Dear Veronique Garçon,

together with this letter, you receive the revised version of our manuscript submitted to Biogeosciences (ID: bg-2013-326).
Before going through the comments provided by the two anonymous referees, I would like to thank on behalf of all authors these referees and you for the constructive criticism and the helpful comments which really helped improving the manuscript.

In the following I will go through the different aspects raised by the referees, and provide a reply to each of these comments. As some of the more general comments were stated by both referees, I will first go through these comments, and subsequently will go through the individual aspects of their feedback.

After the points raised by the referees, I will list the additional changes we applied to the manuscript.

Our replies to all comments are be written in italic.

A. Comments stated by both referees

- comment #1: The manuscript is too long and needs to be shortened, e.g., by moving parts of the manuscript to an appendix.
- ***reply:*** *As already discussed in our first replies to the referees' comments, we aimed for a clear reduction of the length of the manuscript. Regarding the main text of the manuscript (excluding "Data availability" section, Appendix and Acknowledgements, Figures and Table) we received a shortening from originally 46,5 pages to 41 pages (PDF format of the BG Discussions forum). However, it has to be noted that this even includes the addition of two new sections (2.4.2 in the Methods, and 3.3.2 in the Results and discussion) including the grid cell based analysis, adding up to 4 pages. Thus, considering only the content of the original manuscript we achieved a shortening by 10 pages.*
This was also achieved by moving the section with the evaluation of the MLD criterion (3.1 in the original manuscript) to the appendix. We decided to do so as this evaluation is not important for the storyline of the manuscript, nevertheless, it is important to provide as the applied criterion differs substantially from common MLD criteria.
We furthermore shortened as many parts of the manuscript as possible, e.g., the mass balance analyses (Sect. 3.5 to 3.8 in the original manuscript, now 3.4 to 3.7) were reduced by about 1/3 in terms of lines of text. Further shortening was achieved by reducing the data and model description in the Methods section (Sect. 2.1 and 2.3), and by removing the equations for the statistics given in the Taylor diagram (Sect. 3.1.3) as those are presented in Taylor (2011) which we refer to. In the original Sect. 3.4 (now 3.3.1) we also achieved some reduction by removing the comparison of the annual values to the summer values, as it did not add much to the discussion. The corresponding values were also removed from Table 1.

- comment #2: The manuscript needs a clear research question, e.g., analysis of anthropogenic influence on North Sea O2 dynamics or actual O2 levels vs. natural background levels.
- ***reply:*** *We worked on this issue by rephrasing the second last paragraph of the Introduction (page 6), now clearly stating the questions we aim to answer with this study. This is to describe the North Sea O2 dynamics under stratified conditions in its current state and to demonstrate the capability of ecosystem models to represent and interpret the temporal evolution and spatial distribution of the North Sea O2 conditions. The latter provides the basis for further analyses with respect to, e.g., climate change etc.*
With respect to the suggested investigation of the anthropogenic influence or the comparison to

natural background levels, we have to say that this would go beyond the scope of this study. This would require the analysis of additional scenarios ("pristine conditions") and would lead to an interesting, but different story. In the Conclusions and perspectives we now refer to this aspect as an example for potential future research based on the present study (page 40, centre paragraph).

B. Further comments by referee #1

- comment #1: Move parts of the extended (i.e., qualitative) validation to an appendix.
- reply: *We intensively talked about this aspect in our internal discussions. On the one hand, we agree that the validation represents quite a big part of the manuscript, on the other hand, a sound validation is the basis for all further analyses. In addition, the qualitative validation provides the reader with an overview of the North Sea O2 conditions on different temporal (seasonal and inter-annual) and spatial scales. Leaving only the Taylor diagram in the main manuscript would still provide the information about the model skill, but would miss these important qualitative information.*
For this reason, we did not consider to move the entire qualitative validation to an appendix. Moving only parts, e.g., individual sub-figures, to an appendix, while still discussing the aspects shown by these sub-figures in the main text, would also not be very useful, as it does not reduce the length of text. As we consider the different aspects presented in the qualitative validation as crucial for the description of the North Sea O2 conditions, we finally kept the corresponding figures as is, but aimed to shorten the descriptions given in the text as much as possible.

- comment #2: Clearly separate Results from Discussion section.
- reply: *As argued in our first reply, and as agreed on by the editor, we did not separate these two sections completely. Instead, we aimed to separate Results and Discussion within each section (and subsection) more distinctly. That means, that now every section first provides an objective description of the corresponding results, and second the interpretation of these results. Where applicable, we included a discussion in relation to existing literature thereafter. We hope this sufficiently improved the readability.*

- comment#3: Clearly separate Methods from Results/Discussion section.
- reply: *This separation was done and we hope it helps the readability as well. The equations previously listed in Sect. 3.2.3 (now 3.1.3.) were removed from the manuscript as say are described in Taylor (2011). The definition of the different regions of analysis and the algorithm for the determination of the reference depth used for the analysis of the 4x4 regions was moved to the Methods section (new Sect. 2.4.1 for 4x4 regions, Sect. 2.5 for the 2x2 regions, i.e. mass balance analyses).*

- comment #4: How representative are the 4x4 regions for their surrounding areas.
- reply: *To evaluate this aspect, we included the grid cell based approach of the oxygen deficiency index (ODI) presented in Sect. 3.3.2. At the end of this section we make a statement regarding the representativeness of the selected regions, which we consider as given due to the similarity of the ODI within these regions. With respect to the inclusion of the ODI into the manuscript, the referee may argue that we included the mathematical description of the ODI in this Results/Discussion section. In fact, we were thinking of moving the equations to the corresponding new Methods section (2.4.2). The problem with this is, that the set of parameters, by which the ODI is described, and the equations actually are a result of the analysis based on Table 1 and the matching of simulated bottom O2. Moving the ODI equations to the Methods section would anticipate too much information. For this reason we decided to include these equations in the Results/Discussion section.*

C. Further comments by referee #2

- comment #1: Clarify the context of the manuscript: hypoxia vs. O2 deficiency.
- *reply:* *First, we replaced all occasions of "hypoxia", "hypoxic" etc. by "O2 deficiency" or "low O2 conditions". Second, we include the OSPAR threshold of 6 mg O2 L-1 in the very first line of the introduction to define the terms "O2 deficiency" and "low O2 conditions" as used in this study. In a later part of the introduction, we refer back to the difference between hypoxia and O2 deficiency (page 4, last paragraph).*
The change from "hypoxia" etc. to "O2 deficiency" also resulted in a change of the title, in which we replaced "depletion" by "deficiency" as observed and simulated O2 levels are far above depletion.

- comment #2: Include a conceptual map of the three different zones of O2 dynamics.
- *reply:* *We did not exactly include such conceptual map, but included the sections about the ODI approach, as described in comment #4 of block B. In the discussion of the ODI results, we refer to the different causes resulting in high/low risk of O2 deficiency indicated by the ODI.*

- comment #3: Shorten the methods section.
- *reply:* *As described in our reply to comment #1 in block A, we shortened the description of the model and the validation data used. However, the Methods section became longer in order to separate the Methods from the Results/Discussion. Considering only the original content of the Methods section, we achieved a reduction from 8 to 6 pages.*

- comment #4: The information that spatially resolved O2 measurements in late summer provide a synoptic picture of North Sea O2 conditions is an important aspect for monitoring authorities.
- *reply:* *We also consider this as valuable information for monitoring authorities, therefore, we included this in the Conclusions section (page 39, centre paragraph).*

- comment #5: Include average water column depth, maximum MLD and O2 concentrations at end of stratification in Table 1.
- *reply:* *With respect to this, our first reply was actually wrong, as the maximum MLD is not identical for all regions. We looked at the median MLD of the single regions and and among these, the maximum value was 25m. Nevertheless, we consider it more helpful to include the average MLD which, in combination with the average water depth, allows the reader to define an average water column. Thus, we included average MLD, average duration of stratification, average water depth and final O2 concentrations in Table 1. The initial O2 saturation concentration was removed as it did not add much to the discussion.*

D. Technical corrections by referee #2

- correction #1: Abstract, line 12: Is bottom layer not always below thermocline?
- *reply:* *We rephrased this sentence, now reading as: "[...] driving the oxygen dynamics inside the entire sub-thermocline volume and directly above the bottom." (Abstract, second paragraph)*

- correction #2: *Page 12546, line 7: indicates that respiration only occurs below the thermocline, which is obviously not the case*
- *reply:* *We rephrased this part of the text, now reading as: "[…] which limits the vertical exchange of O2 between the oxygenated surface layer and the deeper layers. In combination with events of enhanced primary production, and the subsequent degradation of organic matter, this favours the evolution of O2 deficiency […]". (page 3, first paragraph)*

- correction #3: Page 12547, lines 6-18: Reference to oxygen depletion and low oxygen concentration but no information on the corresponding concentration that was observed? Please provide information on concentration if available.
*- **reply:** We removed one reference (Queste et al., 2013) as no exact concentration was available from their publication, and added the value found in the other publications (< 3 mg O2 L-1; see page 4, centre paragraph).*

- correction #4: Page 12547, line 22: In relation to figure 1 and use of the <6 mg O2 L-1 is much higher than the normal hypoxia threshold. Even if we acknowledge that biological impacts may occur at levels above the lower hypoxia threshold levels closer to the 6 mg O2 L-1 threshold are likely to have minimal impacts on organisms that are resident in stratified environments.
*- **reply:** As already mentioned in the reply to comment #1, block B, we replaced the term "hypoxia" by "O2 deficiency" throughout the entire manuscript.*

- correction #5: 12556, line 11: Why use the phrase so-called?
*- **reply:** We removed "so-called".*

- correction #6: Page 12563, line 1: State the values rather than say less than?
*- **reply:** We included the actual value of 6.96 mg O2 L-1 (page 18, second paragraph of Sect. 3.1.2)***.**

- correction #7: Page 12569, line 7: Yellow boxes?
*- **reply:** Here, "red boxes" is correct and we replaced it correspondingly.*

- correction #8: Page 12572, line 16: Give the rate value.
*- **reply:** We included the reduction rates for the two areas, now reading as: "[…] yielding 0.71 and 0.63 kt O2 d−1 for region B and C, respectively." (page 24, first paragraph)*

E. List of (additional) relevant changes

1. Title was changed to: "Looking beyond stratification: a model-based analysis of the biological drivers of oxygen **deficiency** in the North Sea." This relates to the replacement of the terms "hypoxia/hypoxic" and "O2 depletion" throughout the entire manuscript.

2. Methods previously included in some of the Results/Discussion sections are now included in the new Methods sections 2.4 (including 2.4.1) and 2.5.

3. Original Results/Discussion section 3.1 was moved to Appendix A (including Fig. 3, now Fig. A1). This results in a change in the section and figure numbering in the subsequent sections.

4. Original Results/Discussion section 3.4 (now 3.3) was subdivided into two subsections (3.3.1 and 3.3.2). This relates to the addition of the grid cell based analysis (oxygen deficiency index (ODI)) presented in Sect. 3.3.2. The former Sect. 3.4 can now be found in Sect. 3.3.1.

5. Values for the entire year were removed from Table 1 (see also last paragraph of comment 1, block A).

6. Fig. 6c and d (previously Fig. 7c and d) were replaced by two figures with a higher resolution colour scale, which allows to see a few more details in the minimum bottom O2 concentrations.

7. The figures for the mass balances were changed (Figs. 8, 9, and 10; previously Figs. 9, 10 and 11)). They now show vertically integrated fluxes (i.e., g O2 m-2) and O2 concentrations (mg O2

L-1). This was done as we realised that for the better understanding of the processes, the change in the O2 inventory is more helpful, rather than changes in concentration. In addition, we now used a daily varying MLD, i.e., integration layer, for Fig. 8a and b, as this emphasises the efficient separation of the oxygenated surface layer from the layers below the thermocline, due to thermal stratification.

8. We added “O2” to the units of all O2 related values (i.e., concentrations, fluxes and rates of change).

F. Comment on the marked up PDF with the changes between the originally submitted manuscript and the revised version

The marked PDF which is attached to this letter of response was created with latexdiff. Due to some difficulties of latexdiff in combination with tables, the former Table 1 was manually replaced by the revised Table 1. Thus, changes in Table 1 itself are not marked in the attached document. For a description of these changes the referee/editor is referred to comment 5, block C, and comment 5, block E.

With this we would like to conclude and thank you again for your support.

Kind regards
Fabian Große

on behalf of all authors

<u>Attachments:</u>
marked up PDF file indicating all changes between the originally submitted manuscript and the revised version

Manuscript prepared for Biogeosciences Discuss.
with version 2014/07/29 7.12 Copernicus papers of the LaTeX class copernicus.cls.
Date: 30 January 2016

Looking beyond stratification: a model-based analysis of the biological drivers of oxygen ~~depletion~~ deficiency in the North Sea

F. Große[1], N. Greenwood[2,3], M. Kreus[4,5], H. J. Lenhart[1], D. Machoczek[6], J. Pätsch[5], L. A. Salt[7], and H. Thomas[8]

[1]University of Hamburg, Department of Informatics, Scientific Computing, Bundesstraße 45a, 20146 Hamburg, Germany
[2]Centre for Environment, Fisheries and Aquaculture Science (Cefas), Lowestoft, Suffolk, NR33 0HT, UK
[3]University of East Anglia, School of Environmental Sciences, Norwich, NR4 7TJ, UK
[4]University of Hamburg, Institute for Hydrobiology and Fisheries Science, Olbersweg 24, 22767 Hamburg, Germany
[5]University of Hamburg, CEN, Institute of Oceanography, Bundesstraße 53, 20146 Hamburg, Germany
[6]Federal Maritime and Hydrographic Agency, Bernhard-Nocht-Straße 78, 20359 Hamburg, Germany
[7]CNRS, UMR 7144, Equipe Chimie Marine, Station Biologique de Roscoff, Place Georges Teissier, 29680, Roscoff, France
[8]Dalhousie University, Department of Oceanography, 1355 Oxford Street, Halifax, Canada

Correspondence to: F. Große (fabian.grosse@uni-hamburg.de)

Abstract

~~The problem of low~~ Low oxygen conditions, often referred to as ~~hypoxia, occurs~~ oxygen deficiency, occur regularly in the North Sea, a temperate European shelf sea. Stratification represents a major process regulating the seasonal dynamics of bottom oxygen~~. However~~, yet, lowest oxygen conditions in the North Sea do not occur in the regions of strongest stratification. This suggests that stratification is an important prerequisite for ~~hypoxia~~oxygen deficiency, but that the complex interaction between hydrodynamics and the biological processes drives its ~~development~~evolution.

In this study we use the ecosystem model ~~HAMSOM-ECOHAM5~~ HAMSOM-ECOHAM to provide a general ~~characteristic~~ characterisation of the different ~~North Sea oxygen regimes~~zones of the North Sea with respect to oxygen, and to quantify the impact of the different physical and biological factors driving the oxygen dynamics ~~below the thermocline and in the bottomlayer~~inside the entire sub-thermocline volume and directly above the bottom.

~~We show that~~ With respect to oxygen dynamics, the North Sea can be subdivided into three different ~~regimes in terms of oxygen dynamics~~zones: (1) a highly productive, non-stratified coastal ~~regime~~zone, (2) a productive, seasonally stratified ~~regime~~ zone with a small sub-thermocline volume, and (3) a productive, seasonally stratified ~~regime with a~~zone with a large sub-thermocline volume~~, with regime~~ . Type 2 ~~being highly susceptible to hypoxic conditions~~reveals the highest susceptibility to oxygen deficiency.

~~Our analysis of the different processes driving the oxygen development reveals that inter-annual~~ Inter-annual variations in the oxygen conditions are caused by variations in primary production, while spatial differences can be attributed to differences in stratification and water depth. In addition, we show that benthic bacteria represent the main oxygen consumers in the bottom layer, consistently accounting for more than 50 % of the overall consumption.

By providing these valuable insights, we show that ecosystem models can be a useful tool for the interpretation of observations and the estimation of the impact of anthropogenic drivers on the North Sea oxygen conditions.

1 Introduction

The problem of low Low oxygen (O_2) conditions (concentrations $< 6\,\mathrm{mg\,O_2\,L^{-1}}$; OSPAR-Commiss often referred to as hypoxia, occurs O_2 deficiency, occur regularly in the North Sea. A major process regulating the seasonal dynamics of bottom O_2 is the occurrence and duration of thermal stratification (e.g. Greenwood et al., 2010; O'Boyle and Nolan, 2010) (e.g., Greenwood et al., 2010; O'Boyle a which limits the vertical exchange of O_2 between the oxygenated surface layer and the deeper layers, and separates the productive and respiratory regimes of . In combination with events of enhanced primary production, and the water column (surface and subsurface). Both effects favour in synergy the occurrence subsequent degradation of organic matter, this favours the evolution of O_2 depletion events (e.g. Diaz and Rosenberg, 2008) . However, even though deficiency (e.g., Diaz and Rosenberg, 2008) . Although the northern North Sea reveals strongest stratification, lowest O_2 concentrations occur in the central North Sea, which is shallower and where the duration of stratification is shorter and shows highest inter-annual variability. Thus, one can argue that stratification is an important prerequisite for hypoxia, but the O_2 deficiency, but its severity and duration of low conditions is controlled by the complex interaction between the hydrodynamical condition and the biogeochemical processes involved.

