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Marine litter ensemble transport simulations in the southern North Sea

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Highlights:

- Model-based analysis of weather related variations in litter transport pathways
- Estimated impacts of assumed source regions
- Analysis of wind drift effects on litter transport pathways
- Estimated direction of litter origin observed at monitoring sites

Keywords: marine debris, Lagrangian transport modeling, wind drift, seasonal variation, source–receptor relationship

ABSTRACT

The drift of marine litter in the southern North Sea was simulated with the offline Lagrangian transport model PELETS-2D. Assuming different source regions, passive tracer particles were released every 28 hours within a nine-year period. Based on pre-calculated hourly wind and ocean current data, drift simulations were carried out forward and backward in time with and without the assumption of extra wind forces influencing particle movement. Due to strong variability of currents, backward simulations did not allow for the identification of particular source regions influencing given monitoring sites. Neither accumulation regions at open sea could be identified by forward simulations. A seasonal signal, however, could be identified in the number of tracer particles that reached the coastal areas. Both particle drift velocity and variability of drift paths further increased when an extra wind drift was assumed.

1 Introduction

Large amounts of marine litter have been found in most of the world's oceans (Barnes et al., 2009; UNEP, 2009). Since the beginning of the 20th century, the amount of marine litter has increased (Fiscus and Kozloff, 1972; Fowler, 1987) and its composition has changed (van Franeker et al., 2011). Nowadays, plastics account for 40–100% of litter abundance at the sea surface and at beaches (Barnes, 2005; Clemens et al., 2011; Derraik, 2002; OSPAR, 2007; Thiel et al., 2011). Plastic items are often floating at or just below the sea surface and degrade slowly (Andrady, 2011; O'Brine and Thompson, 2010).

The high persistence and ubiquity of marine litter may have adverse ecological impacts via the ingestion of micro- and meso-plastics by seabirds (van Franeker, 1985; van Franeker et al., 2011) or via the entanglement of marine animals in derelict fishing gear (Jones, 1995; Laist, 1987), for instance. Buoyant marine litter items, such as pieces of Styrofoam, are presumed to be transport vehicles for invasive species (Gregory, 2009).

In the last two to three decades, many surveys have been conducted at European beaches, at the sea surface, in the water column, and at the seabed in order to estimate litter distribution and abundance. These surveys were carried out within the frameworks of international treaties, such as the "Oslo-Paris Convention for the Protection of the marine Environment of the North-East Atlantic (OSPAR)" (OSPAR, 2007) as well as by activities of NGOs, e.g. the Fishing For Litter campaign of KIMO at the British coast (KIMO, 2008).

The Marine Strategy Framework Directive (MSFD) of the European Union (Directive 2008/56/EC) (European Parliament and European Council, 2008) aims to achieve a good environmental status (GES) according to eleven descriptors including pollution with marine litter. The GES is scheduled to be achieved by 2020 requiring the EU member states to design and establish monitoring programs to control the effectiveness of mitigation measures. These measures could include substantial reduction of input and load of marine litter. Litter found at beaches, floating on the sea surface, or deposited at the sea floor should be analyzed in terms of trends, compositions, spatial distributions, and its source (Schulz et al., 2013). In this context, transport modeling can be helpful to explain temporal and spatial variation of survey results and source–receptor relationships of marine litter. Recently several modeling studies on marine litter were published (Ebbesmeyer et al., 2012; Kako et al., 2011; Lebreton et al., 2012; Lebreton and Borrero, 2013; Martinez et al., 2009; Maximenko et al., 2012; Potemra, 2012; van Sebille et al., 2012; Yoon et al., 2010). So far, however, only few studies dealt with the North Sea (Maes and Nicolaus, 2012; van der Molen et al., 2012).

In the present study we explore the average as well as the variability of floating litter drift in the southern North Sea, using model based long-term reconstructions of meteo-marine conditions as a realistic surrogate for real conditions during a period of about one decade. Two setups are defined:

- Backward simulations: Tracer particles are released quasi-continuously within a period of nine years near two OSPAR marine litter monitoring beaches and advected backward in time. The objective is to narrow the range of potential source regions of stranded marine litter.
- Forward simulations: Particles are released in two selected source regions and advected forward in time. The objective is to identify drift pathways and possibly accumulation regions of floating litter items in the German Bight. For one particular coastal receptor region (comprising a beach section actually monitored) the temporal variation of tracer particle density reflecting weather and current related effects is analyzed.

In both setups the behavior of litter items floating at or below the sea surface are compared with each other.

2 Material and Methods

2.1 Study Area

The North Sea is a semi-enclosed shelf sea adjacent to the northern Atlantic Ocean (Figure 1). It is connected to the Atlantic via the English Channel between England and France/Belgium (A) with a minimum width of 34 km (Strait of Dover) and via the Norwegian Sea between Scotland and Norway (C). North-East Atlantic waters enter the North Sea around the Isles of Shetland and flow southward along the British coast, while water masses leave the North Sea northward along the Norwegian coast. Several major European rivers, such as River Rhine (b) and River Elbe (d), for instance, as well as the Baltic Sea (B) discharge into the North Sea. Residual currents in the North Sea are orientated counter-clockwise but their actual strengths and directions much depend on prevailing weather conditions (OSPAR, 2010; Pohlmann, 2006). Sea surface accumulation zones of buoyant debris, such as marine litter, have not been identified yet.

The North Sea hosts many different human activities like shipping, fishery, and upcoming offshore wind energy generation. A heavily frequented shipping lane leads through the English Channel to the large ports of Antwerp, Rotterdam and Hamburg and into the Baltic Sea (Barry et al., 2006). Routes of fishing vessels and non-commercial ships are less confined. Coastal waters of the North Sea are important for tourism, sports, and recreational activities. Exploitation of natural resources (e.g. oil and gas) as well as industrial and agricultural activities in river catchments entails pollution problems. However, despite ecological stressors such as eutrophication coastal waters are biologically diverse and productive ecosystems. In particular the Wadden Sea bordering the Dutch, German und Danish coastline is an important nursery ground for fishes and many other marine species.

