Technical Report No. 8

Secchi depth calculations in BALTSEM

October 2012

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Baltic Nest Institute

The Baltic Nest Institute

The Baltic Nest Institute host the Nest model, a decision support system aimed at facilitating adaptive management of environmental concern in the Baltic Sea.

Nest can be used to calculate required actions needed to attain politically agreed targets for the Baltic Sea ecosystem. By modeling the entire drainage area, Nest is a novel tool for implementing the ecosystem approach in a large marine ecosystem. The main focus of the model is on eutrophication and the flows of nutrients from land to sea.

Reducing the nutrient input to the sea and thus decreasing the negative environmental impacts is a politically prioritized area of international cooperation. Baltic Nest Institute can contribute to this process by formulating policies that are fair, transparent and cost-efficient. The main target group for the Nest Decision Support System is HELCOM and regional water directors in the riparian countries.

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Secchi depth calculations in BALTSEM

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1 Introduction

Secchi depth measurements have been carried out for over 100 years in the Baltic Sea and the changes in Secchi depth give indications of the development of phytoplankton biomass in response to eutrophication (Sanden & Hakansson 1996, HELCOM 2009, Fleming-Lehtinen & Laamanen 2012). In the implementation of the ecosystem approach to Baltic Sea management, indicators based on Secchi depth are unique in that targets representing a good environmental status can be obtained from actual observations, whereas most other indicators lack observational evidence of a reference state representing conditions before substantial eutrophication.

In the on-going revision of the HELCOM Baltic Sea Action Plan, new targets on e.g., Secchi depth have been developed (HELCOM 2012). The following step is to use modeling to find nutrient inputs to the Baltic Sea, so called Maximum Allowable Inputs, that result in ecosystem changes so that eventually the good environmental status indicated by the targets is reached. This modeling effort is carried out using the coupled physical-biogeochemical model BALTSEM developed at BNI (Savchuk et al. 2012). The BALTSEM model resolves the Baltic Sea horizontally with 13 sub-basins, but each of these with high vertical resolution. The biogeochemical model includes inorganic and bioavailable organic nitrogen, phosphorus and silica, three phytoplankton groups, zooplankton and oxygen. Benthic nutrient regeneration and retention are modeled in addition.

This report describes a statistical post-processing algorithm to calculate Secchi depth from BALTSEM results to provide additional accuracy and confidence of Secchi depth estimates compared to the simplistic intrinsic transparency calculations within the BALTSEM model. The additional quality in the Secchi depth calculation results is of major importance for the results of the calculation of the Maximum Allowable Inputs.

2 BALTSEM Secchi depth algorithm

2.1 Secchi depth in the Baltic Sea

Secchi depth measurements have been used in oceanography to assess the transparency of seawater since the 19th century (a description of the history of Secchi depth measurements in the Baltic sea is given by Aarup 2002) and provide a long-term climatology of the net effect from the components affecting water transparency. Secchi depths have decreased in the Baltic Sea since the beginning of the 20th century, which is primarily attributed to increased phytoplankton biomass due to eutrophication, e.g. Sanden & Hakansson (1996). Chlorophyll-*a* measurements provide a more specific proxy for phytoplankton biomass, but are available only since 1980 in most Baltic Sea areas. Therefore, Secchi depth continues to be an important indicator of ecological status and has defined target values in the Baltic Sea (HELCOM 2009, 2012).

Light penetration in seawater is determined by scattering and absorption. Light scattering changes the direction of light without affecting the energy of photons, whereas absorption converts light energy into other forms. Absorption therefore directly reduces the light flux, while scattering affects it both directly as it diverts light from its initial path as well as indirectly by increasing the path length of photons through a medium, amplifying absorption. The combined effect of absorption and scattering on underwater radiance is called attenuation (Dera 1992).

In coastal and inland waters, light attenuation is caused by water itself, colored dissolved organic matter (CDOM), phytoplankton pigments, and suspended solids. The light attenuation by water itself is well known, while the contributions to attenuation by CDOM, phytoplankton pigments and suspended solids are highly variable in the Baltic (Babin 2003, Fleming-Lehtinen & Laamanen 2012, Kratzer et al. 2003, Lund-Hansen 2004, Paavel et al. 2011).

In the Baltic Sea, light attenuation by CDOM is highest in the Bothnian Bay and the Neva Bay in the eastern Gulf of Finland (Hojerslev et al. 1996). CDOM absorption therefore shows a clear negative correlation with increasing salinity towards the North Sea area (Figure 1). In addition to these regional differences in CDOM concentration, the spectral absorption properties of CDOM also show spatial variation. Light absorption by CDOM decreases exponentially with wavelength. The exponential slope of CDOM absorption can be related to the biogeochemical composition of the dissolved matter and is shown to vary regionally (Kowalczuk et al. 2006, Stedmon et al. 2007, Stedmon et al. 2010) and seasonally (Kowalczuk et al. 2005, Kowalczuk et al. 2006). Close to river mouths CDOM exhibits the optical characteristics of terrestrial organic matter, whereas the slope of the absorption spectrum flattens towards the central areas of the Baltic Proper (Stedmon et al. 2007).

