Fachbereich Mathematik/Informatik

Marine Litter in the North Sea - Transport Modelling for Identification of Source and Receptor Regions

Mariner Müll in der Nordsee - Transportmodellierung zur Identifikation von Quell- und Zielregionen

Masterarbeit
Umweltsysteme und Ressourcenmanagement

Bearbeiter: Daniel Neumann

Betreuer: Prof. Dr. Michael Matthies
Universität Osnabrück, Fachbereich Mathematik/Informatik
Dr. Ulrich Callies
Helmholtz-Zentrum Geesthacht, Institut für Küstenforschung

Abgabedatum: 07. August 2012

Abstract

The continuous input of marine litter, in particular plastic debris, poses a serious threat to marine and coastal environments due to slow decomposition and associated long residence times at sea. Plastic fragments with diameter down to the micro scale are found in stomachs of fishes, seals and seabirds. In the frame of the EU Marine Strategy Framework Directive (MSFD) concepts for litter monitoring and reduction have to be proposed and implemented for achieving a good environmental status till 2020.

In the first part of this thesis, Lagrangian passive tracer simulations are conducted to model the transport of marine litter observed during ship-based surveys. A set of marine debris observations obtained between summer 2006 and summer 2008 in the German Bight represents the input for a two-dimensional particle tracking algorithm calculating 80-day backward trajectories based on hourly surface current and wind fields available from Bundesamt für Seeschifffahrt und Hydrographie (BSH) and the Deutscher Wetterdienst (DWD), respectively. The resulting particle trajectories are analysed focussing on possible marine litter source locations, on the spatio-temporal variability in the litter origin and the benefit of ship-based surveys of the sea surface. The outcomes show that exact predictions of litter source locations is not possible. However, specifying rough directions of litter origin or even better identifying likely non-source locations is possible. If by the EU Marine Strategy Framework Directive (MSFD) the realisation of ship-based surveys should be demanded in future, these surveys should be performed periodic and frequently in the western and south-western German Bight for achieving good comparable litter data.

In the second part the long-range transport and accumulation of marine litter in the southern North Sea are modelled by calculation half-a-year forward trajectories. Areas of high ship density and river estuaries are assumed to be source regions of litter. The ensemble simulations are evaluated with respect to the spatio-temporal variability in particle transport, abundance and residence times at coast lines and at the open sea. The aim is to estimate differences in the origin of litter at regularly monitored German beaches. The results suggest that the majority of items affected by wind drift as a plastic bottle swimming atop the sea surface is transported nearshore with a high probability of being washed ashore. Land-based litter in particular affects coastal regions close to its sources. In contrast, sea-based submerged litter not exposed to winds often remains at considerable distance to the coast. Seasonal trends in the pollution of monitored beaches by marine litter can be expected according to these simulation results.

We conclude that ensemble simulations of weather-driven transport provide valuable information for the proper evaluation of operational marine litter monitoring.

Zusammenfassung

Der weiter andauernde Eintrag von Müll und insbesondere Plastikmüll ins Meer stellt, auf Grund seiner geringen Abbaurate und der daraus resultierenden hohen Aufenthaltszeit, ein ernstzunehmende Gefahr für die marine und küstennahe Umwelt dar. Plastikfragmente unterschiedlicher Größe wurden und werden in Fischen, Seehunden und Seevögeln gefunden. Im Rahmen der Umsetzung der Meeresstrategie-Rahmenrichtlinie (MSRL) sollen Konzepte zum Monitoring und zur Senkung von marinem Müll vorgeschlagen und umgesetzt werden. Das Ziel ist, einen guten Umweltzustand (GES) bis 2020 zu erreichen.

Im ersten Teil dieser Arbeit, wird der Transport von schwimmendem Müll auf der Meeresoberfläche mit einer Lagrangen Teilchendriftsimulation berechnet. Die Grundlage für diese Simulationen bilden Müllzählungen, die zwischen Sommer 2006 und Sommer 2008 von Bord eines Forschungsschiffes aus in der Deutschen Bucht durchgeführt wurden. Zu jeder Beobachtung werden anhand eines Transportalgorithmus Teilchentrajektorien 80 Tage in die Vergangenheit zurück gerechnet. Hierfür werden vom Bundesamt für Seeschifffahrt und Hydrographie (BSH) berechnete Oberflächenströmungen und Winddaten des Deutschen Wetterdienstes (DWD) verwandt. Bei der Auswertung der Simulationsergebnisse wird ein besonderes Augenmerk auf die Identifikation möglicher Müllquellen, auf die räumliche und zeitliche Variabilität im Teilchentransport und eine erste Bewertung von schiffsgebundenen Müllbeobachtungen gelegt. Es zeigt sich, dass eine genaue Angabe von Quellregionen nicht möglich ist. Allerdings können Quellrichtungen und vor allem nicht-Quellgebiete ausgegeben werden. Wenn man sich im Rahmen der Umsetzung der MSRL für schiffsgebundenen Müllzählungen entscheiden sollte, sollten diese Zählungen regelmäßig mit kurzen Periodenlängen in der westlichen oder südwestlichen Deutschen Bucht durchgeführt werden, um brauchbare Ergebnisse zu erzielen.

Im zweiten Teil steht Langstreckentransport und Akkumulation von marinem Müll in der südlichen Nordsee im Mittelpunkt. Dabei wird ausgehend von Schifffahrtsrouten und Flüssen als Quellen, der Mülltransport für ein halbes Jahr vorwärts berechnet. Dabei werden die Simulationen insbesondere in Hinblick auf räumliche und zeitliche Variationen im Teilchentransport, in der Verteilung und der Aufenthaltszeit in Küstennähe ausgewertet. Ein Ziel ist es, Unterschiede in der Müllzusammensetzung an unterschiedlichen Stränden abzuschätzen. Müllteile, deren Transport mittel bis stark durch Wind beeinflusst wird, werden unabhängig ihrer Quellregion dicht an Küsten entlang getrieben. Daher ist die Wahrscheinlichkeit, dass solcher Müll an Strängen angespült wird, groß. Vom Festland stammender Müll belastet insbesondere die Küstenregionen nahe der Müllquelle wie Strände neben Flussmündungen. Hingegen halten Müllteilte, die auf hoher See ins Wasser gelangen und deren Transport nur gering vom Wind beeinflusst wird, oft einen deutlichen Abstand zur Küste. Nach den Simulationsergebnissen kann man davon ausgehen, dass die Müllbelastung und zusammensetzung an Stränden saisonalen Schwankungen ausgesetzt ist.

Wir schlussfolgern, dass Vielteilchen-Transportsimulationen mit Wettereinfluss ein wichtiger Bestandteil der Auswertung eines operationellen marinen Müll-Monitorings sind.

Acknowledgement

The work on my Master's Thesis was primarily performed at the *Institute for Coastal Research* of the *Helmholtz-Zentrum Geesthacht*. A preparation phase took place at the *Institute for Environmental Systems Research* of the *University of Osnabrück*. Without the following people and organisations, which supported the preparation and the realisation of my work on the thesis in various ways, it would have been more difficult to organise or even impossible.

First of all, I want to thank Prof. Dr. Michael Matthies of the University of Osnabrück. He provided material for an enquiry on marine litter during my internship at the *Deutsche Bundesstiftung Umwelt* (DBU) and offered me a Master's thesis topic on this way. Besides several meetings for discussing the topic of marine litter in general and the progress of the thesis, he established the contact to Ulrich Callies and David Fleet and inviting me to on an UBA R&D project related to the implementation of the MSFD.

Dr. Ulrich Callies who is my second supervisor and head of department *Modelling for the Assessment of Coastal Systems* introduced me into *PELETS-2D*, answered many questions and was open to several discussions regarding the master's thesis. I appreciate his manner in which he expressed constructive criticism to some parts of the thesis.

David Fleet provided much background information on marine litter and offered a meeting for discussion about the topic of marine litter and about my master's thesis, which I gratefully accepted.

Another thanks goes to my colleagues in the departments *Modelling for the Assessment of Coastal Systems* and *Coastal Climate* at the HZG for pleasant coffee breaks and answering numerous questions to hydrodynamic models, North Sea topography and software, namely Dr. Frank-Detlef Bockelmann, Dr. Hartmut Kapitza, Dr. Jens Kappenberg, Dr. Jens Meywerk and Dr. Walter Puls.

Elena Aranovich, Alexandra Gorontzi and Hendrik Niemeyer proofread parts of the thesis and gave many constructive remarks.

Mathias Menninghaus, Sebastian Lotter and Philip Münch - all three students of the subject *Applied Systems Science* - handed me their thesis and project reports on topics related to mine, which promoted my work. Further they were open to enquiries and answered them gladly.

A very special thanks goes to my parents Hannelore and Dietrich Neumann who supported and encouraged me in various ways during the master's thesis and the time before.

Three organisations supported my project. Without the HZG a realisation of this work would not have been possible, providing models, computing infrastructure for my simulations, a desk and a good working environment, in general. Additionally, they offered an employment for the time of my thesis which I gratefully accepted. The Stiftung der Deutschen Wirtschaft (Foundation of German Business, sdw) granted a scholarship in November 2008 and supported me since then financially and ideally, indirectly funding my thesis. Concerning the sdw, special thanks goes to Girina Holland who is desk officer at the sdw and my contact person there. The University of Osnabrück did indirect support me by providing a workplace and a good working environment, too.

Finally, I thank Lars Gutow from the *Alfred Wegener Institute* (AWI), who provided ship-based observations of marine litter, und the *Bundesamt für Seeschifffahrt und Hydrographie* (BSH), which provided hydrodynamic currents, - both needed for my simulations.

Contents

1. Introduction

plastic.is.everywhere is the name rather unknown experimental band. Unfortunately, their name reflects the reality. In our history the oceans were seen as vast giant area which is endless in its capacity to store waste without letting it reappear again and without feedback on animals and humans. This, however, is not correct. Nowadays we realise marine litter and especially marine plastics have a negative effect on ecosystems and in the long run on human well-being. Gregory [2009] gives a good overview on that topic. Birds, seals and turtles entangle in fishing net fragments and plastic rings [Fowler, 1987]. Marine life forms and bird ingest plastic, which reduces their fitness and eventually leads to starvation [van Franeker, 1985, van Franeker et al., 2011b, Weiss, 2006]. Buoyant pieces of marine litter drifting over thousands of kilometres are a transport vector for invasive species [Barnes, 2002, Barnes and Fraser, 2003]. Abandoned fishing nets damage or destroy valuable habitats, such as coral reefs [Donohue et al., 2001, Dameron et al., 2007]. Ships are damaged by marine litter resulting in negative economic impact on fishermen and trading companies [Takehama, 1989, Nash, 1992, Hall, 2000, Mouat et al., 2010, McIlgorm et al., 2011] and injuries or even human deaths [Moore, 2008, p.]. Municipalities perform expensive beach clean-ups in order to present clean beaches to tourists [Hall, 2000, Mouat et al., 2010]. Litter abundance varies spatially and temporary. Much of the (partly uncoordinated) effort has been put in measuring or estimating abundance and composition of marine macro litter with different survey setups identifying considerable spatial and temporal variability [Fleet et al., 2003, OSPAR, 2007a, Barnes et al., 2009, Hinojosa et al., 2011]. Rees and Pond [1995], Velander and Mocogni [1999] and Ryan et al. [2009] present and compare some of these setups. The negative effect of micro-plastics, their abundance in the sea water and in the beach sand as well as survey setups and analytical laboratory procedures have been a topic of controversy among scientists. Cole et al. [2011] and Andrady [2011] present the current knowledge on origin, abundance and impact of micro-plastics.

Already in the late 1960s a small group of scientists, politicians and environmentalists recognised marine litter as a problem [Buchanan, 1971, Scott, 1972, 1975], but it kept a long time out of the focus of public interest. With the London Convention and MARPOL 73/78 (more details in the appendix A.1) governments agreed on the first international laws on marine pollution including plastic litter. In the 1980s Vauk and Schrey [1987] and Vauk and Vauk-Hentzelt [1991] performed the first marine litter surveys on a regular basis at German coasts: Every third day for marine litter from 22 March 1983 to 19 March 1984 a 60 m beach in the south-west of Helgoland was surveyed [Vauk and Schrey, 1987]. van Franeker [1985] started the first large-scale analysis on plastic litter in the stomach of fulmars (lat. fulmarus glacialis = dt. Eissturmvogel) which he is still working on today.

However, it was not until the beginning of the 21st century, that marine litter and especially marine plastics came into the focus of public interest and the mass media: movies, such as *Plastic Planet* and *Plastic Oceans* [Plastic Planet, 2009, Plastic Oceans, 2012], exhibitions (e.g. an exhibition of the Mellum Rat [Mellumrat, 2012] about plastic litter on beaches), News Paper and Magazines articles, such as Weiss [2006] in the L.A.Times and Stockinger [2012] in the Spiegel, TV documentaries as *ZDF plant e. - Müllhalde Meer* [Hermes, 2012], publications of environmental NGOs like Greenpeace [Allsopp et al., 2006], WWF [White, 2006] and NABU [Detloff and Ossenkop, 2010] and governmental organisations like UNEP [UNEP, 2009, 2011] to name some examples.

Regarding legislation, recently, in 2008, the EU Marine Strategy Framework Directive (MSFD, [European Union, 2008]) was adopted in order to achieve a **g**ood **e**nvironmental **s**tatus (GES) of the marine environment. Eleven descriptors outline the GES focussing on the marine ecosystem status and different types of marine pollution, including one descriptor (Descriptor 10) on marine litter. The GES is scheduled to be achieved by 2020, demanding from the EU member states amongst others to design and establish monitoring programmes by July 2012 and July 2014 in order to measure and determine the environmental status, the development and the implementation of programs of measures to restore the GES by 2015 and 2016, respectively. Currently, the member states have fallen behind in suggesting monitoring programmes.

Regarding marine litter monitoring in the German Bight, many surveys, that have been performed in the last three decades that lead to good basic knowledge considerably expended by the broad experience in monitoring other pollutants such as oil, radioactive elements, nutrients and toxic substances. Additionally, large amounts of monitoring raw data have been collected and can be found at different institutions. One important work, however, is still to be done - in the frame of the MSFD and in general. Namely, to gather this data, process it and examine which data sets are serviceable in order to identify *good* survey setups and adequate survey location yielding serviceable data. Particle transport simulations are powerful tools in processing such data and dealing with the following tasks:

- design of surveys and future monitoring concepts
- evaluation of existing survey setups and monitoring concepts
- identification of marine litter sources on the base of monitoring data
- estimation of litter composition in certain survey areas on the base of assumed marine litter sources
- identification of accumulation regions

For more than two decades particle transport simulations have been applied on different topics for instance on oil pollution and propagation of toxic chemicals in oceans. However, studies on the application of those simulations on marine litter were published just recently [Kako et al., 2011, Lebreton et al., 2012, Maximenko et al., 2012, Ebbesmeyer et al., 2012, Potemra, 2012, van der Molen et al., 2012, Maes and Nicolaus, 2012]. In this thesis the Lagrangian particle transport simulation *PELETS-2D* is employed to simulate current- and wind-driven transport of marine litter and to deal with some of the tasks mentioned above. It was developed and maintained at the Helmholtz-Zentrum Geesthacht (HZG) [Callies et al., 2011] with the aim to realise and evaluate particle ensemble simulations and to track single particles on hydrodynamic fields.

2. Material

2.1. Modelling

For more than two decades particle transport simulations have been applied on the surface drift of oil [Dick and Soetje, 1990, Chrastansky et al., 2009, Chrastansky and Callies, 2009, Liu et al., 2011], on the transport of chemicals [Taylor, 1987], heavy metals [Tappin et al., 1997], nutrients, radioactive isotopes [Hill et al., 1986, Schönfeld, 1995] and other suspended matter [Puls et al., 1997] in the water column and validation of hydrodynamic models [Breton and Salomon, 1995]. Several studies on the application of drift simulations on marine litter have been published [Kako et al., 2011, Lebreton et al., 2012, Maximenko et al., 2012, Ebbesmeyer et al., 2012, Potemra, 2012] and presented [van der Molen et al., 2012, Maes and Nicolaus, 2012], in the past years.

For the work in this thesis the Lagrangian particle transport model *PELETS-2D* is applied on marine litter transport. Lagrangian and Eulerian models have to be distinguished as they differ in the observer's frame of reference. In the Lagrangian model the observer is located on a fluid parcel or particle during its journey. In the Eulerian models the observer's location is fixed in space observing passing fluid parcels or particles. Measuring and modelling concentrations of chemicals at several locations relates to the Eulerian approach, while tracing one certain molecule independent of the knowledge of the other molecules relates to the Lagrangian one.

The particle drift (synonym: drift = transport) is induced by hydrodynamic and wind fields not calculated by *PELETS-2D*. It involves hourly pre-calculated currents from external sources. Hydrodynamic fields obtained by the models *TELEMAC-2D* (HIPOCAS data set), *TRIM*, *UnTRIM*, *BSHcmod* V3 and *BSHcmod* V4 are available at the HZG for simulations. The model used in this study is *BSHcmod* V3, which is briefly described in 2.1.2. The wind fields for simulations with wind drift are provided by the *Deutsche Wetterdienst* (DWD). *PELETS-2D* and the application of the wind drift are described in 2.1.1

Gästgifvars et al. [2008] gives a good overview of the history of ocean modelling.

2.1.1. PELETS-2D

P*rogram for* ***e****valuation of* ***L****agrangian* ***e****nsemble* ***t****ransport* ***s****imulations* in two dimensions (*PELETS-2D*) is a Lagrangian transport model that allows to perform and evaluate ensemble simulations, acquired by a set of several single stochastic-influenced simulations. The program needs the input of pre-calculated hydrodynamic and wind fields. In contrast, in some other models hydrodynamic and transport calculations are coupled. The decision for one of both setups depends on the model purpose and the available computational resources or rather time. Using pre-calculated fields reduces computing time, in situations which require repeated performance of simulations on the same spatial and temporal interval. Transported particles are only tracers and they do not interact with the ocean currents. Additionally, in hydrodynamic models, not to every computed time step ocean current data is written out which leads to jumpy current directions in some coastal regions. Coupled models do not have these disadvantages, but their major disadvantage is the increased computing time. The employment of surface currents obtained by high-frequency (HF) radar technology offers an alternative to hydrodynamic models [Abascal et al., 2012].

Menninghaus [2011] and Callies et al. [2011] compare *TELEMAC-2D*, *TRIM* (solely in [Callies et al., 2011]), *UnTRIM* and *BSHcmod* V3 using *PELETS-2D* ensemble simulations. In that comparison, non of the models neither is declared as the best one nor are errors in one of the models uncovered. Callies et al. [2011] describes considerable differences in the particle drift on different hydrodynamic fields pointing out that "*deposition, re-suspension or any other aspect of a substances fate*" [Callies et al., 2011] were neglected in their simulations for reducing complexity. Menninghaus [2011], however, would recommend *TELEMAC-2D* as hydrodynamic model for the use with *PELETS-2D*, if he had to choose one. Therefore, these studies help marginally in deciding on one of the offered hydrodynamic models. For the current data set employed in this study a certain frame is given: It has to provide surface currents of the years 2006 to 2008 and preferable of a longer period (see introduction to chapter 3 for reasons). Additionally, wind data should be part of the data set. Table 2.1 illustrates availability of different hydrodynamic data sets for years 1990 to 2012.

hydrodynamic models	1990	…	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	wind	comment
	year																	
TELEMAC-2D	■	■	■	■	■	■	■	■										
TRIM	■	■	■	■	■	■	■	■	■	■	■							
UnTRIM											■							
BSHcmod V3				■	■	■	■	■	■	■	■	■					■	
BSHcmod V4												■	■	■	■	■	■	

Table 2.1.: Availability of data set of different hydrodynamic models from 1990 to 2012. …

The *BSHcmod* V3 current data set is used as base for the simulations in chapters 3 and 4 fulfilling the stated requirements exclusively. Composite plots in sections 3.2, 4.1 and 4.2 cover the years 2000 to 2008, because *BSHcmod* V3 data is available for that period (see time-line in table 2.1). These currents, however, have the lowest spatial resolution. In subsection 2.1.2 the *BSHcmod* is presented more in detail.

In *PELETS-2D* particles are either drifted by ocean currents only or alternatively by ocean currents and wind forces. The *wind drift factor* w, which is an empirical value, scales the influence of the wind forces on the particle drift. It is declared as percentage or decimal number. Assume $\vec{d_h}(s,t)$ equals hydrodynamic surface currents and $\vec{d_w}(s,t)$ equals the wind 10 m above the sea surface at location s and time t. Then the forcing vector $\vec{d}(s,t)$ on a particle at location s and at time t calculates as follows:

$$\vec{d}(s,t) = \vec{d_h}(s,t) + w \cdot \vec{d_w}(s,t) \tag{2.1}$$

The wind drift factor of a buoyant item in a transport simulation strongly depends on the surface currents of the underlying hydrodynamic model. Three-dimensional hydrodynamic models consist of several discrete vertical layers having wind fields and the sea floor as upper and lower boundary conditions, respectively. The vertical parametrisation is chosen according to the model purpose leading to different thickness of the layers, including the surface layer. Depending on the depth of the surface layer the influence of the wind on this layer's hydrodynamic currents varies and, therefore, the value of the wind drift factor has to be adjusted: thicker surface layer ⇒ higher wind drift factor; thinner surface layer ⇒ lower wind drift factor. Dick and Soetje [1990] performed drift simulations of oil on *BSHcmod* V3 currents and suggest wind drift factors between 0.8 % and 5.8 %. Probably wind forces affect some marine litter items stronger than oil requiring wind drift factors above 6 %. Though, wind data 10 m above sea level is employed implying considerably weaker wind forces at the sea surface and wind drift factors below 50 %. Therefore, in section 3.1, simulations with up to 20 % wind drift are presented. Wind drift factors of 10 % and above, however, lead to particle trajectories looking similar to random walks. Thus, wind drift factors in simulations presented in section 3.2 and chapter 4 do not exceed 5 %.

Items observed at the surface of North Sea, do not drift there for ever but leave it by sinking, being washed ashore and drifting into neighbouring waters. *PELETS-2D* stops the transport of particles, if at least one of the three following cases occurs: *(a)* it (particle) leaves the model domain, *(b)* it is washed ashore or grounds and *(c)* it falls dry. Dry-falling does not equal grounding/ashore-washing. Dry-falling denotes an artificial placement of a particle on dry land occurring when this particle is drifted on unfavourable current data onto dry land caused by numerical inaccuracy. Grounding indicates the natural process of washing particle on beaches. The model domain denotes the region within which particles are drifted. *PELETS-2D* theoretically does not restrict this region. Usually hydrodynamic and wind data sets, however, do not contain data for each location on the world but only for certain regions. In table 2.2 spatial boundaries of the *BSHcmod* V3 are noted defining the model domain. If a particles exceeds one of these boundaries and leaves the model domain, it is stopped automatically.

Drift simulations are always afflicted with errors resulting from *(a)* spatial and temporal discretisation, *(b)* the inaccuracy of modelled wind and hydrodynamic data and *(c)* small-scale phenomenons in the real ocean currents - not to mention human impacts as the influence of ships on local drift vectors. Single deviations during the transport process of particles sum up to large errors. Resulting, not even one week of backward predictions is reliable with respect to the real trajectories of buoyant items [Rixen and Ferreira-Coelho, 2007, Vandenbulcke et al., 2009, Abascal et al., 2012]. The situation is comparable to the weather forecast. During one week, however, a particle is not drifted far enough for this studies purpose. Simulations over 80 days (80 days = 1920 hours) are a good trade-off between accuracy on the one hand side and meaningful trajectory length on the other one. Hence, trajectories are integrate 80 days backward in sections 3.1 and 3.2. For the research aim in chapter 4, 80-day simulations with 0 % to 1 % wind drift produce too short trajectories. Therefore, they are calculated half-a-year (4320 hours = 180 days $\approx$ 0.5 year) forward. The validity of those trajectories, however, is highly questionable.

Additionally, no deterministic trajectories of single particles are calculated. Instead, several particles are injected under equal conditions and transported with influence of noise, in order to take into account model inaccuracy. The process is denoted as diffusion in *PELETS-2D*, although it is no diffusion in the conventional sense. In fact, the resulting ensemble of particle trajectories can be understood as probability distribution of the particle drift. Hence, *PELETS-2D* enables simulations forward and backward in time creating a probability distribution of particle locations X days before the initial time or respectively Y days after it.

By default the random numbers applied as noise are normal distributed with zero mean and $2D \cdot dt$ variance with the horizontal eddy diffusivity D and the length of the integration time step dt. According to Schönfeld [1995] the diffusion coefficient D depends on the characteristic length scale l with the reference length scale l_0 and the reference diffusivity $D(l_0)$ as follows:

$$D(l) = D(l_0)\left(\frac{l}{l_0}\right)^{\frac{3}{4}} \tag{2.2}$$

The characteristic length scale l is calculated on the base of the contour length of the model's grid cells. For more information please read Schönfeld [1995]. See also van Dam [1981] and Heemink [1990] for more information the choice of diffusion coefficients in water.

In the introduction several tasks for particle transport simulations are listed. From the technical implementation of the particle transport in *PELETS-2D* the following technical issues arise:

- influence of the wind drift different categories of marine litter items,

- accuracy of trajectory ensembles compared to real world measurements,
- needed spatial and temporal resolution of input data
- for simulations needed input parameters which should be measured during surveys
- Are two-dimensional transport models sufficient or are three-dimensional models needed?

The exact real sources and trajectories of buoyant objects are not predictable independent of the duration of simulations, of the hydrodynamic data and of the monitoring data quality. However, it can be stated from which direction they approximately originate and where these objects probably originate **not** from. A correlation between a rough direction of the source and the debris composition or between direction of the source and location of the item observation would be a good start for identifying marine polluters and tackling the problem of marine litter.

2.1.2. BSHcmod V3 and V4

The ***BSH*** *operational* ***c****irculation* ***mod****el* (*BSHcmod*) is a three-dimensional hydrodynamic model developed by the ***B****undesamt für* ***S****eeschifffahrt und* ***H****ydrographie* (*BSH*, enlg. Federal Maritime and Hydrographic Agency). Operational means, that it runs twice a day and produces forecasts for 60 hours in future predicting temperature, salinity, currents and water levels in the North and Baltic Sea and being base for flood and rough sea warnings for the German coast and German waters. An oil transport module is additionally integrated [Dick and Soetje, 1990].

The *BSHcmod* models tidal cycles. Though, it does not allow dry-falling of the sea ground because of algorithmic reasons, leaving a minimum water level in theoretically dry areas. The river inflows of Rhine, Ems, Jade/Weser and Elbe are covered by the boundary conditions (Some more rivers are include but the information could not be obtained in time for this thesis.), influencing the North Sea currents not directly but introducing salinity gradients in coastal regions with medium to long term effects on the hydrodynamics. Currents are calculated on uniform rectangular nested grids. In *BSHcmod* version 4 (differences between V3 and V4 see below), the outer grid reaches northward till $66°N$ and westward till $21°W$ into the North East Atlantic. The first nested grid with a higher resolution covers the complete North and Baltic Sea and the second nested - again with a higher resolution - the German Bight and German parts of the Baltic Sea.

	model	extend		mesh size
		North Sea	Baltic Sea	
grid 1	*BSHcmod* V3	$55.5°N$, $6°E$	$56.5°N$, $15°E$	$1\ nm \approx 1.85\ km$
	BSHcmod V4	$56.5°N$, $6°E$	$56.5°N$, $15°E$	$0.5\ nm \approx 0.93\ km$
grid 2	*BSHcmod* V3	$59.5°N$, $4°W$	full	$6\ nm \approx 11.11\ km$
	BSHcmod V4	$60°N$, $4°W$	full	$5\ km$
grid 3	*BSHcmod* V3	-	-	-
	BSHcmod V4	$48°$ to $66°N$, $21°W$	-	$10\ km$

Table 2.2.: Extend and mesh size of the grids on which the *BSHcmod* V3 and V4 calculate hydrodynamic currents. The diagonal lines are needed for *PELETS-2D* simulations and are not part of the original *BSHcmod* grids.

Till 2008 *BSHcmod* Version 3 was operational not having an outer grid and ending at $59.5°N$ and $4°W$. With the introduction of Version 4, the grids were narrowed, their boundaries modified and supplemented by a third one. Table 2.2 contains the exact spatial extents of the grids and their mesh size. Additionally the vertical coordinate system was changed in Version 4 [Dick and Kleine, 2007]. For information on older versions of *BSHcmod* please read Kleine [1994] and Dick et al. [2001]. At the HZG hourly hydrodynamic fields from 2000 to 2008 and 2008 to today calculated by *BSHcmod* V3 and *BSHcmod* V4, respectively, are available being obtained on a daily basis from the *BSH*. For 2008 ocean currents produced by both models exist.

2.2. Ship-based debris survey data

Thiel et al. [2011] present an statistical analysis on ship-base observations of marine debris. Their data set partly forms the base of *PELETS-2D* backward simulations in chapter 3.

Marine debris was surveyed on random transects from aboard the research vessel *RV Heincke* during summer 2006 and summer 2008 in order to estimate debris abundance and composition at sea. The transects' locations are plotted in figure 2.1 being clustered in the three regions Helgoland (HEL), East Frisia (EF) and White Bank (WB). Surveys were perform during good sighting conditions and calm sea recording floating objects at a distance of $\approx 20\ m$ to $\approx 70\ m$ from one side of the ship. Exact time and the GPS coordinates of each observation were written down together with object type and manufacture material. On the base of transect length and observation stripe width the density of different marine debris categories - natural and anthropogenic wood, multiple algae species, multiple litter categories and other - was estimated. For detailed information on the survey method and for the statistical analysis on debris see Thiel et al. [2011]. Lars Gutow (one of the co-authors of Thiel et al. [2011]) provided the observation for further processing.

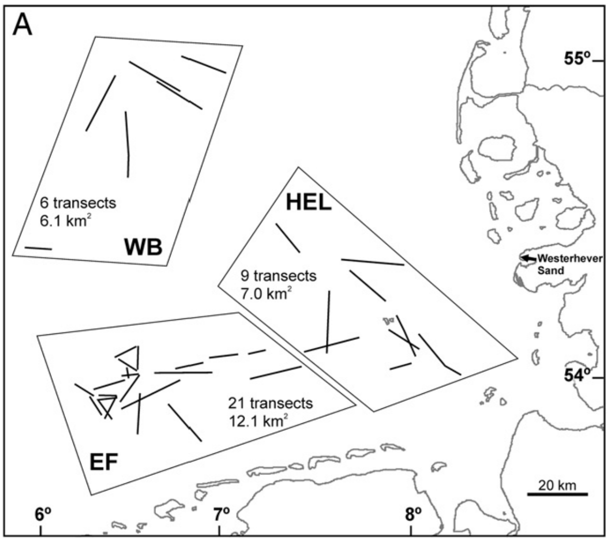


Figure 2.1.: Figure 2(A) of Thiel et al. [2011]: *Flotsam survey transects in the three study sectors (WB=White Bank, EF=East Frisia, HEL=Helgoland) of the German Bight. The total number of transects and the total surveyed area are indicated for each sector.*

Sebastian Lotter - an Applied Systems Science (Angewandte Systemwissenschaft) Bachelor's student - performed simulations based upon algae observation of the presented data set in his Bachelor's Thesis [Lotter, 2011]. Additionally, the publication of his results is in progress. In this study the plastic observations are refined.

The data set contains 808 litter sightings linked with size, material and item type and having been recorded on one of 36 non-recurring surveyed transects during two years (July 2006 - August 2008). These numbers and a look at the transect locations in figure 2.1 reveal that the observed items are spatially and temporally wide distributed. Additionally, with about 22 sightings per transect the number of observations is quite low for statistically valid conclusions.

However, 36 transects located in the German Bight yield spatially better resolved data than the one long transect in Barnes and Fraser [2003] - at least for the purpose of this work.

2.3. Geography

The description of the particle transport in the North Sea is considerably facilitated when geographic locations instead of coordinates are used. Hence, the main purpose of this section is the presentation of the later needed geographic knowledge, briefly describing also the hydrographic properties of the North Sea.

The North Sea is bordered by Great Britain in the west, by Norway in the North, by Denmark in the east and by Germany, the Netherlands and Belgium in the south being connected with the Baltic Sea in the north-east by the Skagerrak and with the Atlantic Ocean in the south-west and the north-west by the Channel and an unnamed passage, respectively. The strait splitting the Channel from the North Sea is denoted as Strait of Dover. If the connection between North Sea and (North East) Atlantic Ocean is mentioned in this thesis, the northern connection is indicated, whereas to the south-western connection to the Atlantic is always referred as Channel or Strait of Dover. The British and German coasts are quite long, leading to considerably variable observations at different coastal locations at the same time. Therefore, deliberately the names England and Scotland for parts of the one and Lower Saxony and Schleswig-Holstein for part of the other country are used. The islands near-shore to the Netherlands, Lower Saxony and Schleswig-Holstein are denoted as West, East and North Frisian Islands, respectively. At $54.2°N$ and $7.9°E$ the German island Helgoland is located, being the only one offshore. It is located in the German Bight, which denotes the North Sea partition approximately southern of $55.5°N$ and eastern of $5.5°E$. To the coast line from Belgium via the Netherlands and Germany to Denmark is referred as continental coast. The Jade, Weser and Elbe estuaries are alternatively denoted as Elbe-Weser estuaries because the three are located near each other.

Several rivers transport freshwater inter the North Sea, influencing the North Sea hydrodynamics not directly by their flow but create spatial salinity gradients in coast waters, inducing hydrodynamic currents. More important in annual average are the water inputs by the Baltic Sea through the Skagerrak and by the North East Atlantic through the Channel as well as from the North around the Shetland Islands, while The major discharge of North Sea water takes place along the Norwegian coast into the Atlantic Ocean (Dietrich et al. [1980, p.443, p.542] or Pickard and Emery [1990, p.208]). The words Atlantic Ocean, Atlantic and North East Atlantic are used synonym. In annual average a counter-clockwise circular current exists in the North Sea leading to mainly northward direction currents along coast of Denmark and Schleswig-Holstein and eastward directed ones along Dutch and Lower Saxon coast (Loewe et al. [2005, p.48], Loewe et al. [2006, p.66] or Loewe [2009, p.83]). For a more detailed view on the hydrography please read for instance Dietrich et al. [1980] or Pickard and Emery [1990].

The map in figure 2.2 contains further geographic location and river names used in the following chapters.

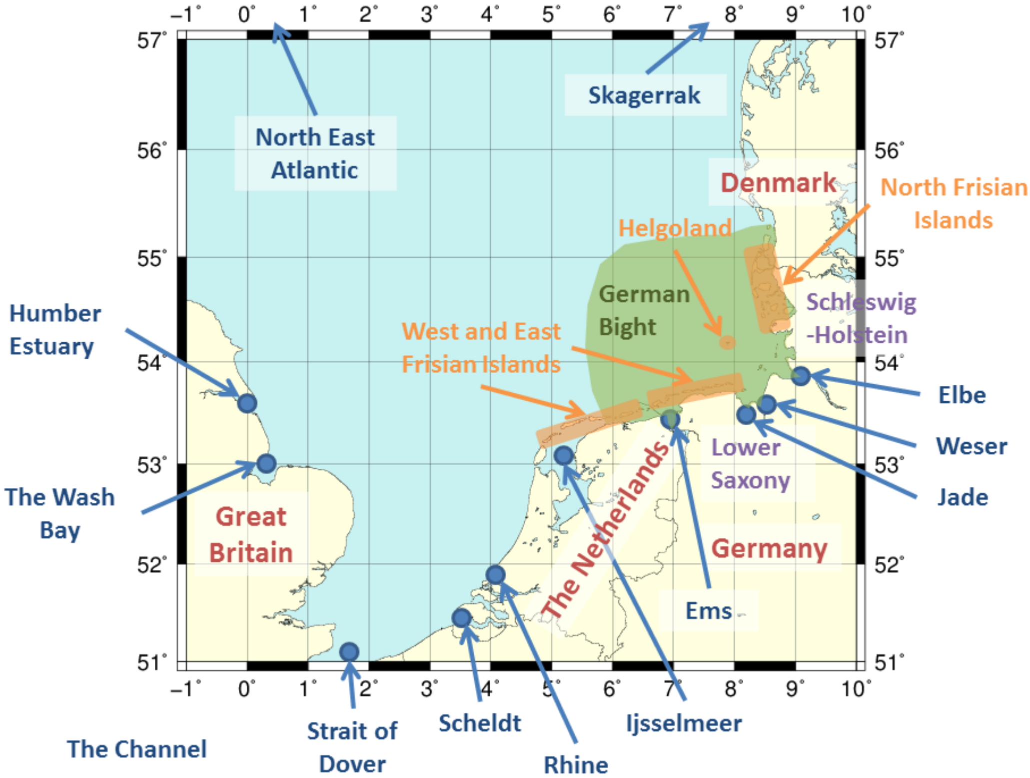


Figure 2.2.: River estuaries, countries, islands and further geographic locations in the southern North Sea.

3. Backward simulations

This chapter deals with evaluating the value of ship-based observations of marine litter for identifying litter sources and estimating long term trends. For this purpose those observations as base for 80-day backward simulations with *PELETS-2D* are employed. Several litter observations at the sea surface, in the water column, on the sea floor, at beaches and in biota have been performed in the past without having been standardised in preparation, primarily focussing on small areas for a short period of time. The results of those observation are not comparable with each other. Thus they do not help to identify spatial inhomogeneities and temporal trends. However, a few long term or large scale monitoring data sets exist. In the frame of the MSFD a new large scale, long term and standardised monitoring is likely to be undertaken. This monitoring is expected to produce utilisable and comparable litter observations. The compartments and setups for this monitoring concept have still to be defined. In this context, the establishment of ship-based surface surveys at the sea is possible.

For instance, Thiel et al. [2011] and Barnes and Fraser [2003] present debris observations which were performed on journeys of research vessels on standardised yet different protocols. The authors of the first publication provided their data for the employment in particle transport simulations after having performed statistical analysis on it [Thiel et al., 2011]. Section 2.2 deals with the data and the survey method. Simulations on the base of their observations are performed in order to get to know *PELETS-2D* and to introduce different representations of simulation data. The influence of wind drift on particle transport and the advantages of differently located observation regions are presented and discussed in this section. Importing an arbitrary heap of observation data into a particle drift simulation, however, might not suffice for working on those tasks satisfactorily. Therefore, it is important to find out whether the data of Thiel et al. [2011] is appropriate. Observations of a fictive monitoring form the base for simulations performed in chapter 4 in order to overcome possible shortcomings of real observations. The monitoring data of different regions is compared, focussing on possible particles' source locations and seasonal variations in particle drift pathways. For this comparison, single events and composites, aggregating several events, are described and discussed.

3.1. Backward simulations with ship-based observations

In this section, the first steps in estimating the current pollution of the North Sea by marine litter and identifying sources of marine litter are gone forward. Marine litter observations by Thiel et al. [2011] provide particles' initial time and location for 80-day backward simulations with *PELETS-2D*. Reasons for 80-day period are given in the description of *PELETS-2D* (subsec. 2.1.1). At first one set of simulations to observations from 5th August 2006 is discussed in depth introducing different data plots and showing the effect of wind drift. Discussions of further simulations and a short comparison of three hydrodynamic models follow.

