmap elements to address this mission.

There are five main components of the roadmap: Drivers, Actions, Capabilities, Promoters and Outcomes. The Drivers describe the underlying motivation while the Actions, which this report has focused on, identify specific tasks and activity areas. Capabilities name the types of entities that can together supply the expertise to accomplish the desired actions. Promoters are the enabling and funding organizations who can put things into motion and influence the process. As the roadmapping process evolves, the entity and organization types can be supplemented with specific names (like DOE). The Outcomes are the pre-determined end products and accomplishments the roadmap aims to achieve. When designed collaboratively by multiple entities and organizations, the roadmap inherently achieves a community of stakeholders who are vested in the plan's success.

Figure 6.1 presents a composite picture of the metocean characterization roadmap. It is intended as a high-level framework for addressing the existing gaps in metocean knowledge, thereby facilitating future offshore wind development in the United States. The roadmap is designed to be an impetus for developing a detailed action plan centered on the three recommended categories. Example action items include:

1. New Measurements
   A. Initiate field campaigns near BOEM-designated wind resource areas
   B. Develop and validate new metocean sensors and floating platform technologies
   C. Foster innovative multi-site deployment scenarios
2. Analysis and Prediction Modeling
   A. Improve wind/wave modeling and forecasting capabilities
   B. Update wind maps and extreme event statistics
   C. Advance plant wake and energy prediction modeling

3. Public-Private Synergy
   A. Engage in stakeholder collaboration and outreach
   B. Promote public-private data sharing and research
   C. Foster best practices and standards for metocean characterization

Table 6.2 Roadmapping Elements

Components	Detail
Drivers	• Untapped Offshore Wind Opportunities • Lack of Reliable Metocean Data • Project Risk and Cost Reduction
Actions	• New Measurements • Modeling Improvements • Public-Private Synergy
Capabilities	• Research Laboratories • Universities • Engineering & Consulting Firms • Instrument Firms • Ocean Data Clearinghouses
Promoters	• Government • Industry • Investors & Lenders • Utilities
Outcomes	• Tailored Data and Data Products • Advanced Marine Instrumentation • Best Practices & Standards • Site-Optimized Project Designs and Costs • Reduced Project Risks • Stakeholder Consensus Building

The time frame to carry out the roadmap is assumed to be a minimum period of 10 years. The most critical path will be the development and deployment of offshore measurement systems, which will be the most expensive components as well. Deployment involves a regulatory approval process, which can take 1-2 years prior to any installation activity. Once systems are commissioned, several years of data collection will be needed to enable the derivation of data products and achievement of modeling improvements.

The metocean roadmapping process described here has objectives that are similar to those comprising DOE's new Atmosphere to Electrons (A2e) initiative (DOE, 2014). The A2e program is a multi-year, multi-stakeholder initiative tasked with improving the understanding of wind resource characteristics and their interactions with land-based and offshore wind turbines and wind plants. Planned activities include experimental measurement campaigns and next generation model development. Facilitated by a collaborative research and development framework, A2e's goal is to improve wind plant performance and mitigate risk and uncertainty to achieve large reductions in the cost of energy.

