Multi-decadal reconstruction and probabilistic representation of weather-related variability in North Sea coast chronic oil pollution

Dissertation

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Alena Chrastansky

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Prof. Dr. Dr. h.c. Hans von Storch
(Meteorologisches Institut der Universität Hamburg)

und

Dr. Ulrich Callies
(Helmholtz-Zentrum Geesthacht)

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Prof. Dr. Jürgen Oßenbrügge
(Leiter des Fachbereichs Geowissenschaften)

Abstract

In the North Sea, ship-related chronic oil pollution is a serious problem which endangers the marine and coastal environment. In this study, wind-related spatial and temporal variability in the exposures of the German North Sea coast to this kind of oil pollution is investigated. Using Lagrangian passive tracer transport simulations a drift-climatology is established describing a manifold of possible oil spill drift paths originating from the main shipping routes in the southern North Sea. Detailed meteorological-marine reconstructions (www.coastDat.de) provide a realistic representation of weather and weather-induced currents for the years 1958 − 2003. The resulting multi-decadal drift statistic is used for evaluating the exposure of different regions along the German North Sea coast to hypothetical chronic oil pollution in dependence of the location of oil spills, their spatial distribution and prevailing atmospheric conditions. Multivariate statistical analysis reveals that both spatial and inter-annual variability in coastal oil pollution can be linked to a large extent to varying wind conditions. A comparison of simulated annual advection rates with corresponding beached bird survey data suggests that changing weather conditions may mislead the interpretation of the data with regard to an estimate of changes in the general level of chronic oil pollution. The oil spill drift reconstructions, however, allow for a quantification of the wind influence and for normalization of the observation data so that wind-related misinterpretations can be avoided. A flexible representation of the threat analysis is achievable by representing both model results and forcing data in the form of conditional probabilities (Bayesian Network). By this means, a convenient examination of the oil spill drift statistics depending on variable external forcing is possible, which facilitates the communication and application even for non-scientists.

Zusammenfassung

In der Nordsee sind illegale Öl-Einleitungen aus der Schifffahrt ein ernstzunehmendes Problem, welches die marine Umwelt und die Küsten gefährdet. In der vorliegenden Arbeit werden die Gefährdungspotentiale möglicher Ölverschmutzungen an der deutschen Nordseeküste hinsichtlich der windinduzierten räumlichen und zeitlichen Variabilität dargestellt. Mittels Lagrangeschen passiven Transportsimulationen ist eine Driftklimatologie erstellt worden, die eine Vielzahl möglicher Öl-Driftwege ausgehend von den Hauptschifffahrtsrouten der südlichen Nordsee beschreiben. Dabei ermöglichen detaillierte meteorologische und marine Rekonstruktionen (www.coastDat.de) eine realistische Darstellung von Wetter- und Strömungsverhältnissen für die Jahre 1958 − 2003. Basierend auf der multi-dekadischen Driftstatistik wird gezeigt, inwiefern unterschiedliche Küstenabschnitte in Abhängigkeit vom Ort der Öleinleitung, der räumlichen Verteilung von Öleinleitungen und den atmosphärischen Gegebenheiten in veränderlichem Umfang potentieller chronischer Ölverschmutzung ausgesetzt sind. Eine multivariate statistische Analyse zeigt, dass die räumliche und zeitliche Variabilität hinsichtlich der Küstengefährdung zu einem großen Teil auf vorherrschende Windverhältnisse zurückzuführen ist. Der Vergleich von den simulierten jährlichen Advektionsraten mit entsprechenden Aufzeichnungen aus Spülsaumkontrollen legt nahe, dass Schwankungen in den Beobachtungsdaten größtenteils Wetteränderungen widerspiegeln. Basierend auf den Öldriftsimulationen kann der Windeinfluss jedoch abgeschätzt und die Datenreihe bereinigt werden, so dass Missinterpretationen im Zusammenhang mit Wetterschwankungen vermeidbar werden. Eine flexible Form der Gefahrenanalyse kann durch die Darstellung der Modellergebnisse und deren zugrunde liegenden Antriebsdaten als bedingte Wahrscheinlichkeiten erreicht werden (Bayes'sches Netz). Dies ermöglicht eine komfortable Untersuchung der Driftstatistiken in Abhängigkeit der beeinflussenden Faktoren, was die Kommunikation und Anwendung vor allem in einem nicht-wissenschaftlichen Umfeld vereinfacht.

Contents

List of Papers

This thesis is based on the following peer-reviewed journal articles:

Chrastansky, A. & U. Callies (2009): Model-based long-term reconstruction of weather driven variations of chronic oil pollution along the German North Sea coast. Marine Pollution Bulletin 58 (7), pp 967 − 975.

Chrastansky, A., U. Callies & D.M. Fleet (2009): Estimation of the impact on prevailing weather conditions on the occurrence of oil-contaminated dead birds on the German North Sea coast. Environmental Pollution 157, pp 194 − 198.

Chrastansky, A. & U. Callies (2009): Using a Bayesian network to summarize variability in numerical long-term simulations of a meteo-marine system: drift climatology of assumed oil spills in the North Sea. Environmental Modeling & Assessment (submitted on June 17th, 2009).

Weisse, R., H. von Storch, U. Callies, **A. Chrastansky,** F. Feser, I. Grabemann, H. Guenther, A. Pluess, T. Stoye, J. Tellkamp, J. Winterfeldt & K. Woth (2009): Regional Meteorological-Marine Reanalyses and Climate Change Projections: Results for Northern Europe and Potentials for Coastal and Offshore Applications. Bulletin of the American Meteorological Society 90 (6), pp 849-860.

1 Introduction

1.1 Motivation and aim of the study

A proper identification of significant environmental changes requires a detailed knowledge about natural variability of dynamical systems. Sufficient information about their state and variations over multiple past decades are therefore essential. Observational data, however, are often inappropriate for that purpose. Such datasets generally include incomplete or inhomogeneous records and are in many cases available just in insufficient temporal and spatial resolution or coverage. Retrospective analyses or reanalysis, on the other hand, reconstruct past conditions by assimilating existing observations into a 'frozen' state-of-the-art numerical model. In this way, a homogeneous database can be established for a sufficient long time-period. At the same time, the conditions can be reproduced even for places where no measurements are available. On this account, reanalysis data gain more and more importance for retrospective long-term investigations.

Based on global atmospheric reanalysis data, a consistent set of meteorological and marine reconstructions (hindcasts) for the North Sea exists. Using a chain of dynamical regional models, various parameters describing both atmospheric (wind speed, wind direction, etc.) and marine (u and v currents, sea surface height, etc.) conditions were generated in physical agreement and in high spatial and temporal detail (Weisse et al., 2009; cf. Appendix A). The North Sea high-resolution reconstructions can be found in the CoastDat database (www.coastDat.de). Initially, the CoastDat hindcasts covered a 45-year period (1958 − 2002), but were later extended to the years 1948 − 2006. Several validation studies (cf. for example Feser, 2006; Weisse et al. 2005; Weisse & Plüß, 2006; Weisse & Günther, 2007; Winterfeldt & Weisse, 2009) demonstrate that the CoastDat reconstructions generally represent a reasonable description of the North Sea past conditions. Usually, such detailed meteorological-marine hindcasts provide basis for climate-related studies. The investigation of long-term changes in the storm activity in the North Sea and northeastern Atlantic (Weisse et al., 2005) or the multi-decadal analysis of extreme storm surges and ocean wave heights (Weisse & Plüß, 2006; Weisse & Günther, 2007) are just a few examples.

In the present study, for the first time the detailed coastDat hindcasts are exploited to treat an environmental problem: the examination of natural variations in the exposure of the German North Sea coast to (illegal) oily discharges from ordinary ship traffic - which is referred to as "chronic oil pollution" (Camphuysen, 2007). Especially prevailing weather conditions are influential whether a coastal section is affected by chronic oil pollution or not. The description and quantification of natural wind-related spatial and temporal variations regarding advection processes towards the coast is essential for a thorough threat assessment or the accurate interpretation of monitoring data, for instance. Hence, driven by the coastDat weather and sea-state reconstructions, a Lagrangian hydrodynamic tracer transport model (PELETS − Program for the Evaluation of Lagrangian Ensemble Transport Simulations) is utilized to simulate possible drift paths of hypothetical oil spills. Hypothetical illegal oil spills from shipping are thereby represented as ensembles of passive tracers that are initialized along the main shipping routes in the Southern North Sea every 28 hours within a 46-year period (1958 − 2003). The numbers of oil spills that reach the German North Sea coast indicate the general threat for resulting in coastal oil pollution. The drift-climatology established in this way properly describes the whole spectrum of natural wind-driven variability in coastal chronic oil pollution during the years 1958 − 2003 with a reasonable frequency of advection towards the German North Sea coast.
The generated oil spill transports are a refinement of the rather physically oriented information from the CoastDat dataset. Whether an oil spill actually affects coastal regions, however, is influenced also by other processes than winds and currents. Oil weathering, for instance, decreases the probability that oil reaches the coast, but is not considered in the model runs. Regarding chronic oil pollution, important details that are necessary for the assessment of weathering intensities - i.e. the oil type or the presence and activity of oil degrading bacteria - usually remain unknown. Nevertheless, such influencing parameters can be roughly taken into account by statistically lowering the oil spills lifetime in hindsight. Since from each drift simulation hourly information

about the time and location of each tracer particle (oil spill) is recorded, in offline post-processing a re-weighting of the oil spill advections according to their travel times and specific half-lives is possible. Repeated computational and time-consuming model runs for considering other substance characteristics can be avoided by this approach. The lowered oil persistence truthfully gives more importance to oil spills originating from regions closer to the coast.

The rare data regarding both the amount of spilled oil and resulted coastal oil pollution leads to difficulties in the validation of the model results - especially when analyzing multiple decades. Very often, beached, oil-contaminated sea birds are utilized as indirect indicators of chronic oil pollution and for trend assessment. For this study, reliable data from Germany are available for the winter months of the years 1992 − 2003. Comparisons of inter-annual variations of the simulated, re-weighted advection rates with corresponding statistics from these beached bird surveys showed good accordance. At the same time, however, their agreement raises the question if the wind has such a dominant impact on the occurrence of beached oil-contaminated sea birds that wind variations visible in the survey data could lead to misinterpretations.

For ship accidents, enough details are known for precisely forecasting the oil spill behaviour and the accompanied risk for coastal regions. In contrast, there is usually no or just lacking information about illegal oil spills from chronic oil pollution. For a thorough threat analysis, the investigation of individual (observed) oil spill incidents is not sufficient. Of interest is the assessment of general exposures in any (mean or rare) weather conditions and, more importantly, how probable such situations are. Exactly this information is contained in the established drift climatology. A problem, however, may be the integration of the simulations in practical applications (i.e. planning of monitoring strategies or of protective measures). The data representation using static illustration methods such as tables or graphs contained in publications usually focus on the authors' research interests. Additional analyses of the data are generally very time-consuming and require scientific programming. Hence, a more flexible but compact format becomes necessary, which summarizes the essentials of the exhaustive ensemble drift simulations. In this thesis, the use of a Bayesian Network is proposed to achieve this goal.

1.2 Thesis objectives and outline

The present thesis aims the reconstruction and investigation of weather-related variability in German North Sea coast chronic oil pollution based on multi-decadal ensemble tracer transport simulations. Spatial and temporal variations as well as their connection to weather variations are investigated and their relevance for the interpretation of monitoring data (using the example of German beached bird surveys) discussed. In addition, a probabilistic data representation by means of a Bayesian Network is proposed. These partial studies are published in three publications (Chrastansky & Callies, 2009a; Chrastansky et al., 2009; Chrastansky & Callies, 2009b), which can be found in the Chapters 3, 4 and 5. Each of these sections can be read independently. A content-related outline of the thesis objectives is given in the following.

a) Spatial and temporal weather-related variations in oil pollution exposures

A proper assessment of spatial and temporal variations in chronic oil pollution along the German North Sea coast is necessary for a detailed threat assessment. As the German North Sea coast is situated against winds and currents in various ways, the position of an oil release, its distance to the coast and the prevailing weather conditions are key factors that influence the probability that a given coastal area will be affected by chronic oil pollution. Hence, in Chrastansky and Callies (2009a; cf. chapter 3) a sensitivity-study analyses how the relative impact of oil pollution on coastal stretches varies dependent on the oil spill location (cf. section 3.4.1). Spatial variations of the mean threat due to seasonally varying wind conditions are thereby indicated by considering the mean winter (October − March) and summer (April − September) conditions. For a thorough contingency analysis, uncertain factors such as unknown source-strengths are also of importance. In an example study, it is shown how such uncertain factors can be considered by combining the simulated contributions to coastal pollution with a spatial inhomogeneous source-strength according to ship traffic density. In addition, the influence of varying weather conditions on the advection rates towards the German North Sea coast is analysed on regional and inter-annual scale (cf. section 3.4.2). Using a multivariate statistical method (Canonical Correlation Analysis), it is investigated to what extent variations in oil pollution exposures can be attributed to changing weather conditions. The relevance of governing weather patterns regarding the threat of oil pollution along different coastal stretches is thereby examined for winter and summer. Considering average annual transport rates, both the year-to-year variability and the weather-related long-term changes become assessable. The connection of inter-annual variability to the North Atlantic Oscillation is thereby also investigated.

b) Estimation of the wind impact on beached bird survey data

As seabirds are very vulnerable to marine oil pollution, the numbers of beached oil-contaminated bird corpses are assumed to reflect chronic oil pollution levels. The statistics of beached bird surveys, however, show a distinct year-to-year variability, which hampers the interpretation of the monitoring data. In Chrastansky et al. (2009; cf. chapter 4), the simulated advection rates are exploited to analyse and quantify the impact of weather variations on the occurrence of beached, oil-contaminated seabirds on the German North Sea coast (cf. section 4.3). Therefore, the focus is laid on two representative seabird species of different habitats: the Guillemot (*Uria aalge*), which is a seabird that lives predominantly in offshore regions, and the Common Scoter (*Melanitta nigra*), a coastal bird species (cf. section 4.3.1). Based on the study results it is further investigated if the simulated advection rates can be used for normalization of the observation data in order to reduce wind effects in the recordings and to relieve their interpretation (cf. section 4.3.2). An additional study in Chrastansky and Callies (2009a; cf. chapter 3) analyses whether the wind impact differs regarding various sections of the coast (cf. section 3.4.3). For a comparing study between advection rates and corresponding monitoring statistics regarding the northern (Schleswig-Holstein) and the southern part (Lower Saxony) three coastal seabirds are utilized that appeared numerously in beached bird survey data (Eider Duck (*Somateria mollissima*), common scoter (*Melanitta nigra*) and the red-throated diver (*Gavia stellata)*).

c) Probabilistic representation of the simulation results using a Bayesian Network

The established long-term drift-climatology provides a useful basis relevant for many practical applications. Its utilization within inter-disciplinary projects, however, may be hampered due to the requirement of sufficient resources and specific evaluation tools. On this account, the final study of this thesis presented in Chrastansky and Callies (2009b; cf. chapter 5) proposes the use of a Bayesian Network for summarizing the essentials of the ensemble drift simulations. Based on the causal relationships of the integrated variables, the transport simulations are described probabilistically in dependence on variable external forcing (cf. section 5.2 and 5.3). The exhaustive drift database is thereby exploited for determining the conditional probability distributions of the involved variables, so that reliable weather and resulting sea-state conditions are covered in agreement with the frequency of their occurrence. A problem is the characterization of weather conditions in the Bayesian Network as winds are not constant during an oil spill drift. In this study, different approaches are suggested for the integration of weather conditions (cf. section 5.2.2). The study shows further, how the network can be complemented with additional but uncertain parameters that were not objects of the original physically formulated drift simulations (i.e. oil weathering using various substances half-life or including estimations from monitoring data) (cf. section 5.3.1 and 5.3.2). Based on example studies (cf. section 5.4) the informative use of Bayesian Networks for extensive threat analyses even under imprecise or uncertain knowledge as well as its convenient and flexible handling is illustrated. The presented probabilistic network is easily modifiable or extendable according to the target applications.

This thesis is completed by an introducing chapter (chapter 2) regarding marine oil pollution in general (section 2.1) and North Sea ship-related chronic oil pollution in particular (section 2.2) as well as a concluding chapter (chapter 6), which summarizes the main findings. A detailed description about the CoastDat dataset and some examples for further applications can be found in Appendix A.

2 General overview

2.1 Marine oil pollution

Because of its physical and chemical characteristics, oil is a harmful substance that can lead to far reaching damages in the marine environment. Physically, in case of oil contamination surfaces of flora and fauna are usually covered with a sticky, air-impermeable coating. The sticky oil film leads to a suffocation of plants and disturbs essential functions of mammal's fur and bird's feather coats. Very often, outward oil contamination leads to death. Direct and indirect oil absorption, on the other hand, either through intake of food or during the animal cleansing itself, can have a negative impact on the reproduction rate and may lead to a damnification of eggs and larvae, malformations and abnormal behaviour of living creatures.

Experts estimate that globally more than one million tonnes of oil are entering the marine environment every year (International Maritime Organization, 2006). The sources of oil pollution are thereby diverse (cf. Table 2.1). Naturally, oil seeps lead to an annual input of approximately 600.000 tonnes of oil. Nearly the same amount, however, originates from human off- and onshore activities such as oil exploration and production as well as shipping operations.

Spills from shipping take the major part (up to 37%) of man-made oil pollution in marine waters including both ship accidents and normal shipping operations (International Maritime Organization, 2006). Accidental discharges from ships aggregate to approximately 163.000 tons per year, spectacular but exceptional spills are not being considered in this estimation. Fortunately, tremendous incidents like the Exxon Valdez incident in 1989 near Alaska (Peterson et al., 2003) or the Prestige accident in 2002 close to the coast of Spain (Alonso-Alvarez et al., 2007), in which several thousand tons of oil had been released, remain rare. A larger amount of oil, however, originates from discharges during shipping operations. Although these ship-based discharges are usually on a small scale, this so-called “chronic oil pollution” is estimated to amount to about 208.000 tonnes per year. The majority of chronic oil pollution results from illegal oil releases including discharges of fuel oil sludge (~89%) and bilge oils (~0.9%), oily ballasts (~0.4%) as well as tank washings (~9%) (International Maritime Organization, 2006).

Table 2.1: Estimations of oil entering the world’s marine environment from sea-based sources (after International Maritime Organization, 2006).

	oil input in tons	**oil input in percent**
Ships	457.000	36,7%
Offshore exploration and production	20.000	1,6%
coastal facilities	115.000	9,2%
small craft activities	53.000	4,3%
natural seeps	600.000	48,2%

2.2 North Sea chronic oil pollution

The North Sea hosts several important seaports such as the harbours of Rotterdam, Hamburg or Antwerp, and is a relevant connection between the Atlantic Ocean and the Baltic Sea. Hence, this maritime area is amongst the busiest waterways worldwide. In the entire North Sea area nowadays round 420.000 ship movements are registered per year (GAUSS, 2000; Volckaert et al., 2000); about 160.000 are recorded alone in the German part of the North Sea (GAUSS, 2000). Due to the high volume of traffic, an enormous potential for oil pollution is inherent, documented by relatively frequent oil spills that were observed along the North Sea main shipping routes (Reineking, 2005) and especially in the southern part of this area (cf. i.e. map on http://serac.jrc.it/midiv/maps/northsea/aerial/oilspill_bonn_1998_2004.pdf [Nov. 2009]). In 1999, the North Sea became a “special area” - a region that is considered highly vulnerable to oil pollution (International Maritime Organization, 2002). Although ever since any discharge of oil is prohibited, chronic oil pollution - mainly illegal oil discharges - is still prevailing. Bathia and Dinwoodie (2004) estimated that between 15.000 and 60.000 tons of oil is released illicitly into the North Sea every year.

Aware of the serious problem of chronic oil pollution in the North Sea region, the adjacent countries cooperate to control and reduce illegal oil releases from ships in this area. The Bonn Agreement from 1969 was established to help on the protection of the North Sea marine environment from oil (Carpenter, 2007). The contracting parties, namely Belgium, Denmark, France, the Netherlands, Norway, Sweden, the United Kingdom and Germany, conduct since 1986 control flights over the North Sea international waters. The aim is the detection of oil spillages and discharges of other harmful substances. Aerial surveillances are performed irregularly and on varying routes, with major emphasis on the predominant traffic regions (von Viebahn, 2001). In more recent time new techniques such as satellite observations are additionally used (Brekke & Solberg, 2004; Carpenter, 2007). In case an oil spill has been observed, oil response activities are immediately initialized by the responsible party whenever it is possible (Bernem & Lübbe, 1997). The difficulty in combating oil pollution is that oil can only be successfully removed during a short time window after discharge. Oil spreading and the accomplished thinning of the oil film make the cleaning efforts - i.e. oil skimming or oil dispersion - ineffective. Analysing an oil sample taken from the detected spill can give an indication on the oil's origin and can thus help to convict the offender (Bernem & Lübbe, 1997; Theobald, 1993).

The aerial surveillance spill statistics serve also as assessment basis to protocol temporal changes in the level of chronic oil pollution. The monitoring by aerial surveillances, however, comes along with major uncertainties. In contrast to well-documented ship accidents with according oil release, unauthorized oil discharges remain in 9 of 10 cases unobserved (Schallier et al., 1996). The limited spatial coverage of each flight as well as the limited amount of flight hours makes it impossible to observe every oil spill. Admittedly, satellite based oil spill indication has a high spatial coverage. Natural patterns on the water surface that look similar to oil spills in satellite images (called look-alikes), however, may lead to false alarms (F. Ziemer and H. Krasemann (GKSS), personal communication).

Further, beached bird surveys are a method for monitoring chronic oil pollution levels. Sea birds, especially species that dive for food, are very vulnerable to oil pollution. Even a small amount of oil that contaminates the sea bird's feather coat may result in death of the particular bird. The oil reduces the feather coat's isolation ability as well as

water-repellence. The seabirds have then difficulties in swimming and hunting and have no protection against low temperatures any more. As a result, the bird freezes to death, starves or is drowned (Bernem & Lübbe, 1996). As oil samples taken from the bird's feather coat indicated that the majority of birds died from ship-related chronic oil pollution (Dahlmann et al., 1994), these bird findings can be used as measure to protocol the effectiveness of implemented reduction and controlling efforts.
In Germany, first monitoring of beached oil-contaminated seabirds started in the mid-1980s. Since 1997, beached bird surveys were included in the common package of the Trilateral Monitoring and Assessment Programme (TMAP) for monitoring the Wadden Sea region along the coasts of the Netherlands, Germany and Denmark (Fleet, 2006) - a program aiming in establishing a scientific basis for the status assessment of the North Sea's Wadden Sea ecosystem, enacted in 1994. Beached bird surveys are conducted twice per month in winter seasons. At this time of the year, oil persists longer due to reduced evaporation rates and birds are physically weakened because of the low temperatures and strong winds.

Although oil-contaminated sea birds are an indicator of chronic oil pollution, the beached bird survey statistics must be interpreted with caution. There are several circumstances that may lead to in- or decreased finding rates. Bird's habitation variations, weakening of birds due to diseases, extreme outdoor temperatures or variations in the breeding rates are examples for factors that influence the number of dead birds (Camphuysen et al., 2005, Fleet & Reineking, 2000, 2001). The usage of the oiling rate - the percentage of oiled birds that were found during the beached bird surveys - for chronic oil pollution level measurement should solve this problem (Fleet & Reineking, 2001). Wind conditions, however, may also lead to variations in both the oil spill and the corpse drift (Fleet, 2006) and thus to problems in data interpretation.

3 Model-based long-term reconstruction of weather-driven variations in chronic oil pollution along the German North Sea coast

Alena Chrastansky & Ulrich Callies
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Abstract

Lagrangian passive tracer transport simulations covering the 46-year period 1958−2003 were utilized to compare the exposures of different parts of the German North Sea coast to ship-related chronic oil pollution. Assuming the spatial distribution of oil releases to be proportional to estimated ship traffic density, detailed drift reconstructions allowed for the reconstruction of wind-induced inter-annual variations in coastal pollution. For the winter months, a statistical relationship between simulated advective transports and prevailing sea surface pressure fields was established via Canonical Correlation Analysis. Wind effects were found to be more important for the northern (Schleswig-Holstein) than for the southern (Lower Saxony) part of the German North Sea coast. For Schleswig-Holstein, simulations showed consensus with beached bird survey data from this region. Proper identification of weather-driven inter-annual and spatial variations in monitoring data helps to avert misjudgments with regard to trends in the general level of chronic oil pollution.

3.1 Introduction

Chronic oil pollution in the North Sea is a serious problem with consequences such as bird die-offs occurring along the German coast. An increased awareness of the distinctive effects of chronic oil pollution has resulted great efforts to reduce the amount of oil spilled into the sea (International Maritime Organization, 1982, 2002; Reineking & Vauk, 1982). Finally, in 1999 the North Sea was declared a so-called “Special Area” (International Maritime Organization, 2002) resulting in the prohibition of any oil discharge, including oil dumping from ships. Discoveries of oil-contaminated sea birds that were not correlated with recorded ship accidents (Fleet & Reineking, 2000) as well as oil spills observed by aerial surveillance (Carpenter, 2007) provide evidence that chronic oil pollution is a persisting problem. The quantification of continuous oil pollution, however, is difficult. Schallier et al. (1996), for instance, estimated that approximately 90% of chronic oil pollution in the North Sea has not been detected by aerial surveillance (Schallier et al., 1996). On this account and in addition to the statistics of observed oil spills, other indicators are used to estimate changes in the general level of oil pollution, e.g. the results from beached bird surveys.

