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

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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.

Keywords: hydrodynamic modelling, coastal oil pollution, Lagrangian trajectories, North Sea, beached bird surveys

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, Lahousse & Jacques, 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

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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 2 outlines our general approach (Section 2.1). The hydrodynamic data upon which our Lagrangian simulations were based is described in more detail in Section 2.2. The description of model aspects is followed by a short summary of beached bird survey data (Section 3). Section 4 discusses the outcomes of our Lagrangian tracer simulations (Section 4.1) and their dependence on the mean prevailing weather conditions (Section 4.2). In Section 4.3 the results of our simulations are contrasted with the beached bird survey data. Finally, we summarize our conclusions in Section 5.

2 Drift reconstructions

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 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 2.2). In addition to current-induced particle drift components, an extra wind drift factor was introduced (for details see section 2.2).
The relative extents to which different areas along the German North Sea coast are exposed to hypothetical oil spills (see section 4.1) were assumed to be proportional to the number of simulated particle trajectories that reach the different target regions (cf. Figure 1b). The assumption of a limited particle life time gives more importance to particles that originate from source regions closer to the coast.
Initially (section 4.1a), 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 4.1b) 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 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).

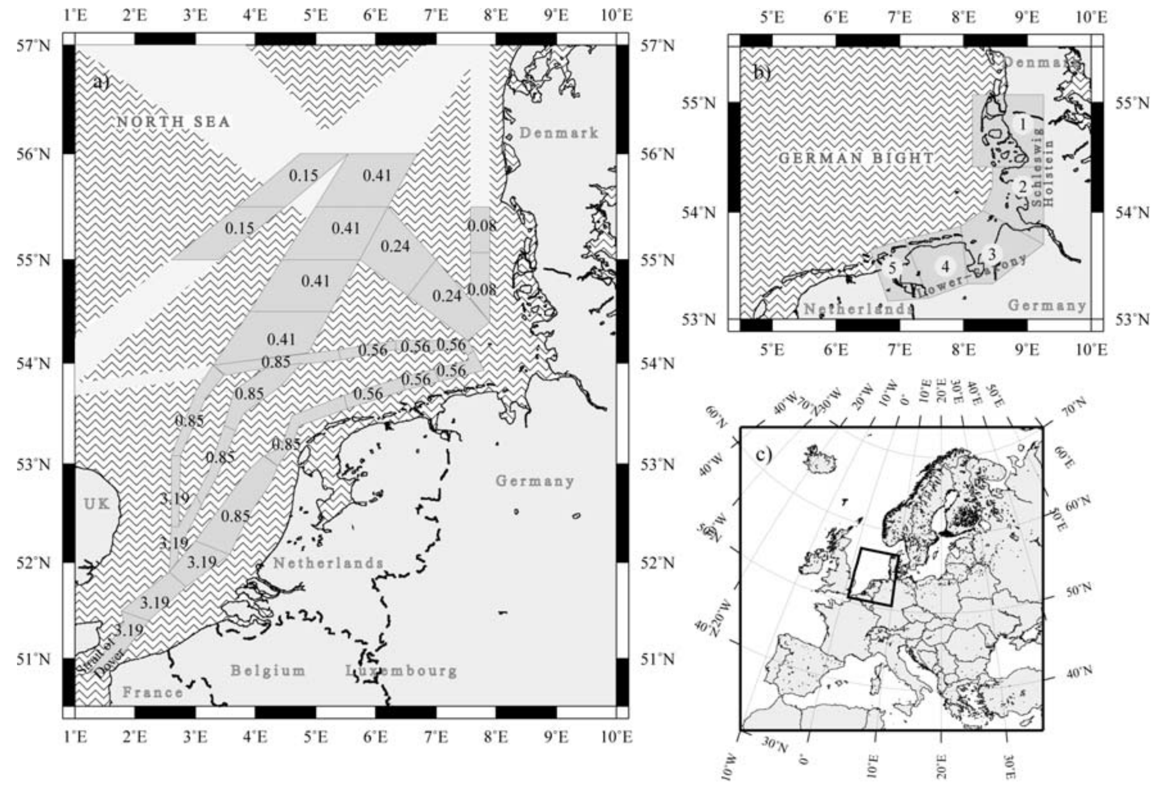

Figure 1: Particle source and target regions of the model set-up. The particle source regions along the major shipping routes of the North Sea (grey shaded areas in panel a) show the assumed weighting factors for modeling oil incidence rates as proportional to the ship traffic density (derived from ship 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).

