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Analysis of climate change impacts on the ecological system of the western Baltic Sea

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Abstract

Climate observations for the Baltic Sea show a warming of 0.85 °C throughout the last 100 years. Projections for the 21st century indicate an accelerated warming trend and changes in precipitation patterns. These changes could have an impact on the ecological system of the Baltic Sea, as described in the *Assessment of Climate Change for the Baltic Sea Basin*. This study models these ecological impacts in using a simple ecological model that was applied to the habitat type 'reefs' within the marine *Special Areas of Conservation* (SACs), according to the European Habitat Directive. Based on results from the REMO regional climate model, changes of the ecological system of the Baltic Sea were modelled. Furthermore, the most important reef characteristics and climate factors which induce ecological impacts in the area were identified. Results indicate that the trophic level and light conditions of a SAC determine the direction and the magnitude of climate-induced ecological impacts. The most important climate element was found to be precipitation over land which controls the runoff and, therefore, the nutrient and freshwater input into the ecosystem of the Baltic Sea.

1 Background and motivation

The Baltic Sea is the world's largest brackish sea. Compared to its water volume, the catchment area is very large; meanwhile, water exchange with the adjacent North Sea is limited to three narrow passages (Little Belt, Great Belt, The Sound). Eutrophication and pollution by harmful substances, therefore, is an important issue for the protection of the Baltic Sea (HELCOM 2003). Several international agreements were signed in order to protect terrestrial and marine environments in general (e. g. Habitat Directive, Water Framework Directive) and, specifically, the Baltic Sea environment (e. g. HELCOM). Throughout the last few decades, climate change has become an issue of rising importance for the protection of both terrestrial and marine environments (Kirby 2003). Compard to a mean global warming of 0.05 °C/decade from 1861 to 2000, the Baltic Sea region has experienced a considerably strong warming of 0.08°C/decade. Furthermore, regional climate projections indicate that this trend will continue for the next 100 years, suggesting further warming of 3 to 5°C and associated changes in precipitation patterns (HELCOM 2007). Hence, ecosystem changes have been observed by several authors, including changes in sea surface temperature (SST), ice sheet cover, and river runoff (Graham 2004, Madsen & Højerslev 2009, Omstedt et al. 2004). If this trend continues, it is expected that climate change will also affect the water exchange between the North Sea and the Baltic Sea, and the salinity and hydrographic conditions in the Baltic Sea (HELCOM 2007, Omstedt et al. 2004).

The ecosystem of the Baltic Sea is strongly governed by salinity and oxygen gradients. A continuous decrease in salinity is observed from the North Sea connection to the northeasternmost part of the Baltic Sea. Furthermore, the presence of a distinct halocline, seperating the saline water of the North Sea from the much fresher Baltic Sea water, inhibit vertical water exchange (HELCOM 2003). Due to the topography of the Baltic Sea, which is characterized by many basins separated by ridges, the inflow of saline North Sea water to the Baltic Sea is limited to strong storm events that can produce salt water inflows (Lass & Matthäus 1996). Both the basin structure and the stable halocline explain why the Baltic Sea ecosystem is very sensitive to variations of climatic parameters.

The estimation of future climate change on the scale of the Baltic Sea is only possible by means of regional climate models that have a high spatial resolution and incorporate the Baltic Sea as a driving climate factor (Hagedorn et al. 1998). Several models have been presented during the last decade. A project named PRUDENCE compared the results and presented projections for future climate changes in Europe (Christensen & Christensen 2007). One of these models with a horizontal resolution of 50 km was the REMO model (Jacob & Podzun 1997). For more regional predictions, e. g. high resolution simulations for Germany, the model was downscaled to a 10 km resolution (Jacob et al. 2008). Due to its high resolution and its good agreement with data published by the PRUDENCE project (Figure 1) and Hagedorn et al. (1998) within the region of the south-western Baltic Sea, these data were used for the presented analysis. Figure 1 shows the projections for temperature and precipitation changes between 1961-1990 and 2071-2100 of several regional and global climate models that were applied to the Baltic Sea during the PRUDENCE project. The Baltic Sea area was divided into 4 subregions, separating land from sea regions and the north-eastern from the south-western parts. Figures 1a and b show projected changes of temperature and precipitation for the period between 1961-1990 and 2070-2099 in winter and summer months, respectively (HELCOM 2007). In comparison, simulation data on the German Baltic Sea, located in the south-western part of the Baltic Sea, are derived from the REMO-UBA project and are indicated as boxes, representing the range of data as annual mean.