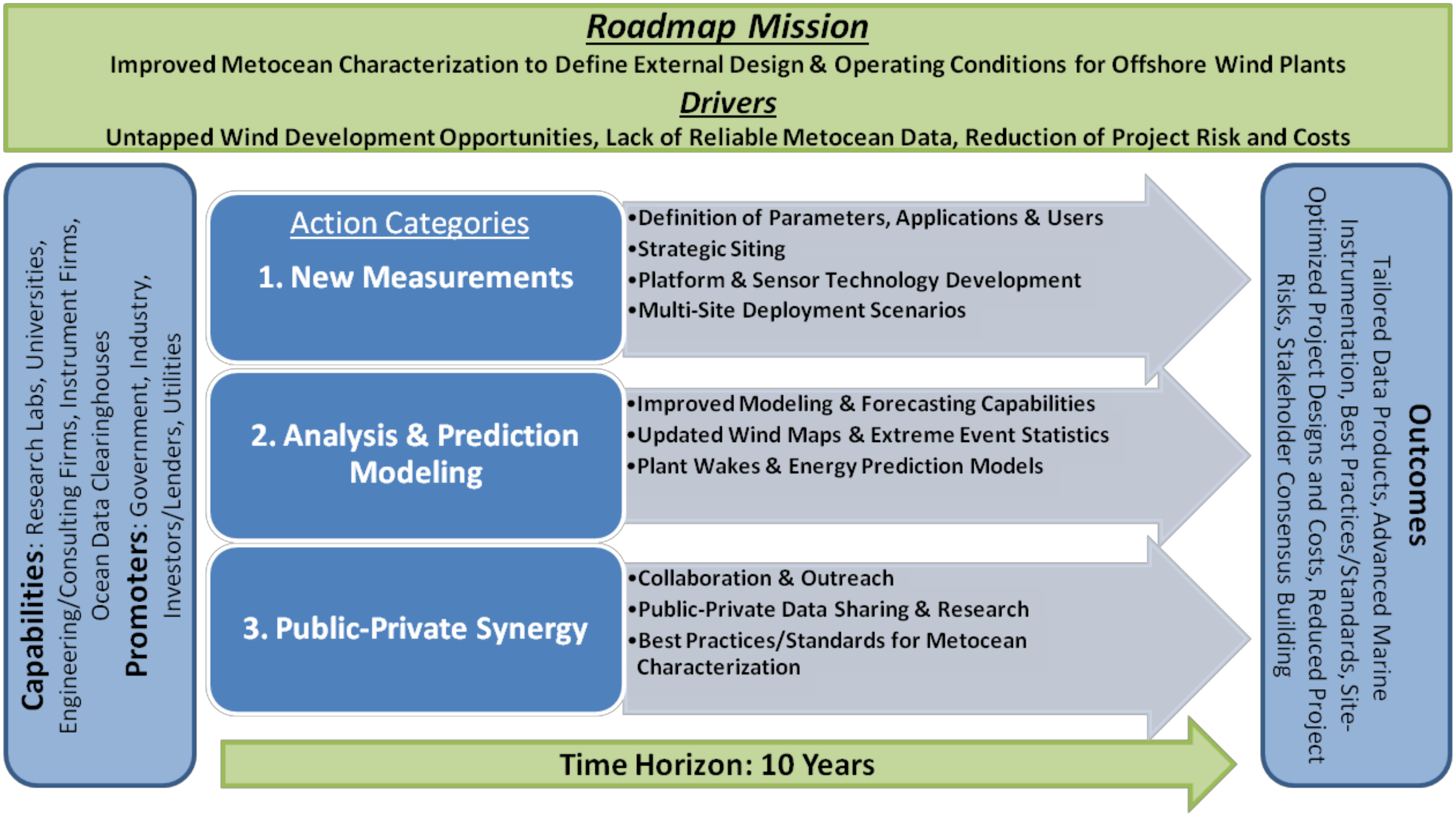

Figure 6.1 Proposed Roadmap for Offshore Metocean Characterization

Given the overlapping objectives, stakeholders and timeframes, it may be advantageous to align or integrate the metocean roadmapping process with the A2e initiative. Such coordination would likely facilitate the startup of the metocean action plan while leveraging existing resources and avoiding duplication of effort.

6.3 Conclusion

The progress of offshore wind energy development in the United States hinges on several factors: promotional policies, favorable energy markets, declining capital costs, technology compatibility with the marine environment, and risk adoption by first-mover developers. With the exception of the Gulf of Mexico, most of the country's offshore waters have experienced little if any construction of industrial, commercial or energy-related facilities. Consequently there is a lack of experience in offshore development and a corresponding lack of physical data and knowledge about the harsh marine environment. Offshore wind energy, which has realized over 20 years of development in Europe, is now poised to expand into the United States. To succeed here, it must invest in pioneering activities to define the metocean environment, which has key differences (such as hurricanes) from European ocean conditions. Given the broad range of stakeholders having vested interests in this success—policy makers, regulators, investors, utilities, and the public at large—it is imperative that these pioneering activities be coordinated and collaborative.