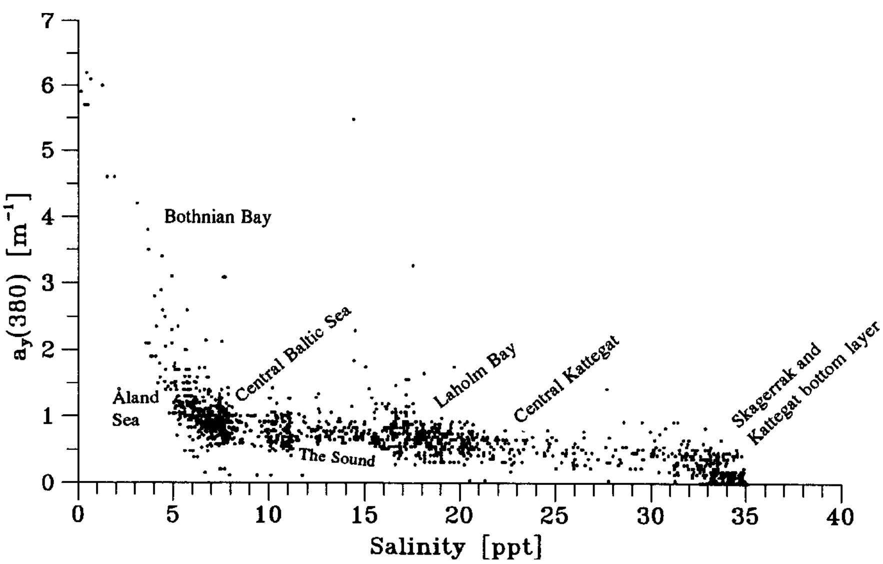

Figure 1: Salinity-CDOM light absorption relationship in the Baltic Sea (Hojerslev et al. 1996)

To calculate Secchi depth from state variables included in the BALTSEM model (i.e. simulated phytoplankton concentrations) we have adapted the bio-optical model that relates Secchi depth to CDOM absorption and chlorophyll-*a* developed during the TARGREV project (HELCOM 2012). The TARGREV bio-optical model is used here with a BALTSEM CDOM proxy, which is derived from estimates of terrestrial dissolved organic carbon inputs of major rivers (see 2.3).

2.2 TARGREV bio-optical model

The Secchi depth calculations in BALTSEM are based on a bio-optical model developed during TARGREV (HELCOM 2012), which computes Secchi depth from generalized absorption and scattering properties of CDOM and spring or summer phytoplankton in the Baltic Sea. The bio-optical model was developed from *in situ* observations of absorption by CDOM and phytoplankton (scaled to chlorophyll-*a*) and Secchi disk depths collected at the Finnish Institute of Marine Research (FIMR) and the Finnish Environment Institute (SYKE) in the Bothnian Bay, Bothnian Sea, Gulf of Finland, Northern Baltic Proper, Gotland Basin, Bornholm Basin and Arkona Sea in 2008 – 2011, and subsequent optical modelling of the underwater light field using the radiative transfer approximation software Hydrolight 5 (Sequoia Scientific). CDOM absorption is parameterized as being proportional to the absorption at a reference waveband and the generalized relation between CDOM absorption slope and concentration as observed in the combined dataset from all Baltic Sea basins. For phytoplankton summer communities, the bio-optical model thus suggests the following relationship between Secchi depth, chlorophyll-*a* and CDOM concentrations:

$$SD_{opt} = 54.2 \cdot (0.155 + aCDOM + 2.77 \cdot chl)^{-0.554} + chl^{0.414} - aCDOM^2 \cdot (2.97 + 1.35 \cdot chl)^{-1.33} - 7.58 \qquad \text{Equation 1}$$

where $aCDOM$ is the CDOM absorption at reference wavelength 375 nm, chl the chlorophyll-*a* concentration (in mg m^{-3}) and SD_{opt} is the predicted Secchi depth (in m) based on the radiative transfer approximation computations.

A correction for modelled vs. observed Secchi disk depth at high transparency is also used here (for Secchi depth > 5.13 m), as the model appears to overestimate Secchi depth at high transparency:

$$SD = \frac{\ln(SD_{opt}) - \ln(1.2066)}{0.2822} \quad if\ SD_{opt} > 5.13 \text{ m} \qquad \text{Equation 2}$$

In HELCOM (2012) this 'observer correction' is applied to SD_{opt} > 5.5 m, but this limit is adjusted here to SD_{opt} > 5.13 m as the point where corrected and uncorrected values are equal, resulting in a monotonous function, which is advantageous for parameter estimation (see 2.6).

2.3 BALTSEM CDOM proxy

A rough prognostic calculation of CDOM is done with the BALTSEM model with the aim of capturing some of the long-term variations due to varying river runoff. The long-term setup of BALTSEM from Gustafsson et al. (2012) enabling simulations 1850-2006 is used and a state-variable representing CDOM is introduced. It is slowly degrading at a constant half-time of 5 years. The CDOM proxy is introduced assuming basin specific concentrations in rivers and in the North Sea water entering through the open boundary, see Table **1**. The concentrations are obtained using the measurements of DOC and DON in rivers around the Baltic obtained by Stepanauskas et al. (2002). First the flow weighted averaged concentrations of DOC and DON are determined to each basin, thereafter the CDOM proxy concentration is assumed to be equal to $DOC - 5.7 \times DON$, where 5.7 is the C:N Redfield ratio. Thus, it is assumed that CDOM is proportional to the excess DOC in the riverine water in the sense of biologically produced material.

Table 1: Basin-specific CDOM proxy concentrations assumed for rivers and the North Sea boundary

BALTSEM Basin	CDOM proxy (mg C m^{-3})
Kattegat, Danish Straits, Arkona and Bornholm basin	1400
Gotland Sea	3300
Bothnian Sea	4300
Bothnian Bay	5600
Gulf of Riga	7500
Gulf of Finland	6100
Skagerrak boundary	300

