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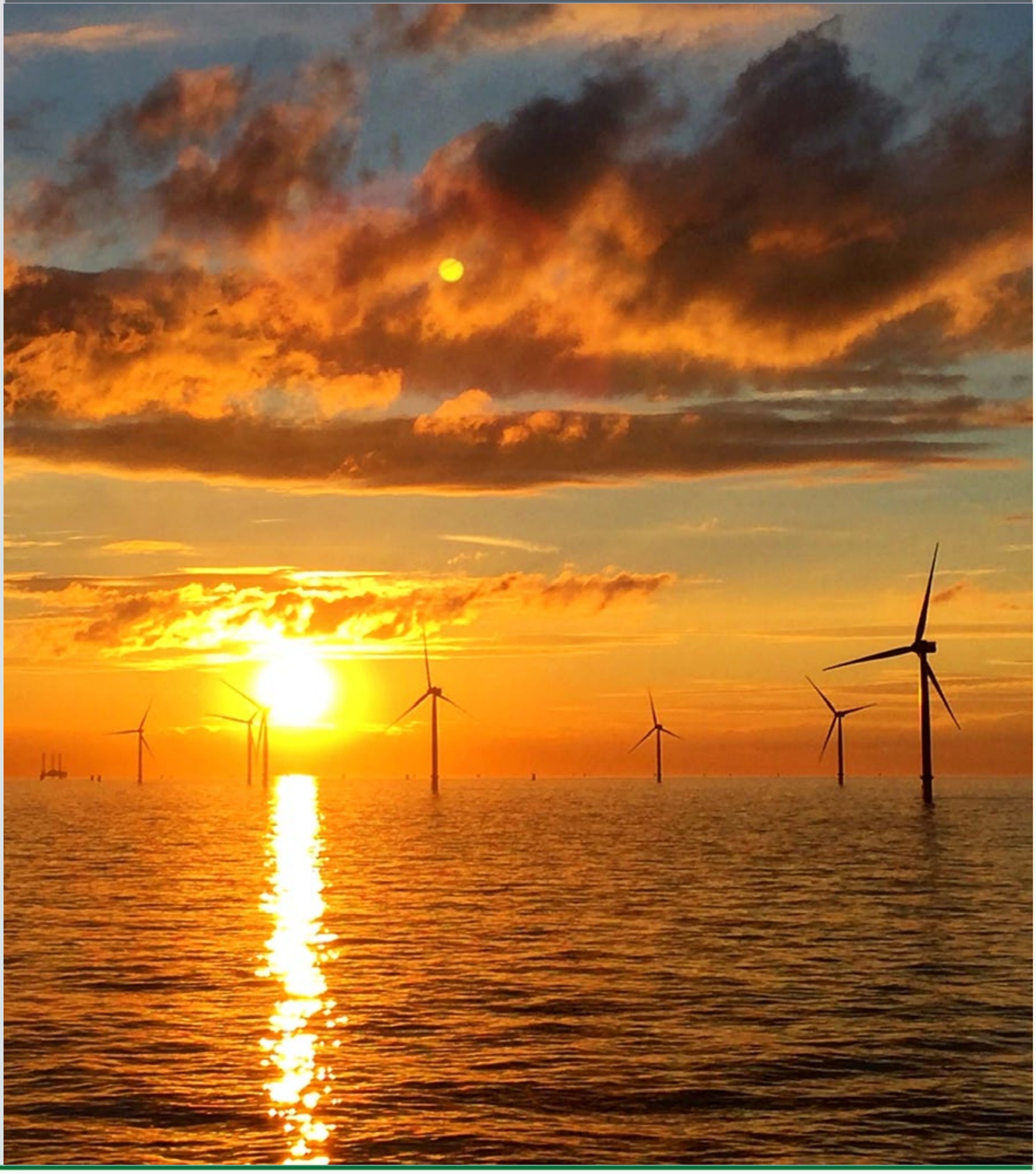
RENEWABLE ENERGY

Workshop on Research Needs for Offshore Wind Resource Characterization

Summary Report

October 2019



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Cover photo was provided by Siemens Gamesa Renewable Energy.

Nomenclature or List of Acronyms

ABL	atmospheric boundary layer
BOEM	Bureau of Ocean Energy Management
CFARS	Consortium for Advancement of Remote Sensing
CFD	Computational Fluid Dynamics
DIAL	differential absorption lidar
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DTU	Technical University of Denmark
ENSO	El-Nino Southern Oscillation
ERCOT	Electric Reliability Council of Texas
HPC	high-performance computing
HRRR	high-resolution rapid refresh
IEC	International Electrotechnical Commission
IFORM	Inverse-First Order Reliability Method
m	meter
MBL	marine boundary layer
MHK	marine hydrokinetic systems
MOST	Monin-Obukhov Similarity Theory
NOAA	National Oceanic and Atmospheric Administration
NREL	DOE’s National Renewable Energy Laboratory
NWP	numerical weather prediction
NYSERDA	New York State Research and Development Authority
O&M	operation and maintenance
OCS	Outer Continental Shelf
PNNL	DOE’s Pacific Northwest National Laboratory
R&D	research and development
RANS	Reynolds-Averaged Navier-Stokes
RAP	rapid refresh
s	second
SAR	synthetic aperture radar
SWAN	Simulating WAves Nearshore
TKE	turbulence kinetic energy
TI	turbulence intensity

UAV	unmanned aerial vehicle
UV	ultraviolet
WRF	Weather Research and Forecasting

Executive Summary

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy's Wind Energy Technologies Office convened "Research Needs for Offshore Wind Resource Characterization," a workshop in Alexandria, Virginia, on March 5–6, 2019. Wind resource characterization includes meteorological information to estimate annual energy production, forecasts to ensure economical and reliable wind energy integration, and turbulence characterization for developing and applying design load criteria. The purpose of the workshop was to bring together representatives from the offshore wind industry and marine environmental research community to share views on meteorological and oceanographic information needed to successfully develop offshore wind projects in the United States. It was also intended to identify current industry knowledge gaps that can be effectively addressed by researchers with current and emerging observational and modeling tools. The workshop was in response to one of the key challenges articulated in the National Offshore Wind Strategy: reducing costs and technology risks through improved offshore wind power resource and site characterization. The strategy noted that "a better understanding of the unique meteorological, ocean, and seafloor conditions across U.S. offshore wind development sites will allow for optimized designs, reduced capital costs, greater safety, and less uncertainty in preconstruction energy estimates, resulting in reduced financing costs." The workshop built on the National Offshore Wind Strategy, as well as previous workshops and reports that have informed this research area, providing the basis for future investment in offshore resource characterization research.

The 1.5-day workshop involved 55 participants with comparable numbers of representatives from industry, academia, national laboratories, and federal agencies. The meeting included a small number of participants from Europe. The structure was to seed discussions with presentations by national and international leaders in their respective disciplines, followed by discussion among all participants. Discussion began with current industry needs and gaps for metocean information from the European perspective as well as considering unique aspects of the U.S. offshore environment. Those topics were followed by discussion of information needs specifically to address offshore wind system design requirements. These sessions provided the context for the third primary area of discussion, which was current capabilities and challenges for the research community in providing the needed information. Participants noted several significant gaps in the current ability to observe the atmosphere and ocean offshore, which provides an opportunity to develop new instrumentation. Key scientific challenges articulated in the discussions were:

- *Stably stratified atmospheric conditions*: It is important to account for atmospheric stability in models for wind energy forecasting. However, when the stratification is stable, internal boundary layers and other complicated layering can occur, and these phenomena are not well accounted for in current model physics.
- *Depth of the marine atmospheric boundary layer*: Many model calculations depend on this variable, and it is likely not correctly calculated, especially under stable conditions. Improvements in our ability to measure boundary layer height offshore will be needed to address this issue.
- *Depth and characteristics of the surface layer*: The assumptions behind current weather forecast model physics addressing this lowest layer of the atmospheric boundary layer are frequently not applicable offshore, and how the physics of the model can better describe more realistic offshore conditions is not well understood.
- *Wind shear across the rotor layer*: The area where the wind turbine rotor operates is subject to coastal circulations such as low-level jets, which can generate substantial variation of wind speed with height (shear) through mechanisms that are not captured well in current models. Evaluating and improving model performance for these effects is needed.
- *Fully coupled wind-wave-wake models*: Contemporary wind models typically use wave forecasts or some other source to prescribe the lower boundary for atmospheric models offshore. In general, there is feedback between the winds and the waves. In other words, winds drive wave development and the wave

roughness controls the change of wind with height through friction. In current practice, there is typically no coupling between winds from resource characterization models and the waves. Adding algorithms to provide this coupling is expected to significantly improve wind modeling offshore. This will be needed, for example, to address engineering information when winds and waves are moving in different directions. These models will ultimately need to include coupling with wake models both for more accurate wake generation and to assess impacts that plant wakes may have on the wave field itself.

This input will inform DOE, other state and federal agencies, research institutions, and industry stakeholders in making decisions about potential research and development (R&D) efforts supporting the development of offshore wind energy in the United States.

Table of Contents

List of Figures

1 Introduction

1.1 Motivation

The U.S. Department of Energy (DOE) convened the "Research Needs for Offshore Wind Resource Characterization" workshop in Alexandria, Virginia, on March 5–6, 2019. The purpose of the workshop was to bring together representatives of the offshore wind industry and marine environmental research community to share views on meteorological and oceanographic (also known as metocean) information needed to successfully develop offshore wind projects in the United States. It was also intended to identify current industry knowledge gaps that can be effectively addressed by researchers with current and emerging observational and modeling tools. This input will inform DOE, other state and federal agencies, research institutions, and industry stakeholders in making decisions about potential research and development (R&D) efforts supporting the development of offshore wind energy in the United States.

The workshop was held in response to one of the key challenges articulated in the National Offshore Wind Strategy: reducing costs and technology risks through improved offshore wind power resource and site characterization (Gilman et al. 2016; also see Appendix B1). The strategy noted that "a better understanding of the unique meteorological, ocean, and seafloor conditions across U.S. offshore wind development sites will allow for optimized designs, reduced capital costs, greater safety, and less uncertainty in preconstruction energy estimates, resulting in reduced financing costs." The workshop built on the National Offshore Wind Strategy, as well as previous workshops and reports that have informed this area, and it provides context for future government investment in offshore resource characterization.

About this Report

This report is an account of presentations and discussions that occurred during the Workshop on Research Needs for Offshore Wind Resource Characterization in Alexandria, Virginia on March 5–6, 2019. The workshop was organized by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy's Wind Energy Technologies Office, who was the facilitator. The report was prepared by DOE's Pacific Northwest National Laboratory with contributions from Argonne National Laboratory, Lawrence Livermore National Laboratory, and the National Renewable Energy Laboratory. The speakers' comments and viewpoints offered in open discussion have been captured to the best abilities of the authors, who take full responsibility for any mischaracterization or inaccuracies.

Facilitated by representatives from DOE's Argonne National Laboratory, Lawrence Livermore National Laboratory, the National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory (PNNL), the workshop focused on the following four sessions:

- Session 1: Industry Requirements for Offshore Wind Information
- Session 2: Metocean Information for Loads Engineering
- Session 3: Current State of Offshore Modeling and Observations
- Session 4: Needs for Metocean Information Improvement

The topical order of the sessions was intended to begin with an opportunity for the wind industry and structural engineers to articulate their views regarding key metocean information needed to successfully develop and operate wind plants offshore in the United States. The discussion then moved to an assessment of the current availability of that information as well as information that is available but potentially underused. The workshop concluded with a focus on metocean information gaps and what R&D is needed to fill them. This discussion was framed with the following overarching questions for the workshop:

- What metocean information does industry need to more cost-effectively develop offshore wind energy in the United States?
    - Of this information, what is satisfactorily available in the United States from modeling or observations? What gaps have been filled in the last five years?

  - What metocean information is uniquely needed for structural engineering offshore?
  - What information is needed to inform standards, including for conditions unique to the United States?
  - What currently lacking information would be most valuable if it were readily available?
- What is the capability of current science to provide the metocean information needed by the offshore wind industry?
  - What variables can we currently observe directly or infer from analyzing observations? Where are the gaps?
  - What can we currently effectively simulate with numerical models? Where do errors arise?
  - What is needed to bring modeling and observations to the point of providing the metocean information that industry needs?

In order to stimulate subsequent group discussion, the first three sessions each began with one or two keynote talks by recognized leaders in the topic area, focused on how specific knowledge is applied and what gaps exist. For Session 1, Charlotte Hasager of the Technical University of Denmark (DTU) and Michael Drunsic of WSP provided an overview of the needs of offshore wind project developers and operators (slides available in Appendix C1–2). In Session 2, Amy Robertson of NREL provided an overview of key inputs needed for the design of offshore wind systems (Appendix C3). In Session 3, James Edson of Woods Hole Oceanographic Institution and David Turner of the National Oceanic and Atmospheric Administration (NOAA) provided perspectives on the current capabilities for modeling and measuring the metocean environment together with directions ripe for additional progress (Appendix C4–5). Session 4 was a general discussion that focused on identifying the most promising opportunities for improving and expanding metocean information within the context of the deployment of U.S. offshore wind energy.

1.2 Attendee Demographics

Participation in the workshop was by invitation with the objective of engaging representatives of the offshore wind industry, federal agencies, national laboratories, and the academic research community in comparable numbers. In addition, several participants with experience in offshore wind energy in Europe were also invited. The workshop drew a total of 55 participants. In addition, one industry invitee was unable to send a representative to the workshop but did provide questions and comments ahead of time that informed some of the discussion. The distribution of participants is shown in Figure 1.

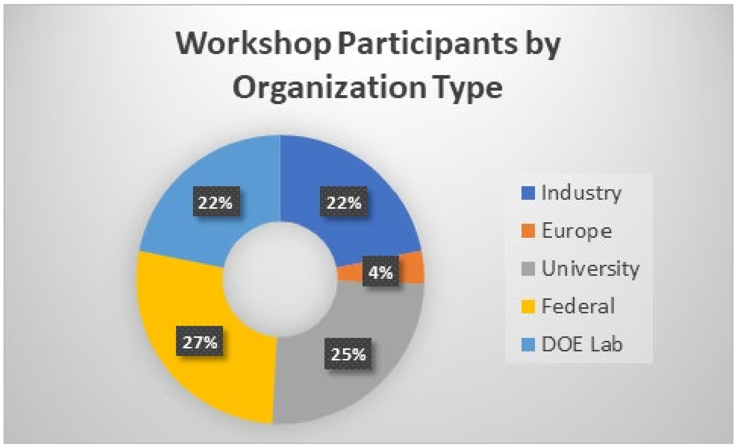

Figure 1. Distribution of workshop participants by organization type.

2 Session 1: Industry Perspective on Metocean Information Needs

The first session of the workshop focused on determining industry requirements for offshore metocean information. Charlotte Hasager from DTU Wind Energy offered a European perspective (presentation available in Appendix C1), and Michael Drunsic from WSP USA presented a U.S. perspective (Appendix C2), stimulating a one-hour discussion on industry needs regarding metocean information to more cost-effectively develop offshore wind energy.

2.1 European Perspective on Metocean Requirements

2.1.1 Wind Farm Wake and Clusters

Offshore wind plant wakes and their impact on clusters of offshore wind plants are a continuing topic of research. Illustrations of the impact of wind plants on the downstream atmosphere were provided in the form of fog clearing behind the wind plant due to entrainment of dry air from the top of the boundary layer (Figure 2, Hasager et al. 2017). This was modeled by the Weather Research and Forecasting (WRF) model, and cluster effects (impacts of one wind plant's wake on others nearby) can also be seen on synthetic aperture radar (SAR) imagery.

To successfully model wakes from large offshore wind plants, it is important to use a wake model that includes the superposition of wakes and accounts for atmospheric stability. One such wake model is Fuga (Ott and Nielsen 2014). In thermodynamically stable conditions, turbulence is rather low, and wake deficits can be observed up to 10 miles downwind of a wind plant. In unstable conditions, however, wakes dissipate much faster and are observed only to about 3 miles downwind.

Figure 2. Photograph of Horns Rev. 2 wind plant from January 25, 2016, showing individual wind turbine wakes delineated in the fog with clearing in the overall plant wake downwind of the wind plant. Photo by Bel Air Aviation Denmark–Helicopter Services.

2.1.2 Wind-Wave Coupled Models

DTU uses wind-wave-wake coupled models that take into account the dynamic relationship between wind, wave, ocean, and wind plant wakes (Volker et al. 2015; Du et al. 2017; Larsén et al. 2017; Larsén et al. 2019). Coupled WRF-SWAN (Simulating WAves Nearshore) simulations remove the need for a roughness parameterization. These coupled models can be used to forecast metocean conditions, assess the wind resource assessment while accounting for plant wake effects, operate and maintain offshore wind plants, and obtain key design parameters such as extreme winds and waves. It was found that using a wave model (SWAN) affects winds at hub height, and this was important and most accurate for 50-year extreme events. SWAN seems to have problems in coastal zones, and this is also the area where higher resolution is needed in models due to pronounced gradients in wind speed.

2.1.3 Leading Edge Blade Erosion

A topic that led to an active discussion was the impact of precipitation on leading-edge erosion of turbine blades. Erosion damage is mainly generated during heavy precipitation with big drops or hail, which is relatively rare in northern Europe. Larger drops, with their higher fall speeds, do more damage, and these may be more common in the United States. By reducing the tip speed of the blades during the hours of such precipitation, however, the leading-edge lifetime can be significantly extended with limited loss of energy production (Bech et al. 2018).[1] Control strategies to slow down the blades have shown to decrease the loss of

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[1] www.rain-erosion.dk

income due to erosion, inspection, and repair. The Bech et al. study was focused on extending lifetime, and energy yield assessments were not considered.

There are many sources of blade degradation besides precipitation, e.g., sea salt, ultraviolet (UV) radiation, and temperature variations. Once there is a crack, sea salt gets into the structure and causes corrosion of turbines. Discussion indicated that with appropriate coating of the blades, erosion could be minimized or potentially eliminated. This raised the question of whether the industry needs better damage models for blade lifespan/performance. Power production typically declines about 2% when the blade is damaged (Ehrmann and White 2014). This is more of an issue in an offshore environment because of difficulties in maintenance.

2.1.4 Spatial Wind Speed Gradients

A major need for offshore development is to characterize gradients in mean winds with distance from shore. Satellite SAR wind maps are good at capturing coastal wind speed gradients and power production and at quantifying offshore wind resources (Ahsbahs et al. 2018). Such observations have been used in a project involving NREL at potential wind plant locations on the U.S. East Coast, where they showed large departures from WIND Toolkit simulations. Errors in the WIND Toolkit (https://www.nrel.gov/grid/wind-toolkit.html) are indicative of errors in atmospheric models commonly used for wind resource characterization. SAR winds have been extrapolated from 10 m to hub height with a stability correction method (Badger et al. 2016). To validate satellite measurements, buoys providing surface wind measurements have been used on the U.S. East Coast and Europe, but tall meteorological masts and scanning lidars, which provide winds at hub heights, would be preferable. Lidar is a type of meteorological instrument that can measure wind speed, direction, shear, gusts and wake turbulence remotely with laser beams and represents an emerging alternative to conventional meteorological towers.

2.1.5 The New European Wind Atlas

For resource assessment and spatial planning, the New European Wind Atlas was developed with the goal of reducing overall uncertainties in determining wind conditions (http://www.neweuropeanwindatlas.eu). The atlas extends 100 km offshore with 30 minute temporal resolution and takes advantage of mesoscale models, satellite winds (Karagali et al. 2018), and measurements.

2.2 U.S. Industry Needs for Offshore Wind Information

Objectives for developers are to maximize revenue, minimize cost, enhance safety, and minimize environmental impact. To achieve this, they need to know:

- What are variations in the wind resource, average wind speeds, and ocean characteristics over time and across a development area?
- What design is suitable and cost effective?
- How will the project be constructed safely in regard to vessels, real time monitoring, forecasting?
- What operating strategy should be employed?
- What types of technologies are appropriate in a given area?
- How will metocean conditions affect operations and maintenance (O&M) activities, including project access, service operations vessels, and crew transportation operations?
- What are impacts of metocean conditions on the environment (water quality, marine traffic, safe passages for vessels)?

Metocean information is required over the whole lifecycle of a project (Figure 3). The more data a developer has access to, the less uncertain the project becomes. A metocean campaign is an iterative process and starts with planning in the early stages of a project.

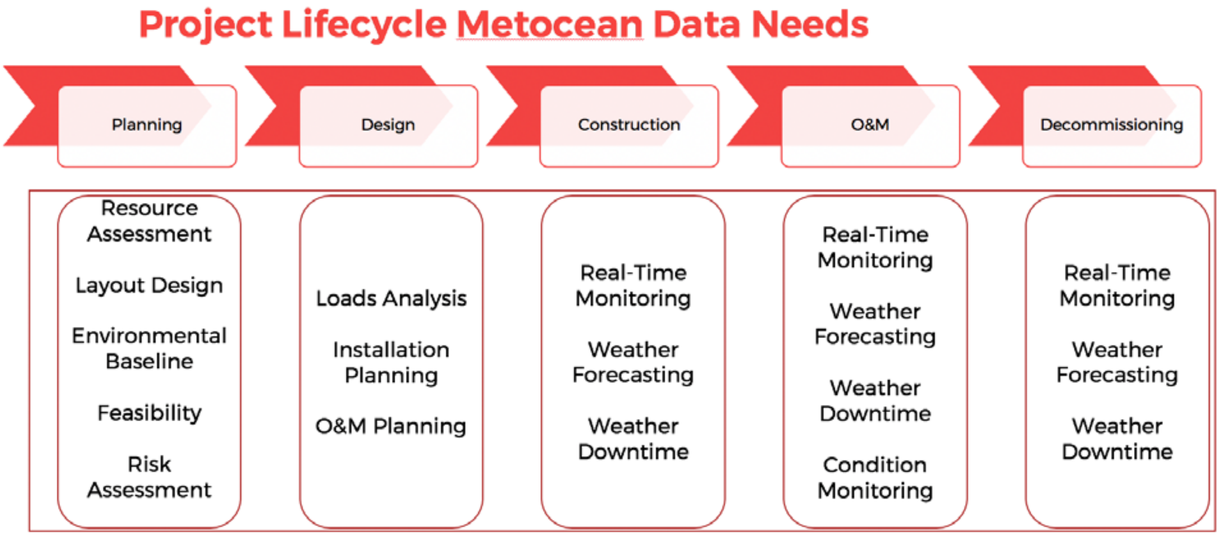

Figure 3. Metocean information that is required over the whole lifecycle of a project (source: Michael Drunsic).

2.2.1 Unique Weather Situations in the United States

In the United States, there is a limited amount of metocean data available, and the industry has limited offshore wind experience. At the same time, the industry must deal with unique coastal boundary layer complexities such as hurricanes, Nor'easters, sea breezes (Seroka et al. 2018), and low-level jets (Pichugina et al. 2015). Sea breezes are common, can increase temporal and spatial variability in power production, and are important for understanding time value of offshore wind power. For example, sea breeze events later in the day correspond to peak load. Hurricanes are the key design driver for certain locations, and research is needed to refine understanding of hurricanes. Hurricanes attract special attention with focus on developing 500-year events for robustness. Challenges with hurricanes include difficult overall risk assessments in hurricane-prone regions, breaking waves, joint wind-wave conditions (especially during wind/wave misalignments), and how long-term changes in weather patterns may affect the frequency and intensity of these storms. They become most critical south of Virginia, and strong seas due to hurricanes can weaken a structure's foundation for many days or a week prior to the actual arrival of a hurricane. Sometimes this preconditioning is followed by sudden wind shifts, which can cause failures. Nor'easters are similarly very strong storms, but they generally move through a given area quite quickly. Low-level jets pose challenges because they may influence loading and power production of turbines, and their observed shear profile varies significantly from modeled ones used for turbine design and estimates of annual energy production. The U.S. West Coast has a harsher wave climate, with large waves and long periods relative to the East Coast or Gulf of Mexico owing to the long Pacific Ocean fetch. Additional challenges include deep water, strong currents, and minimally-validated wind resource data.

2.2.2 Measurements

In situ measurements are critical both for wind resource assessment and for model validation. Lidars are becoming increasingly accepted by industry and are now de facto standards for offshore wind resource assessments (Carbon Trust 2016). Buoy-mounted lidar systems are dominating U.S. measurement campaigns. The Carbon Trust maintains a list of offshore lidar campaigns. Lidars are cheaper, more flexible, and easier and faster to deploy than fixed meteorological tower masts. Lidars can measure across the entire rotor area. Challenges with lidar data include limited validation opportunities, no established turbulence measurement methods, continuing evolution of the technology, and data scarcity above ~130 m. The need for scanning lidar data was highlighted because they are more reliable. The limited validation opportunities in the United States could be mitigated by using lidars that are calibrated in Europe. However, this might pose a problem if European validation conditions are significantly different from operational conditions in the United States. One suggestion was to collaborate with Asian developers, since there are strong similarities between the east Asian offshore environment and the U.S. East Coast. Longer term, national reference stations would provide significant value to the industry. Such a reference station could include a scanning lidar and should include a met mast. It was noted that scanning lidars are great research instruments, but they cannot be used alone at this point. It would be important to have at least one vertical lidar. Improving the lidar technology to measure at higher altitudes will be important.

Data sources beyond lidars and reference stations include publicly available data sets (NREL Wind Prospector (http://maps.nrel.gov/wind-prospector), MarineCadastre.gov, Northeast Ocean Data (https://www.northeastoceandata.org/), Mid-Atlantic Ocean Data Portal (http://portal.midatlanticocean.org/), and U.S. Met-Ocean Data Center for Offshore Renewable Energy (http://www.usmodcore.com/)), purchased hindcast data sets, in situ measurements (which are often proprietary), satellite observations, and numerical weather prediction forecasts (e.g., from the National Weather Service). Emerging instruments, such as drones or radar systems, might become a less expensive alternative. It was noted than an offshore met mast of 80–100 m costs around $10–20 million, and adding height adds dramatically to the cost. One possibility of extending the range of the measurements to hub height and beyond would be to incorporate remote sensing technology, such as lidars, on top of a shorter mast.

It would be advantageous if proprietary lidar data could be shared with research organizations or with other parties to quantify uncertainties, but this is difficult for companies due to confidentiality agreements. One idea was to share data through operational modeling efforts. Through a comparison between models and observations, results could be shown without making the data themselves public.

In order to capture all the types of data needed (listed below), one suggestion was to set up a chain of marine observing stations with a set of measurements for wind characterization, thermodynamic profiles, precipitation, and buoys. Ideally this would be deployed long-term to determine the offshore climate. Multiple sensors can take advantage of economies of scale, lowering the cost of each individual platform. Another suggestion was to revisit the POWER project, a DOE-funded study that offered advice on where to deploy measurements offshore (NOAA 2014). Finally, the New European Wind Atlas project leveraged “ships of opportunity” (i.e., operational ships), which were instrumented and provided data over a large area for an extended period.

2.2.3 Standards

Standards are currently being developed for measuring metocean/offshore conditions. A Recommended Practice is being developed under the American Wind Energy Association’s Offshore Wind Technical Advisory Panel, Metocean working group with the aim of providing guidance on metocean topics by consolidating information from various sources, including recent research. Existing international standards (e.g., from the International Electrotechnical Commission and International Standards Organization) provide guidance on data needs to develop and apply design standards. Guidance around measurements and modeling is being developed but is limited particularly in the characterization of tropical cyclone/hurricane conditions, ice conditions (especially relevant for the Great Lakes), and characterization of breaking waves. A challenge with standards is to provide sufficient guidance while not being overly prescriptive. Floating lidar guidance is available from The Carbon Trust (Carbon Trust OWA 2018b, a). A need was expressed for better data to inform design standards. The offshore wind energy community could also leverage other research and standards from civil engineering and structural reliability research such as the inverse first-order reliability method IFORM (Winterstein et al. 1994; Eckert-Gallup et al. 2014). Industry participants affirmed the usefulness of best practice documents and advised their continued development.

2.2.4 Modeling

During the discussion, participants noted that WRF models turbulence kinetic energy (TKE), but industry primarily uses turbulence intensity (TI). These quantities are not related to each other in any simple way.

Therefore, a way to extract TI from WRF is needed. In Europe, the available data sets enable an empirical mapping between the two variables, but in the United States more limited data increases the uncertainty. Floating lidars could potentially be used to get TI values, or research projects designed to find different approaches to quantify TI. In any case, offshore turbulence measurements are needed.

Participants reiterated that resource model validation is limited, due to measurements not being available in the United States. This validation is needed across various wave climates.

There was some discussion of atmospheric large-eddy simulation as a tool to simulate winds and turbulence in detail, but the method still faces issues with small-scale surface interactions.

2.2.5 Scales

There is a need to understand how wind varies from region to region and from site to site on a diurnal basis. Any anomalies are going to impact the grid. Grid management temporal resolutions should go down to 5 minutes; hourly data are not enough, especially for grid integration. For automatic generation control, the 1-minute scale is important. Also, rather large areas should be analyzed. The wind industry needs both forecasts and statistical analyses. For grid integration, spatial correlations of variables across scales are important.

2.2.6 Extreme Events

Information about the frequency of extreme events is needed, including the effects on their frequency due to changing weather patterns. Therefore, long periods of measurements are needed because the probability of capturing extreme events in short-duration measurement campaigns is small. But these extreme events can have a critical impact on the grid. For example, an unforecasted, rapid decrease in wind speed in the ERCOT (for Electric Reliability Council of Texas) area resulted in a rapid loss of power over the entire Texas wind generation area. An extreme event could be defined as the most unusual correlation profiles that can strongly impact the grid. It would be advantageous to come up with a terminology of extreme events that distinguishes between power generation extreme events and weather extreme events. One approach suggested for estimating extreme event probabilities is I-FORM (for Inverse First Order Reliability Method), described in Eckert-Gallup et al. (2014).

Based on discussion in Session 1, the information in Sections 2.2.7–2.2.9 is considered important for offshore wind energy development and operations:

2.2.7 Atmospheric Data Needs

Key information needed by industry about the atmosphere as articulated in Session 1 is summarized below.

- Thermodynamic and dynamic profiles (profiles of air temperature, sea temperature, relative humidity, vector wind velocity) are needed, ideally at 20 m vertical resolution from near the surface to above the rotor layer (and ideally higher), to indicate stability and potential stability changes. Wind shear is important for design standards. In the last 5 years, a buoy-based thermodynamic profile was developed that can identify icing conditions. Air temperatures correlated with wind conditions are important for assessments of wind turbine performance.

- Cloud top cooling information is needed for accurate boundary modeling.

- To study wakes, aircraft data could be useful if the inversion height can be correctly captured by aircraft. If the inversion height is above the rotor, different types of wakes will be captured.

- Data on ancillary parameters are needed for operational strategies, including: precipitation, lightning, hail, rain drop sizes and intensity, fall speed of hydrometeors, how far thunderstorms reach offshore, visibility and ceiling height for birds and bats, and solar radiation. As of the time of the workshop, these were not readily available through modeling or observations.

- Information about ice spray and sea ice is needed.
- For standards processes, it would be useful to better understand coherence across the rotor disk and the true wind spectra. Coherence is useful for blade design and can help with assumptions for design load cases. Turbulence can be measured on buoys with sonic anemometers.
- Profiles of turbulence shear stresses through the entire atmospheric boundary layer (ABL) are needed.
- Horizontal variability of wind speeds over an area is needed to successfully analyze coastal gradients in wind speed. It is currently not clear how well these gradients are simulated nor is the best way to measure them settled. Effective measurement will likely require some combination of scanning and buoy-based radar and lidar remote sensing systems.
- Measurements above and in the water should be combined. For example, underwater cold pools can well up and influence sea breezes. They could be altered by offshore wind plants due to increased ocean mixing and could affect marine biology and fisheries.
- More measurements of fluxes and variances, including profiles of turbulence shear stresses throughout the entire ABL, are needed to validate models.
- It would be advantageous for industry to have access to a national map of design applications (such as design of blade, turbine, or support structures) that map the conditions of waves and wind. Such a map would use simulations of long-term conditions, and extreme conditions.
- Industry needs long-term statistics as well as forecasts.
- Recognizing the challenge of making observations in the marine environment, research should prioritize developments that reduce cost of measurements and increase confidence in measurements.

2.2.8 Ocean Data Needs

Key information needed by industry about the ocean as articulated in Session 1 is summarized below.

- Thermodynamic profiles are also needed in the ocean.
- Wave, tidal, and current conditions are required for design, installation, and O&M.
- Wind–wave correlation is important during operational conditions for monopile design.
- Downward-looking microwave radars could be used to measure the wave profile (steepness, breaking waves). This is important to determine when the wave strikes the foundation, and to assess the survival of structures to different types of breaking waves. This could be supplemented with time series capabilities, using cameras for example.
- Information is needed down to the mud line, for example regarding currents.

2.2.9 Uncertainty

Undefined or large uncertainty in measurements and estimates of the wind resource lowers the value of the measurements or estimates to utilities. The key motivation for reducing uncertainty is to make sure that designs are sufficiently robust and that enough conservatism is available so that projects can be approved. Quantification and reduction of uncertainty represents a significant opportunity to reduce costs. Ultimately, the ratepayers and wind project developers absorb the costs of increased risk and uncertainty. Turbulence is a key factor in risk that could be used to reduce costs. Having good estimates of uncertainty is important to understand how conservative industry can be in their estimates. Different types of uncertainty should be considered such as uncertainties of events or phenomena or uncertainties of the duration of the events. This is another argument for long-term measurements to capture unusual combinations of events in different areas. In general, being able to instrument an area prior to development can reduce uncertainty. We could also utilize high-performance computing (HPC) to examine hurricane statistics to improve our baseline. Synthetic hurricane simulations (e.g., 10,000-year simulations) could be undertaken to cover tails of distributions.

3 Session 2: Information Needs for Engineering

The second session of the workshop addressed the gaps in measurements, understanding, and modeling tools related to the task of erecting turbines and their support structures in the offshore environment, emphasizing characteristics of relevance to the stress and fatigue loads, from the perspective of wind power plant design, construction, and maintenance. Amy Robertson from NREL initiated the session with an overview of existing techniques and standards, followed by a list of challenges and major knowledge gaps. Her presentation (Appendix C3) was followed by a group discussion.

While generic offshore wind energy issues were included for completeness, special emphasis was given both to issues still plaguing the European industry and to characteristics differentiating the U.S. offshore environments from those of northern Europe, where technologies have matured over recent decades. Particular concern was given to severe storms common in the U.S. East and Gulf Coast regions, as well as the deeper waters off the U.S. West Coast, which will require novel platform architectures.

The presentation began with a description of current International Electrotechnical Commission (IEC) standards, which presently exist for both turbines and fixed-bottom platforms in the offshore environment. Standards for floating systems are still pending. Key design parameters required to satisfy the standards include both the usual atmospheric parameters required on land as well as several sea state parameters, as described below.

Atmospheric parameters of relevance include those defining the wind speed, direction, turbulence, shear, and gustiness. Wind speed parameters include annual average hub height wind speed and its temporal distribution (Weibull or Rayleigh) including 1- and 50-year extreme values. Wind direction parameters include average inclined flow, temporal distribution (wind rose) and 1- and 50-year expected extreme direction change. Turbulence is characterized by the turbulence intensity as a function of wind speed. Shear information includes normal and extreme model parameters. Gusts are characterized in terms of extreme values (1-year and 50-year expected values) as well as coherence parameters, including those associated with direction changes. All of these atmospheric parameters are based upon ten-minute averages.

Sea state parameters of relevance include water level, wave state, current, and wind/wave joint information, as well as sea ice, sea floor, and marine growth information. Water level information includes both tidal parameters and expected 50-year storm surge extrema. Wave state information includes significant wave height (1- and 50-year expected values), peak period (1- and 50-year) and extreme crest (50-year), as well as parameters for spectra and breaking waves. Current information includes expected extreme values over 1 and 50 years. Wind/wave joint statistical information on wave height and peak period relative to wind speed and direction are also required. Sea ice information is also required where relevant. Sea floor and marine life information is required for support structures and cabling, including local and global scour and sea floor depth variability, as well as marine life profiles and thickness. Sea state parameters are based upon three-hour averages.

Standard measurement platforms in the offshore environment include NOAA buoys, which measure both wind speed and direction at 5 m above sea level, over 8-minute averages, and wave height, peak spectral period, and direction of the dominant period, over 20-minute averages. All data are reported hourly. Issues with these measurement platforms include the absence of many parameters required by the standards, measurement over different periods than required by the standards, and measurement of winds at a low altitude relative to the rotor swept area. Floating lidar buoys are an emerging technology that can provide wind speed and direction profiles across the rotor swept area (during most conditions) at the required averaging interval. However, their ability to measure turbulence and overall accuracy are not sufficiently characterized.

Additional atmosphere and sea state parameters beyond those described above have been identified as important to improve design and operation of offshore wind plants. For the atmosphere, these include atmospheric stability, which impacts distributions of wind speed, direction and turbulence, and gust information, including the time duration, shapes, and directions of gust features, ABL height, and seasonal variability of wind characteristics. Obtaining data sampled at least once per second and at a vertical resolution of 10 m throughout the ABL (up to 300 m) is an aspirational goal. Forward-looking lidars that could detect incoming flow and wave features could also be assets for controls and operations.

A recent NREL study (Robertson et al. 2019) of the impact of 18 different atmospheric flow parameters on 12 turbine load characteristics identified turbulence and shear to be the most important atmospheric parameters. A similar study is planned for the offshore environment, for which additional parameters of importance are hypothesized to include the depth dependence of current, more detailed information on marine growth, including thickness and density, and how growth impacts different underwater components. Measurements at more than one location are also required, such as to characterize bathymetry. Further joint probability information between wind and wave state was also identified.

Additional modeling areas were identified, including the need for validation data within an operating wind plant. Among the desired parameters are time-series data of extended atmospheric parameters (e.g., coherence) and measurements to provide correlations between metocean parameters and loads and wake behavior within and between wind turbines and wind plants. Modeling of wakes, plant layout, and control strategies, including those incorporating forward-looking wind and wave state measurements as well as forecasting products, would be useful.

Finally, better knowledge of extreme conditions is needed. Major concerns are hurricanes, which will require unique load cases that characterize wind direction information, including veer relative to hub height—calculated over 3-second to 1-minute intervals—and wave/surge characteristics. The hypothesis that extreme localized structures may dominate loading may require different gust prescriptions than the current IEC model. We also need additional knowledge about breaking wave characteristics and impacts, which will require load sensors and/or cameras, since wave elevation measurements may not be sufficient. Finally, we need better tools to estimate extremes that may not be captured within a given time-series of observations.

3.1 Discussion

The discussion following the presentation reiterated the extreme engineering conditions encountered in the offshore environment due to the combined effects of atmospheric and ocean parameters affecting plant design and construction. While important everywhere, the impacts of stress loading are magnified in the offshore environment due both to the additional issue of sea state parameters directly impacting support structures within the water, but also to the interaction of these features with the atmosphere generating additional sources of fatigue within the atmospheric flow (see Figure 4). Understanding and predicting both oceanic and atmospheric sources of fatigue loading are essential to designing and constructing wind plants that can operate reliably in offshore conditions.

The first issue brought up in the discussion was the representativeness of any given year relative to global atmospheric oscillations operating over intra-annual or longer timescales, such as the El-Nino Southern Oscillation (ENSO), which has an average occurrence of 4–7 years. A “table top statistical analysis” was identified as a gap. Statistics for longer-term oscillations might require consulting with reanalysis data, given that observations often do not extend for sufficient durations to capture ENSO and other cycles. Also, some locations exhibit stronger correlations (e.g., Texas and Canada) than others. PNNL performed a 32-year wave hindcast and saw correlation of wave height with El Nino index on the West Coast. Other oscillations, such as the Pacific Decadal and the Arctic Oscillation, are multidecadal in nature, Hence, they require even longer datasets to determine their impact on local wind resources on a given short duration measurement campaign.

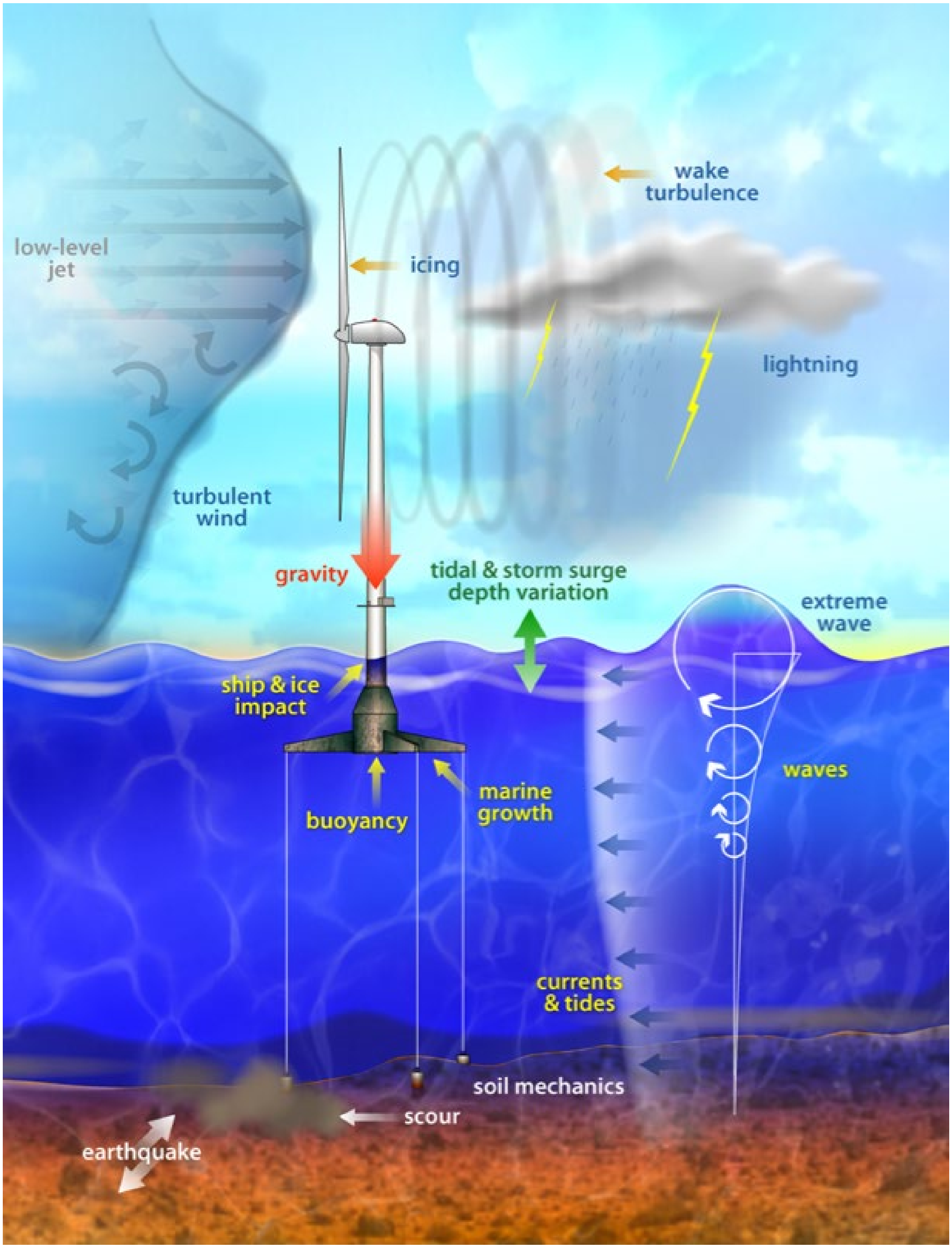

Figure 4. Depiction of the many metocean challenges facing offshore wind plant engineering. (Figure provided by NREL.)

It was also mentioned that real hurricanes do not maintain the symmetric shape depicted in the slide given by Dr. Robertson citing a study using an idealized hurricane in WRF (Worsnop et al. 2017). Not only will such symmetric hurricanes not occur near the U.S. East Coast, but in addition there will be sensible impacts on atmosphere and wave state emanating for 1000 miles in advance of the storm, and waves and swell may not match the wind and wave directions encountered during the passage of the storm.

Next was a discussion of sea state parameters. While much emphasis is given to wave state, current is also very important for sub-structure design, especially deep waters off Hawaii and California, for example. While current information is most critical in the upper ocean, information at depth is also useful. Bathymetry and soil conditions are likewise important, and even in shallow water heterogeneity is an issue for pile driving. While bathymetry and soil data are often fairly well characterized in areas of oil exploration, most other areas are relatively unknown. Salinity is also important. Subsurface information is needed all the way down into the mudline, perhaps 80–100 m below the sea floor, for moorings (perhaps not so deep for floating structures). While data below the sea surface are somewhat sparse in many areas, we do have technologies to measure these parameters. Reanalysis of ocean data may be helpful for some wave and current data; however, there is much uncertainty in those products, which is a challenge.

Many technologies presently exist to measure, monitor, and improve our understanding of surface waves, including downward-looking wave radars and microwave radiometers, which can estimate surface roughness. Cameras can also be useful; however, we are not sure how reliable cameras are in harsh environments, nor are we sure of their costs. The National Data Buoy Center often employs cameras that examine buoys and damage. Many of those buoys have accelerometers as well, which allow for measurement of swell and wave characteristics, so often 20-hertz data are readily and cheaply obtainable. Unfortunately, those data are usually discarded for storage reasons, but the raw data could be obtained and archived.

Some regional operational forecast products (e.g., from NOAA) have included a near-shore wave prediction system (using SWAN and WAVEWATCH-III models, which can also decompose the wave field into swell and wind-driven waves), for about the last 5 years. These products can be compared with buoys for validation and correlation. However, it is not known if those data have been archived. The community needs joint probabilities between atmospheric variables (winds and turbulence intensity) and waves, but that information is challenging to obtain. The Army Corps of Engineers field test facility at Duck, NC, is working on new lidar observational capabilities that can measure wave faces, for example, that may be of interest. Individual waves and their impacts on structures must be measured in order to validate models. However, we also want to know how those waves originate. Downward-looking radars and cameras could be effectively and inexpensively used together to obtain much useful information. The major question about the cameras is their durability. Will they survive hurricanes and exposure to salt water?

In lieu of observations, models can provide some ocean and wave parameters of interest. However, there are considerable uncertainties in models that the industry does not have a good handle on dealing with. There are many different models used by different customers for different needs. In the offshore environment there is the added risk that an extreme event could destroy a wind plant. There is thus also a need to distinguish between resource uncertainty and extreme event uncertainty. Some customers need long-term information about storms, waves, extreme winds and seas, etc. While models may be useful, in short, before we can trust the models, they must be validated.

Model validation and documentation are critically important to users. There is a lot of art to modeling, which is a barrier to adoption. New approaches require documentation on input, methods, validation, and calibration, so the models can be understood by third-party users. Industry is most comfortable with models that have been used a long time and improved on incrementally, rather than adopting wholly new approaches. There is room for innovation, but not for overly expensive processes that are not well validated or that industry does not have much experience with. Use of extensive lidar data for validating simulations can be found in the Consortium for Advancement of Remote Sensing (CFARS) working group.

Another need is simultaneous measurement of wave and platform or machine response, which will require coupling of cameras and sensors in the in situ environment. We often measure what happened, but we are not sure what caused it. An additional concern is that offshore wind turbines are different and bigger than land-based turbines and may be designed using criteria that were intended for land-based turbines. Turbine size itself could be a design condition.

There are still many gaps in wind-wave and fluid-structure interaction modeling. We know, for example, that well-quantified wave processes at relatively low wind speeds are not necessarily those that dominate wind-wave interactions at wind speeds of 25 m/s or more. Thus, modeling waves generated by high winds is considerably less certain. Such wind conditions would primarily affect structural loads, since the turbines would be shut down. Workshop participants shared several active programs in wind-wave research. Rutgers University is using WRF coupled with the Regional Ocean Modeling System. The National Center for Atmospheric Research has done simulations with one-way wave coupling where the wave state impacts turbulence and flow in the ABL. However, it is not known to what height the impacts extend, and how important the interactions are in higher wind conditions. Researchers at the University of Maine are investigating how winds and waves affect each other using joint observations of winds and waves together with spectral analysis. University of Maine data are available to researchers. The DOE-sponsored Exawind project is developing modern HPC tools at the national laboratories to simulate machine/fluid interactions; however, thus far these tools have only been able to simulate two machines in a volume of fluid, and even this simulation does not resolve all the important scales of the flow, use an appropriate turbulence model, or properly characterize the sea surface. Participants suggested that wind tunnel data may help with model validation, but there is a question of whether the results scale to the real ocean and atmosphere.

A final topic was how HPC-based, high-fidelity simulation tools being developed at universities and DOE’s National Laboratories can be useful to industry. Even though many of the cutting-edge models are not sufficiently developed or validated for widespread industry adoption, industry does rely heavily on those datasets and tools as they mature, and it is valuable for the research community to continue down that path. Developers will have add-ons for custom projects, but will continue to lean heavily on widely used, research-based models. Developers prefer an incremental approach to model development with lots of testing and validation.

High-performance computing is not a major barrier to industry on an individual task basis; however, utilization for a portfolio of projects, or across the United States on a national scale, is still out of reach. Industry recognizes that HPC-intensive tools and resulting datasets could inform lower order models that industry could use directly. The adoption of new techniques into the supply chain, including HPC, ultimately moves forward when banks are comfortable. The finance community looks to trusted advisors in industry engaging with the research community for validation of emerging techniques. Industry educates, but the banks have the last word. Lidars are an example of a technology that was slowly vetted via trusted advisers until it became bankable. A similar process is occurring now for floating lidars: confidence increases over time.

4 Session 3: Responses of the Scientific Community

The third session of the workshop was opened by Dave Turner (NOAA/Earth System Research Laboratory), summarizing the state-of-the-art of current metocean modeling capabilities (Appendix C4), followed by James Edson’s (Woods Hole Oceanographic Institution) summary of current metocean observational capabilities (Appendix C5). This was then followed by discussions with the goal to identify the largest observational and knowledge gaps driving the unresolved physics issues that affect the characteristics of winds and turbulence.

4.1 Current State-of-the-Art: Modeling

NOAA uses a unified modeling strategy for its operational weather forecasts. Currently, the Rapid Refresh (RAP) modeling system is used for short-term (out to 42 hours) weather forecasting. RAP is an hourly-updated assimilation and model forecast system that is run over North America at 13 km resolution (Benjamin et al. 2016) with a finer-resolution (3 km) High-Resolution RAP (HRRR) (Smith et al. 2008) nested model covering the conterminous United States. The RAP/HRRR models assimilate a wide range of observations and are initialized hourly to provide situational awareness and short-range forecasts.

RAP/HRRR models have previously been used in offshore wind evaluation efforts, demonstrating that the spatial patterns of mean annual 80-m wind agree well with previous studies (James et al. 2017). However, there are many unresolved physics issues challenging NOAA's and other numerical weather prediction (NWP) models that were discussed during the session and are summarized in Section 4.3.

4.2 Current State-of-the-Art: Observations

Numerous platforms have recently been developed and built to support instruments that characterize the offshore boundary layer. The measurement capabilities from such platforms include direct measurements of surface fluxes of momentum, heat, and moisture. Towers, unmanned aerial vehicles (UAVs), and remote sensing devices such as lidars are being used to measure profiles of mean wind speed, temperature, and turbulence. Integrated offshore networks of towers, buoys, and mobile assets are also being developed to provide the data required to improve numerical models and forecasts. Information needed for such improvements includes the following quantities and characteristics:

- Direct measurements via eddy correlation of momentum, heat, and moisture exchange from vessels in the marine surface layer. These are challenging because these measurements are affected by the motion of the platform. Platform motion data are needed to correct the measurements.

- Accurate parameterization of these surface fluxes, accounting for observed atmospheric stability, sea-state, and wave-age.

- Measurements of mean wind speed, temperature, and humidity profiles within the offshore boundary layer. The absence of remote sensing instrumentation for vertical profiling of temperature and humidity over the ocean is a major impediment. Although wind profiling instrumentation is more available than thermodynamic profiling systems, a challenge is that buoy systems generally do not have the power to penetrate through the surface layer for profiling through the marine boundary layer (MBL).

- Measurements of turbulence and turbulent fluxes throughout the depth of the offshore boundary layer.

- Measurements of wind-wave interaction in fetch- and depth-limited coastal environments.

- The depth of the marine atmospheric boundary layer, which is the continuously turbulent layer in contact with the ocean surface and which can be 1 km deep. This can be difficult to observe well. Devices such as ceilometers use vertical aerosol gradients, but these gradients are not always at the top of the layer. Thermodynamic profiling systems are useful, but they are rarely deployed over the ocean. The cessation of TKE typically marks the top of this layer, but TKE is difficult to observe well, especially over long observational periods.

- Technology to satisfactorily resolve vertical stratification in elevated layers using remote-sensing systems does not yet exist. Due to this limitation, current remote sensors are also unable to retrieve the thin, lower inversion layers that can strongly influence wind turbine wakes. Vertical resolution of a few tens of meters (20–30 m) is necessary for this purpose.

4.3 Key Science Challenges Discussion

Atmospheric stability: A recurring major theme throughout this session and the workshop in general were the unresolved physics questions around stably stratified conditions, when warm air masses advect over the cold ocean.

The need for a fully coupled wind-wave-wake model: Such coupled models that also account for wake effects are needed for forecasting metocean conditions and for wind resource assessment. A major challenge in this area is the model initialization near the shore. High-resolution observations near the coastal zone are necessary to initialize and constrain these models. However, the continental shelves are currently a source of observational gaps as autonomous platforms cannot operate effectively in shallow waters near the shore.

Wind plant wakes: Each wind turbine has a narrow and distinct wake in stable conditions, with the wake deficit extending up to 15 km downwind. For unstable conditions, the wakes dissipate much earlier (~3 km downwind). A wake model such as Fuga (Ott and Nielsen 2014) is needed that can use stability information appropriately for optimal wind plant design.

Wind plant blockage effect: The wind plant blockage effect results in the reduction of winds upstream of the wind plant and is not yet fully understood from the physics perspective.

Wind shear across the rotor layer: Vertical wind speed variability can be quite large (Pichugina et al. 2017), as in the case of low-level jets, and it is not clear how well the models capture wind shear across the rotor layer. WRF-modeled winds during coastal low-level jet events do show large vertical wind shear across the turbine rotor plane. However, the results need to be validated by measurements.

Sensitivity of 80 m winds to planetary boundary layer parameters: Similar to sensitivity studies over complex terrain (Yang et al. 2017; Berg et al. 2019), sensitivity of hub-height wind speed to various parameters (dissipation of TKE, Prandtl number, turbulence length scales) needs to be conducted over water in order to improve model performance.

Subgrid-scale process contributions: Many important physical processes occur at physical scales well below the resolution of numerical models. For example, turbulence occurs at scales as small as centimeters, while the HRRR model resolution is 3 km, and typical NWP model resolution is on the order of 10 km. Contributions of these subgrid-scale processes need to be accurately parameterized using model-predicted variables such as gradients, mean values, etc.

The depth and characteristics of the surface layer: The physics of the surface layer (approximately the lowest 10% of overall boundary layer depth) is not known very well over the ocean. Approaches using Monin-Obukhov Similarity Theory (MOST) are frequently employed to calculate wind speed and other profiles in the surface layer above the wave boundary layer height, which itself changes with wind speed. However, MOST rests on a number of assumptions such as a constant turbulence flux layer, horizontal homogeneity, and temporal stationarity that are commonly violated in the atmospheric surface layer. In addition, MOST is considered accurate in the surface layer above the wave boundary layer height, which itself changes with wind speed. Improvements in the surface layer characterization are necessary to account for the wave–atmosphere interactions.

