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Paul Halloran
Topical Editor
GMD

Revision gm-2020-318

Dear Paul Halloran (GM editor)

Hereby, I submit the revised version of the manuscript gm-2020-318

Optical model for the Baltic Sea with an explicit CDOM state variable: a case study with Model ERGOM (version 1.2) (changed title)

Thomas Neumann, Sampsa Koponen, Jenni Attila, Carsten Brockmann, Kari Kallio, Mikko Kervinen, Constant Mazeran, Dagmar Müller, Petra Philipson, Susanne Thulin, Sakari Väkevä, and Pasi Ylöstalo

First of all, we would like to thank the two referees and you for the careful consideration of the manuscript and many helpful comments. We followed every of the referees' suggestions and think that the manuscript has improved considerably.

An appendix with our detailed response to the referees' comments together with a marked-up manuscript is attached at the end of the letter. Thank you for time and effort to consider the submitted manuscript.

With best regards,

Thomas Neumann

Appendix

First of all, we would like to thank two referees for the thorough reviews of our manuscript. We followed every suggestions and think that the manuscript has improved considerably.

In the following, we respond to the referee's specific remarks. Remarks are shown in blue and our response in black.

Section numbers used in our response refer to the revised manuscript.

Review #1 (M. Baird):

Major comments.

1. The authors are occasionally loose with the use of CDOM vs. CDOM absorption and this becomes confusing. For example, p2 L17 is CDOM absorption; L26 'amount of CDOM'. Is this a load, concentration, rate of absorption?

We went through the manuscript (MS) and clarification whether CDOM concentration/content or CDOM absorption is meant. We also clarified in the model section (2.1.3) that we consider CDOM as a substance in the water with different properties. One of these properties is light absorption.

2. While it is not entirely clear, the authors appear to attribute the improvement of their CDOM equation compared to the salinity relationship to the inclusion of nonconservative behaviour CDOM. Instead, I suspect the majority of the improvement is due to the use of the 65 stations to better set the inflow concentrations of CDOM. If they run a simulation with the non-conservative terms set to zero they would be able to quantitatively compare the importance of one over the other. The comparison should also include a complete description of the salinity-CDOM absorption parameterization so that we understand the comparison. For researchers such as myself considering both options in a coastal model, this would double the value of the paper.

We are sorry that the message is not obvious enough from the MS. Of course, the improvement could be achieved only due to high quality forcing data from EO methods. We made this statement more pronounced in the abstract. The diversity of riverine CDOM is also obvious from the new Fig. 4.

We performed an additional simulation with photobleaching switched off as suggested by referee #1. Results are shown in appendix 1. In appendix 1, we also provide the salt-CDOM absorption relation from Neumann, 2015. This relation is hyperbolic and therefore implicitly accounts for degradation.

3. The authors use a neural network to determine the CDOM component of absorption at 440 nm at 65 sites. This is a key innovation. They then undertake a convoluted set of calculations, including choosing an arbitrary 75th percentile value, in order to turn the satellite-determined absorption into a CDOM concentration which is then multiplied by kcdom in Eq. 5 to obtain the component of vertical attenuation due to absorption CDOM. Is this complicated pathway even necessary? Absorption is inherently additive. Furthermore, the degradation rate is proportional to concentration, which is itself proportional to absorption. So, could you not simply have a model tracer CDOM absorption at 440, and applying the mixing and non-conservative terms to this tracer?

The referee is right; the model would be simpler just by considering CDOM absorption only. However, as outlined in our response to comment #1, we want to have CDOM as a “substance”, eventually subject to further biogeochemical processes in the model. We clarified it in the MS.

4. I presume the use of the 75th percentile is about trying to determine the CDOM absorption in the freshwater end member. Given that there is a hydrodynamic model, the authors could use salinity in the hydrodynamic model to determine the unique freshwater endmember for each of the 65 sites? I know you started with the feeling that salinity vs CDOM doesn’t work, but I think this is because the Baltic has 65 different freshwater end members.

Yes, the 75th percentile is assumed to represent the freshwater portion of the river water before it is mixed with sea water. We also tested 90th percentile and then decided to proceed with 75th percentile in this first test to demonstrate the feasibility of the method. There is certainly more that can be done to finetune and streamline the process.

The combined model/EO approach to determine the CDOM endmember for the rivers seems to us not straight forward and should be subject for a follow up study. One problem is the high spatial resolution of EO data which we cannot match with a model at the moment. Nevertheless, this high resolution in EO is essential to get values from the river mouths. A further problem will be that the model is not able to reproduce river plumes one by one. Reasons are the coarse temporal resolution of runoff available for most rivers. But also uncertainties in the meteorological forcing and nonlinear features like filaments may prevent a one by one projection of the model plume on the EO plume. The idea is brilliant, but we think a sound evaluation is needed and it seems to us it is beyond the scope of this study.

5. One of the key findings is the variability in CDOM absorption at the 65 stations. Fig. 4 illustrates this, but much more could be shown. I suggest splitting the two panels into 2 figures, and showing the map as large as Fig. 1, but with the 65 sites with symbols collected by mean absorption at 440. For some researchers this alone would be an important result.

Following the referees recommendation, we split Fig. 4 and replaced Fig. 4b by a new map showing EO based CDOM absorption in the rivers used (new Fig. 4 in the revised MS).

Minor comments.

Title: “Radiation model” might imply a more sophisticated, directional model of light. Perhaps “Optical model” is less specific?

We followed the recommendation and changed the title accordingly.

P1 L17 what does divergence mean in this context?

We use absorption now.

P2 L27 always have a space between a quantity and its units.

Done

P2 2nd para. Paragraph goes from discussing non-conservative behaviour (2nd sentence), conservative behaviour (4th) to non-conservative again (5th). I understand what you are trying to say, and of course the point of the paper is in part the non-conservative behaviour. Paragraph just needs a more logical flow.

We re-phrased the paragraph.

P3 EO processors – does this mean software, theory?

It is a set of algorithms, we clarified it in the MS.

P3 L9 water leaving reflectance is a tautology.

We modified the sentence.

P3 L12 coastal waters of Finland

We modified the sentence.

P5 L15 'behaves conservatively',

We modified the sentence.

P5 Eq. 8. Replace '2' in the equation with a parameter, the fraction of SWR in total solar radiation.

We introduced a new parameter r.

What is the difference between PAR(z) and I(z)?

The referee is right, there is no difference. We substituted I(z) by PAR(z).

Are you sure about exponential term in Eq 8.

Yes, we think this term accounts for the light attenuation at depth z depending on model tracer concentrations above depth z. We made it more clearly in the text.

The K_PAR in front of the integral doesn't seem write.

Thanks, it is a typo.

For equations, paper "Edwards, A.M. and Augerâ˘AR˘Méthé, M., 2019. Some guidanceon using mathematical notation in ecology. Methods in Ecology and Evolution, 10(1),pp.92-99." Is helpful.

We are thankful for this hint and considered the recommendations.

P5 L10 K_CDOM is a parameter, not a statistical relationship.

Here, K_CDOM(S) is meant, we correct the MS accordingly.

P5 L10 CDOM absorption?

Yes, it should be absorption, corrected.

P5 L14. Isn't DON part of the DOM? In which case are the last two terms in Eq. 5 double counting?

The last term in Eq. 5 (Eq. 4 in the revised manuscript) is terrestrial CDOM. It is part of a general DOM, but we treat it separately in the model. DON, also part of DOM, is produced in the model by phytoplankton and is a separate state variable as well. We think there is no double counting. The schematic of the biogeochemical model in the appendix may illustrate the different state variables.

P5, 2nd last line. 'depending on sun zenith angle, which is a function of latitude and time of day"

We thank the referee for clarifying this statement.

P6 L8 per m3

Corrected.

P6 L22 Whet is "Basis"?

We changed it into fundamentals.

P7 Title 3.3 Model configuration?

Most parts of this section are now in a new section "Circulation and biogeochemical model". The section "Model configuration" dose not exists anymore.

P7 A schematic of the biogeochemical model would help here.

A schematic is given in Appendix B.

Fig. 3b colorbar caption should be delta a(440).

The delta appeared much too thin in the pdf. Corrected in a revised figure version.

P9 First paragraph – this discussion needs to be more quantitative.

We introduced quantitative measures in this paragraph.

Review #2 (S. Losa):

General comments:

1) An edit is required for the title (please follow recommendation of reviewer 1)

Done, see response to review #1.

2) In the abstract, please present more precisely the evaluation results (including comparison of "the traditional" approach). How exactly did the model performance with the new light attenuation parameterisation improve, given which particular evaluation criteria?

