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

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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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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
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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 *ST*ream model) and the ocean model *HAMSOM* (*HAM*burg *SH*elf *O*cean *M*odel). *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 30×30 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* (*Hamb*urg *Schelfmeer/Ozean Modell*). 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 30×30 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.

Contents

1	Introduction	1
	References	4
2	Renewable Energy Wind	7
2.1	Utilization of Wind Energy: Historical and Technical Background	7
2.1.1	Today’s Wind Turbines	8
2.2	Wind Farming in the North Sea: Example Germany	10
2.2.1	The North Sea	10
2.2.2	Germany’s Exclusive Economic Zone (EEZ)	11
2.2.3	Wind Farm Alpha Ventus	12
	References	14
3	Models, Data, and Methodology	15
3.1	Models	15
3.1.1	Hamburg Shelf Ocean Model	15
3.1.2	Mesoscale Transport and Stream Model	16
3.2	Data	18
3.2.1	Climatological and Reanalysis Data	18
3.2.2	Measurements	19
3.3	Methodology	19
3.3.1	Model Box Simulations: TOS-01	20
3.3.2	North Sea Simulations: TOS-02	27
	References	32
4	Analysis 01: OWF Effect on the Atmosphere	35
4.1	Observed Effects	35
4.2	Modeled Effects	36
4.2.1	Mesoscale 01: Broström	36
4.2.2	Mesoscale 02: METRAS	39
	References	50

5	Analysis 02: OWF Effect on the Ocean	51
5.1	Common Description of the Impact on the Ocean	51
5.1.1	Moment Analysis of OWF Effect on Ocean	52
5.1.2	Temporal Analysis of OWF Effect on the Ocean	56
5.2	Theoretical Analysis of Rising OWF Effect on the Ocean	62
5.2.1	Analysis of Dynamical Pattern Under Barotropic Conditions	64
5.2.2	Analysis of Vertical and Horizontal Exchanges	68
5.2.3	Assessment and Integration of Effect Analysis	79
5.3	Analyzing OWF's Effect on the Ocean Under Various Assumptions	81
5.3.1	Analyzing Consistency of OWF Effect on Ocean	81
5.3.2	Analyzing OWF Effect on the Ocean Depending on Wind Speed	87
5.3.3	Analyzing OWF Effect on the Ocean Depending on Wind Park Power	94
5.3.4	Analyzing OWF Effect on the Ocean due to Wind Forcing Based on the Broström Approach	100
5.3.5	Analyzing OWF Effect on the Ocean in Case of Full Meteorological Forcing	105
5.3.6	Analyzing OWF Effect on the Ocean Depending on the Depth of the Ocean	110
5.4	Evaluation of Modeled OWF Effect on the Ocean	114
	References	124
6	Analysis 03: Future Scenario—OWF Development Within German EEZ	127
6.1	Case Study I: Estimation of OWF's Impact by different Wind Directions	128
6.1.1	Effect on the Atmosphere Over the German EEZ Based on Case Study I	128
6.1.2	Effect on the Ocean in the German EEZ Based on Case Study I	132
6.2	Case Study II: OWF's Impact Based on a Real Meteorological Situation	140
6.2.1	Effect on the Atmosphere Based on Case Study II	141
6.2.2	Effect on the German Bight Based on Case Study II	143
	References	144
7	Summary, Conclusion, and Outlook	145
8	Appendix I: List of Data and Personal Correspondences	149
8.1	Personal Correspondence	149
8.2	Data Overview	149

- 9 Appendix II: Addition to WEGA Cruise and Result Presentation . . . 151**
 - 9.1 WEGA Cruise 141 151
 - 9.1.1 Impressions of WEGA Cruise 141 151
 - 9.1.2 CTD Probe 151
 - 9.1.3 ADCP 154
 - 9.2 Comment on Result Presentation 157
- About the International Max Planck Research School for Maritime Affairs at the University of Hamburg 161**

Abbreviations

Variables

ζ	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