The depth of the marine boundary layer (MBL): The depth of the MBL (z_i) is an important parameter used in the prediction of many other parameters, such as the convective velocity scale (w*) and gust velocity, that in turn are used to calculate wind speed, shear, and turbulence across the rotor plane. Under some conditions, the overall depth of the MBL can be less than the maximum rotor height, causing particular challenges in accurately describing shear across the rotor. As noted above, improvements in the z_i observational capabilities are necessary.

Sensitivity of wind to relative wave direction: Ocean waves (swell) often travel in directions other than along the mean wind. This misalignment of swell propagation direction with the wind has implications for most predictions, and the results change with wave height, stability, and geostrophic wind speed, and results differ depending on latitude due to the Coriolis parameter (Patton et al. 2019).

Wind gust parameterization: Confidence on how to account for gustiness above the surface layer is low, and it is even lower on how to parameterize gustiness caused by coherent structures such as roll vortices at higher wind speeds. Workshop attendees noted that it is important to be able to characterize the accuracy of wind gust parameterizations.

Supporting observations: To address the current key science challenges above and to validate the model performance, workshop participants highlighted the need for long-term observations. These are also critical for emerging machine learning models for subgrid scale parameterization, as well as for better defining tails of sample distribution tails to infer, for example, extreme events.

In general, a wide range of long-term observations is necessary that spans all seasons (under all wind and stability conditions). These observations need to have sufficient horizontal density to define the gradient in the mean wind field offshore. High vertical resolution profiles are also needed, and participants suggested that these could be satisfied by augmenting remote sensing systems with drones, aircraft, radiosondes and other in situ measurement platforms. Such platforms are particularly useful for intensive operational periods within longer measurement campaigns.

The list below reflects participant input regarding specific observations. All information is needed across the rotor and integrated with waves simultaneously (* denotes observations needed from the top of the wave boundary layer to the lower part of the free troposphere):

- Profiles of wind direction/horizontal and vertical wind speed*
- Profiles of temperature and humidity*
- Profiles of stability*
- Surface fluxes of momentum, temperature and humidity
- MBL depth
- Profiles of TKE*
- Wave characteristics: height (spectra), propagation direction relative to the pressure gradient driving the flow (Ug)
- Cloud properties (e.g., base and top height, thickness, liquid water path, phase, etc.)
- Precipitation properties (e.g., rate, mean droplet size)

4.4 Information Resources to Advance the Science

Discussion in the workshop highlighted current active programs and significant observational facilities that are directed toward or have the potential for advancing offshore wind energy in the United States. These are listed below.

- The National Offshore Wind Research and Development Consortium, managed by the New York State Research and Development Authority (NYSERDA) and partially funded by DOE, is running a series of Program Opportunity Notices for wind plant technology advancement, wind resource and physical site characterization, and installation, operations and maintenance: (https://www.energy.gov/eere/wind/national-offshore-wind-rd-consortium).
- NYSERDA has recently announced the execution of multi-year contracts that will be deploying buoy-mounted lidars providing publicly available metocean data 20 miles from the shore in the New York Bight (https://www.nyserda.ny.gov/About/Newsroom/2019-Announcements/2019-01-31-NYSERDA-

Announces-Contracts-for-Collecting-Environmental-and-Metocean-Data-in-Support-of-Offshore-Wind-Energy-Development)

- Texas Tech University has developed a DOE-funded prototype X-band radar system (DOE-X), having a 0.5° beam width and 10 m vertical resolution, to advance wind plant complex flow measurements. Dust, pollen, and insects serve as scatterers of such a system. Two early-stage commercial units of the X-band system have been deployed for DONG Energy (now Ørsted) in the United Kingdom to monitor the Westernmost Rough offshore wind plant (Schroeder et al. 2017). However, it was noted that due to the lack of scatterers in the offshore environment, the Texas Tech radar cannot serve as a wind resource assessment tool but rather could be used for process studies.

- Windcube profilers (lidars) are available in New York along the shoreline. Data may be available for research requests.

- Martha's Vineyard Coastal Observatory is a research and engineering facility operated by Woods Hole Oceanographic Institution (http://www.whoi.edu/mvco). It provides real-time and archived coastal oceanographic and meteorological data off the Massachusetts coast.

- Rutgers University has a large number of current and emerging capabilities including underwater observatories, manned submersibles, remotely operated vehicles, autonomous vehicles, research vessels, oceanographic profiling (maps of water currents, water clarity, water temperature, salinity, and some acoustic properties; https://marine.rutgers.edu/nurp/facilities.html#underwater)

- NOAA is redesigning the Tropical Atmosphere Ocean array. While the array is in a region not suitable for wind plant considerations, metocean measurements (radiation, surface fluxes) may still be valuable.

- DOE's Atmospheric Radiation Measurement user facility is heavily instrumented (including UAVs) and available for proposals (https://www.arm.gov/research/campaign-proposal).

- Argo is a global array of free-drifting profiling floats that measure the temperature and salinity of the upper 2 km of the ocean (http://www.argo.ucsd.edu). However, it was noted that these floats may be less useful for sea surface temperature observations because they surface only every 10 days.

- The following were highlighted as emerging measurement capabilities:
    - Saildrones (https://www.saildrone.com): Wind and solar powered unmanned surface vehicles equipped with metocean sensors
    - University of Washington Applied Physics Laboratory's autonomous wave glider: an autonomous surface vehicle for measuring waves and winds using wave motion for propulsion (http://www.washington.edu/news/2017/09/20/wave-glider-surfs-across-stormy-drake-passage-in-antarctica/)
    - Oregon State University's Robotic Oceanographic Surface Sampler: semi-autonomous research platform to gather physical properties of the upper ocean and the lower atmosphere (Nash et al. 2017)
    - Woods Hole Oceanographic Institution's X-SPAR: low-cost spar buoy for air-sea flux measurements (https://cclayson.whoi.edu/x-spar)
    - Boulder Environmental Sciences and Technology's marine profiling microwave radiometers: continuously provide water vapor and temperature profiles. (http://www.boulderest.com/products.html) If the added scanning capability is used, vertical resolution of ~30 m could be achieved.

  - DOE's two lidar buoys installed at various locations for periods of time in partnership with other organizations to provide a comprehensive set of metocean measurements (https://wind.pnnl.gov/lidarbuoys.asp)
  - Marine boundary layer radar wind profiling technology: lightweight, low power usage, suitable for buoy or small boat installation (https://qinetiq-na.com/products/metsense/wippr)
  - Vaisala's Differential Absorption Lidar (DIAL) for humidity profiling
  - UAVs/drones for atmospheric profiling in wind energy areas

5 Summary of Key Input and Recommendations

As noted at the beginning of this report, two overarching questions framed participant contributions and discussions at the workshop:

- What metocean information does industry need to more cost-effectively develop offshore wind energy in the United States?
- What is the capability of current science to provide the metocean information needed by industry offshore?

5.1 Industry Information Needs

Several previous workshops, strategy documents, and studies have articulated measurement and modeling needs for offshore wind energy in the United States. It was not the purpose of this workshop to simply restate those findings, especially with respect to established basic required information. For convenience of reference, some of that previous work is excerpted and summarized in Appendix B of this report. Rather, the discussion focused on needed information that is not currently well defined or that remains difficult to obtain.

5.1.1 Wind Plant Development and Operations

5.1.1.1 European Experience

Numerous large offshore wind energy power plants have been installed in Europe. Notable lessons from that experience include the following:

- Horizontal gradients of offshore winds—The land–water boundary generates circulations that cause strong horizontal variability of winds. Satellite data has confirmed that models often err in simulating coastal winds.
- Need for coupled wind–wave models—Dynamic interactions between winds and ocean waves have been shown to affect winds at hub height, and models need to account for this to be accurate.
- Wind plant wakes—Combined wakes from one or more wind plants can degrade the performance of downstream wind plants, especially under conditions of thermodynamically stable stratification. Accurate representation of this phenomenon has not been fully solved.
- Erosion from precipitation—Leading edges of blades and consequent turbine performance can be degraded through impacts with liquid and solid precipitation. Accurately characterizing and predicting precipitation offshore (including collecting data for validation) is an active research area.

5.1.1.2 U.S. Information Needs

Metocean information is needed over the entire life cycle of a project. This includes assessment of the wind resource and its variation over time and across the development area as well as forecasting wind and sea conditions for grid integration, safe installation, and safe operations.

There are distinct complicating phenomena that affect offshore wind plants in the United States. While not unique to U.S. coasts, sea breezes and low-level jets are prominent features of the East Coast. Tropical storms and hurricanes in the summer and nor'easters in the winter are phenomena that are unique to the eastern United States relative to Europe, owing to the presence of the Gulf Stream and the continent to the west. In addition, the relatively cool near-shore water compared to the Gulf Stream and to the land (in summer) leads to frequent thermodynamically stable stratification and consequent wind shear that is greater than usually assumed over oceans. Off the West Coast of the United States, prominent topography, deep water, upwelling, and a very long wave fetch combine to generate challenging sea conditions and cloud-topped, stably stratified boundary layers only a few hundred meters deep with very strong shear at the top.

Within the context of these complexities, key information needed by the wind industry includes:

- Observing standards: Currently standards do not exist for the wind industry for measuring met/ocean variables offshore, although such standards are being developed through the American Wind Energy Association.
- Observations of hub height winds: Such data remain scarce in the United States, particularly publicly available data to facilitate validation of numerical models used in wind resource characterization. The increasing acceptance of Doppler lidar systems provides hope that this gap can be filled in the near future, especially if industry can be encouraged to share proprietary data with research organizations.
- Vertical profiles of winds and thermodynamic properties: These variables should be routinely measured. Wind shear informs design standards, and thermodynamic stability has a profound effect on wind shear.
- Turbulence properties: Wind coherence across the rotor disk and true wind spectra are important for standards applications, including blade design and design load cases.
- Validated models: The scarcity of offshore observations has resulted in very limited validation of the models used for offshore resource characterization. Further, some variables, such as turbulence intensity, are needed by the wind industry but are not directly generated by atmospheric models. Data are also needed to validate the conversion of direct model output to variables needed by the wind industry.
- Variability over spatial and temporal scales: Good descriptions of wind variability are needed from diurnal time scales to five-minute scales for grid management, to one-minute scales for automatic generation controls. Regional and site-to-site wind variations also need to be accurately described.
- Extreme events: Better information about the probability of extreme events is needed, including how long-term changes in weather patterns may affect the frequency of extreme events. Also needed is a common terminology for extreme events that can distinguish between extreme events in power generation and in weather.
- Quantified uncertainty: Poorly defined uncertainty adds cost to wind plant development and operations. Uncertainty in the wind resource needs to be quantified, validated, and reduced where possible.

5.1.2 Information Needs for Engineering

IEC maintains standards for turbines and fixed-bottom platforms, but standards for floating platforms have not yet been established. Standards articulate a suite of key required metocean design variables. While the standards call for measurements of these variables, in many cases such measurements are not routinely available. For example, observations from NOAA buoys are reported hourly while the standards specify 10-minute averages as the basis for wind distributions. Moreover, such measurements are made a few meters above the ocean surface and scaled up to hub height, which can introduce significant error. Information beyond that described in current standards has also been identified as important for the design and operation of offshore wind plants. This includes the following:

- Atmospheric stability: This affects all dynamic variables in ways that are frequently not accounted for.

- Turbulence and shear: A recent sensitivity study of the impact of atmospheric flow variables on 12 terrestrial turbine load characteristics showed that these two variables were most important for loads. It is expected that these will be similarly important offshore, although additional uniquely offshore variables such as depth-dependence of currents may also need consideration.

- Joint metocean and load measurements: The lack of concurrent metocean and load measurements offshore represents a significant gap. This should include time series from which statistical measures such as coherence can be determined.

- Wake behavior: The dependence of wakes within and between wind plants on metocean variables needs to be better understood. This will likely require a combination of high-fidelity modeling and suitably chosen observations for validation.

- Extreme conditions: Hurricanes, in particular, will call for the development of unique load cases. Extreme localized atmospheric structures may require different gust descriptions than the current IEC model. The impact of associated wave conditions, particularly breaking waves, needs to be quantified.

- Subsurface information: The impact of metocean conditions on structures depends in part on seabed characteristics. Such information may be needed down to the mudline, which can be 80–100 m below the seabed.

- Operational model improvements: In general, while industry participants welcomed model improvements, there was strong sentiment that such improvements are most helpful when they are evolutionary. Operational modeling changes that deviate too far from current practice face challenges in finding industry acceptance.

5.2 Responses from the Scientific Community

The current state of the art in NWP in the United States is NOAA’s integrated modeling system, which uses the RAP and HRRR models to assimilate data hourly and provide forecasts to 36 hours with 3 km horizontal resolution. While these models are very successful for operational weather forecasting, the lack of data offshore has limited evaluation of their performance, particularly for variables of interest at hub height. The lack of offshore data for assimilation similarly increases the potential for error in offshore areas. Beyond the simple need for more observations, however, there are needs for additional scientific development of these models. These areas of scientific challenge include the following:

- Stably stratified atmospheric conditions: It is important to account for atmospheric stability in models for wind energy forecasting. However, when the stratification is stable, internal boundary layers and other complicated layering can occur, and these are not well accounted for in current model physics.

- Depth of the marine atmospheric boundary layer: Many model calculations depend on this variable, and it is likely not correctly calculated, especially under stable conditions. Improvements in our ability to measure boundary layer height offshore will be needed to address this.

- Depth and characteristics of the surface layer: The assumptions behind current weather forecast model physics addressing this lowest layer of the atmospheric boundary layer are frequently violated offshore, and how to make the model physics more general is not well understood.

- Wind shear across the rotor layer: Coastal circulations such as low-level jets can generate substantial shear in the rotor layer through mechanisms that are not captured well in current models. Evaluating and improving model performance for these effects is needed.

- Fully coupled wind–wave–wake models: Current models typically use wave forecasts or some other source to prescribe the lower boundary for atmospheric models offshore. It is expected that models could be significantly improved, however, by coupling wind and wave models so that model winds drive developing wave fields, which then provide lower boundary conditions to the wind model. This will be needed, for example, to address engineering information needs under conditions of wind–wave misalignment. These models will ultimately need to include coupling with wake models both for more accurate wake generation and to assess impacts that plant wakes may have on the wave field itself.

Addressing the challenges above will require both conventional and extended observational capabilities. In general, the observations will be most beneficial if they cover the full spectrum of atmospheric conditions, which generally means sampling over a full annual cycle. This is a continuing challenge, since there are few offshore platforms that can support such long-term measurement operations offshore. Some needed information could be partially provided by shore-based systems that scan out to sea, such as dual-Doppler radars. Other emerging possibilities could include buoy-based remote sensing systems such as radar or microwave radiometers for deeper wind profiling and atmospheric temperature and humidity structure. Unmanned aerial systems (UASs) increasingly can carry sophisticated meteorological instruments over the horizon on repeated flights over an extended period. Some needed measurements remain challenging to obtain. Key measurements needed to support the science needed to improve current models include the following:

- Eddy correlation fluxes over the depth of the offshore boundary layer: These are important diagnostic variables for model performance and improvement. The stress tensor as well as scalar fluxes (moisture and sensible heat) are needed. There is not yet an effective way to obtain this information with remote sensing systems, making long-term measurements a particular challenge.

- Wind speed, temperature, and humidity through the depth of the atmospheric boundary layer: Wind speed is at least partially available through systems such as buoy-mounted lidars. However, the current lack of a demonstrated system to obtain temperature and humidity is a significant impediment.

- Wind–wave interaction: Needed for the fetch- and depth-limited (East Coast) environments where wind plants are being installed.

- Boundary layer depth: A noted above, this is an observation that is difficult to make accurately.

5.3 Conclusion

This section has highlighted key points from presentations and associated discussion that occurred during the Workshop on Research Needs for Offshore Wind Resource Characterization. Many of the points in this section were visited multiple times during the workshop, underscoring their importance both to industry and to the scientific community. While the emphasis here has been on science challenges and challenging information needs, there is a wealth of conventional data available offshore and some sophisticated instrumentation operating notably along the Atlantic Coast. Section 4.4 summarizes some of these resources. This summary, and the report in general, provide a view of areas where research and potentially instrument development are likely to lead to significant advances both in our fundamental understanding of the offshore environment and our ability to model it for the benefit of the emerging U.S. offshore wind industry.

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Appendix A – Key Variables Needed for Offshore Wind Energy Characterization

Many parameters required to evaluate models used for forecasting wind energy, assess feasibility of wind turbines, and understand the impact of weather on a structure have been established for some time. We thus did not try to list them in the body of the report. However, we felt that an articulation of at least a significant subset would be a helpful reference as an appendix. Below we have summarized the needed information in a tabular form. The variables are segregated in four different categories: (1) atmospheric state and meteorological variables, (2) wind variables, (3) surface and near-surface variables, and (4) below-surface variables. An attempt is also made to indicate whether the variable is required for wind industry and model evaluation purposes, required for structural engineering purposes, or is required for wind farm resource characterization. The variables mentioned below are based on those presented in Bailey et al. (2015) *AWS report*. Variables discussed in this workshop but not listed in the Bailey et al. reference are colored in red.

Table A.1. Atmospheric State and Meteorological Variables.

Variable Name	Units	Comments	Wind Industry	Structural Engineering	Resource Characterization Science
Air Temperature	Kelvin	Profile of air temperature from surface to 2 km or higher at hourly timescales	X	X	X
Water Vapor Mixing Ratio	Grams per kilogram	Profile of water vapor mixing ratio from surface to 2 km or higher	X		X
Barometric Pressure	Pascals	Profile of air pressure from surface to 2 km or higher	X	X	
Lower Tropospheric Stability	Kelvin	Difference between potential temperature at 700 hPa and the surface	X		
Precipitation Rate	Millimeter per hour	Profile from surface to 2 km or higher	X	X	X
Hydrometeor Diameter	Millimeter	Profiles from surface to 2 km. Used for impact on the blades and in radiative transfer calculations.	X	X	
Cloud and Precipitation Layer Height and Occurrences	Meter	Profiles from surface to 2 km used for radiative transfer calculations	X		X
Condensate Loading	Grams per cubic meter	Profiles from surface to 2 km used for radiative transfer calculations	X		

Variable Name	Units	Comments	Wind Industry	Structural Engineering	Resource Characterization Science
Radiative Fluxes	Watts per meter squared	Profiles from surface to 2 km either measured or from radiative transfer model, used for model evaluation	X		
Lightning	Flashes per second	Amount of lightning in the wind farm area		X	X

Table A.2. Wind Variables

Variable Name	Units	Comments	Wind Industry	Structural Engineering	Resource Characterization Science
Wind Speed	Meter per second	Profiles from surface to 2 km on hourly timescales. Needed especially at the hub height and to calculate gusts.	X	X	X
Wind Shear	Meter per second	Profiles of change in wind speed with height from surface to 2 km at hourly timescales. Needed especially across the rotor.	X		X
Wind Direction	Degree	Profiles from surface to 2 km on hourly timescales. Needed especially at the hub height.	X	X	X
Wind Veer	Degree	Profiles of change in wind direction with height from surface to 2 km at hourly timescales. Needed especially across the rotor.	X		X
Vertical Wind Speed	Meter per second	Profiles of vertical wind from surface to 2 km	X		
Turbulence Dissipation Rates	Meter squared per second cubed	Dissipation rates at the hub height and across the rotor derived from high-resolution measurements of horizontal or vertical wind	X		
Turbulence Intensity	Unitless	Standard deviation of horizontal wind speed over mean wind speed	X		

Table A.3. Surface and Near-Surface Variables

Variable Name	Units	Comments	Wind Industry	Structural Engineering	Resource Characterization Science
Sensible Heat Flux	Watts per meter squared	Transfer of heat from the ocean surface to the atmosphere. Calculated using eddy covariance technique or bulk aerodynamic technique.	X		
Latent Heat Flux	Watts per meter squared	Transfer of moisture from the ocean surface to the atmosphere. Calculated using eddy covariance technique or bulk aerodynamic technique.	X		
Sea Surface Temperature	Kelvin	Skin temperature of the ocean surface	X		X
Conductivity	Siemens per meter	Conductivity of the water		X	
Salinity	Grams per kilogram	Salinity of the ocean mixed layer		X	X
Wave Height	Meter	Height of the significant wave in the wind farm area	X	X	X
Wave Direction	Degree	Direction of significant wave in the wind farm area	X		
Still Water Level	Meter		X	X	
Storm Surge	Meter	Typical storm surges observed in the wind farm area		X	X

Table A.4. Below Surface Oceanographic Variables

Variable Name	Units	Comments	Wind Industry	Structural Engineering	Resource Characterization Science
Water Current Speed	Meters per second	Profile of the speed of the water current within the wind farm area		X	X
Water Current Direction	Degree	Profile of the direction of the water current within the wind farm area		X	
Bathymetry	Meter	Ocean bathymetry in the wind farm area		X	X
Soil Type	Unitless	Type of soils present in the wind farm area		X	X

Appendix B – Background Documents

As noted in the introduction, this workshop built on previous workshops, strategy documents, and meetings. In the sections below, this appendix summarizes several significant preceding efforts.

B.1 National Offshore Wind Strategy

The National Offshore Wind Strategy was released in 2016 and was jointly written by DOE and the U.S. Department of the Interior (DOI). The report builds on a previous report released in 2011. The report highlights the potential value of offshore wind to the United States, the need for a national strategy, and presents a credible set of approaches and actions to facilitate responsible development of U.S. offshore wind industry.

The report first outlines the significant opportunity that offshore wind presents to the United States. It first describes the abundant wind resources on U.S. coastal waters and the significant siting and development opportunities that exist. The report then outlines how the increased demand for electricity combined with scheduled power plant retirements create a unique opportunity for offshore wind to fill that gap. The report then describes some locations where offshore wind could be competitive with incumbent forms of generation and be less reliant on subsidies. The report then describes the significant electrical system benefits for system operators, utilities, and ratepayers that offshore wind energy provides. Finally, the report describes the various environmental and economic external benefits provided by offshore wind, including reduction in greenhouse gases, decreased air pollution, reduced water consumption, greater energy diversity and security, and increased economic development and employment.

Acknowledging these many benefits, the report then describes at length the key challenges that remain in supporting a robust and sustainable wind industry in the United States. These challenges are broken down into three strategic themes: reducing costs and technology risks, supporting effective stewardship, and increasing understanding of the benefits and costs of offshore wind.

In describing the first theme, the report first notes the high cost of offshore wind cost and its inability to compete with incumbent forms of electricity generation without subsidies. The report then describes several avenues to lower costs. The first focuses on offshore wind power resource and site characterization. Here the report describes the need for better understanding of unique metocean and seafloor conditions that will allow for optimal designs, reduced capital costs, greater safety, less uncertainty in preconstruction energy yield assessments, and reduced financial costs. The report then describes the need for offshore technological advancements, including increasing turbine size and efficiency, reducing mass in substructures, and optimizing wind plants at a system level. Finally, the report describes the need for installation, operation, maintenance, and supply chain solutions. Specifically, the report notes the complexity and risk associated with installation, operation, and maintenance activities, and the need for specialized infrastructure that does not yet exist. The report emphasizes reducing the need for such specialized assets and leveraging existing infrastructure to help unlock major economic development and job creation opportunities.

The report then discusses the need to support effective stewardship. Specifically referring to the nation’s ocean and Great Lake waters, the report describes how effective stewardship of these resources will help ensure an efficient, consistent, and clear regulatory process. Specifically, the report highlights the need for predictable review timelines and some flexibility in the review process given the early stage of offshore wind development. The report then describes the importance of addressing key environmental and human-use concerns, specifically the need for more data to verify and validate impacts on sensitive biological resources and existing human uses of ocean space to allow increased efficiency of environmental reviews.

Finally, the report discusses the need for increasing understanding of the benefits and costs associated with offshore wind. First, the report focuses on electricity delivery and grid integration, highlighting that impacts of significant offshore wind on electricity grids needs to be better understood at state and regional levels. Furthermore, the costs and benefits of different transmission infrastructure configurations need to be characterized. The report then describes ways to quantify and communicate benefits and costs of offshore wind to key stakeholders to inform decisions on near-term offtake agreements, other project-specific matters, and policies affecting offshore wind.

B.2 Offshore Resource Assessment and Design Conditions

The Offshore Resource Assessment and Design Conditions report was released in 2012 and authored by DOE. The report distills an aggregation of research, comments received at public sessions, and contributions from experts. The two purposes of the report are to provide an initial overview of information required by a range of stakeholders to effectively deploy marine hydrokinetic systems (MHK) and wind energy systems offshore, and to identify gaps in that required information. Information in the report is split into five broad application areas: facility design, energy projections and performance monitoring, technology and design and validation, operations planning and site safety, and short-term forecasting. The report is intended to inform development of priorities and strategies for acquiring information to support the development of offshore renewable energy. In this summary, only content relevant to offshore wind is provided whereas information relevant to MHK systems is not provided.

The report first discusses the information needed to design offshore energy plants to achieve maximum performance as a whole including accounting for interactions among individual devices (e.g., turbine array effects). The report notes that design begins with site selection, which depends on metocean and geotechnical conditions. A summary table of required variables and current gaps is provided in Table B.1.

Table B.1. Facility Design Information Requirements and Gaps. Information availability in the table is designated “A” for currently available, “E” for emerging availability, and “G” for gap.

Information	Availability	Comments
Near-surface wind speed (10 min. average), wind direction	A	This information is used to drive wave models for MHK applications. In addition, surface winds can be scaled up to hub height, although validation of the methods and accuracy offshore is limited.
Long-term frequency distributions of wind speed (hub height)	G	Distributions are available from prognostic meteorological models, but validation of hub-height winds and turbulence from these models is limited offshore.
Shear (hub height), natural turbulence	G	Nature turbulence is characteristic of inflow rather than wakes.
Turbulence intensity (hub height)	G	This includes wake-modulated turbulence.
Air temperature	A	
Atmospheric pressure	A	
Lightning	A	Lightning detection networks currently cover significant offshore areas.
Ice loading, ice accretion	E	Ice loading—the stresses of sea ice on structures—is generally distinguished from ice accretion—the weather-related accumulation of ice.
Significant wave height, direction, period	A	

Information	Availability	Comments
Joint wind, wave-height, wave direction	G	
Tidal elevation	A	
Current profile over water column	A	IEC standards indicate that surface current is sufficient for wind; however, during hurricanes, inertial oscillations may cause strong subsurface current shears in hurricane wakes.
Salinity	A	
Water temperature	A	
Bathymetry	A	
Seabed scour	E	

The report next discusses the information needed to estimate future energy output from a deployment based on site criteria over the lifetime of the project. The report largely bases these needs from the IEC 61400-12-1 standard and points out the lack of suitable offshore observations at hub-height and the role that remote sensing can play. The report also points out the value of modeled data included reanalysis products and mesoscale models that provide longer time-series and robust spatial coverage. A summary table of required variables and current gaps is provided in Table B.2.

Table B.2. Energy Projections and Performance Monitoring Requirements and Gaps for Wind Technologies

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

Information	Availability	Comments
Turbulence intensity (hub height)	G	
Precipitation type and amount	G	Advanced tools are needed to detect and monitor precipitation and other particles that can detrimentally affect energy production
Humidity	E	
Air density	E	
Air temperature	A	
Atmospheric pressure	A	
Vertical temperature profiles	E	

The report then discusses the information needed to design and validate energy-generating devices that can withstand physical loads while operating at optimum efficiency in the marine environment. A particular focus of this section is on extreme events. A summary table of required variables and current gaps is provided in Table B.3.

Table B.3. Technology Design and Validation Requirements and Gaps for Wind Technologies.

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

Information	Availability	Comments
Atmospheric pressure	A	
Air temperature	A	
Vertical temperature profiles	G	
Salinity	A	
Water temperature	A	
Bathymetry	A	
Seabed geology	E	
Seabed scour	E	

The report next discusses the information needed to effectively schedule and execute construction, operation, and maintenance activities, including safe facility access and response to extreme events. The primary required information are wind and associated power forecasts from both NWP for short to day-ahead forecasts and local observations (e.g., remote sensing) for very short-term forecasting. The need for historical information is also noted for maintenance planning in optimal weather conditions. A summary table of required variables and current gaps is provided in the tables below.

Table B.4. Operations Planning Information Requirements and Gaps.

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

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

Table B.5. Adaptive Operations Information Requirements and Gaps.

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

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

Table B.6. Site Safety Information Requirements and Gaps.

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

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

The report finally discusses the information needed to initialize, constrain, and improve appropriate forecast models for predicting winds, waves, and currents hours to days in advance. The main challenges noted are the modeling of complex physical processes and the lack of observations to both validate and drive the models. A summary table of required variables and current gaps is provided in Table B.7.

Table B.7. Summary of Gaps for Forecasting.

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

B.3 Metocean Data Needs Assessment for U.S. Offshore Wind Energy

The role and need of vital metocean information needed for developing offshore wind energy in the United States was well-documented by a report prepared by AWS Truepower for the Department of Energy (Bailey et al. 2015). The primary goals of the report were to (1) illustrate the multi-disciplinary and multi-stakeholder nature of required metocean information, (2) address how the required metocean information can be acquired, and (3) recommend a set of activities for characterizing metocean conditions for offshore wind energy development. Many of the parameters mentioned in Appendix A are stemming from this report. This report was partly based on a workshop titled "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) in 2014. The report first explained the different types of metocean information, its users, and applications in wind resource characterization. This was done during different phases of a wind plant, as the required metocean information changes significantly during these different phases.

This was followed by a summary of the key atmospheric, water surface, and sub-surface parameters and derived statistics needed for the various stages of offshore wind facility development, construction, and operations. Many of these are mentioned in Appendix A. The report also discussed instruments that could be used to observe or derive many of the variables. The instruments to observe atmospheric state and wind variables include anemometers, thermometers, barometers, lidars, sodars, and radiometers. While the instruments to measure the water surface and below-surface properties include level gauges, flow meters, wave buoys, acoustic Doppler profilers, radars, and scatterometers. The report argues for deployment of these sensors over land near coastal regions, over water through buoys, and on an offshore fixed platform to make long-term relevant measurements. They also advocate for using measurements from instruments onboard satellites, aircrafts, and autonomous unmanned vehicles to supplement the ground-based measurements. The temporal and spatial resolution of the different metocean variables were also discussed and mentioned in Appendix A. Very specific importance and guidance was given and advocated for thoroughly documenting the operational attributes and data sources. They also tabulated the currently available data products, mostly through NOAA, that could be used to characterize environments along the east and west coasts of the United States and Gulf of Mexico.

The report advocated for using models of various hierarchy to understand metocean phenomena and where the observations are lacking. The models discussed included numerical weather prediction models that yield metocean information every 1–6 hours at mesoscale spatial resolutions (20 km–200 km), and microscale models like (1) mass-conserving model, (2) linear flow models, (3) Computational Fluid Dynamics (CFD)/Reynolds-Averaged Navier-Stokes (RANS) models, and (4) large-eddy simulation models that are used to perform detailed turbulence-turbine interactions. The report brought specific attention to the use of combinations of the microscale models to study wind turbine wakes and their effects to improve their representation in the NWP models. The report also pointed out several wave and coupled ocean-atmosphere models (e.g., WAVEWATCH) that could be used to model oceanic flow, especially as affected by coastal winds and bathymetry.

The report concluded with recommended activities for improving the characterization of metocean conditions in the United States. The recommended activities fall into three categories: (1) new measurements to supplement current metocean observations, (2) analysis and prediction modeling, and (3) public-private synergy. Detailed recommendations were made on all three categories with specifics on type of sub-activities and potential pitfalls. A roadmap for 10 years is proposed that brings together all recommended activities, stakeholders, and DOE programs. The schematic of the roadmap is shown below.

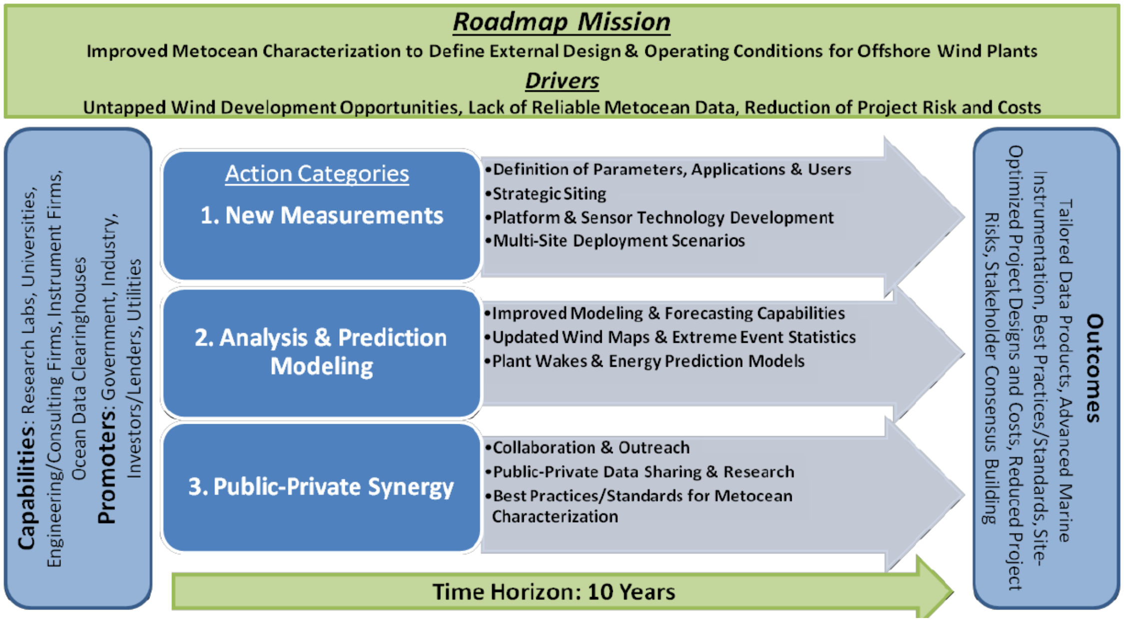


Figure B.1. Proposed roadmap for offshore metocean characterization by AWS Truepower.

B.4 Metocean Characterization Recommended Practices for U.S. Offshore Wind Energy

Prepared by DNV KEMA Renewables, Inc. (DNV GL).

DNV KEMA Renewables, Inc. (part of DNV GL) prepared a report in 2018 to serve as a guide to offshore wind energy developers and BOEM on best practices to reliably collect, analyze, and use site-specific metocean data. The document provided the stakeholders of offshore wind power a comprehensive guide for ways for collecting effective metocean information. The scope of this guideline covered the data necessary to support proper design, installation, operation, and maintenance of offshore wind facilities located within U.S. waters on the federal Outer Continental Shelf (OCS). The report was built from a survey of 26 documents (peer-reviewed articles and reports) containing detailed information on offshore wind energy.

The primary metocean information was divided into following categories (1) movement of water—levels and flows; (2) wind conditions; (3) sea states—waves; (4) atmospheric parameters including temperature, precipitation, icing, and other meteorological conditions; (5) physical ocean parameters including temperature, salinity, sea ice, and other conditions; and (6) joint conditions, such as wind and wave conditions. The lifecycle of an offshore wind project was divided into four main phases: (1) Planning and Design, (2) Transportation and Installation, (3) Operation and Maintenance, and (4) Decommissioning.

During the planning phase of the wind farm project, first a feasibility assessment, conceptual design, permitting, construction planning, and operations and maintenance (O&M) planning should be performed. Due to the initial phase, most of the required data should come from NWP models within the proposed area. The data should be used to develop reliable power output curves, determine wake effects, and assess overall performance of the wind facility performance, including project losses, identification of any potential data gaps, and evaluation of existing data and any potential field campaign for data collection. It is also very important to characterize any potential project losses due to waves and current conditions—necessary for assessing site accessibility, lighting frequency—required to assess lighting-related losses, icing conditions—icing downtime and icing-related performance degradation, precipitation (hail and rain, especially)—important for informing blade and other performance degradation losses, and air temperature—required to quantify frequency and duration of high/low temperature losses. The metocean variables required during this phase along with their spatial and temporal resolution is similar to that mentioned in Appendix A and hence is not mentioned here. The primary difference is the requirement of long-term forecast and hindcast data from NWP models, for characterizing seasonal, annual, and decadal occurrences of extreme events (e.g., tropical cyclones, El Nino, etc.). The events occurring with 100- to 500-year recurrence periods also need to be identified along with events forecasted to increase in frequency due to climate change.

The data required during the transport and installation phase is similar to that mentioned in Appendix A, but with very high spatial resolution (~10 meters) within the project area at 3-hourly or finer timescales. Due to the difficult nature of transporting the wind turbines offshore, it is important to use the latest forecast from weather models. The O&M phase also requires similar types of data to the transport and installation phase, with real-time monitoring and forecasting. Power production forecasting is relevant at time scales beyond day-ahead (e.g., hour ahead, 6-hour ahead), and on higher frequencies for ramp events. It is worth noting this for both O&M planning purposes, as well as grid interconnection requirements, or other planning related to potential grid curtailment. The decommissioning phase probably will happen several decades after initial installation and can last several months. It will also require detailed forecast and hindcast information from NWP models for ensuring safe take-down and transport of wind turbines back onshore.

The report demonstrates a need for a measurement campaign that characterizes critical metocean variables in the proposed wind project area prior to installation. From a temporal perspective, the minimum duration of a measurement campaign should not be less than one year to cover seasonal variability, but the campaign should preferably cover at least two full years to support assessment of inter-annual variability. A longer-term continuous campaign is preferred that provides continuity from development through construction and operations. The instruments proposed for measuring winds are (1) anemometers, (2) wind vanes, (3) sodars, (4) lidars, and (5) Doppler radars. The relative merits and shortcomings of these different instruments are tabulated in Table B.8. The atmospheric and state variables could be characterized with instruments deployed onboard a (1) tall mast, (2) fixed platforms, and (3) floaters. Although there are some significant advantages for using a fixed platform for making metocean measurements, it is vastly more expensive than floating platforms. Floating platforms are easily re-deployable and relatively inexpensive; however, they could not be used for making measurements under high-wind conditions. Wave measurements could be made using (1) wave staff, (2) wave-following buoy, (3) pressure sensor below the ocean surface, (4) acoustic Doppler current profiler, (5) microwave radar, and (6) laser. The merits and shortcomings of these instruments are tabulated in Table B.9. The report also makes suggestions for using current meters and satellite remote sensing instruments for measuring ocean currents and tides within the project area. The report advocates for using data from several satellite instruments in synergy with that from the ground-based instruments. It is necessary to quality control the data, include the metadata of the instruments, and make the data available in generic formats to all of the stakeholders.

Table B.8. Overview of Wind Measuring Instruments for a Field Campaign Aimed at Characterizing Offshore Wind Resources

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

Table B.9. Overview of Wave Measuring Instruments for a Field Campaign Aimed at Characterizing Offshore Wind Resources

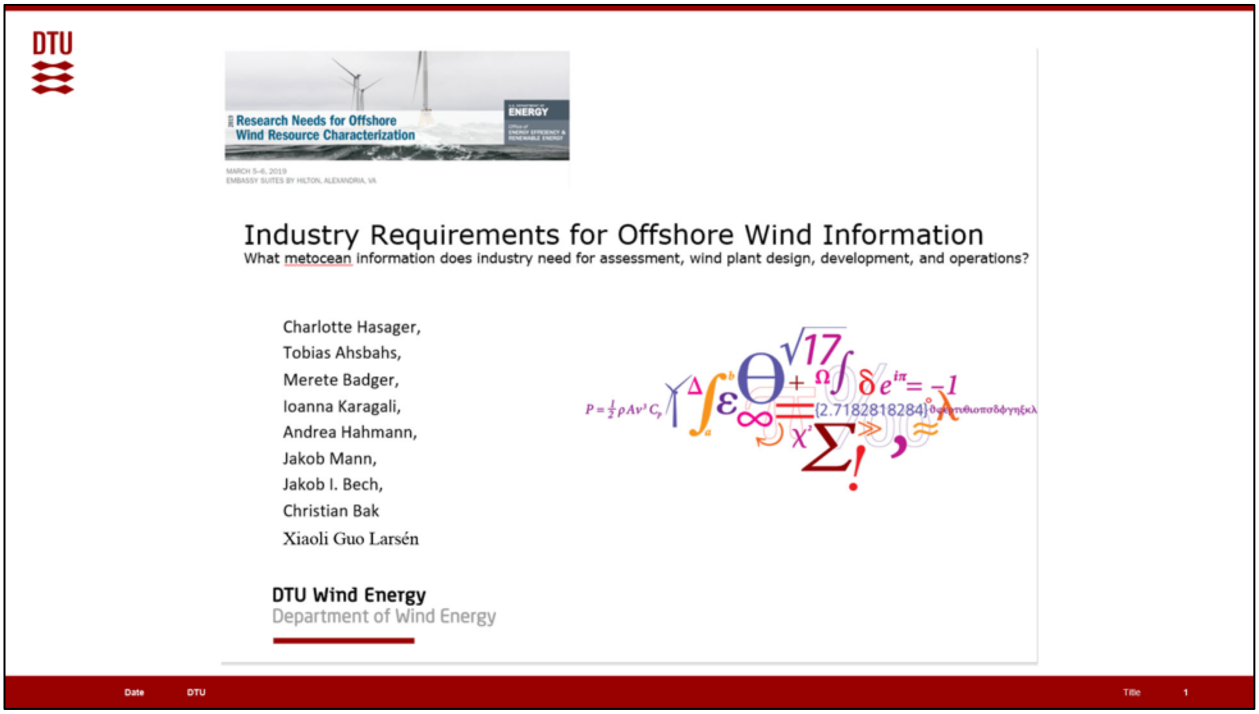
Measurement Device	Requires Platform	Cost	Maintenance Labor	Application	Limitations
Wave staff	Yes	Very Low	Low	Preliminary assessment	Only non-directional measurements; interference of the structure
Wave-rider buoy	No	High	High	All phases of facility lifecycle	May not capture extreme crests; at risk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

The report advocates for using models of various hierarchies and physics for characterizing metocean environment in the wind farm area, and for understanding the interactions between different processes. These include re-analyses and large-scale and regional-scale atmospheric models that yield long-term forecasts of various atmospheric, oceanic, and wave variables. These models give forcing to detailed numerical modeling at the site using (1) wind models such as CFD models, (2) hydrodynamic current and water-level models, and (3) wave models. Special attention should be given for validating the model output and for generating ensemble statistics from the model output. Special consideration was given to using models for characterizing the frequency and intensity of tropical and extra-tropical cyclone conditions within the wind farm area. Parametric models, mesoscale models, tropical cyclone models, and models using synthetic storms in a Monte Carlo framework could be used for accomplishing this.

The last chapter was devoted to document visualization of the raw data collected by the instruments or reported by the models and for calculating advanced variables required for wind resource characterization. Examples of these include joint distribution of wind speed and wave heights, and spatial distribution of atmospheric stability in the wind farm area. These variables can be used to identify different physical processes behind the data. The variables are calculated using several methods like Inverse-First Order Reliability Method (IFORM) mentioned below, extreme value method, filtering method, harmonic analysis, empirical orthogonal function, spectral analysis, and others.

Appendix C – Speaker Slides

C.1 Session 1: Charlotte Hasager



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2019 Research Needs for Offshore Wind Resource Characterization

U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

MARCH 5-6, 2019
EMBASSY SUITES BY HILTON, ALEXANDRIA, VA

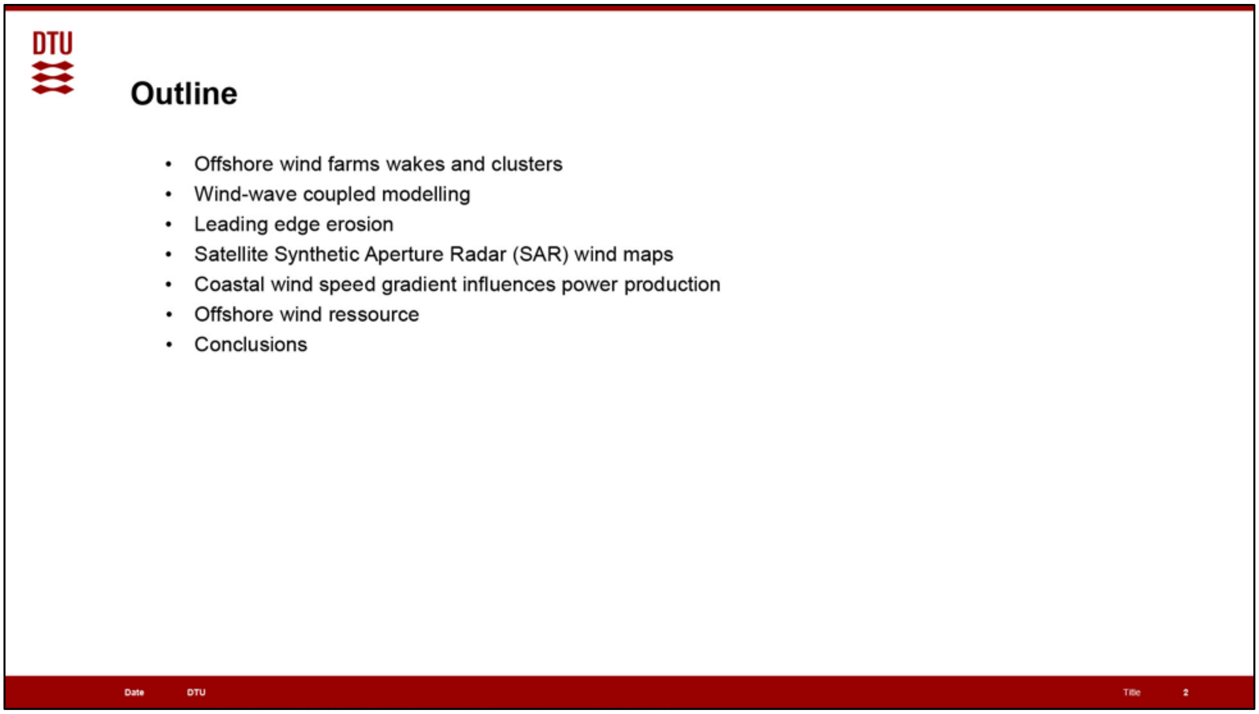
Industry Requirements for Offshore Wind Information

What metocean information does industry need for assessment, wind plant design, development, and operations?

Charlotte Hasager,
Tobias Ahsbahs,
Merete Badger,
Ioanna Karagali,
Andrea Hahmann,
Jakob Mann,
Jakob I. Bech,
Christian Bak
Xiaoli Guo Larsén

DTU Wind Energy
Department of Wind Energy

Date DTU Title 1



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Outline

- Offshore wind farms wakes and clusters
- Wind-wave coupled modelling
- Leading edge erosion
- Satellite Synthetic Aperture Radar (SAR) wind maps
- Coastal wind speed gradient influences power production
- Offshore wind ressource
- Conclusions

Date DTU Title 2

DTU

Offshore wind farm wakes and clusters

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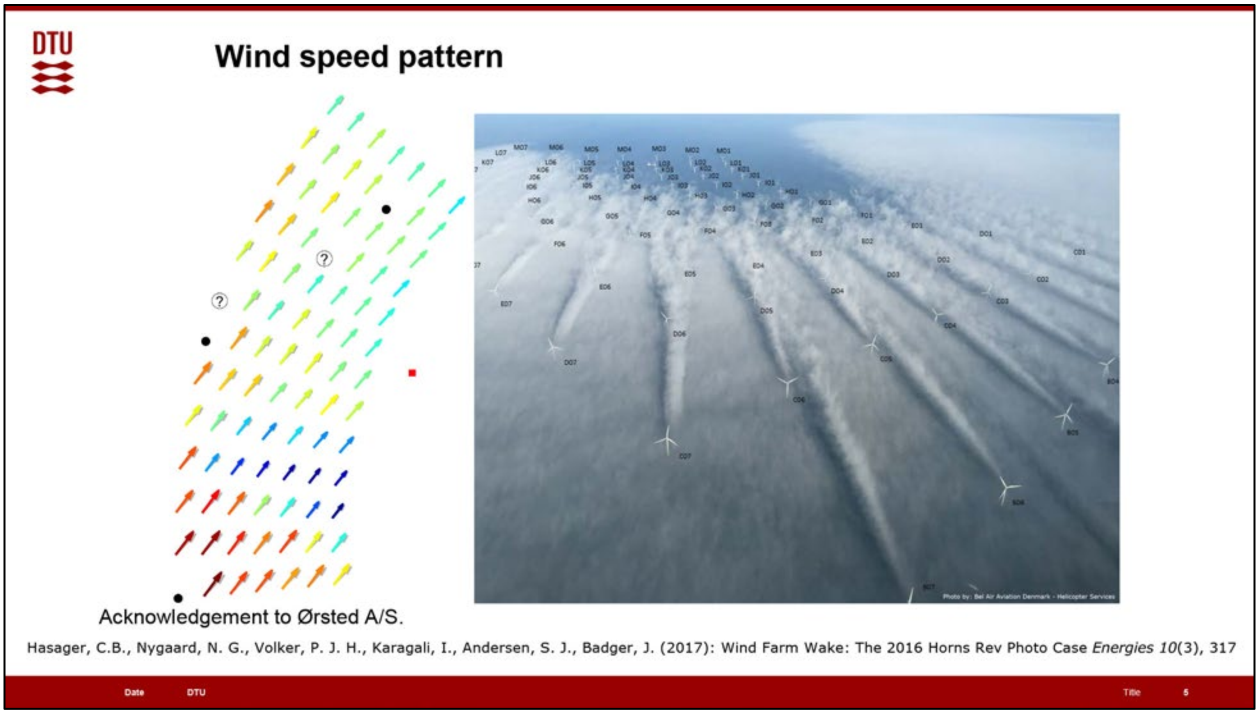
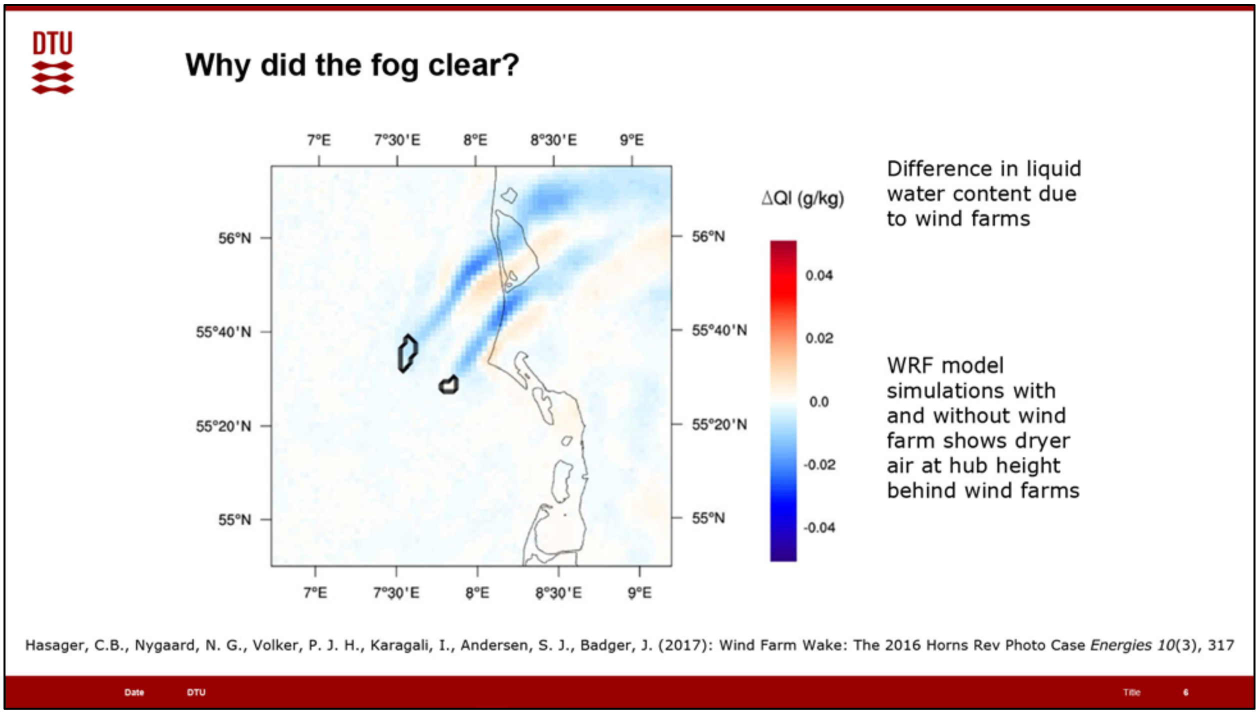
Photo by: Bel Air Aviation Denmark - Helicopter Services



Wind speed pattern

Acknowledgement to Ørsted A/S.

Hasager, C.B., Nygaard, N. G., Volker, P. J. H., Karagali, I., Andersen, S. J., Badger, J. (2017): Wind Farm Wake: The 2016 Horns Rev Photo Case *Energies 10*(3), 317

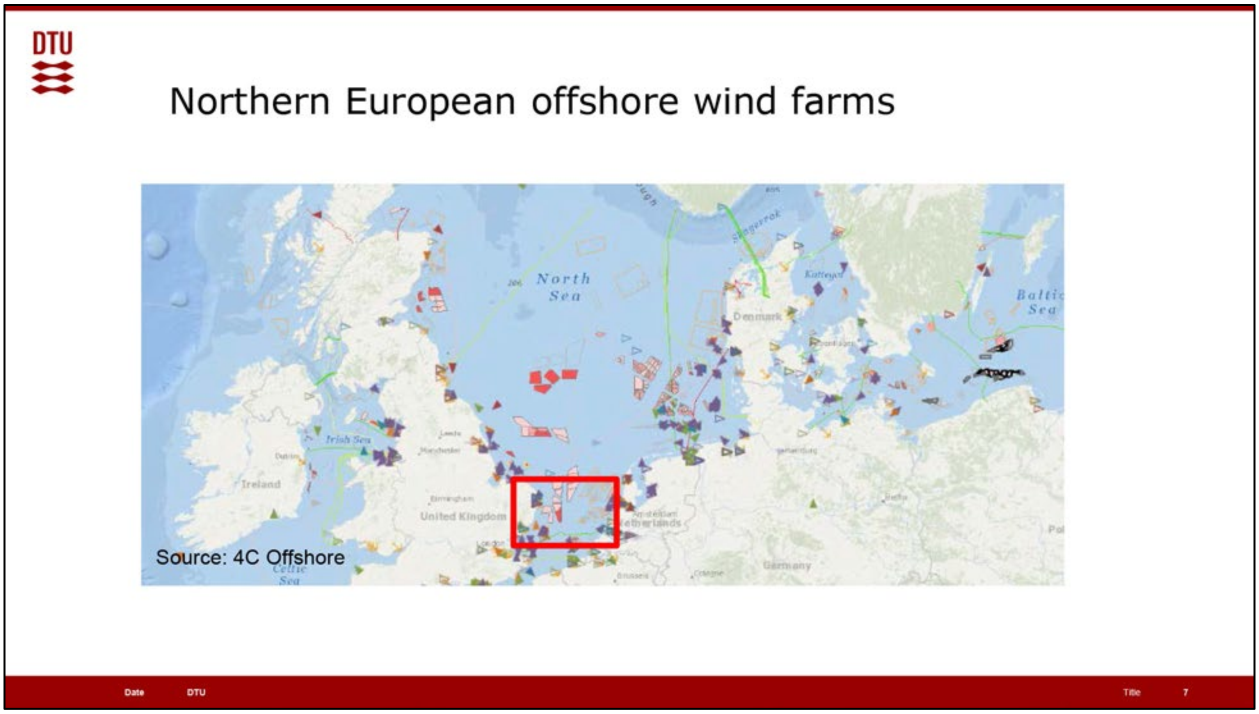


Why did the fog clear?