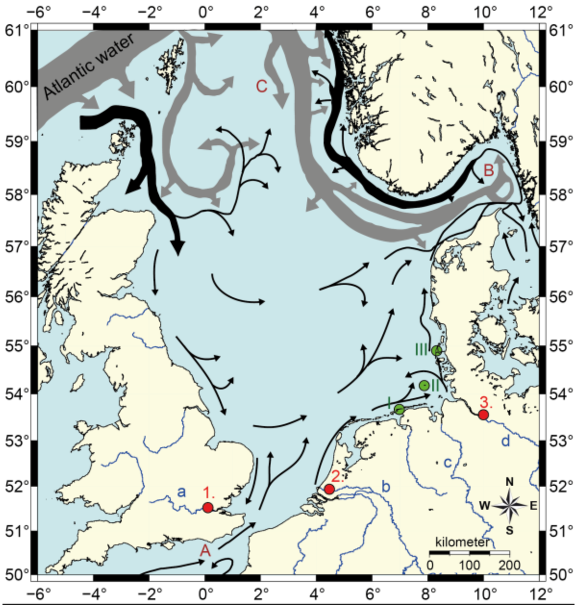

Figure 1: Map of the North Sea in Europe. Red dots with numbers from 1 to 6 represent important cities, brown roman numbers I–III islands, blue lines with lower-case letters a–d important rivers flowing into the North Sea, and green capital letters A–C linkages to other water bodies. 1: London, 2: Rotterdam, 3. Hamburg; I: Juist, II: Helgoland, III: Sylt; a: Thames, b: Rhine, c: Weser, d: Elbe; A: English Channel, B: Skagerrak, C: Norwegian Sea. Surface currents are represented by arrows adopted from Thiel et al. (2011) [Figure 1] and OSPAR (2000) [Figure 2.5]. The widths of arrows indicate the amounts of transported water. Grey arrows represent nearly pure Atlantic water.

2.2 Model

In our study, litter is represented by inert particles, disregarding physical or chemical degradation. Simulations were performed with the Lagrangian particle tracking model PELETS-2D developed and maintained at the Helmholtz-Zentrum Geesthacht (Callies et al., 2011). PELETS-2D is an offline simulation tool, which means that it is to be coupled to pre-calculated current and wind fields. Particle trajectories are calculated on a 2-dimensional triangular grid, which represents the sea surface. Vertical transport – e.g. sinking of particles – is not included. PELETS-2D allows for simulations both forward and backward in time. Subscale particle movements are parameterized as 2-dimensional random diffusion (zero mean and $2D \cdot dt$ variance) with eddy diffusivity D defined as function of length scale l (i.e. local grid resolution),

$$D = D_0 \cdot (l/l_0)^{4/3}$$

where reference diffusivity $D_0 = 1\ m^2/s$ holds for the reference length scale $l_0 = 1\ km$ (Schönfeld, 1995). See Callies et al. (2011) for more details on the model.

For the period 2000–2008, marine currents from the top layer (8 m thickness, z-coordinates) of the 3D operational circulation model (BSHcmod) of the Federal Maritime and Hydrographic Agency of Germany (BSH) (Dick et al., 2001) were available on a quarter-hourly basis. The model BSHcmod is run once a day for forecasting water levels and currents including tides. Grid resolution (spherical grid) of BSHcmod is about 1.8 km (Δlon=100''; Δlat=60'') in the German Bight (<55.5°N, >6°10'E) and the western Baltic Sea and about 10 km (Δlon=10'; Δlat=6') in the remaining North and Baltic Sea (<59.5°N, >4°W). Vertically, the model uses z-coordinates with an 8 m surface layer. Dry-falling of areas due to tides is not included. The North Sea grid is nested in a 2-dimensional North-East Atlantic model with about 24 nautical miles (≈44 km) grid resolution. Because BSHcmod is an operational model it is sufficiently validated. For more information on the model we refer to Dick et al. (2001).

Objects floating on the surface experience an additional wind drift. In this study, 5% (wind drift factor 0.05) of the wind at 10 m height were optionally superimposed to ocean currents (drift velocity = oceanic current + wind drift factor · wind). The winds we used are the same already used in BSHcmod, provided by operational forecasts of the Deutscher Wetterdienst (DWD). The forecasts are calculated by their GME/LE model system (Doms and Schättler, 1999).

Unfortunately, appropriate wind drift factors are hard to specify and differ a lot among different buoyant items. Even for submerged items, such as derelict fishing gear, inclusion of an extra wind drift may be needed to counteract insufficient vertical resolution of the underlying hydrodynamic model. For instance, one may have to superimpose an extra wind forcing onto average currents from a 10 m surface layer to obtain results comparable to those based on average currents from a just 1 m surface layer – the latter as a whole already being more exposed to wind forcing. For items floating at the surface (e.g. plastic bottles), however, extra wind drift is the clearly dominant forcing effect.

Already a wind speed of 5 m/s, corresponding with a gentle to moderate breeze (Beaufort scale: 3–4), in combination with a small wind drift factor of 0.01 results in an extra wind drift of 0.05 m/s. This value is in the same order of magnitude as strong residual currents in the North Sea (Loewe, 2009). The factor we used throughout this study was five times larger – corresponding to an extra wind drift of 0.25 m/s for a gentle to moderate breeze – and wind speeds often exceed 5 m/s.

For oil drift modeling based on BSHcmod currents, wind drift factors between 0.008 and 0.058 were applied (Dick and Soetje, 1990). For advecting litter items, Yoon et al. (2010) proposed a wind drift factor of the form $0.03\ (A/W)^{0.5}$ with A and W being the item's cross sections normal to the wind direction above and below the sea surface, respectively. Buoyancy ratios (A/W) between 0 and 100 estimated for three item types (lighter, plastic container and plastic bottle) lead to a wide spectrum of effective wind drift factors ranging from 0.0 (no wind drift) to 0.3. Yoon et al. (2010) found that simulations in the Japan Sea assuming wind drift factors larger than 0.1 were less well correlated with monitoring data of floating plastic items than simulations with lower factors. We assume 5% to be an upper limit for the wind drift factor. This choice is discussed in the section 4.

Simulated trajectories close to shore lines involve much uncertainty arising from limited resolution of coastline details as well as difficulties to model the subscale process of beaching and potential resuspension. Therefore in this study, beaching of particles was not taken into account and coasts are represented as reflecting boundaries. Model boundaries to the Atlantic Ocean (59.5° N, 4° W) are open, particles cannot re-enter the model domain. All open boundaries, however, were sufficiently far away from the study area to not affect particle transport patterns in the model area. Particles originating from outside the model domain are not taken into account in this study.

