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Modelling the Impact of Climate Change on Phytoplankton Dynamics and the Oxygen Budget of the Elbe River and Estuary (Germany)

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ABSTRACT: Our results show that in the Elbe river and estuary system climate change could affect phytoplankton dynamics and the oxygen budget by altering external forces like river discharge and water temperature. A model-based approach is chosen to describe and quantify the impacts by using a 1-d hydraulic model (HYDRAX) coupled with a water quality model (QSim). The model QSim represents the main processes determining the oxygen and nutrient budget as well as the algal and zooplankton growth in an aquatic system. The coupled models are applied to the Elbe River (585 km) and the connected mesotidal estuary (142 km). This approach is realized as part of the research program KLIWAS of the German Ministry of Transport. The multi-model approach of KLIWAS has generated a range of feasible projections for the whole Elbe River, its estuary, and the coastal regions. A long-term run (1998-2010) of the water quality of the Elbe River and estuary is used as a reference state. The results demonstrate that the model is able to represent the intra-annual and inter-annual variability of phytoplankton dynamics and the oxygen contents. The simulations proof the major importance of river discharge on both state variables. A decreased river flow increases the water residence time and supports thereby the algal growth. The riverine produced algal biomass leads to a higher input of living algae and related detritus from the river into the estuary. There the living algae die off due to light limitation in the deep section of the Elbe Estuary. During their decay the algae respire more oxygen than they produce. In addition oxygen is consumed by heterotrophic bacteria utilizing the degradation products of the algal biomass. Both processes have a significant impact on the oxygen deficit during summer in the Elbe Estuary. An increase in temperature has the following effect: If the water temperature becomes higher than the optimum temperature for algal growth, lower algal biomass is produced and transported into the Elbe Estuary causing less severe oxygen deficits. At least the impact of climate change on the phytoplankton dynamics and the oxygen for near (years 2021-2050) and far future (years 2071-2100) scenarios is estimated by a model-based sensitivity analysis and evaluated by comparison with the reference state.

Keywords: Water quality modelling, Elbe Estuary, Climate change, Oxygen, Phytoplankton

1 INTRODUCTION

The potential impacts of climate change on the water quality, and more specifically the oxygen budget and the phytoplankton development of estuaries, can be derived from existing knowledge of the ecological functioning of these systems (Palmer et al. 2009, Rabalais et al. 2009, Najjar et al. 2010). In addition, mechanistic models are able to quantify such implications and become therefore useful tools for climate change predictions (Cox & Whitehead 2009). Nevertheless, climate change related implications are hard to identify, because water quality is and will be very much dependent on human activities, including water management policies of coastal regions and catchments. Especially, the interaction of climate induced changes and eutrophication in estuaries is an important issue (Howarth et al. 2000). Two driving forces of water quality are directly altered under climate change, river discharge and air temperature. Due to altered hydrographic conditions of the catchment, which controls dilution, flow velocity and residence times, the load of phytoplankton and organic carbon entering the estuary is altered too. These factors are influencing the oxygen balance of the estuaries. Here, we investigate, with the aid of the water quality model QSim, the response of the oxygen budget in the estuary to climate change induced temperature variations and changing freshwater discharge from the watershed. A first approach for the river part of the Elbe is described in Quiel et al. (2010).

Today, pronounced oxygen minima can be observed in the freshwater region of the Elbe Estuary. These oxygen deficits, which occur mainly during summer, are of major ecological significance as they can have a negative impact on the benthic community and fish (Bergemann et al. 1996). The oxygen balance of the Elbe Estuary is governed to a large extent by the input of algal biomass and organic and inorganic matter from the river part of the Elbe. The algae transported from the river into the estuary die off in the estuary mainly due to insufficient light conditions in the region of Hamburg harbour and because of zooplankton grazing. The microbial degradation of the algal biomass and related products as fecal pellets consumes oxygen and as a consequence, a significant oxygen depletion in summer develops (Bergemann et al. 1996, Yasseri 1999, Kerner 2007). First approaches to quantify the oxygen budget of the Elbe Estuary are described in Bergemann et al. (1996) and recently by Schöl et al. (in press).