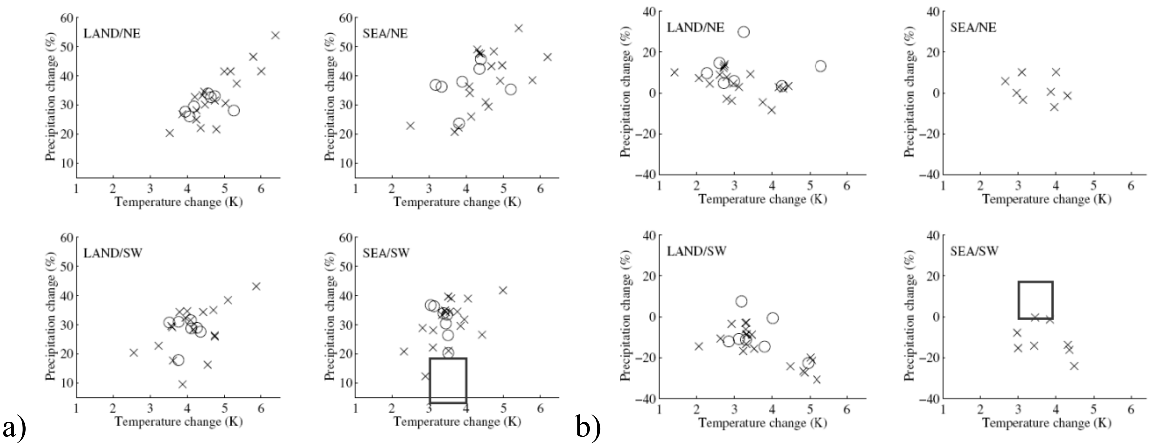

Figure 1: Seasonal PRUDENCE data (circles and crosses) in winter (a) and summer (b) compard to annual mean REMO-UBA data (boxes) (after: HELCOM 2007, modified)

These major climatic changes expected for the coming century will have significant effects on the ecosystem and the pelagic and benthic communities in the Baltic Sea. The BALTEX Assessment of climate change (BACC) reviews the climate projections for the Baltic Sea Basin and describes possible impacts on its ecosystem (HELCOM 2007).

2 Study objectives

The goal of this study is the analysis and visualization of possible climate change impacts on the benthic communities of the reefs within the SACs of the German Baltic Sea. It aims to assess climate induced environmental impacts as reported by the authors of the BACC and to model them qualitatively. The study is focussed on mineralogenic reefs in the German Baltic Sea, due to their exceptional ecological value in terms of species diversity and abundance, and because they are protected by the Habitat Directive which defines them as a “natural habitat of Community interest”. According to the Habitat Directive, “reefs can be either biogenic concretions or of geogenic origin.

They are hard compact substrata on solid and soft bottoms, which arise from the sea floor in the sublittoral and littoral zone. Reefs may support a zonation of benthic communities of algae and animal species as well as concretions and corallogenic concretions" (EC 2007: 13).

The study area includes regions in the German Baltic Sea that are designated as "Special Areas of Conservation" (SACs) by the Habitat Directive. Based on the international law of the sea, the German part of the Baltic Sea (with regard to nature conservation) is defined as the Exclusive Economical Zone (EEZ) and the zone of 12 nautical miles (Figure 2).

As a consequence of climate change, benthic communities' extent will change as they reach their distribution limit due to temperature and salinity changes. This study does not investigate these changes explicitly, but rather takes a more general look as to whether the reefs are expected to preserve their ecological function as an important habitat for various species. According to the findings described in the BACC, a simple weighted sum model was developed, using these sums to describe the impact of climate change on specific processes and to estimate if the habitats are endangered by climate change or if they even benefit from it. Furthermore, the most important driving factors were identified by the multiple linear regression method. In particular, the main goals and objectives of this study can be summarized as follows:

- Review of climate-induced impacts on the ecosystem of the Baltic Sea and on the habitat type of the reefs in specific
- Development of a simple weighted sum model in order to estimate climate-induced impacts on reefs within Special Protection Areas in the German Baltic Sea
- Identification of the most important driving factors triggering changes in the ecosystem of reefs

3 Location and methods

3.1 Study sites

The selection of the study sites was very much dependent on the availability of information and data. Compared to the availability of data on terrestrial ecosystems, data regarding marine ecosystems are relatively limited. Following the Habitat Directive, Germany has designated a total of 4,622 SACs (BfN 2008), 54 of them being (partially or completely) located in the German Baltic Sea. Many coastal SACs have both terrestrial and marine components. In order to ensure that a reef in such a 'divided' SAC is functioning as a marine habitat, a minimal reef area of 100 ha was needed to select the investigated sites. In the German Baltic Sea there are 21 SACs fulfilling this condition (Figure 2).

The designation process of SACs is clearly defined by the Habitat Directive. Therefore, it is necessary to assess data about sediment types, hydrology, submarine vegetation, and the current state of these ecosystems (Krause et al. 2008). These data are summarized in a standard data form (EC 2007).

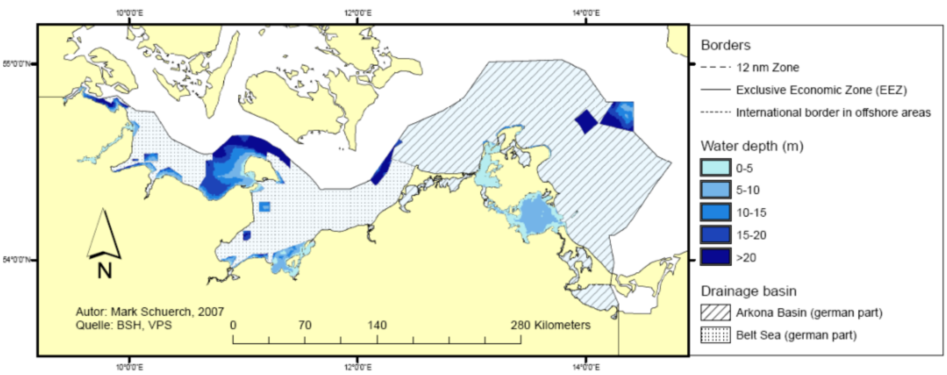

Figure 2: Overview over the selected study sites in the German Baltic Sea (Data: BSH 2007)

The selected study sites are marked by different physical characteristics: The mean water depth illustrated in Figure 2 ranges from 1.4 m to 26.8 m. Furthermore, the study sites are located in two different drainage basins, the Belt Sea in the west and the Arkona Basin in the east (Figure 2). Also, the degree of water exchange with the open Baltic Sea is very variable between the selected study sites. Some SACs, e. g. Schleimünde in the western part and the sites within the Bodden waters in the eastern part of the study area, are much more enclosed than other areas that are located at the open coast or in the deep parts of the Baltic Sea.

