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Overview

Offshore winds mapped from satellite remote sensing

Charlotte Bay Hasager*

Around 2000 wind turbines in 58 offshore wind farms produce wind energy in the Northern European seas and many new wind farms are foreseen. The wind resource assessment is costly to observe using traditional meteorological masts and therefore atmospheric modeling is state of the art. However, to reduce the uncertainty on the model results on the offshore wind resource, it is necessary to compare model results with observations. Observations from ground-based wind lidar and satellite remote sensing are the two main technologies that can provide new types of offshore wind data at relatively low cost. The advantages of microwave satellite remote sensing are (1) horizontal spatial coverage, (2) long data archives, and (3) high spatial detail both in the coastal zone and of far-field wind farm wake. Passive microwave ocean wind speed data are available since 1987 with up to six observations per day with near-global coverage. The data are particularly useful for investigation of long-term wind conditions. Scatterometer ocean surface wind vectors provide a continuous series since 1999 with twice-daily near-global coverage. Both types of data have grid cells around 25 km. In contrast, synthetic aperture radar (SAR) wind maps can be retrieved at 1-km grid resolution. SAR-based wind maps have been used for wind resource assessment far offshore and in the coastal zones with good results when compared to e.g., meteorological data and mesoscale model results. High-resolution SAR data show very long far-field wind farm wakes. Thus wind farm wake loss is foreseen in wind farm clusters.

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INTRODUCTION

Offshore wind power in European Seas consists of approximately 2000 wind turbines in 58 wind farms across 10 countries. The fully grid-connected capacity is 6 GW.[1] The potential production of wind energy is a function of the wind climate at each installed wind turbine. Observations of the wind climate at hub height from tall meteorological masts are sparse in both time and space due to relatively high installation and operational costs. Thus it is a challenge to quantify the future 30-year offshore wind climate accurately at every point in space, even if assuming no changes in the wind climate as compared to the last 30 year's wind climate. The wind shadowing effects of nearby wind turbines and from clusters of wind farms need to be addressed to accurately describe the potential wind energy production.

State-of-the-art atmospheric modeling of the wind conditions and resource assessment is described in Ref 2. Whether planning wind farms at coastal locations, far offshore, or on land in complex, forested terrain, it is necessary to compare the model results with observations of winds to decrease the uncertainty on the modeled wind statistics. Obtaining higher certainty on the potential wind power may reduce the financial investment cost. This is in particular relevant for the future large offshore wind farms where the need to drive down cost is acute.[3]

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New observation methodologies to quantify the wind climate offshore are hot topics in research and development. There is need to supplement meteorological mast wind observations from one location to a wider area i.e., spatial horizontal extrapolation. There is need to use observed winds from masts collected during a shorter period of time to estimate potential winds for longer time-scales i.e., temporal extrapolation. Finally, when winds are observed at relatively low levels from a short mast or from satellite remote sensing where the winds are observed at 10 m above sea level, there is need to extrapolate in the vertical direction to hub-height i.e., vertical extrapolation.

This article provides a brief introduction on the marine atmospheric boundary layer (MABL), coastal atmospheric processes, and remote sensing. Examples using satellite remote sensing data for mapping offshore winds are presented.

MARINE ATMOSPHERE

The MABL is defined as the air masses above the sea stretching from the sea surface to the boundary-layer top above which is the entrainment zone from few hundred meters to more than a kilometer.[4–6]

The MABL is relatively unknown compared to the boundary layer over land. The basic parameterizations of the atmospheric boundary layer are from intense observations conducted over land in Kansas in 1968 and Minnesota in 1973 in the United States. These observations later have been supplemented by many other observational data sets and modeling activities. Over the sea trough, the progress has been slow, due to on the one hand theoretical problems and on the other hand several major observation technical problems associated with high cost and/or high risk.

There are several significant differences between the MABL and the atmospheric boundary layer over land.[4,6] The roughness of sea is lower than for most land cover types and the roughness of sea is a function of wind speed and wave generation e.g., wave age and fetch i.e., distance to coast. Over the sea the height of the boundary layer is typically relatively shallower than over land, and the heat exchange (heat flux) is very different due to, among other things, the heat capacity of the sea is much higher than the heat capacity of soil, canopy, and urban environments. The marine mixing processes, tidal processes, and up- and down-welling influence the heat storage capacity of the ocean. Cold and warm ocean currents transport energy around. The atmospheric turbulence over sea is generally lower than over land. The low ambient turbulence in the MABL has implication for how far downstream any disturbance to the general atmospheric flow may exist. The marine atmospheric chemical composition is markedly different from air masses over land which results in specific atmospheric–chemical relationships e.g., higher corrosion risk offshore.