In the present paper we compare the exposures of different coastal areas in the German Bight to ship related oil pollution by simulating the drift of hypothetical oil spills from various locations. A large sample of simulations was performed using model-based reconstructions of realistic weather conditions that occurred within a 46-year period (1958 − 2003). The assumption of traffic-related, spatially inhomogeneous oil inputs allowed for a quantitative estimate of wind-related temporal variability of coastal oil pollution. Correlations between prevailing sea level pressure (SLP) fields and the advection of oil spills towards the coast were statistically analyzed with Canonical Correlation Analysis. Finally, we employed survey data on beached, oil-contaminated sea birds for a qualitative validation of our simulations. The investigations presented here contribute to a better understanding of the inshore advection processes of oil pollution and may provide useful information to improve monitoring strategies.

The paper is structured in the following way: Section 3.2 outlines our general approach (Section 3.2.1). The hydrodynamic data upon which our Lagrangian simulations were based is described in more detail in Section 3.2.2. The description of model aspects is followed by a short summary of beached bird survey data (Section 3.3). Section 3.4 discusses the outcomes of our Lagrangian tracer simulations (Section 3.4.1) and their dependence on the mean prevailing weather conditions (Section3.4.2). In Section 3.4.3 the results of our simulations are contrasted with the beached bird survey data. Finally, we summarize our conclusions in Section 3.5.

3.2 Drift reconstructions

3.2.1 Conceptual design

Variability of the exposure of German North Sea coastal regions to chronic marine oil pollution was estimated by means of hydrodynamic drift simulations. Past research involving the analyzes oil samples taken from beached bird corpses has ascertained that heavy fuel oil (deliberately) discharged from ships is the main pollutant in this area (Dahlmann et al., 1994). Aerial observations reveal that the majority of illegal and accidental oil spills in the North Sea are encountered along the busy shipping routes (Reineking, 2005). Hence, source regions for hypothetical oil spills were defined to contain the main shipping lanes in the southern part of the North Sea (cf. Figure 3.1a). We confined ourselves to the investigation of regional differences and weather related variations. The effects of possible changes in the magnitude of oil discharge were not the subject of our study.

Oil drifts were represented by simple Lagrangian passive tracer transport calculations. However, by re-weighting the tracer particle density according to an assumed exponential particle decay time of 21 days (overall integration time was 60 days) we approximately included the effects of oil weathering processes. A realistic spectrum of prevailing weather conditions was taken into account by performing the trajectory calculations based on reconstructed atmospheric wind and two-dimensional North Sea current fields. High resolution simulated fields stored on an hourly basis, for a 46-year period (1958 − 2003), were taken from the coastDat data base (cf. section 3.2.2). In addition to current-induced particle drift components, an extra wind drift factor was introduced (for details see section 3.2.2).

The relative extents to which different areas along the German North Sea coast are exposed to hypothetical oil spills (see section 3.4.1) were assumed to be proportional to the number of simulated particle trajectories that reach the different target regions (cf. Figure 3.1b). The assumption of a limited particle life time gives more importance to particles that originate from source regions closer to the coast.

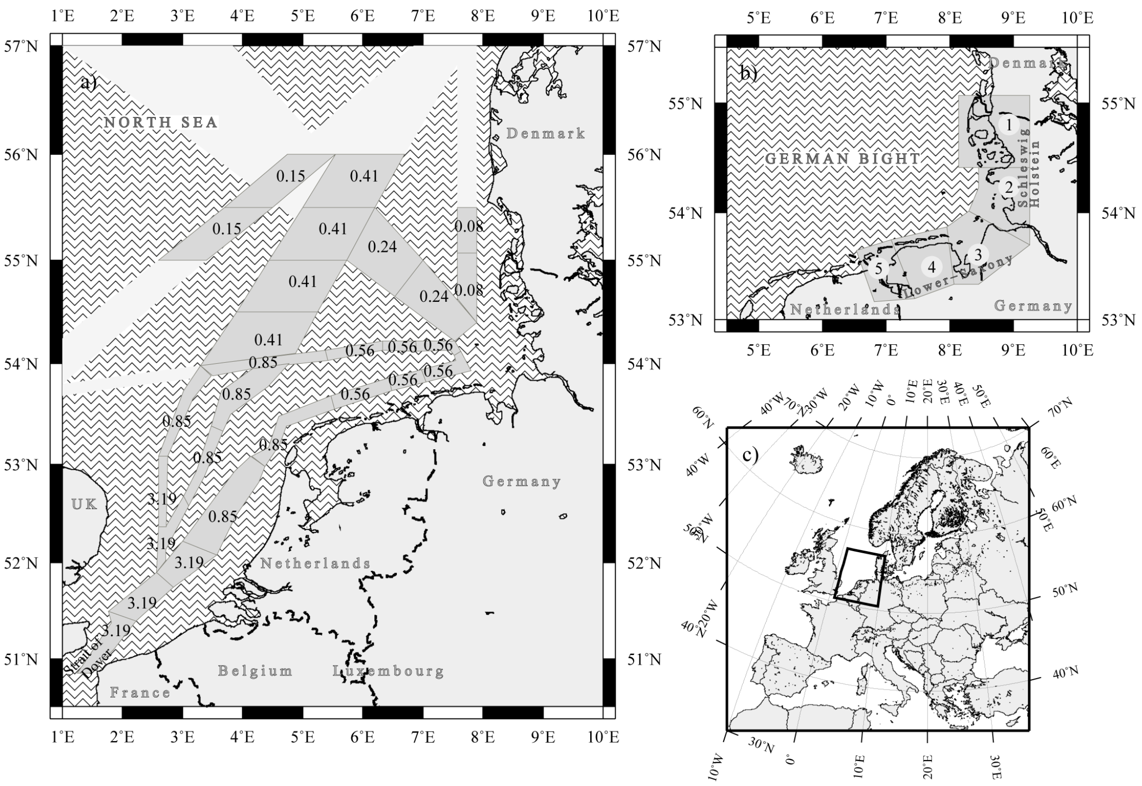

Figure 3.1: Particle source and target regions of the model set-up. The particle source regions along the major shipping routes of the North Sea (grey shaded areas in panel a) show the assumed weighting factors for modeling oil incidence rates as proportional to the ship traffic density (derived from ship occurrence estimations from Golchert & Benshausen (1987)). Because of the distance to the coast the bright regions of the shipping lanes weren't included in the simulations. Target regions (panel b) along the German North Sea coast are labeled 1-5 for further reference. Panel c provides the geographical orientation of the region of interest (framed).

Initially (section 3.4.1.1), spatial variations of the probability that an oil spill occurs are not taken into account. In this case, model simulations describe the extent to which coastal regions would be affected by a hypothetical oil spill as a function of their locations, irrespective of the oil spill's incidence rate. In a second step (section 3.4.1.2) we assume that the probability of an oil spill is proportional to the density of vessel traffic, which leads to a re-weighting of the trajectory drift calculations. From large ensembles of detailed simulations we derived the annual mean conditions for summer (April − September) and winter (October − March), respectively. In section 3.4.2 multivariate statistics are used to describe the relationship between spatial variations of the potential endangerment of the German North Sea coastal areas and changing weather conditions as represented by SLP fields. Inter-annual variations in advection processes caused by changing weather conditions are also investigated. For this analysis we focused on the winter months because this is when beached bird surveys are regularly taken (cf. section 3.3).

3.2.2 Lagrangian simulations and underlying data

Tracer transport simulations were based on state-of-the-art detailed re-analysis of past atmospheric and sea state conditions, stored in the coastDat data base (www.coastDat.de) on an hourly basis. Hindcasts of two-dimensional marine currents on an unstructured triangular grid with a spatial resolution varying between about 100 m near the coast and a couple of kilometers in offshore regions (Plüß, 2004) were obtained by running the finite element model TELEMAC-2D (Hervouet & van Haren, 1996). Regional atmospheric fields forcing the marine model at its upper boundary originated from re-analyzed NCEP/NCAR data (Kistler et al., 2001) after dynamical downscaling with the regional climate model SN-REMO (Meinke et al., 2004). For the drift calculations, an extra wind-induced drift component of 1.8% of the 10m wind was superimposed to the current-induced drift, which seems appropriate for both oil slicks (Dick & Soetje, 1988) and bird corpses (Bibby & Lloyd, 1977).

Simulations cover a period of 46 years. Within 1958 − 2003, drift simulations for ensembles of 2.700 particles each were initialized every 28 hours. At each time step a random velocity component was used to represent effects of horizontal diffusion. Although we used 2D velocity fields for advection, a random vertical particle motion was included to allow for reduced wind forcing when particles submerge.

3.3 Beached bird survey data

The effects of marine oil pollution on sea birds vary, depending on the behavior and distribution of the particular sea bird species (Camphuysen, 1998). Auks and divers, for instance, are often found during beached bird surveys as they are predominantly afloat and dive for food. Species that are distributed in the vicinity of the busy shipping routes are more endangered than coastal bird species. The latter are at risk only when an oil spill reaches the coast (Chrastansky et al., 2009). Most sea birds prefer hunting in calm water. As oil slicks cause such calm water surfaces, sea birds actively seek for oil spills (Reineking & Vauk, 1982). This makes beached oil-contaminated sea birds particularly effective indicators of chronic oil pollution in the marine environment (Camphuysen, 1995; Camphuysen & Heubeck, 2001; Fleet & Reineking, 2000, 2001).

Beached bird surveys are part of the Trilateral Monitoring Program of Denmark, Germany and the Netherlands (Fleet & Reineking, 2001; TMAP, 1997). In Germany, beached bird surveys are performed regularly in winter months (October − March) when sea birds are more vulnerable to oil pollution due to low temperatures and stormy weather. In addition, the decomposition rate of oil is slower (Fleet & Reineking, 2001, Reineking & Vauk, 1982). Volunteers scan the monitoring areas twice per month, at defined dates, and document bird corpse findings according to given guidelines (Fleet & Reineking, 2000). In this manner it is ensured that the resulting data is homogeneous and suitable for trend assessments.

For this study, we used beached bird survey data that cover winter months of the period from 1992 to 2003. We concentrate on three sea bird species that live close to or at the coast. Eider Duck (*Somateria mollissima*), Common Scoter *(Melanitta nigra*) and the Red-throated Diver (*Gavia stellata*) are found relatively frequently at the German coasts, which makes them suitable for statistical analyses. The beached bird survey data were used to validate the simulated oil advection (section 3.4.3).

3.4 Results and Discussion

3.4.1 Spatial variations of the seasonal mean threat of coastal oil pollution

3.4.1.1 Dependence on the location of an oil spill

The location of an oil spill, its distance to the coast and the prevailing wind conditions are key factors that influence the probability that a given coastal area will suffer from pollution. In this section we investigate how different target regions would be affected by hypothetical oil spills at different locations. We considered seasonal averages (summer and winter, respectively) over detailed drift simulations with realistic time-dependent forcing (cf. section 3.2).

Figure 3.2 shows results for hypothetical oil releases at different locations along all major shipping routes in the southern part of the North Sea. At all locations an identical number of particles were released. The circle sizes (areas) provide information about the relative overall potential of each assumed source region to pollute the German North Sea coast, as estimated from the fraction of simulated tracer particles that reach the coast. Hence, circle sizes reflect the relative importance of both differing travel times (assuming an exponential particle decay time of 21 days) and differing probabilities of hitting the German sector of the coast. As expected, the threat of the coast becoming polluted with oil generally decreases for more distant oil spills. For each source region the circles are partitioned with regard to the five color-coded target regions.

As a result of seasonal variations in wind conditions, the hypothetical oil spills in the inner German Bight would, on average, tend to affect more southern coastal regions during the summer as compared to during the winter. In winter there are stronger and more frequent westerly winds which imply a generally stronger impact of hypothetical oil spills in the most western regions, close to the Strait of Dover.

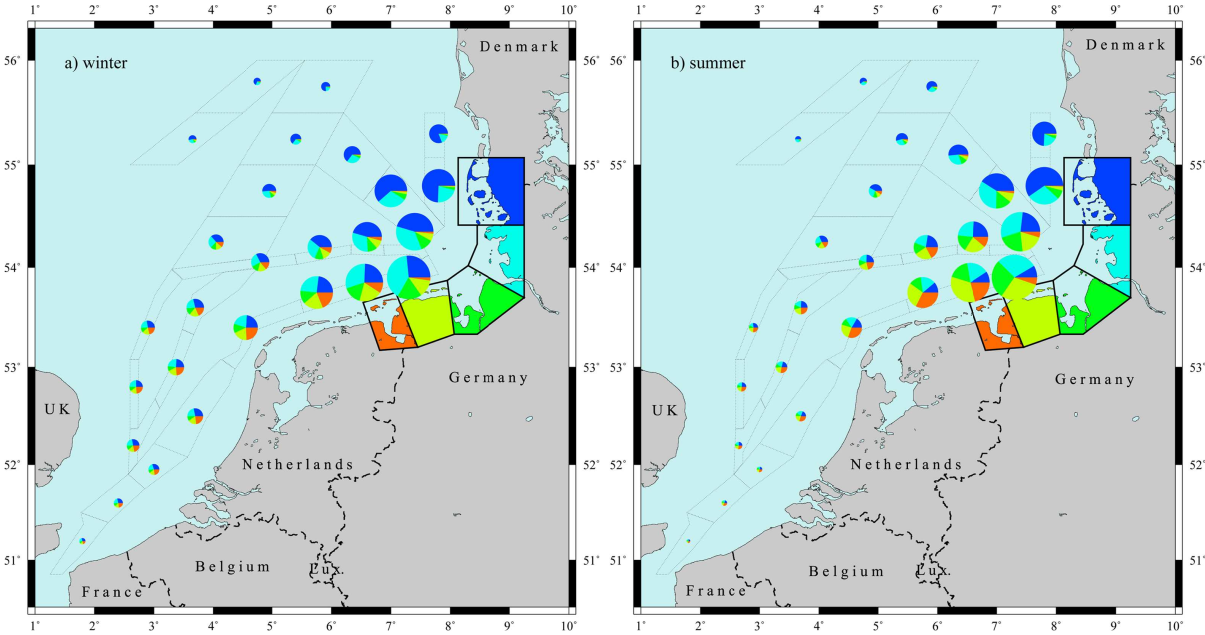

Figure 3.2: A comparison of the mean potential impacts of hypothetical oil spills at different locations on five different coastal regions (color-coded boxes). Circle sizes represent the relative overall amounts of mass that are advected to the German coast, given oil spills of the same magnitude and assuming tracer particles with an exponential decay time of 21 days. Colored wedges indicate how advected material is distributed among the five target regions. The mean conditions shown are based on particle drift simulations started every 28 hours within the 46-year period 1958 − 2003 for a) the winter half-year (Oct. − Mar.) and b) the summer half-year (Apr. − Sep.).

3.4.1.2 Re-weighting simulations with estimated oil spill incidence rates

In the previous section, we did not take into account spatial variations in the probability that a hypothetical oil spill actually occurs. This study does not aim for a quantitative estimate of the total amount of oil pollution, but rather confines itself to a consideration of spatial variability. For this purpose, we assume that the amount of chronic oil pollution is proportional to the density of vessel traffic, as estimated by Golchert & Benshausen (1987), for instance (cf. Figure 3.1a). Results of re-scaling the outcomes presented in Figure 3.2 according to the weighting factors in Figure 3.1a are shown in Figure 3.3.

It should be noted that the relative exposure of the five target regions to a hypothetical pollution at any given location remains unaffected by the assumption of spatial variations of source strengths. The same holds for seasonal differences. However, the relative importance of western source regions near the Strait of Dover compared to those in the northern German Bight, for instance, is clearly larger than it would be if oil spills occurred everywhere with the same frequency. In winter, simulated contributions from pollution in the distant westerly regions become comparable even to those from proximal areas in the inner German Bight.

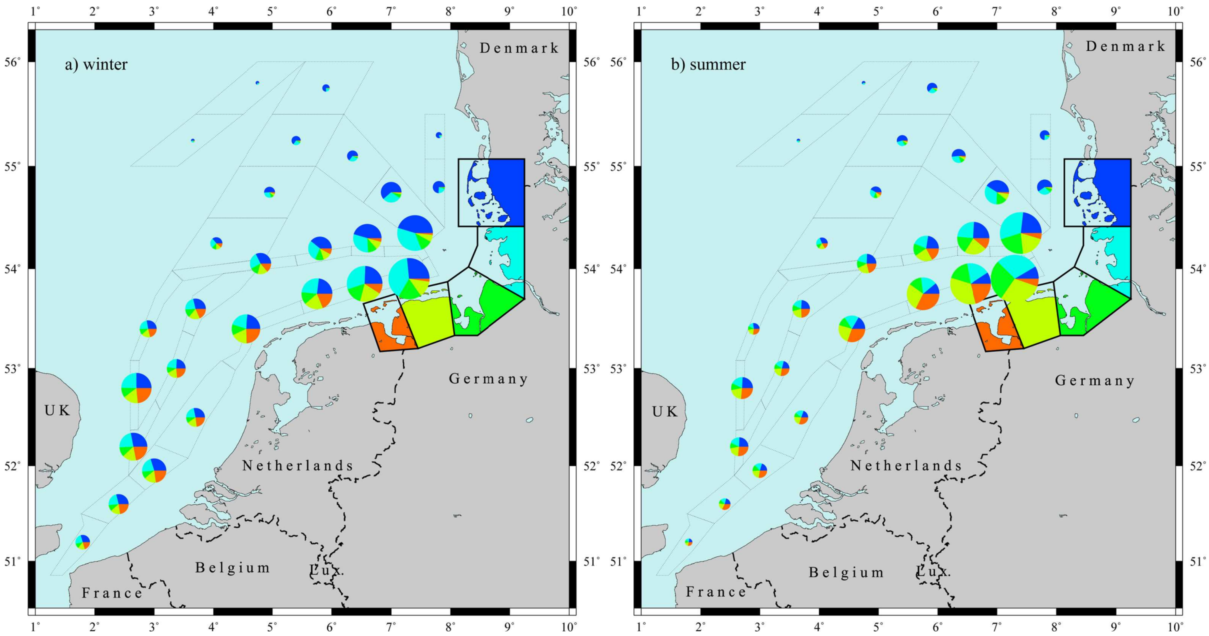

Figure 3.3: Mean relative contributions of oil spills at different locations to the pollution of five different coastal regions (color-coded boxes). The estimations are based on the assumption that source strengths are proportional to vessel traffic density. Circle sizes represent the overall amounts of oil that are advected to the German coast, assuming tracer particles with an exponential decay time of 21 days. Colored wedges indicate how advected material is distributed among the five target regions. The mean conditions shown are based on particle drift simulations started every 28 hours within the 46 year period 1958 − 2003 for a) the winter half-year (Oct. − Mar.) and b) the summer half-year (Apr. − Sep.).

Contrasting Figure 3.2 with Figure 3.3 provides an example of how weather-driven tracer transport simulations may be combined with assumptions about other more uncertain aspects of the pollution problem to finally arrive at an overall impact assessment. In light of the great uncertainty of estimated pollution source strengths, different weighting factors may be attempted in order to explore the range of uncertainty of the overall analysis.

3.4.2 Weather driven variability of simulated advection

3.4.2.1 Analysis of governing weather patterns

The purpose of this section is to statistically attribute the regional variability of oil advection towards the German coast to variable weather conditions. The outcomes of particle cloud transport simulations for each season (winter and summer half year, respectively) during the years 1958-2003 and corresponding SLP fields from the NCEP/NCAR re-analysis data set (Kistler et al., 2001) were subjected to Canonical Correlation Analysis (CCA) (e.g. von Storch & Zwiers, 1999). From the NCEP/NCAR data set an area covering 30°W to 40°E and 70°N to 40°S was selected. Tracer particles from all source regions along the shipping route were pooled into one simulation, again assuming a decay time of 21 days for particle concentrations (cf. section 3.2.1).
Three consecutive mean SLP patterns that were representative of the first three weeks of each particle cloud's drift time were combined into one data set. This data set was then contrasted with simulated particle advection to individual target regions. The outcomes of subjecting the two data sets to CCA are characteristic triples of SLP anomaly patterns, variations of which explain a certain percentage of the variability of simulated coastal pollution in a selected target region.
For the winter season, the relevance of weather effects turns out to strongly depend on the selected coastal area. While advection towards both region 1 and 2 correlates well with SLP (correlation 0.77 and 0.71, i.e. explained variances of 59.1% and 50%, respectively), this correlation is weaker for the advection towards regions 3, 4 and 5 (correlations 0.55, 0.51 and 0.55; explained variances 29.8%, 26.0% and 30.0%). The correlated SLP patterns for these two groups differ. The SLP anomaly patterns that most efficiently control advection processes towards target region 1, for instance, represent changing pressure differences between Scandinavia and the Bay of Biscay. The triple of

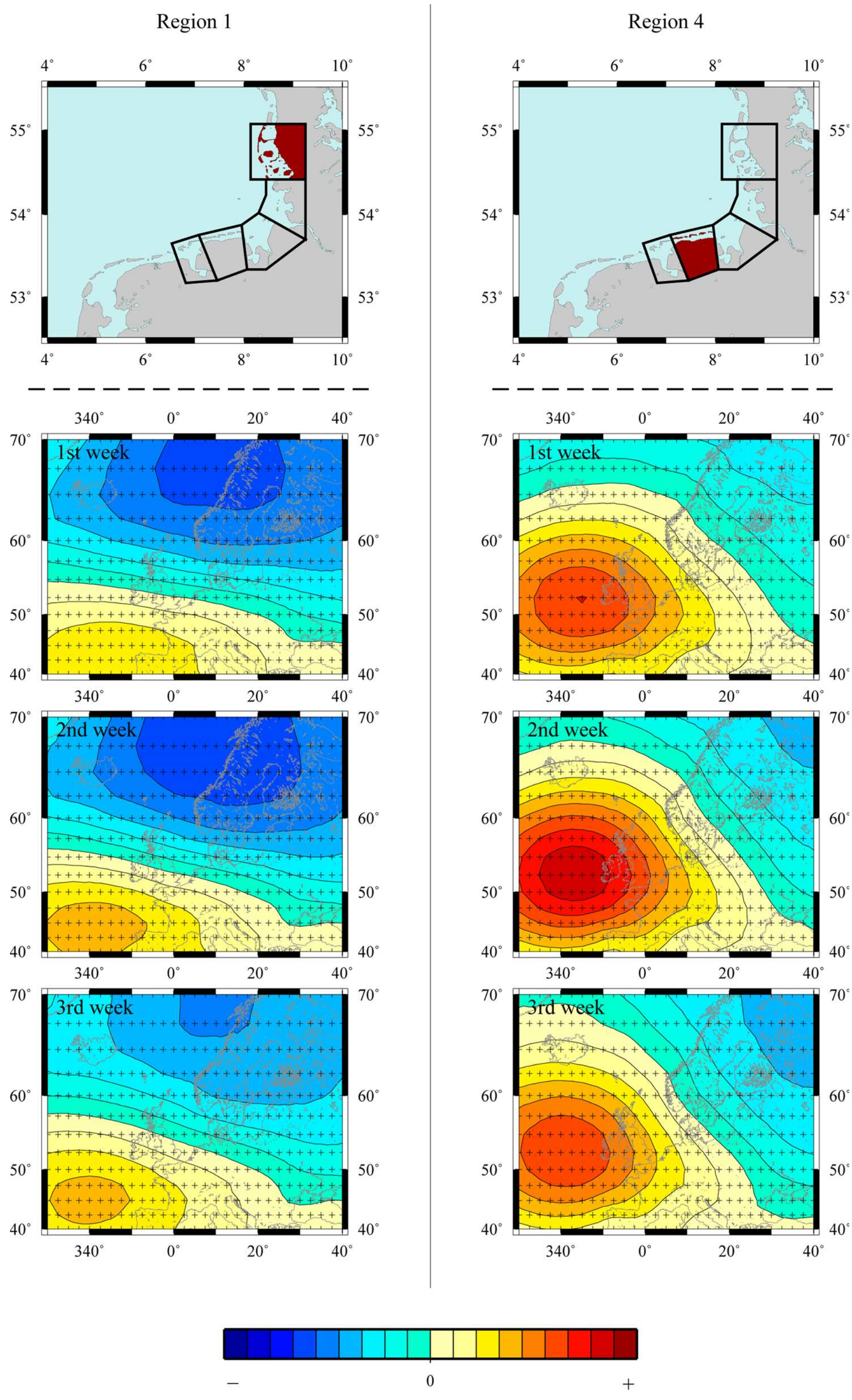

Figure 3.4: Each of the two columns in the figure displays a pair of correlated CCA patterns, obtained from analyzing the connection between SLP and advective transports towards target region 1 (left column) and target region 4 (right column). Panels in the first row illustrate the locations of the two selected target regions as well as the sign of the advection anomaly (color coded as being positive) that is connected with the triplet of consecutive weekly mean SLP anomalies shown in the panels below them. Correlations are found to be 0.77 (left column) and 0.51 (right column).