3.2 Data

In order to designate SACs, local and national authorities are obliged to collect data about possible Sites of Community Interest. These data are reported in standard data forms and include information about the following parameters:

- Distribution and relative importance of habitat types
- Ecological status and possible threats of habitat types
- Inventory of typical and endangered species

These data were reviewed and fed into a database for all selected study sites. Furthermore, some general characteristics such as the minimal, maximal, and average depth (Figure 2) and the distance of a site to the shore were also analyzed by means of a bathymetry and coastline file (BSH 2007). As an additional measure for the ecological status of the sites, the current status of eutrophication was assessed, using point data for Secchi-depths by Aarup (2002) and various data sets from the Bund-Länder-Messprogramm (BLMP), collected during the time period 1903-2003. As expected, the degree of eutrophication varies throughout the study area, ranging from low Secchi-depths close to the shore and in the eastern section of the study area to rather high values further offshore and in the west.

In order to simulate climate-induced ecological changes in the Baltic Sea ecosystem, it is crucial to include data about the magnitude and the spatial variation of climate change itself. Considering the fact that some study sites have a diameter of only a few hundred metres, it is important to use data with the highest possible spatial resolution. The REMO regional climate model was used by the German Federal Environmental agengy (UBA) to investigate the expected climate changes for Germany (Jacob et al. 2008). It is a regional climate model that is fed by the global climate model ECHAM5-MPI-OM (Jungclaus et al. 2006). While the ECHAM5-MPI-OM is a coupled ocean-atmosphere model, the REMO model is an atmospheric model only. Hagedorn (1998) has shown significant differences between an uncoupled REMO model and a coupled REMO model especially in the central and northern Baltic Sea area. However, simulation results for sensible heat flux, wind, and precipitation show a reasonable agreement with results of the REMO-UBA simulation runs (Hagedorn et al. 1998). Also, results of the REMO-UBA simulation run for temperature and precipitation are within the range of model results presented by the PRUDENCE project (Figure 1).

The REMO-UBA model runs were conducted for the emission scenarios A1B, A2, B1 of the IPCC Special Report on Emission Scenarios (IPCC 2000), and for a control run from 1950 to 2000. More than 100 parameters were modelled for a period from 2001 until 2100 (Jacob 2005a, b). For the purpose of this study, the following parameters of the control run and the A1B scenario were used:

- Temperature (2 m above surface)
- Precipitation (combined convective and stratiform)
- Evaporation over the water surface
- Wind speed (10 m above surface)
- Runoff (combined river and surface runoff)

In order to identify spatial variations of climate changes throughout the German Baltic Sea, the absolute differences between the periods 1950-2000 and 2071-2100 were calculated. Furthermore, all values, except for the parameter temperature, were normalized with the results from the control run in order to be able to classify them into one scheme that contains 10 (11 for temperature) classes ranging from a very strong decrease (-5) to a very strong increase (+5), as illustrated in Table 1.

Table 1: Classification of climate parameters

Class	Temperature	All other climate parameters
-5	<-4.5°	>-20 %
-4	-4.5° - -3.5°	-20 % - -15 %
-3	-3.5° - -2.5°	-15 % - -10 %
-2	-2.5° - -1.5°	-10 % - -5 %
-1	-1.5° - -0.5°	-5 % - 0 %
0	-0.5° -0.5°	
+1	0.5° - 1.5°	0 % - 5 %
+2	1.5° - 2.5°	5 % - 10 %
+3	2.5° - 3.5°	10 % - 15 %
+4	3.5° - 4.5°	15 % - 20 %
+5	>4.5°	>20 %

3.3 Model development

The developed model aims to qualitatively assess impacts of climate change on the ecosystem of the Baltic Sea. The basic assumption of the model is that the product of all processes is a linear function of the involved parameters. Certainly, this assumption is not applicable for exact calculations of the described processes, but rather for a qualitative estimation of the magnitudes. For every parameter a weight is assigned, representing the importance of the parameter for a process. This weight is a positive value if a parameter is positively correlated to its product; on the contrary it is a negative value if a parameter is negatively correlated to its product. The estimation of these weights is based on an extensive literature review. New findings and further knowledge about certain processes can be integrated into the model by modifying these weights. The sum of all weights for one process must be 1. Finally, the weighted sums are added up resulting in a value that is of the same order of magnitude as the initial values (Table 1). Table 2 shows how the model could work for 5 imaginary sites with extreme values for climatic parameters.