COASTAL ATMOSPHERE

In the condition with wind blowing from land toward sea, the wind usually will accelerate; thus higher winds are expected further offshore. Close to the coastline lee effect with lesser wind often prevails.[4] The lee effect may extend decades of kilometers downwind. The lee effect depends upon the coastal orography, land cover, and the thermal properties of air and sea. In unstable conditions (the sea is warmer than the air) the lee effect typically will be shorter than in stable conditions (the sea is cooler than the air). The mixing processes are more efficient in unstable conditions. The effect of atmospheric stability on the logarithmic wind profile is described in Refs 2, 6. Along some coastlines the wind is channeled through valleys near the coast, between islands or along fjords e.g., gap flows.[7,8] An example is katabatic drainage flow with cool air ‘falling down’ from coastal mountains resulting in high winds observed far offshore. The area with relatively higher wind speeds may reach decades of kilometers offshore.[9]

Land-sea breezes are well-known and can be well-developed under certain conditions namely those with marked differences between the land and sea temperature and with relatively weak winds.[4] You may have experienced land-sea breezes. At the beach on a sunny summer day you may feel a relatively cool breeze from the sea. Near sunset the breeze may weaken and stop. After sunset you may at the very same spot suddenly feel the wind reverse and now a warm breeze from land moves from land to sea. Wind blowing along coastline will bend or turn slightly but systematically as a function of the difference in roughness and thermal properties between sea and land. Therefore the wind direction and wind speed may be quite different at nearby coastal sites slightly offshore or inland.

The thermal properties of land and sea and the temperature variation in the vertical are very important factors for the wind climate over the sea and in coastal regions.[4,6] Near-neutral conditions occur frequently over the sea, in particular during strong wind events but both unstable and stable conditions are also frequently observed offshore, at least at the coastal site Horns Rev in the North Sea.[10] The atmospheric stability has not been observed much offshore so it is comforting that meso-scale model results of the atmospheric stability compare well with the offshore coastal observations. The comparison results are good at the longer time scale but not for hourly values.[11]

Systematic observations of winds and temperature over the sea are important to develop and improve on physical theory valid for processes in the atmosphere.

REMOTE SENSING

Remote sensing techniques build on a broad spectrum of concepts from sound (e.g., sodar systems), microwave (e.g., radar), thermal infrared (e.g., radiometer), and light (e.g., laser/lidar). Observations of ocean winds can be obtained from advanced remote sensing principles using ground-based, airborne, and satellite-based methods.

Ground-Based Remote Sensing

Ground-based remote sensing using lidar and sodar have been tested offshore. Sodar appear less useful offshore due to frequent occurrences of near-neutral winds where sodar fails to observe.[12] In contrast, wind profiling lidars situated on various rigs and platforms across the North Sea have been operated successfully for extended periods of time with high data availability.[13] Nacelle-based wind lidar methods are also promising.[14] Floating wind profiling lidar concepts may be the next generation observational platforms. At the scientific level WindScanner[15] is a very strong new concept for in-depth research on marine and coastal winds, but major experimental campaigns with the new technology have to be performed first.

Airborne Remote Sensing

It is possible to install remote sensing instruments on aircrafts and fly for research e.g., to study the wind farm wake of large offshore wind farms. Very detailed ocean wind observations have been collected using manned aircraft with synthetic aperture radar[16] (SAR) but it is costly. Recently un-manned aerial vehicles (UAV) have gained interest and may be next generation observation technology platforms for research or monitoring of marine winds.

SATELLITE REMOTE SENSING

The state-of-the-art technology available to immediately progress our current knowledge on the offshore wind climate—without waiting for new measurement campaigns—is utilization of satellite remote sensing of ocean surface wind fields.

Satellite remote sensing is based on measurement techniques using Earth observation (EO) space-borne instruments. Thermal infrared radiometers observe the sea surface temperatures. Optical visible and near-infrared bands on various instruments provide ocean parameters such as chlorophyll and turbidity. In the context of ocean surface wind retrieval only microwave remote sensing is useful. Microwave radiation has the advantage of penetrating clouds thus observations are available also during rainy or cloudy conditions. There are two main categories of microwave observations from space: passive microwave observations and active (radar). Both types of microwave data are available both day and night. The all weather and day and night recording provide a very stable observational data set.