We extended the abstract accordingly.

3) Introduction should be extended more intensively by references to the state-of-the-art of the investigated problem and related studies (see my specific comments), which would show the present study in line with already existing research and would further emphasise the added value.

We have taken this recommendation into account together with the hints from the specific comments.

4) The manuscript could benefit from a restructuring. In particular, Part 2: I would suggest to introduce/organize a separate section: 2 Methods and data and started first (Section 2.1) with model description
- general (MOM-ERGOM) model description
- Radiation (optical) model development
- Implementation in ERGOM
followed by
- data description (Section 2.2) including data processor etc. to prescribe required boundary conditions;
- and further details on the experiment set up including forcing and initial conditions and further followed by validation/evaluation metrics (Section 2.3)

Following the recommendations of referee #2, we restructured the sections of the manuscript. We introduced a section "Methods and data" with two subsections "Model development and description" and "CDOM boundary data". Both subsections are further structured into subsubsections.

5) Generally, I would also recommend elaborate a bit more on the results (however I do not list specific comments with respect, except for a request on quantitative estimates of the discussed correlations).

We are more specific now, especially for quantitative estimates.

Specific comments:

P1. L13-16: It would be nice to support your statements by related references (sentencewise).

We feel that the two sentences refer to quiet fundamental knowledge. A good summary is given by Nelsen&Siegel, 2002 which we use as a reference.

P1. L17: Please add related references in support to the statement ("Water temperature is affected by CDOM absorption as well"). For instance: Hill, 2008; Kim et al, 2015; Kim et al., 2018; Gnanadesikan et al., 2019, Soppa et al., 2019, Pefanis et al. 2020.

We are very grateful for the comprehensive support by referee #2 and recognized the relevant literature.

L19: Provide related references

We added a related reference.

P2. L2: Even for open ocean several studies showed a better representation of the light path when explicitly accounting for light absorption by chlorophyll and CDOM (Kim et al. 2015, Kim et. 2016, Groeskamp&Iudicone, 2018, Pefanis et al., 2020). Nevertheless, I agree that for coastal ecosystem it is extremely crucial (Cahill et al. 2008; Jolliff&Smith, 2014; Juhls et al. 2020).

We added a related reference which highlights the impact of river plumes.

P2. L3: I would suggest "parameterisation of light (penetration)" instead of "parametrization of model"

We changed the text accordingly.

P2. L4: "autochthonously" instead of "autochthonous"

We changed the text accordingly.

P2. L14-15: the authors might want to add the following references: Dutrkiewicz et al. 2015, Pefanis et al. 2020

We added relevant references.

P2. L15: "In relation to the Baltic Sea, a necessary prerequisite …."

We think that a lack of riverine CDOM data is not only the case for the Baltic. In this relation we refer to Pefanis et al. (2020) who note this problem also for Arctic rivers.

P2. L19: A rephase is required: "... we discuss the effect of the new development (proposed model extension?) on the ... Baltic Sea ... "

We changed the text accordingly.

P2. L21: please consider editing of this sentence.

We changed the text accordingly.

P3. L7-9: An edit is required for this sentence. As an example: "It utilizes an artificial neural network (ANN) first to remove ... and then to estimate ... "

We changed the text accordingly.

P3. L11: "gelbstoft" - please use English term :-)

We substituted gelbstoff by yellow substances.

P3. L11: "440 nm" (space in between)

Done

P3. L12: "measurements from Finland" - please provide a related reference and/or link

The data used in the calibration have not yet been published, but the method is similar to the one described Attila et al. (2013). We also added a reference to the use of the flow-through device (Lindfors et al. 2005).

P3. L15: "… by Koponen et al. (2007) and Attila et al. (2013)."

Done.

P3. L20: "The cases…" instead of "Cases"

Done.

P5. L2: I would suggest: "as in the study by Neumann et al. "instead of "proposed by"

We changed the text accordingly.

P5. L17-18: please provide a supporting reference to the statement.

A supporting reference has been added.

P5. Equation 8: please edit the integral part of the equation.

Due to a typo, KPAR was a factor in front of the integral which have been deleted. However, we think the integral itself is correct. It accounts for the depth dependence of the contributing concentrations in the model. We changed the manuscript and explain it in the manuscript.

P6. L16-21: consider combining the corresponding text in one paragraph.

We merged the paragraphs.

P7. L7: "0.5 m" and "2 m" instead of "0.5m" and "2m"

Done.

P7. L19: CDOM as a product of phytoplankton is neither considered. Right?

That's right. In the current version, we consider terrestrial CDOM only since in the Baltic Sea *in situ* produced CDOM is a small fraction of total CDOM. We made this fact more pronounced in the related paragraph.

Part 4: since there is no a discussion part, the best title would be "Results and discussion" (not just "Results")

The referee is right, we changed the section title.

P7. L27-28 (second sentence of Part 4): strictly speaking it might also impact the physics, but probably not in the current set up… Somehow, it was not clear enough from Parts 2/3 if the authors consider CDOM effect on the shortwave radiation penetration (and related physical processes) in general or only as a role of CDOM absorption in attenuation of the light available for phytoplankton production/growth. Please provide required emphasises.

We noted the small, and therefore not shown, impact on physics in section "impact on biogeochemistry (3.2)". The small effect is due to the fact that CDOM light absorption was also included in the former model version but with the salinity approximation for CDOM. In section "model configuration", we mention now that the estimated short wave absorption feeds into the ocean model as well.

P7. L28-32: these sentences should belong to the "Method" part.

We think it fits best here (Sec. Results and discussion), since it describes how we prepared the various observational data for comparison with model data. We simply used available observations and think that an own section on these data is not useful.

P9. L4-3: "the correlation is low" – please provide quantitative estimates if possible.

Done

P9. L4-5: "correlation improves …" – provide the quantitative estimates (r = ...)

Done

P9. L13-20: The text belongs to one (joint) paragraph.

Done.

P9. L31-32: might belong to the "Method"

We think it fits best here. We simply used available observations and think that an own section on these data is not useful.

Part 5 Conclusions: reads rather as "Summary and conclusions"

The title is changed into "Summary and conclusions":

P10. L7: editing is required for "an approach for light absorption" As a suggestion: "...an approach for accounting for the light absorption due to ..." Or "...an approach for approximating/considering the light absorption due to ..."

We changed the sentence accordingly.

P10. L10: "A common approach uses CDOM-salinity relationship for …" Readds too general, please rephrase, since not all studies in existence use CDOM-salinity relationships to represent CDOM in models.

We agree with the referee and changed it into “an often applied …”.

P12, L5: the authors might want to refer to the study by Dutkiewicz et al. (2015).

We are grateful for this hint and added the reference.

Figures

Figures 2, 4: to improve the quality of the figure please increase the size of the font used.

We revised the figure.

Figure 3: increase the size of the figure panels.

We increased the figure panels.

Figure 6 caption: "… based on its relation to salinity" instead of "based on salt."

We changed the caption accordingly.

Radiation Optical model for the Baltic Sea with an explicit CDOM state variable: a case study with Model ERGOM (version 1.2)

Thomas Neumann[1], Sampsa Koponen[2], Jenni Attila[2], Carsten Brockmann[3], Kari Kallio[2], Mikko Kervinen[2], Constant Mazeran[4], Dagmar Müller[3], Petra Philipson[5], Susanne Thulin[5], Sakari Väkevä[2], and Pasi Ylöstalo[2]

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Abstract. Colored dissolved organic matter (CDOM) in marine environments impacts primary production due to its absorption effect on the photosynthetically active radiation. In coastal seas, CDOM originates from terrestrial sources predominantly and causes spatial and temporal changing patterns of light absorption which should be considered in marine biogeochemical models. We propose a model approach in which Earth Observation (EO) products are used to define boundary conditions of CDOM concentrations in an ecosystem model of the Baltic Sea. CDOM concentrations in riverine water derived from EO products serve as forcing for the ecosystem model. For this reason, we introduced an explicit CDOM state variable in the model.

We show that the light absorption by CDOM in the model can be improved considerably compared to traditional approaches where, e.g., CDOM is estimated from salinity. The model performance increases especially with respect to spatial CDOM patterns due to the consideration of single river properties. A prerequisite is high quality CDOM data with sufficiently high spatial resolution which can be provided by the new generation of ESA satellite sensor systems (Sentinel 2 MSI and Sentinel 3 OLCI). Such data are essential, especially when local differences in riverine CDOM concentrations exist.