Difference in liquid water content due to wind farms

WRF model simulations with and without wind farm shows dryer air at hub height behind wind farms

Hasager, C.B., Nygaard, N. G., Volker, P. J. H., Karagali, I., Andersen, S. J., Badger, J. (2017): Wind Farm Wake: The 2016 Horns Rev Photo Case *Energies 10*(3), 317



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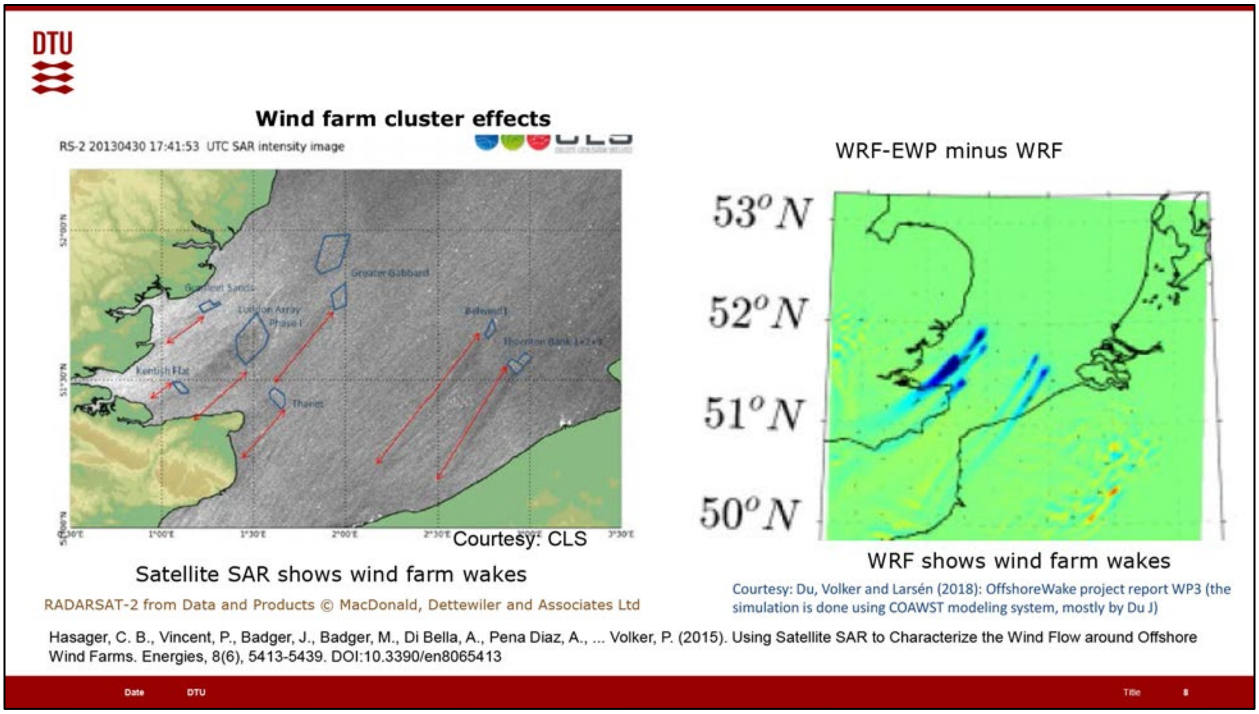
Northern European offshore wind farms

Source: 4C Offshore

Date DTU Title 7



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Wind farm cluster effects

RS-2 20130430 17:41:53 UTC SAR intensity image

Courtesy: CLS

Satellite SAR shows wind farm wakes

RADARSAT-2 from Data and Products © MacDonald, Dettewiler and Associates Ltd

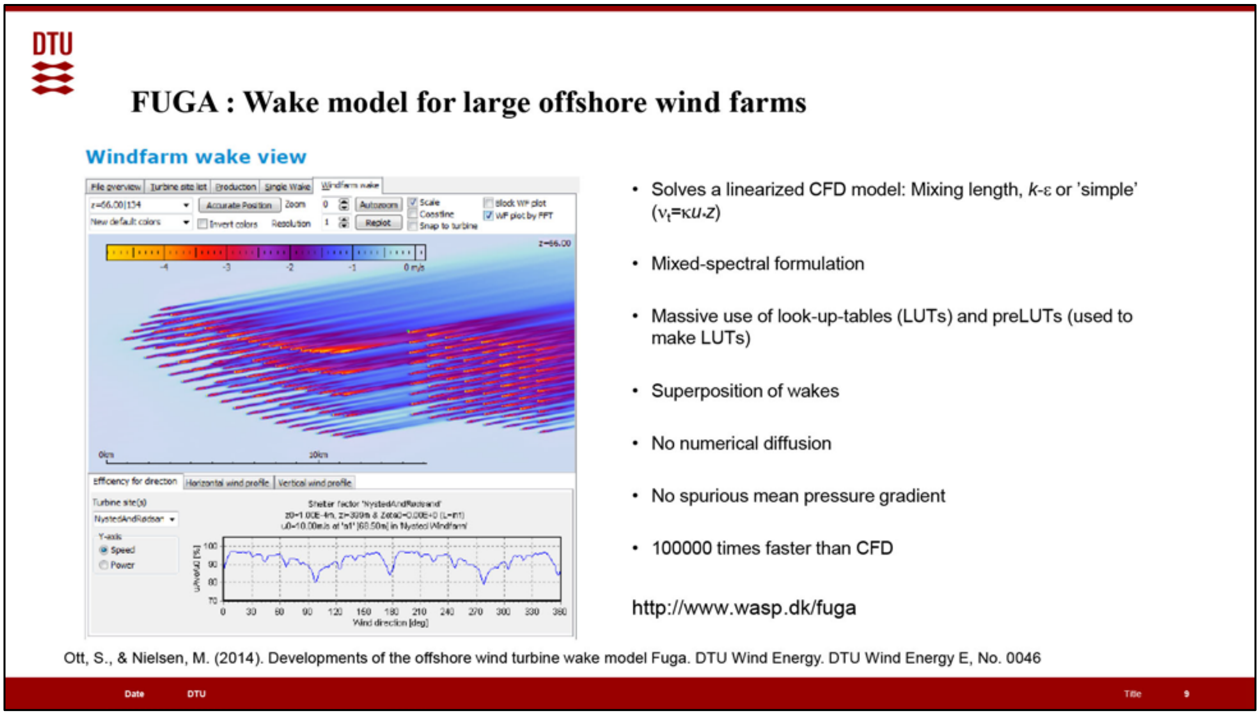
WRF-EWP minus WRF

WRF shows wind farm wakes

Courtesy: Du, Volker and Larsén (2018): OffshoreWake project report WP3 (the simulation is done using COAWST modeling system, mostly by Du J)

Hasager, C. B., Vincent, P., Badger, J., Badger, M., Di Bella, A., Pena Diaz, A., ... Volker, P. (2015). Using Satellite SAR to Characterize the Wind Flow around Offshore Wind Farms. Energies, 8(6), 5413-5439. DOI:10.3390/en8065413

Date DTU Title 8

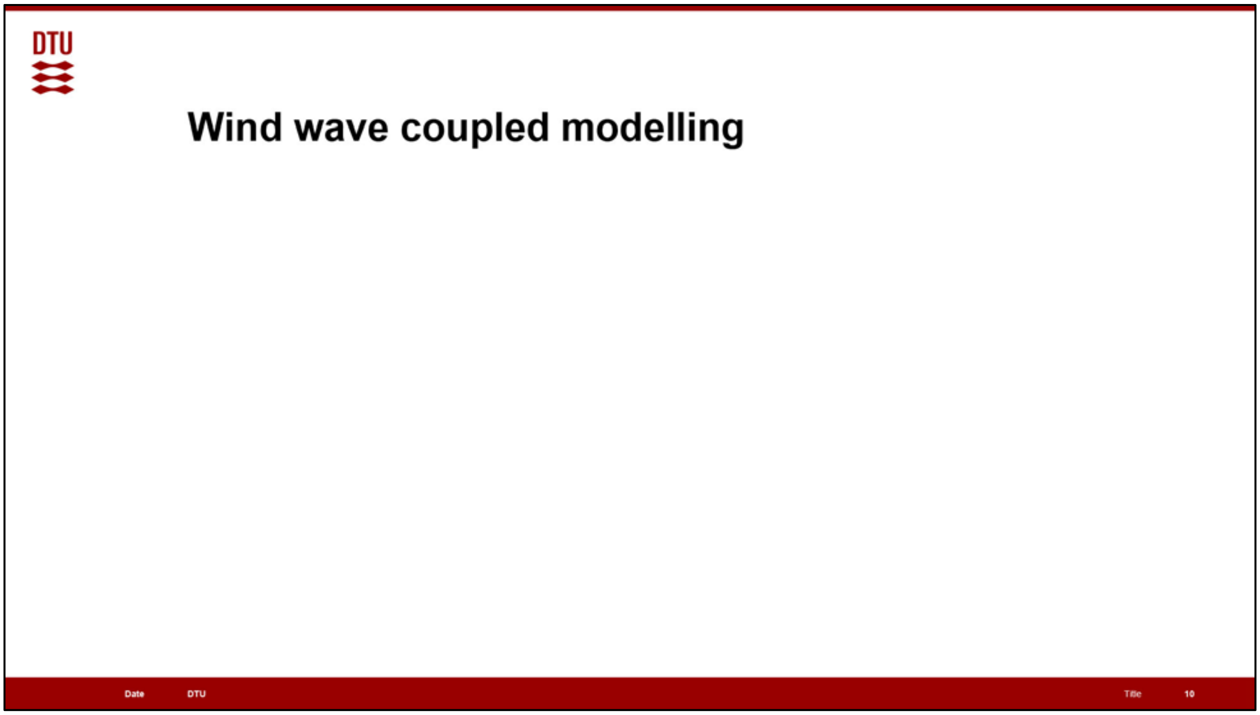


FUGA : Wake model for large offshore wind farms

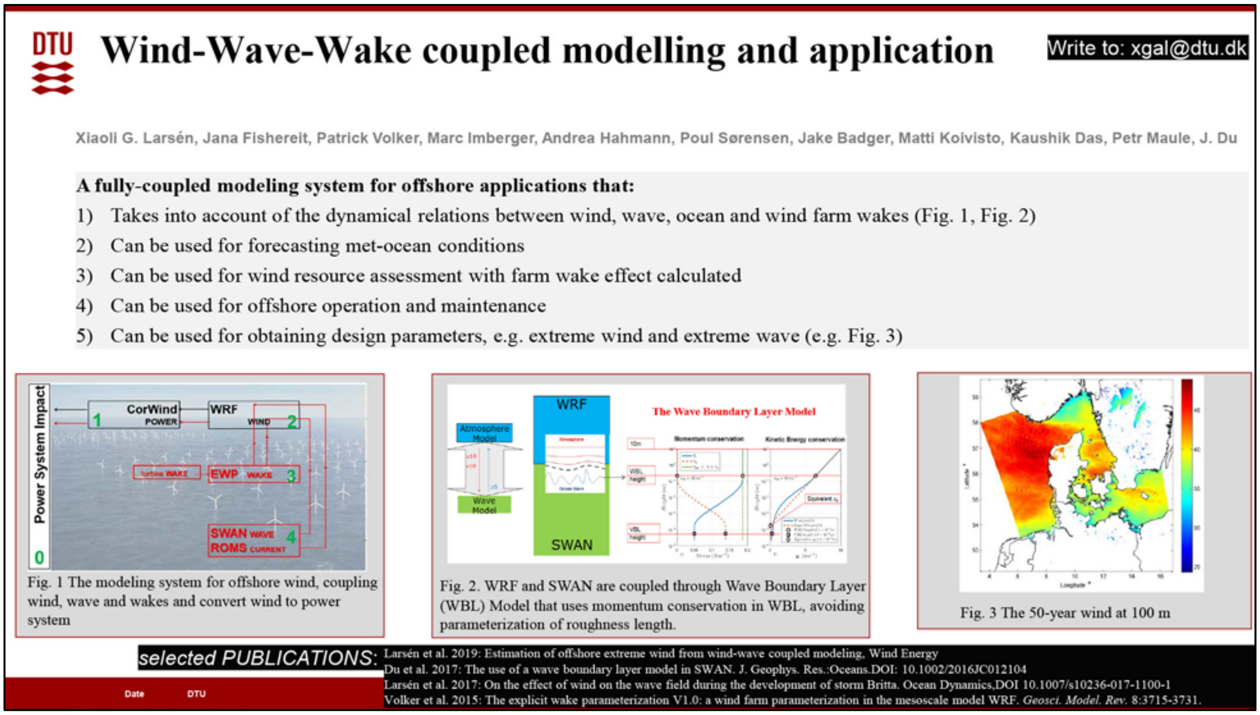
- Solves a linearized CFD model: Mixing length, *k*-ε or 'simple' ($\nu_t = \kappa u_* z$)
- Mixed-spectral formulation
- Massive use of look-up-tables (LUTs) and preLUTs (used to make LUTs)
- Superposition of wakes
- No numerical diffusion
- No spurious mean pressure gradient
- 100000 times faster than CFD

http://www.wasp.dk/fuga

Ott, S., & Nielsen, M. (2014). Developments of the offshore wind turbine wake model Fuga. DTU Wind Energy. DTU Wind Energy E, No. 0046



Wind wave coupled modelling



Wind-Wave-Wake coupled modelling and application

Write to: xgal@dtu.dk

Xiaoli G. Larsén, Jana Fishereit, Patrick Volker, Marc Imberger, Andrea Hahmann, Poul Sørensen, Jake Badger, Matti Koivisto, Kaushik Das, Petr Maule, J. Du

A fully-coupled modeling system for offshore applications that:

1) Takes into account of the dynamical relations between wind, wave, ocean and wind farm wakes (Fig. 1, Fig. 2)
2) Can be used for forecasting met-ocean conditions
3) Can be used for wind resource assessment with farm wake effect calculated
4) Can be used for offshore operation and maintenance
5) Can be used for obtaining design parameters, e.g. extreme wind and extreme wave (e.g. Fig. 3)

Fig. 1 The modeling system for offshore wind, coupling wind, wave and wakes and convert wind to power system

Fig. 2. WRF and SWAN are coupled through Wave Boundary Layer (WBL) Model that uses momentum conservation in WBL, avoiding parameterization of roughness length.

Fig. 3 The 50-year wind at 100 m

selected PUBLICATIONS:

Larsén et al. 2019: Estimation of offshore extreme wind from wind-wave coupled modeling, Wind Energy
Du et al. 2017: The use of a wave boundary layer model in SWAN. J. Geophys. Res.:Oceans.DOI: 10.1002/2016JC012104
Larsén et al. 2017: On the effect of wind on the wave field during the development of storm Britta. Ocean Dynamics,DOI 10.1007/s10236-017-1100-1
Volker et al. 2015: The explicit wake parameterization V1.0: a wind farm parameterization in the mesoscale model WRF. *Geosci. Model. Rev.* 8:3715-3731.

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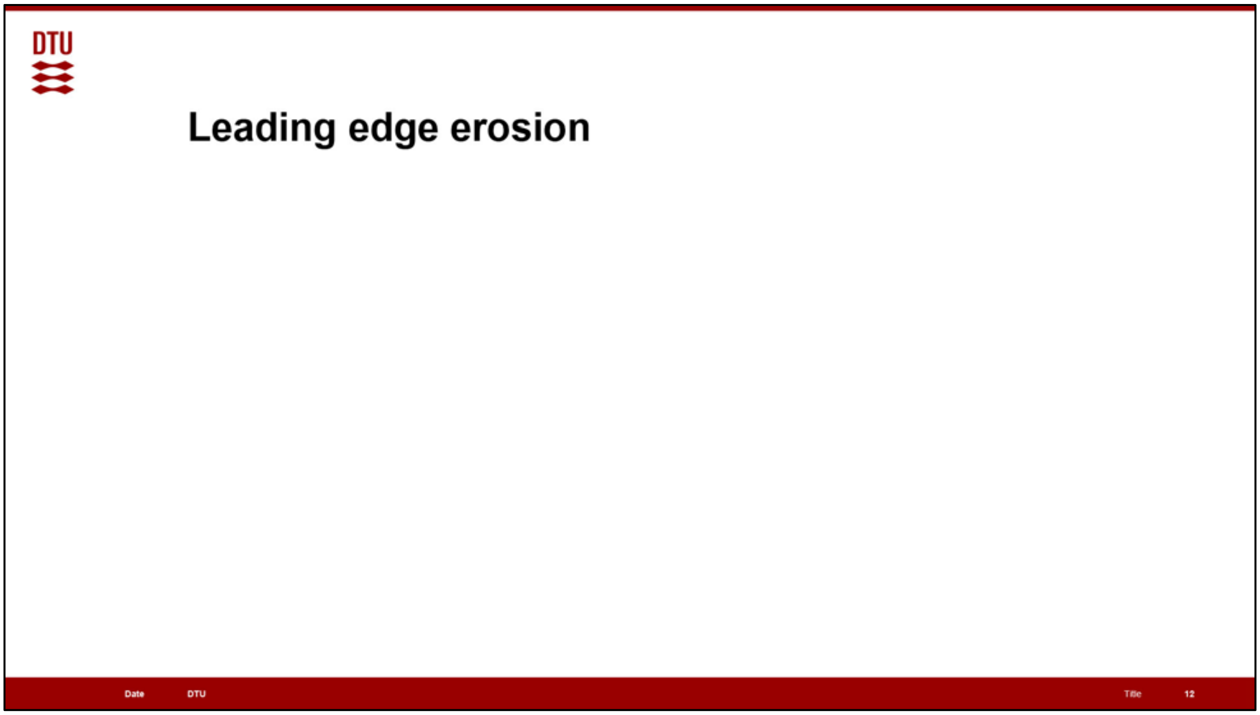


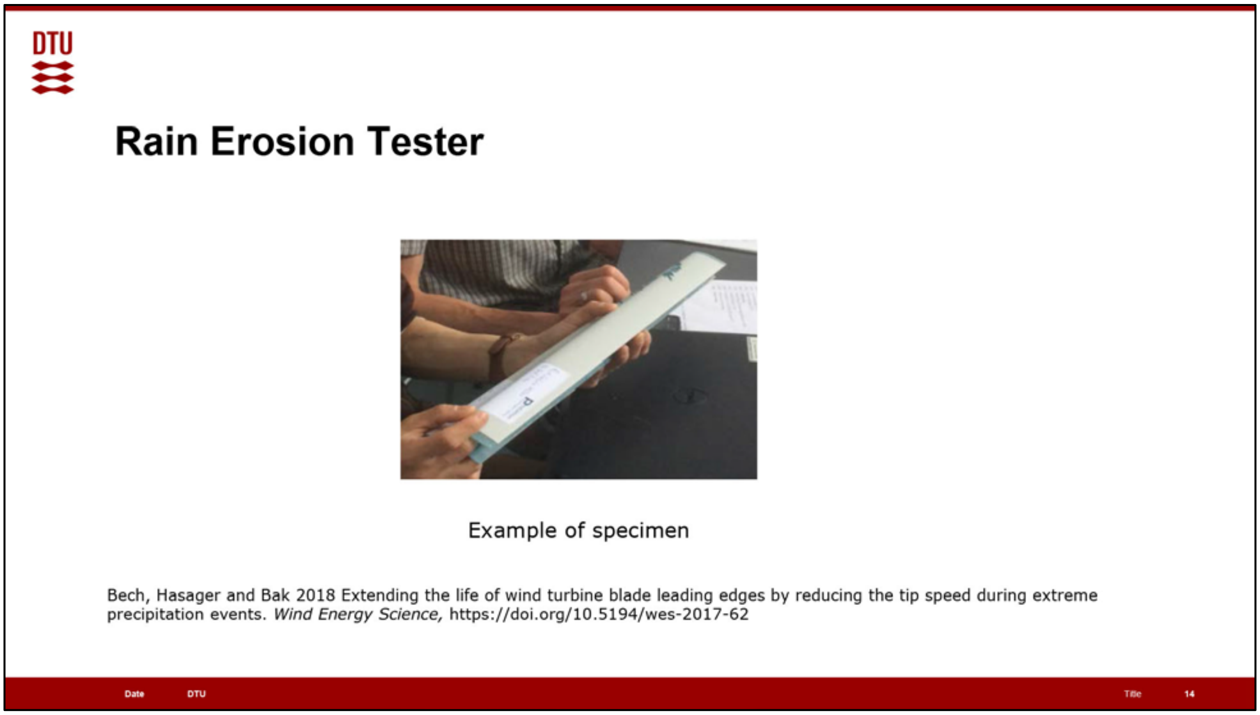
Leading edge erosion

Date DTU Title 12

1. **Research hypothesis:** Erosion damage is mainly generated during heavy precipitation (big drops of rain or hail), which occurs in a very little fraction of the turbines operation time. By reducing the tip speed of the blades in these few hours a significant extension of the leading edge lifetime can be obtained with negligible loss of production.
2. **Methodology:** Define rain and hail erosion classes to quantify leading edge blade in-field and in lab testing. Correlations between rain intensity, droplet size, impact speed, materials properties, etc. will be established.
3. **Measurement Device:** Low-cost prototype for precipitation measurement on site and real time warning device enabling modern control of wind turbines.
4. **Erosion safe mode:** A safe mode control based on the erosion classes to control the wind turbine, reducing the tip speed under severe conditions – preventing aerodynamic degradation and reducing maintenance costs.

Innovationsfonden

www.rain-erosion.dk



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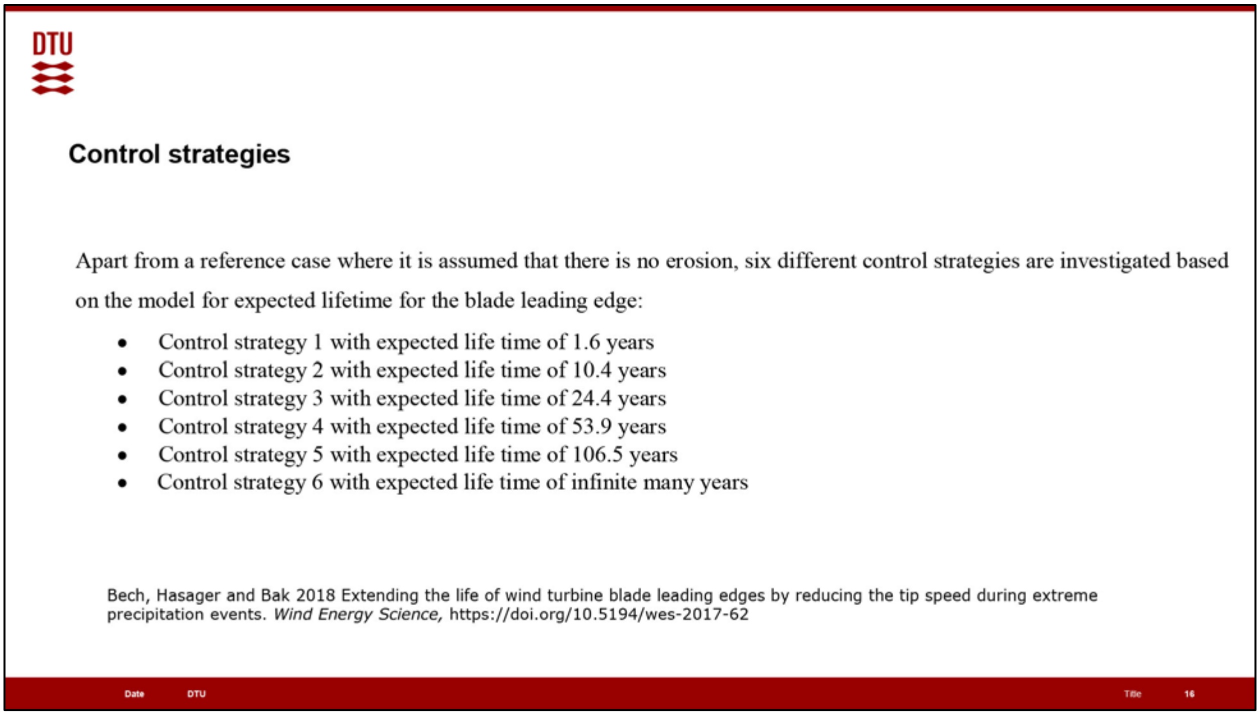
Rain Erosion Tester

Example of specimen

Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science,* https://doi.org/10.5194/wes-2017-62



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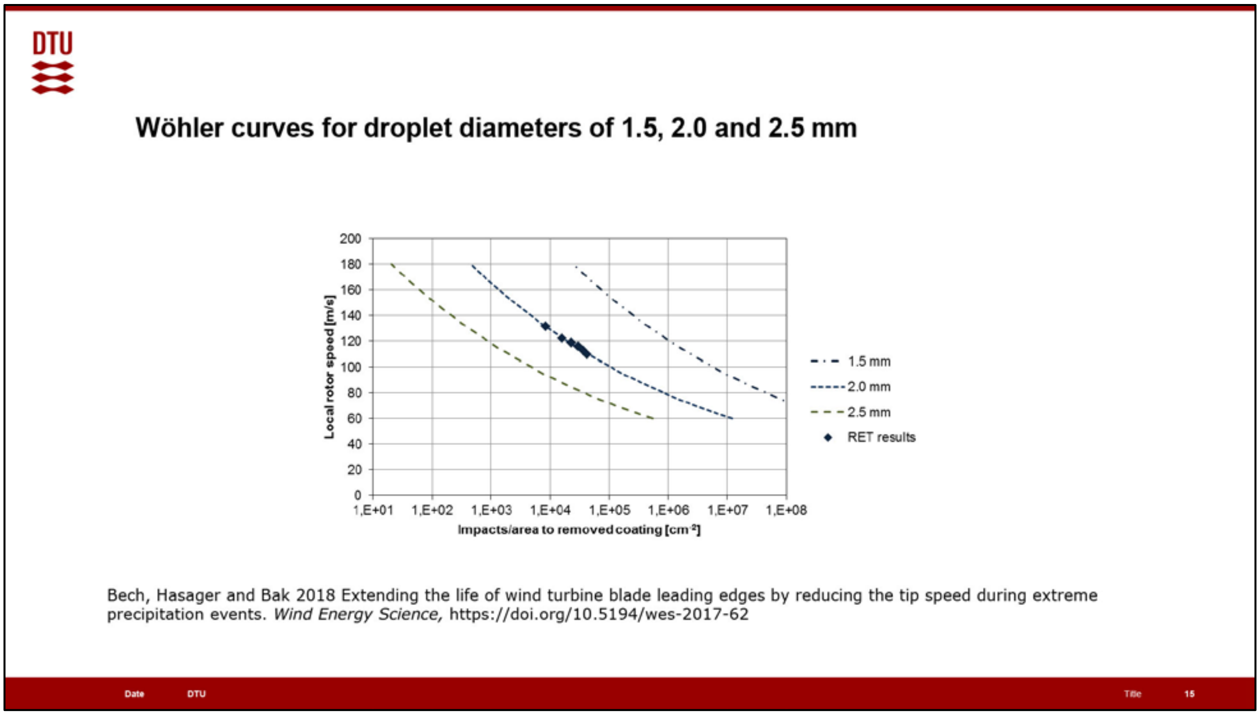
Control strategies

Apart from a reference case where it is assumed that there is no erosion, six different control strategies are investigated based on the model for expected lifetime for the blade leading edge:

- Control strategy 1 with expected life time of 1.6 years
- Control strategy 2 with expected life time of 10.4 years
- Control strategy 3 with expected life time of 24.4 years
- Control strategy 4 with expected life time of 53.9 years
- Control strategy 5 with expected life time of 106.5 years
- Control strategy 6 with expected life time of infinite many years

Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science,* https://doi.org/10.5194/wes-2017-62

Date DTU Title 16



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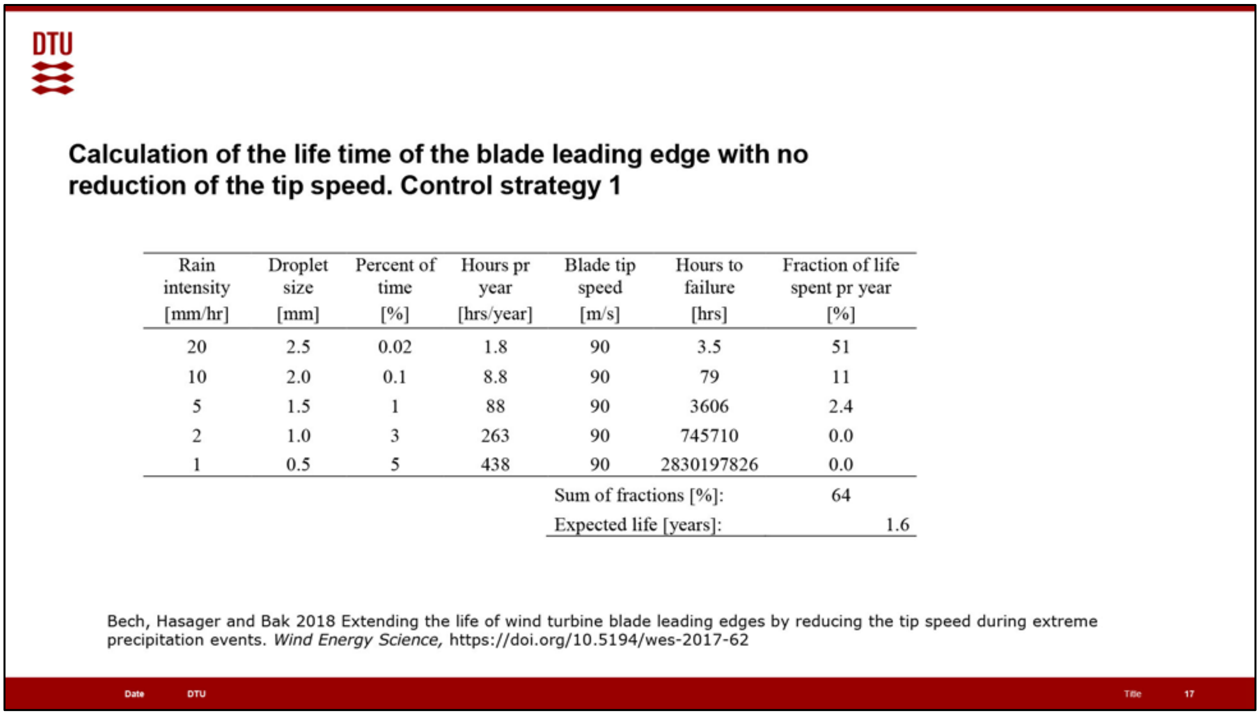
Wöhler curves for droplet diameters of 1.5, 2.0 and 2.5 mm

Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science,* https://doi.org/10.5194/wes-2017-62

Date DTU Title 15



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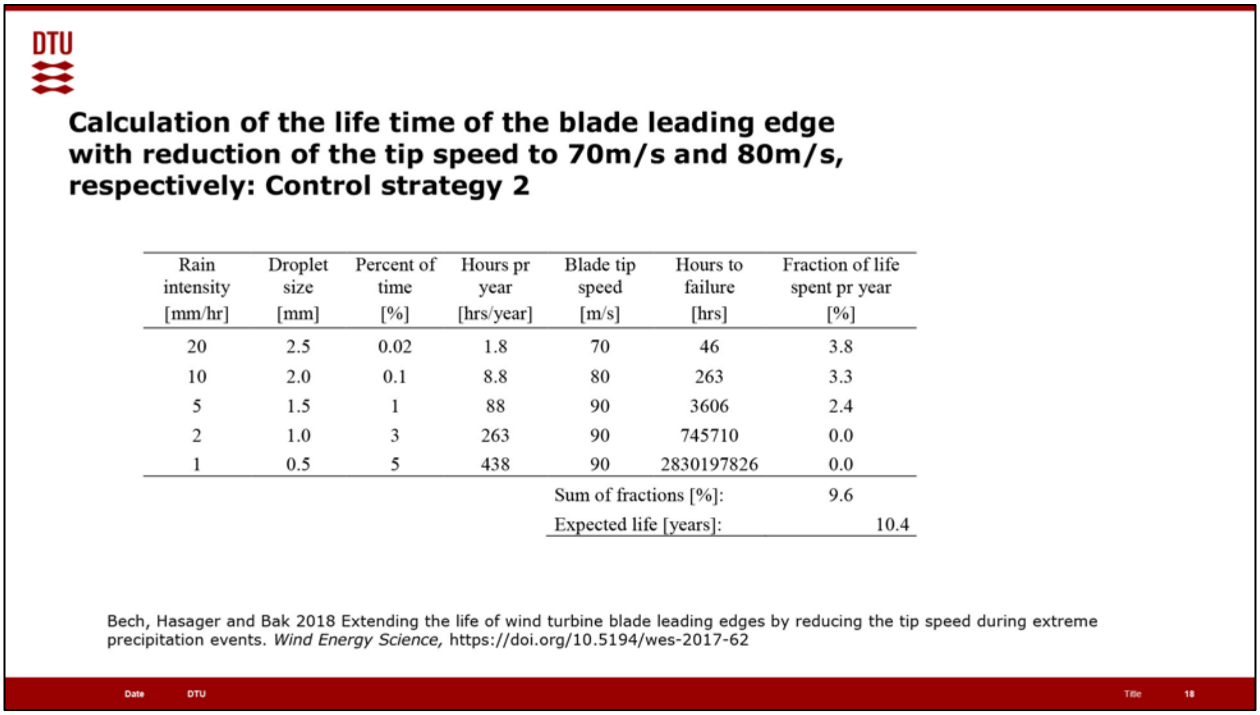
Calculation of the life time of the blade leading edge with no reduction of the tip speed. Control strategy 1

Rain intensity [mm/hr]	Droplet size [mm]	Percent of time [%]	Hours pr year [hrs/year]	Blade tip speed [m/s]	Hours to failure [hrs]	Fraction of life spent pr year [%]
20	2.5	0.02	1.8	90	3.5	51
10	2.0	0.1	8.8	90	79	11
5	1.5	1	88	90	3606	2.4
2	1.0	3	263	90	745710	0.0
1	0.5	5	438	90	2830197826	0.0
				Sum of fractions [%]:		64
				Expected life [years]:		1.6

Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science,* https://doi.org/10.5194/wes-2017-62



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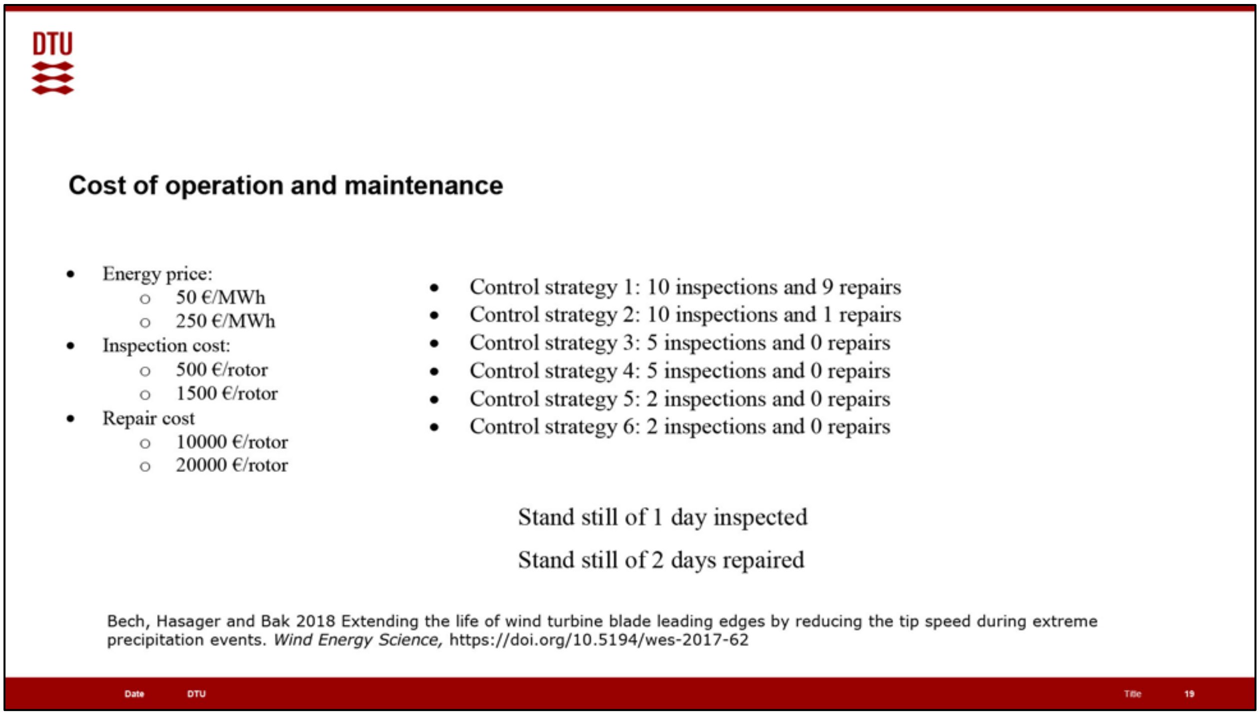
Calculation of the life time of the blade leading edge with reduction of the tip speed to 70m/s and 80m/s, respectively: Control strategy 2

Rain intensity [mm/hr]	Droplet size [mm]	Percent of time [%]	Hours pr year [hrs/year]	Blade tip speed [m/s]	Hours to failure [hrs]	Fraction of life spent pr year [%]
20	2.5	0.02	1.8	70	46	3.8
10	2.0	0.1	8.8	80	263	3.3
5	1.5	1	88	90	3606	2.4
2	1.0	3	263	90	745710	0.0
1	0.5	5	438	90	2830197826	0.0
				Sum of fractions [%]:		9.6
				Expected life [years]:		10.4

Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science,* https://doi.org/10.5194/wes-2017-62



Cost of operation and maintenance

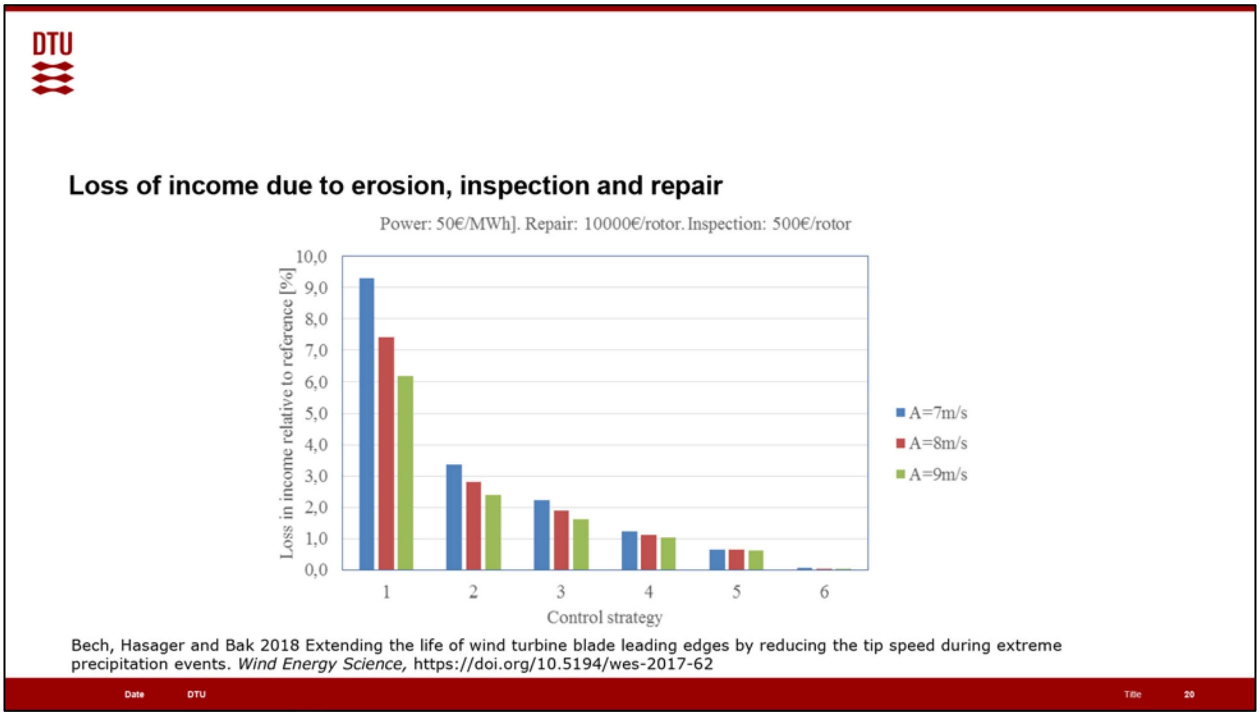
- Energy price:
  - 50 €/MWh
  - 250 €/MWh
- Inspection cost:
  - 500 €/rotor
  - 1500 €/rotor
- Repair cost
  - 10000 €/rotor
  - 20000 €/rotor

- Control strategy 1: 10 inspections and 9 repairs
- Control strategy 2: 10 inspections and 1 repairs
- Control strategy 3: 5 inspections and 0 repairs
- Control strategy 4: 5 inspections and 0 repairs
- Control strategy 5: 2 inspections and 0 repairs
- Control strategy 6: 2 inspections and 0 repairs

Stand still of 1 day inspected

Stand still of 2 days repaired

Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science,* https://doi.org/10.5194/wes-2017-62



Loss of income due to erosion, inspection and repair

Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science,* https://doi.org/10.5194/wes-2017-62

Satellite SAR wind maps

Coastal wind speed gradient and power production

Offshore wind resource

Satellite SAR wind data archive at DTU

- 30,000+ ENVISAT ASAR scenes (2002-2011)
- 150,000+ Sentinel-1 A/B SAR scenes (2014->)

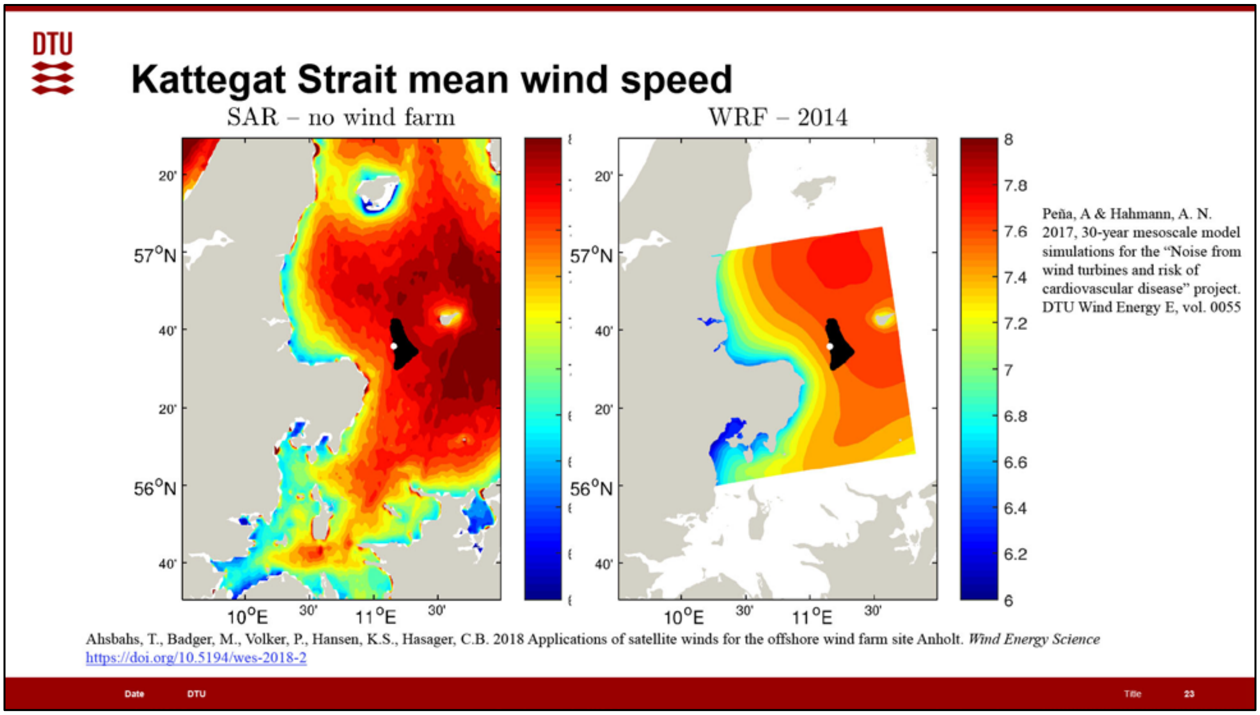
https://satwinds.windenergy.dtu.dk/

Total suitable records: 195194

Page size 20

Page: 1 /9760

You can select/adjust area of interest by holding CTRL key and drawing a bounding box



Kattegat Strait mean wind speed

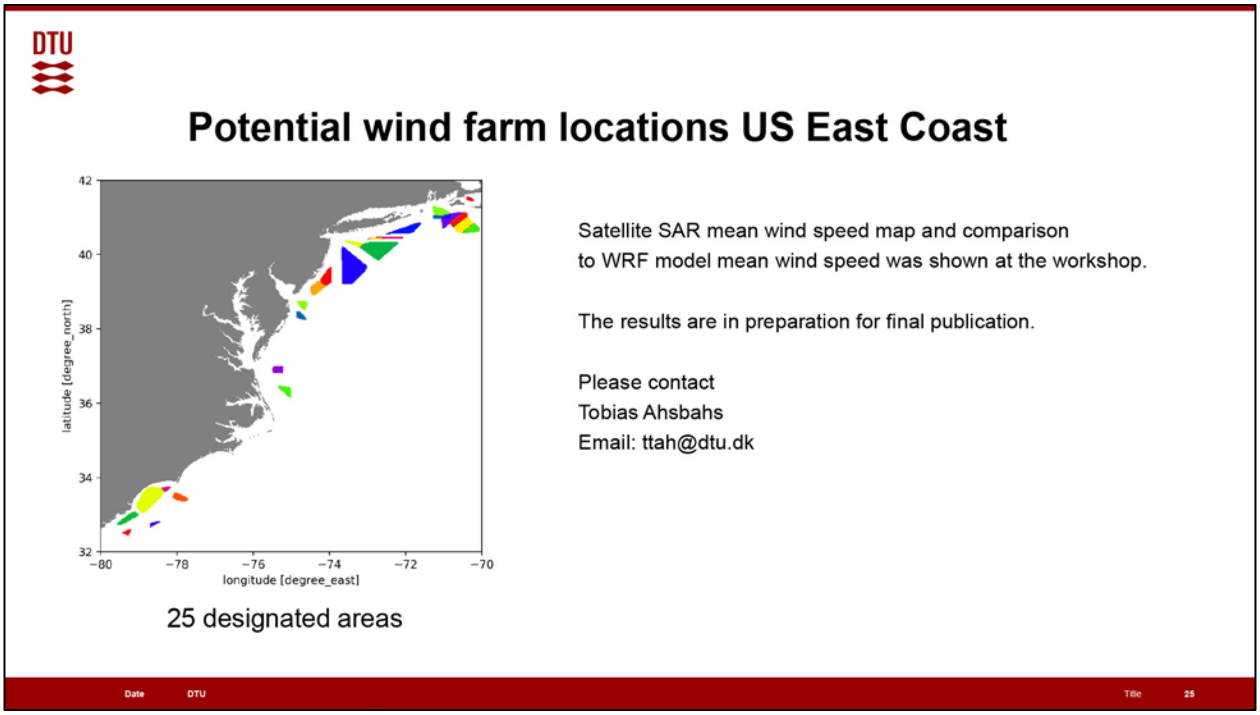
SAR – no wind farm

WRF – 2014

Peña, A & Hahmann, A. N. 2017, 30-year mesoscale model simulations for the "Noise from wind turbines and risk of cardiovascular disease" project. DTU Wind Energy E, vol. 0055

Ahsbahs, T., Badger, M., Volker, P., Hansen, K.S., Hasager, C.B. 2018 Applications of satellite winds for the offshore wind farm site Anholt. *Wind Energy Science* https://doi.org/10.5194/wes-2018-2

Date DTU Title 23



Potential wind farm locations US East Coast

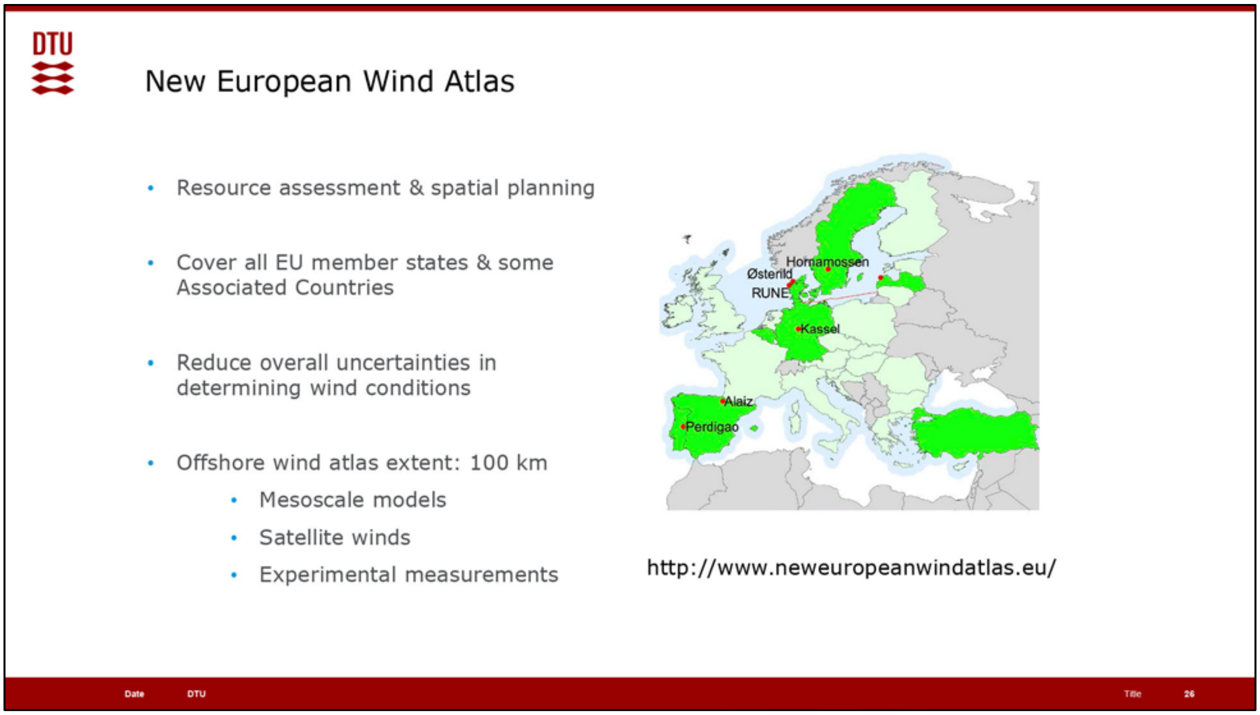
25 designated areas

Satellite SAR mean wind speed map and comparison to WRF model mean wind speed was shown at the workshop.

The results are in preparation for final publication.

Please contact
Tobias Ahsbahs
Email: ttah@dtu.dk

Date DTU Title 25



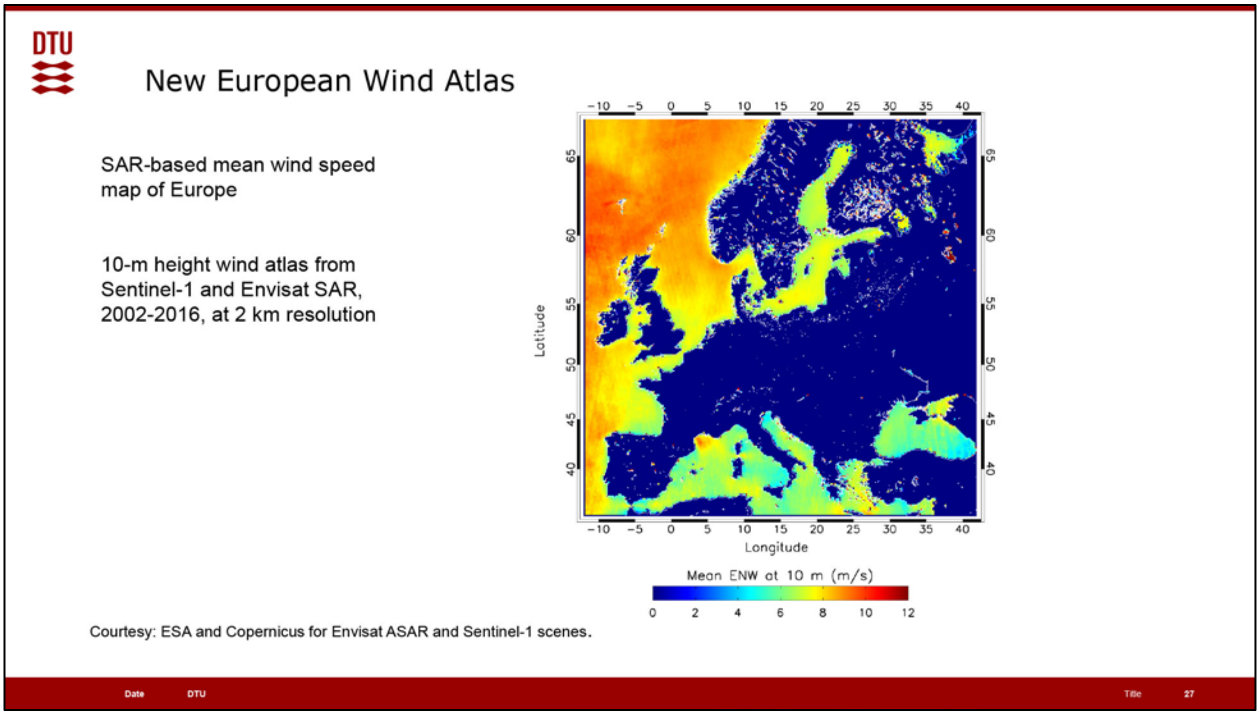
DTU

New European Wind Atlas

- Resource assessment & spatial planning
- Cover all EU member states & some Associated Countries
- Reduce overall uncertainties in determining wind conditions
- Offshore wind atlas extent: 100 km
  - Mesoscale models
  - Satellite winds
  - Experimental measurements

http://www.neweuropeanwindatlas.eu/

Date DTU Title 26



DTU

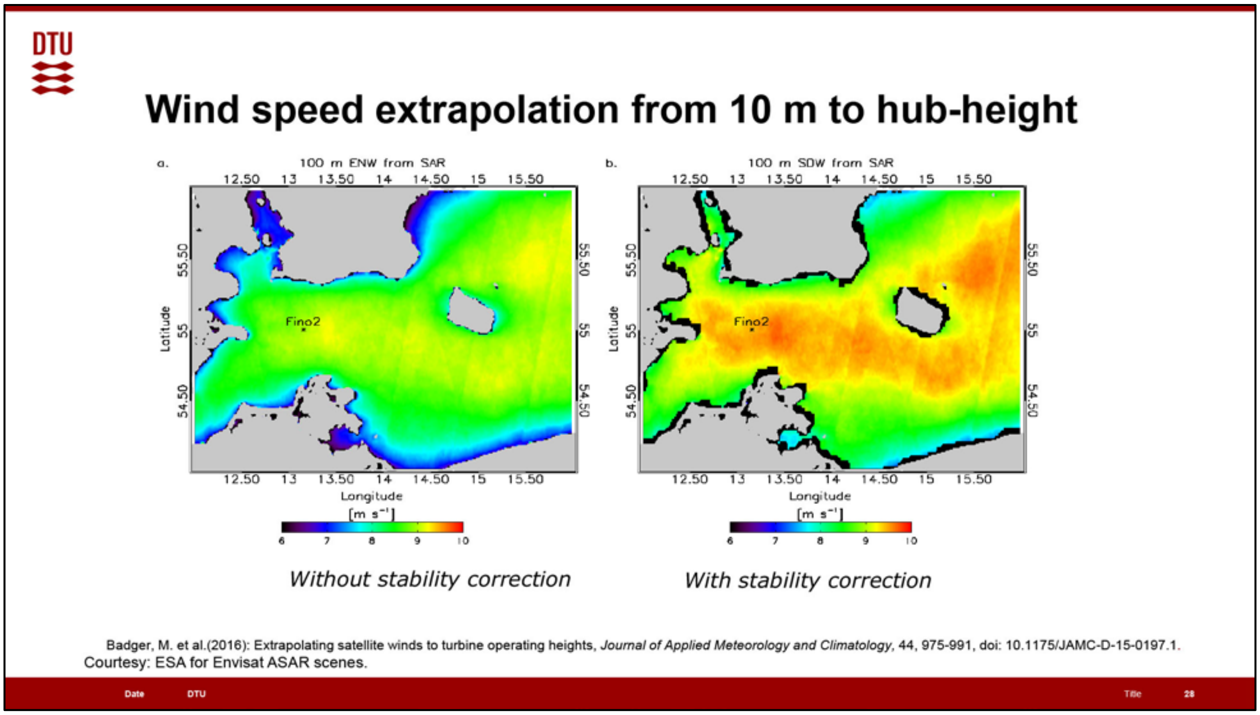
New European Wind Atlas

SAR-based mean wind speed map of Europe

10-m height wind atlas from Sentinel-1 and Envisat SAR, 2002-2016, at 2 km resolution

Courtesy: ESA and Copernicus for Envisat ASAR and Sentinel-1 scenes.

