Impact of secondary hard substrate on the distribution and abundance of *Aurelia aurita* in the western Baltic Sea

Janßen, H.[1,*], Augustin, C.B.[1,2], Hinrichsen[3], H.H., Kube, S.[4]

[1] Leibniz Institute of Baltic Sea Research Warnemuende (IOW), Seestrasse 15, 18119 Rostock-Warnemuende, Germany
[2] University of Rostock, Aquaculture and Sea-Ranching, Faculty of Agricultural and Environmental Sciences, Justus-von-Liebig-Weg 6, 18059 Rostock, Germany
[3] GEOMAR - Helmholtz Center for Ocean Research Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany
[5] University of Rostock, Institute of Biosciences, Aquatic Ecology, Albert-Einstein-Str. 3, 18059 Rostock, Germany

* Corresponding author. Tel. +49 381 5197 469, E-mail address: holger.janssen@io-warnemuende.de

Abstract

This study assessed the impact of secondary hard substrate, as being introduced into marine ecosystems by the establishment of wind farm pillars, on the occurrence and distribution of the moon jelly *Aurelia aurita* in the southwestern Baltic Sea. A two-year data sampling was conducted with removable settlement plates to assess the distribution and population development of the scyphozoan polyps. The data collected from these samples were used to set up a model with Lagrangian particle technique. The results confirm that anthropogenic created hard substrate (e.g. offshore wind farms) has the potential to increase the abundance of the *Aurelia aurita* population. The distribution of wind farm borne jellyfish along Danish, German and Polish coasts indicates conflicts with further sectors, mainly energy and tourism.

1. Introduction

The generation of renewable energy by offshore wind farms is likely to increase significantly in the western Baltic Sea despite of current delays in the implementation of already approved wind farms. In March 2012 Denmark passed a new Energy Agreement with the target of 100% renewable energy in 2050 (ENS, 2012). Already in 2020 half of the energy consumption shall be covered by wind farms. The energy concept of the German Government aims at a share of 50% for offshore wind farms in the national energy production by 2050 (BMU, 2011). A capacity of 25 GW shall be installed offshore until 2030. Sweden's energy policy foresees a 50% share of renewable energies with 10 TWh offshore wind energy production in 2020 (Regeringskansliet, 2009). This will lead to a considerable expansion of today's offshore wind farms in the western Baltic Sea, where single wind farms have already been built in Danish and German waters during recent years.

A number of studies researched local impacts of wind farms on benthic communities in the region (e.g. Birklund & Petersen, 2004; DHI, 2000; DHI, 2006a; DHI 2006b; Petersen & Malm, 2006). Wind farms as well as other fixed offshore installations such as platforms, piles and pillars act as artificial reefs (Petersen & Malm, 2006; Maar et al., 2009; Wilhelmson et al., 2006; Wilhelmson & Malm, 2008). These provide substrate for organisms which would not be able to settle on the original soft sediments (Svane & Pedersen, 2001). This issue is of high relevance in the western Baltic Sea where predominant soft-sediments (Emeljanov et al., 1993; Hermansen & Jensen, 2000) limit the spectrum of organisms. An organism that might benefit from this additional secondary hard substrate is the moon jellyfish *Aurelia aurita*. Scyphozoans like *A. aurita* have a life cycle consisting of planktonic sexually-reproducing medusae and benthic asexually-reproducing polyps (Möller, 1979; Gröndahl, 1988; Lucas, 2001). The benthic polyps need hard substrate to settle on. From these polyps ephyrae are released by strobilation and further develop into medusae. The medusae in turn reproduce by the release of planula larvae which develop again into polyps. In accordance with these development stages *A. aurita* populations are found predominantly in those areas where suitable hard substrata are available for the benthic scyphistoma (Lucas, 2001).

Several studies suggest that anthropogenic installations might favor problematic occurrence of massive numbers of jellyfish (Duarte et al., 2013). These so called jellyfish blooms were related to factors such as climate warming, eutrophication, overfishing, aquaculture, invasion of non-native species by marine traffic and maritime constructions (Purcell et al. 2007). The increasing amount of artificial underwater hard substrate by maritime constructions is

expected to provide new habitats especially for the settlement and reproduction of benthic stages of scyphozoan jellyfish such as *A. aurita*. Considering rising numbers of marinas, harbor expansions, wind farms, which are located in the western Baltic Sea (Janßen et al., 2013), increased benthic polyp colonies and subsequently increased medusa blooms are likely for the Baltic Sea.

Jellyfish species are of high ecological importance by its functional value in the marine pelagic ecosystem acting as predator for native zooplankton and competitor for commercially important planktivorous fish species. If scyphomedusae occur with high abundance they have impacts on zooplankton communities (Barz & Hirche, 2005). A reduction of zooplankton and herring larvae populations caused by *A. aurita* in the western Baltic is documented e.g. by Möller (1980a) and Schneider & Behrends (1998). Experiments showed also predation on cod larvae (Baily & Batty, 1984; Titelman & Hansson, 2006). This is of importance for the southwestern Baltic as it is characterized by various Marine Protected Areas (MPA) administered under European Natura 2000 legislation. As shown by Barz et al. (2006) also remote areas might be affected by the occurrence of *A. aurita* due to drift over larger distances.

Up to 21 wind farms are planned in the study area, of which three are already build and four recently received an approval. The present study modeled the impact of secondary hard substrate on the occurrence and distribution of juvenile *A. aurita* on a regional scale by using a hydrodynamic model with particle tracking technique. The study is structured into four steps. First, data on the spatial and temporal patterns of *A. aurita* occurrence were collected by in situ experiments in the southwestern Baltic Sea. Secondly, to assess the spatial movement of *A. aurita* towards and also from secondary hard substrate at wind farms, a drift model with particle tracking technic was set up on the basis of this these sampling data. Thirdly, the potential abundance of *A. aurita* released from wind farms was estimated on the basis of current wind farm construction plans. Finally the drift simulation results have been analyzed to further identify affected areas and possible conflicts.

2. Material & Methods

2.1 Data sampling

The seasonal and temporal distribution of benthic developmental stages (polyps) and pelagic developmental stages (ephyrae and medusae) of *Aurelia aurita* were studied in 2009 and 2010 in the southwestern Baltic Sea.

To assess the distribution and population development of the scyphozoan polyps, off-shore polyp settlement experiments were carried out in Fehmarnbelt and in Mecklenburg Bight. Mooring systems with removable settlement plates were installed at 4 stations in the southwestern Baltic Sea in Mecklenburg Bight in July 2009 (Fig. 1).

[Figure 1 about here]

Areas with a water depth more than 15 m allowed polyp sampling at two different water layers (above and below the halocline). At these stations, two settlement frames, were installed above each other on the same mooring (Fig. 2). Each settlement frame had about 1 m diameter and consisted of 12 removable settlement plates, attached to three horizontal arms (Fig. 2). The rectangular settlement plates were made of concrete and had a total settling area of 190 cm^2 (horizontal settling area on the upper and bottom side each 75 cm^2, vertical settling area 40 cm^2).

[Figure 2 about here]

Planula larvae released in summer and autumn were expected to attach on the plates and develop into polyps during autumn and winter. Concrete was chosen as material because wind farm foundations and piles in the southwestern Baltic with typical water depths below 40 m may partly or fully be made out of concrete (Larsen et al., 2005; STRABAG, 2013). Such an example is the existing Lillgrund wind farm southeast of Sweden (Vattenfall, 2008). Another common material for the construction of wind farm piles in the case study region is steel with epoxy or polymer coatings. *A. aurita* polyps are able to settle also on this substrate (Ishii & Katsukoshi, 2010) and their abundance on polymeric materials may be higher than on concrete (Holst & Jarms, 2007). Sampling of settlement plates and counting of polyps was carried out monthly during the annual polyp growth and strobilation period in two successive years (October 2009 - April 2010, November 2010 - April 2011). In this study we only present the polyp abundances for the second measured settling season (November 2010 - April 2011) after 1.5 years of mooring deployment. This means that the moorings were

exposed to planula larvae settling for two seasons (summer 2009 and summer 2010) before sampling.

Settling plates were collected either by craning the whole mooring out of the water on a research vessel or by scientific scuba diving. In case of craning, the settling frames were submersed in habitat water tanks on board of the vessel during removing the settling plates. For transport to the laboratory the removed plates were placed in habitat water containers and stored at habitat temperature. Polyps were counted and measured alive at each settling side of the plate under a stereomicroscope within 1 day after sampling. The abundance of polyps attached upright at the upper side of the plate, upside down on the bottom side of the plate and horizontally positioned on the vertical edge was calculated separately and was expressed as polyps cm^{-2}.