1 Introduction

Colored dissolved organic matter (CDOM) is a major light absorption constituent in the marine environment and especially in coastal seas. The spectral absorption characteristic of CDOM follows an exponential function with highest absorption towards shorter wavelengths (e.g. Nelson and Siegel, 2002). By modifying the underwater light climate, CDOM has an impact on primary productivity, e.g. in clear water sufficient light intensity to enable phytoplankton growth is available down to greater depths than in turbid waters (Dutkiewicz et al., 2015). Water temperature is affected by CDOM absorption as well. In turbid water, the short wave light divergence absorption is located in the upper water column increasing the temperature while in clear water a thicker layer is warmed but to a lesser degree (Jolliff and Smith, 2014). This process impacts especially the sea surface temperature (SST). Model studies show an SST increase up to 2 K in coastal regions when colored organic materials are considered (Gnanadesikan et al., 2019).

Jerlov (1976) developed a classification for different water masses based on specific optical properties. This classification is widely used in numerical ocean models (e.g., Griffies, 2004). For global models, this parametrization works reasonablereasonably well. However, coastal ecosystems with substantial terrestrial runoff require more detailed parametrization of models. light penetration. Especially variable light attenuation in river plumes and their environs affect the hydrodynamic and ecological response (Cahill et al., 2008).

Marine CDOM comprises humid substances (gelbstoffyellow substances) of terrestrial origin, and autochthonous autochthonously produced CDOM. Its degradation is governed by photochemical bleaching and bacterial activity. In freshwater dominated systems, like the Baltic Sea, terrestrial CDOM dominates (e.g., Stedmon et al., 2010, and references herein). Salinity and CDOM absorption In such systems, salinity and light absorption due to CDOM show a robust relationship (Neumann et al., 2015)indicating a conservative behavior. However, the . The relationship is hyperbolic (instead of linear) due to indicating the degradation processes.

For coupled physical-biogeochemical models of freshwater influenced coastal seas, a spatially resolved CDOM concentration is important for realistic light climate estimates. Based on the nearly conservative character of CDOM, statistical models have been developed which estimate absorption from salinity and e.g. chlorophyll (Kowalczuk et al., 2006; Neumann et al., 2015). These models usually deliver reasonable results. However, two distinct disadvantages are prominent: (i) uncertainties in model salinity propagate into the biogeochemical model and (ii) variability in CDOM riverine load (Skoog et al., 2011; Asmala et al., 2013) cannot be resolved. These disadvantages can be eliminated by introducing an independent CDOM state variable into the biogeochemical model (Dutkiewicz et al., 2015). A necessary prerequisite are boundary data for riverine CDOM loads of sufficiently good quality which is not commonly available for most rivers (Pefanis et al., 2020).

In this study, we present the generation of CDOM boundary data with the aid of satellite imagery, the implementation of a CDOM state variable in the biogeocemical model ERGOM (Ecological ReGional Ocean Model, Leibniz Institute for Baltic Sea Research (2015)), and we discuss the the generation of CDOM boundary data with the aid of satellite imagery, and we discuss the effect of the new development. We use the Baltic Sea as a study area.

the proposed model extension on the Baltic Sea ecosystem.

2 CDOM data from Earth Observation products

The aim of the development is to improve modeled CDOM data compared to available statistical models (Sect. 1). *In situ* data of CDOM loads are not available in sufficient spatial and temporal resolution, i.e. in the Baltic Sea, CDOM is not a parameter of the HELCOM (www.helcom.fi, last access: 22 September 2020) monitoring program. New instruments and technologies in Earth Observation (EO), now in operation, are ideal tools to overcome these limitations.

2 Methods and data

2.1 Characteristics of satellite data

In order to estimate the amount of CDOM coming from a river, it is necessary to derive it from observations within the river or as close to the discharge point as possible. The rivers in the Baltic Sea are usually small and thus high resolution (HR) instruments such as Sentinel-2 Multi Spectral Instrument (S2-MSI) are required. The MSI has a spatial resolution of 10-60depending on the central wavelength of the band. Water quality products are usually generated in 60resolution in order to reduce noise. This is sufficient for estimating the CDOM absorption of most rivers.

Two Sentinel-2 satellites are currently in orbit: S2A was launched on 23 June 2015

2.1 Model development and description

We start presenting the optical model including an explicit CDOM state variable, its implementations as part of a biogechemical model, and S2B on 7 March 2017. Together they provide a global revisit time of 5 days next to equator. Due to the high latitude of the Baltic Sea , the revisit time amounts to 2–3 days in this area.

Despite the frequent cloud cover, sufficient observations can be gathered to monitor river CDOM throughout the open water season (typically from March-April to October in the northern Baltic Sea).

2.2 Earth Observation processor for CDOM absorption estimation

EO processors are designed to convert the radiance signal acquired by the satellites into values of geophysical parameters. The estimation is based on the scattering and absorption features of the material suspended or dissolved in water. In addition to CDOM, these materials include phytoplankton cells, represented by Chlorophyll a (Chl-a), and suspended particulate matter.

One commonly used water quality processor is Case 2 Regional Coast Color (C2RCC) (Brockmann et al., 2016). It utilizes one artificial neural network (ANN) to first remove the effects of the atmosphere from the signal (atmospheric correction) and another to estimate inherent optical properties (IOPs) of water from the water leaving reflectance.

For estimation of CDOM absorption (a_{CDOM}), we utilized the C2RCC (version 1) output called a_{dg} (combined absorption by detritus and gelbstoff) which was calibrated to $a_{CDOM}(440)$ (absorption coefficient by CDOM at 440) values with in situ measurements from Finland with this equation:

$$a_{CDOM}(440) = 0.0654 \cdot a_{dg}^{1.45} + 0.2$$

A similar local calibration method has provided good results with other water quality parameters in earlier studies such as Koponen et al. (2007); Attila et al. (2013).

The data processing and extraction are done in a Calvalus massive parallel processing system (http://www.brockmann-consult.de/calvalus, last access: 22 September 2020). Data extraction areas are manually defined in the vicinity of the mouths of 69 rivers that represent ERGOM input locations (Fig. 1). Location of model rivers (black squares). The green line is the coastline of the 3model. We refer to the labeled river later in the text. The map was created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/), using published bathymetry data (Seifert et al., 2008)The areas are designed so that islands, mixed pixels and shallow areas are excluded. All valid pixels (not masked as land or cloud by the pixel classification processor Idepix) within each area and image are collected and analyzed, and the 75th percentile value is chosen to represent the river a_{CDOM}. Cases in which the number of valid pixels is less than 50% of all available pixels from an area are removed from the analysis. Assumedly, these represent cases with partial cloud cover and they are discarded to keep only estimates with highest quality and low uncertainty. The arithmetic means of the 75th percentile pixel values of all valid days within each calendar month during years 2017–2019 are then computed for each extraction area.

We are aiming at providing the ecosystem model ERGOM with an annual cycle of CDOM loads based on monthly data. Since optical EO methods cannot provide a_{CDOM} estimates in darkness and throughout times with ice coverage, the values for the winter months have been interpolated. As a result, the dataset contains a_{CDOM} value for each month for each of the areas under investigation (69 extraction areas in total). Figure 2 shows four examples of the annual CDOM absorption cycle. The behavior of the data follows well the annual cycle: spring values are high due to the terrestrial matter brought into the coastal water by melting snow, summer values are low due to lower influx and the fall values are higher due to increasing rainfall. The aggregated monthly values of a_{CDOM} based on EO data (S2 & C2RCC V1) for four ERGOM input locations in the western coast of Finland. Location of the rivers is shown in Fig. 1.

3 Radiation model development

In this section, we describe the basics of the model development and the implementation.

2.1 Fundamentals of the radiation model development

we briefly introduce the circulation and biogechemical model used for this study.

2.0.1 Fundamentals of the optical model

Starting point of the development is the radiation model proposed optical model as in the study by Neumann et al. (2015). The photosynthetical active radiation (PAR) follows an exponential decay with depth z:

$$PAR(z) = PAR(0) \cdot \exp(-K_{PAR} \cdot z), \tag{1}$$

K_{PAR} is the underwater bulk light attenuation and is described by 5 components:

$$K_{PAR} = k_w + k_c \cdot Chl + k_{det} \cdot DET + k_{don} \cdot DON + K_{CDOM}(S), \tag{2}$$

k_c, k_{det}, and k_{don} are material specific constants and Chl, DET, and DON are concentrations of chlorophyll, detritus, and dissolved organic nitrogen, respectively. These concentrations are state variables of the ecosystem model ERGOM or, in the case of chlorophyll, can be estimated from model phytoplankton (Sect. 2.0.1). k_w is the attenuation coefficient for pure water. In Neumann et al. (2015), K_{CDOM} $K_{CDOM}(S)$ is a statistical relationship between *in situ* salinity and CDOM attenuation absorption for the Baltic Sea derived from observations . (Eq. A. For the new approach, we use the additional state variable CDOM:

$$K_{CDOM} = k_{cdom} \cdot CDOM \tag{3}$$

The PAR attenuation now reads:

$$K_{PAR} = k_w + k_c \cdot Chl + k_{det} \cdot DET + k_{don} \cdot DON + k_{cdom} \cdot CDOM \tag{4}$$

Terrestrial CDOM behaves relatively refractory nearly conservatively in the ocean. An indication is the linear salinity–CDOM relationship in the northern Baltic (Harvey et al., 2015; Neumann et al., 2020). This is due to the fact of high freshwater supply with high CDOM concentrations. However, this relation does not apply to the central Baltic. In this region with longer residence time, the effects of CDOM degradation processes become more pronounced and observable (Skoog et al., 2011).