Table 2: Exemplary calculation of the variable salinity

Site number	Δ Precipitation	Weight	Δ Evaporation	Weight	Δ Runoff	Weight	Δ Salinity
1	5	-1/3	-5	1/3	5	-1/3	-5
2	-5	-1/3	5	1/3	-5	-1/3	5
4	5	-1/3	5	1/3	5	-1/3	-2
5	-5	-1/3	-5	1/3	-5	-1/3	2
Site 1: Δ Salinity = (-1/3)*(5)+(1/3)*(-5)+(-1/3)*(5) = -5							

3.4 Hydrography

Due to the presence of a relatively distinct halocline in the Baltic Sea, changes in the hydrographical conditions provide the starting point for modelling environmental impacts. These changes include the stability of the water column in general, the presence of a seasonal thermocline, and the depth of the halocline. In summer, when the surface water is warm, a distinct thermocline separates the warm surface water from the cold bottom water. In winter, when surface temperatures drop to the temperature of maximum density, a mixing of the upper water column down to the halocline is possible. Winter temperature and salinity of surface water, therefore, are the parameters that influence the stability of the water column and determine if the water column above the halocline is mixed during late winter, renewing the water with oxygen-rich surface water. Possibly higher winter temperatures and lower salinities would inhibit such a mixing (Matthäus 1996).

Further down in the water column, the halocline separates the fresher surface water from the more saline bottom water and inhibits vertical water exchange. The consequence is that the bottom water is depleted of oxygen and H_2S may be produced, killing macrophytes and zoobenthos in these regions. Areas that are located below the permanent halocline are, therefore, exposed to oxygen depletion. No oxygen-rich water is added through vertical mixing, but only through inflow of saline North Sea water (Matthäus 1996). Due to the fact that inflow events are controlled by meteorological circumstances rather than climate change (Matthäus & Schinke 1994, Schinke & Matthäus 1998), this parameter is not considered in this study. Therefore, the depth of the halocline and the stability of the water column are assumed to be the only hydrographic parameters determining the probability of oxygen depletion. If the halocline is lowered, due to enhanced freshwater input or more intense wind conditions, the extent of oxygen depletion is reduced.

3.5 Organic matter

Vertical exchange processes are not only important in terms of oxygen depletion, but also for the development of phytoplankton. Primary production within the water columns is dependent on water column stability as nutrients are transported upwards where the presence of light makes primary production possible (HELCOM 2007). The availability of nutrients in general is assumed to be dependent on surface and river runoff. Anthropogenic nutrient input is not specifically considered.

Due to their dominance in the study area, three species of phytoplankton were included in this study: Cyanobacteria, dinoflagellates, and diatoms (Wasmund et al. 2008). The composition of phytoplankton is important for the whole ecosystem (HELCOM 2007). Many factors have to be considered when studying the development of phytoplankton. One important physical characteristic is the hydrography of the water. Due to their physiology, cyanobacteria and dinoflagellates prefer stable water columns, while diatoms prefer a more mixed water column because they rely on passive mobility (Sommer 1996). Since settling velocities of phytoplankton vary between different species, the composition of phytoplankton has a significant influence on the abundance of nutrients at the seafloor and, therefore, on the development of benthic macrophytes and zoobenthos. The settling velocity of diatoms with some metres per day is much higher than the settling velocities of dinoflagellates and cyanobacteria (Sommer 1996, Wasmund et al. 2008). The combined effect of primary production, composition of phytoplankton species, and the influence of bacterial activity determine the amount of organic matter that sinks to the ground and is available for benthic macrophytes and zoobenthos.

3.6 Benthic macrophytes

Besides the amount of sinking organic material, the degree of water turbidity is crucial for the development of benthic macrophytes (Jones et al. 1983, Asaeda et al. 2001). The turbidity is high when primary production is high. In the proposed model it is assumed that turbidity is only important in disphotic regions (twilight zone of the seafloor), whereas in euphotic regions (zone with sufficient sunlight for phohtosythesis) it is assumed that light availability is not a limiting factor within the time frame of the presented model. In aphotic regions (zone without sunlight) no marcrophytes will develop. For the purpose of this study, the disphotic zone is defined as the zone where the euphotic depth is ranging from 5 m below the seafloor to 5 m above the seafloor. The euphotic depth is calculated using the Secchi-depth, as shown in Equation 1 (Stuhr 2006):

$$\text{(Equation 1) } Euphotic\ depth = \frac{(Secchi - depth)}{1.7} * \log(100) - \log(1)$$

These prerequisites ask for an individual treatment of euphotic, disphotic, and aphotic zones because limiting factors for macrophyte growth are different (Table 3). Within the disphotic zone, the trophic level of an area has to be accounted for because nutrient availability is higher in eutrophic areas than in oligotrophic areas. For this reason nutrients are not considered as a limiting factor for eutrophic areas in the disphotic zone, but they are in meso- and oligotrophic areas (Table 3). For classification of the trophic status of a water body the classification published by the 'Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern' (LUNG) was used (taken from Rödiger 2003). Accordingly, water bodies with a Secchi-depth less than 4 metres are eutrophic (summarizing term for hypertrophic, polytrophic, very eutrophic, and eutrophic), water bodies with a Secchi-depth between 4 and 6 metres are mesotrophic, and water bodies with a Secchi-depth more than 6 metres are oligotrophic.