To assess the abundance of pelagic developmental stages of *A. aurita*, monthly samples were taken at 12 stations in the southwestern Baltic Sea between June 2009 and December 2010 (Fig. 1). The medusae field survey in the southwestern Baltic Sea covered an area between Kiel Bight in the West and Darss Sill in the East. Samples were taken by using a MultiPlanktonSampler (MPS, opening area 0.25 m^2, mesh size 500 µm), which was towed horizontally with a maximum inflow speed of about 1 m s^{-1}. Two electronic flow-meters measured the filtrated water volume (100-200 m^3). Collected ephyrae and medusae of *A. aurita* were counted alive directly after sampling and the bell size (diameter) of each individual was determined. Specimens <0.5 cm were considered as ephyrae. The abundance of ephyrae and medusae was calculated (individuals m^{-3}) from the number of counted specimens and the filtrated volume of water.

2.2 Hydrodynamic model and particle tracking technique

To assess the distribution of *A. aurita*, both from today's potential habitats and from additional settlement areas provided by offshore wind farms, a hydrodynamic model and Lagrangian particle technique was used. A comprehensive description of those methods was published by Lehmann (1995) and Hinrichsen et al. (1997). The hydrodynamic model used in this study is based on the free surface Bryan-Cox-Semtner model (Killworth *et al*., 1991) which is a special version of the Cox numerical ocean general circulation model (Bryan, 1969; Semtner, 1974). The Baltic Sea model domain comprises the entire Baltic Sea. The horizontal resolution is 2.5 km, with 60 vertical levels specified. The Baltic Sea model is driven by atmospheric data provided by the Swedish Meteorological and Hydrological

Institute (SMHI: Norrköping, Sweden) and river runoff taken from a monthly mean runoff database (Bergström & Carlsson, 1994). Prognostic variables of the model are the baroclinic current field, the 3-D temperature, salinity and oxygen distributions, the 2-D surface elevations and the barotropic transport, all of them available at six hour intervals. Physical properties simulated by the hydrodynamic model agree well with known circulation features and observed physical conditions in the Baltic. A detailed description of the equations and modifications made, necessary to adapt the model to the Baltic Sea can be found in Lehmann (1995) and Lehmann & Hinrichsen (2000a). A detailed analysis of the Baltic Sea circulation has been performed by Lehmann & Hinrichsen (2000b) and by Lehmann *et al.* (2002). Data on the number and location of *A. aurita* at different life stages for particle tracking was gained from the sampling studies (see sampling results below). In accordance with the sampling results each simulation run started in November with strobilation starting in December. And the simulation stopped in June when most juvenile medusae were from this time on able to move actively and to change water layers.

The model was run for a time period of 12 years (1997-2008). To establish a Lagrangian view of the simulated circulation, drifters can be placed in the modeled flow fields at every 3-D position within the model domain. Moreover, the initial release locations of the drifters can be chosen independent of the vertical resolution of the model's grid. Simulation of juvenile medusae (ephyrae) drift patterns were obtained from three-dimensional Eulerian flow fields from the hydrodynamic model by utilization of a Lagrangian particle tracking technique. The drifters were allowed to leave the vertical positions where they initially were released, thus the positions of the drifter varied over time as a result of the three-dimensional velocities experienced. Furthermore, along the tracks, the data contained information on the temporal evolution of hydrographic properties (temperature, salinity) as well as on bottom depths.

Simulations of intra- and interannual variations in the drift routes of the juvenile medusae were performed for their reproduction periods from 1997 to 2008. For the whole simulation period, ephyrae were released as Lagrangian drifters in coastal and shallow water areas of the western Baltic at depths between the surface and 10 m (Fig. 2). The water depth for the release of drifters was chosen in accordance with results of the polyp settlement experiments (cf. chapter 3.1 and tab. 1 below). However, the total area where strobilation of ephyrae from polyps in the western Baltic could take place is unknown. Every drifter release position located in coastal or shallow waters represents an area of approximately of 25 km^2. It was

assumed that all these drifter release areas have the potential to contribute to juvenile medusae populations, as polyps can find sheltered areas with their preferred conditions (cf. Möller, 1979; Möller, 1980b; Gröndahl, 1988) and adequate natural (hard-bottom substrate, rocks) and anthropogenic hard substrate (marinas, ports, hardened shorelines etc.) is available (Tauber, 2012).

A total of 7104 ephyrae were inserted as particle drifters into the modeled flow fields at 10-day intervals, i.e. every 10 days a new batch of ephyrae was started to drift. The release dates started the 1st of November and ended the 28th of February, thereby covering the presently known reproduction period of this species. The whole set of drifter batches were tracked until the 15th of April, when the drifters were re-located in the vertical domain (0 - 10 m). The latter was necessary to be done to realistically start vertical feeding migrations of the juvenile medusae on zooplankton species/stages (Hernroth & Gröndahl, 1985). Afterwards the drifters were tracked until 30th of June utilizing the same parameters and requirements as during the drift period before.

Furthermore, in order to demonstrate the degree of retentive or dispersive variability of the drift patterns of the juvenile medusae we have calculated how many of them were located in different regions of the western and central Baltic Sea at the end of the simulation period.

A second goal of our drift analyses was to estimate the impact of anthropogenic created hard substrate (e.g. offshore wind farms) on the final distribution of the juvenile medusae. For this purpose, at the positions of planned as well as at positions of already established offshore wind farms (Fig. 3) additional batches of ephyrae drifters were released into the modelled flow fields covering the same time periods and requirements as for the "regular" released drifter batches.

[Figure 3 about here]

3. Results

3.1 Field sampling of polyp and medusa distributions

The abundance of settled polyps varied between 0.1 individuals cm^{-2} and 6.1 individuals cm^{-2} above the halocline during the sampling period between November 2010 and April 2011 in the investigation area. Highest polyp abundances were observed at the bottom side of the settling plates compared to lower abundances on the upper side and the vertical edge (tab. 1).

The mean abundance in the entire investigation area was 1.07 individuals cm^{-2} above the halocline. Below halocline the abundance reached up to 1.7 individuals cm^{-2} during the investigation period (mean 0.3 individuals cm^{-2}). Polyps were not equally distributed across the settling plate surface but occurred in patches. The highest patch density was observed with 30 individuals cm^{-2}.

[TABLE 1 about here]

According to current construction plans the majority of wind farms in the case study region shall be built with monopiles. A typical diameter for these piles is about 6 m and about 830 piles are planned. Based on the sampling results for vertical substrate and considering a recruitment rate of six ephyrae per polyp during one reproductive season (Holst & Jarms, 2010) this could potentially lead to 4.64 bn individuals being released from wind farm piles in the upper 10 m of the water column. On the settlement plates no polyps were found on vertical surfaces below 10 m water depth.

Considering the entire medusae investigation area (Kiel Bight in the West to Darss Sill in the East), the mean abundance of *A. aurita* medusae was 0.095 individuals m^{-3} in summer 2009. Peak values of up to 0.4 and 0.6 individuals m^{-3} were measured in June and July in the region of Darss Sill. The abundance decreased in autumn 2009 (mean 0.013 individuals m^{-3}). In 2010 the abundance of *A. aurita* varied constantly around 0.02 individuals m^{-3} from summer to autumn. In both years, there was a tendency of higher abundances in the eastern part of the medusae study area (Darss Sill) compared to the western study area (Kiel Bight; tab. 2).

[TABLE 2 about here]

3.2 Model

A general interesting feature of the cumulative distribution, representing the whole number of medusae initially released between 1997 and 2008, is that some open sea areas (central Arkona and Bornholm Basin) as well as the northern coastal and shallower regions of the Bornholm Basin exhibit a low probability of medusae occurrence (cf. fig. 7). Secondly, there are predictions obtained for other areas to be permanently associated with high abundances of medusae (e.g. Kattegat). The relative final mean distributions of all released drifters between 1997 and 2008 show that the majority of juvenile medusae remained within the release areas

(Fig. 4), transport between the release areas as well as losses out of the release areas were only of minor importance. Figure 5 shows final mean particle distributions for ephyrae released at the locations of planned and partly already existing offshore wind farms.

[FIGURE 4 about here]

[FIGURE 5 about here]

Marked differences in drift characteristics of juvenile medusae are apparent when comparisons are made between simulations conducted for different years. During the reproduction periods 2000/2001 and 2006/2007 a wide coverage of juvenile medusae in almost the whole western Baltic Sea area was obtained. The most striking differences between the two time periods could be related to medusae abundances in the Polish coastal environment (Fig. 6).

