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The influence of large offshore wind farms on the North Sea and Baltic Sea – a comprehensive literature review

Suzanna Clark, Friedhelm Schroeder, Burkard Baschek

42 pages with 9 figures and 4 tables

Abstract

This literature review summarizes research on the environmental impacts of offshore wind farms, identifies gaps in current knowledge related to offshore wind energy, and makes recommendations for future research. The offshore wind energy industry in Europe is expected to grow rapidly: in the European Union, 69 wind farms in 11 countries have a combined capacity greater than 6.5 gigawatts (GW), and some projections predict a capacity of 40 GW by the year 2020. Despite expectations for the construction of large-scale offshore wind farms, little research has studied the effects of offshore wind farms on oceanography. Most research has focused on biotic effects including noise, bird collisions, mammalian avoidance, and the artificial reef effect. The following review will hypothesize the largest potential wind farm-induced impacts to oceanography and consequences that could result from changes to oceanography.

Oceanographic processes that could be affected by offshore wind farms are downstream turbulence, surface wave energy, local scour, inflowing currents, and surface upwelling. Existing research predicts that most wind farm-induced changes will be within the wind farm footprint or within natural variations. Some studies hypothesize that “extreme” scenarios could cause irreversible changes to shoreline deposition, upwelling patterns, or bottom oxygen levels, but this review found no research that quantified these changes with confidence. Potential connections exist between offshore wind farms, the alteration of oceanographic processes and changes to local sediment, nutrient, or phytoplankton regimes, but these connections have not been studied and are only speculative. Current numerical modeling research does little to predict the effects of large-scale construction, potential cumulative effects of multiple farms, or far-field effects at the coast.

This review therefore recommends that future numerical models focus on wind farms with hundreds of turbines, the interactions of multiple wind farms, and downstream changes due to wind farms. Observational studies are also necessary to validate the models, and extensive site-specific data collection is necessary to compare any changes to the natural ocean state. The conclusions and recommendations from this review will be used to inform research related to the Coastal Observation System for Northern and Arctic Seas (COSYNA) at the Helmholtz-Zentrum Geesthacht, which uses data from a marine observation network in the North Sea to validate and improve coastal modeling results. One core question that COSYNA seeks to address is how the offshore wind farms will locally and remotely affect the physical dynamics, sediment transport, and biological processes in the North Sea. The gaps in research and potentially relevant offshore wind farm impacts as identified by this review will guide future COSYNA projects including data collection, model development, and research cruise campaigns.

Author Keywords: offshore wind farms, wave field, sediment, currents, nutrients, phytoplankton

Der Einfluss großer Offshore Windparks auf die Nord- und Ostsee – eine umfassende Literaturübersicht

Zusammenfassung

Diese Literaturübersicht fasst die Forschung zum Umwelteinfluss von Offshore Windparks (OWP) zusammen, identifiziert Wissenslücken und gibt Empfehlungen für zukünftige Forschungsthemen. Es ist zu erwarten, dass die Offshore Windenergieindustrie in Europa weiterhin schnell wachsen wird: 69 Windparks in 11 Ländern der Europäischen Union haben bereits eine Kapazität von mehr als 6,5 Gigawatt (GW); Kapazitäten von 40 GW werden für das Jahr 2020 erwartet.

Trotz dieser hohen Erwartungen wurden bisher vergleichsweise wenige Untersuchungen über die Effekte von OWPs auf ozeanographische Prozesse durchgeführt. Die Forschung konzentrierte sich bisher mehr auf die Biologie, einschließlich des Einflusses von Lärm, Kollisionen mit Vögeln, Einfluss auf Säugetiere wie Schweinswalen und dem „künstlichen Riff-Effekt“ von Offshore-Anlagen. Die folgende Literaturübersicht befasst sich mit dem Einfluss und den möglichen Folgen, die aus Änderungen der physikalischen und biogeochemischen Gegebenheiten resultieren.

Ozeanographische Prozesse, die durch OWPs tangiert werden könnten, sind Turbulenz in Lee, Oberflächen-Wellenenergie, lokaler Kolk, auftretende Strömungen sowie Auftrieb. Bisherige Forschungen sagen Änderungen nur in unmittelbarer Nähe der OWPs voraus bzw. nehmen an, dass deren Auswirkungen in der natürlichen Variabilität untergehen. Einige Studien spekulieren, dass in „extremen“ Szenarios irreversible Änderungen an Küstenerosion/-deposition, Auftriebsmustern oder bodennahen Sauerstoffkonzentrationen möglich sind. In dieser Literaturübersicht konnten jedoch keine belastbaren quantitativen Untersuchungen gefunden werden, die diese Thesen stützen. Mögliche Zusammenhänge zwischen OWFs und Nährstoff- bzw. Phytoplankton-Regimes werden postuliert, konnten jedoch bisher nicht durch Untersuchungen belegt werden und sind somit Spekulation. Auch numerische Modellstudien konnten bisher wenig zur Erkenntnis über den Einfluss von großen Offshore-Anlagen, von kumulativen Effekten einer Vielzahl von OWFs sowie über den Ferneffekt an den Küsten beitragen.

Diese Literaturstudie empfiehlt deshalb, dass sich zukünftige Untersuchungen mit numerischen Modellen auf große OWFs mit hunderten von Turbinen, die Wechselwirkung zwischen vielen OWFs und ozeanographische Änderungen in Lee von OWFs konzentrieren. Quantitative Messungen sind notwendig um die Modellrechnungen zu validieren. Zusätzlich sind umfangreiche Langzeitmessungen nötig, um den Einfluss von OWFs aus dem natürlichen „Rauschen“ herauszufiltern.

Die Schlussfolgerungen und Empfehlungen dieser Übersicht werden auch für eine Fokussierung des im Helmholtz-Zentrum, Geesthacht entwickelten COSYNA-Systems (Coastal Observation System for Northern and Arctic Seas) benutzt. COSYNA ist ein modell-unterstütztes marines Beobachtungssystem, mit dem zukünftig auch Effekte von OWFs auf die Ozeanographie der Nordsee untersucht werden sollen. Die Wissenslücken, die in dieser Literaturübersicht identifiziert wurden, werden zukünftig ein Leitfaden für COSYNA- Fragestellungen, in Datenerhebung, Modellentwicklung und Schiffkampagnen darstellen.

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1 Introduction

The number and size of offshore wind energy farms have significantly increased in the North and Baltic Seas in recent years. The current offshore wind energy capacity in Europe consists of more than 6.5 gigawatts in 69 wind farms operated by 11 different countries (Corbetta *et al.*, 2014). Of this capacity, Germany operates 520 MW, or 8%. Germany's offshore presence, however, is increasing, as is the size of the average offshore wind project (from 286 MW in 2012 to 482 MW in 2014), which indicates large-scale future growth in the German EEZ and other European waters (Corbetta *et al.*, 2014) (Figure 1; Figure 2).

Despite the projections for large-scale offshore wind energy construction, little research exists about the effects of offshore wind farms (OWFs) on oceanographic processes, such as wave energy, turbulence, or residual or tidal currents. Most studies have addressed effects on the surrounding biota through noise, bird collisions, mammal avoidance, and the creation of artificial reefs. Consequently, of the articles concerning OWFs, their construction, and their subsequent impacts on the surrounding environment, this review found 10% to be related to physical oceanography and 5% to be related to biogeochemical oceanography.

A literature review was completed as background information for future and existing research projects at the Helmholtz-Zentrum Geesthacht, such as COSYNA ("Coastal Observing System for Northern and Arctic Seas"), CoastDat, or coastmap. One core question is how the offshore wind farms will locally and remotely affect the physical dynamics, sediment transport, and biological processes in the North Sea. The literature review will identify gaps in research and potentially relevant offshore wind farm impacts to guide future projects including data collection, model development, and research cruise campaigns.

This review identifies impacts that could become significant with the construction of many closely-spaced, large-scale OWFs. Priority was given to research about the North Sea and Baltic Sea, but the limited availability of information sometimes made it necessary to use research from around the globe. Included are peer-reviewed scientific articles, government reports, company-issued environmental impact assessments, reports from environmental consulting firms, and engineering reports. Meteorology is included to provide a well-rounded picture. This paper provides a review of the current literature related to offshore wind farms, as given in the section "existing knowledge". The section on "potential effects" is only a representative sample of the existing research and should not be regarded as comprehensive, as the potential connections between OWF construction and oceanographic phenomena are complex and poorly understood

After outlining essential background information, the following paper will identify gaps in the research and suggest which phenomena are most likely to be affected by offshore wind farm construction. The paper is then divided into chapters based on broad research categories: internal turbulence and mixing, surface wave energy, sediment dynamics, biogeochemistry, mesoscale flows, upwelling and downwelling, and meteorology. Each chapter will first summarize the state of offshore wind farm research in that category before projecting potential cascading effects from the alteration of the given phenomenon. The paper concludes by addressing major gaps in current research and providing recommendations for continued research.

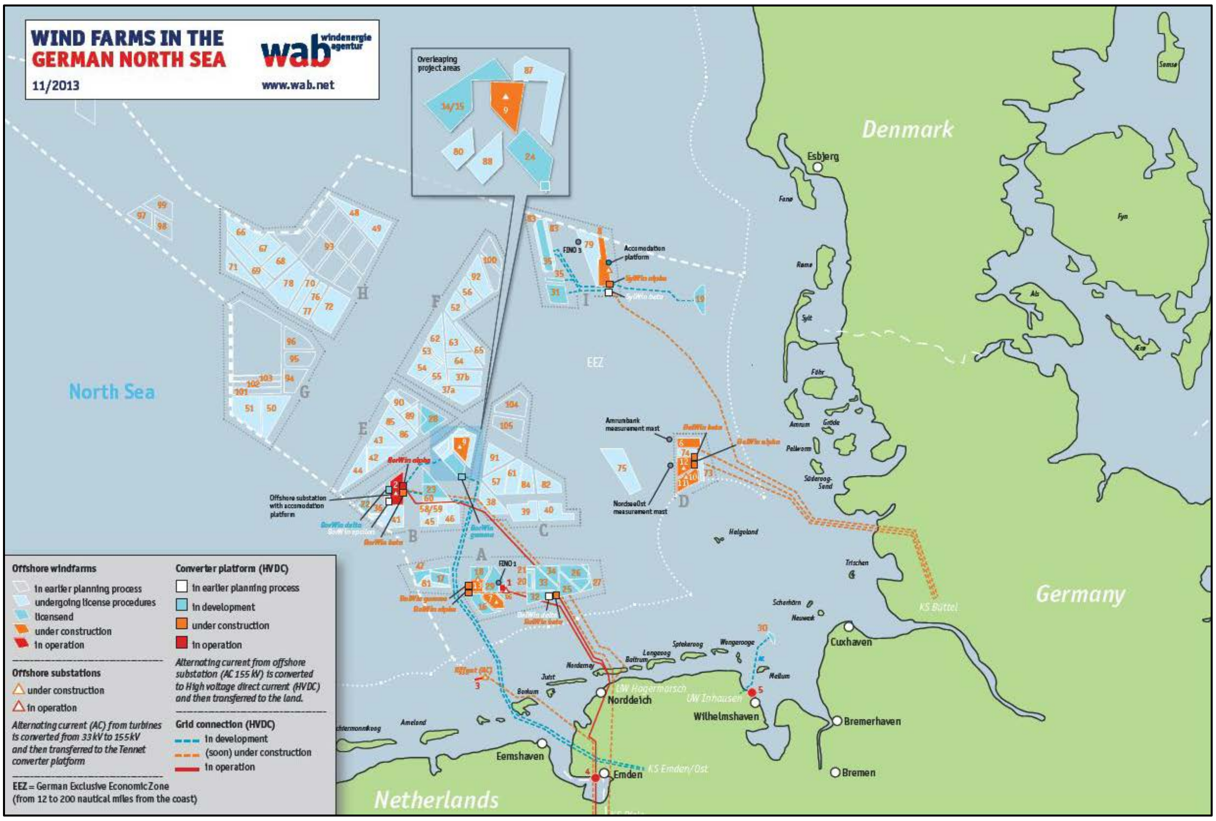

Figure 1 - Map of projected OWF construction in the German Exclusive Economic Zone (EEZ) of the North Sea. Light blue shapes indicate farms undergoing licensing procedures, medium blue shapes are farms that are in development, orange shapes are farms that are under construction (WAB WINDENERGIEAGENTUR, 2013 Reprinted with Permission)