SLP anomalies with north-south pressure gradients (cf. left column of Figure 3.4) implying stronger westerly winds (Holton, 2004), suggest increased advection towards target region 1. The SLP patterns found to be correlated with advection towards target region 2 (not shown) look similar.

The right column of Figure 3.4 shows the sequence of SLP anomaly patterns that is most strongly correlated with particle advection towards the more southern target region 4. A high-pressure anomaly to the west of Ireland causes intensified northerly winds in the German Bight and therefore stronger advection towards the coast of Lower Saxony.

All analyzed SLP patterns were remarkably stable during the three week period, although the CCA seems to put a minor emphasis on the second week after the particle simulation was started. This might indicate the characteristic time scale of the overall advection processes.

A generally lower correlation between SLP and advection towards the southern target regions could possibly be attributed to the fact that the major shipping routes are very close to the coast of Lower Saxony. Oil slicks from these areas may hit the coastline within a short period of time when winds blow from the north. A CCA considering SLP conditions just for the first seven days of each particle cloud drift time gave a weekly mean SLP anomaly field that explained 33.4% of the advection variability towards target region 4 (compared to 26.0% in the above analysis). In contrast, the explained variance for target region 1 dropped to 41.0% (former value: 59.1%) when the same CCA set-up was utilized. These results of the statistical analysis confirm that the relevant time scales of advection to different sectors of the German coast may vary.

As opposed to the CCA for the winter season, the CCA for the summer months suggests no significant correlation between mean SLP fields and advective drifts. This might reflect effects of either generally lower wind speeds or less persistent large-scale wind patterns.

3.4.2.2 Regional differences in inter-annual variation

Changes in the mean wind conditions may affect the likelihood of oil pollution in different coastal areas in various ways. On average, focusing on the winter half-year, the analysis of the simulated level of coastal oil pollution showed markedly higher advection towards the northern target regions 1−2 than towards the southern regions 3−5 (overall ratio about 5:3). For all target regions, however, a substantial year to year variability is noticeable. Figure 3.5 shows the (standardized) annual winter mean levels of tracer particles that reach target regions 1 and 4 (colored lines in panel a and b, respectively) and also the corresponding means of the CCA time coefficients (black lines) for the SLP anomaly patterns shown in Figure 3.4. Apparently, advection towards region 1 is enhanced during the second half of the investigation period**.** Existing trend-like variations of advection on the scale of decades may produce signals in proxy data such as beached bird survey data (cf. section 3.4.3), which can easily be mistaken as changes in the general level of chronic oil pollution.

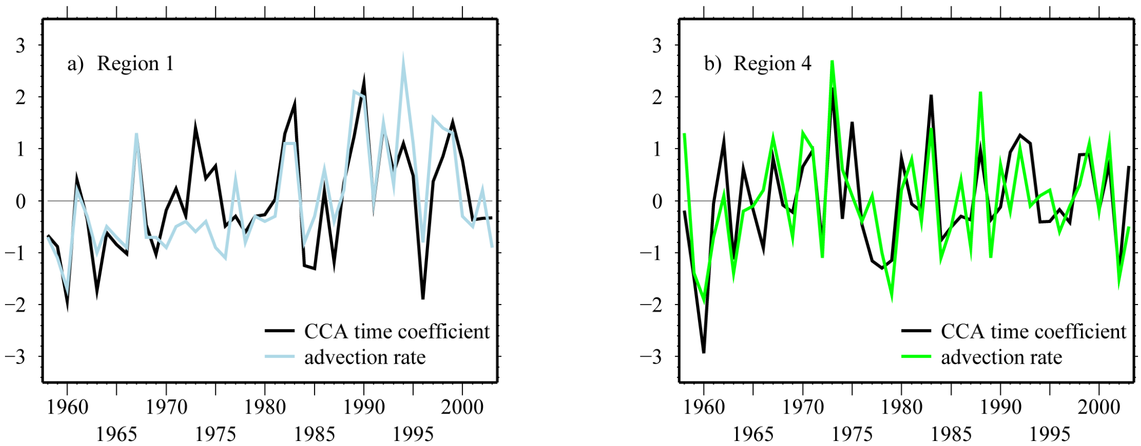

Figure 3.5: Annual levels of simulated tracer particles that arrived at target regions 1 and 4 (colored lines of panels a and b, respectively) along the German North Sea coast during the period 1958 − 2003 (winter half year: Jan. - Mar. and Oct. - Dec.). Particles with an assumed decay time of 21 days were initialized along the main shipping routes in the southern North Sea area with an initial density according to the weighting factors specified in Figure 3.1a. The black lines in the panels show the corresponding CCA time coefficients for the triplets of SLP anomaly patterns shown in Figure 3.4 (cf. section 3.4.2.1).

Figure 3.6 displays the time series of the winter mean CCA time coefficients for the SLP anomaly fields in comparison to the North Atlantic Oscillation (NAO) index. The NAO index represents the SLP difference of (normalized) pressure data recorded in Iceland (Stykkisholmur) and Portugal (Lisbon) (Hurrell, 1995). For target region 1, the correlation between the winter mean CCA coefficient and the NAO index is quite high (correlation 0.72). Given the correlation of 0.77 between the CCA time coefficients and the advective transports to that area, it does not come as a surprise that the probability of coastal oil pollution along the northern parts of the German North Sea coast follows the value of the NAO index (correlation 0.59, not shown). For the southern part of the German North Sea coast, however, the situation is very different. Amplitudes of the SLP anomaly fields governing advection towards target region 4 (correlation 0.51) are virtually uncorrelated with the NAO index (correlation 0.13). Hence, the advection processes towards the southern section of the coast cannot be explained by variations of the NAO index either (correlation 0.13, not visualized).

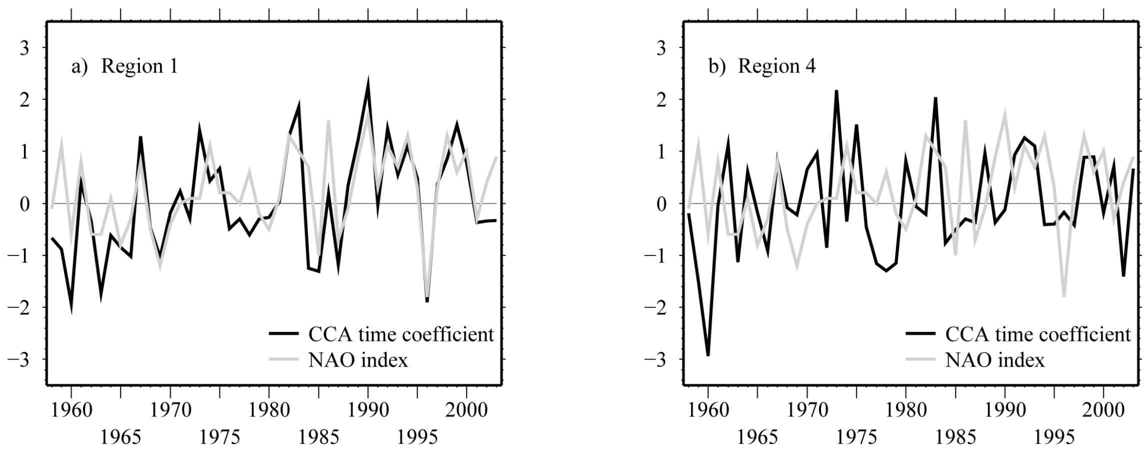

Figure 3.6: Comparison of winter mean amplitudes of the SLP anomaly fields derived from CCA (cf. Figure 3.4) and the NAO index. Results are shown for target region 1 and target region 4 (panels a and b, respectively), all values are displayed in standardized form.

3.4.3 Comparison of simulation results with monitoring data

We compared the simulated inter-annual variation of coastal oil-pollution with data from the German beached bird surveys (cf. section 3.3). The numbers of collected oil-contaminated seabird corpses depend not only on the level of oil pollution but also on the advection rates of both oil slicks and bird corpses. Variability arising from the latter aspect is reflected in our simulations, while the level of pollution was supposed to be constant in our study.

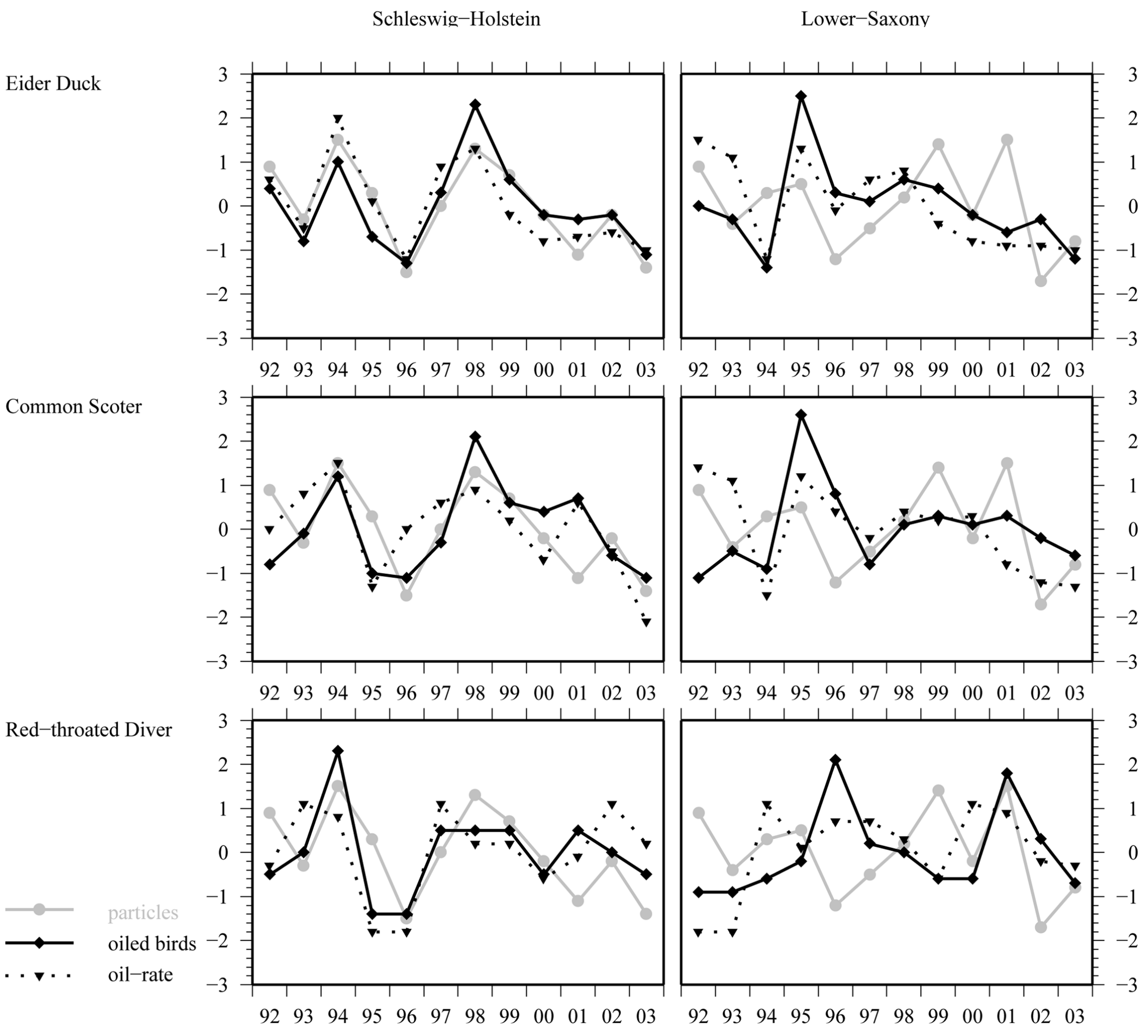

Figure 3.7: The surveyed numbers of beached birds (black, solid) and corresponding oil-rates (black, dotted) in Schleswig-Holstein (left) and Lower Saxony (right) during 1992 − 2003 are illustrated here. Data is shown for three different bird species. Grey lines represent simulated particle advection from the major shipping routes towards the respective regions. Starting from an initial particle density proportional to traffic density (cf. Figure 3.1a), we assumed an exponential particle decay constant of 21 days. All values are displayed in standardized form.

Homogeneous and reliable beached bird data were not available prior to 1992. For three key coastal bird species, we considered the number of collected bird corpses as well as the oil-rates (percentages of collected beached birds that were oiled). Oil-rates are supposed to be largely unaffected by variations in the population size, for instance. For the comparison with our simulations, we divided our area of interest into a northern (targets 1 and 2, called Schleswig-Holstein) and a southern part (targets 3 − 5, called Lower Saxony; cf. Figure 3.1b). The choice of only two sub-areas ensured that sufficiently high numbers of bird corpses were collected in these regions.

According to Figure 3.7, for each of the selected coastal bird species (Eider Duck, Common Scoter and Red-throated Diver) the inter-annual variability in corpses reported in Schleswig-Holstein is similar and resembles the simulated inter-annual variations in coastal oil pollution. The time series of oil-rates also look similar (Chrastansky et al., 2009).

In the southern region, Lower Saxony, we found hardly any correlation between the simulated strength of particle advection and beached bird survey data (right panels in Figure 3.7). This discrepancy is consistent with our result that wind effects are less influential in Lower Saxony (cf. section 3.4.2). With heavy vessel traffic prevailing close to the coast (Reineking, 2005) and major oil pollution documented by aerial surveillance (von Viebahn, 2001), oil pollution proximal to the coast may be one reason why oil victims are found independently of persistent weather conditions.

3.5 Conclusions

The chronic pollution along the German North Sea coast caused by oil dumping from ships depends on a) the locations of oil spills, b) their frequency and strength and c) prevailing weather conditions. Our tracer simulations based on multi-decadal high-resolution reconstructions of atmospheric winds and marine currents allowed for an assessment of factors a) and c) and their combined effects. Due to a lack of precise data concerning b), we assumed the spatial distribution of pollution was proportional to vessel traffic density, not taking into account time dependence of the general level of pollution.

Ensemble transport simulations for particle clouds were performed to compare the exposures of different coastal areas to hypothetical oil pollution at various locations in the southern part of the North Sea. Pollution from almost any location along the major shipping routes was found to potentially affect the German coastline, if a decay time of 21 days is assumed for the pollutant. The most severe threat results from oil spills in the inner German Bight. Given a high level of oil pollution in connection with dense ship traffic, however, the threat even from distant regions in the east of the Dover Strait may reach a comparable level if strong westerly winds prevail, particularly in winter. Our simulations showed also for other source locations a moderate seasonal dependence of the risk that certain coastal regions would be affected. Particularly in winter, for instance, Lower Saxony is unlikely to be affected by oil spills north of about 54.5°N.

According to our simulations, on average, the northern part of the German North Sea coast is most exposed to ship-related oil pollution. While simulated inter-annual variations and trend-like variations over several years are similar in each of the target regions 2−5, the most northern part of Schleswig-Holstein (target region 1) behaves differently in the sense that simulated particle advection was enhanced within about the second half of the period of our study.

Multivariate statistical data analysis (CCA) allowed for establishing a coupling between simulated particle advection and the mean weather conditions during the period of particle integration. For the winter half year (October − March), SLP anomaly patterns could be identified, which explain between approximately 30% and 60% of the variability of simulated advection, depending on the coastal section considered. The results suggest that in winter, changing weather conditions are much more influential for the coast of Schleswig-Holstein (targets 1 and 2) than for Lower-Saxony (target 3-5). For the summer half-year (April − September) a similar relationship could not be established. While winter seasons exhibited a correlation between the NAO index and advection processes towards the coast of Schleswig-Holstein, no such relation holds for the coast of Lower Saxony.

For the northern part of the German North Sea coast (Schleswig-Holstein), inter-annual variations in beached bird survey data, available for the winter months of the years 1992 − 2003, were found to be in accordance with our weather-driven hydrodynamic simulations. This was not the case, however, for the southern part of the coast (Lower Saxony). Our results suggest that a proper identification of weather-related signals in the monitoring data is a more immediate problem for survey data from Schleswig-Holstein than for those from Lower-Saxony, where variations in the survey data seem to be governed by factors other than changing weather conditions. Reasons for these regional differences may comprise both different orientations of the coastlines relative to the main wind directions as well as the particularly short distance between the coast of Lower Saxony and the main shipping routes.

Acknowledgements

We would like to express gratitude to David M. Fleet from the Schleswig-Holstein Agency for Coastal Defence, National Park and Marine Conservation for providing the beached bird survey data and the contribution of his knowledge and experience. We also want to acknowledge Uda Tuente and Dirk Reichenbach from the Central Command for Maritime Emergencies for very useful discussions about marine oil pollution. The author(s) would like to thank Stefan Garthe from the Research and Technology Centre Westcoast (FTZ) for providing information about the distribution and behavior of seabirds. We are also very grateful to Karl-Heinz van Bernem from the GKSS Research Center for fruitful discussions and his support of our study. Finally, we want to show our appreciation to Brittany L. Potter for proofreading.

4 Estimation of the impact of prevailing weather conditions on the occurrence of oil-contaminated dead birds on the German North Sea coast

Alena Chrastansky, Ulrich Callies & David M. Fleet
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Abstract

Chronic oil pollution by illegal oil dumping in the North Sea is difficult to quantify. Beached, oil contaminated sea birds, however, may be used as an indirect indicator. Reconstructing the drift of oil slicks and sea bird corpses in the southern North Sea for the period 1992 − 2003 by means of a two-dimensional numerical transport model driven by re-analysed weather data, we show with an example of two common sea bird species that the variability observed within the number of corpses registered during beached bird surveys for the German coast primarily reflects the inter-annual variability of prevailing weather conditions. This should be taken into account when interpreting the data. We propose normalization of beached bird survey data based on numerical drift simulations to improve the recognition of trends in the level of chronic oil pollution.

4.1 Introduction

While oil spills resulting from ship accidents attract much public interest, less dramatic, ongoing sources of oil pollution receive less attention. However, major oil pollution of the marine environment is caused by accidental discharges that occur during normal shipping operations or by illegal oil dumping, such as tank washing or the disposal of bilge water (Dahlmann & Theobald, 1988; Dahlmann et al., 1994). Shipping routes in the North Sea are among the busiest worldwide and the vast traffic in this area causes damage to the marine biota (Bernem & Lübbe, 1997; Bundesamt für Seeschifffahrt und Hydrographie, 2008; Lozán et al., 2003; Reineking, 2005). The amount of oil spilled into the sea, however, is difficult to estimate, as chronic oil pollution often goes undetected (Schallier et al., 1996). To approximate trends in the magnitude of chronic oil pollution, continuous surveys of oil contaminated sea birds, typical victims of oil pollution, are conducted. However, the number of beached birds is also influenced by other factors including, for instance, wind conditions (Camphuysen et al., 2005; Fleet & Reineking, 2000, 2001). This complicates the interpretation of beached bird surveys.

In this study, we show that neglecting the impact of changing weather conditions could for some species lead to a misinterpretation of beached bird survey data. For the investigation, results from beached bird surveys carried out on the German coast during the period 1992 – 2003 are utilized. We focus on two common sea bird species, namely Guillemot (*Uria aalge*) and Common Scoter (*Melanitta nigra*). Based on our results presented herein, an approach for normalisation is proposed. This efficiently reduces the meteorological signal and allows for a better assessment of possible trends in the number of corpses found during the surveys and hence in the general level of chronic oil pollution.

4.2 Data and Methods

4.2.1 Beached bird survey data

Beached, oil contaminated sea birds have been used as an indicator of chronic oil pollution since the 1960’s (Fleet & Reineking, 2000). With the increasing recognition of the problem of oil pollution in the marine environment, the monitoring area has been enlarged and the beached bird surveys have been improved. On the German North Sea coast, surveys have been performed by volunteers twice a month during the winter season (October to March) since 1984. The results of beached bird surveys are used as an indirect measurement of chronic oil pollution. Analyses of oil samples indicate that the majority of birds are contaminated by heavy fuel oil from shipping (Fleet & Reineking, 2001).

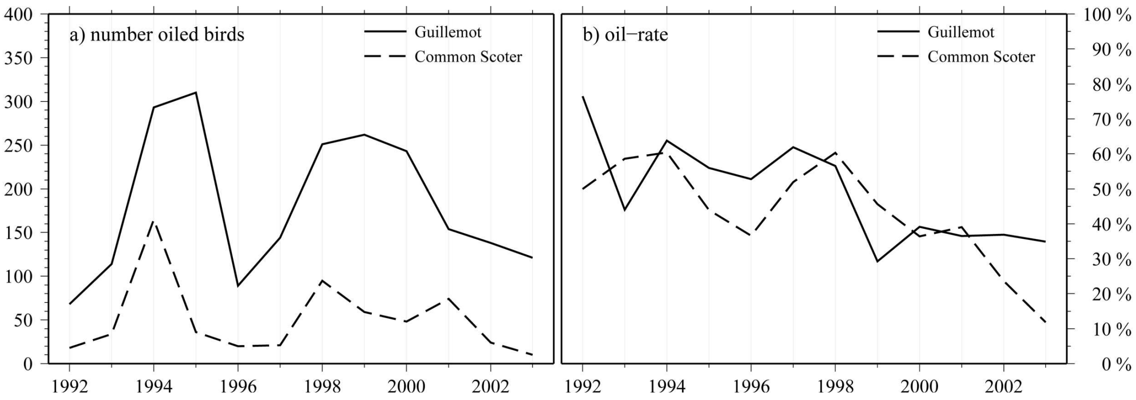

Figure 4.1: (a) Number of beached, oiled Guillemot (solid line) and Common Scoter (dashed) at Germany's North Sea coast and (b) the percentage of beached Guillemot (solid) and Common Scoter (dashed) that were oiled within the period 1992 – 2003 (Jan.–Mar., Oct.–Dec.).

Figure 4.1.a illustrates the annual number of oil contaminated Guillemot (*Uria aalge*, solid line) and Common Scoter (*Melanitta nigra*, dashed) beached on the German North Sea coast for 1992 – 2003. These are relatively numerous bird species that are vulnerable to oil pollution (Fleet & Reineking, 2001, 2004; Garthe, 2003). During the winter, the Guillemot are distributed predominantly offshore in and around busy shipping routes (Stefan Garthe, personal communication). For this reason this species is preferred for the indication of chronic oil pollution (Fleet & Reineking, 2000). Common Scoters live at or near the coast.

Of note is the huge variability in the data presented in Figure 4.1. In addition to oil pollution several other factors affect the number of birds recorded. For example, the number of oiled birds depends on the distribution and the size of their population (Camphuysen & Heubeck, 2001). To normalise the results, the percentage of beached sea birds that were oiled, denoted as the oil-rate, is used as an indicator (Fleet & Reineking, 2001) (Figure 4.1.b). However, circumstances such as mass mortality as a result of either extremely low temperatures, avian diseases or nutrition deficiencies also influence the oil-rate (Camphuysen et al., 2005; Fleet & Reineking, 2000, 2001). In addition, wind conditions regulate the number of beached sea birds and in some circumstances the oil-rate. To our knowledge, the quantification of the impact of weather conditions on beached bird data has not been studied systematically.

4.2.2 Modelling approach

Although aware that wind influenced the number of corpses recorded on the German North Sea coast, there was no attempt to standardise its effect in the past (Fleet & Reineking, 2004). In our study we exploit model based high resolution information about past atmospheric winds and North Sea currents (www.coastdat.de) to improve the quantitative handling of wind effects on beached bird survey data. Based on Lagrangian drift simulations (cf. section 4.2.3) we attempt to produce a detailed picture of weather related annual variability within the beached bird survey data.

Given oil pollution at a certain location, it is impossible to say exactly when and where contaminated birds will die. Therefore, as wind drift factors happen to be similar for oil slicks and bird corpses (Bibby & Lloyd, 1977; Dick & Soetje, 1988), tracer particles are considered to be representative for drift behaviour of both items.

In order to describe ship related chronic oil pollution, source regions for tracer particles are defined that contain the major shipping routes in the North Sea (Golchert & Benshausen, 1987; Reineking, 2005) (Figure 4.2). For each source region the number of simulated tracer particles reaching the German coast is re-weighted according to a) the estimated density of ship traffic and b) particle travel time, assuming an exponentially decreasing particle weight. The latter emphasizes the particles originating from regions closer to the coast.