Definition Box 1 (event and ensemble simulations)**.** A unit of all particles started within one hour independent of their initial locations is called an *event.* Events are denoted according to their initial date and time (in hours). An arbitrary number of particles may be started at the same time and place which is called an *ensemble simulation.*

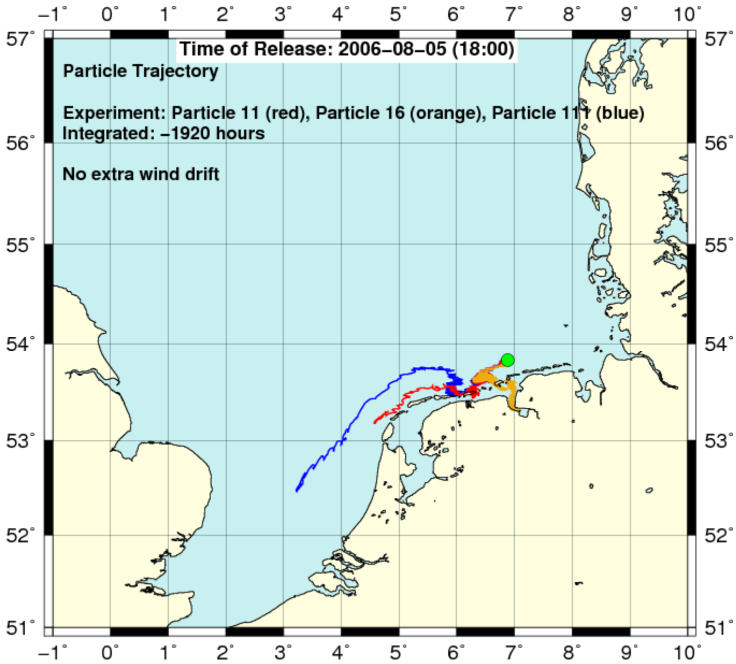


Figure 3.1.: Three particle trajectories (different colors) of 80-day backward simulations without wind drift started at 5th August 2006, 18 o'clock. The green circle marks the initial location.

Example Box 2 (event)**.** All particles started at 5th Aug. 2006 after 5 p.m. and till inclusive 6 p.m. form the event 2006080518.

Before describing and discussing the results, the simulations setup is introduced. All observations obtained within one hour are united as one *event* (see boxes 1 and 2 for definition and an example). For each observation 20 particles are released at the specific location and time and are transported 80 days backward. Thus, each event contains an integral multiple of 20 particles and at least 20. The drift of each particle is individually affected by noise so that the probability for two equal trajectories is close to zero. Simulations are performed without and with wind drift applying the wind drift factors 0.005, 0.01, 0.02, 0.05, 0.1 and 0.2. See subsection 2.1.1 for more information on the wind drift factor and a simple and short mathematical definition.

3.1.1. Event 05/08/2006 at 6 p.m. - tutorial

The discussed simulations are based upon 13 observations obtained at 5th August 2006 between 5 and 6 p.m.. The observations form the event 2006080518 (see box 2). Seven simulations with 260 particles each are performed: one without wind drift and six with increasing wind drift factors. Some plots of trajectories can shown in the figures 3.1, 3.4 and 3.6, but not all 260 are plotted here. To get a first impression of all particle trajectories to one simulation the cumulative travel history (CTH) is plotted in figure 3.2. The boxes 3 and 4 state a definition and an example, respectively. To the values in CTH plots often is referred as particle densities or CTH-densities.

Definition Box 3 (plot types)**.** The North Sea is split into several regions denoted as *target region*. They are chosen to be 0.5° in longitudinal and 0.25° in latitudinal direction in this evaluation. The below described values are calculated per region.

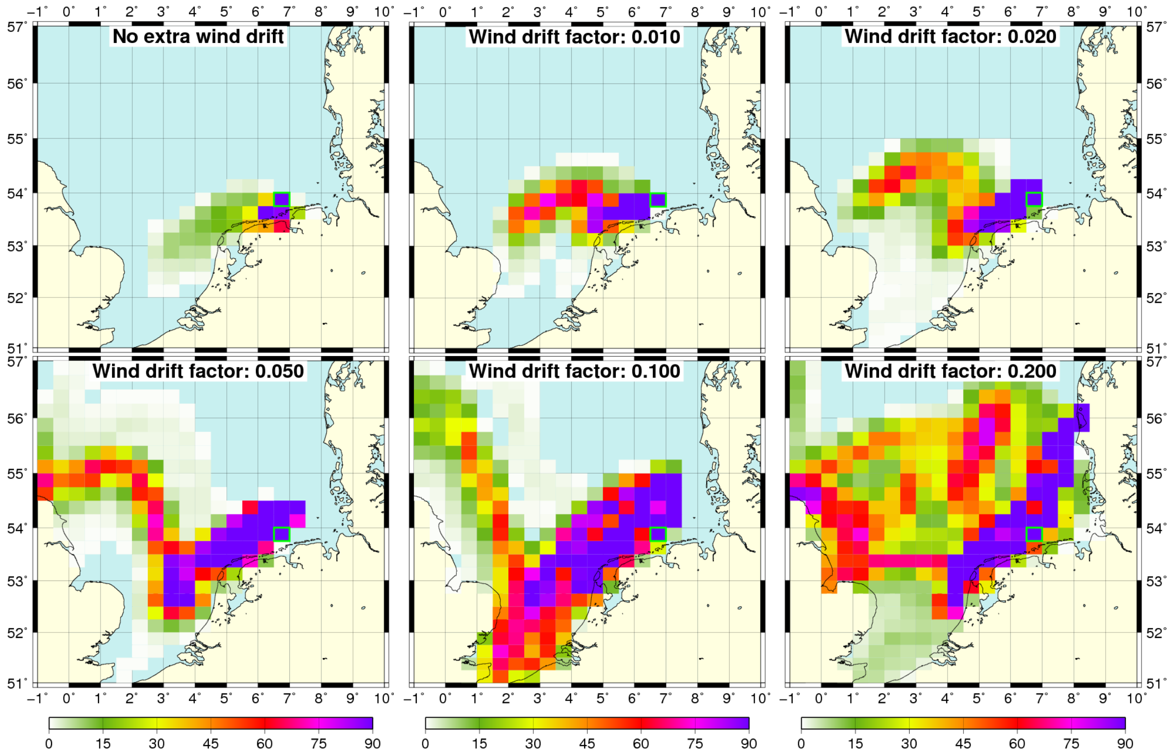
- The ***c**umulative **t**ravel **h**istory* (CTH) of each region is the proportion of particles which ever crossed this region during the simulations. The unit is "% particles per region".
- The ***c**urrent **p**article **l**ocation* (CPL) states the proportion of particles in each region at a chosen time. The unit is "% particles per region".
- The ***m**ean **r**esidence **t**ime* (MRT) is calculated by summing the time each particle resided in a certain region divided by the number of particles in the simulation (not only by those which crossed the region). It states the mean time a arbitrarily chosen particle resides in the certain region. The sum of the MRTs of all target regions equals the duration of the specific simulation. The MRT is given in "days".
- The ***t**ravel **t**ime for* 20 % *of particles* (TT20) equals the time the first 20 % of particle, which cross a certain region at least ones, need till they reach the region the first time. The travel time is given in "days".

Example Box 4 (plot types)**.** Assume a simulation with 1000 particles. During the simulation, 100 particle cross region A remaining there for 6500 days, while in the end 5 particles are located in it. The 20th particles reaches region A after 10 and the 50th particle after 18 days. The following values are calculated (without units):

$$\texttt{CTH} = 100/1000 = 0.1 = 10\ \% \qquad \texttt{TT20} = 10$$
$$\texttt{CPL} = 5/1000 = 0.005 = 0.5\ \% \qquad \texttt{TT50} = 18$$
$$\texttt{MRT} = 6500/1000 = 6.5$$

CTH-densities of simulations without wind drift and with increasing wind drift factors are plotted in figure 3.2: 0 % wind drift top left, 2 % top right, 10 % bottom left and 20 % bottom right. In simulations without wind drift most particles are injected by the Ems river. The remaining particles have their source somewhere close to the south of England, the Strait of Dover or the Dutch coast.

With increasing wind drift factor particles source from further northern locations. The particles moreover seem to drift faster because longer drift pathway. For a wind drift factor of 2 % and above a sharp z-shaped particle drift pathway arises (2 % not plotted). Additionally up to three of 260 particles - estimated by the CTH-densities - have their source close to the Thames Estuary or the Strait of Dover. In simulations with 10 % wind drift, about 10 % to 15 % of the particles source from the Channel and about 5 % to 10 % from the Thames estuary. The majority of the remaining particles originate from the north-western North Sea and pass the British coast in southward direction. Nearly all particles travel along parts of the German and Dutch coasts. Possible source regions are therefore beaches along these coasts and estuaries of Ems, Rhine and Scheldte. Finally, for 20 % as wind drift factor particles travelled back and forth across the southern North Sea. Sources could be all river estuaries and beaches at the German, west Danish, east British coast or Dutch coast. Additionally, particles could originate from each arbitrary location on the open sea. About 5 % to 10 % of the particles are injected close to the Strait of Dover or are drifted through the Channel.



Time of Release: 2006-08-05 (18:00)
Percent of particles having travelled through target regions
Units: Percentage released particles
Experiment: 260 particles released from any locations
Integrated: 1920 hours

Figure 3.2.: Cumulative travel histories (CTH) of simulations with different wind drift factors. From left to right, top: 0 %, 2 %; bottom: 10 %, 20 % wind drift.

The following two paragraphs focus on the discussion of simulations without wind drift with the aid of figures 3.1 and 3.3. Figure 3.1 shows ordinary particle trajectories requiring no explanation, whereas, figure 3.3 visualises *current particle locations* (CPL), *mean residence times* (MRT) and *travel time for* 20 % *of particles* (TT20). The boxes 3 and 4 explain these values by a definition and an example, respectively.

According to the plot of the mean residence time (fig. 3.3, center) the particles have been drifting already 10 to 20 days close to the West Frisian Island and the Ems estuary before they were spotted. The particles could have been spotted already some days earlier. This implies that particles entering this area drift for an arbitrarily long time close to the Ems river before being observed. Thus, the date of insertion of the particles into the sea is uncertain to determine. CPL-densities in figure 3.1 top left indicate that more than 50 % of the particles either already drift between the West Frisian Islands eighty days before the spotting or are injected from the Ems during the 80 days. About 20 % of the particles are located in the south-western North Sea between the Netherlands and the UK eighty days before. The remaining 30 % are drifting in between both locations.

Finally, some single particle trajectories are regarded. The trajectories confirm the description from above: Some particles have their source in the Ems estuary (plots top right and bottom right of fig. 3.1) whereas others come from some place in the south western North Sea (plots top left and bottom left of fig. 3.1).

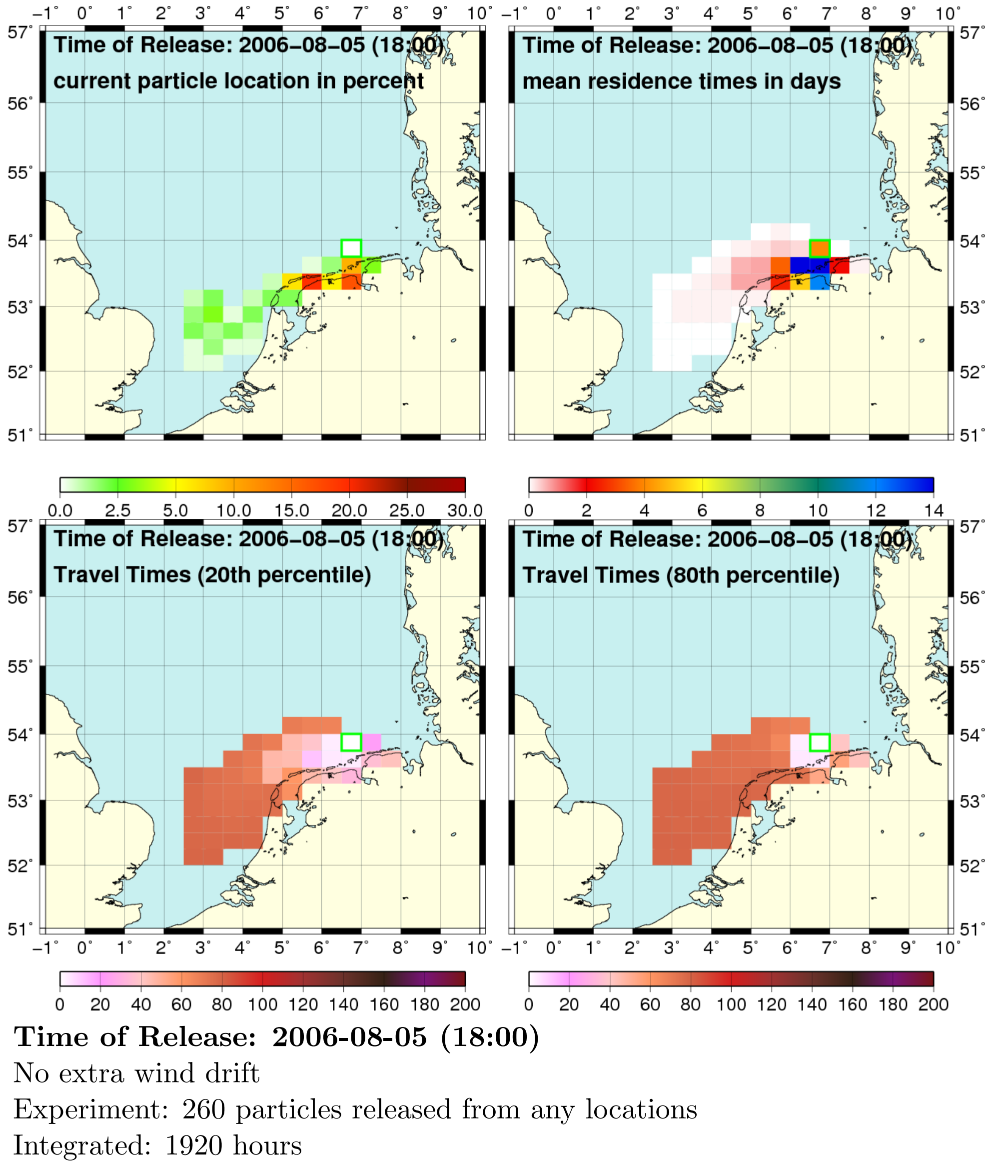
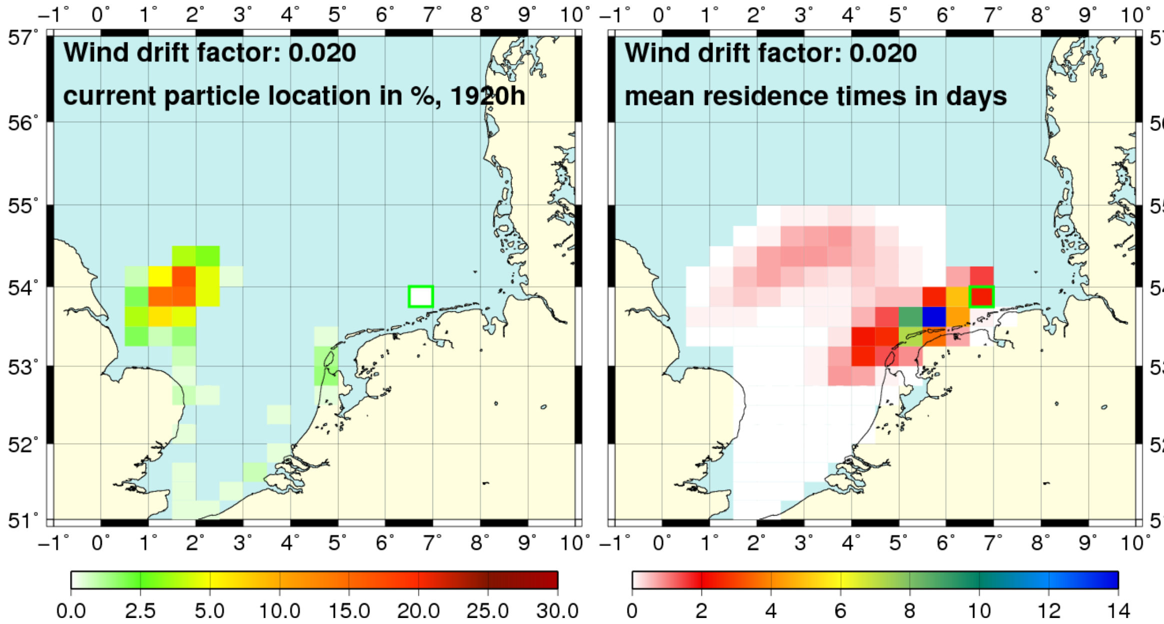


Figure 3.3.: CPL (top left), MRT (top right), TT20 (bottom left) and TT80 (bottom right) plots to a simulations of the event 2006/08/05 18 o'clock without wind drift.

Following, simulations with a wind drift factor of 2 % are regarded. The appropriate plot in figure 3.4 is located top right. The particles remain for a long period of time close to the West Frisian Island *after* they arrived from different directions and *before* they drift to the location of their observation. Only few particles have their source close to the Strait of Dover or the Thames, Rhine or Scheldte estuaries (fig. 3.2, bottom left). Most particles are located north-eastward of the British coast at $54°N$ 80 days before the observations. The particles trajectories on the right hand side of figure 3.5 confirm this: The particles are transported from the British coast to the West Frisian Island, from where they are drifted in repeating circles in eastern direction. Particle number 11 (red) could be injected by some rivers near the Ijsselmeer.

Figure 3.6 contains plots to simulations with 10 % wind drift. 80 days before detection no particles are located in the plotted map section. Therefore, CPL-densities 69 days before observation are plotted in figure 3.6. The particles have their source close to the Scottish coast or they enter the North Sea near the Shetland Islands from the North East Atlantic. They subsequently continue their way southward along the British coast and reside a long time near the Dutch coast as the MRT plot in figure 3.6 indicates. The particle trajectories of figure 3.5 moreover imply



Time of Release: 2006-08-05 (18:00)
Wind drift factor: 0.020
Experiment: 260 particles released from any locations
Integrated: 1920 hours

Figure 3.4.: CPL and MRT plots to 80-day backward simulations with 2 % wind drift on the left and right. The current particle location 80 days before observation is plotted.

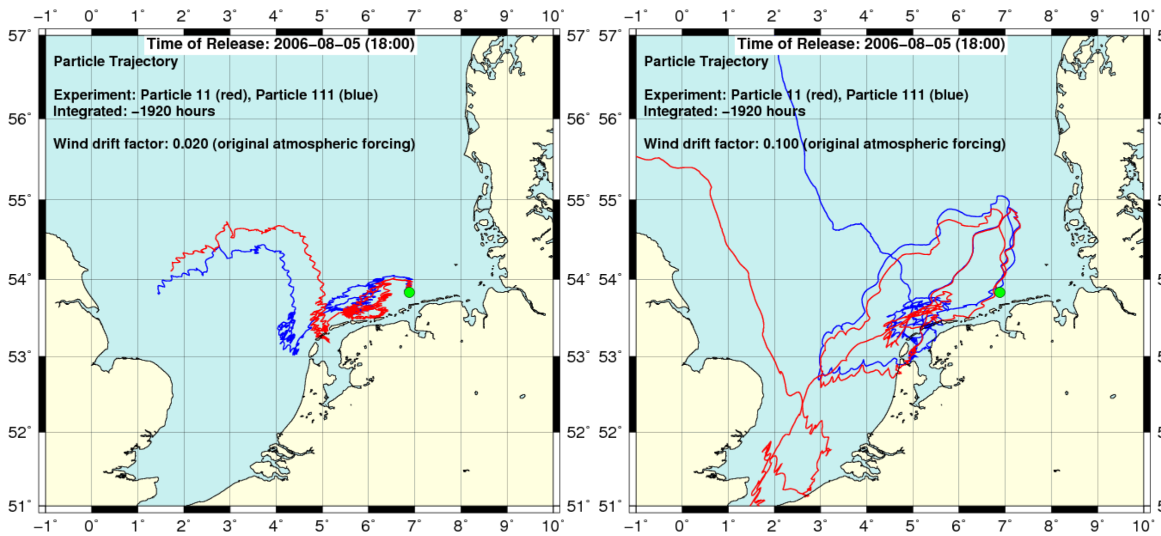


Figure 3.5.: Each two particle trajectories of simulations with 2 % and 10 % to event 2006080518. The green circle marks the initial location.

that the particles are drifted twice across the German Bight before arriving at the continental coast and the final detection.

In the following two paragraphs wind fields from 17th May to 5th August are presented, affecting the transport of wind drifted items of event 2006080518. Exemplary in combination with the wind fields, simulations with 1 % wind drift are visualised in figure 3.7, showing two sharp bends in the particle drift pathways at $54°N$ $4.5°E$ and $53.5°N$ $5°E$.

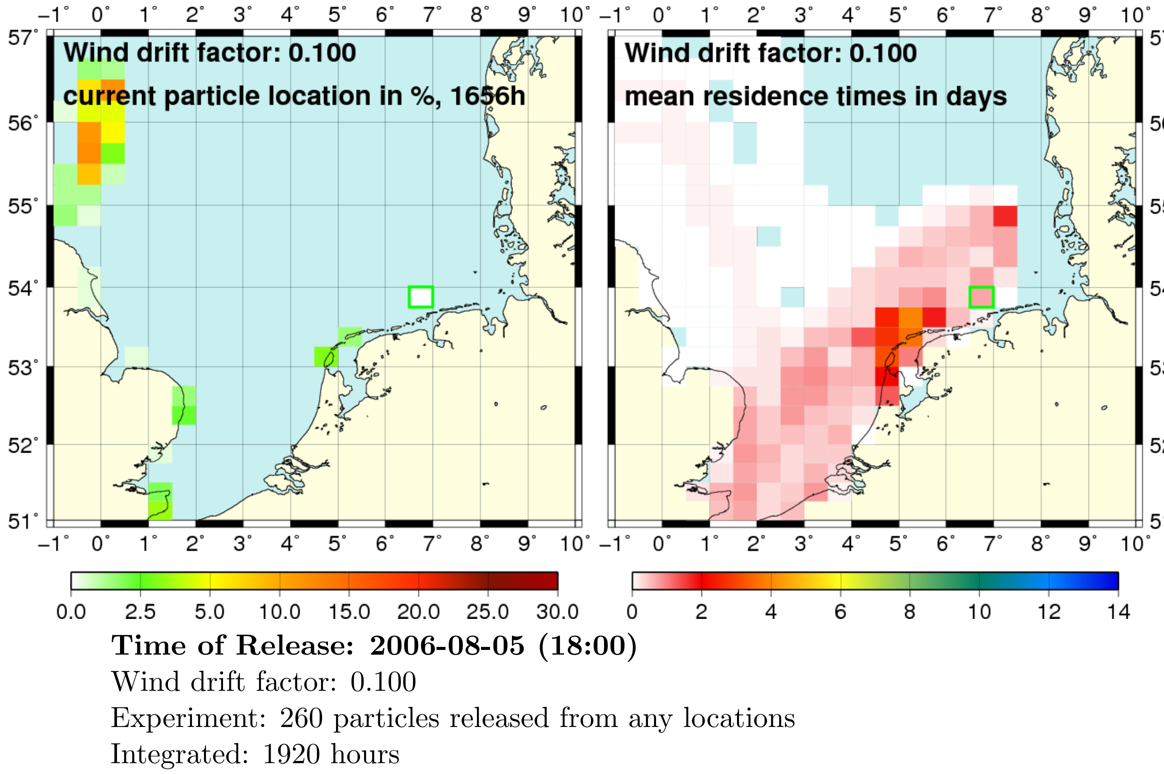


Figure 3.6.: CPL and MRT plots to 80-day backward simulations with 10 % wind drift on the left and right. The current particle location **69 and not 80** days before observation is plotted.

The long black lines with short black ones attached to are denoted as wind barbs, being used by Meteorologists to visualise wind direction and speed. The end, with the short lines attached to, points in the direction from where the wind is blowing. Meteorologists talk about **from where** wind is blowing, while oceanographers talk about **to where** ocean currents flow. For instance in figure 3.7 top left the wind blows from south-south-east with a speed of 40 *knots* at $54°N$ $1°E$ and with 15 *knots* at $55°N$ $7°E$ being indicated by short lines - also denoted as barbs. A half line equals 5 *knots*, a full line 10 *knots* and a pennant 50 *knots*.

Top left in figure 3.7 calculated particle distribution at 17th May 2006 at 6 p.m. - 80 days = 1920 hours before observation - is plotted, being primarily located around $53.5°N$ $2.5°E$ close to the British coast. The wind blows from southern direction, while hydrodynamic currents flow in opposite direction (counter-circular currents, section 2.3). Within the next six days (1776 hours = 74 days before observation) the wind direction gradually changes to south-west leading to a north-eastward orientated transport. Between the 23rd and 26th May (1704 hours = 71 days before observation) the directed particle motion nearly stops because of fluctuation wind directions and speed as figure 3.7 bottom left suggests. After 26th May the wind starts blowing from north-north-east (fig. 3.7, bottom right), transporting particles to the West Frisian Island till 5th June (1464 hours = 61 days before observation). During the left 60 days particles drift with several changes in their direction of motion towards the observation region, comparable to the trajectories in figures 3.1 and 3.6.

As discussed in the materials chapter and in the introduction of this chapter, the identification of exact source regions is not possible. Therefore, source directions and probable non-source regions are estimated on the base of the simulations results. The CTH-plots in figure 3.2 suggest, that those estimation are not sensible in simulations with wind drift factors above 10 %. Independent of the wind drift factor the particle origin is probably no located western of the observation area

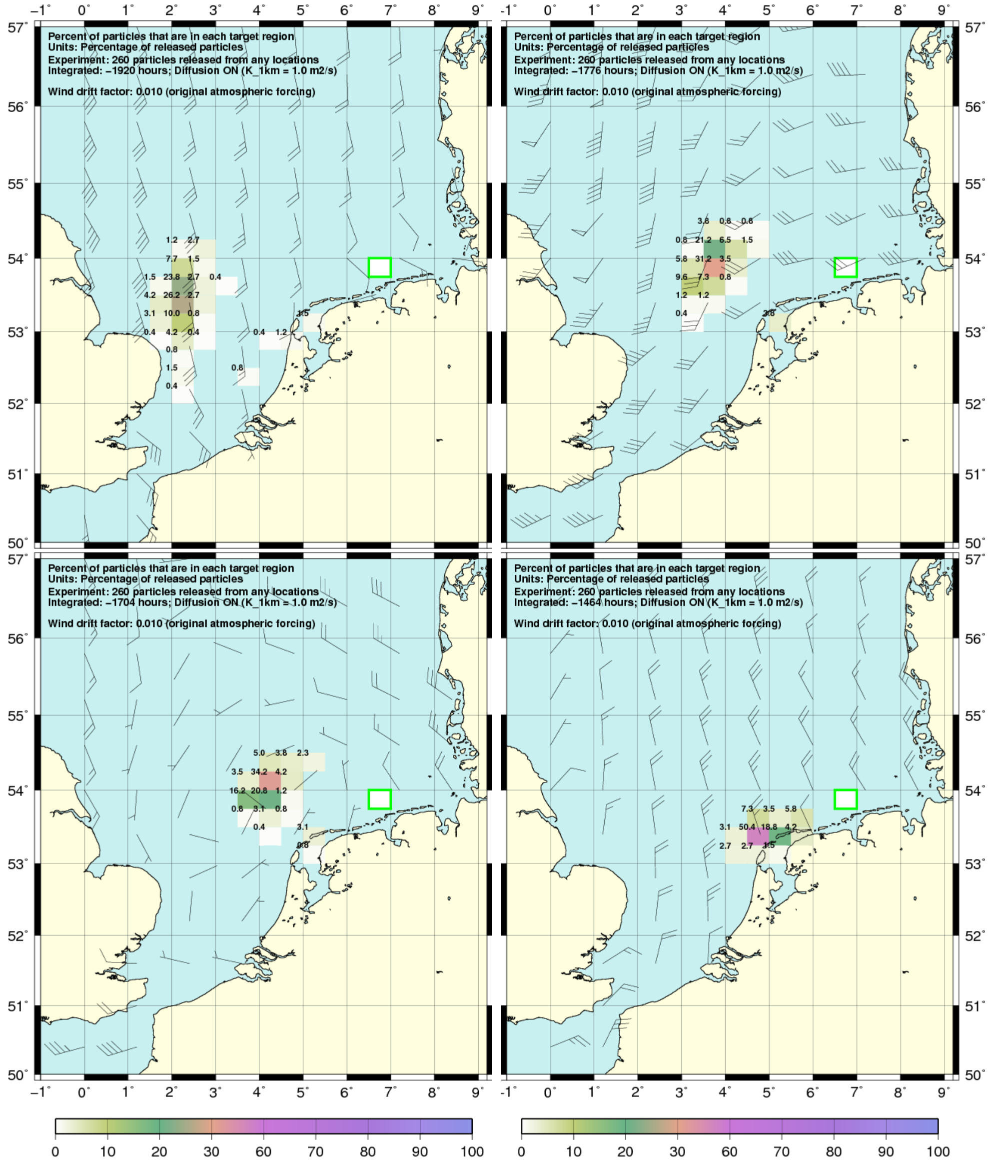
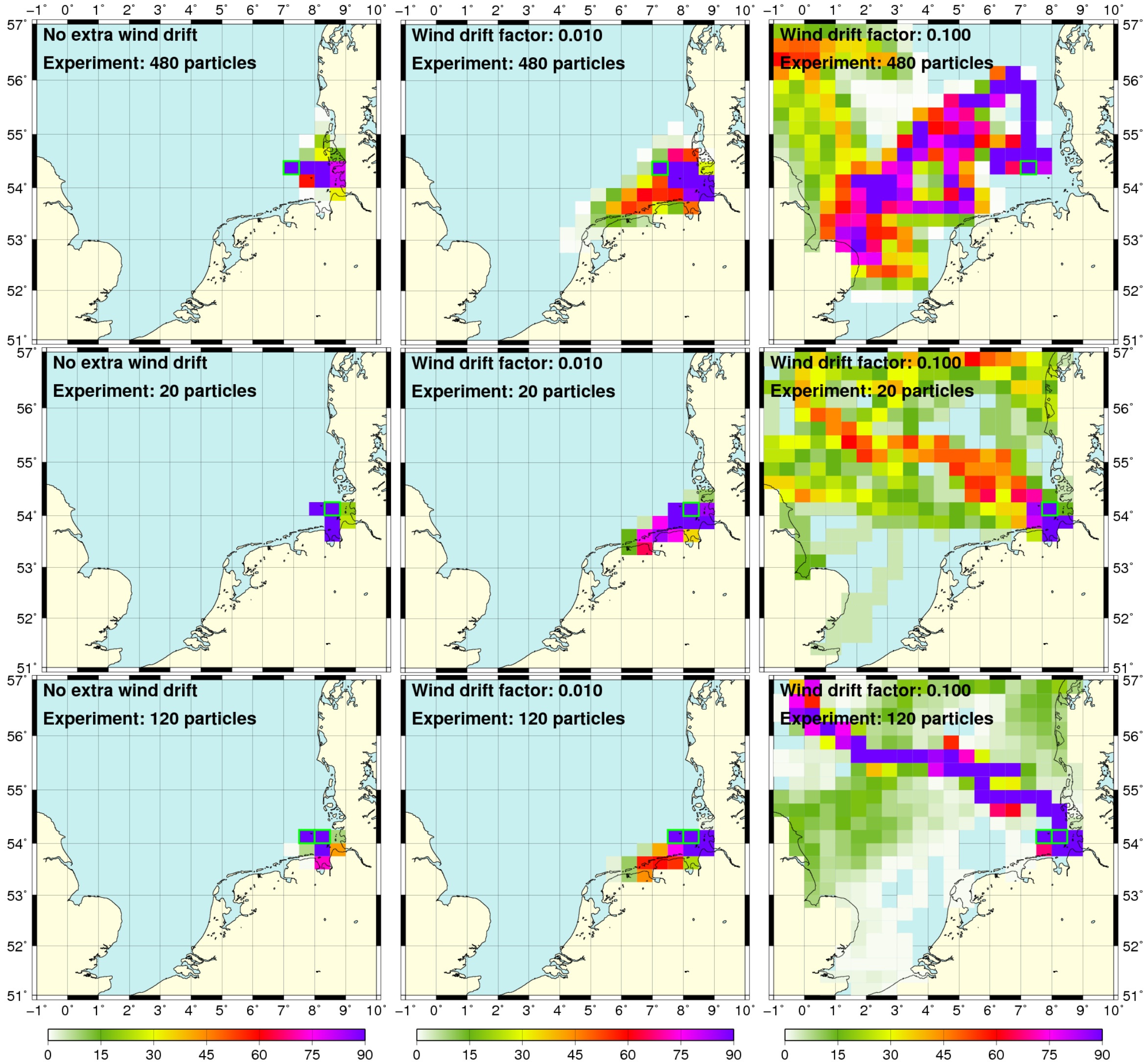


Figure 3.7.: Current particle locations of simulations of event 2006080518 with 1 % wind drift at four different times from top left to bottom right: 80 days (= 1920 hours = 17/05/2006), 74 days (= 1776 hours = 23/05/2006), 71 days (= 1704 hours = 26/05/2006) and 61 days (= 1464 hours = 05/06/2006) before observation. Wind data is visualised by wind barbs which are explained in the text.

excluding the Danish and German coasts as source regions.

In about half of all simulated events the particle drift pathway is similar to the above described one. Moreover, the statement to the non source-regions applies to nearly all simulations with initial locations near to the here presented one, leading to the vague assumption, that most marine debris detected southbound of $54.5°N$ and westbound of $7.5°E$ does not originate from the German or Danish cost.

3.1.2. Three events in the south-eastern German Bight



Percent of particles having travelled through target regions
Units: Percentage released particles
Integrated: 1920 hours

Figure 3.8.: CTH plots to simulations of three events with 0 %, 1 % and 10 % wind drift. From left to right the wind drift factor increases. In each row, one of the events is plotted: 2006-07-25, 20 o'clock; 2007-04-26, 19 o'clock; 2007-05-11, 21 o'clock.

In this subsubsection simulation results of three different events are regarded, aggregating 31 objects having been observed southern of 54.5°N and eastern of 7°E - located near the German coast and roughly around Helgoland. All together 176 observations have their initial position within that area, reflecting about one third of the data set.

Backward integrations over 80 days with the different wind drift factors 0 %, 1 % and 5 % are performed. Figure 3.8 shows CTH plots of the simulation results: one event per row and increasing wind drift factors from left to right. When no wind drift is applied (first column of figure 3.8) particles originate from the German coast. More accurately, the particles of the first event (20060725) probably source from the coast of Schleswig-Holstein, while the German rivers Elbe, Weser and Jade are most likely the particle origin for the two 2007 events, excluding coasts in the western - UK, Netherlands, Belgium - or northern - Sweden, Norway, north of Denmark

- North Sea as source regions.

If 1 % wind drift is applied (center column of fig. 3.8) the particle's source area is extended in western direction along the Lower Saxon and the Dutch coasts, including the East and West Frisian Islands, covering a larger area of sea surface by particle trajectories in 2006 than in 2007. The source of the observed item is probably not located in the northern North Sea or at the British coast.

If 10 % wind drift is applied, the particle drift pathways diversify considerably. The 2006 event's particles (fig. 3.8 top right) source from the Scottish coast or the North East Atlantic and drift southward along the British coast till the Wash Bay, before being transport north-eastward to the observation area. The German and Danish coasts are no possible source regions. In contrast, the particles of the 2007 events eventually source from the Elbe and Jade-Weser estuaries and the surrounding German coast. Particles observed at 26/04/2007 primarily drift through the southern North Sea, passing all bordering coasts - including the German one - and originating eventually from the Channel or the English coast. Those observed five days later at 01/05/2007 primarily drift through the northern North Sea and into the Elbe estuary, passing British, Norwegian and Danish coast. In the first case Norway, whereas in the second case the Netherlands are not expected to be a source region.

Buoyant low wind affected items observed southern of $54.5°N$ and eastern of $7°E$, most likely originate from the German coast or German rivers excluding British, Norway, Sweden, Denmark and the North East Atlantic as source regions, while medium to strong wind affected items cannot be related to certain source directions or non-source regions, in general.

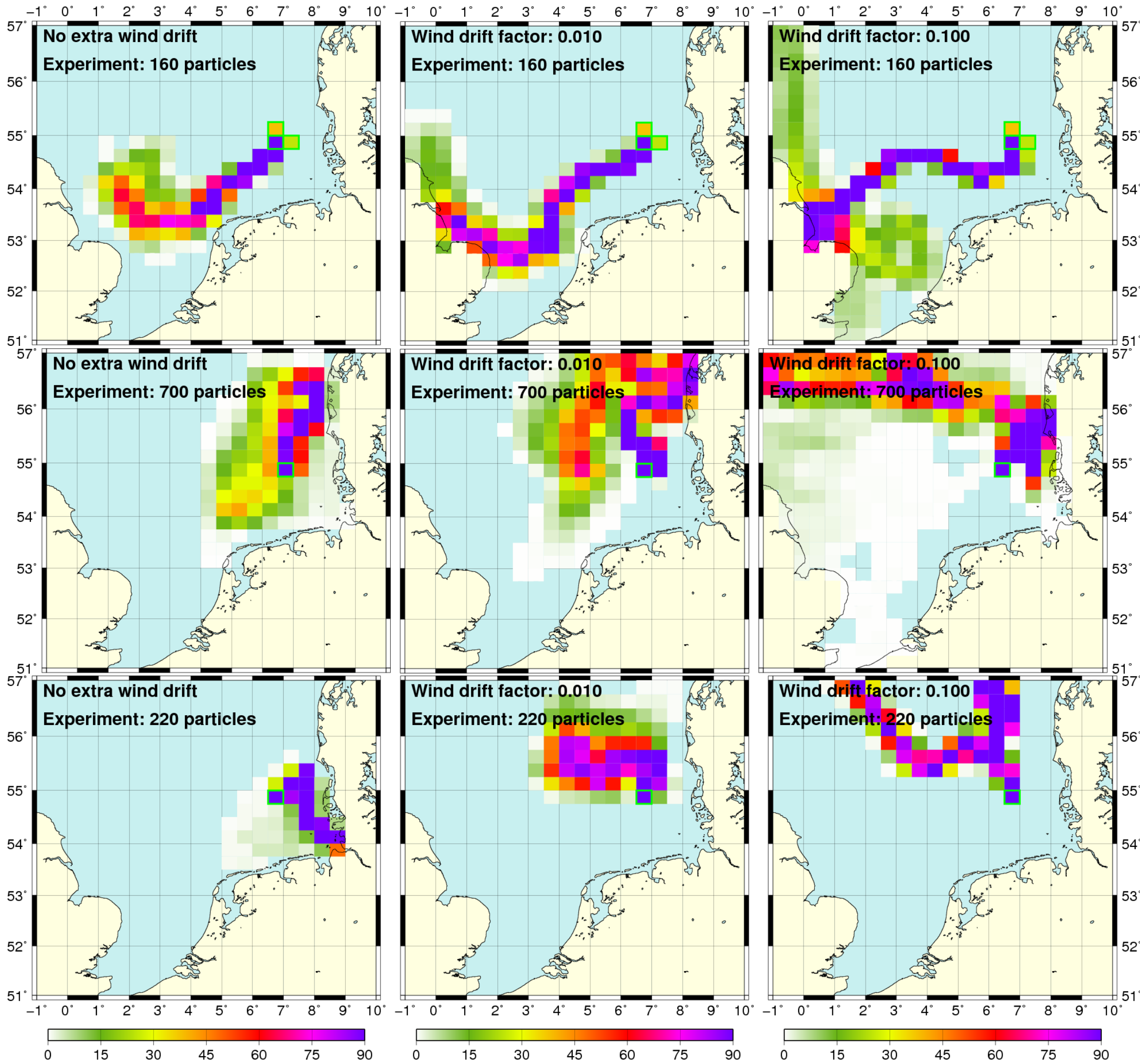
3.1.3. Three events in the northern German Bight

As in subsection 3.1.2 simulations to three events with the wind drift factors 0 %, 1 % and 5 % are present. The events are by name 2006100914, 2007043017 and 2007081117 containing 8, 35 and 11 observed objects, respectively, and being observed between $54.75°N$ and $55.25°N$ and between $6.5°E$ and $7.5°E$. Figure 3.9 shows plots of them, having the same alignment as figure 3.8: One event per row and increasing wind drift factor from left to right. However, the predicted directions of origin are quite different, strongly depending on the observation dates, respectively on the weather conditions.