To address this need, this report recommends a set of activities designed to improve the characterization of metocean conditions for the benefit of offshore wind energy. These activities echo those recently recommended by a cross-section of industry stakeholders (AMS, 2013; Archer et al., 2014). Parallel efforts to advance measurements, modeling and industry collaboration should respond to a long-term vision and a coordinated strategy. The proposed roadmap is designed to suit this purpose. The DOE is the logical agency to lead this initiative, which will require dedicated commitment over several years plus adequate funding from multiple sources.

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APPENDIX: AN OVERVIEW OF OFFSHORE WIND CHARACTERISTICS

The purpose of this Appendix is to provide readers who have little background in offshore wind energy with a primer about the nature of the offshore wind environment. The intent is to provide the context for new wind resource characterization activities in offshore areas of the United States compared to decades of experience in land-based environments. Much of the material in this section is extracted from Brower (2012).

While recognizing the importance of variable wind-wave interactions in the offshore environment (e.g., Kalvig et al., 2014), many of the basic principles and guidelines of wind resource assessment apply equally well on land and offshore. For the most part, the atmospheric instruments and parameters measured are the same, as are the methods used to collect and quality-control data. The same is true for methods to characterize the resource, project the measurements to the turbine hub height, correct for short-term climate variability, and extrapolate the resource to turbine locations using numerical wind flow modeling. However, a common shortfall in offshore wind resource assessment is the lack of measurements near the hub heights of modern wind turbines, i.e., 80 to 120 m above sea level. The cost of tall meteorological masts offshore is so high that at most one is installed per project. Fewer measurements can result in wind resource uncertainties that are higher than for onshore project sites, which typically employ multiple masts. Emerging applications of remote sensing technologies, such as lidar, are a potential replacement for, if not complement to, tall offshore masts. However, remote sensing is a developing technology that is not yet uniformly accepted by all sectors in the United States' wind industry.

The lack of available wind speed measurements at or near the hub height of modern offshore wind turbines contributes significant uncertainty to wind speed estimation. The majority of publicly-available offshore wind data are collected by buoys at anemometer heights of five meters or less. Satellite-derived estimates of ocean winds are available at a 10 m height. Figure A.1 shows a broad range in hub height speed estimates that would result from using a range of power law shear exponents to extrapolate a known wind speed value from 5 m above the surface up to 120 m. The 5-m wind speed value of 6.7 m/s was the measured annual average observed by a north Atlantic buoy in 2013, while estimated 80-m wind speeds varied from 7.5 to 11 m/s. The average shear exponents represent a range of values that are representative of an offshore environment:

- 0.05: Extreme storm conditions, such as Nor'easters
- 0.08: Low end of mean annual offshore wind conditions
- 0.11: IEC-specified shear for extreme conditions for offshore wind turbines (IEC, 2009)
- 0.14: IEC-specified operational conditions for offshore wind turbines (IEC, 2009)
- 0.17: Mean annual near-shore wind conditions (high offshore value)