[FIGURE 6 about here]

To determine the fractions of juvenile medusae which were released from potential natural habitats and were able to reach offshore wind farms at the end of the simulation period (30th of June), we have calculated the mean distances of these fractions apart from the wind farm locations (Fig. 7). Not very surprisingly, with increasing distance range the probability of medusae occurrence increased, but the fraction occurring closest to the wind farm locations (< 20 km) could be remarkably high (> 10%).

[FIGURE 7 about here]

For juvenile medusae, originally released by those subpopulations utilizing offshore wind farms as secondary hard substrate (cf. fig. 3), the probability of particle transport towards shallow or coastal areas (<20m bottom depths) was obtained to be on average extremely high (0.38). This affects coastal but also offshore Marine Protected Areas (MPA), of which a large share underlies an occurrence of wind farm borne jellyfish (Fig. 8). To assess the pressure caused by these jellyfish on MPAs the potential number of additional individuals of *A. aurita* occurring in Natura 2000 sites was calculated for the end of the simulation period (30th of June). This calculation is based on an average polyp concentration of 0.5 polyps cm^{-2} and a strobilation rate of 6 ephyrae/polyp. It neglects mortality e.g. by predation or by bycatches in fisheries. Eight MPAs can potentially be affected by an additional occurrence of more than one jellyfish m^{-2} integrated over the whole water column (tab. 3). Peak values reach up to a potential of 1.3 individuals m^{-2}.

[TABLE 3 about here]

[FIGURE 8 about here]

Spatial analyzes of the drift patterns show a strong transnational dimension of the distribution of wind farm borne jellyfish. In the given example most of the planned wind farms are located in waters under German administration. The majority of *A. aurita* individuals released from them, however, are drifting into none-German waters (71.25% by 30th of June) (tab. 4). Here especially Danish waters are affected where more than a half of all drifters move to.

[TABLE 4]

4. Discussion & Conclusions

The results of our study have provided new knowledge and insight on the potential small to meso-scale ecological impact of human-induced habitat extension of the invertebrate *Aurelia aurita* in the western Baltic. However, local changes of juvenile medusae distributions are sensitive to the time of release. This means that ephyrae transport depends on atmospheric conditions in terms of the direction and of the strength of the prevailing forcing.

This study was focused on the drift of virtual ephyrae and virtual juvenile medusae released into simulated flow fields as passive particles. The chosen model approach might be complicated by individual swimming behavior of the medusae. In this study horizontal swimming was assumed to be generally less important in comparison to the flow fields. Hamner et al. (1994) reported average horizontal swim speed during day times of 2.33 ± 0.30 m min^{-1} with very slow or no swimming during the night while the western Baltic Sea shows average current speeds above 3 m min^{-1}. Nonetheless, to avoid too disperse scatter the annual simulation runs were stopped in June and new drifters restarted from the release areas in the following year. Medusae are also able to actively change their vertical position in the water column (Mackie et al., 1981). However, during the pelagic sampling medusae were generally found in the upper part of the water column (cf. Barz & Hirche, 2005), thus it could not be expected that differences in the vertical position might significantly alter the drift routes.

The results presented in Fig. 8 confirm that anthropogenic created hard substrate (e.g. offshore wind farms) has the potential to significantly increase the settlement probability of scyphozoan polyps, which possibly could lead to an increase in abundance and in an extended spatial distribution of the medusae population of *A. aurita*.

Dependent on temperature, light and salinity conditions the planned installation of about 830 wind mills has the theoretic potential to cause about 4.6 billion ephyrae being released from pile based polyps. These numbers, however, are based on the theoretic potential which is an unsure estimate and dependent on the used material for foundations and piles (e.g. concrete, steel with or without anticorrosive coating, type of coating etc.). Furthermore it neglects mortality, e.g. by predation or by-catch, and will vary from year to year. Also the development of stable habitats around wind farm piles over time (Zettler & Pollehne, 2006) will influence the occurrence of *A. aurita*. Settlement of blue mussels *Mytilus edulis* for instance will increase the potential settling surface area for *A. aurita* larvae on wind farm piles and thus cause an increase of polyp abundances. Moreover, the asexual reproduction of polyps will increase polyp colony densities. Miyake et al. (2002) found up to 88 polyps cm^{-2} in Kagoshima Bay, Japan and Gröndahl (1988) reported up to 40 polyps cm^{-2} in Gullmar Fjord. On the other hand predation on *A. aurita* might increase with the development of complex habitats on and around wind farm piles. However, offshore wind farms will potentially contribute to an increased occurrence of *A. aurita* in Marine Protected Areas of partly more than one additional medusa m^{-2}. Especially in those MPAs with sandbanks *A. aurita* may act as a predator e.g. on copepods and fish larvae with potential impacts on the food web. Single MPAs like Adlergrund or Oderbank serve as spawning areas for cod or herring. In these spawning grounds increased abundance of *A. aurita* may lead to direct impacts on fish recruitment.

Independent from the question with which abundance additional individuals might occur, already the spatial distribution raises new questions for the cross-border management of marine areas. The insertion of larger amounts of secondary hard substrate into marine systems which are dominated by soft sediments may lead to impacts in remote regions over a distance of more than 150 km. While in this study most of the wind farms are located in waters administrated by one nation, here Germany, the impact occurs mainly in neighboring waters, here especially Denmark followed by Sweden and Poland.

The distribution of wind farm borne jellyfish along Danish, German and Polish coasts indicates conflicts with further sectors, mainly fisheries and tourism. Increased appearance of *A. aurita* may impede coastal tourism, e.g. on Darss peninsula, as tourists often perceive jellies in general as annoying. And *A. aurita* is able to clog fishing nets and the distribution if wind farm borne jellies partly overlaps with areas of intense fishing effort (cf. Pedersen et al., 2009). However, so far there are no reports about clogged fishing nets in the Baltic Sea. In

any case the spatial distribution of *A. aurita* across borders gives an example of how impacts of anthropogenic activities in marine region may spread over larger distances.

Within the conditions of the partly brackish Baltic Sea the impact of secondary hard substrate on the occurrence of *A. aurita* concentrates on the Western and Central Baltic Sea. Medusae drifting into the Central Baltic Sea, e.g. into Bornholm Basin, are able to survive decreasing salinities (around 7 PSU between surface and halocline) but may usually not reproduce there (Barz & Hirche, 2005; Janas & Witek, 1993).

Hydrographical conditions and the location of wind farms determine the distribution of wind farm borne jellyfish. It is therefore worth discussing whether Marine Spatial Planning (MSP) should and could be based on the consideration of abiotic and biotic functions to improve a cross-border marine management as well as the management of cross-border environmental impacts (ecosystem-based MSP). According to the UNECE Convention on Environmental Impact Assessment in a Transboundary Context (Espoo/EIA Convention) and the UNECE Protocol on Strategic Environmental Assessment to the Convention on Environmental Impact Assessment in a Transboundary Context (Kyiv/SEA Protocol) a state who plans a project (or develops a plan) with significant cross-border impacts, has to inform affected states as early as possible. This has to include also a broad public participation to bring together all stakeholders. Usually this fails to appear on MSP level as the potential impact of wind farm borne jellies is not detected or not considered as being significant. But as shown in this study an assessment of the cumulative impact of all wind farms is helpful to identify potential conflicts with protection goals or with other economic sectors. In the spirit of the EIA Convention and the SEA Protocol this should be done on a transnational level. And following the MSP definition of the UNESCO-IOC (IOC, 2013) whereupon MSP is public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives, such assessments should be done not only in the framework of a licensing procedure but already on MSP level. As shown in the given example such assessments are able to identify issues which are of relevance for regional development both in the sea and on land.

The present study suggests the applicability of hydrodynamic models to assess the drift and resulting spatial distributions of juvenile *A. aurita* stages in the western Baltic Sea. However, close agreements between observations and simulations could not be expected, hence comparisons of observed spatial distributions of settled medusae with model results have not been performed. Any kind of quantitative comparison requires detailed model input

information, i.e. variations in spatial distributions of polyps, as well as about timing and lengths of the reproduction period. Additionally, during their drift period ephyrae are exposed to processes which are presently not well known, e.g. rate-dependent processes like stage development or mortality due to predation and starvation.