2.3 Setup of experiments and evaluation method

All simulations either forward or backward in time were started every 28 hours over a period of nine years from different initial locations. Trajectories were calculated over 90 days (=2160 hours) – denoted as integration time – both without wind drift and with a wind drift factor of 0.05 (=5%) taken into account. Results were evaluated on a grid of target cells covering the southern North Sea (mesh size: 0.5° in longitudinal and 0.25° in latitudinal direction, cf. black grid in Figure 2).

Using the 28 hour interval between consecutive simulations, the differences between initial times exceed two tide cycles (about 2 × 12.5 hours) by about three hours. Simulations were initialized between the 1^{st} of April 2000 (01:00) and the 31^{st} of December 2008 (05:00) for backward simulations and between the 2^{nd} of January 2000 (01:00) and the 2^{nd} of October 2008 (05:00) for forward simulations, respectively, resulting in 2741 simulations in each of the two setups. Start and end times were chosen in such a way that integration periods of forward and backward simulations, respectively, matched pairwise.

At best the reconstructed history of an object (based on backward simulations) would include the identification of its origin. However, any calculated trajectory provides just an estimate of the track along which an object's origin might be located. Moreover, the integration time is related to the spatial scale and must carefully be selected. A reasonable upper limit for the integration time would be an object's residence time at sea surface (time till it sinks), which is highly variable for the wide spectrum of marine litter. Even sink-reemerge-cycles of items are expected (Ye and Andrady, 1991). To give some examples of time scales: Kako et al. (2011) assumed half a year of buoyancy for bottle caps, Yoon et al. (2010) performed simulations for up to six years in the Japan Sea, other authors simulated the drift of litter for eight (Martinez et al., 2009) and 30 years (Lebreton et al., 2012) in the Pacific Ocean and for ten (Maximenko et al., 2012) and more than one thousand years (van Sebille et al., 2012) globally. Such very long integration times of ten years and longer may be needed on a more global scale in order to evaluate the formation of large gyres. They are definitely meaningless for a limited region like the North Sea. Additionally, with increasing simulation time the uncertainty in the particle trajectories increases. This is due to the fact that oceanic advection shows chaotic behavior: Small changes in the initial conditions (in time and space) may lead to different system behavior. Kjellsson et al. (2013) demonstrated this by analyzing observed drifter trajectories in the Baltic Sea. Within the first 20 days of drift, two drifters which were started close to each other separated by up to 40 km. Thus, 90 days of integration time for simulations in the North Sea region seemed to be a good compromise between uncertainties in particle trajectories on the one hand and a reasonable length of resulting data sets on the other hand.

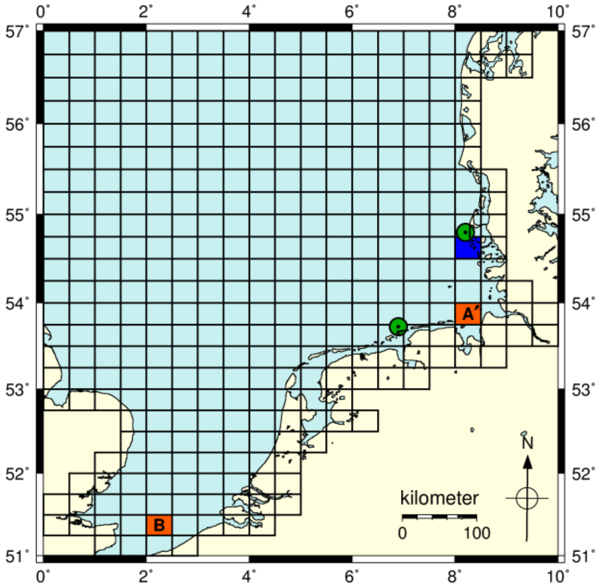

Figure 2: Map of the southern North Sea with two point sources for backward simulations (green circles), two rectangular source regions for forward simulations (orange boxes, A and B), target regions (black grid), and an observation region (blue box).

To achieve a good trade-off between computing time and representativeness of results, 100 particles were released for each simulation from a given initial location. For backward simulations, two independent point sources located seaward from the OSPAR litter survey beaches ID DE5 and ID DE1 on the German islands Juist and Sylt (OSPAR, 2007), respectively, were defined (green circles in Figure 2). For forward simulations, particles were initialized at random locations within two source regions (regions A and B in Figure 2) that coincide with two of the target grid cells. We chose point sources in the case of backward simulations, as the very nearshore grid cells overlapping with land would have caused part of the particles to become trapped behind the islands. Both setups are summarized in Table 1.

	Backward simulations	**Forward simulations**
Source regions	Two point sources close to Sylt and Juist (fig. 2, green circles)	Two source regions in the south-western (A) and south-eastern (B) North Sea (fig. 2, orange boxes)
Particles injected	2 × 100	2 × 100
Direction in time	backward	forward
Evaluation	CTH and TT50 per region on a grid covering the North Sea (fig 2, black grid)	(a) CTH and TT50 per region on a grid covering the North Sea (fig 2, black grid) (b) detailed evaluation of time series of particle densities (source region A only) in an observation region close to Sylt (fig. 2, blue region)

Table 1: Simulation setups with corresponding source region configurations, injected particles, transport direction in time, and method of evaluation (CTH: cumulative travel history; TT50: median of the travel time; see text for detailed description).

The source regions chosen for forward simulations are close to possible input areas of marine litter into the North Sea and may partly represent these areas:

- Source region A: rivers Elbe, Weser and Jade; ports of Hamburg and Bremerhaven and Jade–Weser Port.

- Source region B: rivers Rhine and Thames; ports of Antwerp and Rotterdam; Atlantic Ocean through the Channel.

Many possible source regions remain disregarded. That pertains to sources, for instance, from outside the model domain (van Franeker, 2005), riverine input (Moore et al., 2011), shipping lanes (Horsman, 1982) and other marine sources as fishing industry (Donohue et al., 2001; OSPAR, 2007) and tourists (e.g. recreational boaters). In the real-world North Sea system, marine litter from these sources may overlay litter from the sources discussed in this study. However, for realistic modeling of marine litter transport and distribution, one needs spatio-temporally resolved litter input profiles, which are not available. Van Franeker (2005) recognized that local sources dominated the litter composition on the Dutch island Texel. However, quantitative interpretation of real-world observations based on results of this study is impossible.

