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# On the Effect of Offshore Wind Farms on the Atmosphere and Ocean Dynamics

 Springer

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*“Die Welle beugt sich jedem Winde gern.”*  
*Johann Wolfgang von Goethe, Faust II,*  
*Vers7853/Thales*



# Preamble

The study of the effects of renewable energies on the earth system is quite new and asks for analysis. Especially the renewable energy wind plays a key role in Europe, and so I was very glad to work within that field of research during my dissertation. This book comprises the results of my dissertation, which was created and supported at the University of Hamburg and by the International Max Planck Research for Maritime Affairs (IMPRS-MA).

At this point, I want to use the chance to register some attendants supporting me and my work in the 32 months of my dissertation's progress.

Primarily, I have to thank my first adviser and tutor PD Dr. Thomas Pohlmann for his collaboration, for his offer of the scholarship at the *International Max Planck Research School for Maritime Affairs*, and especially for his professional support.

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A thank goes also to the department of Informatics Scientific Computing of Hamburg University, especially H. Lenhart, for their interest in my work. I am really curious and looking forward to the simulations considering the OWF effect on the North Sea's ecosystem.

Last but not least, I want to mention my family and want to thank them for supporting my academic studies, my conference, and summer school trips, and you are always open to me.

Hamburg, Germany  
May 2014

Elke Ludewig



# Abstract

Nowadays, renewable energy resources play a key role in the energy supply discussion, and especially a heightened interest in wind energy induces intensified installation of wind farms. In the course of a larger demand of renewable energy, offshore wind farms (OWFs) gain increasingly in popularity since over-sea yields are larger and more reliable than over land. In this context, Germany adopts the position of a pioneering nation due to its national interurban offshore wind energy program comprising an intensified construction of wind turbines in the Baltic Sea and, mainly, North Sea. Against this background, it becomes particularly urgent to inquire whether and to what extent such OWF expansion affects our oceans and local climates.

OWFs excite wind speed reduction downstream of wind farms, the so-called wake effect, which impacts the atmosphere's boundary layer; locally disturbs the wind characteristics; and in turn affects ocean dynamics. To study the whole complex in more detail, investigations comprise *model simulations and measurements*. Used models are the atmosphere model *METRAS* (*ME*soscale *TR*ansport and *Stream* model) and the ocean model *HAMSOM* (*HAM*burg *Shelf Ocean Model*). *METRAS* simulations were generated in collaboration with and by courtesy of the Institute for Meteorological of the University of Hamburg. These *METRAS* data represent the meteorological forcing for simulations of the ocean. Measurements were taken around German test wind farm *alpha ventus* supported by the German Federal Maritime Service (BSH).

Analysis regarding OWF effect on the atmosphere and ocean comprises two main studies to determine possible OWF effects and their physical appearance in theory and to estimate possible future integrated changes of the North Sea's marine system based on the offshore construction plan for 2030. Investigations consider different amounts of wind turbines, wind speeds and directions, ocean depths, and forcing assumptions. Model results and measurements show a reasonable agreement supporting the principle validity of the used model approach.

Main results of this study show significant dynamical changes, including a *wind speed reduction* downstream of OWF up to 70 % over an area being 100 times larger than OWF itself, an evolving *dipole structure of the sea surface elevation*

around OWFs, and *up- and downwelling cells* with a horizontal extension of approximately  $30 \times 30$  km, spanning the whole ocean depth. The connected vertical velocities reach magnitudes of 3–4 m/day. In turn, these vertical motions introduce changes in stratification of temperature and salinity, which results in a maximal *excursion of the thermocline* by possibly 10 m. Hence, it can be concluded that offshore wind farms cause an intensified vertical mixing in the ocean, which may result in a fundamental change of the North Sea's ecosystem.

# Zusammenfassung

Heutzutage spielen erneuerbare Energien eine Schlüsselrolle in der Diskussion zukünftiger Energieversorgung. Besonders ein verstärktes Interesse an Windenergie bewirkt einen intensiven Ausbau von Windfarmen. Im Zuge der erhöhten Nachfrage an erneuerbaren Energien gewinnen Offshore Windfarmen (OWFs) vermehrt an Popularität, zumal auf See größere und vor allem zuverlässig Erträge erzielt werden können. In diesem Zusammenhang nimmt Deutschland, infolge des nationalen Offshore Windenergieausbauprogramm, welches eine intensive Errichtung von Windkraftanlagen in der Ostsee und besonders in der Nordsee beinhaltet, eine Vorreiterrolle ein. Vor diesem Hintergrund ist es sehr bedeutsam abschätzen zu können, ob und in welchem Ausmaß ein solcher offshore Windfarmausbau unsere Meere und lokale Klima beeinflusst.