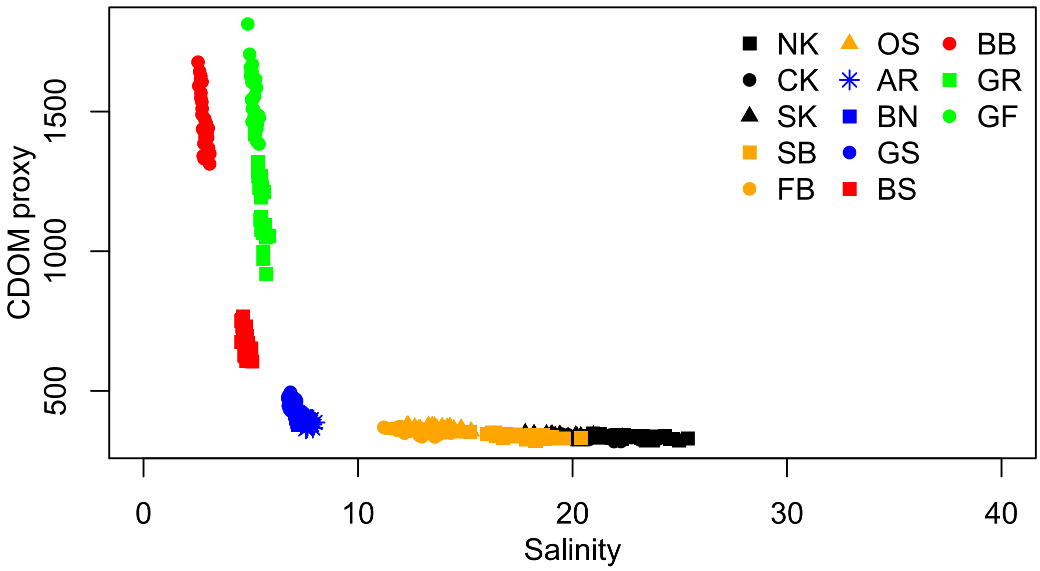

Figure 2: BALTSEM CDOM proxy - salinity relationship simulated for the years 1980 – 2006 (June – September averages). NK = Northern Kattegat, CD = Central Kattegat, SK = Southern Kattegat, SB = Samso Belt, FB = Fehmarn Belt, OS = Öresund, AR = Arkona Basin, BN = Bornholm Basin, GS = Gotland Sea, BS = Bothnian Sea, BB = Bothnian Bay, GR = Gulf of Riga, GF = Gulf of Finland

The BALTSEM CDOM proxy shows a similar relationship to salinity (Figure **2**) as the field observations of CDOM light absorption presented in Hojerslev et al. (1996, c.f. Figure **1**), with a steep decrease in CDOM concentrations within the Bothnian Bay and Bothnian Sea and a much flatter mixing curve throughout the Baltic Proper, Belt Sea and Kattegat. However, the relationship seems to be steeper than observed by Hojerslev et al. in the Bothnian Bay and Bothnian Sea and too flat in the Baltic Proper. This indicates that the BALTSEM CDOM proxy slightly overestimates CDOM concentrations in boreal areas, whereas sources in the Baltic Proper seem to be underestimated. One reason may be that the decay of CDOM is faster for the fresh riverine material near the major sources, than for the older material found further to the south. In addition, there are also internal sources for CDOM that are also neglected in the simple model description.

2.4 Statistical model

To account for the uncertainty in the CDOM proxy used in BALTSEM as well as for regional differences in the slope of the CDOM absorption spectrum, we used a statistical model to estimate basin specific light absorption coefficients for the BALTSEM CDOM proxy, approximating $aCDOM$ in Equation **1** as

$$\boldsymbol{aCDOM = a_{basin} \cdot CDOM_{BALTSEM}} \qquad \text{Equation 3}$$

where a_{basin} is a basin-specific multiplier and $CDOM_{BALTSEM}$ denotes the CDOM proxy introduced in BALTSEM.

Further, we assume that Equation **1** is also valid for the Kattegat, Danish Straits and the Gulf of Riga, which were not included into the calibration dataset of the TARGREV bio-optical model.

2.5 Calibration dataset

The Secchi depth measurements used for calibrating the basin-specific CDOM multipliers in Equation **3** are described in Fleming-Lehtinen et al. (2012) and are identical to the dataset used to develop target transparencies for the Baltic Sea within the HELCOM TARGREV project (HELCOM 2012). However, since BALTSEM is more representative of conditions in the non-coastal areas of the Baltic, we have used a more rigorous definition of the coastal zone and excluded all data within 12 nm distance from land, with exception of the Danish Straits (Samsø Belt, Fehmarn Belt, Öresund), where all available data were used. Observations were then aggregated into monthly means, and summer averages were calculated from the monthly means in June – September.

Phytoplankton concentrations in the surface layer (0 – 10 m) of each BALTSEM basin were extracted from BALTSEM output and converted into chlorophyll-*a*, using a carbon/chlorophyll-*a* ratio of 30. Summer concentrations (June-September) were then calculated by averaging daily model output.

Figures A1 and A2 in the annex to the report show the simulated CDOM proxy and summer chlorophyll-*a* concentrations that were used in calibrating the Secchi depth algorithm.

2.6 Parameter estimation

The basin-specific CDOM multipliers in Equation **3** were then fitted to the summer averages of Secchi depth in 1900 – 2006 using the simulated annealing routine SANN (Belisle 1992) within the R stats library. The unweighted sum of squared model-data deviations was chosen as target function in the optimization. The simulated annealing routine was then applied successively with a stepwise reduction of the initial temperature setting from 1000 to 0.1, until the final parameter set changed by less then 1 %. To achieve higher precision in the Danish Straits, a common CDOM multiplier was fitted for these basins. Thus, the BALTSEM Secchi depth algorithm combines the TARGREV bio-optical model with 11 basin-specific multipliers that describe the relationship between the BALTSEM CDOM proxy and CDOM absorption at reference wavelength in Equation **1.**

3 Algorithm performance

The estimated CDOM multipliers (Table **2**) allow a reasonable fit to observed Secchi depth with correlation coefficients between 0.35 and 0.58 in most basins. However, algorithm performance is lower in the Bothnian Bay, the Bothnian Sea and the Gulf of Riga. In these basins BALTSEM tends to underestimate phytoplankton production, while at the same time the influence of CDOM on Secchi depth is high.