Two processes control CDOM degradation, photobleaching and biological degradation. Moran et al. (2000) study the degradation of terrestrial CDOM in the coastal ocean and find that photobleaching accounts for 80% of the degradation. Furthermore, they show that CDOM decay follows closely simple first-order kinetics. In accordance with these findings, we implement CDOM as

$$\frac{dCDOM}{dt}\frac{\mathrm{dCDOM}}{\mathrm{dt}} = -dr \cdot CDOM \tag{5}$$

with the degradation rate

$$dr = DR\mathrm{dr}_0 \cdot I\mathrm{PAR}(z). \tag{6}$$

$I(z)$ $PAR(z)$ is the ambient PAR at depth z, DR_0 dr_0 is a constant, and $I(z)$ $PAR(z)$ can be estimated as:

$$I\mathrm{PAR}(z) = \frac{I_0}{2}\mathrm{r}\cdot \mathrm{I}_0\cdot \exp(-K_{PAR} - \int\limits_z^0 dz\,\mathrm{dz}' K_{PAR}(z')) \tag{7}$$

I_0 is the solar radiation at sea surface depending on latitude, time, and sun zenith angle. We use 50% of total solar radiation for PAR (e.g., Stigebrandt and Wulff, 1987) since the invisible, long-wave part is absorbed at the water surface., which is a function of latitude and time. Factor r is the fraction of I_0 available as PAR (spectral range 400 to 700 nm). The integral consider the depth dependence of model concentrations of e.g. chlorophyll in Eq. 4.

2.1 Implementation in the biogechemical model ERGOM

2.0.1 Implementation of the optical model

A comprehensive overview about CDOM in the ocean is given in Nelson and Siegel (2002). CDOM content usually is given as the concentration is usually given by a proxy, the light absorption for a specific wavelength, e.g. $a_{CDOM}(440)$ for 440 nm. The spectral distribution can be parameterized by an exponentially decline with wavelength.

$$a_{CDOM}(\lambda) = a_{CDOM}(\lambda_0)\cdot \exp(-s(\lambda - \lambda_0)) \tag{8}$$

s is the exponential slope parameter and varies between 0.015 – 0.025 nm^{-1}. For a given slope s and an absorption $a_{CDOM}(\lambda_0)$, any $a_{CDOM}(\lambda)$ can be estimated for wavelengths longer than 320 nm. We use a reference wavelength of 440 nm.

In the biogeochemical modelThe biogeochemical framework for implementing the CDOM state variable is the model ERGOM. In this model, state variables are given as concentrations of an element, e.g. mol carbon per m^3, because these models primarily describe cycles of elements (carbon, phosphorus, nitrogen etc.). In order to model CDOM, a relationship between CDOM absorption and the concentration is required. Following the Lambert–Beer law, a linear relation exists. Neumann et al. (2020) derived a relationship based on optical measurements and measurements with a calibrated CDOM sensor, which we used to convert CDOM absorption into concentration and vice versa. We have to note that the accuracy of the conversion does not impact the performance of the radiation model . Both the CDOM freshwater loads optical model because both the satellite derived CDOM in freshwater and CDOM in the radiation optical model is given as $a_{CDOM}(440)$. CDOM loads are estimated from concentration times runoff which is available from Gustafsson et al. (2012).

Most model constants used in the model are provided by Neumann et al. (2015). An exception is DR_0 (We use 50% of total solar radiation for PAR (e.g., Stigebrandt and Wulff, 1987) since the invisible, long-wave part is absorbed at the water surface (factor r, Eq. 6)which . dr_0 (Eq. 6) has been estimated with a series of calibration simulations. Aim of the calibration has been was to find an optimal match of observed and simulated absorption values $a_{CDOM}(440)$.

Used constants are listed in Tab. 1. Model state variables in Eq. 4 have to be converted into appropriate units before entering the radiation optical model. We use a volume based concentration. $CDOM$ should be given as absorption because of uncertainties in the absorption–concentration relationship.

Table 1. Constants of the radiation optical model

Const.	Value	Unit
k_w	0.027	m^{-1}
k_c	0.029	$\mathrm{m}^2\,(\mathrm{mg\,Chl})^{-1}$
k_{det}	0.0039	$\mathrm{m}^2\,(\mathrm{mg\,N})^{-1}$
k_{don}	0.0009	$\mathrm{m}^2\,(\mathrm{mg\,N})^{-1}$
k_{cdom}	0.221	1
DR_0 dr_0	8.75e-5	day^{-1}
r	0.5	1

The technical implementation is done by an automatic code generation. Basis is Fundamentals are a set of text files describing the biogeochemistry independently of computer language and the host system. Code templates describe physical and numerical aspects, and are specific for a certain host e.g. a circulation model. All necessary ingredients, the code generation tool, text files, and templates for several systems, can be downloaded from www.ergom.net (last access: 22 September 2020). The same technique is used e.g. in Radtke et al. (2019).

2.1 Model description

2.0.1 Circulation and biogeochemical model

For model testing, we have used a similar setup model system as in Neumann et al. (2015). The circulation model is MOM5.1 (Griffies, 2004) adapted for the Baltic Sea. The horizontal resolution is three nautical miles. Vertically, the model is resolved into 152 layers with a layer thickness of 0.5 m at the surface and gradually increasing with depth up to 2 m. The circulation model is coupled with a sea ice model (Winton, 2000) accounting for ice formation and drift.

Coupled with the circulation model is the biogeochemical model ERGOM. It describes a marine nitrogen and phosphorus cycle. Primary production, forced by PAR, is provided by three functional phytoplankton groups (large cells, small cells, and cyanobacteria). Chlorophyll concentration can be estimated from the phytoplankton groups which is used in the radiation optical model. Dead particles accumulate in the detritus state variable which is another compartment in the radiation optical model. A bulk zooplankton grazes on phytoplankton and constitutes the uppermost trophic level in the model. The metabolism of phytoplankton and zooplankton produces DON which has only little impact on light absorption. Phytoplankton and detritus can sink down in the water column and accumulate in a sediment layer. In the water column and the sediment, detritus is mineralized into dissolved inorganic nitrogen and phosphorus. Mineralization is controlled by temperature and oxygen. Oxygen is produced by primary production and consumed due to all other processes e.g. metabolism and mineralization. Coupled to the nitrogen and phosphorus cycle is a carbon cycle as described in Kuznetsov and Neumann (2013). A schematic of the model structure is provided in Appendix B. The estimated short wave absorption (Sect. 2.0.1) feeds back into the physical part of the model and hence impacts the temperature distribution.

The new CDOM variable in the current model development state is not involved in the biogeochemical processes. This is justified by the fact that CDOM is relatively refractory and has a long residence time. , and autochthonous CDOM produced by e.g. phytoplankton, is a small fraction. In later developments, it will be included in the carbon cycle. For this purpose, it is essential to realize CDOM as a carbon based concentration. If this will be not the case, the CDOM state variable could be implemented as an absorption and thus conversions between absorption and concentration could be prevented.

The model has been forced by meteorological data from the coastDat-2 data set (Geyer and Rockel, 2013). We run the model from 1948—2019. A first run was used to spin up the new CDOM tracer. In a second run, CDOM was initialized with data from the first run. In addition to the 3 nautical miles resolution, we use a 1 nautical mile resolution for the period 2017–2019. The model has been successfully used in several applications (e.g., Neumann, 2010; Neumann et al., 2015).

2.1 CDOM boundary data from Earth Observation products

Aim of the development is to improve the simulated light climate by a more realistic representation of CDOM concentration compared to available statistical models (Sect. 1). However, *in situ* data of CDOM loads are not available in sufficient spatial and temporal resolution, i.e. in the Baltic Sea, CDOM is not a parameter of the HELCOM (www.helcom.fi, last access: 22 September 2020) monitoring program. New instruments and technologies in Earth Observation (EO), now in operation, are ideal tools to overcome these limitations.