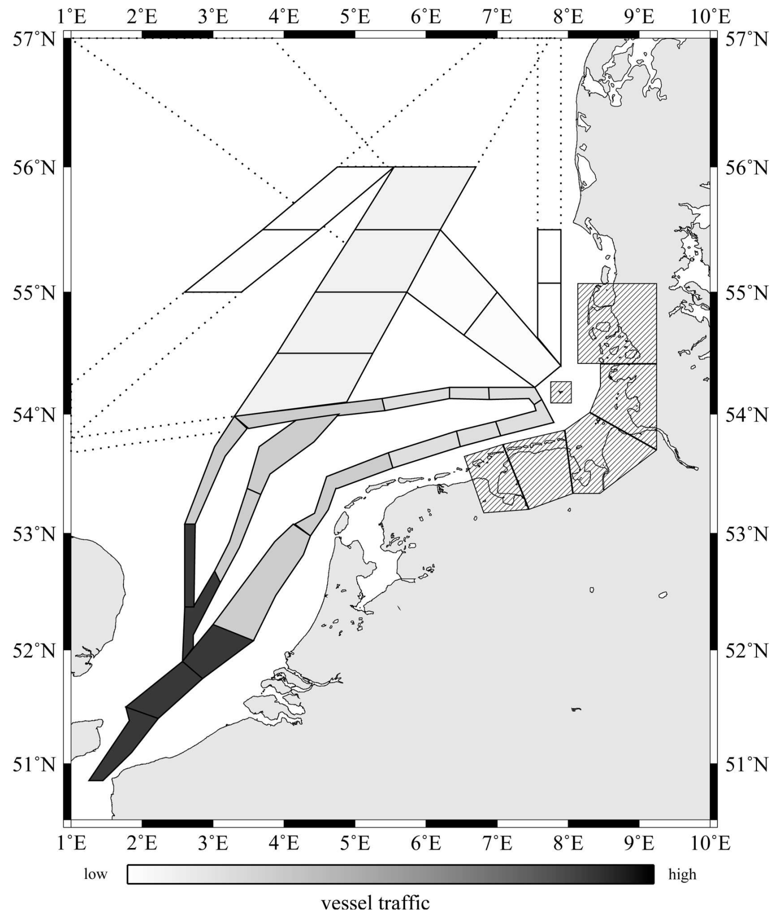

Figure 4.2: Particle source regions containing all major shipping routes (different levels of grey shading represent different densities of shipping traffic (Golchert & Benshausen, 1987; Reineking, 2005)) and target regions along the German coast (hatched).

4.2.3 Numerical simulation of wind drift effects

The Lagrangian trajectories of passive tracers were calculated based on state-of-the-art reanalyses of past atmospheric and sea state conditions in the North Sea. Detailed hindcasts of shelf sea currents with hourly resolution were taken from the coastDat data base (www.coastdat.de). They are the result from running a two-dimensional finite element model (TELEMAC-2D (Hervouet & van Haren, 1996)) on a triangular grid with a variable spatial resolution between a couple of kilometres offshore and about 100 meters near the coast (Plüß, 2004). Hence, the model represents all relevant transport processes including both tidal and weather driven residual currents. Regional atmospheric fields stored in coastDat and employed to force the marine model at its upper boundary were produced based on NCEP re-analyses (Kistler et al., 2001), using the regional climate model SN-REMO (Meinke et al., 2004) for dynamic downscaling. Displacements of tracer particles contain a vertical and horizontal random component. For particles at the water surface, an additional drift of 1.8% of the 10m wind was superimposed (Bibby & Lloyd, 1977; Dick & Soetje, 1988). This additional drift component was assumed to decrease with water depth if particles submerge. To properly resolve the history of weather related drift processes in 1958 – 2003 in the German Bight, drift simulations for ensembles of 2700 particles each were initialized every 28 hours in the vicinity of the major shipping routes. Tracing particle travel times allowed for a statistical re-weighting of the drift simulations assuming particle weights exponentially decrease with a time constant of 21 days, which is clearly smaller than the maximum integration time of 60 days.

4.3 Results and Discussion

4.3.1 Wind signals in beached bird survey data

The weighted numbers of stranded tracer particles are compared with the survey data already pictured in Figure 4.1. The comparison is illustrated in Figure 4.3. Simulations are restricted to the winter months when the surveys are conducted.

Inter-annual variations of the mean numbers of oil contaminated Guillemots and Common Scoters recorded at the tideline in 1992 – 2003 seem to correlate with inter-annual variations of the mean intensity and direction of weather driven marine transports. Similarly, an apparent moderate long term decline in the number of both oiled Guillemots and Common Scoters (cf. Figure 4.1) appears to correspond with a trend in the mean transport conditions. For Common Scoters, the oil-rate shows a similar behaviour. Fluctuations in the oil-rate of Guillemots, however, do not follow the same pattern as the weighted numbers of stranded tracer particles.

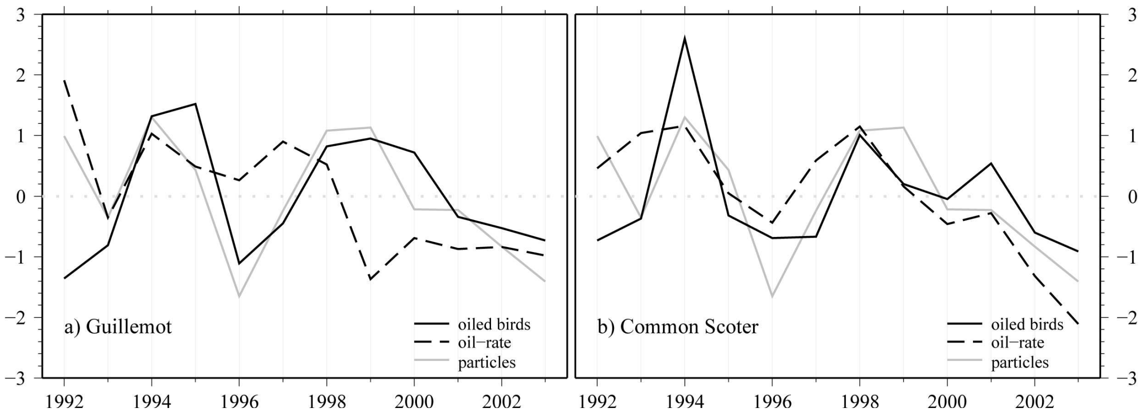

Figure 4.3: Black lines: Survey data re-displayed in standardised form from Figure 4.1.a (number of beached, oiled birds; solid) and Figure 4.1.b (oil-rate; dashed) representing a) Guillemot and b) Common Scoter. Grey line: standardised annual number of simulated tracer particles (selected months: Jan.–Mar., Oct.–Dec.) that reach the German North Sea coast (cf. Figure 4.2) if exponential decay with a decay constant of 21 days is assumed.

We propose the following explanation for this finding: Common Scoters live close to the German North Sea coast (Garthe, 2003). Given a constant level of chronic oil pollution, an increasing (decreasing) advection of oil from the shipping lanes enhances (reduces) the degree of oil contamination of Common Scoters (and other coastal species). This gives rise to a positive correlation between the oil-rate and wind driven advection. For Guillemots, the situation is different. Guillemots occur throughout the southern North Sea area (Garthe, 2003) including the vicinity of all busy shipping routes. It is therefore plausible to assume that their probability to become contaminated is less dependent on weather situations. The initial ratio between oil contaminated corpses and the number of dead Guillemots due to natural causes near the shipping routes, this ratio will not change during advection of bird corpses to the coast. Accordingly, for Guillemots, the oil-rate behaves differently from the absolute number of surveyed oiled corpses. Only the latter is a clear function of prevailing conditions.

Looking at model simulations that cover a longer period of 46 years (1958 – 2003) suggests an existence of trend-like variations on the scale of decades (Figure 4.4). In particular, an increasing trend in attained simulated tracer particles precedes the declining trend after 1994 that is suggested by Figure 4.1 and Figure 4.3. According to Figure 4.4 changing strengths of particle advection towards the German coast are in close correspondence with variations of the North Atlantic Oscillation (NAO) index representing sea-level pressure differences between the Icelandic low and the Azores high (Hurrell, 1995). High index values are accompanied with strong westerly winds so that more tracer particles reach Germany's coastal regions. Particle advection is less effective for low NAO index values. This is also recognizable in the surveyed numbers of oil contaminated sea birds. The very low NAO index value in 1996, for instance, comes along with dominating easterly winds, which leads to a considerably lower number of both collected Guillemots and Common Scoters (cf. Figure 4.3 and Figure 4.4). In 1994 and 1998 on the other hand, high NAO index values coincide with an increased amount of recorded oil contaminated sea bird corpses.

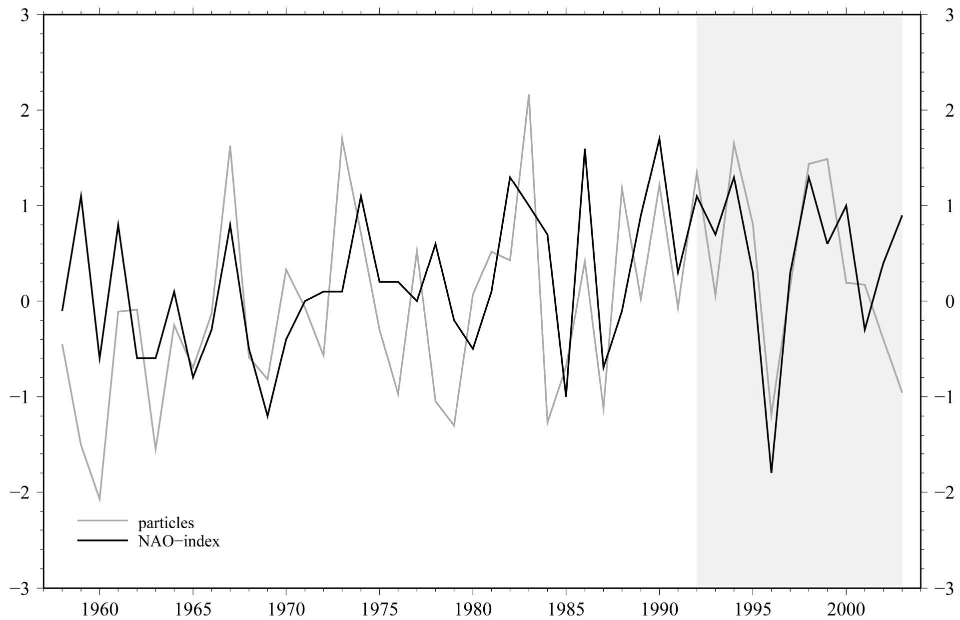

Figure 4.4: Black line: mean NAO index. Grey line: annual numbers of simulated tracer particles that reach the German coast assuming exponential decay with a decay constant of 21 days. All data refer to the selected months (Jan.–Mar., Oct.–Dec.) and have been standardised. Grey shaded: period of the investigated beached bird surveys.

As changing wind conditions affect the drift of both oil slicks and contaminated birds, the close correspondence between variations and trends in the survey data and weather driven model results, respectively, does not come as a surprise. Our study shows that wind conditions may affect the results of beached bird surveys especially the numbers of corpses recorded and in some situations even the oil-rate. When relating the results of beached bird surveys of coastal species to changing levels of chronic oil pollution it is important to take this into consideration.

4.3.2 Data normalisation

To improve the interpretation of the beached bird survey data in terms of trends in the level of oil pollution, we propose statistical normalisation based on the assumption of a linear relationship between simulated passive tracer transports and observations of beached birds (Forsman et al., 2002). We use the following linear regression model

$$y_i = a + bx_i + \varepsilon_i$$

where x_i is the percentage of simulated tracer particles that reach the German coastline in the year i (winter season) and y_i is the corresponding value of either the number of contaminated birds or the oil-rate of the corresponding bird species. Residuals ε_i with zero mean represent inter-annual variations that cannot be (linearly) attributed to variable meteorological conditions. Normalised survey data $\hat{y}_i$ may then be obtained from

$$\hat{y}_i = \bar{y} + \varepsilon_i = y_i - b(x_i - \bar{x})$$

where $\bar{x}$ and $\bar{y}$ denote average values for the period and sea bird species under consideration.

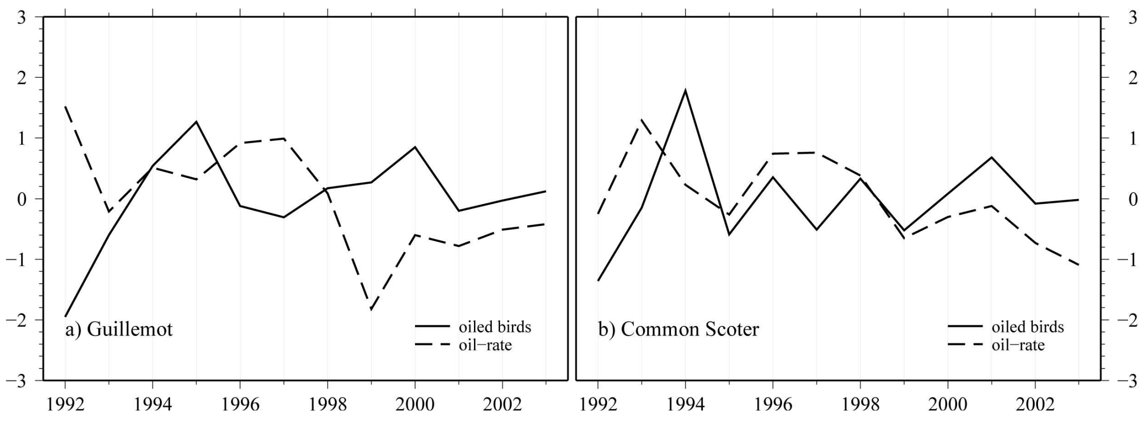

Figure 4.5: Standardised numbers of beached, oiled sea birds (solid) and oil-rates (dashed) after the application of data normalisation for a) Guillemot and b) Common Scoter.

Results of subjecting the standardised survey data from Figure 4.3 to normalisation are shown in Figure 4.5. Lowering (raising) values in years with strong (weak) onshore drift conditions, produces a more uniform time series. The number of oiled Common Scoters in 1994, however, remains on high level in both the original data and the normalised numbers as mass oiling was recorded in that year (Fleet & Reineking, 2001). In October 1998 large numbers of mainly coastal sea birds fell victim to oil that was spilled after the cargo vessel PALLAS grounded on the German North Sea coast (Fleet et al., 1999). The 1998 peak in Figure 4.3.b (Common Scoter) becomes inconspicuous after data normalisation. Hence, if wind conditions had happened to be different, less coastal sea birds, such as Common Scoter, might have been contaminated by oil.

It should be kept in mind that even if normalisation with regard to wind conditions worked perfectly, the time series of beached birds would still remain influenced by other factors (Camphuysen et al., 2005; Fleet & Reineking, 2000, 2001), especially mortality and distribution.

4.4 Conclusions

We conclude from ensemble Lagrangian passive tracer transport simulations that inter-annual variability of wind driven advection towards the German coast is large and has a high impact on the number of oil contaminated, beached Guillemots and Common Scoters beached there. The corresponding oil-rate, however, reacts differently depending on the distribution of the birds involved. The oil-rate of the Common Scoter, a coastal species, for instance, seems to be influenced by wind. In particular, a pronounced negative trend in advective transport during the last decade might lead one to believe that the oil-rate for that species has declined steeply on the German North Sea coast, reflecting a much reduced level of oil pollution in adjacent waters. Using normalised values the decline is in fact not so steep. Model simulations for the period 1958 – 2003 put the negative trend in wind driven transports since about 1994 into the context of a long-term variability that is connected with variations of the NAO index. In contrast, the results of the passive tracer transport simulations show that, for the Guillemot, a species that is distributed predominantly out at sea, the oil-rate supply a true measure of chronic oil pollution levels. Guillemot oil-rates of beached birds in the south eastern North Sea have declined significantly over the last decades and indicate that chronic oil pollution has declined significantly in the region since the mid 1980s

(Camphuysen et al., 2005). Normalisation of survey data on oil contaminated birds assuming a linear relationship with simulated passive tracer advection is proposed to improve interpretation and to avoid misinterpretation of the wind influenced beached bird survey data.

Acknowledgements

We are grateful to Uda Tuente and Dirk Reichenbach (Central Command for Maritime Emergencies) and Stefan Garthe (Research and Technology Centre Westcoast, FTZ) for fruitful discussions and very useful information about the impacts of oil pollution on sea birds. The author(s) would also like to express gratitude to Karl-Heinz van Bernem (GKSS) for his support of our study and Dennis Bray (GKSS) for proofreading.

5 Using a Bayesian network to summarize variability in numerical long-term simulations of a meteo-marine system: drift climatology of assumed oil spills in the North Sea

Alena Chrastansky & Ulrich Callies
Environmental Modeling & Assessment (submitted on June 17th, 2009)

Abstract

Climate-related scientific analyses of meteo-marine systems are often based on numerical long-term simulations at high spatial and temporal detail. Such comprehensive data sets require much resources and specific evaluation tools, which sometimes hampers their use within inter-disciplinary projects. In the present study we propose the use of a Bayesian Network (BN) to represent simulated transports in the North Sea depending on variable external forcing in terms of conditional probabilities. Eliciting probability tables from multi-decadal numerical simulations ensures that all realistic weather and resulting sea state conditions are covered in agreement with the frequency of their occurrence. The probabilistic representation conveniently allows for conditioning numerical simulations on either external forcing (weather conditions) or resulting transports. In the latter case the Bayesian inversion formula becomes involved to transfer information in a direction opposite to causal dependencies encoded in the underlying mechanistic model. We show that conditioning on travel times even allows for taking into account substances with specific half-lives although these were not objects of the original numerical simulations.

5.1 Introduction

Prevailing weather conditions are decisive for the degree to which different coastal stretches are exposed to pollution by oil and other contaminants released on the open sea. For oil spill response planning, for instance, it is important to know characteristic drift velocities and directions of oil slicks. A thorough contingency analysis, however, needs more than a description of mean conditions. The information basis should include details of variability, the frequency of extreme events, and the coincidence of adverse conditions with regard to wind direction, season, wave heights, and drift times, for instance. A state-of-the-art approach for the provision of such consistent information is the long-term (multi-decadal) reconstruction of past conditions based on numerical model simulations.

Weisse et al. (2009; cf. Appendix A) describe the data base coastDat (www.coastdat.de), which compiles coastal and offshore hindcasts of atmospheric and oceanic parameters obtained by downscaling re-analysis data of the global atmosphere and using them as proper forcing for realistic marine simulations. The detailed information encoded in a vast amount of model outputs far exceeds an aggregate statistical description in terms of means and standard deviations, for instance. Chronic oil pollution along the German North sea coast is just one application example among many other analyses of recent and possible future changes the data have already been used for (Weisse et al., 2009; cf. Appendix A). As any oil discharge in the North Sea is prohibited (International Maritime Organization, 2002), the control of marine oil pollution gains more and more in importance (i.e. Camphuysen & Heubeck, 2001; Carpenter, 2007; International Maritime Organization, 1982, 2002; von Viebahn, 2001). Despite regular aerial surveillances, however, in many cases illegal washing of oil tanks or discharge of bilge oil goes undetected (Schallier et al., 1996). Chrastansky et al. (2009) used the information from coastDat to support the interpretation of the numbers of beached oil-contaminated sea birds collected along the coasts of Germany as a proxy for the general level and most probable locations of illegal oil spills.

To estimate weather-driven variations in chronic oil pollution along the German North Sea coast, Chrastansky and Callies (2009a) analyzed ensemble tracer transport simulations based on the re-constructed hydrodynamic fields from coastDat. Within a period of several decades, Lagrangian particle drift simulations were started every 28 hours, each simulation comprising the movements of thousands of particles starting from different source regions. The resulting manifold of drift trajectories covers the whole spectrum of possible developments and represents both mean conditions and the occurrence of rare events. For many practical applications, however, a time consuming full analysis of the extensive data base using scientific programming is neither feasible nor necessary. Instead, the essence of the detailed long-term data in terms of probability distributions of events and related parameters, including coincidences and causal interactions, would be needed in a more compact format. Users might also wish to link information from the data base to information about a specific pollutant's behavior. External information may result from expert knowledge elicitation and be connected with some range of uncertainty.

In this study we propose a probabilistic data description based on Bayesian Network (BN) technology to conveniently summarize the essence of the ensemble drift simulations investigated by Chrastansky and Callies (2009a). In BNs, causal relations are modeled based on the probabilistic relationships among the variables of interest (Jensen, 1996). Calculating probability tables of the BN from the vast amount of numerical simulation results, the graphical representation of the BN encodes marginal and conditional independence relations that reflect the causal structure of the deterministic simulations. Most published applications of BNs in environmental studies rather deal with a combination of expert knowledge, partly formalized in model equations and empirical data. Examples are the prediction of fish and wildlife response to land management strategies (Marcot et al., 2001), the investigation of suspended sediment concentrations in alpine catchments as a function of air temperature (Mount & Stott, 2008) and the intensive analysis of eutrophication processes using diverse judgment methods (Borsuk et al., 2004).

BNs offer several advantages, although the model construction is challenging and not trivial (Kjaerulff & Madsen, 2008). A BN with its intuitive graphical user interface fits the needs of practical decision makers, but may also be useful for training and education purposes. Among others, questions of the following type would be treatable semi-quantitatively without access to the full original data base: Are there any offshore regions in which pollutions are more likely to go undetected than in other regions? In which regions are hypothetical pollutions most hazardous for certain coastal stretches?

How does a threat depend on the strength of evaporation or other weathering processes implying a shorter half-life of oil or other polluting substances? Are there major seasonal differences? What about the uncertainty of such a relationship? These and other similar questions can be answered by conditioning the BN with regard to certain variables. The BN with a graphical structure encoded in a set of (conditional) probability tables can easily be stored on any PC. It makes essential information available without a link to the detailed original data sets the BN was derived from. Different software packages, both commercial and free of charge (a list of software may be found i.e. in Korb and Nicholson (2003) allow for the interactive and flexible exploration of a BN's information content and implications.

The paper is structured in the following way: Initially, Section 5.2 gives an illustration of the hydrodynamic drift simulations (Section 5.2.1) on which the variables' probability elicitation is based. Section 5.2.2 describes the atmospheric parameters employed for representing atmospheric forcing in the BN. A general description of BN technology is given in Section 5.2.3. Construction of our specific BN is explained in Section 5.3, explaining model structure (Section 5.3.1) and elicitation of model parameters (Section 5.3.2). Section 5.4 presents two detailed examples of how the BN can be used for answering specific questions. After a discussion of the BN and its practical utilization in Section 5.5, conclusions are drawn in Section 5.6.

5.2 Material and Methods

5.2.1 Hydrodynamic drift simulations

The objective of our previous study (Chrastansky & Callies, 2009a) was to establish a realistic drift climatology of assumed oil spills in the southern North Sea, focusing on chronic oil pollution in the German Bight. As shipping is considered to be the main source of chronic oil pollution (Camphuysen, 1998, 2007; Dahlmann, 1985; Dahlmann et al., 1994; Reineking, 2005), source regions for tracer particles were defined along the main shipping lanes. Within each of these source regions, 100 randomly distributed tracer particles were initialized every 28 hours within the years 1958 − 2003 and integrated for 60 days. For the present study we confined ourselves to the consideration of 9 source regions (labeled S1 − S9 in Figure 5.1) located within the German Bight. The basic information borrowed from each numerical simulation consists of a) the numbers of particles from each source region that arrive at different target regions (labeled T1-T5 in Figure 5.1) and b) the mean drift-times they need. This information is available for each individual simulation.

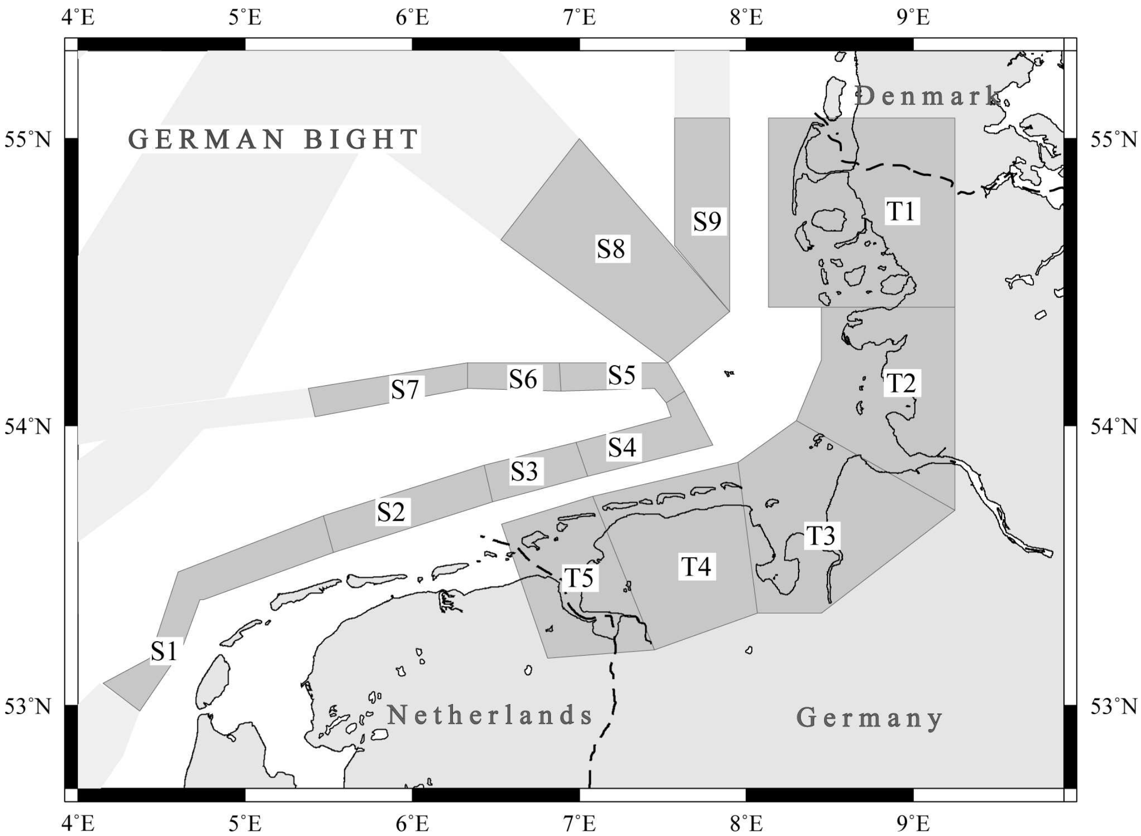

Figure 5.1: Particle source and target regions considered in the study. Source regions along the shipping routes are labeled with S1-S9, target regions with T1-T5. Hypothetical pollutions that originate from more remote sectors of the shipping lanes (light grey shaded) are not taken into account within the present study.