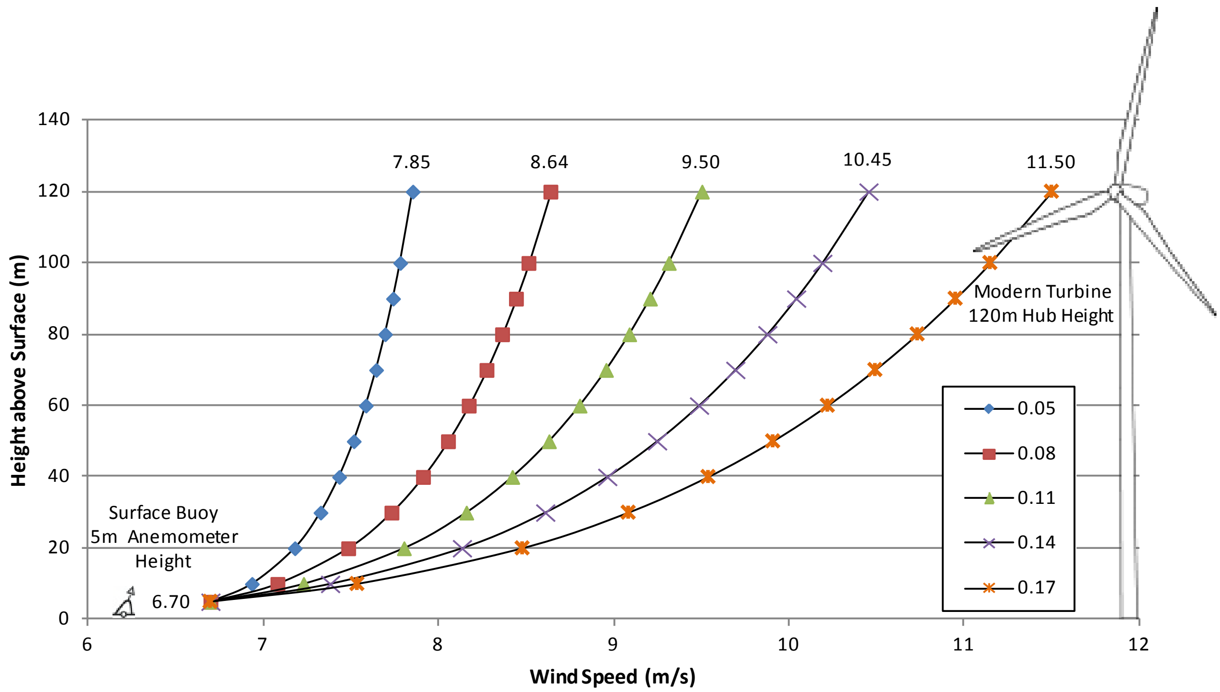

Figure A.1 Wind Speeds Extrapolated to Hub Height from Surface Measurements with the Power Law

Because the shear exponent that should be used cannot be precisely determined without directly measuring the shear, and the shear may also change with height, buoys or satellite-based estimates alone are insufficient for deriving reliable information about hub height wind conditions.

From a meteorology standpoint, offshore wind environments differ from onshore environments in a number of ways. One difference is that the surface roughness (which determines the drag exerted by the surface on the atmosphere) of open water is much smaller than that of most land surfaces. A typical roughness length assumed in numerical modeling for a 'wavy' surface is approximately 0.001 m, although the value varies with wave height and therefore with wind speed. In contrast, most land surfaces have a roughness ranging from 0.03 m to over 1.0 m (Stull, 1988). The low roughness of water means that the wind flow experiences less drag and thus averaged wind speeds tend to be higher than on land at similar elevations. Turbulence generated is generally lower as well, with higher levels of turbulence produced by higher waves (SethuRamen, 1979).

Another difference is that the daily cycle of surface temperature variation is usually attenuated offshore because water has a much greater heat capacity than soil and maintains a more constant temperature between night and day. This characteristic produces, in turn, smaller variations in atmospheric stability and wind shear. Atmospheric stability refers to the tendency for or against the vertical mixing of air due to temperature differences between an air parcel and its surroundings or between the lower atmosphere and the surface. Whereas on land, the mean wind speed can vary greatly between night and day, such patterns are not usually as evident offshore. In general, the average shear exponent is lower in tropical waters (0.07-0.10) than that in temperate and cold waters (0.10-0.15). This is because in the tropics, the water is warm and the atmosphere close to neutrally stable year-round. In colder climates, seasonal variations in the relative temperature of air and water modify the thermal stability and wind shear, producing periods of higher average shear.

Because of the lack of terrain, winds and other meteorological conditions tend to be more spatially uniform offshore, especially farther than around five kilometers from the land. This is fortunate for wind project development, as it means that fewer measurement stations are generally required to characterize the resource accurately within a project area. Even so, surprisingly complex wind phenomena can occur, as follows.