2.1.1 Characteristics of satellite data

In order to estimate the load of CDOM coming from a river, it is necessary to derive it from observations within the river or as close to the discharge point as possible. The rivers in the Baltic Sea are usually small and thus high resolution (HR) instruments such as Sentinel-2 Multi Spectral Instrument (S2-MSI) are required. The MSI has a spatial resolution of 10-60 m depending on the central wavelength of the band. Water quality products are usually generated in 60 m resolution in order to reduce noise. This is sufficient for estimating the CDOM absorption of most rivers.

Two Sentinel-2 satellites are currently in orbit: S2A was launched on 23 June 2015 and S2B on 7 March 2017. Together they provide a global revisit time of 5 days next to equator. Due to the high latitude of the Baltic Sea, the revisit time amounts to 2–3 days in this area. Despite the frequent cloud cover, sufficient observations can be gathered to monitor river CDOM throughout the open water season (typically from March-April to October in the northern Baltic Sea).

2.1.2 Earth Observation processor for CDOM absorption estimation

Earth Observation (EO) processors are a set of algorithms designed to convert the radiance signal acquired by the satellites into values of geophysical parameters. The estimation is based on the scattering and absorption features of the

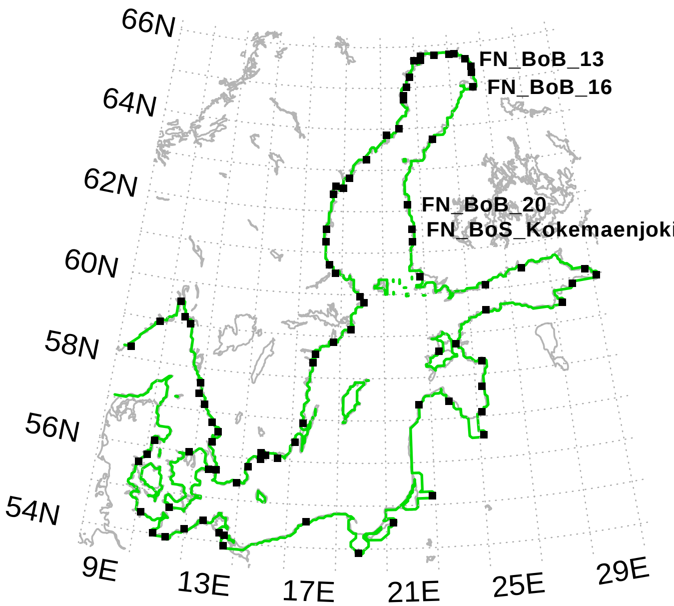


Figure 1. Location of model rivers (black squares). The green line is the coastline of the 3 nm model. We refer to the labeled river later in the text. The map was created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/), using published bathymetry data (Seifert et al., 2008)

material suspended or dissolved in water. In addition to CDOM, these materials include phytoplankton cells, represented by Chlorophyll a (Chl-a), and suspended particulate matter.

One commonly used water quality processor is Case 2 Regional Coast Color (C2RCC) (Brockmann et al., 2016). It utilizes one artificial neural network (ANN) first to remove the effects of the atmosphere from the signal (atmospheric correction) and then another to estimate inherent optical properties (IOPs) of water from the marine reflectance.

For estimation of CDOM absorption (a_{CDOM}), we utilized the C2RCC (version 1) output called a_{dg} (combined absorption by detritus and yellow substances) which was calibrated to $a_{CDOM}(440)$ values (absorption coefficient by CDOM at 440 nm) using this equation:

$$\mathrm{a_{CDOM}}(440) = 0.654 \cdot \mathrm{a_{dg}^{1.45}} + 0.2 \qquad (9)$$

The equation is based on in situ sampling made with a flow-through device (ac-9) (Lindfors et al., 2005; Koponen et al., 2007) during two coastal estuary measurement campaigns. These data are not yet published but a similar local calibration method has provided good results with other water quality parameters in earlier studies such as Attila et al. (2013).

The data processing and extraction are done in a Calvalus massive parallel processing system (http://www.brockmann-consult.de/calvalus, last access: 22 September 2020). Data extraction areas are manually defined in the vicinity of the mouths of 69 rivers that represent ERGOM input locations (Fig. 1). The areas are designed so that islands, mixed pixels and shallow areas are excluded. All valid pixels (not masked as land or cloud by the pixel classification processor

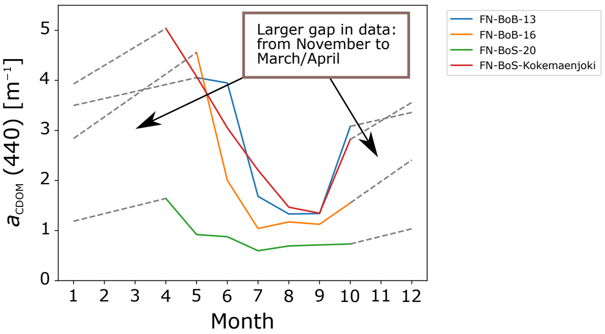


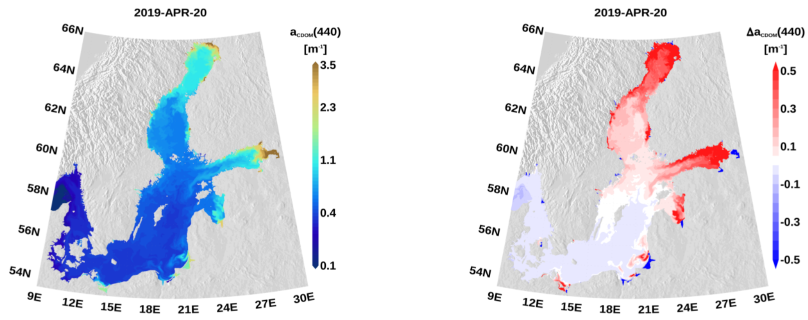
Figure 2. The aggregated monthly values of a_{CDOM} based on EO data (S2 & C2RCC V1) for four ERGOM input locations in the western coast of Finland. Location of the rivers is shown in Fig. 1.

Idepix) within each area and image are collected and analyzed, and the 75th percentile value is chosen to represent the river a_{CDOM}. The cases in which the number of valid pixels is less than 50% of all available pixels from an area are removed from the analysis. Assumedly, these represent cases with partial cloud cover and they are discarded to keep only estimates with highest quality and low uncertainty. The arithmetic means of the 75th percentile pixel values of all valid days within each calendar month during years 2017–2019 are then computed for each extraction area.

We are aiming at providing the ecosystem model ERGOM with an annual cycle of CDOM loads based on monthly data. Since optical EO methods cannot provide a_{CDOM} estimates in darkness and throughout times with ice coverage, the values for the winter months have been interpolated. As a result, the dataset contains a_{CDOM} value for each month for each of the areas under investigation (69 extraction areas in total). Figure 2 shows four examples of the annual CDOM absorption cycle. The behavior of the data follows well the annual cycle: spring values are high due to the terrestrial matter brought into the coastal water by melting snow, summer values are low due to lower influx and the fall values are higher due to increasing rainfall.

3 Results and discussion

In this section, we show the improved model CDOM representation and its impact on the simulation results. Owing to the changed shortwave distribution in the water column, an effect especially on the biogeochemistry is expected. All CDOM data presented are converted into absorption at 440 nm ($a_{CDOM}(440)$). Especially for observations at different wavelengths, we use Eq. 8 with a slope s of 0.018 nm^{-1} (Kratzer and Moore, 2018). For comparison, we show $a_{CDOM}(440)$ values estimated from the CDOM state variable and from model salinity. The models differ only in the estimation of PAR which becomes evident when we show the impact on biogeochemistry.



(a) (b)

Figure 3. Snapshot of simulated surface $a_{CDOM}(440)$ at April 20th 2019 (a) and the difference to the salinity based absorption estimate (b as seen in the 1nm resolution model.

3.1 CDOM absorption

In Fig. 3a, we show the simulated CDOM absorption at the sea surface. The snapshot clearly illustrates the spatial patterns. Strong absorption is visible in the northern Baltic and the river mouths. The difference to the salinity based estimate (Eq. 2) is depicted in the right panel. Strongest differences appear in the Gulf of Bothnia and the Gulf of Finland while in the central Baltic differences are small. Strong differences are also pronounced in river estuaries. Owing to the low salinity, the salt-CDOM relationship overestimates CDOM content in these areas. Furthermore, the new, EO based method considers individual CDOM concentrations of different rivers. Rivers of the northern catchment area carry higher CDOM loads compared to rivers of the south-eastern catchment area due to a high fraction of peat land. The range of a_{CDOM} values is demonstrated in Fig. 4.