Drift simulations were based on pre-calculated hourly hydrodynamic fields stored in the data base coastDat (www.coastdat.de). CoastDat contains high resolution state-of-the-art re-analyses of past atmospheric and sea state conditions, which have already been employed in various case studies (Weisse et al., 2009; cf. Appendix A). Two-dimensional hindcasts of marine currents on an unstructured triangular grid, with spatial resolution varying between about 100 m near the coast and a couple of kilometers in offshore regions (Plüß, 2004), were produced by running the finite element tide-surge model TELEMAC-2D (Hervouet & van Haren, 1996). At its upper boundary the marine model was forced by hourly NCEP/NCAR re-analyzed wind fields (Kistler et al., 2001), regionalized via dynamical downscaling with the nested regional climate model SN-REMO (Meinke et al., 2004). Spatial resolution of the resulting atmospheric forcing is 50 km.

For the tracer drift simulations, wind-induced drift components (1.8 % of the 10 m wind velocity) were superimposed to the movements induced by currents. According to Dick & Soetje (1988), this is a proper parameterization for oil slick movements on the water surface. A random vertical particle motion was included to allow for reduced wind forcing when the tracer particles submerge. Additionally, a random velocity component was used to simulate effects of horizontal diffusion.

5.2.2 Representation of atmospheric forcing

As simulations are started every 28 hours within the years 1958 − 2003, Lagrangian tracer particles experience an exhaustive spectrum of realistic time dependent weather conditions. For a representation in a BN, however, we need to reduce the degrees of freedom in the space of atmospheric forcing. In addition one must also take into account that weather conditions are not constant during a particle cloud’s journey. We used two different approaches.

First, we simply extracted from coastDat a hourly time series of winds simulated for the island Heligoland (54° 11′ N, 7° 53′ E) located in the center of the German Bight. Based on this time series, for each drift simulation corresponding distributions of both wind direction and wind speed were specified, taking into account the first three weeks of particle integration. We assumed the probability of certain wind conditions, which is related with coastal pollution, to be proportional to the time span in which such wind conditions prevailed during a particle cloud’s movement.

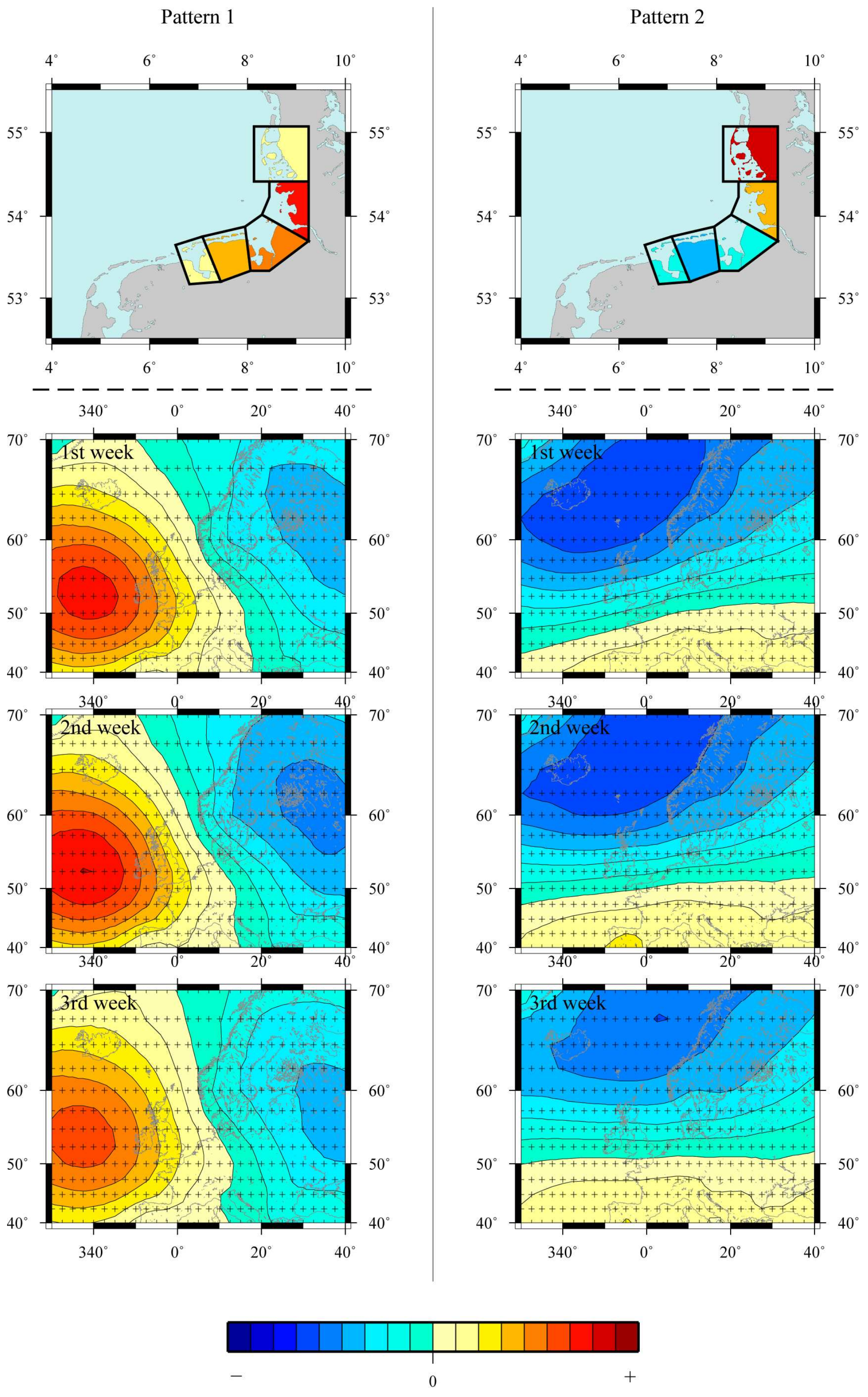

Figure 5.2: Pairs of correlated CCA-Patterns (columns), obtained from analyzing the connection between SLP and advective transports towards the German North Sea coast. Panels in the first row depict the advection anomaly that is connected with the triplet of consecutive weekly mean SLP anomalies shown in the panels below. Correlations are 0.73 and 0.52 for the left and right column, respectively.

Our second approach borrowed from Chrastansky and Callies (2009a) is a bit more involved. To identify weather patterns that are most influential for the spatial distribution of coastal pollution, we subjected atmospheric forcing and the outcomes of corresponding drift simulations to Canonical Correlation Analysis (CCA) (von Storch & Zwiers, 1999). In doing so, we represented the atmospheric states during the first three weeks of each particle cloud's drift time by a set of three consecutive weekly mean sea level pressure (SLP) fields, taken from the NCEP/NCAR re-analysis data set (Kistler et al., 2001). From the subsequent CCA we obtained pairs of correlated anomaly patterns in a) the space of particle advection towards the pre-defined target regions (cf. top panels of Figure 5.2), and b) the space of three consecutive SLP fields (cf. the three lower panels in Figure 5.2).

Columns in Figure 5.2 represent the two most correlated pairs of CCA patterns (correlation coefficients 0.73 and 0.52, respectively). The first triplet of SLP patterns (left column) describes a pressure anomaly associated with northwesterly winds that prevails during the entire three weeks of a particle cloud's drift time. Accordingly, the associated anomaly pattern of particle advection represents an increased particle drift towards all parts of the German North Sea coast. Unlike the first advection pattern, the second (right column) represents anomalies of opposite sign in the northern and southern regions, respectively. The corresponding SLP anomaly is associated with westerly (or diminished easterly) winds.

Variables used in the BN will be wind direction and speed at Heligoland and the CCA time coefficients that represent the time dependent relevance of corresponding anomaly patterns. Variations of the CCA time coefficients are able to explain 32% (first CCA pattern) and 42% (second CCA pattern) of advection variability.

5.2.3 BN technology

A BN is a probabilistic, directed acyclic graph (DAG) consisting of a set of random variables and a set of directed links between them. Graphically, nodes represent the variables while directed edges encode causal dependencies (Kjaerrulff & Madsen, 2008). In our study we employ nodes that describe the degrees of freedom each variable has in terms of a number of discrete states. These states can be either numbered, labeled or represent intervals. They must, however, always be exhaustive and mutually exclusive (Jensen, 1996). Unless any current evidence exists (e.g. observations), generally the probability of a variable (node) being in a given state will be smaller than one. In case a variable (node) is influenced by other variables, edges from the influencing variables, which are called parent nodes, point to the dependent node. Consequently, the latter is called child node (Kjaerrulff & Madsen, 2008). The child node's state probabilities will then be affected by information on the parent nodes. Relationships among parent and child node(s) are encoded in conditional probability tables (CPTs) associated with the child node(s).

A most simple BN with only two variables might represent the relationship between the time of the year (season SN) and prevailing wind conditions (*W*). The graphical model $SN \rightarrow W$ would correspond with the factorization $P(W, SN) = P(W \mid SN)P(SN)$ of the joint probability distribution P(*W*,*SN*) (Pearl, 2000). Although the alternative graphical model W → SN corresponding with the factorization $P(W, SN) = P(SN \mid W)P(W)$ provides an equivalent description, the conditional probability $P(W \mid SN)$ appears preferable to $P(SN \mid W)$, as it properly describes the probability distribution of wind conditions as a function of the seasonal context. Modeling season as a function of wind conditions would be a much less convincing approach.

Given the CPT $P(W \mid SN)$, the marginal probability of wind conditions disregarding their seasonal variations can be obtained as

$$P(W) = \sum_j P(W \mid SN = sn_j)P(SN = sn_j)$$

with sn_j denoting discrete states of the variable *SN*. Our simple example BN would be made up by the two nodes *W* and *SN* and the CPT associated with *W*. In the context of our study the CPT would represent likelihoods extracted from the results of extensive numerical simulations.

Complete graphs of realistic BNs contain very large numbers of edges. As in the above example, different orientations of edges can be chosen. The only constraint to be satisfied is that the graph must not contain any directed cyclic path (Jensen, 1996). The situation changes, however, when edges in the graph are considered for elimination. Full graphs are neither informative nor manageable. Missing edges in a graph, however, imply independence statements that need to agree with either causal reasoning or past experience (Pearl, 1988). The kind of implied independence statements depends on the orientations of remaining edges. We will illustrate this point by the inclusion of the atmospheric pressure field (*P*) as a third variable into our above example.

Figure 5.3a shows a complete graph with edge directions in agreement with causal reasoning. Two edges emanating from node *SN* indicate that pressure is expected to change with the season as well as wind does. On the other hand, large scale patterns of air pressure are the physical drivers of winds. This motivates the orientation of the edge connecting the two atmospheric variables. Panels (b)-(d) of Figure 5.3 show three simplified graphs that arise from the complete graph by the omission of one edge at a time. Implications of the three simplified graphs are profoundly different.

Graph (b) in Figure 5.3 states that, unless evidence of wind conditions (*W*) exists, season (*SN*) is not informative about air pressure (*P*). The situation changes when the current state of variable W is known (conditional dependence (Kjaerulff & Madsen, 2008)). In this case additional evidence on pressure (*P*) would improve existing knowledge about the current season (*SN*). We conclude that the simplified graph (b) is to be rejected.

In graph (c) in Figure 5.3 the physically based link between air pressure and wind has been discarded. The graph states that correlation between the physical variables *W* and *P* can be modeled by changing seasons alone. Given evidence on the current season, any correlation between *P* and *W* is neglected. Again this graph does not provide a proper model of the natural system.

Graph (d) retains the aforementioned physical link between the variables *P* and *W*. At the same time it allows for a seasonal variation of both of the two variables. The seasonal effect on wind (*W*), however, is modeled as being channeled through pressure (*P*), which means that wind variations being unrelated with pressure show no seasonal dependence. We conclude that graph (d) can be considered as a reasonable model. Likewise one could choose graph (b) after inversion of the edge connecting P and *W*. In either case information between season (*SN*) and a physical variable (*W* or *P*) at the end of a serial connection will be transmitted as long as we do not have definite knowledge about the state of the physical variable represented by the middle node.

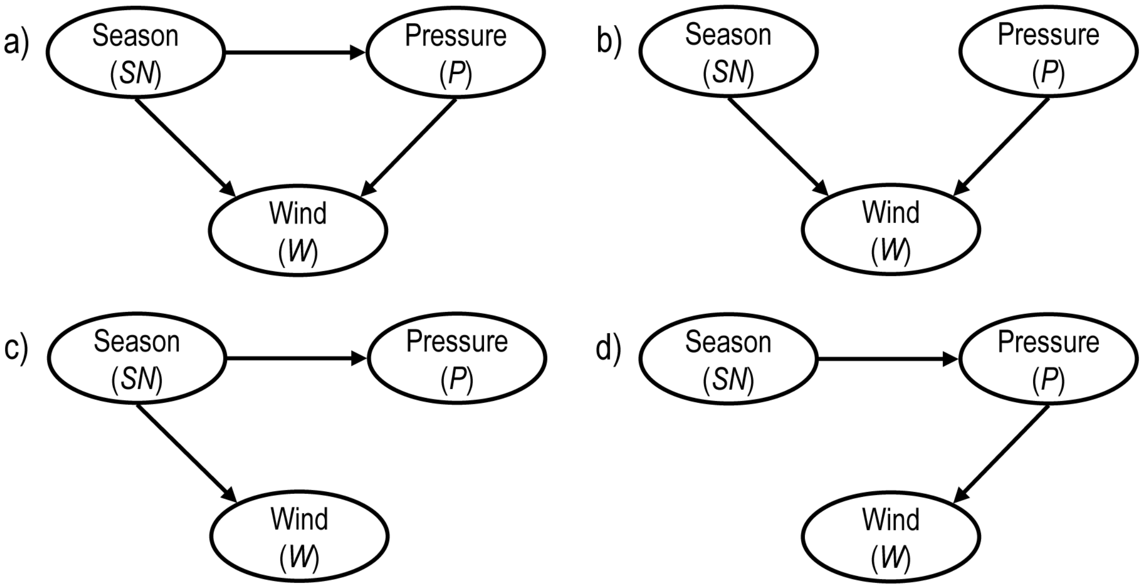

Figure 5.3: Example of a three node BN: a) complete graph, b)-d) simplified graphs with one edge being discarded.

Using the so-called chain rule (e.g. Pearl, 1988), the factorization of the trivariat probability distribution $P(W, P, SN)$ in agreement with the complete graph (a) reads

$$P(W, P, SN) = P(W \mid P, SN)P(P \mid SN)P(SN).$$

Replacement of graph (a) by graph (d) in Figure 5.3 means replacement of this complete factorization by the simplified expression

$$P(W, P, SN) = P(W \mid P)P(P \mid SN)P(SN).$$

The effect of the graph simplification is that instead of the three-dimensional CPT $P(W \mid P, SN)$ now only the two-dimensional CPT $P(W \mid P)$ needs to be elicited. In our study below, time coefficients of two characteristic atmospheric pressure patterns (cf. section 5.2.2) will take the part of pressure in Figure 5.3.

The need for a BN structure that properly mirrors causal relationships has been emphasized by Kjaerulff and Madsen (2008). Another example extracted from our full study illustrates the implications of incorrect independence properties that may be encountered when a BN contains arrows pointing from symptoms to causes.

The objective of our study is to represent the risk of coastal oil pollution depending on the locations of hypothetical oil spills and the distribution of prevailing winds. Given evidence on the past wind conditions, current pollution of some target region is a symptom that allows for narrowing down the location where an oil spill most probably occurred. Hence, at first sight the structure of graph (a) in Figure 5.4 is appealing. It seems to be in line with the practical aim to identify contaminators based on observed pollution and known weather conditions.

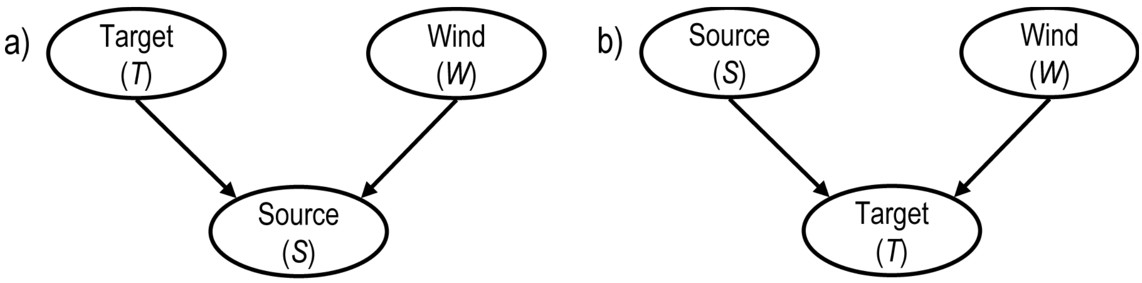

Figure 5.4: Two BNs for the same variables that imply different conditional dependences.

The deficiency of graph (a) is, however, that pollution observed in some target region and knowledge about past wind conditions are assumed to be mutually independent pieces of information. This is obviously incorrect. Offshore winds in the past would lower our expectation of coastal pollution. Conversely, prevailingness of offshore winds would be disconfirmed by the observation of coastal pollution. Posterior probabilities derived from BN (a) in Figure 5.4 will therefore be incorrect. For graph (b) with directions of arrows properly representing cause-effect relations the situation is different. It is obviously true that knowledge about the location of an oil spill is non-informative about wind conditions and vice versa. When, however, pollution in some target region is reported, the situation becomes different. In this case, knowing the past wind conditions allows for narrowing down the source region. Mathematically, converging connections in graph (b) allow for a transmission of information between *S* and *W* whenever evidence on the middle variable Target (*T*) is available (Kjaerulff & Madsen, 2008). Hence, *S* and *W* are conditionally dependent variables.

More examples about the functionality and construction of BNs can be found in Jensen (1996), Kjaerulff and Madsen (2008), Pearl (1988, 2000) and Shipley (2001).

5.3 Model construction

BN model construction always proceeds in two consecutive steps (e.g. Kjaerulff & Madsen, 2008): Identification of the probabilistic network's structure and elicitation of model parameters. We used the software tool Hugin Researcher TM (Madsen et al., 2005) for model construction. Similar tools can be found in Korb and Nicholson (2003), for example.

5.3.1 Specification of model structure

The first step, structure specification, includes the choice of variables. Two variables are central for our problem: the partition of total oil pollution among specified source regions (variable 'Source' or *S*) and the percentages of simulated passive tracer particles that arrive in specified target regions (variable 'Target' or *T*) when choosing initial particle distributions according to *S*. Note that our prototypical network does not deal with a changing level of total pollutant input. Instead, the overall amount of pollutant discharge from all source regions is implicitly assumed to stay on an unspecified constant level.

Both of the nodes *S* and *T* are chance nodes that represent random or uncertain variables. The uncertainty associated with *S* arises from a lack of detailed observations. The BN shown in Figure 5.5 offers two options for dealing with this situation. The user may choose either a uniform distribution (predefined in node 'uniform Distribution' (*O1*)) or a distribution estimated from aerial surveillances (predefined in node 'observed Distribution' (*O2*)). The user's choice is controlled by two states the selector node 'Switch' (*SW*) may attain (Kjaerulff & Madsen, 2008).

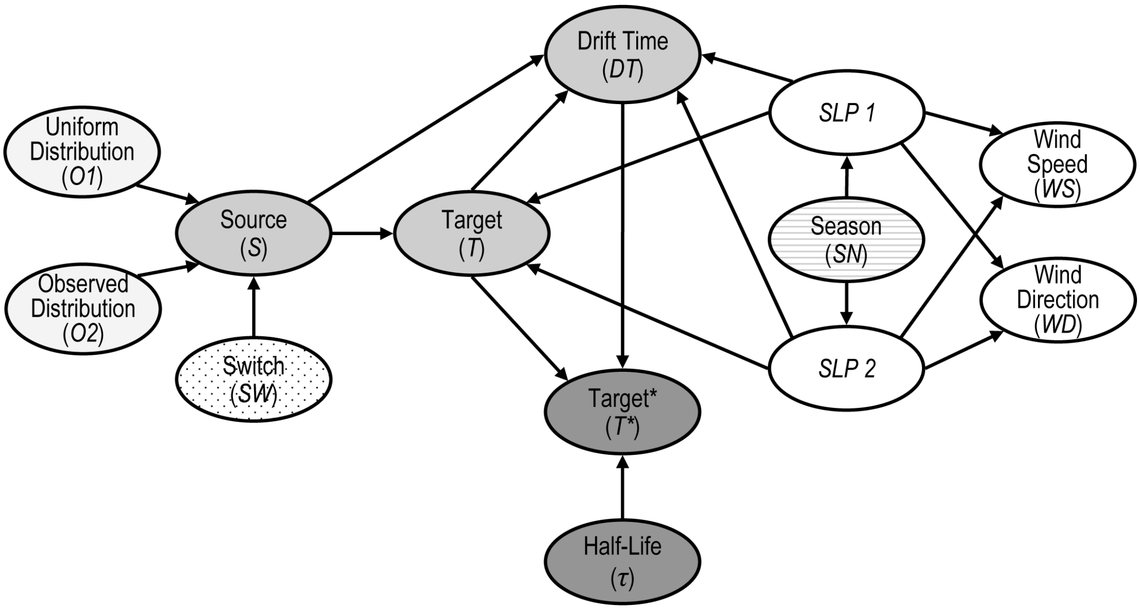

Figure 5.5: A BN representing the climatology of weather driven transports of assumed oil spills. Different shadings are used for grouping related variables.

The drift model underlying our BN assumes that the water pollutant behaves like a passive tracer. This is obviously not realistic. The chance node 'Drift Time' (*DT*), however, implemented as a child of *S* and *T*, provides a probability distribution of particle travel times. This information allows the user to re-weight passive tracer advection according to some specified half-life time τ. Assuming exponential decay processes, more realistic estimates of the pollutant's arrival in various target regions (*T**) can be achieved. Note that specification of τ is outside the scope of the underlying tracer simulations. Instead the corresponding node establishes an interface for linking the pre-calculated transport climatology to external expert knowledge in the context of a more specific practical application.

Our BN's structure should of course reflect the causal structure inherent in the generation of the underlying drift simulations. Motivated by the study of Chrastansky and Callies (2009a), we introduced time coefficients of CCA patterns for SLP, obtained from correlating SLP fields with simulated particle advection rates (cf. Section 5.2.2), as the primary representatives of atmospheric forcing. The nodes *SLP 1* and *SLP 2* correspond with the time coefficients of the two SLP anomaly patterns shown in Figure 5.2.

Additional nodes 'Wind Speed' (*WS*) and 'Wind Direction' (*WD*) corresponding with local conditions at Helgoland are introduced. According to the BN in Figure 5.5, however, acquiring evidence on local winds does not modify estimates of particle advection or corresponding travel times (conditional independence of *T* and *WS*, for instance) given that evidence for both *SLP 1* and *SLP 2* already exists. The situation is different when evidence on CCA time coefficients is missing. Another consequence of the selected BN structure is that *WS* and *WD* are conditionally independent given *SLP 1* and *SLP 2*. This assumption appears justified if the CCA time coefficients are proper surrogates for large scale wind fields and local wind speed components do not much depend on wind direction.

Nodes in the BN's right hand side subdomain (white nodes in Figure 5.5) enable a user to condition drift simulations on states of atmospheric forcing. In this way both particle advection and corresponding drift times can be studied as functions of prevailing wind conditions, for instance. Alternatively, a user might be interested in seasonal variations of coastal pollution (node *SN*). In keeping with causal relationships, information on the choice of a specific season is transmitted through changing probability distributions of CCA time coefficients for SLP.

5.3.2 Definition of states and elicitation of model parameters

Each node in Figure 5.5 needs the definition of discrete states the corresponding variable may attain. For source node *S* these states are labeled according to the 9 source regions (S1 − S9) tracer particles may be released from (cf. Figure 5.1). Probability distributions in *O1* and *O2* refer to the same set of states. While the uniform distribution in *O1* is merely a matter of definition, the distribution *O2* was elicited based on German aerial surveillance data (Carpenter, 2007; von Viebahn, 2001) from the years 2000 − 2005.

States of target nodes *T* and *T** refer to the five target regions (T1 to T5) shown in Figure 5.1. Additional states 'none' are introduced to deal with the situation that oil pollution does not affect parts of the German coast. Travel time *DT* is resolved with 6 intervals of non-uniform lengths (0-5 days, 5-10 days, 10-15 days, 15-20 days, 20-30 days and 30-60 days). An additional state 'infinite' covers the case that no oil hits the German coast within the maximum simulation time of 60 days. This state corresponds with the state 'none' in variable *T*. Possible values of half-life τ were chosen as 5, 10, 20, 30 and 50 days.