Figure 3 illustrates two different ways, which we used for aggregating model results. In both of the two panels of Figure 3, grey arrows represent single simulations. The first way of aggregation is to summarize the particle transport history of each simulation (blue box of panel (a)). This is done by calculating two types of key figures for each target cell (black grid in Figure 2):

- Cumulative travel history (CTH) [% particles]: proportion of particles, which crossed the considered target region at least once during the entire simulation.
- Median of the travel time (TT50) [days]: time elapsed till 50% of all particles that ever crossed the target region of interest entered this region the first time (50% percentile = median).

CTH values depend on the size of cells of the underlying grid so that their interpretation should focus on spatial patterns rather than absolute values in individual regions. The coastline is a reflecting boundary – particles do not beach – but particles may get caught in bays. Because the number of simulations (n=2741) is quite high, the averages of CTHs and TT50s over all simulations from 9 years (2000 - 2008) will be considered in section 3.1. In this case reference to specific points of time (e.g. release times) is lost (cf. Fig. 3(a)).

Alternatively, we may be interested in particle densities in a certain region at a given time, e.g. the date for which monitoring data were compiled. In this case we may consider the set of simulations as one simulation with a quasi-continuous release and collect particles of different “age” from different simulations at given times (boxes in Figure 3(b)). Resulting time series of particle concentrations were evaluated for one cell near the island of Sylt selected from the grid of target regions (blue box in Figure 2). Only forward simulations started in source region A were taken into account for this purpose.

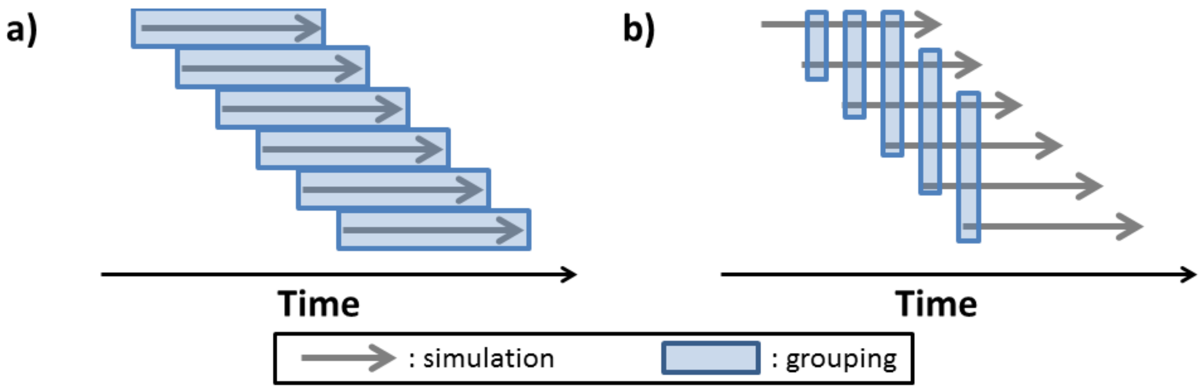

Figure 3: Two concepts for combining simulations started at different times. (a) Mean conditions after given travel times, obtained by averaging over all simulations irrespective of their time of initialization. (b) Actual conditions at specific points of time, combining contributions from all overlapping simulations irrespective of their travel time.

3 Results

Section 3.1 describes average patterns of cumulative travel history (CTH) and median travel time (TT50). Different source regions and the effects of wind drift are considered. Section 3.2 takes a different perspective on forward simulations by studying time series of local particle concentrations.

3.1 Mean Transport patterns

3.1.1 Backward Simulations

Figure 4 shows CTH plots for two example backward simulations initialized near the island of Juist. Irrespective of initial times differing by just two weeks, i.e. much less than the integration time of 90 days, the results of the two simulations differ substantially with regard to both the main direction from where particles arrived (south-west in March 2007 and east in April 2007, respectively) and the total distance covered. In the following we will describe the overall picture obtained by averaging a large number of such detailed simulations. It should be kept in mind, that the effect of a pronounced short-term variability will be a spatial smoothing of the mean patterns of transport.

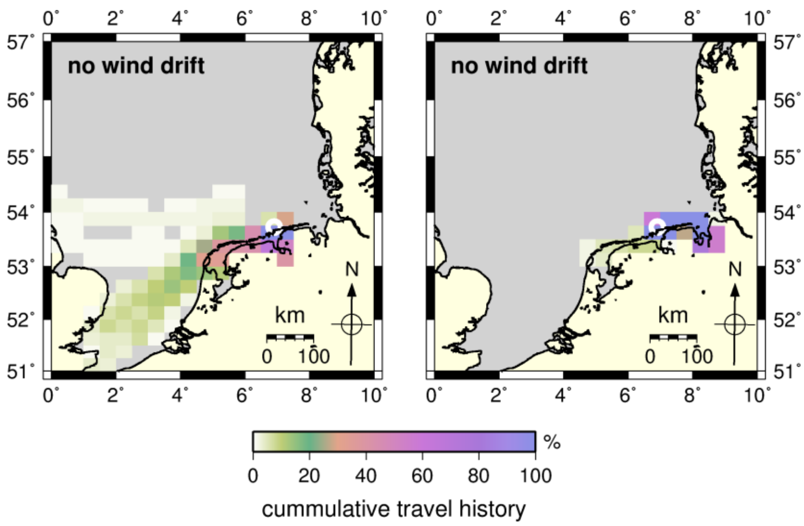

Figure 4: CTH-plots of two simulations 90 days backward in time. No wind drift was taken into account. Simulations were started at 21st of March 2007 (left) and 4th of April 2007 (right), respectively.