Nevertheless, our numerical simulations provide detailed information about the current patterns that allow the identification of transport features, which can be inferred neither from theoretical analyzes nor from extensive field experiments. As a novel opportunity, the drift model results could in combination with favorable environmental forcing conditions investigate the role of newly generated habitats (e.g. offshore wind farms as secondary hard substrata) that are potentially susceptible to lead to species outbreaks. Because our modeling approach reflects the high degree of the predictive capacity of circulation and operational models, it could be used to determine the probability that an outbreak could occur at specific locations and times with respect to the interaction of different specific drivers (e.g. climate and anthropogenic changes).

Acknowledgement

Literature cited

Barz, K., Hirche, H.-J., 2005. Seasonal development of scyphozoan medusae and the predatory impact of *Aurelia aurita* on the zooplankton community in the Bornholm Basin (central Baltic Sea). Mar. Biol. 147 (2), 465-476. doi: 10.1007/s00227-005-1572-2

Barz, K., Hinrichsen, H.-H., Hirche, H.-J., 2006: Scyphozoa in the Bornholm Basin (central Baltic Sea)–The role of advection. J. Mar. Systems 60 (1–2), 167–176. doi: 10.1016/j.jmarsys.2006.01.002

Baily, K.M., Batty, R.S., 1984. Laboratory study of predation by *Aurelia aurita* on larvae of cod, flounder, plaice and herring—development and vulnerability to capture. Mar. Biol. 83: 287–291. doi: 10.1007/BF00397461

Bergstrøm, S., Carlsson, B., 1994. River runoff to the Baltic Sea: 1950-1990. Ambio 23(4-5), 280−287.

Birklund, J., Petersen, A.H., 2004. Development of the fouling community on turbine foundations and scour protections in Nysted Offshore Wind Farm, 2003. Energi E2 A/S Report June 2004: 39 p.

BMU, 2011. Eckpunktepapier der Bundesregierung zur Energiewende vom 6.6.2011. Bonn/Berlin: German Federal Environmental Ministry.

Bryan, K., 1969. A numerical method for the study of the circulation of the world ocean. J. Phys. Oceanogr. 15, 1312−1324.

DHI Water and Environment, 2000. VVM-redegorelse for Havmollepark ved Rodsand. Vurderng af virkningen pa hydrografi, vandkvalitet og morfologi. Baggrundsraport vol.19 SEAS. Horsholm.

DHI Water and Environment, 2006a. The hard bottom communities on foundations in Nysted Offshore Wind Farm and Schönheiders Pulle in 2005 and development ofthe communities in 2003–2005. Final Report. ENERGI E2 A/S, Hørsholm. http://www.nystedhavmoellepark.dk/, last assessed: 18 February 2013.

DHI Water and Environment, 2006b. Surveys of the Benthic Communities in Nysted Offshore Wind Farm in 2005 and changes since 1999 and 2001. Final Report.ENERGI E2 A/S, Hørsholm. http://www.nystedhavmoellepark.dk/, last assessed: 18 February 2013.

Duarte, C.M., Pitt, K.A., Lucas, C.H., Purcell, J.E., Uye, S., Robinson, K., Brotz, L., Decker, M.B., Sutherland, K.R., Malej, A., Madin, L., Mianzan, H., Gili, J.M., Fuentes, V., Atienza, D., Pagés, F., Breitburg, D., Malek, J., Graham, W.M., Condon, R.H., 2013. Is global ocean sprawl a cause of jellyfish blooms? Frontiers in Ecology and the Environment 11:2, 91-97. doi: 10.1890/110246

Emeljanov, E., Neumann, G., Lemke, W., 1993. Bottom Sediments of the Western Baltic. 1:500,000. Warnemuende/Moscow.

ENS, 2012. Aftale mellem regeringen og Venstre, Dansk Folkeparti, Enhedslisten og Det Konservative Folkeparti om den danske energipolitik 2012-2020. Copenhagen: Danish Energy Agency.

Gröndahl, F., 1988. A comparative ecological study on the scyphozoans *Aurelia aurita*, *Cyanea capillata* and *C. lamarckii* in the Gullmar Fjord, western Sweden, 1982 to 1986. Mar. Biol. 97, 541–550.

Hamner, W.M., Hamner, R.R., Strand, S.W., 1994. Sun-compass migration by *Aurelia aurita* (Scyphozoa): population retention and reproduction in Saanich Inlet, British Columbia. Mar. Biol. 119, 347-356.

Hermansen, B., Jensen, B., 2000. Digital Sea Bottom Sediment Map around Denmark. Danmarks og Groenlands Geologiske Undersoegelse, Rapport 68, 2000.

Hernroth, L., Gröndahl, F., 1985. On the biology of *Aurelia aurita (L.)*: 2 major factors regulating the occurrence of ephyrae and young medusa in the Gullmar Fjord, Western Sweden. Bul. Mar. Sci 37 (2), 567-576.

Hinrichsen, H.-H., Lehmann, A., St.John, M.S., Brügge, B., 1997. Modeling the cod larvae drift in the Bornholm Basin in summer 1994. Cont. Shelf Res. 17, 1765–1784.

Holst, S., Jarms, G., 2007. Substrate choice and settlement preferences of planula larvae of five Scyphozoa (Cnidaria) from German Bight, North Sea. Mar. Biol. 151 (3), 863-871.

Holst, S., Jarms, G., 2010. Effects of low salinity on settlement and strobilation of Scyphozoa (Cnidaria): Is the lion's mane *Cyanea capillata* (L.) able to reproduce in the brackish Baltic Sea? Hydrobiologia 645, 53-68.

International Oceanographic Commission (IOC), 2013: Marine Spatial Planning Initiative, http://www.unesco-ioc-marinesp.be/marine_spatial_planning_msp, last assessed: 18 February 2013.

Ishii, H., Katsukoshi, K., 2010. Seasonal and vertical distribution of *Aurelia aurita* polyps on a pylon in the innermost part of Tokyo Bay. Journal of Oceanography 66 (3), 329-336.

Janas, U., Witek, Z., 1993. The occurrence of medusae in the Baltic and their importance in the ecosystem, with special emphasis on *Aurelia aurita*. Oceanologia 34, 69–84.

Janßen, H., Kidd, S., Kvinge, T., 2013. A spatial typology for the sea: a contribution from the Baltic. Mar. Pol. 42, 190-197. doi: 10.1016/j.marpol.2013.03.001

Killworth, P.D., Stainforth, D., Webbs, D.J., Paterson, S.M., 1991. The development of a free-surface Bryan-Cox-Semtner ocean model. J. Phys. Oceanogr. 21, 1333–1348.

Larsen, J.H.M, Soerensen, H.C., Christiansen, E., Naef, S., Vølund, P., 2005. Experiences from Middelgrunden 40 MW offshore wind farm. Copenhagen offshore wind conference 2005, 1–8.

Lehmann, A., 1995. A three-dimensional baroclinic eddy-resolving model of the Baltic Sea. Tellus 47A, 1013–1031.

Lehmann, A., Hinrichsen, H.-H., 2000a. On the thermohaline variability of the Baltic Sea. J. Mar. Systems 25, 333–357.
Lehmann, A., Hinrichsen, H.-H., 2000b. On the wind driven and thermohaline circulation of the Baltic Sea. Phys. Chem. Earth (B) 25, 183-189.

Lehmann, A., Hinrichsen, H-H., Krauss, W., 2002. Effects of remote and local atmospheric forcing on circulation and upwelling in the Baltic Sea. Tellus 54A,299-316.

Lucas, C.H., 2001: Reproduction and life history strategies of the common jellyfish, *Aurelia aurita*, in relation to its ambient environment. Hydrobiologia 451, 229-246.

Lynam, C.P., Gibbons, M.J., Axelsen, B.E., Sparks, C.A.J., Coetzee, J., Heywood, B.G., Brierley, A.S. ,2006. Jellyfish overtake fish in a heavily fished ecosystem. Current Biology 16, R492-R493.

Maar, M., Bolding. K., Petersen, J.K., Hansen, J.L.S., Timmermann, K., 2009. Local effects of blue mussels around turbine foundations in an ecosystem model of Nysted off-shore wind farm, Denmark. J. Sea Res., 62, 159–174. doi:10.1016/j.seares.2009.01.008

Mackie, G.O., Larson, R.J., Larson, K.S., Passano, L.M., 1981. Swimming and vertical migration of *Aurelia aurita* (L) in a deep tank. Mar. Behav. Phys. 7 (4), 321-329. doi: 10.1080/10236248109386993

Möller, H., 1979. Significance of coelenterates in relation to other plankton organisms. Meeresforschung 27 , pp. 1–18.

Möller, H., 1980a. Scyphomedusae as Predators and Food Competitors of Larval Fish. Mar Res 28, 90-100.