Our study was performed in the framework of a multi-model approach that generated a range of feasible projections for the whole Elbe catchment including its estuary and the coastal regions (BfG et al. 2014). The projections of air temperature are generated from different regional climate models, while the projections for discharge are based on hydrological models. All projections are derived from global climate models and the IPPC emission scenario A1B (IPCC 2007). By using the results of a sensitivity analysis for air temperature and discharge processed with the model QSim, the projected changes of both parameters and their effects on the water quality of the Elbe Estuary are evaluated.

2 METHODS

The deterministic model QSim is used for water quality simulation. The oxygen budget, the nutrient and phytoplankton dynamics are calculated for the reference period (1998-2010) and validated with measurements.

Based on a "delta change approach" (Hay et al. 2000, Andréasson et al. 2004) model simulations are used to investigate the response of the water quality to climate change. Based on this approach the future periods have not been simulated, but instead of it sensitivity simulations have been performed. Thereby the model input variables air temperature and river discharge are modified by a delta value (river discharge +20%, -20%, -40% / air temperature +2°C und +4°C and combinations).

As a result of the sensitivity analysis response surfaces for the different water quality parameters are produced. A relationship to the climate and hydrologic projections resulting from the model chain can be established by integrating the changes of air temperature and river discharge (Lingemann et al. 2013, Imbery et al. 2013) in such response surfaces. Due to the multi-model approach of KLIWAS a bandwidth of climate induced changes for the discharge and the air temperature for the near (2021-2050) and the far future (2071-2100) is determined.

2.1 *The model QSim*

The water quality model QSim (Quality Simulation) simulates physical, chemical and biological processes in rivers (Kirchesch & Schöl 1999, Schöl et al. 2002, Becker et al. 2010, Matzinger et al. 2012). The model QSim comprises a heat module, which calculates the water temperature, seven biogeochemical modules for process description of the seston budget, pH-value, nutrients dynamics of nitrogen, phosphorous and silicium, organic carbon and oxygen content, three biological modules for phyto- and zooplankton and benthic filter feeders (not applied for the Elbe) and a sediment module which calculates early diagenesis of sediment dynamics including oxygen, carbon and nutrient fluxes. A brief description for the biological modules and references are provided in Schöl et al. (in press).

QSim is coupled off-line with the one dimensional hydrodynamic model HYDRAX which simulates unsteady flow in a network of water bodies (Oppermann 1989, Oppermann 2010). QSim and HYDRAX are integrated under the graphical user interface GERRIS (BfG 2013).

The standard set of parameters which is either based on literature or on own experimental results was adjusted for the model application of the Elbe River and Estuary (Schöl et al. in press). The coefficient of absorption for yellow substances at 440 nm was increased by the factor 10 to parameterise the effect of high seston content of the Elbe Estuary.

2.2 *Model area*

The model area starts about 367 km below the source of the Elbe and ranges from the border between the Czech Republic and Germany (km 0) to the North Sea at Cuxhaven (km 727). Thus, it comprises the stretch of the river up to the tidal weir of Geesthacht (km 0 to km 586) and the estuary (km 586 to km 727). The river reach is modelled to get a consistent input data set for the water quality simulations at the entrance to the estuary. The influence of the four major and six smaller but furthermore relevant tributaries is modelled by boundaries. The 1d approach is extended by the implementation of groyne fields along the river stretch influencing the main channel by lateral transfers (Schöl et al. 2006).

2.3 *Input data*

2.3.1 *Hydrology, water level and meteorology*

The upper model boundary at km 0 as well as the main and larger tributaries are forced with daily discharge data, while for the smaller tributaries only yearly mean discharge is known. Depending on availability, daily or monthly data are applied for discharges of the sewage plants. The lower model boundary is forced with the water level of the gauging station Cuxhaven-Steubenhöft.

Regarding the meteorological data, daily sum of the global solar radiation (J/cm²), minimum and maximum air temperature (°C), mean relative humidity (%), mean wind velocity (m/s) and mean cloud cover have been provided as daily data by the German Weather Service.

The data from four stations along the river reach (Dresden, Wittenberg, Magdeburg, Seehausen) and from two stations (Hamburg-Fuhlsbüttel and Cuxhaven) along the estuary were used.