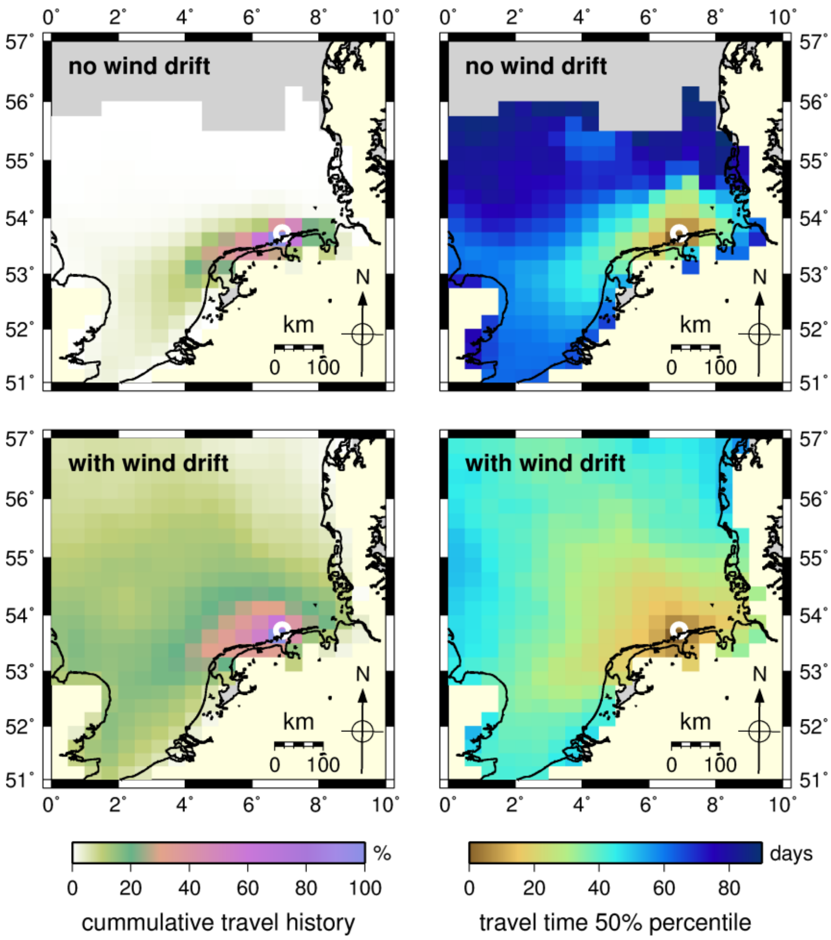

Figure 5: Means of cumulative travel history (CTH) on the left and median travel time (TT50) on the right. 2741 backward simulations without (top) and with (bottom) wind drift, respectively, were averaged. All simulations were started from an assumed observation region located to the north of the island of Juist (near 54°N and 7°E, white framed circle).

Figure 5 shows average (in the sense of panel (a) in Figure 3) CTH (left) and TT50 (right) patterns without (top) and with wind drift (bottom). The patterns are based on 2741 backward simulations, each simulation with 100 particles started from near the island of Juist (white framed circle in Figure 5). The CTH reflects predominant advection from the west and south-west – independent of the assumed wind drift. With wind drift included, however, the area of past particle positions is much more extended and less well delimited. As to be expected, travel times (TT50) are much reduced by wind drift. A second effect of wind drift, however, is the occurrence of a sector of particular fast advection from the north-west.

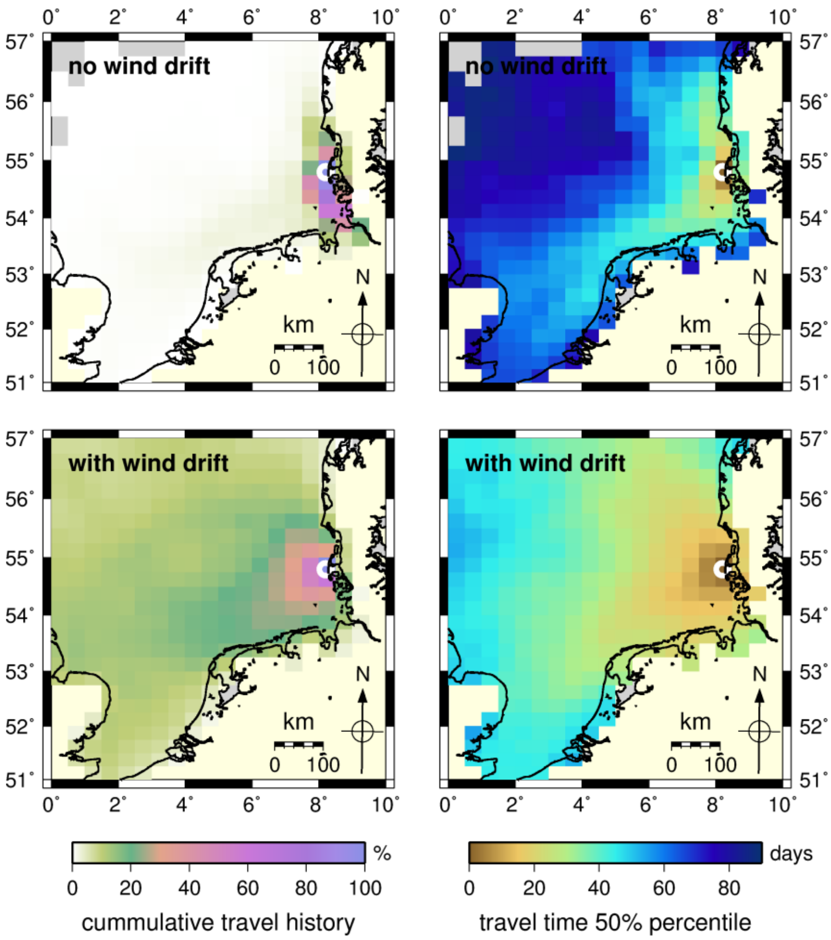

Figure 6: Same as figure 5 except of the point source, which is located to the south-west of the island of Sylt (near 55°N and 8°E, white framed circle).

Figure 6 differs from Figure 5 by the fact that backward particle trajectories were now started from the white framed circle near Sylt. CTHs calculated without wind drift make the Elbe estuary a candidate region for the origin of litter observed at Sylt. Corresponding travel times are of the order of one month. With wind drift included, again the history of particle tracks is less well specified, although a preference for advection from the south-west is discernible. Again median travel times (TT50) suggest particularly fast advection from either south-west or north-west direction.

3.1.2 Forward Simulations

Results of forward simulations initialized near the English Channel (source region B) and in the south-eastern German Bight (source region A) are presented. Figures 7 and 8 show plots in the same format we already used for backward simulations.

For simulations without wind drift, the top CTH plot in Figure 7 (particle source region A) indicates low numbers of particles passing through coastal regions and river estuaries, respectively. CTH and travel time (TT50) plots indicate that on average particles move fast northward out of the German Bight. A few particles were advected into the central North Sea and no particles arrived at the British coast.

