MarCoast II - Marine and Coastal Environmental Information Services

Ballast Water Option

APPLICATION OF ECOLOGICAL NICHE MODELLING AND EARTH OBSERVATION FOR THE RISK ASSESSMENT AND MONITORING OF INVASIVE SPECIES IN THE BALTIC SEA

Issue 1.0 – 02.07.2013

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Content

1 Scope of the Document

This report describes the work that has been performed in the Ballast Water Option in the framework of the ESA GSE project Marcoast-2. The Option was dedicated to provide an assessment of the combination of Earth Observation data with modelling and biological data for questions arising with the ballast water topic.

2 Introduction

International shipping is seen as the most important introduction vector for accidental marine translocation by discharging ballast water in the ports of destination (e.g. Nehring 2005). The International Maritime Organization (IMO), recognizing the importance of ballast water as a vector, and therefore, developed 2004 the new International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention (IMO (International Maritime Organization), 2004)). When the Convention will come into force ships will have to manage their ballast water before discharging it. The Guidelines of the BW Convention ruled the different methods ways to manage the ballast water (IMO 2007). Regulation A-4 of the BW Convention recognizes that vessels operating in some regions, such as enclosed seas, or on short journeys, may have the opportunity to grant for an exemption from ballast water management. These exemptions will only been granted on basis of a certain Risk Assessment, to investigate if invasive species are living in the donor port and might have the possibility to be transferred by ballast water and could survive in the recipient port.

The aim of this work is to assess the use of remote sensing data in invasive species detection and ballast-water risk assessment and decision-making. On the one hand remote sensing data are used as input for the ecological niche modelling (environmental layers); namely, climatologies of Sea Surface Temperature and photosynthetically active radiation. In combination with other ecological layers such as salinity or nutrients and with occurrence data of species, the Ecological Niche Modelling models and projects the potential ecological niches for the species on a map.

We show the application of this method for 6 species of phytoplankton, potentially invasive for the Baltic area. Probability distribution maps obtained for the species are discussed in the context of Baltic shipping routes and the risk of spread between different port areas. The potential of niche modelling as a risk assessment tool is discussed in relation to currently used methods based on salinity matching.

In another application, we show how remote sensing data can assist in the monitoring of algal blooms caused by invasive species. Data on ocean colour are analysed for algal bloom detection and correlated with in-situ data.

3 Methods

This chapter describes the methods of the Ecological Niche Modelling as well as the principles of satellite ocean colour and how it can contribute to the investigation of invasive species and ballast water topics.

3.1 Ecological Niche Modelling (ENM)

3.1.1 Principles of ENM

As research in biodiversity becomes global, to tackle environmental issues such as invasive species, novel computational research tools are needed to synthesize data from multiple species over broad geographical areas. In this project, we use computational pipelines developed through the BioVeL project (http://www.biovel.eu) that merge large amounts of species occurrence data with climatic and environmental information. In this case study of Baltic invasive phytoplankton species, we show that we can retrieve occurrence data for invasive species from species repositories and monitoring programmes. We use the occurrence data in combination with marine environmental layers such as mean salinity, mean sea surface temperature, distance to land, mean photosynthetically available radiation and nutrient availability to project the potential ecological niches for the species on a map (Figure 1).

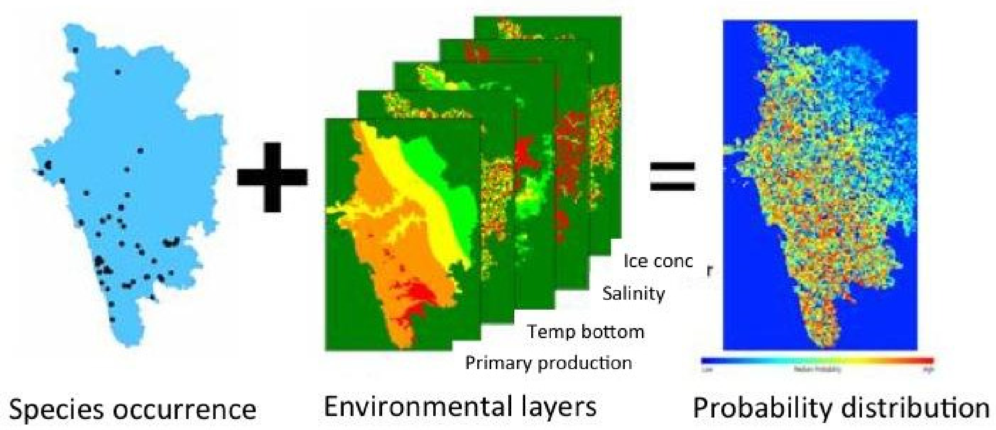


Figure 1: General principles of Ecological Niche Modelling

Ecological niche modelling (ENM) has become a widely used approach to analyse species distributions and to predict changes in biodiversity patterns (Wiley et al. 2003, Guinan et al. 2009, Kulhanek et al. 2011). The most common approach for niche modelling is based on the definition of the fundamental niche, where a set of environmental factors or a multidimensional space of resources determines the persistence of a species (Hutchinson 1957). Thus, with relatively few variables characterizing the abiotic environment of the species in the form geo-referenced raster layers, potential distribution models can be generated.

The current niche modelling workflow (Figure 2) developed by the BioVeL project (https://wiki.biovel.eu/display/doc/Ecological+Niche+Modelling+Workflow) takes as input occurrence data, a set of environmental layers and a choice of modelling algorithm. The workflow interacts with a niche modelling Web Service to generate models remotely using openModeller (Munoz, 2011). A manual interaction step allows algorithm selection and parameter selection for the chosen algorithm. The ENM workflow uses occurrence and environmental data to model species distribution based on a variety of algorithms, including GARP, Climate Space Model, Bioclimatic Envelopes, Support Vector Machines and others. In our explorative modelling, we used the Mahalanobis Distance algorithm (Farber, 2003) by means of the openModeller Environmental Distance with a set of parameters indicating the centroid of the input points to be used as a reference for distance calculation, and forcing distances to be translated into chi-square probability distribution values. This approach requires only presence points and does not need prior knowledge of the species' origin and dispersal ability (no pseudo-absence or background points need to be generated).

However, in order to obtain valid forecasts of species distributions, it is essential to specify the appropriate set of parameter values for a given input data set (occurrences, mask, and layers). The parameter values typically vary among different input data sets and hence are difficult to predict beforehand. Therefore, we developed a fully automated workflow able to explore the parameter space for a given input data set and algorithm, with the purpose to identify the parameter values that produce an optimal model for a given input data set. Based on a set of input data and a given set of parameter values, a model test is performed as a statistical evaluation of the model prediction.

Here an internal test is run using 100% of the points used to create the model. The internal test calculates a receiver-operating characteristic (ROC) curve, area under the curve (AUC) and threshold-dependent statistics (accuracy and omission) using a fixed threshold (0.5). Thereafter the parameter values are optimized until the AUC has reached its maximum value. The optimization is very useful as it gives much more accurate projections of species distributions. Without the optimization, ENM workflow analyses rely on default parameter values or parameter free algorithms such as the Mahalonobis algorithm. In both cases resulting models which are not sufficiently accurate yield low AUC values. The parameter optimization allows to obtain much better AUC values.

Mean AUC (area under the curve) of the receiver-operating characteristic (ROC curve) for each species was estimated and used to test the model´s discriminatory power. ROC analysis involves plotting sensitivity (i.e., proportion of known presences predicted present, = 1 − false negative rate) against 1 − specificity (i.e., proportion of known absences predicted present, = false positive rate). A model was only considered useful, when the average AUC was ≥ 0.7.

The results of the ENMs were presented as Potential Distribution Maps (PD-Maps), showing the potential distribution of a species in a particular geographic region at a particular time (Muñoz et al. 2011).

Because of the efficient exploration of the parameter space, the optimization procedure also allows running a number of different ENM algorithms for a particular input data set. It thereby provides more comprehensive insight and can test the consistency among different analytical approaches. This can give more confidence to the conclusions of an ENM study.

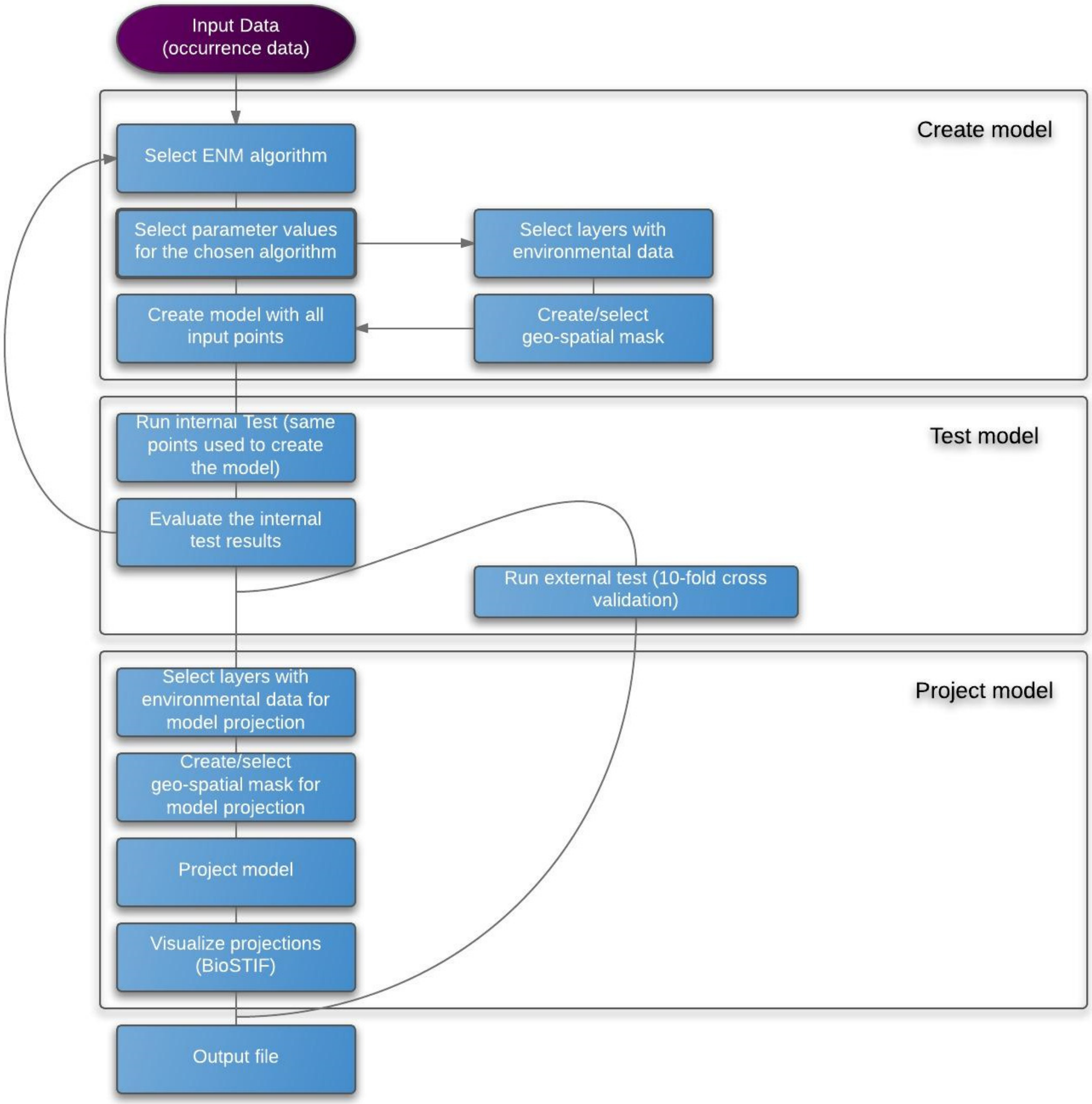


Figure 2. Diagram of the ecological niche modelling workflow. In the first part (Create Model) the user selects the modelling algorithm, parameter values, environmental layer selection, and geospatial mask selection. The model is then created using all input points inside the mask, and if the algorithm requires background or pseudo-absence points, they are also sampled from the masked region. In the second part (Test Model) a statistical evaluation of the model prediction is performed. In the third part (Project Model) the user selects the layers and masks for model projection. The projections and associated occurrence points are visualized through the web-based BioSTIF interface.

Global marine layers used in our study came from Bio-Oracle (http://www. bio-oracle.ugent.be/) with a resolution of 5 arcmin (Tyberghein et al. 2012), and were used to study abiotic factors such as mean sea surface temperature, mean salinity and mean photosynthetically available radiation. Detailed specifications for the layers presented below are derived from the materials and methods used to build the Bio-Oracle dataset (http://www.oracle.ugent.be/DATA/Other/Appendix.pdf).

Layer for **Photosynthetically Available Radiation (Einstein/m2/day)** comes from remote sensing, with a spatial resolution of 5 arcmin (9.2 km), using data from the SeaWiFS sensor for monthly climatologies between 1997 and 2009. Photosynthetically available radiation indicates the quantum energy flux from the sun in the spectral range 400-700 nm reaching the ocean surface (http://oceancolor.gsfc.nasa.gov/).

Layer for **Sea Surface Temperature (°C)** comes from remote sensing, with a spatial resolution of 5 arcmin (9.2 km), using data from the aqua-MODIS sensor for monthly climatologies between 2002 and 2009. Sea surface temperature is the skin temperature of the water at the ocean surface, and indicates the temperature of the topmost nanometres of the ocean water column (http://oceancolor.gsfc.nasa.gov/).

Layer for **Mean Salinity (PSS)** comes from in situ measured oceanographic data, from the World Ocean Database 2009. Data used are standard level data for surface taken between 1961 and 2009. Salinity indicates the dissolved salt content in the ocean (http://www.nodc.noaa.gov/).

Layer for **Nitrate (µmol/l)** comes from in situ measured oceanographic data from the World Ocean Database 2009. Data used are standard level (OSD) data for surface taken between 1928-2008. The data contains both [NO_3] and [NO_3+NO_2] data, meaning chemically reactive dissolved inorganic nitrate and nitrate or nitrite (http://www.nodc.noaa.gov/).

Layer for **Phosphate (µmol/l)** comes from in situ measured oceanographic data from the World Ocean Database 2009. Data used are standard level (OSD) data for surface taken between 1922-1986. The data contains reactive ortho-phosphate concentration [HPO_4^{-2}] in the ocean (http://www.nodc.noaa.gov/).

Layer for **Silicate (µmol/l)** comes from in situ measured oceanographic data from the World Ocean Database 2009. Data used are standard level OSD & CTD data for surface taken between 1930 and 2008. This data indicates the concentration of silicate or ortho-silicic acid [$Si(OH)_4$] in the ocean (http://www.nodc.noaa.gov/).

Other marine layers used in our analyses (such as 'mean annual distance to land' or 'Mean annual sea ice concentration') came from AquaMaps (http://www.aquamaps.org/download/main.php) with a resolution of 30 arcmin (Kaschner et al. 2010). The data set of AquaMaps is built on long-term averages of temporally varying environmental variables (Ready et al. 2010) and contains geography layers such as distance to land, an important factor for coastal species.

The ecological requirements of the species which were investigated in this study have been determined from literature.

3.2 Satellite Data

3.2.1 Principle of Ocean Colour

The light coming from the sun on its way to earth and finally to the measuring sensor onboard of a satellite undergoes a number of processes within the atmosphere and the water (Figure 3). These processes - absorption and scattering - that we can obtain information about the respective surfaces. The ocean colour is distinguished by the absorption and scattering by water constituents such as phytoplankton, suspended sediment or coloured dissolved organic matter and water itself. The single components influence the light in different wavelengths and thus the light that is measured at the sensor carries the information about their composition and concentrations. However, the light passes the atmosphere twice on its way and the processes in the atmosphere are much stronger influencing the light and therefore "disturbing" the signal from the water. Thus, a proper correction of the atmosphere is required before retraining the information about water constituents. The retrieval of water constituents becomes a challenging approach in coastal water which can become quite complex concerning the constituents, combining suspended sediment entering by rivers inflow, chlorophyll concentration from phytoplankton blooms and absorbing substances such as dissolved organic matter (CDOM). The Baltic Sea is characterised by a high concentration of CDOM, which has a high absorption and reduces the light availability in the short wavelengths.

Different methods for obtaining information about the respective water constituents have been developed during the past years. For open oceans where only chlorophyll is influencing the water colour, experimental-empirical algorithms such as band ratios, colour indices provide reliable results. In more complex coastal waters, these techniques are not applicable any more. This requires multivariate algorithms which are based on radiative transfer modelling and which consider specific optical properties of the water constituents.

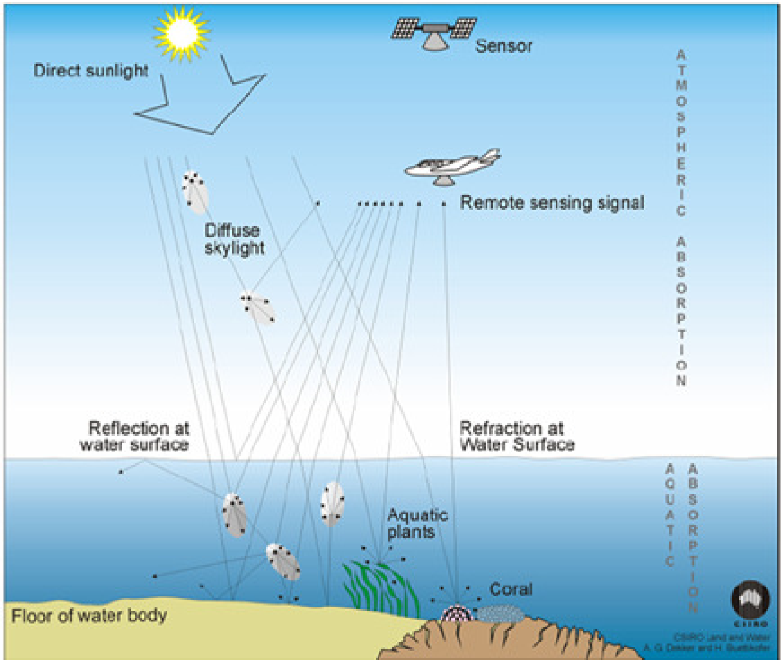


Figure 3. Processes within the Atmosphere and the water

3.2.2 MERIS Data

MERIS Sensor onboard of ENVISAT was designed for the detection of water constituents in open oceans, but especially in coastal areas. An example of the chlorophyll concentration retrieved from MERIS acquisition is shown in Figure 4. Spatial resolution of 300 m provides currently the best available spatial resolution for an ocean colour sensor. MERIS data, which are available from 2002 - 2012, are further investigated here for the applicability of algal bloom detection in the contents of blooms caused by alien species.