The North Sea is a temperate, semi-enclosed shelf sea adjacent to the northeastern Atlantic ocean. It has an average depth of about 90 m (Ducrotoy et al., 2000) with northward increasing bottom depth. The North Sea circulation is characterised by a cyclonic pattern mainly driven by the southward Atlantic inflow across the shelf edge defining its northern boundary. Lenhart and Pohlmann (1997) showed that about 85 % of the incoming Atlantic water is recirculated north of the Dogger Bank, a shallow area with water depth less than

40 m and 300 km of zonal extent at about 55° N, 2° E (Kröncke and Knust, 1995). The circulation south of the Dogger Bank is governed by the inflow through the English Channel and follows the continental coast. Northwest of Denmark At the southern tip of Norway it joins the Norwegian coastal current leaving the North Sea at its northern boundary.

Stratification in the North Sea reveals some significant substantial regional differences. While the shallower southern parts are permanently well-mixed due to the strong influence of the M_2 tidal component (Otto et al., 1990), the deeper parts north of 54° N reveal seasonal, mostly thermal stratification (e.g. Burt et al., 2014; Pingree et al., 1978; van Leeuwen et al., 2015) (e.g., Burt et al., 2014; Ping Seasonal haline stratification occurs to a lesser extent along the Norwegian coast. The transition between these permanently mixed and seasonally stratified regions occurs gradually (Pingree et al., 1978). In consequence, even areas relatively near to the coast, which are affected by high riverine nutrient run-off, often reveal stratified conditions at sub-seasonal timescales (e.g. Burt et al., 2014) (e.g., Burt et al., 2014) .

The In the 1980s, events of O_2 depletion, occurring deficiency reaching values below 3 mg O_2 L^{-1} occurred regularly in the southeastern and southern stratified southeastern central North Sea under stratified conditions (Brockmann and Eberlein, 1986; Brockmann et al., 1990; Queste et al., 2013; Rachor and Albrec can be classified as "persistent seasonal" according to Kemp et al. (2009) . The and in the German Bight (Brockmann and Eberlein, 1986; Brockmann et al., 1990; Rachor and Albrecht, 1983) . During this time, the problem of low O_2 conditions in the North Sea reached public awareness in relation to the eutrophication problem during the 1980s, when eutrophication as demersal animals died across a large area due to these low O_2 concentrations (von Westernhagen et al., 1986). Eutrophication, or in other words, high anthropogenic nutrient loads mainly supplied by rivers (Brockmann et al., 1988; Jickells, 1998; Rabalais et al., 2010), may raise the ambient nutrient concentrations followed by an increase in biomass production. Under given physical conditions, eutrophication thus causes an enhanced supply of organic matter sinking into the subsurface layer and thus reinforces O_2 consumption near the sea floor due to bacterial remineralisation.

Even though the second International Conference on the Protection of the North Sea (INSC-2) prescribed a 50 %-reduction of river nutrient loads (inorganic nitrogen and phosphorus) in order to mitigate the effects of eutrophication (de Jong, 2006), low bottom Fig. 1 shows that O_2 concentrations remain deficiency remains a persistent problem in the North Sea up to the present dayas shown in Fig. 1. The ecological disturbance of different levels of low concentration is summarized and described in detail, for instance, by Friedrich et al. (2014) and Topcu et al. (2009) . According to Kemp et al. (2009) these events can be classified as “persistent seasonal”. Low bottom O_2 concentrations may lead to the cause death of benthic organisms or fish eggs as well as avoidance of the affected areas by benthic species. Therefore, low O_2 concentration constitutes concentrations constitute a major indicator of eutrophication (category 3 indicator, i.e. “evidence of undesirable disturbance”; OSPAR-Commission, 2003) and (category 3 indicator, i.e., “evidence of undesirable disturbance”; OSPAR-Commission, 2003) and concentrations lower than $6\,mg\,O_2\,L^{-1}$ result in the classification as so-called “problem area” in terms of eutrophication within the OSPAR assessment (Claussen et al., 2009). In the present study the term “oxygen deficiency” is used in this OSPAR context rather than “hypoxia”. While O_2 deficiency is clearly defined within OSPAR by the $6\,mg\,O_2\,L^{-1}$ threshold, hypoxia refers to the negative impact of low O_2 concentrations on organisms. An overview of the impact of hypoxia on marine biodiversity can be found in Vaquer-Sunyer and Duarte (2008) . Further descriptions on the ecological disturbance of different levels of low O_2 concentrations are summarised by Friedrich et al. (2014) and Topcu et al. (2009) .

Despite the relevance of the bottom O_2 concentration concentrations for the assessment of the ecological status of an ecosystem, O_2 measurements are sparse and either temporally or spatially limited. In addition, it is difficult to place the measurement at the right time and location to obtain a comprehensive picture of the duration and spatial extent of summer O_2 depletion events deficiency (Friedrich et al., 2014). One way to address this problem is to analyse the available data towards their confidence level representativeness of available data with respect to eutrophication assessment (Brockmann and Topcu, 2014).

Only in recent years continuous measurements for the North Sea became have become available by, for instance, the SmartBuoy programme of Cefas (Centre for Environment, Fisheries and Aquaculture Science, UK; Greenwood et al., 2010) or the MARNET programme (MARine Monitoring NETwork in the North Sea and Baltic Sea) of the BSH (Federal Maritime and Hydrographic Agency, Germany). These monitoring programmes provide daily time series of O_2 and related parameters (e.g., temperature, salinity, chlorophyll) in different depths and allow for the analysis of the temporal development evolution of stratification and O_2 concentration concentrations at the location of observation.

Greenwood et al. (2010) published the first data from continuous measurements of bottom oxygen concentration O_2 concentrations for two sites (North Dogger and Oyster Grounds"North Dogger" and "Oyster Grounds") in a European shelf sea. From these measurementsUsing these measurements, the dynamic interaction between stratification and the development evolution towards low bottom O_2 concentration concentrations can be observed, as well as the rapid recovery to saturated O_2 conditions after the breakdown of stratification due to mixing in autumn.

Queste et al. (2013) presented an approach to extend However, even these continuous measurements did not provide sufficient information to fully understand the processes which caused the observed O_2 evolution. Greenwood et al. (2010) and Queste et al. (2013) , who extended the findings by Greenwood et al. (2010) to a the spatial scale using data from a survey in survey data from August 2010 , and ICES historical data. They found that the summer depletion near the Dogger Bank is not a recent phenomenon, however, its severity may have changed during the years. Their study showed, that in 2010 the largest part of the depletion zone was located in the central North Sea at about 57N. They furthermore pointed out that it was likely caused by enhanced primary production in combination with the isolation of the deeper layers due to stratification and topographic features. Nevertheless, the question remains why this low concentration occur in regions of less intense stratification compared to the northern North Sea.

As stated by Greenwood et al. (2010) , refer to "plausible mechanisms" like vertical mixing or advection when the measurements could not be explained in detail. In consequence, Greenwood et al. (2010) stated, that the data provided insight into the processes affecting the O_2 dynamics but it will require models models are required to further elucidate the significance of the seasonal drivers. Ecosystem models

Ecosystem models produce a temporally and spatial consistent picture on O_2 and can therefore provide insight into the balance between the physical and biological factors and processes governing the development evolution of the bottom O_2 concentrationconcentrations. Thus, they can help to understand and interpret measurements of O_2 and related parameters and can further describe the history of events of low O_2 conditions.

In this study we use the three-dimensional physical-biogeochemical model system HAMSOM-ECOHAM5 to fill the gap between assessment requirements and data availability. The model provides temporally and spatially resolved information for HAMSOM-ECOHAM to provide a detailed description of the current state of the North Sea ecosystem allowing for the identification and characterisation of the key factors determining the inter-annual dynamics of the sub-thermocline and bottom in terms of its O_2 concentration in different regions conditions, and the processes leading to low bottom O_2 concentrations. The interpretation of the model results will enable the following questions to be answered: What are the main drivers for the O_2 dynamics in the various subregions of the North Sea. ? Why are certain North Sea regions more susceptible to low O_2 conditions than others despite similar stratification patterns?

For this purpose, we first validate the simulated bottom O_2 concentration concentrations with respect to its temporal development their temporal evolution and spatial distribution in order to show that the model used captures the main features. ConsequentlySubsequently, we present a regional characteristic characterisation of the parameters controlling the bottom O_2 dynamics and finally propose a simple O_2 deficiency index which extends this characterisation to the entire North Sea. Finally, we analyse the governing processes in terms of inter-annual and regional variations variability in their individual contribution to the O_2 ~~development.~~evolution, including a detailed interpretation of the continuous O_2 measurements at North Dogger (Greenwood et al., 2010) .

2 Material and methods

2.1 The ECOHAM model

Our study is based on the coupled physical-biogeochemical model system ~~HAMSOM-ECOHAM5~~HAMSOM-ECOHAM. The physical model HAMSOM (HAMburg Shelf Ocean Model; Backhaus, 1985) is a baroclinic primitive equation model ~~with a free surface and uses~~ using the hydrostatic and Boussinesq approximation (Pohlmann, 1991). HAMSOM ~~is defined with a finite difference approach on an Arakawa C-grid (Arakawa and Lamb, 1977) using z coordinates. It is used to provide~~ provides the temperature (T) and salinity (S) distribution, in addition to the ~~fields for advective flow~~ advective flow fields and the vertical turbulent mixing coefficient, which are used as forcing for the biogeochemical model ~~ECOHAM5~~ ECOHAM (ECOsystem model HAMburg~~, version 5). An additional horizontal turbulent diffusion is not applied as Lenhart and Pohlmann (1997) found, that the applied advection scheme (component upstream) causes an already high numerical diffusion.~~). For a detailed description of HAMSOM the reader is referred to Pohlmann (1991)~~, further~~ . Further information on the application of HAMSOM can be found in Backhaus and Hainbucher (1987) and Pohlmann (1996).

The biogeochemical model ~~ECOHAM5 is the successor of ECOHAM4 (Lorkowski et al., 2012; Pätsch and Kühn, 2008) and~~ ECOHAM (Lorkowski et al., 2012; Pätsch and Kühn, 2008) represents the pelagic and benthic cycles of carbon (~~C~~C), nitrogen (~~N~~N), phosphorus (~~P~~P), silicon (~~Si) and . As an extension to the classical NPZD (nutrients-phytoplankton-zooplankton-detritus) models, a representation of the "microbial loop" (Azam et al., 1983) is implemented using one functional group of bacteria. The model comprises the following state variables: 4 nutrients (nitrate,~~

ammonium, phosphate, silicate), 2 functional groups of phytoplankton (diatoms, flagellates) and zooplankton (micro- and mesozooplankton), slowly and fast sinking detritus, labile and semi-labile dissolved organic matter (DOM), bacteria, dissolved inorganic carbon (DIC) , total alkalinity Si) and O_2. Furthermore, a module for the equilibrium chemistry of inorganic C is implemented allowing for the calculation of the air-sea flux of . The C:N:P ratios for phytoplankton, zooplankton and bacteria are fixed, but were chosen individually for each group (Lorkowski et al., 2012) . The C:N:P ratios for detritus and DOM can evolve freely. Pelagic primary production is parametrised following Steele (1962) and light availability is limited by light attenuation of water, planktonic self-shading and suspended particulate matter (SPM).

The O_2 module within the ECOHAM5 ECOHAM model incorporates physical and biogeochemical processes determining the pelagic O_2 concentration (Pätsch and Kühn, 2008) . concentrations (Pätsch and Kühn, 2008) .

The air-sea exchange of O_2 at the sea surface constitutes an important physical factor besides the effects of advective transport and vertical diffusion in the interior water column. The air-sea flux of O_2 in the present application is parametrised according to Wanninkhof (1992).

In relation to the biology, the O_2 cycle is linked to the C C cycle by photosynthesis, zooplankton respiration and bacterial remineralisation. While photosynthesis is a source of O_2, the latter ones work act as O_2 sinks. A further sink of O_2 is nitrification, the bacterial transformation of ammonium to nitrate. By this process , which Within ECOHAM, this process is light-dependent , and links the O_2 cycle is linked to the N cyclewithin ECOHAM5to the N cycle. Nitrification only occurs under aerobic conditions (i.e.concentration >0, concentrations >0 mg O_2 L^{-1}), which is a realistic constrain for the pelagic North Sea environment. It is light-dependent, being stronger under low light conditions. Pelagic denitrification is implemented, but is negligible as it only occurs under anaerobic conditions. Pelagic anaerobic ammonium oxidation (anammox) is not implemented, however, it can be neglected for the same reason. Except for primary production, the biological processes involved in the O_2 cycle are not temperature-dependent in the present model setup.

For the representation of the benthic remineralisation processes a simple sediment module is used. A layer of zero extent is defined below the ~~last~~ deepest pelagic layer of each water column. There the deposited organic matter is collected and remineralised (Pätsch and Kühn, 2008). The benthic remineralisation of the organic matter is defined as a first-order process with relatively high remineralisation rates ~~inhibiting~~ preventing year-to-year accumulation of deposited matter. The released dissolved inorganic matter is returned directly into the pelagic bottom layer. Different remineralisation rates are applied to organic ~~C, N, P and Si~~ C, N, P and Si (opal), resulting in different ~~delays~~ time scales for the release into the pelagic. In ~~ECOHAM5~~ECOHAM, the O_2 cycle ~~(Pätsch and Kühn, 2008)~~ is affected by the benthic remineralisation in a direct and indirect way. First, the remineralisation in the sediment is accompanied by the direct reduction of the O_2 ~~concentration~~ concentrations in the pelagic bottom layer above. Second, inorganic nitrogen is released from the sediment in the form of ammonium, which can be nitrified within the water column under O_2 consumption. ~~Nitrification is light-dependent, being stronger under low light conditions.~~ According to Seitzinger and Giblin (1996), who suggested a tight coupling between benthic nitrification and denitrification, benthic denitrification depends on the benthic O_2 consumption in our model. Direct benthic nitrification and benthic anammox ~~had to be~~ are neglected as the sediment has zero vertical extent (Pätsch and Kühn, 2008).

For a more detailed description of the ECOHAM model, including the full set of the differential equations and parameter settings of ~~ECOHAM5, including the different elemental ratios~~ECOHAM, the reader is referred to Lorkowski et al. (2012). ~~Values of~~ A detailed description and analysis of the O_2 ~~saturation concentration presented during the course of this study were calculated according to Benson and Krause (1984) using simulated T and S~~module can be found in Müller (2008) .

2.1.1 Model setup and ~~external~~ forcing data

The model domain extends from 15.25° W to 14.083° E and from 47.583 to 63.983° N and comprises the ~~whole~~ entire North Sea, large parts of the northwestern European continental shelf ~~(NECS)~~ and parts of the adjacent northeastern Atlantic. The horizontal resolution is

$1/5^{\circ}$ with 82 grid points in latitudinal direction and $1/3^{\circ}$ with 88 grid points in longitudinal direction. The horizontal grid of the model domain is shown in Fig. 2. The vertical dimension with a maximum depth of 4000 m is resolved by 31 z-layers with a surface layer of 10 m~~and thicknesses successively increasing with depth from 5 up to 1000in the layers below~~. The vertical has ~~as~~ a resolution of 5 m between 10 and 50 m depth, which is relevant for the calculation of the MLD (Sect. 2.2~~. The described grid is applied to both models, HAMSOM and ECOHAM5~~). Below 50 m, the layer thicknesses successively increase with depth.

The model system was run over the period 1977 to 2012. HAMSOM was initialised with a monthly-averaged climatology based on the World Ocean Atlas ~~data set~~ (WOA; Conkright et al., 2002). The meteorological forcing was ~~calculated~~ derived from NCEP/NCAR reanalysis data (Kalnay et al., 1996; Kistler et al., 2001) and provides 6 hourly information for air temperature, cloud coverage, relative humidity, wind speed and direction. Short wave radiation was calculated from astronomic insulation and cloud coverage applying a correction factor of 0.9 (Lorkowski et al., 2012) . The data were interpolated ~~into~~ to the model grid and time step according to O'Driscoll et al. (2013) and Chen et al. (2014). Daily freshwater run-off data for 249 rivers were provided by Cefas and represent an updated dataset of that used by Lenhart et al. (2010) covering the ~~whole~~ entire simulation period. The same dataset encompassed nutrient loads used for the ~~ECOHAM5~~ECOHAM.

At open boundaries, surface elevation was prescribed as a fixed (Dirichlet) open boundary condition (OBC) according to the M2 tide, while for horizontal transport velocities radiation OBCs were applied. For tracers (T and S) radiation and radiative-nudging OBCs were used in the case of inflow and outflow, respectively. A detailed description of the OBCs is provided by Chen et al. (2013). The HAMSOM simulation was carried out with a 10 min time step.

~~ECOHAM5~~ ECOHAM was run off-line with a time step of 30 min using the ~~daily~~ 24-hour averages of the hydrographic and hydrodynamic fields generated by HAMSOM. In the model setup used, short wave radiation is attributed to the first layer (surface) only and the specific effect of light attenuation due to SPM and planktonic self-shading on the thermal structure is not taken into account. ~~This approach is similar to the case of very~~

large concentrations of shading material. In a sensitivity run we allowed light to penetrate into deeper layers accounting for light attenuation by water, SPM and phytoplankton. On average, A sensitivity study allowing for deeper light penetration and feedback on the thermal structure during April–September 2002 (year of highest primary productivity) showed a minor decrease in the T difference between surface and bottom (-0.12 ± 0.10) and in the stratification period (-2 ± 5.6). The maximum decrease in average summer T difference was less than 0.5and confined to only a small area in the eastern central North Sea. The average effect of phytoplankton shading amounted to about 5.confirmed this effect to be only of minor importance (not shown).