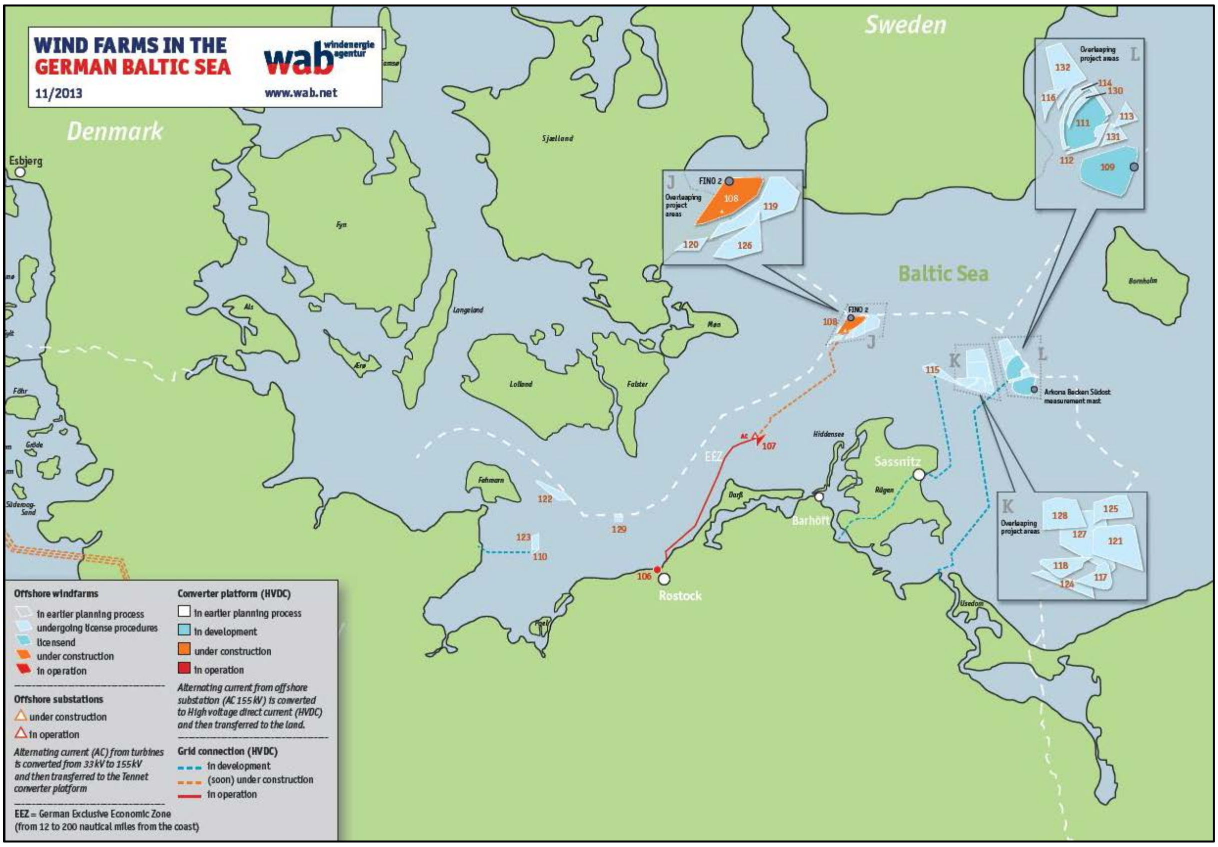

Figure 2 - Map of projected OWF construction in the German Exclusive Economic Zone (EEZ) of the Baltic Sea. Light blue shapes indicate farms undergoing licensing procedures, medium blue shapes are farms that are in development, and orange shapes are farms that are under construction. (WAB WINDENERGIEAGENTUR, 2011 Reprinted with Permission)

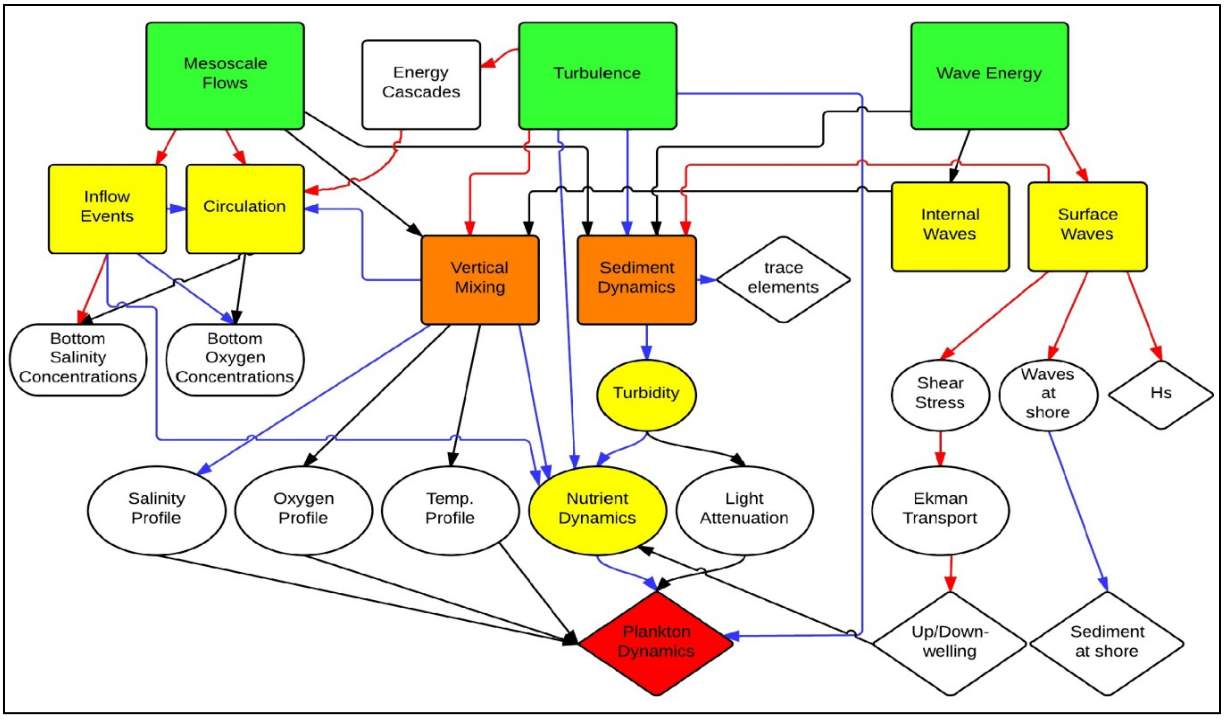

Figure 3 - Flow chart of potential cause-and-effect pathways among OWF-induced impacts. Green boxes are directly affected by OWFs, red shapes are connected to the most impact pathways (23), followed by orange shapes (11-20) and yellow shapes (5-10). Red lines indicate connections that have already been researched, blue lines indicate connections drawn from existing research

The North Sea

1.1 Political Setting

The North Sea is bordered by six countries: the United Kingdom, Belgium, the Netherlands, Germany, Denmark, and Norway. It is subject to river runoff influenced by agriculture and industry, and its uses include but are not limited to shipping, gravel dredging, fisheries, oil and gas industry, marine protected areas, and tourism (Scibior, 2007). Offshore wind farms are a recent addition to human activities in the North Sea: in German waters, almost 600 megawatts (MW) or over 100 turbines are in operation, over 2000 MW are under construction, and almost 30,000 MW are either licensed or in the licensing stage (WAB - Windenergie Agentur).

1.2 Physical Oceanography

The North Sea is a semi-isolated shelf sea ranging from 51°N to 62°N with a mean water depth of 70 to 90 m, depending on the defined boundaries (Otto et al., 1990; Huthnance, 1991; Ducrotoy et al., 2000). Water depth increases from South to North and is relatively shallow and uniform (Otto et al. 1990), with the exception of the Norwegian Trench, which reaches up to 700 m depth in the Skagerrak. The Sea is in a temperate environment with strong seasonal variability: winter storms can generate large surface waves that induce mixing and suspend sediments (Otto et al. 1990). Currents are predominately controlled by the M2 lunar tide with a period of 12.4 hours (Otto *et al.*, 1990), resulting in a broad cyclonic motion (Howarth, 2001). A Kelvin Wave enters the North Sea from north of the British Isles and moves counterclockwise, creating large tidal variations in areas such as the German Bight and the Wadden Sea (Howarth, 2001).

The North Sea can be divided into the Northern North Sea and the Southern North Sea according to wave characteristics, water depth, and stratification. The Northern North Sea typically has greater depths, larger extreme and mean wave heights, and stronger stratification. Thermal stratification occurs in the North Sea in the summer (Otto *et al.*, 1990), and saline stratification is caused by river runoff in coastal waters (Huthnance, 1991). The shallower waters of the Southern North Sea are more likely to be well-mixed than the deeper waters in the north.

Ducrotoy *et al.*, 2000; Huthnance, 1991; and Howarth, 2001

1.3 Geology

The North Sea is dominated by sandy sediments, with patches of gravel and muddy regions (Huthnance, 1991). Sand features in the North Sea can range from small ripples to sand waves (Otto et al. 1990) and can come to within 10 m of the surface near shorelines (Huthnance, 1991). The three forcings behind sand transport are tides, wind, and waves, which act at differing strengths depending on the region in the North Sea (van der Molen, 2002). Net bedload sediment transport is caused by residual currents that are due mostly to the M4 lunar tide, but storms can create residual currents and surface waves that are energetic enough to cause sediment transport (Otto *et al.*, 1990).

1.4 Biogeochemistry

Atlantic inflows are the largest source of nitrate, nitrite, phosphate, silicate, and ammonia, while riverine inputs and resuspension influence the local scale (Huthnance, 1991; Prandle et al., 1997). Nutrients in the North Sea also undergo strong seasonal cycles, with maximum concentrations in mid-January and maximum consumption in early May (Prandle, *et al.*, 1997; Radach & Lenhart, 1995; Vermaat, *et al.*, 2008).

1.5 Meteorology

Winds in the North Sea are typically westerlies, but variations exist and southerlies and easterlies may produce secondary circulation patterns (Otto *et al.*, 1990). Wind forcing is the second-most dominant factor to currents, following tides, and is particularly important during storms, when wind forcing can generate a current response up to 25 m deep within a few hours (Howarth, 2001).

2 The Baltic Sea

The Baltic Sea is a large, brackish estuary with a positive water balance, permanent halocline, and seasonal thermocline (Fennel and Seifert, 2008): salinity is the main factor to both stratification and overturning circulation (Döös *et al.*, 2004). The Baltic ranges from 54°N to 66°N, with temperate conditions in the South and sub-Arctic conditions in the North (Fennel and Seifert, 2008). The southern regions of the Baltic Sea typically have a surface salinity of 7-8 PSU and are subject to highly variable winds and storms that create small-scale and mesoscale phenomena such as eddies, coastal jets, and up- and downwelling. In contrast, the northern regions can have salinity as low as 4 PSU and are subject to ice in the winter. The varying degrees of salinity are a result of the positive water balance and limited connection to the North Sea through the Danish Sounds. Due to the shallow Danish Sounds (18 m at the Darss Sill), water exchange with the deeper Baltic Proper (as deep as 230 m in the Gotland Deep) and ventilation of the subsurface waters are restricted and episodic (Fennel and Seifert, 2008).

