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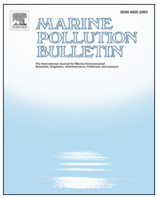

Distribution and trajectories of floating and benthic marine macrolitter in the south-eastern North Sea

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ABSTRACT

In coastal waters the identification of sources, trajectories and deposition sites of marine litter is often hampered by the complex oceanography of shallow shelf seas. We conducted a multi-annual survey on litter at the sea surface and on the seafloor in the south-eastern North Sea. Bottom trawling was identified as a major source of marine litter. Oceanographic modelling revealed that the distribution of floating litter in the North Sea is largely determined by the site of origin of floating objects whereas the trajectories are strongly influenced by wind drag. Methods adopted from species distribution modelling indicated that resuspension of benthic litter and near-bottom transport processes strongly influence the distribution of litter on the seafloor. Major sink regions for floating marine litter were identified at the west coast of Denmark and in the Skagerrak. Our results may support the development of strategies to reduce the pollution of the North Sea.

1. Introduction

Marine litter has accumulated over recent decades in all habitats of the world's ocean from urban coastal waters (Browne et al., 2011) to most remote, supposedly unspoiled environments, such as the polar regions (Obbard et al., 2014) and the deep sea (Bergmann and Klages, 2012, Pham et al., 2014). Marine litter is causing harm to a great variety of organisms (Kühn et al., 2015), affects the functioning of marine ecosystems (Green et al., 2015) and has adverse economic and human health effects (Thompson et al., 2009). Although numerous national and international legislative measures have been brought into action to combat marine litter (Hastings and Potts, 2013) quantities of marine litter are still increasing worldwide (Jambeck et al., 2015) indicating a poor control of major litter sources and inappropriate waste management.

There is a consensus that preventing litter from entering the marine environment should be given priority over the removal of litter which has already escaped from controlled waste streams (van Franeker and Law, 2015) because the broad and unselective removal of large quantities of litter from the oceans is inevitably associated with a simultaneous extraction of considerable amounts of marine biological production and damage to sensitive environments. However, the ecological impacts of clean-ups can be reduced if extraction activities are focused on strategically selected and easily accessible sites where litter accumulates, for example, due to local oceanographic conditions (Sherman and van Sebille, 2016). Therefore, a sustainable and environmentally sound strategy to reduce marine litter requires the identification of major input pathways of marine litter as well as an understanding of the trajectories and deposition sites of litter items in the marine environment.

Major sources of marine litter can often be inferred from the litter composition. For example, derelict fishing gear and shipping equipment clearly point at maritime activities as a source. A spatial correlation of the quantities of certain litter items and their supposed source activity strongly indicate local input and deposition. For example, Tekman et al. (2017) identified intensified fisheries activities around the Svalbard archipelago as a source of increasing amounts of litter on the seafloor of the nearby Fram Straight. Alternatively, a diffuse distribution of litter unrelated to possible source activities may indicate near-bottom transport of objects after deposition. Resuspension and near-bottom transport of seafloor litter may be induced by the joint action of waves and tidal currents as well as other environmental factors, such as seafloor topography and river plumes (Schlining et al., 2013).

The global distribution of marine litter and major accumulation

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zones in the oceans, such as the oceanic subtropical convergences, are well known from extensive field surveys and oceanographic modelling (Lebreton et al., 2012; Maximenko et al., 2012; Cózar et al., 2014; Eriksen et al., 2014). However, in coastal waters and shelf sea regions the distribution and trajectories of marine litter are more variable and often less understood due to the diverse coastal sources of marine litter and the difficulties in modelling the trajectories of flotsam in oceanographically complex coastal waters. The prediction of trajectories and distribution patterns of marine litter is further complicated by the poor skill of predicting the sinking of items. The loss of buoyancy of a floating litter item can be induced by colonization by marine organisms (Ye and Andrady, 1991) or by water intrusion upon damage, e.g. in PET drinking bottles. Accordingly, the distribution and composition of litter on the seafloor are the result of at-site deposition from local activities, the import of sinking items from the sea surface, and near-bottom transport. The relative importance of the import of sinking items from the surface may become evident from the degree of similarity in the composition and distribution of litter at the sea surface and on the seafloor with strong correlations indicating frequent import from the sea surface whereas no correlation would indicate that other processes than import from the surface shape the distribution and the site specific composition of benthic litter.

In this study we investigate the distribution and composition of marine debris at the sea surface and on the seafloor of the south-eastern North Sea. We conducted a multi-annual survey which produced an extensive data base on the spatio-temporal distribution of marine litter with considerable spatial coverage. Oceanographic models were used to investigate forward and backward trajectories of real floating items on the scale of the entire North Sea in order to identify potential source regions and important sites of deposition. Additionally, advanced methods of species distribution modelling were applied to benthic litter to identify the processes that shape the distribution of marine debris on the seafloor.