Date DTU Title 27



Wind speed extrapolation from 10 m to hub-height

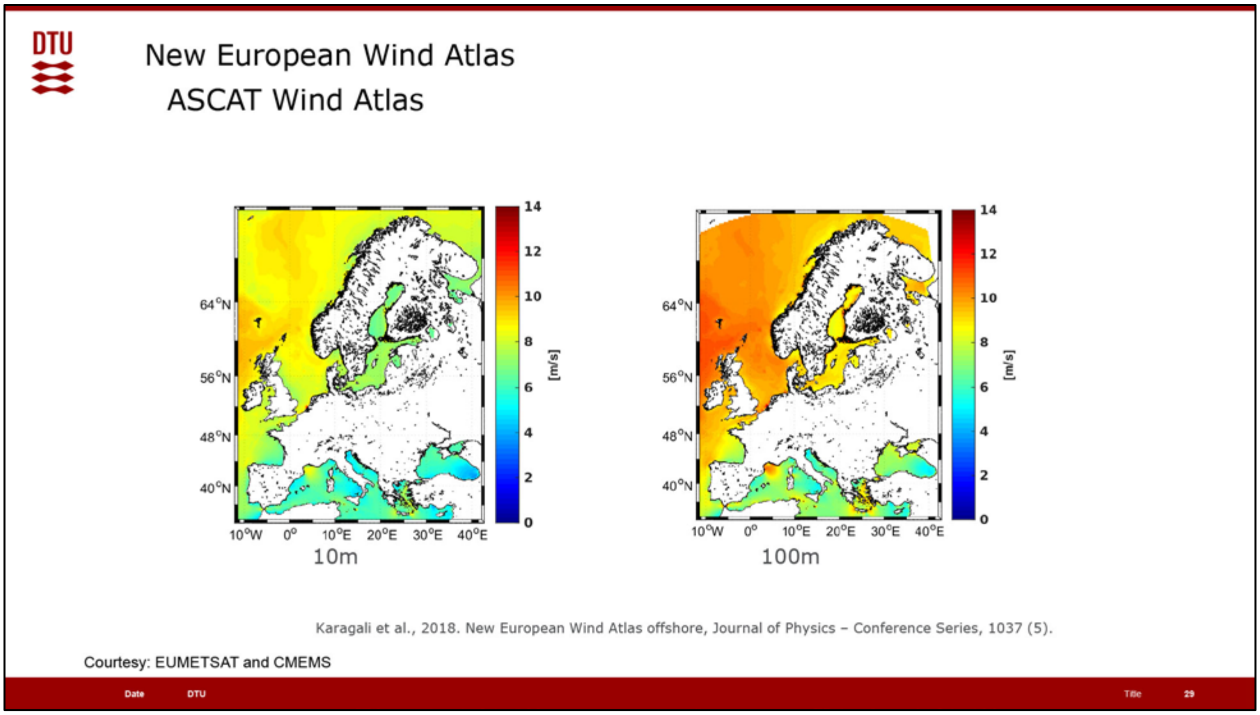
Without stability correction

With stability correction

Badger, M. et al.(2016): Extrapolating satellite winds to turbine operating heights, *Journal of Applied Meteorology and Climatology*, 44, 975-991, doi: 10.1175/JAMC-D-15-0197.1.

Courtesy: ESA for Envisat ASAR scenes.

Date DTU Title 28



New European Wind Atlas
ASCAT Wind Atlas

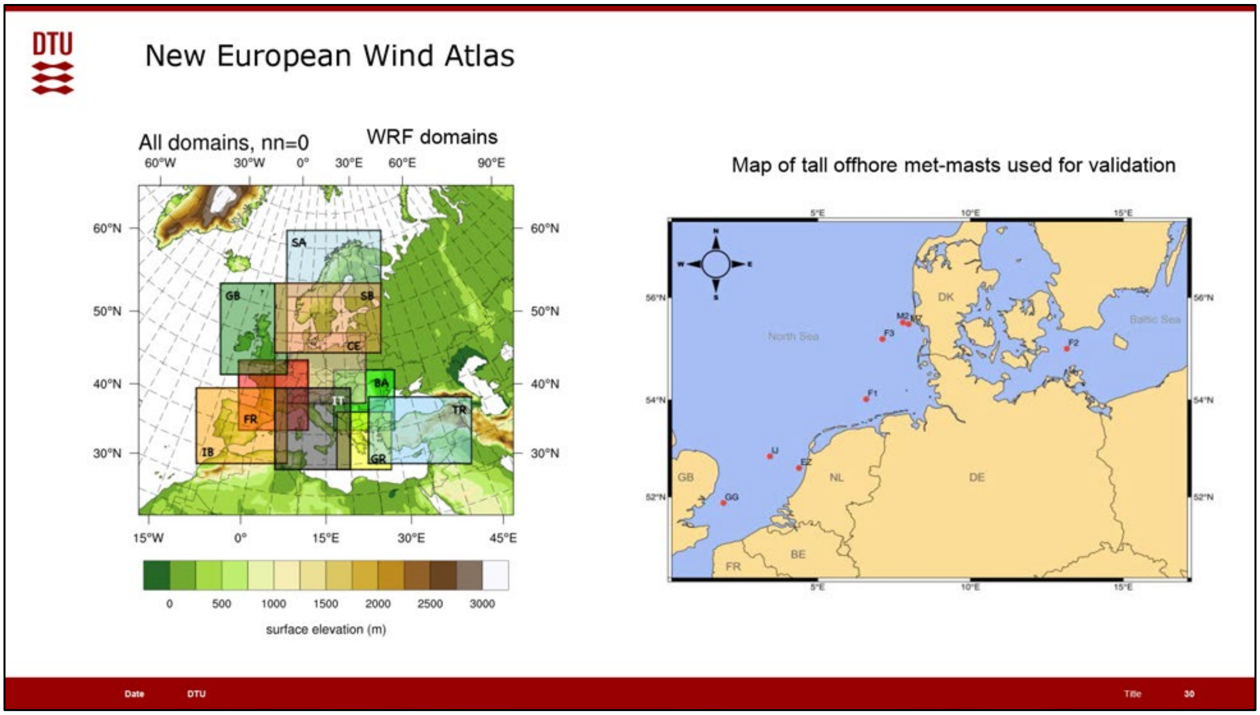
10m

100m

Karagali et al., 2018. New European Wind Atlas offshore, Journal of Physics – Conference Series, 1037 (5).

Courtesy: EUMETSAT and CMEMS

Date DTU Title 29



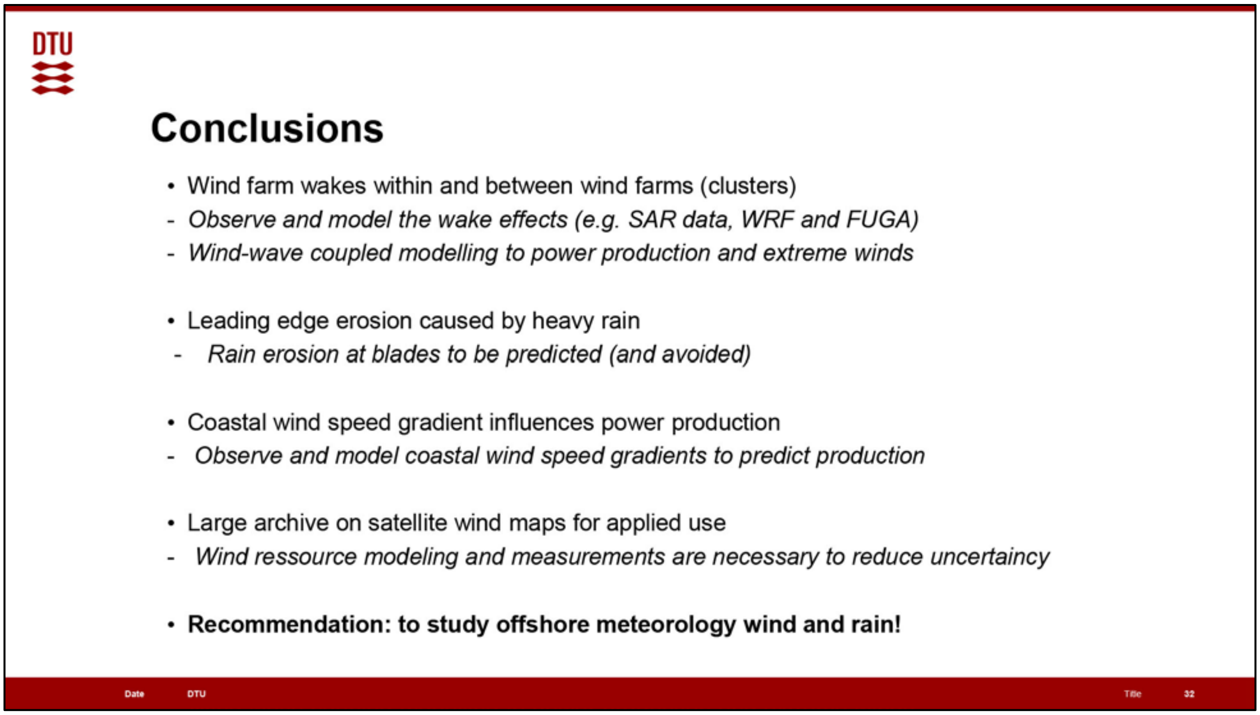
New European Wind Atlas

New European Wind Atlas

- First release at Wind Europe Conference in Bilbao 2-4 April 2019
- Final release at
- Wind Europe Technology Workshop: Resource assessment 2019

27 – 28 June, Brussels, Belgium

The 5th edition of this technology workshop will focus on reducing uncertainty in wind farm resource assessment.



Conclusions

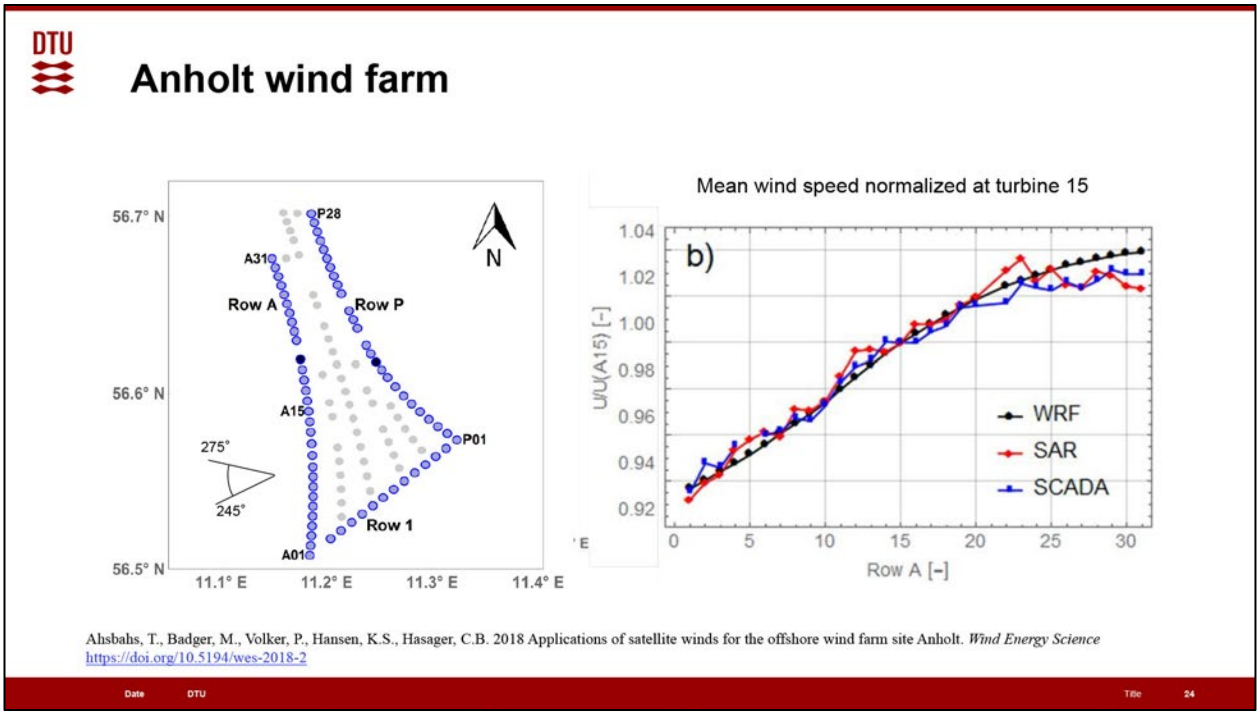
- Wind farm wakes within and between wind farms (clusters)
- *Observe and model the wake effects (e.g. SAR data, WRF and FUGA)*
- *Wind-wave coupled modelling to power production and extreme winds*

- Leading edge erosion caused by heavy rain
- *Rain erosion at blades to be predicted (and avoided)*

- Coastal wind speed gradient influences power production
- *Observe and model coastal wind speed gradients to predict production*

- Large archive on satellite wind maps for applied use
- *Wind ressource modeling and measurements are necessary to reduce uncertaincy*

- **Recommendation: to study offshore meteorology wind and rain!**



Anholt wind farm

Ahsbahs, T., Badger, M., Volker, P., Hansen, K.S., Hasager, C.B. 2018 Applications of satellite winds for the offshore wind farm site Anholt. *Wind Energy Science* https://doi.org/10.5194/wes-2018-2

C.2 Session 1: Michael Drunsic

Industry Requirements for Metocean Information

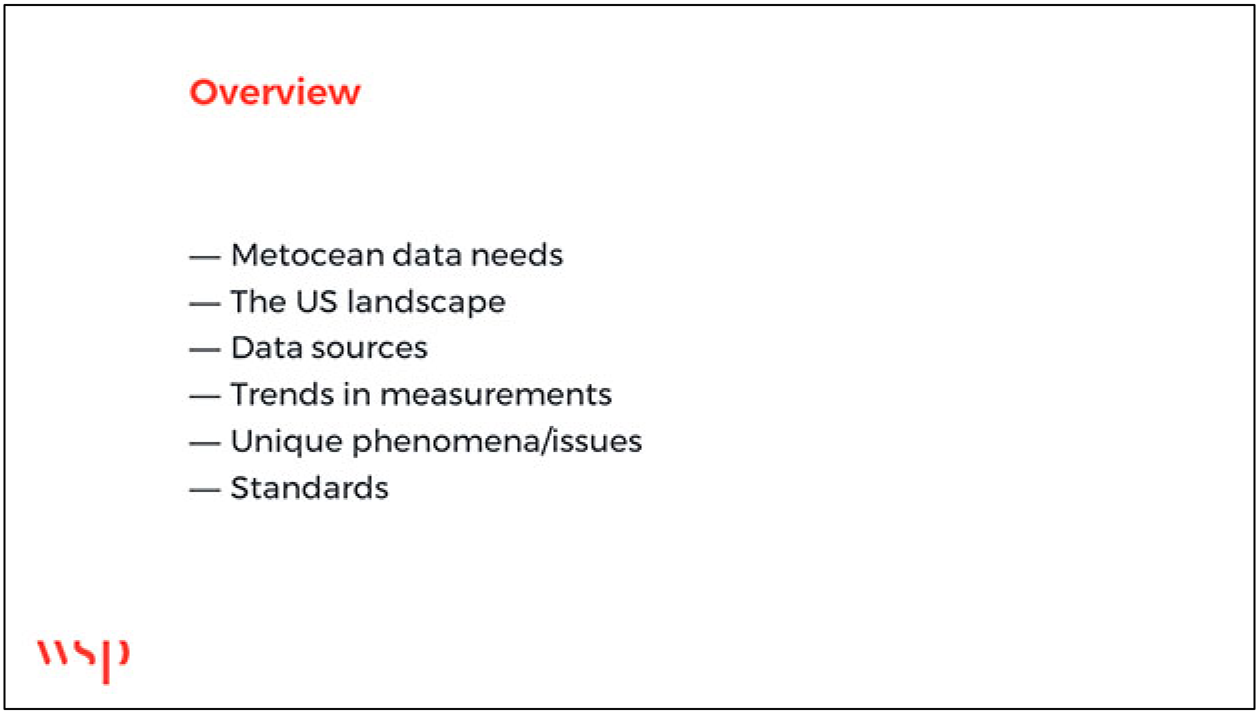
MARCH 5–6, 2019

EMBASSY SUITES BY HILTON, ALEXANDRIA, VA

2019 Research Needs for Offshore Wind Resource Characterization

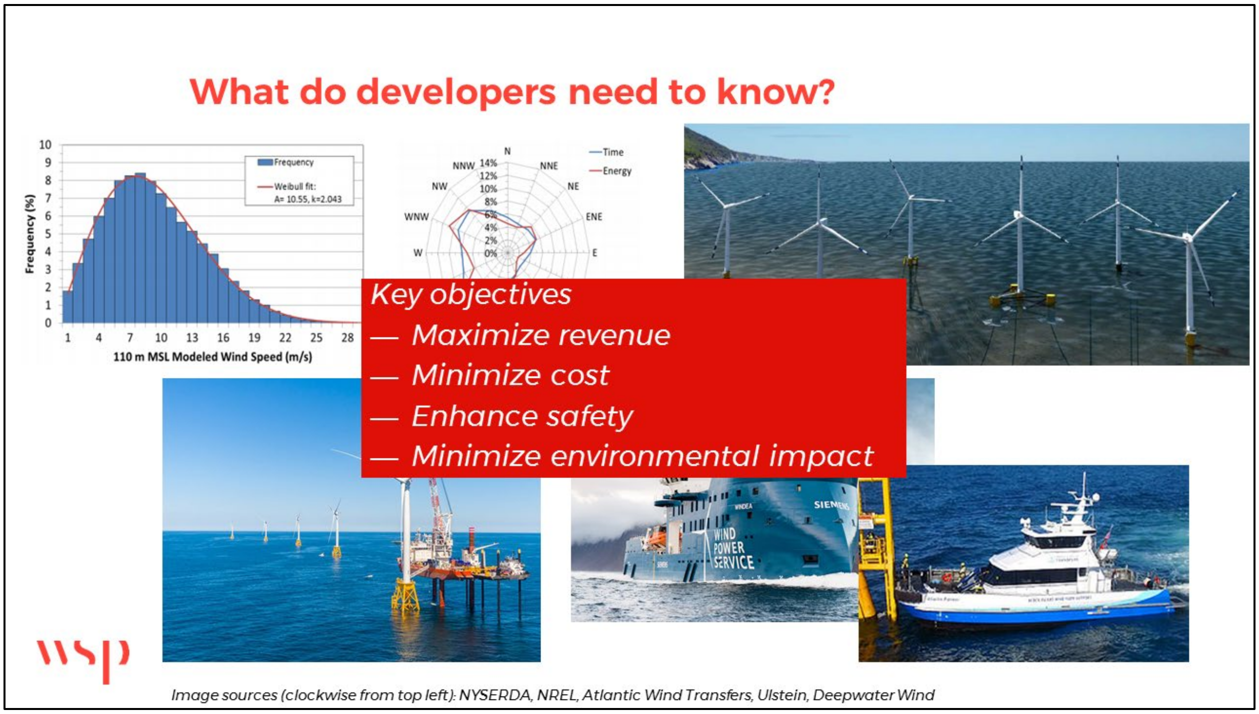
U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY



Overview

— Metocean data needs
— The US landscape
— Data sources
— Trends in measurements
— Unique phenomena/issues
— Standards

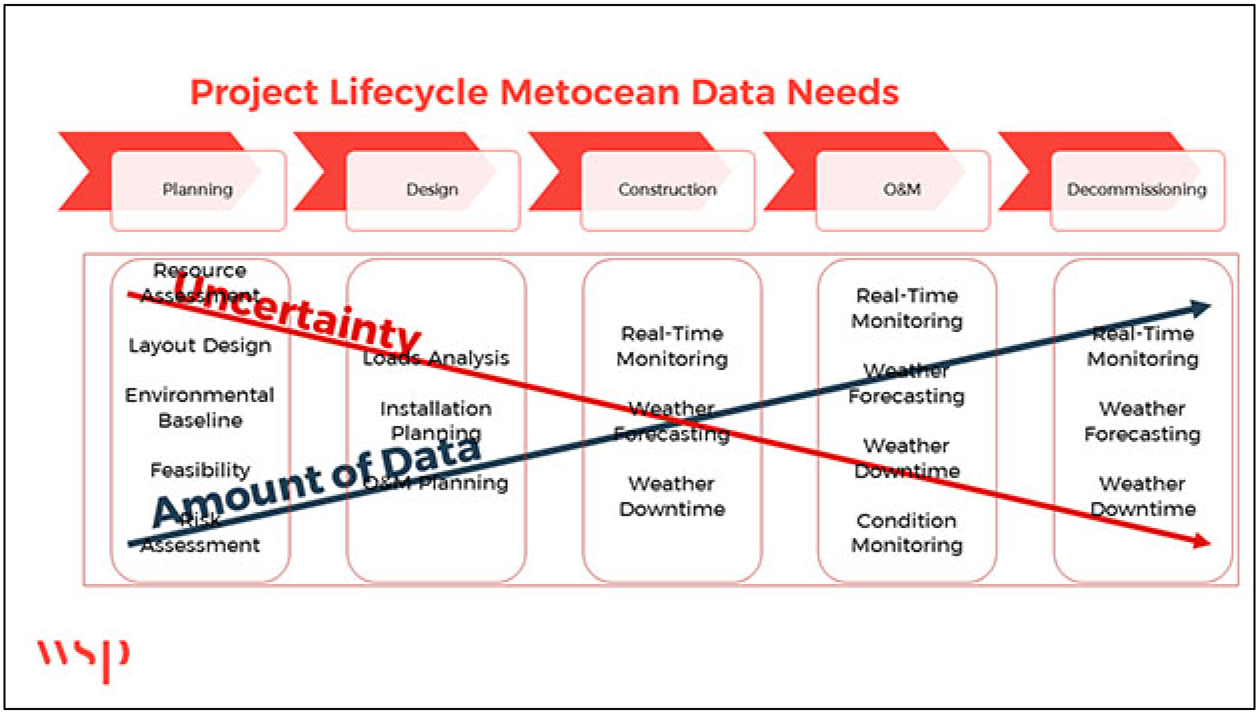


What do developers need to know?

Key objectives

- *Maximize revenue*
- *Minimize cost*
- *Enhance safety*
- *Minimize environmental impact*

Image sources (clockwise from top left): NYSERDA, NREL, Atlantic Wind Transfers, Ulstein, Deepwater Wind



Project Lifecycle Metocean Data Needs

Planning
- Resource Assessment
- Layout Design
- Environmental Baseline
- Feasibility
- Risk Assessment

Design
- Loads Analysis
- Installation Planning
- O&M Planning

Construction
- Real-Time Monitoring
- Weather Forecasting
- Weather Downtime

O&M
- Real-Time Monitoring
- Weather Forecasting
- Weather Downtime
- Condition Monitoring

Decommissioning
- Real-Time Monitoring
- Weather Forecasting
- Weather Downtime

The US Land(Ocean)scape

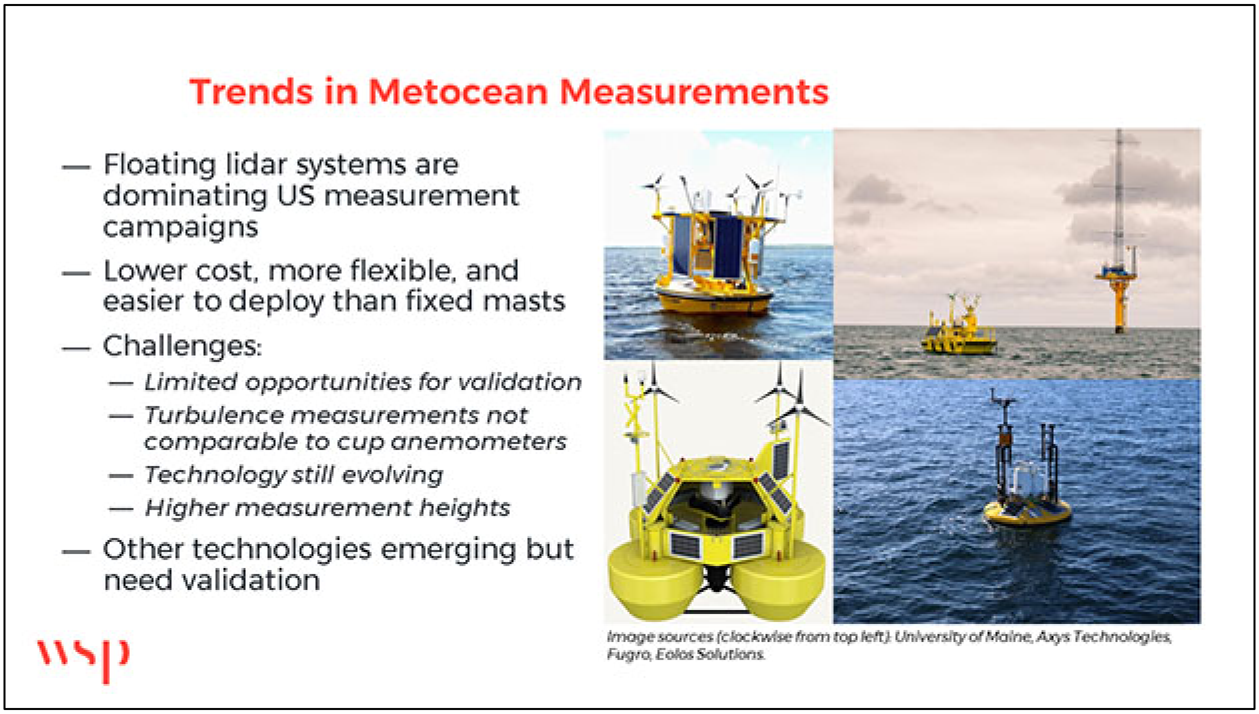
- Limited data
- Limited offshore wind experience
- Unique phenomena
- Diversity of metocean environments

US Lidar Campaigns (through 2017)

Image source: Carbon Trust

Data Sources

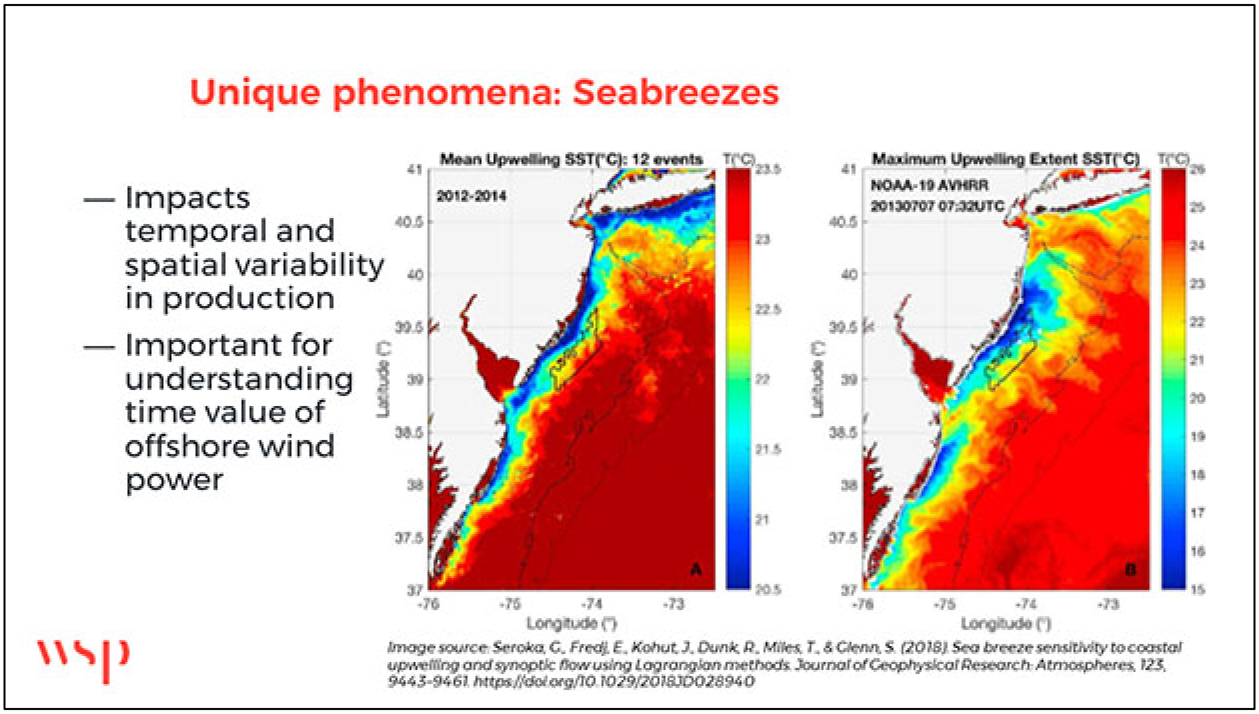
- Publicly available data sets
  - *NREL Wind Prospector (maps.nrel.gov/wind-prospector/)*
  - *MarineCadastre.gov*
  - *Northeast Ocean Data (https://www.northeastoceandata.org/)*
  - *Mid-Atlantic Ocean Data Portal (http://portal.midatlanticocean.org/)*
  - *US Met-Ocean Data Center for Offshore Renewable Energy (http://www.usmodcore.com/)*
- Purchased hindcast datasets
- In-situ measurements (often proprietary)
- Satellite observations
- Forecasts



Trends in Metocean Measurements

- Floating lidar systems are dominating US measurement campaigns
- Lower cost, more flexible, and easier to deploy than fixed masts
- Challenges:
  - *Limited opportunities for validation*
  - *Turbulence measurements not comparable to cup anemometers*
  - *Technology still evolving*
  - *Higher measurement heights*
- Other technologies emerging but need validation

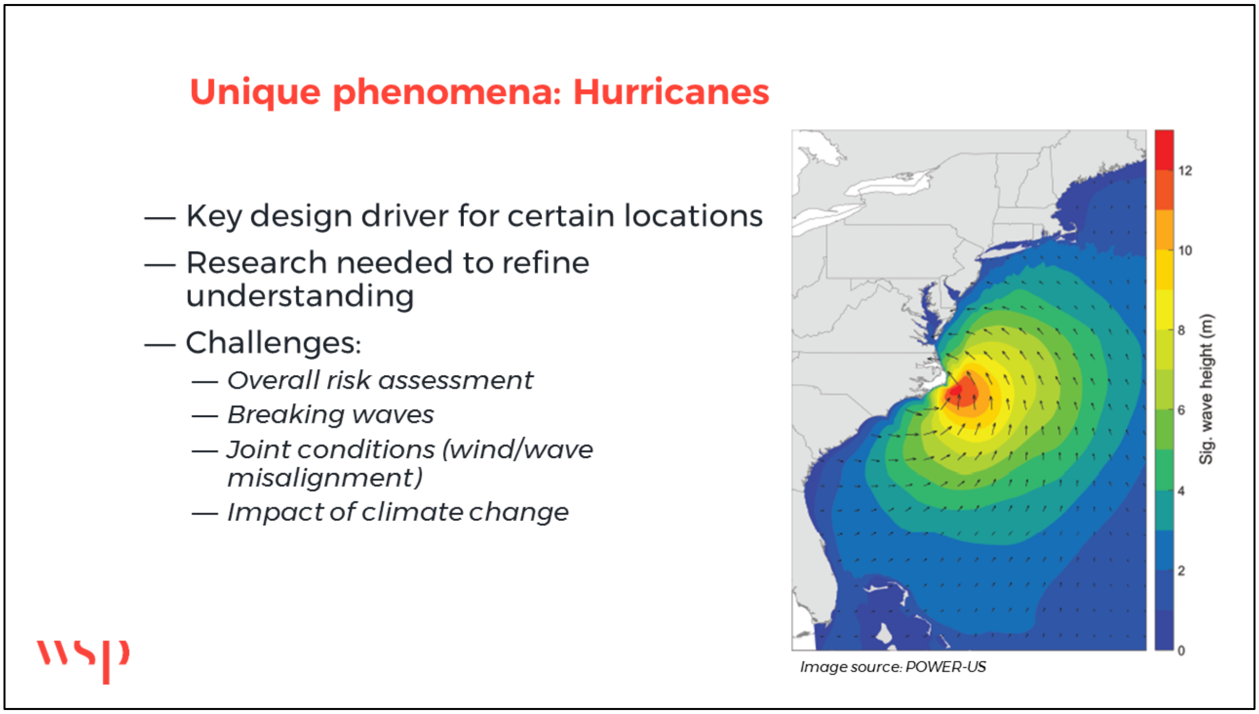
Image sources (clockwise from top left): University of Maine, Axys Technologies, Fugro, Eolos Solutions.



Unique phenomena: Seabreezes

- Impacts temporal and spatial variability in production
- Important for understanding time value of offshore wind power

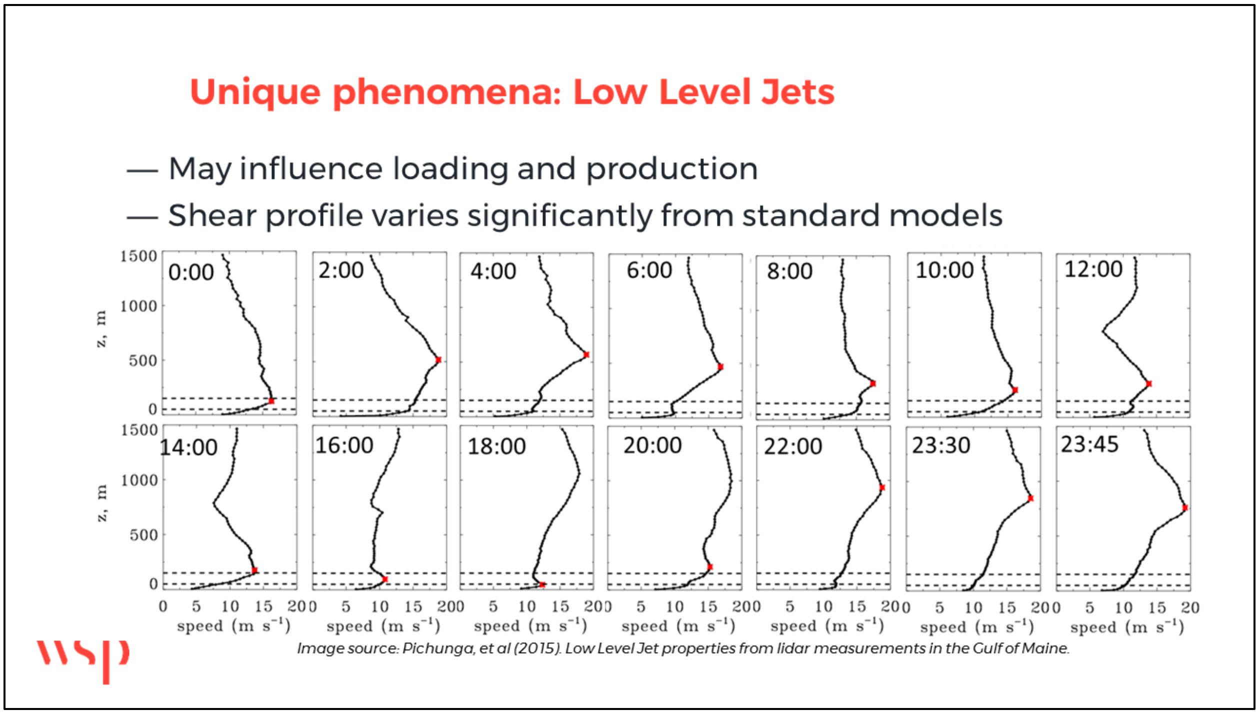
Image source: Seroka, G., Fredj, E., Kohut, J., Dunk, R., Miles, T., & Glenn, S. (2018). Sea breeze sensitivity to coastal upwelling and synoptic flow using Lagrangian methods. Journal of Geophysical Research: Atmospheres, 123, 9443–9461. https://doi.org/10.1029/2018JD028940



Unique phenomena: Hurricanes

- Key design driver for certain locations
- Research needed to refine understanding
- Challenges:
  - *Overall risk assessment*
  - *Breaking waves*
  - *Joint conditions (wind/wave misalignment)*
  - *Impact of climate change*

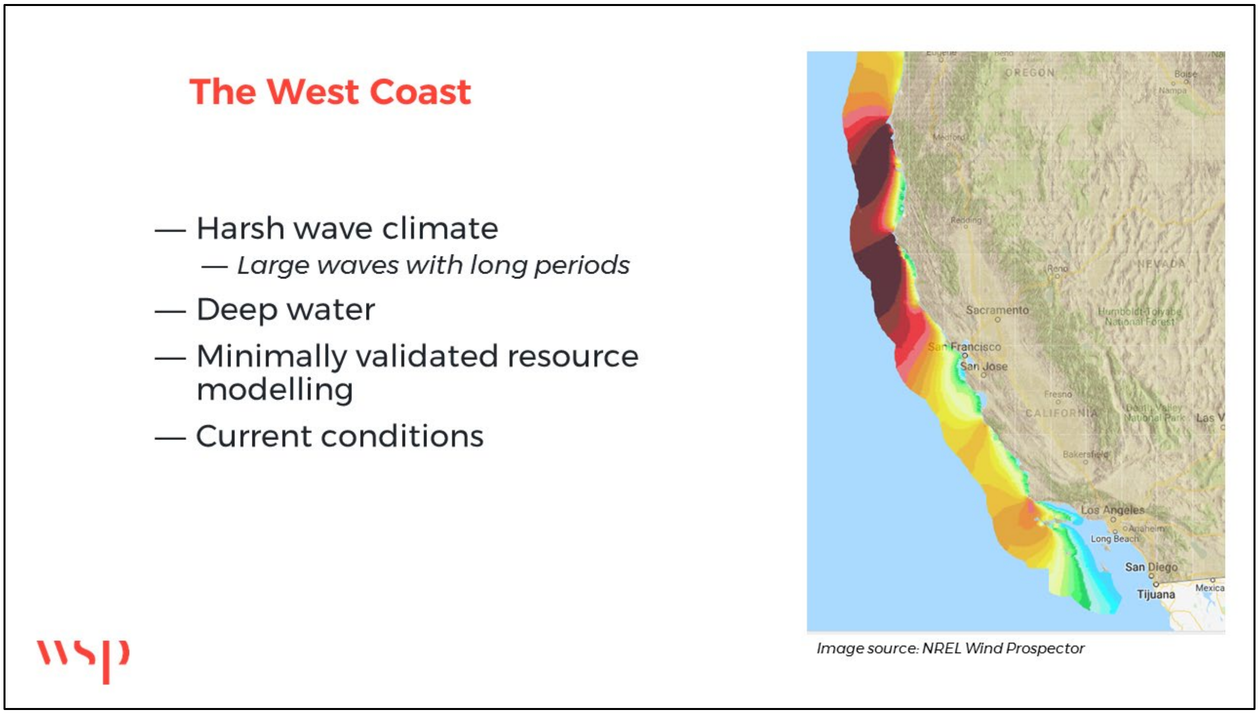
Image source: POWER-US



Unique phenomena: Low Level Jets

- May influence loading and production
- Shear profile varies significantly from standard models

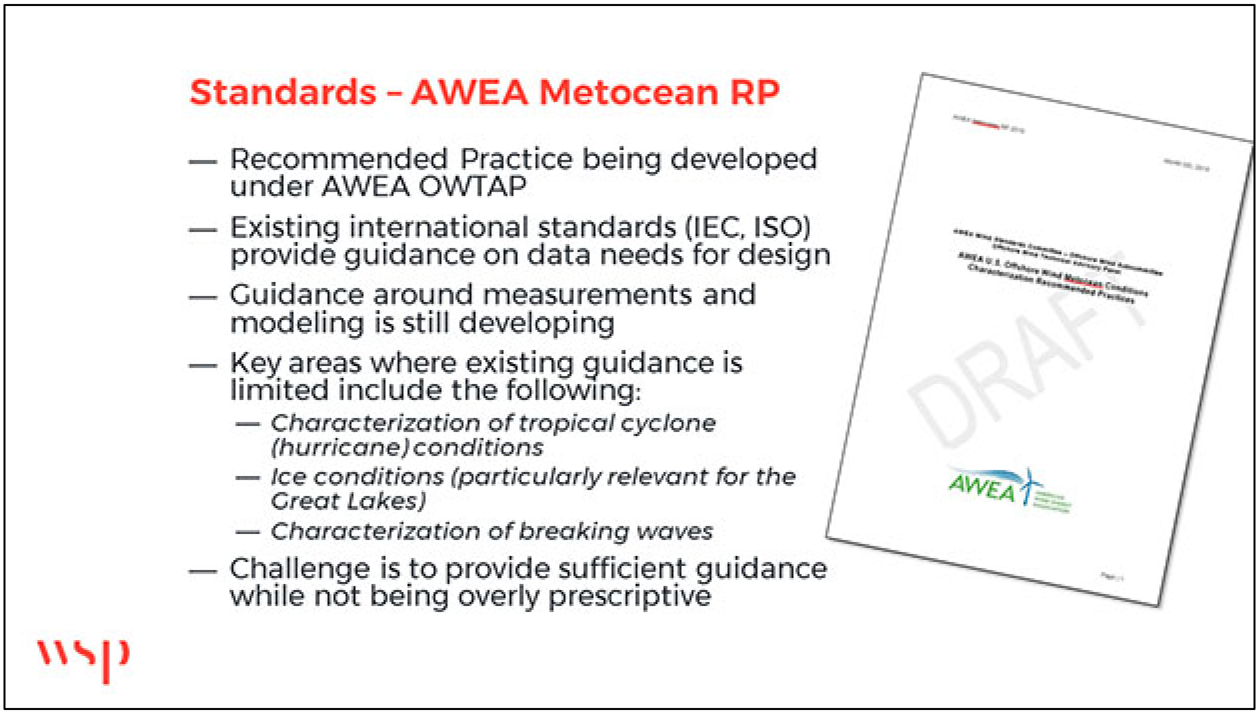
Image source: Pichunga, et al (2015). Low Level Jet properties from lidar measurements in the Gulf of Maine.



The West Coast

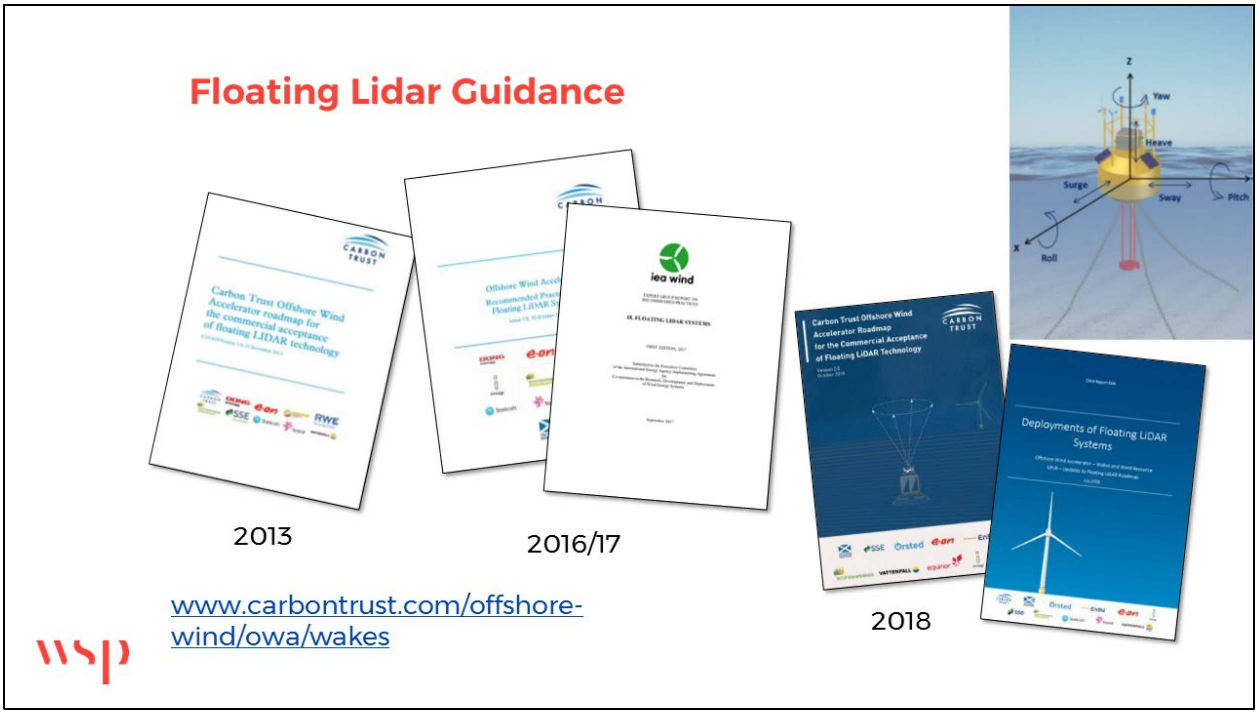
- Harsh wave climate
  - *Large waves with long periods*
- Deep water
- Minimally validated resource modelling
- Current conditions

Image source: NREL Wind Prospector



Standards – AWEA Metocean RP

- Recommended Practice being developed under AWEA OWTAP
- Existing international standards (IEC, ISO) provide guidance on data needs for design
- Guidance around measurements and modeling is still developing
- Key areas where existing guidance is limited include the following:
  - *Characterization of tropical cyclone (hurricane) conditions*
  - *Ice conditions (particularly relevant for the Great Lakes)*
  - *Characterization of breaking waves*
- Challenge is to provide sufficient guidance while not being overly prescriptive



Floating Lidar Guidance

2013

2016/17

2018

www.carbontrust.com/offshore-wind/owa/wakes

Conclusions

- Need for more in-situ measurements
- National reference stations would provide significant value to the industry
- Research should prioritize developments that
  - *Reduce cost of measurements*
  - *Increase confidence in measurements*
  - *Enhance understanding of unique phenomena*
- Continual development of best practices

Thank You!

Michael W. Drunsic
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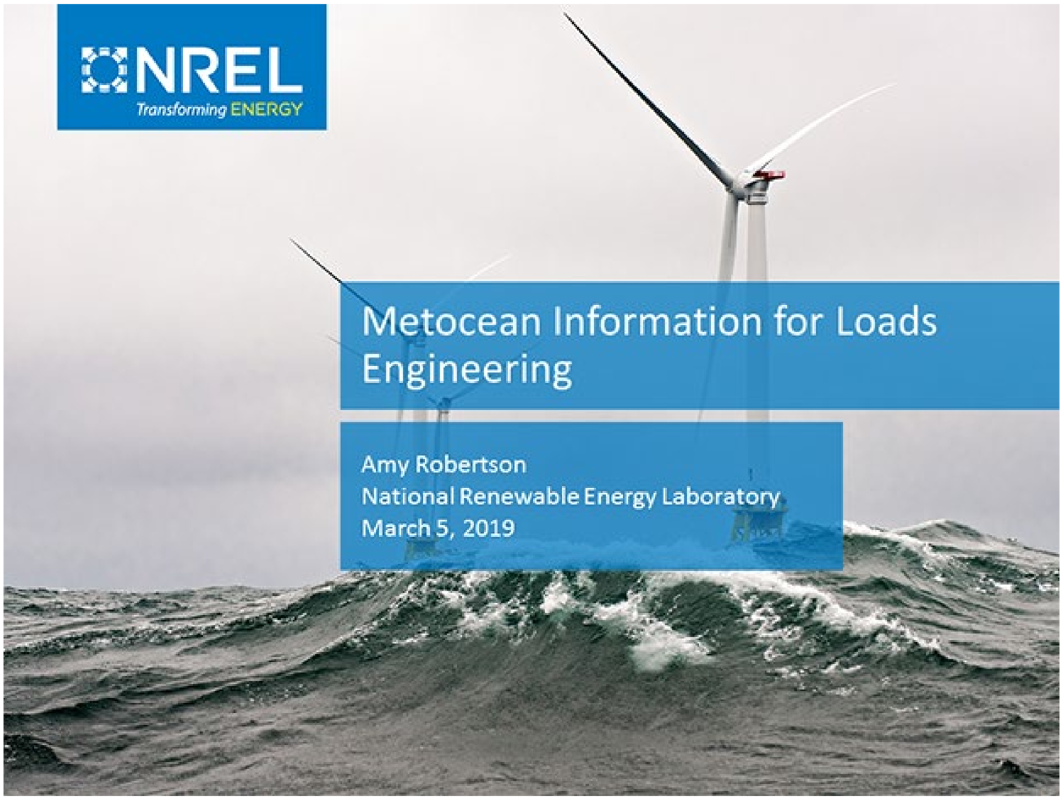
Michael.Drunsic@wsp.com
Direct: +1 617 960-4800
Mobile: +1 603 793-7625

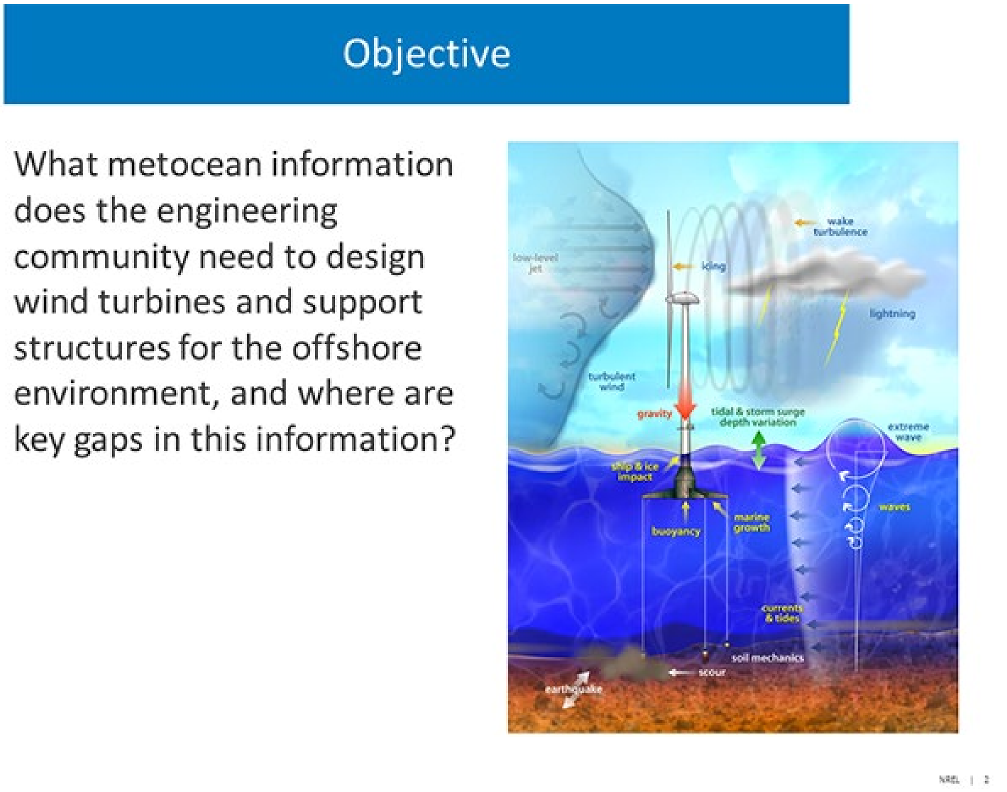
C.3 Session 2: Amy Robertson



NREL Transforming ENERGY

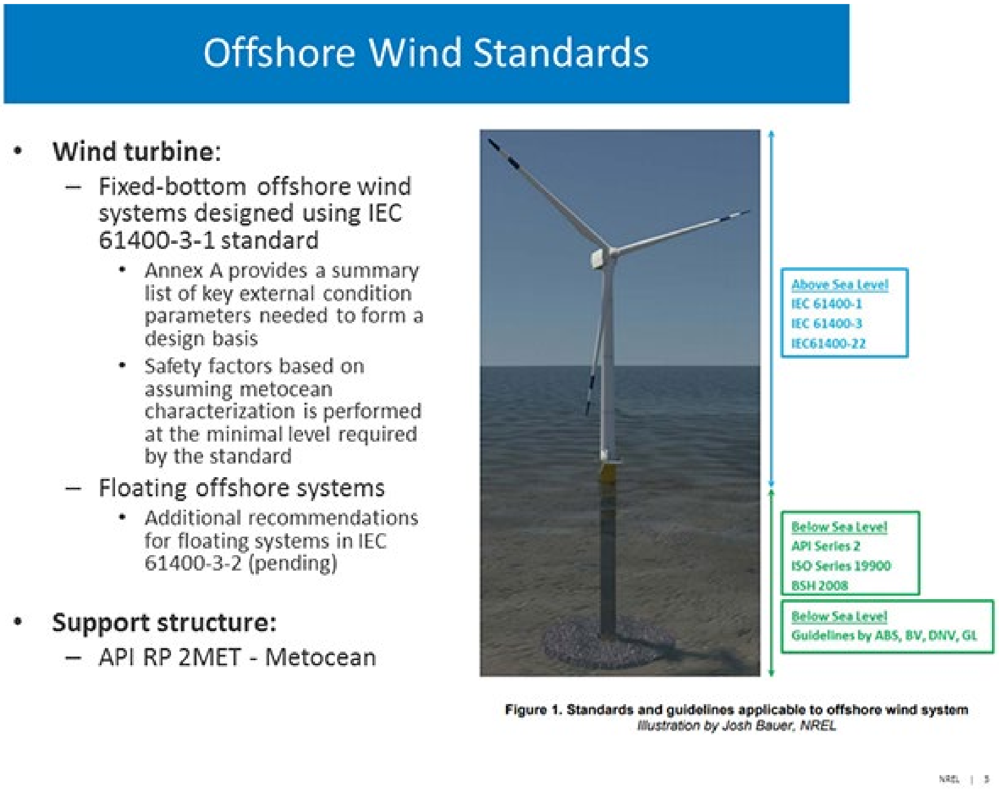
Metocean Information for Loads Engineering

Amy Robertson
National Renewable Energy Laboratory
March 5, 2019



Objective

What metocean information does the engineering community need to design wind turbines and support structures for the offshore environment, and where are key gaps in this information?