For the biogeochemical state variables a climatology of depth-dependent monthly averages was prescribed at the boundaries , and solely for DIC yearly changing data were provided (Lorkowski et al., 2012). To include the effect of SPM on the light climate, a daily climatology from Heath et al. (2002) was usedcovering the whole model domain. Data for atmospheric N N deposition were compiled using a hybrid approach. This was required since the overall simulation period (1977–2012) exceeds the period of data available from the EMEP (Cooperative program for monitoring and evaluation of the long-range transmissions of air pollutants in Europe) model (1995–2012). First, the EMEP results for total deposition of oxidised (NONO_x) and reduced nitrogen (NH_3) were interpolated to the model grid. Second, we calculated the average annual deposition rates for the NONO_x and NH_3 for each grid cell, based on EMEP data for the period the 1995–2012 EMEP data. The resulting spatially resolved arrays of average deposition rates were subsequently normalised by the spatial average of the whole entire domain to yield the spatially resolved anomaly fields. Finally, gridded deposition rates for individual years were obtained using (1) the gridded anomaly fields, (2) EMEP's spatially averaged (over our model domain) deposition rates for year 2005, and (3) long-term trends (normalised with respect to towards year 2005) for the temporal development evolution of European emissions of NONO_x and NH_3 (Schöpp et al., 2003, Fig. 2) (Fig. 2 in Schöpp et al., 2003) . The output of the biogeochemical simulation was stored as daily values (cumulative fluxes, state variable snapshots) for the whole entire domain and simulation period.

2.2 Extracting stratification parameters from model results

Stratification constitutes the prerequisite for the potential ~~development~~ evolution of low O_2 conditions in the North Sea~~, and is defined by its~~. In this study (1) its duration and (2) the mixed layer depth (MLD) ~~. Therefore, these two parameters are crucial for the analysis of the dynamics conducted during the course of this study~~are used to describe stratification. Seasonal stratification in the North Sea is mainly T-driven (Burt et al., 2014) , except for the regions of haline stratification along the Norwegian coast. As observations do not cover the ~~whole~~ entire model domain and simulation period ~~it is inevitable to determine~~ we determined the duration of stratification and the MLD from the simulation results. For this purpose we developed a simple 2-step algorithm based on T. First, the stratified period is determined using a temperature difference criterion:

$$S_{\text{strat}}(x,y,t) = \begin{cases} 1 & \Delta T|_{-H}^{0}(x,y,t) \geq 0.05\,\text{K} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

S_{strat} is a switch defining if a water column at location (x,y) and time t is stratified ($S_{\text{strat}} = 1$) or not ($S_{\text{strat}} = 0$) depending on the temperature difference ΔT between the surface and bottom depth H. The critical temperature difference $\Delta T_{\text{crit}} = 0.05\,\text{K}$ was determined by evaluating different ΔT_{crit} against the temporal ~~development~~ evolution of simulated bottom O_2 at different locations within the model domain. ~~For this purpose, we assumed that even if the surface mixed layer is interrupted due to mixing, this must not necessarily cause a complete overturning of the water column. Thus, even a minor difference in T indicates a bottom layer unaffected from vertical mixing.~~ In addition, periods of stratified conditions are only considered as such, if they last for at least 5 days without any interruption. Otherwise bottom waters are considered to be ventilated again.

In the second step, in the case of stratification the MLD is defined as the depth D where the vertical temperature gradient $\delta T/\delta z$ has its maximum:

$$\text{MLD}(x,y,t) = \begin{cases} D(\max(\delta T/\delta z)) & S_{\text{strat}}(x,y,t) = 1 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

In addition, the discrete model grid implies the definition of the MLD as the bottom depth of the upper of the two layers between which the maximum gradient $\Delta T/\Delta z$ between the centre points of two vertically adjoining grid cells occurs. As the described stratification and MLD criterion differs significantly from common MLD criteria (e.g., Table 1 in Kara et al., 2000) , an evaluation is provided in Appendix A.

2.3 Validation data

For the validation of the model results we used observation data from different sources. The datasets can be subdivided into two types: (1) temporally resolved, localised data and (2) spatially resolved “snapshots”. The first type was used for the validation of the temporal development seasonal evolution of O_2, whereas the second type was used to validate the general spatial patterns and inter-annual variability of bottom O_2 during late summer.

2.3.1 Localised, temporally resolved data – Cefas-SmartBuoy and MARNET

The problem of comparing sporadic measurements with simulated bottom concentrations was clearly shown by Lenhart et al. (2010, Fig. 9a) . They compared bottom concentrations simulated by three different models against in-situ observations at the Dutch monitoring station Terschelling 135. Their first approach to directly compare observations and simulations of a single year revealed significant differences between simulated and observed bottom concentrations, with even lower simulated values falling below 6in late summer. However, due to the sparse data, they could not determine whether these low simulated concentrations represented reasonable results for the corresponding period or not. Consequently, monthly averages and standard deviations of a 15dataset had to be used to unveil if concentrations below 6were within a realistic range during the specific period at the location considered. In our study we use more or less continuous time series of bottom concentrations for the stations Cefas North Dogger and MARNET Ems to overcome this uncertainty in the validation.

Cefas operates a number of autonomous monitoring systems to provide up-to-date reports on marine water quality. One of these so-called "SmartBuoy " moorings is network of SmartBuoys to provide autonomous in situ measurements of physical, chemical and biological parameters (Mills et al., 2005) . A SmartBuoy was located directly north of the Dogger Bank ('North Dogger') at 55°41′ N, 2°16.80′ E (see Fig. 2, region 2) . The SmartBuoy at this station (hereafter "North Dogger") was operational from between 24 -February 2007 , to 15 -September 2008 (Greenwood et al., 2010) . At this site the water depth is 85and the measuring devices were located in 1, 31 and in 85 m depth. T, S and water depth (Greenwood et al., 2010) . O_2 concentrations were continuously recorded in the different depths. The concentrations were measured in a burst of between 5 to 10using an Aanderaa optode (AADI, Norway) with a with a frequency of 5 Hz (accuracy of 0.5at 31). A 0–100m and 85 calibration was conducted annually on each optode and results m . These autonomous O_2 measurements were corrected for drift using O_2 concentrations determined from discrete water samples . These samples were collected and preserved in triplicate according to Winkler, and subsequently analysed on board using an automatic titration system (Sensoren Instrumente Systeme, Germany). For a more detailed description of the data acquisition at North Dogger the reader is referred to Greenwood et al. (2010) to give an accuracy of 0.5 % (Greenwood et al., 2010) . For validation purposes the O_2 concentration data derived from the sensor at 85 m depth were used.

The BSH operates 12 marine monitoring stations within the MARNET programme. This programme focuses on the continuous monitoring of physical properties of sea-water (T, conductivity, concentration and saturation) and hydrodynamic parameters, such as current velocities or sea level, to detect changes in the marine climate and to provide information model applications, e.g. storm surge forecast. At each MARNET station , the saturation

~~is measured hourly in the surface and in the bottom layer using opto-chemical sensors (optodes).~~

~~At station Ems (~~a continuous monitoring station at 54°10′ N, 6°21′ E ~~;~~ ~~(~~(see Fig. 2, region 1~~), which has a bottom depth of 33, the two sensors are located at~~ ; hereafter referred to as station "Ems"). The O_2 saturation is measured hourly using opto-chemical sensors (optodes). Sensors are located in 6 and 30 m depth, respectively, and the bottom depth is 33 m. The applied sensors have a resolution of 0.03 mg O_2 L^{-1} and an accuracy better than 0.26 mg O_2 L^{-1}. Before deploying the sensors a 0–100 % calibration is conducted, and they are re-calibrated after operation to quantify any drift. In addition, a regular on-site validation takes place using a calibrated fast optode (accuracy of ± 2 %) or by applying the Winkler titration (accuracy better than ± 1 %).

2.3.2 Spatially resolved "snapshot" data – the North Sea programme

During the North Sea programme, carried out by the Royal Netherlands Institute for Sea Research (NIOZ) with support from the Dutch Science Foundation (NWO) and the European Union, the North Sea was sampled from 18 August to 13 September 2001, and from 17 August to 5 September 2005 and 2008. The North Sea was covered by an approximate ~~1° × 1°~~ 1° × 1° grid, sampling approximately 90 stations in each of the ~~three years . The station grid was denser in the Southern Bight, which is strongly affected by the major continental freshwater run-offs and to a lesser extent by the Baltic outflow. The station grid was coarser in the more homogeneous central and northern North Sea~~ years (Bozec et al., 2005, 2006; Salt et al., 2013). During each cruise, a total of 750 water samples ~~was~~ were collected for dissolved O_2. In 2001, the O_2 ~~concentration was~~ concentrations were determined by the Winkler titration using a potentiometric end-point determination with an accuracy of ± 2 ~~$^{-1}$~~ µmol O_2 kg^{-1} (less than ± 0.07 ~~$^{-1}$~~ mg O_2 L^{-1} depending on T and S). In 2005 and 2008, the O_2 ~~concentration was~~ concentrations were obtained applying the spectrophotometric Winkler approach with a precision of less than 0.03 mg O_2 L^{-1}. A detailed description of the measurement system used is given in Reinthaler et al. (2006).

The data available were gridded to the model grid (Fig. 2). In the case of multiple measurements for the same model grid cell and date, the average of these measurements was used for validation. To compare our model results to these data, we calculated the averages and standard deviations of our simulation over the observation period of the corresponding year.

3 Results and discussion

2.1 Evaluation Deriving a regional O_2 characterisation of the stratification and MLD criterionNorth Sea

For the present study, the stratificationperiod and MLD constitute the major parameters defining the integration period and water volume used for

2.1.1 Identification of the key parameters

For the development of a regional O_2 characteristic, potential controlling factors were analysed in relation to bottom O_2. Besides stratification, eutrophication is considered as a major driver for developing low O_2 conditions (e.g., Diaz and Rosenberg, 2008; Kemp et al., 2009) . Thus, primary production within the mixed layer and the resulting organic matter export into the layers below the MLD must be considered to be the main source for degradable organic matter. In addition, organic matter can be advected from surrounding waters in the form of phyto- or zooplankton and detritus, subsequently sinking out of the mixed layer.

Another important criterion is the analysis of physical and biological drivers of the North Sea water volume below the thermocline (Druon et al., 2004) . A smaller volume separated from the surface due to stratification holds a lower initial inventory of O_2 dynamics.As seasonal stratification in the North Sea is mainly T-driven (Burt et al., 2014) , we used the simulated T to derive these information according to Eqs. (1)and (2), respectively. The applied critical T difference ($\Delta T_{\text{crit}} = 0.05$) differs significantly from common MLD criteria (e.g Kara et al., 2000, Table 1) , thus, its evaluation is requiredthan a larger volume even though concentrations are similar or even higher in the smaller volume. Thus, our set of O_2-related characteristics consists of: mixed layer primary production (PP_{mld}), horizontal advection of organic matter into and out of the mixed layer ($ADH_{org,in}$ and $ADH_{org,out}$; including phyto-/zooplankton and detritus), vertical organic matter export below the MLD (EXP_{org}; only detritus) and mixing of O_2 below the MLD (MIX_{O_2}), and the sub-MLD volume V_{sub}.

For this purpose, Fig. A1 shows a Hovmller diagram of simulated T at station North Dogger To detect regional characteristics within the North Sea area, we defined four different sub-domains encompassing 4×4 model water columns each (see Fig. 2, region 2)for the year2007, including the MLD (dashed magenta line) derived from the T field. Regarding the onset of stratification in late March it is shown, that the near-surface T (down to 25) starts to increase relatively to red boxes): (A) southern North Sea (SNS) under strong tidal influence, (B) southern central North Sea (SCNS) with high inter-annual variability in stratification, (C) northern central North Sea (NCNS) with a dominant summer stratification each year, and (D) northern North Sea (NNS) with a dominant summer stratification each year and a strong influence of the Atlantic. For all these regions, the T in deeper layers. The beginning of the stratified period on 26 April coincides very well with this slowly developing separation of surface and bottom waters. The maximum vertical T gradient at the onset occurs in 25depth. From that moment stratification according to parameters described above were calculated for the years 2000–2012 relative to a reference depth D_{ref}, which is defined as the bottom depth of the model layer directly below the annual maximum MLD among all four regions. We decided to use a D_{ref} >MLD to ensure that for the different regions all parameters were determined on a comparable level. This implies that the values for PP_{mld}, $ADH_{org,in}$ and $ADH_{org,out}$ are integrated from the surface to D_{ref}, whereas EXP_{org} and MIX_{O_2} are the vertical fluxes through D_{ref}. The same D_{ref} was applied to all regions, but inter-annual variations were allowed.

To determine the annual maximum MLD, we first calculated the stratification period for the 4×4-regions B–D using Eq. (1)persists until 31 October, which may represent a slight overestimation as the maximum T gradient is found in 60depth already, indicating deep mixing. Region A was excluded from this calculation as no persistent MLD developed due to tidal mixing. In this context, $S_{\text{strat}}(t)$ of a region is only 1 if $S_{\text{strat}}(x,y,t) = 1$ for all 16 water columns within a 4×4-region. The daily MLD for each water column within a region was calculated by applying $S_{\text{strat}}(t)$ to Eq. (2), and subsequently the daily MLD of the region is defined as the median of these 16 daily values. The annual MLD for each region was then determined as the median of this daily time series. Finally, the annual maximum MLD among all 4 regions is used to determine the reference depth D_{ref}, which is defined as the bottom depth of the layer directly below this maximum MLD.

During the course of the stratified period we can see that in the first 2 months (April/May)the MLD shows stronger fluctuations in The values for these O_2-related quantities were calculated for individual years relative to D_{ref} and temporally integrated over the period from 1 April to 30 September (hereafter 'summer'). Consequently, the average values over the entire period 2000–2012 are calculated and presented in Table 1, additionally including the average O_2 concentrations at the beginning and end of the summer period as well as the average duration of stratification.

2.1.2 Development of a spatially resolved index for North Sea O_2 deficiency

In order to obtain a North Sea wide indicator for O_2 deficiency under stratified conditions, it is necessary to extend the regionally confined characteristic described in the previous section. For this purpose, we extract the key factors affecting O_2 from this regional information and combine them into a single index – the oxygen deficiency index (ODI). The ODI aims to represent the main spatial and temporal patterns of O_2 deficiency in the North Sea under stratified conditions, while being as simple as possible and incorporating only a very limited number of parameters.

For the calculation of the ODI, we first calculate individual indices for the different parameters taken into account. These indices range between 0 and 1, indicating conditions counteracting and supporting O_2 deficiency, respectively. These indices are calculated for each grid point within the model domain. Consequently, these spatially resolved individual indices are combined into the ODI also yielding values between 0 and 1, indicating low and high risk for O_2 deficiency, respectively. By this a spatially resolved indicator for O_2 deficiency is found which helps to regionalise the North Sea in terms of its actual depth. This is caused by the fact, that near-surface stratification is still relatively weak, O_2 conditions.

The definition of the ODI, which was found to provide a good qualitative representation of the bottom O_2 conditions is presented in Sect. 3.3.1, together with the resulting spatial distribution for the years 2002 and thus, short-term events of mainly wind-induced mixing can still reach depths of 35. These events are indicated by the episodic increase and decrease of surface T. From early June to end of July, the MLD is less variable in depth due to the persistent surface heating and less strong wind events. In late June a short-term decrease in surface T indicating enhanced mixing occurs which also results in a deepening of the MLD.From August until the end of the stratified period the MLD shows a deepening trend which is caused by the decreasing surface heating and increasing wind activity.However, in late August a shallowing of the MLD occurs which is related to an increase in the surface T. 2010.

In general,

2.2 Quantification of driving processes: spatial and temporal variability, and data interpretation

In order to quantify the processes driving the O_2 dynamics in different regions, and to analyse their inter-annual variability, we calculated O_2 mass balances for three different regions encompassing 2×2 grid cells (see Fig. 2, regions 3–5). First, mass balances for the entire volume below the thermocline (hereafter "sub-MLD") in region 3 are compared with the corresponding bottom layer mass balances to identify differences between the bottom layer dynamics and the dynamics within the entire sub-MLD volume. This is done for two years, 2002 and 2010, to analyse inter-annual variations. Region 3 was chosen as it shows the lowest bottom O_2 concentrations within the entire model domain, with the overall minimum in 2002 and relatively high concentrations in 2010. The daily resolved MLD defines the upper integration limit for the sub-MLD mass balances, i.e., the criterion applied for the determination of the stratified period and MLD represents the stratification conditions quite well.However, it should be noted the criterion applied for the determination of integration depth may vary during the stratified period(Eq. The daily MLD is defined as the vertical level of the model grid which is closest to the daily average MLD of the 2×2-region according to Eqs. (1)) may slightly overestimate the end of stratification. In addition, in regions with a less pronounced onset of stratificationand (2).

Second, we compare the O_2 mass balances of the bottom layer for the regions 4 and 5 in 2002 with that of region 3 to unveil regional differences. In a last step the mass balance analysis is applied to interpret the O_2 evolution observed at North Dogger (see Fig. 2, region 2).

The O_2 concentrations and saturation concentrations shown in the different mass balances represent the average values within the analysed volume. Values of O_2 saturation concentrations were calculated according to Benson and Krause (1984) using simulated T and S. The fluxes presented are cumulative changes in the O_2 concentrations of the considered volume, i.e.a less distinct increase in surface T, the determined timing of the onset may be slightly too early. The use of the maximum T gradient to determine the MLD under stratified conditions yields reasonable results, and is closely related to real conditions as the thermocline is defined as the layer with the maximum T gradient.

2.3 Model validation

The validation of , the model results using local timeseries data (Sect. 3.1.1) and spatially resolved snapshot data (Sect. 3.1.2) shows that the HAMSOM-ECOHAM5 model system represents the main features of bottom values at the end of the stratified period reflect the total net change of the O_2 development in the North Sea. A detailed analysis of the validation results is given in the followingconcentrations due to the corresponding physical or biological process. Positive and negative values at the end of the stratification period indicate net gain and loss, respectively. The slope of each line represents the intensity of the corresponding flux at the specific moment in time, i.e., a steep positive (negative) slope implies a strong gain (loss) effect.