The simulation of event on 09/10/2006 14 o'clock without wind drift (fig. 3.9, top left) is presented first. The particles originate from a large area between $53.5°N$ and $54.5°N$ and between $1°E$ and $3°E$, travelling south-eastward at far distance to the English coast. They are not transported further to the continental coast but turn to north-eastern direction, drifting towards the detection area. The coasts of Denmark, Germany, Belgium and England are unlikely source regions. Eventually the items are injected at sea, at the Scottish coast or are transported into the North Sea from the Atlantic Ocean.

If 1 % wind drift is added (fig. 3.9, top center), the particle trajectories remain similar, but run near the British coast, adding that coast to possible source regions while Belgium, Germany, Denmark and Norway remain probable non-source regions. The CTH plots show a longer drift pathway, indicating a faster transport velocity.

If the wind drift is increased to 10 % (fig. 3.9, top right) the drift pathway becomes more complicated. Most of the particles drift from the north along $0°E$ to the Humber estuary at the British coast ($\approx 53.7°N,\ 0°E$), while some particles originate from the Thames estuary and are transported to the first particle group by turning a loop close along the Dutch coast. From the British coast between $53°N$ and $54°N$ all particles travel to observation region within 5 days. Still, Denmark and Germany are unlikely to be source regions.



Percent of particles having travelled through target regions
Units: Percentage released particles
Integrated: 1920 hours

Figure 3.9.: CTH plots to simulations of three events with 0 %, 1 % and 10 % wind drift. From left to right the wind drift factor increases. In each row, one of the events is plotted: 2006-10-09, 14 o'clock; 2007-04-30, 17 o'clock; 2007-08-11, 17 o'clock.

Quite different source and non-source regions are predicted for the particles of the second event (2007043017) (fig. 3.9, center row). In simulations with 0 % wind drift (fig. 3.9, center, left) the particles start near $54°N$ and $5°E$ south-western of the observation region and drift in north eastern direction to the north Danish coast, arriving there 50 days before observation. After remaining at that location for about ten days they are transported south-eastward to their area of observation within 40 days. In Sweden, Germany and the western North Sea probably no sources are located.

In simulations with 1 % wind drift, the drift pathway of the particles keeps quite similar as a the CTH plots in the center row of fig. 3.9 suggest. German and Dutch coast are unlikely to be a source region. The Danish and Norwegian coast are source regions with a high probability, because some particles drift above $57°N$.

Particles drifted with 10 % wind drift or more move considerably fast, travelling from their location of map entry, 25 days before the observation near ($56.5°N$, $1°W$), to the German island *Sylt* within 15 days and to their detection area within 10 as indicated by not plotted CPL-densities and travel times. The particle source is most likely located in the northern North Sea and not in the south, suggesting English, Belgian, Dutch and Lower Saxon coasts as unlikely regions of origin.

Finally, simulations to event 2007081117 are discussed indicating considerable differences in the system behaviour when varying the wind drift factor (fig. figure 3.9, bottom row). In simulations with no wind drift (fig. 3.9, bottom left) the particles primarily originate from the Elbe estuary in Germany and the surrounding German coastal regions, excluding Britain, Denmark and the northern North Sea as possible source regions.

If 1 % wind drift is added (fig. 3.9, bottom center) particles are transported more slowly, originating from north-western direction. The coasts bordering the southern North Sea are not expected to be source regions.

Though, in simulations with 10 % wind drift (fig. 3.9, bottom right), the particle velocity increases considerably, originating from the North East Atlantic or from the Scottish or Norwegian coasts. Entering the map section at $57°N$ $1.5°E$ thirteen days before detection, they are transported south-eastward till close to the observation area, perform a northward orientated loop to the Norway coast and ,finally, drift straightly southward. Denmark, Germany, the Netherlands, Belgium and England are expected to be unlikely source regions.

Summarising, wind drift has a significant influence on the source direction of items observed at 5 p.m., 11th August 2007 and on their transport velocity.

3.1.4. Conclusions on backward simulations with ship-based observations

The marine debris observations of Thiel et al. [2011] offer an introduction in *PELETS-2D*. The wind drift factor and different representations of simulations results - plots of cumulative travel history (CTH), current particle location (CPL), mean residence time (MRT) and travel time of X % of particles (TTX) - are introduced placing particles according to the observation data set. Positive aspects of that data set are exact locations and times of observations, good item descriptions and a relatively accurate defined survey setting allowing statistical evaluations and accurate placement of particles in simulations. However, the observations are wide distributed over an area of more than $\dots km$ (ToDo: which size?) and the time periods of observations are short and irregular distributed between July 2006 and October 2008. No observations at the same time and different places or at different times and the same place are available complicating the distinction between spatial and temporal influences on the particle transport and the identication of outliners. Hence, assumptions to sources of marine litter or to the pollution of the North Sea by marine litter on the base of this data set are quite vague. No statement to ship-bound surveys of the sea surface in general can be made.

The wind drift factor is an important parameter in predicting particle trajectories. Already a small wind drift factor of 1 % clearly affects the particle drift. Particle motion in simulations with a factor ≥ 10 % looks similar to the movement of a ball on a billiard table, moving straight from one boundary to the other. However, it does not seem realistic and small variations in wind direction or particle location lead to considerable variations in particle trajectories. [Dick and Soetje, 1990] use values between 0.8 % an 5.8 % as the wind drift factor of oil in the same model leading to the conclusion, that wind drift factors of light buoyant plastic items - for instance plastic bottles - should considerable exceed those of oil . The transport pathway of those items is nearly independent of hydrodynamic currents and, if the wind direction varies frequently, not predictable. In contrast, drift pathways of low wind affected items are expected to be *good* predictable. Hence, in the following section and chapter, results of simulations with wind drift factors 0 %, 1 % and 5 % are plotted and discussed.

In the end of the presentation of *PELETS-2D* in subsection 2.1.1 the recommendation to give only rough source directions or - even more meaningful - to extract probable non-source regions from simulation results is made, now being supported by this section's findings exemplary illustrated by figure 3.2: Source directions of the particles are approximately equal if the wind drift factor is increased from 0 % to 2 %. The exact locations of particles 80 days before observations, however, are at least 100 km apart in simulations with 0 % and 2 % wind drift. Therefore, giving rough source directions sounds sensible. If simulations with 10 % wind drift are regarded additionally, the angle in which particles have their source located widens considerably. A way of dealing with this uncertainty is to exclude source regions. In the case of figure 3.2 the particles do not pass the Danish coast, the North Frisian Islands and the Elbe-Weser estuaries leading to the conclusion, that in those areas no source regions are located. The statement *For all wind drift factors from* 0 % *and* 10 % *no source regions are located at the Danish coast, at the the North Frisian Islands and in the Elbe-Weser estuaries* is considerably simpler and clearer than listing all possible source regions depending on the wind drift factor.

In order to apply wind drift to real observation data in future, items should be categorised depending on their shape and swimming behaviour when they are observed: The wind drift factor of an abandoned fishing net with a surface marker buoy should exceed one of an abandoned fishing net without such a buoy attached to it. Thus, the notation of the wind drift factor of each sighted item would be helpful, even though it is quite difficult to fulfil: An air-filled plastic bottle provides another contact surface than a full or half-full water-filled plastic bottle. The fill status probably varies and resulting the acting wind drift is not constant over the whole drift time. A compromise is to map each observed item to one of the following categories:

- **no wind drift** for submerged items (e.g. fishing nets)
- **slight wind drift** for in small parts emerged items (e.g. wood)
- **medium wind drift** for heavy emerged items (e.g. buoys)
- **strong wind drift** for light emerged items (e.g. air filled plastic bottles)

The wind drift category should not depend on the item category in general (e.g. bottle, glove, can, piece of Styrofoam) but be noted by the observer individually.

Particles detected western of $7°E$ and southern of $54.5°N$ source primarily from western or south-western direction. Land-based litter detected there likely is injected at British, Belgian and Dutch coasts and not at Swedish, Danish or German ones. Whereas, litter in general could also originate from the Channel. The above defined observation area is denoted the *south-western region* from now on. Particles observed eastern of $7.5°E$ and southern of $54.5°N$ often originate from the Elbe, Weser and Jade rivers or the German coast and sometimes from the west, only rarely sourcing from northern directions. This area is denoted the *south-eastern region*. For observations northern of $54.5°N$ (*northern region*) the partiles' source directions vary considerably indicating no seasonal relation. Supposedly, in the northern North Sea, the ocean currents and drift pathways of particles stronger depend on the present weather conditions than in the southern leading to larger variations. Whereas ocean currents in the southern North Sea resist stronger against short term variations of the weather.

Environmental conditions during surveys and source directions of particles observed in a monitoring region should be as constant as possible implying that the south-western region is most and the northern region least appropriate for a recurring monitoring. Though, the density of available observations data does not allow to test this classification. Additionally, seasonal variations in the particle transport cannot be identified reliable because of temporal inhomogeneous distribution of those observations. Hence, observations, spatially sensible distributed as well as recurring in time, are need. As no real data matching these requirements exist, observations of a fictive monitoring which do match are introduced in the next section (section 3.2). Before this section finishes: one last paragraph.

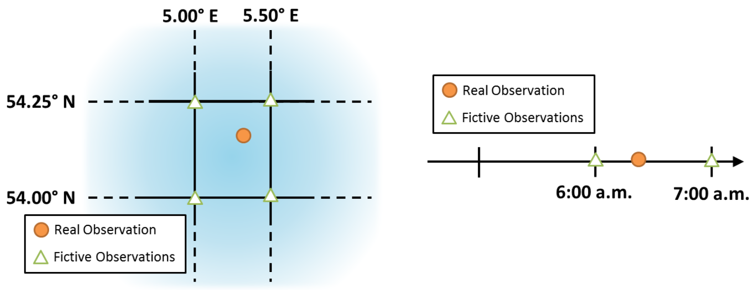


Figure 3.10.: One way of defining fictive observations. Aim of these fictive observations is to test the sensitivity of the particles drift relating to small variations in space and time.

To each observed item - contained in the data set used in this section - the exact time and location of observation are noted. Which influence would it have, if time and/or location of observation were affected by noise? How sensitive do particle trajectories react on small variations in initial time and initial location? To deal with these questions the procedure which is outlined in figure 3.10 could be applied. For each real observation several fictive observations with small deviations in initial time and initial location are injected and drifted. Then the simulations results are compared. That comparison is beyond the scope of this thesis. Hence, the topic is not discussed further in detail. Instead this section is finished.

3.2. Backward simulations with fictive observations

In this section comparing observation region locations with respect to the predicted particle origin and to variations in it is one topics. Additionally, a focus is put on seasonal variations in drift pathways and possible source locations of particles. Rough suggestions for the placement of sea-based monitoring surveys are made, whereas an appropriate frequency of monitoring cruises is no topic. In summary the following three questions arise:

- *Do the travel history and especially possible sources of particles observed in different regions of the German Bight depend on the location of the observation region and on the season?*
- *Where should a monitoring take place and which regions are inappropriate for observations?*
- *Is it possible to map source locations to observations regions of buoyant items?*

The base of the simulations in this section form observations of a fictive monitoring having taken place every 28 hours from March 2006 till December 2008 and being introduced in section 3.2.1. Every event contains 600 particles randomly distributed within four observation regions. In agreement with section 3.1 particle trajectories are calculated 80 days backward applying 0 %, 1 % and 5 % wind drift. In the second subsection plots of single events are presented and discussed, whereas in the third one composites are introduced, aggregating simulation results of several years.

3.2.1. Fictive monitoring data

The observations from Thiel et al. [2011] are spatially and temporally wide distributed, implying unclear distinction between spatial and temporal variations in the particle transport. Therefore, in the next section observations of a fictive monitoring provide the base for simulations yielding a higher resolution in space and time for identifying those variations. The fictive monitoring is assumed to be performed from March 2006 to December 2008 recurring every 28 hours in 12 quadratic regions in the German Bight synchronously. The period from 2006 to 2008 is chosen in agreement with the real observations' periods presented in subsection 2.2. Per survey 600 particles are placed randomly distributed within the regions allocating about 50 particles in each one. The period length of 28 hours is chosen according to the 12.5-hour tidal cycle in the North Sea providing observations in different tidal stages.

Figure 3.11 visualises 10 regions' locations, while two are left out. They are defined on the base of section's 3.1 results and of arbitrariness, including regions close to the German coast, around Helgoland, at the latitude of the German-Danish border and at the longitude of the German-Dutch border. The 10 plotted regions are cumulated to four observation regions being denoted as SW, NW, NE and SE. Whereas SW abbreviates south-west and is mapped to the four south-western yellow-marked regions, NW abbreviates north-west and is mapped to the two north-western red-marked regions and so on. The observation regions are synonymously called observation areas.

This presented fictive setup is not realistic. On the one hand, nearly daily ship-based litter observations synchronously at at least 12 locations in the German Bight require much personnel and, thus, cause high expenditures. On the other hand, not the whole regions but single transects only can be surveyed. The fictive monitoring, however, provides data needed for this study implying that, if this data is not useful for any of the proposed tasks, one should desist from ship based debris surveys in general.

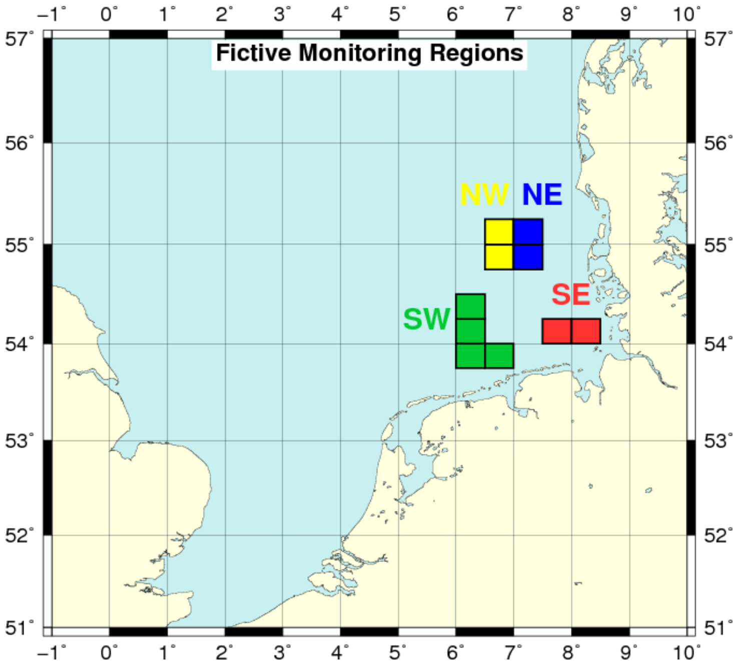


Figure 3.11.: The four observation regions in the south-western (SW, green), north-western (NW, yellow), north-eastern (NE, blue) and south-eastern (SE, red) German Bight. About 50 particles are started in each square region.

3.2.2. Four single events

The particle drift of four single events is described qualitatively and discussed in this section. The focus lies on analysis of the direction of particle origin, depending on observation regions, wind drift factor and seasonal variations of hydrodynamic currents. Therefore, results of simulations with 0 %, 1 % and 5 % wind drift split for the four observations regions are plotted in figures 3.12 to 3.14, depicting the plots alignment in table 3.1.

		wind drift		
		0 % ↓	1 % ↓	5 % ↓
region	south-west →			
	north-west →			
	north-east →			
	south-east →			

Table 3.1.: Arrangement of plots in figures 3.12 to 3.14.

Event 2006071819

Particles of the event 2006071819 observed in the **SW and NW** regions are described first (fig. 3.12 first and second row), whereas, if only one region is regarded, it is mentioned explicitly. of the event 2006071819 (fig. 3.12 first and second row). In simulations without wind drift, the source is located in south-western to western direction. The source direction deviates only slightly, if the wind drift factor is increased to 1 %. However, the particle drift pathway becomes z-shaped. Increasing the wind drift to 5 %, shifts the source considerably northward to Scotland and the to northern connection to the North East Atlantic. For all wind drift factors coasts of Denmark, Schleswig-Holstein and the Elbe-Weser estuary are unlikely to be source regions.

Additionally, particles observed in the NW regions probably do not source from Dutch and Lower Saxon coasts.

Source directions of particles observed in the **NE and SE** regions considerably depend on the wind drift factor as the CTH-plots in the third and fourth row of figure 3.12 suggest. While particles source from Elbe-Weser estuaries in the south-east in simulations without wind drift, the source direction shifts to west and south-west, if 1 % wind drift is added. The particles observed in NE are clearly drifting off-shore over the whole eighty days, whereas those observed in SE move nearshore along the Dutch and German coasts turning loops in turbulent coast currents with a low overall velocity directed eastward as indicated by not plotted particle trajectories. If the wind drift amounts 5 %, particles detected in NE originate from Scotland and the North East Atlantic, not passing the continental coast. The source of particles detected in the SE is located further eastward: Scotland is no probable source region but the North East Atlantic is as well as the coast of Norway.

Event 2008060423

Simulations of event 2008060423 visualised in figure 3.13 show quite similar behaviour in the transport of particle of all observation regions. In simulations with **0** % and **1** % **wind drift**, independent of the observations region particles originate from the south-east, excluding all coasts except the German one as source regions. Particles observed in the northern observations regions have their source slightly more northward at the coast of Schleswig-Holstein and in the Elbe estuary, while those observed in the southern regions primarily source from the Lower Saxon coast and the Elbe-Weser estuaries.

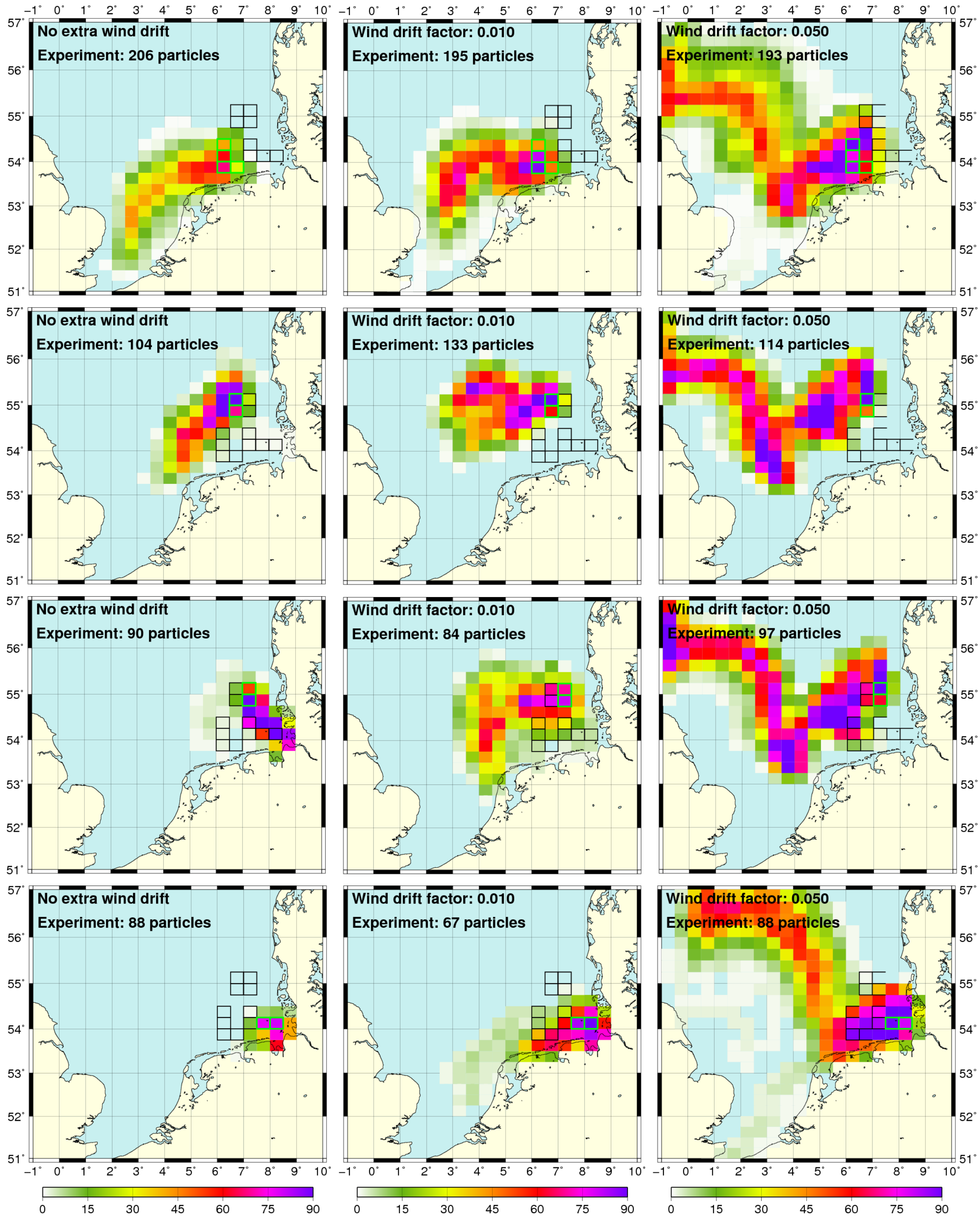
If the **wind drift** factor amounts **5** %, two distinct source regions exists as CTH-plots indicate. One is located in the direction of $57°N$ and $4°E$. For particles observed in the northern regions, the second one is situated directly northward, whereas for particles observed in the southern regions, it is situated near the Elbe-Weser estuaries. The British, Belgian and Dutch coasts are not expected to be source regions.

Event 2006101019

The source direction of particles detected in all observations regions is located in the west to south-west and varies slightly with increasing wind drift factor. In simulations with **0** % and **1** % **wind drift**, the drift pathway is bent to the south, passing the German and Dutch coasts in the case of in the southern regions observed particles. While those observed in the SW regions possibly source from the Channel or from the north along the British coast, the particles observed in the other regions definitely do not source from the Channel.

Though, if **5** % **wind drift** is added, particles observed in the SE region primarily enter the North Sea through the Channel, while those observed in the north seem to be injected mainly in the Wash Bay. The velocity of wind drifted items increases as the stretched particle drift pathway indicates.

Coasts of Norway, Denmark and Germany are not expected to be source regions **independent of the observation region and the wind drift factor**, apart from the Lower Saxon coast which is past by particles observed in the SE region. Additionally, particles observed in the north do not originate from the continental coast, in general.



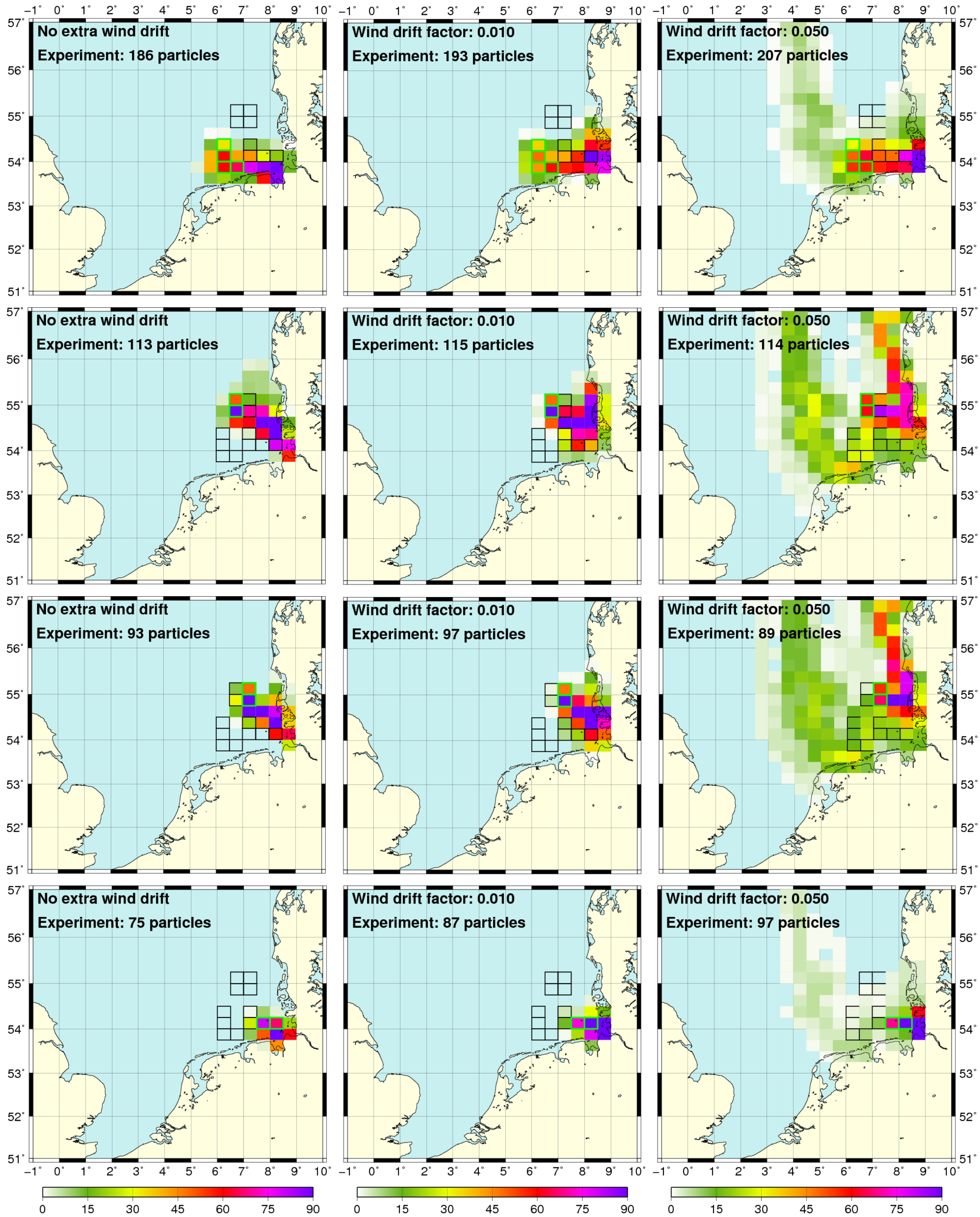
Time of Release: 2006-07-18 (19:00)

Percent of particles having travelled through target regions

Units: Percentage released particles

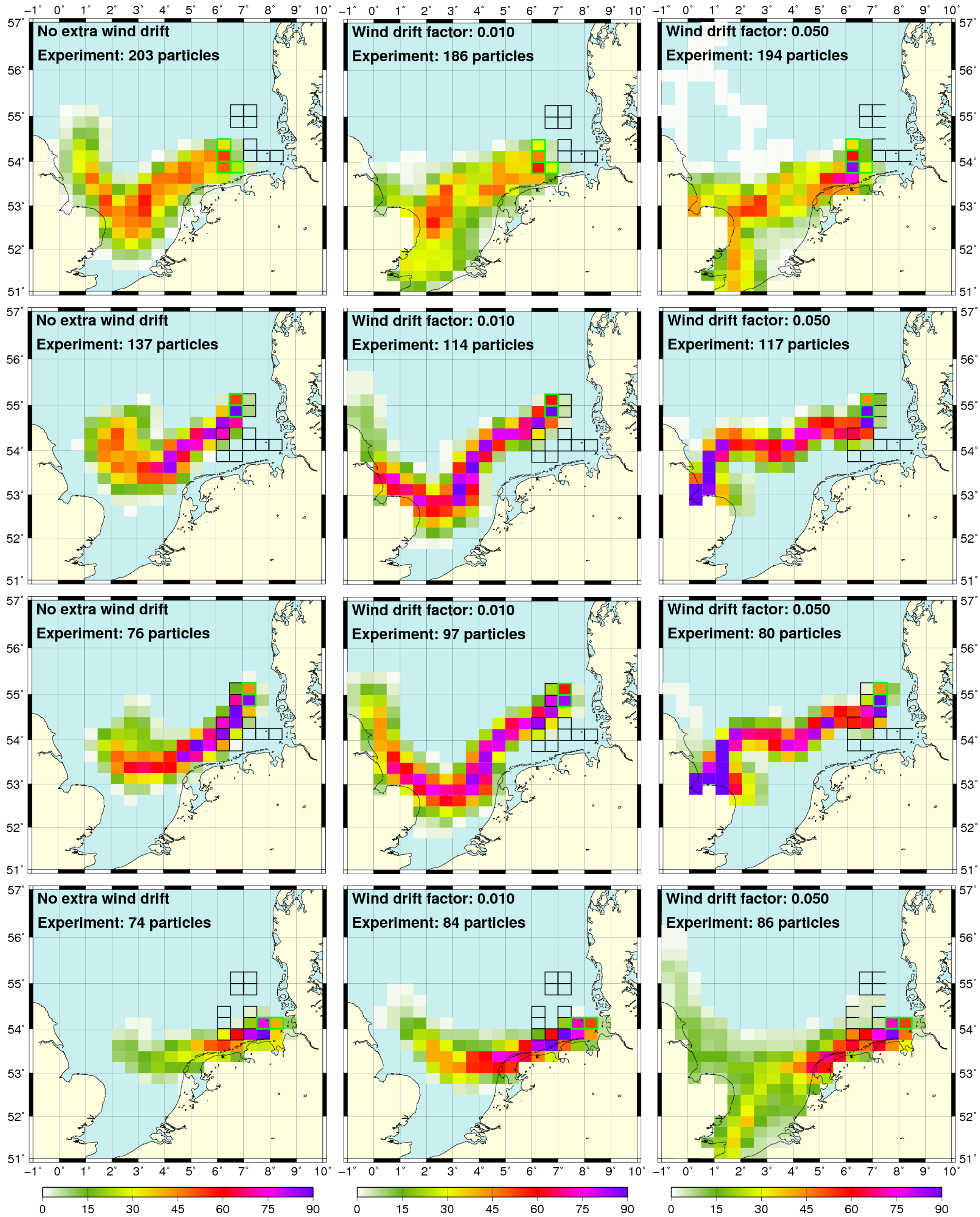
Integrated: 1920 hours

Figure 3.12.: CTH-plots to 80-day backward simulations of particles fictively observed at 18/07/2006 19 o'clock in four observation regions, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by observation region, starting with SW and being followed by NW, NE and SE. The active observation regions is framed in green, while the others are framed in thick black.



Time of Release: 2008-06-04 (23:00)
Percent of particles having travelled through target regions
Units: Percentage released particles
Integrated: 1920 hours

Figure 3.13.: CTH-plots to 80-day backward simulations of particles fictively observed at 04/06/2008 23 o'clock in four observation regions, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by observation region, starting with SW and being followed by NW, NE and SE. The active observation regions is framed in green, while the others are framed in thick black.



Time of Release: 2006-10-10 (19:00)

Percent of particles having travelled through target regions

Units: Percentage released particles

Integrated: 1920 hours

Figure 3.14.: CTH-plots to 80-day backward simulations of particles fictively observed at 10/10/2006 19 o'clock in four observation regions, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by observation region, starting with SW and being followed by NW, NE and SE. The active observation regions is framed in green, while the others are framed in thick black.

Event 2007101307

In simulations of event 2007101307, the most variable drift pathways arise for particles observed in the both southern observation regions, being plotted in the first and last row of figure 3.15. In simulations without wind drift, particles detected in the **SW** region are of diffuse origin with a slight tendency to the east, while with wind drift of 1 % the particles originate from the north-north-west, forming a wide and diffuse drift pathway. If the wind drift factor is increased to 5 %, the source directions shifts to the west narrowing the drift pathway.

Particles detected in the **SE** region clearly originate from the Elbe-Weser estuaries, when no wind drift is added. Applying wind drift of 1 %, however, shifts the particle source direction to the north-north-west. After arriving in the central Wadden Sea from there, particles are drifted several times along the German coast, before being observed. If the wind drift factor amounts 5 %, the particles originate from the Scottish coast and the North East Atlantic in the north-west, primarily being transported south-eastward from $1°W$ to $6°E$ and, after a loop along the northern Danish coast, to the observation region. Instead of drifting to Denmark, some particles move along Dutch and Lower Saxon coasts, before being observed.

Particles detected in the **NW and NE** regions originate from the north, if the wind drift amounts 0 % and 1 %. In simulations without wind drift, the transport pathway is more focussed and it starts in the Skagerrak, rather, while in simulations with 1 % wind drift, particles enter the map section more eastern. If 5 % wind drift is added, the particle behaviour quite equals the one of particles detected in the southern regions shifting the loop further northward. Resulting the Swedish coast and the Skagerrak are additional possibles source regions.

The Channel and the Dutch and English coasts are not expected to be source regions, **independent of the observation region and the wind drift** factor, but apart from strongly wind affected particles observed in the SE region. Additionally, in simulations with 0 % and 1 % wind drift, the British coast is no probable source region.

3.2.3. Aggregating data: composites

Till now plots of single events were regarded, only. This has advantages: Daily variations in ocean currents are apparent, extremal system behaviour is recognised directly and the loss of information is low. However, assumptions made on the base of two or three single events are not necessarily correct for other events and inter- and intra-annual variations are hard to distinguish. Additionally, looking at each event is time consuming. Composite plots provide an alternative by aggregating several events (see definition and example in boxes 5 and 6).

Definition Box 5 (Definition: composite)**.** The aggregation of several events is denoted as a composite. A composite equals an event with the exception, that it contains particles not being started within one hour, only. In this thesis, events of one certain season (summer, autumn, winter, spring) but over several years are united to composites, forming data sets with average behaviour during one season while inter-annual variations are averaged out.

Example Box 6 (Example: composite)**.** In subsection 3.2.3 all events started in January, February and March of the years 2000 to 2008 are united to one winter composite. (The events contain 80 days backward transported particles. During more than half of the integration time of in January, February and March started particles it is winter.)

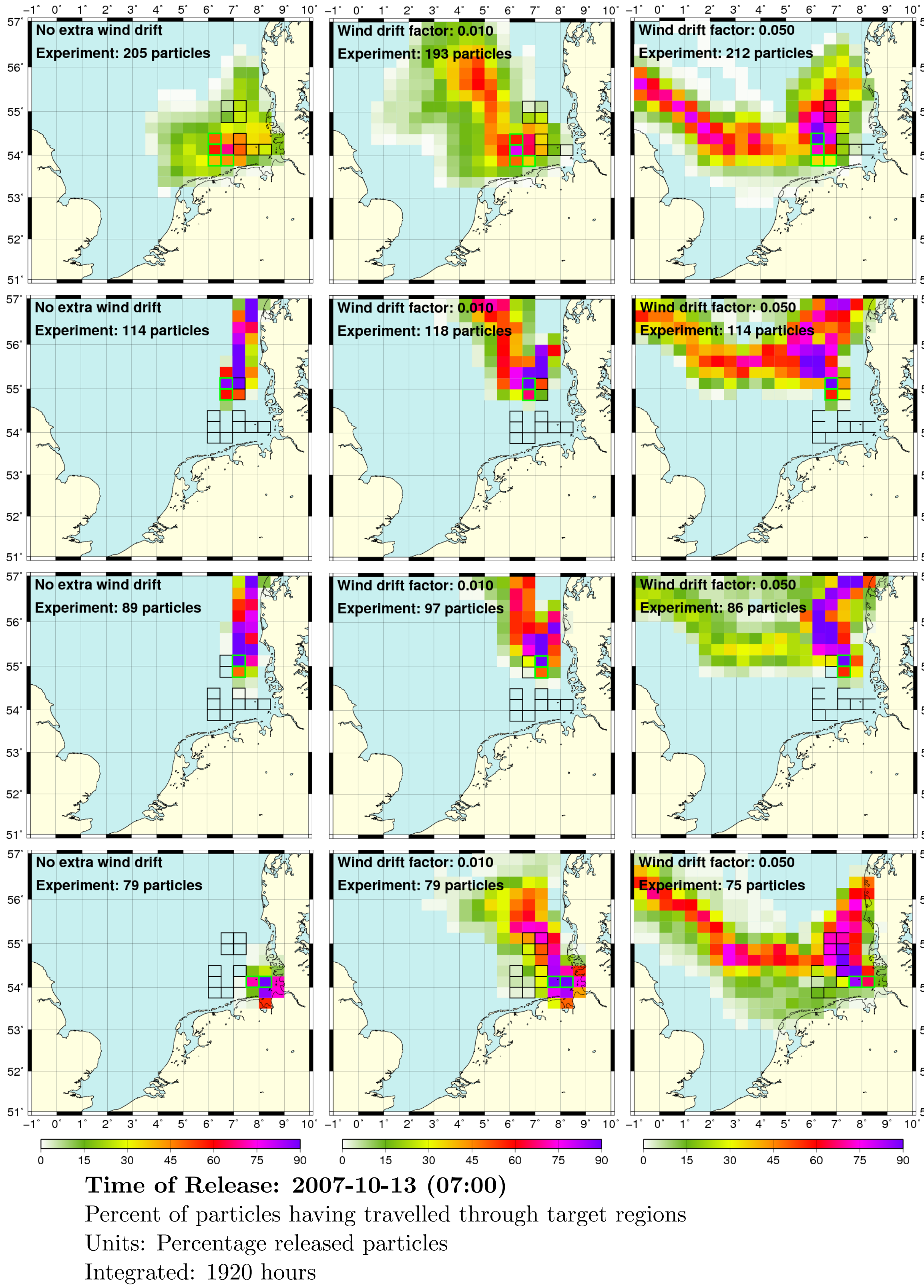


Figure 3.15.: CTH-plots to 80-day backward simulations of particles fictively observed at 13/10/2007 7 o'clock in four observation regions, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by observation region, starting with SW and being followed by NW, NE and SE. The active observation regions is framed in green, while the others are framed in thick black.

Here, the focus concentrates on seasonal and no inter-annual variations in ocean currents and in possible particle origins depending on the location of the observation region. Hence, all events are clustered in four groups for creating composites:

- winter: January, February and March events
- spring: April, May and June events
- summer: July, August and September events
- autumn: October, November and December events

Actually, March is not a winter month. However, at least 50 of 80 days of March events' particles drift time fall within the winter. Whereas at most 30 of 80 days of December events' particles drift time fall within winter. Thus, it is more sensible to map March events to winter, December events to autumn, September events to summer and June events to spring. Because of the availability of *BSHcmod* V3 hydrodynamic currents, winter and spring data of the years 2001 - 2008 and summer and autumn data of the years 2000 to 2007 is aggregated to composite plots, resulting in four plots per wind drift factor and observation region. Figures 3.16 to 3.19 show those plots split by region, each being aligned according to table 3.1 with one wind drift factor per column and one observation region per row. After the plots of single events being described in detail in subsection 3.2.2, the additional knowledge gained by the composite plots is probably low. Nevertheless they are present, mainly as outlook on chapter 4, where primarily those plots are used.

In simulations with **5 % wind drift** the observation location of particles is of low importance. Similar densities - western of $6°E$ and northern of $55.5°N$ - in the CTH-plots in the right column of each figure suggest this. Seasonal variations persist. During **spring** particles travel to nearly any location in the southern North Sea and to all bordering coasts leading to CTH-densities above 5 % in most regions and above 15 % in all coastal ones. Additionally, in no direction a drift path indicated by increased CTH-densities exists.