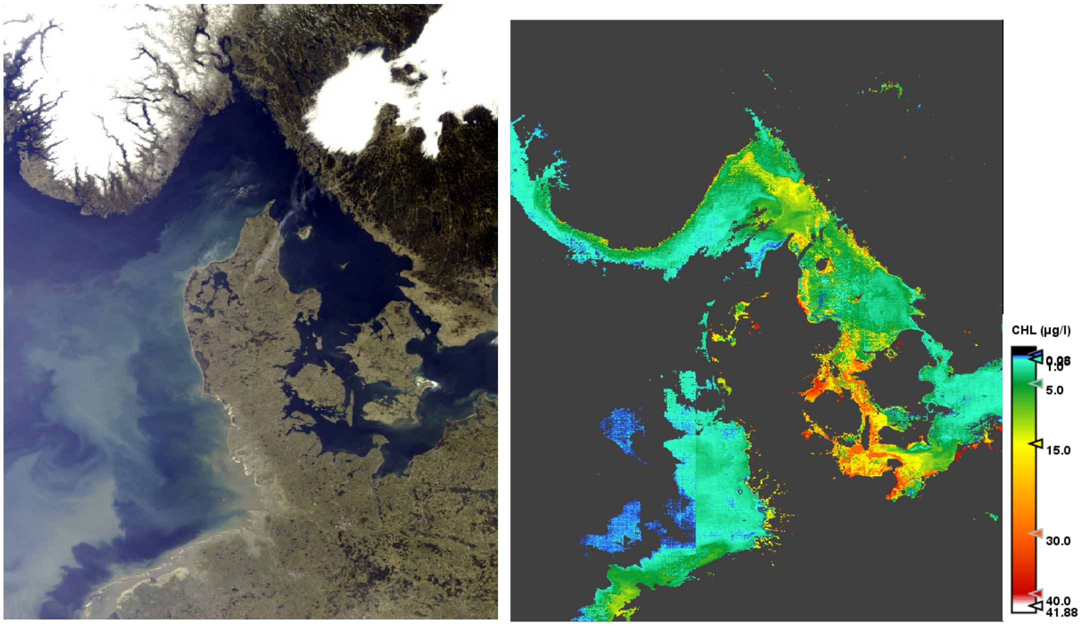


Figure 4. Satellite image (RGB) and derived chlorophyll concentration. Black areas in the right picture are pixels which have been not processed properly due to land, clouds, cloud shadow, sun glint or other influences.

3.2.3 Detection of alien species

Chlorophyll pigments are identified by typical spectral absorption maxima in the blue and red region and thus are reducing the reflected sunlight in the respective wavelengths, which enables the assessment of CHL in satellite data. Satellite data provide a good spatial view on the distribution of chlorophyll concentration and the occurrence of algal blooms. Although different functional groups of phytoplankton have characteristic spectral absorption patterns due to the chlorophyll and the cell structure, it is difficult to identify single species within the water from satellite data. The identification of single species is mainly retrieved by respective in situ data. Thus, our approach was to look for algal blooms which are caused by alien species. The information about the species has been obtained from different data sources (see Table 2).

Nitrogen and phosphorous are usually the main indicators for determining the occurrence and abundances of different species, but these substances cannot be directly detected by remote sensors. However, the amounts are decisive for the growth of plants and an overload of nitrogen can cause a massive development of algae. Algal blooms can therefore be a good indicator of increasing amounts of nutrients in the water, i.e., eutrophication of the water.

4 Niche Modelling Investigations

This chapter describes the modelling of 6 selected invasive species. These species have been selected by different criteria and they are described in more detail in the following sections. This part is followed by the description of the modelling of each species and the discussion of the individual results.

4.1 Investigated Species

4.1.1 Criteria for selecting Species:

For this pilot study we have chosen to model five invasive phytoplankton or microalgae species and one macroalgae species according to the following criteria:

- They have invaded in the last 100 years
- They are tolerant to a wide range of salinities
- They are highly invasive (according to http://www.frammandearter.se)
- They are non-parasitic
- Occurrence data are available from GBIF, ICES and from national monitoring agencies

The following species have been selected:

- *Alexandrium minutum*
- *Pseudochattonella farcimen*
- *Alexandrium ostenfeldii*
- *Prorocentrum minimum*
- *Sargassum muticum*
- *Coscinodiscus wailesii*

4.1.2 Species description

Alexandrium minutum

Synonyms:

- Pyrodinium minutum (Halim) Taylor
- Alexandrium ibericum Balech 1985
- Alexandrium lusitanicum Balech 1985
- Alexandrium angustitabulatum F.J.R.Taylor 1995

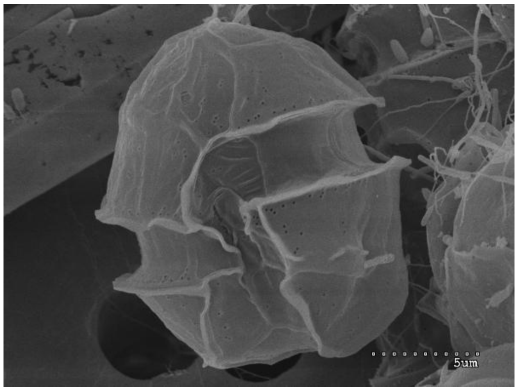


Figure 5. *Alexandrium minutum* (Source: issg database)

Alexandrium minutum (Dinophyceae) is a small boom forming toxic dinoflagellate and is found in warm temperate, coastal and estuarine waters over a number of geographic areas (issg database 2007). In Europe it is found in Ireland, England, northern France, northwest Spain, the North Sea and the Mediterranean Sea (McCauley et al. 2009 and citations therein) and Norway (Andersen et al. 2001).

Invasion history and current distribution within the Baltic Sea

The native area of *A. minutum* is unknown (HELCOM 2010). It is found in Norway (Andersen et al. 2001), at the Swedish west coast (Västerhavet) (Främmande arter i Svenska hav 2012), in the Kattegat, Limfjord, North of Sealand (Helcom 2010). Nehring (1994) described resting cells from Kiel Bight, but *A. minutum* was not reported recently from monitoring programmes (Olenina 2010).

Impacts on native phytoplankton community and habitat

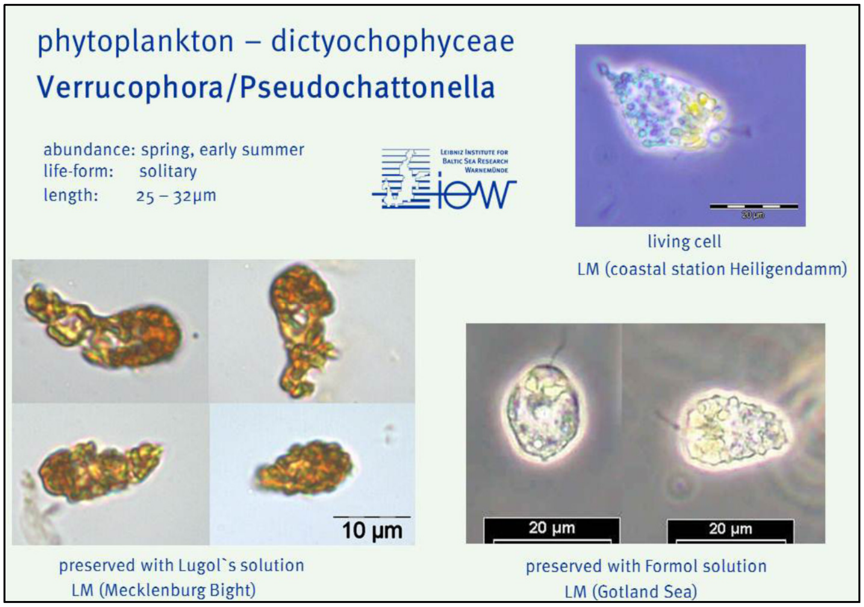
A. minutum produces high concentrations of toxins and is responsible for many global cases for paralytic shellfish poisoning (PSP) in humans. It is the most widespread toxic PSP species in the Mediterranean Sea. Toxins also affect other components of the ecosystem including mammals, birds, fish and zooplankton (issg database).

Pseudochattonella farcimen (Riisberg 2008)

There is a controversial discussion on the species determination and its correct taxonomic group (DAISIE European Invasive Alien Species Gateway, 2006a). For this species different names were found:

- *Chattonella* aff. *verruculosa*
- *Verrucuphora fascima*
- *Chattonella verruculosa* Y.Hara & M.Chihara, 1994
- *Verrucophora verruculosa (Y.Hara & Chihara)* Eikrem, 2007

Pseudochattonella farcimen (Dictyochophyceae) is a small, blooming, toxic, cold water phytoplankton algae (flagellate) and is present in brackish and marine open and coastal waters in the North Sea, Skagerrak, and Kattegat. (DAISIE European Invasive Alien Species Gateway, 2006a; Naustvoll, 2010). Its optimal growth is between 2 and 10°C (Naustvoll, 2010).


phytoplankton – dictyochophyceae
Verrucophora/Pseudochattonella

abundance: spring, early summer
life-form: solitary
length: 25 – 32µm

living cell
LM (coastal station Heiligendamm)

preserved with Lugol`s solution
LM (Mecklenburg Bight)

preserved with Formol solution
LM (Gotland Sea)

Figure 6. *Pseudochattonella farcimen* (Source: Leibniz Institute for Baltic Sea research, Warnemünde)

Invasion history and current distribution within the Baltic Sea

1998 was the first time that *P. farcimen* formed large blooms in southern Norway, the Skagerrak and Kattegat and these caused fish mortality. It was speculated that *P. farcimen* has been introduced to Europe from Japan via e.g. by ballast water (Naustvoll, 2010 and citation therein). Now *P. farcimen* is observed in Denmark, Germany, Sweden and Norway in routine monitoring programs (Naustvoll, 2010) and it appears that has become a natural part of the spring phytoplankton community. In 2001 *P. farcimen* formed a local bloom in the southern part of the Gulf of Gdansk (Łotocka, 2009).

Impacts on native phytoplankton community and habitat

This species is toxic to fish. The toxin is a fatty acid, which affects the gill tissue of fish resulting in the production of mucus, which makes the fish to suffocate (DAISIE European Invasive Alien Species Gateway, 2006a). It has no effect on human health and it is unknown whether this species has genetic effects.

Alexandrium ostenfeldii

Synonyms:

- Goniodoma ostenfeldii Paulsen 1904
- Gonyaulax ostenfeldii (Paulsen) Paulsen 1949
- Goniaulux ostenfeldii (Paulsen) Paulsen 1949
- Heteraulacus ostenfeldii (Paulsen) Loeblich III 1970
- Gessnerium ostenfeldii (Paulsen) L.Loeblich & Loeblich III 1979
- Triadinium ostenfeldii (Paulsen) Dodge 1981
- Gonyaulax phoneus (Woloszynsky & Conrad) Loeblich & Loeblich
- Protogonyaulax phoneus (Woloszynska & Conrad) F.J.R.Taylor
- Glenodinium ostenfeldii Paulsen 1903
- Pyrodinium phoneus Woloszynskia & Conrad 1939
- Goniaulux tamarensis var. globosa Braarud 1945

- Gonyaulax tamarensis var. globosa Braarud 1945
- Gonyaulax globosa (Braarud) Balech 1971
- Gonyaulax trygvei Parke 1976
- Protogonyaulax globosa (Braarud) Taylor 1979

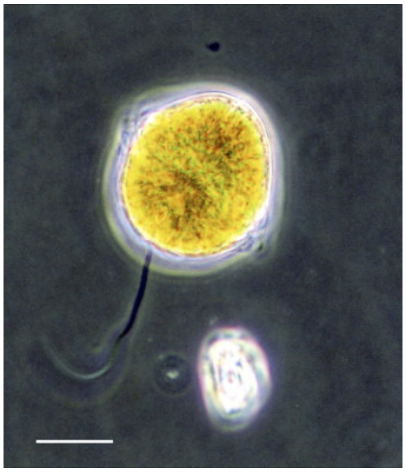


Figure 7. *Alexandrium ostenfeldii* (Source: Kremp et al., 2009)

*Alexandrium ostenfeldii (*Dinophyceae) is a small boom forming PSP-producing dinoflagellate.

Invasion history and current distribution within the Baltic Sea

In the beginning of its invasion history, *A. ostenfeldii* mainly has occupied the Kattegat and the southern Baltic Proper. Blooms were found since 1997 in the Baltic Sea. The first observed bloom was near Öland (Swedish east coast), in 2001 and 2003 blooms were observed in the Gulf of Gdansk. At the Swedish east coast of the northern Baltic Proper, *A. ostenfeldii* was observed for the first time in 2000 and has been more common in monitoring samples since then (Hajdu et al. 2006 and citations within). In the past years, late summer blooms of the bioluminescent dinoflagellate *A. ostenfeldii* have become a recurrent phenomenon in coastal waters of the central and Northern Baltic Sea e.g. blooms in 2003 and 2004 in a shallow embayment of the Åland archipelago at the SW coast of Finland. Tahvanainen et al. (2012) showed that different strains of *A.ostenfeldii* exist, also within the Baltic Sea. The Baltic population is phylogenetically distinct form all other global lineages of this species. This suggests that initial colonization was followed by local differentiation by habitat conditions and therefore subtypes from *A.ostenfeldii* developed, which have different ecological requirements (Tahvanainen et al. 2012).

Impacts on native phytoplankton community and habitat

A.ostenfeldii can produce neurotoxin (PSP), which is dangerous since it can be transferred from the grazing the food chain to consumers (Sopanen et al. 2011). The high magnitude blooms of the PSP producing *A.ostenfeldii* is a recent phenomenon in the northern Baltic Sea (Sopanen et al. 2011).

Prorocentrum minimum (Pavillard) Schiller

Synonyms:

- Prorocentrum marie-lebouriae

- Prorocentrum minimum (Pavillard) J. Schiller

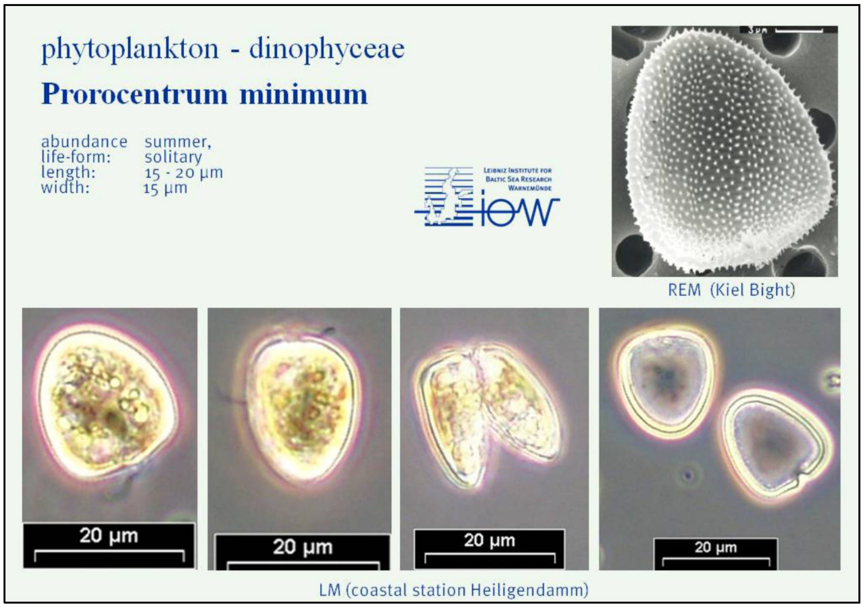


Figure 8. ***Prorocentrum minimum*** **(Source: Leibniz Institute for Baltic Sea research, Warnemünde)**

Prorocentrum minimum (Dinophyceae) is a common, neritic, bloom-forming Dinoflagellate, with a pan-global distribution. It is potentially harmful to humans via shellfish poisoning. Blooms generally occur under conditions of high temperatures, incident irradiances and low to moderate salinities (influenced by freshwater inputs) in coastal and estuarine environments. They are increasing globally (Heil et al., 2005). The physiological flexibility of *P. minimum* in response to changing environmental parameters (e.g. light, temperature, salinity) as well as the ability to utilize inorganic and organic nitrogen, phosphorus, and carbon nutrient sources, suggest that increasing blooms of this species are a response to increasing coastal eutrophication (Heil et al., 2005). There is statistical evidence that *P. minimum* abundance increased with increasing nitrogen (Xu et al., 2010).

Invasion history and current distribution within the Baltic Sea

The native region of *P. minimum* is unknown. In 1981 it reached the Kattegat and is found since 1982 in the Belt Sea area. Now it has become a common element in the summer-autumn phytoplankton community of the Baltic Sea and it also penetrated into low salinity regions of the central Gulf of Finland in 1997 (Hajdu et al., 2005). In 2010 it was not known from the Gulf of Bothnia (Olenina et al., 2010). Abundances have varied greatly within the Baltic Sea (Olenina et al., 2010). It is considered that *P. minimum* was introduced with ballast water discharges and Gollasch et al. (2002) found living cells in Ballast water tanks.

Impacts on native phytoplankton community and habitat

Although *P. minimum* is considered to be non-toxic to marine invertebrates in general (Heil et al., 2005) it forms large blooms with 60-98% of the phytoplankton biomass (Olenina et al., 2010). It such situations the native phytoplankton community is essentially altered.

P. minimum is a good competitor when inorganic nutrients are exhausted because it has the ability to utilize organic substances and to bloom under nutrient limited conditions (Heil et al., 2005; Taş and Okuş, 2011). During blooms the water colour and pH changed and the transparency declined (Heil et al., 2005).

In the Baltic Sea *P. minimum* was categorized as an invasive species on basis of the bioinvasion impact assessment method (BPL) (Olenina et al., 2010).

Sargassum muticum (Yendo) Fensholt

Synonyms

- *Sargassum kjellmanianum* f. *muticum* Yendo

Figure 9. *Sargassum muticum* (Source: NOBANIS)

Sargassum muticum (Phaeophyceae) is a large brown macroalgae. It originates from Japanese waters. *S. muticum* develops best on sheltered, relatively shallow hard substrata or on hard materials on soft substrata and it also appears in belts of native wracks (*Fucus* spp.) (Främmande arter i Svenska hav, 2006).

Invasion history and current distribution within the Baltic Sea

Sargassum muticum is native to the coastal waters of Japan, China, Russia, and Korea in the north-western Pacific (Josefsson and Jansson, 2011). It was possibly introduced with Pacific oysters imported for aquaculture to France in 1960s. Now it is present along most of the Atlantic coasts from Portugal to Norway and also in the North Sea. Secondary spread probably occurred through drifting specimens or branches (Josefsson and Jansson, 2011) or entangled in anchor chains or propellers or hull fouling with ships (Främmande arter i Svenska hav, 2006).

Drift species were found 1985 for the first time off the west coast off Sweden. It has expanded very rapidly since the early 1990s and it is found 2005 north of Helsingborg. It is now established in the Limfjord and along the Kattegat and Skagerrak coasts (Josefsson and Jansson, 2011; Thomsen et al., 2007). It is not known if *S. muticum* become established in the Baltic Sea area, as it may not to be able to reproduce at low salinities (Josefsson and Jansson, 2011). Up to now *S. muticum* is not found in the German (pers. comm.) or in the eastern parts of the Baltic Sea (Josefsson and Jansson, 2011).

Impacts on native community and habitat

The rapid expansion of *S. muticum* along the west coast off Sweden is one of the most striking changes to the algal belts of this area apart from those caused by eutrophication (Främmande arter i Svenska hav, 2006). There are examples that *S. muticum* reduce the slower growing seaweed in the Limfjord (Thomsen et al., 2007). It reduces the sunlight reaching the bottom and pose a threat to the benthic community (Främmande arter i Svenska hav, 2006) and it lead to a large increase in biomass input and thus of detritus in the system (Josefsson and Jansson, 2011). The 'bushy' structure and high densities have also physical impacts, such as higher sedimentation rates. It fouls fishing gear, propellers, hard substrates in harbors (e.g. buoys) or aquaculture (e.g. cages) and clogs water intakes (Främmande arter i Svenska hav, 2006). No effects on human health or genetic effects have been observed (Josefsson and Jansson, 2011).

Coscinodiscus wailesii (Gran & Angst 1931)

Coscinodiscus wailesii (Bacillariophyceae) is a very large centric diatom, typically 175-500 µm in diameter, is a primary producer in the pelagic water column brackish and marine coastal and offshore waters. The seasonal cycle in the North Sea includes highest abundances in April and September to October. It shows a wide tolerance to temperature (0-32 °C), salinity (10 – 35 PSU) and nutrients.