Möller, H., 1980b. A summer survey of large zooplankton, particularly scyphomedusae, in North Sea and Baltic. Meeresforschung 28, 61–68.

Miyake, H., Terazaki, M., Kakinuma, Y., 2002. On the polyps of the common jellyfish *Aurelia aurita* in Kagoshima Bay. Journal of Oceanography 58, 451-459.

Pedersen, S.A., Fock, H.O., Sell, A.F., 2009. Mapping fisheries in the German exclusive economic zone with special reference to offshore Natura 2000 sites. Mar. Pol. 33 (4), 571-590.

Petersen, J.K., Malm, T., 2006. Offshore windmill farms: threats to or possibilities for the marine environment. Ambio 35, 75–80.

Purcell, J.E., Uye, S., Lo, W.T. , 2007. Anthropogenic causes of jellyfish blooms and their direct consequences for humans: a review. Mar. Ecol. Prog. Ser. 350, 153-174. doi: 10.3354/meps07093

Regeringskansliet, 2009. An integrated climate and energy policy - Information sheet about the Government bills 2008/09:162 and 163. Stockholm: Regeringskansliet.

Schneider G, Behrends G , 1998. Top - down control in a neritic plankton system by *Aurelia aurita* medusae - a summary. Ophelia 48: 71-82.

Semtner, A. J., 1974. A general circulation model for the World Ocean. UCLA Dept. of Meteorology Tech. Rep. No. 8, 99p.

STRABAG, 2013. STRABAG Serial System. http://www.strabag-offshore.com, last assessed: 2013-03-12

Svane, I., Petersen, J.K., 2001. On the problems of epibioses, fouling and artificial reefs, a review. Mar. Ecol. 22, 169–188.

Tauber, F., 2012. Meeresbodensedimente und Meeresbodenrelief in der deutschen Ostsee: Datenpositionen und Blattschnitt, Karte Nr. 2930 [Map] 1 : 550 000, 54°N. Hamburg: Bundesamt für Seeschifffahrt und Hydrographie.

Titelman, J., Hansson, L.J., 2006. Feeding rates of the jellyfish *Aurelia aurita* on fish larvae. Mar. Biol. 149, 297–306. doi: 10.1007/s00227-005-0200-5

Vattenfall, 2008. Technical description of Lillgrund Wind Power Plant, Report. Stockholm.

Wilhelmsson, D., Malm, T., 2008. The influence of offshore windpower on demersal fish. ICES J. Mar. Sci. 63, 775–784.

Wilhelmsson, D., Malm, T., Ohman, M.C., 2006. Fouling assemblages on offshore wind power plants and adjacent substrata. Estuar. Coast Shelf. Sci. 79, 459–466. doi:10.1016/j.ecss.2008.04.020

Zettler, M.L., Pollehne, F., 2006. The Impact of Wind Engine Constructions on Benthic Growth Patterns in the Western Baltic. In: Köller, J., Köppel, J., Peters, W. (Ed.): Offshore Wind Energy - Research on Environmental Impacts. Springer, 371 p. 135 illus., 106 in color.

Table 1: Abundance of scyphozoan polyps cm^{-2} ±sd during the polyp reproductive season between November 2010 and April 2011 (second year of exposure)

Station ID	Area	Exposure side	Polyps density below halocline		Polyps density above halocline	
			Water depth [m]	Polyps*cm^{-2}	Water depth [m]	Polyps*cm^{-2}
MS01	Fehmarnbelt	upper	17	0	7	0
		bottom		1.71±1.88		5.5±1.74
		vertical		0.07±0.13		0.5±0.36
MS03	Mecklenburg Bight	upper	22	0	7	0.1±0.18
		bottom		0.1±0.15		6.1±1.97
		vertical		0		0.5±0.38
N10	Mecklenburg Bight	upper			7	0
		bottom				1.15±0.88
		vertical				0.05±0.09
ARN	Mecklenburg Bight	upper			3	0
		bottom				0.45±0.52
		vertical				0.25±0.31

Table 2: Seasonal mean (±sd) of abundance of *Aurelia aurita* medusae (ind m^{-3}) in summer (May-August) and autumn (September-November) 2009 and 2010 at 12 sampling stations in the southwestern Baltic Sea

Station	Summer 2009	Autumn 2009	Summer 2010	Autumn 2010
111	0.018±0.012	0.013±0.023	0.006±0.004	0.007
360	0.121±0.098	0.008±0.012	0.008±0.005	0.008±0.01
361	0.023±0.008	0.007±0.007	0.007±0.009	0.004
33	0.15	0.009±0.012		
36	0.047±0.05	0.013±0.023	0.022±0.009	0.016±0.016
37	0.031±0.01	0.008±0.011		
11	0.155±0.013	0.024±0.039	0.017±0.008	
12	0.005±0.003	0.009±0.012	0.017±0.025	0.031
22	0.005±0.007	0.003±0.005		
46	0.133±0.13	0.019±0.026	0.01±0.009	0.008±0.019
DS1	0.231±0.283	0.014±0.001	0.065±0.096	0.073±0.046
131		0.024±0.01	0.063±0.07	0.02±0.001
Total area	**0.095±0.125**	**0.013±0.017**	**0.022±0.021**	**0.021±0.033**

Table 3: Density of drifters and potential density of ephyrae in Marine Protected Areas

MPA-Name	Site code	Density of drifters [pcs/ha]	Density potential of Ephyrae [Ind./sqm]	area of MPA [ha]	Share of MPA impacted by drifters [%]	Natura2000-Type	Protected elements
Adler Grund og Rønne Banke	DK00VA261	0.018	0.64	32,054	100.00	B	Sandbanks, Reefs, Mammals
Przybrzeżne wody Bałtyku	PLB990002	0.010	0.34	182,284	8.94	J	Birds
Darßer Schwelle	DE1540302	0.005	0.18	29,676	84.93	K	Sandbanks, Reefs, Mammals
Kadettrinne	DE1339301	0.005	0.18	10,003	100.00	B	Reefs, Birds, Mammals, Plants
Adlergrund	DE1251301	0.003	0.10	23,385	100.00	K	Sandbanks, Reefs, Birds, Mammals, Plants
Östliche Kieler Bucht	DE1530491	0.017	0.61	57,993	38.24	J	Birds
Nakskov Fjord og Inderfjord	DK006X088	0.037	1.32	7,199	35.21	F	Birds
Bakkebrædt og Bakkegrund	DK00VA310	0.036	1.25	300	75.00	B	Reefs