The four main types of microwave observations useful for ocean wind retrieval are given in Figure 1. The approximate spatial and temporal scales and dominant application domains are indicated. Passive microwave observations have the longest archive starting in 1987 and with up to six observations each day with near-global coverage using a suite of satellites. Scatterometers have around the same spatial resolution. The continuous data series starts in 1999 and has approximately twice daily global coverage. Scatterometer data in lower and higher spatial resolution are found but more importantly, the scatterometer data provide wind vectors whereas the passive microwave data provide wind speed only. Polarimetric passive microwave data (not indicated in the diagram) provide wind vectors at 25 km resolution as most scatterometers. Only one polarimetric microwave

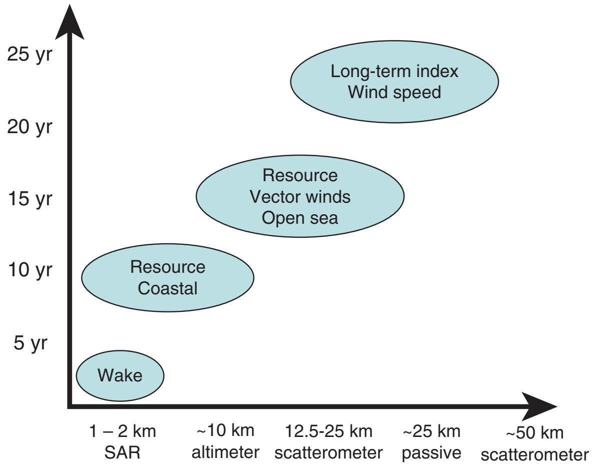

FIGURE 1 | Diagram is showing the main ocean wind satellite technology types, their spatial and temporal resolution, and main application domains.

instrument has been in orbit. It has observed since 2003 and the temporal coverage is few per month. The passive microwave radiometers and scatterometers are in space with the specific goal of providing ocean wind data operationally.

In contrast, the two remaining types of microwave instruments, altimeter and SAR, have other purposes. Therefore only ocean winds are retrieved by expert users.[17] Altimeter provides wind speed whereas SAR provides wind vectors by combining wind direction information from e.g., SAR directional analysis,[18] sea surface Doppler shift[19] or using input from an atmospheric model to the wind product.[20] The archives of altimeter and SAR start in 1992. Both data sets are infrequently in space and time. SAR has very high spatial resolution. Typically the SAR-derived wind products have grid cells around 1 km but in fact higher resolution is possible, say 400 m for very high-resolution SAR images.[21] The particular advantage of SAR is that coastal regions are covered and wind farm wakes can be observed in detail.

SYNTHETIC APERTURE RADAR

In imaging SAR data the spatial resolution is high. The observed quantity is the microwave backscatter from the ocean surface. The backscatter is a non-linear function of the capillary and short gravity waves of the ocean surface that again is a function of the wind speed at 10 m above sea level. The instantaneous surface ocean wind at 10 m above sea level is in near-equilibrium with the small ocean surface waves that may ride on much longer waves. The observed backscatter for a given wind speed depend upon the SAR viewing geometry i.e., the incidence angle, azimuth, and wind direction. The empirical geophysical model functions (GMFs) are established in order to retrieve wind speed and wind direction from backscatter using three antennae or multiple view angles. Several GMF's are available. Satellite SAR data are observed with one antenna. From SAR co-polarized data i.e., vertical transmit and receive (VV) or horizontal transmit and receive (HH), either wind speed or wind direction can be retrieved. Often the wind direction is used from *a priori* knowledge.

Most satellite SAR systems are able to operate in several modes. These range from very high-resolution with the raw cells down to few meters and narrow swath, and up to wide-scan modes with a broader swath 400–500 km and with raw cells around 75 m. When wind speed retrieval is the final goal in the processing, there need to be some spatial averaging of the cells to avoid an inherent noise, so-called speckle noise, coming from the randomness in the microwave backscatter from the ocean surface. Also the longer waves may add noise that is effectively avoided after averaging. In wide-scan mode the resolution of the retrieved wind pixels is around 1 km for Envisat, Radarsat-1/2, and Sentinel-1. When looking at raw SAR data, small hard targets such as ships and wind turbines can be very clear because the backscatter from hard targets is several times larger than the backscatter from the ocean surface.