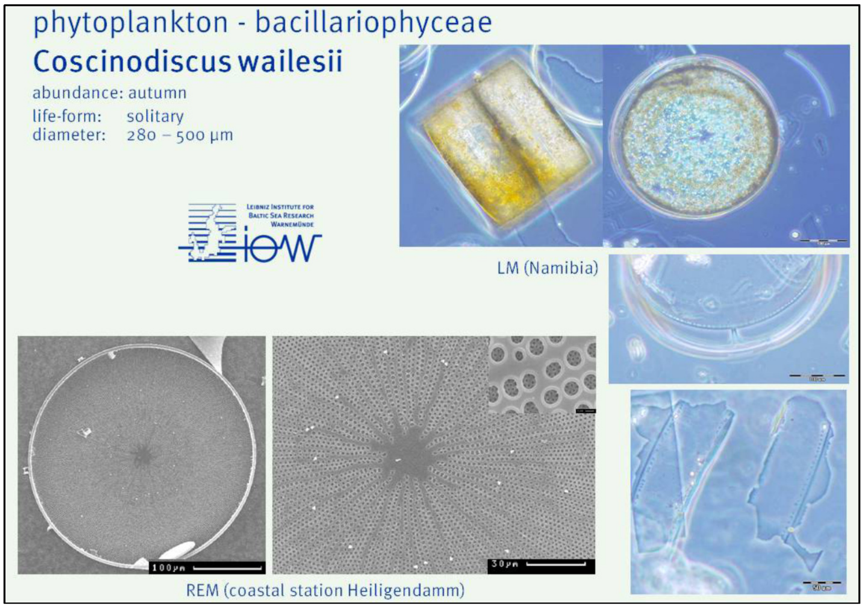


Figure 10. ***Coscinodiscus wailesii*** **(Source: Leibniz Institute for Baltic Sea research, Warnemünde)**

Invasion history and current distribution within the Baltic Sea

C. wailesii is native to the North Pacific and was first detected in Europe near Plymouth in 1977. The first record in the (western) Baltic occurred 1983. Today it is observed from the Atlantic coast of France to Norway (DAISIE European Invasive Alien Species Gateway, 2006b). *C. wailesii* is probably introduced with ballast water discharges. Its resting cells were found in samples from ballast water tanks. Another possible introduction vector is shellfish movements. Cells may be carried within the gut/pseudofaeces of shellfish.

Impacts on native phytoplankton community and habitat

This non-toxic species forms dense blooms and may form up to 90% of the total algal biomass. Especially in blooming situations benthic organisms are threatened. The damage is caused by the copious mucilage, which can aggregate, sink and cover the seabed. The decay of a bloom is likely to cause anoxic conditions. It may also compete with phytoplankton and macroalgae species for space and nutrients (DAISIE European Invasive Alien Species Gateway, 2006b; Laing, 1999). The economic impact is due to clogging of fishing nets and aquaculture cages with extensive mucus. Impact on human health is unknown.

The following table provides an overview on the Ecological requirements of the selected species compiled from literature.

Table 1. Ecological requirements of the selected species compiled from literature. Occurrence in the Baltic: BP (Baltic Proper), CL (Curonian Lagoon), GoF (Gulf of Finland), GoR (Gulf of Riga), K (Kattegat and Belt Sea), KF (Kattegat North coast of Seeland, Isefjord, Roskilde Fjord), LF (Limfjord). Sources: 1 (Olenin 2011), 2 (CABI 2008), 3 (issg database), 4 (Jakobsen et al. 2012), 5 (Lotocka 2009), 6 (Främmande arter i Svenska hav 2006), 7 (Wallentinus 1999), 8 (Hakanen et al. 2012), 9 (Kremp et al. 2009), 10 (Ostergaard Jensen & Moestrup 1997), 11 (Paavola et al. 2005).

Species	Invaded to the Baltic Sea	Occurrence in the Baltic	Introduction vector	T range, °C	S range, ‰	Nutrients, µM	Irradiance	Bloom/ Substrate	Impact
Alexandrium minutum, Dinophyceae	2000s (H)	K, LF, KF (H)	Ballast water, water currents, floating on debris (3)	4-24 (1); 7-37 (2)	3-30 (1); 15-35 (2)			blooming (1); 'blooms are related to low salinities and nutrient rich freshwater inputs in warm, temperate, coastal and estuarine waters (3)	Toxic, PSP (1); toxic to some zooplankton and fish species, PSP (3)
Pseudochattonella farcimen, Dictyocho-phyceae	1998 (H)	K (H); Gulf of Gdansk (5)	shipping (H)	1 to <15 (4); 7,2-9,8 (5); 5-30 (1)	laboratoy values: 10-35 (H); 7,3-7,5 (5); 10-35 (1)		well adapted to low irradiance in Danish waters in late winters and early spring(4);	blooming (1); blooms in January to March (4)	Ichtytoxic (1); Toxicity, aquaculture (H)

Species	Invaded to the Baltic Sea	Occurrence in the Baltic	Introduction vector	T range, °C	S range, ‰	Nutrients, µM	Irradiance	Bloom/ Substrate	Impact
Alexandrium ostenfeldii, Dinophyceae	mid 1980s (10)	whole Baltic (ICES data)		growth occurred: 11,3- 23,7, but can survive lower temperatures (8) (10)	growth occurred: 10 - 40 psu (8) (10); 6 to 20-25 (ICES)	abundance did not significantly correlate with dissolved inorganic nutrient concentrations (9)			toxic, PSP (8) (10)
Prorocentrum minimum, Dinophyceae	1970s (H)	BP,CL, GoF, K, GoR, LF, KF (H)	shipping (H)	3-33 (1)	native: 18-40 and Baltic: 0,5-30 (H); native: 10-40 (11); 0,7-35 (1)	P nutrition have an important role, NH_4 supporting blooms, effectively take up DON, DOP (1)	high irradiance (30-500 µmol photons $m^{-2}s^{-1)}$ (1)	blooming (1)	Toxicity, aquaculture, human health (H); non toxic in the Baltic (1)
Sargassum muticum, Phaeophyceae	1984 (H)	K, LF (H)	introduced with live oysters and now drifting (6)	optimal growth up around +25°C, but perennial basal stalk	native: 18-40, Baltic: 5-30 (H); native: 18-40, Baltic: 18-30 (11);		optimal growth germlings around 45 µEs^{-1}m^{-2}, the older ones	depth to 10m, sheltered, relatively shallow hard substrata or	habitat changes, competition (H)

Species	Invaded to the Baltic Sea	Occurrence in the Baltic	Introduction vector	T range, °C	S range, ‰	Nutrients, µM	Irradiance	Bloom/ Substrate	Impact
				resist temp below 0°C (6)	adults cope well 20 PSU but survive at lower salinities, no reproduction at salinities < 15psu, but germlings can survive 5-6psu (6)		160-190µEs^{-1}m^{-2} (7)	on hard material on soft subtrata (6)	
Coscinodiscus wailesii, Bacillariophyceae (Diatomophyceae)	1977 (H)	K (H)	associated, shipping (H)	0-32 (1)	10-35 (1); native: 18-40, Baltic: 5-30 (H)	NO_3: 0,24-0,97, PO_4: 0,26-0,68, SiO_4: 21-37 (1)	10-150 µmol photons m^{-2}s^{-1} (1)		habitat changes, competition (H); harmful, mucilage, high biomass(1)

Most data were taken from GBIF (Global Biodiversity Information Facility and additionally from the ICES database, from the Swedish monitoring agency (SMHI, Swedish Meteorological and Hydrological Institute) and from the German agencies LLUR (State Agency for Agriculture, Environment and Rural Areas) and LUNG (State Agency for Environment, Nature Conservation and Geology Mecklenburg-Western Pomerania), (Table 2).

Table 2. Sources and number of occurrence records. Groups: PP = phytoplankton, MA = macroalgae.

Species	Group	Sum of occurrence records	GBIF	ICES	Swedish Meteorological and Hydrological Institute (SMHI)	German monitoring agencies LLUR and LUNG
Alexandrium minutum	PP	3077	3077			
Pseudochattonella farcimen	PP	75		16	12 (2007, 2008) Verrucophora farcimen (synonym) 35 (2007-2011) Pseudochattonella verruculosa (synonym)	13 (LLUR 2003-2009) Verrucophora farcimen (synonym)
Alexandrium ostenfeldii	PP	96	50	46		
Prorocentrum minimum	PP	2259	1026		598 (Harmful algae events)	316 (LLUR) 319 (LUNG)
Sargassum muticum	MA	1697	1697			
Coscinodiscus wailesii	PP	3864	3864			

4.2 Modelling the potential of spread in the Baltic Sea

Two different levels of modelling have been performed, in a first stage, explorative modelling was performed for all six species that match the criteria under 4.1.1. Thereafter a deep modelling has been performed of those species where (i) the explorative modelling showed interesting distribution pattern in the Region of interest, and (ii) we did have sufficient data for deep modelling.

4.2.1 Explorative Modelling: Modelling with limited data

Results of the Explorative Modelling are described hereafter for those cases where only a low number of occurrence points were available and no parameter optimization of the Mahalonobis distance algorithm

(Farber, and Kadmon 2003) was performed. In order to filter all environmentally unique points the BioClim algorithm (Nix 1986) was used.

The following table provides a summary of the model settings for the species which have been modelled with the explorative modelling. The settings and results are described in more detail in the sections below.

Table 3: Summary of the occurrence data and layers used as input for the model for the species modelled with the explorative modelling.

Species	**Occurrence Data**	**Filtered occ. data**	**Layers**	**Model**
Alexandrium minutum (Explorative Modelling)	3077	76	Mean nitrate Mean PAR Mean distance to Land Maximum SST Minimum SST Mean salinity	Mahalonobis algorithm Mean AUC= 0.60
Pseudochattonella farcimen (explorative modelling)	75	75	Maximum SST Minimum SST Mean salinity Mean PAR	Mahalonobis algorithm Mean AUC= 0.73
Alexandrium ostenfeldii (explorative modelling)	96	45	Maximum SST Minimum SST Mean PAR	Mahalonobis algorithm Mean AUC= 0.52

1) *Alexandrium minutum*

a) Layers used

- Mean nitrate, 5 arcmin (growth associated with high nitrate)
- Mean photosynthetically available radiation, 5 arcmin
- Mean annual distance to Land, 30 arcmin (coastal blooms)
- Maximum sea surface temperature, 5 arcmin (Water temperature greatly affects growth, with higher temperatures leading to increased growth)
- Minimum sea surface temperature, 5 arcmin
- Mean salinity, 5 arcmin

b) Number of environmentally unique occurrence points after BioClim filtering

- 76

c) Modelling for *Alexandrium minutum* using Mahalonobis algorithm

- Mean AUC= 0.60 (Low model accuracy due to small number of occurrence points)

Figure 11 and Figure 12 show the potential distribution maps for *Alexandrium minutum* (see layers above), derived with the Mahalonobis algorithm. Europe-wide potential distribution for the species with occurrence points as black circles (Figure 11) and zoomed in to the Baltic area (Figure 12). All model results are shown with the same colour palette that indicates the habitat suitability for the respective species from 0-100%.

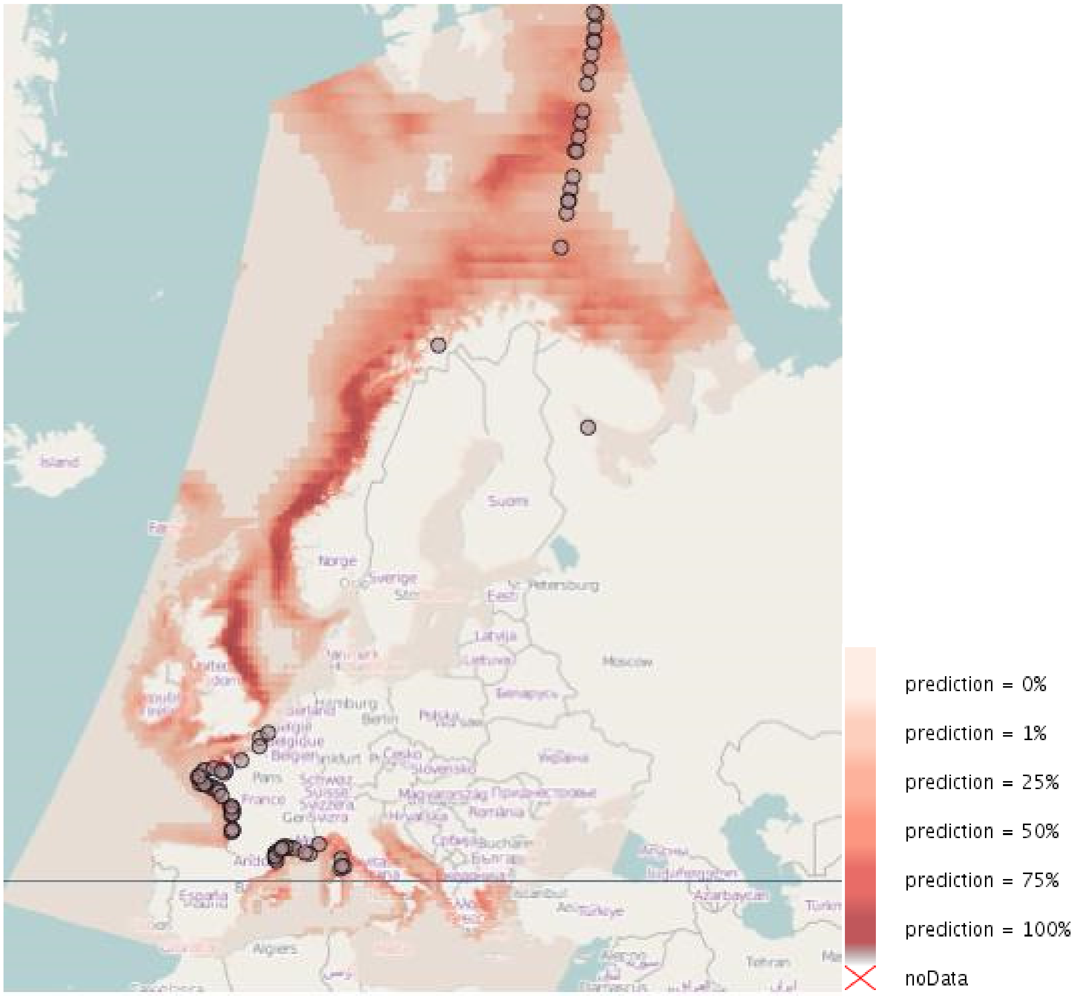


Figure 11. Potential distribution maps for Alexandrium minutum; Europe-wide potential distribution for the species with occurrence points as black circles

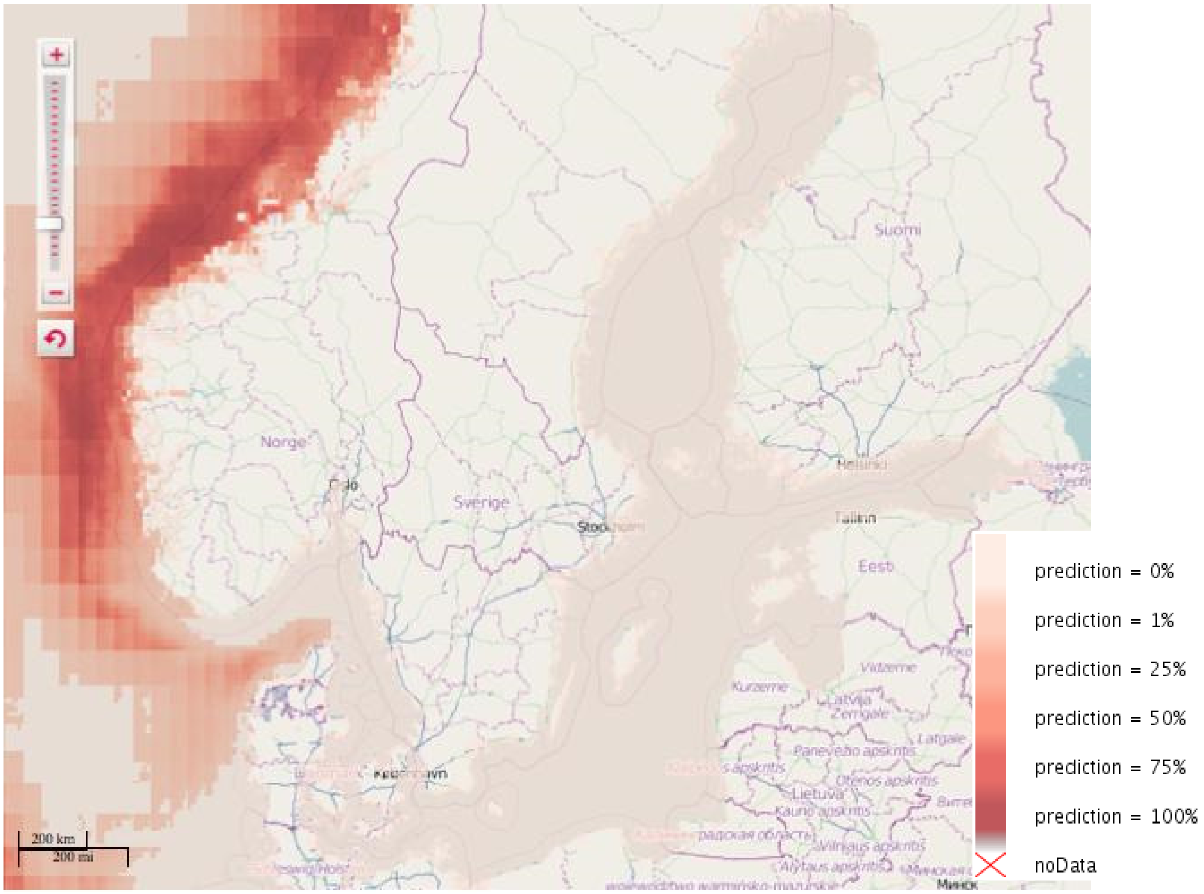


Figure 12. Potential distribution maps for Alexandrium minutum; zoomed in to the Baltic area

The results of the ENM for *Alexandrium minutum* show a low AUC score, reflecting a poor fit of the model and showing that the range of predicted distribution may not be accurate. In nature *A. minutum* is found in Norway (Andersen et al. 2001), at the Swedish West Coast (Västerhavet) (Främmande arter i Svenska hav 2012), in the Kattegat, Limfjord, North of Sealand (Helcom 2010) and Nehring (1994) described resting cells from Kiel Bight, but *A. minutum* was not reported from monitoring programmes (Olenina 2010). Therefore the model results do not fit in the Skagerrak/Kattegat area but fit for the other European regions.

A problem which can be highlighted here is that despite the relatively high number of occurrence records (3077), only 76 environmentally unique points remain after filtering. In addition, most of the occurrence points are outside the Baltic Sea, which can be a problem for modelling in enclosed seas or bays with distinct environmental conditions such as the Baltic Sea (Ready et al., 2010). As most of the occurrence points are outside of the area, the distribution reflects this with a predicted absence in this area. A better species distribution model would be obtained by using more environmentally distinct occurrence records from within and around the Baltic area, i.e. from the Kattegat and Limfjord, where this species has previously been reported.

2) *Pseudochattonella farcimen:* 68 occurrence points

a) Layers used

- Maximum sea surface temperature (Celsius)
- Minimum sea surface temperature (Celsius)
- Mean salinity (PPS)
- Mean Photosynthetically Available Radiation (Einstein/m2/day)

b) Modelling for *Pseudochattonella farcimen* using Mahalonobis algorithm

- Mean AUC= 0.73

Figure 13 and Figure 14: Potential distribution maps for *Pseudochattonella farcimen,* using min and max temperatures, salinity and photosynthetically available radiation (Mahalonobis algorithm). Baltic Sea area (Figure 13) and zoomed-in with occurrence points as black circles (Figure 14). Red colour scale indicates habitat suitability from 0-100%.