OWFs bewirken eine Reduktion der Windgeschwindigkeit in Windrichtung hinter der Windfarm. Diese Reduktion der Windgeschwindigkeit wird als Wake-Effekt bezeichnet. Der Wake-Effekt beeinflusst die atmosphärische Grenzschicht und lokal die Windeigenschaften, was wiederum Auswirkungen auf die Ozeandynamik zur Folge hat. Um den ganzen komplexen Sachverhalt der OWF Auswirkungen zu erfassen, wurden *Modellsimulationen und Messungen* für die Analyse herangezogen. Bei den verwendeten Modellen handelt es sich um das atmosphärische Modell *METRAS* (*ME*soskaliges *TR*ansport und *Strömungsmodell*) und das Ozeanmodell *HAMSOM* (*H*amburg *S*chelfmeer/*O*zean *M*odell). Simulationen mit METRAS wurden in Zusammenarbeit mit dem Meteorologischen Institut der Universität Hamburg erstellt und freundlicherweise dieser Arbeit zur Verfügung gestellt. Diese mit METRAS simulierten Daten dienen als meteorologischen Antrieb der Ozeansimulationen. Messungen wurden rund um den deutschen Testwindpark alpha ventus genommen. Die Messkampagne wurde vom Bundesamt für Schifffahrt und Hydrographie (BSH) unterstützt.

Analysen des OWF-Effekts auf Atmosphäre und Ozean umfassen zwei Hauptstudien, um den möglichen OWF-Einfluss und dessen physikalisches Auftreten theoretisch zu erfassen und mögliche Änderungen des marinen Systems der Nordsee bedingt durch den geplanten Offshore Ausbauplan für 2030. Untersuchungen berücksichtigen verschiedene Mengen und Anordnungen von

Windturbinen, Windgeschwindigkeiten und Modellantrieben. Modellergebnisse und Messungen zeigen eine angemessene Übereinstimmung, die den gewählten Modellansatz und prinzipielle Annahmen bestätigen.

Hauptergebnisse dieser Arbeit bezeugen signifikante dynamische Änderungen, zum einen in Bezug auf das Windfeld mit einer Reduzierung der Windgeschwindigkeit über ein Gebiet, welches hundertmal größer ist als die Windfarmfläche, bis 70 % und zum anderen in Bezug auf den Ozean durch das Auftreten von Wasserstandsänderung mit Dipolstruktur, Up- und Downwellingzellen mit einer horizontalen Ausdehnung von rund  $30 \times 30$  Kilometer über die ganze Meerestiefe. Die damit verknüpften vertikalen Geschwindigkeiten erreichen drei bis vier Meter pro Tag und bewirken eine Änderung in der Ozeanschichtung von Temperatur und Salzgehalt mit einer Auslenkung der Thermoklinen um 10 m rund um den OWF. Daher muss man davon ausgehen, dass OWFs intensives vertikales Mischen verursachen, welches eventuell Änderungen im Ökosystem der Nordsee bewirkt.

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# Abbreviations

## Variables

|           |                                      |
|-----------|--------------------------------------|
| $\zeta$   | Surface elevation [m]                |
| gwind     | Geostrophic wind                     |
| $p$       | Pressure [Pa]                        |
| SST       | Sea surface temperature [°C]         |
| ug        | Geostrophic wind [m/s]               |
| uv10      | Horizontal wind field in 10 m [m/s]  |
| velc. $u$ | Ocean's velocity component $u$ [m/s] |
| velc. $v$ | Ocean's velocity component $v$ [m/s] |
| velc. $w$ | Ocean's velocity component $w$ [m/s] |
| velh      | Ocean's horizontal velocity field    |

## Abbreviations in Analysis

|      |  |
|------|--|
| BTM  | HAMSOM simulations in barotropic mode                    |
| F*   | Forcing fields (F01, F02, F03, F04)                      |
| HD*  | Depth of ocean (HD60, HD30) [m]                          |
| OWF  | Offshore wind farm                                       |
| OWFr | Simulations considering wind turbines                    |
| REFr | Reference without wind turbines                          |
| src* | Source code manipulation                                 |
| T*   | Wind turbine number (T012, T048, T080, T160, T8590) [#]  |
| TOS  | Type of simulation (TOS-01, TOS-2)                       |
| TS*  | Temperature and salinity (TS01, TS02, TS03)              |
| UG*  | Prescribed geostrophic wind speed (UG5, UG8, UG16) [m/s] |
| wd*  | Wind direction (N, NE, E, SE, S, SW, W, NW, N) [°]       |

## **Model and Data**

|        |  |
|--------|--|
| ADCP   | Acoustic Doppler Current Profiler                  |
| CTD    | Conductivity–Temperature–Depth                     |
| ECMWF  | European Centre for Medium-Range Weather Forecasts |
| HAMSOM | Hamburg Shelf Ocean Model                          |
| METRAS | Mesoscale transport and stream model               |
| NOAA   | National Oceanic and Atmospheric Administration    |
| WOA    | World Ocean Atlas                                  |

## **Institutions and Additional**

|       |   |
|-------|---|
| BMU   | Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit |
| BMWi  | Bundesministerium für Wirtschaft und Technologie                |
| BSH   | Federal Maritime and Hydrographic Agency                        |
| BWE   | Bundesverband Wind Energie                                      |
| dena  | Deutsche Energie-Agentur GmbH                                   |
| EEZ   | Exclusive economic zone   |
| IMPRS | International Max Planck Research School                        |