2.3.2 *Water quality parameters, phytoplankton biomass and biological parameters*

Measured water quality data at Schmilka (km 3.9) and Cuxhaven (km 727) are used to force the model at the open boundaries. Also for the main tributaries the water quality is prescribed. Data of the River Basin Community Elbe (FGG Elbe) and of the Observational Network of Water Quality of Hamburg (Institute of Hygiene and Environment) are used.

The main sewage plants situated in the river stretch of the Elbe (Dresden-Kaditz and Magdeburg-Gerwisch) as well as in the Elbe Estuary (Hamburg-Dradenau) are also implemented in the model.

Zooplankton abundances are not recorded in the regular monitoring programme of the Elbe. Therefore, abundances at the upper (km 0) and the lower (km 727) boundaries are estimated with the value of 25 Ind/l. This low abundance is sufficient as an inoculum to enable the development of the zooplankton in dependency of the food supply by phytoplankton.

2.4 *Delta change approach*

In this study altered river discharge and air temperature of twelve model chains have been considered. A model chain consists of the emission scenario A1B, a global climate model, a regional climate model and a hydrologic model. Based on the results of the model chains, the impact of climate change on the air temperature and river discharge is calculated in the context of KLIWAS for different time spans (near future (2021-2050) and far future (2071-2100)) (Lingemann et al. 2013, Imbery et al. 2013).

Table 1 shows the mean change ($Delta_{MC}$ (MC for model chain)) in river discharge and air temperature at the river gauge station Neu Darchau (km 536) near the entry to the estuary for the near future and the far future referring to the reference period (1981-2010). The impact of climate change on the mean air temperature corresponds to projections for a grid cell of 50x50 km at Neu Darchau. The simulation of the water quality of the reference state has been conducted for the years 1998-2010 as for this period an adequate input data set exists.

Referring to the reference period the changes are between -16.43 and + 9.18% for the near future and between -23.71 to +16.64% for the far future. For the air temperatures the changes are between +0.44 and +1.74°C for the near future and between +1.69 and +3.61°C for the far future.

The model chains show for the discharge as well as the air temperature a bandwidth of possible future states. While all projections show an increase in air temperature, no monodirectional change for river discharge is calculated.

Regarding the biological boundary conditions (nutrient concentration, algal biomass) no projections are available for future periods. Therefore, the future periods could not be simulated and instead of it sensitivity simulations based on the delta change approach have been conducted (Hay et al. 2000, Andréasson et al. 2004). Thereby the input data of the variables river discharge and air temperature used for the reference state have been changed by a distinct value. All other input data remained unmodified apart from the water temperature, which has been adjusted to the air temperature by calculating a “climatological” water temperature - which is controlled solely by the heat budget - and a subsequent regression analysis between climatological water temperature and measured water temperature (Hein et al. 2014).

Table 1. Change of discharge ($Delta_{MC}$ Q) and air temperature ($Delta_{MC}$ T) calculated by the different members of the model chains for the near future (NF) and the far future (FF) referring to the reference period (1981-2010).

	$Delta_{MC}$ Q (%)		Delta T_{MC} (°C)	
$ID_{Model\ Chain}$	NF	FF	NF	FF
1	-0.8	3.91	0.54	2.17
2	7.32	6.04	0.44	1.69
3	-6.23	-3.09	0.97	2.79
4	5.88	16.64	0.82	2.49
5	1.09	*	0.76	2.38
6	-2.55	-0.94	0.85	2.51
7	-2.6	-2.28	0.74	2.39
8	-16.43	-23.71	1.60	3.27
9	-13.82	-20.64	1.74	3.54
10	-2.83	-19.59	1.04	2.75
11	9.18	-2.79	1.01	2.41
12	3.19	-17.09	1.37	3.61

* No projections for far future.

As a result of the delta change approach a response surface of a water quality parameter against the two forcing variables air temperature and discharge is produced (see fig. 4). A relationship to the climate and hydrologic projections can be established by integrating the above mentioned $Delta_{MC}$ in the response surfaces.