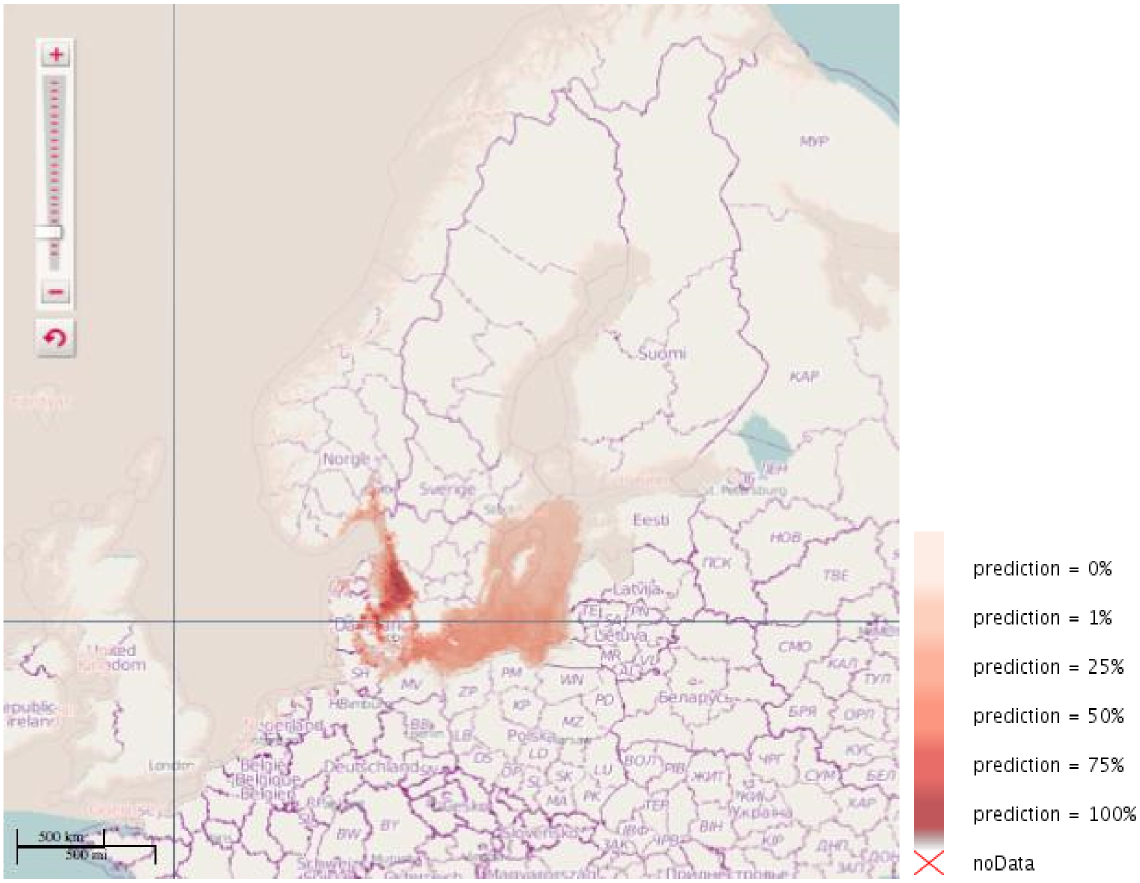


Figure 13. Potential distribution maps for *Pseudochattonella farcimen; Baltic Sea*

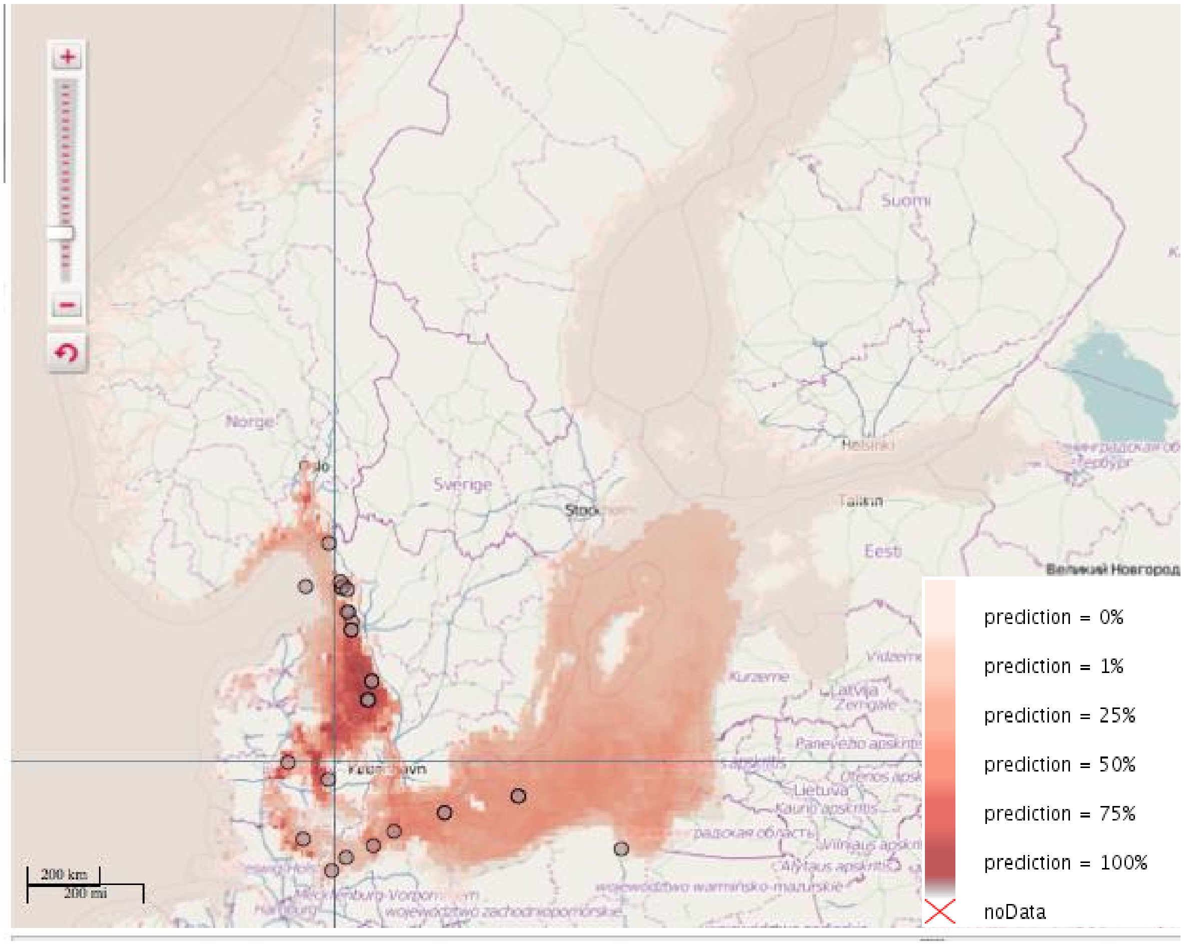


Figure 14. Potential distribution maps for *Pseudochattonella farcimen*; zoomed in map with occurrence points

ENM results for *Pseudochattonella farcimen* show an AUC score of 0.73, which is a reasonable score. However potential distribution results for *Pseudochattonella* should be interpreted with caution. Due to the low number of occurrence points available (68), these could not be filtered for environmentally unique points. Having a number of non-environmentally unique points in the dataset leads to an artificially increased mean AUC, due to resampling of the same points during the model testing. ENM could be improved for this species by using a larger number of occurrence data and filtering them for environmentally unique points. Despite the low AUC score the calculated potential distribution fitted quite well with reality. In nature *P. farcimen* is found in the mainly in Norway (Andersen et al. 2001), in the Kattegat and Belt Sea (HELCOM 2010) but also in the southern Baltic Proper (Wasmund et al. 2012) and in the Gulf of Gdansk (Łotocka, M., 2009) and therefore the model results fit quite well to the real findings. In several years (1998, 2001, 2004 and 2006) in the Kattegat area large blooms of *P. farcimen* were observed which sometimes caused fish mortality (ICES WGHAB Report 2012).

3. *Alexandrium ostenfeldii:*

a) Layers used

- Maximum sea surface temperature (Celsius), 5 arcmin
- Minimum sea surface temperature (Celsius), 5 arcmin
- Mean salinity (PPS), 5 arcmin
- Mean Photosynthetically Available Radiation (Einstein/m2/day), 5 arcmin

b) Number of environmentally unique occurrence points after BioClim filtering

- 45

c) Modelling for Alexandrium ostenfeldii using Mahalonobis algorithm

- Mean AUC= 0.52 (Low model accuracy due to small number of occurrence points)

Figure 15 and Figure 16: Potential distribution maps for *Alexandrium ostenfeldii,* using min and max temperatures, salinity and photosynthetically available radiation (Mahalonobis algorithm). Baltic Sea (Figure 15) area and zoomed-in with occurrence points as black circles (Figure 16). Red colour scale indicates habitat suitability from 0-100%.

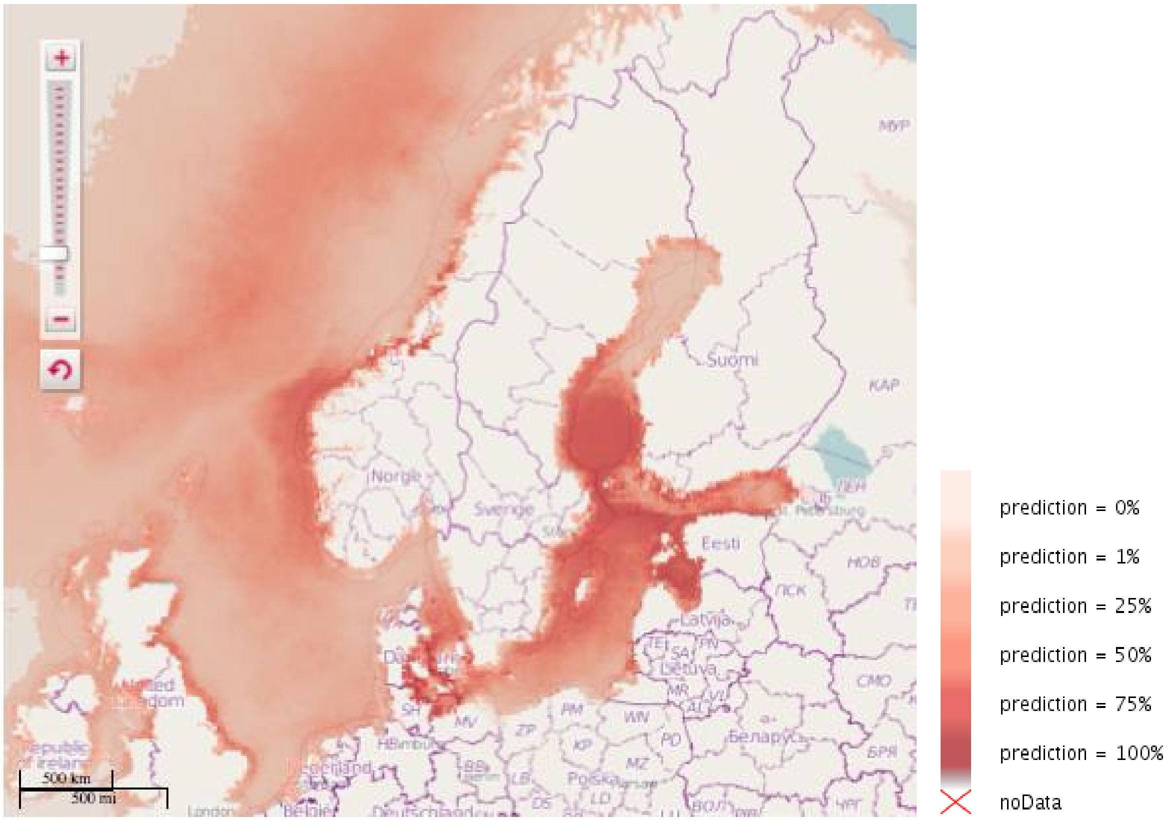


Figure 15. Potential distribution maps for *Alexandrium ostenfeldii*, Baltic Sea

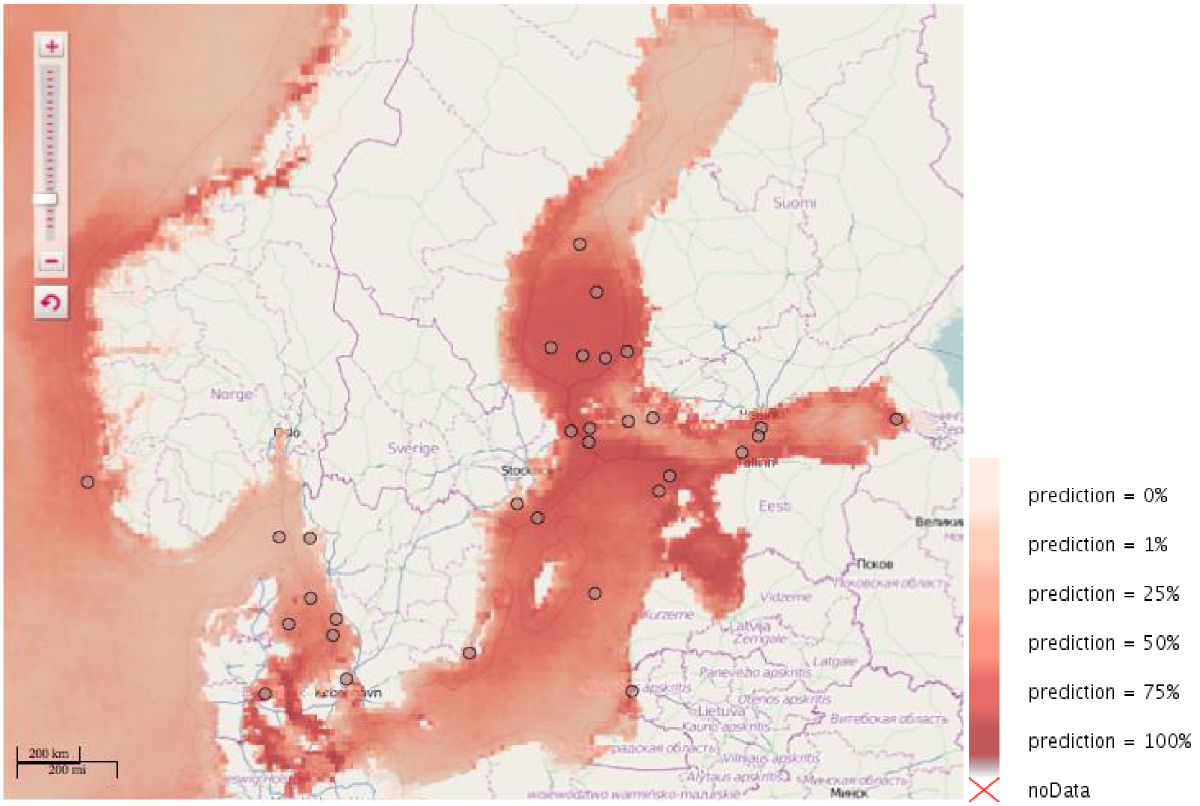


Figure 16. Potential distribution maps for *Alexandrium ostenfeldii,* zoomed-in with occurrence points as black circles

ENM results for *Alexandrium ostenfeldii* should be interpreted with caution. With a mean AUC of 0.52, the potential distribution can be considered unreliable. This is due the low number of occurrence points obtained after the environmentally unique filtering procedure (45). With the minimum number of points required for accurate niche modelling being about 50, more Baltic observations are needed to confirm the potential distribution map. In nature *A.ostenfeldii* is found in the Kattegat (Sweden and Denmark) as well at the east coast of Sweden in the Baltic Sea. Recurrent blooms were observed in coastal waters of the central and Northern Baltic Seas well as in the Gulf of Gdansk (Kremp et al. 2009). Salinity requirements were given between 10 to 40 psu (Ostergaard Jensen & Moestrup 1997), but the blooms in the Northern Baltic Sea occurred at salinities between 6 and 7,5 psu (Tahvanainen et al. 2012).This disagreement can be explained with the fact that initial colonization was followed by local differentiation by habitat conditions so that different strains of *A.ostenfeldii* with different ecological requirements exist (Tahvanainen et al. 2012).

4.2.2 In-Depth Modelling: Modelling with sufficient data

In-depth modelling was performed for species

- Where the explorative modelling suggested highly relevant distribution patterns for the Region of interest
- Where a sufficiently high number of occurrence points available
- Applying data point filtering using BioClim to extract environmentally unique points

- Using the support vector machines algorithm (SVM)
- Performing algorithm parameter optimization

The following table provides a summary of the model settings for the species which have been modelled in-depth. The settings and results are described in more detail in the sections below.

Table 4. Summary of the occurrence data and layers used as input for the model for the species modelled with the in-depth modelling.

Species	**Occ. Data**	**Filtered occ. data**	**Layers**	**Model**
Prorocentrum minimum (in-depth modelling)	2259	173	Mean SST Mean salinity Mean PAR	SVM Mean AUC= 0.88
Prorocentrum minimum (in-depth modelling)	2259	172	Maximum SST Minimum SST Mean salinity Mean nitrate Mean PAR	SVM Mean AUC= 0.82
Sargassum muticum (in-depth modelling)	1697	298	Mean salinity Mean annual distance to land Minimum SST Mean annual sea ice concentration Hard substrate layer (n.a.)	SVM Mean AUC = 0.97
Coscinodiscus wailesii (in-depth modelling)	3864	792	Mean salinity Maximum SST Minimum SST Mean PAR Mean phosphate Mean silicate Mean nitrate	SVM Mean AUC = 0.974

1.a) *Prorocentrum minimum*

a) Layers used

- Mean sea surface temperature (Celsius), 5 arcmin
- Mean salinity (PPS), 5 arcmin
- Mean photosynthetically available radiation (Einstein/m^2/day), 5 arcmin

b) Number of environmentally unique occurrence points after BioClim filtering

- 173 points

c) Modelling for Prorocentrum minimum using SVM (Support vector machine)

- Mean AUC= 0.88

Figure 17 and Figure 18: Potential distribution maps for *Prorocentrum minimum,* using mean surface temperature, salinity and photosynthetically available radiation (SVM algorithm). Baltic Sea area (Figure 17) and zoomed-in with occurrence points as black circles (Figure 18). Red colour scale indicates habitat suitability from 0-100%.