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, von Storch & Feser, 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 2700 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 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, Callies & Fleet, 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 4.3).

4 Results and Discussion

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

a) 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 2).
Figure 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.

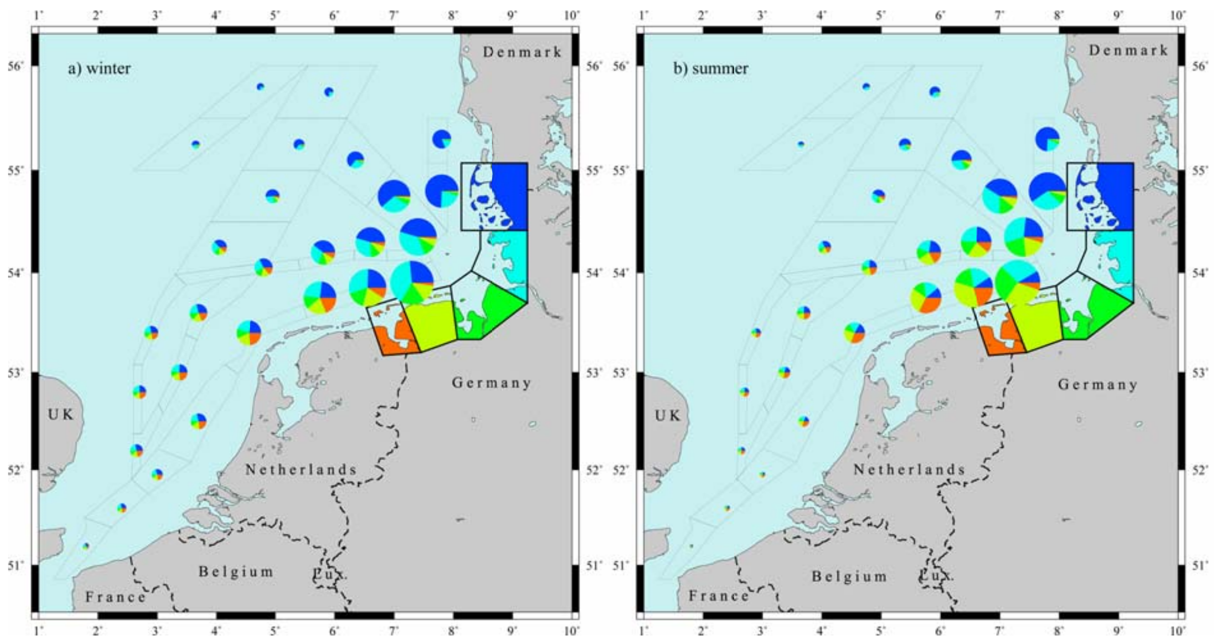

Figure 2: A comparison of the mean potential impacts of hypothetical oil spills at different locations on five different coastal regions (color-coded boxes). Circle sizes represent the relative overall amounts of mass that are advected to the German coast, given oil spills of the same magnitude and assuming 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.).

b) 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 1a). Results of re-scaling the outcomes presented in Figure 2 according to the weighting factors in Figure 1a are shown in Figure 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.

Contrasting Figure 2 with Figure 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.