3 RESULTS

3.1 *Reference state*

The model results for the reference period (1998 to 2010) are validated by comparison with measured data derived from a continuous measuring station situated in the freshwater region of the Elbe Estuary at km 629 (Schöl et al. in press). For water temperature the seasonality is well reproduced by the model, indicated by a high value for the Nash-Sutcliffe efficiency (NSE, (Moriasi et al. 2007)) of 0.967 (fig. 1, left). In winter the deviation is slightly higher than in summer which can be explained by the lack of heat discharge from cooling plants, with the highest impact during winter time. For oxygen concentrations (fig. 1, middle) the model efficiency is lower with a value of 0.758. Nevertheless, the seasonal dynamics and especially the low oxygen contents in summer are adequately reproduced by the simulations (Schöl et al. in press). The algal biomass (chla) differs more strongly from measured data resulting in a comparable low NSE of 0.007. In most of the years the simulated chla concentrations in spring and early summer underestimate the observations.

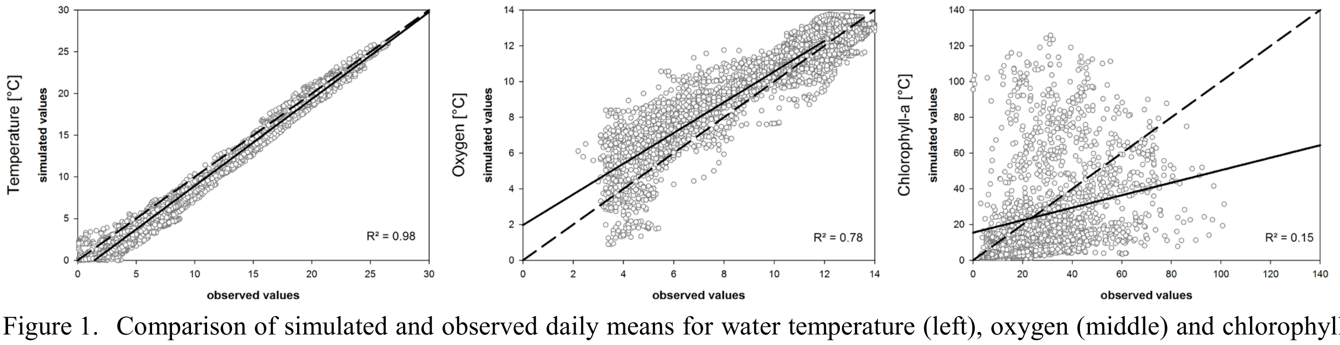

Figure 1. Comparison of simulated and observed daily means for water temperature (left), oxygen (middle) and chlorophyll a (right; fluorometric measurements are multiplied by factor 1.7) in the Elbe Estuary at km 629. Dashed line represents optimal fit, continuous line shows trendline of simulated values. R^2 is the coefficient of determination for simulated values referring to the trendline (Measured data: Institute for Hygiene and Environment, Hamburg).

3.2 *Climate Sensitivity*

The climate sensitivity of the system is illustrated by cumulative distribution functions for a period of 13 years for chlorophyll a at the weir of Geesthacht (km 586) and for oxygen at Seemannshöft (km 629).

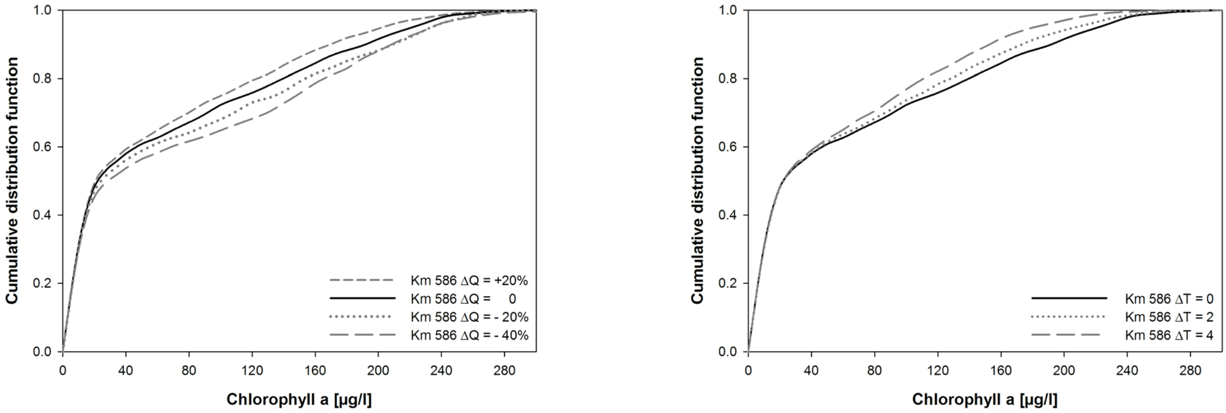

Figure 2. Cumulative distribution function of chlorophyll (daily means) for the reference period (1998-2010) and three sensitivity simulations based on altered river discharge (+20%, -20% und -40%) (left) and two simulations based on increased air temperature (+2°C und +4°C) (right) at km 586 (Geesthacht).