Table 2: Estimated basin specific CDOM mutlipliers a_{basin} and correlation coefficients (r) and root mean square errors (RMSE) of the model-data fit (NK = Northern Kattegat, CD = Central Kattegat, SK = Southern Kattegat, SB = Samso Belt, FB = Fehmarn Belt, OS = Öresund, AR = Arkona Basin, BN = Bornholm Basin, GS = Gotland Sea, BS = Bothnian Sea, BB = Bothnian Bay, GR = Gulf of Riga, GF = Gulf of Finland)

Basin	a_{basin}	r	RMSE	Basin	a_{basin}	r	RMSE
NK	3.20E-03	0.40	2.48	BN	9.63E-03	0.35	1.07
CK	2.83E-03	0.38	1.25	GS	8.22E-03	0.53	1.54
SK	-1.75E-05	0.38	1.04	BB	6.28E-03	0.15	2.25
Straits	5.29E-03	0.42	1.31	BS	3.43E-03	0.25	1.62
AR	1.04E-02	0.46	0.96	GR	5.13E-03	0.29	1.73
				GF	2.86E-03	0.58	1.33

As indicated by correlation coefficients and RMSE errors (Table 2), summer Secchi depths estimated from the BALTSEM output correspond reasonably to the observed long-term changes in all basins except the Gulf of Riga. The long-term decline in Secchi depth is described well in the Kattegat, the Danish Straits and the Baltic Proper (Arkona Basin, Bornholm Basin, Gotland Sea). In the Bothnian Sea the simulated Secchi depths fail to capture the decrease in Secchi depth since the mid 1970s, while in the Bothnian Bay the model simulations show a correct long-term average, however with lower variability than the observations. Most likely the available data undersamples the spatial variability within the basin. As indicated by correlation coefficients and RMSE, the Secchi depth algorithm performs poorly in the Gulf of Riga.

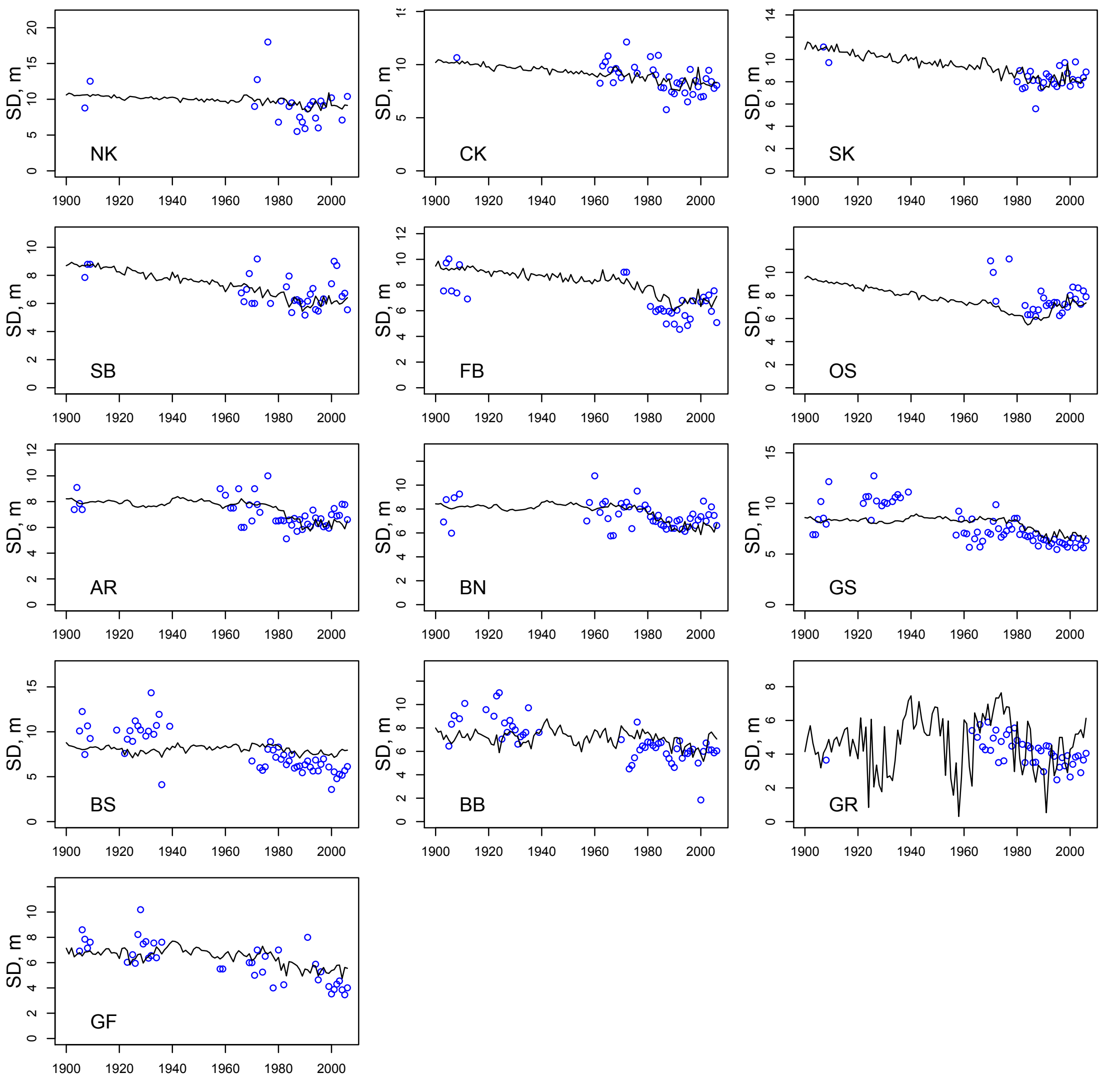

Figure 3: Simulated long-term dynamics of summer Secchi depth in the BALTSEM subbasins (NK = Northern Kattegat, CD = Central Kattegat, SK = Southern Kattegat, SB = Samso Belt, FB = Fehmarn Belt, OS = Öresund, AR = Arkona Basin, BN = Bornholm Basin, GS = Gotland Sea, BS = Bothnian Sea, BB = Bothnian Bay, GR = Gulf of Riga, GF = Gulf of Finland). Dots denote summer means of Secchi depth observations, black lines show model simulation.