Both datasets were compared against *in situ* data collected from monitoring stations in coastal waters of Finland and from the Northern coast of Sweden. As shown in Fig. 5, the improvement becomes obvious. With the salinity method, the correlation is low ($\mathrm{R}^2 = 0.15$) and there are some clear overestimates (difference between $a_{CDOM}(440)$ from salinity and the one-to-one line more than 2 m^{-1}) while most data points are underestimated. With the EO CDOM method, the correlation improves significantly ($\mathrm{R}^2 = 0.61$). There are no large overestimates and the data points move closer to the one-to-one line. Large *in situ* values ($a_{CDOM}(440) > 3\ \mathrm{m}^{-1}$) are still underestimated with the new EO method. This underestimation is most likely caused by the following two major inaccuracies in the present version of the model input:

- The coast has many small rivers. Not all of them are yet included in this version.

- In river estuaries with low bottom depth or complex morphological structure, the shapes and formulations of the extraction areas do not sufficiently capture the incoming CDOM loading from the river. In order to avoid EO observations contaminated by bottom reflectance it was necessary to use pixels that are sufficiently far from the shoreline. Therefore, pixels of the extraction area may not represent river water as it has been already mixed with sea water. In some cases, this leads to lower concentrations especially during the low runoff season.

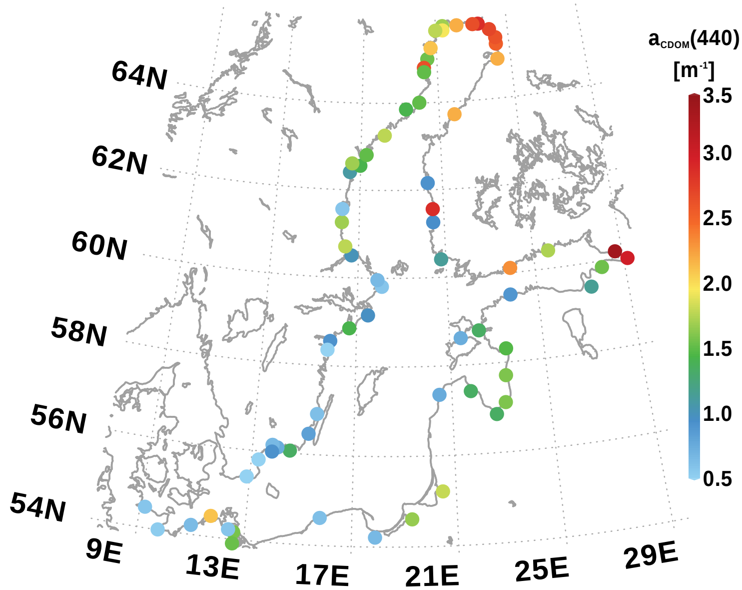


Figure 4. Mean a_{CDOM} of the individual rivers used in the model. The map was created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/), using published bathymetry data (Seifert et al., 2008).

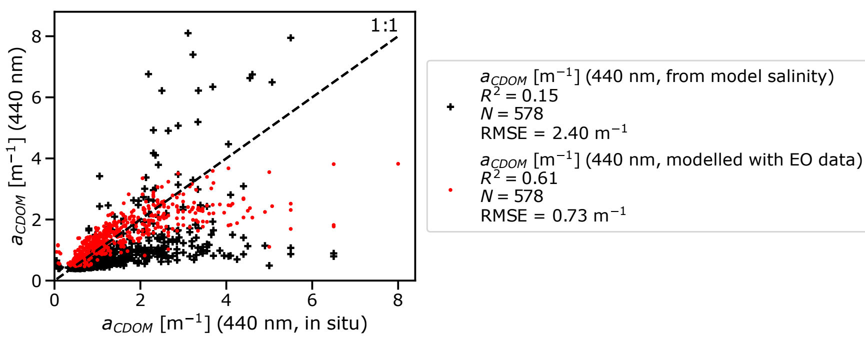


Figure 5. In situ *In situ* a_{CDOM} (x-axis) vs. ERGOM a_{CDOM} (y-axis) estimated from salinity (in black) and ERGOM a_{CDOM} with the EO method (in red)and the location of stations (triangles in (b)).

Surface a_{CDOM}(440) time series at 6 stations. Location of the stations is shown in (d). Absorption estimates based on simulated CDOM are shown in black, based on a conversion from simulated salinity in green, and red diamonds are observations. The map was created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/), using published bathymetry data (Seifert et al., 2008).Figure 6 demonstrates the different CDOM absorption estimates. Shown are time series of surface CDOM absorption at 6 stations (Fig. 6d). The green curve is the salinity based estimate and the black curve the estimate from model CDOM concentration. Red diamonds are *in situ* observations.

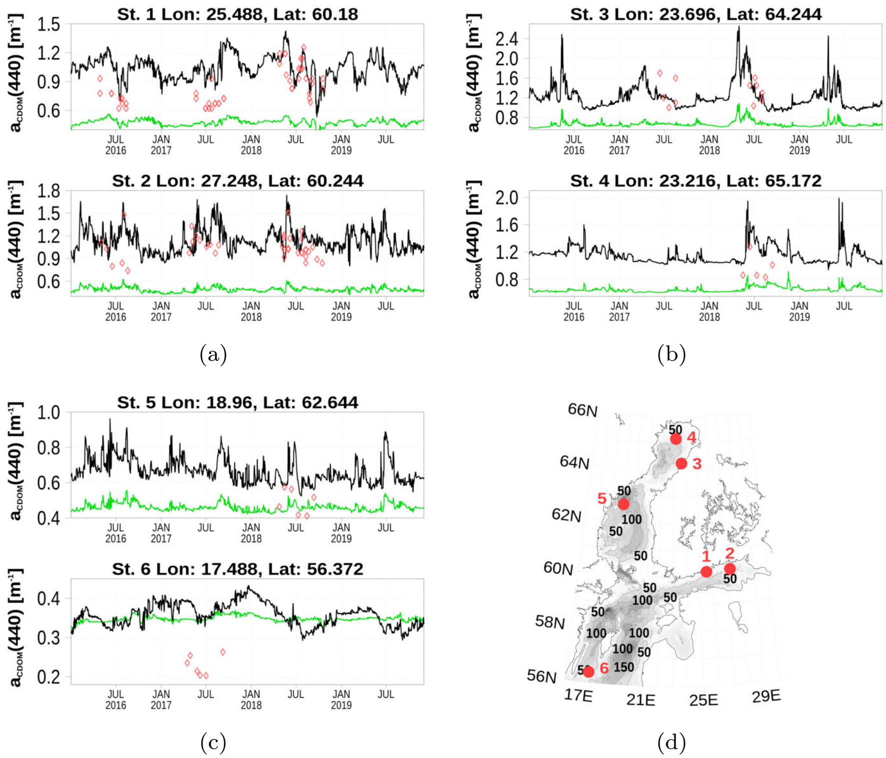


Figure 6. Surface $a_{CDOM}(440)$ time series at 6 stations. Location of the stations is shown in (d). Absorption estimates based on simulated CDOM are shown in black, based on a conversion from simulated salinity in green, and red diamonds are observations. The map was created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/), using published bathymetry data (Seifert et al., 2008).

At stations 1–4, absorption values from simulated CDOM are much closer to observations compared with salt based estimates. The absorption difference at stations 5 and 6 is less pronounced which is also evident from Fig. 3. The seasonal variability is stronger for absorption derived from the model CDOM variable (compared to salt based absorption) and reflects the observed variability. The reason is the annual cycle of riverine CDOM concentration in addition to the runoff cycle. In the central Baltic Sea, both methods overestimate CDOM absorption.