3 Results and discussion

3.1 Model validation

3.1.1 Temporal ~~development~~ evolution of bottom O_2

Figure 3 shows the comparison of simulated bottom O_2 against time series data at the Cefas station North Dogger for the years 2007 (a) and 2008 (b) and the MARNET station Ems during 2010 (c) and 2011 (d). The indicated stratification period was derived from the simulated temperature fields using Eq. (1).

At North Dogger, observed and simulated bottom O_2 ~~concentration~~ concentrations show a steady decrease beginning with the onset of ~~the~~ stratification. While ~~the~~ stratification according to Eq. (1) starts a bit earlier compared to that described by ~~(Greenwood et al., 2010)~~ Greenwood et al. (2010) , the beginning of the decrease in bottom O_2 ~~concentration~~ concentrations coincides well. The ~~good agreement in the~~ simulated and observed O_2 ~~concentration at this point in time also shows that the spring T distribution is reproduced well as this value reflects mainly the saturation concentration~~concentrations at this time are in good agreement.

Some small-scale fluctuations in the observations like the ~~small~~ minimum in the O_2 ~~concentration~~ concentrations at 15 April 2007, are not fully reproduced by the simulation. However, the general ~~development~~ evolution is represented well by the model. The average ~~reduction rate~~ O_2 reduction in the simulation is slightly ~~lower compared to the observationswhich can be seen~~ less than in the observations, visible in the difference between the concentrations at beginning and end of the stratified period. The decrease in the O_2 ~~concentration~~ concentrations in 2007 suddenly ends with a mixing event between 10 and 12 November. ~~It is shown, that stratification~~ Stratification ends a bit earlier in the simulation, with the result that simulated bottom O_2 starts to recover while the observed ~~concentration continues to declineuntil the mixing event, reaching an~~ concentrations continue to decline, reaching a minimum of 6.4 $mg\,O_2\,L^{-1}$. The observed O_2 concentration at the end of the stratified period is about 6.8 $mg\,O_2\,L^{-1}$, while the simulation results in about 7.4 $mg\,O_2\,L^{-1}$.

~~Unfortunately, the critical period in the development towards the minimum concentration is not covered in~~ In 2008, ~~as the measurement ceased on the 14 September 2008. Nevertheless,~~ we can see a similar slight overestimation of simulated O_2 ~~concentration, but to a lesser degree compared to 2007. This~~ concentrations, but less than in 2007 which is again due to a faster ~~rate of reduction~~ O_2 decline in the observations. ~~In addition~~As in 2007, some minor fluctuations ~~can be seen~~ visible in the observations ~~, which~~ are not represented by the model~~. However, as in 2007~~ , but the general trend of bottom O_2 is represented well by the simulation. It should be noted, that at station North Dogger, the centre depth of the model bottom layer is equal to 76 m (bottom depth of 82 m), while the sampling was conducted in 85 m depth. This ~~difference~~ may also affect the difference between simulated and observed O_2 concentrations.

~~The consistent slight overestimation of simulated bottom compared to the observation is likely to result from a consistent overestimation of summer bottom T, and thus vertical mixing, by the physical model HAMSOM (not shown). Nevertheless, keeping in mind the limited horizontal resolution of the model, the comparison to the observations at North Dogger is promising at it shows that the model is capable of reproducing the main features of seasonal bottom development as well as its inter-annual variability.~~

At MARNET station Ems the observed bottom O_2 ~~concentration shows~~ concentrations show significantly larger intra-seasonal fluctuations than at ~~Cefas station~~ North Dogger. This applies to both years 2010 ~~(panel c)~~ and 2011~~(panel d)~~, and mainly results from the ~~lower bottom~~ shallower station depth, i.e., sampling depth (sensor in 30 m). The water column of the model at this location encompasses 6 vertical layers and is 35 m deep with a centre depth of the deepest grid cell of 32.5 m.

In 2010, ~~stratification starts to develop in late March, however, breaks down again and finally forms in late April lasting until mid-August.~~

~~The~~ the onset of O_2 ~~reduction~~ decline in the observations is in good agreement with the beginning of the ~~decrease~~ decline in the simulated O_2 ~~concentration~~concentrations. Stratification lasts shorter and less persistent than at North Dogger. From late May to late June, the observed bottom O_2 reveals a steep decrease which is not fully represented in the simulation, but shows the remarkable drop in observed O_2 in the second half of June , even though to a lesser extent. The same applies to and the subsequent increase in observed bottom O_2in early July, which is less distinct in the simulation. The replenishment of bottom in both, simulation and observation, occurs at a similar point in time, even though a bit earlier in the observations. This indicates, that the timing of the final breakdown of stratification is in good agreementto a lesser extent. However, it has to be noted that the model tends to overestimate bottom O_2 in 2010, revealing a maximum difference of about 1 . The minor differences at the beginning and end of the year, representing mainly the saturation concentration, show that the general physical setting provided by the model is reasonable, even though some features during the summer period are not fully representedmg O_2 L^{-1}.

In contrast to 2010, continuous 2011, persistent stratified periods derived from the simulation do not exceed 2 months at station Emsin 2011. This is also present in the T observation (not shown). Consequently, the temporal development evolution of bottom O_2 represents mainly the temporal development evolution of the O_2 saturation concentration. The concentrations. Again large fluctuations of up to ± 2 visible mg O_2 L^{-1} can be seen in the observations indicate the presence of different water masses as station Ems is episodically influenced by the coastal freshwater signal. In addition, the tides may have an effect on the short-term. These events are not represented in the simulation due to the low spatial resolution and the daily output time step of the simulationwhich are not fully reproduced by the model. Besides these short-term changes the difference between simulated and observed bottom concentration are concentrations is less than 0.8 mg O_2 L^{-1} with higher summer values in the simulation.

The differences between simulated and observed validation of bottom O_2 concentration at the beginning and end of at the year are less than during the summer period staying below $\pm$stations North Dogger and Ems shows that the HAMSOM-ECOHAM model is capable of reproducing the main features of the bottom O_2 dynamics at these two stations. The minor differences in the concentrations ($< \pm$ 0.4 . This and the relatively good agreement in the temporal development of bottom during the stratified period mg O_2 L^{-1}) at the beginning and end of the year, representing mainly the saturation concentrations, show that the general ~~features of bottom~~ physical setting provided by the model is reasonable. The slightly slower O_2 ~~at station Ems in 2011 are captured by the model .~~reduction in the simulation may indicate an underestimation of the biological consumption, e.g., due to benthic remineralisation. Intra-seasonal fluctuations at both stations are not fully reproduced, due to the limited spatial resolution of the model grid. Additionally, the tides may have an effect at station Ems on the short-term. However, they are not resolved due to the daily time step of the simulated current fields.

3.1.2 Spatial distribution of late summer bottom O_2

~~The profile data collected within the North Sea programme during late summer 2001, 2005 and 2008 provide a highly valuable dataset as they reveal spatial patterns in the North Sea distribution as well as inter-annual variations within this region.~~ Figure 4 shows the spatial distribution of the average simulated and observed O_2 concentrations in the model bottom layer for the years 2001 (~~panel~~ a), 2005 (~~panel~~ b) and 2008 (~~panel~~ c), and the standard deviation (STD) related to the averages in 2005 (~~panel~~ d). The averaging period for the simulations corresponds to the complete observation period for each year, listed in the bottom right corner of each panel.

~~Comparing the simulated and gridded observed bottom concentrations for all three years it is shown that the simulation tends to overestimate the bottom concentration in most areas, however, the general spatial and inter-annual variations visible in the observations are represented well by the model.~~ In 2001, the observations show the lowest ~~concentration~~ concentrations of all years with minimum values of 5.9 $mg\,O_2\,L^{-1}$ in the area 54–57° N, 4.5–7° E. This minimum is similarly present in the model ~~results with values slightly below 7. Considering the maximum concentrations in the North Sea, the observations yield values of 9.3~~yielding 6.96 $mg\,O_2\,L^{-1}$. Maximum observed concentrations were found off the southern tip of Norway ~~and values between 8.7 to 8.8~~(9.3 $mg\,O_2\,L^{-1}$) and in the deepest parts of the Norwegian Trench (8.7 to 8.8 $mg\,O_2\,L^{-1}$). The very high observed value at the northwesternmost sampling site represents an outlier due to the decreasing vertical resolution of the model in greater depth.

~~The comparison of the differences between~~ In 2005~~and 2001 with respect to the 2001 minimum area shows that~~ , the observed minimum values are about 0.3 ~~higher in 2005~~ mg O_2 L^{-1} higher than in 2001. This relative increase compared to 2001 is reproduced well by the simulation showing a similar increase by about 0.2 ~~in this area in 2005.~~ mg O_2 L^{-1}. The observations show lowest bottom O_2 a bit north and south of the simulated minimum, but still relatively low values less than 7.2 mg O_2 L^{-1} in the centre of the simulated minimum. Highest observed ~~values~~ concentrations of 9.3 mg O_2 L^{-1} are located in the very deep area at the eastern end of the Norwegian Trench, and in the inner German Bight~~yielding an concentration of 9.3. The~~ . In the German Bight, the model indicates only slightly higher values ~~in the German Bight area~~ compared to 2001, ~~due to the low grid resolution. In~~ while in the northern North Sea, the simulation shows lower values compared to 2001, which can be seen in the observations as well.

In 2008, the observations reveal significantly higher bottom O_2 concentrations in the area of the 2001 minimum, compared to the previous years. In contrast, observed concentrations in most other parts of the North Sea are lower than in 2001 and 2005. The overall minimum concentration in 2008 of 7.2 mg O_2 L^{-1} is reached close to the Dutch coast. ~~Analysing the simulated bottom with respect to this inter-annual change in the spatial pattern, we can see that simulated bottom also yields lower values in~~ In the southern North Sea, the simulation yields lower bottom O_2 concentrations, and significantly higher values in the 2001 minimum area. For the western central and northern North Sea the picture is different. Here, the observations result in consistently lower values compared to 2001 and 2005, whereas the simulated O_2 shows higher values in most areas, except for the eastern Norwegian Trench.

The simulated STD in 2005 is mainly representative for the years 2001 and 2008 as well. It shows that in most areas of the North Sea the changes in bottom O_2 during August/September are very low throughout a period of 3 to 4 weeks, indicated by a STD of less than 0.1 mg O_2 L^{-1}. The observations also show only small STDs in most areas.

In general, the basin-wide distributions of simulated bottom O_2 represent the ~~spatial patterns shown in the observations~~ observed spatial patterns and their inter-annual variations quite well, even though absolute values are not always reflected. Both observed and simulated bottom O_2 concentrations show that the 50 m-isobath (broadly along 54° N, 0° E to 57° N, 8° E; Thomas et al., 2005) marks the separation line between the northern regions unaffected ~~of~~ by low O_2 conditions and the southeastern parts, which are more vulnerable to low O_2 concentrations. In addition, the model demonstrated ~~to be~~ it is capable of capturing inter-annual variations in the bottom O_2 ~~development~~evolution. In combination with the results of the ~~temporally resolved~~ time series validation (Sect. 3.1.1), this confirms, that the described model setup provides reliable information on the internal physical and biological processes driving the O_2 dynamics in the North Sea.

~~As the comparison of the simulated bottom concentration with the observed ones showed that our model is able to reproduce the main features of late summer concentrations, the standard deviation of the simulation during the observation period gives useful insight in the temporal variability of during a period of 3 to 4 weeks in late summer. Figure 4d shows the standard deviation of the simulation and observation for 2005. The picture given for the simulation in this year is mainly representative for the years 2001 and 2005 as well. It shows that in most areas of the North Sea the changes in~~ The small STD of simulated bottom O_2 ~~during August/September are very low throughout a period of 3 to 4 weeks, indicated by a standard deviation of less than 0.1. This in turn implies that measurements taken around this period can be considered as representative for late summer conditions. In addition, the small standard deviations for the simulation confirm~~ confirms that using the ~~average~~ averages over a period of up to 4 weeks provides a reasonable measure for most areas. ~~This implies that observations taken in late summer~~ In addition, these small values imply that measurements taken late August/early September (before the breakdown of stratification~~represent a~~) can be considered as a representative synoptic picture of the late summer bottom O_2 conditions.

However, the validation presented in Sect. 3.1.1 showed that in some areas lowest concentrations of bottom O_2 may occur remarkably later in the year (see Fig. 3a). Consequently, the picture obtained from observations taken in August/September does not necessarily reflect the spatial distribution of minimum bottom O_2 concentrations. In addition, two areas east and west of the 2001 minimum region reveal higher variability during the sampling period indicated by a standard deviation of up to 0.45. In the western one, stratification may break down earlier in the year due to the combined effect of lower water depth and the onset of autumn storms, resulting in enhanced mixing. This , which underlines the importance of choosing the appropriate point in time to conduct measurements with respect to for the monitoring of low O_2 conditions.

The small standard deviation STD of the observations, which is a result of the data gridding, shows that in most regions vertical O_2 gradients near the bottom are negligible. However, at the southeastern edge The high values of 0.75 and 0.59 $\mathrm{mg\,O_2\,L^{-1}}$ southeast of the Dogger Bank and northwest of Denmark, high values of 0.75 and 0.59, respectively, show that low conditions (compare low average values at the corresponding locations in Fig. 4b) can occur in a relatively thin layer above the bottomrespectively, result from the fact that values above and below the thermocline were taken into account for the averaging.

3.1.3 A quantitative assessment of the model performance

The Taylor diagram (Fig. 5; Taylor, 2001) provides a quantitative assessment of the model performance with respect to simulated bottom O_2 concentrations in relation to the validation data used in Sect. 3.1.1 and Sect. 3.1.2: (a) station Cefas North Dogger (see Fig. 3a and b) station MARNET Ems (see Fig. 3c and d) the spatially resolved data (see Fig. 4a–c). For this purpose, we merged the observations and corresponding simulation data of the different years into one continuous series of data for each of the three datasets. The Taylor diagram presents the correlation coefficients (COR), standard deviations (STD) STDs and centred root-mean-square differences (RMSD) of the simulation relative to the observation. The two latter values observations. STDs and RMSDs are normalised by the STD of the corresponding observations.

The correlation coefficient COR between observation X and simulation Y is calculated as follows for each of the three datasets:

$$\text{COR}(X,Y) = \frac{1}{N \cdot \text{STD}(X) \cdot \text{STD}(Y)} \cdot \sum_{i=1}^{N} (X_i - \overline{X})(Y_i - \overline{Y}).$$

Here, N equals the number of observation-simulation pairs. The index i indicates a single value of the considered dataset, while $\overline{X}$ and $\overline{Y}$ represent the average values. The unnormalised STD of a dataset Z (observation or simulation) is calculated as:

$$\text{STD}(Z) = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (Z_i - \overline{Z})^2}.$$

The unnormalised RMSD between observation X and simulation Y is calculated as:

$$\text{RMSD}(X,Y) = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} \left[(X_i - \overline{X}) - (Y_i - \overline{Y})\right]^2}.$$

The statistics for the time series data confirm the good agreement between simulation and observation shown in Fig. 3. For both stations, COR is high with values of about 0.95 and the normalised RMSD is less than 0.38. The RMSD values are mainly due to the larger range and higher (seasonal and sub-seasonal) variability in the observed bottom O_2, which is also indicated by the normalised STDs of about 0.73 and 0.82 for Cefas North Dogger and MARNET Ems, respectively. For the spatially resolved data, COR reaches only about 0.64. This lower correlation was also shown in Fig. 4 by the inter-annual variations in the simulations and observations between year 2008 and the previous years, when the simulation revealed a relative change inverse to that in the observations in the northern North Sea. The normalised RMSD of 0.77 is about twice as high as for the time seriesresulting in 0.77, which can be attributed to the greater regional differences in the observed bottom

O_2 concentration concentrations with higher maximum and lower minimum values. The normalised STD equals 0.67 which also indicates the less strong spatial differences gradients in the simulation. These statistics confirm the picture given by Fig. 4, which showed that the spatial patterns in the observed bottom O_2 concentration concentrations are basically reproduced by the model, with only slight shortcomings with respect to the amplitude of the bottom O_2 concentration concentrations and inter-annual variations in some regions of the North Sea.

In summary, the validation based on time series and spatially resolved observations showed that our model system is capable of reproducing the main temporal (seasonal and inter-annual) and spatial features of bottom O_2 in the North Sea. Hence, the analysis of the O_2 dynamics based on HAMSOM-ECOHAM5 HAMSOM-ECOHAM will provide valuable insight in temporal and spatial variations of the North Sea O_2 dynamics.

3.2 Simulated stratification periods and minimum bottom O_2

In Fig.Figure 6a and b the longest continuous stratification period and b show the spatial distribution of the longest persistent stratification periods (after Eq. (1) derived from using simulated T is presented) for the years 2002 (a) and 2010(b), respectively. Both years show similar stratification patterns which are in good agreement with the different stratification regimes described by Pingree et al. (1978) and van Leeuwen et al. (2015) . The resulting with stratification periods of > 180 > 180 days for in large parts of the central and northern North Seaare in good agreement with van Leeuwen et al. (2015) . They applied a density-based stratification criterion on model results to subdivide the North Sea into areas of different stratification characteristics, and showed that most areas of the seasonally stratified central and northern North Sea reveal stratification periods of 170 to 230.