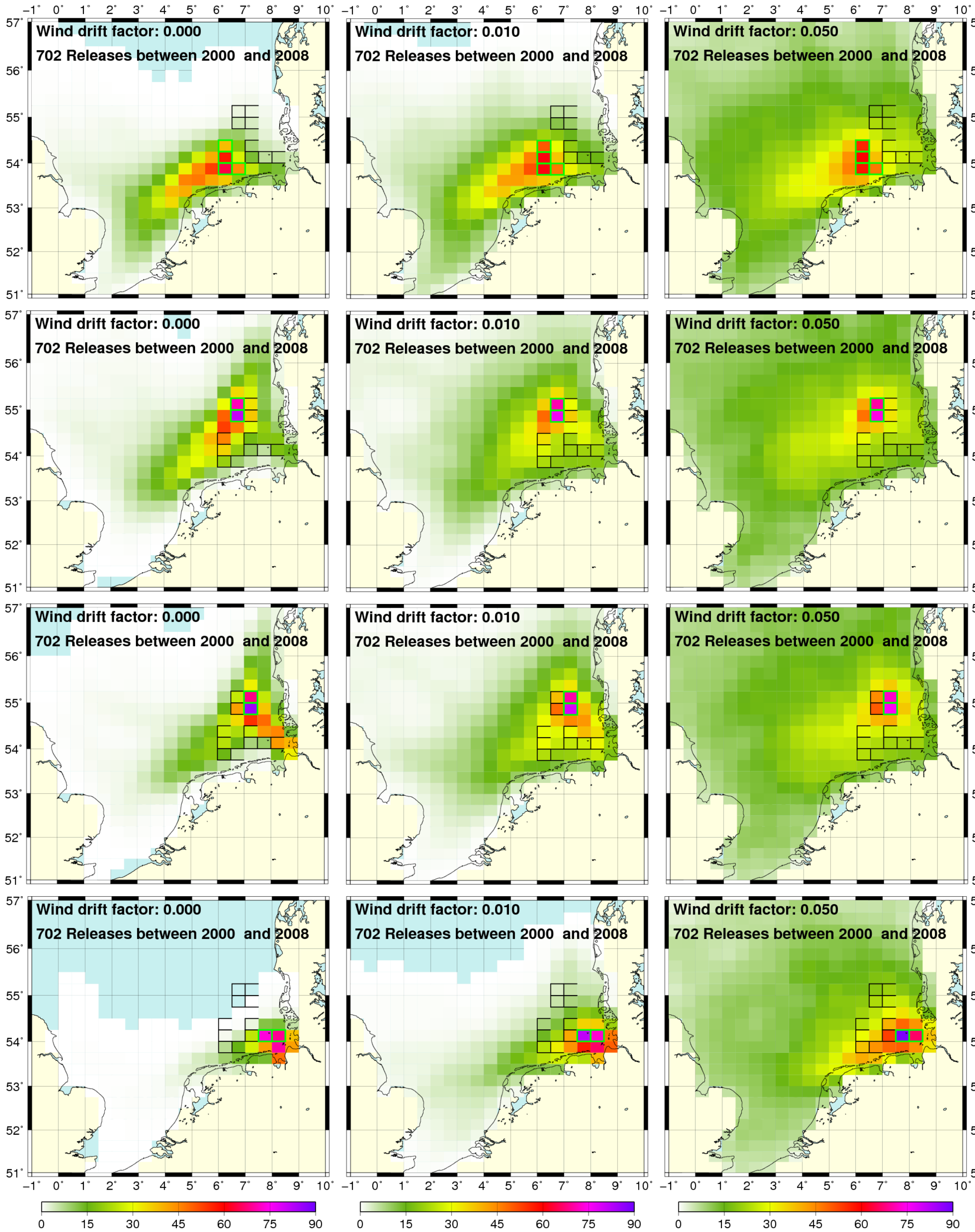
Summer particles arrive the observation regions from south-western directions, probably not sourcing from Belgian, Dutch or Danish coasts. Depending on the location of the observation region, coasts of Lower Saxony and Schleswig-Holstein could be the origin of particles.

The system behaviour during **autumn** and **winter** lies between that during the other two seasons: Most open sea regions are crossed by at least 5 % of particles and all coasts except of the Danish and Norwegian ones are possible source regions. At the same time a particle transport from the west is apparent.

However, during **no season** a clear long drift path develops. Remarkable are quite high particle densities 80 days before observation in the Humber estuary, the Wash Bay and the Thames estuary (not plotted). These could be real source locations but more likely the particles are captured in those estuaries by strong *backward wind* force.

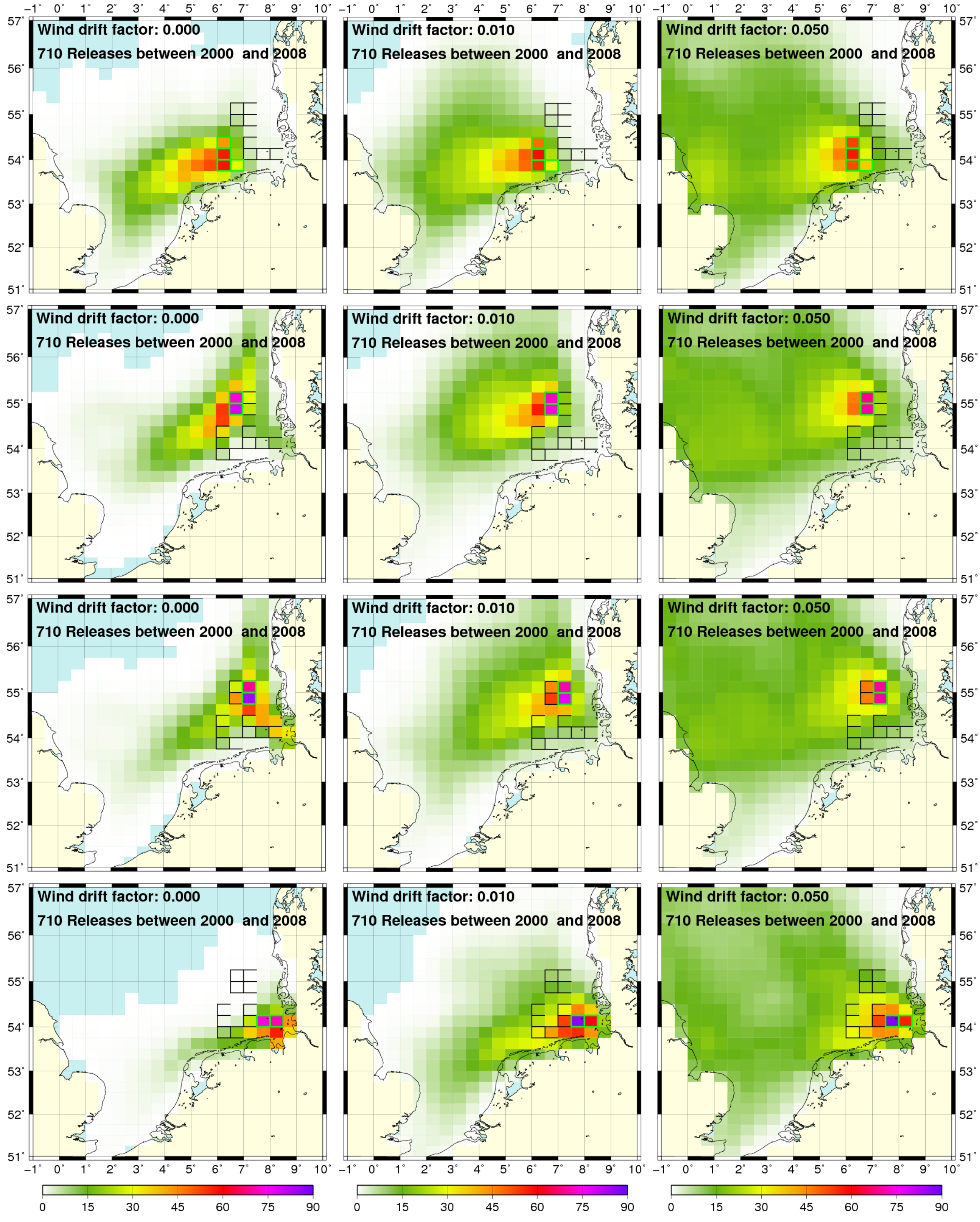
Composite plots to **0** % and **1** % **wind drift** are described in one, because the basic system behaviour mostly equals: If a main drift path is present, it exists in both simulations without and with 1 % wind drift, being less focussed, if wind drift is applied. Throughout the year, particles observed in the two **southern regions** source originate from western directions and in the case of the SE region, additionally from the Elbe-Weser estuaries and the Lower Saxon coast, as indicated by CTH-densities.

Particles observed in the **northern regions** source from three directions: south-west from the Channel and the British coast, north from Norway along the Danish coast or south-east from the Elbe-Weser estuaries. If 1 % wind drift is applied to particles during autumn, no particle transport from the north into the northern observation regions takes place being the only deviation between 0 % and 1 % wind drift simulations. Spring and summer particles



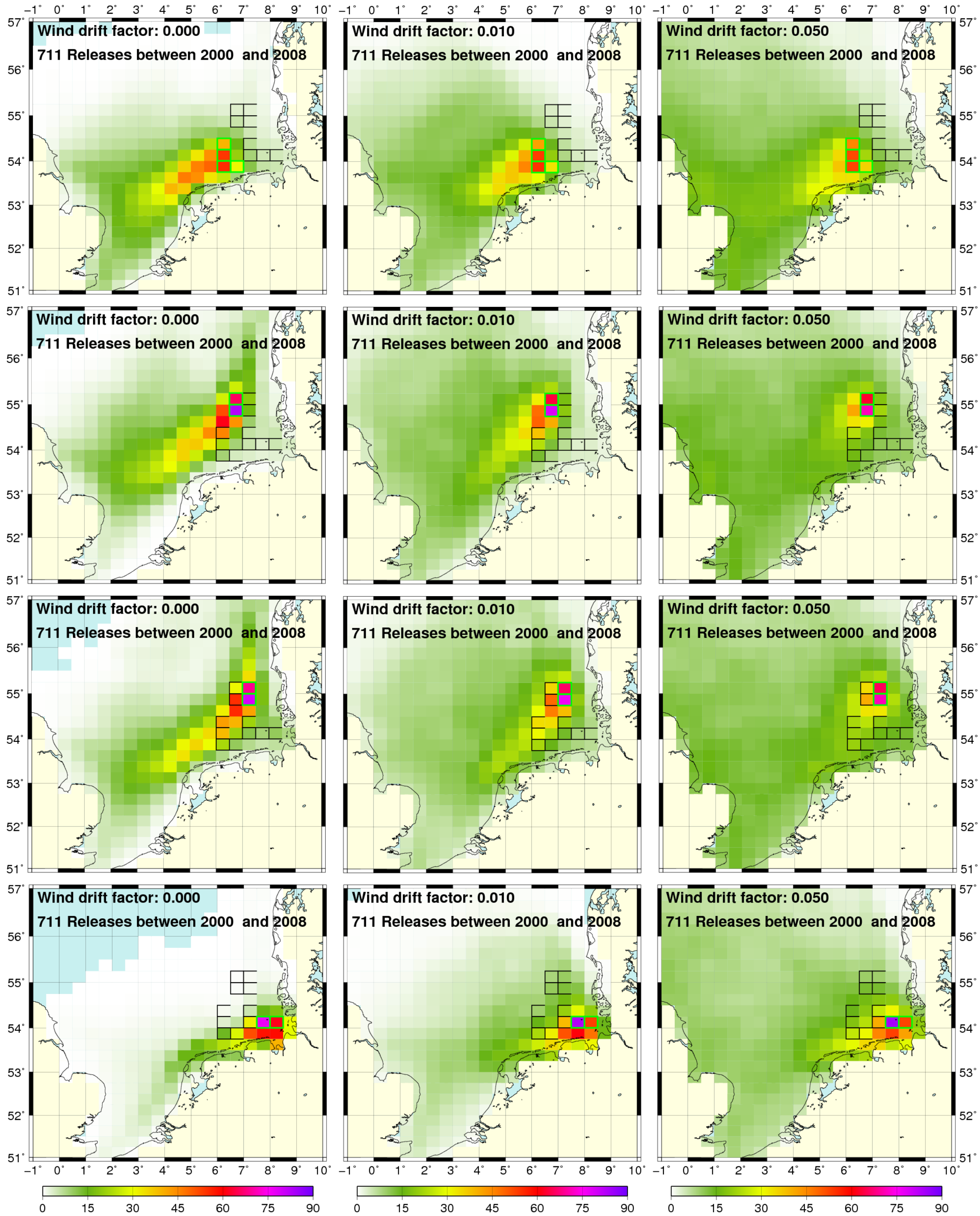
711 Releases between 2000-10-01 (11:00) and 2008-12-31 (23:00)
Percent of particles that are in each target region
Units: Percentage of released particles
Constraint: Only events from month 04 05 06
Integrated: 1920 hours

Figure 3.16.: CTH-composite-plots to 80-day backward simulations of particles fictively observed during April, May and June 2000 to 2008 in four observation regions, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by observation region, starting with SW and being followed by NW, NE and SE. The active observation regions is framed in green, while the others are framed in thick black. The about 35000 particles (≈ 700 events with each ≈ 50 particles) are primarily drifted during spring.



711 Releases between 2000-10-01 (11:00) and 2008-12-31 (23:00)
Percent of particles that are in each target region
Units: Percentage of released particles
Constraint: Only events from month 07 08 09
Integrated: 1920 hours

Figure 3.17.: CTH-composite-plots to 80-day backward simulations of particles fictively observed during July, August and September 2000 to 2008 in four observation regions, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by observation region, starting with SW and being followed by NW, NE and SE. The active observation regions is framed in green, while the others are framed in thick black. The about 35000 particles (≈ 700 events with each ≈ 50 particles) are primarily drifted during summer.



711 Releases between 2000-10-01 (11:00) and 2008-12-31 (23:00)

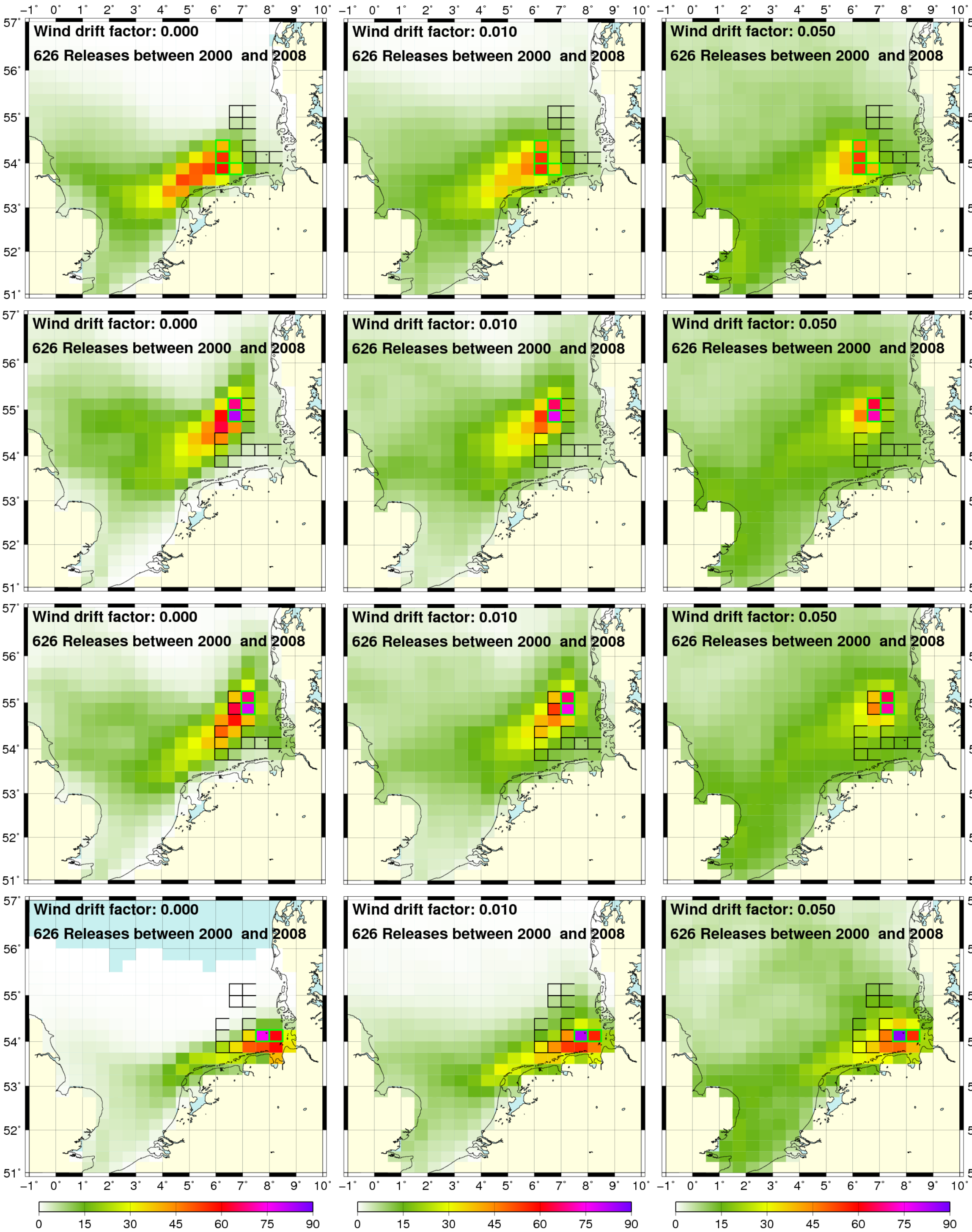
Percent of particles that are in each target region

Units: Percentage of released particles

Constraint: Only events from month 10 11 12

Integrated: 1920 hours

Figure 3.18.: CTH-composite-plots to 80-day backward simulations of particles fictively observed during October, November and December 2000 to 2008 in four observation regions, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by observation region, starting with SW and being followed by NW, NE and SE. The active observation regions is framed in green, while the others are framed in thick black. The about 35000 particles ($\approx$ 700 events with each $\approx$ 50 particles) are primarily drifted during autumn.



711 Releases between 2000-10-01 (11:00) and 2008-12-31 (23:00)
Percent of particles that are in each target region
Units: Percentage of released particles
Constraint: Only events from month 01 02 03
Integrated: 1920 hours

Figure 3.19.: CTH-composite-plots to 80-day backward simulations of particles fictively observed during January, February and March 2000 to 2008 in four observation regions, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by observation region, starting with SW and being followed by NW, NE and SE. The active observation regions is framed in green, while the others are framed in thick black. The about 35000 particles ($\approx$ 700 events with each $\approx$ 50 particles) are primarily drifted during winter.

observed in the NE region primarily originate from the Elbe-Weser estuaries, as CTH-densities in the third row left of figures 3.16 and 3.17 indicate, arriving mainly from the south-west during the rest of the year. Particles observed in the NW regions source from the south-west throughout the year.

For **all observation regions** applies: During winter the transport from the west is strongest and most focussed compared to all seasons, while during summer it is weakest. During spring many particles drift through the inner German Bight and along the German coast before they are observed.

3.2.4. Conclusion and discussion on backward simulations with fictive observations

This section is focussed on observations of a fictive monitoring performed in four regions - SW, NW, NE and SE - in order to model the monitoring of marine litter. Three questions in the introduction of this section framed the focus of the evaluation.

In the SW region primarily items from south-western directions are expected to be observed. One half of those items originally sources from Scotland or the Atlantic inflow close to the Shetland Islands, drifting southward along the British coast and turning towards the north-east close to $53°N$. The other half originates from the Channel and the Atlantic Ocean drifting north-eastward through the Strait of Dover to the observation region. Hence, items observed in the SW region possibly source from the coasts of France, the UK, Belgium and the Netherlands. Additionally, the shipping routes from the Atlantic Ocean to Rotterdam and Hamburg and the fishing grounds in the southern North Sea are possible source regions of marine litter detected there. The SW region is well suited for monitoring litter which enters the German Bight constituting a sum parameter of litter from the Atlantic and most westward located sources.

The SE region, which includes the Island Helgoland is affected by litter from the Elbe-Weser estuaries and from south-western located sources. Submerged not-wind-affected items primarily source, from those river estuaries (results of simulations without wind drift; examples items: fishing nets and water filled plastic bags;) whereas strong wind-affected items mainly originate from the south-west (results of simulations with 5 % wind drift; examples items: pieces of Styrofoam and air filled plastic bottles;). Additionally, litter injected on shipping routes close to the SE regions could be detected. Under constant weather conditions the SE observations of buoyant items are suitable as sum parameter for the pollution by ships close to the Lower Saxon coast and by the rivers Elbe, Weser and Jade. If litter trends for the SE region and the river inflows were available, the pollution caused by ships could be estimated by their difference.

In the two northern observation regions, items, which source from the north, south-west and south-east, are expected to be observed. These items are not drifted continuously from all three directions into the observation regions, but the source direction varies frequently. In the NW region mainly items from the south-west are observed throughout the year. Whereas, in the NE region items from the south-east predominate during summer and spring and those from the south-west during autumn and winter. In the evaluated simulations, particles observed in the NE region has the most variable drift pathway and source locations. Thus, it represents the least sensible region for the establishment of litter monitoring.

The SW region lies at the top and the SE and NW regions in the middle of this ranking. The latter region could be valuable for monitoring the amount of marine litter injected in the German Bight.

Independent of the observation region particles from the south-west drift faster during winter probably being forced by winds blowing predominantly from south-western directions. According to composite plots, the number and magnitude of seasonal variations is quite low eventually caused either by a bad choice of the temporal interval for the composites (here: three month) or by strong daily, weekly or monthly variations in ocean currents and wind. CTH-densities of single events suggest the latter reason (not plotted): During August 2007 particles detected in the SW region arrive from the south-west and west as usual, whereas in the end of September 2007 no clear direction of particle origin is noticeable. Finally, in the mid-November, particles clearly source from the north. Thus, a considerable change in the source direction within about three month is apparent, suggesting that shorter time scales are more appropriate for forming composites. This scale has to be estimated properly before composite plots are created for evaluation.

It has been clearly shown, that a weak correlation between location of the observation regions and the direction, from where particles source, exists. This correlation decrease with increasing wind drift factor. For strongly wind-affected items an identification of their origin only on the base of the observation location seems impossible, as quite similar CTH-plots of different observation regions of simulations with 5 % wind drift suggest. Under these circumstances, assumptions about where no litter came from are more sensible and more reliable than any other assumption about possible source locations. Whereas, source directions of not or slightly wind-affected items can be estimated on the base of the observation region and drift models. But even in simulations without wind drift, these regions cannot be mapped exactly to source locations.

Observation regions close to river estuaries provide the possibility to measure the litter input by these rivers. However, no other possible marine litter sources as for instance a shipping route should be in range. Alternatively, measuring the sum of all litter originating from one direction at different locations may help estimating the litter input between these locations. In doing so it has to be kept in mind, that particle drift pathways may vary on monthly basis.

4. Forward simulations

In this chapter, the focus shifts from ship-based observations at the sea to the pollution of beaches by marine litter from different sources in the German Bight. Litter accumulations regions and estimating seasonal and regional variations in the beach litter composition are identified. In further studies, suggestions should be made on what parameters people have to focus when performing beach litter surveys and analysing beach litter data (e.g. the OSPAR beach litter monitoring). The estimations here are a first shot. Additionally, the transport of particles in the northern North Sea is regarded in order to identify accumulation regions there and to evaluate whether litter items remain a long time in the North Sea or leave it fast towards the Atlantic Ocean or the Baltic Sea. For that purpose, particles are injected in different configurations of source regions and drifted half-a-year forward from there, applying wind drift factors 0 %, 1 % and 5 %. Backward simulations which start at beaches are not performed, because the resolution of hydrodynamic currents in coastal areas is too low for calculating particle transport in appropriate quality. A homogeneous initial particle distribution in section 4.1 serves as a base for identifying accumulations regions and the out-flowing litter. Whereas three shipping routes and several river estuaries in section 4.2 form source regions for predicting litter compositions of different coastal regions.

In 80-day simulation (80 days = 1920 hours) without wind drift possible accumulation regions do not develop because particle trajectories are too short. Therefore, half-a-year forward simulations (0.5 years ≈ 180 days = 4320 hours) are performed starting four times a year (≈15. Jan., ≈15. Apr., ≈15. Jul. and ≈15. Nov.) from July 2000 to April 2008, leading to eight events per season. For the identification of seasonal variations four runs per year are the least possible number. However, simulations took quite long and the results occupy a lot of hard disc space (about 1.3 GB per event with homogeneous distribution and about 0.3 GB per event with other distributions leading to about 240 GB).

Simulations of the October event (≈ 15. Oct. - 15. Apr.) enclose the whole winter (thus, representing the particle drift during winter), those of the January events the whole spring and so on. This mapping is sensible for a comparison with section 3.2 and enables a clearer and simpler description and understanding of seasonal variations.

		wind drift		
		0 % ↓	1 % ↓	5 % ↓
cumulative travel history in % (CTH)	→			
travel time of first 20 % of particles in days (TT20)	→			
mean residence time in days (MRT)	→			

Table 4.1.: Arrangement of plots in figures ...

Primarily composite plots (see boxes 5 and 6 on page 35 in subsection 3.2.3 for definition and one example) visualise results in this chapter aggregating several events by season and averaging annual variations out. In some situations single events are plotted. Additionally, it is useful to consider not only *cumulative travel history* plots (CTH) but also plots of the *travel time for the* *first* 20 % *of particles* (TT20) and the *mean residence time* (MRT) (see boxes 3 and 4 on page 17 in subsection 3.1.1 for definition and examples). The plots in figures containing composites are arranged identically in all sections as follows: CTH plots in the first, TT20 plots in the second and MRT plots in the last row; results of simulations with 0 % wind drift on the left, with 1 % in the center and with 5 % on the right. Table 4.1 illustrates the arrangement.

4.1. Homogeneous initial distribution

We start with the discussion of half-a-year forward simulations from a homogeneous distribution of 8700 particles in the area between $49.5°N$ and $57.0°N$ and $3.0°W$ and $9.0°E$. For detailed evaluation of special sources or currents the whole area is split in 87 source regions, each with 100 particles initially. Alternatively, placing all particles in just one big source region would have been also possible. Figure 4.1 shows the location of the 87 source regions in the North Sea and the Channel. Events where started quarterly from 07/2000 to 04/2008. Ocean currents of the *BSHcmod* V3 are used.

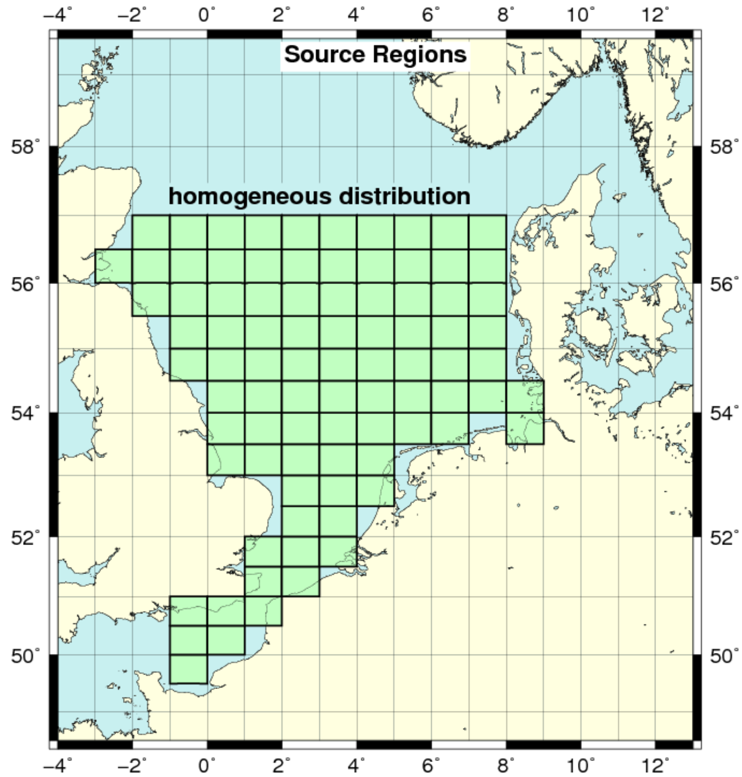


Figure 4.1.: Map with initial particle distribution: The map contains 87 regions. In each region 100 particles are placed randomly. Dry land is excluded as possible initial location of a particle. Thus, 8700 particles are distributed approximately homogeneously between $49.5°N$ and $57.0°N$ in latitudinal and $3.0°W$ and $9.0°E$ in longitudinal direction.

In this subsection we focus on the identification of accumulation regions and main drift pathways of marine litter in the whole North Sea. Regarding the surface currents of the North Sea (see section 2.3), buoyant marine debris could be transported in two ways. It could be drifted *(1st)* in a counter-clockwise circular direction several times through the entire North Sea or *(2nd)* in northern direction along the Norwegian coast out of the North Sea into the Atlantic Ocean. Both cases are supported by our simulation results. In contrast to subsection 4.2, we regard the whole North Sea in this subsection. The *BSHcmod* V3 simulates ocean currents up to $59.5°N$

and 4.0°W (subsection 2.1.2). Therefore, northern of this latitude or western of this longitude no current data is available. Particles which would leave this model region are stopped at their last location and not drifted anymore. Artificial accumulation regions are the consequence. Particles do not ground in the performed simulations and resulting they are not washed ashore and lie at beaches till they recaptured by the sea. Drift of particles is suspended only if they fall dry or leave the model domain. See section 2.1 for information on dry-falling, stranding and leaving the model domain.

4.1.1. January events

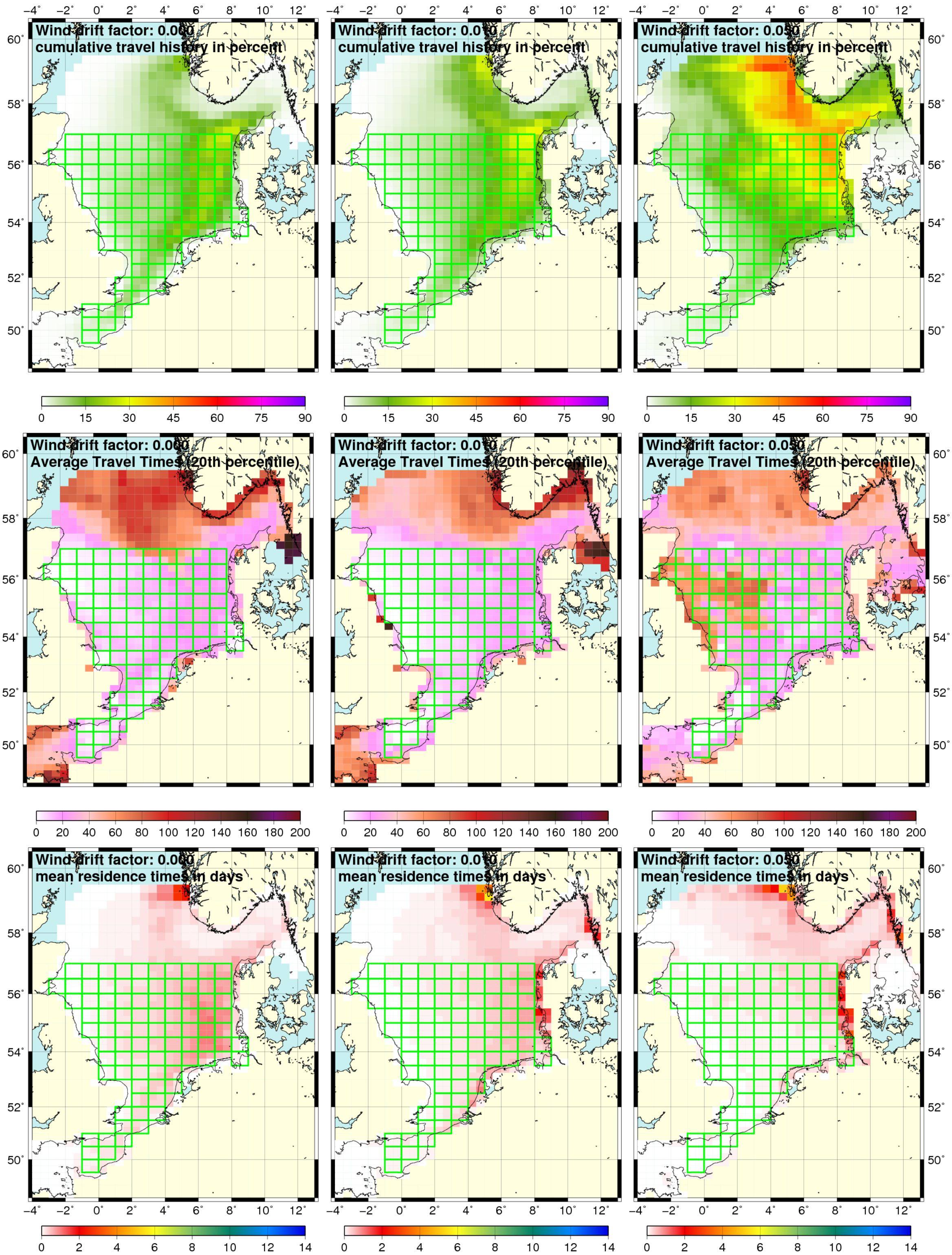
Figure 4.2 contains CTH, TT20 and MRT composite plots of half-a-year forward simulations with 0 %, 1 % and 5 % wind drift having been started in January 2001 to 2008. The plots are aligned according to table 4.1. The behaviour of particles of the January events lies between that of the July and October events on the one and the April events on the other side. In simulations without wind drift, about 30 % to 50 % of the particles injected in the North Sea are transported into the Skagerrak. Some remain there but the majority is drifted on an u-shaped path along the Norwegian coast into the North-East Atlantic. The TT20s in the center left plot of figure 4.2 suggest this order. The CTH-densities in the top left plot suggest the quantities. The other 50 % to 70 % of particles are far distributed in other regions of the North Sea. The MRTs in the German Bight and northward of it till 57° exceed the average MRTs, which indicates long residence times of particles there. We assume a mixture of both. Probably some of the remaining particles are drifted in counter-clockwise direction by North Sea currents. We cannot prove it with the available data.

If 1 % wind drift is added, the proportion of particles entering the Skagerrak increases and more particles advance deeper into it. As in simulations without wind drift, most particles are drifted on an u-shaped path from the Skagerrak into the North East Atlantic as CTH-densities in figure 4.2 indicate. Compared to simulations without wind drift, the particle drift pathway is wider and a faster transport is indicated. Low MRTs at open sea lead to the conclusion, that particles are washed ashore, earlier. Particles affect especially the Danish west coast, the North Frisian Islands and parts of the coast of Schleswig-Holstein and Sweden as CTH-densities reveal.

If the wind drift factor is increased to 5 %, the amount of particles drifted into the Skagerrak and later into the Atlantic Ocean increases again, indicated by higher CTH-densities in figure 4.2 top right. The transport velocities out of the German Bight, into the Skagerrak and towards the Atlantic rise. Although, the CTH-densities in the western North Sea increase, the MRTs in these regions do not, which suggest, more particles are drifted into these regions but do reside for a rather short period of time. The MRTs at the south-eastern Scottish coast are noticeable increased. This fact in combination with low CTH-densities suggest long residence times of a few particles at that coast.

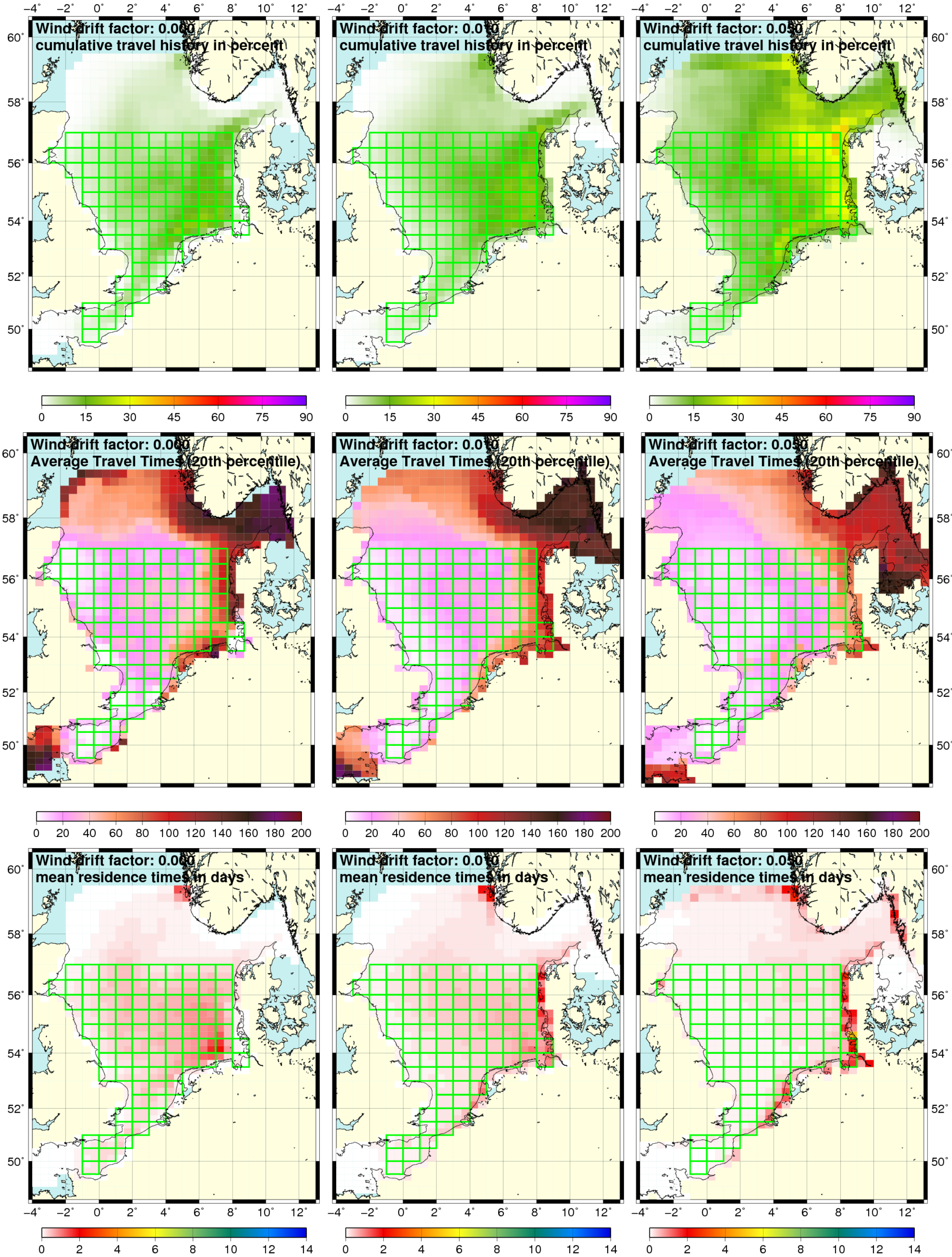
In simulations with 0 % and with 1 % wind drift nearly no particles enter the Kattegat, while for 5 % the CTH-densities rise considerably, indicating a particle drifted till Zealand (Main island of Denmark with Copenhagen on it).