Offshore Wind Standards

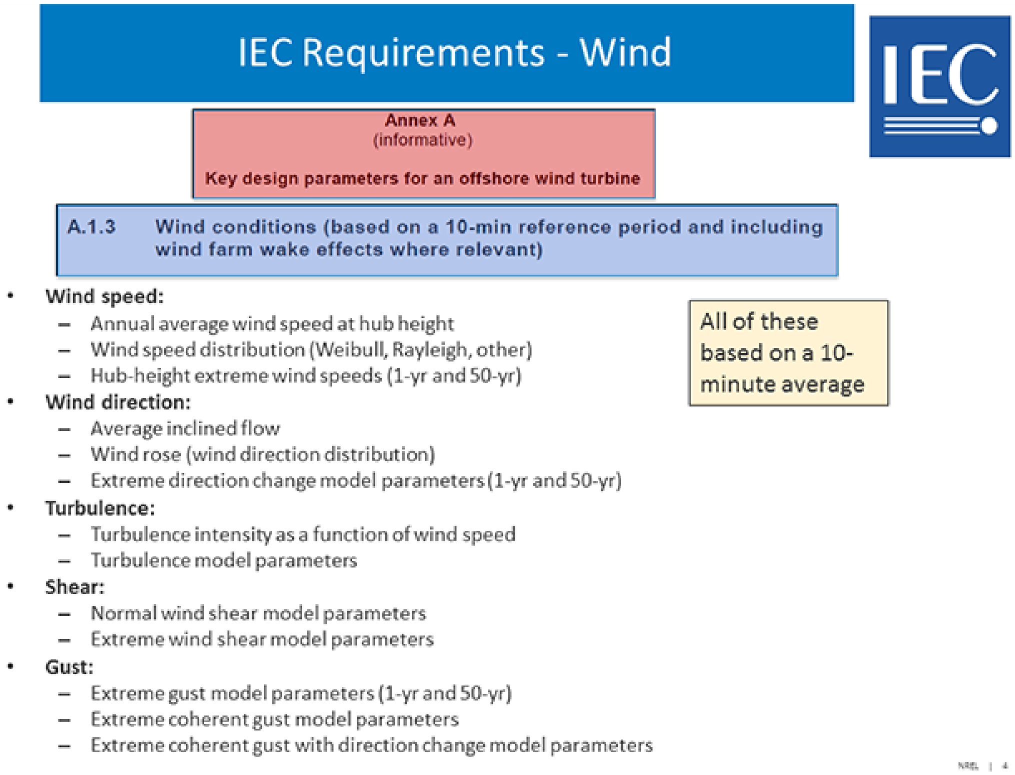
- **Wind turbine:**
  - Fixed-bottom offshore wind systems designed using IEC 61400-3-1 standard
    - Annex A provides a summary list of key external condition parameters needed to form a design basis
    - Safety factors based on assuming metocean characterization is performed at the minimal level required by the standard
  - Floating offshore systems
    - Additional recommendations for floating systems in IEC 61400-3-2 (pending)
- **Support structure:**
  - API RP 2MET - Metocean

Above Sea Level
IEC 61400-1
IEC 61400-3
IEC61400-22

Below Sea Level
API Series 2
ISO Series 19900
BSH 2008

Below Sea Level
Guidelines by ABS, BV, DNV, GL

Figure 1. Standards and guidelines applicable to offshore wind system
Illustration by Josh Bauer, NREL



IEC Requirements - Wind

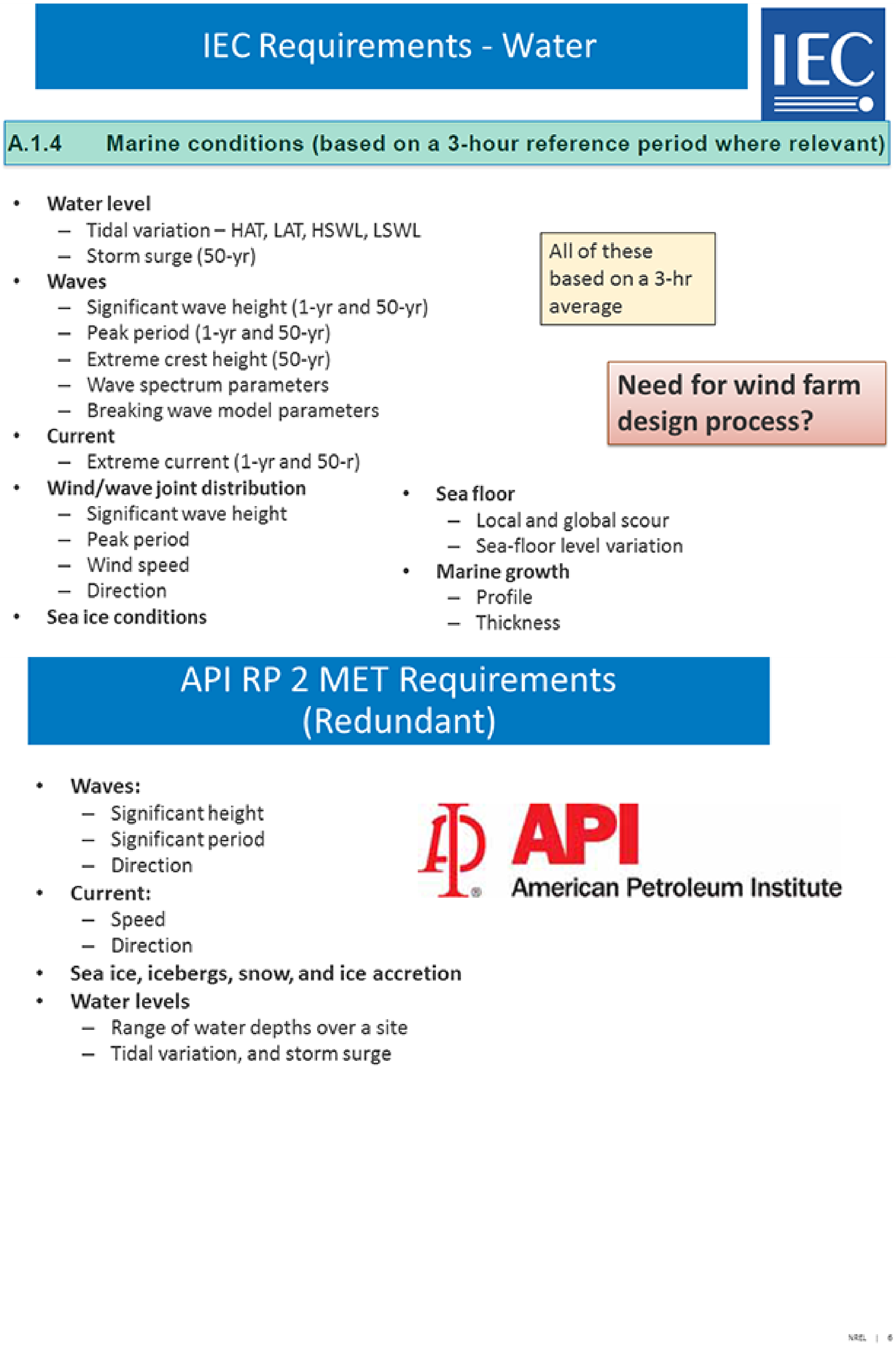
Annex A
(informative)

Key design parameters for an offshore wind turbine

A.1.3 Wind conditions (based on a 10-min reference period and including wind farm wake effects where relevant)

- **Wind speed:**
  - Annual average wind speed at hub height
  - Wind speed distribution (Weibull, Rayleigh, other)
  - Hub-height extreme wind speeds (1-yr and 50-yr)
- **Wind direction:**
  - Average inclined flow
  - Wind rose (wind direction distribution)
  - Extreme direction change model parameters (1-yr and 50-yr)
- **Turbulence:**
  - Turbulence intensity as a function of wind speed
  - Turbulence model parameters
- **Shear:**
  - Normal wind shear model parameters
  - Extreme wind shear model parameters
- **Gust:**
  - Extreme gust model parameters (1-yr and 50-yr)
  - Extreme coherent gust model parameters
  - Extreme coherent gust with direction change model parameters

All of these based on a 10-minute average



IEC Requirements - Water

A.1.4 Marine conditions (based on a 3-hour reference period where relevant)

- **Water level**
  - Tidal variation – HAT, LAT, HSWL, LSWL
  - Storm surge (50-yr)
- **Waves**
  - Significant wave height (1-yr and 50-yr)
  - Peak period (1-yr and 50-yr)
  - Extreme crest height (50-yr)
  - Wave spectrum parameters
  - Breaking wave model parameters
- **Current**
  - Extreme current (1-yr and 50-r)
- **Wind/wave joint distribution**
  - Significant wave height
  - Peak period
  - Wind speed
  - Direction
- **Sea ice conditions**
- **Sea floor**
  - Local and global scour
  - Sea-floor level variation
- **Marine growth**
  - Profile
  - Thickness

All of these based on a 3-hr average

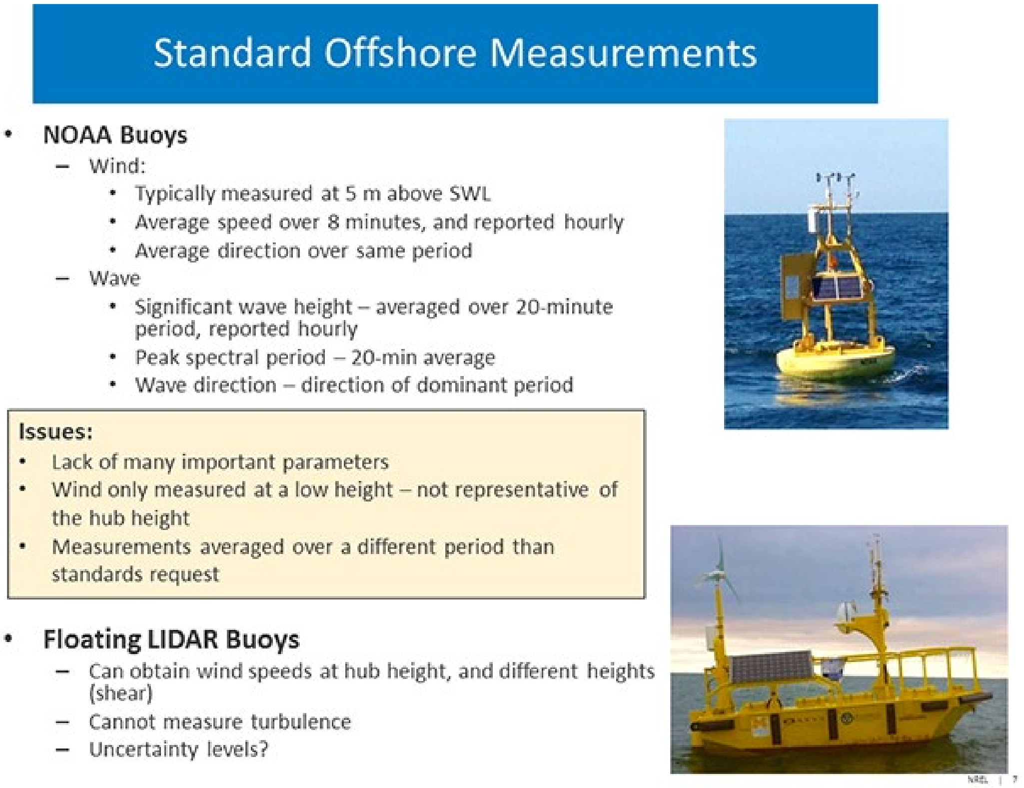
Need for wind farm design process?

API RP 2 MET Requirements (Redundant)

- **Waves:**
  - Significant height
  - Significant period
  - Direction
- **Current:**
  - Speed
  - Direction
- **Sea ice, icebergs, snow, and ice accretion**
- **Water levels**
  - Range of water depths over a site
  - Tidal variation, and storm surge

API American Petroleum Institute

NREL | 6



Standard Offshore Measurements

- **NOAA Buoys**
  - Wind:
    - Typically measured at 5 m above SWL
    - Average speed over 8 minutes, and reported hourly
    - Average direction over same period
  - Wave
    - Significant wave height – averaged over 20-minute period, reported hourly
    - Peak spectral period – 20-min average
    - Wave direction – direction of dominant period

Issues:

- Lack of many important parameters
- Wind only measured at a low height – not representative of the hub height
- Measurements averaged over a different period than standards request

- **Floating LIDAR Buoys**
  - Can obtain wind speeds at hub height, and different heights (shear)
  - Cannot measure turbulence
  - Uncertainty levels?

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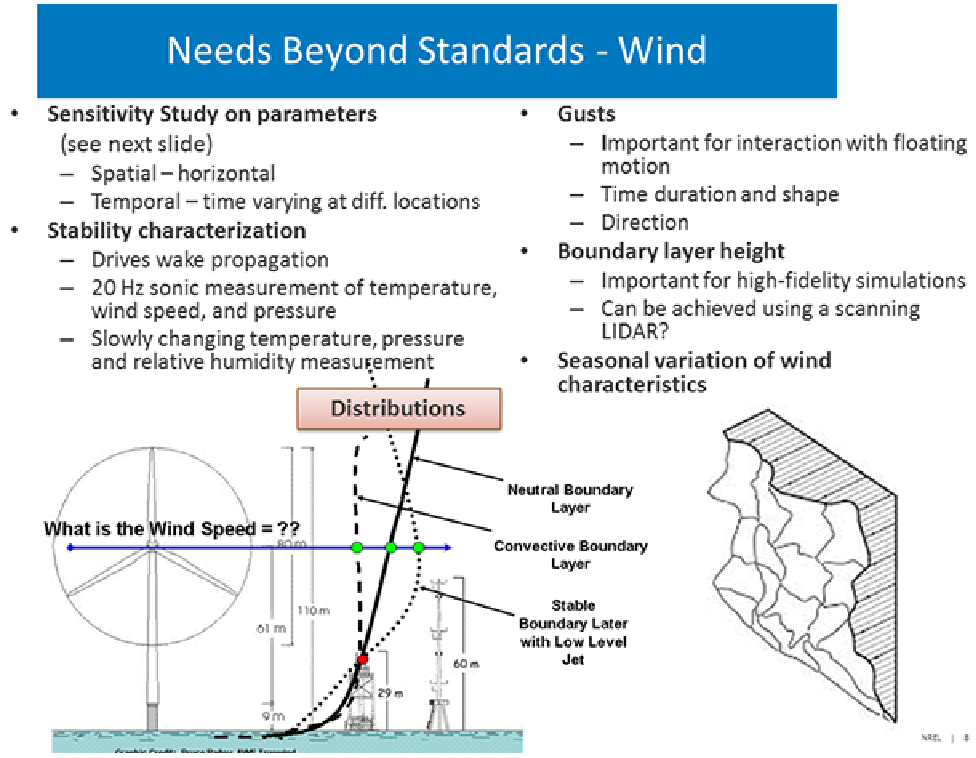
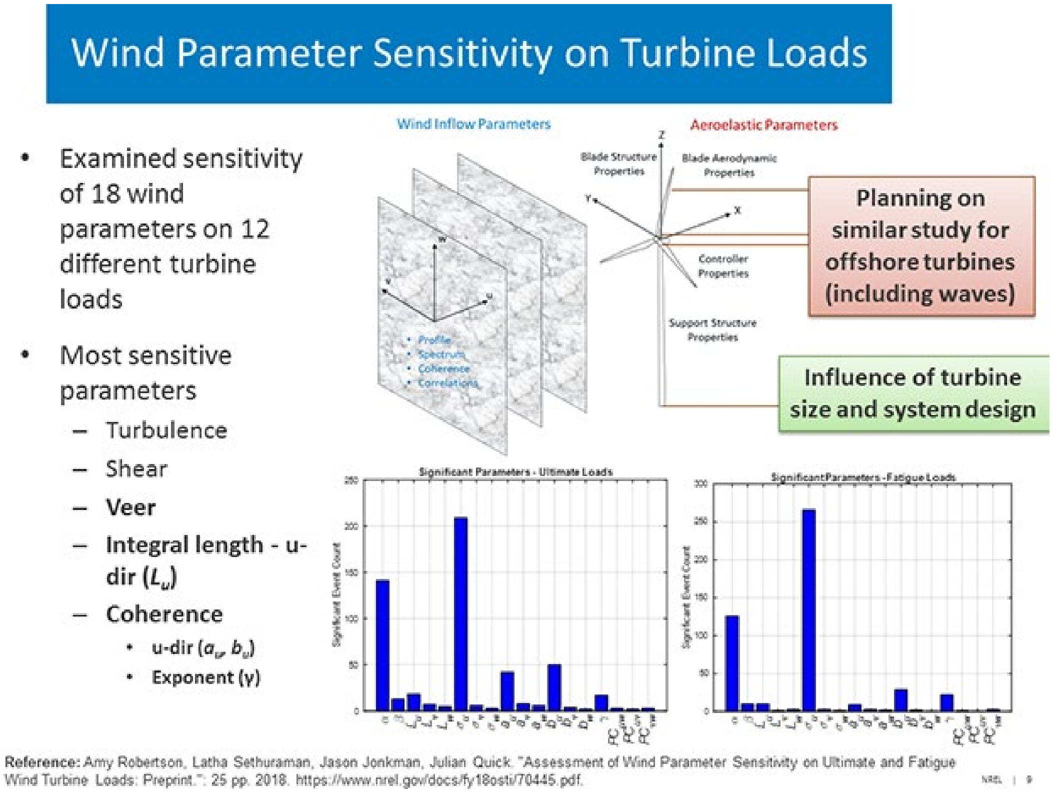


Needs Beyond Standards - Wind

- **Sensitivity Study on parameters** (see next slide)
  - Spatial – horizontal
  - Temporal – time varying at diff. locations
- **Stability characterization**
  - Drives wake propagation
  - 20 Hz sonic measurement of temperature, wind speed, and pressure
  - Slowly changing temperature, pressure and relative humidity measurement
- **Gusts**
  - Important for interaction with floating motion
  - Time duration and shape
  - Direction
- **Boundary layer height**
  - Important for high-fidelity simulations
  - Can be achieved using a scanning LIDAR?
- **Seasonal variation of wind characteristics**

NREL | 8



Wind Parameter Sensitivity on Turbine Loads

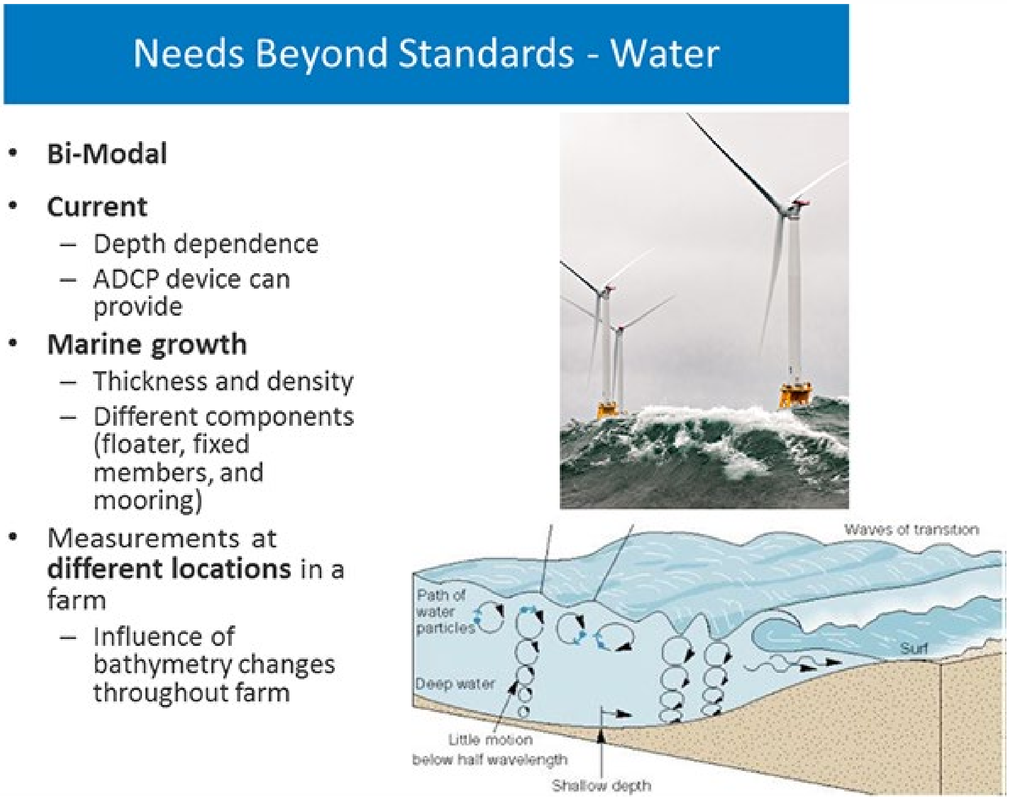
- Examined sensitivity of 18 wind parameters on 12 different turbine loads
- Most sensitive parameters
  - Turbulence
  - Shear
  - **Veer**
  - **Integral length - u-dir (L_u)**
  - **Coherence**
    - **u-dir (a_u, b_u)**
    - **Exponent (γ)**

Planning on similar study for offshore turbines (including waves)

Influence of turbine size and system design

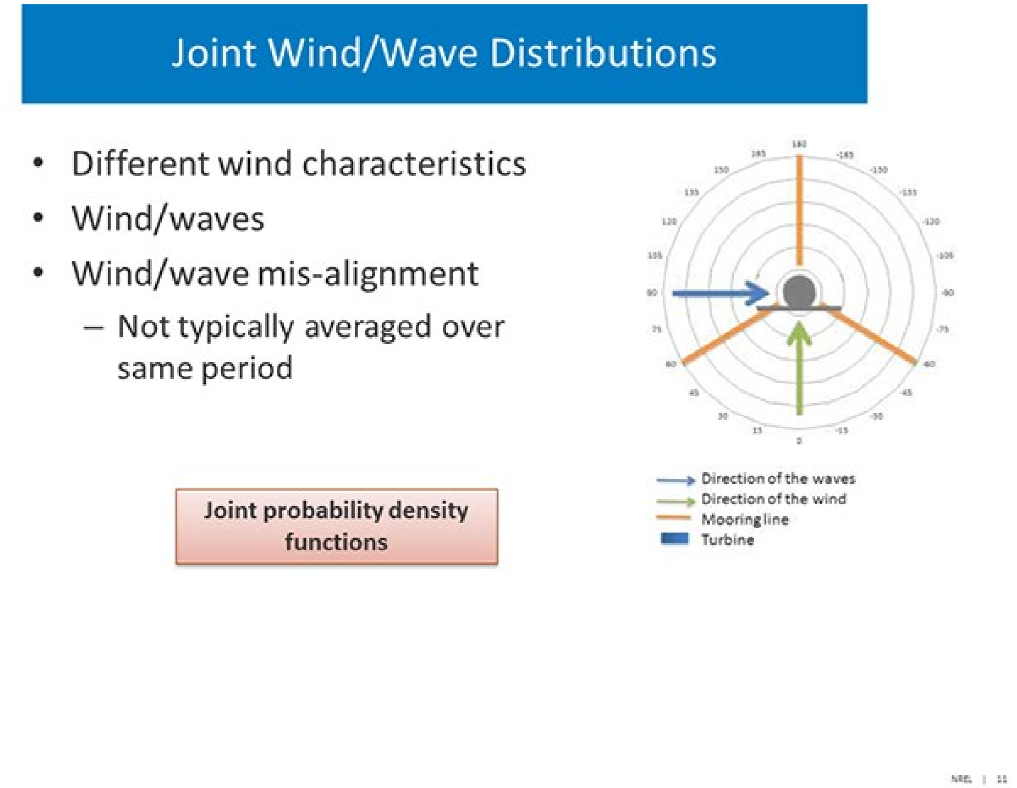
Reference: Amy Robertson, Latha Sethuraman, Jason Jonkman, Julian Quick. "Assessment of Wind Parameter Sensitivity on Ultimate and Fatigue Wind Turbine Loads: Preprint.": 25 pp. 2018. https://www.nrel.gov/docs/fy18osti/70445.pdf.

NREL | 9



Needs Beyond Standards - Water

- **Bi-Modal**
- **Current**
  - Depth dependence
  - ADCP device can provide
- **Marine growth**
  - Thickness and density
  - Different components (floater, fixed members, and mooring)
- Measurements at **different locations** in a farm
  - Influence of bathymetry changes throughout farm

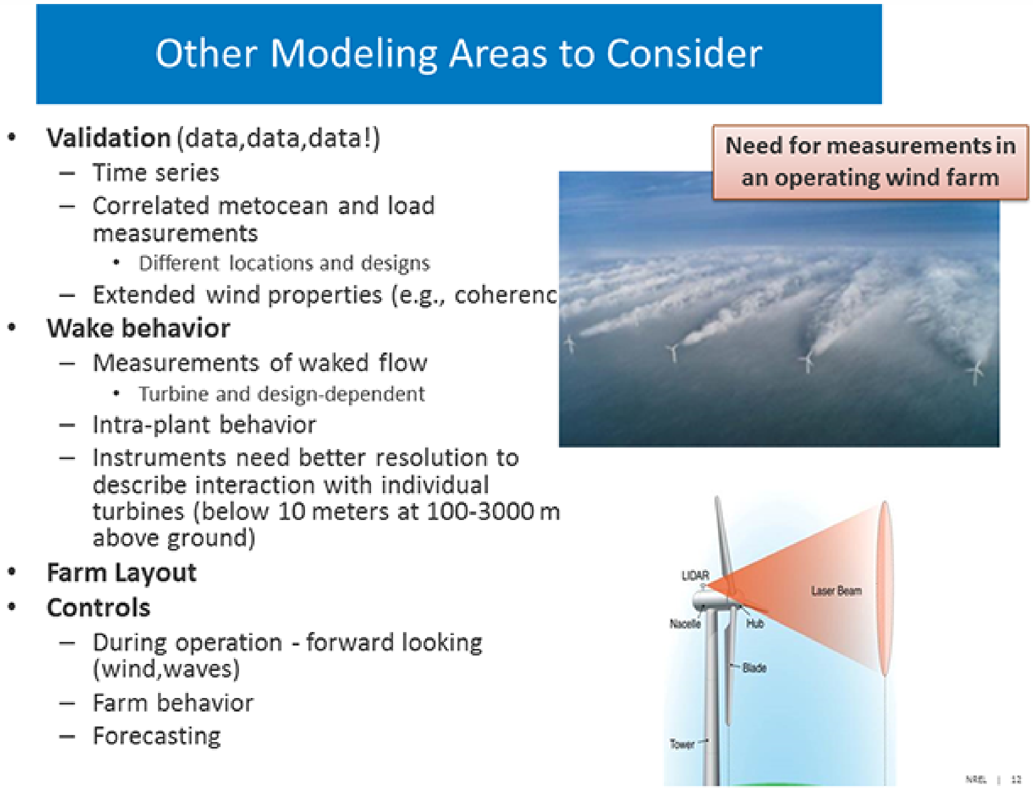


Joint Wind/Wave Distributions

- Different wind characteristics
- Wind/waves
- Wind/wave mis-alignment
  - Not typically averaged over same period

Joint probability density functions

NREL | 11

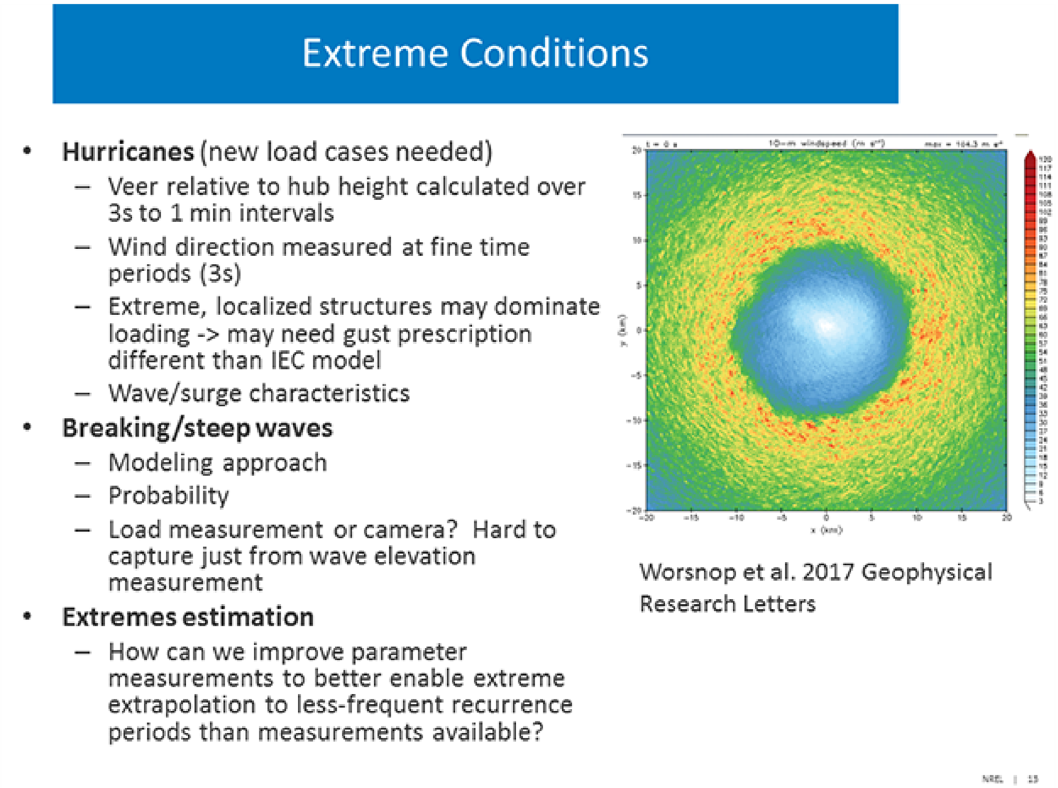


Other Modeling Areas to Consider

- **Validation** (data,data,data!)
  - Time series
  - Correlated metocean and load measurements
    - Different locations and designs
  - Extended wind properties (e.g., coherenc
- **Wake behavior**
  - Measurements of waked flow
    - Turbine and design-dependent
  - Intra-plant behavior
  - Instruments need better resolution to describe interaction with individual turbines (below 10 meters at 100-3000 m above ground)
- **Farm Layout**
- **Controls**
  - During operation - forward looking (wind,waves)
  - Farm behavior
  - Forecasting

Need for measurements in an operating wind farm

NREL | 12



Extreme Conditions

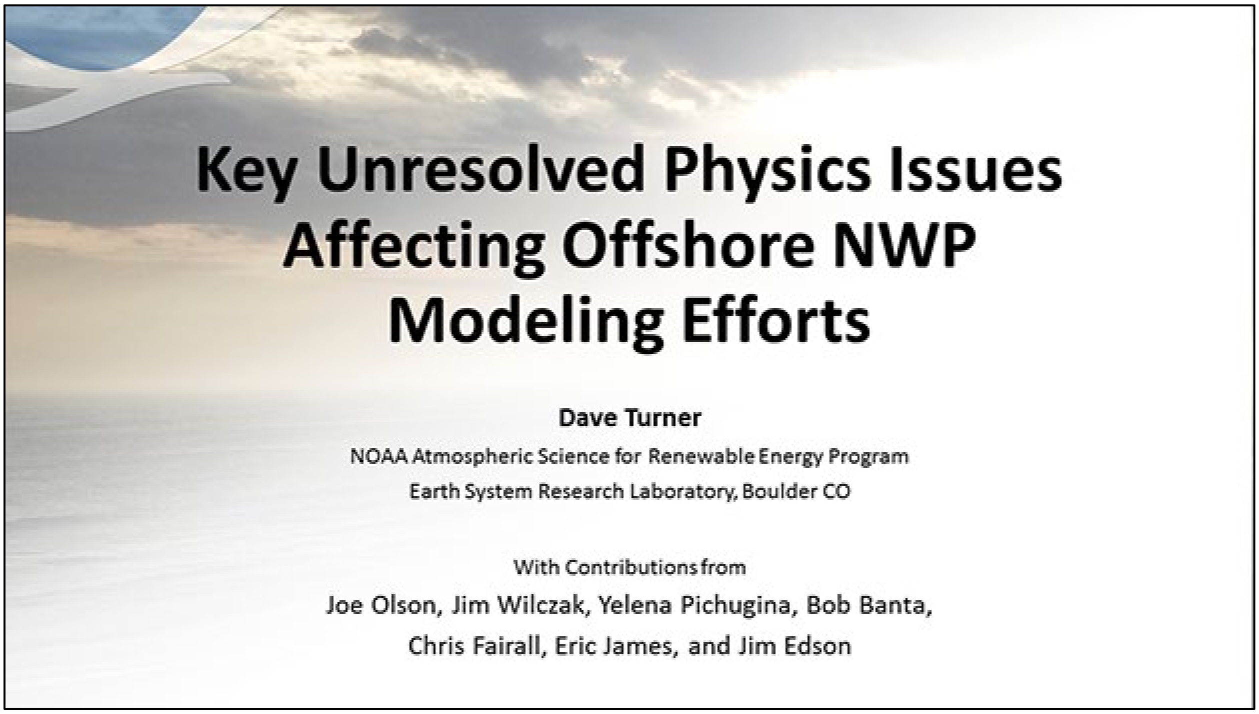
- **Hurricanes** (new load cases needed)
  - Veer relative to hub height calculated over 3s to 1 min intervals
  - Wind direction measured at fine time periods (3s)
  - Extreme, localized structures may dominate loading -> may need gust prescription different than IEC model
  - Wave/surge characteristics
- **Breaking/steep waves**
  - Modeling approach
  - Probability
  - Load measurement or camera? Hard to capture just from wave elevation measurement
- **Extremes estimation**
  - How can we improve parameter measurements to better enable extreme extrapolation to less-frequent recurrence periods than measurements available?

Worsnop et al. 2017 Geophysical Research Letters

Thank You

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

C.4 Session 3: Dave Turner

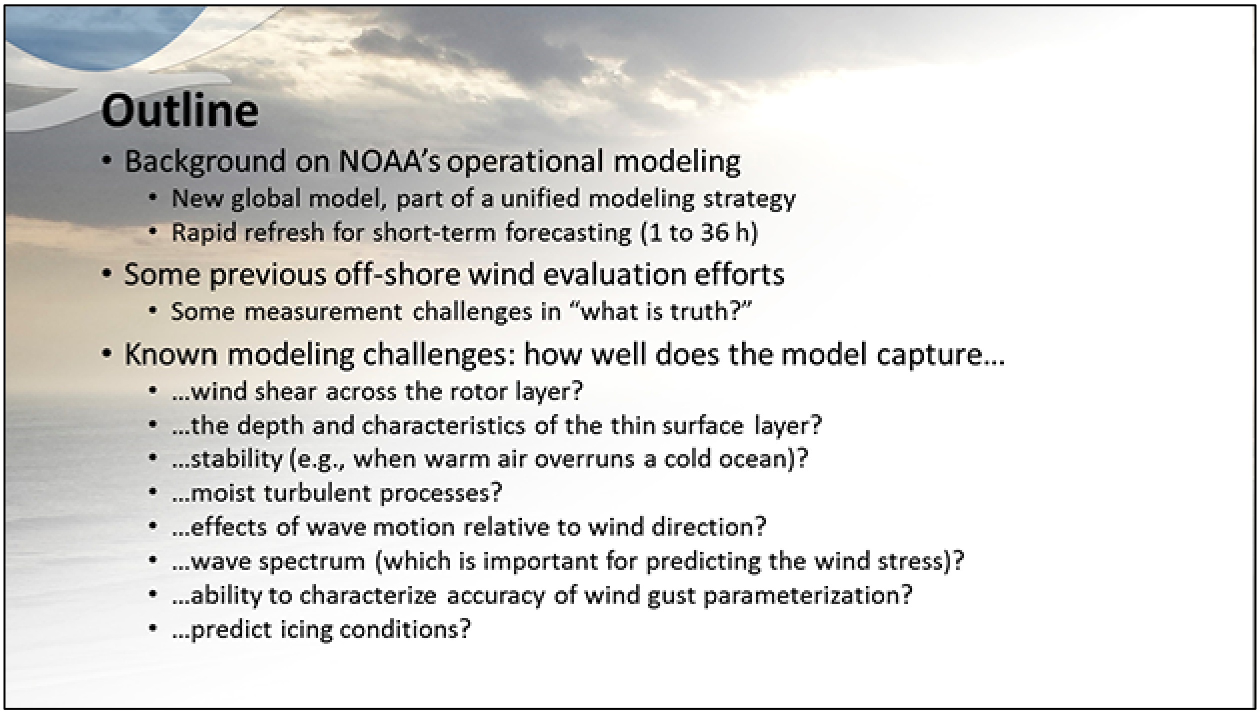


Key Unresolved Physics Issues Affecting Offshore NWP Modeling Efforts

Dave Turner

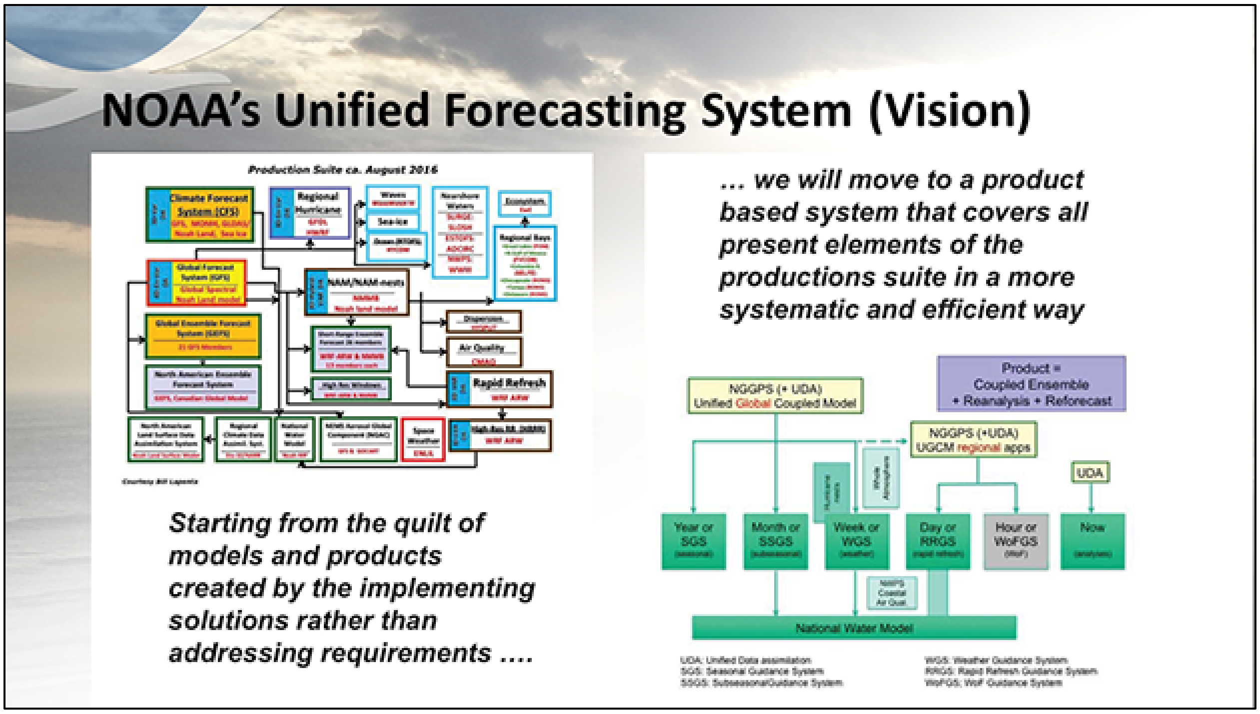
NOAA Atmospheric Science for Renewable Energy Program
Earth System Research Laboratory, Boulder CO

With Contributions from
Joe Olson, Jim Wilczak, Yelena Pichugina, Bob Banta,
Chris Fairall, Eric James, and Jim Edson



Outline

- Background on NOAA's operational modeling
  - New global model, part of a unified modeling strategy
  - Rapid refresh for short-term forecasting (1 to 36 h)
- Some previous off-shore wind evaluation efforts
  - Some measurement challenges in "what is truth?"
- Known modeling challenges: how well does the model capture…
  - …wind shear across the rotor layer?
  - …the depth and characteristics of the thin surface layer?
  - …stability (e.g., when warm air overruns a cold ocean)?
  - …moist turbulent processes?
  - …effects of wave motion relative to wind direction?
  - …wave spectrum (which is important for predicting the wind stress)?
  - …ability to characterize accuracy of wind gust parameterization?
  - …predict icing conditions?

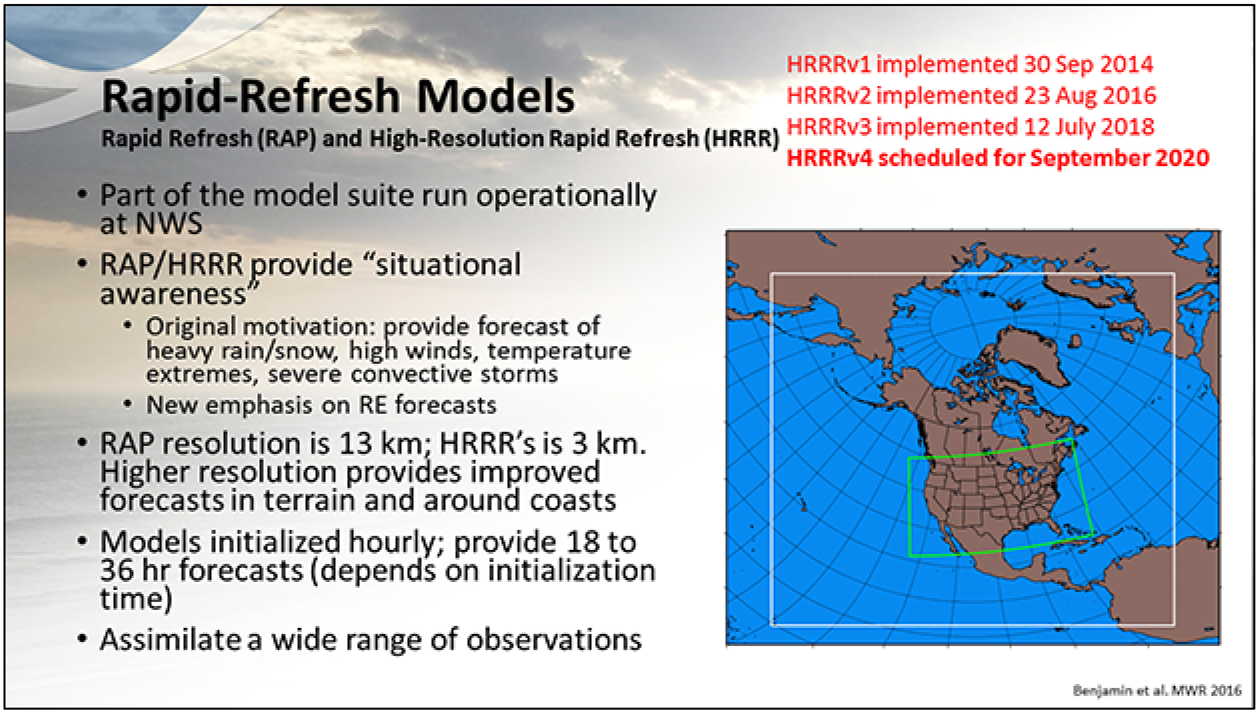


NOAA's Unified Forecasting System (Vision)

Starting from the quilt of models and products created by the implementing solutions rather than addressing requirements ….

… we will move to a product based system that covers all present elements of the productions suite in a more systematic and efficient way

UDA: Unified Data assimilation
SGS: Seasonal Guidance System
SSGS: SubseasonalGuidance System
WGS: Weather Guidance System
RRGS: Rapid Refresh Guidance System
WoFGS: WoF Guidance System



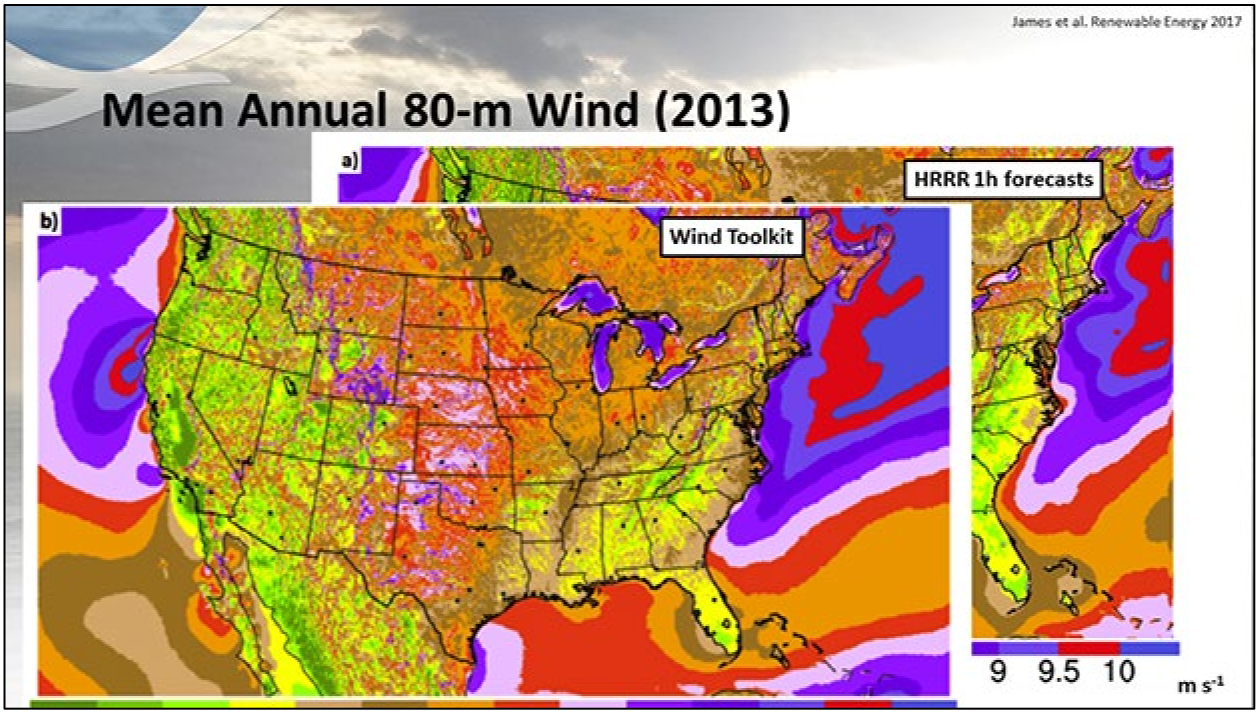
Rapid-Refresh Models

Rapid Refresh (RAP) and High-Resolution Rapid Refresh (HRRR)

HRRRv1 implemented 30 Sep 2014
HRRRv2 implemented 23 Aug 2016
HRRRv3 implemented 12 July 2018
HRRRv4 scheduled for September 2020

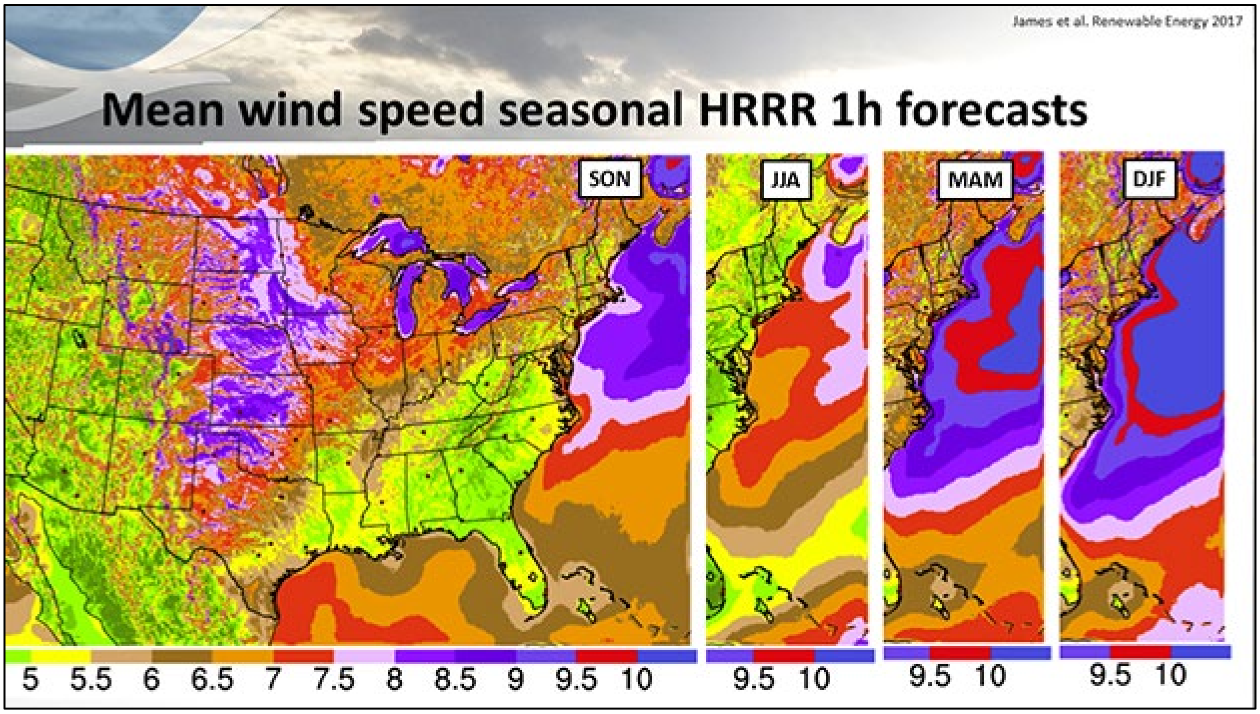
- Part of the model suite run operationally at NWS
- RAP/HRRR provide "situational awareness"
  - Original motivation: provide forecast of heavy rain/snow, high winds, temperature extremes, severe convective storms
  - New emphasis on RE forecasts
- RAP resolution is 13 km; HRRR's is 3 km. Higher resolution provides improved forecasts in terrain and around coasts
- Models initialized hourly; provide 18 to 36 hr forecasts (depends on initialization time)
- Assimilate a wide range of observations

Benjamin et al. MWR 2016



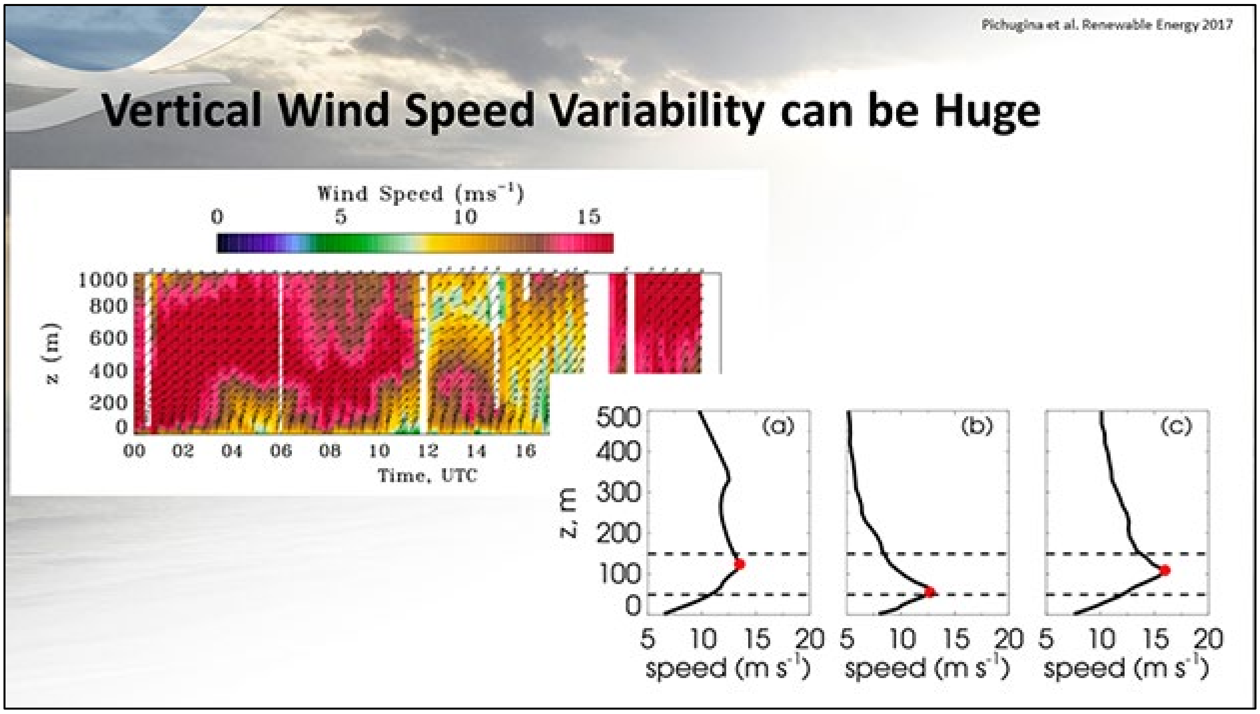
James et al. Renewable Energy 2017

Mean Annual 80-m Wind (2013)