Comparing the corresponding minimum concentration concentrations of bottom O_2 (Fig. 6c and d) the simulation results show significant differenceswhich one would not expect when only comparing the duration of stratification. The minimum bottom O_2 concentration concentrations in 2002 in the region from 55–56.5° N, 4.5–7.5° E constitutes constitute the lowest O_2 concentration during the whole concentrations during the entire period 2000–2012 reaching values of below 5.8 mg O_2 L^{-1}. In contrast, the duration of stratification in this area is similar or even longer in 2010 than in 2002. The O_2 concentrations in 2002 are even below the O_2 threshold applied by OSPAR (6 mg L^{-1}; OSPAR-Commission, 2005) (6 mg O_2 L^{-1}; OSPAR-Commission, 2005) and persist for about one month (not presented). In contrast, 2010 represents a year with relatively high minimum bottom O_2 concentrations being above 7.3 in the whole mg O_2 L^{-1} in the entire model domain.

The areas directly north and south of the Doggerbank also reveal lowered lower bottom O_2 concentrations in both years. This

The stratification periods derived from the simulation are in good agreement with the different stratification regimes described by Pingree et al. (1978) and van Leeuwen et al. (2015) . The latter applied a density-based stratification criterion on model results to subdivide the North Sea into areas of different stratification characteristics, and showed that most areas of the seasonally stratified central and northern North Sea reveal stratification periods of 170 to 230 days.

The increased potential for low O_2 conditions north and south of the Doggerbank is in good agreement with corresponds well to observed bottom O_2 time series in these regions (Greenwood et al., 2010). Queste et al. (2013) also observed lower bottom O_2 concentrations north of the Dogger Bank in August 2010, however, they found the minimum concentrations a bit further north around 57° N.

The discrepancy between minimum O_2 concentration concentrations in the two years compared to and the quite similar stratification patterns demonstrates that stratification is an important prerequisite for low O_2 conditions, but other factors control the actual development. This poses the question which physical and biological processes drive physical or biological factors do have a strong effect on the O_2 dynamics in the North Seaduring the summer stratified period. Based on the processes driving depletion, our primary hypothesis is that the production and aggregation of organic matter within the mixed layer, subsequently sinking and being remineralised below the thermocline, is the main cause for low conditions in the deeper layer..

3.3 An O_2-related characteristic of the North Sea

Besides stratification, eutrophication is considered as a major driver for developing low conditions (e.g. Diaz and Rosenberg, 2008; Kemp et al., 2009) . This implies that biogeochemical factors play an important role for the near-bottom development in general, not only for depletion. Increased primary production within the mixed layer and the resulting enhanced organic matter export into the layers below the MLD represent the main source for degradable organic matter in the deeper layers. Therefore, these quantities must be considered when characterising different regions of the North Sea with respect to . In addition, organic matter can be advected from surrounding waters in the form of phyto- or zooplankton and detritus, subsequently sinking out of the mixed layer.

Another important criterion is the water volume below the thermocline (Druon et al., 2004) . A smaller volume separated from the surface due to stratification holds a lower initial inventory of than a larger volume even though concentrations are similar or even higher in the smaller volume. Thus, our set of -related characteristics consists of: mixed layer primary production (PP_{mld}) , horizontal advection of organic matter into and out of the mixed layer ($ADH_{org,in}$ and $ADH_{org,out}$; including phyto-/zooplankton and detritus), organic matter export below the MLD (EXP_{org}; only detritus), mixing of

3.3.1 Key parameters

Table 1 shows the 2000–2012 summer (1 April to 30 September) averages of the quantities considered as potentially relevant for O_2 below the thermocline (MIX_{O_2}) and the sub-MLD volume V_{sub}.

To detect regional characteristics within the North Sea area, we defined 4 different sub-domains encompassing 4×4 model water columns each for the regions A–D (see Fig. 2, red boxes): (A) southern North Sea (SNS) under strong tidal influence, (B)southern central North Sea (SCNS) with high inter-annual variability in stratification, (C) northern central North Sea (NCNS) with a dominant summer stratification each year, and (D) northern North Sea (NNS) with a dominant summer stratification each year and a strong influence of the Atlantic. For all these regions, the parameters described above were calculated for the years 2000–2012). The quantities were calculated relative to a reference depth D_{ref}, which is defined as the bottom depth of the model layer directly below the annual maximum MLD among all four regions. We decided to use a D_{ref} >MLD to ensure that for the different regions all parameters were determined on a comparable level. This is especially important for MIX_{O_2}, as the vertical gradient may show significant differences depending on whether it is determined between the two layers above and below the thermocline, or between two layers both below the MLD. This implies that the values for PP_{mld}, $\text{ADH}_{\text{org,in}}$ and $\text{ADH}_{\text{org,out}}$ are integrated from the surface to D_{ref}, whereas EXP_{org} and MIX_{O_2} are the temporally integrated vertical fluxes through D_{ref}. The same D_{ref} was applied to all regions, but inter-annual variations were allowed.

To determine the annual maximum MLD, we first calculated the stratification period for the 4×4-regions B–D using Eq. (1). Region A was excluded from this calculation as no persistent MLD developed due to tidal mixing. In this context, $S_{\text{strat}}(t)$ of a region is only 1 if $S_{\text{strat}}(x,y,t) = 1$ for all 16 water columns within a 4×4-region. The daily MLD for each water column within a region was calculated by applying $S_{\text{strat}}(t)$ to Eq. (2), and subsequently the daily MLD of the region is defined as the median of these 16 daily values. The annual MLD for each region was then determined as the median of this daily time series. Finally, the annual maximum MLD among all 4 regions is used to receive the reference depth D_{ref}.

Table 1 shows the averages over the period 2000–2012 of the above described critical quantities for all four regions (A–D). The annual values were calculated relative to a D_{ref} of 25 which corresponds with the bottom depth of the layer below the maximum MLD for each year and region according to Eqs. (1) and (2) . In 2005 and 2007m. In addition, the stratification period (t_{strat}), D_{ref} was reset to this depth, as the actual D_{ref} was equal to the minimum bottom depth of region A, not allowing for the calculation of all parameters. The different quantities are compared for two different integration periods: the whole year and

1 April to 30 September (hereafter "summer")average MLD (D_{mld}), average bottom depth (D_{bot}) and area of the regions are provided.

The mixed layer net primary production, PP_{mld}, is strongest in the coastal region A and shows decreasing values towards the central North Sea. On an annual basis In the SCNS region Bhas a level of about 92, PP_{mld} accounts for about 87 % compared to the of that in the highly productive coastal region A. The corresponding value for the NCNS region C and NNS region D is about 80 % and 88 %, respectively.The small differences between annual and summer PP_{mld} are related to the fact that most of the production takes place from April to September.

Despite the high highest PP_{mld} at the coast, Table 1 in the coastal region A, the SCNS region B shows the strongest contribution of gross advection of organic matter, $ADH_{org,in}$ and $ADH_{org,out}$, for the SCNS region B. This feature would not be visible by looking only at net advection, since the difference in the net fluxes is again largest for region A. Both regions show positive net advection of organic matter, while the two northern regions C and D are characterised by a negative advective net fluxnegative net advection, i.e.loss of organic matterdue to advective transport. Regions C and D , advective loss in organic matter. The latter regions are located north of the Dogger Bank, which means they are within the recirculation system of thus, they are affected by the northern Atlantic inflow. In this region, net advection results in a loss in organic matter as the recirculated northward flowing water has higher concentrations of organic matter than the incoming Atlantic water.Interestingly, the model reveals the highest ADH_{org} for region B even exceeding ADH_{org} in the highly productive region A which is also affected by the strong continental coastal current.

The vertical export of organic matter, EXP_{org}, below D_{ref} is clearly linked to the production of organic matter, consistently adds up to about 12–14 % of PP_{mld}, indicating the clear link between these quantities. Region B obtains yields an EXP_{org} of 75 % of that in the coastal region A, which corresponds with a higher net advective organic matter import import of organic matter of 6.7 $\mathrm{g\,C\,m^{-2}}$ in region A-, compared to only 1.6 part $\mathrm{g\,C\,m^{-2}}$ in Region B. EXP_{org} in region C reaches only about 65relative to region A. For region D the annual and summer values reach about 77and D reach about 69 % of the corresponding values in the coastal region A. In contrast, the export of organic matter during summer is relatively stable at about 83and 79 % of the annual values for all regions, which is related to the fact that the major part of primary production occurs during the stratified period. relative to region A, respectively.

The vertical mixing of O_2, MIX_{O_2}, is highest within the coastal region A because the tidal mixing inhibits the development of a seasonal thermocline. How persistent the ventilation works throughout the year is nicely illustrated by the fact that the value for the 6period is nearly half the annual value. It is interesting to note that the annual values for the vertical mixingin the two northern regions C and D are higher than the one for the SCNS region B. However, the dramatic impact of the occurrence of a strong seasonal thermocline is clearly shown in the reduction of the vertical mixing fluxes to about 7and adds up to 116.1 in the two northern regions and to about 36g O_2 m^{-2}, which is due to strong tidal mixing. The stratification period, t_{strat}, of 151 in region B relative to the annual values. As stratification days in region B lasts is shorter than in region C (220 days) and does not cover the whole periodfrom April to September, the impact on the vertical flux for entire summer period. Thus, MIX_{O_2} in region B is overestimated. When taking into account only the period when all regions – except region A – are stratified, the flux reduces to about 17of the annual fluxsignificantly larger than in regions C and D.

The evolution of the O_2 concentration at the beginning of the year reveals minor differences between the regions with a range of 8.9–9.3. Comparing these values to those at the beginning of April , it can be seen that the concentrations between the beginning and end of the summer period reveals some interesting aspects in relation to the previously mentioned parameters. The O_2 concentration is continuously increasing during the first three months of the year reaching values concentrations at 1 April show significant differences between the regions ranging between 9.5 mg O_2 L^{-1} (region C and D) and 10.1 . This increase is caused mainly by decreasing T resulting in a higher solubility, i.e. higher saturation concentration $O_{2,\mathrm{sat}}$. However, all considered regions show an increase in the actual mg O_2 L^{-1} (region A). The O_2 concentration higher than that in $O_{2,\mathrm{sat}}$, ranging between about 14concentrations at the 30 September yield values between 7.7 higher values in region B and 33mg O_2 L^{-1} (region A) and 8.3 higher values in region A. This suggests that the onset primary production during this early period causes the additional increase mg O_2 L^{-1} (region D). This implies a consistently decreasing O_2 consumption during summer from region A to D. This spatial gradient in the O_2 concentration on a North Sea wide scale. consumption is opposite to that in t_{strat}, which shows a steady increase from region A to D.

In order to give an impression of the impact of the organic matter export EXP_{org} on the O_2 dynamics of the water volume below the MLD, V_{sub}, we link the amount of exported organic matter to the amount of O_2 available within V_{sub} assuming the organic matter is remineralised to its full amount completely in the area of settlement. Based on the O_2 concentration at the beginning of April, the total amount of O_2 results in available is 1365 kt for region B and 4590 kt for region C. The total amount of exported organic matter is calculated as the product of EXP_{org} and the total area of the considered region. This calculation yields 130 C kt C and 115 C kt C for the regions B and C, respectively. As O_2 consumption and C C release occur with a molar ratio of 1 : 1 during bacterial remineralisation (Neumann, 2000), the equivalent of total mass of in can be calculated by using the molar masses of C (12.0107) and (2 × 15.994). Finally, we receive we obtain the daily O_2 consumption in by dividing by the total duration of the considered 6 months-period (= 183=183 days). Division of the initial mass of , yielding 0.71 and 0.63 kt O_2 d^{-1} for region B and C, respectively.

The initial O_2 mass is calculated as the product of the initial O_2 by this daily concentration and V_{sub}. Division of the this mass by the daily consumption rate provides an estimate of the amount of time required for the consumption of the entire amount of O_2 available in the volume below the MLDV_{sub}. This calculation yields a period of 719about 2 years for region B, whereas the corresponding value for region C is significantly higher with 4348almost 12 years. This great difference between the resulting periods (factor 6), compared to the relatively small difference between the daily consumption rates (factor 1.1), illustrates clearly the large influence of the sub-MLD volume, V_{sub}, on the temporal evolution of the O_2 concentrations below the MLD.

If we base this calculation The same calculation based on the threshold of 6 mg O_2 L^{-1} used by OSPAR (OSPAR-Commission, 2005) , the results for the two regions diverge even more yielding yields a consumption period of 283and 4270 days for region Band C, respectively. As EXP_{org} shows only minor spatial variability between the two regions , these great differences in the resulting consumption illustrate clearly the large influence of , which indicates the relatively high potential for O_2 deficiency in this region.

This characteristic based on the four different North Sea regions demonstrated that the duration of stratification alone cannot explain the temporal evolution of sub-MLD O_2 concentrations. It shows the great importance of the organic matter export which drives the biological O_2 consumption. In addition, the volume below the MLD , V_{sub}, on the temporal development of plays a key role as it governs the amount of O_2 which is available throughout the stratified period, and in combination with the organic matter export defines whether O_2 deficiency may occur or not. Thus, these three quantities can be considered as the key parameters for the O_2 concentration. dynamics of the seasonally stratified North Sea.

3.4 Driving mechanisms and inter-annual variability of sub-thermocline dynamics

As shown in Fig. 6, similar stratification periods in different years do not necessarily lead to similar distributions of

3.3.1 The oxygen deficiency index (ODI)

With the definition of the ODI, we aim for a simple approach to represent the main spatial and temporal patterns of O_2 deficiency in the North Sea. Therefore, in the first step a further simplification of the key parameters found in the previous section is worthwhile. The strong link between organic matter export and surface primary production allows for the use of the latter one as a proxy. Bottom depth can be used as an indicator for the sub-MLD volume assuming only minor fluctuations of the MLD during the summer stratified period. In addition, the bottom depth directly influences the amount of organic matter reaching the bottom layer, relative to the amount being produced near the surface.

Finally, the following key factors are used for the calculation of this index: (longest continuous) stratification period (t_{strat}; in days), summer surface primary production ($\mathrm{PP}_{\mathrm{mld}}$; in $\mathrm{g\,C\,m^{-2}}$; 1 April to 30 September), and bottom depth (D_{bot}; in m). The individual dimensionless indices for these three quantities, ranging between 0 and 1, are calculated differently. The calculation of the stratification and production indices, I_{strat} and I_{pp}, is based on the work by Druon et al. (2004) and reads as:

$$I_{Q_i}(x,y) = \min\left(1, \max\left(0, \frac{Q_i(x,y) - Q_{i,\mathrm{min}}}{Q_{i,\mathrm{max}} - Q_{i,\mathrm{min}}}\right)\right), \text{ with } Q_1 = t_{\mathrm{strat}},\ Q_2 = I_{\mathrm{pp}}. \quad (3)$$

$I_{Q_i}(x,y)$ represents the index corresponding to the actual value of the quantity $Q_i(x,y)$ with its defined upper and lower threshold, $Q_{i,\mathrm{max}}$ and $Q_{i,\mathrm{min}}$. For t_{strat} the upper and lower threshold are set to 50 and 150 days, respectively. These values were found by comparing the spatial distributions of simulated t_{strat} and minimum bottom O_2 for the entire period 2000–2012. Minimum stratification periods in regions with relatively low minimum bottom O_2 concentrations are about 60 days, and areas with stratification periods of above 150 days are considered as seasonally well-stratified. The lower threshold for PP_{mld} was set to 120 $\mathrm{g\,C\,m^{-2}}$ as $\mathrm{PP}_{\mathrm{mld}}$ does not reach lower values in most parts of the North Sea. The upper threshold was set to 200 $\mathrm{g\,C\,m^{-2}}$ as such high values and even above are simulated in the southeastern North Sea.

For the depth index, I_{D}, a different definition was chosen as the highest potential for O_2 deficiency occurs in areas of intermediate depths, where seasonal stratification can develop and the O_2 inventory is limited due to a small volume below the thermocline. Therefore, we defined I_{D} as follows:

$$I_{\mathrm{D}}(x,y) = \begin{cases} \max\left(0, \frac{D_{\mathrm{bot}}(x,y) - D_{\mathrm{min}}}{D_{\mathrm{peak}} - D_{\mathrm{min}}}\right) & D_{\mathrm{bot}}(x,y) < D_{\mathrm{peak}} \\ 1 - \min\left(1, \frac{D_{\mathrm{bot}}(x,y) - D_{\mathrm{peak}}}{D_{\mathrm{max}} - D_{\mathrm{peak}}}\right) & \text{otherwise.} \end{cases} \quad (4)$$

D_{bot} represents the actual bottom depth at location (x,y). This suggests that stratification constitutes a mandatory condition for low $D_{\mathrm{peak}} = 40$ m is the bottom depth we found to be most favourable for O_2 conditions, but inter-annual variations in other physical and biological factors determine whether the sub-thermocline deficiency in the North Sea. The lower threshold $D_{\mathrm{min}} = 25$ m corresponds to the maximum MLD we found for the shallower southern North Sea. The upper threshold $D_{\mathrm{max}} = 90$ m was chosen to exclude the areas where the initial O_2 conditions fall below a critical level or not.

We calculated inventory is sufficient to prevent O_2 mass balances for the years 2002 and 2010 for region 3, encompassing 2×2 model grid cells (see Fig. 2), to analyse the different dynamics deficiency due to the large volume below the thermocline(hereafter "sub-MLD") resulting in the significant .

Finally, the ODI combines the three individual indices according to the following equation:

$$\mathrm{ODI}(x,y) = I_{\mathrm{D}}(x,y) \cdot \sum_{i=1}^{2} w_{Q_i} I_{Q_i}(x,y), \text{ with } w_{Q_1} = 1/3,\ w_{Q_2} = 2/3. \quad (5)$$

Here, I_{Q_i} and w_{Q_i} represent the index for a quantity and the related weight, respectively. The values for t_{strat} are referred to by Q_1 and those for $\mathrm{PP}_{\mathrm{mld}}$ by Q_2. The equation for ODI implies that it is zero in areas where $I_{\mathrm{D}} = 0$. The stronger weighting of $\mathrm{PP}_{\mathrm{mld}}$ implies that inter-annual variations of the minimum bottom variabilities in the ODI are more strongly affected by variations in summer surface productivity than by the duration of stratification.