Table 4: Occurrence of ephyrae drifters per nation

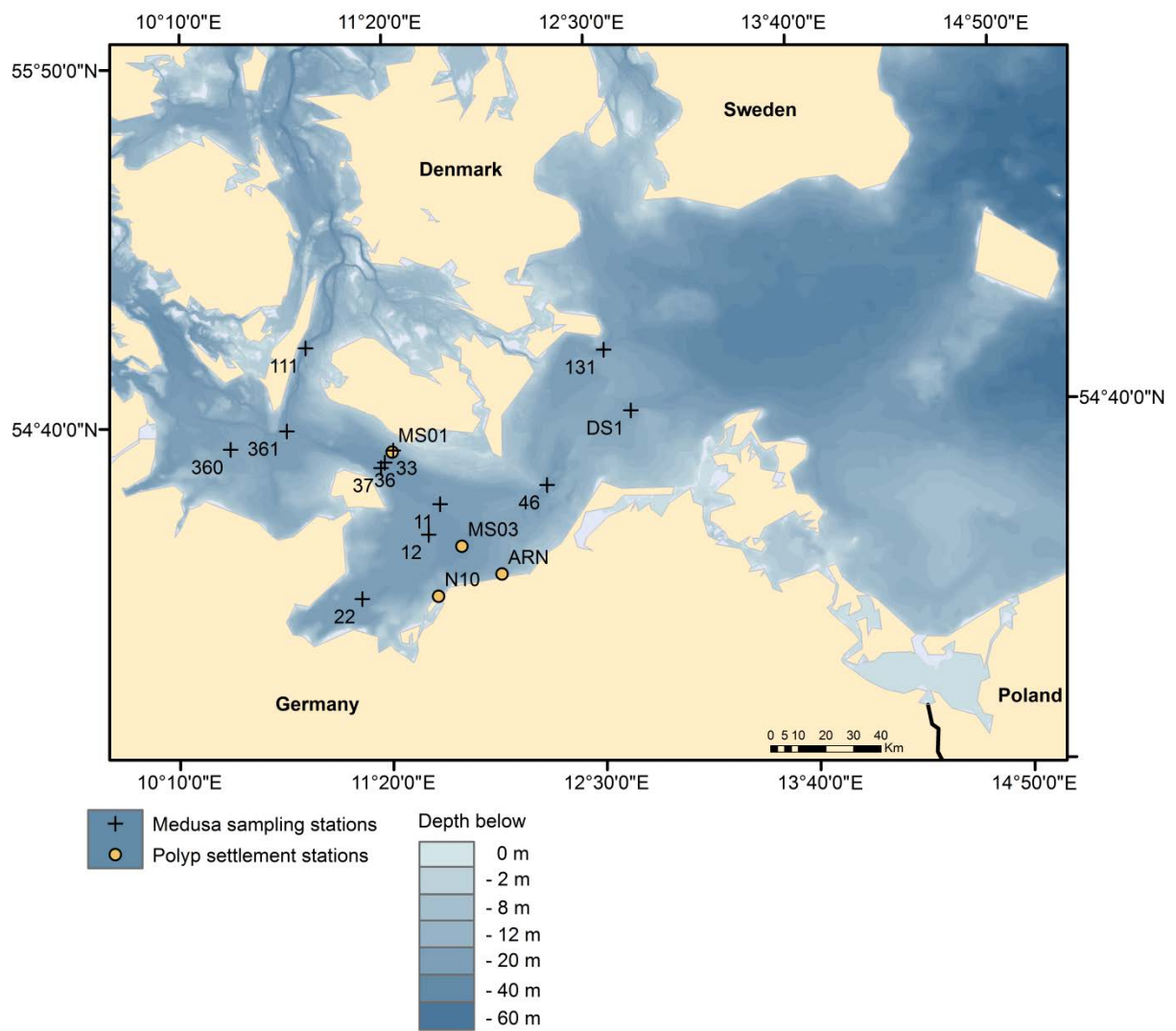| Waters administrated by	Drifter [pcs.]	Percentage [%]	potential individuals [bn. pcs.]
Denmark	7232	54.79	2.54
Germany	3796	28.76	1.33
Poland	760	5.76	0.27
Sweden	1412	10.70	0.50
TOTAL	13200	100	4.64

Fig. 1

Fig. 1: Overview about stations of polyp settlement experiments and medusa sampling
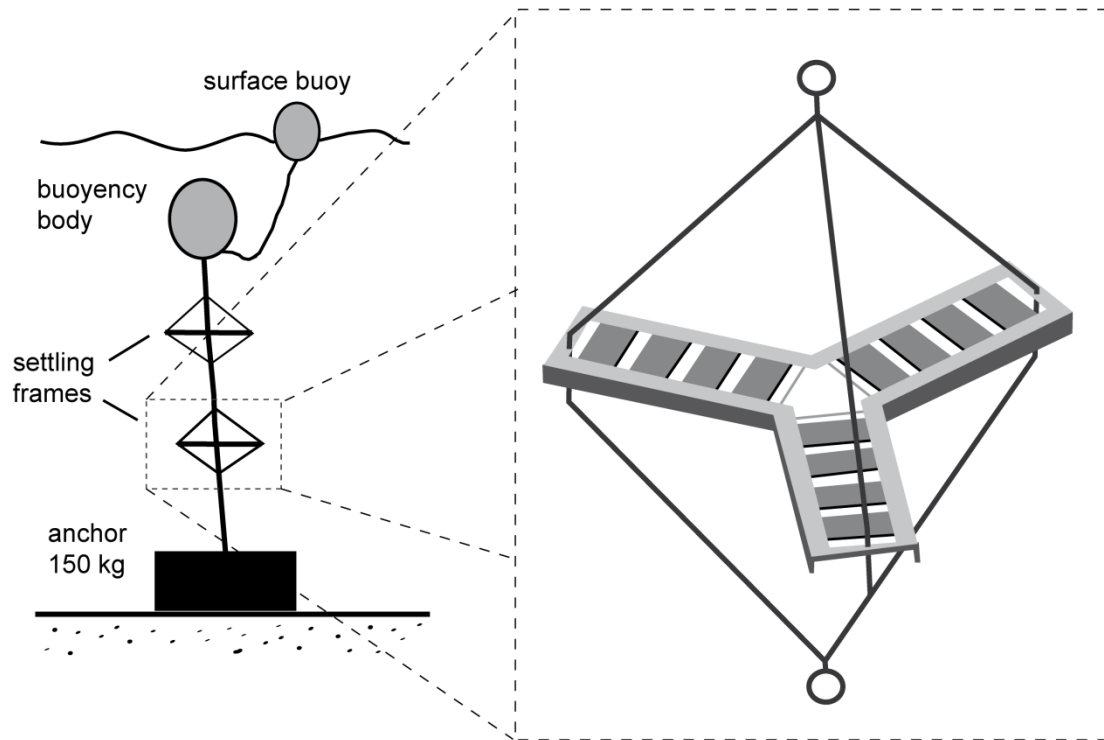
Fig. 2

Figure 2: Polyp settlement mooring system (left), settlement frame with settling plates (right).
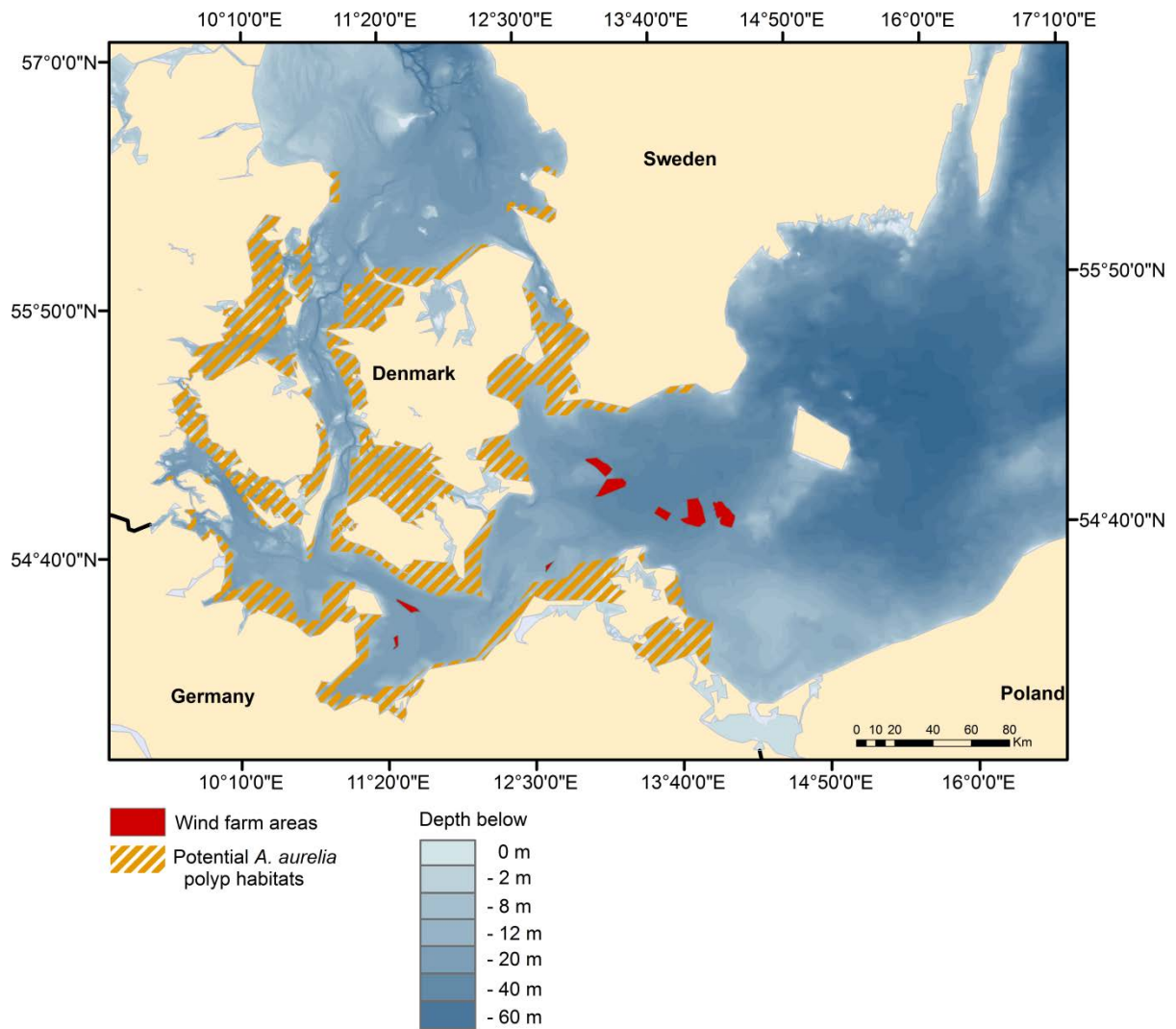
Fig. 3