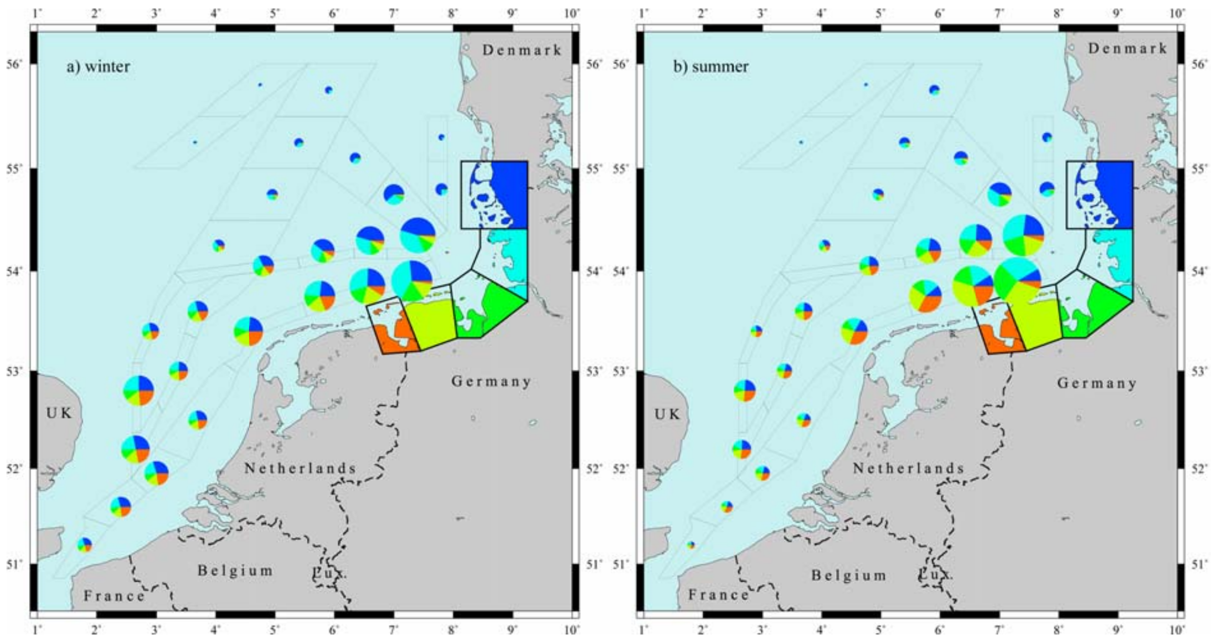

Figure 3: Mean relative contributions of oil spills at different locations to the pollution of five different coastal regions (color-coded boxes). The estimations are based on the assumption that source strengths are proportional to vessel traffic density. Circle sizes represent the overall amounts of 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.).

4.2 Weather driven variability of simulated advection

a) 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. 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 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 SLP anomalies with north-south pressure gradients (cf. left column of Figure 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 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.