Figure 17. Potential distribution maps for *Prorocentrum minimum,* SVM algorithm, Baltic Sea

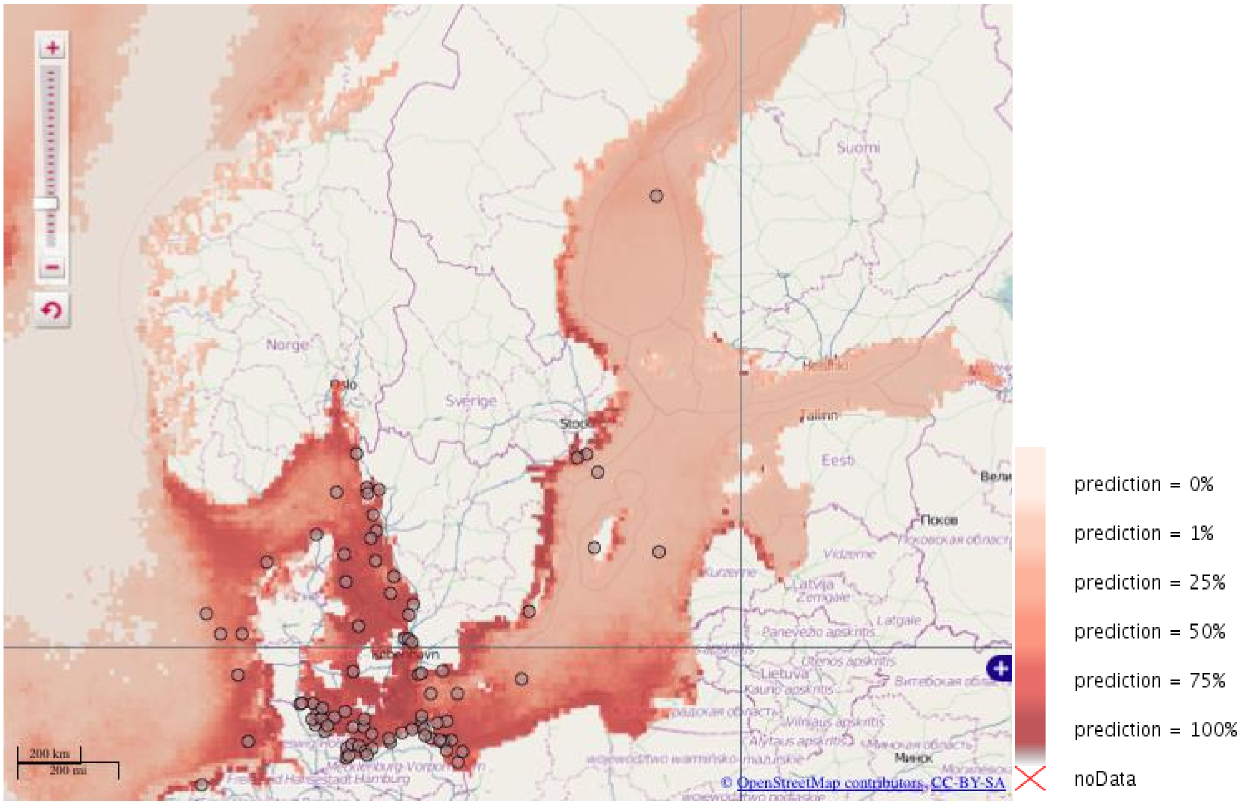


Figure 18. Potential distribution maps for *Prorocentrum minimum,* SVM algorithm zoomed-in with occurrence points as black circles

ENM results for *Prorocentrum minimum* show a reliable model, with a mean AUC of 0.88. This potential distribution was obtained with 173 environmentally unique points and 3 environmental layers: sea surface temperature, salinity and photosynthetically available radiation. This distribution correlates well with observations for this species in the Kattegat, Belt Sea and Baltic proper. Observations have been reported from the Curonian Lagoon, Bay of Gdansk, Gulf of Riga and Gulf of Finland.

To improve the potential distribution map and take into account additional parameters, we ran the model again for this species using 5 environmental layers (below).

This model result which is not based on nutrient layers (see below) seems to fit better with the nature distribution of *P. minimum.* The results show a probability of occurrence of *P. minimum* in the Irish Sea, around the Shetland Islands and also in the German Bight and in all these three areas *P. minimum* is found in nature. In the Baltic Sea *P. minimum* is found in all regions with exception of the Gulf of Bothnia (Olenina et al. 2010) and its potential to grow at salinities below 5 psu confirming its potential to penetrate also into the Bothnian Sea (Hajdu et al. 2000). Therefore the calculated probability in the eastern part of the Baltic Sea seems to be too low.

1.b) *Prorocentrum minimum*

a) Layers used

- Maximum sea surface temperature (Celsius), 5 arcmin
- Minimum sea surface temperature (Celsius), 5 arcmin
- Mean salinity (PPS), 5 arcmin
- Mean nitrate, 5 arcmin
- Mean photosynthetically available radiation (Einstein/m^2/day), 5 arcmin

b) Number of environmentally unique occurrence points after BioClim filtering

- 172

c) Modelling for Prorocentrum minimum using SVM (Support vector machine)

- Mean AUC= 0.82

Figure 19 and Figure 20: Potential distribution maps for *Prorocentrum minimum,* using maximum sea surface temperature, minimum sea surface temperature, mean salinity, mean nitrate and mean photosynthetically available radiation (SVM algorithm). Baltic Sea area (Figure 19) and zoomed-in with occurrence points as black circles (Figure 20). Red colour scale indicates habitat suitability from 0-100%.

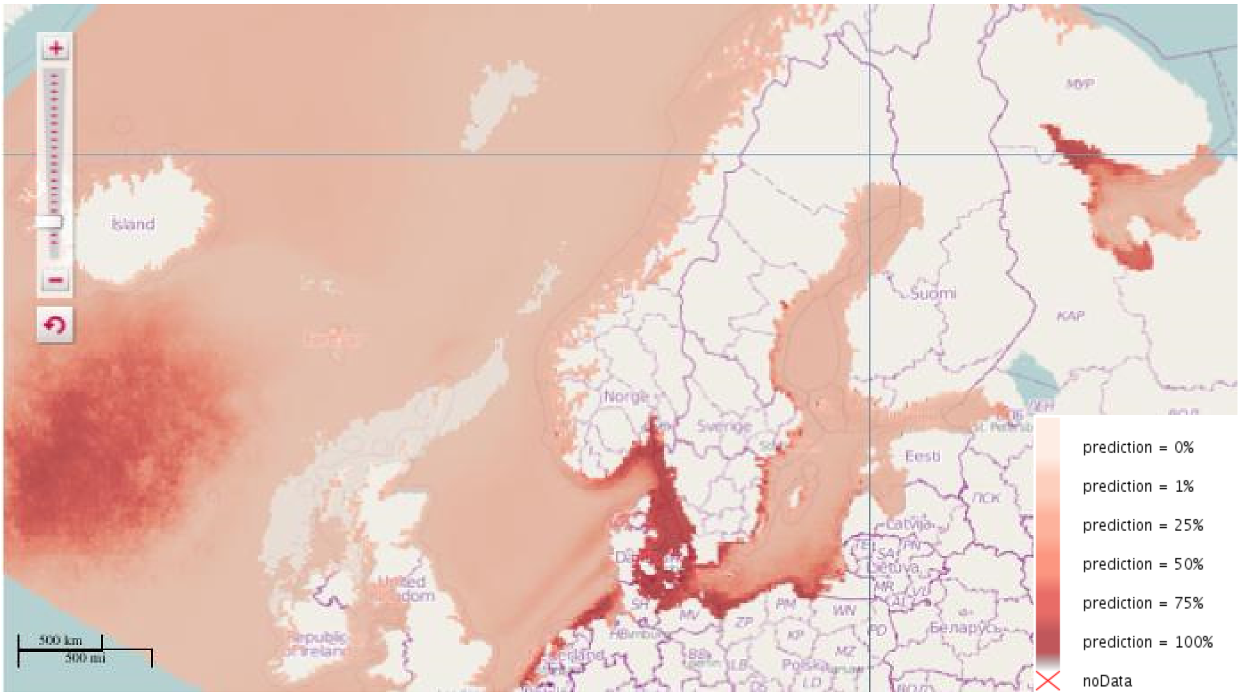


Figure 19. Potential distribution maps for *Prorocentrum minimum*, Baltic Sea

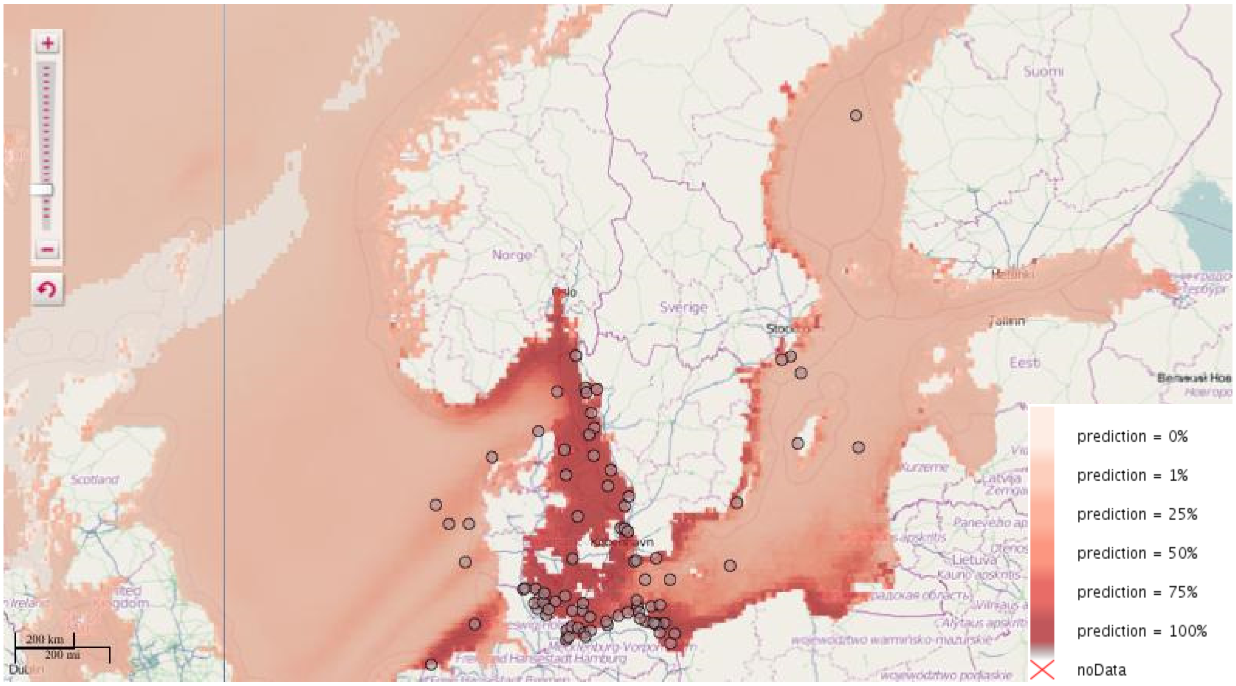


Figure 20. Potential distribution maps for *Prorocentrum minimum*, zoomed-in with occurrence points as black circles

ENM for *Prorocentrum minimum,* using 172 environmentally unique points and 5 environmental layers (maximum sea surface temperature, minimum sea surface temperature, mean salinity, mean nitrate and mean photosynthetically available radiation) gives a mean AUC of 0.82, showing the model is reliable. Modelling with the additional parameter nitrate, which is important in bloom formation for this species, yields a similar potential distribution map as in 1.1, with a more narrow distribution. According to this model, *Prorocentrum* has a lower probability of distribution in the Skagerrak, Danish west coast, Limfjord and Gulf of Riga.

As described above the results, which are based only on temperature, salinity and radiations and not on nutrients gave a distribution, which fitted better to the natural findings of *P.minimum.*

2. *Sargassum muticum*

a) layers used

- Mean salinity 5 arcmin (High tolerance to a range of salinities (> 5 PSU), although fertilization does not take place below 16 PSU).
- Mean annual distance to land 30 arcmin (Coastal species)
- Minimum sea surface temperature 5 arcmin (Low temperature and ice may be and inhibiting factor for growth, as the alga requires a temperature >8oC for more than 4 months)
- Mean annual sea ice concentration 30 arcmin
- Hard substrate layer -Not available- (This species grows on hard substrates only)

b) number of environmentally unique occurrence points after BioClim filtering

- 298

c) Modelling for Sargassum muticum using SVM (Support vector machine)

- Mean AUC = 0.97

Figure 21 and Figure 22: Potential distribution maps for *Sargassum muticum,* using mean salinity, mean annual distance to land, minimum sea surface temperature and mean annual sea ice concentration (SVM algorithm). Baltic Sea area (Figure 21) and zoomed-in with occurrence points as black circles (Figure 22). Red colour scale indicates habitat suitability from 0-100%.

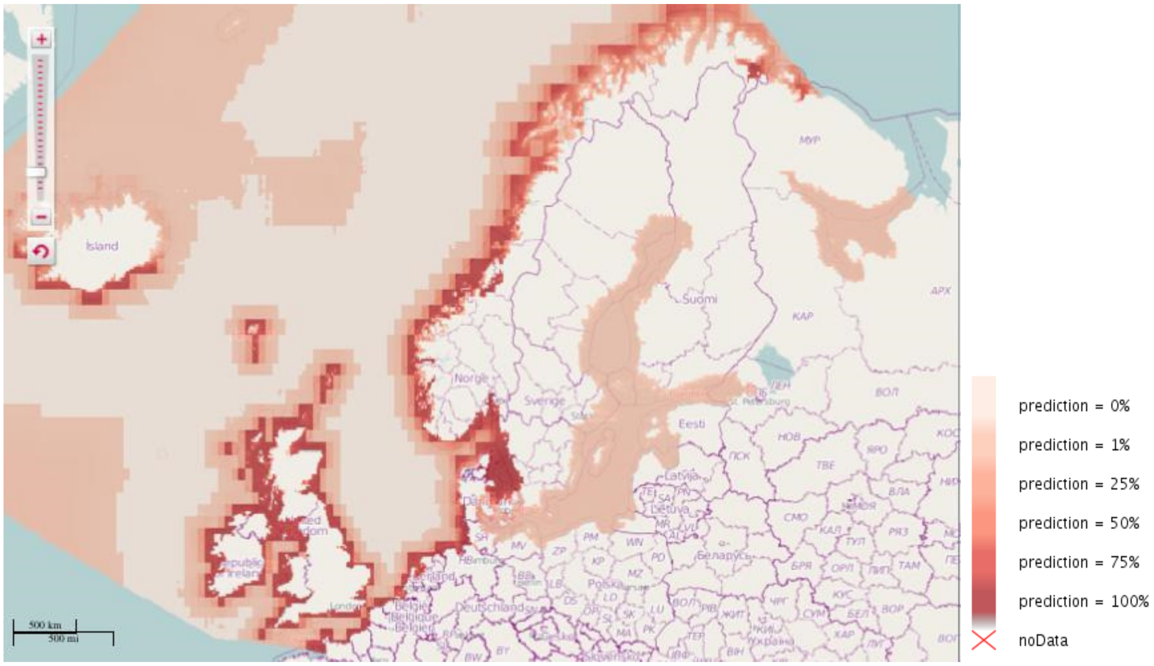


Figure 21. Potential distribution maps for *Sargassum muticum*

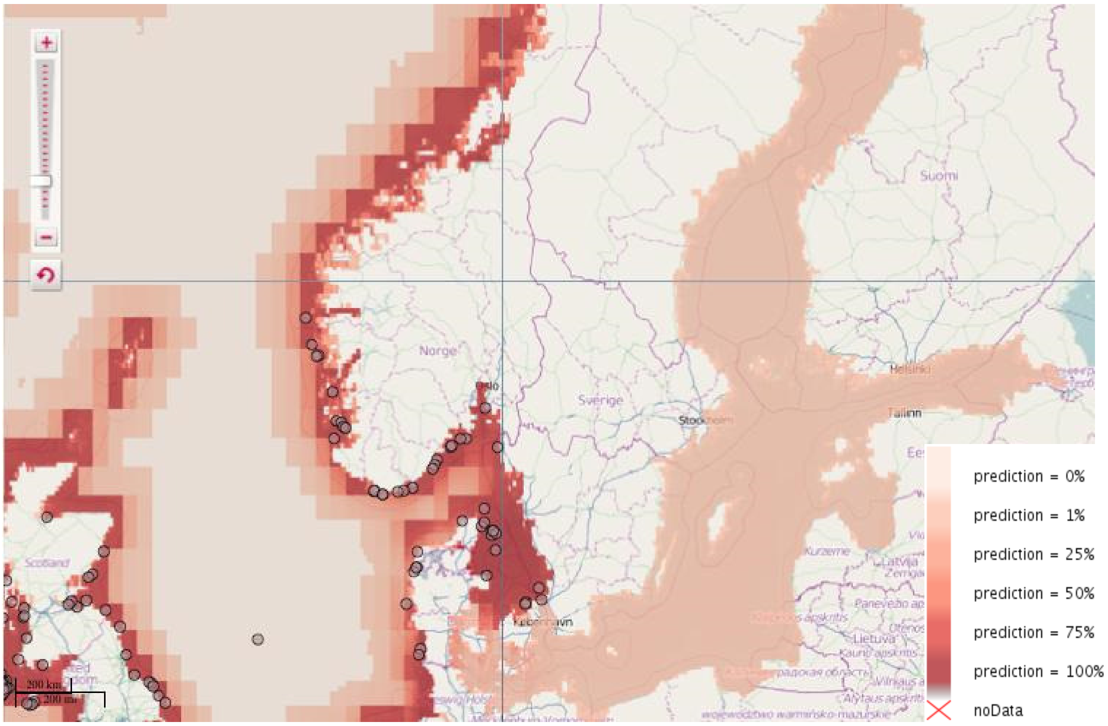


Figure 22: Potential distribution maps for *Sargassum muticum,* zoomed-in with occurrence points as black circles

ENM for *Sargassum muticum* with 298 environmentally unique points gives a mean AUC of 0.97, showing the model is reliable. The probability distribution map shows that this species is limited to high salinity areas of the Baltic including the Skagerrak and the Kattegat, which correlates with the lack of reproduction at salinities below 15 psu for this species. Its distribution is projected to extend in the North Sea, along the coasts of Norway and the UK. Layers used for this species included salinity, temperature, distance to land and sea ice concentration. Low temperature and ice may also be an inhibiting factor for this species as, the alga requires a temperature >8oC for more than 4 months. The model could be further improved by using an environmental layer mapping sediments types, as this species needs hard substrates for holdfast attachment. The calculated distribution fits very good with the published occurrence data. In Denmark *S.muticum* is found in the whole Kattegat area including the Sound and the Limfjord (Thomsen et al. 2007) and in Sweden it is established in the Skagerrak and Kattegat (Främmande arter i Svenska hav 2006), whereas it was not found in the German part of the Baltic Sea, but at the German North Sea coast.

3. *Coscinodiscus wailesii*

a) Layers used

- Mean salinity, 5 arcmin
- Maximum sea surface temperature, 5 arcmin
- Minimum sea surface temperature, 5 arcmin
- Mean photosynthetically available radiation, 5 arcmin
- Mean phosphate, 5 arcmin
- Mean silicate, 5 arcmin
- Mean nitrate, 5 arcmin

b) number of environmentally unique occurrence points after BioClim filtering

- 792

c) Modelling for Coscinodiscus wailesii using SVM (Support vector machine)

- Mean AUC = 0.974

Figure 23 and Figure 24: Potential distribution maps for Coscinodiscus wailesii, using mean salinity, maximum sea surface temperature, minimum sea surface temperature, mean photosynthetically available radiation, mean phosphate, mean silicate, mean nitrate (SVM algorithm). Baltic Sea area (Figure 23) and zoomed-in with occurrence points as black circles (Figure 24). Red colour scale indicates habitat suitability from 0-100%.