Long-Term Wind Variability

Wind variability during years result in variations in seasonal and annual energy production.[12,22] Wind observations during several years from 10 to 30 years are relevant for wind energy application. The passive microwave ocean wind observations are mainly from the special sensor microwave/imager (SSM/I) on-board the satellite platforms F08 to F18 from the Defense Meteorological Satellite Program of the United States starting in 1987 and continuous to present. Also Advanced Microwave Scanning Radiometer, AMRS-E and AMSR-2, use passive microwave technology. With up to six observations per day for any location of the ocean far offshore, the long-term ocean wind data are available.[23] At Remote Sensing Systems[24] and Jet Propulsion Laboratory[25] the data are stored and publicly available. In recent years major efforts have been made to produce a very reliable ocean wind data set by reprocessing the data.[26]

Comparison of the produced wind power in Denmark mainly from land-based wind turbines and the observed winds from SSM/I far offshore in the North Sea and Baltic Sea from 1988 to 2005 showed fair agreement.[12] The comparison was made using the wind-index i.e., the produced wind power per year normalized with the long-term mean. However, it was noticed that the winds far offshore appeared to have less variation between years than the wind-index of produced power on land. It indicates more steady winds far offshore. Long-term correction of wind speed is a research topic in wind energy.[22] A new result on the long-term annual wind speed variation at Dogger Bank in the North Sea as observed from SSM/I F08, F10, F11, F13, F14, F15, F16, and F17 in the years 1988–2012 separated into 5 m/s wind speed bins is shown in Figure 2. The winds far offshore are seen to be rather variable from year to year.

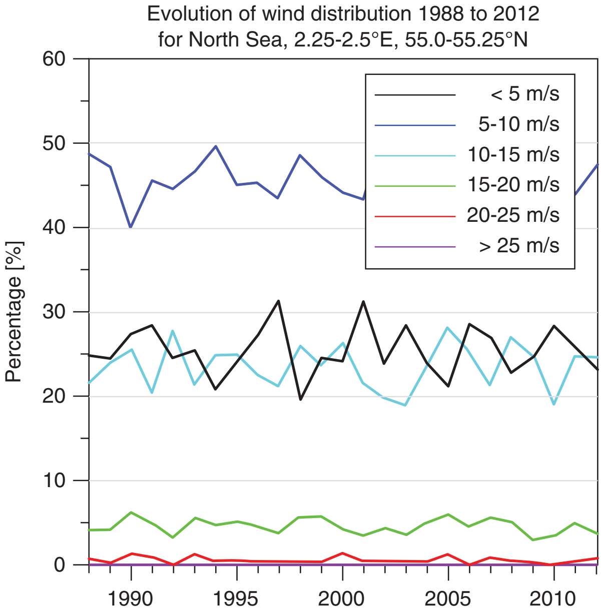

FIGURE 2 | Wind speed distribution of the annual mean values of wind speed in six 5 m/s wind speed levels observed from 1988 to 2012 from SSM/I at Dogger Bank at 10 m above sea level.

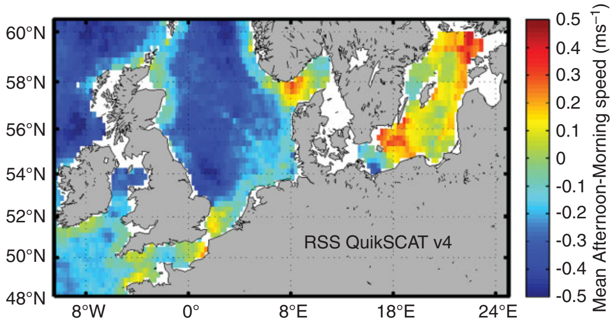

FIGURE 3 | Ocean mean wind speed difference between afternoon and morning passes observed from QuikSCAT from Remote Sensing Systems from November 1, 1999 to October 31, 2009. White areas show low data availability.

Wind Resources

Wind resource statistics describe the long-term wind characteristics for a site. Traditionally the wind speed distribution and wind directional distribution are calculated and graphed e.g., in the European Wind Atlas.[27,28] The methodology is based on wind observations from one or more meteorological masts from which wind speed and wind direction have been observed hourly for at least 1 year, preferable several years at several heights above ground. The wind data are then filtered and cleaned for poor observations and finally used for calculation of the observed wind climate. This method can be used offshore when reliable meteorological wind data are available.