More regular Secchi depth observations are available starting from the early 1970ies in most Baltic subbasins. A comparison between modeled and observed summer values (Figure **4**) illustrates, that spatial gradients and interannual variability are mostly represented well. However, in some basins, e.g. the Kattegat, the BALTSEM algorithm overestimates recent Secchi depth measurements.

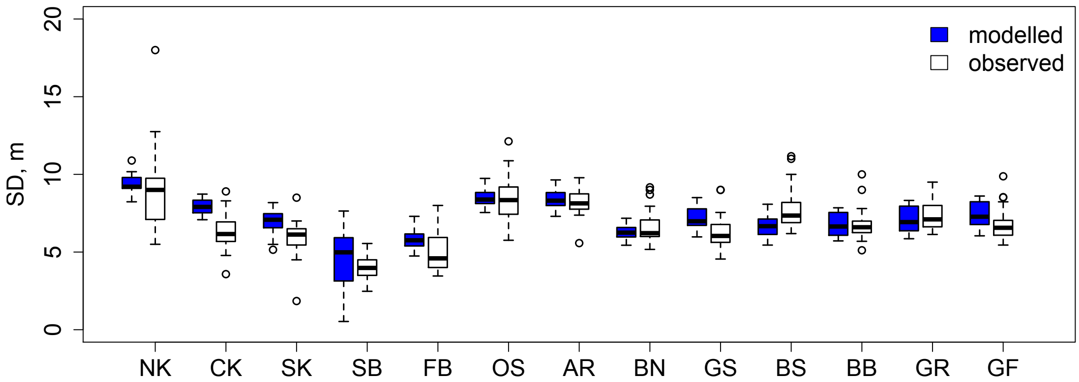

Figure 4: Modelled and observed Secchi depth during 1970 – 2006. (NK = Northern Kattegat, CD = Central Kattegat, SK = Southern Kattegat, SB = Samso Belt, FB = Fehmarn Belt, OS = Öresund, AR = Arkona Basin, BN = Bornholm Basin, GS = Gotland Sea, BS = Bothnian Sea, BB = Bothnian Bay, GR = Gulf of Riga, GF = Gulf of Finland)

To illustrate the importance of CDOM in the BALTSEM Secchi depth algorithm, we have compared Secchi depth calculated at actual BALTSEM CDOM proxy concentrations to Secchi depth in the absence of CDOM ($CDOM_{BALTSEM}=0$, Figure **5**). In the Kattegat and Danish Straits the BALTSEM Secchi depth algorithm attributes about 90 % of the simulated Secchi depth to non-CDOM light attenuation. This fraction is attributed to chlorophyll *a*, since the TARGREV bio-optical model and hence the BALTSEM Secchi depth algorithm does not account explicitly for other sources of light attenuation. The influence of CDOM increases in the Baltic Proper (Arkona Basin, Bornholm Basin and Gotland Sea) and the Gulf of Finland, where non-CDOM is responsible for about 70 % of Secchi depth, whereas in the Bothnian Bay and Gulf of Riga roughly half of Secchi depth is attributed to CDOM light attenuation.