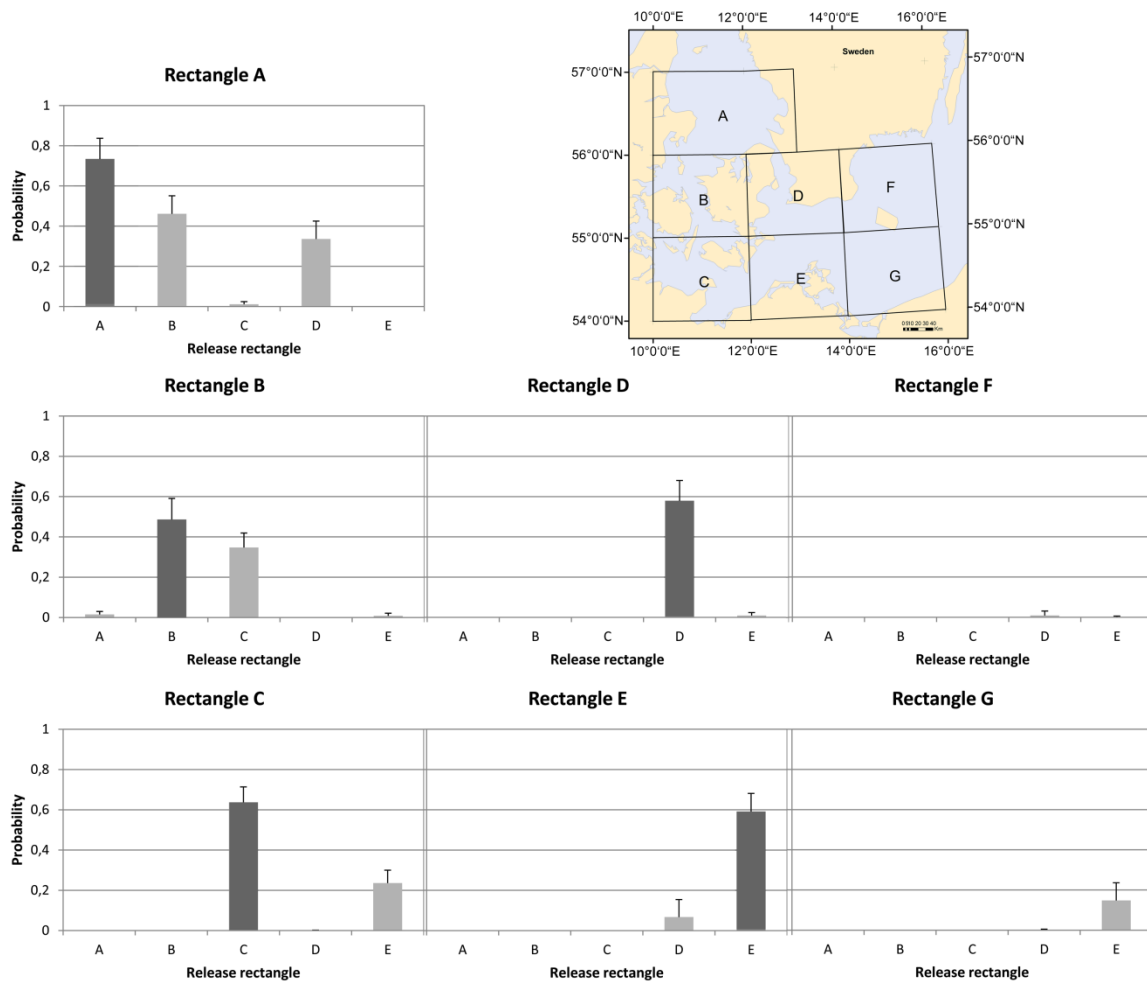Fig. 3: Release areas for ephyrae drifters, a) coastal habitats, b) planned off-shore wind farm areas

Fig. 4

Fig. 4: Occurrence probability of ephyrae drifters as a function of release areas by the end of the simulation period (30th of June) (dark columns: drifters stay within the release rectangle)

Fig. 5
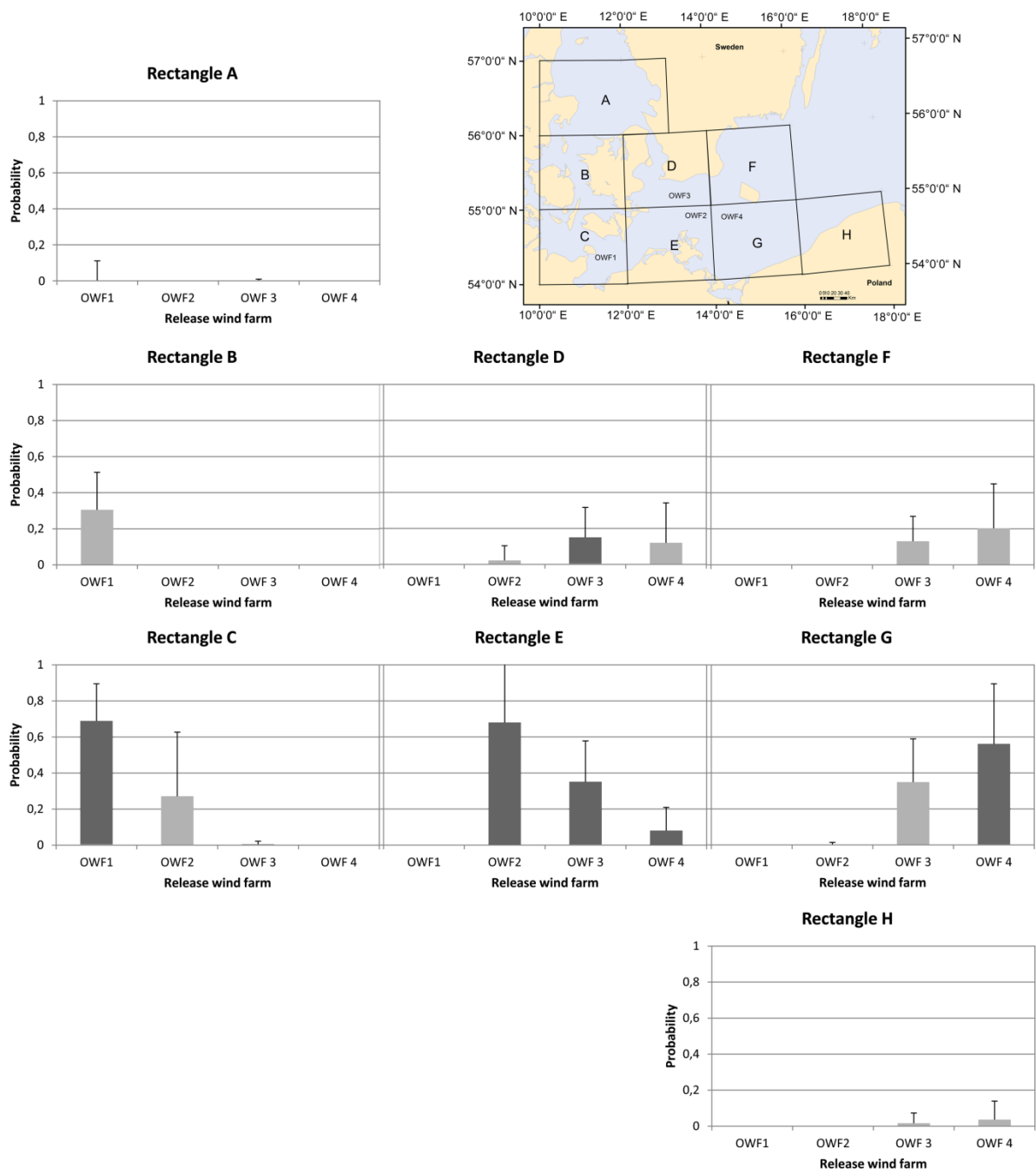
Fig. 5: Occurrence probability of ephyrae drifters released by offshore wind farms (OWF) by the end of the simulation period (30th of June) (dark columns: drifters stay within the vicinity of the release area)