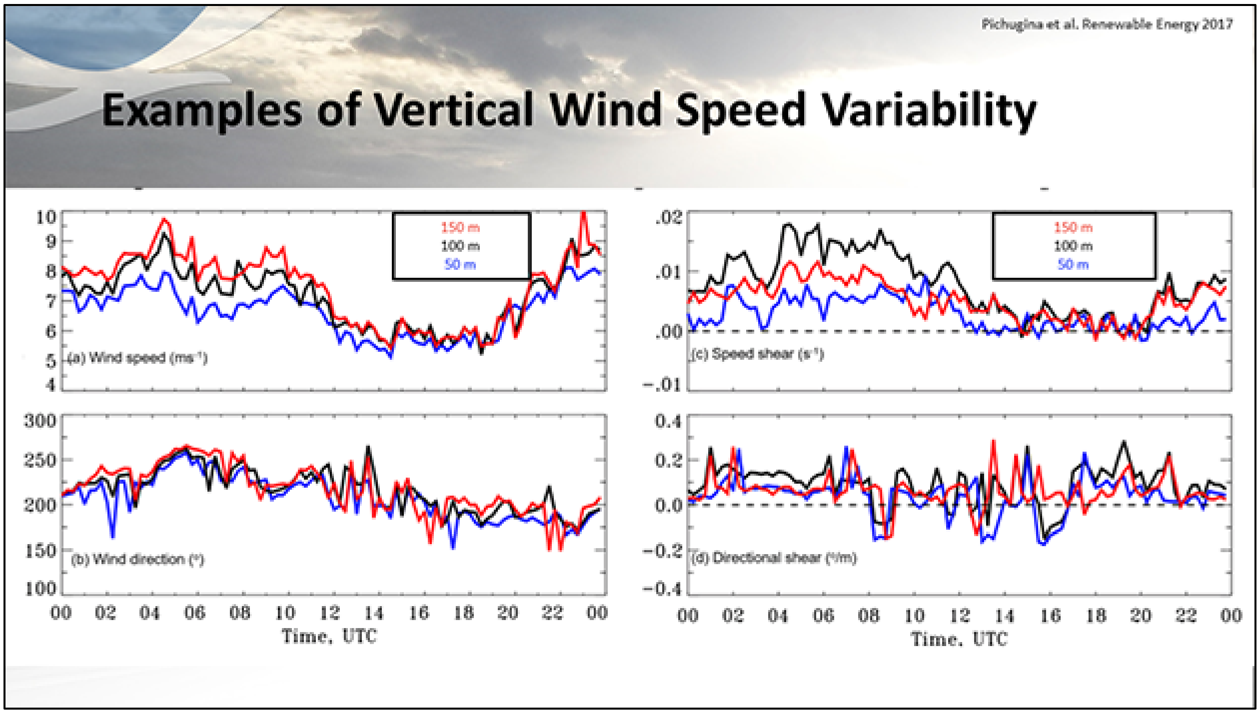
James et al. Renewable Energy 2017

Mean wind speed seasonal HRRR 1h forecasts



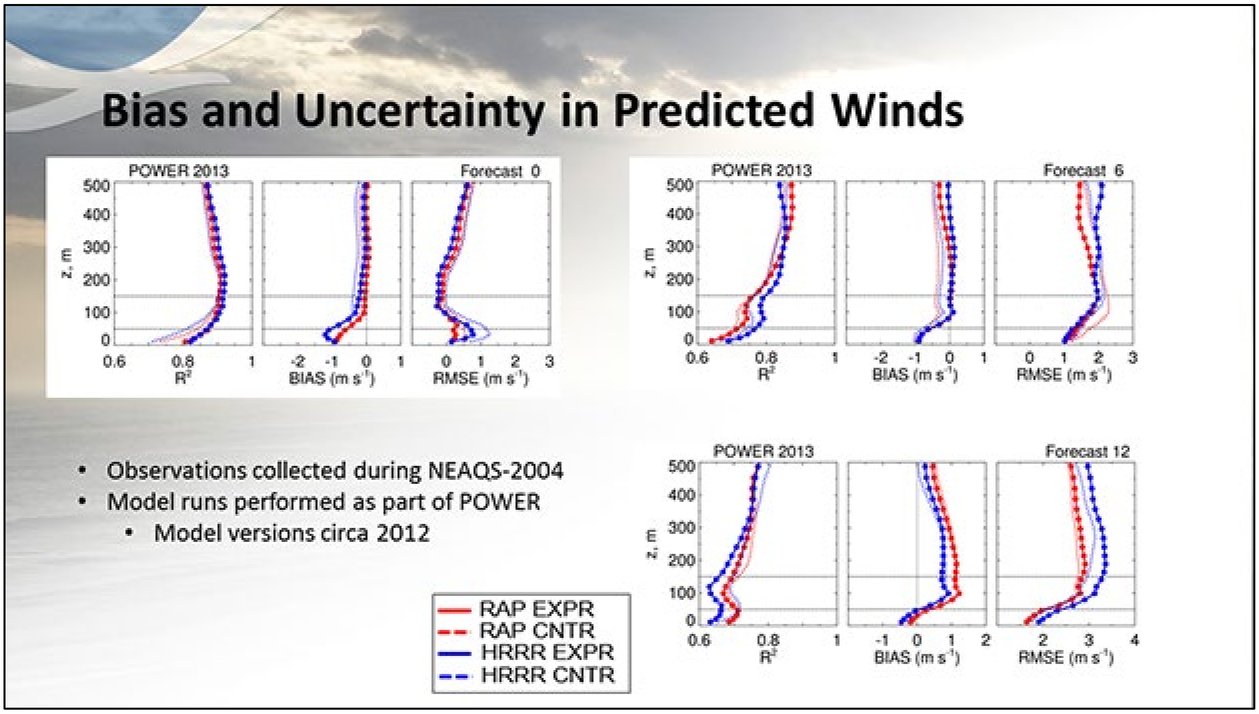
Pichugina et al. Renewable Energy 2017

Vertical Wind Speed Variability can be Huge



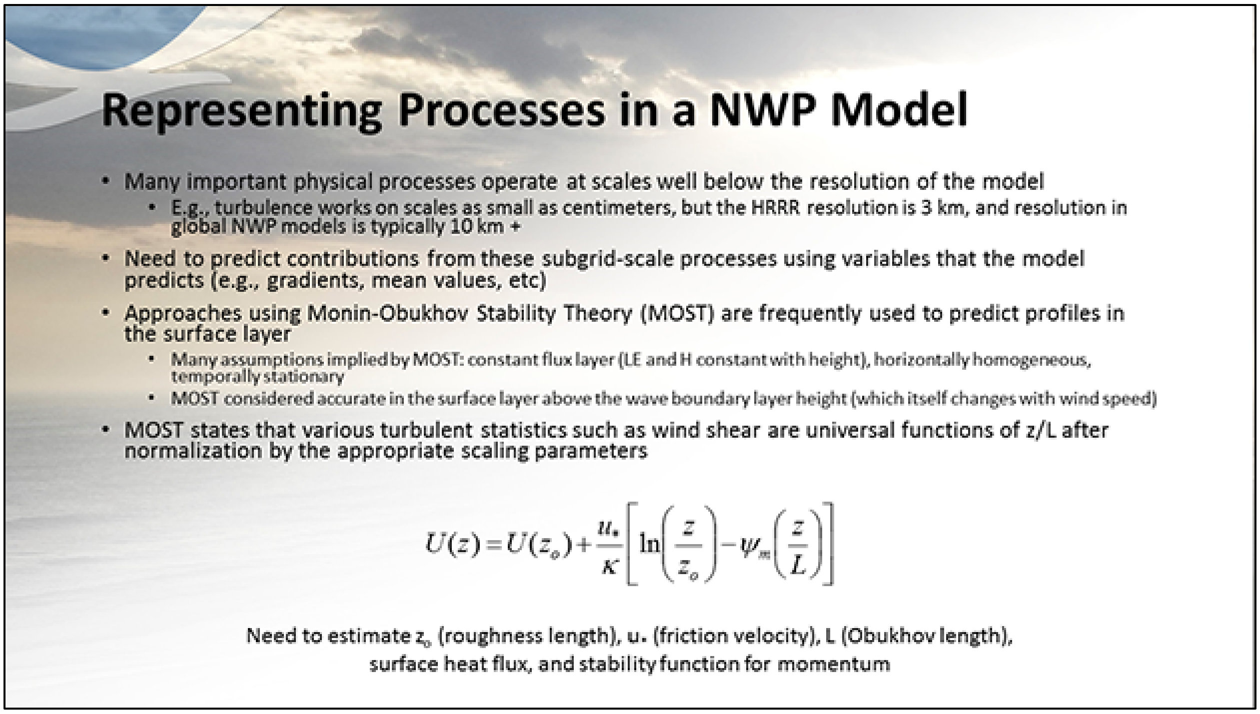
Pichugina et al. Renewable Energy 2017

Examples of Vertical Wind Speed Variability



Bias and Uncertainty in Predicted Winds

- Observations collected during NEAQS-2004
- Model runs performed as part of POWER
  - Model versions circa 2012

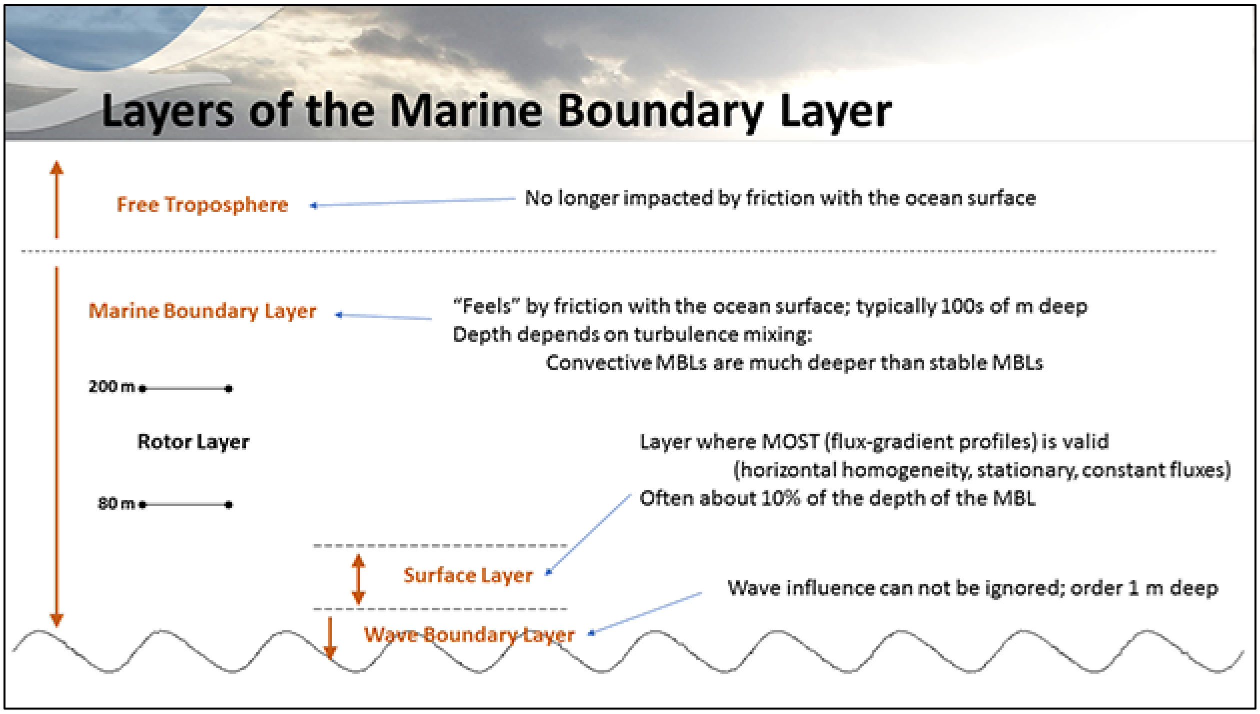


Representing Processes in a NWP Model

- Many important physical processes operate at scales well below the resolution of the model
  - E.g., turbulence works on scales as small as centimeters, but the HRRR resolution is 3 km, and resolution in global NWP models is typically 10 km +
- Need to predict contributions from these subgrid-scale processes using variables that the model predicts (e.g., gradients, mean values, etc)
- Approaches using Monin-Obukhov Stability Theory (MOST) are frequently used to predict profiles in the surface layer
  - Many assumptions implied by MOST: constant flux layer (LE and H constant with height), horizontally homogeneous, temporally stationary
  - MOST considered accurate in the surface layer above the wave boundary layer height (which itself changes with wind speed)
- MOST states that various turbulent statistics such as wind shear are universal functions of z/L after normalization by the appropriate scaling parameters

$$U(z) = U(z_o) + \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_o}\right) - \psi_m\left(\frac{z}{L}\right)\right]$$

Need to estimate z_o (roughness length), u_* (friction velocity), L (Obukhov length), surface heat flux, and stability function for momentum



Layers of the Marine Boundary Layer

Free Troposphere

No longer impacted by friction with the ocean surface

Marine Boundary Layer

“Feels” by friction with the ocean surface; typically 100s of m deep
Depth depends on turbulence mixing:
Convective MBLs are much deeper than stable MBLs

200 m

Rotor Layer

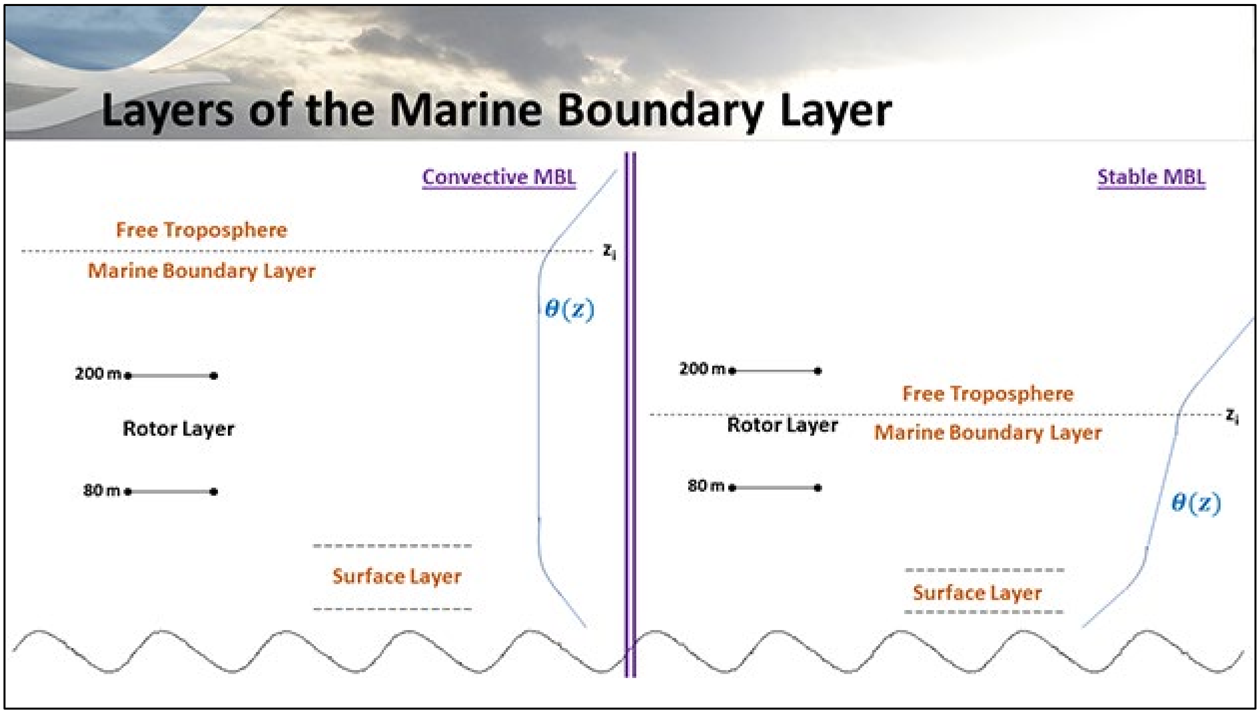
80 m

Layer where MOST (flux-gradient profiles) is valid
(horizontal homogeneity, stationary, constant fluxes)
Often about 10% of the depth of the MBL

Surface Layer

Wave influence can not be ignored; order 1 m deep

Wave Boundary Layer



Layers of the Marine Boundary Layer

Convective MBL

Free Troposphere

z_i

Marine Boundary Layer

$\theta(z)$

200 m

Rotor Layer

80 m

Surface Layer

Stable MBL

200 m

Free Troposphere

Rotor Layer

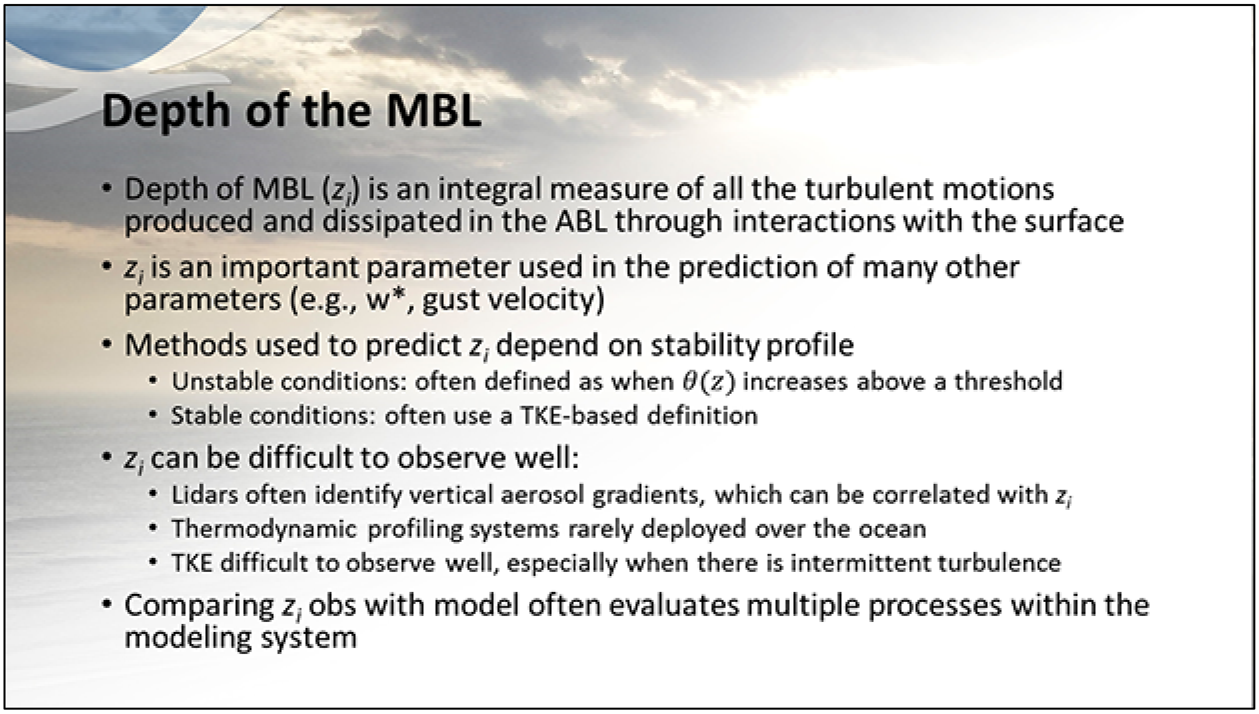
z_i

Marine Boundary Layer

80 m

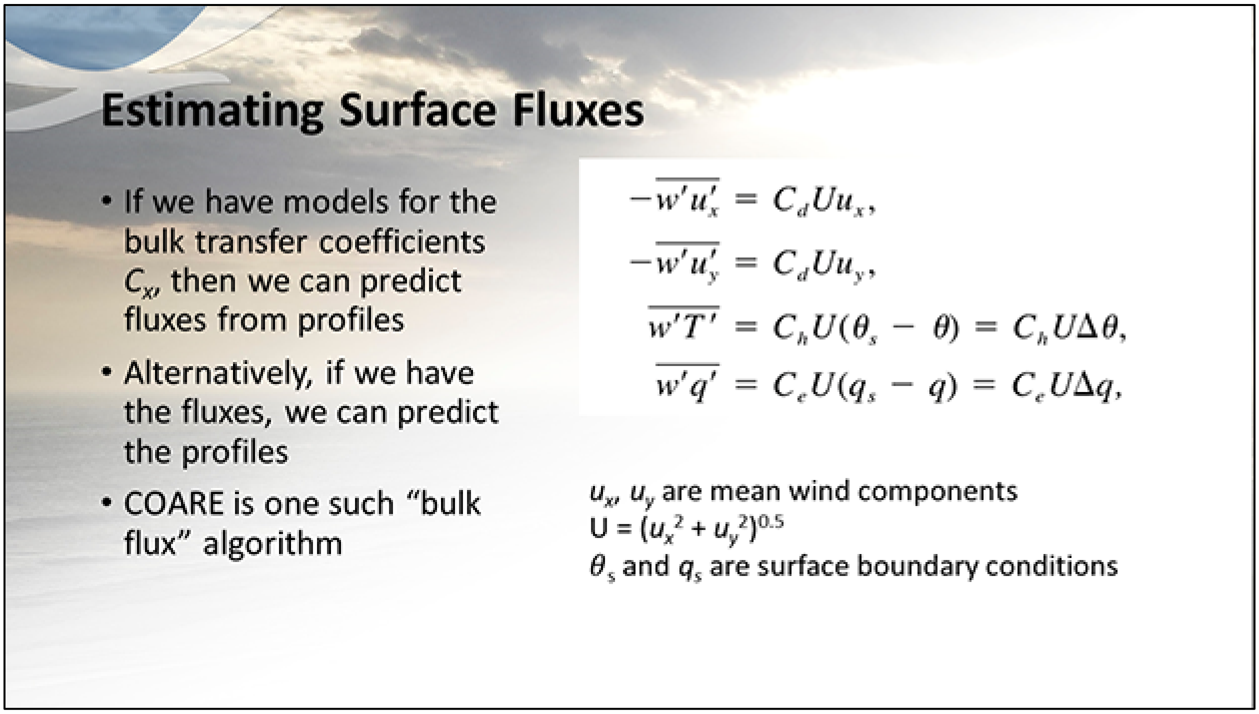
$\theta(z)$

Surface Layer



Depth of the MBL

- Depth of MBL (z_i) is an integral measure of all the turbulent motions produced and dissipated in the ABL through interactions with the surface
- z_i is an important parameter used in the prediction of many other parameters (e.g., w*, gust velocity)
- Methods used to predict z_i depend on stability profile
  - Unstable conditions: often defined as when $\theta(z)$ increases above a threshold
  - Stable conditions: often use a TKE-based definition
- z_i can be difficult to observe well:
  - Lidars often identify vertical aerosol gradients, which can be correlated with z_i
  - Thermodynamic profiling systems rarely deployed over the ocean
  - TKE difficult to observe well, especially when there is intermittent turbulence
- Comparing z_i obs with model often evaluates multiple processes within the modeling system



Estimating Surface Fluxes

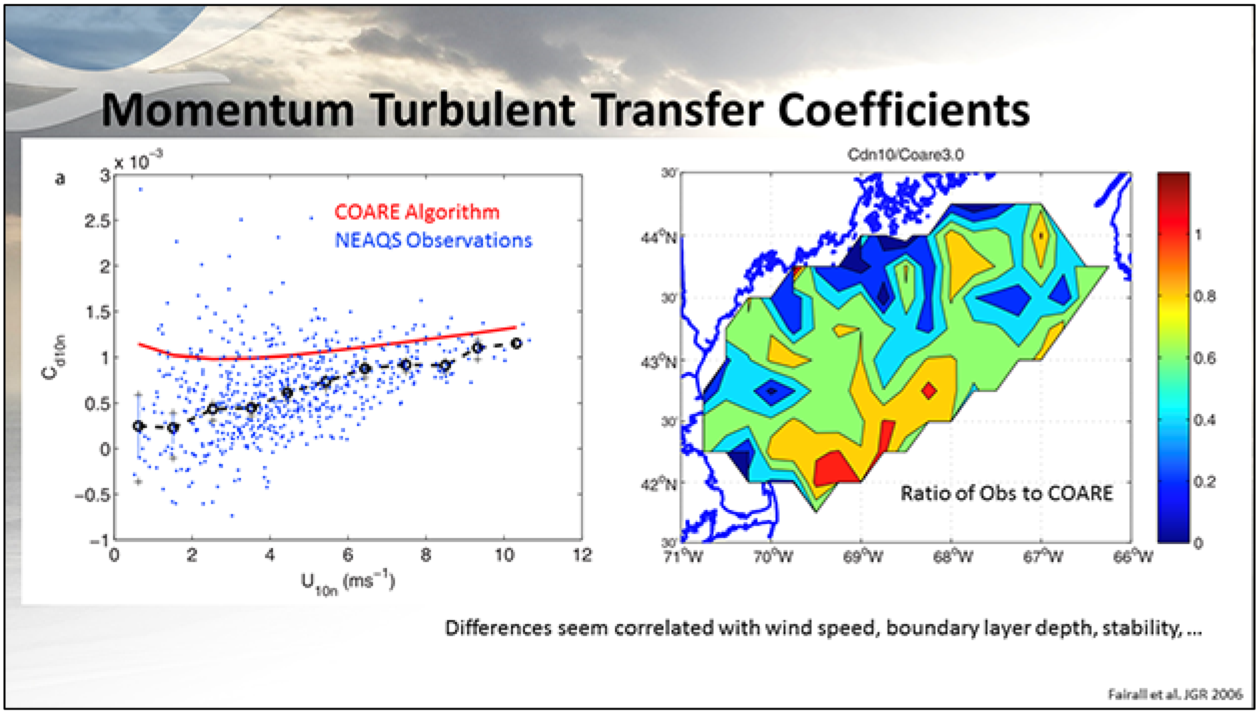
- If we have models for the bulk transfer coefficients C_x, then we can predict fluxes from profiles
- Alternatively, if we have the fluxes, we can predict the profiles
- COARE is one such "bulk flux" algorithm

$$
\begin{aligned}
-\overline{w'u'_x} &= C_d U u_x, \\
-\overline{w'u'_y} &= C_d U u_y, \\
\overline{w'T'} &= C_h U(\theta_s - \theta) = C_h U \Delta\theta, \\
\overline{w'q'} &= C_e U(q_s - q) = C_e U \Delta q,
\end{aligned}
$$

u_x, u_y are mean wind components

$U = (u_x^2 + u_y^2)^{0.5}$

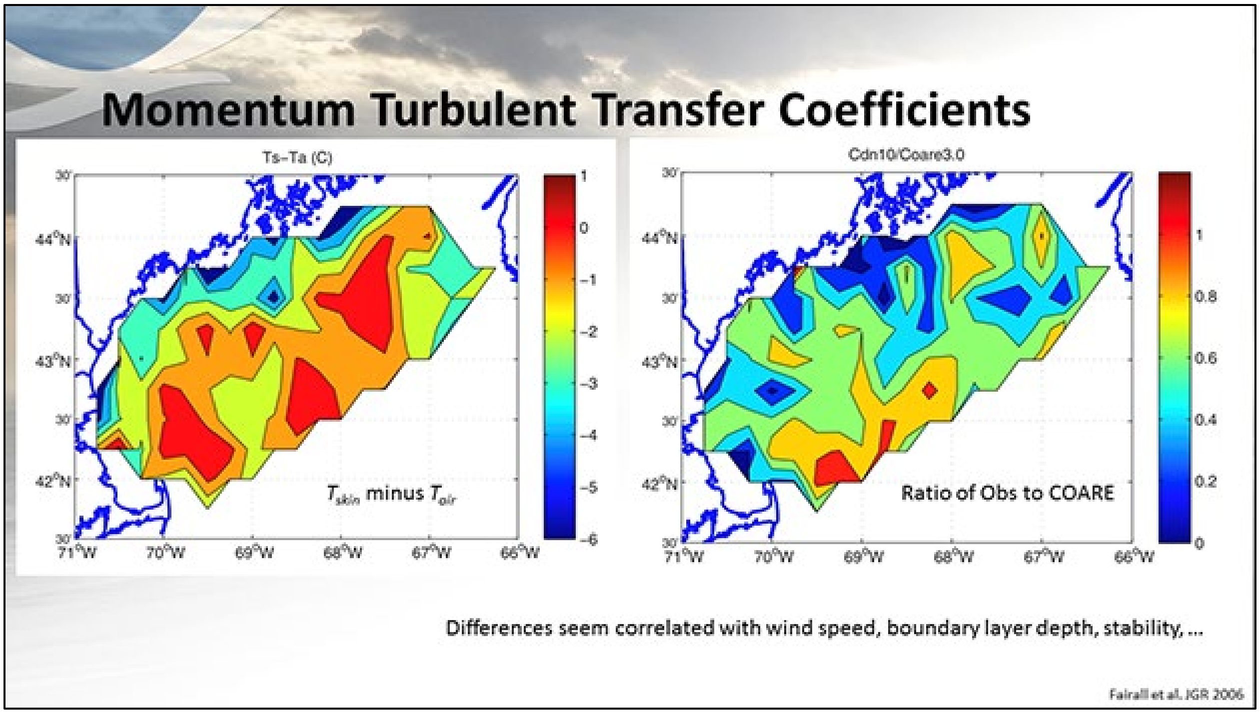
θ_s and q_s are surface boundary conditions



Momentum Turbulent Transfer Coefficients

Differences seem correlated with wind speed, boundary layer depth, stability, ...

Fairall et al. JGR 2006



Momentum Turbulent Transfer Coefficients

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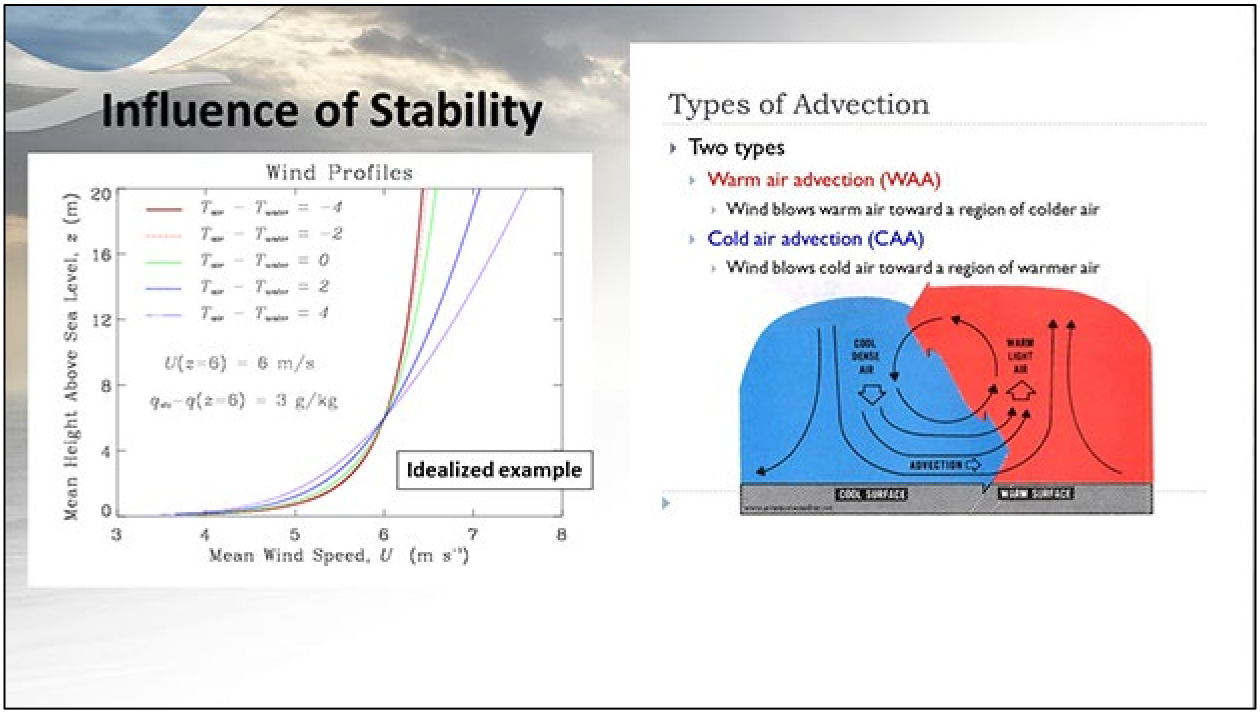
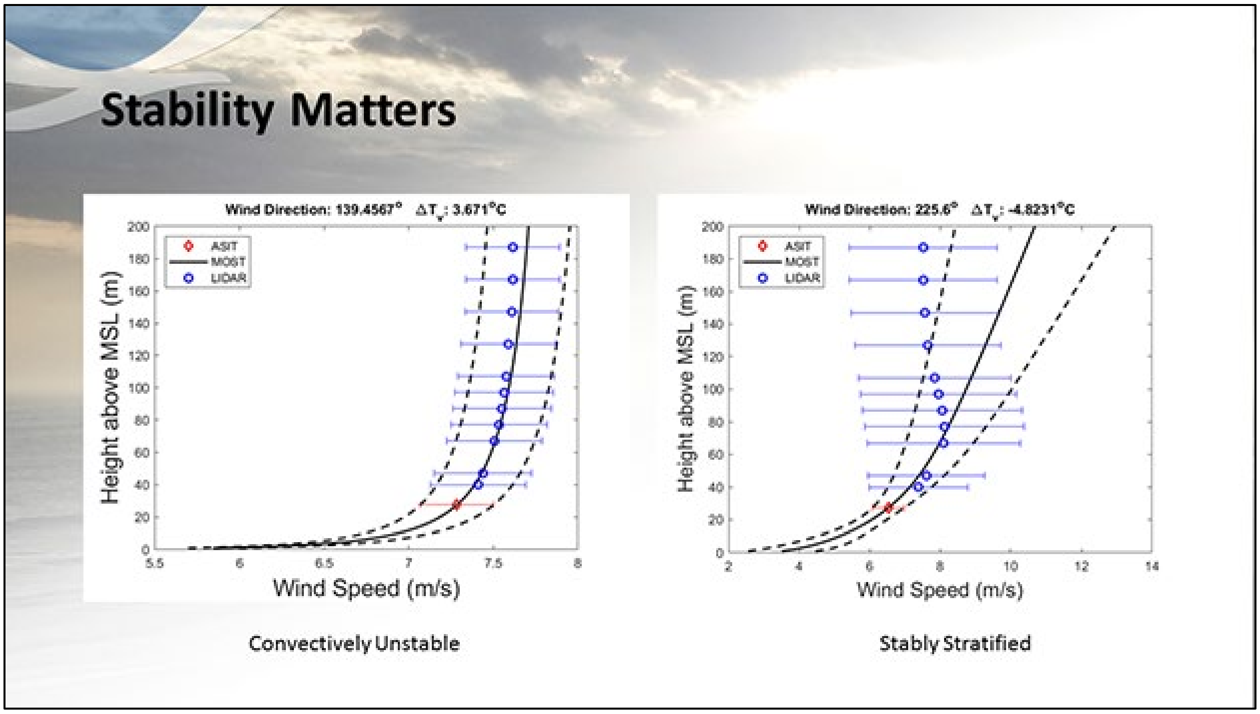


Influence of Stability

Idealized example

Types of Advection

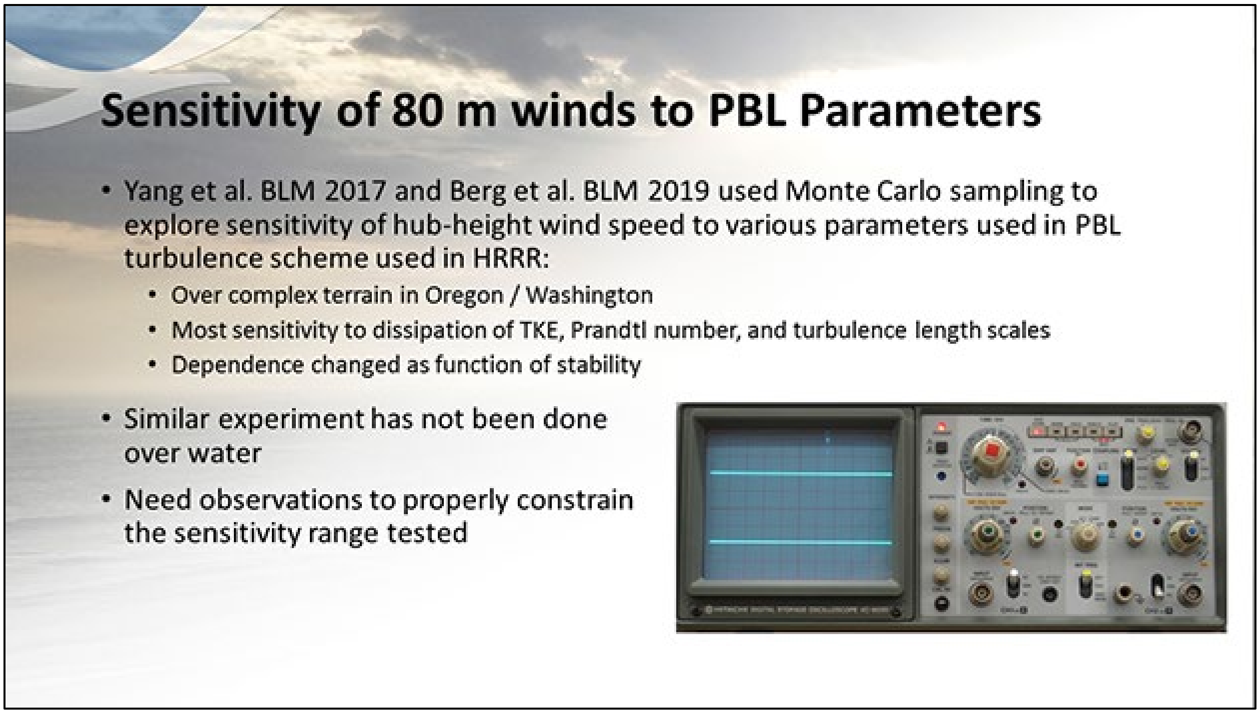
- Two types
  - Warm air advection (WAA)
    - Wind blows warm air toward a region of colder air
  - Cold air advection (CAA)
    - Wind blows cold air toward a region of warmer air



Stability Matters

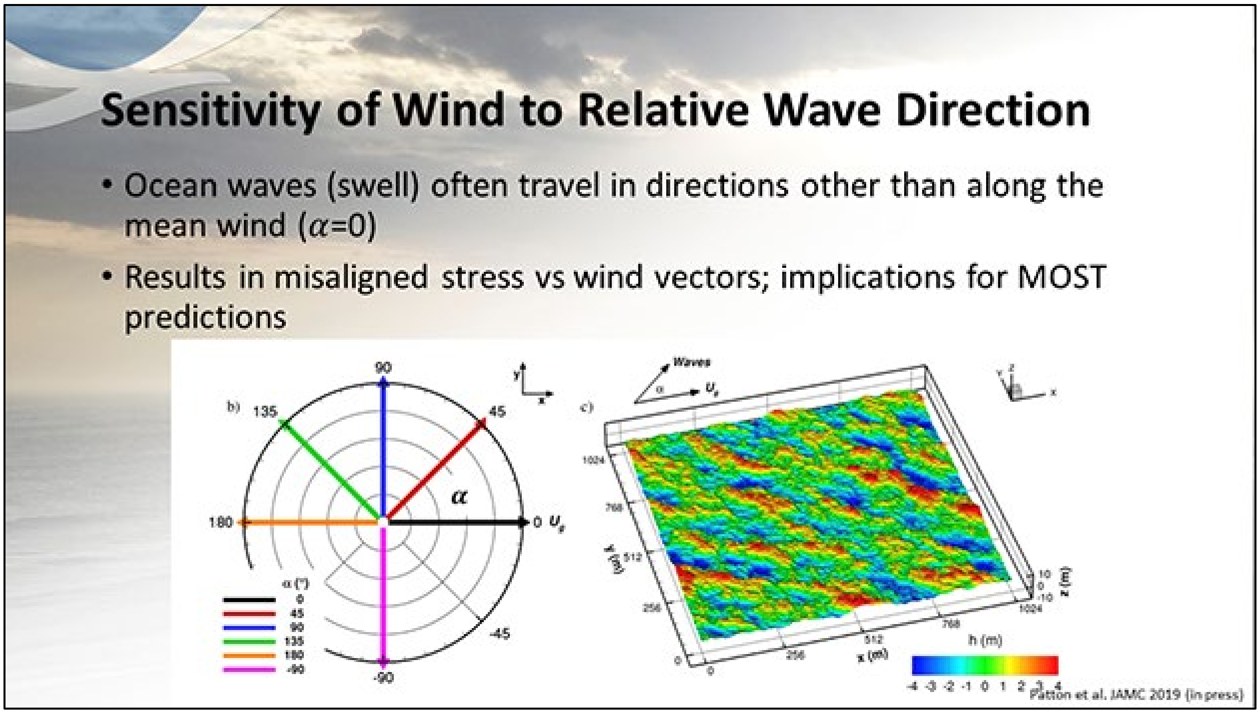
Convectively Unstable

Stably Stratified



Sensitivity of 80 m winds to PBL Parameters

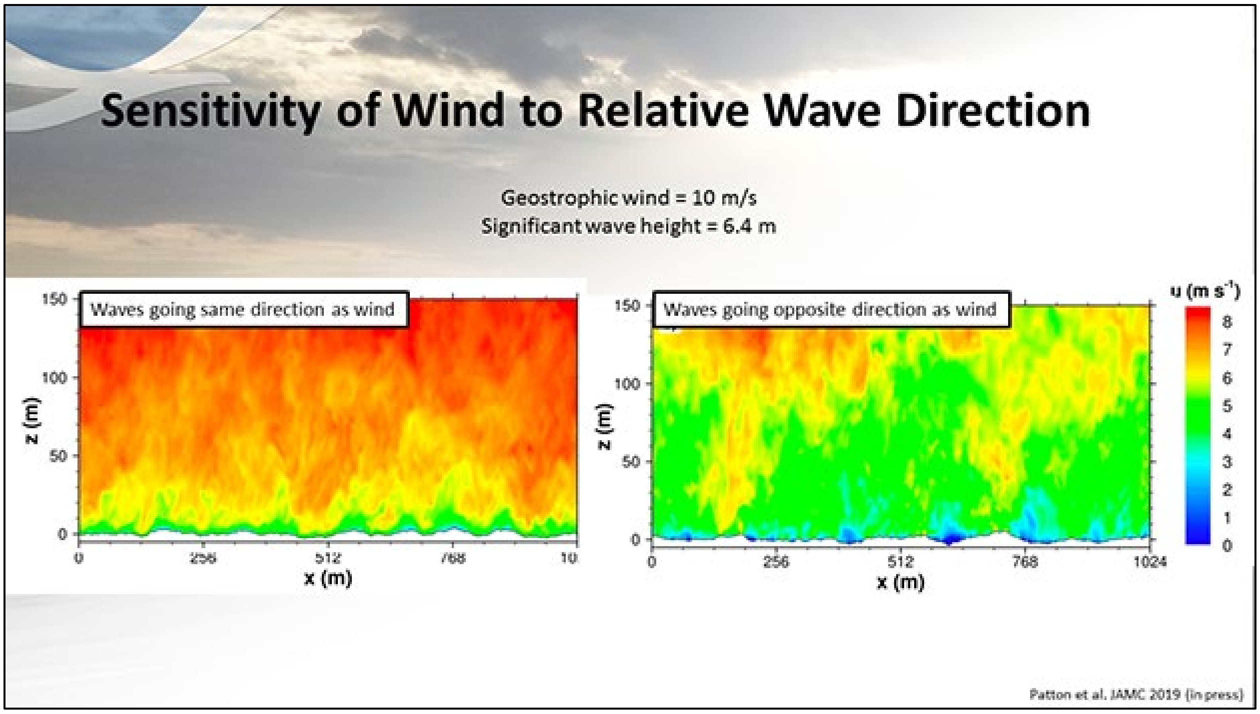
- Yang et al. BLM 2017 and Berg et al. BLM 2019 used Monte Carlo sampling to explore sensitivity of hub-height wind speed to various parameters used in PBL turbulence scheme used in HRRR:
  - Over complex terrain in Oregon / Washington
  - Most sensitivity to dissipation of TKE, Prandtl number, and turbulence length scales
  - Dependence changed as function of stability
- Similar experiment has not been done over water
- Need observations to properly constrain the sensitivity range tested



Sensitivity of Wind to Relative Wave Direction

- Ocean waves (swell) often travel in directions other than along the mean wind (α=0)
- Results in misaligned stress vs wind vectors; implications for MOST predictions

Patton et al. JAMC 2019 (in press)



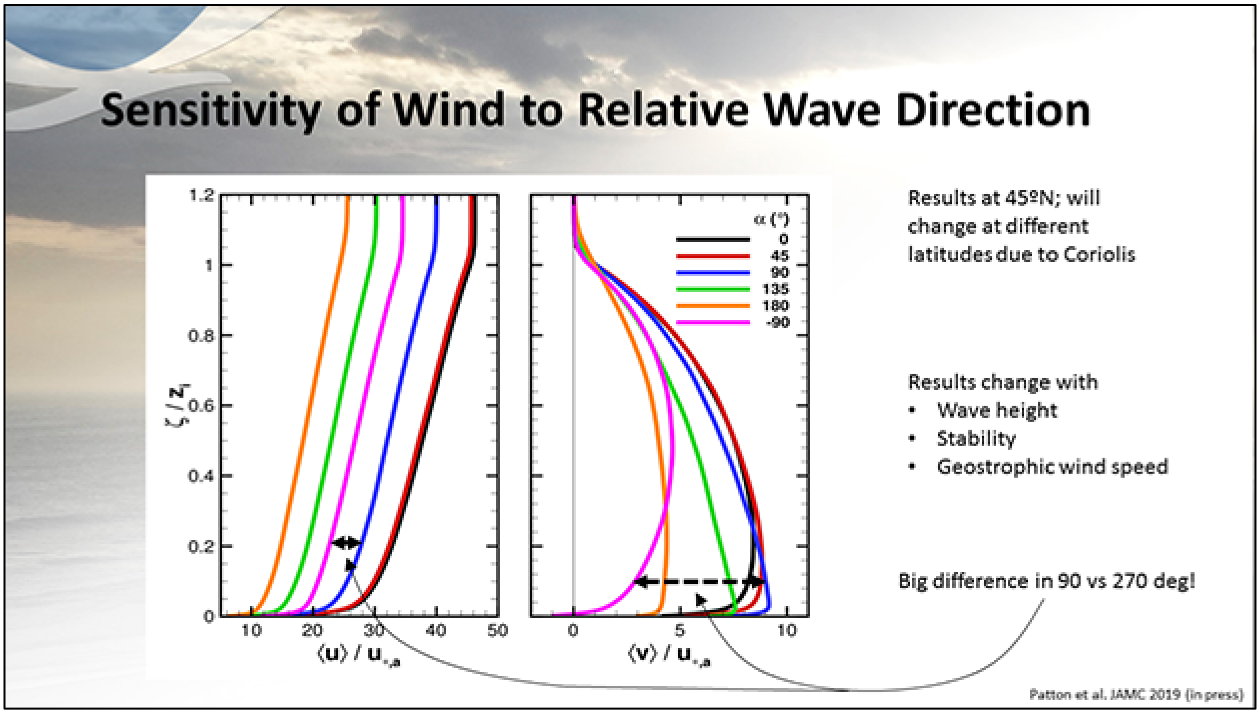
Sensitivity of Wind to Relative Wave Direction

Geostrophic wind = 10 m/s
Significant wave height = 6.4 m

Waves going same direction as wind

Waves going opposite direction as wind

Patton et al. JAMC 2019 (in press)



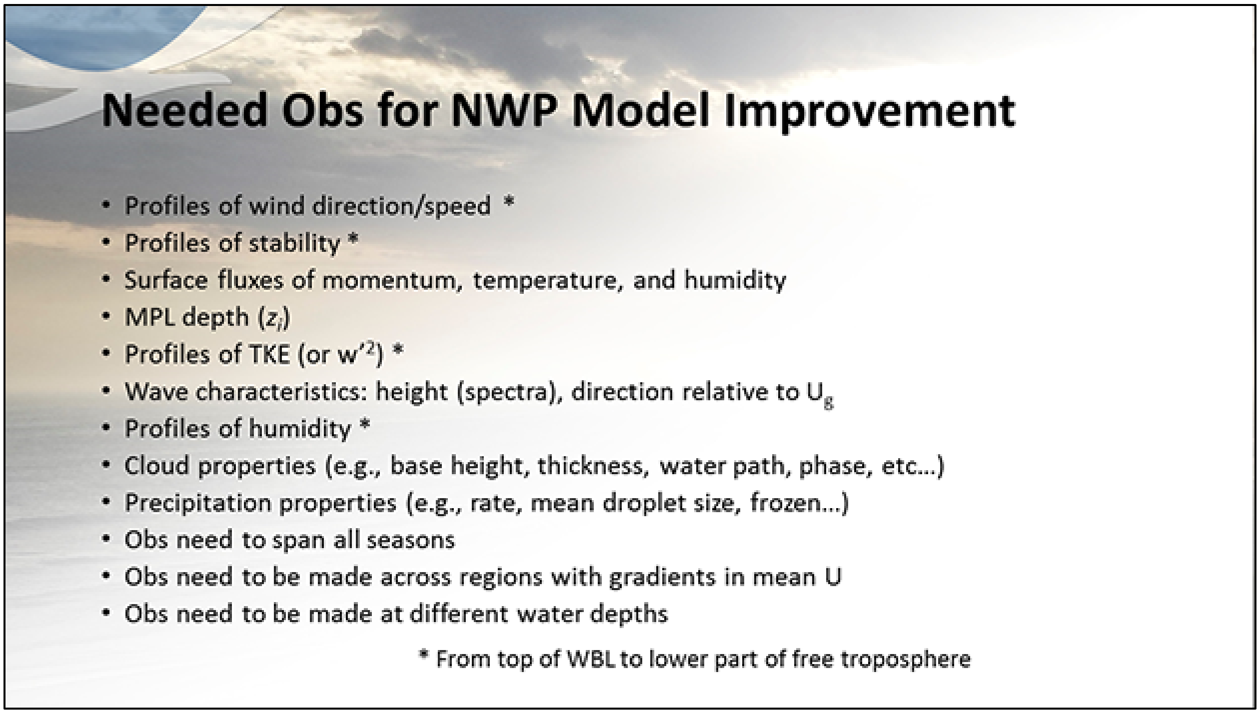
Sensitivity of Wind to Relative Wave Direction

Results at 45ºN; will change at different latitudes due to Coriolis

Results change with
- Wave height
- Stability
- Geostrophic wind speed

Big difference in 90 vs 270 deg!

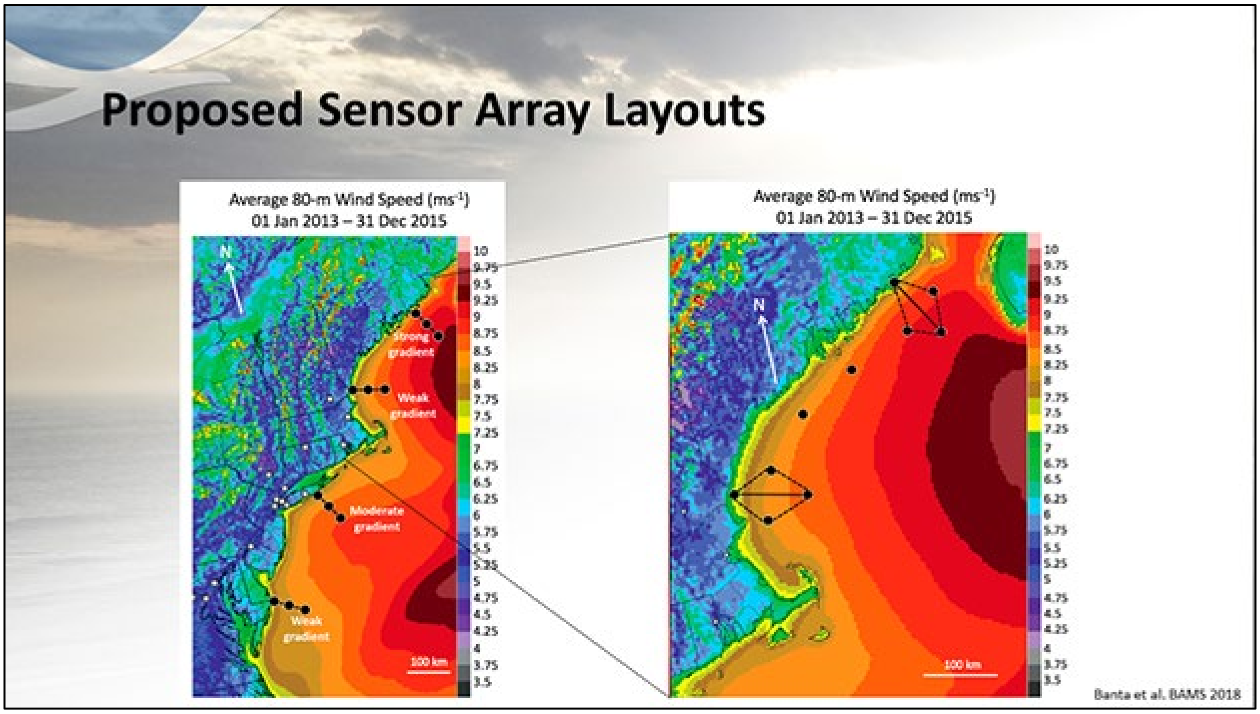
Patton et al. JAMC 2019 (in press)



Needed Obs for NWP Model Improvement

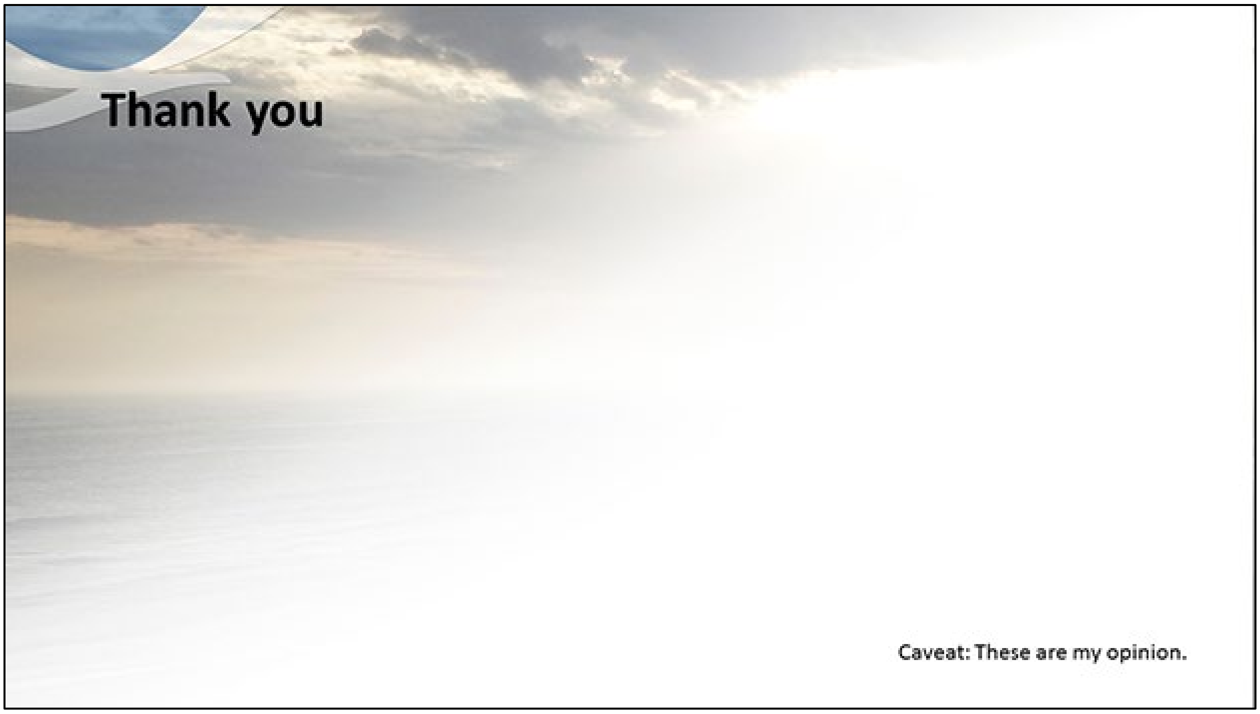
- Profiles of wind direction/speed *
- Profiles of stability *
- Surface fluxes of momentum, temperature, and humidity
- MPL depth (z_i)
- Profiles of TKE (or w'^2) *
- Wave characteristics: height (spectra), direction relative to U_g
- Profiles of humidity *
- Cloud properties (e.g., base height, thickness, water path, phase, etc…)
- Precipitation properties (e.g., rate, mean droplet size, frozen…)
- Obs need to span all seasons
- Obs need to be made across regions with gradients in mean U
- Obs need to be made at different water depths

* From top of WBL to lower part of free troposphere



Proposed Sensor Array Layouts

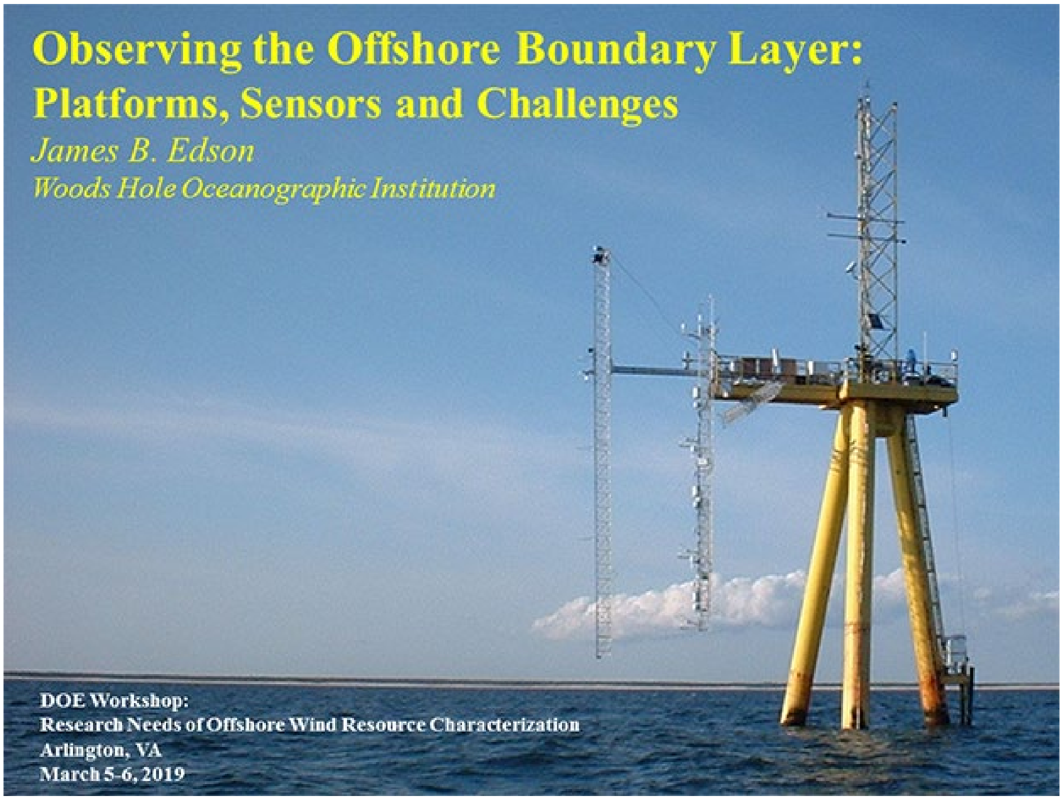
Banta et al. BAMS 2018



Thank you

Caveat: These are my opinion.