For offshore locations lacking *in-situ* observations, the state-of-the-art method for assessing the wind resource is using mesoscale modeling. The advantage of mesoscale models as compared to microscale modeling is that the influences of land masses even at rather long distances are possible to model. Also the general conditions of thermal variations between ocean and atmosphere (the atmospheric stability) are included in mesoscale modeling. Thus mesoscale models may give accurate wind climate estimates, yet without some kind of comparison to observations, it is not possible to keep the uncertainty sufficiently low. The optimal *in-situ* observation is from tall meteorological masts or wind profiling lidar observing at hub-height, but without such data satellite remote sensing may be used for comparison. Alternatively satellite data may be used in combination with mesoscale modeling.

Ocean surface vector winds observed from the SeaWinds scatterometer on-board the satellite QuikSCAT from NASA provide the longest ocean vector winds archive. It spans 10 years from 1999 and consists of twice daily near global coverage. All satellites mentioned in this article are in sun-synchronous orbit i.e., orbiting across the Equator and above the poles in a regular pattern. For QuikSCAT this resulted in local observations once per day in the morning, once per day in the late afternoon, local time. The differences in mean wind speed afternoon minus morning show distinct patterns in the Northern European Seas, see Figure 3. Systematic diurnal wind speed variations are noticed. Relatively stronger afternoon winds are found in the Baltic Sea and stronger morning winds in the North Sea. Wind resource statistics based on QuikSCAT have been estimated in the Northern European Seas,[29,30] the Mediterranean Sea,[31] in the seas offshore China,[32] and globally.[33]

Wind resource assessment from SAR is based on far fewer samples than is traditional from meteorological masts, thus the overall accuracy is lower. Furthermore, the individual wind maps are only accurate with comparison statistics around 1.5 m/s root mean square errors comparing to meteorological mast observations.[34,35] Despite these facts the offshore wind resource observed from SAR and compared to wind resource statistics from three offshore masts in the North Sea showed results of better accuracy than typically obtained from mesoscale modeling.[36] The results are for 10 m above sea level. One reason for the relative good results using SAR may be due to the fact that the spectral energy in SAR is very high. In other words, the SAR-retrieved satellite winds very effectively resolve the horizontal spatial wind structures.[37]