- **Mountain and island blocking.** Coastal mountains and islands can act as a barrier creating a zone of low wind speeds especially downwind but also upwind as the flow diverges around the obstacle. This effect can extend many kilometers offshore depending on the atmospheric conditions and the size of the barrier. Figure A.2 shows an example of blocking by mountains on the island of Maui, Hawaii.
- **Gap flows.** Similar to mountain passes on land, gaps between and around coastal mountains and islands can concentrate the wind and generate high wind speeds. Figure A.2 shows such channeling (in red) between the mountainous Hawaiian islands of Maui, Lanai, and Molokai. Note how the wind direction, indicated by the arrows, is deflected by high pressure on the upwind side and by low pressure on the lee side of the islands. Significantly reduced wind speeds caused by mountain blocking are evident in the blue and purple areas.

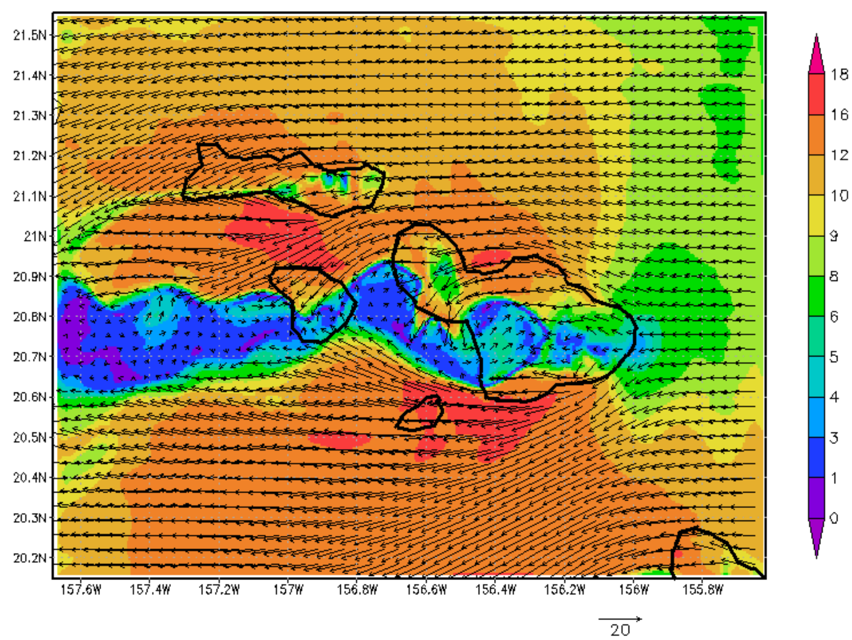

Figure A.2 Numerical Simulation of Wind Speeds (m/s) and Directions at 80 m Height Around the Islands of Maui, Lanai, and Molokai.
(Source: AWS Truepower)

- **Coastal barrier jets.** When synoptic conditions favor a flow more or less along the coastline, the terrain elevation and surface roughness on land can act to concentrate the flow and create a low-level jet with high wind speeds. Figure A.3 shows a numerical simulation and a synthetic aperture radar image of such a jet (at 10 m above the surface) off the north shore of the St. Lawrence River in Canada.