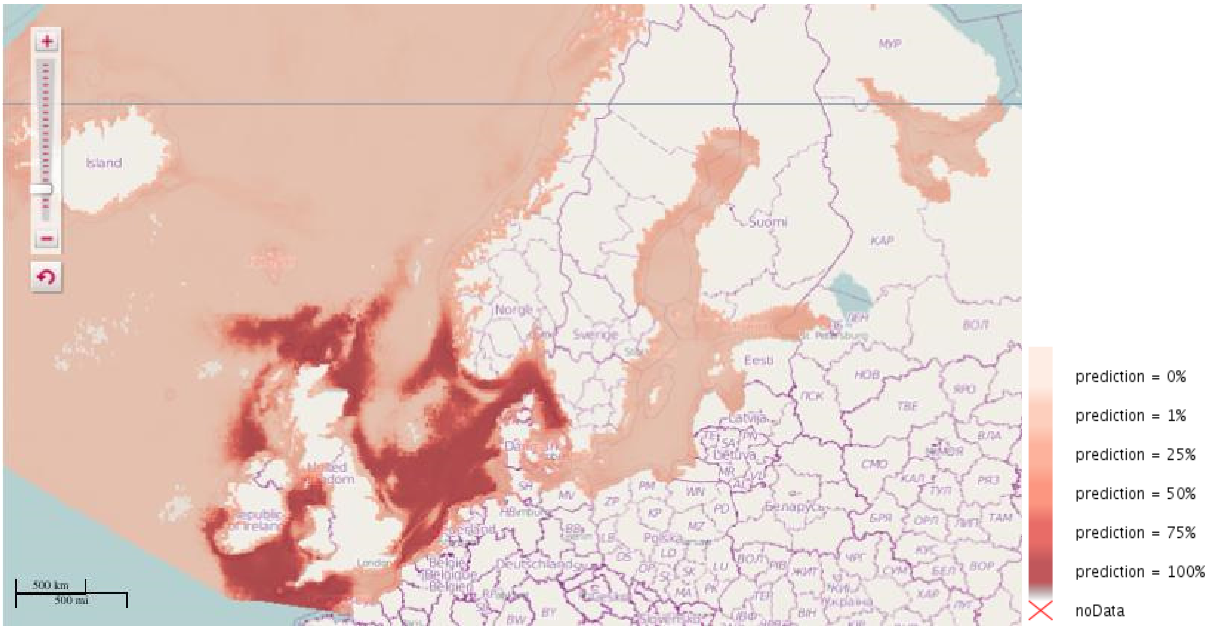


Figure 23. Potential distribution maps for *Coscinodiscus wailesii*

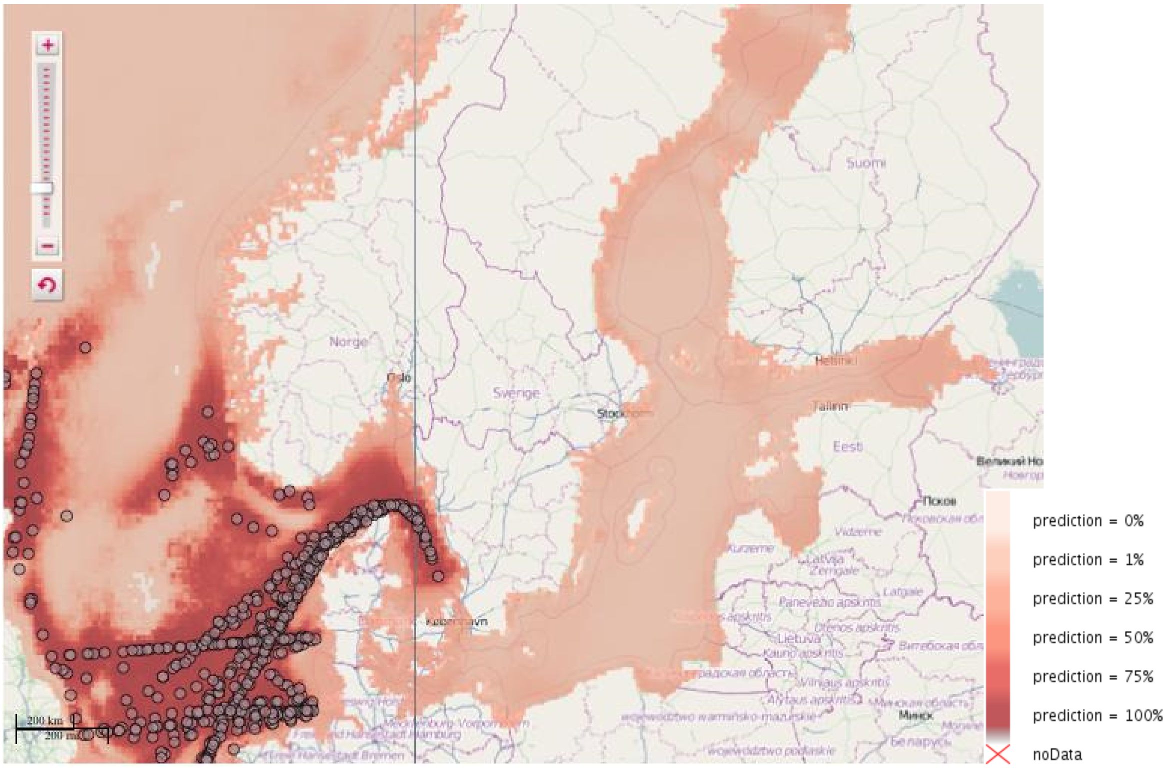


Figure 24. Potential distribution maps for *Coscinodiscus wailesii, zoomed-in with occurrence points as black circles*

ENM for the diatom *Coscinodiscus wailesii*, with 792 environmentally unique points, gives a very high mean AUC of 0.97, showing the model is reliable. The zoomed in map shows the occurrence data was systematically gathered for this species along a transect, giving a high number of environmentally unique points, excellent for niche modelling. The potential distribution map shows that the species is limited to higher salinity areas of the Baltic, the Skagerrak and the Kattegat, where salinities are higher than 15 PSU. This correlates with the salinity tolerance for this species in the range of 10-35 PSU. This species does not appear to pose an invasion risk to the Baltic proper, due its high salinity requirements.

The model results fit well with the finding of *C. wailesii* in the nature compared to the distribution described by Edwards et al. (2001) for the North Sea with high findings in the southern North Sea and the Skagerrak. Within the Kattegat, Belt Sea and German Baltic Sea it is more complicate to compare the model results with real findings since the distribution descriptions for the real findings differ between literature sources. Daisie (2006b) described a distribution of this species in the whole Kattegat, Belt Sea area as well as in the Arkona Sea and also Nehring (2005) noted findings in the German parts of the Baltic Sea. But in recent German monitoring programmes C. wailesii was not found in the German Baltic Sea and also in the ICES database are only single findings from the Kattegat area. Therefore it seems that the calculated distribution fits also well compared to the natural distribution in the Kattegat and Baltic Sea. The findings in the Baltic Sea area described by Nehring (2005) could be due to water inflow situations from the Skagerrak and C. wailesii was transported with the water. Therefore this species is probably not established in the Kattegat and Belt Sea. Also Olenina (2010) mentioned only rare findings of C. wailesii in low numbers from the Belt Sea in monitoring samples from 1980 to 2008.

4.3 Detection of algal blooms using satellite data

Several large blooms of *Pseudochattonella farcimen* have been observed in the Kattegat. They occur mainly during and after the spring bloom time. In 2011, the SMHI report Oceanographic Unit No 2, 7-15 March 2011; AlgAware - Algal Situation in Marine Waters Surrounding Sweden has reported about the spring bloom which also was formed by *P. farcimen* (SMHI 2011a) observed in two stations.

The report summarizes the occurrence of species within the spring bloom as follows:

"The phytoplankton flora was poor in the Skagerrak area and small flagellated species dominated the samples. The integrated (0-20 m) chlorophyll concentrations were low but within normal for this month.

Traces from the spring bloom were obvious in the Kattegat area and the species Pseudochattonella sp., which is toxic for fish was blooming at N14 close to the coast and at Anholt E, farther out. The integrated (0-20 m) chlorophyll concentrations were high but within normal for this month.*

At two of the Baltic stations, BY2 and Ref M1V1, the presence of several chain forming diatoms revealed that spring bloom was close. Apart from this, there were mostly small flagellates, ciliates and small spheric colony forming cyanobacteria in the phytoplankton samples. Enhanced integrated chlorophyll concentrations were found in the Southern Baltic." (SMHI report Oceanographic Unit No 2, 7-15 March 2011)

Especially for the Kattegat, high concentrations of *P. farcimen* were found and it is reported that the bloom was moving northwards and reached the Skagerrak area Mid March. The SMHI report covering the period from 6th to 13th of April describes the end of the bloom with only a few *P. farcimen* cells remaining in the samples (SMHI 2011b).

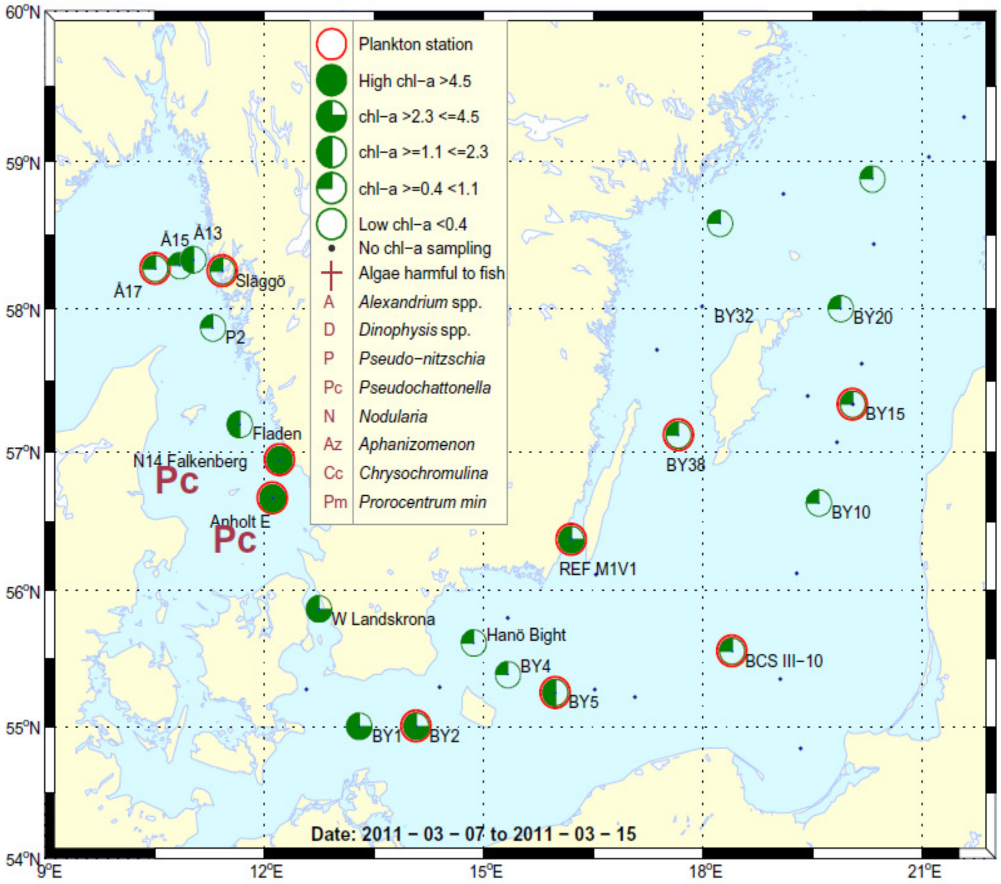
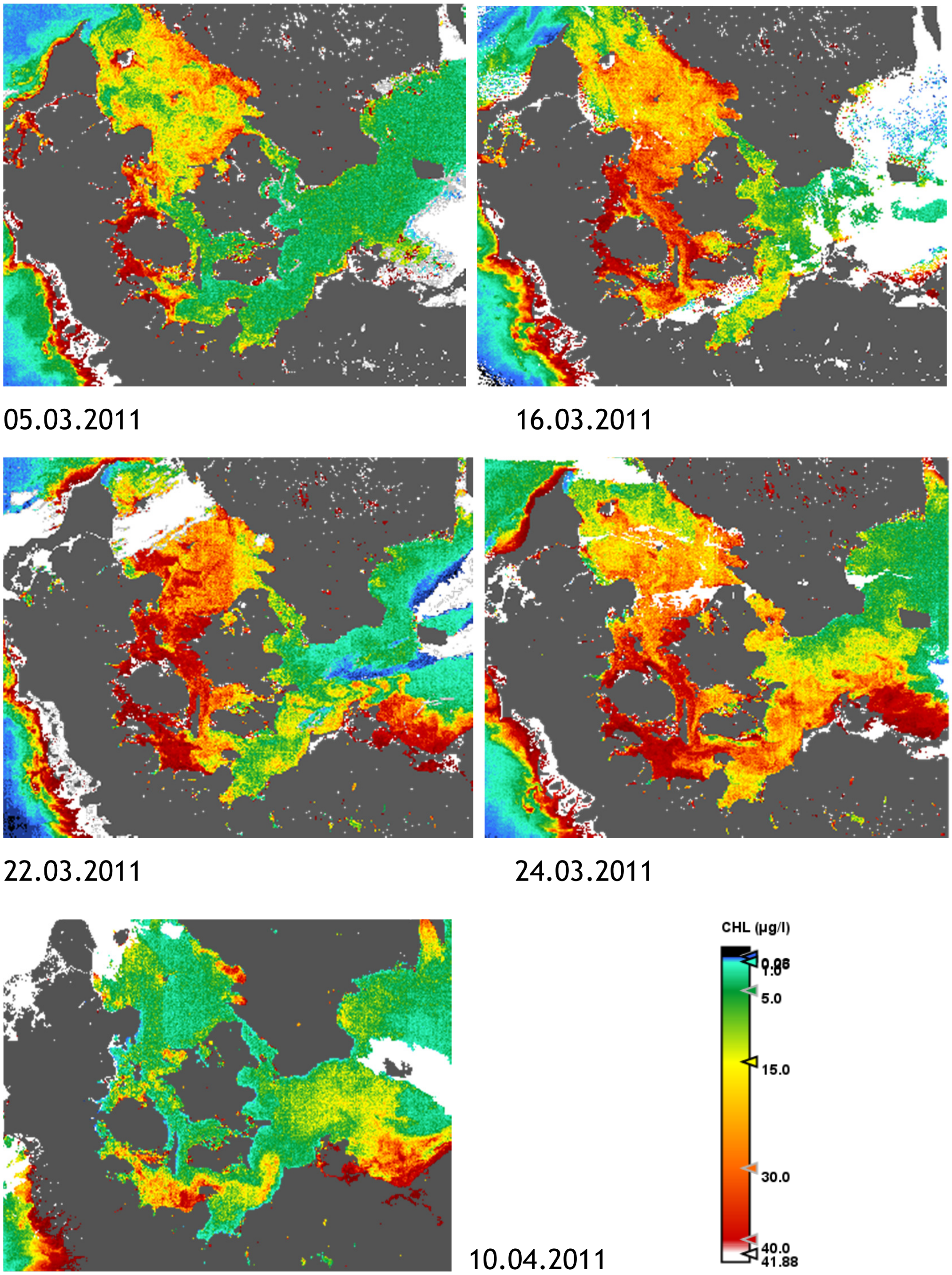


Figure 25. Map showing species distribution in March 2011 in the western Baltic Sea. The map shows weighted mean of chlorophyll a, µg/l (0-20 m) at sampling stations. Presence of harmful algae at stations where species analysis is performed is shown with a symbol. An empty circle indicates that there has been no sampling at that station. Source: SMHI Oceanographic Unit No 2, 7-15 March 2011

The following images show the chlorophyll concentration derived from satellite data. The images start in March 2011 and end in April 2011, showing the development and end of the algal bloom which was reported in the above mentioned reports. Beginning of March, already high concentrations in the Little Belt and high concentrations in the Kattegat can be observed. Mid of March the areas with concentrations higher than 5 and also 10 mg/m³ have increased and are decreasing until Mid of April.



05.03.2011 16.03.2011

22.03.2011 24.03.2011

10.04.2011

Figure 26. Chlorophyll Concentration in the Kattegat in 2011 showing the development of an algal bloom during March and its decrease beginning of April (10.04.2011)

Further investigations of the spatial extend of the bloom has been performed. We have defined a reference area for which we extracted the spatial extent of different chlorophyll concentrations during the blooming period. The reference area for this is shown in Figure 27. The chlorophyll concentration has been classified into 3 classes and the area which is covered by the respective classes is shown in Figure 28.

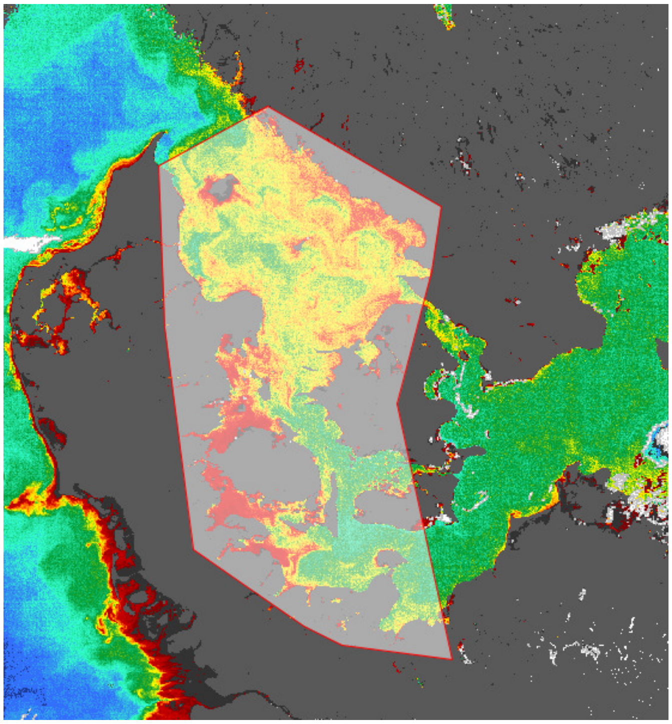


Figure 27. Reference area for investigating the spatial extent of different chlorophyll concentration classes.

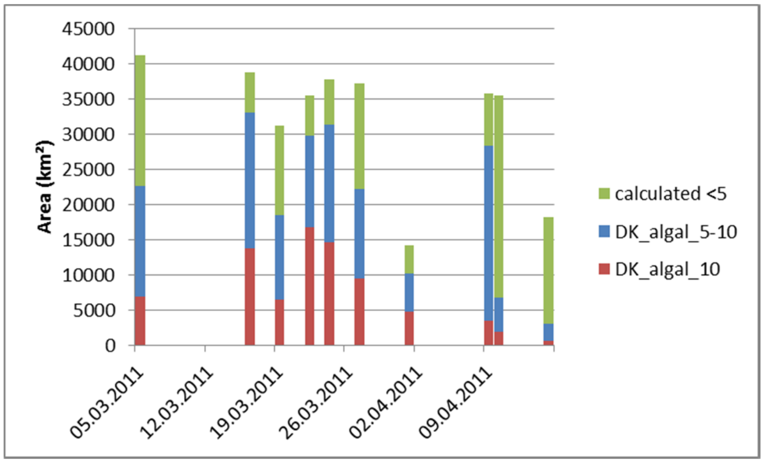


Figure 28. Spatial extent of certain chlorophyll classes during the blooming period

The total height of the columns shows the total number of pixels with valid chlorophyll values on the respective day. The total number of valid pixels within the reference area changes due to cloud coverage and other influences/failures of the processing. In order to take this into account, the relative portions of the areas in relation to the reference area have been calculated and are shown in Figure 29.

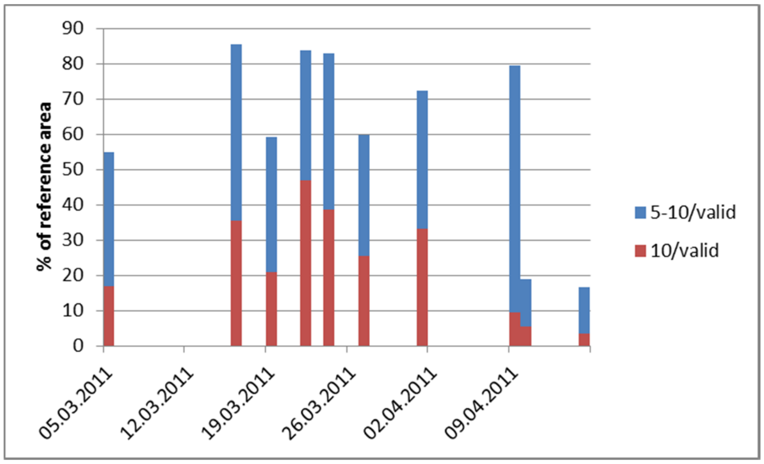


Figure 29. Relative portions of the area compared to the actual number of valid pixels, in order to minimize the influence of different numbers of valid pixels.