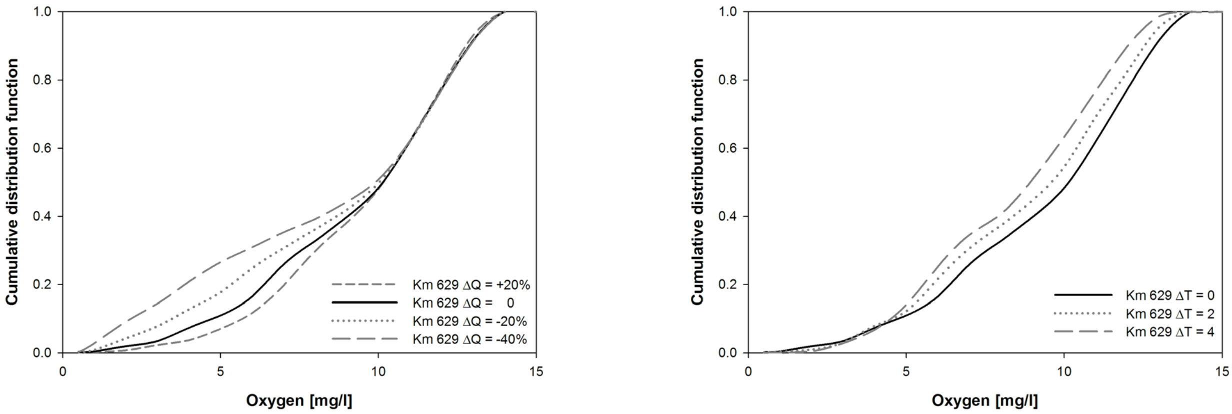

Figure 3. Cumulative distribution function of oxygen (daily means) for the reference period (1998-2010) and three sensitivity simulations based on altered river discharge (+20%, -20% und -40%) (left) and two simulations based on increased air temperature (+2°C und +4°C) (right) at km 629 (Seemannshöft).

A reduction of river discharge favours due to longer retention times the algal growth in the Elbe so that more algal biomass is transported into the Elbe Estuary (fig. 2, left). These conditions lead to low oxygen contents due to microbial degradation of the algal related organic carbon (fig. 3, left). On the other hand an increase of river discharge by 20% causes lower chla concentrations and a considerable improvement of the oxygen situation.

Increased air temperatures cause a decrease in algal biomass. The temperature optimum of the modelled algae species is exceeded so that the algal growth is reduced (fig. 2, right). The input of algal biomass in the estuary decreases and consequently the oxygen content in the region of Hamburg harbor is improved (fig. 3, right). The effect is only apparent for oxygen concentrations between 0 and 4 mg/l at Seemannshöft. At high air temperatures a decrease in oxygen concentrations occurs, because of the lowered solubility of oxygen in water. This effect is obvious at contents higher than 4 mg/l (fig. 3, right).

3.3 *Projections*

A total amount of 23 projections for the near and far future have been elaborated in KLIWAS. All projections show an increase in mean air temperature (table 1). Regarding the mean water discharge into the estuary seven projections for the near future and eight for the far future show a decrease. Whereas five, respectively three projections show an increase for near and far future. When these signals are introduced into the aforementioned response surfaces produced by the sensitivity simulations the climate induced changes of water quality in the Elbe Estuary can be deduced. In the following this methodology is applied to water temperature and oxygen content at measuring station Seemannshöft (km 629) (fig. 4).