Table 3: Limiting factors for different light conditions and trophic states

Light conditions / trophic class		Light as limiting factor	Nutrients as limiting factor
Euphotic zones			X
Disphotic zones	Eutrophic	X	
	Mesotrophic	X	X
	Oligotropic	X	X
Aphotic zones		No growth of macrophytes	

Following Table 3, the weights for sinking organic material, representing nutrients supply, and for primary production, representing the degree of turbidity, as parameters for the growth of benthic marcrophytes are estimated as shown in Table 4. For euphotic zones the weighting is simple because enough light is available so that the development is only dependent on the amount of sinking organic material. In disphotic zones light availability is of great importance in eutrophic zones because nutrients are very unlikely to be a limiting factor, but of less importance in oligotrophic zones where nutrients are more likely to be the limiting factor.

Table 4: Input weights for the calculation of macrophyte development

Light conditions / trophic class		Weight for primary production	Weight for sinking organic material
Euphotic zones		0	1
Disphotic zones	Eutrophic	-0.9	0.1
	Mesotrophic	-0.7	0.3
	Oligotropic	-0.5	0.5
Aphotic zones		0	0

3.7 Zoobenthos

The term zoobenthos is a collective term for animal organisms living on the seafloor. Compared to macrophytes that only grow where light conditions are favourable, zoobenthos are not directly dependent on sunlight, but very much dependent on oxygen availability. As described above, the oxygen situation, especially in the deep basins of the Baltic Sea, is very critical. It is highly dependent on the hydrographic situation, the amount of sinking organic material, and the abundance of benthic macrophytes. If the water column above the sea floor is rather stable, oxygen consuming degradation processes of sinking organic material and macrophytes will induce oxygen depletion. If the water column is less stable, oxygen from the surface layer is mixed into the deeper zones (HELCOM 2009). The development of zoobenthos is also dependent on food resources. Sinking organic material as well as benthic macrophytes are important food sources for all kinds of zoobenthos. Following the concept of limiting factors, the study sites are divided into three groups of different trophic states in order to assign weights for the calculation of the estimated development of zoobenthos. It is assumed that oxygen is only a limiting factor in eutrophic zones, while oxygen and nutrients are the limiting factors in mesotrophic zones, and only nutrients are the limiting factor in oligotrophic zones (Table 5).

Benthic macrophytes can have a negative influence on the development of zoobenthos because they enhance the depletion of oxygen. This phenomenon is already captured by the calculation of the probability for oxygen depletion (not illustrated in detail). At the same time macrophytes serve as an important food source and refuge for zoobenthos. Considering the limiting factors of nutrients and oxygen availability and the positive effects of macrophytes, the weights for the development of zoobenthos can be summarized as shown in Table 5. In eutrophic regions, where primary production is high and nutrient availability is very high, the most important factor for the development of zoobenthos is the probability of oxygen depletion. Nutrient is no problem for their development. The exact opposite can be assumed for the oligotrophic zones, where the probability of oxygen depletion is neglectable, but nutrient availability is limited. The importance of macropyhtes does not depend on the trophic level; their function for zoobenthos is of the same importance in eutrophic, mesotrophic, and oligotrophic regions (Table 5).

Table 5: Input weights for the calculation of zoobenthos development

Trophic class	Limiting factor oxygen	Weight for the probability of oxygen depletion	Limiting factor nutrients	Weight for sinking organic material	Weight for the abundance of macrophytes
Eutrophic	X	-0.7		0	0.3
Mesotrophic	X	-0.3	X	0.3	0.4
Oligotropic		0	X	0.7	0.3

3.8 Habitat-specific climate sensitivity

Reefs were the type of habitat (as defined by the Habitat Directive) studied, assuming that the climate sensitivity is a function of the qualitative development of benthic macrophytes and zoobenthos. Additionally, the ecological value (ranging from 0 = 'habitat does not exist within the site' to 3 = 'very high ecological value'), as reported in the standard data forms of the designated SACs, was included, assuming that habitats with high ecological values are more vulnerable than habitats with low ecological values. The calculation of a number for the exposure of a habitat was concretely performed using Equation 2:

(Equation 2) *Exposure = Ecological value (1 - 3) - ΔZoobenthos (-5 - 5) - ΔMacrophytes (-5 - 5)*

3.9 Identification of most important driving factors

In order to identify the driving factors that are responsible for the exposure of a SAC towards climate change, the method of multiple linear regression was applied (Wisemann 2008). The combined influence of the weight of a specific parameter and the projected change of this parameter was investigated. Table 6 shows the regression analysis for the change in salinity as it was modelled. While B is the value for the slope of the calculated regression, the standardized Beta-coefficient (bold numbers) shows the correlation of each variable to the independent variable.

The non-standardized coefficient B shows the weights that the model assigns to every parameter that influences the salinity (Table 2). When analysing the correlation of each parameter with resulting salinity, the high Beta-value indicates that the spatial variation of the runoff has the strongest influence on the resulting salinity variations.

Table 6: Multiple linear regression analysis (dependent variable is salinity)

Parameter	Non standardized coefficients		Standardized coefficients	Significance
	B	Standard Error	Beta	
(Constant)	$-8.189*10^{-8}$	0.000		0.050
Runoff	-0.333	0.000	**-0.821**	0.000
Evaporation	0.333	0.000	**0.235**	0.000
Precipitation	-0.333	0.000	**-0.326**	0.000

4 Results

In the following section, the results will be presented with focus on the spatial variations of the investigated parameters and the resulting exposure of the habitats. Furthermore, the driving factors for these variations will be presented.