The Baltic Sea’s limited ventilation and permanent halocline often lead to hypoxia and anoxia in the deeper basins. The halocline ranges from 60 to 80 m deep in the Baltic Sea, inhibiting vertical mixing and preventing the oxygenation of waters below 120 m (Gustafsson, 1997). The vertical mixing that does occur is forced predominately by wind energy (Kullenberg, 1977) and the breaking of internal waves (Meier *et al.*, 2006), but it does not interact with the deepest waters. Saline, oxygenated inflows from the North Sea are thus important for deep water ventilation: the saline water follows isopycnals and is also advected to hypoxic basins in the Baltic Sea. Large-scale barotropic inflows typically occur in the winter and have decreased in frequency in recent decades, while medium-scale baroclinic inflows usually occur in the summer and have become more frequent (Meier *et al.*, 2006).

Inflow events are important not only to deep water ventilation but to general circulation in the Baltic Sea, also known as the *Baltic Haline Conveyer Belt* (Döös *et al.*, 2004). Because there is no deep water formation in the Baltic Sea, the inflow of high saline water from the North Sea and its overturning cells near the Arkona Basin force the large-scale circulation. An overturning cell of saline North Atlantic water enters through the Danish Sounds, mixes with fresh water runoff to form brackish water, and exits again through the Danish Sounds. The average water mass residence time in the Baltic is 26-29 years, but this can vary widely: some water that enters through the Danish Sounds exits relatively quickly without penetrating the Baltic Proper (Döös *et al.*, 2004).

The Baltic Sea is one of the largest eutrophication zones in the World, a problem that is the direct result of agricultural runoff and limited ventilation. The countries surrounding the Baltic Sea are Denmark, Germany, Poland, Lithuania, Latvia, Estonia, Russia, Finland, and Sweden. River runoff averages 14,150 m^3s^{-1} (Gustafsson, 1997), and since 1950, increased agricultural runoff has increased the input of Nitrogen and Phosphorus, creating algal blooms in the spring and summer. Following a large algal bloom, phytoplankton die and sink to the deep waters, where they promote decomposition, respiration, and the consumption of oxygen (Vermaat *et al.*, 2008). The increase in nutrient runoff in the 20th Century has led to increased incidents of anoxia and an even greater reliance on inflow events for deep water oxygenation (Fennel and Seifert, 2008; Meier, et al.,2006).

3 Wind Park Impacts – Turbulence and Vertical Mixing

3.1 Existing Research

A related, non-OWF study found that the Western Bridge of the Great Belt Fixed Link in Denmark induced turbulence for 400 m downstream of each individual pile when the Froude number was greater than 1 (supercritical flow) (Lass *et al.*, 2008). Measurements with an Acoustic Doppler Current Profiler (ADCP) also revealed an increase in acoustic back scatter downstream of the piles at 15 m deep, suggesting mid-layer turbulence (Lass et al. 2008). The resultant increase in vertical mixing could cause “an irreversible density exchange” between the deep and shallow waters of Baltic Sea inflows (Lass et al. 2008). As a similar, though more widely spaced, group of underwater piles, an OWF could also increase internal turbulence. Unfortunately, this review found little additional research for comparison: observational studies about internal mixing downwind of an OWF are rare, as most studies use models to predict the effect of monopiles on turbulence and vertical mixing.

Hammar, *et al.* (2010) reviewed simulations from the Swedish Meteorological Hydrographic Institute (SMHI) and the Danish Hydraulic Institute (DHI) on the effects of 30 monopiles in 20 square km at three proposed wind farm sites: Skottarevet, Kriegers Flat, and Lillgrund Wind Park. For all three locations, the cumulative structure-induced variations did not exceed natural variations. Mixing at Skottarevet Wind farm increased by 1% over background levels (Karlsson, et al. as cited in Hammar et al. 2010), mixing at Kriegers Flat increased by less than 1% over background levels (Lindow et al., as cited in Hammar et al. 2010), and mixing at Lillgrund was local and did not affect hydrography overall (Moller and Edelvang as cited in Hammar et al. 2010). The effect on mixing was likely smaller than downstream of the bridge piles because of differences in pile spacing, a smaller number of piles per area, and a weaker current.

Burchard, Jansen, and Lass (2009) modelled mixing in Baltic Sea inflows due to the construction of wind farms. According to Burchard, *et al. (2009),* entrainment behind a cylinder increased by two orders of magnitude behind a pile, but entrainment intensity depended on several parameters such as the Froude number the Ekman number, and the ratio of water depth to cylinder diameter. This review found no studies that measured turbulence downstream of an operating wind park. Site-specific factors and lack of field data prevent the accurate prediction of the effects of future construction, which could range from negligible to very significant.

3.2 Potential Impacts

3.2.1 Changes in Turbulence

Lass *et al.* (2008) and Hammar *et al.* (2010) suggested that turbulence level, settling rates and plankton growth are affected by OWFs. Homogenous turbulence in the surface mixed layer (SML) decreases particle suspension time, while inhomogeneous turbulence (decreasing at the water surface and again at the boundary with the thermocline) increases particle residence time (Ross, 2006). Residence time can also increase 30-40% when the ratio of eddy diffusivity to sinking velocity is greater than 10 (Ross, 2006). Changes in turbulence could thus affect the residence times of non-swimming plankton as well as suspended sediment concentrations.

The direct effects of turbulence on phytoplankton dynamics were explained in a series of non-OWF studies by Alcaraz, *et al.* (2002), Arin, *et al.* (2002), and Maar, *et al.* (2002), which studied the combined effects of turbulence and nutrients on phytoplankton growth. Temporally intermittent turbulence caused faster respiration rates, longer-lasting autotrophy, a higher production-to-respiration ratio, and an increase in net primary production (Alcaraz, *et al.* 2002*)*. Added nutrients caused an even greater shift in the phytoplankton regime: the fraction of large cells (d> 50μm) under turbulent conditions with added nitrogen and phosphorus was up to 178 times higher than that under turbulent conditions with no added nutrients (Arin *et al.*, 2002). The problem is thus more complex than results of increased turbulence alone. There might also be cascading effects: as plankton dynamics change, nutrient dynamics could change because of increased uptake during plankton growth and physical export during organic matter settling.

Because research has shown that small-scale turbulence can affect the diffusion of materials, the light field, the nutrient distribution, and the size and chemical composition of plankton (Alcaraz, et al. 2002), attention should be given to possible wind-farm-induced changes to turbulence that may influence other phenomena as well.

3.2.2 Vertical Mixing

In the North Sea, stratification in the water column is important to the carbon pump, biomass distribution, and currents. The alteration of the water column stratification via vertical mixing could cause cascading effects among these phenomena. Up to 40% of one season's sequestered carbon in the North Sea is transported to the Atlantic Ocean before the next growing season, and 52% of this carbon transport occurs below the thermocline (Holt *et al.*, 2009). The sequestered carbon must remain isolated from atmospheric exchanges so that it can be transported. Changes to the water column stratification via vertical mixing could remove this isolation and reduce the removal of carbon.

The location of stratified waters and fronts is also important. Surface chlorophyll-a concentrations, often an indicator of phytoplankton communities, are higher in frontal waters than in mixed or stratified waters, and chlorophyll-a concentrations tend to increase after the onset of stratification (Richardson *et al.*, 1985). A study in the Irish Sea found that surface chlorophyll-a values ranged from 1.35 μg/L in mixed and stratified waters to 2.43 μg/L in frontal waters. The effect of stratified waters was more pronounced when values were averaged to 30 m: chlorophyll-a values were as low as 1.30 μg/L in mixed waters, but rose to 1.75 μg/L in stratified waters and 2.17 μg/L in frontal waters (Table

1). Disrupting vertical stratification or the formation and location of stratified regions might alter plankton dynamics. Finally, fronts between mixed and stratified waters drive currents in the North Sea by preventing transverse exchanges across fronts (Howarth, 2001). Altering either the location, strength, or size of a front could alter currents.

This review has not found any studies that concern whether a large OWF could affect vertical mixing and stratification on submeso- or mesoscales, but previous research (Lass et al., 2008, Hammar et al., 2010, Burchard et al., 2009) has predicted that OWFs might have an effect on turbulence and vertical mixing. These in turn might change large-scale horizontal gradients, thus affecting mesoscale flows. Large scale alterations of either vertical mixing or turbulence could also impact phenomena from phytoplankton growth to carbon sequestration. It is currently uncertain how large an OWF-induced change might be in an OWF with hundreds of turbines.

Table 1 – Chlorophyll-a concentrations in the Irish Sea (Richardson, et al. 1985)

	Frontal Waters	Stratified Waters	Mixed Waters
Surface	2.43 µg/L	1.36 µg/L	1.35 µg/L
Averaged to 30m	2.17 µg/L	1.75 µg/L	1.30 µg/L

4 Wind Park Impacts - Surface Wave Energy

4.1 Existing Research

4.1.1 Changes Due to Reflection and Diffraction

4.1.1.1 Near Field

Few observational studies exist about surface wave energy in an OWF. The research in this review was either theoretical or site-specific modelling for a planned OWF. In addition, the difference between “far-field” and “near-field” wave effects has not been agreed upon, but in this review near-field wave effects are within the wind farm and up to two km downwind, while far-field wave effects occur at least two km downwind of the wind farm.

Linton and Evans (1990) calculated changes to an incoming wave field due to four piles in a square configuration, which was originally used at oil platforms, but may apply to wind farms as well. Wave amplitude increased up to 2.2 times the original amplitude on the immediate wave ward side of the pile, while wave amplitude decreased up to 40% on the leeward side. The location of maximum amplitude change depended on wavelength, but the size of amplitude change was not affected by incoming wave direction. Amplitude patterns became increasingly complicated with two rows of four piles, indicating an interaction between piles despite the localized nature of the phenomenon. This idealized numerical experiment therefore suggests that wave reflection and diffraction at individual piles can compound to create a general increase in wave amplitude on the wave ward side of the farm and a decrease in amplitude on the leeward side of the farm. Changes to surface wave energy will also be increasingly difficult to predict as the number of turbines increases. Additional studies with more turbines have calculated complicated patterns of reflection and diffraction, including nearly resonant waves when critical wavelengths interact with 100 piles (Maniar and Newman, 1997).

Christensen, et al. (2013) and Ponce de Leon, Bettencourt, and Kjerstad (2011) modelled changes to significant wave height (H_s) in an OWF (Figure 4, Figure 5). Both studies focused on the effects of reflection and diffraction, because underwater friction and drag caused less than 10% of wave energy dissipation in the modelled OWF (Christensen *et al.*, 2013). A single monopile can reduce the total wave energy of irregular waves by up to 4.24% for up to 80 m behind a pile (Ponce de Leon et al. 2011), reflect up to 70% of short wavelength energy, and increase wave height up to 2-3% in front of a pile (Christensen et al. 2013). Some models have calculated an increase in wave height for up to 2 km upstream of an OWF (Christensen et al. 2013). These studies support the findings of Linton and Evans (1990), indicating an increase in significant wave height upwind of an OWF and a decrease downwind. Long waves (wavelength at least ten times the diameter of the pile) were not affected by reflection (Christensen et al. 2013). The size and spacing of the pillars in relation to the incoming wavelength must therefore be considered in models of a wave field through many piles. When reduction occurs, significant wave height is reduced under most combinations of wind speed, water depth, and fetch (Christensen et al. 2013).