Regarding the development of the high concentration area (>10mg/m³), there is a clear increase from beginning of March until end of March and then a slow decrease until mid of April where almost no high concentrations occur any more. And it can be seen that days with lower numbers of valid pixels due to cloud coverage influence this trend and should be considered carefully.

Concerning the SMHI report 2011a, *P. farcimen* was detected mainly at the stations Falkenberg and Anhold. Figure 30 shows the time series at these stations and a third station (Fladen) without occurrence of *P. farcimen*. At all three stations, a clear spring bloom with high concentrations can be detected, while the Falkenberg and Anhold stations show a clear peak Mid of March while the chlorophyll concentration at Fladen already decreases.

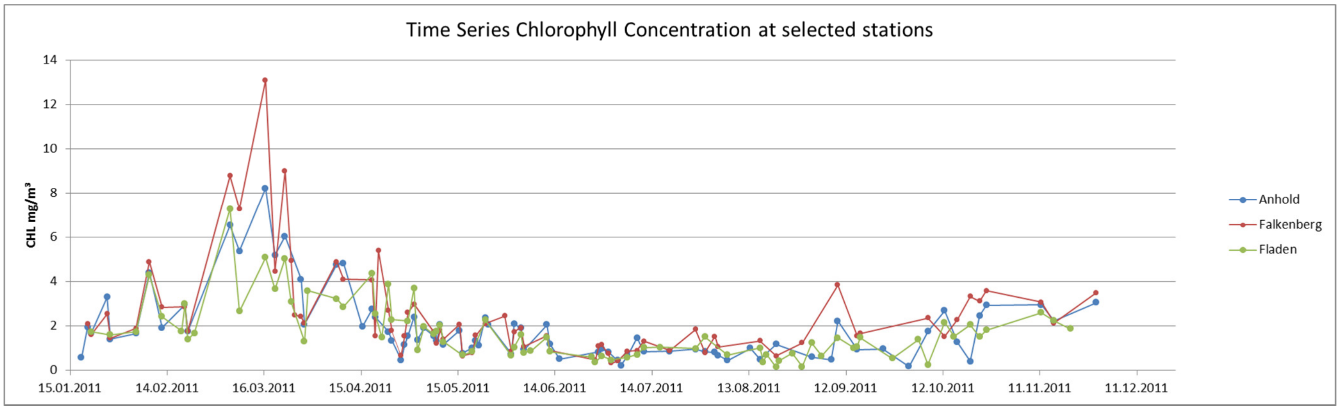


Figure 30. Development of the algal bloom in 2011 at 3 different measurement stations

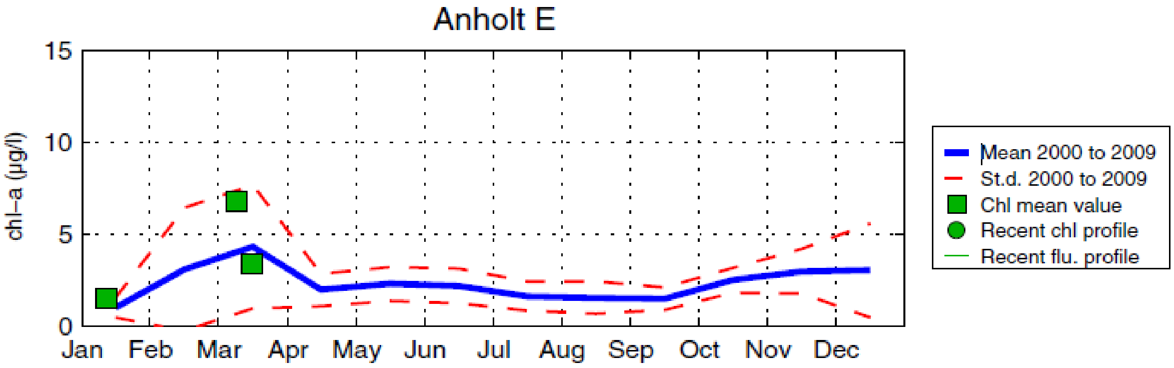


Figure 31. Chlorophyll distribution at Station Anholt E showing a climatology mean (2000-2009) derived from R/V Argos; source: SMHI 2011a

Further investigations have been performed to find smaller bloom events of invasive species in the Baltic Sea by literature research, mentioned in different sources but these could generally not be detected in the satellite data. This might be due to a small extent of the bloom, too low concentrations or stations which were too close to the land.

Comparison of the chlorophyll concentration in spring 2007 (Figure 32) and 2011 (Figure 33) derived from satellite data in comparison with the occurrence data of *Pseudochattonella.*

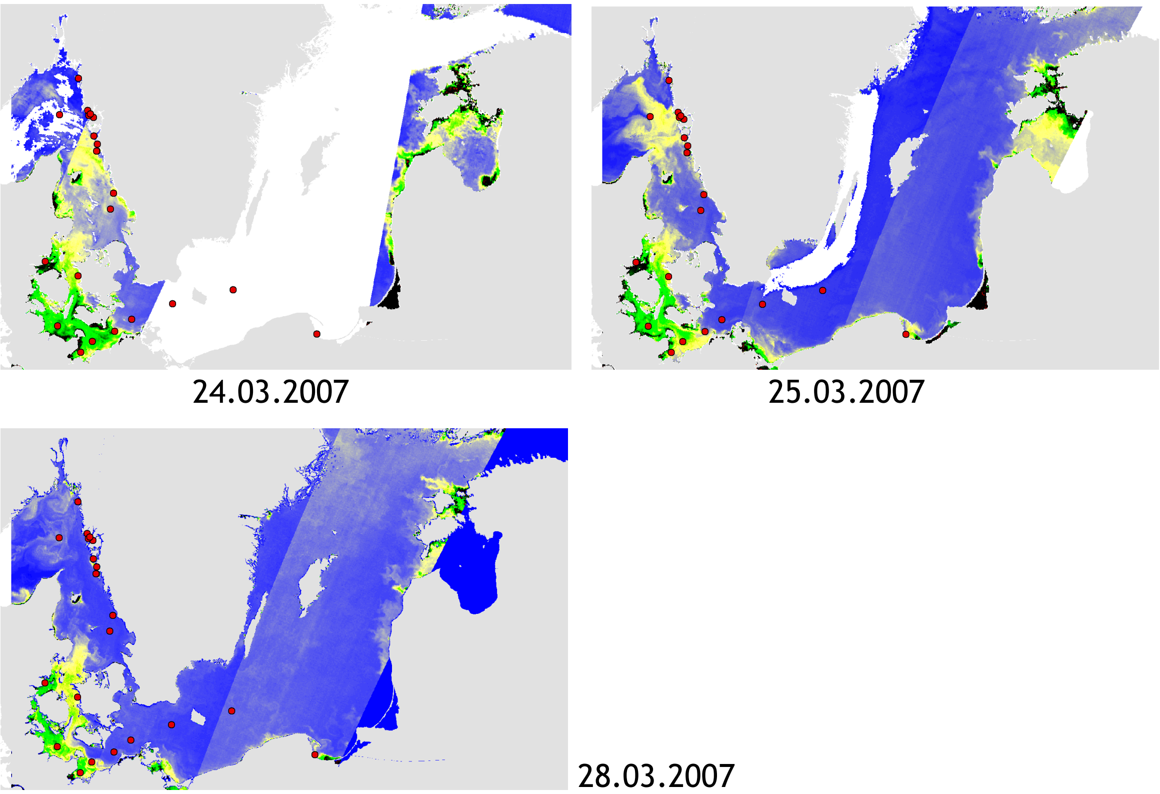

24.03.2007
25.03.2007
28.03.2007

Figure 32: Chlorophyll concentration in the Baltic Sea in spring 2007 overlaid by the occurrence data of Pseudochatonella

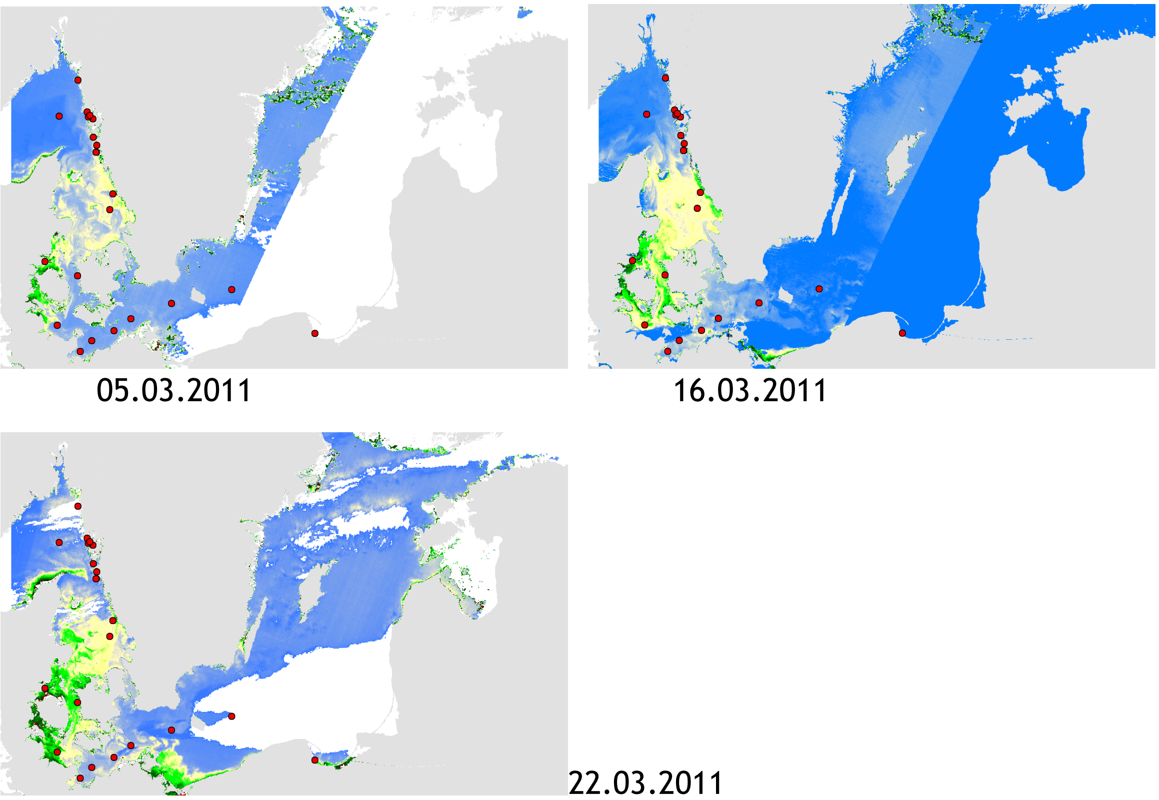
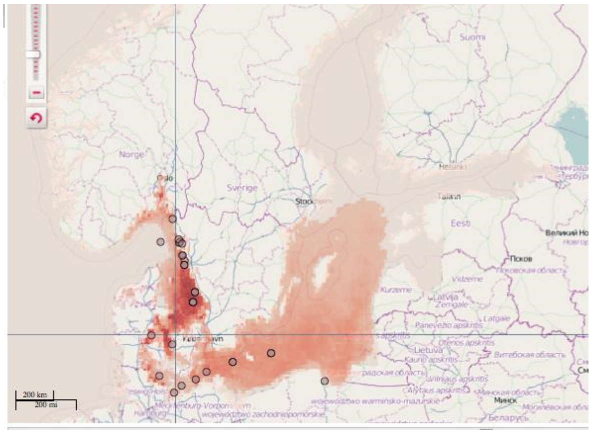


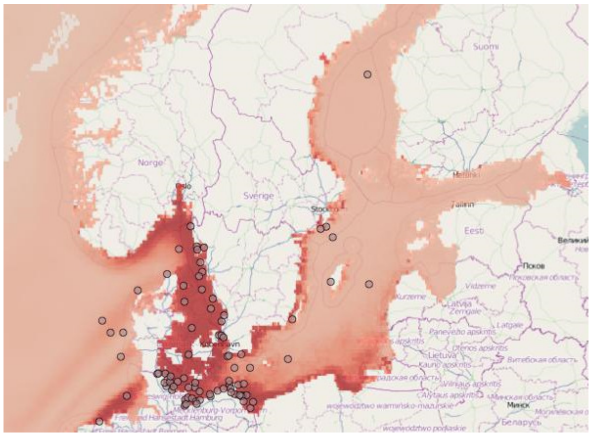
Figure 33: Chlorophyll concentration in the Baltic Sea in spring 2011 overlaid by the occurrence data of Pseudochatonella.

4.4 Comparison of detected algal bloom with Model results

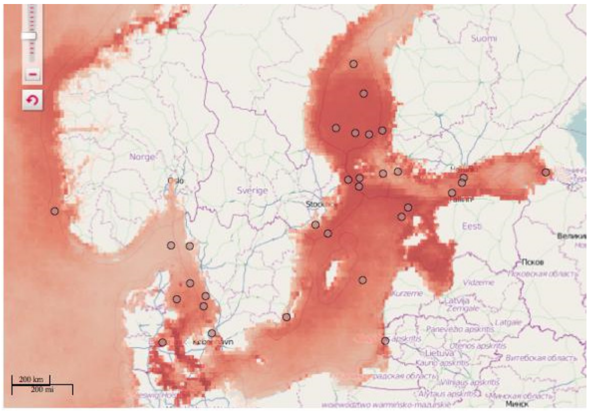
One objective of this study was to combine the information derived from satellite data and model results. It can be stated that the highest risk of intrusion of invasive species is in the Kattegat region, where all species show a probability to live. The Kattegat region is the main area where the spring blooms occur, thus showing in almost all years also very high chlorophyll concentrations in the satellite data. However, the detection of different species is not possible with the EO data.



Pseudochatonella farcimen



_*Prorocentrum minimum*



Alexandrium ostenfeldii

Figure 34. Potential distribution maps for selected species with highest potential to invade into the Baltic Sea

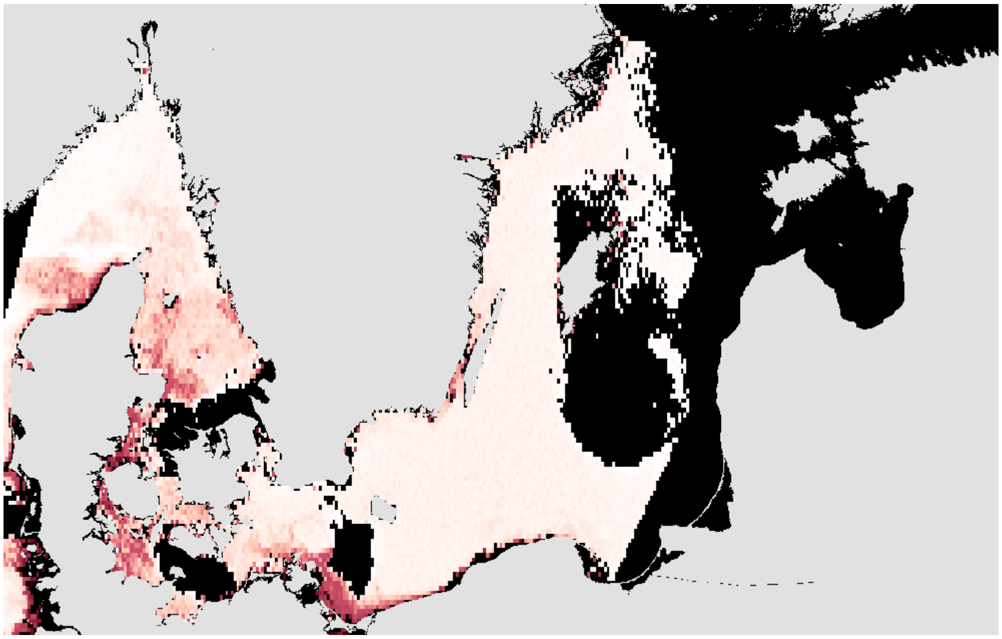


Figure 35: CHL Concentration from Satellite showing high concentration where also a high probability has been calculated for the species to survive - in the Kattegat region.

5 Discussion of results

5.1 Conclusion on model results

For the species *Alexandrium ostenfeldii, Coscinodiscus wailesii* and *Sargassum muticum* the model results fit quite well with their observed distributions (see Chapter 4.2). The calculated distributions for the other three species fit in parts good and in parts not good with their observed distributions; *A. minutum* is found in the Kattegat, but the model result calculated a zero probability, for *Pseudochattonella farcimen* the calculated probability seems to be too high for the eastern part of the Baltic Sea , whereas for *Prorocentrum minimum* the calculated probability is too low for the eastern part of the Baltic Sea, since this species is found in the whole area of the Baltic Sea with exception of the Gulf Bothnia.

But all in all, the results seem to be quite encouraging for further investigations (modelling) since despite the facts that for some species only few occurrence data, only layers based on yearly mean values and limited knowledge about their ecological requirements were available (see Chapter 5.2) the model results and real occurrence in nature fitted quite well.

Generally the model results have to be interpreted with caution, since some species are able to adapt to their new environment. Some species are able to develop different strains, which tolerate the specific abiotic conditions in a new environment, and that makes it difficult to predict in which habitat or under which abiotic conditions a certain species could live e.g. *Alexandrium ostenfeldii*. That means that some species are very flexible and able to react on changing habitat conditions.

5.2 Requirements of Niche modelling

5.2.1 Occurrence records

It is important to note here that the accuracy of modelling is dependent on the availability of sufficient numbers of up-to-date and high quality occurrence records. The higher the number of areas sampled where the species is known to live, i.e. an area covering the entire distribution of the species, the better the accuracy of model prediction will be. The more accurate the information provided to the algorithm, the more accurate the resulting model will be. This includes information about all areas where a species is known to occur, including occurrence data from the native range of the species for invasive species. For some algorithms, absence data are also required for model creation. This highlights the need for high quality data from monitoring if ENM is to be implemented as a risk assessment tool.

In our example, in the case of the dinoflagellate *Alexandrium minutum*, our model shows that the probability distribution of this species in the Baltic Sea proper is 0% (Figure 12). This can be correlated with the fact that no occurrence records have been recorded for this species in the Baltic proper and all modelling is based on records from the Mediterranean Sea, the Atlantic coast of France and the English Channel (Figure 5). The model predicts a low probability of potential distribution for this species in the Skagerrak (Figure 6), but on the whole this species present a low risk to the Baltic Sea due to low habitat suitability based several environmental factors combined: nitrate, mean photosynthetically available radiation, mean annual distance to land, temperature and salinity.

5.2.2 Environmental layers

High resolution environmental layers are also important in modelling to produce high resolution prediction maps. Layers used in this study are derived from in situ measured oceanographic data and from remote sensing and ranged from 5 arcmin (9.2 km) for temperature, salinity, nutrients and radiation to 30 arcmin for geographical layers such as distance to land, giving a coarser resolution to model projections using this layer (Figure 11 and Figure 12). Other environmental layers such as substrate layers (hard bottom/sediment) could add further information for the modelling of some of our species. For example, the invasive macroalgae *Sargassum muticum*, or Japanese wire weed, grows attached to rocks by a holdfast. For modelling this species, a hard substrate layer would be required but was not available. This highlights the fact that high resolution and relevant environmental data in the form of raster layers are necessary to produce accurate probability distribution maps for the species. The inclusion of satellite product as environmental layers was one of the steps to integrate the different methods. The layers derived from satellite data could be reduced in their spatial resolution for future applications as the original data have a spatial resolution of 1km.