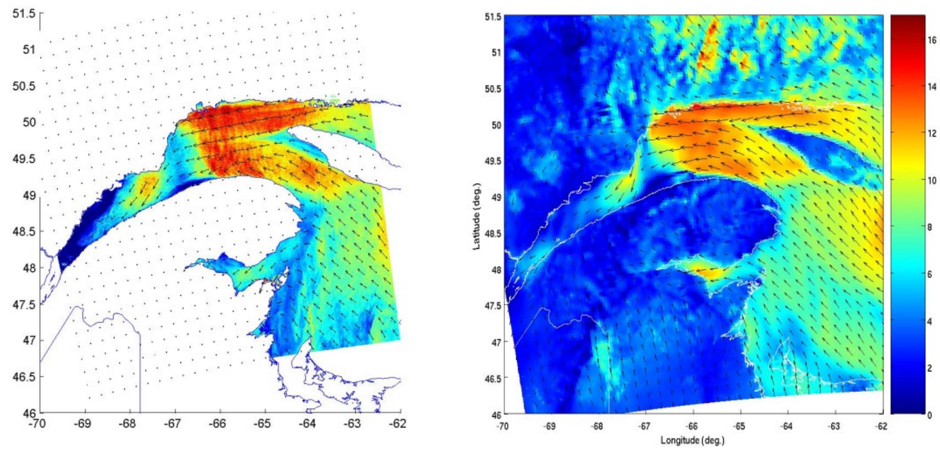

Figure A.3 Synthetic Aperture Radar Image from the Radarsat-1 Satellite (*left*) and Numerical Simulation from the MC2 model (*right*).
(Beaucage et al. 2007)

- **Roughness transitions.** When the wind comes off land, the abrupt decrease in roughness generates a zone of gradually increasing wind speed near the surface, called an internal boundary layer (IBL, yellow line), whose depth grows with distance offshore (Figure A.4). Above this IBL, the original wind profile is unaffected. Depending on the wind direction, distance from shore, and rate of growth of the IBL, the transition may occur either above or below the hub height of the turbines in an offshore wind project.

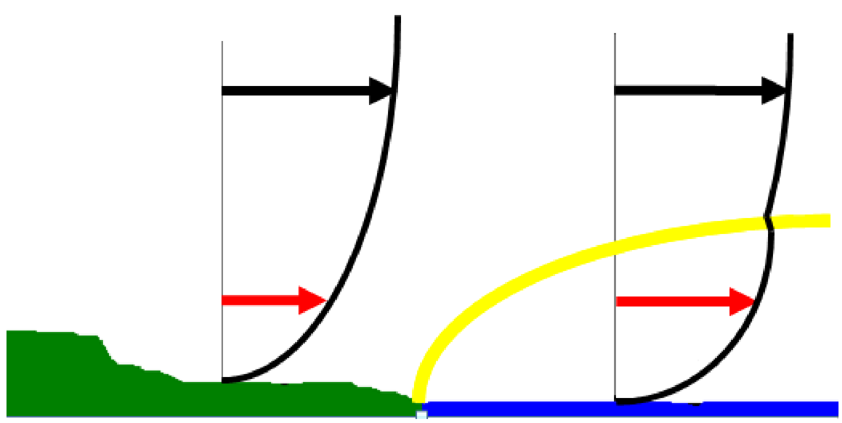

Figure A.4 Schematic Representation of the Evolution of a Wind Speed Profile as the Wind Moves off the Land over Water (from left to right).
(Source: AWS Truepower)

- **Stability transitions.** In addition to a decrease in roughness, wind coming off the land can sometimes encounter a large difference in surface temperature, which produces changes in the atmospheric stability. For example, if warm air moves over cooler water, as might occur on summer days in middle and upper latitudes, the lower portion of the boundary layer becomes thermally stable. This can cause winds in the upper portion of the boundary layer to decouple from the surface layer, allowing strong winds to build at heights near and above the hub heights of wind turbines. This same phenomena is seen over land, where it contributes to the formation of the low level jet.

- **Mesoscale circulations.** Surface temperature and moisture gradients can create mesoscale wind circulations. A classic example of a temperature-driven circulation is a sea or lake breeze (Figure A.5). On a typical summer day, as the sun heats the land surface, the air above it tends to warm and rise, causing relatively cool, moist air to be pulled in from over the water. (The opposite circulation – a land breeze – can occur at night as the land cools, but it is usually less pronounced.) In the absence of a strong background synoptic wind, a sea breeze front can progress as much as 50 km inland from the coastline (Stull 1988).