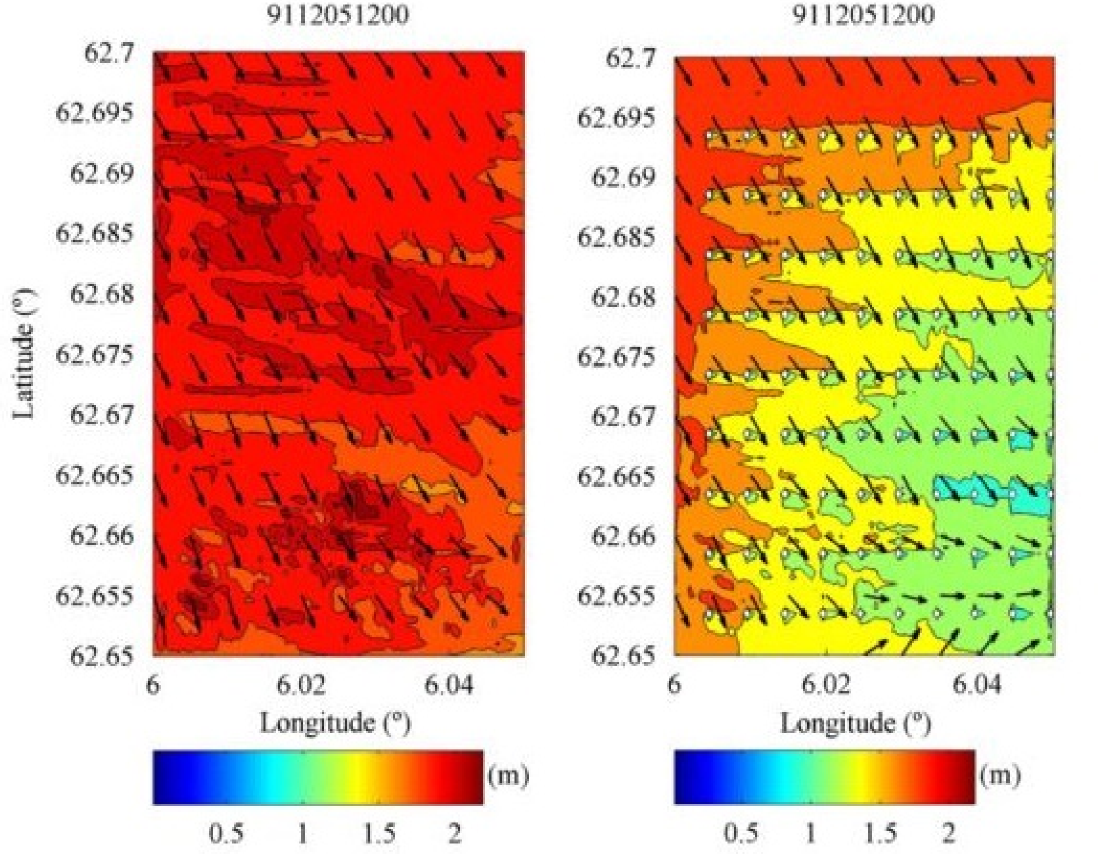

Fig. 12. SWAN H_s (m) maps for 5th December 1991 at 12 UTC (left-without windmills; right-with 90 windmills).

Figure 4 - Model results from Ponce de Leon, et al. (2011), predicting a decrease in Hs due to the construction of an OWF.[1]

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[1] Reprinted from Continental Shelf Research, S. Ponce de Leon, J.H. Bettencourt, N. Kjerstad, “Simulation of irregular waves in an offshore wind farm with a spectral wave model”, p. 1552, Copyright 2011, with permission from Elsevier

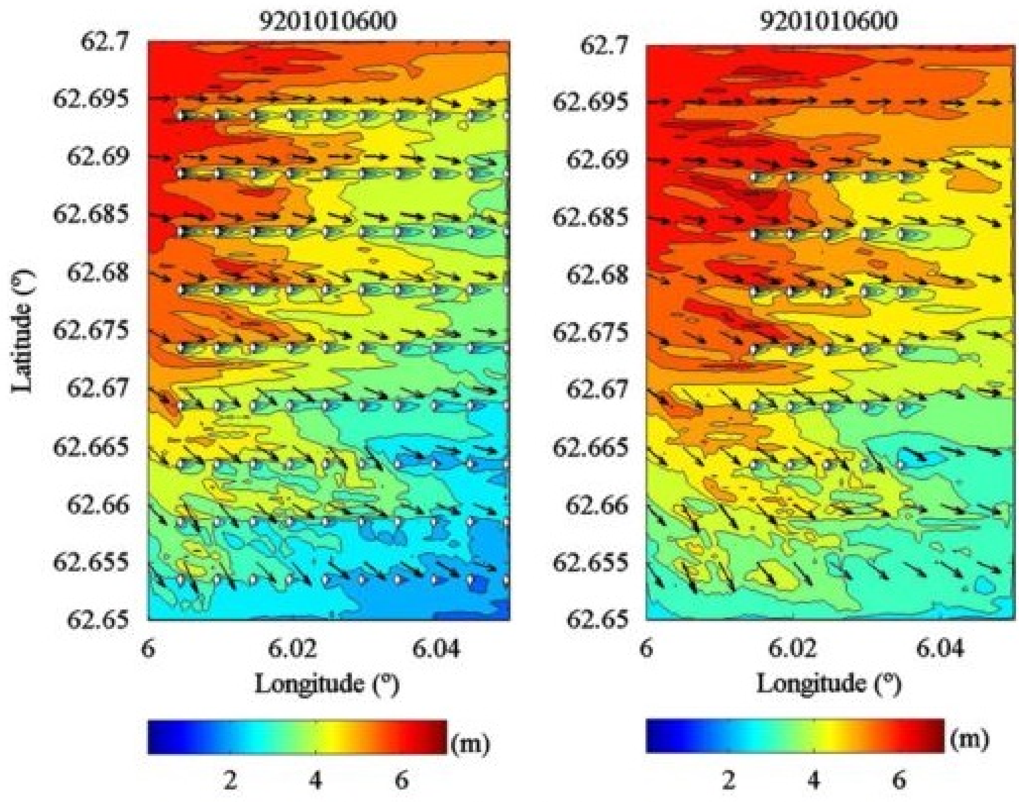

Fig. 16. Computed SWAN H_s (m) maps, accounting the 90 (left) and 30 (right) windmills for 1st January 1992 at 06 UTC.

Figure 5 - Model results from Ponce de Leon, et al. (2011) showing a larger decrease in Hs downwind of an OWF with more piles.[2]

4.1.1.2 Far Field

Despite the changes to H_s within and near OWFs, this review found few existing studies about far-field changes to wave energy, significant wave height, or wave direction. The studies about changes to wave height at the shore typically modelled a maximum change of only 1-2% (Cooper and Beiboer, 2002; Alari and Raudsepp, 2012). As with many other phenomena, only the effects of one moderate-sized OWF on far-field sediment dynamics have so far been studied. Accurate predictions of potential far-field impacts require models and observations of many scenarios of large OWFs.

Table 2 - Changes to wave height at the shore as the result of offshore wind farm interference

Authors	Distance to Coast	Change in Wave Height
Cooper and Beiboer (2002)	1.5 km	0.5-1.5%
Cooper and Beiboer (2002)	7 km	< 0.5 %
Alari and Raudsepp (2012)	15-20 km	0.5-1 cm (0.25-2%)

4.1.2 Changes Due to Reduced Wind Stress

4.1.2.1 Near Field

Two studies modelled the potential reduction of wind speed downwind of an OWF and consequent effects to wind waves, but they reached different conclusions about the size of the wind impact in

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[2] Reprinted from Continental Shelf Research, S. Ponce de Leon, J.H. Bettencourt, N. Kjerstad, “Simulation of irregular waves in an offshore wind farm with a spectral wave model”, p. 1554, Copyright 2011, with permission from Elsevier

comparison to reflection and diffraction. Rodriguez and Harris (2012) calculated that reflection and diffraction played a larger role for the reduction of H_s than reduced wind speed. In contrast, the model of Christensen et al. (2013) predicted that wind speed is the dominant factor to significant wave height reduction at all downwind distances when the 10 m wind speed is greater than 30 m/s. For wind speeds below 30 m/s, wind stress caused 2/3 of H_s reduction at 2 km downwind ("near-field"). The contrasting findings of Christensen et al. (2013) and Rodriguez and Harris (2012) suggest that site-specific parameters are important and emphasize the need for further research. (For more details related to significant wave height reduction due to wind stress, refer to Section 8.1.)

4.1.2.2 Far Field

The same two studies (Christensen et al., 2013; Rodriguez and Harris, 2012) modelled far-field effects of an OWF wind wake. Christensen *et al.* (2013) stated that a wind wake can reduce surface friction and affect H_s up to 15 km downwind. Rodriguez and Harris (2012) compared synthetic aperture radar (SAR) data from Christiansen and Hasager (2005) with their own model to map a wind wake that extended 20 km downwind from their test site. They also argued that wind stress changes coupled with reflection and diffraction could alter wave patterns at the shoreline, but did not provide numerical predictions. The studies therefore agree that an OWF wake extends far-field, but disagree about how much this wind wake affects surface waves. (For more details related to significant wave height reduction due to wind stress, refer to Section 8.1.)

4.2 Potential Impacts

The alteration of surface waves in OWFs can have cascading effects through the connection of surface waves to water column stratification and bottom dynamics. For example, surface waves can erode the halocline (Meier *et al.*, 2006), so OWFs could change the depth and strength of the pycnocline by altering surface wave direction, height, or period. Wave energy also often affects sediment resuspension and subsequent nutrient dynamics.

5 Wind Park Impacts - Sediment Dynamics

5.1 Existing Research

Changes to sediment dynamics can be local near-field effects or larger-scale far-field effects. Near-field effects are within the wind farm and include scour and suspended particulate matter. Far-field dynamics are outside the wind farm footprint and include shoreline erosion or changes to deposition location.

5.1.1 Near Field

Large changes to suspended sediment concentrations (SSC) will likely occur during wind farm construction through pile driving and cable laying, but construction-induced changes are temporary (Hiscock *et al.*, 2002) and may be negligible (Eynde et al. 2010). Construction at C-Power and Belwind Offshore Wind Farms, for example, caused no significant change to turbidity and increases to suspended sediment were within natural variations (Eynde *et al.*, 2010).

Although the effects of construction are temporary, OWFs could alter sediment dynamics during operation via scour. Local scour (around the base of each turbine) is a common engineering issue, and some studies have claimed that local sour is the only issue: larger-scale scour is avoidable with proper pile spacing (Cooper and Beiboer, 2002). A model of DanTysk Wind Farm forecast local scour up to 2 m deep, but deposition was 1.5 m thick and largely compensated for erosion (Ahrendt and Schmidt, 2010). The same model forecast broad, shallow erosion (decimeter scale) up to 80 m from a single pile, which was within natural variations and caused no cumulative changes to sediment. Most studies about local scour focus on changes to the stability of the piles rather than the local oceanic environment. Oceanographic research can complement engineering studies to predict the local effect of OWFs on sediment.

Besio and Losada (2008) modelled sediment transport patterns for scenarios of differing structure-induced friction, pile spacing, and incoming wavelength at a series of piles surrounded by porous rings (cages). Each scenario induced patterns of alternating erosion and deposition, the scale of which depended on the wave field's incoming wavelength. Nearly resonant waves of sediment transport occurred within the wind farm: large suspended sediment concentrations occurred at wave nodes and small suspended sediment concentrations occurred at anti-nodes. Besio and Losada (2008) also claimed that the exterior piles sheltered the inner structures so that structures on the wave ward side of the wind farm have the largest effect on sediment transport. This information could be used to select a location for OWF construction so that the sensitive sediment environments are in the sheltered interior. Yet these are only qualitative predictions: quantitative predictions are lacking. Both relative and absolute quantitative predictions will allow for the calculation of cascading effects to nutrients, light attenuation, etc., which are important to ecosystem health.

Wave-induced resuspension occurs in waters up to 80 m deep (Almroth-Rosell *et al.*, 2011), such as the shallow waters of the southern Baltic (Jönsson, 2006; Seifert *et al.*, 2009). Jönsson (2006) found that a wave height greater than 0.5-1 m high and a wave period longer than 3-5 seconds can cause resuspension in areas of the southern Baltic Sea where the water depth is less than 20 m, indicating that shallow areas might be susceptible to even smaller changes in wave height. At many locations, wave height and peak wave period must increase simultaneously to suspend sediment (Jönsson, 2006; van der Molen *et al.*, 2013); reducing just one factor via an OWF installation could therefore prevent resuspension. Deeper areas are affected only as the wind and wave intensities increase simultaneously, so some offshore wind farm locations might not have as large of an effect. Site-specific studies are therefore important.