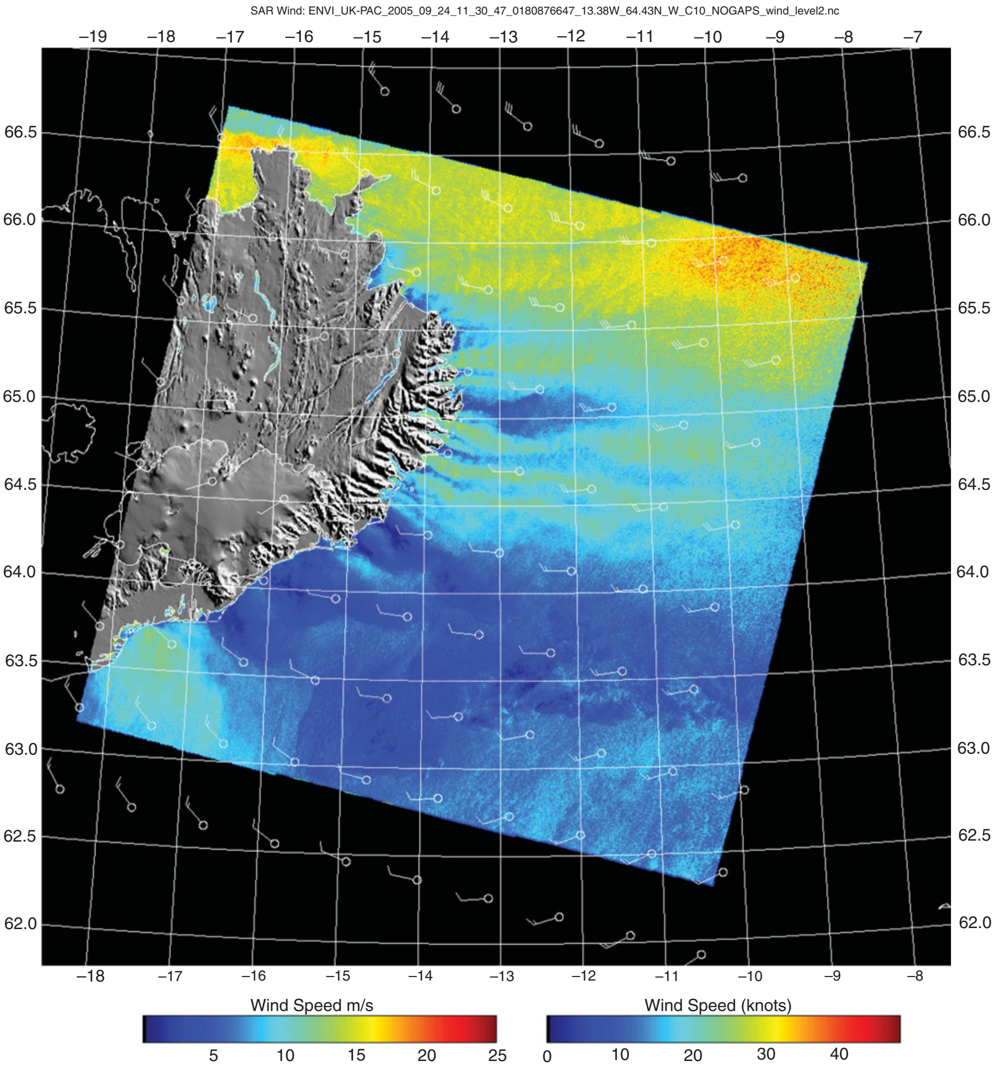

FIGURE 4 | Envisat ASAR wind speed map from Iceland observed September 24, 2005 at 11.30 UTC. The wind arrows are from the NOGAPS global atmospheric model.

SAR-based wind maps cover the coastal zone. Near coastlines neither micro- or meso-scale models fully resolve the many diverse atmospheric phenomena well. The wind resource in the coastal zones is the most challenging to assess and the spatial wind gradients are typically large. An example of coastal wind gradients observed from SAR is shown in Figure 4. The atmospheric flow is from the east. Along the western coast of Iceland gap flow and lee effects are mapped and seen to extend several decades of kilometers downwind. The US Navy's Operational Global Atmospheric Prediction System Model (NOGAPS) is used as *a priori* wind direction input to retrieve wind speed from the Envisat ASAR wide-swath scene. The NOGAPS model data are interpolated in time and space to match the satellite data. NOGAPS data is available at 6-h intervals mapped to a 1° latitude/longitude grid.[38] Interesting examples of many other coastal and offshore wind conditions mapped from SAR are available in Ref 7.

The main limitation of satellite-based wind resources estimation is that the results are valid at 10 m above sea level. There is strong need to extrapolate to hub-height. Research is on-going.[39]

Wind Farm Wake

In engineering wake modeling the focus is on the near-field wake.[40–42] This information is crucial for the planning of the lay-out of the turbines in a wind farm. The aim is to ensure high energy production and to avoid high load, hence fatigue of the turbines. In addition, the necessary underwater inter-array cable cost has to be taken into consideration. The far-field