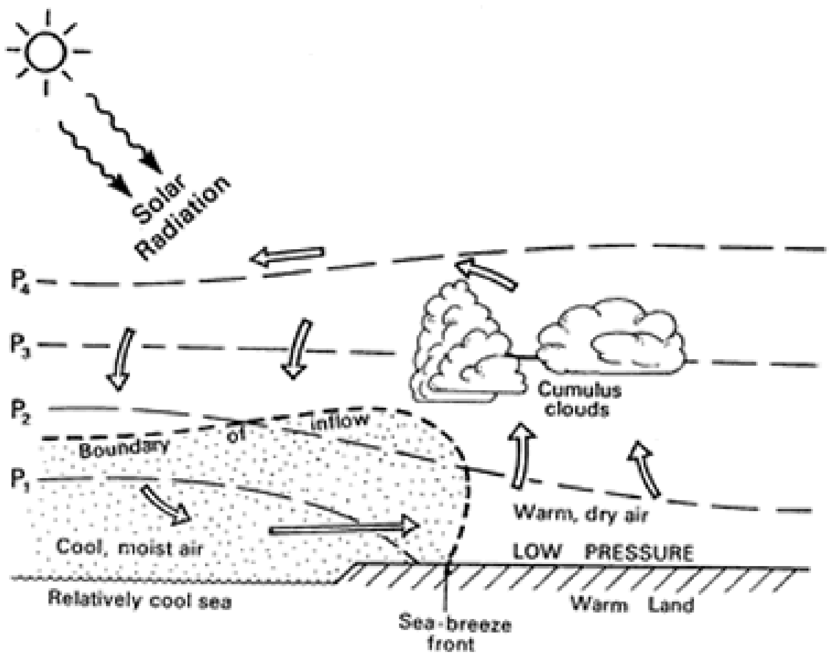

Figure A.5 A Schematic Representation of a Sea Breeze Circulation.
(Source: http://www.rmets.org/activities/schools/local_winds.php#sea)

When the large-scale flow reinforces the sea-breeze circulation, it can create a high-speed, low-level jet. Research suggests, for example, that such a jet appears off the coasts of New York and New Jersey periodically during the warm season (Colle and Novak 2010). Figure A.6 illustrates this phenomenon from a numerical simulation of a composite of 40 summer days at 4 pm local time. The simulation shows that when such jets form, wind speeds above 10 m/s can extend from about 50 m to 300 m in height from near the coast up to several tens of kilometers offshore. The large zone of intense winds that is formed could benefit offshore wind energy production.

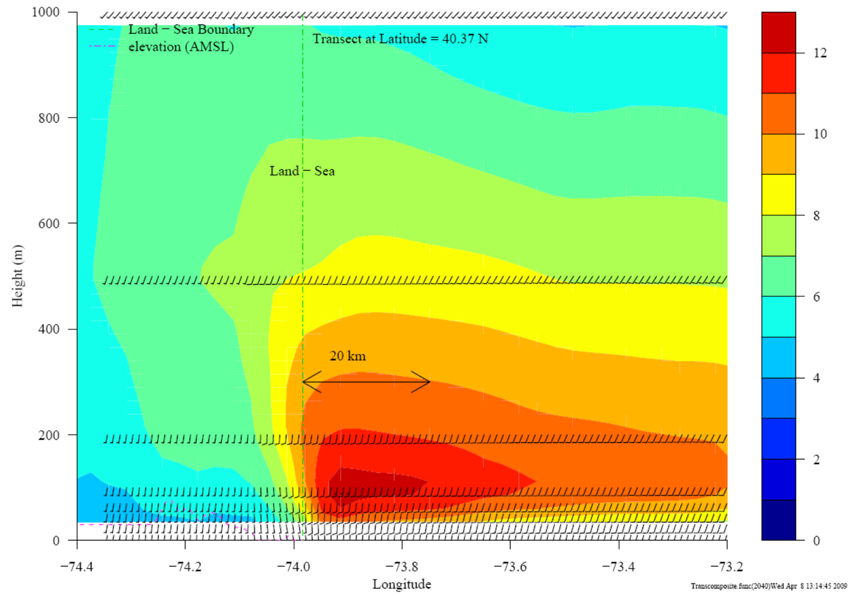

Figure A.6 A Cross-Section of Mean Wind Speeds in m/s as a Function of Height (vertical axis) and Longitude (horizontal axis) off the New Jersey Coast.