5.1.2 Far Field

Predictions for the effects of OWFs on far-field sediment dynamics range from insignificant (Ponce de León *et al.*, 2011) to the "reduction in beach width and even its disappearance" depending on the local regime (Esteban *et al.*, 2011). The disagreement between studies emphasizes that this phenomenon is poorly understood. Factors to the local sediment regime include natural sediment flux, nearshore bathymetry, and the distance between the wind farm and the shore (Kenyon and Cooper, 2005). The predicted impact of a wind farm on coastal erosion is small when the natural sediment flux is away from the shore, a sandbank prevents beach erosion, or the wind farm is far enough away to avoid interaction with the coast (Kenyon and Cooper, 2005). Few studies, however, have quantified far-field changes to sediment dynamics. A model of a "worst-case scenario" off of Denmark (30 turbines spaced 300 m apart, 1 kilometer offshore) forecast that peak suspended sediment concentration (SSC) could change up to 3% and shift location by 300 m, but the overall deposition area would remain unchanged (Cooper and Beiboer, 2002). A model of a "typical scenario" (30 turbines in 3 rows of 10 spaced 400 and 700m apart) 7 km off of Denmark forecast changes that were at the edge of instrument accuracy and therefore not reliable for accurate predictions (Cooper and Beiboer, 2002). This review has not found research that studied the cumulative effect of multiple wind farms on sediment dynamics. Although research suggests that changes to sediment dynamics will be local, the *combined* effects of multiple large-scale wind farms could alter net sediment transport and deposition, thereby affecting shorelines and bathymetry.

5.2 Potential Impacts

Changes to sediment in OWFs are important because sediment dynamics are a driving force in biogeochemistry in the coastal ocean. Sediment resuspension could release toxic compounds (Hiscock *et al.*, 2002) and create temporary and local reductions in nutrients and oxygen (Hiscock *et al.*, 2002) (Jönsson, 2005, 2006). Petersen, et al. (1997) simulated reoxidation of contaminated sediments and measured a release of up to 2% of particulate-bound heavy metals Cadmium, Copper, and Zinc (Petersen *et al.*, 1997). Surface sediments at a study site in the Baltic Sea were sites of organic degradation and a source of phosphorus to the water column (Rydin *et al.*, 2011), and sediments are thought to contribute up to 18% of the nitrogen and phosphorus input in the North Sea (Vermaat *et al.*, 2008). The effects of sediments on nutrients emphasize the need to understand the effect of OWFs on sediment resuspension.

The relationship between OWFs and sediment size might also be important to nutrient dynamics. In the Gulf of Gdansk, fine sediments (< 0.0625 mm) account for 70% of the variation of total phosphorus, with the highest total phosphorus levels found in areas with plentiful clay minerals and aluminum oxides (Łukawska-Matuszewska and Bolałek, 2008). The average median sediment size within Horns Rev Offshore Wind Farm increased after wind farm construction from 345 µm in 2001 to more than 500 µm in 2003 and 2004 (Pedersen *et al.*, 2005). If OWFs alter the size distribution of sediments, they could also affect the distribution of nutrients that adsorb to these sediments. These two studies were not conducted at the same location, however. Site-specific information is important to determine the effect of sediments on nutrients, oxygen, and contaminants at each proposed wind farm location.

6 Wind Park Impacts - Mesoscale Current Changes

Research concerning OWF-induced changes to tides and currents agrees that currents accelerate on the flanks of the farm and decelerate inside and downwind of the farm. Most models have yielded changes within natural variations. The average modelled wind farm to-date is about 100 turbines, which is significantly smaller than the projected construction in the North Sea (up to 7,000 turbines, (WAB - Windenergie Agentur)). However, this should be a focus of study, as tides and currents are important transport mechanisms for nutrients and biota.

The research focus on inflows has been in the Baltic Sea, with one study so far modelling potential OWF-induced changes to inflows. Baltic Sea inflows ventilate oxygen-poor bottom water and control geostrophic currents by establishing a horizontal density gradient. As of yet there is no research related to the effect of OWFs on North Sea inflow currents from the North Atlantic via the English Channel or the northwest North Sea.

6.1 Existing Research

6.1.1 Currents and Tides

Ahrendt and Schmidt (2010) modelled changes to a 0.1 m/s current around a single pile, showing an increase in current velocity of 0.1 m/s on the pile flanks and a decrease in current velocity of 0.01 – 0.025 m/s (10-25%) on the lee side of the pile. The same study modelled 144 piles in a background current of 0.128 m/s, and calculated that the overall current velocity in the park was reduced by 3%. Current reduction due to one pile does not linearly scale as piles are added, because changes are only very close to the pile; other factors such as pile size and spacing must be considered to determine larger-scale effects of OWFs on current velocity. Mittendorf, *et al.* also (2001) modelled an increase of current velocity on wind park flanks and a reduction downwind of the wind park (Mittendorf, K.

Zielke, W., Hoyme, 2001). The model predicts only small changes to the current, which agrees with claims from other studies that reductions in current velocities will be negligible (Cooper and Beiboer, 2002; Zhang et al., 2009; Ahrendt and Schmidt, 2010).

Zhang, *et al.* modelled (2009) OWF-induced changes to tides in the Yangtze estuary and Hangzhou Bay and predicted that tidal amplitude would neither increase nor decrease by more than 1 millimeter, or 0.3%. Similarly, Cooper and Beiboer (2002) predicted changes of about 1% to the current speed and 0.5° to the direction of tidal currents offshore of the United Kingdom under a "worst case scenario" (Table 3). An OWF's influence on currents also depends on the number of piles, the pile spacing, and the angle of incidence between the incoming current and the wind park (Zhang *et al.*, 2009). This review found no research concerning the compounding effects of multiple obstructions, such as if a second wind farm were to interact with the reduced current velocity from the first wind farm. Additional research should therefore investigate the effects of multiple wind parks before it can be concluded that the projected constructions in the North Sea will have no effect on tidal currents.

Table 3 - Modelled changes to tidal currents resulting from an offshore wind farm construction (Cooper and Beiboer, 2002)

Scenario	Change in Speed	Change in Direction
"Worst Case"(30 turbines 1.5 km from shore, 300m spacing)	**1%**	**0.5 °**
"Typical" (30 turbines 7 km from shore, 400-700m spacing)	**<< 1%**	**< 0.5°**

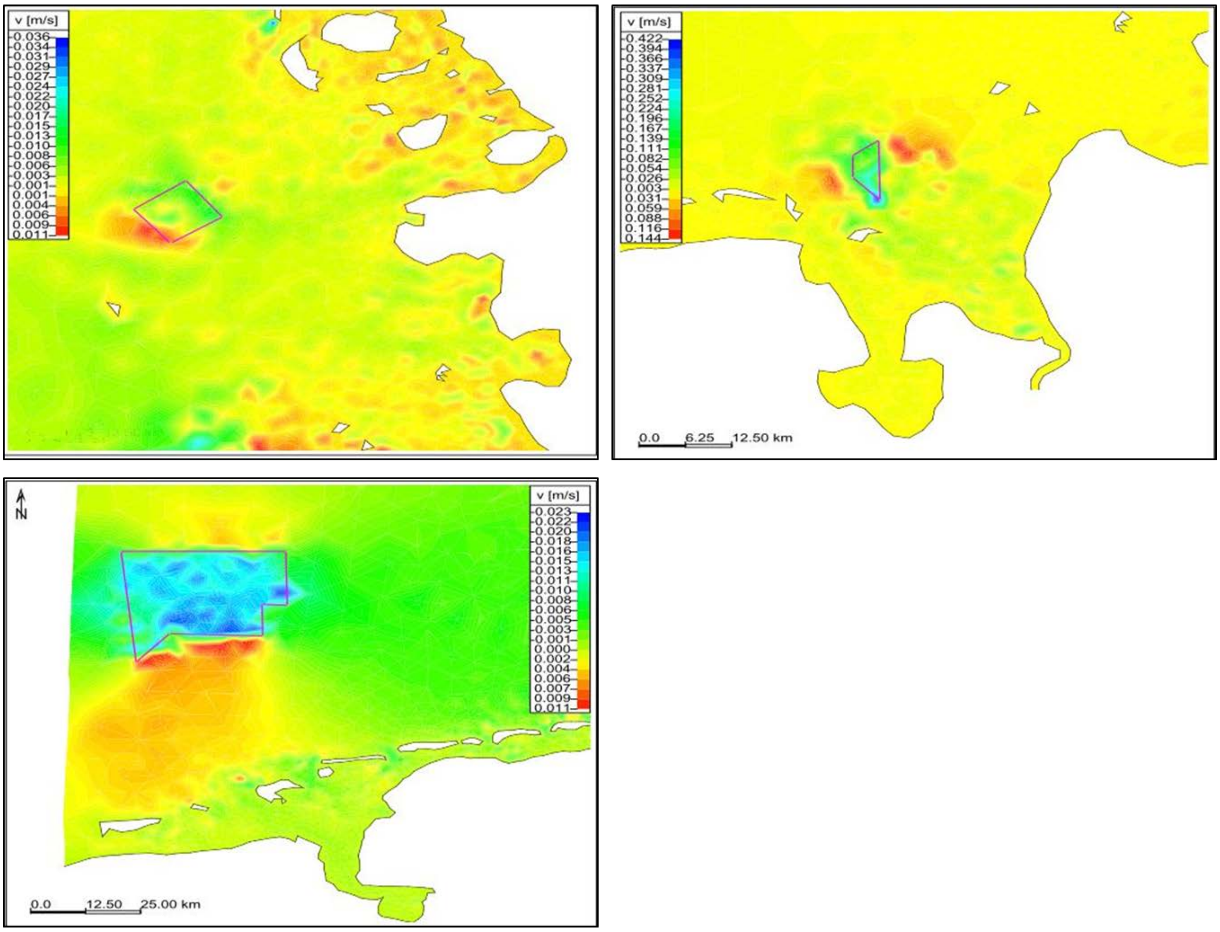

Figure 6 - Modelled changes to current velocity around three wind parks: Helgoland (Top Left), Weser (Top Right), and Borkum (Bottom) (Mittendorf, et al. 2001). Note that the colors scales are not the same.[3]

6.1.2 Baltic Inflows

Lass *et al.*(2008) found that bridge pile-induced turbulence affected Baltic Sea inflows and created a reverse baroclinic pressure gradient that overcame the background barotropic pressure gradient and caused a flow out of the Baltic below 15 m. This phenomenon is specific to the Baltic Sea because of its stratified waters and inflow events and is not likely to affect overall circulation if the number of piles is small. Large-scale construction, however, could have unknown consequences.

Rennau, *et al.* (2012) modelled mixing in Baltic Sea inflow due to the construction of wind farms (Figure 7). Offshore wind farm construction according to plans approved in 2010 could decrease bottom salinity by 0.1 PSU (Burchard *et al.*, 2008), which is less than the natural variation of 5-10 PSU. The same study simulated an “extreme” scenario, in which wind turbines spaced 400 and 800 m apart filled a 20 kilometer-long channel resulting in the decrease of bottom salinity by 0.3 PSU over the course of the channel. Turbine-induced mixing could also cause fresh water inflow to occur two m higher in the water column and the highest density inflow events between the North and Baltic Sea to disappear (Rennau *et al.*, 2012), which would reduce oxygenation of deep water in the Baltic Sea. As a semi-enclosed brackish body of water with strong stratification and a positive water balance, the Baltic Sea relies upon inflows of North Sea water for ventilation (Fennel and Seifert, 2008). Inflow events in the Baltic Sea are critical to circulation, nutrient dynamics, oxygen, and salinity levels, and their

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[3] Reprinted from Institut für Strömungsmechanik, Leibniz Universität Hannover, K Mittendorf, W. Zielke, „Untersuchung der Wirkung von Offshore-Winenergie-Parks auf die Meersströmung Einleitung 2 . Modellierung eines Windparks in einem hydrodynamischen Modell”, p. 13, Copyright 2001, with permission from the University of Hannover

disruption could have multiple consequences (Fennel and Seifert, 2008; Gustafsson, 1997) Due to large uncertainties, accurate estimates are currently difficult: changes in salinity could result from factors other than the wind farms (Burchard et al., 2008). Large discrepancies could be the result of many variables, including different modelling methods, initial hydrography conditions, or wind farm layout. A lack of accurate estimations does not imply that wind farms are not an issue to Baltic Sea inflows, however, but emphasizes the need for more research and specific modelling scenarios.