The ODI ranges between 0 (low risk of O_2 concentration. This region shows the lowest bottom deficiency) and 1 (high risk). It is calculated for each water column (x,y) within the model domain to obtain a spatially resolved picture of the risk of O_2 concentration deficiency in the North Seaduring most simulated years and is located a bit west of the absolute minimum .

The ODI resulting from the simulated stratification duration (t_{strat}), summer surface primary production ($\mathrm{PP}_{\mathrm{mld}}$) and model topography for the years 2002 and 2010 is shown in Fig. 7a and b, respectively. It can be seen that the ODI tends to be higher in 2002 than in 2010 in the region where minimum bottom O_2 is lowest in both years (see Fig. 6c). This was done to show how). The ODI also shows slightly higher values in the region directly north of the Doggerbank which corresponds with the lowered bottom O_2 in this region. The inter-annual variations in the sub-MLD processes affect the the sub-MLD variability of the minimum concentrations in this region is also well-reproduced by the ODI. Especially in 2002, the highest ODI coincides with the lowest concentrations in the entire domain. In 2010, the highest ODI is located a bit south of the minimum O_2 which also controls the concentrations, which is mainly caused by the high surface production in this region. Along the northern British coast, the ODI also shows high values for both years which is in good agreement with the slightly lower minimum bottom O_2 development in the bottom layer. The annual median MLD was determined analogous to that for the 4×4-regions as described in Sect. 3.3.in this area, however, ODI values tend to be too high and do not represent the slightly lower minimum O_2 concentrations off the eastern Scottish coast around 57–58 °N as the bottom depth in this area exceeds 90 m (i.e., $I_{\text{D}} = 0$). Directly northwest of Denmark, the ODI also yields higher values for both years with higher values in 2002. This corresponds well with the simulated bottom O_2 concentrations in this area, even though ODI values are too high, compared to ODI values in the central North Sea.

The sub-MLD With respect to the factors selected for the calculation of the ODI, Table 1 shows that stratification alone is not sufficient to explain the North Sea O_2 mass balances for 2002 and 2010 are presented in Fig. 8a and b, respectively. The shown actual dynamics. While the reduction in the O_2 concentration and saturation concentration represent the average values within the analysed volume. The fluxes presented are cumulative changes in the concentrations is steadily decreasing from region A to D, stratification duration is characterised by a steady increase from region A (80 days) to D (226 days). Regarding the PP_{mld}, the strongest O_2 concentration of the considered volume, i.e. , the values at the end of the stratified period reflect the total net change of the reduction occurs in the regions of highest productivity A and B. In the northern regions, the higher PP_{mld} in region D does not correspond with stronger reduction in O_2. As t_{strat} is also higher in this region, another factor is needed to describe the basic O_2 concentration due to the corresponding physical or biological process. Positive and negative values at the end of the stratification period indicate net gain and loss, respectively. The slope of each line represents the intensity of the corresponding flux at the specific moment in time, i. e.a steep positive (negative) slope implies a strong gain (loss) effect. dynamics. The reduced effect of surface production in the northernmost area is likely to result from the dilution effect due to the higher V_{sub}. Considering the bottom depth D_{bot} as a proxy for V_{sub}, it is shown that the strongest decrease occurs in the shallower regions A and B with average depths of about 40 m, while the regions deeper than 90 m (C and D) show a weaker decrease.

We analyse the Net advection of organic matter, which is not taken into account in the ODI, appears to be of minor importance for subsurface O_2 relative to the local surface production as the net advective input of organic matter is significantly less than the local production. The O_2 concentrations at the beginning of the stratified period were also not taken into account as they show lower values in regions with higher minimum concentrations and vice versa.

In summary, the ODI represents well the spatial and inter-annual variations of minimum bottom O_2 concentrations despite the small set of controlling factors. This confirms that a simple combination of only stratification duration, organic matter production and bottom depth is sufficient to reproduce the main spatial and temporal patterns of the minimum bottom O_2 in the seasonally stratified North Sea. Thus, the findings from Table 1 can be applied to most parts of the North Sea. In addition, the similarity of the ODI inside the regions analysed in Sect. 3.3.1 and inside the regions selected for the mass balance analyses (see Fig. 2, regions 2–4) and their surrounding areas shows that these regions can be considered as representative, allowing for a meaningful analysis of the O_2 dynamics in these regions.

3.4 Driving mechanisms and inter-annual variability of sub-thermocline O_2 dynamics

The previous analyses showed that stratification constitutes a necessary condition for low O_2 conditions, but inter-annual variations between the different processes affecting sub-MLD especially in the biological factors mainly control the O_2 in relation to the setting defined by stratification in dynamics. However, for a better understanding of the O_2-controlling processes below the thermocline, and the interplay of physics and biology, a more detailed analysis is provided by the mass balances in Fig. 8. As the bottom O_2 dynamics are also influenced by the processes in the mid-water, Fig. 8a and b show the O_2 mass balances for the sub-MLD volume (V_{sub}) in region 3 (see Fig. 2) for the years 2002 and 2010. The algorithm for the calculation of the median MLD , which defines the upper limit of the analysed volume, resulted in 152010, respectively.

The stratification characteristics are similar for both years, with an average MLD of 15.19 m for both years. Consequently, the volume considered is identical with about 60.7and 15.99 m for 2002 and 2010, respectively. The temporal evolution of the MLD (dash-dotted grey) is also similar, with deeper MLDs at the beginning and end of the stratified period and few events of enhanced mixing, indicated by mixed layer deepening, during the summer months (May to August). The stratification period (grey area) lasts 187 days in both years. The only difference with respect to stratification period and MLD is the timing of the onset and breakdown of stratification. In , only differing by a later onset (and breakdown) in 2010 stratification already starts on (11 Marchwhereas in) compared to 2002 the onset occurs 20later. (31 March).

The comparison of the sub-MLD O_2 concentrations concentration (solid magenta) at the beginning of the stratified period shows that the concentration of 9.81in 2002 is about 9.81 mg O_2 L^{-1}, being about 0.33 mg O_2 L^{-1} lower than in 2010. The concentrations at At the end of stratificationalso are lower in , the 2002 reaching about 7.13value of 6.85 . The corresponding value in 2010 is about 0.64mg O_2 L^{-1} is about 0.81 higher. mg O_2 L^{-1} lower than in 2010. Accordingly, the net decrease in O_2 during the 2002 stratified period is more than 0.31higher in 2002 by factor 1.2 higher than in 2010.

The diverging temporal development of the In 2002, the clearly diverging temporal evolution of simulated O_2 concentration and the corresponding saturation concentration $O_{2,sat}$ (concentrations ($O_{2,sat}$; dash-dotted magenta) reveals that the decrease in different O_2 evolution is caused not only by decreasing O_2 solubility. This implies that other physical and/or biological Hence, other factors must play an important role for the O_2 development evolution below the MLD. In, addition, the only minor differences in $O_{2,sat}$ at the beginning of the stratified period between 2002 and 2010 reveal, that differences in solubility only have a minor effect on inter-annual variations in this region and instead are caused by variations in other physical and biological factors affecting .

3.4.1 The influence of advection and mixing

The comparison of advection (ADV_{O_2}; including horizontal and vertical components; dashed blue linelight blue) and vertical mixing (MIX_{O_2}; turbulent diffusion; dashed dark blue) for the years 2002 and 2010 shows strong annual and inter-annual variations. ADV_{O_2} regularly changes its influence on the sub-MLD O_2 concentration concentrations during stratification in both years. However, comparing the temporally integrated effect, ADV_{O_2} causes a net gain of about 0.8325.8 g O_2 m^{-2} in 2002, whereas in 2010 it results in a net loss of about −0.217.0 . Interestingly, advection g O_2 m^{-2}. Advection positively affects the O_2 concentration concentrations during the last 2–3 weeks of the stratified period in both years. In 2002, this strong increase is accompanied by a slight net increase in the O_2 concentration and even precedes the recovery of the concentration due to enhanced vertical mixing. This suggests that advective input of oxygenated water from surrounding regions can play an important role for the recovery of the sub-MLD concentration especially in the later phase of the stratified period. concentrations.

The vertical mixing of O_2 through the mixed layer (MIX_{O_2}) adds up 26.9 g O_2 m^{-2} and 18.3 g O_2 m^{-2} in 2002 has a positive effect on the concentration throughout the whole stratified period adding up to a total gain in concentration of almost 1.6and 2010, respectively. In late April and late June 2002, two events of strong downward mixing occur causing enhanced mixing cause a rapid gross increase in the O_2 concentration. In concentrations, in the latter case , MIX_{O_2} is even strong enough to trigger even resulting in a net increase in the concentration. This mixing event coincides with a decrease of $O_{2,sat}$ by −0.05on 1 July which represents the strongest decrease in $O_{2,sat}$ during the whole year.

In 2010, MIX_{O_2} also provides a net gain in O_2integrated over time, but is about 0.65lower than in 2002. During the first 3 weeks of stratification. During August 2002, MIX_{O_2} shows a remarkably stronger positive even has a negative effect on O_2than in 2002, which suggests that in this phase the thermocline is not yet fully developed and still allows for enhanced vertical mixing. However, after this period MIX_{O_2} weakens and finally has almost no net effect on the sub-MLD concentration from end of April until late September. During this phase the vertical mixing even causes temporary declines in , e.g. in mid-June, which result from the fact that highest concentrations do not occur directly at the surface, but around the MLD. The lower concentrations directly at the surface result from the higher T, and thus, lowered solubility. Consequently, events of wind-induced MLD deepening can bring warmer, less oxygenated water from the uppermost layer into the colder deeper layers causing these slight reductions in the sub-MLD , which coincides with a very shallow MLD of 10 m (= bottom of first model layer). In 2010, this negative effect on O_2 concentration.

With respect to ADV_{O_2} the sub-MLD mass balances reveal that the is even more persistent, lasting from late April to mid-August. The increased positive net effect of advection on the concentration in region 3 is quite different between the years. In 2002, ADV_{O_2} causes a net increase of ADV_{O_2} and MIX_{O_2} during the 2002 stratified period relates to the stronger spatial O_2 about half as important as the vertical mixing, whereas in 2010 advection causes a net decrease of the gradients due to the local O_2 concentration.minimum in region 3.

To obtain information on the inter-annual variabilities in the changes in concentration due to advection and vertical mixing during the whole period 2000–2012 we compare the standard deviation (STD) of these physical factors with respect to the cumulated affect during the stratified period. In addition, the comparison of the effect in 2002 and 2010 to the corresponding averages helps to classify these two years in relation to the effect of the physics. As the duration of stratification varies between the different years within this period we calculate the annual average The daily rates of change in O_2 (averaged over the stratification period) due to these factors by dividing their integrated effect during the stratified period by the duration of stratification in the corresponding year. By this we obtain for the different years provide a comparable measure of their effect on sub-MLD O_2, independent of the duration of stratificationduring the different years.

The average values for the whole . The averages of these daily rates for the entire period 2000–2012 result in 0.00050.008 $\pm$ 0.00170.060 g O_2 m^{-2} d^{-1} for ADV_{O_2} and 0.00810.153 $\pm$ 0.00340.042 g O_2 m^{-2} d^{-1} for MIX_{O_2}. The small positive value for ADV_{O_2} shows that on average, advection is only a minor source of O_2. However, however, the large relative STD of 327in ADV_{O_2} STD indicates the large inter-annual variability during the analysed period. This implies that advection can provide both, a remarkable gain or loss, during different years. The average and STD for MIX_{O_2} show that vertical mixing causes an consistently causes a net increase in sub-MLD O_2in most years. .

3.4.2 Biological drivers of the sub-thermocline O_2 dynamics

The comparison of the effects of advection and vertical mixing showed that in 2002 both factors provide favourable conditions for uncritical sub-MLD concentrations, whereas in 2010 the integrated effect of advection and mixing is less beneficial for the O2 concentration, even though it is still positive. However, it has to be kept in mind, that MIX_{O_2} is mainly driven by the vertical gradient in the concentration and higher biological consumption below the MLD would result in a stronger MIX_{O_2} under similar stratification conditions. The significantly lower simulated minimum concentration in 2002 compared to 2010 emphasises the great importance of the biological processes for the sub-MLD development.

In contrast to the integrated effect of the physical factors, it is shown that the integrated effect of the biological processes causes Fig. 8a and b shows that the biological processes cause a net loss in O_2. The only source process for O_2 is primary production (PP; dashed light blue) which causes a gross increase in of about 1.06of about 61.8 in both years. The analysis of g O_2 m^{-2} and 44.5 g O_2 m^{-2} in 2002 and 2010, respectively. Considering the biological sink processesreveals that the , pelagic remineralisation of organic matter (REM_{pel}; dashed light green) has the strongest effect on the sub-MLD O_2, exceeding even the integrated effect of benthic accounting for 50 % of the overall biological consumption. Benthic remineralisation (REM_{sed}; dashed yellow) , accounts for 18.8 %, while zooplankton respiration (RES_{zoo}; dashed dark green) and nitrification (NIT; dashed red) ~~. Among the last-mentioned processes RES_{zoo} has the strongest effect on the concentration and NIT is least affecting . This~~ contribute 22 % and 8.8 %, respectively. This order in the relative importance is a consistent picture throughout the ~~whole~~ entire period 2000–2012 ~~. However, the individual fluxes show remarkable inter-annual variations, especially comparing the two years presented~~(not shown).

In 2002, REM_{pel} is strongest among all years 2000–2012 causing an O_2 consumption of about ~~-3.08~~103.1 g O_2 m^{-2}. In contrast, 2010 represents the year with the ~~second~~ lowest REM_{pel} being about ~~0.72~~26.0 g O_2 m^{-2} less than in 2002. ~~In terms of~~ For RES_{zoo} ~~the difference between the two years is also large with a~~ 2010 ~~value of 0.74which is 0.60~~yields a value of 24.7 ~~less than in 2002 (77~~g O_2 m^{-2} which represents only 55 % of the 2002 value~~). For RES_{zoo}, the~~ . The 2002 ~~value also constitutes the highest~~ and 2010 values constitute the highest and lowest among all years, ~~while the 2010 value marks the lowest value. In 2002,~~ respectively. The same applies to REM_{sed} ~~is again the highest value of the whole period 2000–2012 with about~~ with a 2002 value of $-$~~1.18~~28.5 ~~reduction, while the consumption in~~ g O_2 m^{-2}, and a 2010 ~~represents the second lowest value and is 0.46~~value of -23.3 ~~less than in 2002 (55~~g O_2 m^{-2} (61 % of ~~the~~ 2002 value). NIT is also strongest in 2002 ~~with an integrated change in the concentration by about~~ resulting in $-$~~0.56~~18.1 ~~. In terms of NIT,~~ g O_2 m^{-2}. In 2010~~also~~ , NIT shows values about ~~12~~13 % below the average value of $-$~~0.40~~13.0 $\pm$ ~~0.08, and is 0.21lower than the 2002 value. In terms of REM_{sed} and NIT, the 2010 values account for only about 61 and 62~~2.5 ~~of the 2002 values, respectively. This similarity shows the link between these two processes. NIT is light-limited being higher under low light conditions, thus it mainly occurs in deeper layers where REM_{sed} constitutes the major source for ammonium.~~ g O_2 m^{-2}.

The integrated effect of all biological sink processes (REM_{pel}, REM_{sed}, RES_{zoo} and NIT) adds up to $-$~~6.16~~204.8 g O_2 m^{-2} in 2002, and ~~a 2~~to 136.4 ~~lower value~~ g O_2 m^{-2} in 2010, i.e., the total biological O_2 consumption in 2002 is ~~almost~~ 1.5 times higher than in 2010 and 1.2 times higher than the ~~average value of -5.10~~2000–2012 average of 169.9 $\pm$ ~~0.63~~21.2 ~~of the period 2000–2012. Interestingly, the~~ g O_2 m^{-2}. The relative contribution of the individual processes to the overall biological O_2 consumption shows only minor inter-annual variations during the analysed period. REM_{pel} has an average relative contribution of ~~53.3~~53.6 ± ~~1.8~~1.7 %, while REM_{sed} accounts for ~~17.3~~17.2 ± ~~1.1~~0.9 %. For RES_{zoo} and NIT the average relative contributions result in 21.6 ± ~~1.6~~1.5 % and ~~7.7~~7.6 ± ~~1.0~~0.8 %, respectively.

~~According to our primary hypothesis the amount~~ The export of organic matter ~~which is produced in the upper layers and subsequently sinks into the sub-MLD zone must be significantly higher in 2002 than in 2010. The comparison of the summer PP within the upper~~ below 25 m depth (not presented; calculation analogous to Table 1) ~~reveals a 1.3 times higher value in 2002. The export of organic matter below this depth~~ in 2002 is nearly 1.6 times larger than in ~~2010. As zooplankton is not considered in this comparison, the mismatch between the factors for PP and EXP_{org} is likely to result from higher zooplankton growth, i.e. organic matter production~~2010, which is ~~also indicated by the 81higher zooplankton respiration in 2002 compared to 2010 (see Fig. 8a and b). The good agreement between~~ in good agreement with the differences in ~~EXP_{org} and~~ the integrated effect of the biological O_2 sinks~~confirms that the supply of detrital matter to the deep layers is the driving force of sub-MLD consumption. In this context, it should be noted that 2002 represented an exceptional year in terms of especially high riverine input of organic matter and nutrients into the North Sea (Lenhart et al., 2010) . Thus, the increased nutrient availability is likely to be the main cause for the low conditions during this year.~~.