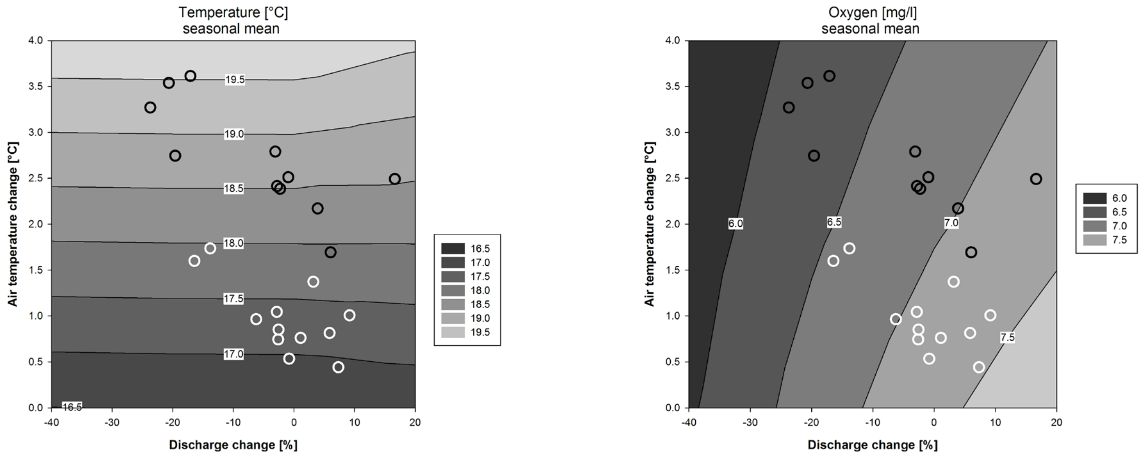

Figure 4. Response surfaces of water temperature (left) and oxygen concentration (right) (seasonal mean for the period 01.04.-31.10.) in the freshwater part of the Elbe Estuary at station Seemannshöft (km 629) based on sensitivity simulations with integrated projections for the near (white circles) and the far future (black circles).

Derived from the response surfaces the subsequent changes can be determined for this station (fig. 5): The seasonal mean (April till October) water temperature increases between +0.4 and +1.4 °C in the near future and between +1.4 and +3.0°C in the far future (fig. 5, left). The modelled value for the reference state from 1998 until 2010 is 16.5°C.

The seasonal mean of the oxygen content in the Hamburg harbour is decreasing in most of the projections (10) for the near future (between -0.8 and -0.03 mg O_2/l), only two projections show a small increase (fig. 5, right). All projections for the far future show a decline of the oxygen content by -1.2 to -0.2 mg O_2/l. The changes refer to a reference value of 7.4 mg O_2/l.

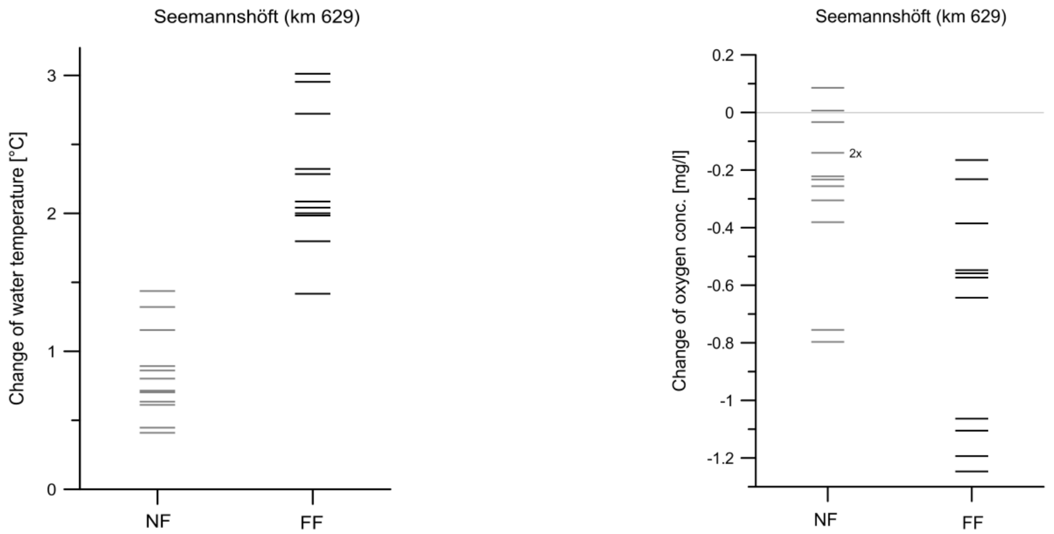

Figure 5. Change of water temperature (left) and oxygen concentration (right) (seasonal mean for the period 01.04.-31.10.) in the freshwater part of the Elbe Estuary at station Seemannshöft (km 629) for the near future (NF) and far future (FF). The results are based on model simulation with the water quality model QSim and the delta-change approach.