States of the nodes *SLP 1* and *SLP 2* were defined in terms of multiples of the standard deviation of the corresponding time series (note that CCA time coefficients are related to SLP anomalies and therefore have zero means): State 'o' comprises values within +/- 0.5, state '+' ('-') values between 0.5 and 1.5 (-0.5 and -1.5), and state '++' ('--') values that exceed 1.5 (-1.5) standard deviations. Wind direction *WD* is resolved by the 8 states SW, W, NW, N, NE, E, SE and S. States 0-9 of wind speed *WS* follow the Beaufort (bft) classification (World Meteorological Organization, 2008). The season node *SN* differentiates between four seasons 'spring' (Mar-May), 'summer' (Jun-Aug), 'fall' (Sep-Nov), and 'winter' (Dec-Feb).

For the chance nodes *T*, *DT*, *SLP 1*, *SLP 2*, *WS*, and *WD*, conditional probability tables (CPTs) were elicited from pre-calculated drift simulations and corresponding atmospheric forcing. Extensive data tables with many samples containing values for the node itself and each of the node's parent nodes can easily be extracted from the outputs of these long-term simulations. Each line of such a data table corresponds with the results of one particular simulation.

For the data table combining *WS* and *WD* with *SLP 1* and *SLP 2*, however, a slightly modified approach to parameter elicitation was used. The CCA time coefficients (nodes *SLP 1* and *SLP 2*) refer to three consecutive weekly mean SLP fields that cover the first three weeks of a given particle cloud's journey (cf. Figure 5.2). For the wind variables *WS* and *WD*, specification of corresponding characteristic values for longer periods is difficult due to problems with averaging wind directions. We therefore extended the data table by replicating each sample with replacement of the wind related values. The number of lines containing the same wind values was chosen according to the relative frequency of their occurrence within the three week period.

Parameter elicitation for the re-scaled target node *T** needs no recourse to the data base of numerical simulations. Instead a simple data table was generated based on an exponential decay formula.

For the three marginal nodes *SW*, *SN*, and τ we chose a non-informative (i.e. uniform) prior distribution.

5.4 Two example studies using the BN

Figure 5.6 shows the BN from Figure 5.5 together with probability distributions for all variables (except *O1* and *O2*). Probabilities of variables to be in certain states are specified in terms of percentages and additionally displayed by bar charts. Two initial assumptions were made. The first assumption is (option O1 of selector node *SW*) that oil pollutions are equally probable for each source region, ignoring information from aerial surveillance data. In addition, we assume that half-life of the hypothetical pollutant is 20 days (selected state of node τ).

Due to the above assumptions, all distributions shown in Figure 5.6 (except for *T**) are marginal distributions of the underlying numerical simulation results. According to node *T*, about 46% of passive tracer particles from any source region does not reach the coast within the simulation period of 60 days. Drift times of the remaining 54% of passive tracer particles vary substantially. In most cases the assumed half-life $\tau = 20$ days is exceeded. Hence, when the passive tracer assumption is relaxed, even about 81% (instead of 46%) of the pollutant is estimated to remain undetected (node *T**). All percentages mentioned are averages over the whole spectrum of possible wind conditions represented by the nodes *SLP 1*, *SLP 2*, *WS*, and *WD*. Also season *SN* remains unspecified.

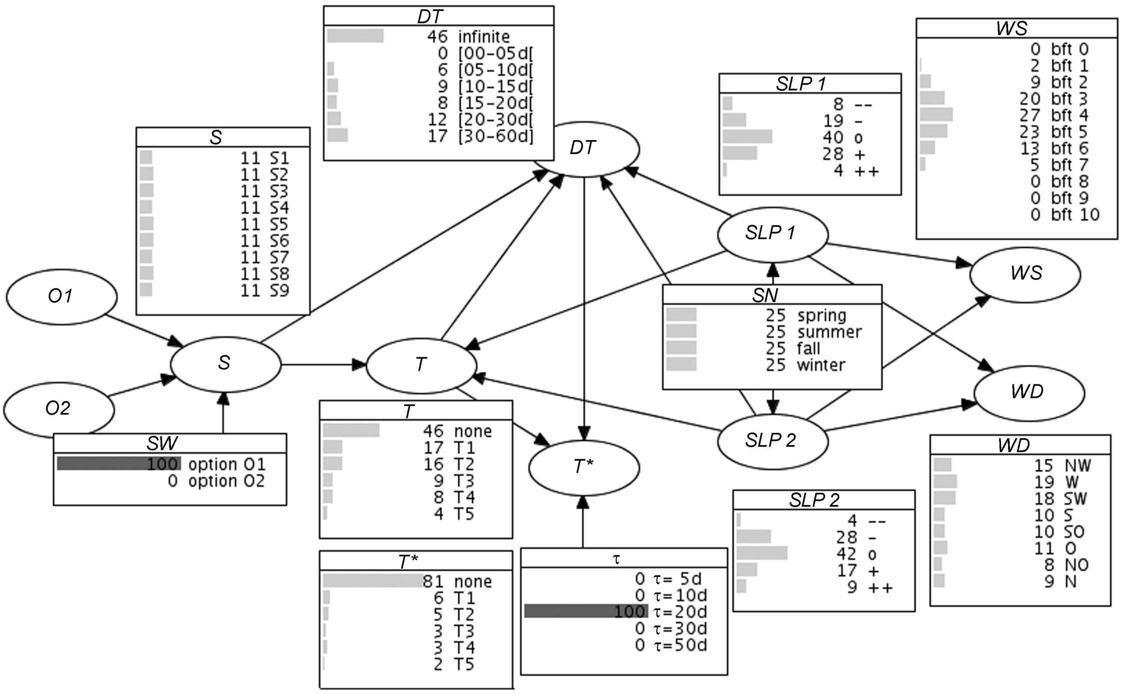

Figure 5.6: The oil drift BN with evidence for the pollutant's half-life τ=20 days. Each source region is assumed to be equally probable as the origin of an oil spill (option O1 in switch *SW*).

5.4.1 Effects of pollution from a specific source region

Assume now that we are interested in a comparison of the consequences of oil spills within different source regions. Figure 5.7 shows probability tables for those nodes from the BN that are affected by setting node *S* to state ‘S4’. Instantiation of node *S* suspends the choice (via *SW*) of any prior spatial distribution of pollutant discharge. The fraction of passive tracer particles hitting the coast clearly increases (only 24% of the particles remain in state *T* = none). Coastal stretches for which pollution increases when conditioning on source S4 are target regions T2-T4, whereas regions T1 and T5 are found to be less threatened by source S4 than on average by all source regions. The distribution of particle travel times is shifted towards substantially smaller values as compared with the unconditional distribution. As a consequence, differences between distributions *T* and *T** are expressed as a percentage shrink.

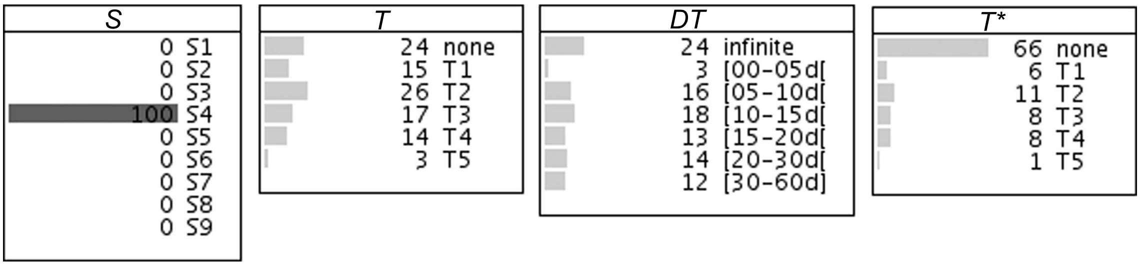

Figure 5.7: Probability tables of the Source (*S*), Target (*T*), Drift Time (*DT*), and Target* (*T**) after introducing evidence *S*=S4 and τ=20d. Only distributions that differ from those in Figure 5.6 are shown.

The actual threat of the coast depends on how fast a pollutant is degraded. This degradation rate differs for different oil types and is therefore an uncertain parameter within a risk analysis. The BN in Figure 5.6, however, allows for a quick overview of the effects different half-lives τ would have. State ‘none’ in node *T** (i.e. no pollution) has a probability of 92% for τ=5d and 47% for τ=50d (not shown). None of the other variables is affected by the choice of τ.

By now we did not restrain the season in which an assumed oil spill occurs. The probability distributions for coastal pollution arising from hypothetical releases in source S4 in different seasons are shown in Figure 5.8. The overall threat of coastal pollution along the German North Sea coast is most dangerous in summer (about 88%). Target regions T2, T3 and T4 are most exposed to pollution from source S4 in both spring and summer. In winter the overall probability of coastal pollution from a release in source region S4 decreases to only 68%. Target region T1, however, experiences an opposite seasonal trend with a maximum risk in winter (~21%) and a minimum in summer (~9%). Differences arise from different orientations of coastal stretches relative to prevailing wind directions. In fall and in winter westerly and south-westerly wind component preponderate. In spring and summer, on the other hand, southerly winds become less and northerly winds more frequent.

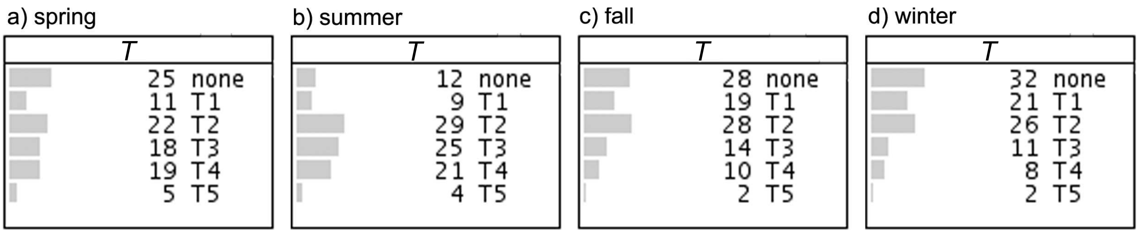

Figure 5.8: Changing probability distributions of pollution in coastal target regions T1-T5, assuming that a hypothetical oil spill in source region S4 takes place in different seasons (panels a-d).

This dependence is well illustrated by conditioning target variable *T* on pressure pattern *SLP 1* (instantiating *SLP 2* with ‘o’). According to Figure 5.9, the instantiation of *SLP 1* with ‘+’ (panels a) makes summer the most probable season (55%). Hence, similar to Figure 5.8b, the threat much focuses on target regions T2, T3 and T4. The selected SLP pattern corresponds with sometimes strong north-westerly winds that shield target region T1 from pollution from the more southern source region S4. The overall probability that under the assumed weather conditions oil from region S4 reaches any part of the German North Sea coast is, however, 98% assuming passive tracers (node *T*) and 47% or 10% assuming a half-life of 20 or 5 days, respectively (node *T**, not shown).

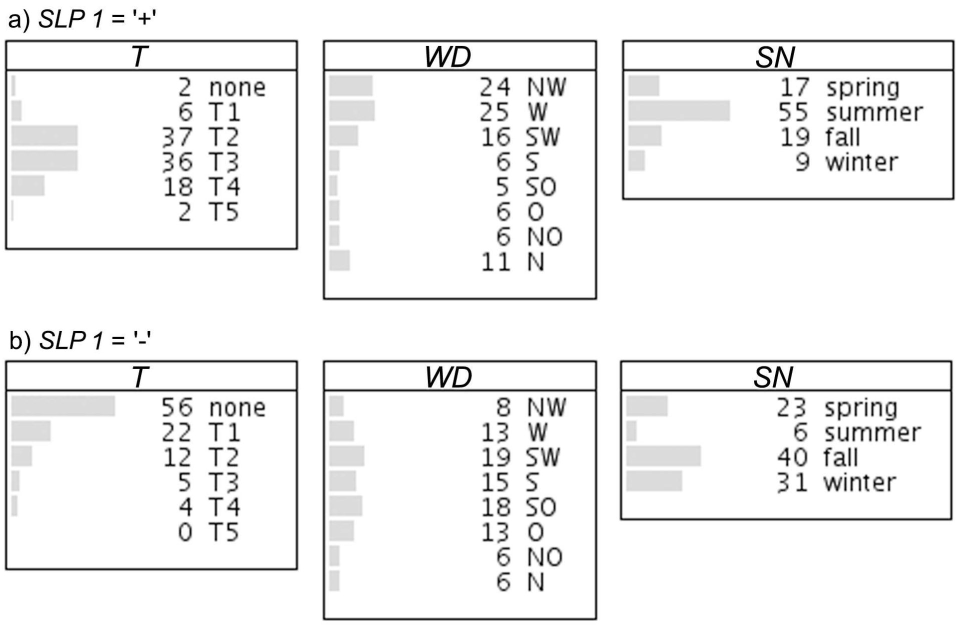

Figure 5.9: Changing probability distributions for nodes *T*, *WD*, and *SN* when node *SLP 1* is conditioned on state ‘+’ (upper panels) or ‘-’ (lower panels). A hypothetical pollution is assumed to take place in source region S4. *SLP 2* is instantiated with ‘o’.

Instantiating instead node *SLP 1* with state ‘-’ (Figure 5.9b) makes summer season very unlikely (only about 6%). Most probable seasons are now winter and fall. Southerly winds produce the highest risks for target T1 and (to a minor extent) also for target T2. Risks for more southern target regions are low. Again this finding is consistent with differences between the seasonal plots of Figure 5.8. The overall threat for the German coast is much smaller than in the former case (44% assuming passive tracers; 15% assuming a substance half-life of 20 days (not shown)). Travel times are clearly longer than for *SLP 1* being in state “+” (not shown).

5.4.2 Threat of pollution to a specific coastal area

The numerical simulations underlying our BN are made up of trajectories integrated forward in time. For addressing the question of to which extent different source regions of a hypothetical pollutant pose a threat to particular coastal stretches, backward trajectory simulations would be an option. In a probabilistic framework, however, the Bayesian inversion formula allows for deriving the same type of information also from ensembles of forward simulations.

The probability of particle advection towards some given target region depends on both the region, where the pollution takes place, and prevailing wind conditions. Figure 5.10 shows how the selection *T** = T3 produces a non-uniform probability distribution of possible source regions, mainly reflecting their different distances. Instantiation of *T** instead of *T* brings the assumed substance half-life of 20 days into play. In response to this choice the distribution of drift times shifts towards much smaller values than those that would hold if evidence was provided for passive tracer particles instead (i.e. *T* = T3 instead of *T** = T3; not shown). For similar reasons the probability of the pollution arising from the nearby source region S4 is enhanced by taking half-life into account (31% for *T** = 3 but only 22% for *T* = 3). Choosing a substance half-life of only 5 days raises the probability of pollution stemming from source region S4 to even 47% (not shown). If in addition the spatial spill distribution estimated from aerial observations is taken into account (‘option O2’ in node *SW*), region S4 becomes the by far most probable source region (probability 68%). Individual probabilities of all other source regions are then below 15%. In addition to its effects on the probabilities of source regions, instantiation of *T* or *T** also replaces the marginal distributions of all meteorological variables by modified conditional distributions. According to Figure 5.10, the probability of *SLP 1* being in state ‘+’, for instance, is 53% (unconditional value: 28%).

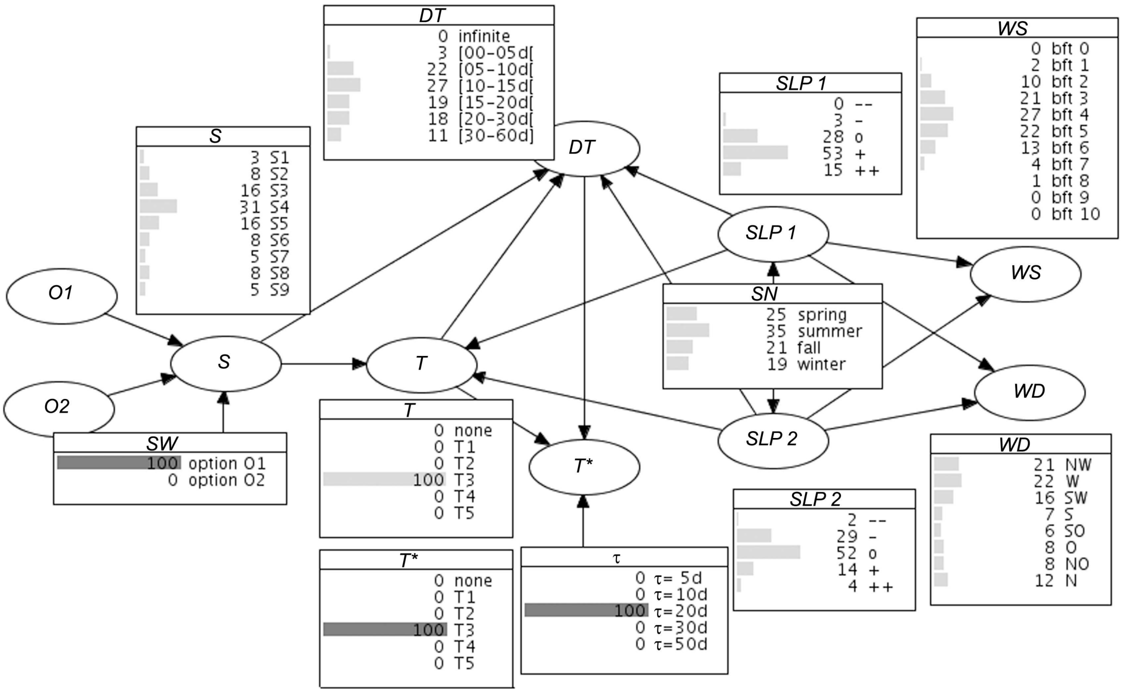

Figure 5.10: The oil drift BN with evidence for coastal pollution in target region T3 and a pollutant's half-life τ=20d. Prior probabilities for pollution being discharged in different source regions are assumed to be identical (option O1 in switch *SW*).

Another important aspect is that specification of target regions makes source regions and atmospheric conditions conditionally dependent. Given evidence on pollution in any target region, wind conditions become informative about the distribution of possible source regions and vice versa. Assume that we are interested in exploring possible impacts of the distant source region S1 on target region T3. Figure 5.11 shows a selection of panels from Figure 5.10 that substantially change when setting *S* to state S1. The two lines of panels in the Figure 5.11 differ with regard to the choice of τ (cf. last column).

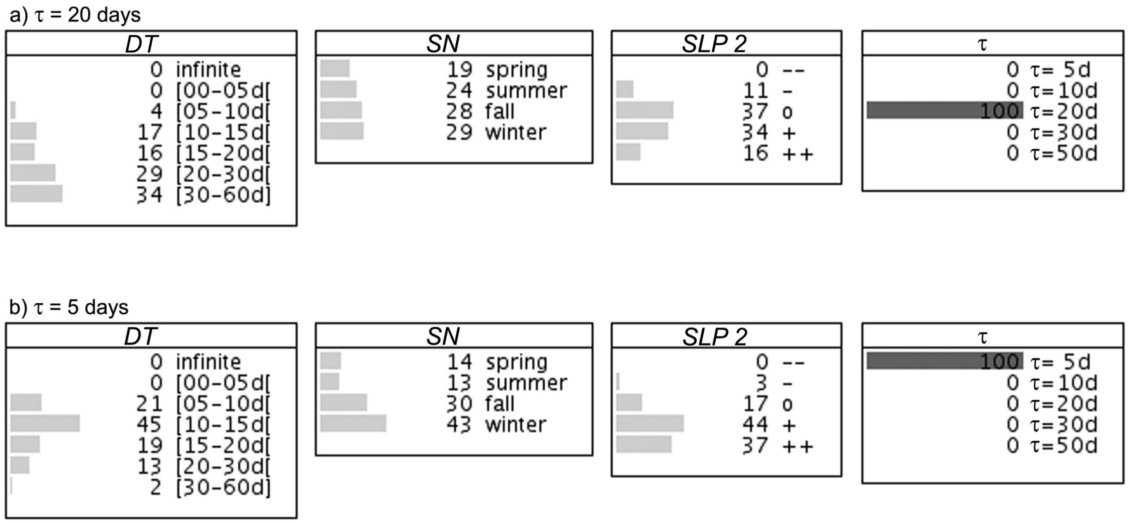

Figure 5.11: Probability tables for the nodes Drift Time (*DT*), Season (*SN*), CCA time coefficients corresponding to the second Sea Level Pressure Pattern (*SLP 2*), when the pollutants half-life τ is a) 20 days and b) 5 days. Additional evidence is given on Source *S*=S1 and pollution being in target region *T*=T3.

For τ= 20d, the distribution of drift times shifts to values higher than for unspecified source regions (cf. Figure 5.10), reflecting a relatively long distance to be covered between source A and target T3. The corresponding drift processes need atmospheric forcing associated with state ‘o’ or ‘+’ of node *SLP 2*. When a smaller substance half-life of only 5 days is presumed, drift times are enforced to shrink again, probabilities of states ‘+’ and even ‘++’ of node *SLP 2* further increase. The preferred season is now clearly winter (probability 43%), in contrast with summer in Figure 5.10.

5.5 Discussion

The BN we discussed represents the essentials of numerical Lagrangian drift simulations. The structure of the underlying mechanistic model made it simple to define the BN’s structure in line with causal reasoning. Parameter elicitation, the second step of model construction, could be based on a large ensemble of numerical simulations covering the full spectrum of realistic weather conditions that occurred during a time span of several decades.

The probabilistic representation in a BN allows for conditioning variables on either weather conditions or the resulting simulated coastal pollution, for instance. In the latter case the Bayesian inversion formula is the basis for information transfer in directions opposite to causal dependences. Different software packages (e.g. Korb & Nicholson, 2003) allow for the propagation of any combination of evidence throughout the whole network.

Our numerical simulations were confined to physical components (advective transports). The corresponding basic BN was then complemented, however, by nodes that represent parameters being more uncertain. We chose substance half-life τ, which is not treated in the model, as an example. Another example we explored (not shown) was to specify a wind dependent probability for illegal oil dumping, taking into account that contaminators supposedly try to remain undetected. It turned out, however, that conditioning on wind speed at the time of discharge did not substantially change the climatology of subsequent drifts and resulting coastal pollution. These two examples illustrate how sensitivities regarding the values of uncertain parameters may be estimated from a BN without the need to repeat time consuming numerical simulations.

There are many different ways our prototypical network could be modified or extended for other applications. Weathering processes represented by the half-life τ might be modeled in more detail as function of prevailing atmospheric conditions, for instance. For the hydrodynamic simulations, we assumed an extra drift component of 1.8% of the 10m wind velocity to be superimposed to movements induced by currents. In a more general BN, this specific assumption might be relaxed. Instead, an extra node describing wind drift as an uncertain parameter might be established as an additional parent node of *T* and *DT*. Re-calibration of conditional probability tables for the latter two nodes would need, however, extended numerical ensemble simulations.

The season node *SN* in the network provides an important interface for the inclusion of biologically oriented aspects. Vulnerability of a bird species depends on its habitat and on its seasonal molding and breeding behavior. One may ask to which degree, under which circumstances, and from which primary sources of pollution a given bird species is most endangered. Chrastansky et al. (2009) showed that the interpretation of beached bird survey programs benefits from detailed numerical drift simulations.

Another type of observation to be combined with the results of numerical modeling is aerial surveillance data. In Section 5.4.2 prior probabilities for oil discharge were assumed to be the same in each source region (cf. Figure 5.6). Accordingly, the posterior distribution for *S* (Figure 5.10) given pollution in target region T3 should be read as the sensitivity of region T3 with regard to hypothetical pollutions in different source regions. A more realistic estimate of the posterior probability that a given pollution stems from a certain source region is obtained when data from aerial surveillances are introduced as prior probability distributions (i.e. option O2 in switch *SW*).

5.6 Conclusions

Long-term simulations with process-based numerical models have become a state-of-the-art tool for the assessment of changing natural environments. In climate research, complex models are used for both the reconstruction of past climate variability and the construction of possible future scenarios. Model-based reconstructions providing kind of laboratory for risk-assessment studies have also been used as a surrogate for natural conditions (Weisse et al., 2009; cf. Appendix A).

Traditionally, the essentials of long-term simulations and corresponding scientific analyses are made available in the form of written papers. Such static presentations naturally focus on a perspective chosen by the author. A modified view at the simulated data will usually need direct access to the full data base. For many studies, e.g. studies with a wider interdisciplinary scope, this will often be beyond the means. But even during the design of more in-depth analyses it is often desirable to know about relevant features and relations represented in comprehensive simulations. Our study has shown how the technique of Bayesian networks might be employed to meet such demands.

In a first step, a BN will always reflect its designer's scientific interests, focusing on specific variables or aspects of co-variability in a data set. Our example illustrated, however, the modular structure a BN representing numerical simulations usually will have. Elicitation of the conditional probability table for any given node remains local in the sense that data tables just need to contain information of those variables that directly influence the node of interest. As a result, an existing BN can often be extended without recalibration of most of its already existing components.

We introduced a half-life τ of the drifting substance to give a practical example of how generic passive tracer simulations under realistic weather conditions can be linked with a specific substance's properties. This very efficient approach avoids repeated computationally demanding numerical simulations and might be useful particularly in the context of contingency planning with regard to substances, whose properties are defined vaguely. Another aspect we tried to illustrate is the combination of numerical simulations with monitoring data. A BN, however, might also encompass more qualitative expert knowledge.

A crucial problem to be solved for a successful representation of detailed simulations in a BN is the reduction of dimensionality. In the present study we utilized the results of canonical correlation analysis adapted from a previous study for a simplified description of weather conditions in terms of weekly mean sea level pressure patterns. One might also use different techniques, employ different variables, and refer to different scales in space or time. The BN approach we proposed for the description of output from large numerical simulation models, however, is unable to substitute such use of common multivariate statistical tools.