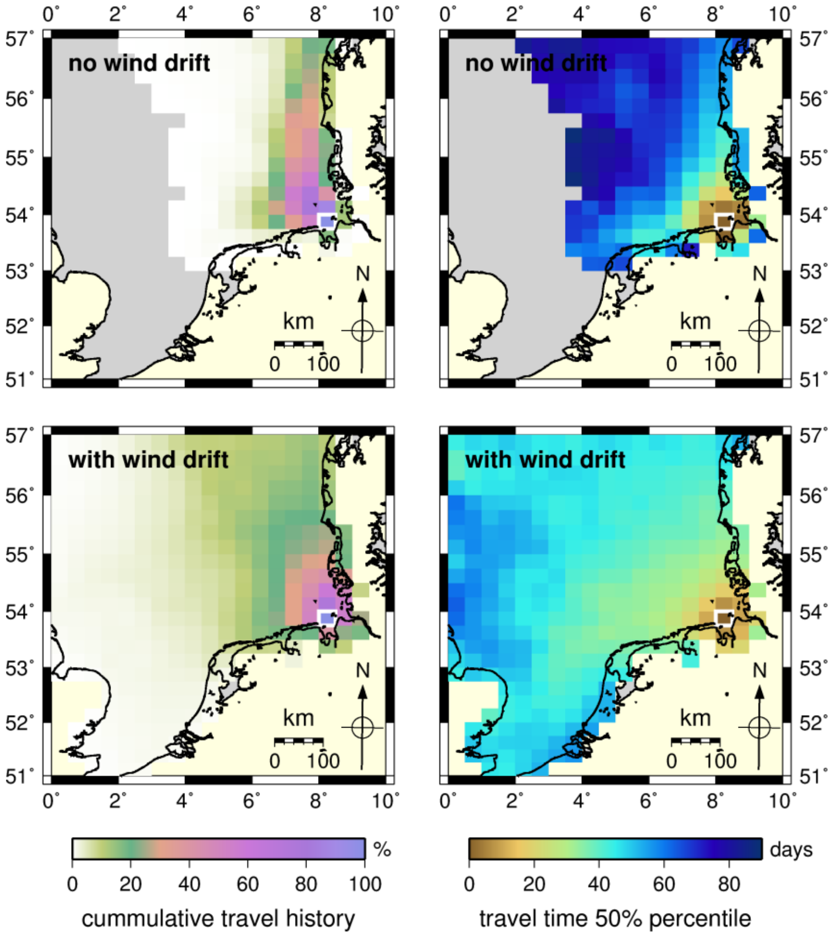

Figure 7: Means of cumulative travel history (CTH) on the left and median travel time (TT50) on the right. 2741 forward simulations without (top) and with (bottom) wind drift, respectively, were averaged. All simulations were started from a fictive source location in the south-eastern German Bight (source region A, white box near 54°N and 8°E).

In simulations with wind drift (Figure 7 bottom left), particle CTHs in coastal regions were high compared to simulations without wind drift (significant with α = 95%; figure SI1 and tables SI3 and SI4 in supplementary information). Particles were generally more dispersed leading to higher CTH values in the central North Sea. Lower TT50 values also show that on average particles were advected considerably faster northward as well as in western and north-western directions.

Particles injected in source region B (Figure 8) were advected northeastward along the Belgian, Dutch and German coast and then northward. Regions of highest CTHs were found to be similar in simulations without and with wind drift, respectively, stretching along the route parallel to the coast. However, dispersion becomes intensified by taking into account an extra wind drift. Another implication of extra wind drift is that coastal regions become more affected (significant with α = 95%; see figure SI1 and tables SI1, SI2 and SI4 in supplementary information), which qualitatively agrees to simulations started in source region A.

An important result to be mentioned is that in our forward simulations we did not find any indication for particle accumulation in any region of the open North Sea – neither in CTHs nor in particle residence times (not shown).

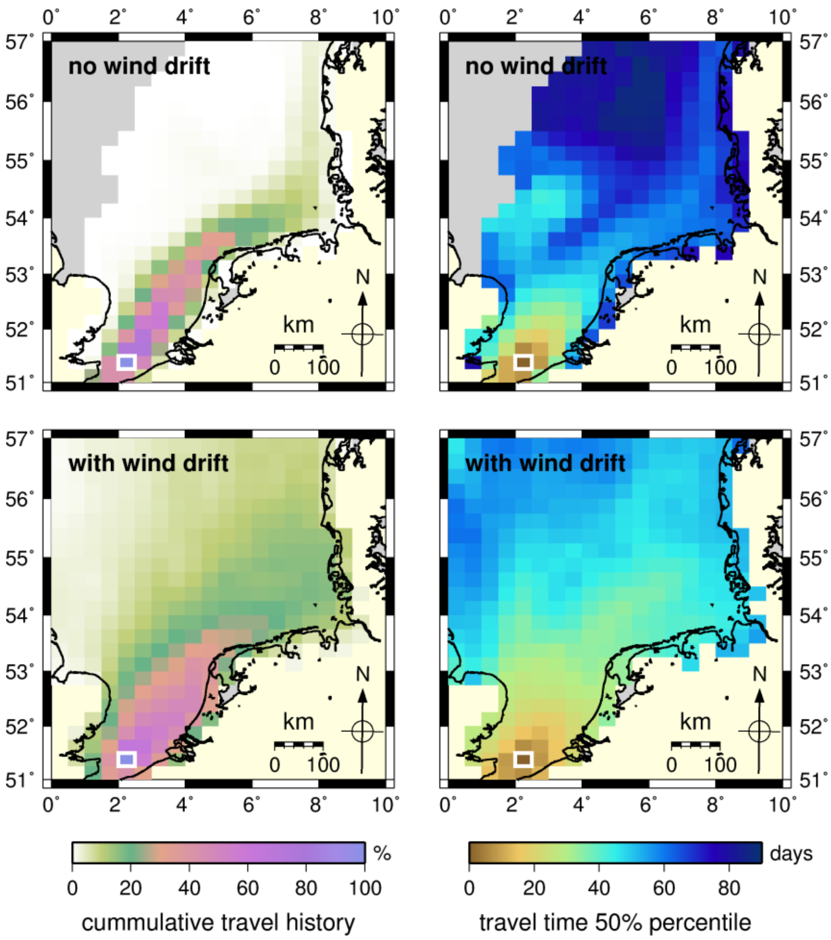

Figure 8: Same as figure 7 except of the source region, which is located near the English Channel (source region B, white box near 51°N and 1.5°E).