3.2 Impact on biogeochemistry

As an example of the changed light absorption impact on the biogeochemistry, we show annual mean profiles of selected variables in Fig. 7. We have chosen station 4 from Fig. 3 since at this station the CDOM absorption is considerably increased due to the new, EO based, radiation optical model and it is located in the center of the Bothnian Bay. Owing to the increased CDOM absorption, PAR is reduced in the EO model approach (Fig. 7a) as expected. Consequently, primary production (PP) is reduced (Fig. 7b). However, in the uppermost layer, PP is increased. As a result of reduced PP, phytoplankton concentration

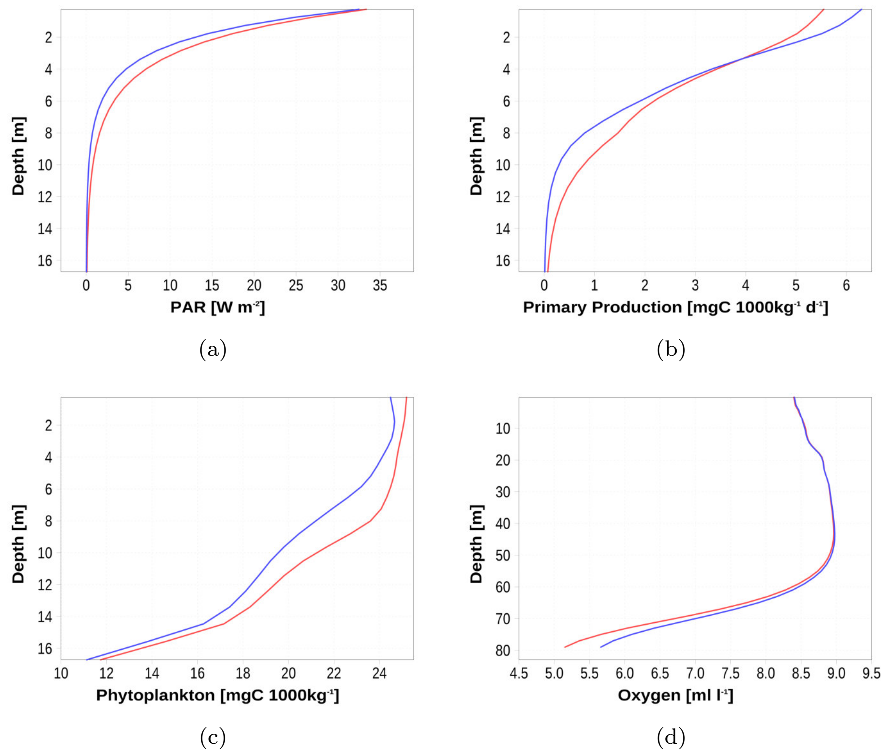


Figure 7. 2018 annual mean profiles at station 4 (Fig. 6d). Blue curve shows data from the model with an explicit CDOM state variable and the red curve is from the model with CDOM absorption estimates based on saltits relation to salinity. For oxygen (d), we show the whole water column.

shows lower values (Fig. 7c). An integrated response is the increased bottom oxygen concentration (Fig. 7d). Less net PP results in less accumulation of organic matter in the deep water of the basin and subsequently reduced oxygen consumption. The impact on water temperature is small (order of 0.01 K, not shown). The effect is a temperature increase in the surface layer and a lower temperature below.

We demonstrate changes in the biogeochemistry with a climatology of surface nutrient concentrations at three stations in Fig. 8. For this analysis, we use data from the 3 nautical miles model version because of the longer simulation period. Shown are data from the EO model (black) and the previous (salinity based) model (green) together with observations (red). In the Gulf of Finland at station KAS-11, the spring bloom related nutrient depletion is delayed by 2 weeks (Fig. 8a and b). Sufficient PAR intensity, initiating a bloom, is available later in the season. The winter nutrient concentrations are elevated compared to the salinity model version. At the Bothnian Bay station (Fig. 8c and d), the spring bloom delay is less pronounced. In this area, the longer sea ice coverage dominates the PAR in spring. At station BY15 in the Baltic Proper (Fig. 8e and f), the difference between both model versions is small due to similar CDOM absorption (Fig. 6).

4 Summary and conclusions

In this study, we propose an approach for considering light absorption due to terrestrial CDOM in a marine ecosystem model for the Baltic Sea. An explicit consideration is necessary if large amounts of terrestrial CDOM enter the marine system and strong coastal-sea gradients develop. In such cases, a uniform light absorption due to CDOM cannot account for the *in situ* light climate in a sufficient way. A common An often applied approach uses CDOM-salinity relationships for CDOM absorption estimates (Kowalczuk et al., 2006, 2010; Neumann et al., 2015) but with distinct disadvantages (see Sect. 1).

Our approach uses an explicit CDOM state variable as part of the biogeochemical model. In order to improve the simulated absorption compared to the salt approximation, a high quality data set of riverine CDOM loads is necessary. This has been accomplished by using earth observation data from Sentinel 2 Sentinel-2 MSI. The high spatial resolution (10 m–60 m) allows to observe the river mouths directly. A difficulty in the regions of higher latitude like the Baltic Sea area is the insolation, the occurrence of sea ice, and the frequent cloud cover in winter. Continuous observations are not possible during this time. We have used a linear interpolation to bridge the winter data gap. This could be validated by ground truth measurements in winter possibly guiding for another than linear interpolation.

The results (Sect. 3) show that the proposed approach clearly improves the ability of the model to estimate CDOM and thus light absorption especially in the northern parts of the Baltic Sea where the impacts of terrestrial CDOM are large. This underlines the performance of the combined approach to increase the predictive capability of ecosystem models. The method can be further improved by adding more rivers to the model and improving the quality of CDOM data from Sentinel 2 MSI.

For the model CDOM, we have applied a light sensitive degradation. Although this is the dominating degradation process for terrestrial CDOM (Moran et al., 2000), bacterial breakdown contributes to the degradation as well. Technically, such a process can easily be implemented. However, to our knowledge comprehensive process studies in the Baltic Sea are not done yet. Therefore, we have decided that bacterial breakdown is subject to later developments.

We consider only terrestrial CDOM in our model. In regions with high runoff, like the Baltic Sea, terrestrial CDOM is the dominating fraction (Harvey et al., 2015; Stedmon and Markager, 2003). However, a further step toward a more sophisticated model could be the inclusion of autochthonous CDOM . as e.g. in Dutkiewicz et al. (2015).

Code and data availability. *In situ* absorption observations are available from http://eo.ymparisto.fi/data/water/Baltic_SeaLaBio/. Monthly CDOM absortion data are available from http://eo.ymparisto.fi/data/water/Baltic_SeaLaBio/CDOM_input_to_ERGOM/. Model data can be accessed via https://thredds-iow.io-warnemuende.de/thredds/catalogs/projects/SeaLaBio/catalog_sealabio.html.

The code of the biogeochemical model is available at www.ergom.net (last access: 22 September 2020). The ocean model "Modular Ocean Model MOM 5-1", used in this study, is available from the developers respository https://github.com/mom-ocean/MOM5 (last access: 1 December 2020). The meteorological forcing is archived at https://cera-www.dkrz.de/WDCC/ui/cerasearch/entry?acronym=coastDat-2_COSMO-CLM (last access: 1 Decenber 2020). The version of the model code used to produce the results in this study is archived on Zenodo at https://doi.org/10.5281/zenodo.4299873 (last access: 1 December 2020). In addition to the source code, the archive includes initial fields and boundary conditions exept the meteorological forcing.

Nitrate and phosphate date used for model comparision are available from the ICES database https://ocean.ices.dk/Helcom/Helcom.aspx?Mode=1 (last access: 30 Aril 2021).

Sample availability. Simulated CDOM data: https://wwwi4.ymparisto.fi/i4/eng/tarkka_beta/index.html?type=ERGOM_CDOM&date=2019-12-01&lang=en&zoom=5&lat=61.46508&lon=32.98851

Appendix A: Impact of photobleaching

Photobleaching accounts for slow decomposition of CDOM. Although, the CDOM decomposition is slow compared to decomposition of e.g. *in situ* detritus, in water bodies with longer residence time it becomes important. For example, in the salt – CDOM absorption relationship, decomposition is considered by a hyperbolic function (Neumann et al., 2015, eq. 10):

$$a_{CDOM} = 1.26\,S^{-0.627}\ [m^{-1}] \qquad (A1)$$

We demonstrate the effect of the implemented photobleaching on the model CDOM concentration by comparing a simulation without photobleaching with the control run. The 3 nautical miles setup was used for this study. The photobleaching was switched of in 1980 and then the simulation was continued until 2019. Figure A1 shows the differences developing due to lacking a degradation process. Absorption values are far away from observations and even after 40 simulation years, a new steady state is not achieved (Fig. A1a). Spatial patterns after 39 simulation years show that largest differences occur in the central basins. Differences are smaller in freshwater dominated regions (Fig. A1b) like river estuaries. Small differences are also in the vicinity of the open boundary toward the North Sea.

Appendix B: Simplified schematic of the biogeochemical model ERGOM

In Fig. B1, we show the structure of the biogeochemical model ERGOM. Ellipses are state variables and rectangles are processes describing the transfer from one to another state variable. The meaning of the state variable symbols are given in Table B1.