The starting point for the conducted calculations was the climate projections derived from the REMO model. The parameters temperature (summer, winter, and annual mean), precipitation, runoff, evaporation, and wind velocity were fed into the developed model. Subsequently, the results for the hydrographic parameters, the development of organic material, and the consequences for the development of macrophytes and zoobenthos are presented. This finally leads to the derivation of the exposure values for every habitat.

4.1 Climate projections

Temperature change was divided into the three sub-parameters summer temperature, winter temperature, and annual mean temperature. The general trend for all subsets shows a slight gradient from west to east that can be explained by an increasing continental influence in the eastern part of the study area. While the annual mean temperature increases by about 2.8 to 3.1 °C, there is a seasonal variability as summer temperatures show a slightly lower increase of 2.6 to 2.9 °C, while winter temperatures increase by 3.4 to 3.9 °C. After classifying these values according to Table 1, no spatial variation can be observed for the annual mean and summer temperatures because all values fall into the same class (+3), while the increase of winter temperatures still represents a slight gradient to the east.

Precipitation is the parameter with the largest variation in the study area, ranging from a very slight decrease (-5 %) to a strong increase (+17 %). The most remarkable feature is a clear gradient from land to sea, leading to an increase of precipitation over the sea and to a decrease over the land. Due to the increasing continental influence, this trend is even stronger in the eastern part of the study area, causing considerable decreases over the inlands of Mecklenburg-Vorpommern. Although the values for precipitation change over the land are not directly included in the model, they nevertheless have a significant influence on the runoff parameter.

Consequently, the spatial variation of the runoff that is calculated for the two drainage basins (Figure 2) by averaging the values within the two drainage basins, displays the strong gradient of the precipitation changes. The average runoff into the Arkona Basin is expected to decrease by about 23 % while the average runoff into the Belt Sea is expected to decrease by only about 6 %.

As expected, the changes for evaporation are closely linked to the temperature values, showing a strong increase between 20 and 25 % with a gradient towards the eastern part of the study area.

The expected change for wind velocity ranges between 1 and 4 % increase with slightly higher values over the sea and towards the east. After reclassification, however, the very slight increase of wind velocity is uniform in the study area.

4.2 Hydrographic parameters

The hydrographic situation is highly dependent on climatic changes. Due to the expected decrease in runoff, especially in the Arkona Basin (-23 %), model results indicate a general trend to higher salinities. According to the BACC authors (HELCOM 2007), the halocline might migrate downwards in case of a stronger freshwater inflow. Consequently, higher salinities are assumed to contribute to a lifting of the halocline. Furthermore, lower salinities account for a lower stability of the water column although a significant increase in winter temperatures is much more important and, therefore, responsible for a trend to a more stable water column.

4.3 Organic material

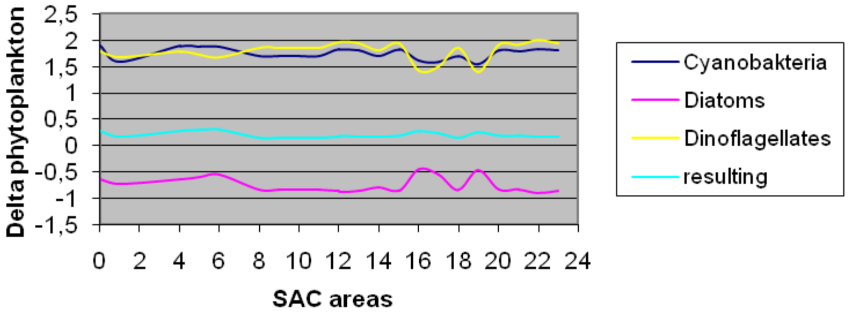

Figure 3: Change in phytoplankton composition and resulting sinking organic material

The changes of the hydrographic parameters induce changes in the composition of phytoplankton species. The stabilization of the water column favours the development of cyanobacteria and dinoflagellates (Figure 3). While the higher summer temperatures also favour cyanobacteria, the dinoflagellates profit from the fact that cyanobacteria improve the nutrient availability through their ability of nitrogen fixation (HELCOM 2007, von Bröckel 2005). Contrary to this, diatoms are inhibited because of the stabilization of the water column (Figure 3).

Figure 3 illustrates the modelled net effect of the changes of composition on the amount of organic material sinking to the ground. The effect is calculated by assuming a constant concentration of phytoplankton with a certain composition, and by considering a change of composition of the three species. Regarding the different settling velocities, it becomes clear that a decrease of diatoms, going along with an increase of cyanobacteria, could theoretically induce a decrease in phytoplankton sinking to the ground. The results provided by the model indicate that the changes in composition result in a very slight increase of phytoplankton sinking to the ground, especially because the decrease of diatoms is very weak and because dinoflagellates, with a settling velocity higher than cyanbacteria and lower than diatoms, are also increasing considerably.

As the multiple linear regression analysis shows, the development of the sinking organic material is more dependent on the nutrient input than on the composition of phytoplankton. As runoff is decreasing, especially in Arkona Basin, primary production and, therefore, the amount of sinking organic material is also decreasing.

