

QUANTIFICATION OF WATER MASS TRANSFORMATIONS  
IN THE ARKONA SEA – IMPACT OF OFFSHORE WIND FARMS

QUANTAS-OFF

Final Report

Authors:

Hans Burchard<sup>1</sup>, Alfred Leder<sup>2</sup>, Mark Markofsky<sup>3</sup>,  
Richard Hofmeister<sup>1</sup>, Frank Hüttmann<sup>2</sup>, Hans Ulrich Lass<sup>1</sup>,  
Jan-Erik Melskotte<sup>2</sup>, Peter Menzel<sup>1,2</sup>, Volker Mohrholz<sup>1</sup>,  
Hannes Rennau<sup>1</sup>, Stefan Schimmels<sup>3</sup>,  
Artur Szewczyk<sup>1</sup>, and Lars Umlauf<sup>1</sup>

1. Leibniz Institute for Baltic Sea Research Institute Warnemünde  
at the University of Rostock
2. Chair of Fluid Mechanics, University of Rostock
3. Institut of Fluid Mechanics and Environmental Physics in Civil  
Engineering, Leibniz Universität Hannover

Warnemünde, Rostock & Hannover, June 2010



Federal Ministry for the  
Environment, Nature Conservation  
and Nuclear Safety

The project onto which this report is based has been funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety under project reference numbers 0329957, 0329957A and 0329957B. The authors are responsible for the contents of this publication.

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Baltic inflow events and their ecological role . . . . .	1
1.2	Offshore wind farms in the Western Baltic Sea . . . . .	6
1.3	Objectives of the QuantAS projects . . . . .	6
1.3.1	QuantAS consortium . . . . .	6
1.3.2	Social Impact . . . . .	10
1.3.3	The Fehmarn Belt project: a spin-off from QuantAS-Off . .	10
1.3.4	QuantAS-Off key questions . . . . .	11
1.3.5	Description of Workpackages . . . . .	12
1.4	Oceanographic methods . . . . .	16
1.4.1	Observational methods . . . . .	16
1.4.1.1	CTD measurements . . . . .	16
1.4.1.2	ADCP measurements . . . . .	21
1.4.1.3	MSS measurements . . . . .	24
1.4.1.4	Moorings . . . . .	25
1.4.1.5	Cruises . . . . .	26
1.4.2	Numerical model . . . . .	27
<b>2</b>	<b>Results for natural mixing (IOW)</b>	<b>29</b>
2.1	Field observations . . . . .	29
2.1.1	Detection of medium-intensity inflow events by field observation.	29
2.1.2	Spatio-temporal evolution of the dense bottom currents. . .	32
2.1.3	Direct observation of the dense bottom currents in the Arkona Basin and Bornholm Channel. . . . .	34
2.1.4	Analysis of transverse structure of the dense bottom currents	38
2.2	Numerical modelling . . . . .	42
2.2.1	Idealised modelling of the medium-intensity inflow events . .	42
2.2.2	Realistic modelling of the medium-intensity inflow events . .	44
2.2.3	High-resolution modelling of transverse structure of channelised dense bottom currents . . . . .	48
2.2.4	Numerical study of physical and numerical mixing . . . . .	50