We expect a BN fitted to an existing set of long-term numerical simulations to be subject to permanent development. Extensions and improvements of the BN may arise from new scientific analyses and subsequent applications of the data. On the other hand, an evermore detailed BN might inspire the conception of new investigations or help to promote the data base. The BN's intuitive graphical presentation helps to make a data base accessible even for non-scientific users. Furthermore, the data representation based on the BN technology is fast and flexible enough to be run in the background of web applications. BN manipulations based on libraries written in Fortran, C or Java can be blended with common internet programming languages. For a more intuitive display of calculated probabilities and regions they refer to, the BN output might be combined with GIS items such as geographical maps.

Acknowledgements

We would like to express gratitude to Dirk Reichenbach and Uda Tuente from the Central Command for Maritime Emergencies for providing the German aerial surveillance data, useful discussions and their interest in our study.

6 Résumé and closing remarks

In the present thesis, weather-related variability of ship-related chronic oil pollution along the German North Sea coast is described by means of multi-decadal hydrodynamic ensemble drift simulations.

From random locations along the main shipping routes in the southern North Sea, the drift of hypothetical oil spills is traced taking a broad spectrum of weather and sea state conditions during the years 1958 − 2003 into account. The resulting drift statistic describes advection processes towards the German North Sea coast in accordance of weather situations and the frequency of their occurrence. In post-processing, weathering processes are roughly considered using a pollutants half-life of 21 days.

The simulation results provide basis for a statistical investigation of the exposures to ship-related chronic oil pollution (cf. Chrastansky & Callies, 2009a). As expected, the location of the oil discharge is principally decisive for the coastal region that is threatened. Generally, oil spills that occur in the vicinity of the coast are more dangerous than from extent regions. The situation becomes different when the regional intensity of chronic oil pollution is additionally considered. Based on the assumption that its strength is proportional to the ship traffic density, the drift simulations suggest that especially in winter coastal oil pollution caused by spills from distant areas close to the Strait of Dover becomes increasingly probable.

On average, the northern stretches of the German North Sea coast (Schleswig-Holstein) are most exposed to ship-related chronic oil pollution. Seasonal differences in the exposures indicate that the direction and strength of prevailing winds are influential. For instance, in winter the southern part of the German North Sea coast (Lower Saxony) is approximately by a quarter less affected by oil spills from the northern half of the German Bight than in summer. Using a multivariate statistical method (Canonical Correlation Analysis (CCA)) it was analysed to which extent the spatially and temporarily varying oil advection rates can be explained by changing weather conditions. A significant coupling could be established just for the winter months. The analysis suggests that the wind influence is a more dominant feature regarding advection towards Schleswig-Holstein. Wind-induced inter-annual and trend-like variations in the simulated advection rates within the analysed 46-year period are not identical for the different coastal sections of Germany. For the most northern region, for example, the simulated advection is enhanced in the second half of the investigated period. A comparable increasing trend becomes not visible for the other regions. A connection to the North Atlantic Oscillation (NAO) could be established, however, just for Schleswig-Holstein.

Recordings of oil-contaminated dead bird findings along the German North Sea coast are often used for trend-assessment in the general level of chronic oil pollution in North Sea waters. For this study, reliable statistics covering the winter months of the years 1992 − 2003 are available. The comparison of the modelled annual oil advection rates to corresponding beached bird statistics indicates that neglecting the wind impact could lead to misinterpretations in the general level of oil pollution. There is, however, a difference when analyzing the trends in oil pollution levels on basis of monitoring data from bird species that live close to the coast (i.e. the Common Scoter (*Melanitta nigra*)) and such birds that are predominantly in offshore regions (i.e. the Guillemot (*Uria aalge*)) (cf. Chrastansky et al., 2009). While the annual numbers of oil-contaminated Common Scoters and Guillemot reflect the inter-annual variations in the simulated advection towards the German North Sea coast, the oil-rate (percentage of birds that are oiled) behaves dissimilarly. The inter-annual variability of the Common Scoter's oil-rate is in agreement with the variations within the simulated advection rates. Hence, the decreasing trend visible in the oil-rate of this particular species can be most widely attributed to varying wind-conditions. The oil-rate of the Guillemot, on the other hand, seems to be a true measure for chronic oil pollution in adjacent waters without a notably weather influence. The normalization of the beached bird survey data based on a linear relationship between the monitored and the modelled data is suggested to avoid misinterpretations due to wind impacts. Moreover, the study suggests that the wind impact is a more severe problem when interpreting monitoring data from the northern regions (cf. Chrastansky & Callies, 2009a). This agrees with the findings from the CCA. Reasons for a reduced wind influence regarding Lower Saxony are presumably the west-east orientation of the southern coast as well as the proximity to the busy shipping lanes.

The model-based long-term reconstruction of potential chronic oil pollution along the German North Sea coast provides a useful basis for contingency analyses or the interpretation of monitoring data, for instance. As the resource-intensive database is inappropriate for its integration in many practical studies, a probabilistic data representation using a Bayesian Network is proposed (cf. Chrastansky & Callies, 2009b). The Bayesian Network established here focuses on specific variables appropriate for describing chronic oil pollution in the North Sea and resulting weather-dependent advections towards the German North Sea coast. The presented Bayesian network illustrates how such numerical simulations can be linked comfortably and effectively with external data and assumptions. For example, as the representation of variable weather conditions during an oil spill journey is difficult, the results of CCA are adapted for describing weather situations. By this means, also an reduction of the network's complexity is achieved. In addition, the optional determination of probabilities regarding illegally spilled oil in various regions is included, which provides the opportunity for the consideration of aerial surveillance data. Another example for dealing with uncertainties is how the oil's properties are hold adjustable by offering a set of possible half-life values. Although the exhaustive drift simulations are presented in the Bayesian Network, the computationally demanding access to the database is usually not necessary when using this method - unless single trajectories are of interest. It also allows problem-specific modifications, whereas readjustment is only required for variables with direct influence. The presented Bayesian Network allows the access to the oil spill simulations even for non-scientific users.

Chronic oil pollution is not only a problem for North Sea waters, oil discharges from shipping has been observed along any traffic routes of the world's oceans (International Maritime Organization, 2006). In many other countries, monitoring programs similar to the German beached bird surveys are conducted (i.e. Newfoundland (Wilhelm et al., 2009), Southern British Columbia (O'Hara et al, 2009), Denmark (Skov et al., 1996)). For proper trend assessments of the general level of oil pollution, however, the examination of probable wind impacts reflected in observation data collected also in other regions is necessary.

Similar to the wind influence on the drift behaviour of oil, the advection of other substances (i.e. chemicals) and objects (i.e. garbage or drift wood) towards the coast is affected by winds. Referring to the presented approach, numerical modelling could provide a suitable tool for the quantification of the wind influence visible in diverse monitoring data and their subsequent data normalization. The physical (hydrodynamic) formulation of the transports easily allows for the incorporation of substance-specific characteristics in post-processing. In this study, for instance, the oil-characteristics are achieved by limiting the oil's life-time using an appropriate half-life. One has to make sure, however, that the selected wind-drift factor in the utilized hydrodynamic transport model is suitable for the item of interest. Nevertheless, a problem poses the definition of source regions. In case of chronic oil pollution, it was known that the majority of oil is spilled along the main shipping routes in the North Sea area. Hence, the source regions were defined to contain them. Regarding other substances or objects, this may be not so clear. Defining a grid covering the marine region of interest as source regions may provide a solution.

The probabilistic data representation using a Bayesian Network yields a method to investigating different substances or objects at the same time. If the reconstructions of these substances/objects differ in the superimposed wind drift factor, for instance, this can be achieved by introducing i.e. appropriate selector nodes.

Appendix

A Regional meteorological-marine reanalyses and climate change projections: Results for Northern Europe and potentials for coastal and offshore applications

Ralf Weisse, Hans von Storch, Ulrich Callies, Alena Chrastansky, Frauke Feser, Iris Grabemann, Heinz Günther, Andreas Pluess, Thomas Stoye, Jan Tellkamp, Jörg Winterfeldt & Katja Woth

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Abstract

A compilation of coastal weather analyses and climate change scenarios for the future for northern Europe from various sources is presented. They contain no direct measurements but results from numerical models that have been driven either by observed data in order to achieve the best possible representation of observed past conditions or by climate change scenarios for the near future. A comparison with the limited number of observational data points to the good quality of the model data in terms of long-term statistics, such as multiyear return values of wind speed and wave heights. These model data provide a unique combination of consistent atmospheric,

oceanic, sea state, and other parameters at high spatial and temporal detail, even for places and variables for which no measurements have been made. In addition, coastal scenarios for the near future complement the numerical analyses of past conditions in a consistent way. The backbones of the data are regional wind, wave, and storm surge hindcasts and scenarios mainly for the North Sea. We briefly discuss the methodology to derive these data, their quality, and limitations in comparison with observations. Long-term changes in the wind, wave, and storm surge climate are discussed, and possible future changes are assessed. A variety of coastal and offshore applications taking advantage of the data is presented. Examples comprise applications in ship design, oil risk modeling and assessment, or the construction and operation of offshore wind farms.

A.1 Introduction

Coastal and offshore applications require appropriate planning and design. For most of them, statistics of extreme wind, waves, and storm surges are of central importance. To obtain such statistics long and homogeneous time series are needed.

Usually such time series are hardly available. In most cases observations are either missing, cover too short periods, or are lacking homogeneity, that is, long-term changes in the time series are not entirely related to geophysical changes on the scale of interest, but are partly due to changes in instrumentation, measurement technique or other factors, such as changes in the surrounding of the measurement site.

There are in principle two approaches to address these issues (cf. WASA, 1998). One is the use of proxy data that are considered to be more homogeneous and are available for longer periods. An example is the use of pressure data to derive indices for changes in storm activity (e.g. Schmidt & von Storch, 1993). The other approach is to use numerical models driven by reanalysis data over sufficiently long periods and at high spatial and temporal resolution (e.g., Günther et al., 1998).

Both approaches have advantages and disadvantages. While proxy data can generally be used to reconstruct indices for rather long time periods (up to centuries), their spatial resolution remains limited and proxy data must be available at sufficient detail and quality. Hindcasts, on the other hand, are limited to periods for which global reanalyses are available (now about 60 yr) and by the quality of the involved models.

In the following we describe a set of coastal and offshore hindcasts based on global re-analysis data. The hindcasts are complemented with consistent climate change scenarios for the future. Data obtained from these exercises are integrated into a joint database referred to as "coastDat" (available online at www.coastdat.de). In the following the model setup and experimental design are briefly described. Subsequently, some representative examples are provided in which coastDat has been applied for the analysis of recent and potential future changes. Finally, applications are shown in which coastDat has been used to address coastal and offshore problems. An outlook for further applications is offered at the end of this paper.

A.2 Model Set-up and Simulations

We used the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR) global reanalysis (Kalnay et al., 1996) in combination with spectral nudging[1] (von Storch et al., 2000) to first drive a regional atmosphere model (Table A.1) for an area covering most of Europe and the adjacent seas. Initially the model was integrated for the years 1958-2002, with a spatial grid size of about 50 km x 50 km. The period has been extended later and currently covers the 60 yr of 1948-2007. Full model output is available for every hour within this 60-yr period.

From this atmospheric simulation, near-surface marine wind fields have been used subsequently to drive high-resolution wave and tide-surge models (Table A.1). While the wave model was run in a nested mode with a coarse grid (about 50 km x 50 km) covering most of the northeast Atlantic and a fine grid (about 5 km x 5 km) covering the North Sea south of 56°N, the tide-surge model was run on an unstructured grid with typical grid spacing of about 5 km in the open North Sea and largely increased values (up to 80 m) near the coast and in the estuaries. As for the atmospheric part, full model outputs have been stored every hour. In this way a high-resolution meteorological-marine (metocean) dataset for the North Sea covering the last six decades of years has been created. Figure A.1 shows an example of conditions obtained for 21 February 1993.

[1] Here a height-dependent nudging coefficient was applied to the large scale (>750 km) zonal and meridional wind speed components above about 850 hPa.

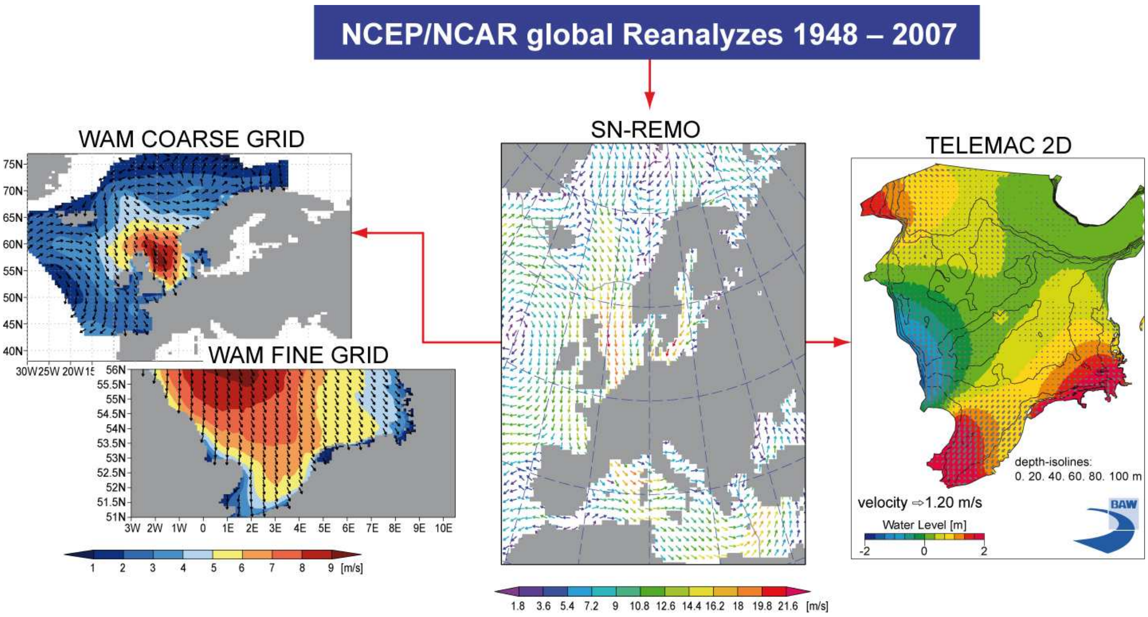

Figure A.1:. Layout of the consistent metocean hindcast 1948-2007 for the southern North Sea. From the (middle) regional atmosphere hindcast hourly wind fields were used to force a (right) tide-surge and a (left) wave model hindcast. The figure shows an example of consistent metocean conditions obtained from the hindcast for 1200 UTC 21 Feb 1993. (middle) Near-surface (10 m height) marine wind fields (ms−1), and corresponding wind direction obtained from the regional atmospheric reconstruction. (left) Corresponding significant wave height fields (m) and mean wave direction from the coarse and the fine grid wave model hindcast. (right) Tide-surge levels (m) from the corresponding tide-surge hindcast. After Weisse and Günther (2007).

An impression of the extent to which this approach is capable of providing a reasonable reconstruction of the observed wind and wave climate is given in Figure A.2. Shown are the observed and hindcast wind speed and direction as well as significant wave height, period and wave direction for a 3-month period at station K13 (53.22°N, 3.22°E). In principal, a good agreement can be inferred. For instance, the storm event on 21 February which caused observed significant wave heights of more than 6 m, is reasonably reproduced for all parameters. On the other hand, there are also events with larger discrepancies, such as the one around 1 March for which wave heights are considerably underestimated, which in this case was caused by too-low wind speeds in the atmospheric hindcast. When compared with scatterometer data, the hindcast wind fields in general show a reasonable agreement, and it was found that in coastal areas, especially in such with complex topography, hindcast wind fields are significantly improved compared to those from the driving reanalysis (J. Winterfeldt and R. Weisse, 2009, personnel communication).

Table A.1: List of regional models, model areas, and forcing data used in the coastDat reconstructions and climate scenario simulations referred to in this study. The listing is not exhaustive. For a full list we refer to the coastDat Web page (online at www.coastdat.de).

Model time span	**Name (model reference, setup Reference)**	**Model area**	**Grid distance**	**Forcing data**
Reconstructions				
Atmosphere 1948-2007	REMO (Jacob & Podzun, 1997) (Feser et al., 2001)	Western Europe / adjacent seas	0.5° x 0.5°	NCEP-NCAR reanalyses
Waves 1948-2007	**WAM** (WAMDI, 1988) (Weisse and Günther, 2007)	North East Atlantic, North Sea south of 56° N	Two nested grids 50 km x 50 km, 5 km x 5 km	Near-surface wind fields from REMO reconstruction
Tide surge 1958-2002	**TELEMAC2D** (Hervouet & Haren, 1996) (Weisse & Pluess, 2006)	North Sea	Unstructured grid 5km - 80 m (coastal areas)	Near-surface wind and pressure fields and from REMO reconstruction
Climate scenario simulations				
Waves 1961-1990, 2071-2100	**WAM** (WAMDI, 1988) (Grabemann & Weisse, 2008)	North East Atlantic, North Sea	Two nested grids 50 km x 50 km, 5 km x 5 km	Near-surface wind fields from RCAO (Räisänen et al. 2004)
Tide surge 1961-1990, 2071-2100	**TRIM** (Casulli & Stelling, 1998) (Woth et al., 2006)	North Sea	10 km x 10 km	Near-surface wind and pressure fields and from RCAO (Räisänen et al. 2004)

A comparison of observed and hindcast storm indices for Lund in Sweden is shown in Figure A.3. Generally, it can be inferred that the observed year-to-year variability is captured reasonably by the hindcast, although some bias may occur. For marine near-surface wind fields, Winterfeldt (2008) demonstrated that, compared to the driving reanalysis, an improvement is obtained mainly in coastal areas. More validation can be found for the atmospheric part in Feser (2006), for the tide-surge simulation in Weisse and Pluess (2006), and for the wave model hindcast in Weisse and Günther (2007).

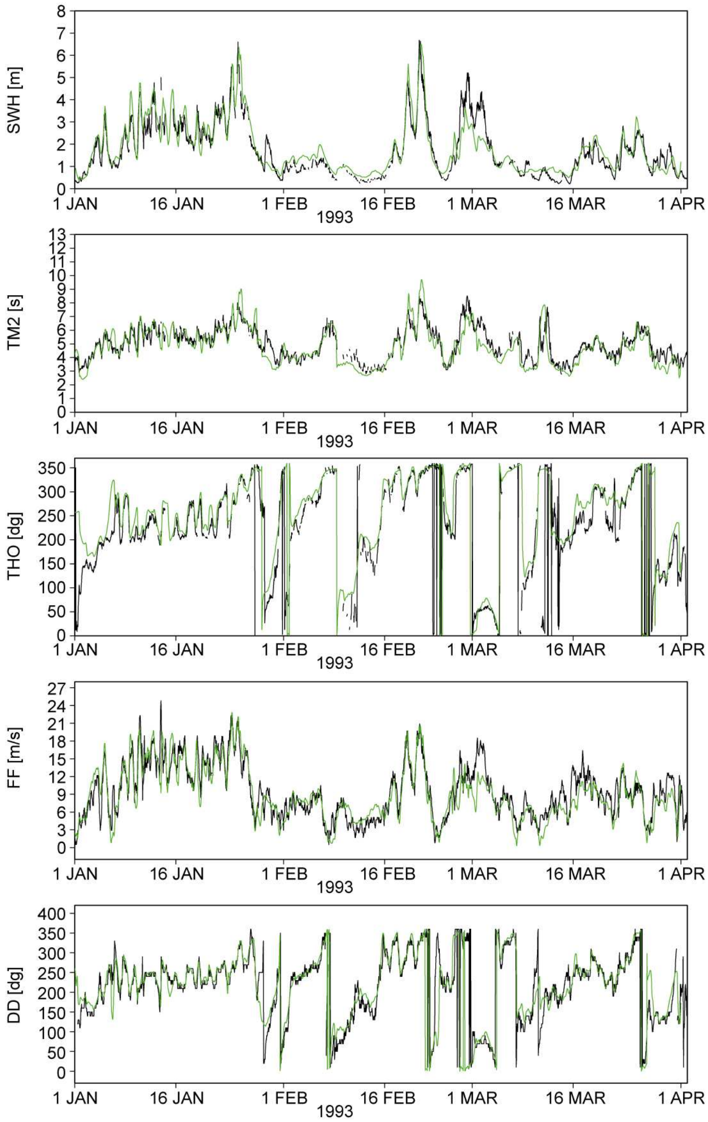

Figure A.2: (from top to bottom) Time series of significant wave height (SWH, m), Tm02 wave period (TM2, s), mean wave direction (THQ, ° coming from), wind speed (FF, ms−1) and wind direction (DD, ° coming from) at K13 for a 3-month period from 1 Jan 1993 to 31 Mar 1993. Observations (black), model results (green). After Weisse and Günther (2007).

Scenarios for future climate conditions have been obtained in a similar way. Here the global reanalysis has been replaced by an ensemble of different global climate change simulations. We have used four sets of simulations using A2 and B2 emission scenarios[2] for 2071-2100 with two different global climate models. These simulations were

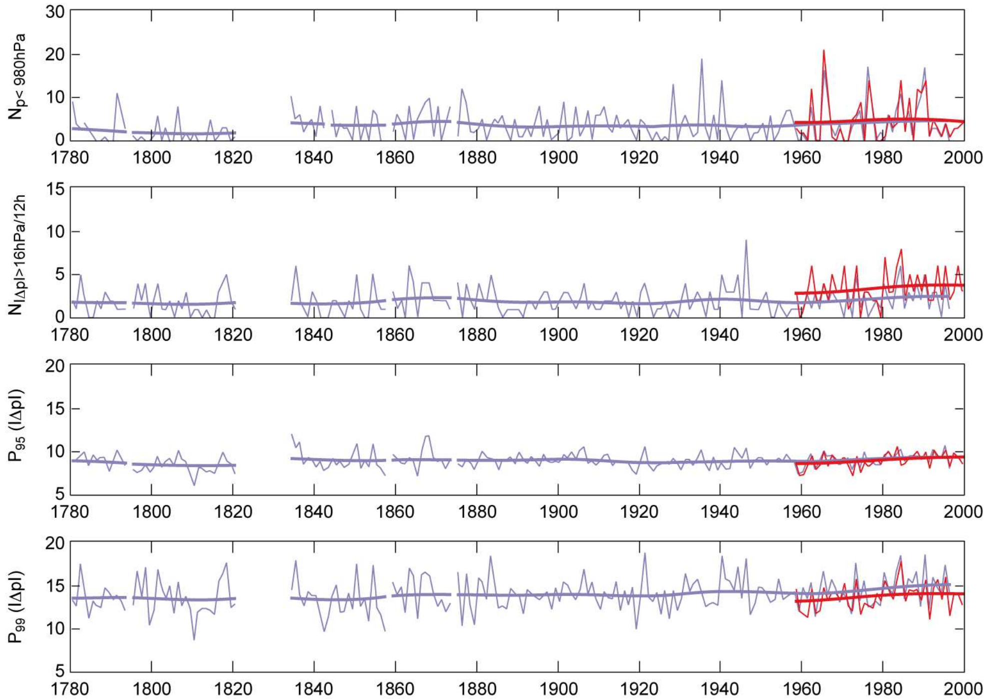

Figure A.3: Comparison between different storm indices for Lund, Sweden. (from top to bottom) Annual number of pressure readings of less than 980 hPa; annual number of strong pressure tendencies exceeding 16 hPa in 12 h; annual 95th and 99th percentiles of strong pressure tendencies. Obtained from observations after data from Bärring and von Storch (2004) (blue), obtained from coastDat (red).

downscaled approximately on a 50 km x 50 km grid by the Swedish Meteorological and Hydrological Institute in the framework of the Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects (PRUDENCE) project (Christensen et al., 2002) with the regional model Rossby Centre Regional Atmosphere-Ocean Model (RCAO) (Räisänen et al., 2004). From these simulations,

[2] Here A2 and B2 refer to scenarios according to the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES; Nakicenovic & Swart, 2000) representing a more pessimistic (A2) and a more optimistic (B2) view regarding the development of future greenhouse gas concentrations.

near-surface wind and pressure fields have subsequently been used to produce high-resolution scenarios of possible wave (Grabemann & Weisse, 2008) and storm surge conditions (Woth, 2005; Woth et al., 2006) for the North Sea (Table A.1). While the size of this ensemble is still somewhat limited because of computational constraints, it allows not only for an estimate of potential future metocean conditions, but also for a first rough guess about the underlying uncertainties.

A full listing of regions, parameters, and periods presently contained in coastDat may be obtained from the coastDat Web site (online at www.coastdat.de).

A.3 Recent and Possible Future Changes

The coastDat dataset was used by Weisse et al. (2005) to analyze long-term changes in storm activity over the North Sea and the northeastern North Atlantic. They found an increase in storm activity from about 1960. Storm activity peaked around 1990-95, after which a decrease was inferred. These results are consistent with those obtained from proxy data for the area. For instance, Alexandersson et al. (2000) and an update in Solomon et al. (2007) report a similar behavior based on the analysis of upper-geostrophic wind speed percentiles derived from station pressure data. Covering a longer period than the coastDat hindcasts in particular, theses studies showed that the 1960-90 increase in storm activity was not unusual, but that activity levels reached in the mid-1990s were comparable to that at the beginning of the twentieth century. Long-term changes in extreme storm surges and ocean wave heights based on the coastDat dataset were analyzed by Weisse and Pluess (2006) and by Weisse and Günther (2007). In particular, they found that the changes correspond to that of storm activity with increases in storm surges and wave heights between about 1960 and 1990, decreasing thereafter.