4 DISCUSSION

The simulations of ecologically relevant parameters like water temperature, oxygen content and plankton biomass is connected to a model chain of climate change projections ranging from atmospheric simulations to hydrological models. The output of such climate change model cascades have many restrictions and uncertainties. Modelling errors of individual models can accumulate within model chains (Noguer et al. 1998, Kleinn et al. 2005, Möck et al. 2013). Assumptions like CO_2-emisson scenarios, the downscaling of regional atmospheric models and the bias-corrections of hydrological models add further uncertainties. The delta change approach used in this study overcomes some of these drawbacks. The simulation of the water quality becomes independent of the errors and uncertainties of the climate and hydrologic models and only the uncertainties and errors of the water quality model are represented in the simulation results. Another advantage is that the response surface resulting from the delta change approach shows a bandwidth of system responses due to a bandwidth of changes in the input variables (here: air temperature and river discharge). Principally, by filling the climate and hydrologic projections into the response surfaces only the explicit effect of one climate change projection is depicted. Additionally, by considering the area adjacent to the projection point the robustness of the system response can be evaluated. Even more benefit of this approach is gained if like in KLIWAS an ensemble of projections is considered.

A disadvantage of the delta change approach is that changes in the seasonal pattern of the input variables air temperature and river discharge are not taken into account as a constant shift of both parameters is assumed. Prolonged low flow periods in summer, as predicted by some model chains, may lead to more severe oxygen depletions in the Elbe Estuary. The occurrence of these ecologically critical situations might be underestimated in this study.

Air temperature is the only meteorological factor considered in this sensitivity analysis. Climate change also influences wind velocity, humidity and solar radiation. These changes were neglected as it is assumed that they have minor effects on the water quality.

Nutrients and algae entering the modelling domain via tributaries and other sources have to be prescribed in form of boundary conditions in water quality simulations. Sixteen concentrations need to be specified for the QSim model at each boundary. These conditions were kept constant in all sensitivity simulations outlined for this study. Although changes in the boundary conditions, e. g. nutrient loads, may have a significant effect on the water quality in the Elbe Estuary they are neither covered by this study nor within the KLIWAS program by modelling the climate induced changes in the emission of nutrients from point and diffuse sources (agriculture, sewage plants etc.).

In summary, three dominant mechanisms triggered by air temperature and river discharge have been recognized to cause the climate change effects of water quality of the Elbe Estuary, particularly the oxygen content.

1. A decreased discharge, which causes increased retention times in the Elbe River, results in an increased algal growth and thus a larger amount of algal biomass entering the estuary. The microbial degradation of this biomass by heterotrophic bacteria and grazing of zooplankton then causes strong oxygen deficits in the freshwater part of the Elbe Estuary.
2. The rise of air temperature and consecutively of water temperature can have a reverse effect. The temperature optima for algal growth is exceeded during crucial summer situations, reducing the algal biomass entering the estuary. The model approach of QSim concerning the modelling of algae does neither take into account that the considered algal species can adapt to a new temperature regime nor is it able to simulate a change in the composition of the algal species (Thomas et al. 2012, Anderson et al. 2013).
3. The solubility of oxygen in water, declining with rising temperature, directly reduces the oxygen concentration in the river and estuary.

5 CONCLUSIONS AND OUTLOOK

Climate induced changes in river discharge and air temperature have an effect on the oxygen content of the Elbe Estuary for the near and far future. However, the bandwidth of the projections of the model chain and the uncertainties in the climate and hydrologic models have to be taken into account by interpreting the model results. Nevertheless, the delta change approach shows that the climate induced decrease of discharge and the related increase in algal production in the river has a clear effect on the water quality of the Elbe Estuary.

Prevention of negative climate induced effects can be achieved by decreasing the algal biomass due to sustainable restoration measurements including reduction of nutrient emissions in the Elbe catchment. Furthermore, in the Elbe Estuary more shallow areas may mitigate the critical oxygen situation. The effects of these options in addition to the climate induced effects should be investigated by further model studies.

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