C.5 Session 3: James Edson



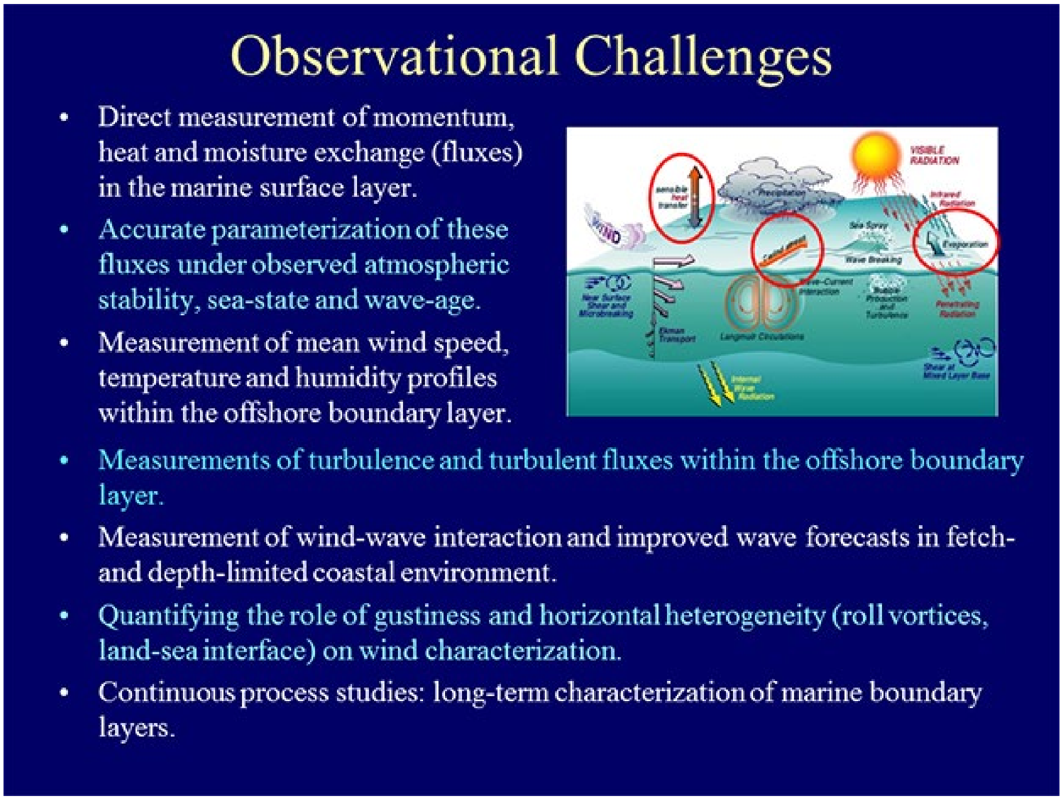
Observing the Offshore Boundary Layer:

Platforms, Sensors and Challenges

James B. Edson

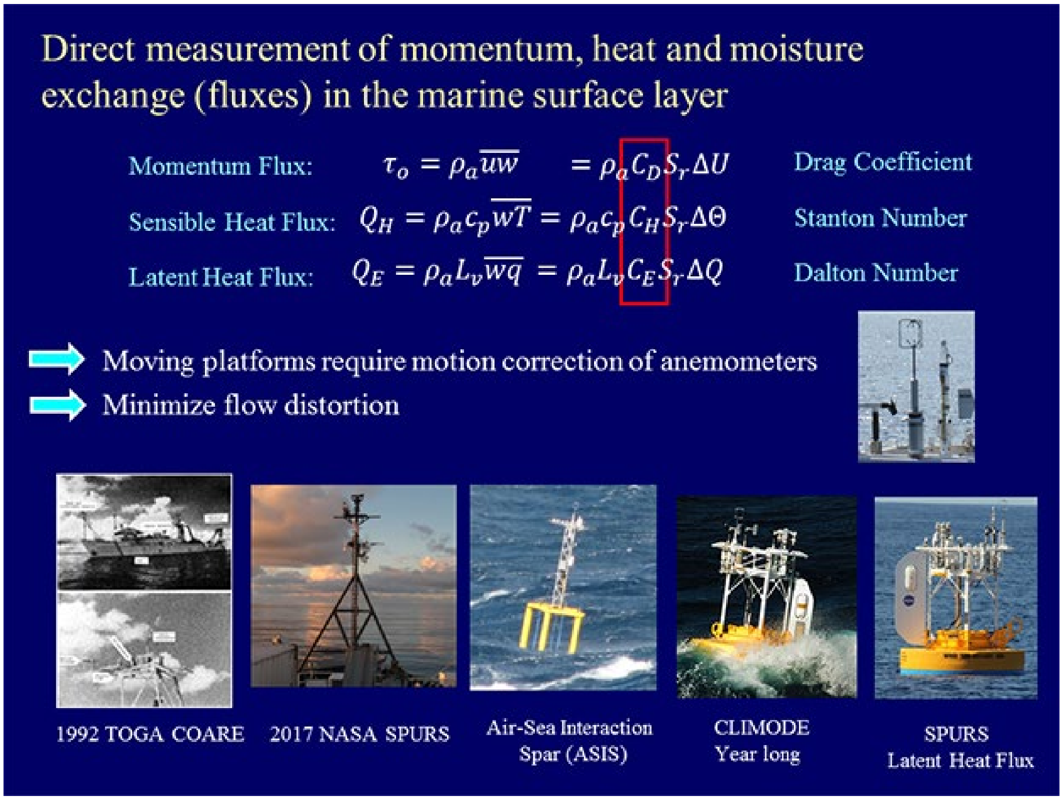
Woods Hole Oceanographic Institution

DOE Workshop:
Research Needs of Offshore Wind Resource Characterization
Arlington, VA
March 5-6, 2019



Observational Challenges

- Direct measurement of momentum, heat and moisture exchange (fluxes) in the marine surface layer.
- Accurate parameterization of these fluxes under observed atmospheric stability, sea-state and wave-age.
- Measurement of mean wind speed, temperature and humidity profiles within the offshore boundary layer.
- Measurements of turbulence and turbulent fluxes within the offshore boundary layer.
- Measurement of wind-wave interaction and improved wave forecasts in fetch- and depth-limited coastal environment.
- Quantifying the role of gustiness and horizontal heterogeneity (roll vortices, land-sea interface) on wind characterization.
- Continuous process studies: long-term characterization of marine boundary layers.



Direct measurement of momentum, heat and moisture exchange (fluxes) in the marine surface layer

Momentum Flux: $\tau_o = \rho_a \overline{uw} = \rho_a C_D S_r \Delta U$ Drag Coefficient

Sensible Heat Flux: $Q_H = \rho_a c_p \overline{wT} = \rho_a c_p C_H S_r \Delta\Theta$ Stanton Number

Latent Heat Flux: $Q_E = \rho_a L_v \overline{wq} = \rho_a L_v C_E S_r \Delta Q$ Dalton Number

- ➡ Moving platforms require motion correction of anemometers
- ➡ Minimize flow distortion

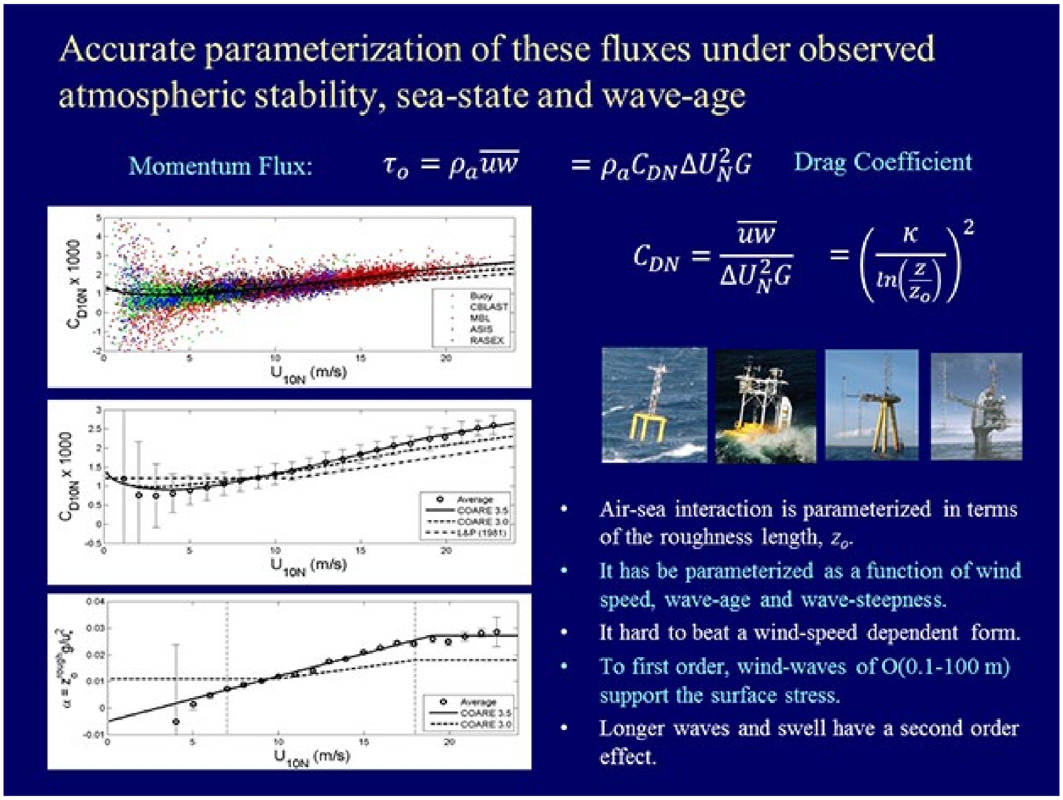
1992 TOGA COARE

2017 NASA SPURS

Air-Sea Interaction Spar (ASIS)

CLIMODE Year long

SPURS Latent Heat Flux

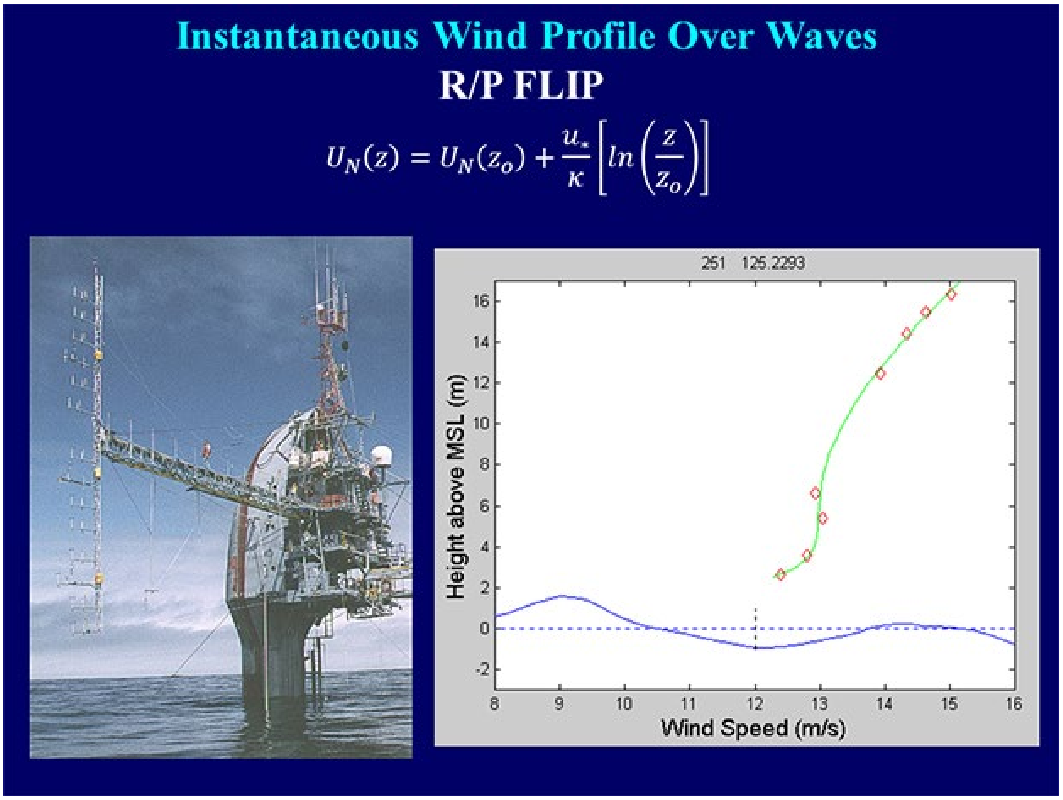


Accurate parameterization of these fluxes under observed atmospheric stability, sea-state and wave-age

Momentum Flux: $\tau_o = \rho_a \overline{uw} = \rho_a C_{DN} \Delta U_N^2 G$ Drag Coefficient

$$C_{DN} = \frac{\overline{uw}}{\Delta U_N^2 G} = \left(\frac{\kappa}{ln\left(\frac{z}{z_o}\right)}\right)^2$$

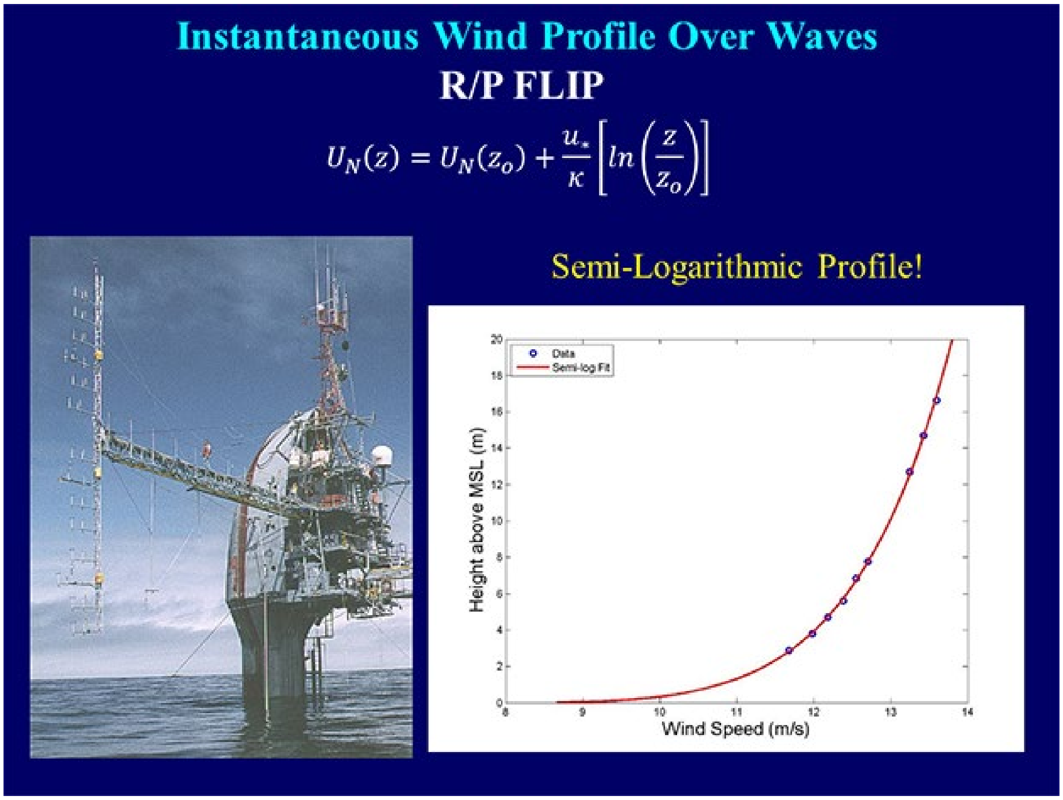
- Air-sea interaction is parameterized in terms of the roughness length, z_o.
- It has be parameterized as a function of wind speed, wave-age and wave-steepness.
- It hard to beat a wind-speed dependent form.
- To first order, wind-waves of O(0.1-100 m) support the surface stress.
- Longer waves and swell have a second order effect.



Instantaneous Wind Profile Over Waves

R/P FLIP

$$U_N(z) = U_N(z_o) + \frac{u_*}{\kappa}\left[ln\left(\frac{z}{z_o}\right)\right]$$

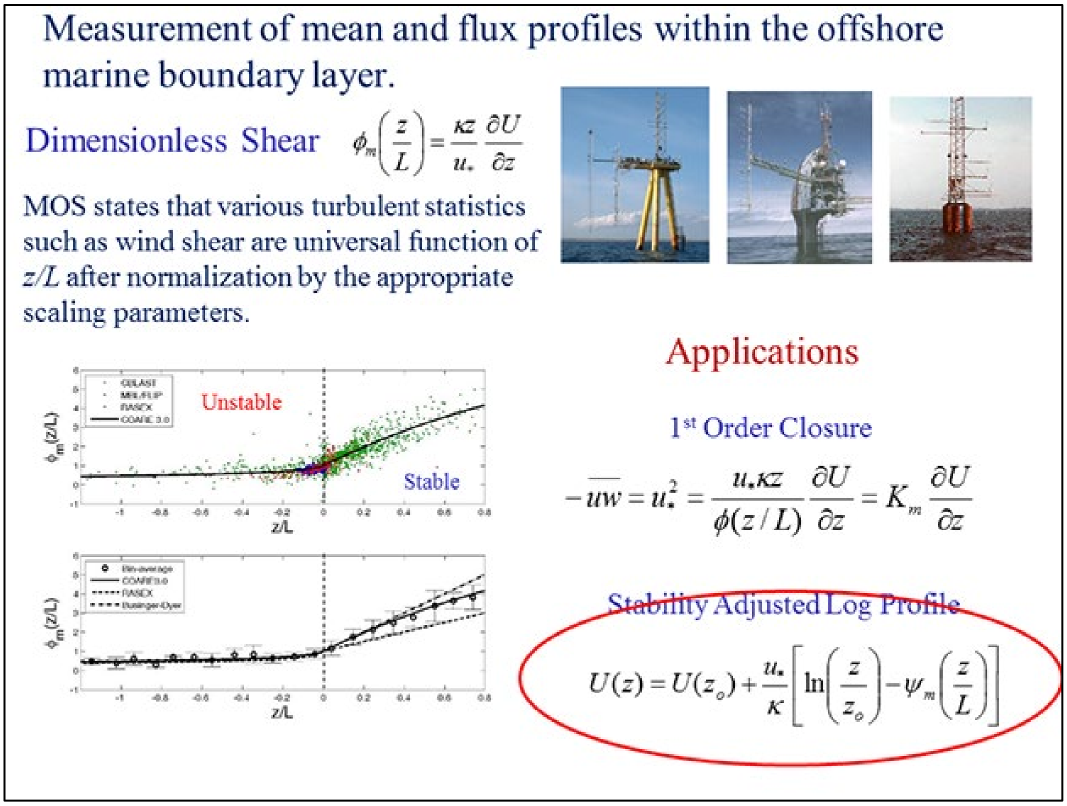


Instantaneous Wind Profile Over Waves

R/P FLIP

$$U_N(z) = U_N(z_o) + \frac{u_*}{\kappa}\left[ln\left(\frac{z}{z_o}\right)\right]$$

Semi-Logarithmic Profile!



Measurement of mean and flux profiles within the offshore marine boundary layer.

Dimensionless Shear $\phi_m\left(\frac{z}{L}\right) = \frac{\kappa z}{u_*}\frac{\partial U}{\partial z}$

MOS states that various turbulent statistics such as wind shear are universal function of z/L after normalization by the appropriate scaling parameters.

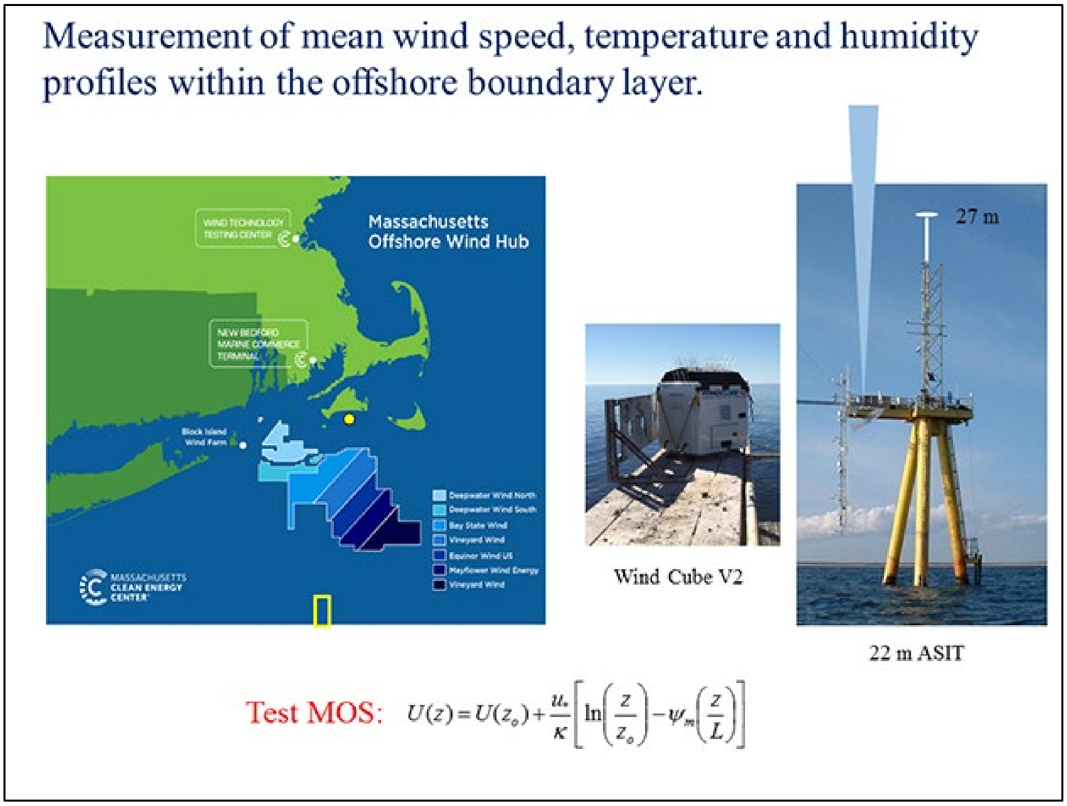
Applications

1st Order Closure

$$-\overline{uw} = u_*^2 = \frac{u_*\kappa z}{\phi(z/L)}\frac{\partial U}{\partial z} = K_m\frac{\partial U}{\partial z}$$

Stability Adjusted Log Profile

$$U(z) = U(z_o) + \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_o}\right) - \psi_m\left(\frac{z}{L}\right)\right]$$

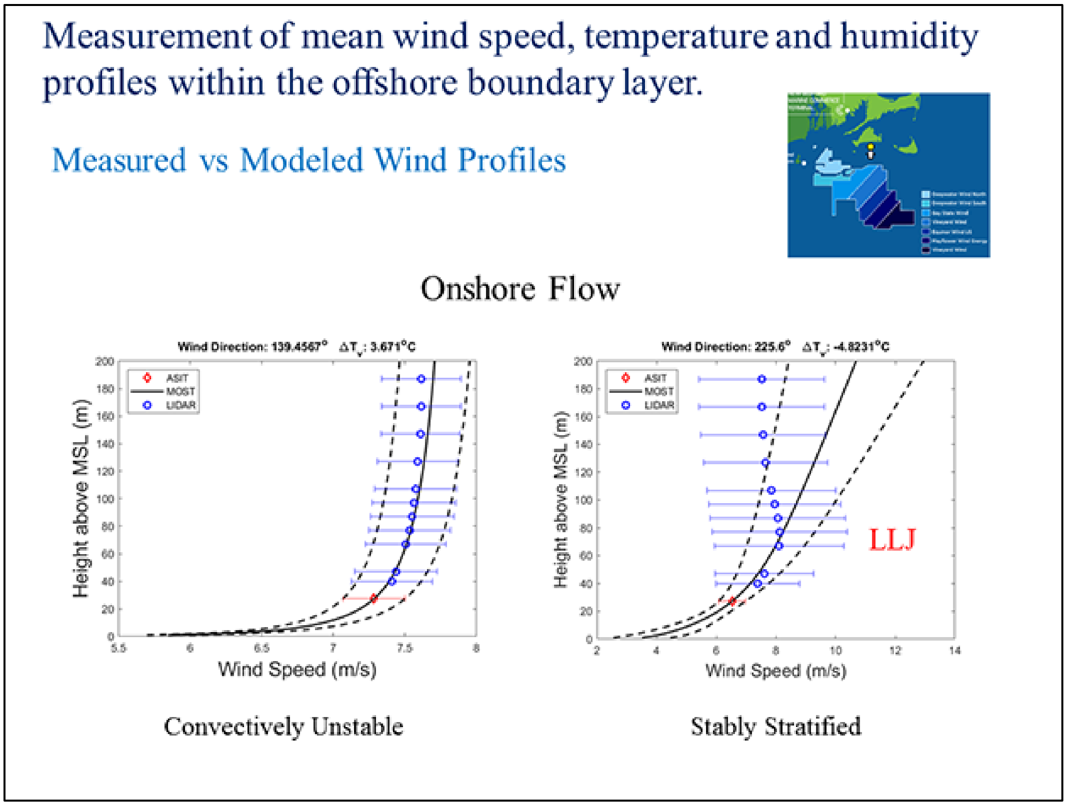


Measurement of mean wind speed, temperature and humidity profiles within the offshore boundary layer.

Wind Cube V2

22 m ASIT

Test MOS: $U(z) = U(z_o) + \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_o}\right) - \psi_m\left(\frac{z}{L}\right)\right]$



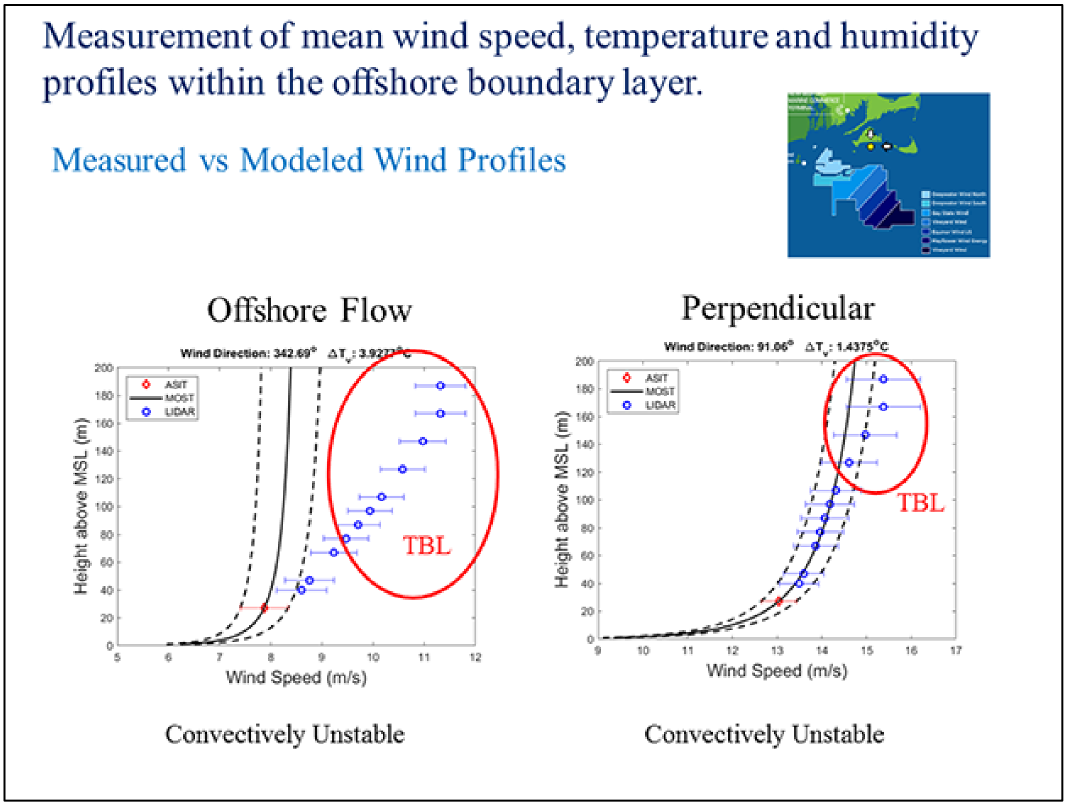
Measurement of mean wind speed, temperature and humidity profiles within the offshore boundary layer.

Measured vs Modeled Wind Profiles

Onshore Flow

Convectively Unstable

Stably Stratified



Measurement of mean wind speed, temperature and humidity profiles within the offshore boundary layer.

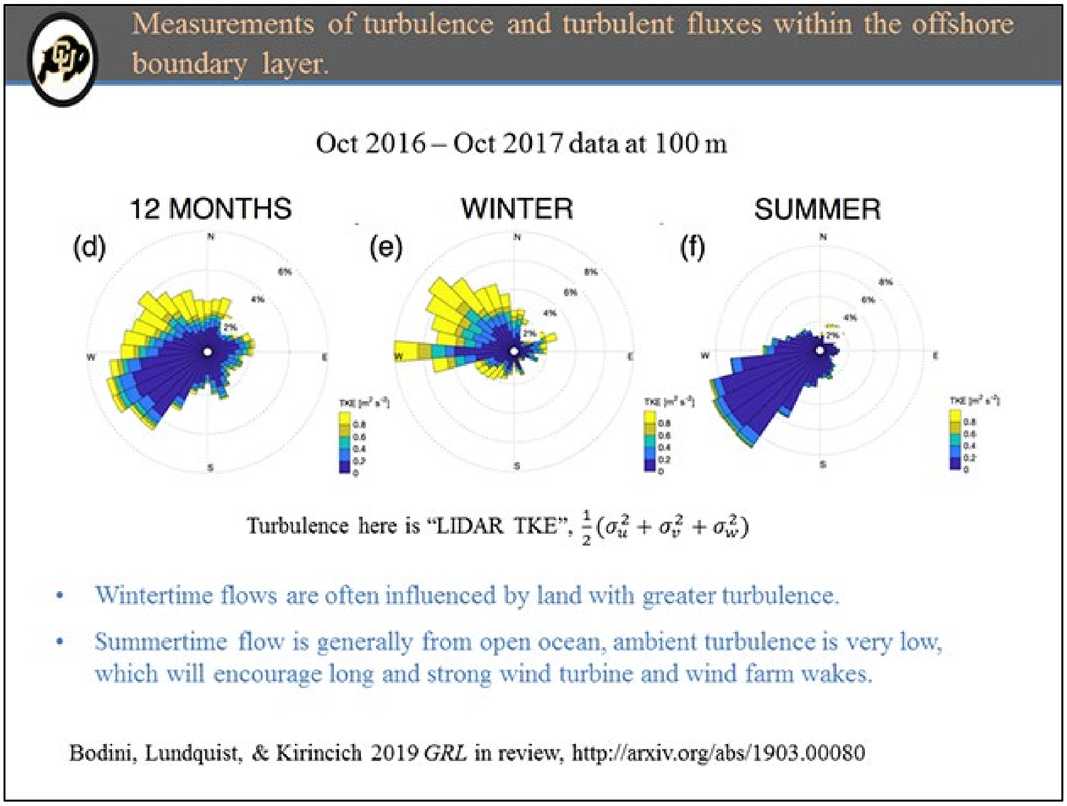
Measured vs Modeled Wind Profiles

Offshore Flow

Perpendicular

Convectively Unstable

Convectively Unstable



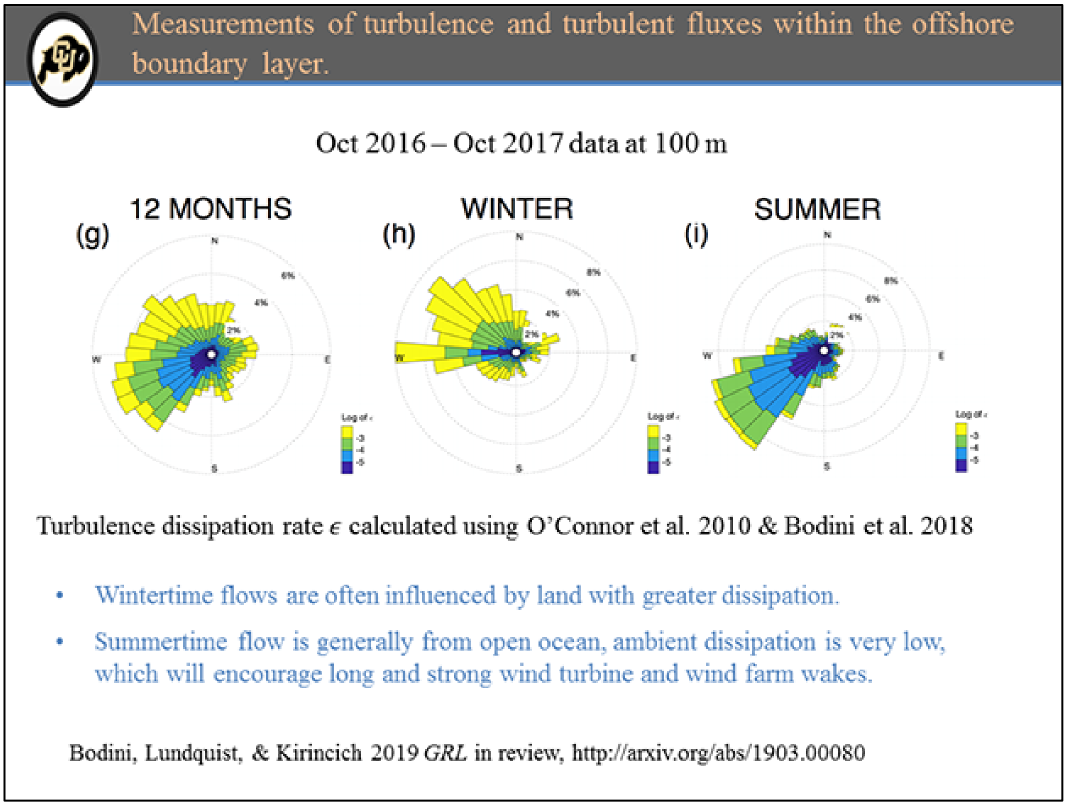
Measurements of turbulence and turbulent fluxes within the offshore boundary layer.

Oct 2016 – Oct 2017 data at 100 m

Turbulence here is "LIDAR TKE", $\frac{1}{2}(\sigma_u^2 + \sigma_v^2 + \sigma_w^2)$

- Wintertime flows are often influenced by land with greater turbulence.
- Summertime flow is generally from open ocean, ambient turbulence is very low, which will encourage long and strong wind turbine and wind farm wakes.

Bodini, Lundquist, & Kirincich 2019 *GRL* in review, http://arxiv.org/abs/1903.00080



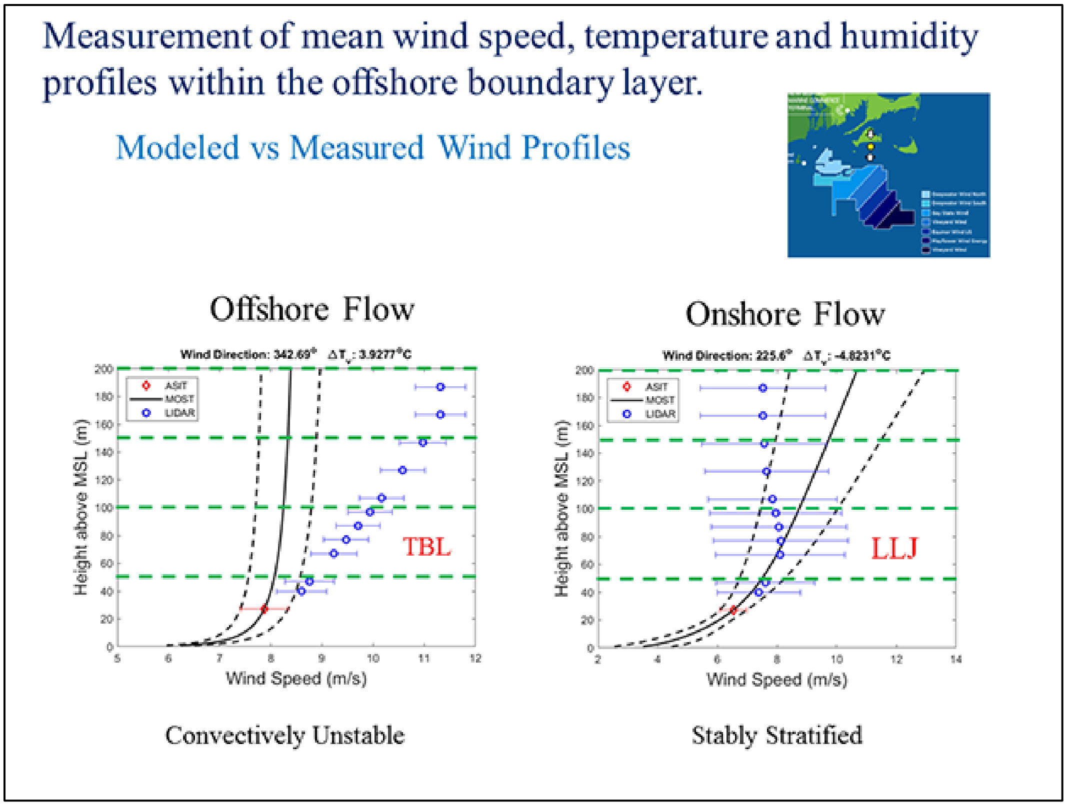
Measurements of turbulence and turbulent fluxes within the offshore boundary layer.

Oct 2016 – Oct 2017 data at 100 m

Turbulence dissipation rate ϵ calculated using O'Connor et al. 2010 & Bodini et al. 2018

- Wintertime flows are often influenced by land with greater dissipation.
- Summertime flow is generally from open ocean, ambient dissipation is very low, which will encourage long and strong wind turbine and wind farm wakes.

Bodini, Lundquist, & Kirincich 2019 *GRL* in review, http://arxiv.org/abs/1903.00080



Measurement of mean wind speed, temperature and humidity profiles within the offshore boundary layer.

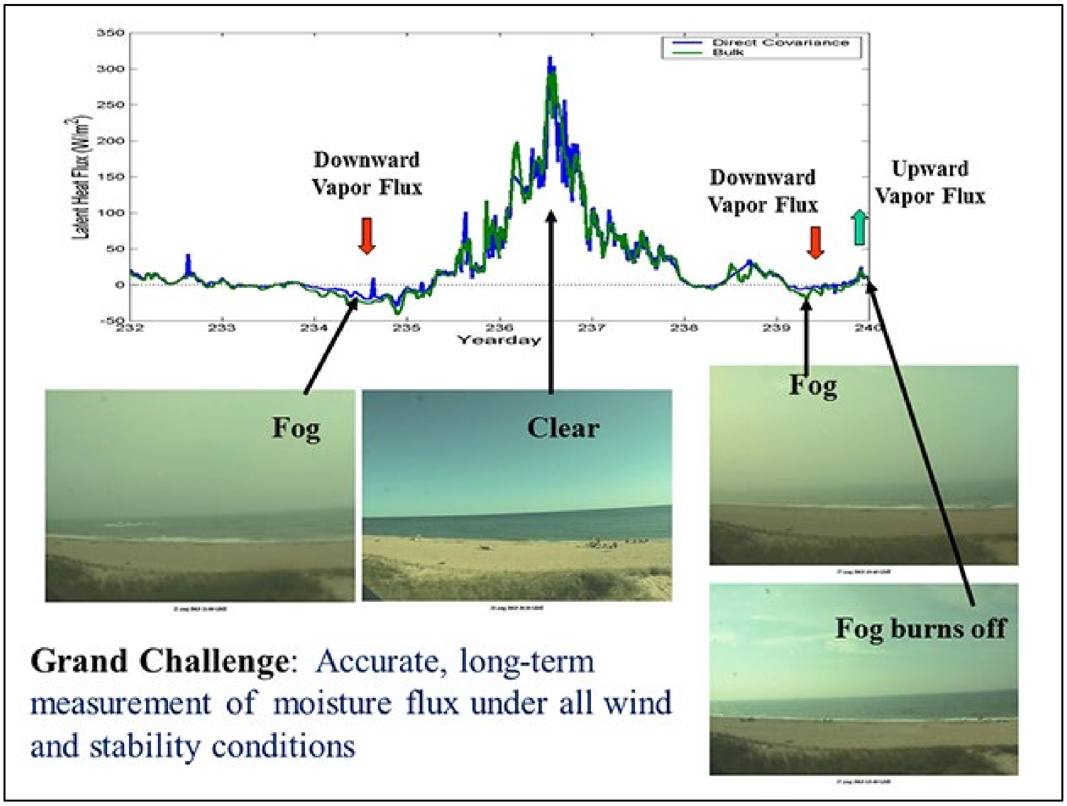
Modeled vs Measured Wind Profiles

Offshore Flow

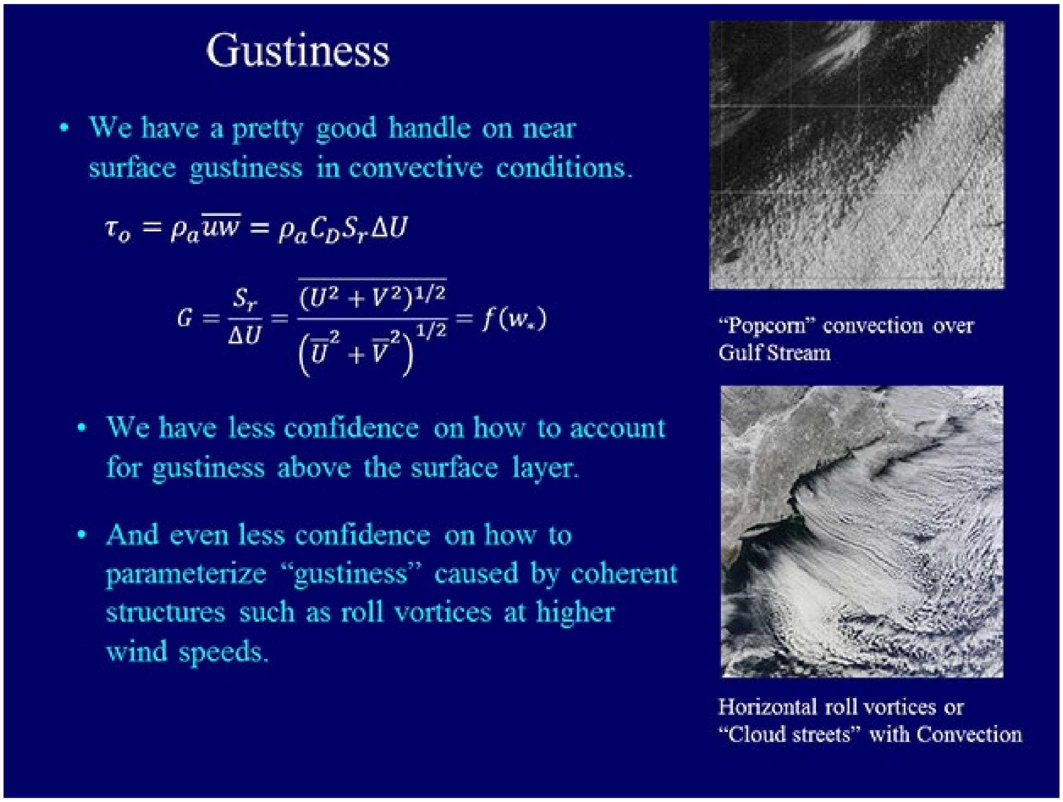
Onshore Flow

Convectively Unstable

Stably Stratified



Grand Challenge: Accurate, long-term measurement of moisture flux under all wind and stability conditions



Gustiness

- We have a pretty good handle on near surface gustiness in convective conditions.

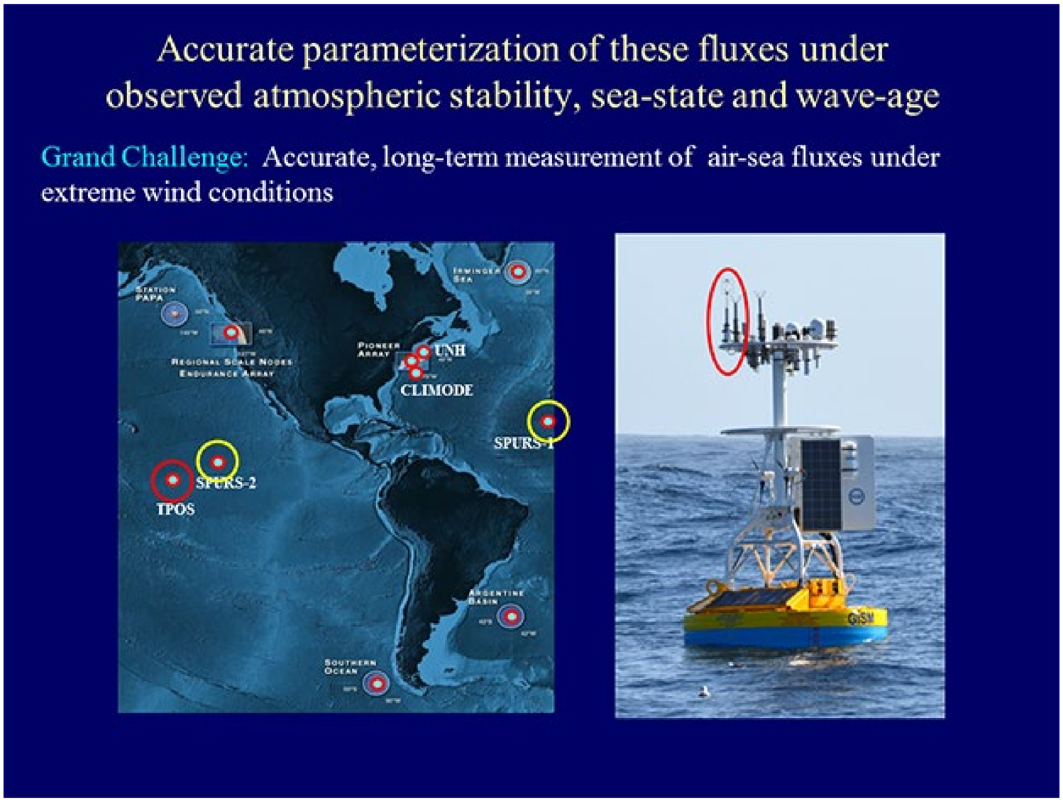
$$\tau_o = \rho_a \overline{uw} = \rho_a C_D S_r \Delta U$$

$$G = \frac{S_r}{\Delta U} = \frac{\overline{(U^2 + V^2)^{1/2}}}{\left(\overline{U}^2 + \overline{V}^2\right)^{1/2}} = f(w_*)$$

- We have less confidence on how to account for gustiness above the surface layer.
- And even less confidence on how to parameterize "gustiness" caused by coherent structures such as roll vortices at higher wind speeds.

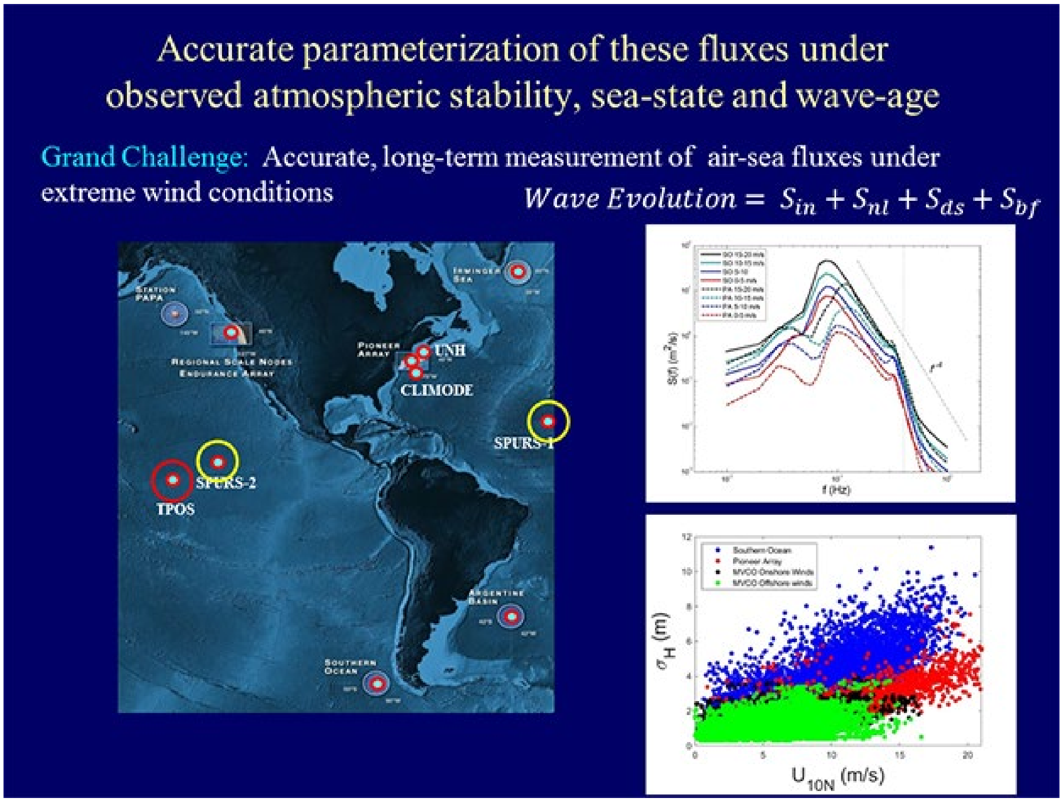
"Popcorn" convection over Gulf Stream

Horizontal roll vortices or "Cloud streets" with Convection



Accurate parameterization of these fluxes under observed atmospheric stability, sea-state and wave-age

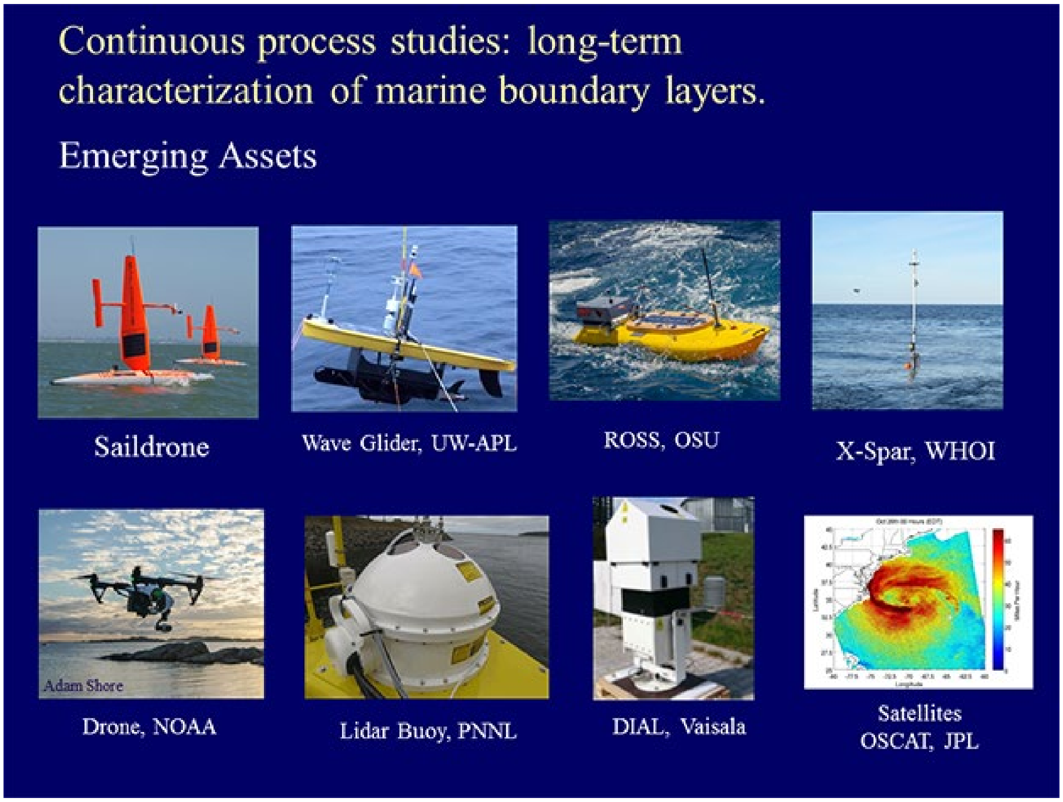
Grand Challenge: Accurate, long-term measurement of air-sea fluxes under extreme wind conditions



Accurate parameterization of these fluxes under observed atmospheric stability, sea-state and wave-age

Grand Challenge: Accurate, long-term measurement of air-sea fluxes under extreme wind conditions

$$Wave\ Evolution = S_{in} + S_{nl} + S_{ds} + S_{bf}$$



Continuous process studies: long-term characterization of marine boundary layers.