Changes of the North Sea storm surge climate in an ensemble of climate change simulations that form part of the coastDat data set were analyzed by Woth (2005) and Woth et al. (2006). Figure A.4 shows the changes in extreme storm surge levels expected toward the end of the century. Although regional details differ among the different models and scenarios, all point toward a moderate increase in severe storm surge levels along most of the Netherland, German and Danish coast lines. When compared to the natural variability estimated from the coastDat hindcast (Weisse &

Pluess, 2006) climate change-related increases in storm surge heights are found to be smaller for most of the Netherlands and Danish coast, while they are significantly larger along most of the German coastline (Woth et al., 2006).

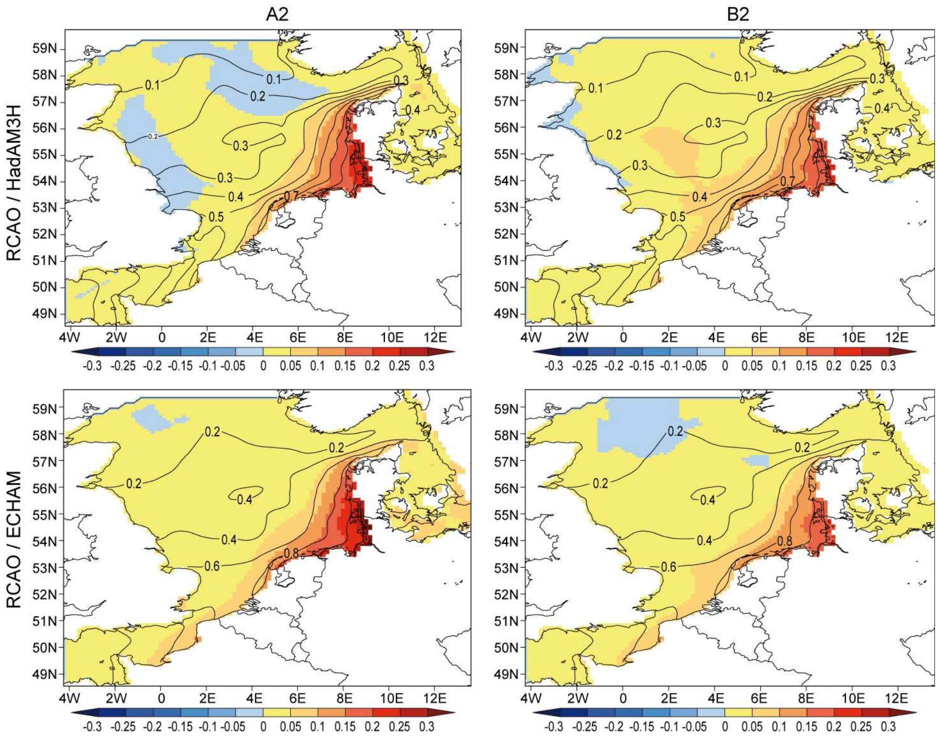

Figure A.4: Differences (colors) of annual 99.5 percentiles of storm surges between possible future (2071-2100) and present day (1960-90, contour lines) weather conditions obtained from tide-surge simulations using forcing from different climate models and emission scenarios. (left) Response for the A2-emission scenario. (right) Response for the B2-emission scenario. Storm surge response for near-surface wind speeds from the RCAO regional climate model driven by two different global climate models(top, HadAM3H; bottom, ECHAM5) after data and methods described in Woth (2005) and Woth et al. (2006).

Using near-surface marine wind speeds from the same set of scenario simulations, Grabemann and Weisse (2008) performed a similar ensemble of wave model simulations. Although the same wind forcing was used, changes appeared to be more diverse. In particular, regional patterns of changes in severe wave conditions differ and the magnitude of the changes strongly depends on the choice of the atmospheric model from which wind fields have been used.

A.4 Applications of coastDat

The coastDat dataset has been used for a variety of coastal and offshore applications. This comprises applications in ship design, oil risk modeling and assessment, and the construction and operation of offshore wind farms. In the following a few examples will be provided.

a) Optimization of ship operation profiles

Operation profiles of RoRo[3] vessels operating on fixed routes in the North Sea were simulated over decades of years with environmental conditions (wind, water depth, sea state) provided by the coastDat dataset (Friedhoff & Maksoud, 2005). Operation profiles (such as velocity or power) were varied under the constraint that the operations are time critical, that is, the individual trips need to be finished within a given time window, as long as permitted by safety requirements (weather conditions). Results for a 200-m RoRo vessel operating on a 332-nm round-trip between Zeebrügge, Belgium, and Immingham, United Kingdom, are provided in Friedhoff and Abdel-Maksoud (2005). For the 3,650 trips simulated within a 10-yr period they found fuel consumption to be increased by about 9% when compared to calm weather conditions and attributed the effect to the additional power required to face with the environmental conditions caused by wind, waves and water levels. They also showed that operation profiles may be optimized compared to conventional approaches such that operation costs are reduced and delay becomes minimal. They concluded that databases such as coastDat may provide valuable tools to optimize ship design with respect to the expected environmental conditions on the route.

b) Environmentally based optimization of ship design

Operability and safety on board, both constrained by severe weather conditions, are important factors for short sea shipping, especially for RoRo and RoPax[4] vessels. In ship design, sea-keeping simulations are used to account for these factors (Cramer et al., 2002). Generally, the motion of a ship in a sea state depends on several design parameters (e.g. hull form, location of the center of gravity, radii of gyration etc.) and it cannot generally be concluded that a specific sea state is more or less severe for the ship

[3] RoRo vessels are ships designed to carry wheeled cargo (cars, trucks, trailers, etc.). The term is used in contrast to vessels that use cranes to load and unload cargo.
[4] RoPax vessels describe RoRo ships that accommodate passengers, in addition.

than others. Instead, the reaction of the ship to a design modification has to be determined for each sea state by direct simulations (Cramer et al., 2002). In case the intended operating area and operation schedule are known already during the design phase, this information can be used to simulate the ship's motion in environmental conditions to be expected in the operation area during the lifetime of the vessel and to optimize the design with respect to the intended operational profile. Detailed wind and sea state information over decades of years as given by coastDat are an excellent source of data for this kind of application.

The coastDat dataset has been used by the Flensburger Schiffbau-Gesellschaft to assess and optimize a RoRo-ferry operating in the North Sea. Design parameters such as limiting accelerations and roll angles (Henning et al., 2006), slamming impact loads (Stoye et al., 2008) and others have been investigated. When exceedance probabilities of operational limits were found to be unacceptable, design modifications had to be performed. For example, when the occurrences of high roll angles need to be reduced, passive roll-stabilization tanks may be installed to modify the eigenfrequency of the roll motion, making the ship more seaworthy in a given sea state. An alternative is the installation of active fin stabilizers that compensate the roll moment caused by waves up to a certain degree, provided that the ship's speed is sufficient. From coastDat, statistics about weather down times, for example, for operation with or without fin stabilizers, may be derived. The latter provides decision support for the ship operator on whether the improvement of the sea-keeping behaviour is worth the investment into a roll stabilisation system.

c) Offshore wind farms

In the North Sea there are presently substantial efforts underway regarding the construction and implementation of offshore wind farms. Design and planning of construction and maintenance, etc., require long and homogeneous environmental data that are seldom available at the site. There is presently considerable interest in the use of statistics derived from coastDat for such purposes. Weisse and Günther (2007) have shown that there is a reasonable agreement of such statistics when estimated from observations and from coastDat data.

Because coastDat data are available for 60 yr at high spatial and temporal resolution, the data are often used to estimate the magnitude of rare events that may have considerable impacts on the site, such as the 50-yr return value for near-surface wind speed or significant wave height. Also, joint probability distributions, such as any combination of wind speed, wind direction, significant wave height, wave periods and wave direction, are frequently requested and needed during the design process. A unique feature of coastDat is the estimation of duration-related statistics, for instance, how long severe sea-state conditions may last on the site. Similarly, statistics of weather windows may be derived. For instance, the time window within which wave heights, on average, remain below a given threshold (e.g., 2 m) may be required to plan equipment and maintenance schemes, or to estimate whether it would be feasible, at a given probability, to arrange the site within a given time frame, for example, a season.

d) Coastal protection

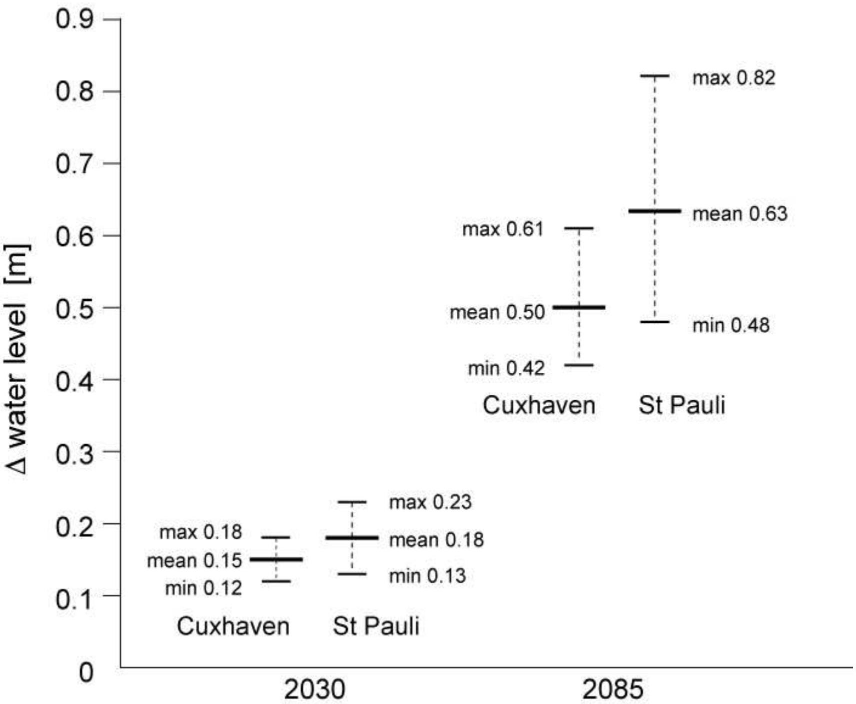

Figure A.5: Projections of climate change-related modifications in extreme high waters in Cuxhaven (North Sea) and Hamburg, St. Pauli (Elbe estuary) in 2030 and 2085 based on coastDat scenarios from different regional models and emissions scenarios. Because the results from the different scenarios do not differ significantly the mean value is indicated across all models and scenarios. The minimum and maximum range for all scenarios and models is shown in addition. A sea level rise of 9 cm by 2030 and of 33 cm by 2085 is included. After Grossmann et al. (2007).

On the basis of coastDat local scenarios for future high water levels for coastal tide gauges have been constructed (Grossmann et al., 2007). A statistical relationship was constructed between observed high water levels at the North Sea and at the tide gauge Hamburg (St. Pauli) located about 80 km upstream within the estuary of the Elbe. Subsequently, storm surge projections from coastDat were used to elaborate on potential future changes for Hamburg (Figure A.5). According to Grossmann et al. (2007) an increase of the annual maximum high water levels in Hamburg of about 20 ± 20 cm appears possible and plausible for the time horizon of 2030. In 2085, the mean scenario for St. Pauli amounts to an increase of 64 ± 50 cm. These calculations employ a mean sea level rise of 9 cm for 2030 and of 29 and 33 cm (accounting for different scenarios) for 2085, respectively.

e) Oil risk modeling

A toolbox [Program for the Evaluation of Lagrangian Ensemble Transport Simulations (PELETS-2d)] for Lagrangian drift modeling based on fields from coastDat has been developed. An oil chemistry model may also be included and wind drift may or may not be taken into account. The latter represents an essential forcing factor when oil spills or drifting materials are considered.

On the basis of coastDat, PELETS-2d has been applied to a number of problems including the assessment of fresh water signals at Helgoland, the comparison of station data with ship-based measurements, or the assessment of oil-related risks. An example is shown in Figure A.6. Here oil accidents along a major shipping route have been considered based on coastDat. In order to estimate travel time statistics, such oil accidents have been represented by passive tracer simulations initialized once every 28 h over about five decades of years. Subsequently, potential impacts on different target regions have been examined. Such target regions may be defined, for instance, by their potential sensitivity to the stranding oil. Figure A.6b shows an example of a travel time distribution that was obtained from such simulations. It can be inferred that, depending on weather conditions, eventually 65% of all particles reached the target region. The most frequent travel time was found to be about 2-3 days. In some cases, however, travel times could be as small as 12 h. The latter has considerable consequences for emergency concepts to be implemented.

The analysis could be further refined by assuming that the frequency of accidents but also the efficiency of oil fighting may actually depend on the current metocean conditions in each case. All information needed for such studies would again be available from coastDat.

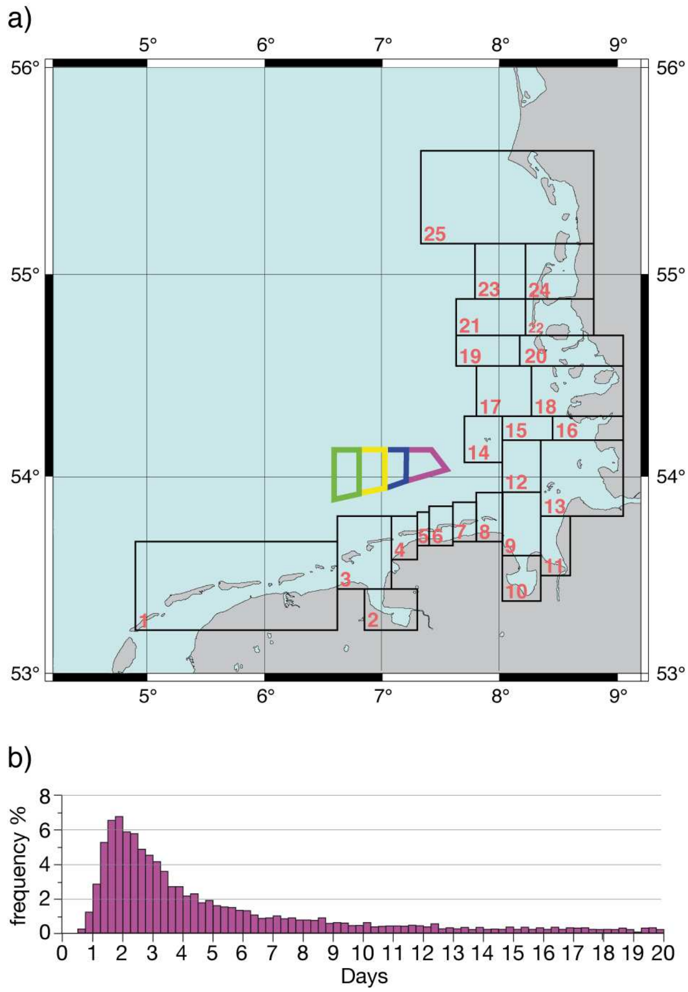

Figure A.6: (a) Section of the North Sea. Green, yellow, blue and magenta boxes denote areas in the vicinity of major shipping routes in which passive tracer simulations representing hypothetical oil accidents have been initiated. The black boxes labeled with red numbers indicate target regions in which the impact of the accidents has been investigated. (b) Frequency distribution of the travel time that passive tracer particles started within the magenta source region need to reach target region 14 (Helgoland). The analysis is based on 65% of the initial tracer particles that actually affect the target region within 13,615 simulations that were started within the period 1958-99. Weathering of spilled oil was disregarded in this study.

f) Assessment of chronic oil pollution

The coastDat dataset in combination with PELETS-2d has also been used for the interpretation of chronic oil pollution (Chrastansky et al. 2009). Chronic oil pollution predominantly results from illegal oil dumping and represents a major threat for the marine environment. It is, however, difficult to quantify, and often the number of oil-contaminated beached birds is used as an indirect indicator. It turns out that for trend assessments the latter may be misleading. Chrastansky et al. (2009) show an example of two common sea bird species where the variability observed within the number of corpses registered during beached bird surveys for the German coast primarily reflects the inter-annual variability of prevailing weather conditions (Figure A.7). In other words, variations within the number of beached birds may be at least partially a result of changes and variations in atmospheric wind conditions, and changes over several years are not necessarily a proof that chronic pollution has reduced as a result of the implemented measures. Chrastansky et al. (2009) therefore concluded that atmospheric variability needs to be accounted for in the interpretation of such data.

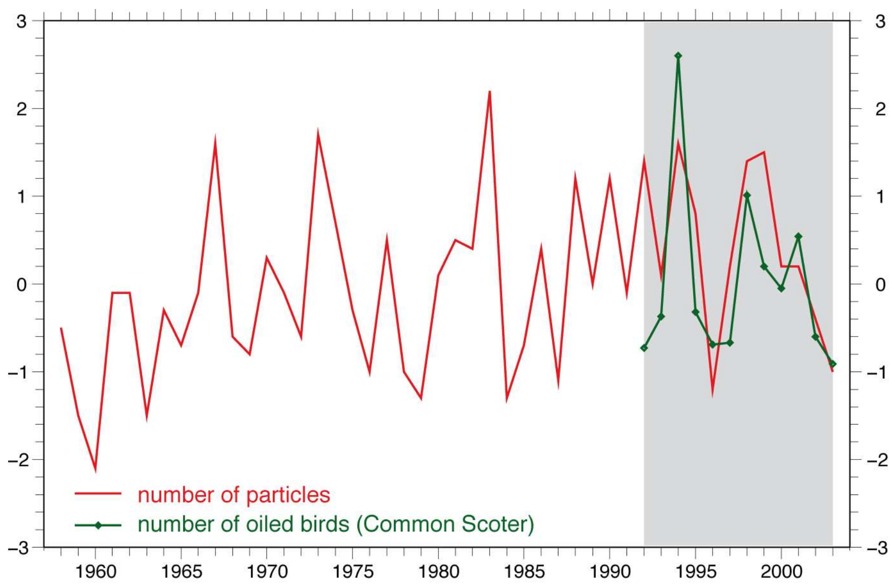

Figure A.7: Number of beached oil-contaminated birds (Common Scoters) observed at the German coast (1992-2003) and number of beached tracer particles simulated with PELETS-2d based on coastDat (1958-2003) assuming a constant level of chronic oil pollution. All data are shown as anomalies normalized by standard deviation. After data and methods described in Chrastansky et al. (2009).

g) Assessment of Policy Regulations

The weather stream generated in coastDat has also been used for an assessment of a policy regulation, namely, the outphasing of lead in gasoline in Europe. After an initial increase until the early 1970s, national and Europe-wide regulations have been adopted, so that since the late 1980s the presence of lead in the atmosphere has been greatly reduced. The questions were as follows: how much lead has been deposited over the past decades in Europe and how successful has the regulation been? To study this, gridded estimates of emissions were derived [for details refer to von Storch et al. (2003) and references therein] which were transported subsequently using the daily winds available from the coastDat dataset. Finally, the deposition, using in particular the rainfall from the atmospheric coastDat reconstruction, was determined. The result of this exercise were emitter-recipients matrices for all European countries, and estimates of the net input into European marginal seas. As an example, Figure A.8 shows the estimated deposition into the Baltic Sea for the period 1958-95, which clearly displays the initial phase of growing pollution and then the stepwise reduction. The figure also shows the available estimates from measurements campaigns and their consistency with the model based reconstruction.

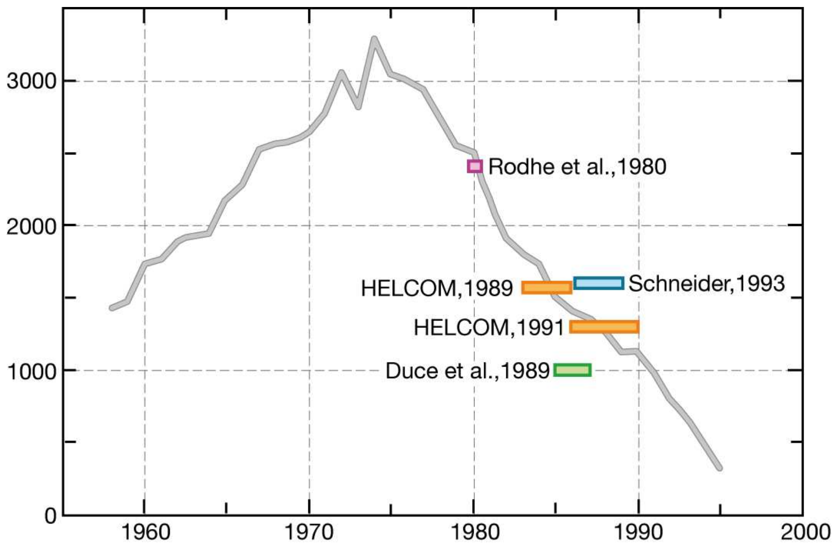

Figure A.8: Annual lead deposition (tons) over the Baltic Sea, from measurement-based estimates (colored bars) and the simulations (gray line) described in von Storch et al. (2003).

h) Other Applications

There are a number of other applications not addressed in detail here. These include applications related to water quality studies or the definition of safety criteria for navigation. Data may also be used for comparison of in-situ data taken at different platforms. For example, data from a fixed station have been compared with measurements taken on a ferry passing nearby. Here, usually a better agreement between observations could be obtained when currents from coastDat were used to simulate water transports between the two observational sites. The time dependent simulated travel times provided an estimate of the time-dependent time lag that had to be taken into account for a proper comparison of the two observational time series (for more details see www.coastdat.de).

Data from coastDat have also been used for some terrestrial applications. For example, terrestrial biosphere models were driven with atmospheric input from coastDat to analyze gross primary productivity over Europe (Jung et al., 2007) or to examine and assess the European 2003 carbon flux anomaly (Vetter et al., 2008).

A.5 Summary and Outlook

The coastDat dataset consists of a set of coastal analyses and scenarios for possible future developments. It constitutes a consistent meteorological-marine (metocean) dataset at high spatial and temporal resolution available for the last 60 yr. It was shown that the statistics of extreme events can be estimated from coastDat at a reasonable degree of approximation. Thus far the dataset has been developed mainly for the North Sea and adjacent areas. Efforts are presently underway to transfer the approach to the statistics of polar lows (Zahn et al., 2008) or tropical regions (Feser & von Storch 2008a, 2008b). Other extra-tropical regions such as the Baltic Sea are also considered.

In face of the limited observational material available for many coastal and offshore areas, regional climate datasets such as coastDat may represent particularly useful tools for many applications, if adequately designed. They not only provide some knowledge about the meteorological-marine conditions at places and times at which no measurements have been made, but in the prospect of ongoing and future climate changes such regional climate datasets may serve as a reality substitute within which the robustness of possible (adaptation) options for many applications may be tested. Here we have provided some examples ranging from ship design, to coastal protection, oil risk modeling or the construction and operation of offshore wind farms.

The purpose of generating and validating regional climate datasets such as coastDat is not to build or to construct a forecast system for the region. Rather, the ultimate goal is to describe and to assess ongoing and possible future climate change and to provide tools and data from which reliable *statistics* of meteorological-marine climate conditions and changes may be derived. We have shown that such information is of particular interest for a broad range of practical applications and, from our experience, the quality and the design of the dataset benefit considerably from the feedbacks provided by the different user groups. Among others, upcoming versions of coastDat will therefore foster enhanced spatial resolution of the regional atmosphere model, improved coastal physics in the wave modeling part, or larger ensemble sizes with respect to the regional climate change scenarios. Further, and similarly to the effort on assessing the success of European Union regulations on the use of leaded gasoline, attempts are underway to simulate and to assess long-term changes of persistent organic pollutants (POPs) in the marine environment, in particular for the North Sea and the Baltic Sea (Aulinger et al., 2007; Matthias et al., 2008a, b).

Summarizing, and in addition to the analysis of existing observational data, we believe that comprehensive model-based regional climate datasets such as coastDat may provide a valuable source of information for the analysis of regional changes and the identification of options for actions especially in data sparse coastal or offshore regions.

Acknowledgments

Figure A.3 and the comparison therein were kindly provided by Lars Bärring from the Swedish Meteorological and Hydrological Institute where imilar analyses are in progress. Mrs. Gardeike kindly prepared Figures A.5 and A.8. We are also grateful for her help in improving the quality of all other figures.

List of Abbreviations

BN	Bayesian Network
bft	Beaufort scalar
CCA	Canonical Correlation Analysis
CPT	Conditional Probability Table
DAG	Directed Acyclic Graph
GIS	Geographical Information System
IPCC	Intergovernmental Panel on Climate Change
NAO	North Atlantic Oscillation
NCEP/NCAR	National Center for Environmental Prediction - National Center for Atmospheric Research
PC	Personal Computer
PELETS	Program for the Evaluation of Lagrangian Ensemble Transport Simulations
PRUDENCE	Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects
RCAO	Rossby Centre Regional Atmosphere-Ocean Model
SN-REMO	Spectrally Nudged Regional Model
SLP	Sea level pressure
SRES	Special Report on Emission Scenarios
TMAP	Trilateral Monitoring and Assessment Program

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