~~Besides the differences in the temporally integrated effect of the individual biological processesbetween 2002 and 2010, Fig. 8a and b reveal some differences in their development during the stratified period. In 2002, the mixing events~~ Considering the interaction of physical and biological processes, two events of enhanced mixing in late April and late June ~~show~~ 2002 (Fig. 8a) reveal direct and indirect effects of enhanced vertical mixing on the biological processes. The mixing-induced renewal of the nutrient pool causes short-term increases in PP around the MLD. Consequently, the ~~reduction~~ consumption due to RES_{zoo} and REM_{pel} is enhanced. In addition, the ~~mixing causes~~ increased EXP_{org} ~~which also triggers stronger~~ also enhances REM_{pel}. The change in the O_2

concentration concentrations during these events shows that only the stronger event in late June causes a net increase in O_2, whereas O_2 continuously decreases during the weaker event in late April. This suggests that only sufficiently strong mixing results in a positive net effect It should be noted that the shown strengthening in the different biological effects is also influenced by the change in the MLD (i.e., integration depth), however, is also visible when considering a constant MLD (not shown).

Furthermore, PP shows the strongest effects on O_2 , while during events of less strong mixing, biological consumption can balance or even exceed the combined positive effect of ventilation and increased PP. when the MLD is shallowest, which indicates the existence of a deep chlorophyll maximum in the layer between 10 m and 15 m. This also explains the negative influence of MIX_{O_2} during these periods as O_2 concentrations are highest in this layer due to high PP. The generally only minor positive or even negative effect of MIX_{O_2} during most parts of the stratified period also emphasises the importance of stratification for the sub-MLD O_2 dynamics as it efficiently limits the O_2 supply into these layers.

3.5 Bottom layer dynamics of the North Sea minimum zone

The analysis of the different physical and biological processes contributing to the development The good agreement between the inter-annual differences in EXP_{org} and the integrated effect of the biological O_2 sinks confirms that the supply of detrital matter to the deep layers is the driving force of sub-MLD O_2 concentration unravels the complexity behind the different processes affecting the formation of a low consumption. The strong influence of pelagic remineralisation demonstrates its crucial role for the bottom O_2 zone. However, as lowest concentrations usually concentrations as it directly affects the potential O_2 supply from the mid-water into the bottom layer.

3.5 Bottom layer dynamics of the North Sea O_2 minimum zone

Even though the dynamics in the mid-water affect the bottom O_2 levels, lowest concentrations occur in the bottom layerit is important to know . In order to show which processes are the main contributors to the O_2 dynamics in this layer~~. For this purpose~~, Fig. 8c and d show the mass balances for the bottom layer ~~of~~ in region 3 for 2002 and 2010. The ~~bottom layer~~ average bottom depth in this region is 47.75 m, and the model bottom layer encompasses a volume of about 14.4 ~~which accounts for less than 24of the total sub-MLD volume (V_{sub})~~km^3.

~~Comparing the~~ The O_2 ~~concentration in the bottom layer~~ concentrations at the beginning of the stratified period~~to that in V_{sub}, we see only slightly lower values in the bottom concentrations for both years, yielding~~ , 9.79 and 10.12 mg O_2 L^{-1} for 2002 and 2010, respectively~~. This constitutes a relative difference between bottom concentration and sub-MLD concentration of less than 0.2for both years. These small differences match our expectations, as the water column is considered to be well-mixed before the onset of stratification. In contrast, the difference in the bottom concentration~~ , are similar to those in V_{sub}. The concentrations at the end of stratification~~between the bottom layer and V_{sub} is worth mentioning. In 2002, the bottom concentration results in~~ , 6.76 ~~being 0.37~~mg O_2 L^{-1} in 2002 and 7.55 ~~lower than in V_{sub}. In~~ mg O_2 L^{-1} in 2010, ~~the bottom concentration yields 7.55which is 0.22lower compared to~~ show larger differences to those for V_{sub}. ~~That means, bottom reduction in 2002 is about 13faster than in V_{sub}, and still about 10faster in 2010.~~

The ~~analysis of the~~ effect of the physical factors, ADV_{O_2} and MIX_{O_2}, on the bottom O_2 ~~concentration provides a different picture compared to~~ is different to that for V_{sub}. While in 2002 ADV_{O_2} shows a similar effect on O_2 as for the sub-MLD O_2~~with a contribution of about 75relative to the contribution to sub-MLD~~ , its effect in 2010 is opposite to that for V_{sub}~~. However, its integrated effect in 2010 is only slightly positive with a value of about 0.1~~, resulting in a minor increase of about 1.1 ~~on the bottom concentration~~g O_2 m^{-2}. During the last 3 weeks of stratification in 2002, the same positive effect of ADV_{O_2} as in the sub-MLD mass balance is shown, initiating the recovery of the bottom O_2 before MIX_{O_2} intensifies~~at the end of the stratified period. This underlines that the gain in due to advection can balance or even exceed the still ongoing consumption in the final phase of stratification.~~

~~With respect to~~ . MIX_{O_2} ~~the mass balances also reveal differences between the bottom layer and V_{sub}. In 2002, the effect on the bottom increased compared to its influence on~~

the sub-MLD by factor 3.6. In 2010, we see a similar increase by factor 3.4, and different to its has a consistently positive effect on the sub-MLD , MIX_{O_2} is continuously increasing the bottom O_2 concentration during the whole stratified period. The significant gain in the integrated effect of MIX_{O_2} as well as the consistent picture given for both yearsresults from the fact that the bottom layer shows generally lower than the layer directly above due to benthic remineralisation. This persistent gradient drives the downward diffusion of into the bottom layer. in both years. Its integrated effect is increased relative to V_{sub} by the factor 1.7 and 1.4 in 2002 and 2010, respectively.

Considering the The relative contribution of the biological processes consuming O_2 sinks in the bottom layer the picture also changed compared to that for is also different to the sub-MLD : as shown for the years 2002 and 2010, the comparison of the average value of volume. The 2000–2012 reveals that averages reveal that in the bottom layer REM_{sed} accounts for 50.1 ± 1.2 % of the total biological O_2 consumptionwhich represents the largest contribution, while REM_{pel} contributes to 32.2 ± 1.4 %. This reveals that Thus, aerobic remineralisation consistently adds up to more than 80 % of the biological O_2 consumption in the bottom layer. The shift in the relative contribution between these two processes occurs due to This shift results from the different volumes considered, and the fact that in ECOHAM5 REM_{sed} only has a direct effect on the deepest pelagic layer. That means, the absolute change in mass of Average O_2 consumption due to REM_{sed} is identical in both cases, while the change in concentration differs in relation to the different volumes consideredresults in values between 3.9 and 6.5 mmol O_2 m^{-2} d^{-1}.

To demonstrate the effect of REM_{sed} on bottom , we calculated the total changes in mass of due to REM_{pel}, and due to the REM_{sed} and REM_{pel} for V_{sub} and the bottom layer and finally calculate the ratio of their effect on V_{sub} to that For RES_{zoo}, the influence on the bottom layer. The total change in mass is calculated by multiplying the changes in the O_2 concentration with the corresponding volumes for the period 2000–2012 (not including 2008 due to shallower mixed layer). This yields that the total change in mass concentrations is lower than in V_{sub} due to REM_{pel} is about 4.7 ± 0.1 times larger than in the bottom layer. In contrast, the change in mass due to the combined effect of REM_{pel} and REM_{sed} is only about 2.4(11.3 ± 0.1 times larger for V_{sub}. In addition, the ratio between V_{sub} and the bottom layer volume is equivalent to about 4.2. This shows that REM_{pel} is less efficient in the bottom layer than in the other parts of V_{sub} and emphasises the great importance of REM_{sed} for the dynamics of bottom .

Regarding the rate of consumption due to benthic remineralisation, our model yields values between 3.9 and 6.5for region 3. These values are in the same order as those derived from observations giving a range from 7 to 251.2 for a nearby station (Upton et al., 1993, station 3) , however, rather at the lower end of this range. This suggests, that our model may slightly underestimate benthic remineralisation resulting in higher bottom concentrations compared to observed values.

As shown in Fig. 8 the influence of RES_{zoo} on the bottom concentration is lower than in V_{sub} as % during 2000–2012). This relates to the fact that zooplankton tends to stay in the upper part of the water column where phytoplankton concentrations are higher. Its relative contribution accounts for only 11.3±1.2during the years 2000–2012. NIT represents the weakest sink for bottom O_2 with an average contribution of 6.4 ± 0.6 % during these years. The standard deviations for RES_{zoo} and NIT are relatively high compared to their average contribution indicating higher inter-annual variationsPP as a potential source for O_2 is negligible in the bottom layer due to light limitation.

The analysis of the processes clearly shows vertical mixing is the only efficient gain term for O_2 in the bottom layerclearly shows that benthic . Benthic aerobic remineralisation constitutes the major driver for the development of low O_2 conditions deficiency in the North Sea O_2 minimum zone. Pelagic , although pelagic aerobic remineralisation still has a significant effect on bottom O_2, but accounts for a remarkably lower proportion than in the whole entire sub-MLD volume. This large impact of the two remineralisation processes is in good agreement with the common picture of bacterial respiration being the driving process for low conditions under stratified conditions (e.g. Diaz and Rosenberg, 2008) . In addition, the comparison of the sub-MLD and bottom layer mass balances for the two years showed that the processes in the pelagic zone, especially pelagic remineralisation, are crucial for the bottom concentrations as they define the potential supply into the bottom layer. In combination with the inter-annual differences in surface PP presented and the subsequent enhanced export of organic matter in 2002, this confirms that sufficiently long stratification provides the basis for low conditions, but the biological processes constitute the key element for the development of depletion. The simulated benthic remineralisation rates are in the same order as those derived from observations giving a range from 7 to 25 mmol O_2 m^{-2} d^{-1} for a nearby station (station 3 in Upton et al., 1993) , however, rather at the lower end of this range.

3.6 Spatial variability in the North Sea bottom O_2 dynamics

In order to unveil the regional differences in North Sea dynamics, Fig. 9shows the mass balances for the sub-MLD volume of two regions in the southern (panel a) and Figure 9a and b show the bottom O_2 mass balances of regions 4 (southern North Sea) and 5 (northern North Sea(panel b) in 2002 (see Fig. 2 for location of regions4 and 5) in comparison to that for region 3 (Fig. 8a).

Regarding the stratification characteristics, region 4 and 5 show some differences compared to region). Both regions show different stratification periods than in region 3. Even though the MLD according to Eqs. (1) and (2) also results in 15for both regions , the stratification periods differ. In region 4, the period between the first and last day of stratification accounts for only 163 days compared to 187 in region 3. Additionally, stratification is temporarily intermittent in late April and early July. In region 5, stratification lasts for 211 days without any interruptions. Considering the onset of stratification, stratification in region 4 and 5 starts 3and 1earlier than in region 3, respectively.

For a better understanding of the different effects of physical and biological factors in the different regions, it has to be kept in mind that the The water depths and bottom layer volumes also differ between the three regions. Region 3 has an average water depth of 47.75 m and a bottom layer volume of about 14.4 km^3, while region 4 is characterised by an average depth of 45 m and a bottom layer volume of 11.9 km^3. The greatest difference occurs for the region Region 5 , which has an average bottom depth of 99.2599.23 m and a bottom layer volume of 16.3 km^3.

The temporal development of in the bottom layer shows some significant differences for both regions between the three regions. Besides the lower O_2 concentrations at the beginning of the stratified period in both regions (9.79, regions 4 (9.74and 9.46 in region 3, 4 and mg O_2 L^{-1}) and 5 , respectively), the (9.46 mg O_2 L^{-1}) are lower than in region 3. In contrast, both regions show higher concentrations at the end of stratification for both regions are higher than in compared to region 3. These values reach 6.98 mg O_2 L^{-1} in region 4 and 7.61 mg O_2 L^{-1} in region 5, compared to 6.76 mg O_2 L^{-1} in region 3.

In region 4, the temporary breakdown of stratification in early July causes a remarkable increase in sub-MLD due to enhanced mixing visible in the sudden increase of MIX_{O_2}. This increase even exceeds the biological consumption, and the bottom pool is fully replenished which is illustrated by the match between and $O_{2,sat}$. It should be noted, that the strongest intense mixing in late June/early July, indicated by the steep increase in MIX_{O_2}precedes the interruption of stratification according to Eq. (1). This is caused by the fact that the complete overturning of the water column, and thus the vanishing of the surface-to-bottom T difference, requires more time than the breakdown of , causes the breakdown of stratification and the near-surface thermoclinecomplete replenishment of bottom O_2. Integrated over the stratified period the effect of MIX_{O_2} is almost 1.5 times higher than in region 3. In region 5, MIX_{O_2} represents a significantly lower supply of O_2accounting for only 16 and 11of that in region 3 and 4, respectively. This , which mainly relates to the significantly greater water depth resulting in favouring more stable stratificationas wind-induced mixing only affects the upper tens of metres. ADV_{O_2} has an opposite effect in regions 4 and 5 relative to region 3, however, showing only minor negative effects integrated over timeintegrated effects.

The comparison of the biological processes shows that as in region 3 the effect of bottom PP is negligible in region 4 and 5, due to light limitation. The integrated effect of the integrated biological O_2 consuming processes reveals that among the three regions, consumption is largest in region 4 exceeding even that of region 3 by consumption in region 4 is about 167 % . Biological less than in region 3. Referring to changes in O_2 consumption in region 5 accounts for only about 29concentrations, the consumption even exceeds that in region 3 by about 6 %of that in region 3. In that context, it is worth mentioning that the summer PP in the upper , due to the thinner bottom layer, and corresponds with an EXP_{org} below 25 m depth (calculation analogous to Table 1) in region 4 is similar to region 3, while the EXP_{org} below this depth is even being 19 % higher than in region 3. The difference between EXP_{org} and PP can also be attributed to local zooplankton production. The good agreement in the relative differences of EXP_{org} and biological consumption between region 3 and 4 confirms the strong link between these two factors in shallower regions. In In the deeper region 5, the upper layer PP and EXP_{org} account for only 78 and accounts for 62 % of that in region 3, respectively.while biological O_2 consumption accounts for only 35 % of that in region 3.

InterestinglyDespite the differences in the overall biological O_2 consumption, the relative contributions of the different sink processes in region 4 are in the same order as in region 3. REM_{sed} represents the largest contributor with about 54.6 % of the total biological consumption, while REM_{pel} accounts for 27.2 %. For RES_{zoo} and NIT the relative contributions result in 13.6 and 4.6, respectively. ConsequentlyThus, the combined effect of REM_{sed} and REM_{pel} accounts for 81.8 % which is similar to region 3.

Comparing the rates of benthic remineralisation derived from the simulation to literature for region 4, which lies within the Oyster Grounds area, provides a similar picture as for region 3. The simulation yields a benthic remineralisation rate of about Average daily benthic remineralisation rates are higher than in region 3 and yield 8.9 for 2007, while observational studies near this site obtained rates between 5.6 mmol O_2 m^{-2} d^{-1}. The relative contributions for RES_{zoo} and NIT result in 13.6 and 30.6(Lohse et al., 1996; Weston et al., 2008) . This confirms the picture from region 3, that the model most likely underestimates the impact of benthic remineralisation on the bottom . In addition, this higher rate in region 4 compared to region 3 underlines the high potential for low conditions in the Oyster Grounds under persistent seasonal stratification. This is in good agreement with the findings by Greenwood et al. (2010) , who observed bottom concentrations less than 64.6 in this area%, respectively.

The comparison of the relative contribution of REM_{pel} and REM_{sed} in region 5 reveals some changes ~~with respect to these two processes.~~ compared to regions 3 and 4. REM_{sed} accounts for about 70 % of the total biological O_2 consumption, while REM_{pel} contributes to only about 20 %. ~~With respect to the volume and corresponding greater thickness of the bottom layer we would expect a lower relative contribution of REM_{sed} compared to the other regions. However, the~~ This relates to the generally lower amount of organic matter exported into the deeper layer (63 % of that in region 3)~~results in a lower concentration~~ , due to the greater bottom depth, resulting in lower concentrations of pelagic bacteria. On the one hand, this causes lower O_2 consumption due to REM_{pel}, and on the other hand, enhances REM_{sed} relative to REM~~$_{sed}$~~$_{pel}$ as more organic matter ~~is deposited and remineralised in the sediment~~reaches the bottom.

Considering the combined effect of stratification ~~, i.e. mixing, water depth and bottom layer volume,~~ and biological consumption ~~, it is shown,~~ in region 4 reveals that the shorter ~~duration of stratification and~~ stratification period and the strong mixing prohibit the ~~occurrence of strong mixing in region 4 prohibit the development~~ evolution of low O_2 conditions ~~, even though biological consumptionis larger than in region 3. In region 5 stratificationlasts longer than in the other two regions without any interruptions, however, the biological consumption is significantly lower than~~ in this region, despite the highest biological consumption. The higher benthic remineralisation rate compared to region 3 underlines the high potential for low O_2 conditions in the Oyster Grounds under persistent seasonal stratification. This is in good agreement with the findings by Greenwood et al. (2010) , who observed bottom O_2 concentrations less than 6 mg O_2 L^{-1} in this area. As in region 3~~and 4 as less organic matter is supplied to the deeper layers. In addition, the water depth, i.e. , the sub-MLD volume, in region 5 is significantly larger~~ , the simulated benthic remineralisation rate lies at the lower end of the range of 5.6 to 30.6 mmol O_2 m^{-2} d^{-1} obtained from observational studies near this site (Lohse et al., 1996; Weston et al., 2008) . This suggests that the model most likely underestimates benthic remineralisation rates.