4.4 Macrophytes and zoobenthos

As described above, the calculations for the development of macrophytes and zoobenthos were conducted depending on the light and eutrophication status of the site. All the SACs can, therefore, be classified into 5 groups (Figure 4):

- Euphotic zones: Areas with less than 10 m depth, close to the shore and with exchange of water with the open Baltic Sea
- Disphotic-eutrophic zones: Areas with less than 10 m depth, close to the shore and with limited exchange of water with the Baltic Sea
- Disphotic-mesotrophic zones: Areas with water depth between 10 and 22 m, located more than 5 km from the shore
- Disphotic-oligotrophic zones: Areas with water depth between 10 and 22 m, located more than 5 km from the shore
- Aphotic zones: Areas with more than 22 m water depth

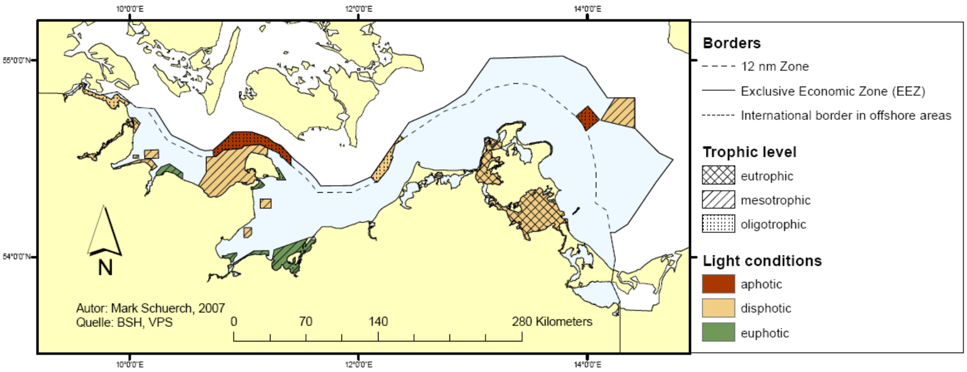

Figure 4: Trophic level and light conditions in the study sites (Data: BSH 2007, Aarup 2002, Daschkeit et al. 2007)

Model results indicate that the development of macrophytes within each group is similar; however, results in the Arkona Basin vary from the results in the Belt Sea (Figure 5). In euphotic zones the macrophytes show a slight decrease which is a little more pronounced in the Arkona Basin (Figure 5: group 4) than in the Belt Sea (Figure 5: group 3). Contrary to this, macrophytes are increasing in disphotic-eutrophic zones whereas this trend is much weaker in the only area located in the Belt Sea (Figure 5: group 2) and when compared to the very shallow and enclosed areas in the Bodden waters (Figure 5: group 1). No changes for the growth of macrophytes were calculated for all disphotic-oligotrophic, disphotic-mesotrophic, and aphotic zones. By means of a linear regression it can be shown that the Secchi-depth can explain most of the differences between the groups, although this is not surprising as the weights for the calculations are very much dependent on the trophic state and the light conditions in a site. Further analyses of the model results show runoff being the most important climatic driving factor for the development of the macrophytes, and explaining most of the differences inside the groups. The reasons for the importance of the runoff are its large gradient in the study area and the fact that many parameters in the ecological system of the Baltic Sea are dependent on the input of nutrients and freshwater into the system. Therefore, results show a significantly different development of macrophytes in areas with a very strong decrease of runoff (Arkona Basin) compared to areas with a weaker decrease (Belt Sea).

As described above, the development of zoobenthos is very much dependent on the oxygen situation which is mainly determined by the depth of the halocline and by the development of macrophytes. The regression analysis of model results shows that the development of macrophytes is the most important factor influencing the oxygen situation which, in turn, is the most important factor influencing the development of zoobenthos. In general, model results indicate that zoobenthos are stagnant or decreasing in all investigated areas and that this trend is the most pronounced in euphotic-oligotrophic and euphotic-mesotrophic zones (Figure 6: groups 4 to 6) because this is where macrophytes are decreasing most of all. Meanwhile, in the eutrophic-disphotic zones where marcrophytes are increasing most rapidly, oxygen depletion is inhibiting an increase of zoobenthos (Figure 6: group 1).

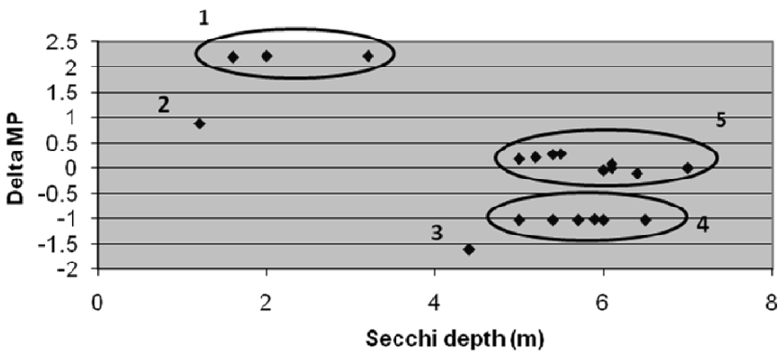

Figure 5: Macrophyte changes for 5 groups of study sites:

1 – Eutrophic-disphotic areas in the Arkona Basin: Bodden water; 2 – Eutrophic-disphotic areas in the Belt Sea: Schleimündung; 3 – Euphotic areas in the Arkona Basin; 4 – Euphotic areas in the Belt Sea; 5 – Mesotrophic- and oligotrophic-disphotic areas, aphotic areas