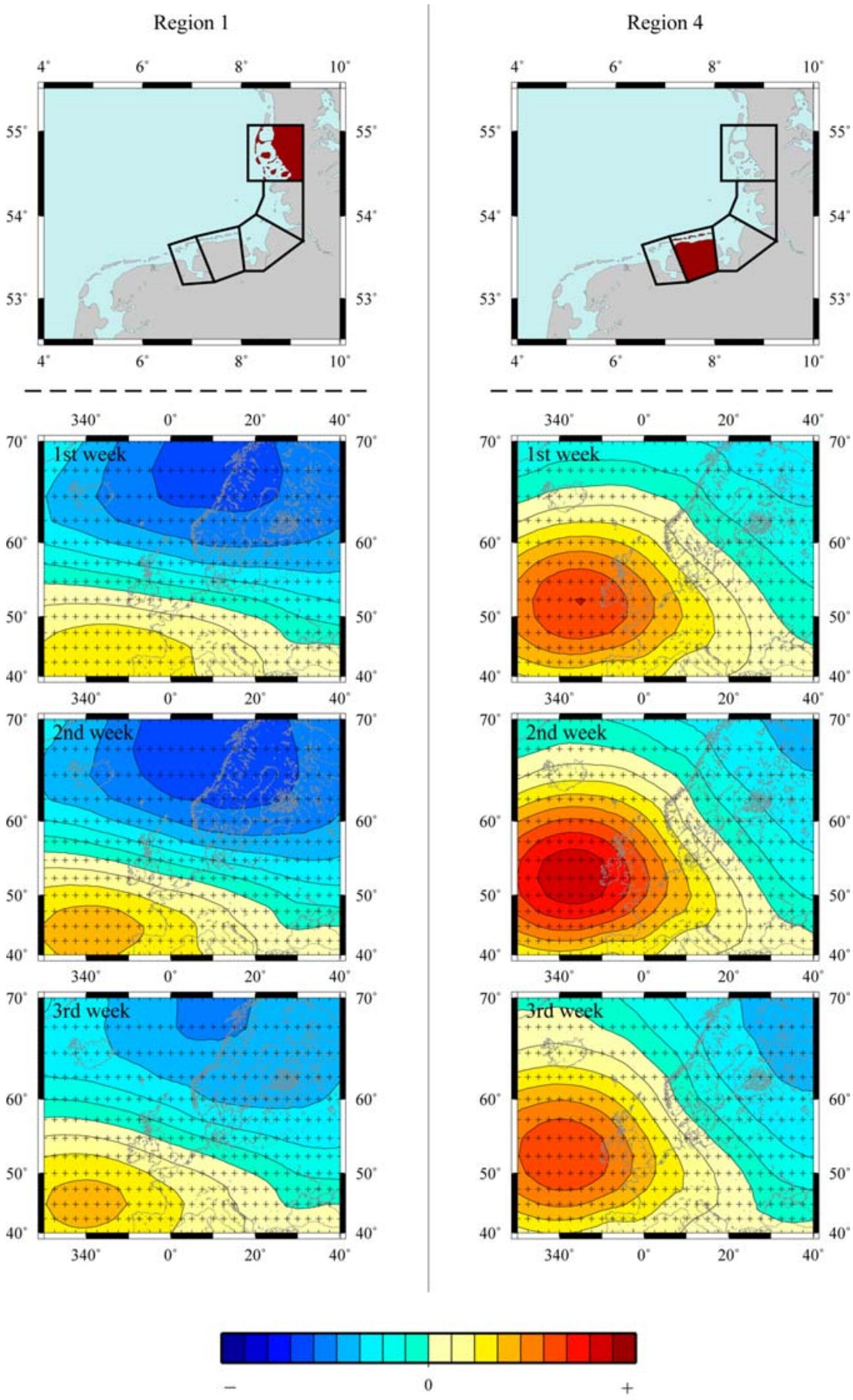

Figure 4: Each of the two columns in the figure displays a pair of correlated CCA patterns, obtained from analyzing the connection between SLP and advective transports towards target region 1 (left column) and target region 4 (right column). Panels in the first row illustrate the locations of the two 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).

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.

b) Regional differences in inter-annual variations

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 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 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 4.3), which can easily be mistaken as changes in the general level of chronic oil pollution.