The composite plots provide great assistance, if many simulations of several years have to be aggregated as in this case. The aggregation of data often leads to a loss of information as a comparison with two single simulations of the January 2007 event with 0 % and 5 % wind drift reveal. CTH-densities are plotted in figure 4.6 on the left and in the center, whereas the plot on the right is focussed, later. The not wind affected particles injected in January 2007 drifted are divided in two groups. While one remains in the southern North Sea, the other one is drifted northward at first into the Skagerrak and then into the North East Atlantic. TT50s (not shown) indicate the drift pathway of the latter group, whereas CPL-densities (not plotted) suggest the



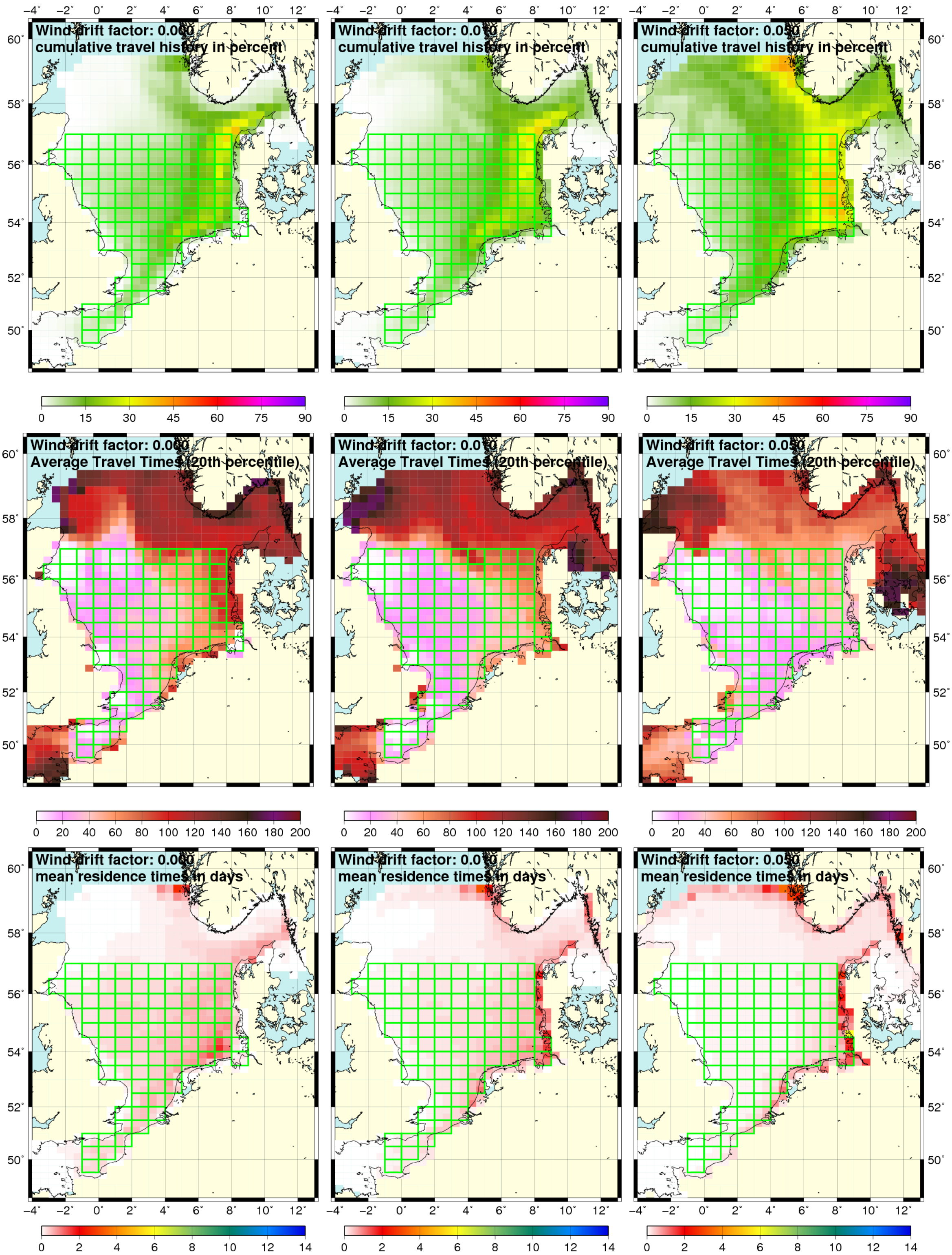
8 Releases between 2001-01-13 (13:00) and 2008-01-14 (13:00)
Experiment: 8700 particles released from any source
Integrated: 4320 hours

Figure 4.2.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from a homogeneous particle distributions in January 2001 to 2008, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 69600 particles are drifted.



8 Releases between 2001-04-14 (19:00) and 2008-04-12 (19:00)
Experiment: 8700 particles released from any source
Integrated: 4320 hours

Figure 4.3.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from a homogeneous particle distributions in April 2001 to 2008, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 69600 particles are drifted.

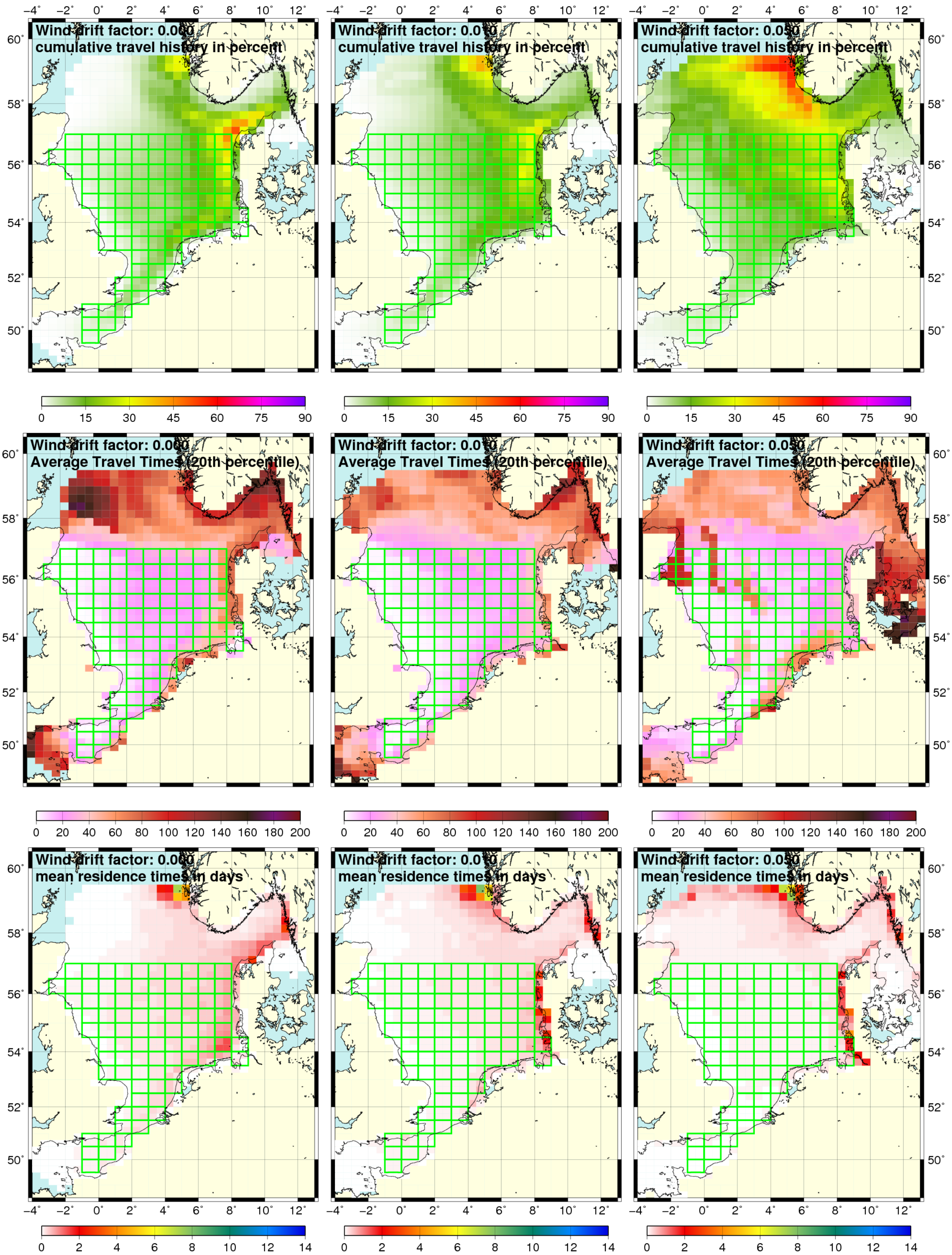


8 Releases between 2000-07-15 (01:00) and 2007-07-14 (01:00)

Experiment: 8700 particles released from any source

Integrated: 4320 hours

Figure 4.4.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from a homogeneous particle distributions in July 2000 to 2007, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 69600 particles are drifted.

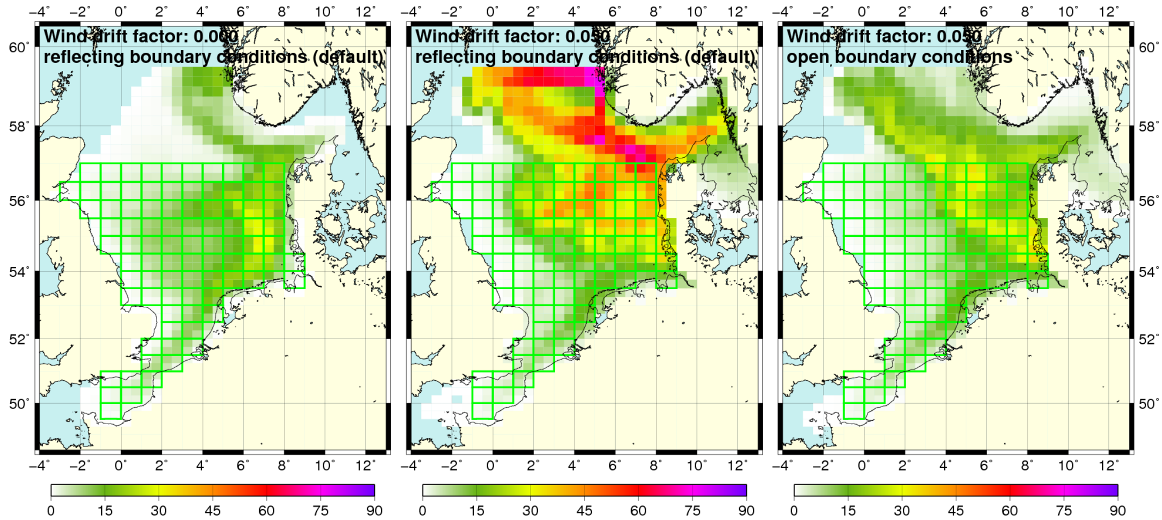


8 Releases between 2000-10-14 (07:00) and 2007-10-13 (07:00)

Experiment: 8700 particles released from any source

Integrated: 4320 hours

Figure 4.5.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from a homogeneous particle distributions in October 2000 to 2007, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 69600 particles are drifted.



Time of Release: 2007-01-12 (13:00)
Experiment: 8700 particles released from any source
Percent of particles having travelled through target regions
Units: Percentage released particles
Integrated: 4320 hours

Figure 4.6.: CTH plots to 180-day forward simulations with 0 % and 5 % wind drift and default boundary conditions started at 12/01/2007 13 o'clock from a homogeneous initial distribution are shown on the left and in the center. On the right, CTH-densities of a simulation with 5 % wind drift and an open boundary to the North East Atlantic, started at the same date, are plotted.

bisection. Simulations with 1 % wind drift develop in the same way. Possibly the particles which remain in the North Sea are drifted on a counter-clockwise circular course through the North Sea. This assumption is neither proved nor disproved by the available simulation results.

If 5 % wind drift is applied, the majority of particles gathers in the central North Sea and is drifted in two loops to a final location western of Denmark: central North Sea → Danish west coast → Shetland Islands (Actually till $1°E$, $59.5°N$) → Norwegian Coast → Skagerrak → final location western of Denmark. The CPL-densities (not shown) clearly indicate the final location.

This behaviour is caused by reflecting boundary conditions at the passage from the North Sea into the Atlantic. Obviously keeping all particles in the North Sea leads to an overestimation in the particle abundance within the North Sea and to wrong results. For comparison, on the right hand side of figure 4.6 a CTH plot to a simulation with 5 % wind drift and with open boundaries towards the Atlantic is shown. The CTH-densities are considerably lower, which indicates a strong influence of the boundary conditions. Also open ones lead to wrong results, because particles are not able to return into the North Sea after they left it, leading to an underestimation of the particle number. In general, the area of interest should be located far distant to boundaries to avoid their negative influence.

Plots to simulations of the year 2005 (not shown) indicate an anomaly in the transport of particles through the Strait of Dover: A larger-than-normal number of particles drifts from the North Sea into the Channel. The anomaly exists in simulations without and with wind drift, but in those without it the anomaly is most obvious. A look into the BSH Report No.44 to the state of the North Sea 2005 Loewe [2009, pp.83] and a comparison with the reports for the years 2003 and 2004 Loewe et al. [2005, 2006, p.48/p.66] confirms the observation. During the first month of 2005 the outflow of water masses from the North Sea into the Channel was high while the inflow from the Channel was low. In 2003 the in- and outflows were both low and in 2004 they were both high leading to an approximately neutral mass budged.

4.1.2. April events

Figure 4.3 contains composite plots of simulations of the April event in the default alignment. We start with simulations without wind drift. If one compares the CTH-densities for the April events with those of the January events, one notices lower CTH-densities in the Skagerrak and considerably lower ones in the northern North Sea above $58°N$. Thus, less particles are drifted into the Skagerrak and later into the North East Atlantic. Also the transport velocity is lower as TT20 plots indicate. The MRTs in the Skagerrak are primarily below 0.1 *days*. The MRTs close to $5°E$ and $59.5°N$ exceed average MRTs. This suggests that particles actually leave the current model domain there and are stopped. The MRTs in regions of the German Bight reach values above 1.0 *day* and up to 2.2 *days*, doubling those of the January events. The situation in and around the Channel and at the Dutch, German and Danish coasts is comparable to that for the January events.

If 1 % wind drift is added, the number of particles drifted into the Skagerrak increases. Higher CTH-densities suggest this. Also the amount of particles leaving the North Sea northward increases. The wind forces the particles, being located in the German Bight, against the coast of Denmark and Schleswig-Holstein. There they remain for some time. The increased CTH-densities (top row) and the increased MRTs (bottom row) in the center column of figure 4.3 suggest this. The situation in the Channel does not change.

If the wind drift factor is increased to 5 % the CTH-densities in the whole North Sea increase. Probably the wind drifts particles fast and disordered through the North Sea which leads to this picture. The MRTs become more homogeneous over the whole North Sea with a slightly falling gradient from east to west. The MRTs in coastal regions remain high as in the simulations with 1 % wind drift. The number of particles in the Skagerrak and at the northern boundary of the model domain increase - higher CTH-densities there - and a few particles drift through the Kattegat till Zealand. We observed this already for the January event. The CTH-densities at the boundary of the model domain increase in the whole area from $1°W$ to $5°E$. We expected an increase mainly close to $5°E$ and remind the reader of the observations in the bottom row of figure 4.6 and our conclusions. The simulations results in the northern North Sea should be regarded with caution. Finally, we come to the Channel: The CTH-densities increase slightly and MRTs decrease slightly. This indicates, that particles are drifted disordered through the Channel and leave it fast.

4.1.3. July and October events

Plots of the July and October events are shown in figures 4.4 and 4.5. The arrangement of plots in these figures corresponds to table 4.1 and the figures 4.2 and 4.3. Primarily, events started in October are described below. The system behaviour for the July event is similar to that for the October event but often CTH-densities and TT20s are lower. We mention deviating behaviour for July. The particle drift of the October event is the most directed and focussed among the considered events. More than 40 % of particles (see CTH-densities in fig 4.5 top left) enter the Skagerrak and 20 % do this already 60 days (TT20s in fig 4.5 center left) after the simulation started. As for the January event, most particles leave the Skagerrak again, drift along the Norwegian coast and leave the North Sea between $3°N$ and $5°N$ into the North East Atlantic. The amount of particles remaining in the Skagerrak exceeds that of January and April events. High CTH-densities, higher CPL-densities after half a year (not plotted) and higher MRTs, especially at the Swedish coast, suggest this. Also more particles enter the Kattegat. The proportion between particles remaining in the Skagerrak and particles leaving it towards the Atlantic stays approximately equal. The Danish coast and the North Frisian Islands are considerably more affected by particles than in simulations of January and April events. Higher CTH-densities suggest this. Close to Helgoland the MRTs have a local maximum. This is a known phenomenon in simulations with *PELETS-2D* and also appeared in our forward simulations from other constellations of source regions. In the conclusion to this this section (subsection 4.1.4) and in the conclusion to this whole chapter (section 4.3) it is briefly discussed. In the Channel and the western North Sea no difference to the other events is noticeable.

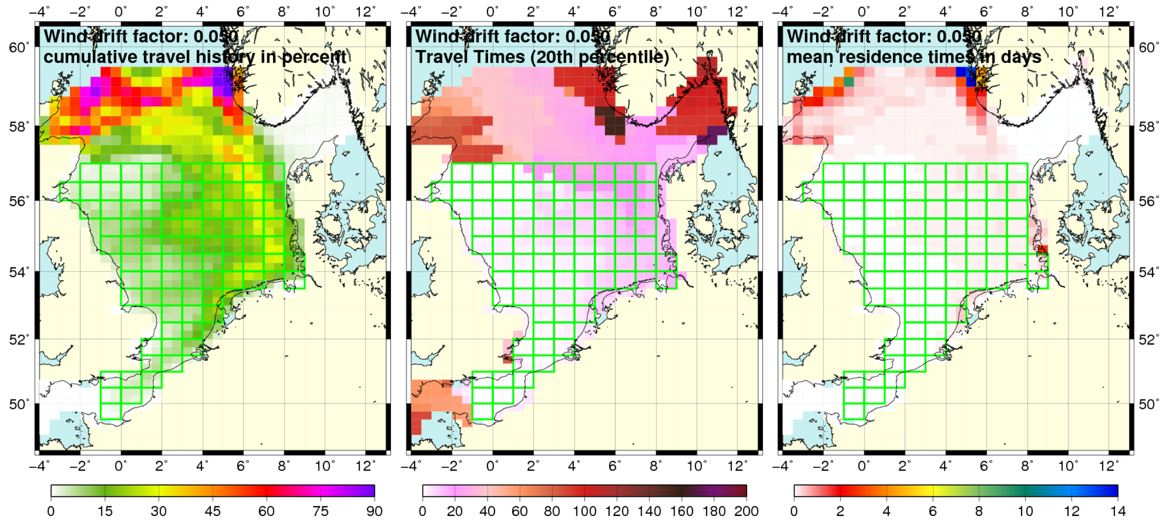
If 1 % wind drift is added, the amount of particles transported into the Atlantic Ocean increases. High CTH-densities (fig. 4.5 top center) along the Norwegian coast suggest this. The CTH-densities and MRTs in the Skagerrak decline. This indicates, that particles drift partly from the eastern North Sea directly into the North-East Atlantic. The CTH-densities in the remaining open sea do not change. The MRTs (fig 4.5 bottom center) in the eastern North Sea decline, except those in coastal regions. The latter ones increase strong. Additionally the CTH-densities at coasts of Denmark and Schleswig-Holstein increase. These two facts indicate, that wind forces particles against those coasts, leading to an accumulation there. Also the Dutch and Lower Saxon coasts seam more affected by particles (also increased CTH-densities). The particles behaviour in the Channel does not change. If the wind drift factor rises to 5 % the residence times of particles in the Channel decrease - lower MRTs - but the number of particles, which have at least once been in the Channel, increases - higher CTH-densities. As for the January event the CTH-densities in the open water of the whole North Sea and the Skagerrak increase and MRTs take more spatially homogeneous values which slightly fall from east to west. The MRTs at coasts bordering the Skagerrak increase. From the Skagerrak a low number of particles is even drifted through the Kattegat into the Baltic Sea to the coast of Mecklenburg-Western Pomerania (dt. Mecklenburg Vorpommern). More than 50 % of particles pass the Norway coast on their way into the North East Atlantic. As TT20s indicate, the drift velocity is the fastest compared to simulations of other events and simulations with low wind drift factors. The area which many particles pass on their way into the Atlantic widens considerably. Eventually this is caused by a problem with the boundary of the *BSHcmod* V3 current data. Please look at figure 4.7 and read the paragraph after the next and the conclusion of this subsection for more information on this.

The quantitative behaviour for July is equal. On average the CTH-densities are lower and the TT20s higher. Additionally the drift path from the Danish coast and the Skagerrak to the Atlantic is more narrow.

We take a look on figure 4.7. There plots to a simulation of the October 2002 event with wind drifted are shown. One the left hand side the CTH, in the center TT20s and on the right hand side MRTs are plotted. The particles are drifted towards the Shetland Islands. This is unexpected because around the Shetland Islands surface water currents from the North East Atlantic enter the North Sea (see section 2.3). The wind forcing on the particles needs to be quite strong. They circulate between these Islands and Scotland. After a loop through Moray Firth they are transported to Norway where they partly leave the North Sea. One could expect that the particles would leave the North Sea near the Shetland Islands and be set on inactive. It does not happen as in the simulation of the January 2007 event with 5 % wind drift, visualised in figure 4.6. In the conclusion in the end of this subsection we discuss possible explanations.

4.1.4. Conclusion to forward simulations from homogeneous initial distribution

In this chapter, 180-day forward simulations were evaluated, focussing on the whole North Sea. Particle transport out of the North Sea into the North East Atlantic seemed to be an important process. Because the hydrodynamic currents, on which particles are drifted, end at



Time of Release: 2002-10-17 (07:00)
Wind drift factor: 0.050
Experiment: 8700 particles released from any source
Integrated: 4320 hours

Figure 4.7.: From left to right CTH, TT20 and MRT plots to 180-day forward simulations with 5 % wind drift started at 14/10/2002 7 o'clock from a homogeneous initial distribution are shown.

$59.5°N$, boundary conditions have considerable influence on the system behaviour. Instead of the by default open boundaries, reflecting boundaries adopted. In figure 4.6 (see 4.1) results of simulations with both boundary conditions are plotted side by side for comparison. Both lead to defective results, because no knowledge on the particle transport beyond the boundary is available. Therefore, the presented evaluation has to be regarded with more caution than present anyway.

Regarding the surface currents of the North Sea (see 2.3), buoyant marine debris could be transported in two ways. It could be drifted *(1st)* in a counter-clockwise circular direction several times through the entire North Sea or *(2nd)* in northern direction along the Norwegian coast out of the North Sea into the Atlantic Ocean. Both cases are supported by our simulation results. But before we deal with this topic we focus on the Skagerrak.

In annually average, the surface waters from the Skagerrak and the Channel flow into the North Sea. Contrary to our expectations, especially in simulations of July and October events, a transport of particles into the Skagerrak takes place, which explains the before mentioned particle behaviour. Interestingly, this applies primarily to not by wind drift affected particles. Loewe et al. [2005], Loewe et al. [2006] and Loewe [2009] confirm the inflow of North Sea surface water along the Danish coast into the Skagerrak, during some month. Near the Norwegian coast these surface waters mix with water masses from the Baltic Sea, do a left turn and flow back into the North Sea. Therefore, many particles which enter the Skagerrak from the North Sea should return to the North Sea, later. The simulation results support it (e.g. CTH-densities and TT20s in the left columns of figures 4.2, 4.3, 4.4 and 4.5). Winds from western direction can lead to stranding of buoyant items at Swedish and Norwegian beaches bordering the Skagerrak. High MRTs at these beaches in simulations with 1 % and 5 % wind drift support this assumption. These beaches are possibly accumulation regions for marine litter. In simulations of October events with 5 % wind drift, particles are even transported into the Baltic Sea as the CTH-densities in figure 4.5 top right indicate. Hence, one cannot only expect Marine Litter from the Baltic Sea to enter the North Sea, but also low amounts of Marine Litter from the North Sea to enter the Baltic Sea. Probably those amounts are negligible.

Winds blow primarily from south-western directions during winter and from western to north-western directions during the rest of the year. In simulations for the October events, with increasing wind drift factor, less particles are drifted into the Skagerrak. In simulations of other events, the number of particles drifted into the Skagerrak increases. Judging from the wind directions one could expect, that the effected of increased wind drift is the other way around: The wind forces more particles of October events into the Skagerrak and less of other events.

An ocean current leads from the Skagerrak, along the Norwegian coast and to the North East Atlantic between $3°E$ and $5°E$. Many particles, which leave the Skagerrak, are drifted by this current out of the North Sea - primarily, particles of the July and October events. For particles of January and April events, the behaviour of leaving the North Sea northward is less developed, but present, too. Cause by the reflecting boundary most particles which reach $59.5°N$ return into the North Sea after some time. Particles, which do not travel northward into the Skagerrak or towards the Atlantic, remain widely distributed in the southern North Sea approximately below $56°N$ in simulations without wind drift. Majorly, particles of the January and April events do this. Eventually, these particles are drifted on circular trajectories by counter-wise surface currents. If wind drift is applied and increased, however, the particle abundance in the south-western North Sea declines and disappears. Instead, the wind forces more particles into the North East Atlantic or into the eastern German Bight and to the bordering coasts. Often a combination of both develops: at first to the coasts and then into the Atlantic.

With increasing wind drift factor the area in which particle meet the boundary of the model domain widens westward. The composite CTH-plots in the top rows of figures 4.2 and 4.5 and especially the CTH-plot to the October 2002 event in figure 4.7 point this out well.

In simulations without wind drift, particles are drifted parallel to the coastline in a considerable distance and do not tangent the coast. Some coastal regions are excluded from this. For example Sylt and Amrum - two North Frisian Islands - are affected by not-wind-drifted particles - comparable to submerged marine litter - as the top left plot in figure 4.5 shows. If wind drift is applied, the wind forces particles to those coasts towards it blows, which those of Schleswig-Holstein and Denmark for the German Bight and those of Norway and Sweden for the Skagerrak. In the simulation of the October 2002 event with 5 % wind drift (fig. 4.7), particles accumulate in Moray Firth for some time. It could be, that this accumulation results from a not modelled river inflow. If not, the beaches bordering Moray Firth or the sea ground in this region are possibly accumulations zones of marine litter. Going further south, the English coast is only slightly affected by particles. The transport of particles from the North Sea into the Channel is negligible. In the plots to simulations of the April, July and October events without wind drift, slightly increased MRTs close to Helgoland are present. According to information from Ulrich Callies (personal communication) this local maximum in the MRTs was observed several times in results of simulations with *PELETS-2D* . Hickel [1972] predicts a current circulating around Helgoland. These phenomenon could be responsible for longer residence times of particles close to Helgoland. Other reason for higher MRTs could be numerical errors close to dry land in the simulations. Plots with three-month-average currents in the BSH Reports from 2003 to 2005 Loewe et al. [2005, 2006], Loewe [2009] indicate some turbulent currents around Helgoland. The resolution is too low for more detailed statements.

Let us put this subsection in a nutshell: Many particles leave the North Sea in northern direction in particular those started July and October. Thus, we can expect buoyant marine litter to leave the North Sea partly in spring and summer and to be flushed out of the North Sea during autumn and winter. The retention time of not stranded litter items in the North Sea should be below two years because of the flushing-effect. Two and a half possible coastal accumulation regions are identified: coasts of Sweden/Norway and Schleswig-Holstein/Denmark for sure and Scotland with big uncertainty. However, no accumulation regions at the sea surface like the

North Pacific Gyre [Martinez et al., 2009, Howell et al., 2012] could be detected. One could expect *(a)* another beach litter composition at beaches of Sylt - location of one OSPAR beach litter monitoring beach - compared to other beaches and *(b)* primarily by wind drift affected sea-based litter item at beaches in general. Land-based litter is one topic in the next section.

4.2. Shipping routes and river estuaries

Contrary to subsection 4.1, we focus on the exposure of the German Bight to marine litter injected by different sources. Three main questions are:

- *Do particles form different sources and source regions affected different coastal regions?*
- *Should some beaches be litter free?*
- *What influence do seasonal variations in ocean currents and the wind drift factor have on the location and pollution of possible accumulation regions?"*

The results could help in the analysis of the OSPAR beach monitoring data by giving hints for what anomalies to look for at which beaches. Because of this focus, the discussed plots do not show the whole North Sea but only the southern part.

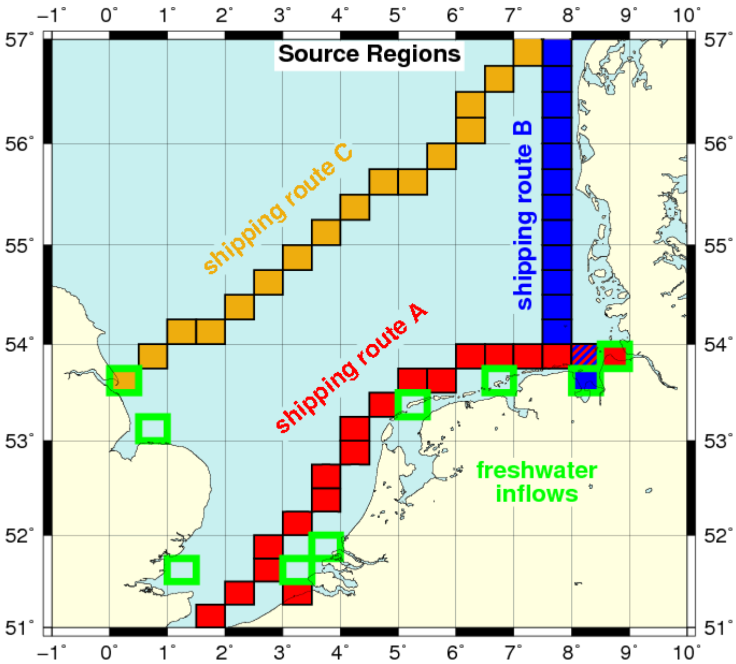


Figure 4.8.: Four maps visualising four sets of source regions. The plots top left, top right and bottom left show shipping routes as sources and the plot bottom right fresh water inflows, mainly river estuaries. The reasons for choosing these three shipping routes are mentioned in the text. In clockwise direction starting top left these are the Humber estuary, the Wash Bay, the Thames estuary, the Rhine and Scheldte estuaries, the Ijsselmeer, the Ems estuary, the Weser-Jade estuary and the Elbe estuary. In each source region of the shipping routes 100 and in each one of fresh water inflow 200 particles are injected. Thus, from routes A and C 1900, from route B 1600 and from the rivers 1800 particles start simultaneously.

Before regarding the transport of marine litter from different sources and identifying the coastal regions which are mainly affected by it, we have to decide on some sources. Marine litter is divided in land-based and sea-based litter. The main source for land-based litter in the North

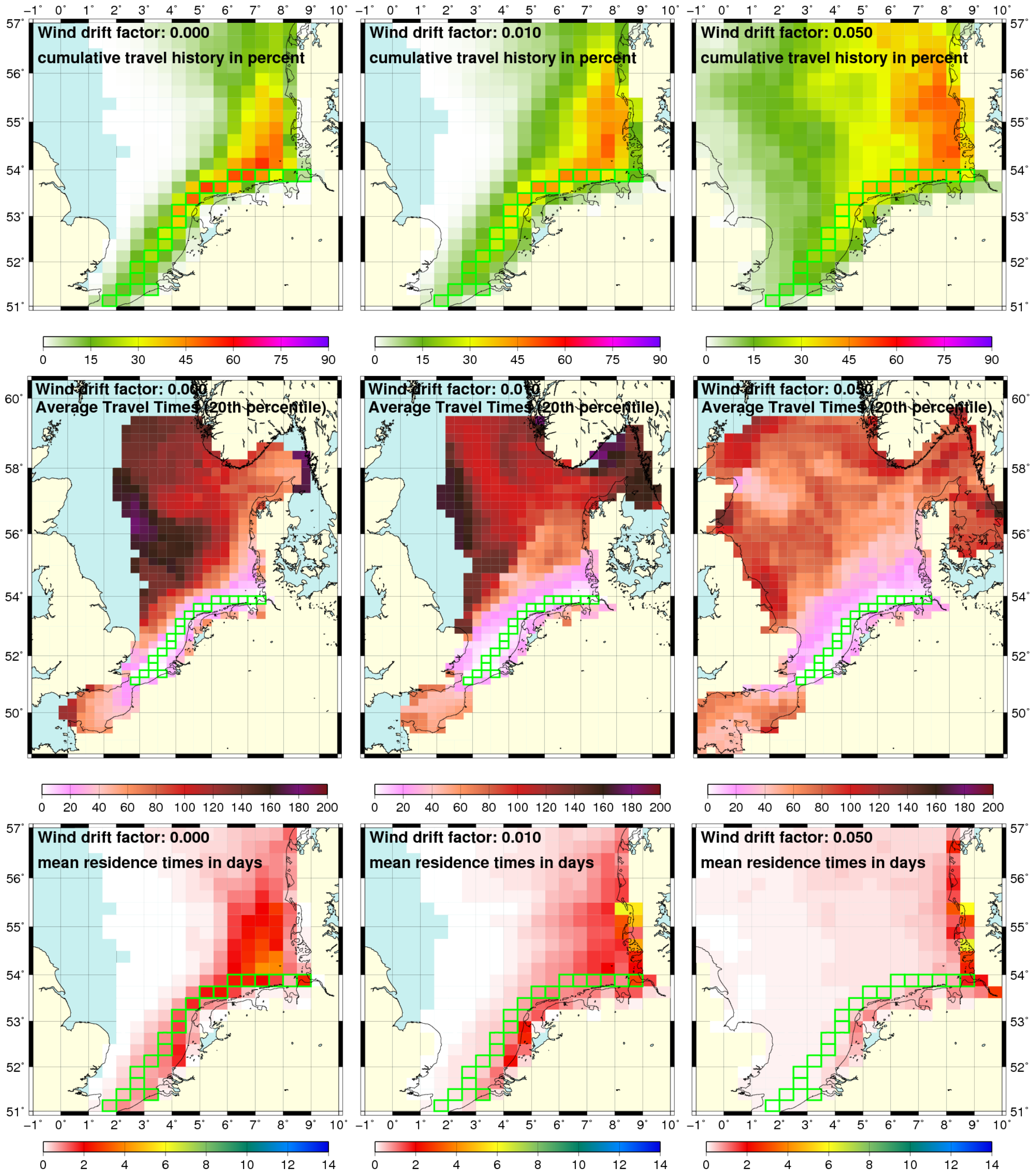
Sea is expected to be river input (ToDo: Reference?). We ignore beach sourced litter. Regarding sea-based litter, Freighter crews, crews and passengers of cruise ships and ferries, fishermen and recreational sailors are possible polluters. We do not focus on one group but choose three shipping routes with high ship density as sources. For simplicity the routes are called *route A*, *route B* and *route C*. Figure 4.8 contains plots of the routes: route A top left, route B top right and route C bottom left. Route A envelopes the ***t**raffic **s**eparation **s**cheme* (TSS, dt. **V**erkehrs**t**rennungs**g**ebiet, VTG) connecting the Channel and the Elbe. A Student of the Osnabrück University estimated the ship-km per predefined grid cell by GPS data in a not till now published research project by Philip Münch. Routes B and C are chosen according to these estimations. The bottom left plot in figure 4.8 shows the river estuaries and other area of fresh water input used as sources in our simulations. In clockwise direction starting top left these are the Humber estuary, the Wash Bay, the Thames estuary, Rhine and Scheldte Estuaries, the Ijsselmeer, the Ems estuary, the Weser-Jade estuary and the Elbe estuary. The Ems transports low amounts of fresh water into the North Sea compared to the other rivers. Nonetheless it was identified as one source river in the backward simulations of sections 3.1 and 3.2. In the following we use the term *river* for simplification and do not distinguish between rivers and other inflows.

Some technical information: The shipping routes A and C consist of 19 source regions, the route B of 16 and the rivers of 9. In each shipping route source region 100 particles and in each river source region 200 particles are injected simultaneously and forward simulated for half a year. The forward simulations start quarterly to the same dates as in subsection 4.1. We start with a discussion of the shipping routes followed by a discussion of the rivers and finally a conclusion.

4.2.1. Shipping route A

In simulations without wind drift seasonal variations are low. In general, the particles are drifted from the source regions at first in eastern direction along the Dutch and Lower Saxon coasts following the shipping routes and then northward along coasts of Schleswig-Holstein and Denmark. The particles of April and July events remain longer in the German Bight - especially close to Helgoland - than those of January and October events. A comparison between the MRTs bottom left in figures 4.3 and 4.4 on the one side and 4.2 and 4.5 on the other one suggest this. The January particles leave the German Bight least focussed as the CTH-densities above $56°N$ reveal. Particles of October events leave the German Bight earlier than those of the other events. July particles produce the largest single MRT in one region (fig 4.11, bottom left). It is located closely to the German island Helgoland. In simulations of the April events some particles are drifted in north-western direction out of the German Bight and than return according to TT20s in figure 4.10 center left. The coast of Schleswig-Holstein and especially the North Frisian Islands are least affected by particles of the April events and most by those of the October events. The East and West Frisian Islands and the southern mainland coast are equally affected throughout the year, whereupon the islands are more affected than the mainland. In general, coastlines which lie not directly in a source region are medium affected by particles.

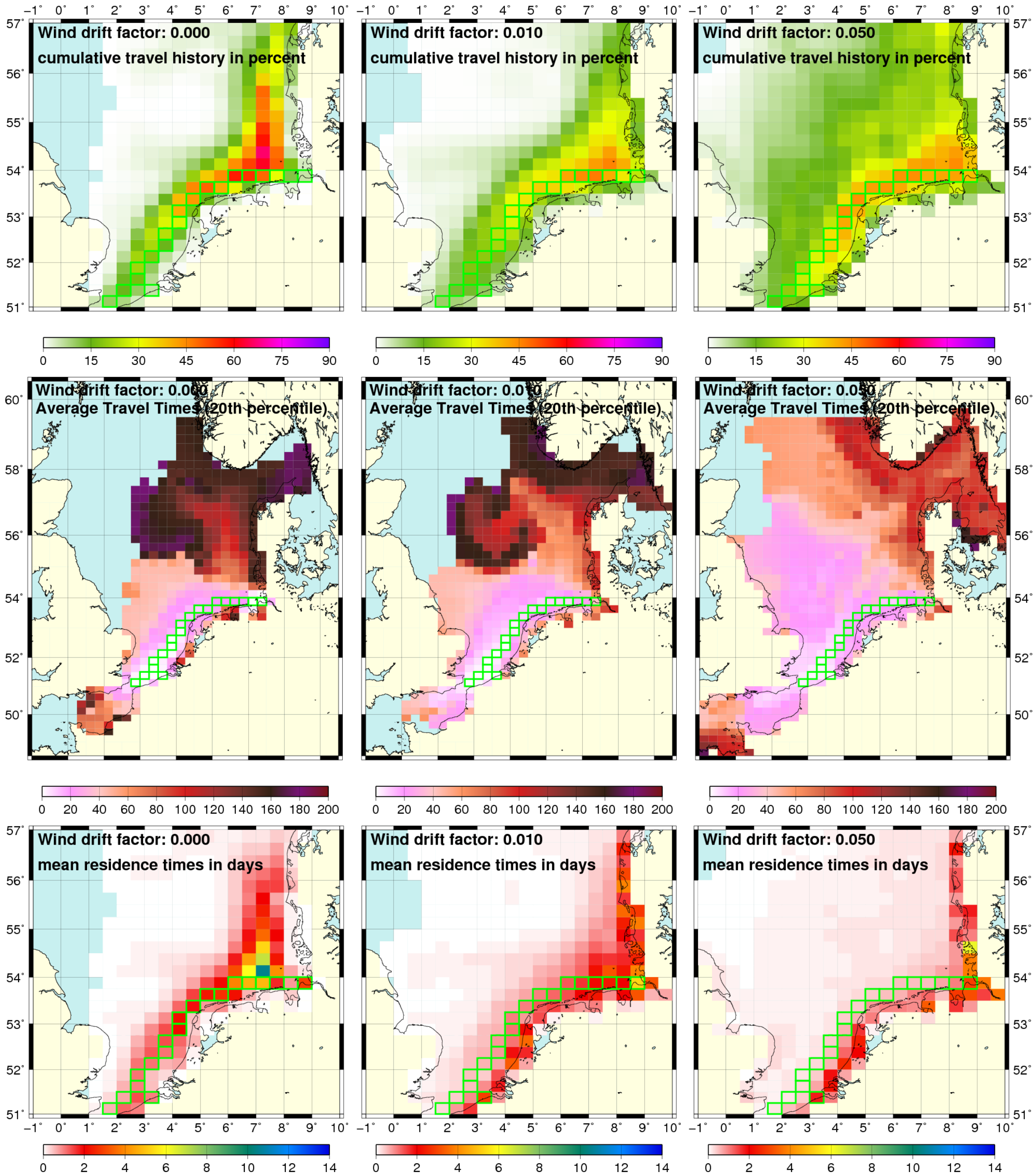
If wind drift is added, the wind forces particles faster through open waters - lower MRTs in the German Bight and especially close to Helgoland in the center and right columns of figures 4.9, 4.10, 4.11 and 4.12 - and towards the continental coasts - higher CTH-densities and higher MRTs in the center and right columns of figures 4.9, 4.10, 4.11 and 4.12. Particles injected in October are transported fast past Belgian, Dutch and Lower Saxon coasts. Low MRTs in these regions show this. More particles than in simulations without wind drift are drifted to the coasts of Schleswig-Holstein and Denmark and into the Elbe river. The MRTs at these coasts and in the Elbe estuary are higher, if wind drift is added, but do not increase, if the wind drift factor is increased. Contrary to the October event, particles of the April and July events are forced against the coast of Belgium, the Netherlands, Lower Saxony and into the enclosed river



8 Releases between 2001-01-13 (13:00) and 2008-01-14 (13:00)
Experiment: 1900 particles released from any source
Integrated: 4320 hours

Figure 4.9.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from shipping route A in January 2001 to 2008, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 15200 particles are drifted.