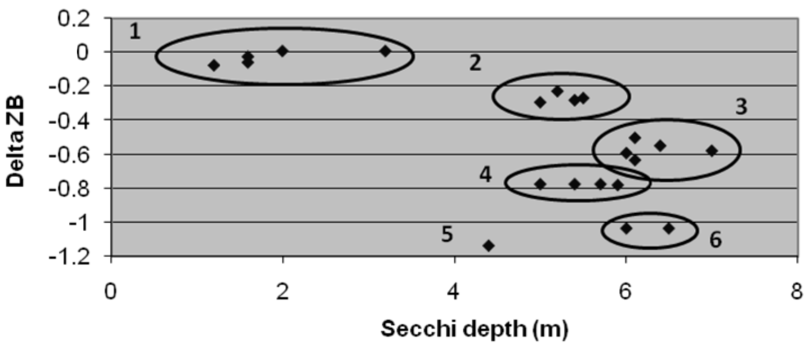

Figure 6: Zoobenthos changes for 6 groups of study sites:

1 – Eutrophic-disphotic areas; 2 – Mesotrophic-disphotic areas; 3 – Oligophotic-disphotic and aphotic areas; 4 – Mesotrophic-euphotic areas in the Belt Sea; 5 – Mesotrophic-euphotic areas in the Arkona Basin; 6 – Oligotrophic-euphotic areas in the Belt Sea

4.5 Exposure of habitats

By combining the information about the current ecological value of the sites with the modelled results for the development of macrophytes and zoobenthos using Equation 2, the exposure of the reefs can be calculated. Results indicate that the exposure of the studied habitats towards climate change, as it is defined in this study, vary considerably (Figure 7). Reefs in eutrophic regions are less endangered because a strong decrease of runoff, especially in the Arkona Basin, improves light conditions in eutrophic regions, causing enhanced growth of macrophytes and, therefore, zoobenthos (Figure 7).

The most endangered reef habitats are located in meso- and oligotrophic regions where a decrease in nutrients leads to a nutrient deficiency and inhibits the development of macrophytes and zoobenthos (Figure 7).

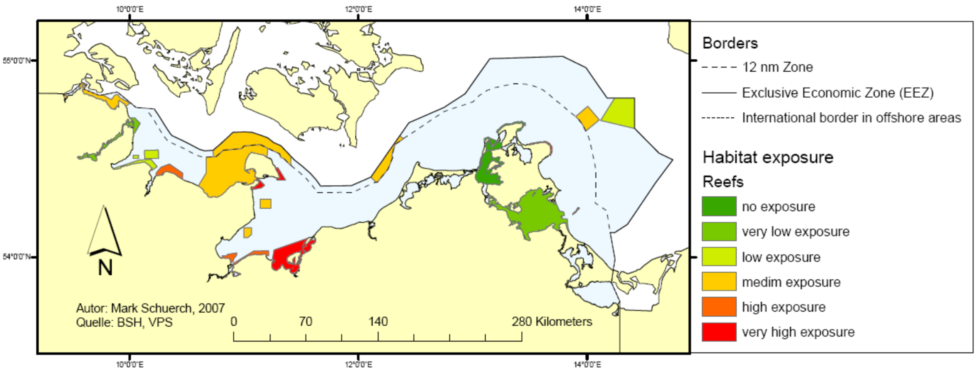

Figure 7: Calculated degree of exposure for all reefs in the investigated SACs (Data: BSH 2007, own calculations)

5 Discussion and conclusion

Climate change and the rising importance of nature conservation issues demonstrate the need for research in the field of climate impacts on natural ecosystems. This study shows a possibility to qualitatively assess possible climate impacts on the protected reef habitats in the Baltic Sea. Due to its very simple approach, the presented results are not thought to be a definite assessment of the exposure of reefs towards climate change, but rather to demonstrate the various opposing effects that have to be considered when investigating climate change impact on natural ecosystems in an integrative manner.

The developed model was very much based upon the findings of the BACC and tried to capture the described processes in a model. The comparison of the model results with the possible consequences described by the BACC showed that the model is able to reproduce these consequences in general. It also showed that the assessment of climate induced ecosystem changes is very much dependent on the scale on which the assessment is conducted. The projections for an average increase of runoff in the whole Baltic Sea, for example, is contrary to an average decrease of runoff in the study area. The model highlights that this difference is very important in terms of ecological impacts because many parameters such as the stability of the water column and the depth of the halocline are changing, having major impacts on the whole ecosystem. In order to assess climate impacts for nature conservation purposes, a regional assessment, as presented in this study, is appropriate.

Furthermore, this study highlights the importance of different site characteristics. The attempt to divide the sites into different groups of light conditions and trophic levels is very rudimentary, but it seems to be a good approach for more integrated assessments of climate change impacts. The distance to the shore, and the water depth of a site have been shown to be a relevant parameter to model results by determining the eutrophic and euphotic state of a site.

The presented model is too simple to reproduce the very complex interactions within an ecosystem. Many possible important processes, such as sea level rise or migration of species, are not considered and all model equations are linear only. On the other hand, the advantage of the simplicity of a weighted sum model is that new findings and new processes can be implemented very easily by adjusting the weights for the involved parameters, adding parameters that influence a certain process, or even adding processes that are not included yet.

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