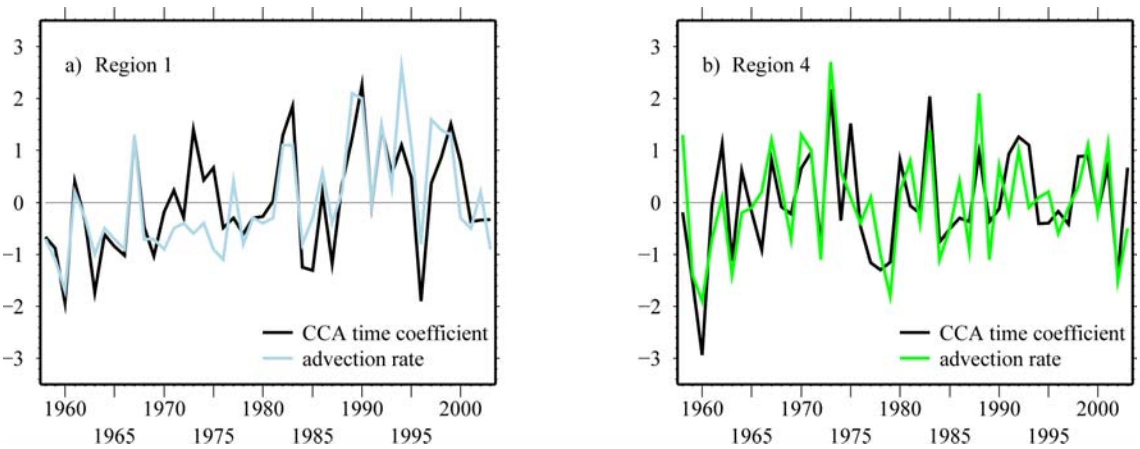

Figure 5: Annual levels of simulated tracer particles that arrived at target regions 1 and 4 (colored lines of panels a and b, respectively) along the German North Sea coast during the period 1958 − 2003 (winter half year: Jan. - Mar. and Oct. - Dec.). Particles with an assumed decay time of 21 days 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 1a. The black lines in the panels show the corresponding CCA time coefficients for the triplets of SLP anomaly patterns shown in Figure 4 (cf. section 4.2a).

Figure 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).

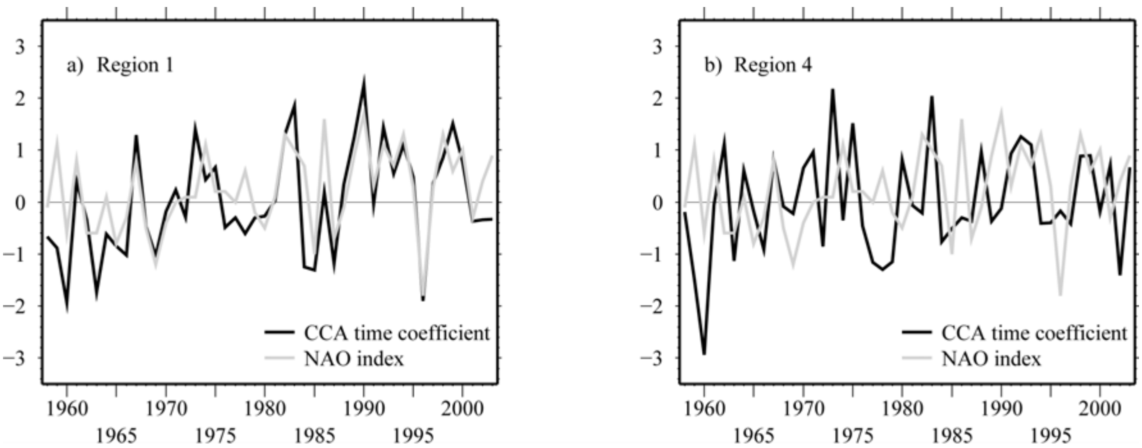

Figure 6: Comparison of winter mean amplitudes of the SLP anomaly fields derived from CCA (cf. Figure 4) and the NAO index. Results are shown for target region 1 and target region 4 (panels a and b, respectively), all values are displayed in standardized form.

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). 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.

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 1b). The choice of only two sub-areas ensured that sufficiently high numbers of bird corpses were collected in these regions.

According to Figure 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, Callies & Fleet, 2009).