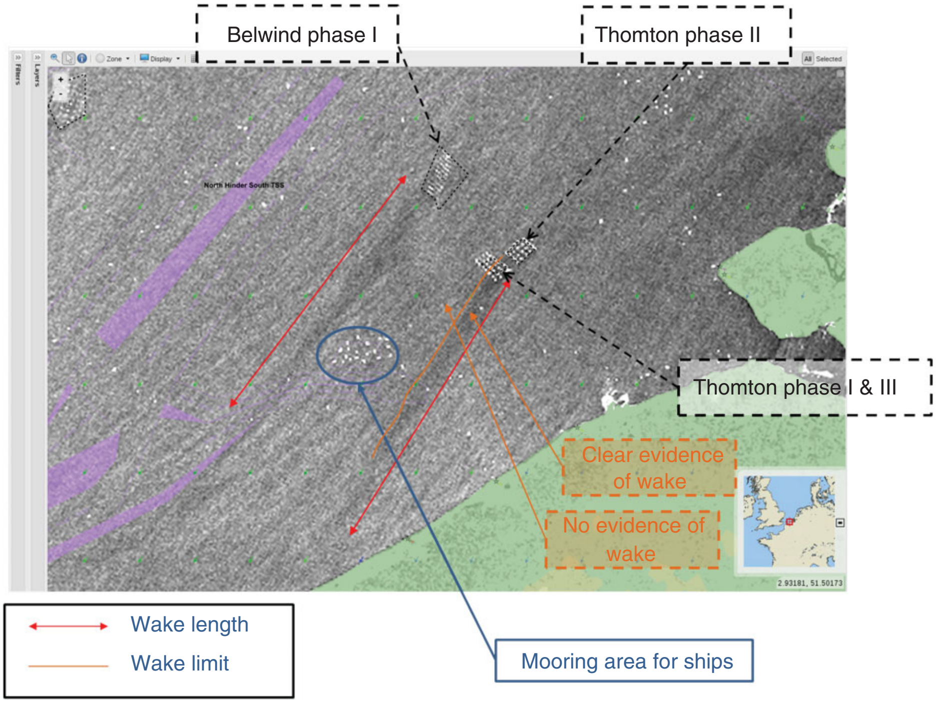

FIGURE 5 | Offshore wind farm wake in the North Sea observed by Radarsat-2. The SAR image is processed by CLS. (Copyright RADARSAT-2 Data and Products © MacDonald, Dettewiler and Associates Ltd.)

wind farm wake has not been modeled so intensely as the near-field wake.

Recently attention on the far-field wake has increased as the development of neighboring large offshore wind farms takes place and there appears to be some power production loss.[3] The future plans for the Northern European Seas indicate many neighboring wind farms. At the first two large offshore wind farms in the world wind data were collected at meteorological masts positioned near the wind farms. At the Nysted 1 wind farm the wake masts were installed at 1 and 4 km downstream and at the Horns Rev 1 wind farm at 2 and 6 km downstream (in both cases east of the wind farms). Satellite and airborne SAR wind speed maps have shown areas of reduced wind speed much further downwind from large offshore wind farms.[21,43]

An example of SAR-based observation of wind farm wakes is shown in Figure 5. The wind is from the northeast near the Belwind 1 and Thomton 1, 2, and 3 offshore wind farms. The wind farm wakes i.e., reduced wind speed areas, are noticed as dark elongated patches. In contrast, the moored ships do not provide wake. Wind turbines and ships are clearly visible as small white spots. Model results of the far-field wake at such long distances are not yet available. Observations from one wind profiling lidar on-board a ship,[44] one floating lidar[45] and three long-range Windscanners are currently being collected at the Alpha Ventus wind farm. The observations are continuous during some time interval which is advantageous for time-series analysis of wakes. Satellite SAR provides only snap-shots but is a cost-effective observation technique for capturing various cases of far-field wakes patterns.

PERSPECTIVES

As already mentioned research on lifting of the winds from 10 m to hub-height is on-going. It is very important for further application of satellite data in offshore wind resource assessment. Other relevant perspectives are use of new satellite sensors. In early 2014 the launch of the European satellite Sentinel-1 with a SAR on-board is expected. A level 2 wind product from Sentinel-1 is foreseen and this will be the first publically available SAR-based wind product. Another perspective is the possible production of a satellite-based ocean wind climate series similar to other essential climate variables using space technology. The European Space Agency supports the development of e.g., sea level, sea surface temperature, and ocean color essential climate variables.[46] Wind data from all the microwave sensors described could be combined into a nearly 30-year long ocean wind product which would be beneficial for offshore wind energy applications among other topics.

SUMMARY

The marine atmospheric environment is relatively poorly understood mainly due to lack of observations. For wind resource assessment this is a critical factor and therefore new observation technologies are investigated. Ground-based lidar is very promising. Satellite remote sensing of ocean winds has taken place during decades but the information is still relatively unknown and not used to its full extent. This include both the long-term perspectives of better understanding long-term variations in ocean winds during several decades and the wind resource statistics far offshore observed with scatterometer.

The winds in coastal zones have larger spatial gradients than farther offshore and in the coastal zone many wind phenomena occur. These are not resolved in detail by the available micro- and meso-scale atmospheric models. SAR-based wind retrieval offer good coastal coverage. The existing SAR archives soon will be enlarged by new observations from Sentinel-1.

The SAR-based high resolution wind maps are able to resolve fine-scale phenomena such as offshore wind farm wakes. Only SAR has provided clear evidence of far-field wakes several decades of kilometers long. Model results on such long wakes do not exist yet but some annual energy production loss in clusters of wind farm is to be expected. The main challenge using satellite-based ocean wind information is to lift the 10 m satellite winds to hub-height. Furthermore, to take full advantage of combinations of satellite remote sensing, atmospheric modeling, and statistical analysis for offshore wind energy a focussed effort is needed.

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