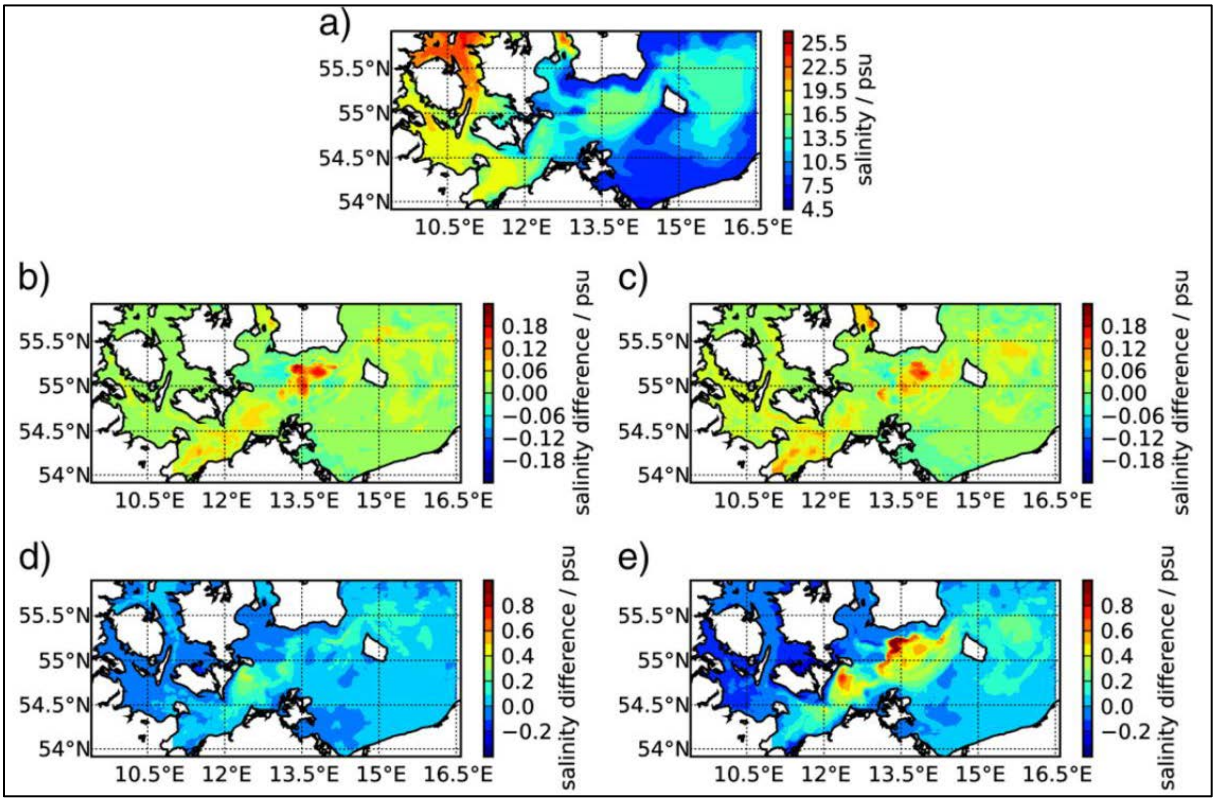

Figure 7 - Modelled changes to salinity in the western Baltic as the result of OWF construction: (a) normal conditions; (b) realistic construction and weak vertical mixing; (c) realistic construction and strong mixing; (d) unrealistic construction and weak mixing; (e) unrealistic construction and strong mixing (Rennau, et al. 2012). Not that the color scales differ.[4]

6.2 Potential Impacts

In the North Sea, currents are an important transport mechanism (Hill *et al.*, 2008) that influences ecosystem dynamics. In addition, bottom currents have been shown to cause resuspension (Lund-Hansen *et al.*, 1993) and are the basic forcing of sand movement in the German Bight and greater North Sea (van der Molen, 2002). The alteration of currents via offshore wind farms could thus result in altered sediment and nutrient cycles. The effects of altered currents would be even stronger if tidal currents are affected asymmetrically (i.e. one phase is more reduced than another), as small changes to tidal currents would then compound over time to alter residual currents and therefore physical transport mechanisms.

In the Baltic Sea, the interference of inflow events via OWF construction could affect other inflow-controlled parameters, such as bottom oxygen levels (Bendtsen *et al.*, 2009) or the circulation of the entire Baltic Sea (Meier *et al.*, 2006). The size of the inflow event is important: large-intensity inflows drive bottom ventilation and medium-intensity inflows cause intermediate layer ventilation (Meier *et*

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[4] Reprinted from Coastal Engineering, H. Rennau, S. Schimmels, H. Burchard, „On the effect of structure-induced resistance and mixing on inflows into the Baltic Sea: A numerical model study", p. 65, Copyright 2012, with permission from Elsevier

al., 2006). Although some argue that only large-intensity inflow events are threatened by offshore wind farm construction (Rennau *et al.*, 2012), medium-intensity inflow events have gained more recognition in recent years, and future offshore wind farm construction research should expand to include different-sized inflow events.

7 Wind Park Impacts - Upwelling and Downwelling

There is very little research concerning wind farm-induced upwelling, but a couple of studies have suggested that wind curl in the wind farm wake could cause upwelling that would be exaggerated by wave forcing. This phenomenon has yet to be explored for large-scale OWFs, with site-specific conditions, or in observational studies. It is worth investigating, however, as upwelling and downwelling are linked to phytoplankton regimes, nutrient cycles, and oxygen distribution among many other chemical cycles and physical transports.

7.1 Existing Research

Wind farms can cause upwelling through wind wakes or the alteration of wave stress. A wind speed of 5-10 m/s can generate upwelling speeds greater than 1 m/day (Broström, 2008) in the wake of a wind farm. The strength of the upwelling increases with the size of the wind farm (Broström, 2008), and the pycnocline displacement increases as the wind farm becomes larger in relation to the Internal Rossby Radius (Paskyabi and Fer, 2012). In addition, the added effect of wave forcing increases the amplitude of the pycnocline displacement (Paskyabi and Fer, 2012) (Figure 8). In a modelled five-day development of pycnocline changes from Paskyabi and Fer (2012), the Stoke’s Drift increased by 0.4% and the surface wave stress decreased by 50%. This review found only two studies that considered the effect of an OWF on surface upwelling and downwelling. The relationship between wind farm size and the strength of the upwelling is important because of the large wind farms currently under proposal: this relationship will determine at what point a large wind farm will have a significant impact.

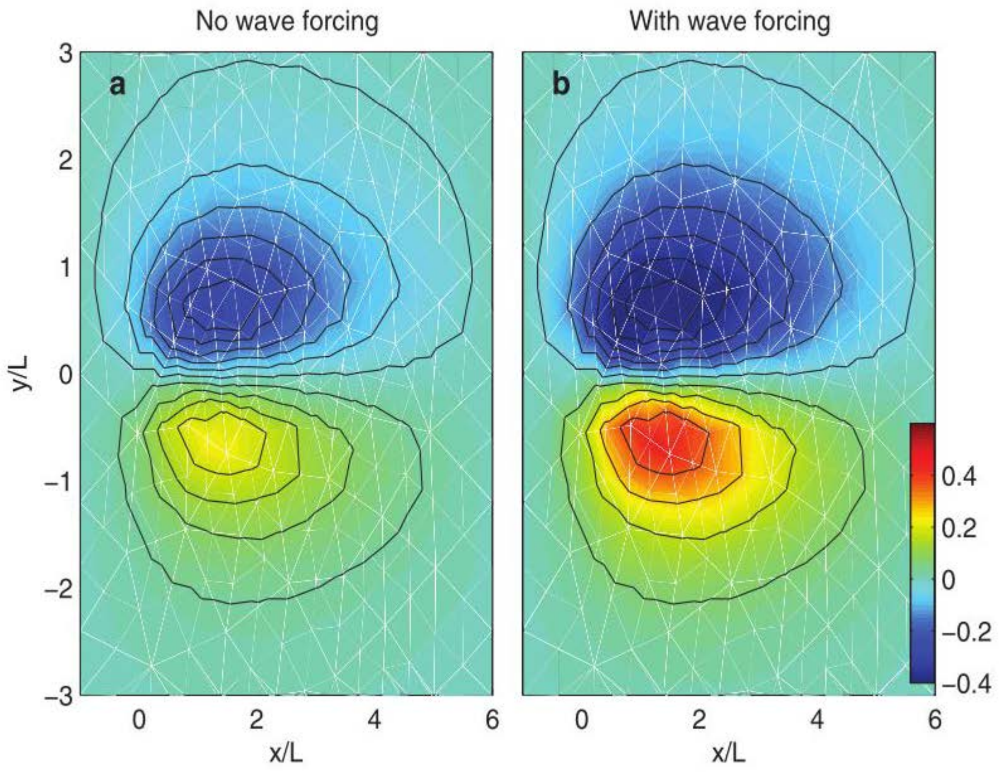

Fig. 2. Non-dimensional thickness of the upper active layer for $\gamma^2 = 1$ for a) no-wave, and b) with wave forcing effect.

Figure 8 - Figure from Paskyabi and Fer (2012) showing changes in pycnocline depth due to upwelling/downwelling downwind of a large OWF.[5]

7.2 Potential Impacts

Upwelling and downwelling patterns affect nutrient and chemical cycles, particularly when the water column is stratified. Changes to upwelling could affect the phytoplankton communities that rely on upwelling for nutrients, while changes to downwelling could alter carbon and detritus exportation (Holt *et al.*, 2009). These changes are important in highly productive coastal regions, which may coincidence with wind farm construction sites.

8 Wind Park Impacts - Atmosphere

8.1 Existing Knowledge

Wind turbines extract energy from wind and create downwind turbulent wakes whose highest velocity deficit is at the turbine hub height (Ainslie, 1988). Onshore, these wakes typically extend two to four blade diameters downwind and the wind speed recovery distance depends on the difference between the turbine-generated turbulence and the ambient atmospheric turbulence (Ainslie, 1988). Offshore, wind wakes could propagate further downwind (Barthelmie *et al.*, 2003), because ambient atmospheric turbulence is typically lower. Christiansen and Hasager (2005) modelled the wind wake of an offshore wind farm and predicted an average peak velocity deficit of 8-9% directly downwind of the wind farm, quantifying the wind wake they observed downwind of Horns Rev Wind Farm with Satellite SAR (Figure 9). Recovery distance for wind velocity ranged from 5 to 20 km depending on the ambient

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[5] Reprinted from Energy Procedia, M. Paskyabi, F. Fer, “Upper Ocean Response to Large Wind Farm Effect in the Presence of Surface Gravity Waves”, p. 250, Copyright 2012, with permission from Elsevier

wind speed, atmospheric stability, and the number of turbines (Christiansen and Hagar 2005). Christensen *et al.* (2013) calculated larger deficits at Horns Rev: the wind speed at hub height was reduced by 80%, and the wind speed at the surface was reduced by 90%. The discrepancy between these two studies could be the result of site-specific parameters, modelling methods, or wind farm size. While research is thorough on the formation and dynamics of individual turbine wakes, the collective effect of many wind farm wakes is less understood. Most research to this point addresses engineering and economic concerns.