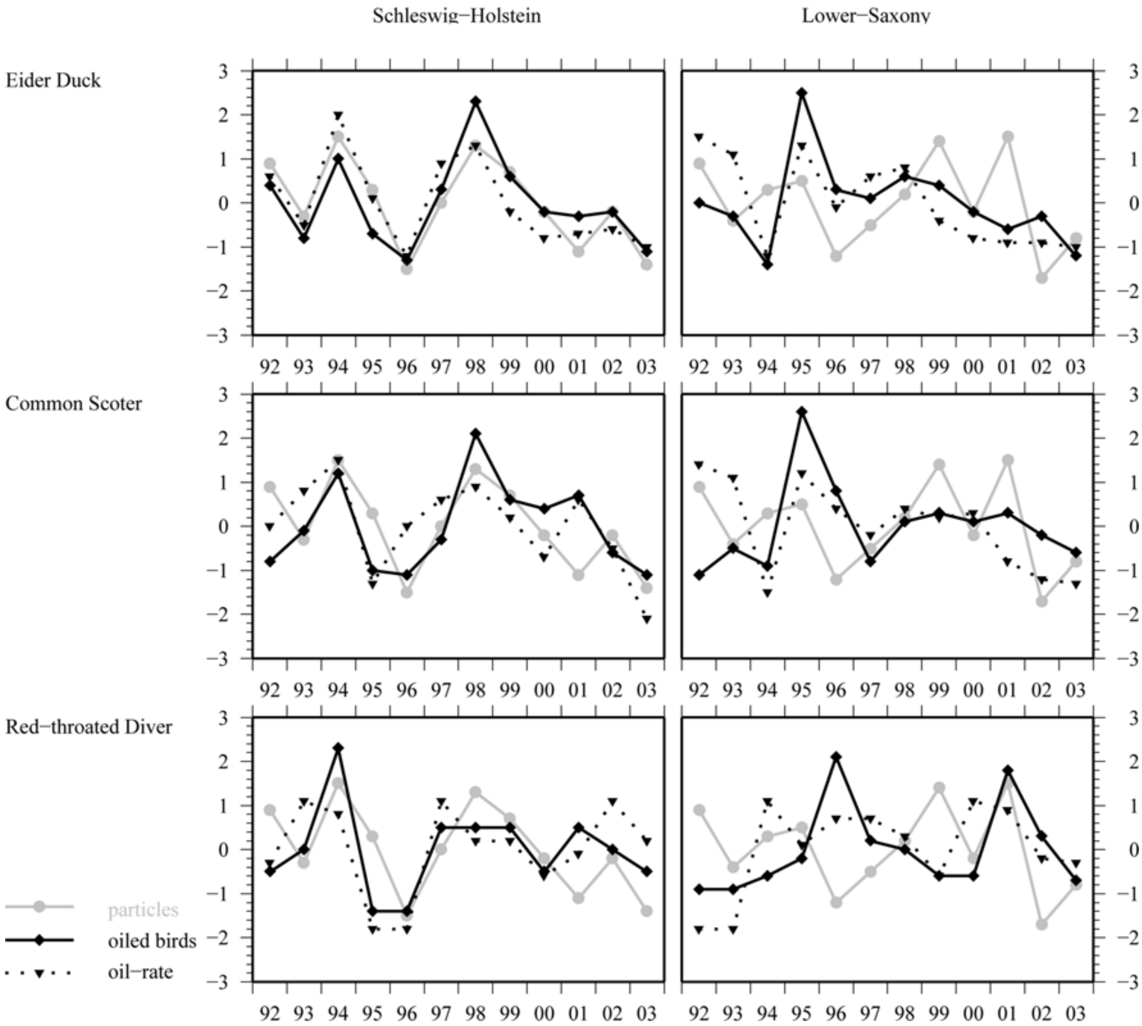

Figure 7: The surveyed numbers of beached birds (black, solid) and corresponding oil-rates (black, dotted) in Schleswig-Holstein (left) and Lower Saxony (right) during 1992 − 2003 are illustrated here. Data is shown for three different bird species. Grey lines represent simulated particle advection from the major shipping routes towards the respective regions. Starting from an initial particle density proportional to traffic density (cf. Figure 1a), we assumed an exponential particle decay constant of 21 days was assumed. All values are displayed in standardized form.

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 7). This discrepancy is consistent with our result that wind effects are less influential in Lower Saxony (cf. section 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.

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.

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