5.2.3 Species biology information

To obtain accurate probability distribution maps, detailed information on biology and ecological requirements and life history strategies needs to be gathered for the species analysed, to inform on the correct choice of environmental layers. This information can be obtained from the literature or from specialized databases such as the Baltic alien species database (http://www.corpi.ku.lt/nemo/alien_species_search.html). For example, in the case of the harmful dinoflagellate *Alexandrium minutum,* growth is associated with high nitrate and water temperature, with higher temperatures leading to increased growth, important factors for the choice of environmental layers. Salinity also affects this species, which can rapidly adapt to low salinity. However, growth is inhibited below 10 PSU (Grzebyk et al. 2003). From this information we can conclude that nitrate, mean sea surface temperature and salinity are relevant parameters which are important for this species to grow, and these can be included as environmental layers to create the niche model.

5.3 Conclusion EO - model - in situ

Satellite data provide the information about the spatial and temporal distribution and evolution of the chlorophyll concentration, while in situ data provide information about the species. A combination of both observation techniques provides a very good picture of the situation. In addition, the probability that a species might occur is provided by the model results. The models show high risk in the Kattegat for a number of species to survive while also the satellite data detect the yearly spring bloom and other blooms in this region.

Limits are set for the spatial resolution of both - the satellite data and the model results. Small blooms and blooms very close to the coast could not be detected by the satellite data in the investigated cases. The spatial resolution of satellites and the model does not provide information about small risk and distribution, e.g. within harbours. Here, in situ data remain the most important data source at the moment and needs to be intensified.

5.4 Risk Assessment tools - possible applications / combination

The results from the ENM can be used for Risk Assessments (RA), which have to be run in frame with the new Ballast Water Convention (BWC) developed by the International Maritime Organization (IMO). Risks and threats posed by translocation of marine organisms are often associated with ship's activity by discharging ballast water and therefore the BWC will regulate the management of the ballast water and sediments in order to reduce the risk for introduction species into the recipient ports. When the BWMC will come into force for all ships it will be forbidden to discharge unmanaged ballast water in the recipient port, except for those which got exemptions from ballast water management. Ships can apply for an exemption from ballast water management on the basis of a risk assessment (RA). These RA determine the probability that a certain species from the donor port could survive in the recipient port. One proposal for such a RA is developed by the North Sea Ballast Water Opportunity (NSBWO) (NSBWO, 2010) and is based on target species (selected invasive species), which have to be determined a priori for the donor and the recipient port, respectively, and their tolerance concerning salinity. Additionally, the environmental matching between donor and recipient is assessed by comparing the salinity conditions in both ports. It is distinguished between unacceptable 'high' and acceptable 'low risk' scenarios and it combines environmental matching with a species-specific approach. For 'high risk' shipping routes no exemption from ballast water management will be granted.

The ENM could support the RA proposed by the NSBWO in two ways:

- since the ENM takes into account more environmental layers than only salinity; e.g. nutrients, radiation or temperature, the outcome of the RA would be more accurate and precise
- the possibility of a species to reach the recipient port on its own (natural spread) that means without having been transported by ballast water can be assessed, e.g. the possibility for natural spread of a certain species can be assessed as zero, if the probability of a species to live in the area between two ports, i.e. along a shipping route, is zero or very low, respectively.

The following examples compare the outcome of the RA proposed by the NSBWO with the assessments which could be done on basis of the results of the ENM.

For the target species *Prorocentrum minimum* all shipping routes within the Baltic Sea are assessed as 'high risk' routes on basis of the RA proposed by the NSBWO, since *P. minimum* has a very high salinity tolerance (0,7 to 35 ‰). The outcome of the ENM is much more detailed. It calculated a much lower probability for *P. minimum* to survive in the more eastern parts (Gulfs of Riga and Finland and Bothnian Sea and Bay) compared to the more western parts of the Baltic Sea (Figure 17 and Figure 18). Therefore a shipping route between e.g. the port of Kiel in the western part of the Baltic Sea to the ports of Helsinki or Tallinn in the eastern part of the Baltic Sea could be assessed as 'low risk' shipping route. See Figure 36 for an overlay of shipping routes on the potential distribution map for *Prorocentrum minimum* and Figure 37 with the potential distribution map for Pseudochatonella.

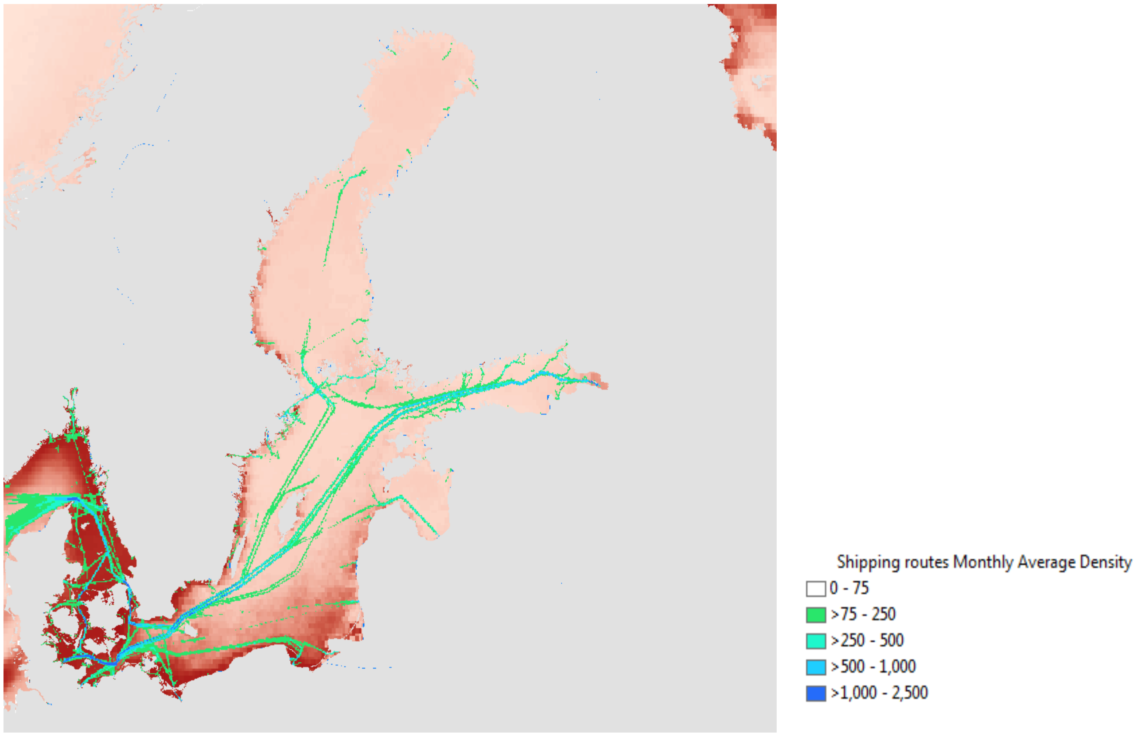


Figure 36. Shipping route overlaying potential distribution map of Prorocentrum, (Algorithm: SVM, layers: Mean sea surface temperature (Celsius), 5 arcmin, Mean salinity (PPS), 5 arcmin, Mean photosynthetically available radiation (Einstein/m2/day), 5 arcmin)

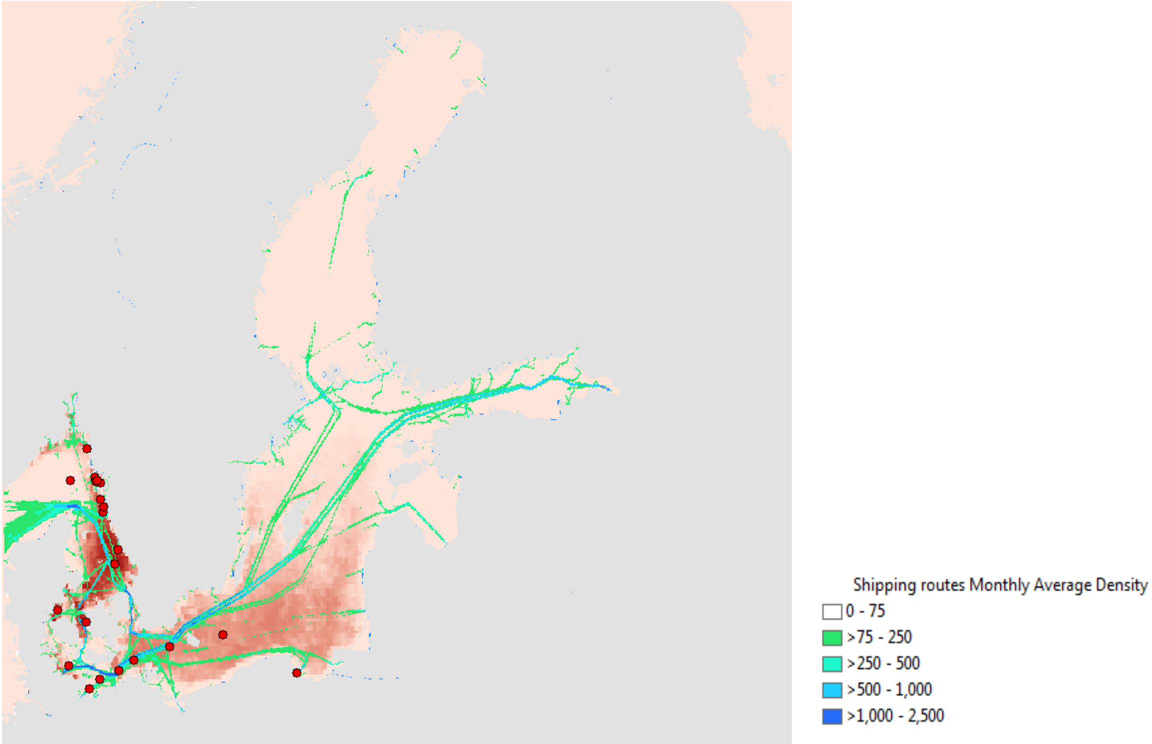


Figure 37. Shipping route overlaying potential distribution map of Pseudochattonella (Algorithm: SVM, layers: Mean sea surface temperature (Celsius), 5 arcmin, Mean salinity (PPS), 5 arcmin, Mean photosynthetically available radiation (Einstein/m2/day), 5 arcmin)

Another example for the comparison of RA and model results is *Alexandrium ostenfeldii*. Since *A. ostenfeldii* tolerates salinities between 6 to 40 ‰ the RA proposed by the NSBWO assesses all shipping routes within the Baltic Sea with exceptions of the ports with very low salinity in the eastern part of the Baltic Sea as 'high risk' shipping routes. The results from the ENM show a more detailed picture, high probability for the species to survive in the Belt Sea, in the Gulf of Riga and the Bothnian Sea as well as in the Belt Sea but low probability that *A. ostenfeldii* could live in the Southern Baltic Sea, near the German coast (Figure 15 and Figure 16). Therefore a shipping route e.g. from Helsinki (high probability) to Swinemünde or Gdansk (low probability) could be assessed as 'low risk' shipping route.

Also the ability for natural spread of species can be assessed with the outcome of the ENM. In the last years *P. minimum* was not found in the Bothnian Sea and Bay whereas it could tolerate the salinities in this area. The results of the ENM show that there is a high probability for *P. minimum* to be able to live some coastal spots at the western part of Bothnian Sea (Figure 17 and Figure 18). But since between these spots the probability for this species to survive is very low, *P. minimum* wouldn't be able to reach the other location on its own. Therefore the transportation with ships is a high risk to spread the species to these spots.

Thus, the way between two harbours should be taken into account for the risk of natural spread. The model results could provide some indications if a species would be able to naturally spread from one harbour to another if the potential distribution map shows high probability in both harbours and between them. Figure 38 shows the potential distribution map for Pseudochattonella and an overlay of two transects between Kiel-Helsinki and between Malmø-Gdansk. The probability of Prorocentrum and Pseudochattonella along both lines is shown in Figure 39 and Figure 40.

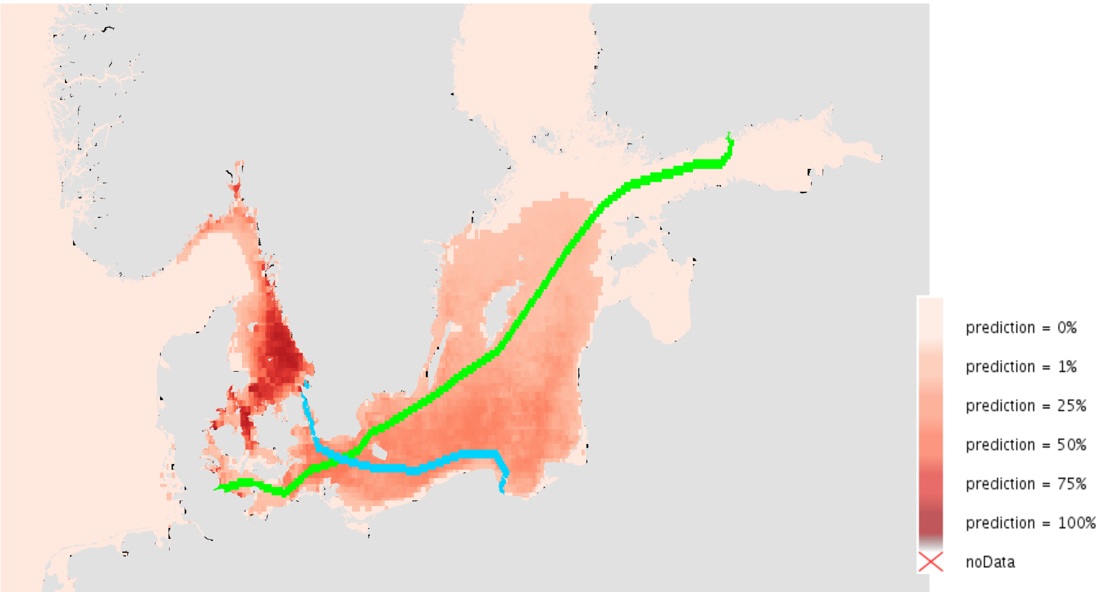


Figure 38. Potential distribution map for Pseudochattonella and overlaid transect between Kiel – Helsinki (green line) and Malmø – Gdansk (blue line).

For the route between Kiel and Helsinki both species show longer segments of low probability and thus it could be assumed that a natural spread of these species would not occur between the two harbours. The route between Malmø and Gdansk shows medium to high probability for both species, thus a natural spread might be more probable here. These graphs shall provide an idea on how to use the data for assumptions on natural spread. Though, some further aspects should be taken into account, such as the full area between harbours (not only transects) or currents.

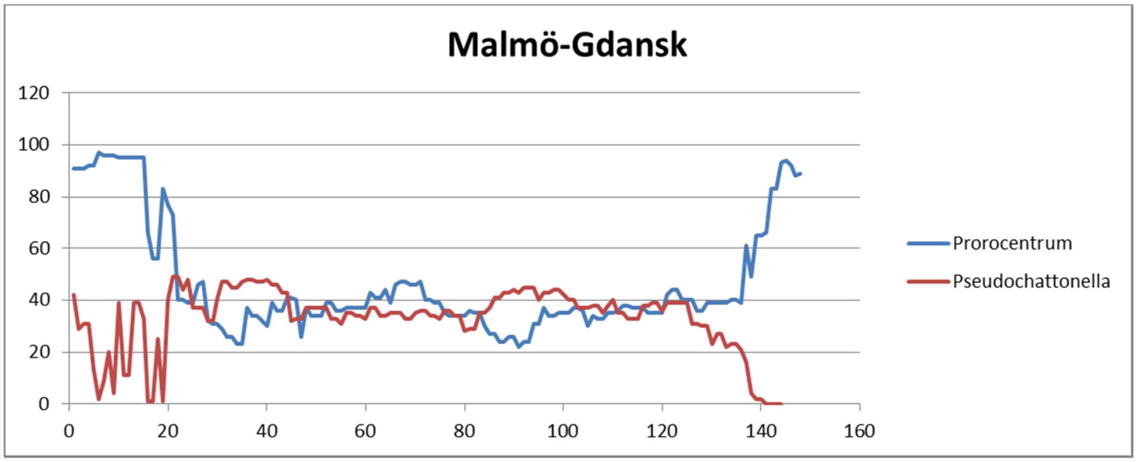


Figure 39. Potential distribution of *Pseudochattonella* and *Prorocentrum* along a line between Malmø and Gdansk

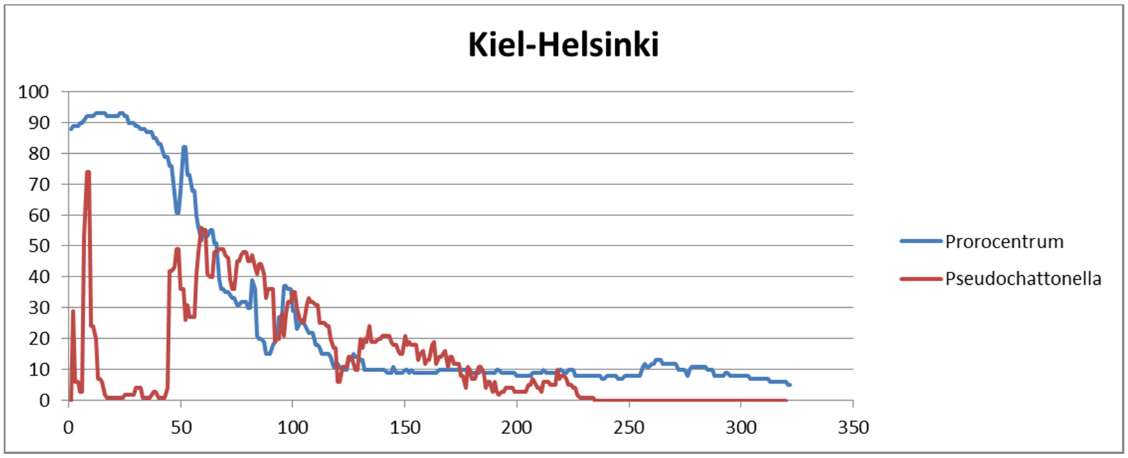


Figure 40. Potential distribution of *Pseudochattonella* and *Prorocentrum* along a line between Kiel and Helsinki

6 Summary/Conclusion

This study shows clearly the urgent need for better aggregation and mobilisation of existing occurrence data, though platforms like GBIF, Swedish LifeWatch (SMHI), ICES, etc. In many cases high quality occurrence data for species of interest exist, but are kept by individual experts or local networks. Such data need to be made discoverable in the future.

In addition the seamless access to more environmental information, e.g. gridded environmental layers for bottom substrate types is essential for ecological niche modelling studies on large temporal, spatial, as well as taxonomic scales. Seasonal information would be more suitable in order to describe the biological requirements of the species.

Interaction between modelling and observation methods needs to be strengthened. The availability of real-time multidisciplinary ocean datasets will be critical for the next generation of biological models of the ocean. A better integration of the modelling workflows and remote sensing data featured in this report with Biodiversity Observatory Networks (so called BON's) will increase the predictive power and decision support potential tremendously. Here especially Early Warning Systems (e.g. www.embos.eu, www.genomicobservatories.org) will deliver essential data on alien species at a very early stage, and before they become invasive.

7 Acknowledgements

These analyses were performed using biodiversity e-science infrastructures BioVeL (www.biovel.eu) and Swedish Lifewatch (www.slu.se/lifewatch).

National monitoring agencies Germany (LUNG and LLUR) for providing in situ monitoring data.

ICES for supporting the download of the data from the ICES database.

This work has been funded by ESA through the GSE Marcoast project (Option Ballast Water)

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*****End of report*****