Author contributions. TN developed the ecosystem model components. SK led the project. SV performed the processing of EO data. PY performed CDOM absorption measurements in the central Baltic Sea. All authors designed the project, and contributed to data analysis and writing the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Table B1. State variables of the biogeochemical model ERGOM

Symbol	State Variable
O_2	dissolved oxygen
N_2	dissolved nitrogen
CDOM	colored dissolved organic matter
DIC	dissolved inorganic carbon
TA	total alkalinity
NH_4	ammonium
NO_3	nitrate
PO_4	phosphate
SO_4	sulfate
S	sulfur
H_2S	hydrogen sulfide
large cells	large cell phytoplankton
small cells	small cell phytoplankton
cyanobacteria	cyanobacteria
$\mathrm{zooplankton}$	bulk zooplankton
$\mathrm{detritus}$	detritus
DOC	dissolved organic carbon
$\mathrm{DOC-N}$	DOC with additional nitrogen
$\mathrm{DOC-P}$	DOC with additional phosphorus
POC	particulate organic carbon
$\mathrm{POC-N}$	POC with additional nitrogen
$\mathrm{POC-P}$	PC with additional phosphorus
sediment detritus	detritus accumulated in the sediment layer
$\mathrm{Fe(III)-PO_4}$	iron-3-phosphate

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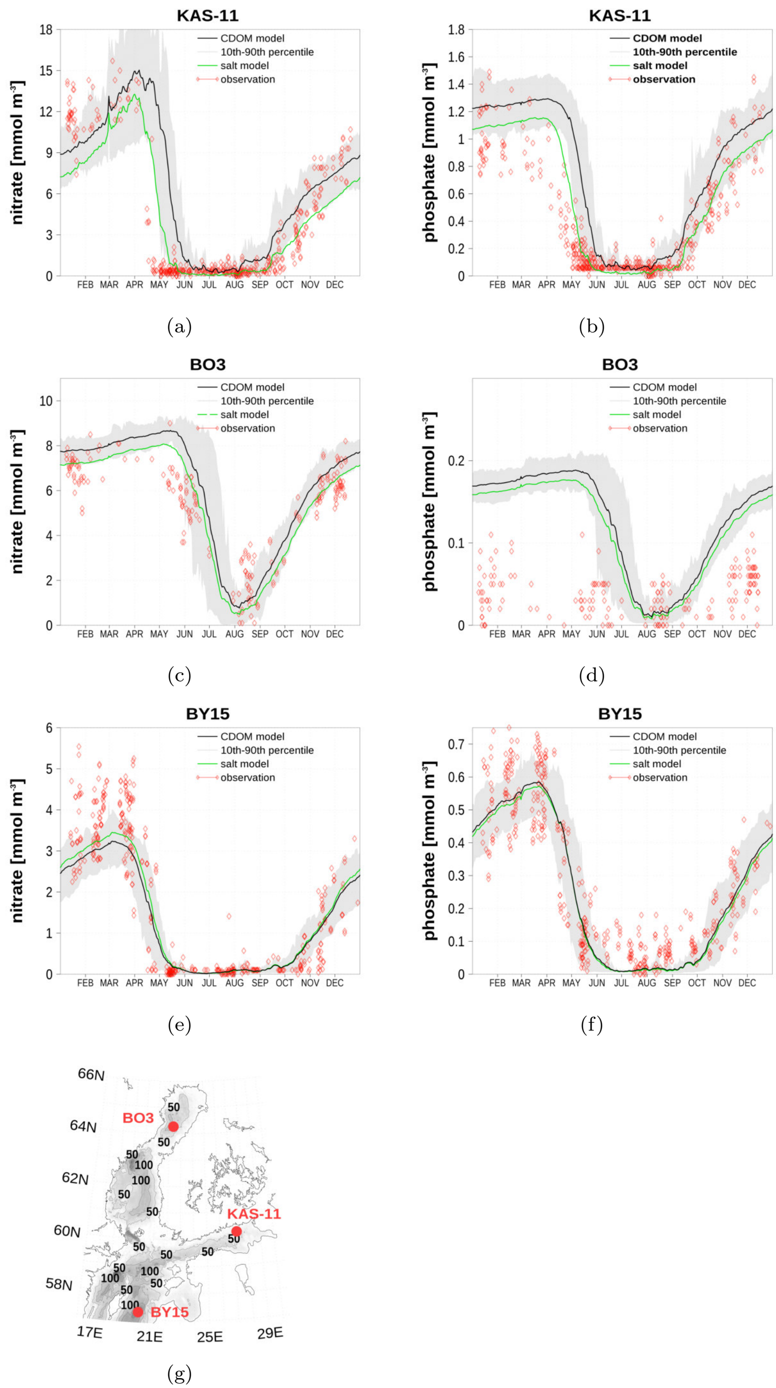

Figure 8. Climatology (1990–2019) of surface nitrate and surface phosphate at 3 stations. Black lines show the new CDOM based model, green line the salt based model, and red diamonds are observation (http://www.ices.dk, last access: 19 June 2020). The shaded area is the range between 10th and 90th percentile of the black line. Simulated data are from the 3 n.m. model version. The map was created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/), using published bathymetry data (Seifert et al., 2008).

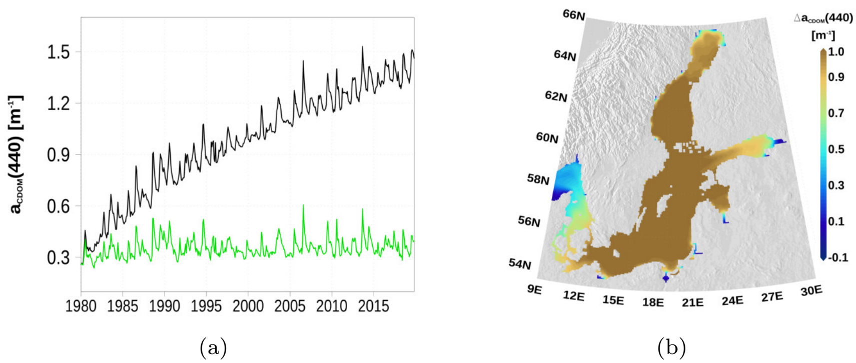

Figure A1. The effect of photobleaching on CDOM absorption. The black line in (a) is from the model without photobleaching at station BY15 (Fig. 8). In (b) the difference in 2018 of the surface CDOM absorption is shown (without photobleaching minus control run). Simulated CDOM concentration have been converted into absorption. The map was created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/), using published bathymetry data (Seifert et al., 2008).

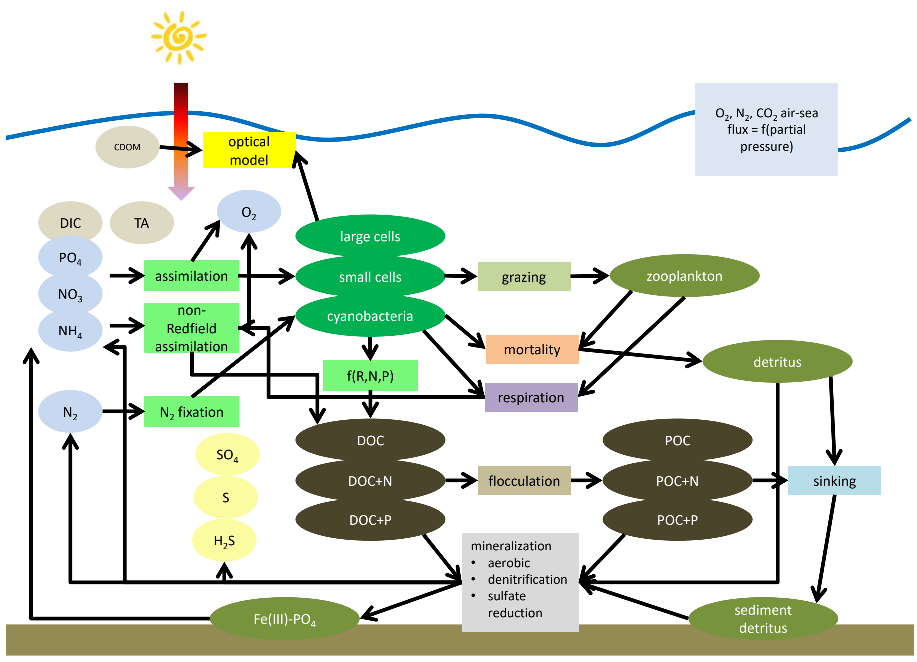

Figure B1. Simplified schematic of the biogeochemical model ERGOM. State variables are shown as ellipses and processes as rectangles.