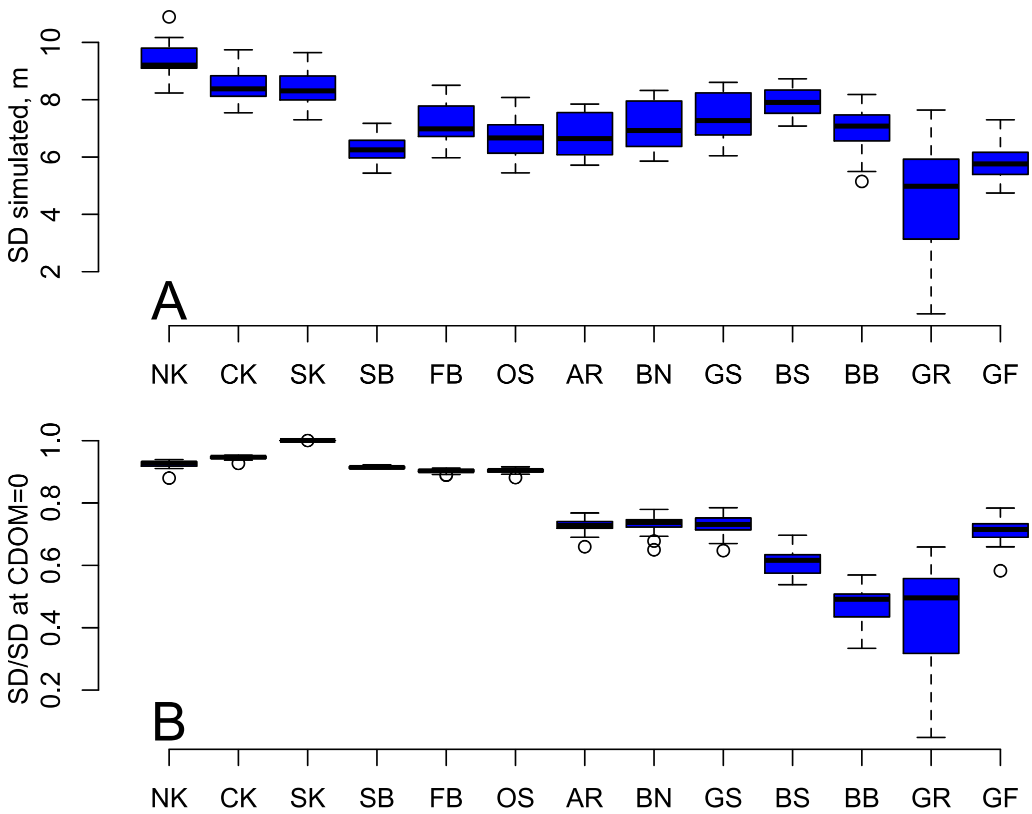

Figure 5: Influence of CDOM on simulated Secchi depth during 1970 - 2006. Box and whisker plots of simulated summer Secchi depth in each subbasin (A) and the fraction of simulated Secchi depth attributable to non-CDOM light attenuation (B) (NK = Northern Kattegat, CD = Central Kattegat, SK = Southern Kattegat, SB = Samso Belt, FB = Fehmarn Belt, OS = Öresund, AR = Arkona Basin, BN = Bornholm Basin, GS = Gotland Sea, BS = Bothnian Sea, BB = Bothnian Bay, GR = Gulf of Riga, GF = Gulf of Finland)

4 Discussion

The simple description of CDOM sources and its dynamics in the Baltic surface waters presented here is sufficient to capture the major spatial differences in its distribution. However, too little is known about CDOM concentrations in the major Baltic tributaries to more precisely specify the model source term. Recently, the Baltic-C project collected total organic carbon data for 63 rivers draining into the Baltic Sea, but the data do not allow to distinguish between dissolved and total organic carbon (c.f. Kuliński & Pempkowiak 2011 and published comment to reviewer #2). Apart from uncertainties in DOC concentrations, different terrestrial sources as well as autochthonous production of CDOM (Aarnos et al. 2012, Osburn & Stedmon 2011, Stedmon et al. 2007) also modify the spectral properties of CDOM. The basin-specific CDOM multipliers used here therefore attempt to compensate both for deviations between BALTSEM CDOM proxy and the actual CDOM concentrations, as well as for differences in spectral properties.

The share of light attenuation assigned to non-CDOM and hence chlorophyll-*a* in the BALTSEM algorithm is generally larger than the values presented in Fleming-Lehtinen & Laamanen (2012). In part this is caused by the observer-correction applied to high Secchi depth values, which assigns relatively low Secchi depth values in clear waters with both low CDOM and chlorophyll *a* concentrations. Nevertheless, the general patter of increasing importance of chlorophyll-*a* from the Bothnian Bay to the Gulf of Finland/Baltic Proper presented in Fleming-Lehtinen & Laamanen (2012) is still captured well in the BALTSEM Secchi depth algorithm.

Only in the Gulf of Riga the BALTSEM Secchi depth algorithm fails to represent the long-term dynamics of Secchi depth. In the Gulf of Riga BALTSEM underestimates summer phytoplankton growth during years with high nitrogen loads and hence high river runoff (c.f. Gustafsson et al. 2012). Because these periods are also characterized by high CDOM inputs, the CDOM basin multiplier is overestimated since the model fit compensates the underestimated phytoplankton light attenuation. As a result estimated Secchi depth strongly depends on river runoff and in particular during years with high river runoff, Secchi depth is underestimated in the Gulf of Riga.

5 Conclusions

The Baltsem Secchi depth algorithm gives a reasonable description of long-term changes in summer Secchi depth in most Baltic subbasins. However, especially in basins with high freshwater input the simulated Secchi depth values are sensitive to CDOM input and hence river runoff. To assess environmental status in these basins, simulated Secchi depth should be supplemented by additional eutrophication sensitive parameters, e.g. winter nutrient concentrations or summer chlorophyll-*a* values.

6 Bilbliography

Aarnos, H., Ylöstalo, P., & Vähätalo, A. V. (2012). Seasonal phototransformation of dissolved organic matter to ammonium, dissolved inorganic carbon, and labile substrates supporting bacterial biomass across the Baltic Sea. *Journal of Geophysical Research*, *117*(G1).

Aarup, T. (2002). Transparency of the North Sea and Baltic Sea–a Secchi depth data mining study. *Oceanologia*, *44*(3), 323–337.

Babin, M. (2003). Variations in the light absorption coefficients of phytoplankton, nonalgal particles, and dissolved organic matter in coastal waters around Europe. *Journal of Geophysical Research*, *108*(C7).

Belisle, C. (1992). Theorems for a class of simulated annealing algorithms on R(d). *Journal of Applied Probability*, *29*(4), 885–895.

Dera, J. (1992). *Marine Physics*. Elsevier Oceanography Series. Elsevier Science, 516 pp.

Fleming-Lehtinen, V., & Laamanen, M. (2012). Long-term changes in Secchi depth and the role of phytoplankton in explaining light attenuation in the Baltic Sea. *Estuarine, Coastal and Shelf Science*, 1–10.

Gustafsson, B. G., Schenk, F., Blenckner, T., Eilola, K., Meier, H. E. M., Muller-Karulis, B., Neumann, T., Ruoho-Airola, T., Savchuk, O.P., & Zorita, Z. (2012). Reconstructing the Development of Baltic Sea Eutrophication 1850–2006. *Ambio*, *41*(6), 534–548.

HELCOM (2012). Approaches and methods for eutrophication target setting in the Baltic Sea region. *Baltic Sea Environment Proceedings,* Draft, 103 pp.

HELCOM. (2009). Eutrophication in the Baltic Sea - An integrated thematic assessment of the effects of nutrient enrichment and eutrophication in the Baltic Sea region. *Baltic Sea Environmental Proceedings No. 115B.*

Hojerslev, N., Holt, N., & Aarup, T. (1996). Optical measurements in the North Sea-Baltic Sea transition zone. I. On the origin of the deep water in the Kattegat. *Continental Shelf Research*, *16*(10), 1329–1342.