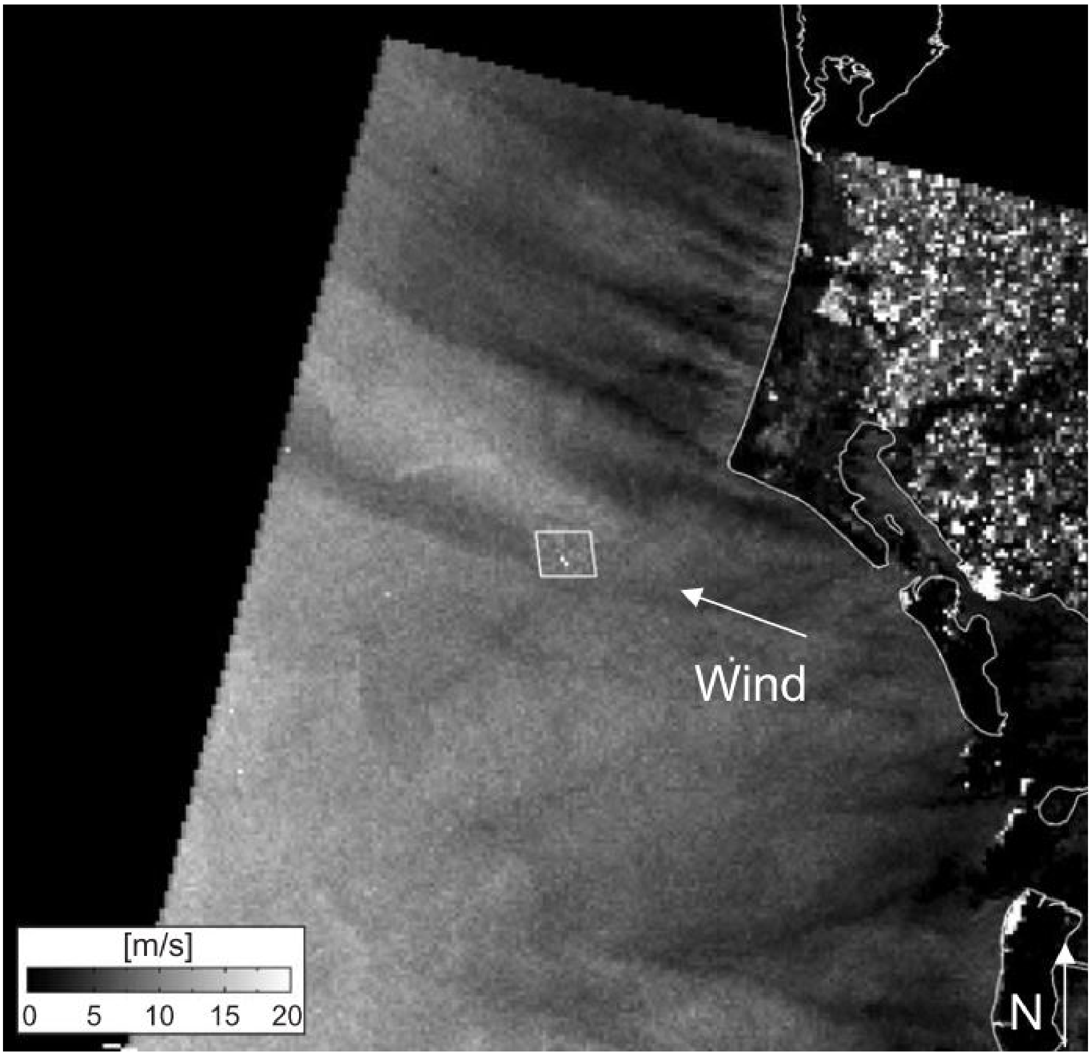

Figure 9 - Satellite SAR image from Christiansen and Hasager (2005): "The wind farm at Horns Rev is indicated (white trapezoid) and a wind wake is seen as dark pixels downstream of the turbines." [6]

Large wind farms generate wakes that can interact with the surface ocean to alter surface wave energy and generate upwelling. Christensen et al. (2013) modelled changes to surface wave energy (Sections 4.1.1and 4.1.2) propagating through a wind farm and found wind wake to be a dominant factor to H_s reduction at all wind speeds. In every scenario, wave height recovered by 99% by 20 km downwind. Rodriguez and Harris (2012) modelled a “downwind turbulent wake” of a proposed OWF that extended 20 km downwind from the test site. The wind wake reduced H_s by up to 3%, and the wind wake combined with reflection and diffraction reduced significant wave height (H_s) by 6.8-8.5%.

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[6] Reprinted from Remote Sensing of Environment, M. Christiansen, C. Hasager, “Wake effects of large offshore wind farms identified from satellite SAR”, p. 259, Copyright 2005, with permission from Elsevier

According to Rodriguez and Harris, however, reflection and diffraction cause at least 75% of reduction in 12 out of 14 scenarios, playing a larger role than reduced wind speed in H_s reduction.

Reduction rates and recovery distances will become more important as many wind farms are constructed in close proximity to each other in the North Sea. Wind wakes could compound to disrupt wind wave generation and ocean-atmosphere exchanges. Yet not all wind waves are affected by an OWF: Christensen *et al*. (2013) calculated that wind waves developed over a longer fetch are less likely to be affected by a wind farm. If H_s is not as important as wave period or direction, then the effect of OWFs on H_s would not be a concern.

As discussed in Section 7.1 (Upwelling and Downwelling), very large wind farms can generate upwelling (Broström, 2008). The strength of the upwelling, both in speed and overall area, depends on the size of the wind farm in comparison to the internal radius of deformation. This stresses the importance of collecting background information before wind farm construction and setting an upper limit to the size of a wind farm. Approved wind farms off the coast of Germany have so far been limited to 80 turbines per construction stage, and more research about the relationship between wind farm size and upwelling intensity is necessary as construction continues.

8.2 Potential Impacts

One study has considered how large-scale wind farm construction might affect ocean-atmosphere exchanges, particularly the latent heat flux. Wang and Prinn (2011) modelled potential changes due to offshore wind farm construction by increasing surface friction in the global oceans. They calculated that increased turbulent mixing in the atmospheric boundary layer could cause an increase in the upward latent heat flux and eventual net cooling at the surface. In the densest construction cases, net cooling reached up to 2°C, with a global average of 1°C. These results are unrealistic, but they reveal that a connection between offshore wind farms, surface friction, and heat flux could exist.

The relationship between large-scale wind farms and local or regional meteorology has so far been investigated for on-shore wind farms. A model of a wind farm in the western United States found that wind farms of various sizes can change seasonal precipitation (Fiedler and Bukovsky, 2011). The effect on climate, however, is little: the model predicted a 1% statistically significant increase in precipitation rates over 62 seasons (Fiedler & Bukovsky, 2011). A similar study modelled wind-farm-induced changes to sea surface meteorology (Baidya Roy, 2004) and found that changes to evapotranspiration were negligible, but a farm of 100 by 100 turbines induced changes in the regional sensible heat flux. In this model, the turbines were both a sink of energy and a source of turbulence, resulting in tens of W/m^2 reduction in the upward sensible heat flux in the early morning hours (Baidya Roy, 2004). From these studies it is clear that the wind energy extraction and localized turbulence created by large-scale wind farms can interact with local meteorology. However, due to differences in surface friction, latent heat flux, and lateral temperature gradients, the meteorological conditions over an ocean are different from those over land. Studies such as this from Fiedler and Bukovsky (2011) should therefore be examples of previous research rather than concrete evidence for wind-farm induced changes. Changes to meteorology would likely not be a problem on a small scale, but as wind farms continuously increase in size, these changes could have a collective influence.

9 Biogeochemistry

The other changes to biogeochemistry identified in this chapter are speculative: this review identifies potential connections between the projected effects of wind farms and the known biogeochemical phenomena in the North and Baltic Seas. These biogeochemical and chemical phenomena have been divided into five broad categories: nutrients, oxygen, inorganic carbon, and metals, and organic micropollutants. Sediments and sediment cycling are inextricably linked with the biogeochemical cycles in both the North and Baltic Seas. For the sake of brevity and to avoid repetition, sediment is incorporated into the other four phenomena. This chapter is not a comprehensive overview, but a sample of potential effects that could be researched in more detail.

Offshore wind farm-induced changes to biogeochemistry will likely be the result of a series of complicated cascading effects and are therefore poorly understood. Molen, Rees, and Limpenny (2013) used a "coupled hydrodynamics-biogeochemistry model" to predict changes to a variety of ecosystem variables and found that a reduced wind speed led to reduced wave height, as expected. A modelled wind speed reduction of 10% affected some biological variables (unnamed in conference proceedings) for a distance of up to 2 diameters around the wind farm. Ecological variables were complex, however, and predicted changes ranged from 3 to 28% depending on the variable or its connection to other variables in the ecosystem. Molen *et al.* (2013) didn't consider other wind farm-induced changes, such as turbulence at the pile or the resulting increase in turbidity, which could also interact with ecosystem variables and create reactions that are more complex than what Molen *et al.* (2013) predicted.

9.1 Nutrients

9.1.1 North Sea

Nutrient supplies in the North Sea are influenced more by the internal cycling of detritus or dissolved organic nitrogen (Hydes *et al.*, 1999) than by river input or Atlantic inflows (Brockmann *et al.*, 1990). Resuspension is an important part of this cycle, because interstitial spaces in North Sea sediment tend to have higher nutrient concentrations than the overlying water (Rutgers van der Loeff, 1980; Law and Owens, 1990).

Vertical mixing could alter the internal cycling of nutrients, mostly by changing physical transport mechanisms that bring nutrients back to the surface waters. Oxygen in sediments is also important, because denitrification, a sink for the North Sea's limiting nutrient Nitrogen (Brockmann *et al.*, 1990), occurs in oxygen-poor sediments (Law and Owens, 1990). Sediment resuspension could alter redox conditions, thereby affecting denitrification and releasing nutrients that are trapped in the sedimentary interstitial spaces. Release of nutrients (especially Nitrogen) to surface waters could cause abnormal phytoplankton growth. Sediment denitrification rates in the North Sea vary by up to three orders of magnitude (Law and Owens, 1990), however, which emphasizes the need to understand site-specific conditions in order to predict the impact of a planned wind farm.

9.1.2 Baltic Sea

In the Baltic Sea, phosphorus surface concentrations are controlled mainly by internal phosphorus/oxygen dynamics and physical conditions (Eilola *et al.*, 2009). The shallow waters in the Baltic Sea do not export as much phosphorus per square meter as the deep waters, but their large surface area and typically oxic conditions make the shallow areas important sinks for phosphorus in the Baltic (Carman and Wulff, 1989). This is particularly relevant to offshore wind farm construction in shallow coastal waters.

The connection between anoxia and phosphorus release will be important if OWFs obstruct oxygenating inflow events from the North Sea. Phosphorus can be sequestered in sediments but is released from sediments under anoxic conditions (Kahru et al., 2000; Eilola et al., 2009). This has been shown to cause phytoplankton blooms, such as *Nodularia spumigena* in the Gulf of Finland (Kahru *et al.*, 2000). In addition, vertical mixing and sediment resuspension of sediments in shallow waters would inhibit the phosphorus sink and change vertical transport, thus altering surface water phosphorus concentrations and potentially causing cascading effects among ecosystems.

9.2 Oxygen

9.2.1 North Sea

Oxygen conditions in the North Sea are site specific: in some locations oxygen variability might be predominantly influenced by storm events, while other locations are influenced by seasonal patterns (Greenwood *et al.*, 2010). In 60% of the German Bight, dissolved oxygen is transported to the sediment via pore water advection (the flow of water through the interstitial spaces in sediment) and promotes respiration in medium and coarse grained sediments (Janssen *et al.*, 2005). Sediment oxygen levels are therefore crucial to ecosystem dynamics. A study about changes to redox potential on the edge of artificial reefs found that changes were substantial only on small spatial scales and in oxygen-poor sediments (Wilding, 2014). At the very edge of an artificial reef, redox potential at 80 mm sediment depth decreased by up to 80 mV, but changes to redox potential did not extend more than 1 meter away from the reef (Wilding, 2014).

It is difficult to draw general conclusions concerning the potential impacts of wind farms on oxygen dynamics in the North Sea, and site-specific environmental impact assessments will be necessary for each proposed wind park. “Oxygen-stressed” environments (Wilding, 2014) should be avoided, as they are more likely to be affected by changes to redox conditions if the wind turbines create an artificial reef effect.

9.2.2 Baltic Sea

The alteration of deep water inflows (Section 6.1.2) or vertical mixing (Section 3.1) via the construction of offshore wind farms could therefore reinforce hypoxic conditions and have cascading consequences in Baltic Sea deep waters. In addition, a study in the Gulf of Finland found that resuspension caused an average of 59% increase in oxygen consumption in almost 9 out of 10 scenarios, indicating that resuspension also affects hypoxic and anoxic conditions (Almroth *et al.*, 2009). In the Baltic Sea there are two ways in which an offshore wind farm could encourage anoxic conditions: the inhibition of inflows and resuspension.