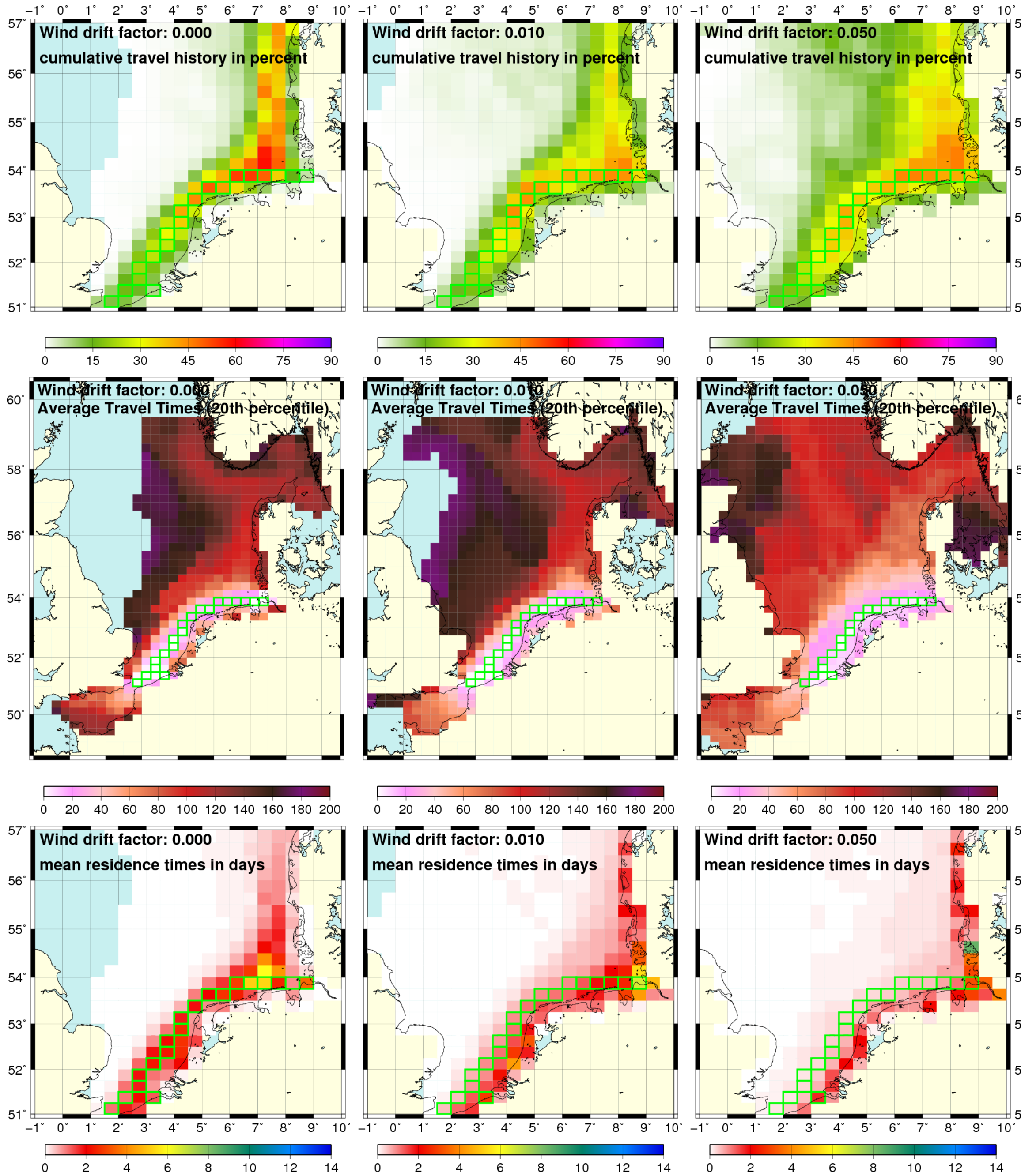
estuaries. Higher MRTs in bottom plots of figures 4.9, 4.10, 4.11 and 4.12 and higher CTH-densities in the top rows of these figures suggest this. The simulations of the January events are in between those of April/July and October. Normally during winter, winds from south-western directions prevail contrary to north-western winds during the rest of the year. The discrepancy



8 Releases between 2001-04-14 (19:00) and 2008-04-12 (19:00)
Experiment: 1900 particles released from any source
Integrated: 4320 hours

Figure 4.10.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from shipping route A in April 2001 to 2008, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 15200 particles are drifted.

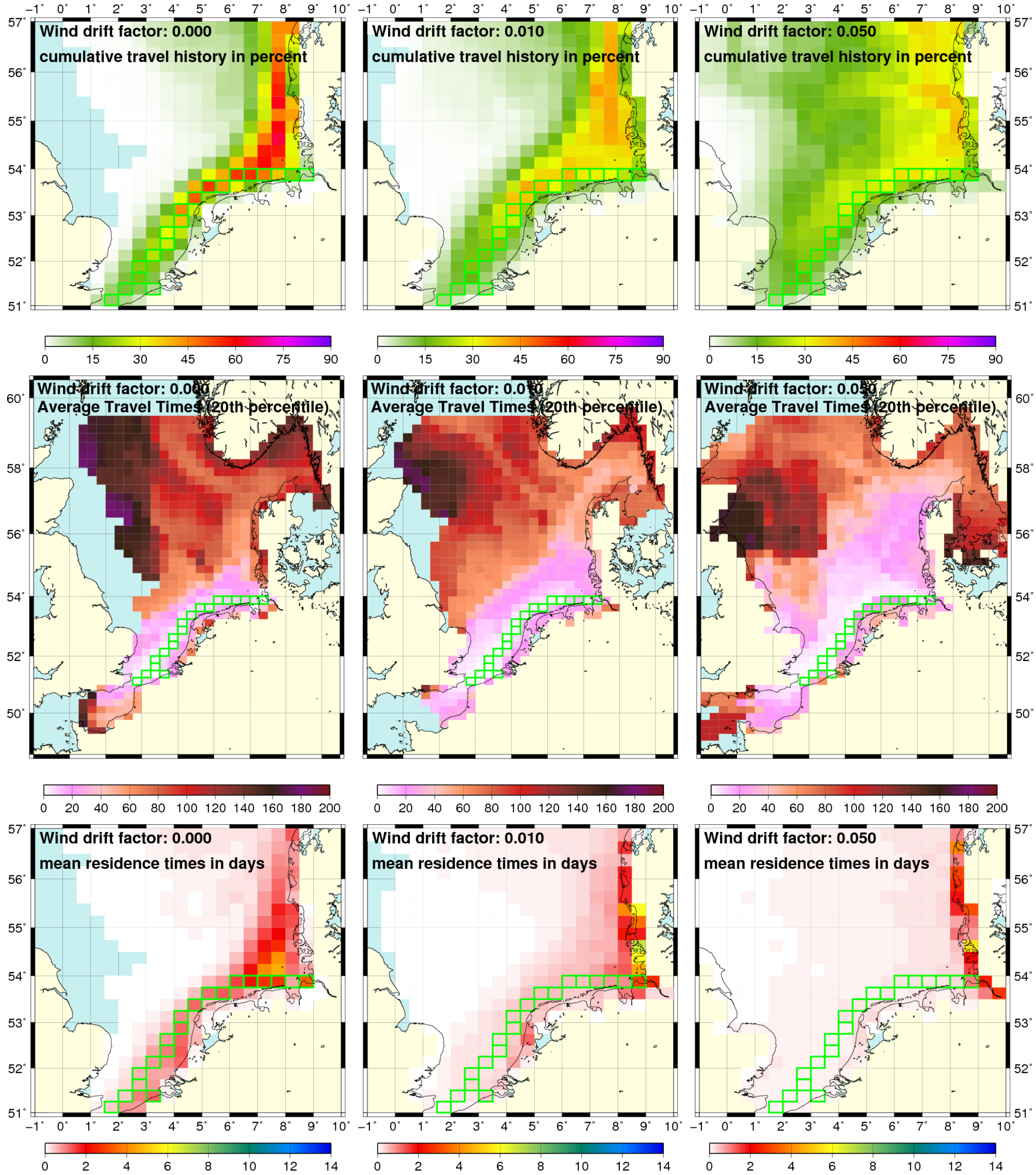
for the October particles seams sensible in this context. With 5 % wind drift some particles are wider distributed over the North Sea away from the coast. This states especially for April and October particles as TT20- and MRT-plots in figures 4.10 and 4.12 bottom center and bottom right indicate. A further difference between simulations with and without wind drift is the



8 Releases between 2000-07-15 (01:00) and 2007-07-14 (01:00)
Experiment: 1900 particles released from any source
Integrated: 4320 hours

Figure 4.11.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from shipping route A in July 2000 to 2007, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 15200 particles are drifted.

transport of particles into the Channel. A nearly seasonal-independent drift of particles into the Channel takes place as the CTH-densities in all four figures indicate. In simulation without wind drift the MRTs of the regions in Channels exceed those MRTs of simulations with wind drift. Therefore, transport of particles from the Channel into the North Sea is stronger in the



8 Releases between 2000-10-14 (07:00) and 2007-10-13 (07:00)
Experiment: 1900 particles released from any source
Integrated: 4320 hours

Figure 4.12.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from shipping route A in October 2000 to 2007, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 15200 particles are drifted.

presence of wind. This assumption goes along with winds commonly blowing from south-western or north-western directions throughout the year.

The April 2006 event is an outliner. In simulations with 5 % wind drift the wind forces particles into the German Bight and barely about 1 % of the particles leaves the area southern of 56°N.

The CTH-densities on the left hand side plot of figure 4.13 reveal it: high CTH-densities close to German, Dutch and Belgian coasts and low close to the Danish coast and in the open North Sea. The particles remain a long time in coastal regions. Especially close to the coast of Schleswig-Holstein the MRTs are quite high (fig. 4.13, center). After half a year of simulation approximately 40 % of the particles are located in the Elbe and Jade-Weser estuaries.

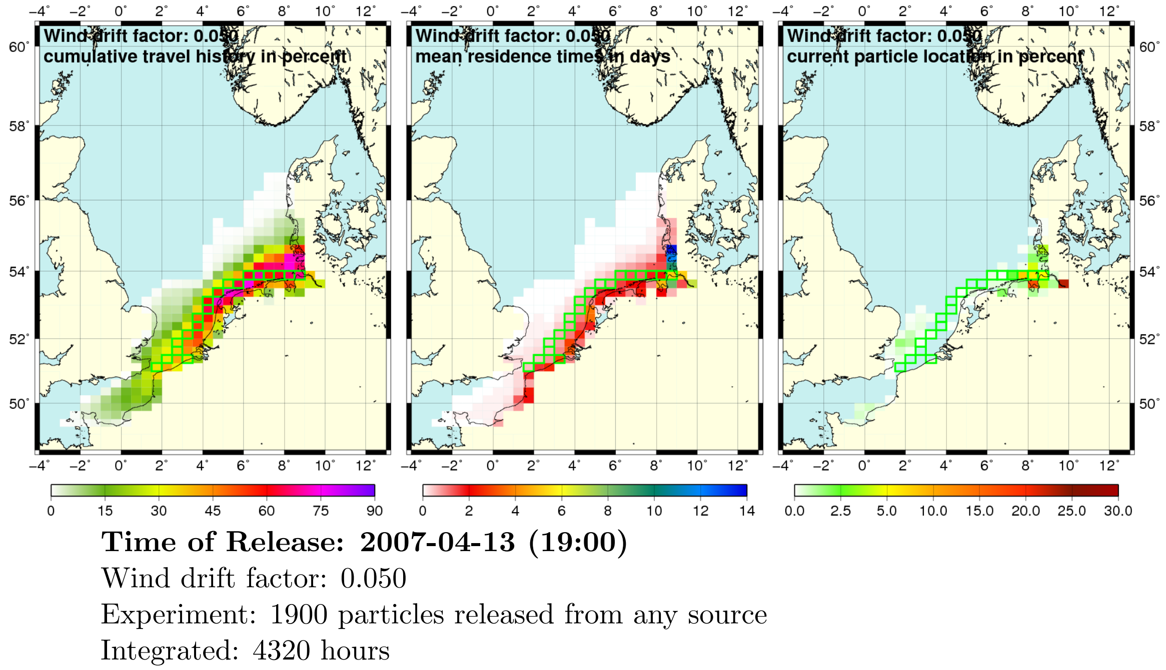


Figure 4.13.: Plots of cumulative travel history (CTH), mean residence time (MRT) and current particle locations (CPL) of a half-a-year forward simulation with 5 % wind drift. 100 particles are injected in each region in April 2006.

4.2.2. Shipping route B

Unfortunately some final figures to shipping route B were deleted accidentally short before the hand-over of the thesis. Instead of showing incomplete figure set, this subsection contains not plots.

Shipping route B leads straight northward from the Weser-Jade estuary along coasts of Schleswig-Holstein and the Denmark and bends of into the Skagerrak. In simulations without and with 1 % wind drift, the coastal regions of the UK, Belgium, the Netherlands and Lower Saxony are exposed partly to low particle CTH-densities and majorly to no particles at all (not plotted). The regionally mainly in northern direction orientated ocean currents cause this. If the wind drift factor amounts 5 % some particles drift unstructured through the North Sea - leading to a wide particle distribution - and pass coasts of the UK, Belgium and the Netherlands closely. The Travel Time plots indicate the unstructured transport and no clear drift path. The CTH-densities remain low with below 2 % at British and Belgian coasts and below 5 % at the Dutch coast which is still quite low. They go up to 15 % to 20 % at the Lower Saxon coasts in April and July.

In simulations without wind drift, the North Frisian Islands and the Danish coast are medium polluted by particles. Notably, the mainland coast of Schleswig-Holstein is quite low affected by particles. Presumably, the North Frisian Islands protect the mainland. Particles of the April event do not drift close to the North Frisian Islands compared to the other events and to the behaviour at the Danish coast. Also for April particles the MRTs in regions at open sea are the highest with up to 3.0 *days*. This implies, that these particles reside longer in the German Bight and drift slower than particles of the other events. The October and January show are the opposite behaviour: Their MRTs at open sea stay below 1.5 *days*. Additionally the North Frisian Islands and the Danish coast are equally affected by particles. Apart from the above mentioned northward transport, a slight westward directed drift occurs. This drift is strongest in April and weakest in October.

If wind drift is added, the pollution of the Danish coast and the North Frisian Islands increases - CTH-densities and MRTs raise considerably. Moreover, the mainland coast of Schleswig-Holstein is affected. A seasonal variation does not develop. Increasing the wind drift factor to 5 % increases the CTH-densities in the coastal regions of Denmark and Germany, whereas the MRTs close to the coasts remain approximately equal or for the October event even decline. Higher MRTs and CTH-densities in river estuaries compared to the surrounding coast prevail in forward simulations from a homogeneous initial distribution (section 4.1) and from shipping route A (subsection 4.2.1). In these simulations residence times in river estuaries and at the surrounding coast do not differ notably. The MRTs at open sea decrease when wind drift is added and decrease further when the wind drift factor is increased. The fastest transport (with wind drift) off-shore occur in simulations of the October events with most MRTs below 0.3 *days* and a few at 0.4 *days*. The above mentioned western particle drift does not differ notably in simulations without and with 1 % wind drift.

However, in simulations with 5 % wind drift, the western drift considerably increases. Additionally, a westward drift of particles along the continental coasts towards the Strait of Dover occurs, which is indicated by the travel time plots. Later, the particles are transported northward along the British coast. Above, we already described the resulting impact on British, Belgian and Dutch coasts.

4.2.3. Shipping route C

Shipping route C connects Hull or Immingham in the Humber estuary with harbours in the Skagerrak or the Baltic Sea. In simulations without wind drift, the particles, which are injected in the south-western source regions, are drifted southward and then south-westward or eastward. In the latter case they pass the Dutch and German Coasts in a far distance. The CTH-densities and MRTs in figures 4.14, 4.15, 4.16 and 4.17 at the Dutch and German - Lower Saxony and Schleswig-Holstein - coasts are negligible. This behaviour remains constant throughout the year. The transport velocity varies seasonally. Particles of April and July events are drifted slower than those of the other events as higher MRTs and TT20s indicate. They probably depend on the velocity and continuity of the central counter-clockwise North Sea currents which varies seasonally and annually. For the October event a local maximum in the MRTs (fig. 4.17 bottom left) close to Helgoland occurs. In simulations of the January and July events particle are drifted into the Channel. Low MRTs of 0.1 *days* and below suggest a fast transport back into the North Sea. Hence, it can be neglected. Interestingly, the transport takes place quite early in the simulation of the January events but substantially later in those of the July event. The pollution of the Danish coast by particles varies seasonally. For the July and October events the CTH-densities amount above 4 % and partly above 20 % whereas for January and April events they remain below 5 % in each region.

If wind drift of 1 % is added the CTH-densities in these regions at least double. An increase of the wind drift factor to 5 % leads to CTH-densities above 10 % for April and above 25 % for January and July all over the Danish coast. For the October event they remain clearly below 20 % because the main cloud of particles drifts several nautical miles past the Danish coast into the Skagerrak. The coast of Schleswig-Holstein, which is nearly particle free in simulations without wind drift, is strongly affected by particles after wind drift is added. We deduce this from high CTH-densities in the top center and top right plots of figures 4.14, 4.15, 4.16 and 4.17. Also the MRTs rise considerably and take regionally above those at the Danish coast. The large number of small Islands and the resulting local variability in the ocean currents may lead to these high MRTs. Additionally low resolution current data (Low compared to the smaller scale variations in the coastline) of the *BSHcmod* V3 combined with many land-obstacles - islands and coasts - could artificially amplify the residence times. When adding wind drift, the TT20s and MRTs in open sea regions decline. This indicates an increased drifting velocity. The mainly southward orientated transport of particles from the south-western source regions decreases already for 1 % wind drift while some particles start drifting northward. For 5 % north- and southward orientated drifts are balanced as the TT20s indicate. It yields to nearly homogeneous CTH-densities in the south-western North Sea with an increasing gradient towards the north-east.

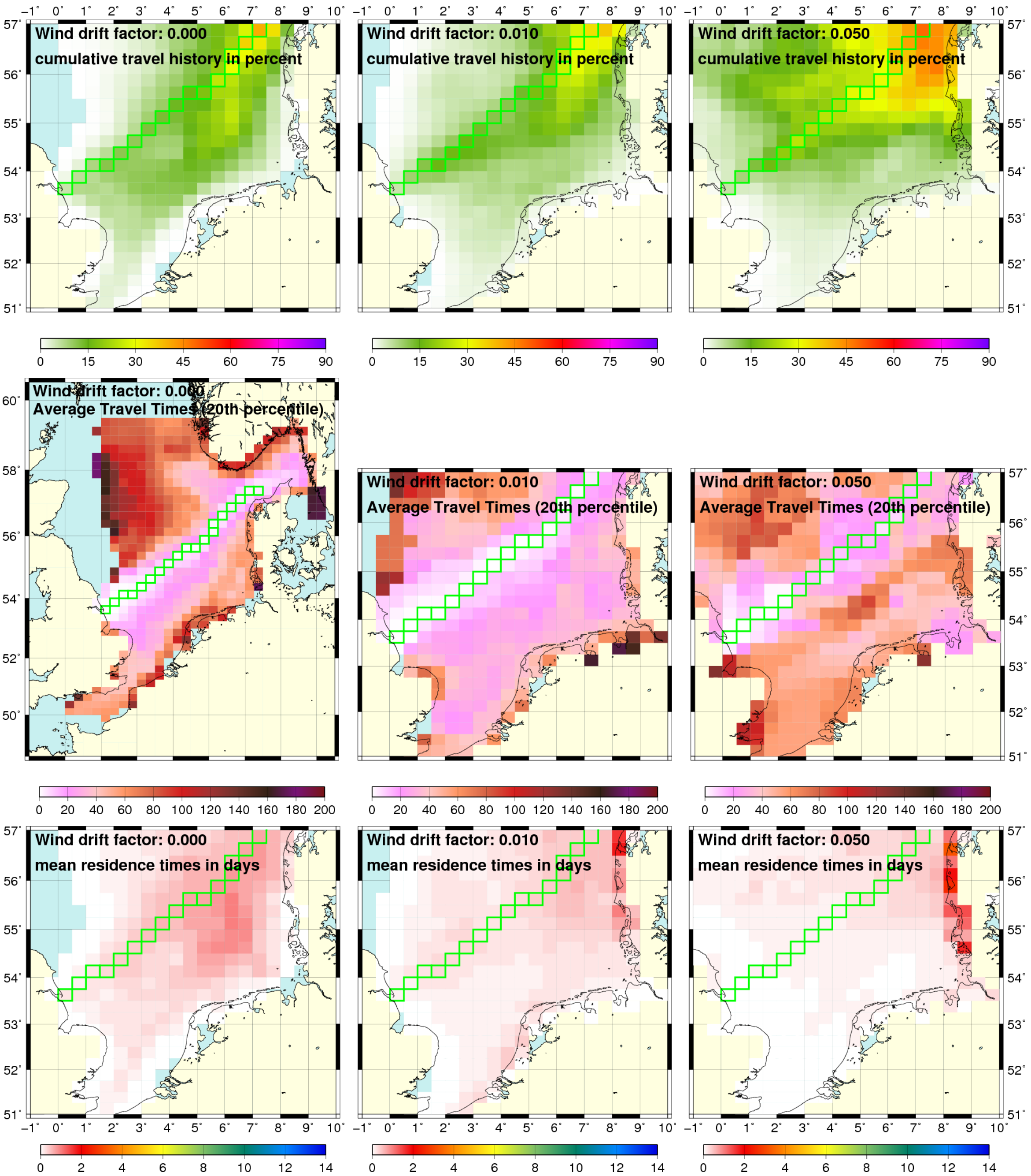
In simulations of January and October events with 5 % wind drift, the particle drift against the Lower Saxon, Dutch and Belgian coasts increases as the CTH-plots in the figures 4.14 and 4.17 suggest. For April and July events, the CTH-densities rise above 10 % in several of these regions starting from clearly below 2 % in simulations without wind drift. Hence, the possible pollution in these regions is multiplied. In simulations of the April events with 5 % wind drift, the MRTs take values above 1 *day* in some Dutch coastal regions. MRTs of the July events partly amount 0.5 *days* and those of January and October events are negligible. Often a correlation between MRTs and CTH-densities can be observed. In those cases an accumulation of particles takes place. In the case present here, the wind during October and January transports particles to many places where they do not remain for long but are drifted soon to other places. This leads to high CTH-densities and low MRTs.

The described composite plots easily mask the annual variations in the simulations. Figure 4.18 contains from left to right two CTH plots of simulations with 5 % wind drift of April 2003 and April 2001 events, respectively, and a MRT plot to April 2003. The system behaviour differs considerably even though the particles are drifted during the same seasons. In 2001, the coasts of Belgium, the Netherlands and Schleswig-Holstein are pretty high polluted as the CTH-densities in the center plot suggest. Also the MRTs in these coastal regions take high values which indicates an accumulation there. Compared to that, particles of the April 2003 never enter the German Bight. The only noticeable by particles affected coastal regions are located in the far north of Denmark. For identification of long term trends or evaluation or planning of monitoring composite plots are sensible and necessary. However, with these plots we want to emphasise the importance of not forgetting the single events.

4.2.4. Rivers

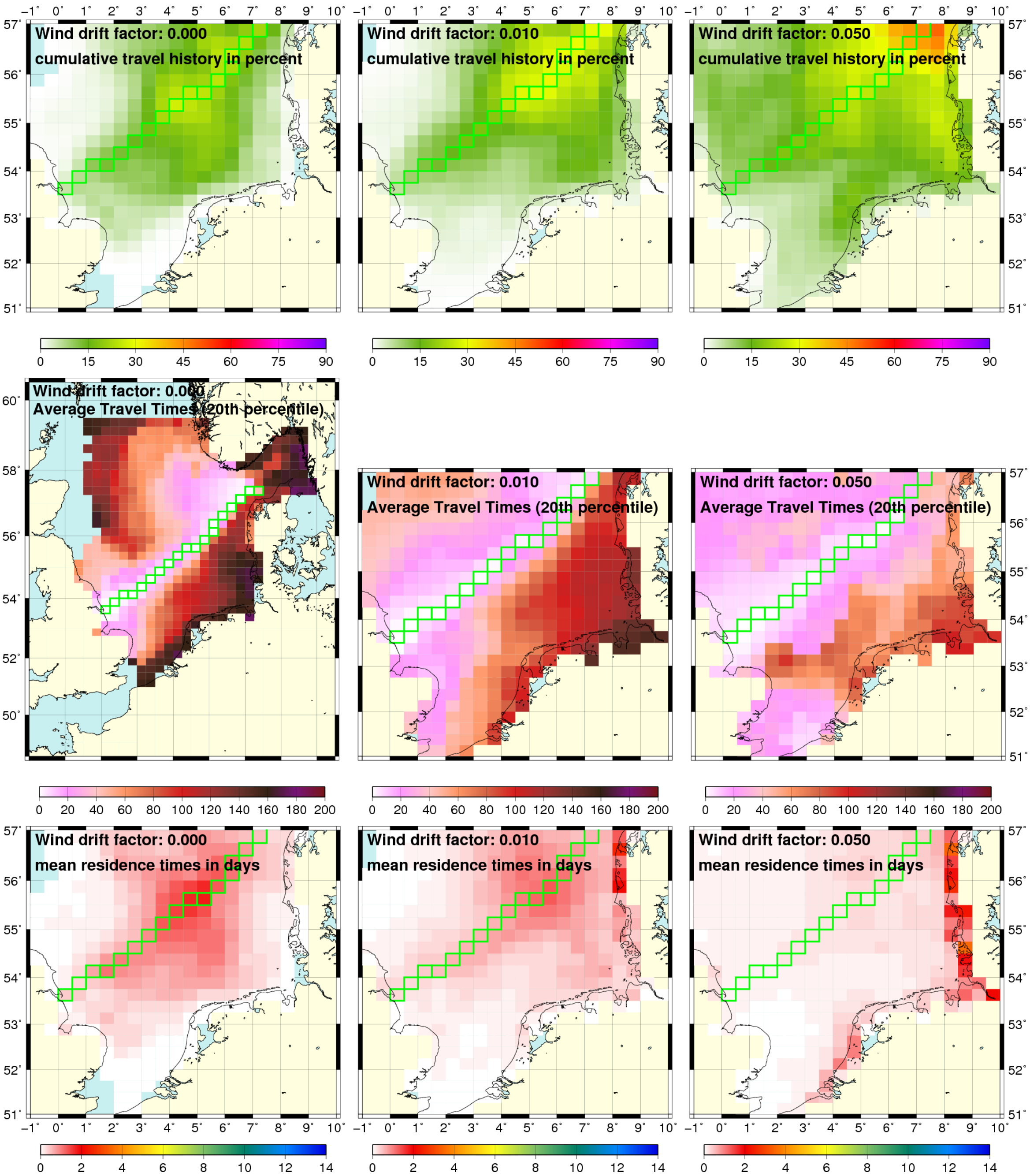
Nine fresh water input regions - primarily river estuaries - are chosen as source regions of particles in the below presented simulations. The particle behaviour at the British coast is not described, mainly because the litter inputs of Scottish rivers and of some smaller English ones are not modelled, potentially affecting the litter deposition at the whole British east coast. Additionally, these rivers are not contained in *BSHcmod* V3 boundary conditions influencing the particle behaviour close to the coast potentially.

In simulations without wind drift, coastal regions eastward or northward adjacent to source regions are strongly affected by particles injected in these regions as increased CTH-densities and MRTs suggest. Also increased are CTH-densities and MRTs in target regions close to Helgoland being also observed in plots to shipping routes A and C (figures 4.11, 4.14, 4.15, 4.16 and 4.17). See subsection 4.2.5 for more details. Additionally in simulations of April events, CPL-densities close to Helgoland exceed those of the surrounding target regions.



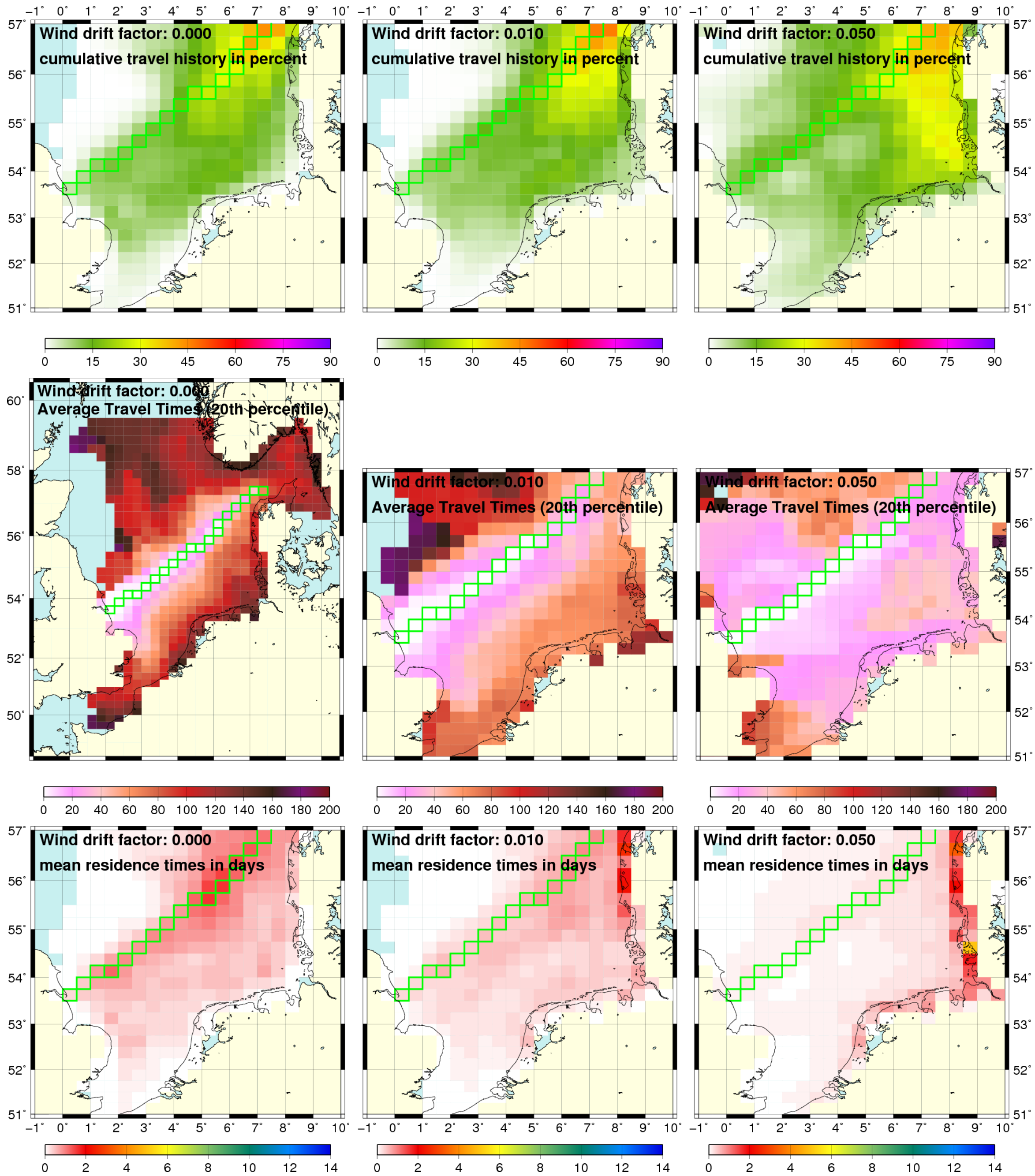
8 Releases between 2001-01-13 (13:00) and 2008-01-14 (13:00)
Experiment: 1900 particles released from any source
Integrated: 4320 hours

Figure 4.14.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from shipping route C in January 2001 to 2008, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 15200 particles are drifted.



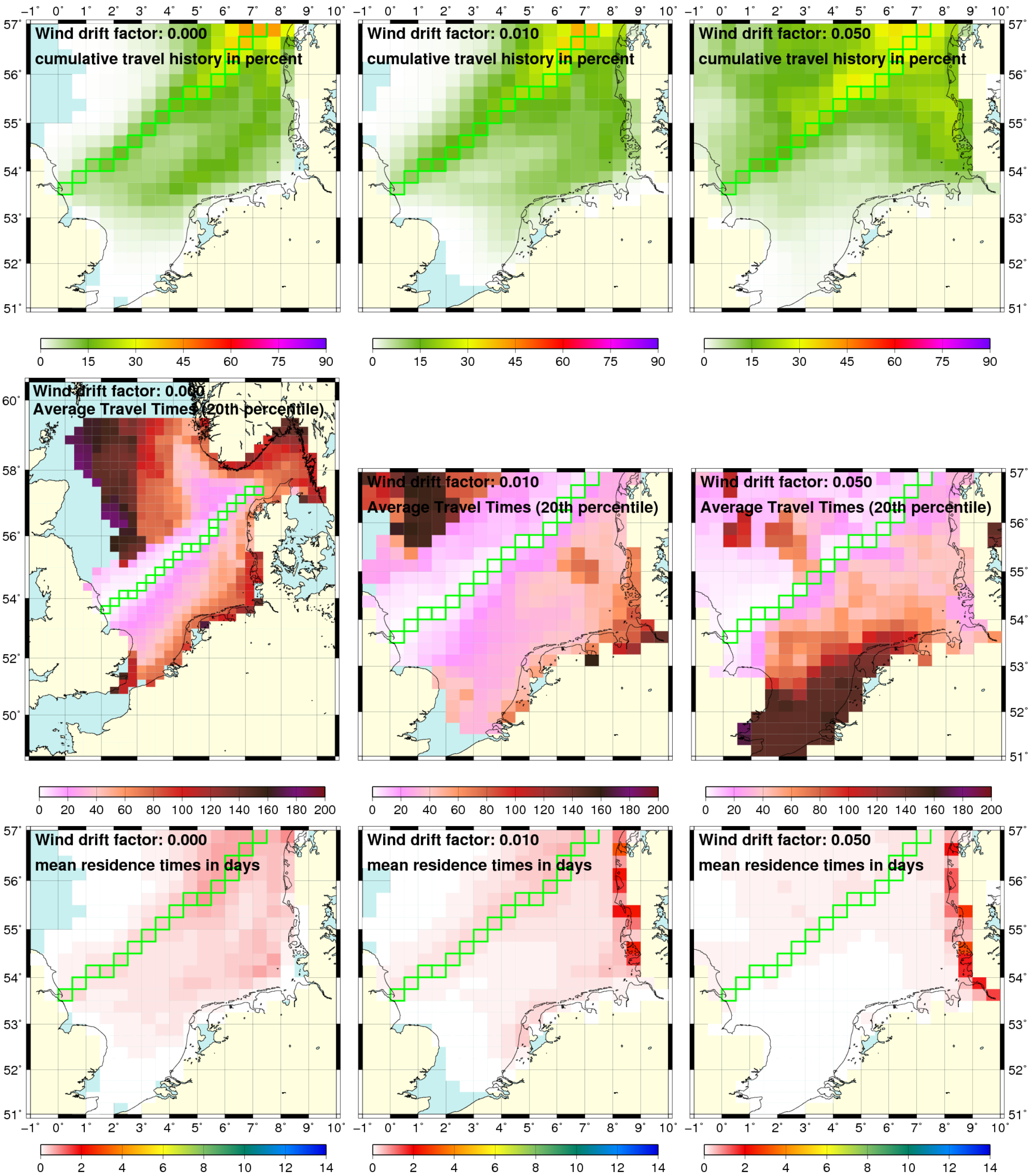
8 Releases between 2001-04-14 (19:00) and 2008-04-12 (19:00)
Experiment: 1900 particles released from any source
Integrated: 4320 hours

Figure 4.15.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from shipping route C in April 2001 to 2008, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 15200 particles are drifted.



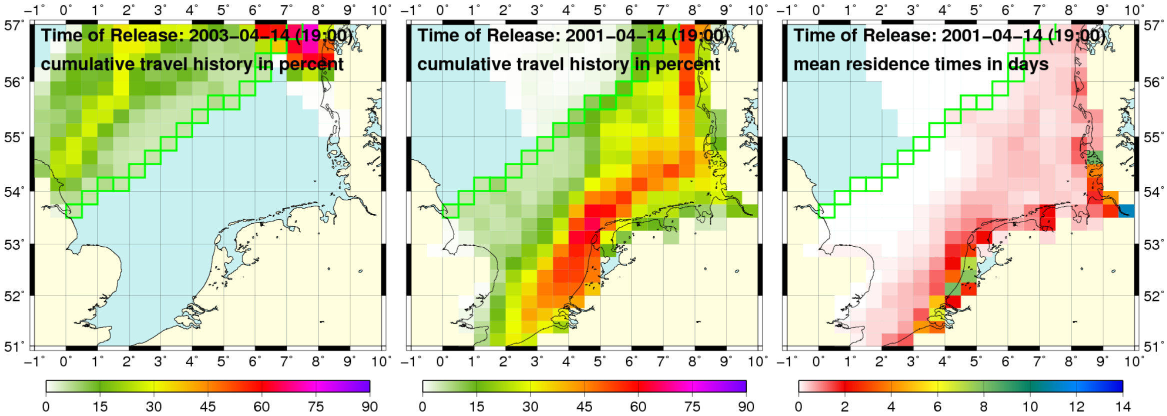
8 Releases between 2000-07-15 (01:00) and 2007-07-14 (01:00)
Experiment: 1900 particles released from any source
Integrated: 4320 hours

Figure 4.16.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from shipping route C in July 2000 to 2007, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 15200 particles are drifted.



8 Releases between 2000-10-14 (07:00) and 2007-10-13 (07:00)
Experiment: 1900 particles released from any source
Integrated: 4320 hours

Figure 4.17.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from shipping route C in October 2000 to 2007, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 15200 particles are drifted.



Wind drift factor: 0.050
Experiment: 1900 particles released from any source
Integrated: 4320 hours

Figure 4.18.: CTH-densities of simulations of April events in 2003 and 2001 with 5 % wind drift on the left hand side and the center, respectively. On the right hand side the MRTs plot relating to the April 2001 event.