2. Material and methods

2.1. Study area

The North Sea, which is part of the north-eastern Atlantic shelf, is a marginal sea with a surface area of 575,300 km^2 (ICES, 1983). The largest exchange of waters between the North Sea and Atlantic Ocean is between the Shetland Islands and Norway. According to Otto et al. (1990) two main water bodies can be distinguished in the North Sea. The water masses in the northern and central parts bear characteristics of oceanic water with surface salinities above 34 (Weichart, 1986; Huthnance, 1991) and seasonal stratification (Pingree et al., 1978). The southern North Sea receives oceanic waters mainly through the British Channel. This area is subject to large continental runoff resulting in salinities below 30 in the coastal regions. Due to strong tides the shallow southern North Sea waters are permanently well mixed. Tidal and wind forcing in concert drive an anti-clockwise residual circulation along the coasts (Otto et al., 1990; Huthnance, 1991; Pohlmann, 2006). Several frontal systems separate the oceanic-like water masses of the central North Sea from the coastal waters.

The German Bight in the south-eastern North Sea is bordered by the Frisian Islands. Large tidal flats extend between these barrier islands and the coast constituting the major part of the Wadden Sea. This shallow water body is one of the most prominent regions of freshwater influence world-wide being under riverine influence of the rivers Rhine, Meuse, Ems, Weser, Elbe and Eider. The runoff from some of these rivers is considerable (e.g. $\sim 1000\ \text{m}^3\,\text{s}^{-1}$ for the river Elbe; Dippner, 1993). Salinity increases from about 30 in the Wadden Sea to 31–33 at the island of Helgoland, which is located about 50 km offshore. Water moves from the German Bight along the Danish coast into the Skagerrak. A pronounced frontal system along the 30 m depth contour separates the coastal waters from the more saline offshore waters of the German Bight (Krause et al., 1986; Budéus, 1989; Becker et al., 1992; Dippner, 1993; Skov and Prins, 2001).

2.2. Quantities and distribution of floating litter

Floating marine litter was quantified between 2006 and 2016 on 9 cruises of the German research vessel *Heincke* in the German sector of the North Sea, which were part of extensive marine benthos surveys. Data collected between 2006 and 2008 have been published previously by Thiel et al. (2011). Floating litter items were counted from aboard the vessel during transits between benthos sampling stations. We recorded type and position of all floating macrolitter items (i.e. objects detectable with the naked eye) within a range of 20 to 70 m perpendicular to the ship's track for the years 2006 to 2008. During subsequent surveys (years 2014 to 2016) objects were recorded within a shorter range of 10 to 20 m. For each transect we recorded the start and end position from a hand-held GPS. The position of each floating litter item was recorded as the observer position at the time when the item was passing by.

Floating litter was recorded only at daytime and during periods of good visibility. During the observations the ship speed varied between about 5 and 11 knots. In total, 78 sea surface transects were surveyed (Fig. 1). The length of transects varied between 4.7 and 25.1 km. The strip transect method was used to calculate the density *D* (items km^{-2}) of floating litter items for each transect (for details see Hinojosa et al., 2011) using the following equation:

$$D = N/((W/1000)\cdot L) \tag{1}$$

where N = the number of items counted, W = the width of the transect and L = the length of the transect in km.

Given the patchy distribution of flotsam visual ship based observations along extended transects are a particularly good method to determine the quantity and distribution of surface litter. The exact position of each single item is recorded allowing for a precise description of mesoscale variations in litter densities. Additionally, the considerable area covered by single transects allows for integration at different spatial scales to obtain representative average densities.

2.3. Quantities and distribution of litter on the seafloor

Densities of litter on the seafloor were determined from beam-trawl hauls which were taken routinely during benthos surveys in the years 2014 and 2016. A 2 m-beam trawl (mesh size: 1 cm) was towed at an average speed of about 1–3 knots. Trawling distance was calculated from the GPS positions where the winch stopped veering (start trawling) and started hauling (end trawling). The beam trawl was operated during day and night time and was largely independent of the sea state allowing for a total of 122 hauls (Fig. 1). All litter items retrieved from the net were identified and counted. Photographs were taken of each item. At two stations numerous fibers from fishing nets were tightly knotted to bunches and could not be counted individually. The number of single fibers in those bunches were estimated from photographs. Eq. (1) was also used to calculate the density *D* of benthic litter items (items km^{-2}) for each haul with W = the width of the beam trawl (here: 2 m) and L = the trawling distance in km.

For the qualitative description of the litter composition at the sea surface and at the seafloor we adopted the litter categories defined by Thiel et al. (2013): plastics, styrofoam, glass, metal, wood, paper and other. Additionally, we added the category “organic matter” (e.g. peels of citrus fruits). Wooden items were recorded as litter if they showed clear signs of manufacturing. We contrasted the composition of the total surface litter and the total seafloor litter (i.e. data from all years pooled) with a χ^2-test based on a 2×8 contingency table.

We tested for correlation of litter densities at the surface and on the seafloor. Densities of floating litter at the surface were estimated on transects between the seafloor stations. To obtain spatially