Kowalczuk, P., A Stedmon, C., & Markager, S. (2006). Modeling absorption by CDOM in the Baltic Sea from season, salinity and chlorophyll. Marine Chemistry, 101(1-2), 1–11.

Kowalczuk, P., Stoń-Egiert, J., Cooper, W. J., Whitehead, R. F., & Durako, M. J. (2005). Characterization of chromophoric dissolved organic matter (CDOM) in the Baltic Sea by excitation emission matrix fluorescence spectroscopy. *Marine Chemistry*, *96*(3-4), 273–292.

Kratzer, S., Håkansson, B., & Sahlin, C. (2003). Assessing Secchi and photic zone depth in the Baltic Sea from satellite data. *Ambio*, *32*(8), 577–585.

Kuliński, K., & Pempkowiak, J. (2011). The carbon budget of the Baltic Sea. *Biogeosciences*, *8*(11), 3219–3230.

Lund-Hansen, L. C. (2004). Diffuse attenuation coefficients Kd (PAR) at the estuarine North Sea-Baltic Sea transition: time-series, partitioning, absorption, and scattering. *Estuarine, Coastal and Shelf Science*, *61*(2), 251–259.

Osburn, C. L., & Stedmon, C. A. (2011). Linking the chemical and optical properties of dissolved organic matter in the Baltic–North Sea transition zone to differentiate three allochthonous inputs. *Marine Chemistry*, *126*(1-4), 281–294.
Paavel, B., Arst, H., Metsamaa, L., Toming, K., & Reinart, A. (2011). Optical investigations of CDOM-rich coastal waters in Pärnu Bay. *Estonian Journal of Earth Sciences*, *60*(2), 102-112.
Sanden, P., & Hakansson, B. (1996). Long-term trends in Secchi depth in the Baltic Sea. *Limnology and oceanography*, *41*(2), 346–351.
Savchuk, O. P., Gustafson, B. G., & Muller-Karulis, B. (2012). *BALTSEM - a marine model for decision support within the Baltic Sea Region*. BNI Technical Report No 7, Baltic Nest Institute, 55 pp.
Stedmon, C. A., Markager, S., Tranvik, L., Kronberg, L., Slätis, T., & Martinsen, W. (2007). Photochemical production of ammonium and transformation of dissolved organic matter in the Baltic Sea. *Marine Chemistry*, *104*(3-4), 227–240.
Stedmon, C. A., Osburn, C. L., & Kragh, T. (2010). Tracing water mass mixing in the Baltic-North Sea transition zone using the optical properties of coloured dissolved organic matter. *Estuarine, Coastal and Shelf Science*, *87*(1), 156–162.
Stepanauskas, R., JØrgensen, N. O. G., Eigaard, O. R., Žvikas, A., Tranvik, L. J., & Leonardson, L. (2002). Summer inputs of riverine nutrients to the Baltic Sea: bioavailability and eutrophication relevance. *Ecological monographs*, *72*(4), 579–597.