2.2.4.1	Physically induced variance decay as measure for mixing . . . . .	51
2.2.4.2	Diagnosing numerically induced variance decay . . . . .	51
2.2.5	Vertically integrated and time-averaged estimate of numerical mixing . . . . .	53
2.3	Major conclusion from natural mixing studies . . . . .	56
<b>3</b>	<b>Estimation of mixing due to structures</b>	<b>57</b>
3.1	Laboratory experiments (UNI-HRO) . . . . .	57
3.1.1	Special definitions for quantification of mixing . . . . .	57
3.1.1.1	Entrainment . . . . .	57
3.1.1.2	Mixing number . . . . .	58
3.1.1.3	Mixing Efficiency . . . . .	60
3.1.2	Experimental Setup . . . . .	60
3.1.2.1	Water channel . . . . .	61
3.1.2.1.1	Specification . . . . .	61
3.1.2.1.2	Optimisation . . . . .	62
3.1.2.2	Traversing System . . . . .	64
3.1.2.3	Measuring System . . . . .	65
3.1.2.3.1	Basics on PIV . . . . .	65
3.1.2.3.2	Basics on LIF . . . . .	69
3.1.3	Experiments . . . . .	70
3.1.3.1	Measurements with velocity profile 1 . . . . .	70
3.1.3.2	Measurements with velocity profile 2 . . . . .	73
3.1.4	Results . . . . .	74
3.1.5	Flow visualisation . . . . .	74
3.1.5.1	Measurements with velocity profile 1 . . . . .	76
3.1.5.1.1	Mixing quantities in the far field behind the cylinder . . . . .	77
3.1.5.1.2	Mixing quantities in the near wake of the cylinder . . . . .	77
3.1.5.1.3	Flow structure in the wake of the cylinder . . . . .	78
3.1.5.2	Influence of the velocity profile on mixing . . . . .	85
3.1.5.2.1	Mixing quantities in the far field behind the cylinder . . . . .	85
3.1.5.2.2	Mixing quantities in the near wake of the cylinder . . . . .	87
3.1.5.3	Influence of the densimetric Froude number on mixing . . . . .	93
3.1.6	Numerical Simulation (UNI-HRO) . . . . .	95
3.1.6.1	QuantAS-Off: Large Eddy Simulation of the laboratory experiment . . . . .	95

3.1.6.2	Large Eddy Simulation . . . . .	96
3.1.6.3	Computational Model . . . . .	98
3.1.6.4	Results . . . . .	99
3.2	Near-field numerical modelling (UNI-HAN) . . . . .	109
3.2.1	Project goals . . . . .	109
3.2.2	Model setup . . . . .	109
3.2.3	Non-stratified flow around a circular cylinder . . . . .	113
3.2.4	Natural density current . . . . .	120
3.2.5	Comparison of different turbulence models . . . . .	122
3.2.6	Entrainment induced by a circular cylinder . . . . .	135
3.2.6.1	Structurally induced mixing without Coriolis forces	139
3.2.6.2	Case of reference: Entrainment induced by a circular cylinder without Coriolis forces . . . . .	140
3.2.7	Parameter Study . . . . .	147
3.2.8	Entrainment Induced by a Circular Cylinder with Coriolis Forces . . . . .	151
3.2.9	Total Entrainment . . . . .	157
3.3	Small-scale in-situ observations (IOW) . . . . .	164
3.3.1	Methods . . . . .	167
3.3.2	The hydrodynamic environment of the bridge . . . . .	168
3.3.2.1	Stratification . . . . .	168
3.3.2.2	Currents . . . . .	170
3.3.3	The wake of a bridge pylon . . . . .	171
3.3.3.1	Eddy streets . . . . .	173
3.3.3.2	Enhanced mixing in the wakes of the bridge pylons	176
3.3.4	Dissipation of turbulent kinetic energy . . . . .	183
3.3.5	Impact of mixing on the baroclinic mean current . . . . .	187
3.3.6	Conclusions . . . . .	189
<b>4</b>	<b>Impact of offshore wind farms on inflows into the Baltic Sea (IOW)</b>	<b>190</b>
4.1	Introduction . . . . .	190
4.2	Parameterisation of structure friction in density-driven bottom currents	193
4.2.1	Model equations . . . . .	193
4.2.2	Structure mixing parameterisation . . . . .	195
4.2.3	RANS model simulations . . . . .	196
4.2.4	Calibration . . . . .	200
4.3	Methods . . . . .	204
4.3.1	Numerical model . . . . .	204
4.3.2	Physical and numerical mixing analysis . . . . .	204
4.4	Impact of parameterisation in idealised 2D and 3D hydrostatic model setups . . . . .	205