(Source: Freedman, et al. 2010)

Average wind conditions in offshore areas of the United States are expected to be significantly stronger than conditions over adjacent land areas. Figure A.7 maps the estimated wind resource at 100 m above the surface for the entire country, including up to 90 km from shore. This analysis was produced jointly by NREL and AWS Truepower using atmospheric modeling techniques and a bias correction methodology using over 1000 validation points (NREL, 2010). The estimated standard error for modeled offshore average wind speeds is approximately 5-7%. More observations of offshore wind conditions, particularly at multiple heights including near 100 m, would not only improve the accuracy of average wind speed estimation, but would also provide more insights into the time and height varying aspects of the wind resource within the swept area of wind turbine rotors.

A close examination of the map indicates that offshore wind speeds near most of the country's shores rival and even exceeds those found in the windiest central portions of the nation. Along the eastern seaboard at a distance of roughly 30 km from shore, speeds at 100 m estimated to average between 9.0 and 10.0 m/s from Maine to New York, 8.0-9.0 m/s from New Jersey to North Carolina, 7.0-8.0 m/s along South Carolina and Georgia, and 6.5-7.5 m/s along Florida's east coast. In the Gulf of Mexico, average speeds of 6.0-7.0 m/s at the same height and distance from shore prevail from the west coast of Florida to Mississippi. Higher speeds of 7.0-8.0 m/s are found from Louisiana to the central coast of Texas, with even higher values (8.0-9.0 m/s) along south Texas. Within the US waters of the Great Lakes, speeds annually average from 7.5 m/s to 9.0 m/s in most areas.

Along the Pacific Coast, the strongest winds are found from northern California to Oregon, averaging 8.0-10.0 m/s. Somewhat lower speeds—7.0-9.0 m/s—are anticipated along Washington State and mid-California. The lowest speeds—4.0-6.0 m/s—are off the coast of extreme Southern California. Alaska's offshore winds are generally in the 8.0-10.0 m/s range, with stronger winds along the Aleutian Island chain. The trade wind regime of Hawaii delivers speeds of 8.0-10.0 m/s and higher to the north and south of each island; winds are significantly lighter to the east of west of the islands.

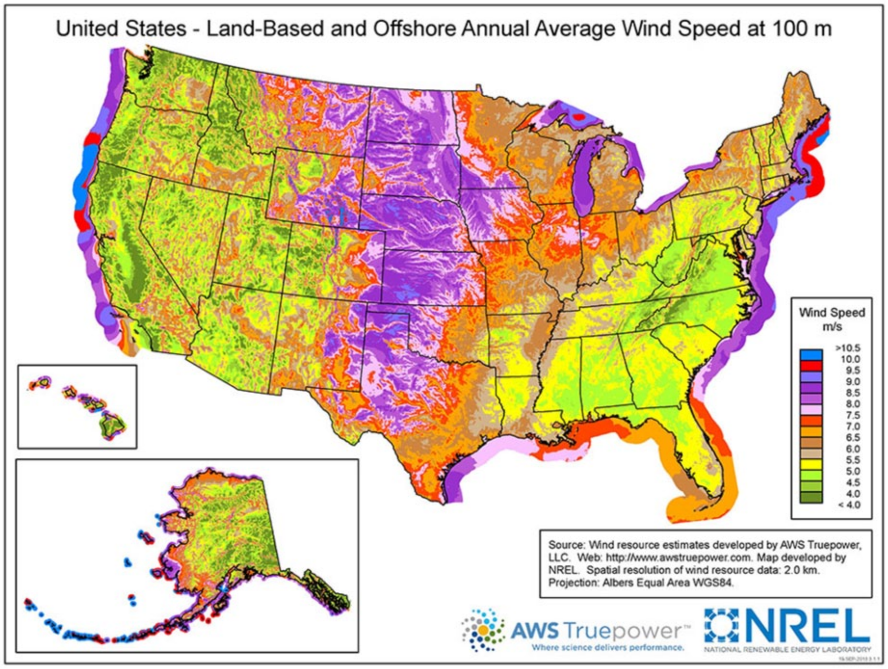

Figure A.7 Annual Average U.S. Wind Speed at 100 m above the Surface, Land-Based and Offshore

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