Annex I

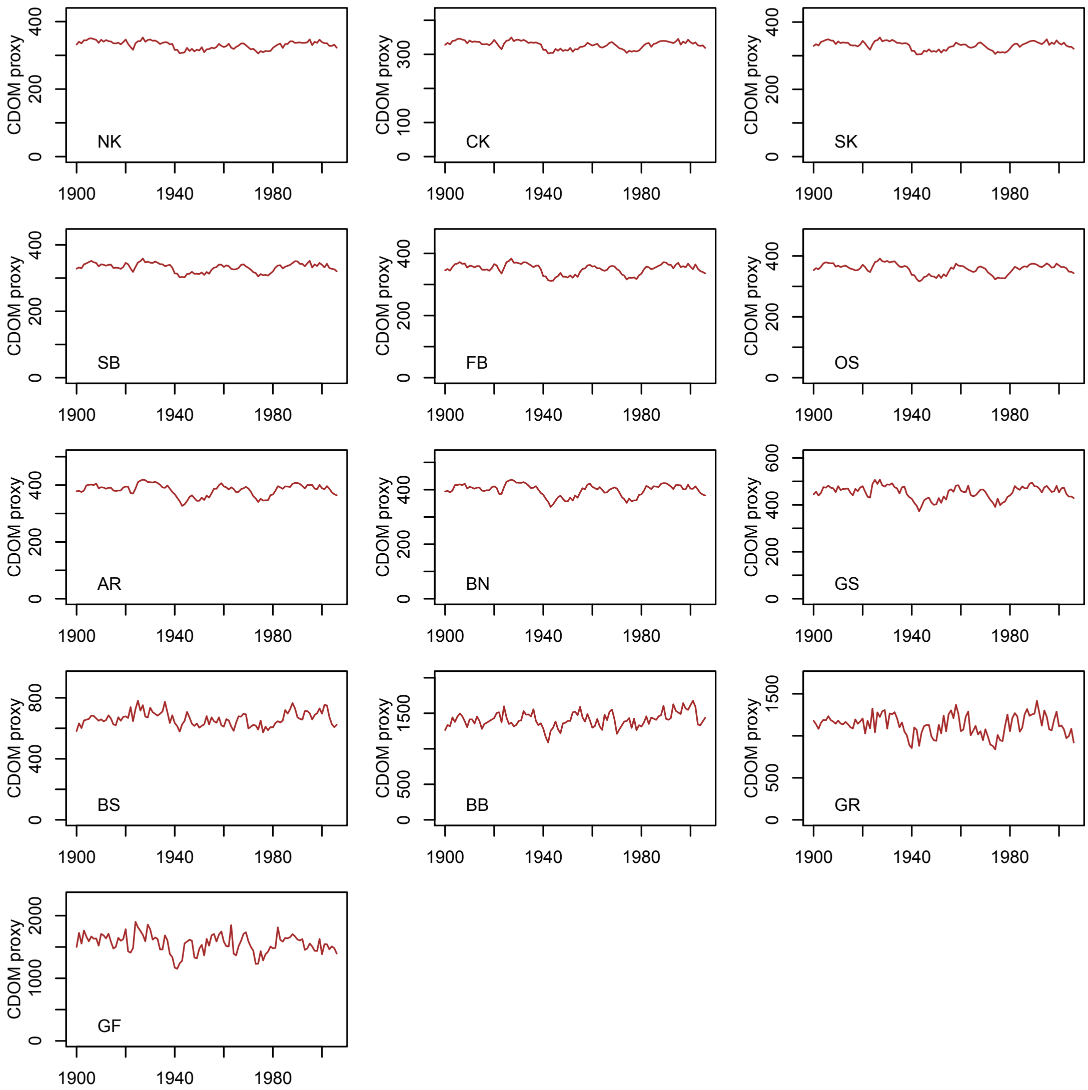

Figure A1: Simulated long-term dynamics of the BALTSEM CDOM proxy in the BALTSEM subbasins (NK = Northern Kattegat, CD = Central Kattegat, SK = Southern Kattegat, SB = Samso Belt, FB = Fehmarn Belt, OS = Öresund, AR = Arkona Basin, BN = Bornholm Basin, GS = Gotland Sea, BS = Bothnian Sea, BB = Bothnian Bay, GR = Gulf of Riga, GF = Gulf of Finland).

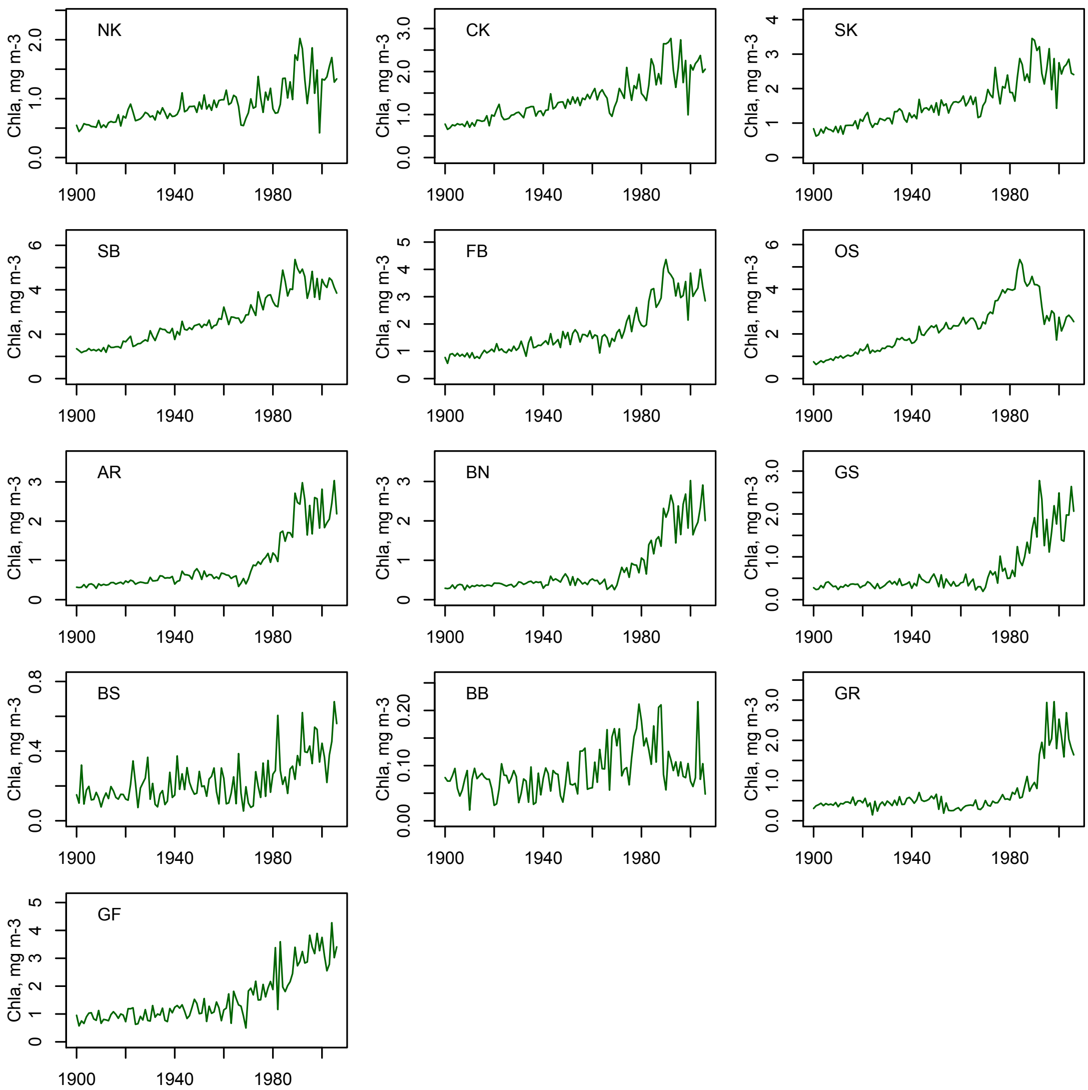

Figure A2: Simulated long-term dynamics of chlorophyll-*a* in the BALTSEM subbasins (NK = Northern Kattegat, CD = Central Kattegat, SK = Southern Kattegat, SB = Samso Belt, FB = Fehmarn Belt, OS = Öresund, AR = Arkona Basin, BN = Bornholm Basin, GS = Gotland Sea, BS = Bothnian Sea, BB = Bothnian Bay, GR = Gulf of Riga, GF = Gulf of Finland).