3.2 Time series of local particle numbers

In the previous subsection we described mean transport pathways either forward or backward in time. In the context of monitoring, however, estimation of weather induced local variability of observations may be of interest for a proper assessment of possible changes in pollution. We chose the ensemble of forward simulations started from source region A (cf. Figure 2) as a basis for such an analysis, referring to a particular observation area near the OSPAR litter monitoring beach DE1 (OSPAR, 2007) on the island of Sylt (blue box in Figure 2). Technically, relative particle densities from all overlapping simulations were combined into relative densities of particles of different age (cf. Figure 3(b)). Figure 9 shows the resulting time series with and without wind drift, respectively. Raw data were smoothed by taking 7-day moving averages of hourly data and plotting them in 24 hour intervals.

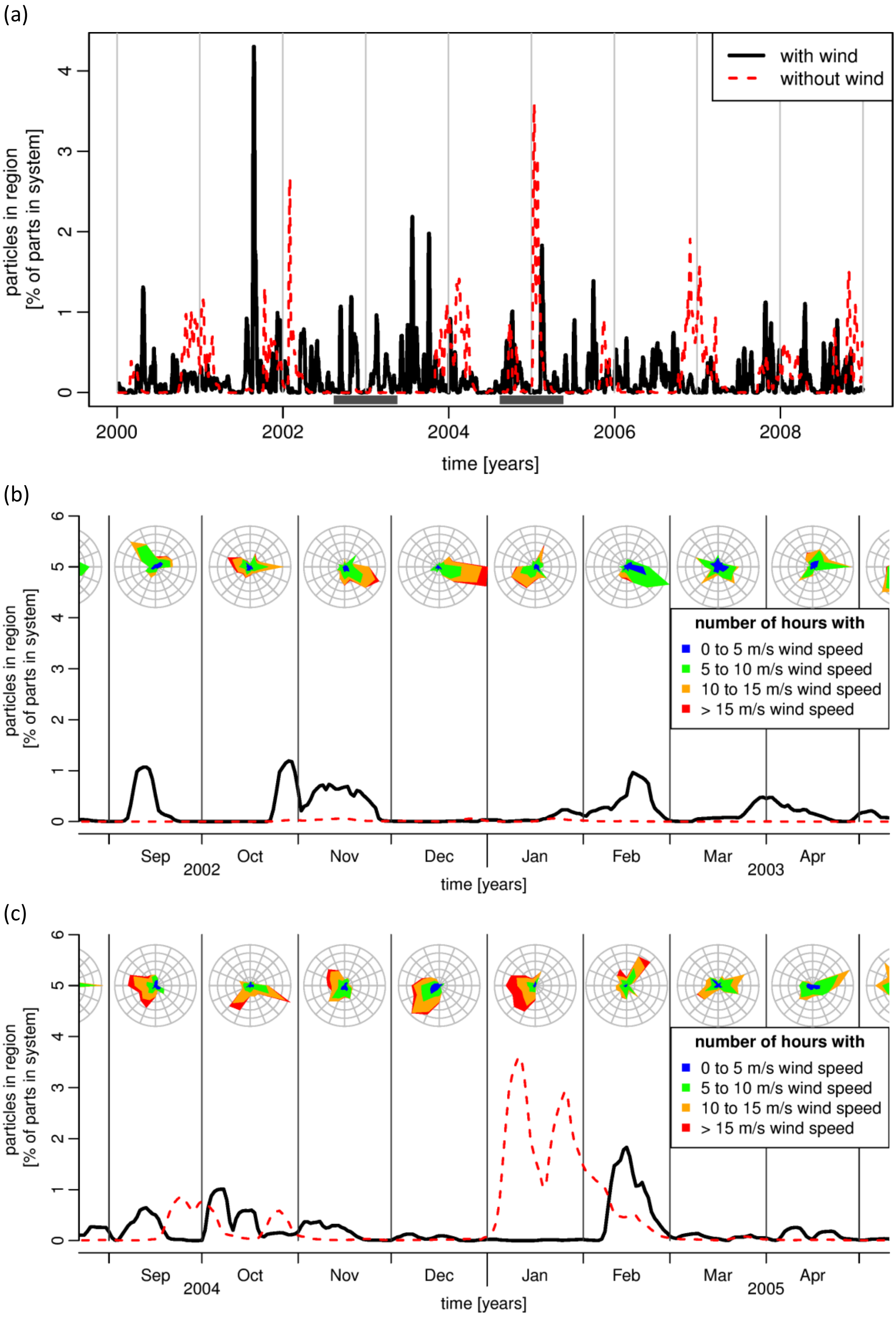

Figure 9: Time series of relative particle densities in the blue grid cell indicated in Figure 2, assuming quasi-continuous release from source region A (see text). Results from simulations without (red dashed lines) and with wind drift (black lines) are shown. Weekly moving averaging was applied for smoothing the data. Plot (a) shows the whole time series from 2000 to 2008 and plots (b) and (c) show sub-periods of eight months lengths – 2002/2003 and 2004/2005, respectively. In plots (b) and (c), a wind rose summarize for each month the corresponding distribution of wind direction (direction from which the wind blows) and speed.

Data without wind drift in Figure 9(a) (red dashed line) suggest a clear seasonal pattern with maximum relative particle numbers during late autumn and winter, although the widths and heights of peaks vary considerably from year to year. A corresponding analysis showed significant autocorrelation for time shifts of about 1, 2, 3, etc. years (see figure SI4 in the supplementary information). The winter episodes of 2002/2003 and 2004/2005 provide two extreme cases with a completely lacking and a very high winter peak, respectively. In Figure 9(b) and (c) these two years are re-plotted with enhanced resolution. As additional information for each month local wind conditions are summarized.

In 2004/2005 and all other years except 2002/2003, there is a major peak in winter sticking out among considerably lower particle numbers during the rest of the year. However, 2004 differs from the other years by two secondary peaks in September and October. Comparing wind data (direction and speed) and particle numbers suggests a correspondence between strong long lasting west winds and the subsequent occurrence of particle number peaks. In all other years (with the exception of 2002/2003 when no such weather conditions occurred) similar situations can be found (see figures SI2 and SI3 in the supplementary information).

The situation for simulations with wind drift included is quite different. Weather related fluctuations occur on considerably shorter time scales and seasonal patterns of enhanced particle densities are discernible. There is also no evident correlation between particle density peaks and monthly averaged wind conditions.

It must be kept in mind that the setup of our simulations imposes an upper limit of 90 days travel time. This truncation primarily affects simulations without wind drift as then particles move less fast.