9.3 Inorganic Carbon

9.3.1 North Sea

Several studies have shown the North Sea to be a substantial sink of carbon dioxide (Section 3.2.2). Estimates for the annual North Sea carbon absorption range from 4.3 Teragrams of Carbon (TgC) (Kempe and Pegler, 1991) to 4.8 TgC (Bozec *et al.*, 2005). In the summer, the monthly flux to the North Atlantic Ocean can reach 2.2 TgC (Bozec *et al.*, 2005). The North Sea and other continental shelf seas contribute substantially to global carbon dioxide sequestration despite their relatively small surface area. Regional European shelf carbon export contributes up to 45% of the carbon flux to the open North Atlantic (Frankignoulle and Borges, 2001), and globally, continental shelf seas may sequester as much carbon as the biosphere (Borges *et al.*, 2006). Shelf seas are also the most likely locations for offshore wind farm construction, because of shallow waters and close proximity to onshore grid connections. Carbon exportation in the North Sea relies on stratification and isolation of sequestered carbon from the atmosphere. In addition, the distribution of carbon dioxide and dissolved inorganic carbon in the North Sea is influenced by vertical mixing (Bozec *et al.*, 2005), which has been shown to be enhanced by underwater piles (Section 3.2.2). The potential for offshore wind farms to interact with carbon sequestration should therefore not be ignored.

9.3.2 Baltic Sea

Because the Baltic Sea is a eutrophic and heterotrophic sea, arguments exist that it is both a source and a sink for atmospheric carbon dioxide. Eutrophic shelf seas such as the Baltic have an area-weighted downward flux of carbon roughly equal to 24 grams of carbon per meter squared per year (Cai *et al.*, 2006). However, the Baltic Sea specifically has been shown to contribute up to 1.05 tetragrams of carbon to the atmosphere annually (Kuliński and Pempkowiak, 2011). The most important carbon sinks in the Baltic Sea are sediments and outflows to the North Sea: up to 7.67 TgC are exported to the North Sea annually, and up to 2.73 TgC are sequestered in sediments (Kuliński and Pempkowiak, 2011).

Vertical mixing is a leading factor to CO_2 concentrations in some Baltic surface waters (Schneider *et al.*, 2002). Increased vertical mixing within wind farms (4.1) could inhibit carbon sequestration by transporting carbon back to the surface and increasing the partial pressure of carbon dioxide in surface waters. In addition, obstruction of the connection to the North Sea could inhibit the transport of carbon to the North Sea and the Atlantic Ocean.

9.4 Metals

9.4.1 North Sea

The highest metal concentrations in the North Sea typically occur near shore, in estuaries, and in fine-grained sediments (Förstner et al., 1982; Chapman, 1992). The impact of offshore wind farms can therefore be minimized by environmental impact assessments and proper site selection away from the shore. In the Southeast North Sea, the highest absolute metal contents for Lead, Iron, and Zinc were found in sediments with grain sizes ranging from 2 to 6 µm (Förstner *et al.*, 1982). The tendency of metals to adsorb to smaller particles might become important if offshore wind farms are found to influence grain size, as suggested by Pederson *et al.* (2005) (Section 5.1). The study was inconclusive about whether the change in grain size was due to natural fluxes or to the offshore wind farm (Pedersen *et al.*, 2005), but such connections should be investigated to determine whether offshore wind farms will affect metal distribution by altering sediment grain size. Wind farms could also have a secondary effect on metals by changing oxygen conditions, as metals typically dissolved into anoxic waters but precipitate in oxygenated waters (refer to Section 9.4.2).

9.4.2 Baltic Sea

As is the case with the North Sea, Baltic sediments with smaller grain sizes tend to have a higher metal concentration: Copper, Aluminum, and Molebdynum concentrations were found to increase in finer organic sediments (Manheim, 1961), as was Mercury (Pempkowiak *et al.*, 1998). The Baltic Proper has also seen elevated concentrations of Cadmium, Zinc, Mercury and Lead since 1996 (Borg and Jonsson, 1996), with enrichment factors of 10 for Cadmium and 2-3 for Zinc, Mercury, and Lead. Metal leaching is particularly a concern in the Baltic Sea because increased incidents of eutrophication in recent decades have led to concerns about anoxia and anoxic sediment's tendency to release some metals to the overlying water. Anoxic sediments in the Baltic proper have been shown to have increased contaminant loads of Cadmium and Zinc (Borg and Jonsson, 1996), and Mercury concentrations up to 25 pM have been measured in anoxic deep waters (Pempkowiak *et al.*, 1998). Some metals (Iron, Manganese, and Cobalt, for example) will precipitate in oxygenated waters, but will dissolve into the overlying water under anoxic conditions (Sundby *et al.*, 1986).

Offshore wind farms could interact with the metal distribution in the Baltic Sea by altering the depositional environment and causing resuspension. Potential impacts range from the transport of metal-contaminated sediments to the release of metals from sediments into the overlying water.

Obstruction of oxygenated deep water inflows into the Baltic Sea could also cause more hypoxia and anoxia in the deep Baltic, which would result in further release of metals to the overlying water.

9.5 – Micropollutants

Persistent organic pollutants (POPs) are of global concern, particularly in marine environments. There are twelve general categories of POPs (Aldrin, Chlordane, Dieldrin, Endrin, Heptachlor, Hexachlorobenzene, Mirex, Toxaphene, Polychlorinated biphenyls, DDT, Dioxins, and Polychlorinated dibenzofurans), which together amount to thousands of organic pollutants. Only a fractional number of POPs are known, and even fewer have been studied. POPs are of concern because their long half-lives combined with volatility at environmental temperatures result in their atmospheric transport over global distances (Jones and de Voogt, 1999). In addition, they are hydrophobic, resistant to metabolism, and lipophilic, resulting in bioaccumulation that mostly affects top predators (including sea mammals and humans) (Jones and de Voogt, 1999). POPs enter the aquatic environment through direct spills, surface water run-off, or atmospheric deposition (whether through molecular diffusion, dry deposition, or wet deposition) (Dachs and Méjanelle, 2010).

(Jones and de Voogt (1999); Dachs and Mejanelle (2010))

Sediments can sequester POPs and support higher concentrations than the overlying water column. Through resuspension POPs can be made available for reintroduction to the atmosphere (O’Driscoll *et al.*, 2013). It is therefore important to understand the role of OWFs in sediment suspension, particularly in regions where POPs may be present. Turbulent vertical diffusion may also be critical to vertical POP distribution (Jurado *et al.*, 2007). Turbulence acts together with other internal processes such as degradation and sedimentation to create a vertical concentration pattern in which surface waters and benthic layers are enriched with POPs while mid-depth waters are depleted. Surface waters are influenced mostly by atmospheric deposition: the depth of influence also depends on internal turbulence. Science agrees that underwater piles will cause turbulence, which logically implies that they could affect vertical POP distribution. To understand the effect of an OWF on vertical POP distribution, it is necessary to understand what the cumulative effect of many underwater piles on turbulence will be as well as the background POP conditions.

9.5.1 North Sea

Sediments in the North Sea are moderately polluted near the Elbe with PCBs (polychlorinated dibenzofurans), and PAHs (polycyclic aromatic hydrocarbons) while un-polluted offshore (Chapman, 1992). In addition, low concentrations of (xeno-)estrogens are present in marine waters off the coast of the Netherlands (Vethaak *et al.*, 2005), and high concentrations (up to 8 times background levels) of nonylphenols have been found in the Elbe estuary and German Bight (Bester *et al.*, 2001). Everaarts and Fischer’s (1986) findings supported these results on a regional scale: they divided the North Sea into three regions according to PCB concentrations (North, Central, and South), and found that PCB concentrations increased from north to south.

Some POPs are likely to have higher concentrations in the southern North Sea due to the close proximity to the industrialized countries of Europe and river input. General trends such as this will be helpful in risk assessments, but they should not be regarded as proof that a particular region will be free of pollution. Given the vast number of possible POP contaminants and the monetary and time-related limitations to field sampling, pollution assessments cannot be 100% certain. In addition, POP cycling in the North Sea is influenced not only by sediment dynamics (Ilyiana, 2011) but also by hydrodynamic processes such as currents (Ilyiana, 2011; O’Driscoll *et al.*, 2013) and turbulence (Section 9.5), both of which may interact with offshore wind farms (Sections 3.1 and 6.1.1).

Therefore, POPs remain a relevant topic in the discussion of the effects of OWFs on sediment and turbulence.

9.5.2 Baltic Sea

Similar to the North Sea, micro contaminant concentrations in the Baltic Sea seem to be highest in the South and near river estuaries. Witt and Trost (1999) found elevated PAH levels in sediment of the Belt Sea and Arkona Sea., and later measured higher PAH concentrations in estuarine samples and hot spots in the Western Baltic (Witt, 2002). Jonsson (2000) observed that PCB sediment concentrations increased from north to south in the Baltic and had not decreased in recent decades, despite new regulations to control the release of POPs. This would imply that river input is an important source of POPs to the Baltic and should be considered when choosing OWF sites, so as to avoid sediments with the highest POP concentrations.

In contrast, Strandberg *et al.* (1998) found that organochlorine levels in offshore suspended particulate matter (SPM) were up to 10 times higher than in coastal SPM. These contrasting findings are likely because of focuses on different compounds. While persistent organic pollutants can be generalized into twelve categories, the compounds within each category undergo different cycles according to their water solubility, sediment adsorption, and volatility (Jonsson, 2000), as well as the relationship between ecological and physiochemical processes in a region (Hedman *et al.*, 2008). The results of these studies, while informative, should therefore not be generalized to all POPs. Offshore windfarm research will be the most successful through the coordination of chemical oceanography, physical oceanography, and biogeochemical oceanography, especially with regards to issues such as persistent organic pollutants.

10 Gaps and Recommendations

The major conclusions from this review are that site-specific background conditions as well as the number and layout of piles affect the size of the wind farm’s impact. The size and complexity of a wind farm’s impact tend to increase with the number of turbines, but potential changes of the current construction scale (up to 80 turbines) are likely to be negligible. These conclusions do not extend to very large-scale construction (hundreds of turbines and dozens of wind farms), however. Uncertainties arising from site-specific conditions, modelling assumptions, and lack of precedence have caused predictions for the impact of large-scale construction to vary from “negligible” to “irreversible”.

The largest gaps in present knowledge of offshore wind farms relate to the scale of future construction: this review did not find any studies that examined the interaction of multiple large-scale wind farms, and only one review that examined a wind farm with hundreds of turbines (Rennau et al. 2012). Some phenomena, such as downwind turbulence, even lack research about the combined effect of multiple piles. Few studies have predicted far-field effects of OWFs, and fewer studies have predicted the far-field effects of very large OWFs. In addition, most OWFs are either in the planning stages or under construction, making observational studies scarce. Yet because so many processes are site-specific, only observational studies can give accurate assessments of the impact of large OWFs. Future model studies should increase their scope to make accurate predictions, and observational studies are necessary to validate model results.

According to existing knowledge, the processes with the largest potential for change are surface wave energy and Baltic inflows. These processes are also connected to many potential impacts and should be extensively studied. Changes to sediment dynamics are less likely, but because of the important role that sediment plays in nutrient dynamics, turbidity, light attenuation, and consequently the ecosystem, changes to sediment cannot be ignored.

Future research must model the effects of large-scale construction using parameters that are as site-specific as possible. Observational studies before, during and after construction are necessary to validate model results, and extensive background data collection will provide an undisturbed state with which to compare changes. This research will then better inform all concerned parties, from fishers to oceanographers, politicians, and developers, and can be applied to other shelf seas with wind farm construction plans.

Table 4 - A summary of existing research. OWF = OWF; "large construction" refers to an OWF with more than 100 turbines

	Observational; One OWF	Observational; Large construction	Model; One OWF	Model; Large construction
Internal Disturbances	1		3	3
Surface Wave Energy			6	
Currents and Inflows			7	3
Sediment Dynamics	6		1	
Upwelling and Downwelling			2	

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