The **April** events in general differs from the other ones: The particle residence times in the German Bight are higher and the particle transport to the eastward located coast and to the north out of the German Bight is less strong resulting in quite low MRTs and CTH-densities at coasts of Denmark and Schleswig-Holstein and implying low pollution of those coastal regions. Simulations of **July and October** events reveal the opposite behaviour: The northward transport of particles out of the German Bight takes place close to the Danish coast along a narrow pathway (MRTs and CTH-densities in the figures 4.21 and 4.22) leading to a higher particle pollution at the Danish coast. The CTH-densities at the Danish coast and the North Frisian Islands mostly exceed 10 % and partly even 20 %, indicating that the North Frisian Islands are considerably polluted by particles. Particles of the **July** event drift less diffuse than those of October, as spatially sharp jumps in the CTH plot of figure 4.21 top left suggest. **January** events' particle transport lies in between that of April on the one and that of July and October on the other side and is not further commented here. The fastest northward transports take place during January and October events indicated by the TT20s. The TT20s of July are remarkably high.

If 1 % wind drift is added, the wind forces particles against the west coast of **Schleswig-Holstein** - affecting North Frisian Islands and mainland coast equally - and Denmark as comparable to simulations from shipping route sources. Increased MRTs and CTH-densities at these coasts indicate that. If the wind drift factor increases to 5 %, the CTH-densities there double at least - during the January event even triple - and the MRTs increase slightly. In simulations with 1 % wind drift, particles of the January, April and July events affect the complete coastlines of the **Netherlands** and **Lower Saxony**. If the wind drift factor is increased to 5 %, the CTH-densities at these coasts rise above 15 % in most regions, exclusively remaining below 10 % in the October event's simulations. The local maximum in MRTs and CTH-densities close to **Helgoland** decreases with increasing wind drift being negligible when the wind drift factor amounts 5 %. Especially with 5 % wind drift, the TT20s in the **western North Sea** are considerably high compared to simulations without wind drift. TT20s as well suggest a northward transport of particles injected by **UK**s source rivers. However, CTH-densities are low indicating a marginal amount of affected particles.

In nearly all simulations independent of the wind drift the MRTs in the **Elbe** and **Jade-Weser** estuary source regions exceed those in other source regions. It could be a natural effect but also a artificially induced one: Source regions of other fresh water inputs are located further out at sea being exposed to higher hydrodynamic velocities. Therefore, particles are more likely drifted faster into other regions.

4.2.5. Conclusion to forward simulations from shipping route and river source regions

The previous subsections deal with the location of possible accumulation regions and the variability of coastal pollution depending on *(a)* location of source regions, *(b)* wind drift factor and *(c)* seasonal variation of hydrodynamic currents. Annually variations are briefly considered. This conclusion starts as general as possible focussing on currents and the wind drift factor, then the focus shifts to seasonal variations in the particle drift and finally some single source regions and single events are discussed. The differences between events starting from rivers and those starting from shipping routes are low.

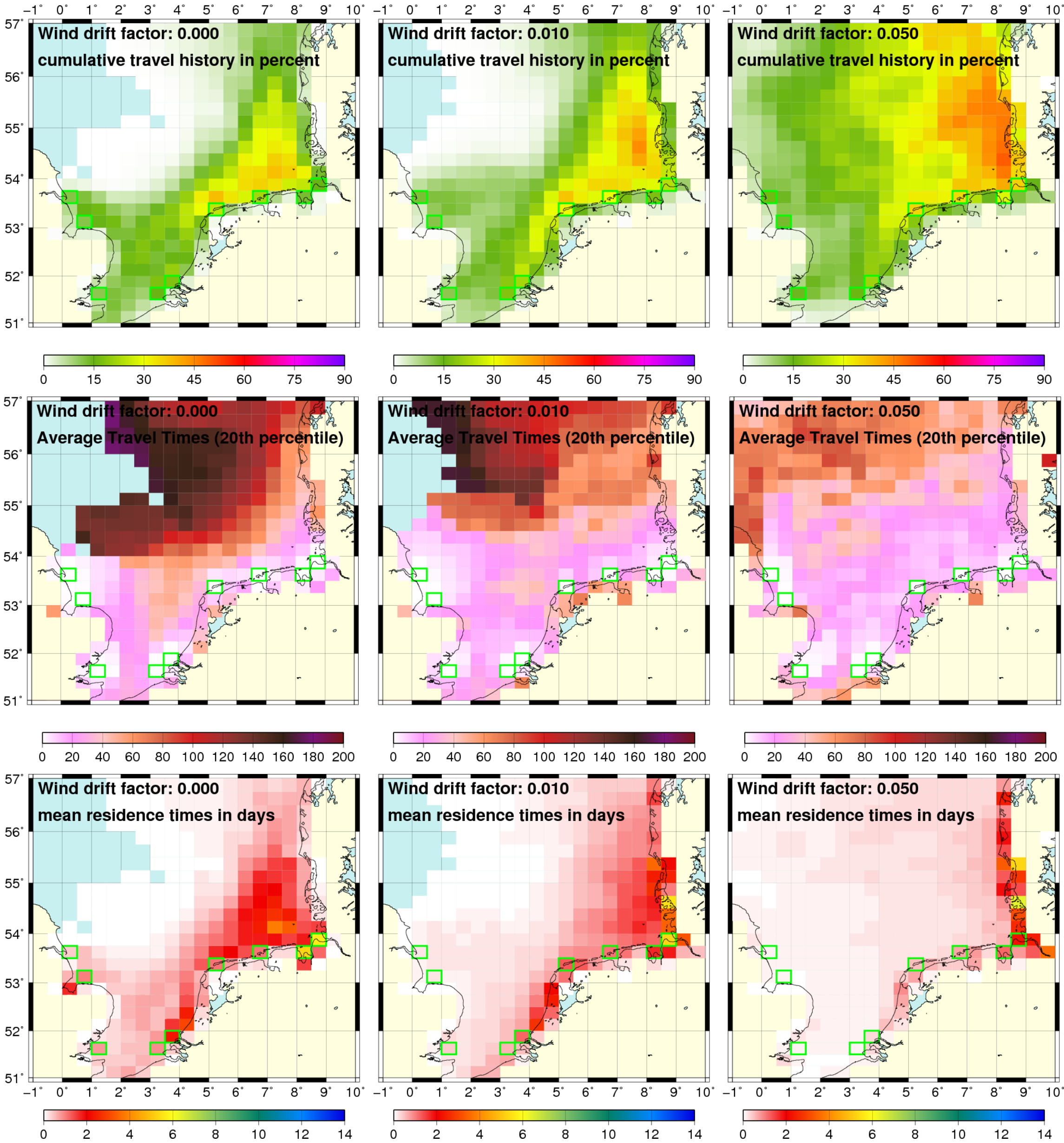
Literature and practical experience state, that the main North Sea current is counter-clockwise orientated (see section 2.3). In simulations with no wind drift particles are approximately drifted this way:

a) southward directed transport close to the UK's coast; The CTH-densities in the western North Sea in figures 4.14, 4.15, 4.16 and 4.17 (route C) indicate it;
b) eastward directed transport in the southern North Sea; Low CTH-densities westward of route B (not plotted) and high and eastward increasing CTH-densities along route A (figs. 4.9, 4.10, 4.11 and 4.12) suggest it;
c) northward directed transport along the Danish coast; common feature in most simulations;
d) No statement possible regarding the expected westward directed transport in the northern North Sea;

Hence, u-shaped hydrodynamic currents are evident, starting at the UK's coast, ending at the Danish one and considerably controlling the particle transport. If wind drift is added, those currents loose their influence on the direction of particle transport leading to a partly more diffuse transport as increased and spatially more homogeneous CTH-densities all over the North Sea indicate.

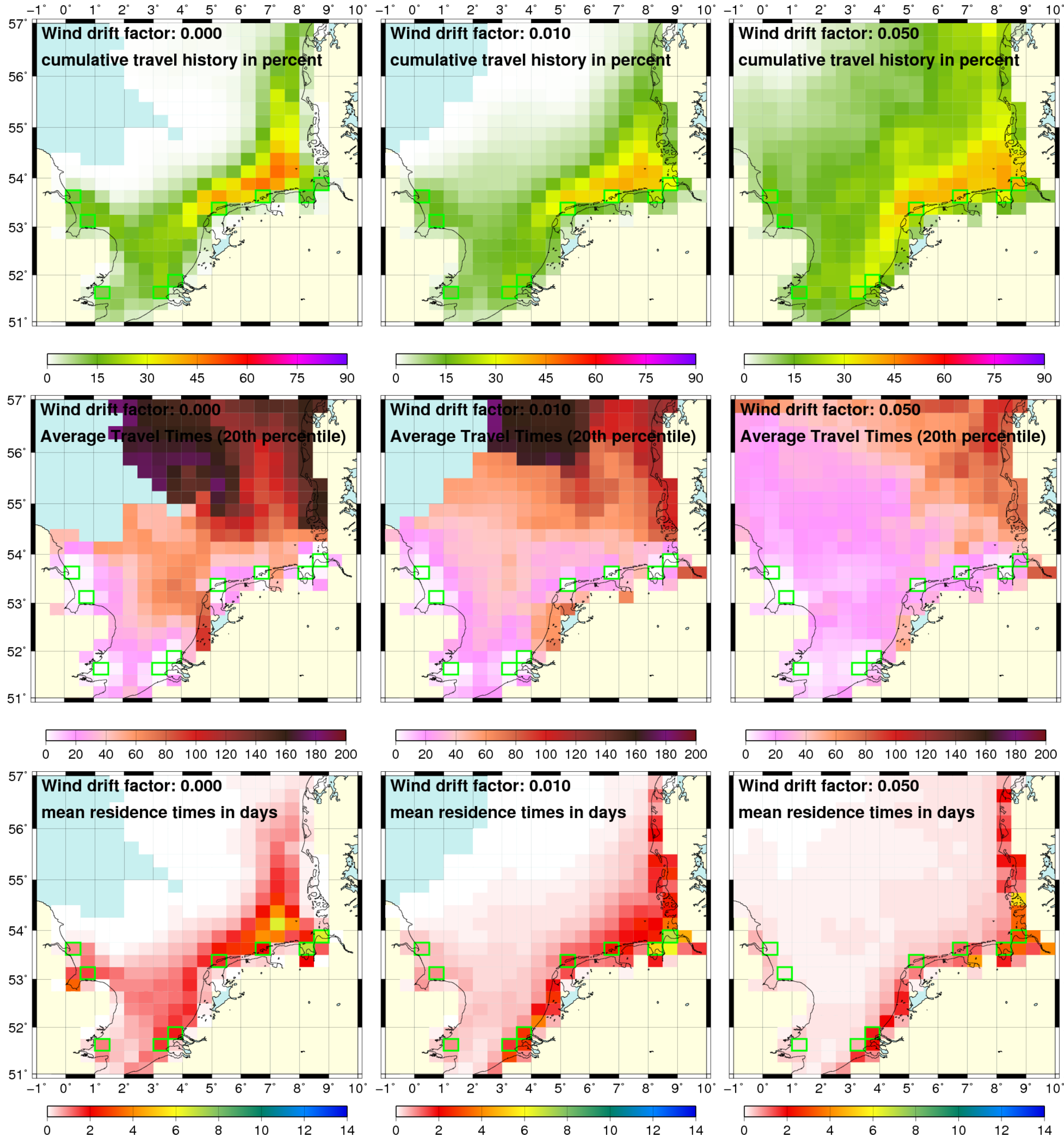
Particle velocities increase with increasing wind drift factor, as lower MRTs at open sea and lower TT20s suggest. In simulations without wind drift, near Helgoland ($7°E$ to $8°E$ and $54.0°N$ to $54.5°N$) a local maximum in MRTs is present in some simulations: bottom left plots in figures 4.9 - 4.12 (route A Jan. - Oct.), 4.14, 4.16 and 4.17 (route C Jan., Jul. and Oct.), 4.19, 4.20, 4.22 (rivers Jan., Apr. and Oct.) and in not plotted MRTs to January and April simulations starting from route B. That observation is already discussed in the conclusion to the homogeneous initial particle distribution (see subsection 4.1.4), stating possible real and model-related reasons for the increased MRTs in that area. The most likely one is, that hydrodynamic currents close to Helgoland are more turbulent leading to higher residence times.

In simulations without wind drift, the coasts of Denmark and the West, East and North Frisian Islands are medium affected by particles, as medium to high CTH-densities indicate. The coast behind chains of islands seams to be protected by these islands being suggested by low CTH-densities and MRTs in those regions. With increasing wind drift factor the MRTs and CTH-densities at coasts, towards which the wind blows particles, considerably increase. Coasts of Schleswig-Holstein and Denmark are affected nearly evenly throughout the year by particles of various sources, while the particle abundance at Dutch and Lower Saxon coasts depends on particle's source regions and the season. Particle densities and MRTs in the Channel decrease with increasing wind drift factor indicating, that it is emptied faster. In simulations with 5 % wind drift the particle transport into river estuaries - especially the Elbe-Weser estuaries - is



8 Releases between 2001-01-13 (13:00) and 2008-01-14 (13:00)
Experiment: 1800 particles released from any source
Integrated: 4320 hours

Figure 4.19.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from 9 river estuaries in January 2001 to 2008, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 14400 particles are drifted.

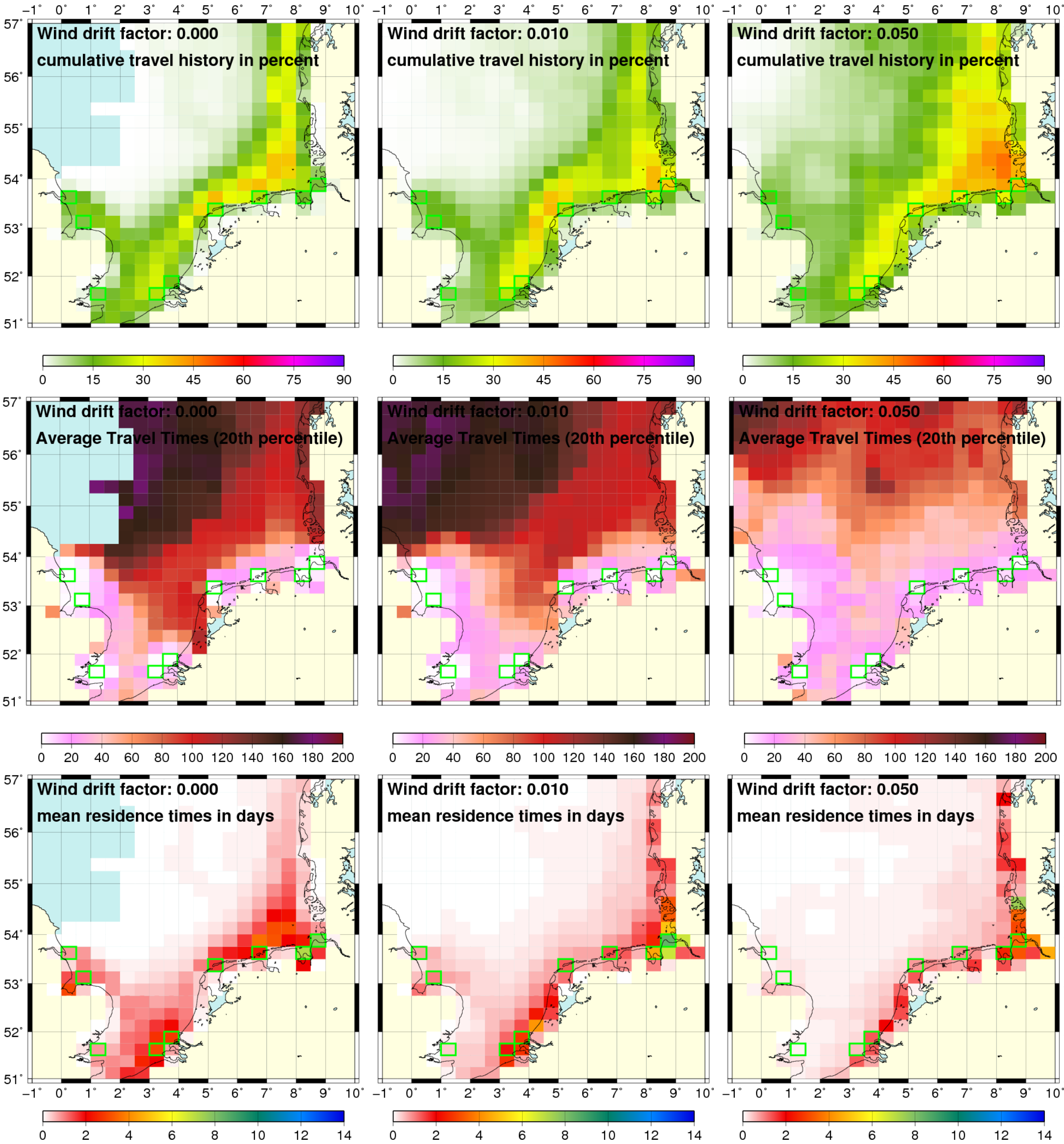


8 Releases between 2001-04-14 (19:00) and 2008-04-12 (19:00)

Experiment: 1800 particles released from any source

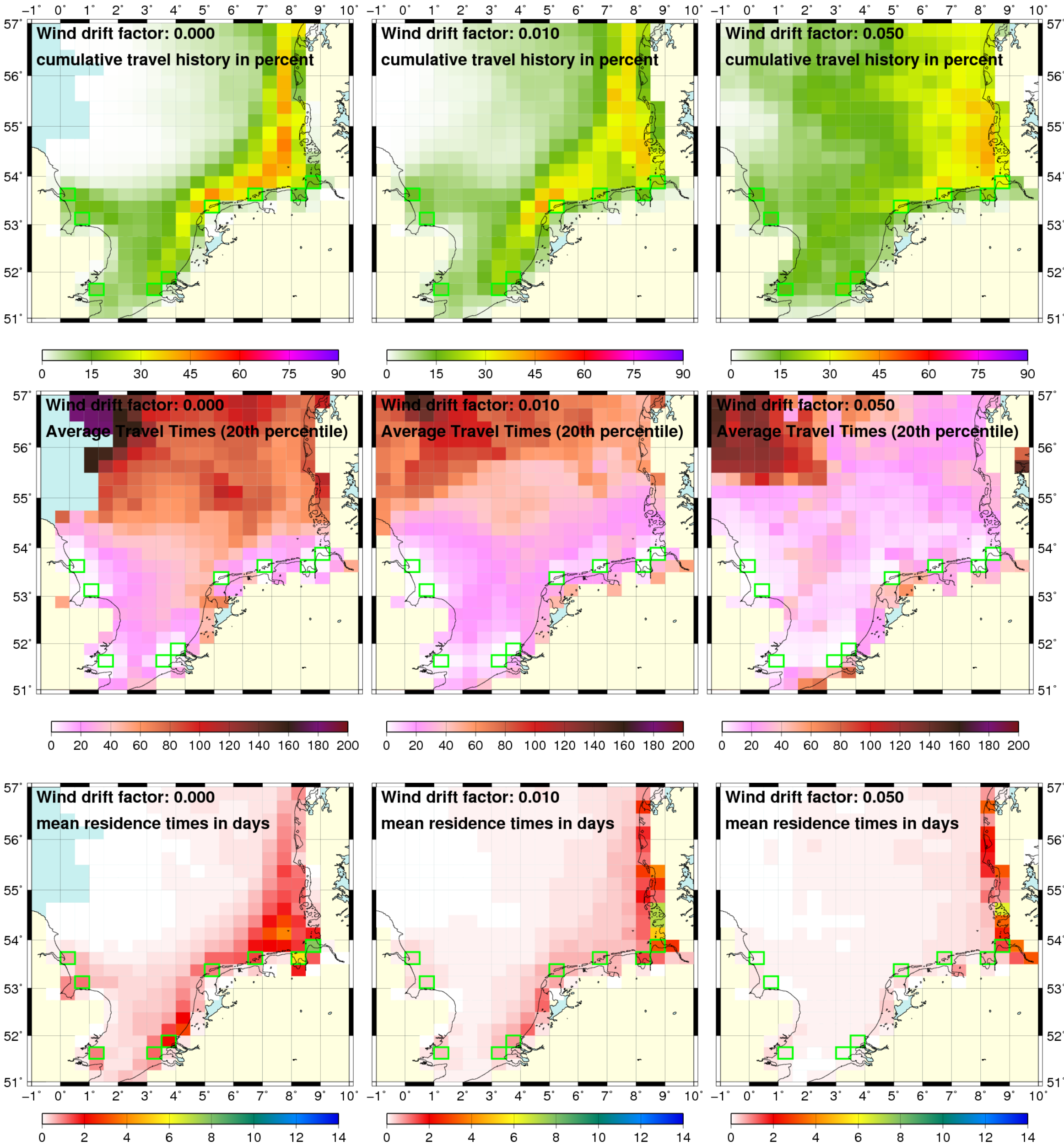
Integrated: 4320 hours

Figure 4.20.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from 9 river estuaries in April 2001 to 2008, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 14400 particles are drifted.



8 Releases between 2000-07-15 (01:00) and 2007-07-14 (01:00)
Experiment: 1800 particles released from any source
Integrated: 4320 hours

Figure 4.21.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from 9 river estuaries in July 2000 to 2007, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 14400 particles are drifted.



8 Releases between 2000-10-14 (07:00) and 2007-10-13 (07:00)
Experiment: 1800 particles released from any source
Integrated: 4320 hours

Figure 4.22.: CTH-, TT020- and MRT-composite-plots to 180-day forward simulations of particles started from 9 river estuaries in October 2000 to 2007, being calculated with 0 %, 1 % and 5 % wind drift and plotted from left to right in the same order. From top to bottom the plots are aligned by plot type, starting with CTH-plots and being followed TT020- and MRT-plots. 14400 particles are drifted.

strong as high CTH-densities and MRTs suggest concerning not only particles injected by rivers but also those by shipping routes A and B. Application of wind drift in general, leads to increased variation in the particle transport between different years as good exemplified by the plots in figure 4.18: Particles starting in mid-April at the south-west of shipping route C are drifted southward towards the continental coast during summer 2001 and northward during summer 2003.

The largest difference in the system behaviour between two seasons exists between summer and winter. Spring and autumn show a transition behaviour. In simulations without wind drift, the particle transport velocities are the highest during winter: MRTs and TT20s fall below those observed during the other seasons. During summer the slowest transport takes place going along with the lowest particle pollution at the North Frisian Islands and the Danish coast compared to other seasons. With increasing wind drift factor those seasonal variations decrease and vanish, while some new arise. In simulations with 1 % and 5 % wind drift, the particle pollution of the Dutch and Lower Saxon coasts during summer and autumn clearly exceeds that one during winter and spring as high differences in CTH-densities and MRTs between April and July on the one and October and January on the other side suggest. Independent of the wind drift, coastal regions close to river estuaries are considerably affected by particles originating from there. If the wind drift factor increases, these particles reach more distant coastal regions. Both statements are supported by high CTH-densities and low TT20s. The time in-rivers-injected particles need till leaving their source region the first time exceeds the time anywhere-at-sea-injected particles need. The surface current velocities at open sea normally exceed the velocity in river estuaries. Hence, particles are faster transported at open sea. Additionally, this first-leave-residence time varies between the river estuaries. Two technical reasons are mainly responsible for this variability: *(a)* The location of the source regions in the river estuaries differ, causing higher residence times if particles are deeper located within them. *(b)* Not all river inflows into the North Sea are modelled implying a slower transport in not modelled ones. Finally, the real volume flows of the river differ which explains different residence times. In the *BSHcmod* V3 the river inflows into the North Sea are constant throughout the year. Therefore, only minor seasonal variations of the residence times in individual river estuaries arise.

4.3. Conclusion to forward simulations

In this chapter, forward simulations are evaluated on the base of composite plots. For each season a plot aggregating simulation results of eight years was created in order to reduce complexity of the model output and to help identify seasonal variation visually without being distracted by annual variations. As figure 4.18 reveals, the averaging of annual variations works well. Some seasonal variations were identified being consistently present in simulations with different source region configurations - more on this in the next paragraph. The annual variation increases with increasing wind drift factor as figure 4.18 shows. Additionally, was stated that the weather has an important influence on the particle drift and must not be neglected. In further studies should be examined whether another separation than a seasonally one leads to the same results.

The seasonal variations in the particles transport and the influence of the wind drift factor on it were described and discussed in detail in the two previous subsections of this chapter. Submerged not-wind-affected items constitute a low pollution potential on beaches. At the same time, some coastal regions are excluded: In simulations without wind drift, the Danish coast and the North Frisian Islands show medium to high and the East Frisian Islands low to medium particle densities. Another exception is provided by the land-based litter: Independent of the wind drift factor, particles injected in rivers closely pass near to the source river located coasts which implies high pollution potential in those coastal regions. Buoyant wind exposed items reach the coast, towards the wind blows them to. The wind direction varies seasonally: from primarily south-western wind in winter to primarily north-western wind in summer. Therefore, in winter, coasts of Belgium, the Netherlands and Lower Saxony receive lower amounts of sea-based litter at their beaches. Primarily litter from land-based sources should be found. In contrast, in summer, land-based and wind affected sea-based litter can be expected there. Buoyant items of all types - submerged and swimming atop - affect the North Frisian Islands and the Danish coast throughout the year omitting Sylt, Amrum and some other islands during summer: particles of the April events often avoid those islands. The mainland coast of Schleswig-Holstein is protected by the offshore islands against sea-based litter. The coastline's shape of the southern west coast of Schleswig-Holstein protects the northern one against land-based litter that comes from the Elbe river. The wind forcing on particles needs to be sufficiently strong to drift them to the mainland coast. Hence, at beaches of the northern west coast of Schleswig-Holstein primarily wind-drifted items should be found. In contrast, at the southern west coast mainly land-based litter from the Elbe and eventually from the Weser and Jade should be washed ashore.

In regions close to Helgoland, items reside longer than in other regions at open sea. Circular currents or eddies could be responsible for this phenomenon (see 4.1.4). Averaged *BSHcmod* V3 ocean currents and real observations should be consulted in order to identify the reason for the local increase. Also in some river estuaries high residence times occur. Possible reasons for this phenomenon were discussed in 4.2.5. The residence times in river estuaries were no topic in this work. If beached litter is analysed with respect to its age, the transport time in the rivers and the residence time in the river estuary would be interesting.

Till now the shipping routes and rivers were described individually or all together without comparing them with each other or highlighting any differences or unique features. Particles injected on shipping route B pollute the British, Belgian and Dutch coasts if they are strongly wind affected. Litter from all shipping routes is very likely to pollute the Danish coast. Low amounts of wind drifted items seem to reach beaches of the Netherlands and Lower Saxony. Though, during summer and autumn medium amounts can be expected in some regions. At the German coast no oil from British oils rigs is registered. This contradicts with the expected abundance of marine litter from shipping route C at those regions. In contrast to plastic litter, oil degrades within one or two weeks at the sea, which the difference explains.

There are four tasks which further studies should focus: *(a)* The different river sources should be regarded separately, especially those for which unique debris compositions can be expected. Additionally, another set of hydrodynamic currents would be more suitable for simulations close to coasts when particles are injected in rivers. *(b)* Source regions should be placed near the Shetland Islands, in the Channel and in the Skagerrak in order to model marine litter entering the North Sea from the Atlantic Ocean and the Baltic Sea. These sources might not provide new insights for beach pollution predictions in the German Bight. They could be useful for predictions of marine litter abundance in the whole North Sea. *(c)* Simulation results close to boundaries have to be regarded with caution in most models. Apparently, this applies for simulations close to the northern boundary of the *BSHcmod* domain. If the outflow of marine litter from the North Sea into the Atlantic Ocean is regarded, a set of hydrodynamic currents which reaches spatially deeper into the North East Atlantic should be used (e.g. those calculated by the *BSHcmod* V4). *(d)* Finally, a 3D drift model would be useful for comparing its results with those of *PELETS-2D* and identifying possible accumulation regions at the sea bed.

5. Conclusion

In this Master's Thesis, the application of the Lagrangian particle transport simulation *PELETS-2D* on real and fictive monitoring data was in the focus, assessing the benefit of ship-based litter surveys and estimating litter compositions at beaches, seasonal variations in the litter transport and correlation between observation regions of marine litter items and their direction of origin.

In the introduction and in the material description, several tasks for the application of particle transport models in connection with marine litter monitoring concepts and observation data evaluation were mentioned, while only a few were covered by this thesis. Chapter 3 examined backward simulations on the base of ship-based litter observations. The employed real observations [Thiel et al., 2011] are too far distributed for dealing with spatio-temporal variability in the litter drift, but good for introducing *PELETS-2D*. Observation data of a fictive monitoring helped identifying spatial correlations between the location of survey regions and the direction of particle origin. Items observed in the south-western German Bight are expected to originate primarily from western directions, whereas for items observed in the north-eastern German Bight the direction of origin varies considerably. In contrast, temporal correlations, such as seasonally recurring variations, could not be identified. During the evaluation the importance of wind drift was recognised, exerting a considerable influence on the particle drift pathway.

In chapter 4, forward simulations were performed and analysed, focussing on estimating beach litter compositions in different regions and seasonal variations in the particle transport along coasts and out of the North Sea. In doing so it was shown, that wind affected items more numerously cross coastal waters than not wind affected ones. The Danish coast and the North Frisian Islands are expected to be more polluted by marine litter than other continental coast and islands. Presumably, medium to strong wind affected items accumulate in German river estuaries, in particular in summer month. It is indicated, that especially at the Dutch coast the litter pollution varies seasonally with minima in the litter abundance during winter. Also during winter a considerable strong leakage of buoyant items - in particular wind affected ones - from the North Sea into the Atlantic along Norway is expected.

According to those two chapters, the wind drift is an important process in particle transport models. Particles move very fast and cross the North Sea in up to 10 days if the wind drift factor amounts 10 % and above - compared to several month for crossing in simulations without wind drift. The uncertainty in the particle drift pathway, however, is high because one small deviation in the weather data or in the particle location may have a strong influence on the particle trajectory, complicating the localisation of source locations. Therefore, particle transport simulations are not suited for estimating neither source locations of strongly wind affected items nor their direction of origin. If the wind drift factor amounts 5 % or lower, particles are considerably slower and calculated trajectories look more realistic, while still large uncertainties affect the particle transport. Results obtained in simulations with wind drift factors between 5 % and 10 % have to be considered individually whether they are usable or not. These limits of 5 % and 10 % are no hard ones but indicate when the system behaviour approximately changes. As discussed in subsection 2.1.1, the wind drift factor is no objective property but depends on the hydrodynamic model.

Uncertainties in the particle transport models are system inherent because the formation of hydrodynamic currents and the transport of items on them are complex processes. Studies with drift buoys and particle transport simulations show [Abascal et al., 2012], that trajectories of real drifted items can be estimated by particle ensemble simulations. Though, no exact source locations of items on the base of calculated trajectories can be determined if no information on the residence time at the sea is available. In contrast, the origin of radioactive isotopes and oil can be estimated on base of their decay and degradation rates, respectively (e.g. Schönfeld [1995]). Plastic waste, however, degrades very slowly, which complicates specifying the residence time (e.g. Ryan et al. [2009]). Therefore, exact source locations of marine litter cannot be determined by particle transport simulations but direction of particle origin and expected non-source regions during the previous months' drift can be.

In several situations within this thesis, the resolution and shape of the numeric grid at coastlines was criticised. A lower grid resolution implicates a new parametrisations and more processes have to be considered causing further uncertainties. Even if a better fitted model looks more sophisticated it does not necessarily provide more accurate and realistic results - they may even be worse. Thus the criticism is questionable. Simulation results close to boundaries, in general, have to be handled with caution. Therefore, particle transport close to coasts - being closed boundaries - should be discussed carefully, independent of the grid resolution. Open boundaries, though, even lead to wrong results because of the lack of knowledge about particle transport beyond them: Marine litter being drifted out of the North Sea along the Norwegian coast into the Atlantic *(a)* remains there or *(b)* returns into the North Sea close to the Shetland Islands. When performing particle transport simulations one has the choice between open or reflecting boundary conditions for modelling real world open boundaries. In the first case, the amount of particles remaining in the system is underestimated, while in the second case, it is overestimated (see "January events" in 4.1). Both choices lead to defective results. To avoid that, modelled particle transport should take place far away from open model boundaries, ideally fulfilling that no particle is able to arrive it till the end of simulation with maximum velocity. Alternatively, the boundaries should be far enough away from the investigation area: For instance, if the particle transport in the German Bight is focussed, hydrodynamic currents ranging till $60°N$ and $4°W$ are sufficient.

Beside horizontal boundaries the sea surface has also vertical open boundaries: real marine litter sinks partly. Two-dimensional particle transport simulations as *PELETS-2D* ignore this fact. Three-dimensional simulations, however, offer sinking and re-emerging of particles, transport and accumulations at the sea floor and transport in the whole water column, seeming much more appropriate for litter transport modelling. But, more processes are to be included and more model parameters are to be determined, increasing the complexity, computing time and especially uncertainty, still ignoring various shapes of real marine litter items. Additionally, a three-dimensional hydrodynamic model is needed.

Chapter 3 dealed with ship-based observations of marine litter whereas chapter 4 was aimed on beach litter surveys. Both survey types are in two aspects fundamentally different. Ship-based surveys provide **point measurements** of marine litter abundance **at the sea surface**, considerably affected by spatio-temporal variations and outliers. In contrast, beach surveys provide **cumulative measurements** of marine litter arriving the coast over a certain time period, including **litter from the sea surface, the water column and the sea floor**. In the latter case, on the one hand outliers are averaged out, while on the other hand one looses a feeling for extreme events. Sea surface monitoring alternatives overcoming some disadvantages are aerial surveys by plane in cooperation with harbour porpoise (dt. Schweinswal) and oil monitoring flights, gillnets or remote sensing. The latter method is at its beginning and represents a passive detection method by identifying areas of probably high litter abundance [Pichel et al., 2007, 2012, Mace, 2012].

If the wind drift factor actually is important for particle transport simulations it has to be measured in surveys for every item in order to be able to calculate reasonably valid trajectories later. Exact wind drift factors cannot be determined - even not, if they were model independent. Therefore, in conclusion of section 3.1 a wind drift factor categorisation schema for marine litter was proposed, offering four categories to which in a second step wind drift factors can be mapped:

- **no wind drift** for submerged items (e.g. fishing nets)
- **slight wind drift** for in small parts emerged items (e.g. wood)
- **medium wind drift** for heavy emerged items (e.g. buoys)
- **strong wind drift** for light emerged items (e.g. air filled plastic bottles)

These categories should not be correlated to item categories on survey sheets but determined individually per item: For instance plastic bottles of various shapes and different fill states are affected differently by wind drift. While assigning items to one of those categories in ship-based sea surface surveys is simple, it is quite difficult when performing beach litter surveys. For instance a water pool could be needed to identify the behaviour of an item in the water, causing more work, but it allows at the same time an additional differentiation of at the sea floor, in the water column and at the sea surface drifted items. Independent of how the categorisation is realised practically, it is a precondition for the expedient employment of particle transport simulations.

Two ways of evaluating litter data arise by the recording of wind drift information: *(a)* Apply statistical methods (e.g. cluster analysis) on the base of the wind drift categorisations. *(b)* Perform particle transport simulations on the base of periodically conducted marine litter surveys, producing estimations on the direction of litter origin. On that base, survey data can be clustered by source direction as preprocessing for further statistical analysis. Alternatively, it can be tested whether outliers in the litter composition can be explained by diverging source directions. However, for identifying outliers comparable long term observation data is needed being partly already provided by the OSPAR beach litter monitoring and comparable to the long term marine data database of the HZG named coastdat [coastDat, 2012].

Monitoring for the sake of monitoring and particle transport modelling just for sake of modelling a complexity system may be sufficient motivations for researchers. The currently far more pressing motivation for working on these topics is the implementation of the Marine Strategy Framework Directive. Four indicators should measure the achievement of descriptor 10 aiming on marine litter [European Union, 2010]. One indicator focusses on the plastic litter abundance in biota while the other three deal with litter- and especially macro- and micro-plastics-abundance at beaches and in the sea. These indicators measure the pollution by marine litter, contributing to an assessment of the marine environment's status and forming the base for a catalogue of measures for the reduction of input and abundance of marine litter. Regarding the legislation on the input of sea-based plastic litter, however, no plastic items should originate from ships nowadays. At the same time the input of land-based litter should be low in European waters because of extensive sewage water treatment and daily municipal cleanups at many tourist beaches. Evidently, these measures on sea- and land-based litter are not sufficient and effective [van Franeker et al., 2011b, OSPAR, 2007a]. Awareness-raising in stakeholder groups is very important for reducing the litter input in short term and its abundance in long term, parallel to monitoring, legislation and monetary benefits. Especially, because the majority of experts agree non-officially, that removing litter from the sea would be practically and financially very expensive or even impossible and, hence, is no option, presently. The annual conducted *International coastal cleanups* [Ocean Conservancy, 2010, 2011, e.g.] and *Fishing for Litter* initiatives managed by KIMO in the North Sea [KIMO, 2007, 2008] and by the NABU in the Baltic Sea are two popular projects for that purpose. Eventually also particle transport simulations can help to explain stakeholders the range of disposed litter.

Bibliography

Ana Julia Abascal, Sonia Castanedo, Vicente Fernández, and Raúl Medina. Backtracking drifting objects using surface currents from high-frequency (hf) radar technology. *Ocean Dynamics*, 62(7):1073–1089, 2012. doi: 10.1007/s10236-012-0546-4. URL http://www.springerlink.com/content/4j3667h26058pt78/?MUD=MP.

Michelle Allsopp, Adam Walters, David Santillo, and Paul Johnston. Plastic debris in the world's oceans. Technical report, Greenpeace, 2006. URL http://www.greenpeace.org/international/Global/international/planet-2/report/2007/8/plastic_ocean_report.pdf.

Anthony L. Andrady. Microplastics in the marine environment. *Marine Pollution Bulletin*, 62 (8):1596 – 1605, 2011. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2011.05.030. URL http://www.sciencedirect.com/science/article/pii/S0025326X11003055.

David K. A. Barnes. Biodiversity: Invasions by marine life on plastic debris. *Nature*, 416(6883): 808–809, April 2002. ISSN 0028-0836. URL http://dx.doi.org/10.1038/416808a.

David K. A. Barnes and Keiron P. P. Fraser. Rafting by five phyla on man-made flotsam in the southern ocean. *Mar Ecol Prog Ser*, 262:289–291, 2003. URL http://www.int-res.com/abstracts/meps/v262/p289-291/.

David K. A. Barnes, Francois Galgani, Richard C. Thompson, and Morton Barlaz. Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1526):1985–1998, 2009. doi: 10.1098/rstb.2008.0205. URL http://rstb.royalsocietypublishing.org/content/364/1526/1985.abstract.

M. Breton and J.C. Salomon. A 2d long term advection-dispersion model for the channel and southern north sea part a: Validation through comparison with artificial radionuclides. *Journal of Marine Systems*, 6(5-6):495 – 513, 1995. ISSN 0924-7963. doi: 10.1016/0924-7963(95)00020-P. URL http://www.sciencedirect.com/science/article/pii/092479639500020P.

J.B. Buchanan. Pollution by synthetic fibres. *Marine Pollution Bulletin*, 2(2):23 – 23, 1971. ISSN 0025-326X. doi: 10.1016/0025-326X(71)90136-6. URL http://www.sciencedirect.com/science/article/pii/0025326X71901366.

Ulrich Callies, Andreas Pluess, Jens Kappenberg, and Hartmut Kapitza. Particle tracking in the vicinity of helgoland, north sea: a model comparison. *Ocean Dynamics*, 61:2121–2139, 2011. ISSN 1616-7341. URL http://dx.doi.org/10.1007/s10236-011-0474-8. 10.1007/s10236-011-0474-8.