4 Discussion

Without wind drift taken into account, mean simulated transport pathways (both forward and backward in time) reflect the well-known anticlockwise residual circulation in the North Sea (OSPAR, 2000; Pohlmann, 2006). Coasts were modeled as reflective boundaries. Nevertheless, a number of particles were caught by bays or headlands. With the process of beaching being unresolved, our results in coastal regions should generally be regarded with care.

With an extra wind drift being included, particle movements become faster and more diverse. CTHs become high near coasts exposed to prevailing westerly winds, which is consistent with ship-based observations after storm events in the Ligurian Sea (Aliani et al., 2003). In contrast to currents, winds are not constrained by bathymetry, which – in combination with higher velocities – causes substantial dispersal of floating objects counteracting accumulation in any region of the open North Sea.

We tested wind drift factors of 1% and 10% in pre-studies (not shown here). In simulations with 1% wind drift, remarkable effects were already similar to those of simulations with 5% wind drift. Simulations with 10% wind drift, however, lead to unrealistically high dispersion and transport rates. We agree with Yoon et al. (2010) that 10% wind drift should be regarded as an upper limit.

In our simulations we did not take into account that a wind induced transport path (denoted as leeway) may also diverge from the downwind direction. Uncertainty arising from this effect must be taken into account in search and rescue models (Breivik and Allen, 2008). We feel, however, that our analysis of mean drift conditions would not benefit from such a more detailed approach introducing even more uncertainty with regard to its proper parameterization.

Integration time is an important parameter influencing results of the analysis. In the literature (see section Material and Methods) a broad range of values was selected depending on the spatial scale of interest and the focus of the study. Residence times of litter at the sea surface would not necessarily be an appropriate choice, considering high uncertainty of particle trajectories integrated over very long periods. Kjellsson et al. (2013) exemplified this uncertainty for real drifters in the Baltic Sea. We feel that for our application in the North Sea, 90 day integration time was a reasonable choice.

To estimate the robustness of our results we compared CTH plots of forward simulations after 50, 70 and 90 days of integration time. For the interested reader, corresponding CTH plots are attached as supplementary material (figure SI5). Note that by definition CTH values will not change when particles cross a certain grid cell repeatedly at later times. Therefore we conclude from the aforementioned plots that CTHs after 90 days are quite robust in 100–200 km distance to each source region. Along major drift paths they may even be robust till 300 to 400 km, depending on the choice of source regions. With respect to source region B, we assume all statements regarding Belgian, Dutch and south English waters to be robust, whereas statements to German and Danish waters have to be considered with care.

Our analysis suggests a seasonal distribution of litter transport towards some coastal regions. For the particular receptor region near Sylt, maxima of pollution occurred in autumn and winter. A comparison to wind conditions indicated that long lasting westerly winds may affect litter density in the vicinity of Sylt. The timing of peaks may be different for other coastal regions exposed differently to seasonally changing wind directions. Phase shifted seasonal patterns were also identified by Schulz et al. (2013) in observational data from the OSPAR beach litter monitoring project (OSPAR, 2007). The seasonal effects became most obvious when an extra wind drift was neglected so that the atmospheric forcing was channeled through responding marine currents. The reason for this may be that the inclusion of direct wind effects means superposition of processes on shorter time scales.

Simulations may be compared to litter monitoring data from the sea surface or from beaches. Figure 4 illustrates that mean transport patterns displayed in Figure 5 combine a lot of short term variability. The time series of local relative particle numbers shown in Figure 9 are another indicator for the strength of this variability. Therefore, simulations would have to be compared with temporally highly resolved litter observation data on a daily basis, for instance. However, such time series do not exist to the best of our knowledge and no operational monitoring program will be able to provide them with justifiable expenditure. Datasets that come close to this quality, are two 20-year beach litter time series in 3-day resolution available for two German islands (Mellum and Minsener Ogg) (Clemens et al., 2011). To compare these time series or those with larger collection intervals with simulated results, the stranding and re-suspension of particles at beaches would be needed to be modeled in PELETS-2D. In sum, we could not compare observations and model results due to the (i) uncertainty in the stranding process, (ii) non-consideration of small scale current patterns in the hydrodynamic model (see Material and Methods), and (iii) lack of knowledge about the spatio-temporal profiles of litter releases.

5 Conclusions

Our ensemble transport simulations of marine litter in the North Sea covered a nine-year period for which detailed fields with high temporal resolution of both marine currents and atmospheric forcing were available. Building on state-of-the-art model simulations allowed for properly taking into account effects of highly variable environmental conditions. Although most of our material presented referred to a description of average conditions, we also illustrated how post-processing detailed drift simulations could support interpretation of time series observed at specific locations.

We simulated litter transport both forward and backward in time. From a monitoring perspective, backward simulations seem appropriate, as they allow for the identification of characteristic sectors from which litter predominantly arrives. Unfortunately, however, such an analysis does not directly tell where the litter originated from. For answering this question, we would have to know the exact time span (drift time) since the litter was released into the water. As litter is assumed to stay floating for long times, drift times of material will often exceed integration time (90 days in our study). However in reality, much additional uncertainty accumulates for longer drift times. As a consequence, the most relevant information with regard to a specific monitoring station seems to be an estimate of from where pollution most likely did not originate. Considering different monitoring stations the related question would be to which extent their regions of influence do not overlap.

Forward simulations allow for studying the impacts of hypothetical source regions. The probably most important benefit from such simulations is the identification of weather related trends in pollution to avoid misinterpretation in terms of trends in the strengths of pollution sources. As an example, Chrastansky et al. (2009) dealt with the monitoring of chronic oil pollution. Our study period of only nine years and our integration time of 90 days were too short to identify possible long term trends beyond the seasonal scale. Identification of long-term trends in average conditions requires multi-decadal hydrodynamic data, which are homogeneous in the sense that the hydrodynamic model used for their generation was not modified (e.g. updated) during the period studied. Such model results are typically generated in climate research. An example tool, on which long-term drift simulations could be based, is the data base coastDat described by Weisse et al. (2009).

By far the largest uncertainty entering any transport calculation is quantification of a proper wind drift factor. Even when experimental data were available, it would obviously be meaningless to provide one value for marine litter as a whole. Alternatively one might draw different wind drift factors for individual tracer particles from estimated or assumed probability distribution. But again the distribution would be uncertain and results might be irrelevant from a practical point of view. We therefore propose provision of simulations with a number of discrete wind drift factors. If users were interested in studying specific items like fishing gears or bottles, for instance, they would have to estimate an appropriate wind drift factor and base their analysis on corresponding simulations.

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