Emerging Assets

Saildrone

Wave Glider, UW-APL

ROSS, OSU

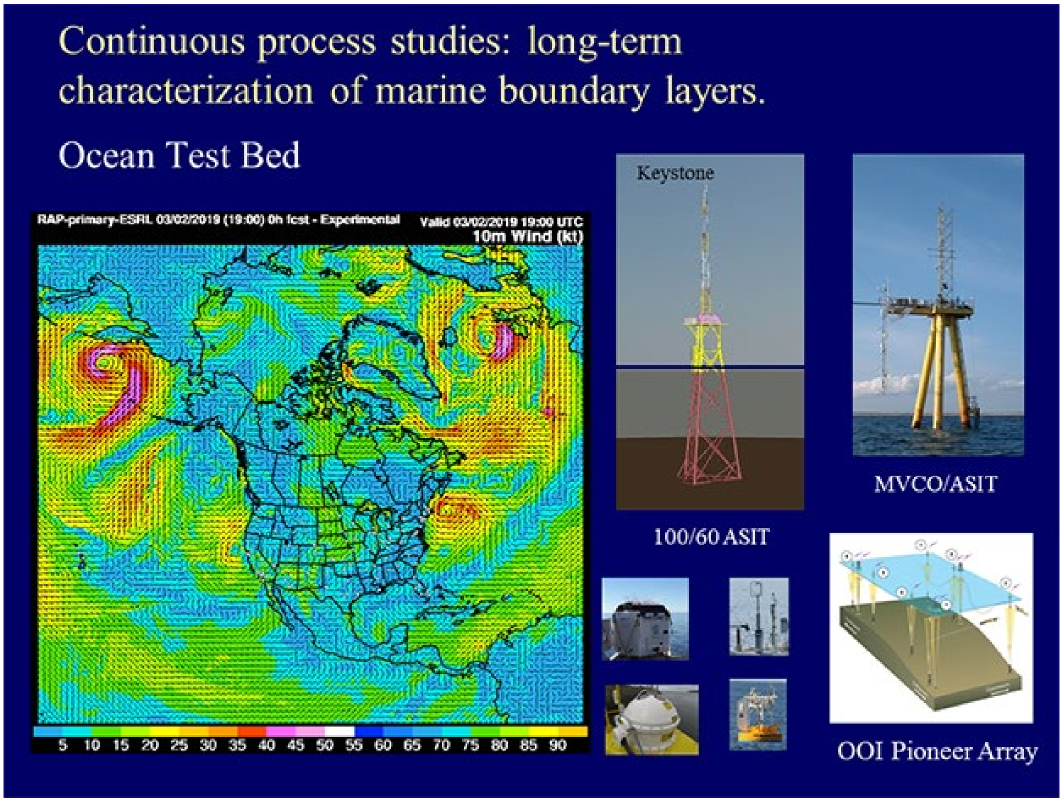
X-Spar, WHOI

Drone, NOAA

Lidar Buoy, PNNL

DIAL, Vaisala

Satellites
OSCAT, JPL



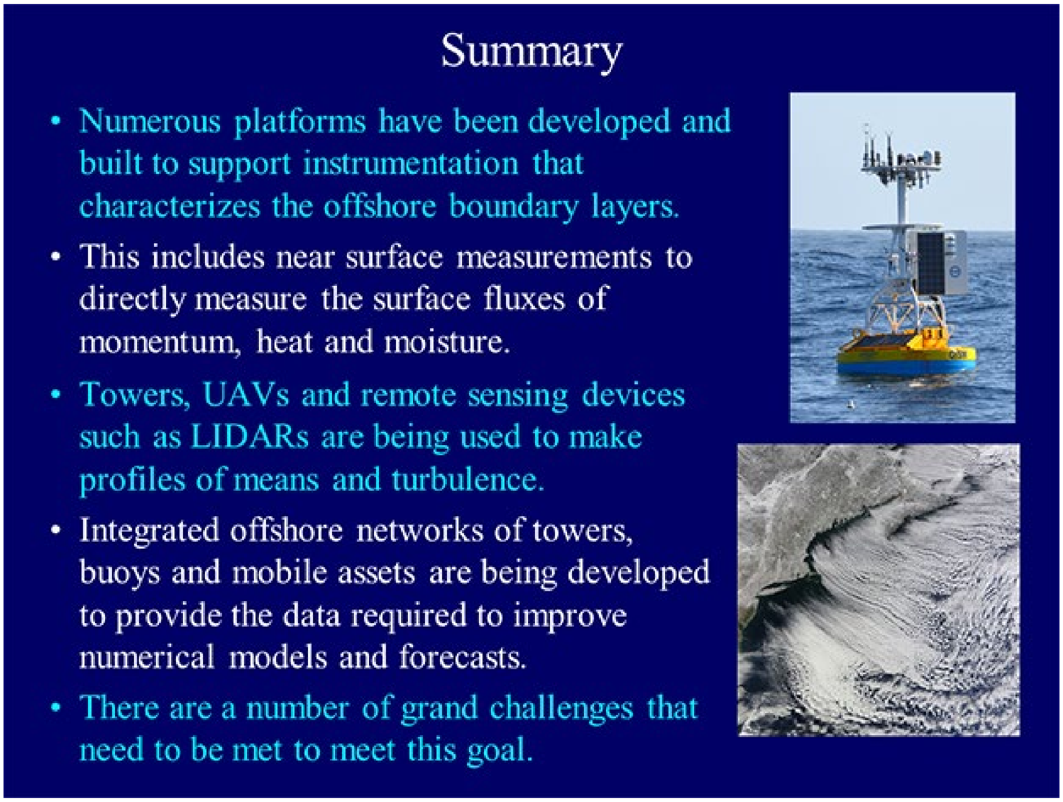
Continuous process studies: long-term characterization of marine boundary layers.

Ocean Test Bed

100/60 ASIT

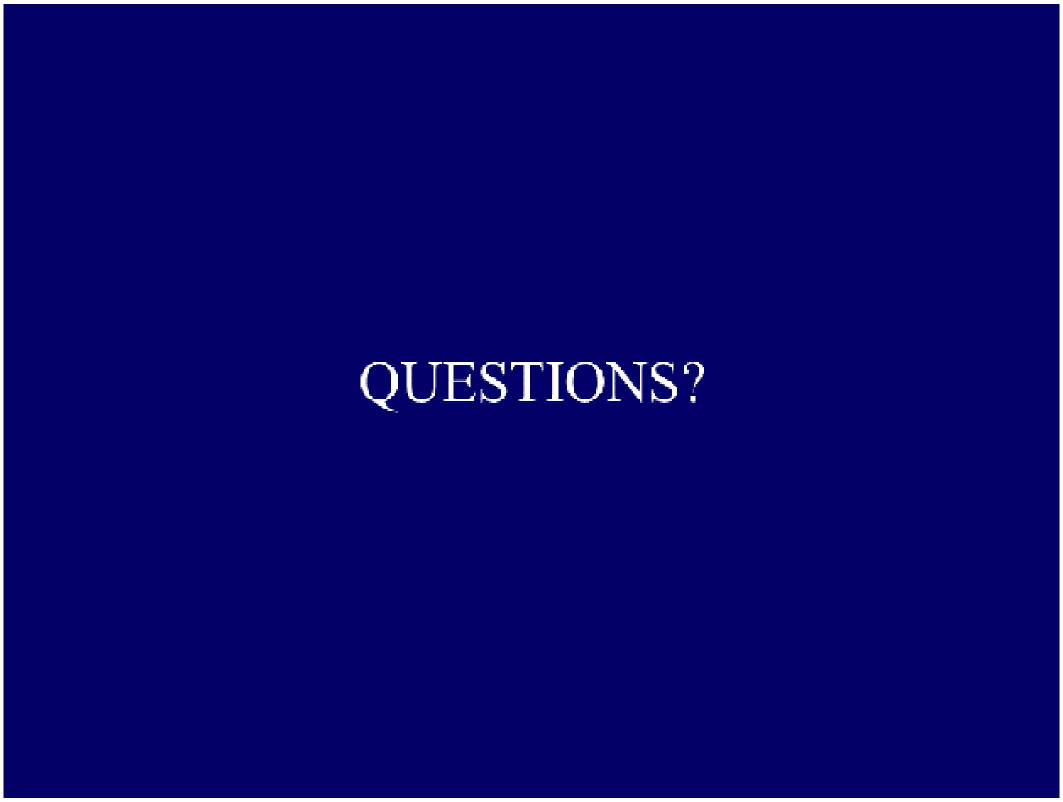
MVCO/ASIT

OOI Pioneer Array

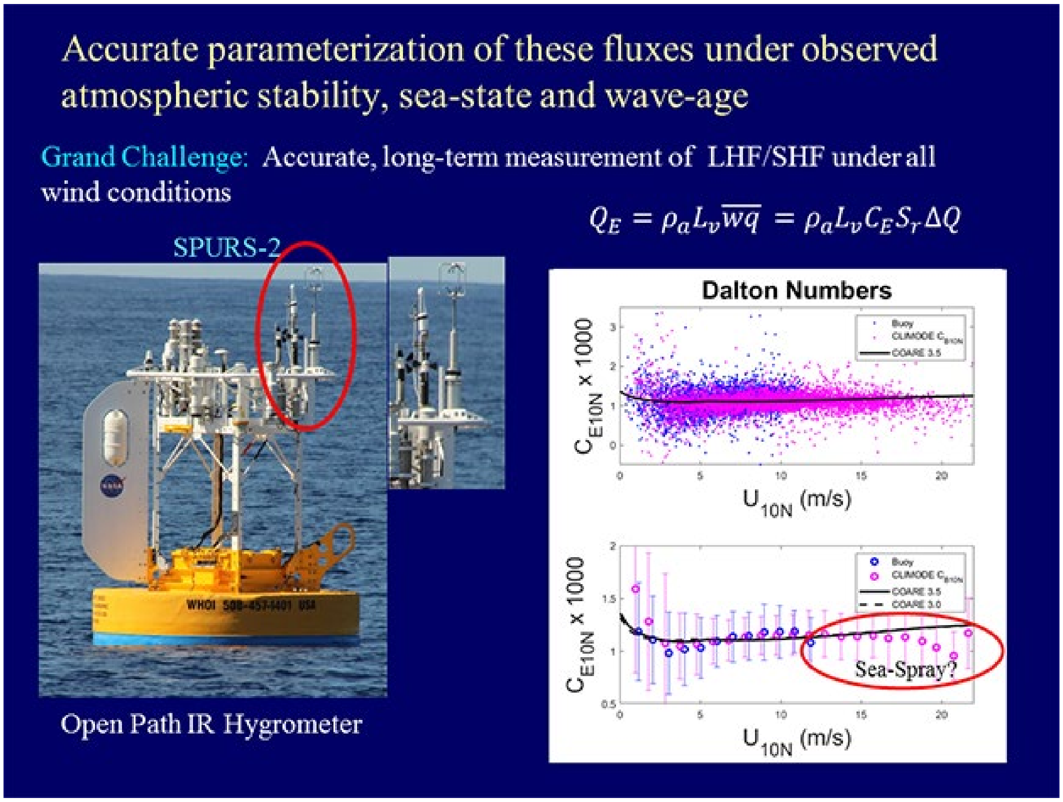


Summary

- Numerous platforms have been developed and built to support instrumentation that characterizes the offshore boundary layers.
- This includes near surface measurements to directly measure the surface fluxes of momentum, heat and moisture.
- Towers, UAVs and remote sensing devices such as LIDARs are being used to make profiles of means and turbulence.
- Integrated offshore networks of towers, buoys and mobile assets are being developed to provide the data required to improve numerical models and forecasts.
- There are a number of grand challenges that need to be met to meet this goal.



QUESTIONS?



Accurate parameterization of these fluxes under observed atmospheric stability, sea-state and wave-age

Grand Challenge: Accurate, long-term measurement of LHF/SHF under all wind conditions

$$Q_E = \rho_a L_v \overline{wq} = \rho_a L_v C_E S_r \Delta Q$$

SPURS-2

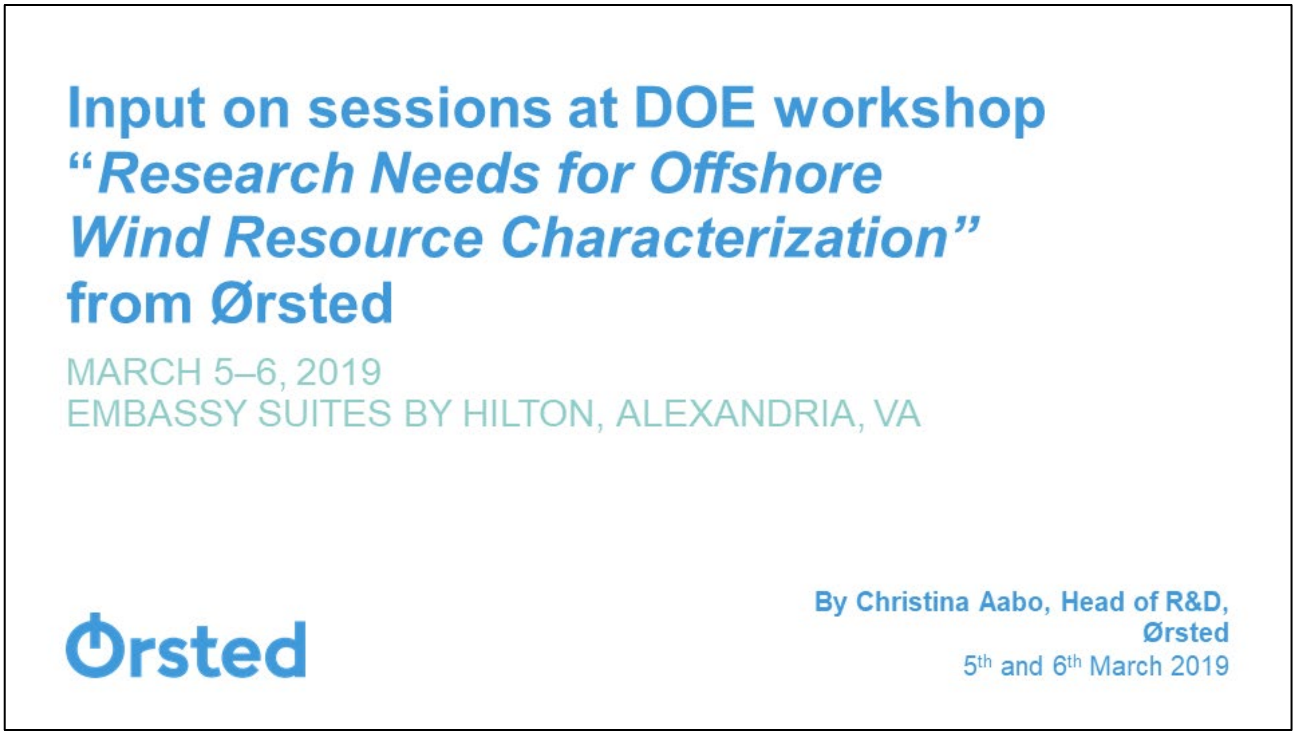
Open Path IR Hygrometer

Dalton Numbers

Appendix D – Other Input from Workshop Participants

Participants at the workshop were invited to provide comments or other input within a short time following the workshop. Ørsted was not able to participate in the workshop but offered material ahead of time to help workshop planners develop the discussion. Other material in this appendix was provided by participants afterward.

D.1 Ørsted

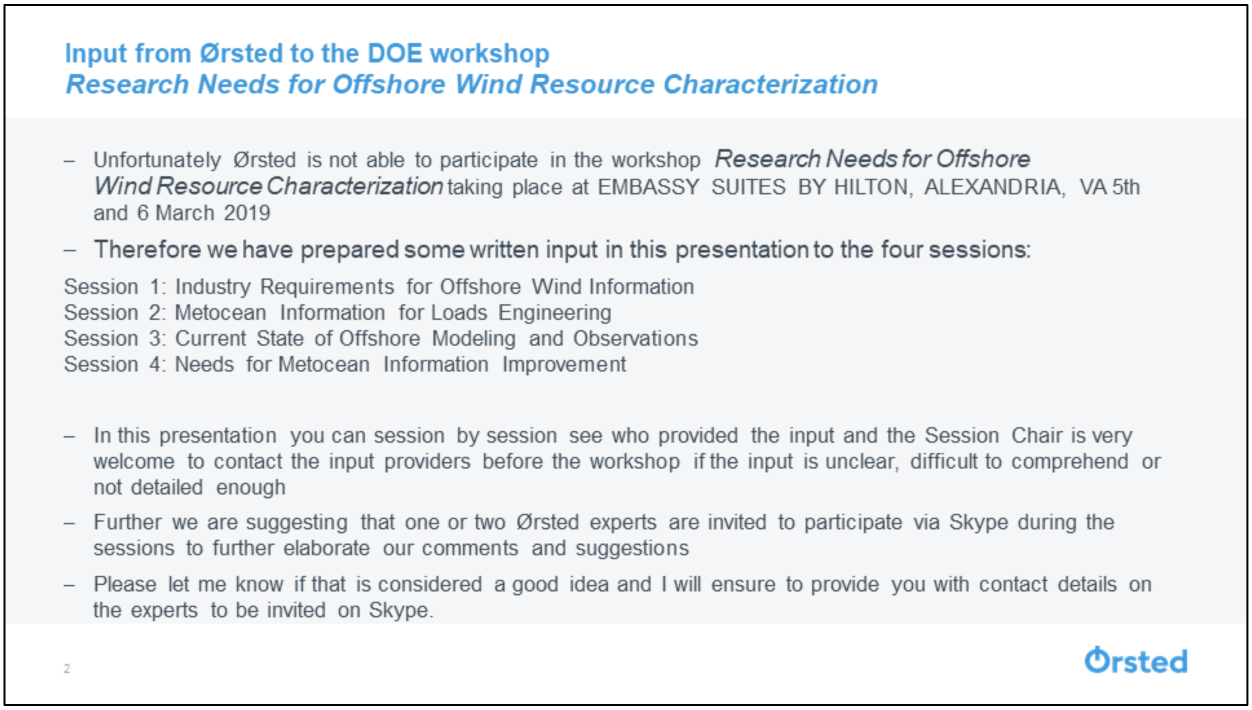


Input on sessions at DOE workshop "*Research Needs for Offshore Wind Resource Characterization*" from Ørsted

MARCH 5–6, 2019
EMBASSY SUITES BY HILTON, ALEXANDRIA, VA

Ørsted

By Christina Aabo, Head of R&D, Ørsted
5th and 6th March 2019

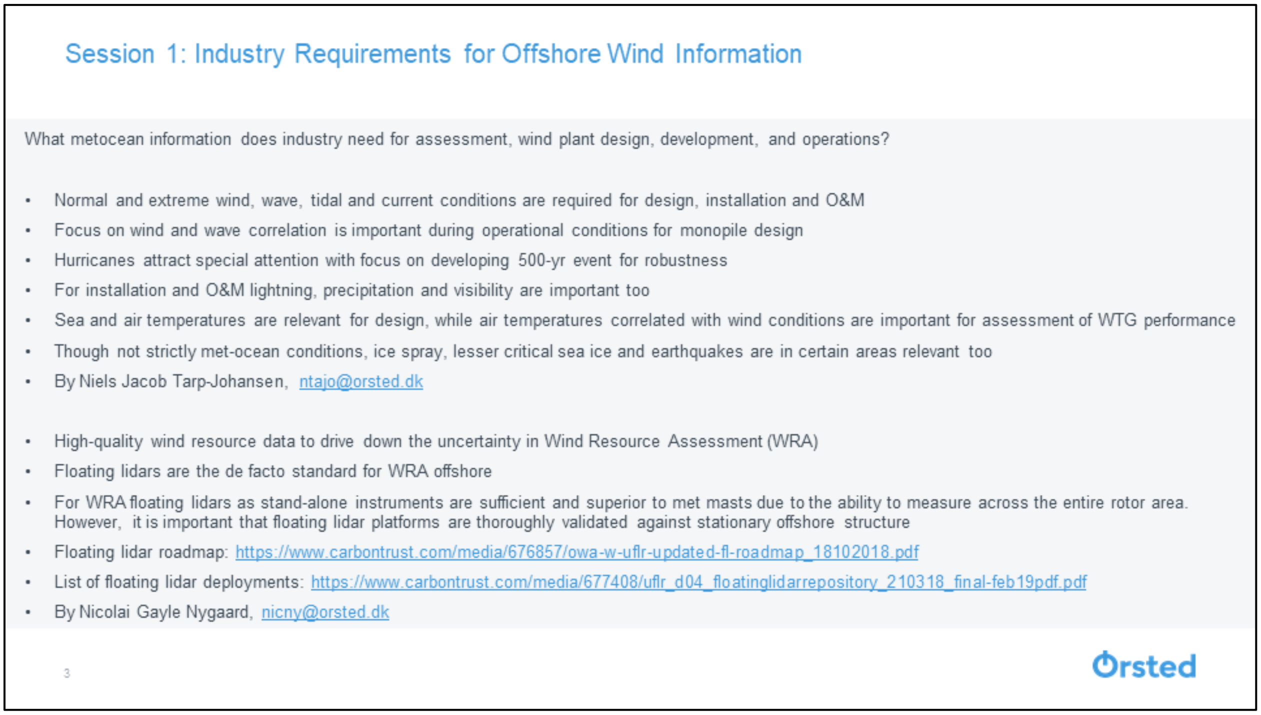


Input from Ørsted to the DOE workshop
Research Needs for Offshore Wind Resource Characterization

- Unfortunately Ørsted is not able to participate in the workshop *Research Needs for Offshore Wind Resource Characterization* taking place at EMBASSY SUITES BY HILTON, ALEXANDRIA, VA 5th and 6 March 2019
- Therefore we have prepared some written input in this presentation to the four sessions:

Session 1: Industry Requirements for Offshore Wind Information
Session 2: Metocean Information for Loads Engineering
Session 3: Current State of Offshore Modeling and Observations
Session 4: Needs for Metocean Information Improvement

- In this presentation you can session by session see who provided the input and the Session Chair is very welcome to contact the input providers before the workshop if the input is unclear, difficult to comprehend or not detailed enough
- Further we are suggesting that one or two Ørsted experts are invited to participate via Skype during the sessions to further elaborate our comments and suggestions
- Please let me know if that is considered a good idea and I will ensure to provide you with contact details on the experts to be invited on Skype.

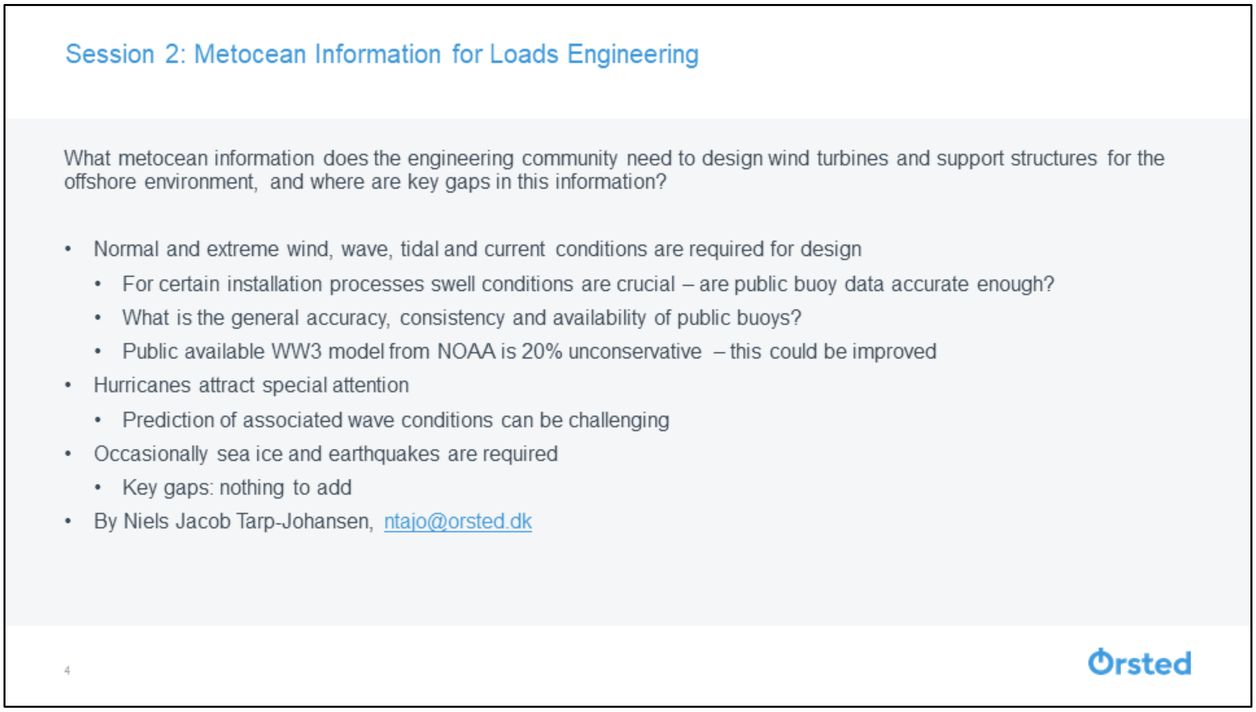


Session 1: Industry Requirements for Offshore Wind Information

What metocean information does industry need for assessment, wind plant design, development, and operations?

- Normal and extreme wind, wave, tidal and current conditions are required for design, installation and O&M
- Focus on wind and wave correlation is important during operational conditions for monopile design
- Hurricanes attract special attention with focus on developing 500-yr event for robustness
- For installation and O&M lightning, precipitation and visibility are important too
- Sea and air temperatures are relevant for design, while air temperatures correlated with wind conditions are important for assessment of WTG performance
- Though not strictly met-ocean conditions, ice spray, lesser critical sea ice and earthquakes are in certain areas relevant too
- By Niels Jacob Tarp-Johansen, ntajo@orsted.dk

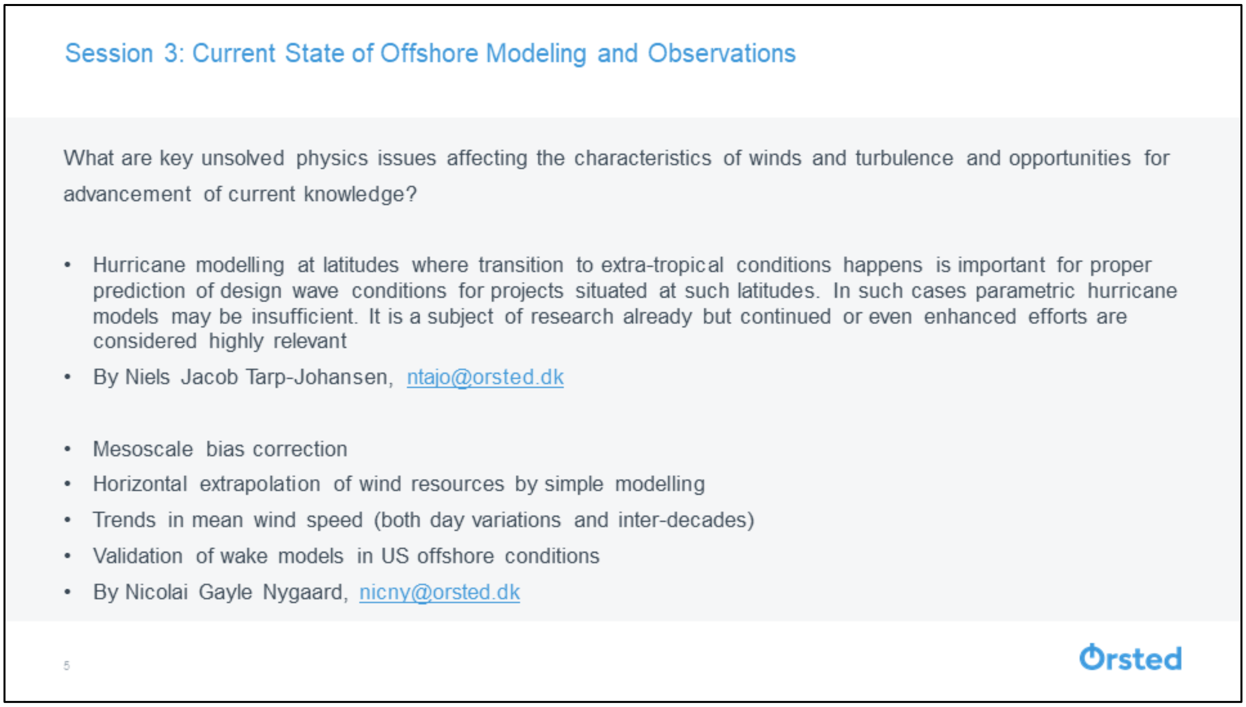
- High-quality wind resource data to drive down the uncertainty in Wind Resource Assessment (WRA)
- Floating lidars are the de facto standard for WRA offshore
- For WRA floating lidars as stand-alone instruments are sufficient and superior to met masts due to the ability to measure across the entire rotor area. However, it is important that floating lidar platforms are thoroughly validated against stationary offshore structure
- Floating lidar roadmap: https://www.carbontrust.com/media/676857/owa-w-uflr-updated-fl-roadmap_18102018.pdf
- List of floating lidar deployments: https://www.carbontrust.com/media/677408/uflr_d04_floatinglidarrepository_210318_final-feb19pdf.pdf
- By Nicolai Gayle Nygaard, nicny@orsted.dk



Session 2: Metocean Information for Loads Engineering

What metocean information does the engineering community need to design wind turbines and support structures for the offshore environment, and where are key gaps in this information?

- Normal and extreme wind, wave, tidal and current conditions are required for design
  - For certain installation processes swell conditions are crucial – are public buoy data accurate enough?
  - What is the general accuracy, consistency and availability of public buoys?
  - Public available WW3 model from NOAA is 20% unconservative – this could be improved
- Hurricanes attract special attention
  - Prediction of associated wave conditions can be challenging
- Occasionally sea ice and earthquakes are required
  - Key gaps: nothing to add
- By Niels Jacob Tarp-Johansen, ntajo@orsted.dk

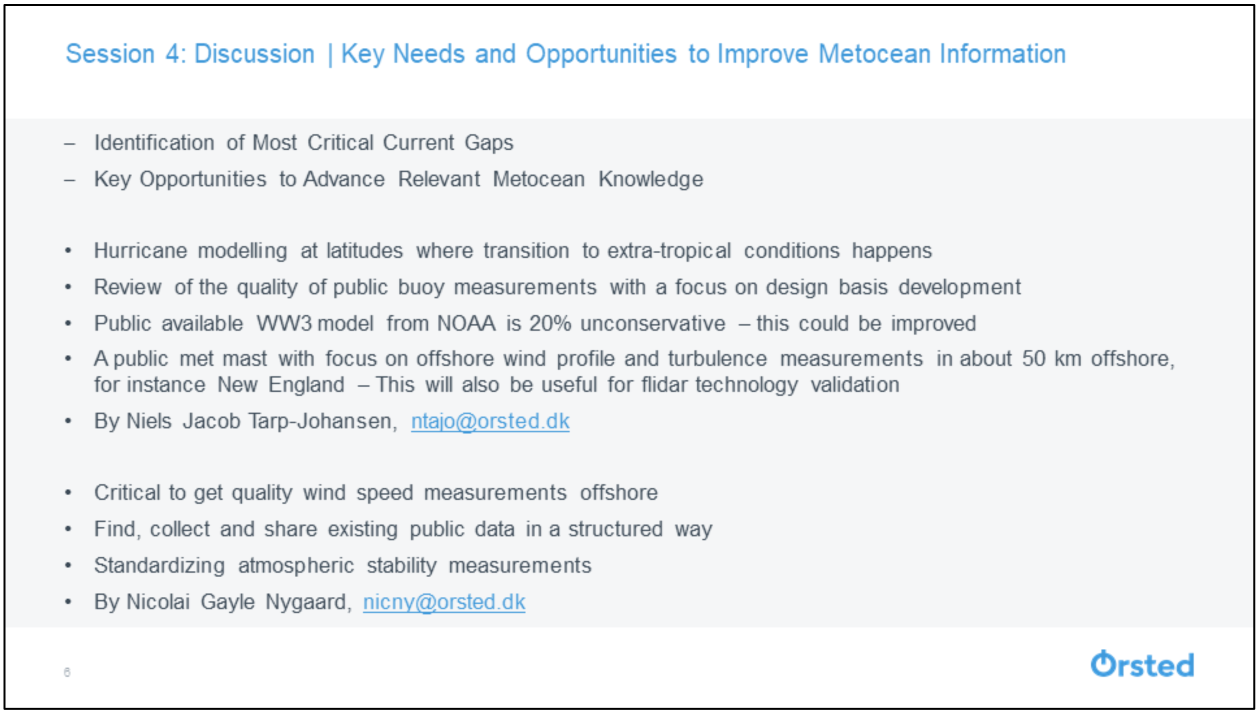


Session 3: Current State of Offshore Modeling and Observations

What are key unsolved physics issues affecting the characteristics of winds and turbulence and opportunities for advancement of current knowledge?

- Hurricane modelling at latitudes where transition to extra-tropical conditions happens is important for proper prediction of design wave conditions for projects situated at such latitudes. In such cases parametric hurricane models may be insufficient. It is a subject of research already but continued or even enhanced efforts are considered highly relevant
- By Niels Jacob Tarp-Johansen, ntajo@orsted.dk

- Mesoscale bias correction
- Horizontal extrapolation of wind resources by simple modelling
- Trends in mean wind speed (both day variations and inter-decades)
- Validation of wake models in US offshore conditions
- By Nicolai Gayle Nygaard, nicny@orsted.dk



Session 4: Discussion | Key Needs and Opportunities to Improve Metocean Information

– Identification of Most Critical Current Gaps
– Key Opportunities to Advance Relevant Metocean Knowledge

- Hurricane modelling at latitudes where transition to extra-tropical conditions happens
- Review of the quality of public buoy measurements with a focus on design basis development
- Public available WW3 model from NOAA is 20% unconservative – this could be improved
- A public met mast with focus on offshore wind profile and turbulence measurements in about 50 km offshore, for instance New England – This will also be useful for flidar technology validation
- By Niels Jacob Tarp-Johansen, ntajo@orsted.dk

- Critical to get quality wind speed measurements offshore
- Find, collect and share existing public data in a structured way
- Standardizing atmospheric stability measurements
- By Nicolai Gayle Nygaard, nicny@orsted.dk

D.2 Harvey Seim—University of North Carolina

Regarding the Tactical Aircrew Combat Training System (TACTS) towers, as I think you know, I was able to access and help develop instrumentation of the TACTS range off Georgia, and tried for a number of years to do the same for the range off North Carolina/Virginia (the Oceana Range, or VA CAPES range, as the Navy likes to refer to them). One of the last significant efforts was about 10 years ago, when I was approached by the NAVFAC Engineering Service Center at Port Hueneme, which was interested in using the towers to make wind measurements in support of offshore wind energy resource assessment (to my amazement). This group had recently decommissioned the platforms, and made an assessment of the platform integrity. They then developed and sent a fairly ambitious plan forward that would have deployed a lidar and a number of anemometers (on stays to address flow distortion) on at least one platform. In the end (after about 1.5 years) the Navy chose not to support it. I was told that if I wished to pursue my deployments (a met package and sodar) I would need to conduct my own safety inspection to seek approval to access the platforms.

D.3 Marian Klein—Boulder Environmental Science and Technology

I would like to summarize my proposal for the offshore wind measurements. It is as follows:

I proposed for the DOE and Bureau of Land Management to finance and permanently deploy and operate a chain of offshore buoys 100–150 km off the coast of the USA (maybe East Coast first). Buoy could be spaced about 100–150 km apart, but I would ask meteorologist about the spacing. The buoys will be equipped with remote sensors capable of measuring wind, temperature, and humidity profiles up to the height of the turbine blades—200 meters currently, 250–300 meters projected in the future. Additional remote sensors providing additional measurements could be added.

1. Such measurements will provide improved characterization of the offshore wind resource and potentially simplify the financing and development options for wind farms.

2. Such additional atmospheric observations from buoys will improve also on shore, or near shore, weather forecasts. Such forecasts are used in the daily electrical load forecasting; thus, the energy consumption forecasts will also improve.

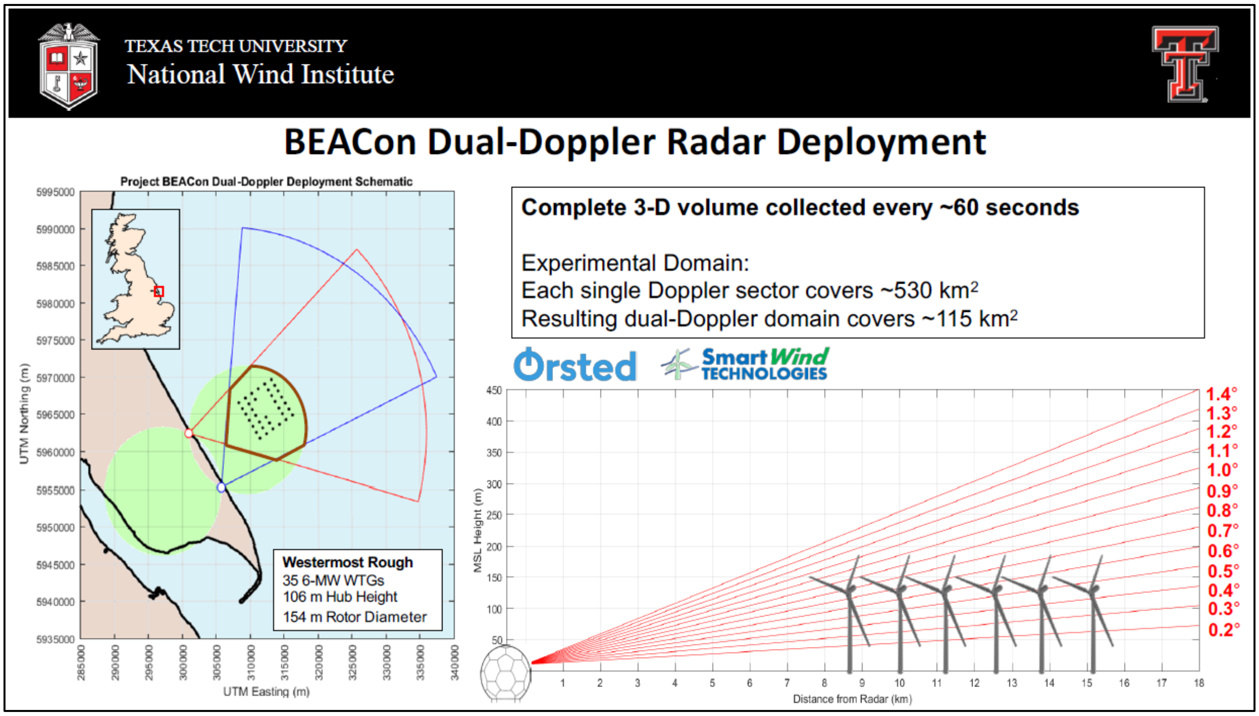
3. A deployment of multiple observational platforms (buoys) will make the technology less expensive per unit.

4. More buoys will be able to provide overall better understanding of offshore weather conditions and provide statistics on various atmospheric conditions.

D.4 John Schroeder—Texas Tech University

Measurements related to traditional offshore wind resource assessment might be advantageous to validate mesoscale forecast models, but these same measurements are not enough to advance wind turbine/plant design practices and/or validate high-fidelity modeling efforts that simulate inter- or intra-plant flows. Hence, there is a need for a diversity of measurements across various scales of motion. An instrumented tower, vertically pointing lidars/radars, and scanning lidars/radars could all be beneficial if nested properly. A measurement campaign targeting an area with an operating offshore wind plant would also be beneficial for studying a wider diversity of issues. A longer duration campaign is more likely to result in a more complete data set, including a more diverse collection of transient weather events that might provide better clues for design.

Could the oil drilling platforms and existing tower in the southern Gulf of Mexico provide a basis for deploying instruments at a reduced cost? The coastline is also relatively unpopulated in this area, which might facilitate easier coastal deployments of assets. The negative of course is that the region is disconnected from the larger wind resource regions of the northeast.



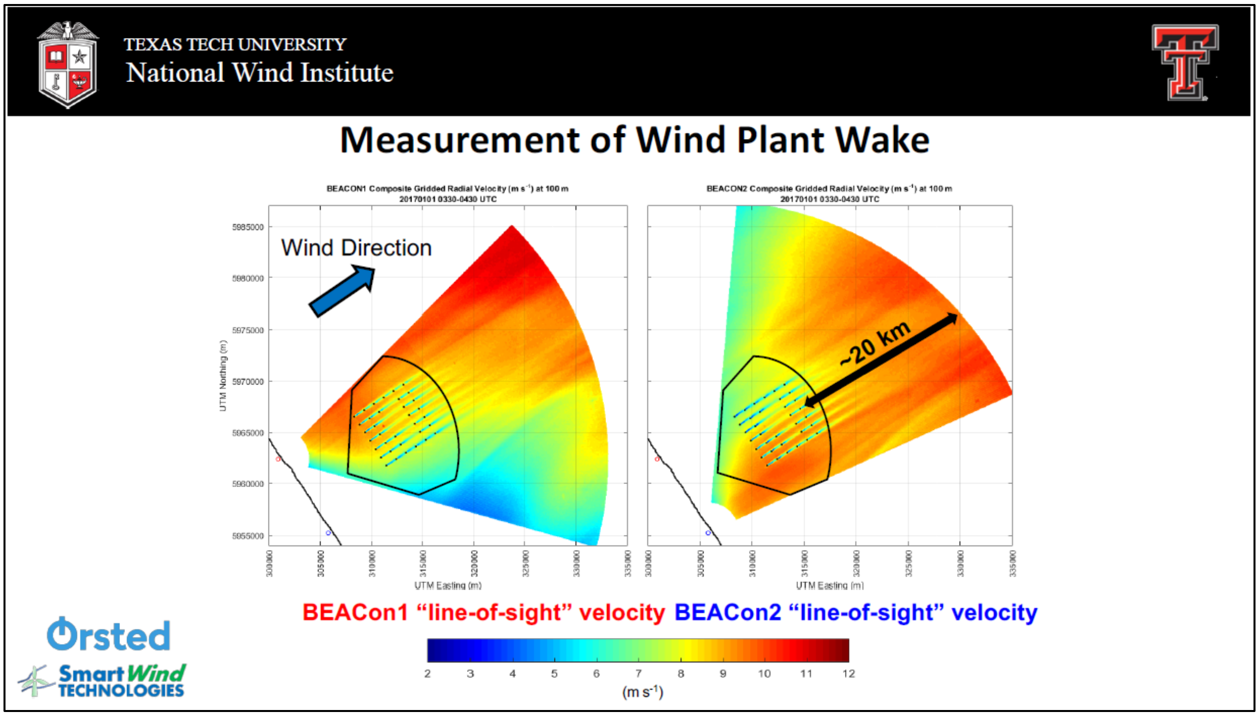
TEXAS TECH UNIVERSITY
National Wind Institute

BEACon Dual-Doppler Radar Deployment

Complete 3-D volume collected every ~60 seconds

Experimental Domain:
Each single Doppler sector covers ~530 km²
Resulting dual-Doppler domain covers ~115 km²

Westermost Rough
35 6-MW WTGs
106 m Hub Height
154 m Rotor Diameter

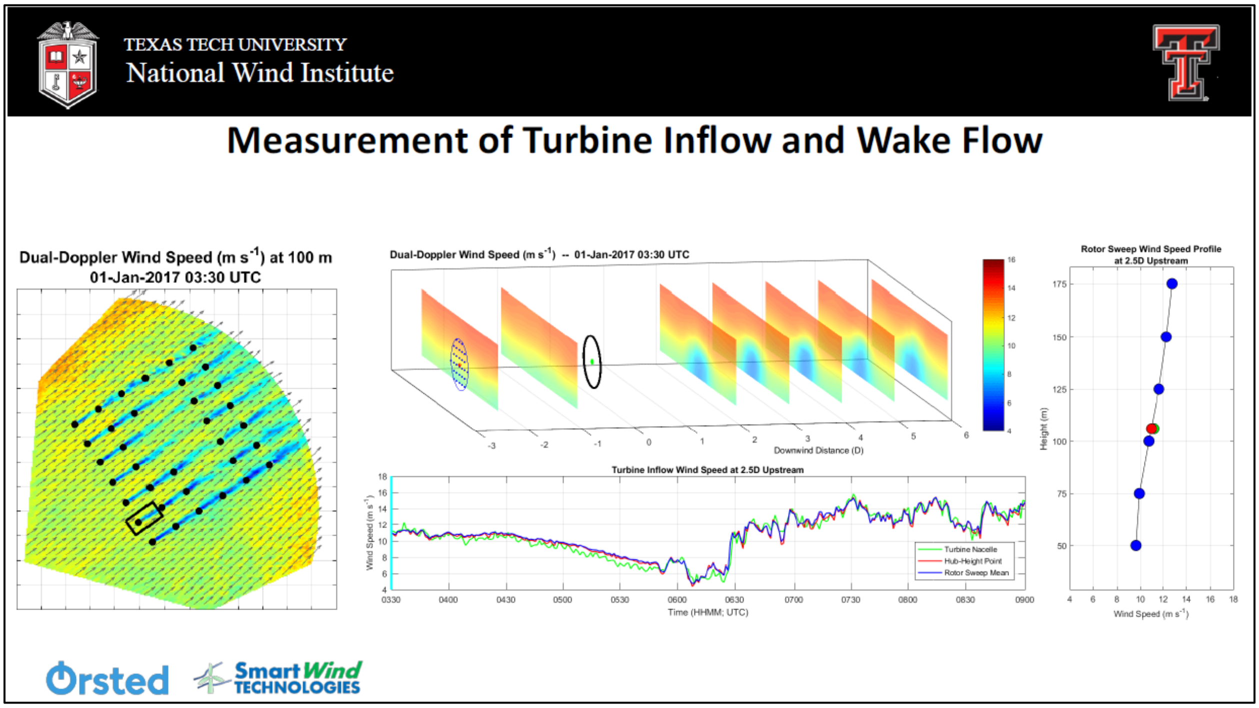


TEXAS TECH UNIVERSITY
National Wind Institute

Measurement of Wind Plant Wake

BEACon1 "line-of-sight" velocity **BEACon2 "line-of-sight" velocity**

Ørsted
SmartWind TECHNOLOGIES



TEXAS TECH UNIVERSITY
National Wind Institute

Measurement of Turbine Inflow and Wake Flow

Ørsted
SmartWind TECHNOLOGIES

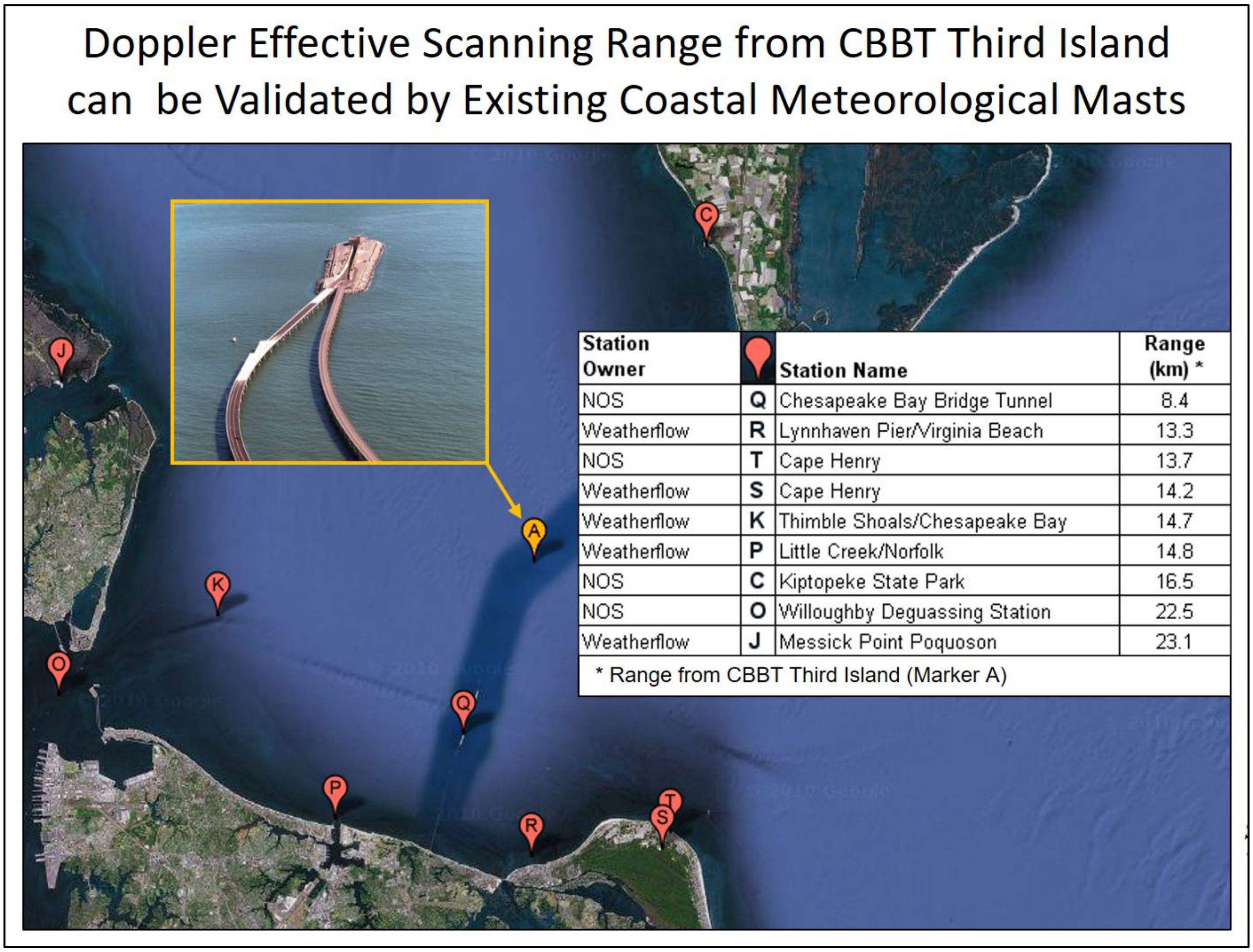
D.5 George Hagerman—Old Dominion University

D.5.1 Spatial Variability of Offshore Wind Resource in Virginia and Maryland Lease Areas

Koch et al. (2014) have discussed spatial variability of offshore wind resources off the U.S. East Coast.

D.5.2 Virginia Renewable Energy Research Leases and Shoreside Supporting Infrastructure

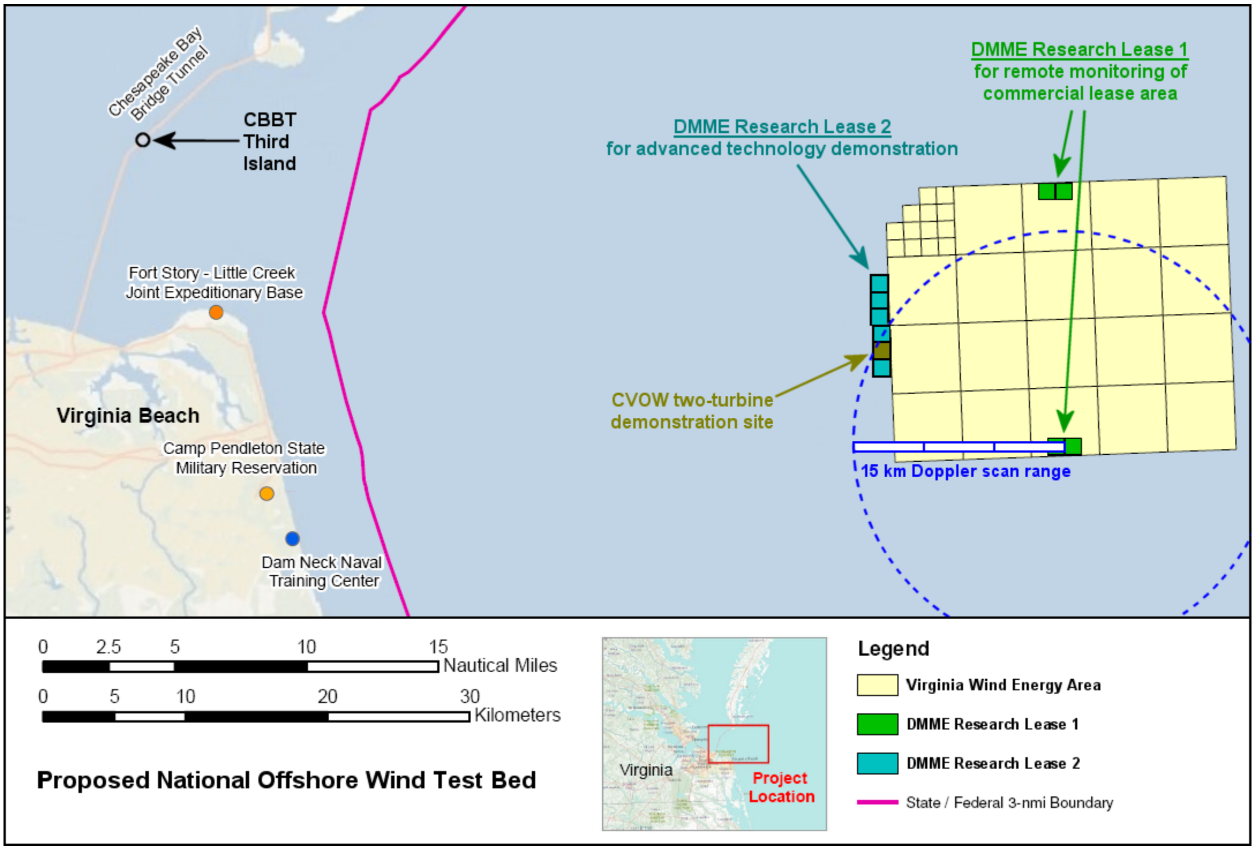
The two images below are taken from Old Dominion University’s response to DOE’s DE-FOA-0001963 Request for Information (RFI).



Doppler Effective Scanning Range from CBBT Third Island can be Validated by Existing Coastal Meteorological Masts

Station Owner		Station Name	Range (km) *
NOS	Q	Chesapeake Bay Bridge Tunnel	8.4
Weatherflow	R	Lynnhaven Pier/Virginia Beach	13.3
NOS	T	Cape Henry	13.7
Weatherflow	S	Cape Henry	14.2
Weatherflow	K	Thimble Shoals/Chesapeake Bay	14.7
Weatherflow	P	Little Creek/Norfolk	14.8
NOS	C	Kiptopeke State Park	16.5
NOS	O	Willoughby Deguassing Station	22.5
Weatherflow	J	Messick Point Poquoson	23.1

* Range from CBBT Third Island (Marker A)



Proposed National Offshore Wind Test Bed

D.5.3 Wavewatch III Re-analysis 31-Year Wind and Directional Wave Hindcast Dataset

The National Centers for Environmental Prediction (NCEP) NOPP Wavewatch III re-analysis Phase 2 hindcasts surface (10m ASL) wind speed and direction covering the 31-year period from 1979 through 1980. Hagerman et al. (2014) provides details, and tabulates 22 offshore-wind-specific grid points that complement the Wave Information Studies standard grid points to provide a variety of transects through the Mid-Atlantic offshore wind lease areas, as shown in a series of maps in Hagerman et al. (2014), which can be accessed through the Bureau of Safety and Environment Enforcement at:

https://www.bsee.gov/sites/bsee.gov/files/tap-technical-assessment-program/672af.pdf

The NCEP re-analysis is documented at http://polar.ncep.noaa.gov/waves/hindcasts/noppphase2.php. Full directional wave spectra time series (3-hour time step) at “virtual buoy” grid points are available within each month-year folder at ftp://polar.ncep.noaa.gov/pub/history/nopp-phase2 →points →buoys →multi_reanal.buoys_spec.buoys.yyyymm.tar.gz. For example, here is the full path for the Jan-1979 directional spectra time series:

ftp://polar.ncep.noaa.gov/pub/history/noppphase2/197901/points/buoys/multi_reanal.buoys_spec.buoys.197902.tar.gz

This dataset can be used for the assessment of extratropical storm extreme design conditions, fatigue assessments, and characterization of site access conditions for offshore construction and for O&M service visits. The Bureau of Safety and Environmental Enforcement (BSEE) Web page at www.bsee.gov/researchrecord/tap-672-development-integrated-extreme-wind-wave-current-and-water-level-climatology has the full study.

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For more information, visit:
energy.gov/eere/wind

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