Alena Chrastansky and Ulrich Callies. Model-based long-term reconstruction of weather-driven variations in chronic oil pollution along the german north sea coast. *Marine Pollution Bulletin*, 58(7):967 – 975, 2009. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2009.03.009. URL http://www.sciencedirect.com/science/article/pii/S0025326X09001180.

Alena Chrastansky, Ulrich Callies, and David M. Fleet. Estimation of the impact of prevailing weather conditions on the occurrence of oil-contaminated dead birds on the german north sea coast. *Environmental Pollution*, 157(1):194 – 198, 2009. ISSN 0269-

7491. doi: 10.1016/j.envpol.2008.07.004. URL http://www.sciencedirect.com/science/article/pii/S0269749108003680.

Thomas Clemens, Eike Hartwig, and Laura Steinbusch. Zur strandmllbelastung der inseln mellum und minsener oog (sdliche nordsee) in den jahren 2004-2009. *Natur- und Umweltschutz (Zeitschrift Mellumrat)*, 10(1):20–28, 2011. URL http://www.mellumrat.de/index5.htm.

coastDat. Homepage of the coastdat database of the helmholtz-zentrum geesthacht, 2012. URL http://www.coastdat.de/.

Matthew Cole, Pennie Lindeque, Claudia Halsband, and Tamara S. Galloway. Microplastics as contaminants in the marine environment: A review. *Marine Pollution Bulletin*, 62(12): 2588 – 2597, 2011. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2011.09.025. URL http://www.sciencedirect.com/science/article/pii/S0025326X11005133.

Oliver J. Dameron, Michael Parke, Mark A. Albins, and Russell Brainard. Marine debris accumulation in the northwestern hawaiian islands: An examination of rates and processes. *Marine Pollution Bulletin*, 54(4):423 – 433, 2007. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2006.11.019. URL http://www.sciencedirect.com/science/article/pii/S0025326X06005078.

Kim Cornelius Detloff and Melanie Ossenkop. Müllkippe meer. Brochure, 2010.

Stephan Dick and Eckhard Kleine. The bsh new operational circulation model using general vertical co-ordinates. *Environmental Research, Engineering and Management*, 3(41):18–24, 2007. URL www1.apini.lt/includes/getfile.php?id=475.

Stephan Dick and K. C Soetje. Ein operationelles ölausbreitungsmodell für die deutsche bucht. *Deutsche Hydrographische Zeitschrift, Ergänzungsheft, Reihe A*, 16:2–43, 1990.

Stephan Dick, S.H. Mueller-Navarra, H. Klein, H. Komo, and Eckhard Kleine. The operational circulation model of bsh (bshcmod) - model description and validation. Techreport, Bundesamt fuer Seeschiffahrt und Hydrographie, 2001. URL http://hdl.handle.net/10068/186797.

Günter Dietrich, Kurt Kalle, Wolfgang Krauss, and Gerold Siedler. *General Oceanography - An Introduction*. John Wiley & Sons, New York - Chichester - Brisbane - Toronto, 2nd edition, 1980.

Mary J Donohue, Raymond C Boland, Carolyn M Sramek, and George A Antonelis. Derelict fishing gear in the northwestern hawaiian islands: Diving surveys and debris removal in 1999 confirm threat to coral reef ecosystems. *Marine Pollution Bulletin*, 42(12):1301 – 1312, 2001. ISSN 0025-326X. doi: 10.1016/S0025-326X(01)00139-4. URL http://www.sciencedirect.com/science/article/pii/S0025326X01001394.

Curtis C. Ebbesmeyer, W.J. Ingraham, Jason A. Jones, and Mary J. Donohue. Marine debris from the oregon dungeness crab fishery recovered in the northwestern hawaiian islands: Identification and oceanic drift paths. *Marine Pollution Bulletin*, 65(12):69 – 75, 2012. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2011.09.037. URL http://www.sciencedirect.com/science/article/pii/S0025326X1100525X. At-sea Detection of Derelict Fishing Gear.

European Union. Directive 2000/59/ec of the european parliament and of the council on port reception facilities for ship-generated waste and cargo residues. Official Journal of the European Union, November 2000.

European Union. Directive 2005/35/ec of the european parliament and of the council on ship-source pollution and on the introduction of penalties for infringements. Official Journal of the European Union, September 2005. URL http://cleanseanet.emsa.europa.eu/docs/public/Directive_2005_35_EC.pdf.

European Union. Directive 2008/56/ec of the european parliament and of the council on establishing a framework for community action in the field of marine environmental policy (marine strategy framework directive). Official Journal of the European Union, June 2008.

European Union. Decision 2010/477/eu of the european commission on criteria and methodological standards on good environmental status of marine waters. Official Journal of the European Union, September 2010.

David Fleet, Jan van Franeker, Jeroen Dagevos, and Merijn Hougee. Marine litter. thematic report no. 3.8. - in: Marencic, h. & vlas, j. de (eds), 2009. quality status report 2009. waddensea ecosystem no. 25. Technical report, Common Wadden Sea Secretariat, Trilateral Monitoring and Assessment Group, Wilhelmshaven, Germany, 2009. URL http://www.waddensea-secretariat.org/QSR-2009/index.htm.

David M. Fleet, Thomas Clemens, Eike Hartwig, Veit Hennig, and Silvia Gaus. Untersuchung der verschmutzung der spülsäume durch schiffsmüll an der deutschen nordseeküste. Final Report Frderungskennzeichen (UFOPLAN) FAZ 202 96 183, Umweltbundesamt (UBA), 2003.

Charles W. Fowler. Marine debris and northern fur seals: A case study. *Marine Pollution Bulletin*, 18(6, Supplement B):326 – 335, 1987. ISSN 0025-326X. doi: 10.1016/S0025-326X(87)80020-6. URL http://www.sciencedirect.com/science/article/pii/S0025326X87800206.

Maria Gästgifvars, Sylvin Müller-Navarra, Lennart Funkquist, and Vibeke Huess. Performance of operational systems with respect to water level forecasts in the gulf of finland. *Ocean Dynamics*, 58:139–153, 2008. ISSN 1616-7341. URL http://dx.doi.org/10.1007/s10236-008-0137-6. 10.1007/s10236-008-0137-6.

Murray R. Gregory. Environmental implications of plastic debris in marine settingsentanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1526):2013–2025, 2009. doi: 10.1098/rstb.2008.0265. URL http://rstb.royalsocietypublishing.org/content/364/1526/2013.abstract.

Karen Hall. Impacts of marine debris and oil - economic and social costs to coastal communities. Technical report, KIMO, 2000. URL http://www.kimointernational.org/KIMOPublications.aspx.

Eike Hartwig. Die müllbelastung der insel scharhörn 1992-1994. *SEEVÖGEL*, 21(Special Issue), 2000. URL http://www.waddensea-secretariat.org/oelvoegel/3muell/scharhoern-2.htm.

Eike Hartwig. Die müllbelastung im mündungsbereich der elbe 1996. *SEEVÖGEL*, 22(3), 2001. URL http://www.waddensea-secretariat.org/oelvoegel/3muell/scharhoern-3.htm.

A.W. Heemink. Stochastic modelling of dispersion in shallow water. *Stochastic Hydrology and Hydraulics*, 4:161–174, 1990. ISSN 0931-1955. doi: 10.1007/BF01543289. URL http://dx.doi.org/10.1007/BF01543289.

Birgit Hermes. Zdf planet e. - müllhalde meer. movie, July 2012.

W. Hickel. Kurzzeitige veränderungen hydrographischer faktoren und der sestonkomponenten in driftenden wassermassen in der helgoländer bucht. *Helgoländer wissenschaftliche Meeresuntersuchungen*, 23:383–392, 1972. ISSN 0017-9957. doi: 10.1007/BF01609684. URL http://dx.doi.org/10.1007/BF01609684.

M.D. Hill, J.R. Cooper, S. Charmasson, and D. Robeau. Mathematical models for the transfer of radionuclides in the marine environment and their use in radiological assessments. Feb. 1986.

Ivan A. Hinojosa, Marcelo M. Rivadeneira, and Martin Thiel. Temporal and spatial distribution of floating objects in coastal waters of central-southern chile and patagonian fjords. *Continental Shelf Research*, 31(3-4):172 – 186, 2011. ISSN 0278-4343. doi: 10.1016/j.csr.2010.04.013. URL http://www.sciencedirect.com/science/article/pii/S0278434310001524. Fjord Oceanography of the Chilean Patagonia.

Evan A. Howell, Steven J. Bograd, Carey Morishige, Michael P. Seki, and Jeffrey J. Polovina. On north pacific circulation and associated marine debris concentration. *Marine Pollution Bulletin*, 65:16 – 22, 2012. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2011.04.034. URL http://www.sciencedirect.com/science/article/pii/S0025326X11002372. At-sea Detection of Derelict Fishing Gear.

IMO. Marpol 73/78, 1973a. URL http://www.imo.org/about/conventions/listofconventions/pages/international-convention-for-the-prevention-of-pollution-from-shi.aspx.

IMO. Marpol 73/78 annex i: Regulations for the prevention of pollution by oil (german), 1973b. URL http://www.bsh.de/de/Meeresdaten/Umweltschutz/MARPOL_Umweltuebereinkommen/index.jsp.

IMO. Marpol 73/78 annex ii: Regulations for the control of pollution by noxious liquid substances in bulk (german), 1973c. URL http://www.bsh.de/de/Meeresdaten/Umweltschutz/MARPOL_Umweltuebereinkommen/index.jsp.

IMO. Marpol 73/78 annex iii: Prevention of pollution by harmful substances carried by sea in packaged form, 1973d.

IMO. Marpol 73/78 annex iv: Prevention of air pollution from ships (german), 1973e. URL http://www.bsh.de/de/Meeresdaten/Umweltschutz/MARPOL_Umweltuebereinkommen/index.jsp.

IMO. Marpol 73/78 annex v: Prevention of pollution by garbage from ships (german), 1973f. URL http://www.bsh.de/de/Meeresdaten/Umweltschutz/MARPOL_Umweltuebereinkommen/index.jsp.

IMO. Marpol 73/78 annex vi: Prevention of pollution by sewage from ships (german), 1997. URL http://www.bsh.de/de/Meeresdaten/Umweltschutz/MARPOL_Umweltuebereinkommen/index.jsp.

Shinichiro Kako, Atsuhiko Isobe, Shinya Magome, Hirofumi Hinata, Satoquo Seino, and Azusa Kojima. Establishment of numerical beach-litter hindcast/forecast models: An application to goto islands, japan. *Marine Pollution Bulletin*, 62(2):293 – 302, 2011. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2010.10.011. URL http://www.sciencedirect.com/science/article/pii/S0025326X10004716.

KIMO. Fishing for litter netherlands 2006-2007, 2007. URL http://www.kimointernational.org/FFLNetherlands.aspx.

KIMO. Fishing for litter scotland 2008-2011 - final report. Report, Kommunenes Internasjonale Miljorganisasjon (Local Authorities International Environmental Organisation), 2008. URL http://www.kimointernational.org/Scotland.aspx.

Eckhard Kleine. Das operationelle modell des bsh für nordsee und ostsee, konzeption und übersicht. Technical report, Bundesamt für Seeschifffart und Hydrographie, 1994.

L.C.-M. Lebreton, S.D. Greer, and J.C. Borrero. Numerical modelling of floating debris in the world's oceans. *Marine Pollution Bulletin*, 64(3):653 – 661, 2012. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2011.10.027. URL http://www.sciencedirect.com/science/article/pii/S0025326X11005674.

Yonggang Liu, Robert H. Weisberg, Chuanmin Hu, and Lianyuan Zheng. Tracking the deepwater horizon oil spill: A modeling perspective. *Eos Trans. AGU*, 92(6):45, 2011. doi: doi:10.1029/2011EO060001. URL http://www.agu.org/pubs/crossref/2011/2011EO060001.shtml.

Peter Loewe. System nordsee zustand 2005 im kontext langzeitlicher entwicklungen. Berichte des BSH 44, Bundesamt für Seeschifffahrt und Hydrographie (BSH), Hamburg und Rostock, 2009. URL http://www.bsh.de/de/Produkte/Buecher/Berichte_/Bericht44/index.jsp.

Peter Loewe, Holger Klein, Stefan Schmolke, Sylvin Müller-Navarra, Gerd Becker, Hartmut Nies, Uwe Brockmann, Natalija Schmelzer, Stephan Dick, Dieter Schrader, Clemens Engelke, Achim Schulz, Alexander Frohse, Norbert Theobald, Wilfried Horn, and Sieglinde Weigelt. Nordseezustand 2003. Berichte des BSH 38, Bundesamt für Seeschifffahrt und Hydrographie, Hamburg und Rostock, 2005. URL http://www.bsh.de/de/Produkte/Buecher/Berichte_/Bericht38/index.jsp.

Peter Loewe, Holger Klein, Gerd Becker, Hartmut Nies, Uwe Brockmann, Stefan Schmolke, Stephan Dick, Dieter Schrader, Alexander Frohse, Achim Schulz, Jrgen Herrmann, Norbert Theobald, Birgit Klein, and Sieglinde Weigelt. Nordseezustand 2004. Berichte des BSH 40, Bundesamt für Seeschifffahrt und Hydrographie, Hamburg und Rostock, 2006. URL http://www.bsh.de/de/Produkte/Buecher/Berichte_/Bericht40/index.jsp.

Sebastian Lotter. Dynamics of floating seaweed in the north sea - a drift simulation-based evaluation of flotsam data. Bachelor's thesis, Institute for Environmental Systems Research, University of Osnabrück, 2011.

Thomas H. Mace. At-sea detection of marine debris: Overview of technologies, processes, issues, and options. *Marine Pollution Bulletin*, 65(12):23 – 27, 2012. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2011.08.042. URL http://www.sciencedirect.com/science/article/pii/S0025326X11004668. At-sea Detection of Derelict Fishing Gear.

Thomas Maes and E. Nicolaus. Uk marine litter monitoring. In *Talk EP07A-2 at 6th SETAC World Congress 2012, Berlin*, Talk EP07A-2 at 6th SETAC World Congress, 2012.

Elodie Martinez, Keitapu Maamaatuaiahutapu, and Vincent Taillandier. Floating marine debris surface drift: Convergence and accumulation toward the south pacific subtropical gyre. *Marine Pollution Bulletin*, 58(9):1347 – 1355, 2009. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2009.04.022. URL http://www.sciencedirect.com/science/article/pii/S0025326X09001787.

Nikolai Maximenko, Jan Hafner, and Peter Niiler. Pathways of marine debris derived from trajectories of lagrangian drifters. *Marine Pollution Bulletin*, 65(12):51 – 62, 2012. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2011.04.016. URL http://www.sciencedirect.com/science/article/pii/S0025326X11002189. At-sea Detection of Derelict Fishing Gear.

Alistair McIlgorm, Harry F. Campbell, and Michael J. Rule. The economic cost and control of marine debris damage in the asia-pacific region. *Ocean & Coastal Management*, 54 (9):643 – 651, 2011. ISSN 0964-5691. doi: 10.1016/j.ocecoaman.2011.05.007. URL http://www.sciencedirect.com/science/article/pii/S0964569111000688.

Mellumrat. Homepage of the mellumrat e.v., 2012. URL http://www.mellumrat.de/.

Mathias Johannes Menninghaus. Beziehungen zwischen quell- und zielregionen in der nordsee - probabilistische charakterisierung und vergleich von ensemble-driftsimulationen basierend auf verschiedenen strmungsmodellen. Master's thesis, University of Osnabrück, 2011.

Charles James Moore. Synthetic polymers in the marine environment: A rapidly increasing, long-term threat. *Environmental Research*, 108(2):131 – 139, 2008. ISSN 0013-9351. doi: 10.1016/j.envres.2008.07.025. URL http://www.sciencedirect.com/science/article/pii/S001393510800159X. The Plastic World.

John Mouat, Rebeca Lopez Lozano, and Hannah Bateson. Economic impacts of marine litter. Technical report, KIMO, 2010. URL http://www.kimointernational.org/KIMOPublications.aspx.

Anne D. Nash. Impacts of marine debris on subsistence fishermen an exploratory study. *Marine Pollution Bulletin*, 24(3):150 – 156, 1992. ISSN 0025-326X. doi: 10.1016/0025-326X(92)90243-Y. URL http://www.sciencedirect.com/science/article/pii/0025326X9290243Y.

Norbert Niedernostheide and Eike Hartwig. Die müllbelastung der insel scharhörn 1991. *SEEVÖGEL*, 19(3), 1998. URL http://www.waddensea-secretariat.org/oelvoegel/3muell/scharhoern.htm.

Ocean Conservancy. Trash travels - 2010 report of international coastal cleanup. Technical report, Ocean Conservancy, 2010. URL http://act.oceanconservancy.org/images/2010ICCReportRelease_pressPhotos/2010_ICC_Report.pdf.

Ocean Conservancy. Tracking trash - 2011 report of international coastal cleanup. Technical report, Ocean Conservancy, 2011. URL http://act.oceanconservancy.org/pdf/Marine_Debris_2011_Report_OC.pdf.

OSPAR. Ospar pilot project on monitoring marine beach litter - monitoring of marine litter in the ospar region. Technical report, OSPAR Commission, 2007a. URL http://www.ollalomar.org/marine_litter/docs/Litter-Pilot-Project-Final-Report.pdf.

OSPAR. Convention for the protection of the marine environment of the north-east atlantic (update of 2007), 2007b. URL http://www.ospar.org/.

OSPAR. Background document for the ecoqo on plastic particles in stomachs of seabirds, 2008. URL http://www.ospar.org/content/content.asp?menu=00120000000010_000000_000000.

OSPAR. Marine litter in the north-east atlantic region: Assessment and priorities for response. Technical report, OSPAR, London, United Kingdom, 2009. URL http://qsr2010.ospar.org/media/assessments/p00386_Marine_Litter_in_the_North-East_Atlantic_with_addendum.pdf.

OSPAR Commission. Quality status report 2000. Technical report, OSPAR Commission, London, 2000a. URL http://www.ospar.org/content/content.asp?menu=00790830300000_000000_000000.

OSPAR Commission. Quality status report 2000, region ii greater north sea. Technical report, OSPAR Commission, London, 2000b. URL http://www.ospar.org/content/content.asp?menu=00790830300000_000000_000000.

OSPAR Commission. Quality status report 2010. Technical report, OSPAR Commission, London, 2010. URL http://qsr2010.ospar.org/en/downloads.html.

William G. Pichel, James H. Churnside, Timothy S. Veenstra, David G. Foley, Karen S. Friedman, Russell E. Brainard, Jeremy B. Nicoll, Quanan Zheng, and Pablo Clemente-Coln. Marine debris collects within the north pacific subtropical convergence zone. *Marine Pollution Bulletin*, 54(8):1207 – 1211, 2007. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2007.04.010. URL http://www.sciencedirect.com/science/article/pii/S0025326X07001397.

William G. Pichel, Timothy S. Veenstra, James H. Churnside, Elena Arabini, Karen S. Friedman, David G. Foley, Russell E. Brainard, Dale Kiefer, Simeon Ogle, Pablo Clemente-Colan, and Xiaofeng Li. Ghostnet marine debris survey in the gulf of alaska - satellite guidance and aircraft observations. *Marine Pollution Bulletin*, 65(12):28 – 41, 2012. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2011.10.009. URL http://www.sciencedirect.com/science/article/pii/S0025326X11005492. At-sea Detection of Derelict Fishing Gear.

George L. Pickard and William J. Emery. *Descriptive physical Oceanography - An Introduction*. Butterworth & Heinemann, 5th enlarged (si units) edition, 1990. ISBN 0-7506-2759-X.

Plastic Oceans. Homepage to the movie plastic oceans, 2012. URL http://www.plasticoceans.net/the-documentary/.

Plastic Planet. German homepage to the movie plastic planet, 2009. URL http://www.plastic-planet.de.

James T. Potemra. Numerical modeling with application to tracking marine debris. *Marine Pollution Bulletin*, 65(12):42 – 50, 2012. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2011.06.026. URL http://www.sciencedirect.com/science/article/pii/S0025326X11003572. At-sea Detection of Derelict Fishing Gear.

Walter Puls, Thomas Pohlmann, and Jürgen Sündermann. Suspended particulate matter in the southern north sea: Application of a numerical model to extend nerc north sea project data interpretation. *Ocean Dynamics*, 49:307–327, 1997. ISSN 1616-7341. URL http://dx.doi.org/10.1007/BF02764041. 10.1007/BF02764041.

Gareth Rees and Kathy Pond. Marine litter monitoring programmes - a review of methods with special reference to national surveys. *Marine Pollution Bulletin*, 30(2):103 – 108, 1995. ISSN 0025-326X. doi: 10.1016/0025-326X(94)00192-C. URL http://www.sciencedirect.com/science/article/pii/0025326X9400192C.

M. Rixen and E. Ferreira-Coelho. Operational surface drift prediction using linear and non-linear hyper-ensemble statistics on atmospheric and ocean models. *Journal of Marine Systems*, 65(14):105 – 121, 2007. ISSN 0924-7963. doi: 10.1016/j.jmarsys.2004.12.005. URL http://www.sciencedirect.com/science/article/pii/S0924796306002879. Marine Environmental Monitoring and Prediction ¡ce:subtitle¿Selected papers from the 36th International Lige Colloquium on Ocean Dynamics¡/ce:subtitle¿ ¡xocs:full-name¿36th International Lige Colloquium on Ocean Dynamics¡/xocs:full-name¿.

Peter G. Ryan, Charles J. Moore, Jan A. van Franeker, and Coleen L. Moloney. Monitoring the abundance of plastic debris in the marine environment. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1526):1999–2012, 2009. doi: 10.1098/rstb.2008.0207. URL http://rstb.royalsocietypublishing.org/content/364/1526/1999.abstract.

W. Schönfeld. Numerical simulation of the dispersion of artificial radionuclides in the english channel and the north sea. *Journal of Marine Systems*, 6(56):529 – 544, 1995. ISSN 0924-7963. doi: 10.1016/0924-7963(95)00022-H. URL http://www.sciencedirect.com/science/article/pii/092479639500022H.

G. Scott. Letter to the editor: The growth of plastics packaging letter. *International Journal of Environmental Studies*, 7(2):131–132, 1975. doi: 10.1080/00207237508709682. URL http://www.tandfonline.com/doi/abs/10.1080/00207237508709682.

Professor G. Scott. Plastics packaging and coastal pollution. *International Journal of Environmental Studies*, 3(1-4):35–36, 1972. doi: 10.1080/00207237208709489. URL http://www.tandfonline.com/doi/abs/10.1080/00207237208709489.

Günther Stockinger. Toxische reisende. *Spiegel*, 19:138, 2012. URL http://www.spiegel.de/spiegel/print/d-85586234.html.

Shuichi Takehama. Estimation of damages to fishing vessels caused by marine debris, based on insurance statistics, 1989. URL http://swfsc.noaa.gov/publications/TM/SWFSC/NOAA-TM-NMFS-SWFSC-154_P792.PDF.

A.D. Tappin, J.D. Burton, G.E. Millward, and P.J. Statham. A numerical transport model for predicting the distributions of cd, cu, ni, pb and zn in the southern north sea: the sensitivity of model results to the uncertainties in the magnitudes of metal inputs. *Journal of Marine Systems*, 13(1-4):173 – 204, 1997. ISSN 0924-7963. doi: 10.1016/S0924-7963(96)00112-1. URL http://www.sciencedirect.com/science/article/pii/S0924796396001121.

A.H. Taylor. Modelling contaminants in the north sea. *Science of The Total Environment*, 63 (0):45 – 67, 1987. ISSN 0048-9697. doi: 10.1016/0048-9697(87)90035-0. URL http://www.sciencedirect.com/science/article/pii/0048969787900350.

Martin Thiel, Ivan A. Hinojosa, Tanja Joschko, and Lars Gutow. Spatio-temporal distribution of floating objects in the german bight (north sea). *Journal of Sea Research*, 65:368–379, April 2011. URL http://epic.awi.de/24150/1/Thi2011a.pdf.

UNEP. Marine litter: A global challenge. Technical report, United Nations Environmental Programme, 2009. URL http://www.unep.org/pdf/unep_marine_litter-a_global_challenge.pdf.

UNEP. Unep year book 2011: Emerging issues in our global environment. Technical report, United Nations Environmental Programme, 2011. URL http://www.unep.org/yearbook/2011/.

G.C. van Dam. *Pollutant Transfer and Transport in the Sea - Vol. 1*, chapter Models of Dispersion, pages 91–160. CRC Press, Inc., Boca Raton, Florida, 1981.

Johan van der Molen, Thomas Maes, L Fernand, and Peter J. Kershaw. Modelling marine litter dispersal in the north sea. In *Talk at EGU General Assembly 2012, Vienna*, 2012.

Jan Andries van Franeker. Plastic ingestion in the north atlantic fulmar. *Marine Pollution Bulletin*, 16(9):367 – 369, 1985. ISSN 0025-326X. doi: 10.1016/0025-326X(85)90090-6. URL http://www.sciencedirect.com/science/article/pii/0025326X85900906.

Jan Andries van Franeker, Christine Blaize, Johannis Danielsen, Keith Fairclough, Jane Gollan, Nils Guse, Poul-Lindhard Hansen, Martin Heubeck, Jens-Kjeld Jensen, Gilles Le Guillou, Bergur Olsen, Kre-Olav Olsen, John Pedersen, Eric W.M. Stienen, and Daniel M. Turner. Monitoring plastic ingestion by the northern fulmar fulmarus glacialis in the north sea. *Environmental Pollution*, 159(10):2609 – 2615, 2011b. ISSN 0269-7491. doi: 10.1016/j.envpol.2011.06.008. URL http://www.sciencedirect.com/science/article/pii/S0269749111003344. Nitrogen Deposition, Critical Loads and Biodiversity.

L. Vandenbulcke, J.-M. Beckers, F. Lenartz, A. Barth, P.-M. Poulain, M. Aidonidis, J. Meyrat, F. Ardhuin, M. Tonani, C. Fratianni, L. Torrisi, D. Pallela, J. Chiggiato, M. Tudor, J.W. Book, P. Martin, G. Peggion, and M. Rixen. Super-ensemble techniques: Application to surface drift prediction. *Progress In Oceanography*, 82(3):149 – 167, 2009. ISSN 0079-6611. doi: 10.1016/j.pocean.2009.06.002. URL http://www.sciencedirect.com/science/article/pii/S0079661109000500.

Gottfried Vauk and Erika Vauk-Hentzelt. Vermüllung eines meeres - plastikmüll in der nordsee. *Biologie in unserer Zeit*, 21(4):217–219, 1991. ISSN 1521-415X. doi: 10.1002/biuz.19910210413. URL http://dx.doi.org/10.1002/biuz.19910210413.

Gottfried J.M. Vauk and Eckart Schrey. Litter pollution from ships in the german bight. *Marine Pollution Bulletin*, 18(6, Supplement B):316 – 319, 1987. ISSN 0025-326X. doi: 10.1016/S0025-326X(87)80018-8. URL http://www.sciencedirect.com/science/article/pii/S0025326X87800188.

Kathy Velander and Marina Mocogni. Beach litter sampling strategies: is there a "best" method? *Marine Pollution Bulletin*, 38(12):1134 – 1140, 1999. ISSN 0025-326X. doi: 10.1016/S0025-326X(99)00143-5. URL http://www.sciencedirect.com/science/article/pii/S0025326X99001435.

Kenneth E. Weiss. Plague of plastic chokes the seas. *Los Angeles Times*, 2006. URL www.latimes.com/news/la-me-ocean2aug02,0,4917201.story?page=1.

Damian White. Marine debris in northern territory waters 2004. Technical report, World Wide Fund for Nature, 2006. URL http://assets.wwfau.panda.org/downloads/mo017_marine_debris_in_nt_waters_2004_1mar06.pdf.

A. Appendix

A.1. Legislation

The *Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter* (London Convention) and the *International Convention for the Prevention of **Mar**ine **Pol**lution from Ships* (MARPOL 73/78) [IMO, 1973a] are the most important international convention on preventing the sea-based pollution of the marine environment. The London convention was adopted in 1972 extended by the London Protocol in 1996 stopping unregulated dumping and incineration activities at sea. It prohibits dumping of industrial and radioactive wastes and all other wastes not enlisted on a so called *reverse list* (Plastic waste is not listed und ,thus, its dumping is prohibited.). The MARPOL convention was adopted in 1973 and extended in 1978 regulating pollution of the marine environment by different pollutants in 5 annexes. In 1997 a sixth annex was added.

- annex I [IMO, 1973b] is an update of the OILPOL convention from 1954 and contains regularions for the prevention of pollution by oil;
- annex II [IMO, 1973c]: regulations for the control of pollution by noxious liquid substances in bulk;
- annex III [IMO, 1973d]: prevention of pollution by harmful substances carried by sea in packaged form;
- annex IV [IMO, 1973e]: prevention of pollution by sewage from ships;
- annex V [IMO, 1973f]: prevention of pollution by garbage from ships;
- annex VI [IMO, 1997]: prevention of air pollution from ships;

Annex V deals with marine litter. Under it some marine regions are defined as *Special Areas* - the North Sea since 1991 and the Baltic Sea since 1988. In those areas more restrictive restrictions apply. Annex V prohibits dumping of waste near coasts in general. The definition of *near* depends on the type of waste. See [IMO, 1973f] for more information. Food disposal outside coastal regions is permitted. Plastic waste disposal is prohibited everywhere. Disposal of all other wastes is only permitted outside special regions. On mixed waste the most stringent disposal requirements apply.

In 1972 the Oslo Convention against dumping and in 1974 the Paris Convention against marine pollution by land-based sources and the offshore industry were adopted. The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR for ***Os**lo and **Par**is Convention*) [OSPAR, 2007b] united and extended both Conventions in 1992 focussing on protecting the marine environment in the North East Atlantic including the North Sea. The Helsinki Convention (HELCOM for ***Hel**sinki **Com**mission*) is the matching part in the Baltic Sea. Fifteen European countries and the European Union signed the OSPAR Convention. Beyond legislative issues it coordinates monitoring efforts as the Ecological Quality Objective (EcoQ) on plastic particles in the stomachs of fulmars [OSPAR, 2008] and marine litter surveys at beaches in the OSPAR region [OSPAR, 2007a]. Despite large legislative efforts on reducing the input of marine litter, the OSPAR Commission states: *The North Sea (1991) and the Baltic Sea (1988) have both been designated as MARPOL Special Areas (Annex V) where the dumping of garbage and litter from ships (e.g. household waste, cargo waste, wire straps, covering* *material, fishing equipment) is prohibited. Dumping of waste is also prohibited under the OSPAR Convention. So far, however, there is no indication of any improvement with regard to litter.* [OSPAR Commission, 2000b, p.40].

Since the end of the 1990 also the European Union deals with marine litter. The EU Directives *on Port Reception Facilities* (Directive 2000/59/EC, [European Union, 2000]) and *on ship-source pollution and on the introduction of penalties for infringement* (Directive 2005/35/EC [European Union, 2005]) were first steps. Recently in 2008 the ***M**arine **S**trategy **F**ramework **D**irective* (MSFD) (dt.: Meeresstrategie-Rahmenrichtlinie (MSRL); Directive 2008/56/EC, [European Union, 2008]) was adopted. 11 descriptors describe a ***g**ood **e**nvironmental **s**tatus* having to be achieved till 2020. Descriptor 10 dealing with marine litter reads as follows: *"Properties and quantities of marine litter do not cause harm to the coastal and marine environment"*. The descriptor is measured by four indicators [European Union, 2010, p.11/24] being defined by the EU Commission Decision *on criteria and methodological standards on good environmental statues of marine waters* (Decision 2010/477/EU, [European Union, 2010]). The national implementation of the MSFD is in progress. Cooperation with OSPAR and HELCOM are established.

A.2. Beach litter monitoring

A.2.1. OSPAR Beach Litter Monitoring

Realising the increase of marine litter in the North-East Atlantic and at European coasts and the negative consequences the OSPAR started working on that topic in the 1990s. After preliminary work of the OSPAR IMPACT working group it was agreed on quantifying the present situation in reference areas and the development of standardised methods in order to assess the abundance and consequences of marine litter in long term. Therefore, the OSPAR ***As**sessment and **Mo**nitoring Working Group* (ASMO) decided on a pilot project for monitoring European beaches at the North-East Atlantic being started in 2001 and finished in 2006 [OSPAR, 2007a]. Surveys were conducted four times a year at 53 reference beaches being located in nine European Countries: Belgium, Denmark (mainland and the Faroe Islands), France, Germany, The Netherlands, Portugal, Spain, Sweden and the United Kingdom. 100 m and 1 km long stretches of beach were surveyed one the base of two different monitoring protocols. Though, not every beach had both stretches and was surveyed four times a year.

During the project period from 2001 to 2006 $353,600$ litter items in 609 $100m$-surveys and $22,400$ items in 335 $1km$-surveys, categorised in eleven and five major groups [OSPAR, 2007a, p.20], respectively. If possible, each item was mapped to one of five different sources [OSPAR, 2007a, p.38]. On average over all 100 m-stretches, 78.01 % of the recorded items consisted of plastic, 7.37 % were sanitaries, 2.87 % were paper or cardboard and 2.96 % consisted of wood [OSPAR, 2007a, fig.8, p.34], while on average at all North Sea 100 m-stretches 74.83 % of the recorded items consisted of plastic, 4.29 % were sanitaries, 3.75 % were paper or cardboard and 4.23 % consisted of wood [OSPAR, 2007a, fig.23, p.49]. These proportions are similar to those presented by Clemens et al. [2011] for the Mellum beach litter monitoring. It should be emphasised that the number of washed up litter items at southern North Sea beaches is half as large as the number of items at Celtic Sea beaches and nearly only a third as large as the number of items at northern North Sea beaches.

Marine litter is also an issue in the OSPAR ***Q**uality **S**tatus **R**eports* (QSR) 2000 [OSPAR Commission, 2000a] and 2010 [OSPAR Commission, 2010]. For more details please read Fleet et al. [2003], OSPAR [2007a], Fleet et al. [2009] or OSPAR [2009].

A.2.2. Mellum Beach Monitoring

The non-profit organisation *Mellumrat e.V.* organises beach litter surveys at the two islands Mellum and Minsener Ogg being located in the Wadden Sea near the outflows of the rivers Weser and Jade. These islands are suitable for debris surveys because they are inhabited except of one voluntary bird watcher. At Mellum two 100 m beach sections are surveyed since 1991 - the one orientated towards the Jade outflow and the other towards the Weser outflow and the open sea, labelled *Mellum-Süd* and *Mellum-Nord*, respectively - and at Minsener Ogg one is surveyed since 1995. The beach section at Minsener Ogg is exposed to the Wadden Sea area between the East Frisian Islands and the main land of Germany.

Debris surveys are performed several times a year depending on the weather conditions and the availability of volunteers. In the past beach sections were surveyed between 6 and 30 times a year. The debris is counted and assigned to nine categories and several subcategories whereas plastic pieces smaller than 2 cm are not recorded. Because of low transport capacities only hazardous debris is transported to the main land while remaining debris, which is the larger share, is deposited behind dunes on the islands.

Müllkategorie	Untersuchung 1991 - 2002	Untersuchung 2004 - 2009
Plastik, Styropor, Schaumgummi	77,8	78,1
Holz	10,0	6,1
Fischereigerät	4,5	4,4
Glas, Porzellan	3,2	2,0
Papier, Pappe	1,5	0,6
Metall	1,4	3,0
Bekleidung	0,7	0,8
Nahrungsmittel	0,5	0,7
Sonstiges	0,4	4,3

Table A.1.: Table 2 of Clemens et al. [2011]: *Prozentuale Verteilung der Müllkategorien der Untersuchungszeiträume 1991-2002 und 2004-2009 auf den Inseln Mellum und Minsener Oog. (Relative distribution (by number) of debris items in categories for the survey periods 1991-2002 and 2004-2009 on the islands Mellum and Minsener Ogg.)*

Table A.1 summarises results of past surveys published in Clemens et al. [2011]. For more information please read Clemens et al. [2011] and Mellumrat [2012].

A.2.3. Scharhörn Beach Monitoring by Jordsand e.V.

In 1980 first surveys of washed up marine debris were conducted at the German island *Scharhörn* [Niedernostheide and Hartwig, 1998]. They were performed at least annually [Niedernostheide and Hartwig, 1998, Hartwig, 2000, 2001] since then. Scharhörn was also one of the German survey beaches during the OSPAR beach monitoring pilot project.

Nowadays, each third day from May to October 100 m of beach is surveyed. Collected debris is assigned to one of eight categories, counted and weighed. Moreover closed bottles, cans and boxes are collected and their content is studies and noted. Except of that and the weighing of items the survey protocol is equal to that applied on Mellum and Minsener Ogg.

A.3. Abbreviations

Abbreviation	Long Form
BAW	Bundesanstalt für Wasserbau (Federal Waterways Engineering and Research Institute)
BSH	Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency)
DWD	Deutscher Wetterdienst (German Weather Service)
EC	European Commission
EcoQO	Ecological Quality Objective
EDF	Electricité de France
EEA	European Environment Agency
EPA	U.S. Environmental Protection Agency
EU	European Union
GES	Good Environmental Status
GESMAP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GPA	Global Programme of Action for the Protection of the Marine Environment from Land-based Activities
HELCOM	Helsinki Commission
HIPOCAS	Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe
HZG	(Helmholtz-Zentrum Geesthacht)
ICES	International Council for the Exploration of the Sea
IFRAMER	French Research Institute for Exploitation of the Sea (Institut français de recherche pour l'exploitation de la mer)
IMO	International Maritime Organisation
IOC	Intergovernmental Oceanographic Commission
KIMO	Local Authorities International Environmental Organisation (Kommunenes Internasjonale Miljorganisasjon)
MARPOL 73/78	International Convention for the Prevention of Pollution From Ships (MARPOL = marine pollution) of the IMO
MSFD	Marine Strategy Framework Directive of the EU (Meeresstrategie-Rahmenrichtlinie)
NOAA	National Oceanic and Atmospheric Administration, USA
OSCOM	Oslo Convention
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic (made from OSCOM and PARCOM)
PARCOM	Paris Convention
SRU	Sachverständigenrat für Umweltfragen (German Advisory Council on the Environment)
UBA	Umweltbundesamt (Federal Environment Agency) of Germany
UNEP	United Nations Environmental Programme
USF	Institut für Umweltsystemforschung (Institute for Environmental Systems Research), University of Osnabrück

Table A.2.: Abbreviations relating to laws, directives, governmental and non-governmental organisations, governmental agencies, research institutes, research projects and other not simulation-related topics.

Abbreviation	Long Form
BSHcmod	BSH circulation model
CPL	Current Particle Location (in percent)
CTH	Cumulative Travel History (in percent)
MRT	Mean Residence Time (days)
PELETS-2D	Program for Evaluation of Lagrangian Ensemble Transport Simulations
TRIM	Tidal, Residual and Inter-tidal Mudflat
TT20	Travel Time for 20 % of particles (in days)
UnTRIM	Unstructured Grid TRIM

Table A.3.: Abbreviations relating to models and evaluation of simulations results

Eidesstattliche Erklärung

Name:	Daniel Neumann
Anschrift:	Blumenhaller Weg 34 49078 Osnabrück
Geburtsdatum:	28. August 1986

Osnabrück, den 07. August 2012

Ich erkläre hiermit an Eides statt, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe; die aus anderen Quellen direkt oder indirekt übernommenen Daten und Konzepte sind unter Angabe des Literaturzitats gekennzeichnet.

Niemand hat von mir weder unmittelbar noch mittelbar geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Masterarbeit stehen. Die Arbeit wurde bisher weder im In- noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

Ich versichere an Eides Statt, dass ich nach bestem Wissen die reine Wahrheit gesagt und nichts verschwiegen habe.

(Daniel Neumann)