Fig. 6

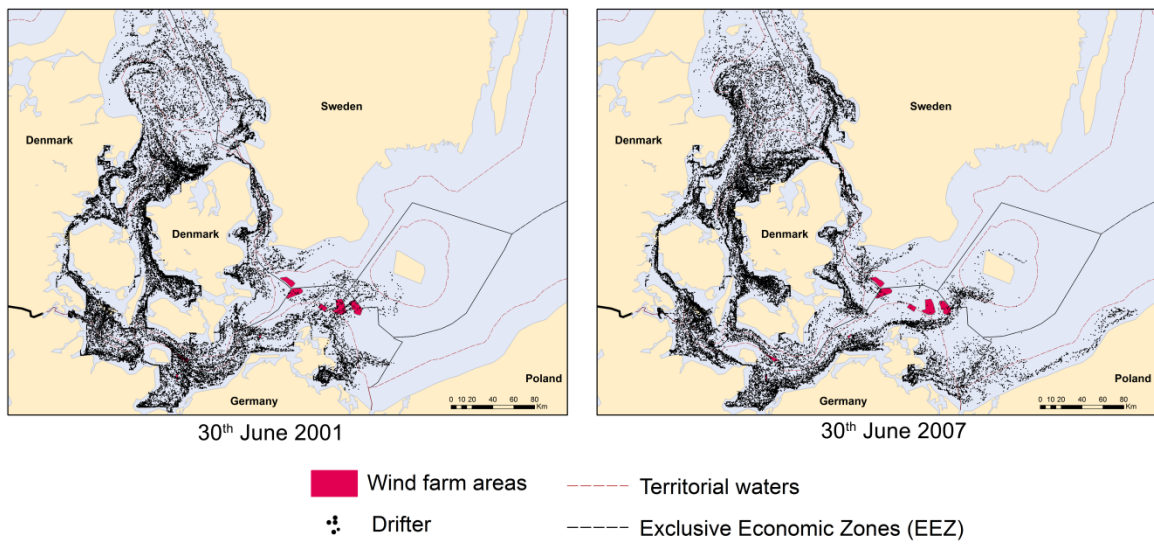30th June 2001   30th June 2007

Fig. 6: Simulation of ephyrae drifters released from natural habitats at the end of the simulation periods 2000/2001 (left) and 2006/2007 (right)
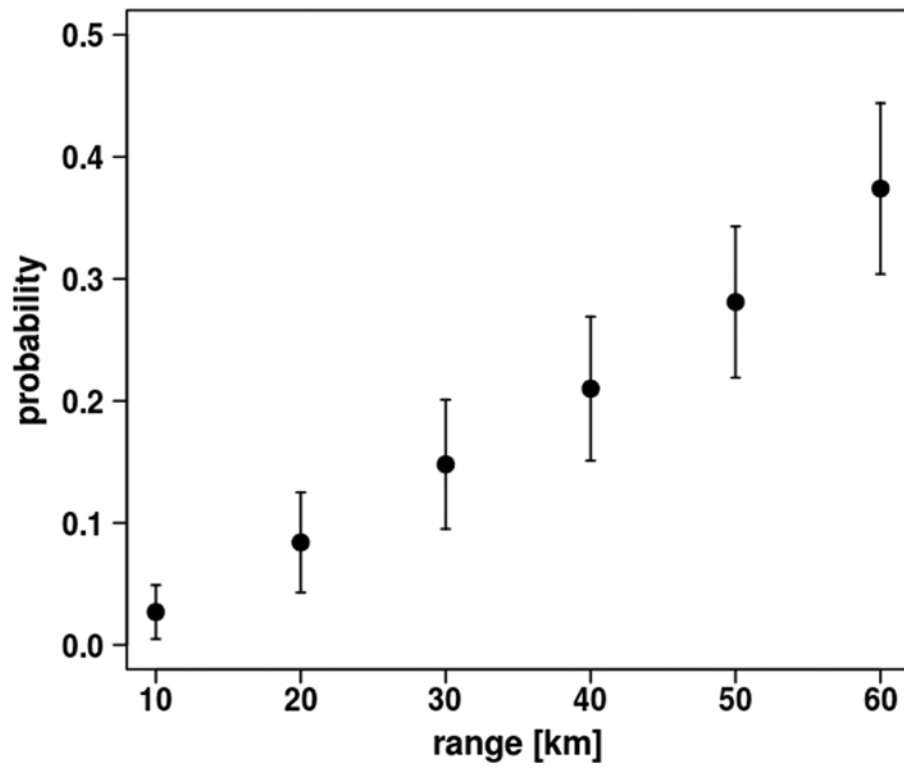
Fig. 7

Fig. 7: Probability for juvenile medusa to occur in the vicinity of offshore wind farms
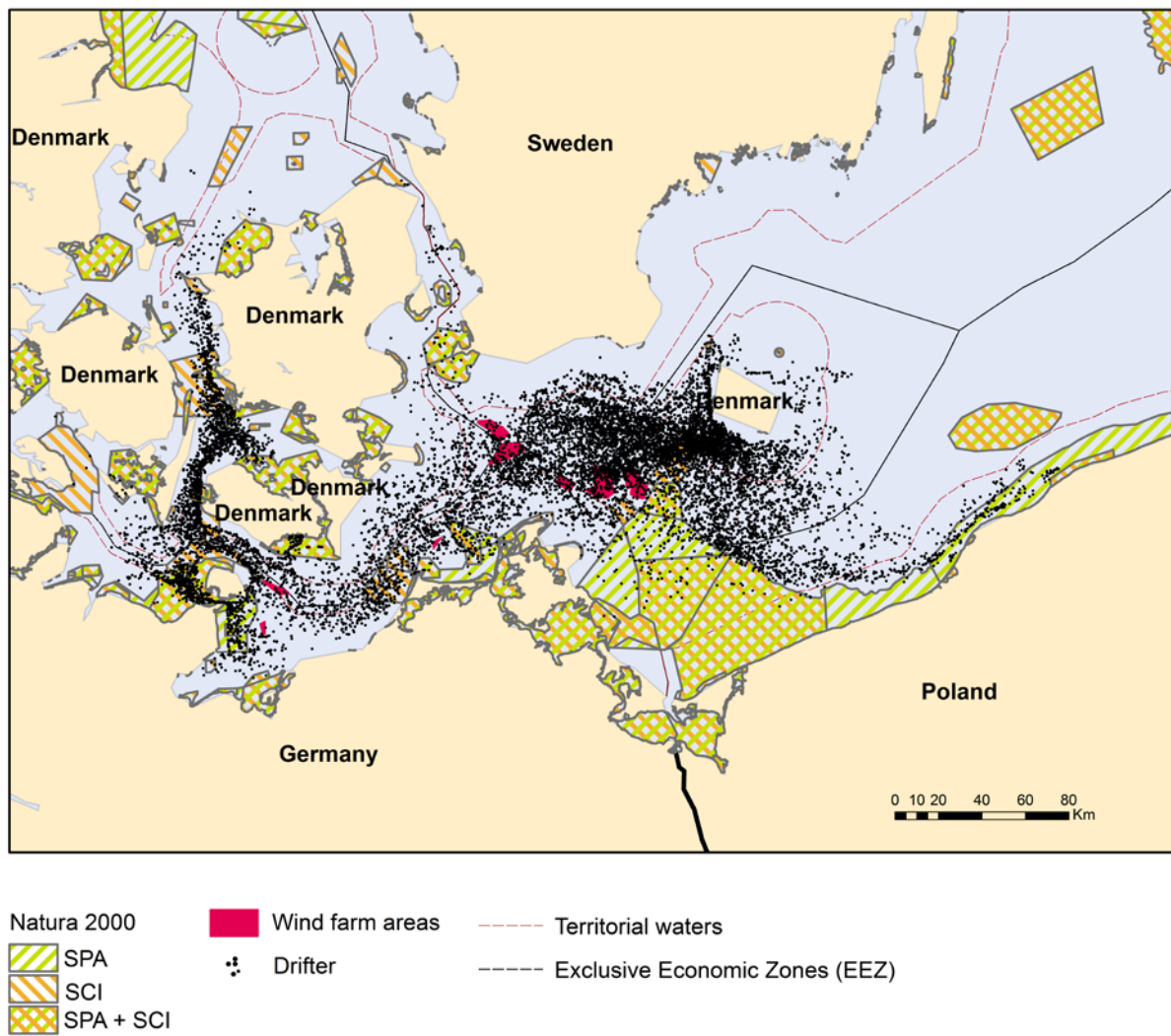
Fig. 8

Fig. 8: Simulation of ephyrae drifters released from wind farms at the end of the simulation period (30th of June) aggregated over the whole simulation time (1997-2008)