In region 5, the export of organic matter into the bottom layer is limited due to the great water depth. Thus, biological consumption in the bottom layer is low, preventing the evolution of O_2 deficiency, even though stratification lasts longer and is more stable than in the other regions. This suggests that region 5 is unlikely to be affected by low bottom O_2 concentrations. However, this region lies in the area where Queste et al. (2013) found a Queste et al. (2013) found bottom O_2 minimum in 2010. They concluded that this minimum resulted from a combination of stratification, limiting the ventilation of the deeper layers with oxygenated surface waters, and the specific bathymetry, which limits the lateral exchange with the -enriched surrounding waters. Our results showed that advection only has a minor influence on the bottom in this area concentrations of about 6 mg O_2 L^{-1} near this area in 2010, which indicates that other processes may have caused this this area can be affected by O_2 minimumdeficiency.

3.7 Interpreting observed bottom O_2 at North Dogger

At The O_2 observations at station North Dogger (see Fig. 2, region 2) continuous bottom data were recorded in the years 2007 and 2008 (Greenwood et al., 2010) . These observations (Greenwood et al., 2010) shown in Fig. 3a and b showed similar O_2 concentrations of about 9.5 mg O_2 L^{-1} at the beginning of the stratified period, but revealed a faster decrease in bottom O_2 during 2007 compared to 2008. As simulation also showed this the simulation showed the same tendency with respect to the inter-annual differences, we want to use the model-based mass balance to explain the differences in the observations between the two years at North Dogger . These mass balances the mass balances for station North Dogger for 2007 and 2008 are presented in Fig. 10a and b, respectively, in order to interpret the observed temporal evolution of bottom O_2.

Calculating the average rates The simulation yields an average rate of O_2 reduction during the stratified period we obtain about −of about 0.009 for 2007. For 2008, the simulation yields a lower mg O_2 L^{-1} d^{-1} in 2007, and a rate of about −0.007. The value for 2007 slightly underestimates the value of −0.012derived from the observation by Greenwood et al. (2010) , however, is still in the same order. Even though the temporal development in 2008 was not discussed in detail by Greenwood et al. (2010) as the data recording ended before minimum bottom was reached, the available data indicate lower reduction rates in 2008 compared to 2007 (see Fig. 3a and b).

This poses the question, which processes affecting vary between the two years. Regarding the supply due to $\mathrm{mg\,O_2\,L^{-1}\,d^{-1}}$ in 2008. The integrated effect of the physical factors, ADV_{O_2} and MIX_{O_2}, it is shown, that the integrated effect of both is quite similar for both years providing a gross increase in O_2 of about 1.3516.3 $\mathrm{g\,O_2\,m^{-2}}$ integrated over the stratified period. The only small temporally integrated effect of ADV_{O_2} shows that even though the North Dogger area is affected by relatively strong advection (Greenwood et al., 2010) , this must not necessarily result in enhanced ventilation in terms of bottom . This relates to the fact that the deeper waters in the surrounding regions show only slightly higher concentrations, which causes an only minor net effect of advection on bottom . This demonstrates, that Thus, the main inter-annual variations are must be related to biological factors.

While the two years show basically similar features in terms The temporal evolution of the biological consumption processes , these processes are characterised by is also similar in both years, with higher rates in 2007 than in 2008. In 2007, the integrated consumption 2007. The integrated effect of all biological sink processes results in −3.440.6 $\mathrm{g\,O_2\,m^{-2}}$, which corresponds with an average reduction rate of −0.0154consumption rate of 0.18 $\mathrm{g\,O_2\,m^{-2}\,d^{-1}}$. For 2008, the simulation yields a by 0.66.8 lower integrated consumption related $\mathrm{g\,O_2\,m^{-2}}$ lower biological consumption due to a by 0.0020.02 lower reduction $\mathrm{g\,O_2\,m^{-2}\,d^{-1}}$ lower consumption rate. This constitutes a relative difference of 13 % between the reduction rates due to biological consumption of the two years. Comparing the For EXP_{org} below 25 m depth during summer (calculation analogous to Table 1), the same relative difference occurs, which again shows the strong link between organic matter export and biological consumptionis found.

Despite the significant inter-annual differences in EXP_{org}, the The relative contribution of the different processes to the overall bottom O_2 consumption shows only minor changes between the two years. In both years REM_{sed} accounts for about 58 %, while REM_{pel} accounts for about 31 %. RES_{zoo} and NIT contribute to about 3 and 8 % in both years, respectively. This shows that inter-annual variations in the O_2 dynamics at North Dogger are mainly driven by differences in the organic matter export. The steeper decrease in bottom O_2 in 2007 results from the enhanced supply of organic matter and the subsequent increased degradation by bacteria. The enhanced release of ammonium due to pelagic and benthic remineralisation consequently triggers an increase in nitrification.

In contrast to the findings by Greenwood et al. (2010) , who argued that the relatively strong advection at North Dogger may ventilate the bottom layers in terms of O_2, our results suggest that advection only has a minor positive effect due to the only slightly higher O_2 concentrations in the surrounding waters. The large contribution of bacterial remineralisation (REM_{sed} and REM_{pel}) accounting for almost 90 % of the overall biological consumption at station North Dogger confirms that the estimates for ~~C~~ C remineralisation rates made by Greenwood et al. (2010) provide reasonable results. However, as NIT also accounts for about 8 % of the total biological O_2 consumption, this process should be considered to obtain more precise estimates for ~~C remineralisation ratesat Station North Dogger~~C remineralisation rates.

~~Our analysis of the observed temporal development of bottom at station North Dogger using the HAMSOM-ECOHAM5 model system showed, that despite minor differences between simulation and observation, ecosystem models can help to interpret measurements with respect to the underlying dynamics. Meire et al. (2013) undertook a similar study for the Oyster Grounds using a one-dimensional physical-biogeochemical model. However, in our study we showed that three-dimensional models can provide the combined benefit of data interpretation and the identification of spatial and temporal patterns in the dynamics.~~

4 Conclusions and perspectives

The North Sea is one of the shelf regions regularly ~~suffering from seasonal hypoxia~~ experiencing seasonal O_2 deficiency in the bottom water (Diaz and Rosenberg, 2008;

Emeis et al., 2015; Rabalais et al., 2010). However, not all areas of the North Sea are similarly affected by low O_2 conditions ~~(e.g. Queste et al., 2013)~~ (e.g., Queste et al., 2013) due to different characteristics with respect to stratification and ~~upper layer productivity. Our study demonstrated that biogeochemical models can be useful to understand and explain these differences.~~ O_2 consumption. Observations and model results suggest that the area between 54–57° N and 4.5–7° E shows the highest potential for low O_2 conditions, but also areas around the Doggerbank experience lowered bottom O_2 concentrations.

~~Our~~ The model-based analysis of different factors affecting O_2 (Sect. 3.3) showed that besides sufficiently long stratification (> 60 days), the upper layer primary production (driving organic matter export) and the sub-thermocline volume are the key parameters influencing the bottom O_2 evolution. Based on this, the North Sea can be subdivided into three different ~~regimes~~ zones in terms of O_2 dynamics: (1) a highly productive, non-stratified coastal ~~regime~~ zone (region A), (2) a productive, seasonally stratified ~~regime~~ zone with a small sub-thermocline volume (region B), and (3) a productive, seasonally stratified ~~regime~~ zone with a large sub-thermocline volume (regions C and D). While the ~~regimes~~ zones of type 1 and 3 are unlikely to be affected by low O_2 conditions due to either continuously ongoing ventilation (type 1) or the large sub-thermocline volume damping the effect of O_2 consumption (type 3), type 2 is highly susceptible to low O_2 conditions. This results from the specific combination of high upper layer productivity and small sub-thermocline volume, which causes a strong impact of the consumption processes on the decrease in the bottom O_2 ~~concentration.~~ concentrations.

The ~~model-derived~~ presented ODI approach demonstrates that this regional characterisation, based on only three controlling parameters, can be applied to most parts of the North Sea. The strong link between upper layer primary production and organic matter export allowed for the further simplification. Similarly, the bottom depth can be used as a proxy for the sub-thermocline volume. Consequently, the ODI is less complex in comparison to the eutrophication risk index (EUTRISK; Druon et al., 2004) , which intends to directly map bottom O_2 ~~mass balances showed that~~ concentrations. In contrast, the ODI is designed to indicate regions with higher risk for O_2 deficiency. As the definition of the ODI is based on parameters which are easily accessible, the ODI may also allow for an operational use as the information on stratification can be derived from operational hydrodynamical models and information on net primary production from satellite data.

While the regional characteristic and the ODI only provide a qualitative picture of the North Sea O_2 dynamics, the model-derived mass balances allowed for the quantification of the governing processes and their inter-annual and spatial variability. Inter-annual variations in the sub-thermocline and ~~in the~~ bottom O_2 ~~development are mainly caused~~ evolution are mainly driven by differences in the upper layer ~~productivity as increased primary productivitydirectly and indirectly enhances the export of organic matter into the deeper layers. Higher primary production results in larger amounts~~ primary productivity. This supports the choice of net primary production as a proxy for the organic matter export in the ODI definition, and its stronger weighting therein. In addition, the mass balances revealed how the different direct and indirect effects of primary productivity influence the O_2 dynamics. Increased primary productivity enhances the export of dead phytoplankton ~~sinking below the thermocline, and increased phytoplankton growth~~ into the deeper layers. Furthermore, it enhances zooplankton growth which causes an additional increase in organic matter production and export. ~~Furthermore,~~ This enhanced zooplankton growth further increases O_2 consumption due to ~~zooplankton~~ respiration. The ~~increased export of organic matter~~ overall increase in organic matter export results in stronger bacterial remineralisation which in turn triggers nitrification due to the stronger release of ammonium.

~~With respect to the biological~~ The mass balances also showed that pelagic bacterial remineralisation constitutes the largest O_2 ~~consumption our study revealed remarkable differences between the dynamics of~~ consuming process within the sub-thermocline volume~~and~~, thus, it is crucial for the O_2 supply from the mid-water into the bottom layer. ~~While pelagic bacteria represent the major consumer in the sub-thermocline volume~~In the bottom layer, benthic remineralisation constitutes the major ~~driver for the bottom development. In addition, our results suggest that the relative contribution of the different~~ O_2 ~~consuming processes in the bottom layer at a certain location depends on the water column depth and is independent of the overall consumption. Benthic remineralisation consistently accounts~~

for sink, which consistently contributes to more than 50 % of the overall bottom O_2 consumption and revealed shows an increasing relative contribution with increasing bottom depth. In contrast, pelagic remineralisation is characterised by a decreasing influence in deeper regions , due to the fact, that as organic matter concentrations within the pelagic bottom layer are lower in greater depth. Its relative contribution to the overall bottom O_2 consumption exceeds consistently consistently exceeds 20 %. The effect of zooplankton respiration varies between almost no effect in deep regions and up to 14 % in shallower areas, whereas nitrification shows only minor variations in its relative contribution (3–8 %). Besides this, the results suggest that the relative contribution of the different O_2 consuming processes in the bottom layer at a certain location depends on the water column depth and is independent of the overall consumption.

While our results showed that organic matter production and the subsequent bacterial remineralisation are the main drivers for the In contrast to the interpretation of O_2 consumption, our study confirmed that vertical mixing represents the only efficient gain term for measurements by Queste et al. (2013) , who proposed that events of mixing and/or advection of oxygenated water are likely to positively affect the bottom O_2 in most regions. In addition, our simulations revealed that advection of concentrations, our analysis suggests that advection usually only has a minor effect on the bottom O_2 -enriched water from the surrounding areas dynamics in most North Sea regions. However, during years of especially low bottom O_2 concentrations it may play an important role for the recovery of sub-thermocline and bottom the O_2 concentrations levels at the end of the stratified period, even before stratification breaks down and vertical mixing replenishes the bottom O_2 concentration.

With respect to the regional distribution of hypoxia in the North Sea, observations and model results revealed that the area between 54–57N and 4.5–7E shows the highest potential for hypoxic conditions, but also areas directly north and south of the Doggerbank experience lowered bottom concentrations. In addition, we showed that during the summer period only very strong mixing results in a net increase in O_2 concentrationsas the enhanced nutrient supply triggers primary production, eventually increasing the biological O_2 consumption, which balances or even exceeds the enhanced O_2 supply.

By providing this valuable insight, the present study The qualitative characterisation and the detailed quantitative analysis demonstrates the potential of ecosystem models to describe key features of the O_2 dynamics as an integral part of the North Sea ecosystem. Model simulations can unveil the complex interplay between hydrodynamical conditions and biological processes, and thus, can help to interpret In combination with the provision of a spatially and temporally consistent picture, this is a strong benefit compared to one-dimensional model studies (e.g., Meire et al., 2013) . With the capability to describe the temporal evolution and spatial patterns of bottom O_2, ecosystem models can be used to obtain a more detailed picture of the spatial extent and duration of low O_2 conditions. This is useful for the detection of regions susceptible to low O_2 conditions which therefore require enhanced management, and is of importance for monitoring authorities as our model showed that temporal variability in late-summer bottom O_2 is small implying that measurements taken during this period provide a synoptic picture of the North Sea O_2 conditions.

In addition, three-dimensional models can provide valuable insight in the O_2 dynamics in the context of the natural variability of the ecosystem. This can be related to weather conditions which result in different stratification patterns of the North Sea, or in variations in the biological production. The latter can be induced by anthropogenic drivers, such as increased atmospheric deposition (Troost et al., 2013) or riverine nutrient input as shown for the exceptionally wet year 2002 (Lenhart et al., 2010). Thus, ecosystem models can help to estimate the impact of these anthropogenic impacts on the bottom O_2 depletion in offshore areas which are susceptible to hypoxiaO_2 deficiency.

With the capability to describe the temporal development and spatial patterns of bottom , ecosystem models can be used to obtain a more detailed picture of the spatial extent and duration of hypoxic conditions. This is useful for the detection of regions susceptible to low conditions which therefore require enhanced management. While this study This study is focused on the general characterisation of the key factors driving the North Sea

O_2 dynamics ~~, detailed studies could, e. g. , further~~ and a description and analysis of the North Sea ecosystem in its present state, including the actual eutrophication status in the "continental coastal region" as defined for the OSPAR assessment (Claussen et al., 2009) . The question on the anthropogenic part of the O_2 deficiency problem in relation to elevated river loads is beyond the scope of this study and would require additional model scenarios taking into account pristine conditions without any anthropogenic contribution (Serna et al., 2010) . Besides the determination of the anthropogenic contribution, further studies are needed to investigate the cause-effect relationship between the ~~high riverine nutrient loads and the major hypoxic event in 2002. In combination with the observational data available, this supports a meaningful discussion of the eutrophication status of the North Sea~~effect of the discharges of inorganic nutrients and organic matter by the rivers (Topcu and Brockmann , 2015) . Kemp et al. (2009) analysed the success of restoring different ecosystems with and without taking into account the organic matter input by rivers. Based on our findings on the processes dominating the bottom O_2 evolution, such studies would allow managers to make informed decisions about necessary management measures.

This assessment can be extended towards new measures to combat eutrophication within the Water Framework Directive (WFD), in which dissolved O_2 plays an important role as one of the five "General chemical and physiochemical elements supporting the biogeological elements" for assessment (Best et al., 2007). As the WFD assessment depends strongly on the description of pristine conditions related to natural nutrient levels (Topcu et al., 2009), ecosystem models can provide insight in the O_2 dynamics under these pristine conditions, and in addition, for the application of the WFD measures (Schernewski et al., 2015) on the North Sea. Even though the WFD regulation is applied only ~~on~~ to a narrow band along the coastline, the question of how nutrient reductions under WFD measures will effect the entire North Sea ecosystem, also in terms of bottom O_2 conditions, is highly relevant. Therefore, O_2 is one of the main descriptors under the Marine Framework Directive (MSFD) for the definition of the "Good ~~environmental~~ Environmental Status" as the target condition.

The article on the "spreading dead zones" by Diaz and Rosenberg (2008) resulted in an increased public awareness of the hypoxia issueO_2 deficiency, also in the context of the debate on climate change. One can start the discussion with the straight forward argument that climate change scenarios show an earlier onset and increased intensity of stratification for the North Sea due to increasing temperatures (Lowe et al., 2009; Meire et al., 2013). In addition, Mathis and Pohlmann (2014) also found an increase in the water temperatures of the North Sea, however, accompanied by a weakening of stratification which would support enhanced ventilation of the bottom water. The increase in temperature will decrease the O_2 solubility in the bottom layer (Weston et al., 2008). Changes in the weather conditions, such as increased precipitation or other extreme events (Rabalais et al., 2010), could furthermore lead to increased nutrient loads triggering higher primary production which could increase the risk of hypoxia low O_2 conditions (Justić et al., 2003). In contrast, Gröger et al. (2013) predicted a North Sea wide reduction in primary production by about 30 % due to reduced winter nutrient import from the Atlantic. Another potential impact was argued by van der Molen et al. (2013), who concluded that the temperature-driven increase in metabolic rates and nutrient cycling will be followed by an increase in primary production. In combination with an increase in the benthic metabolic rates and other constrains, this will eventually lead to a decrease in the bottom O_2 concentrationconcentrations.

As these potential changes in the O_2 conditions will also affect the biological community in biocoenosis of the North Sea (Emeis et al., 2015), it is important to foster the analysis of potential impacts of climate change and changes in nutrient loads on the O_2 dynamics. This study provided evidence that ecosystem models can contribute to the better understanding of the complex interplay of hydrodynamical and biogeochemical processes controlling the bottom O_2 dynamics in the North Sea. This study showed that ecosystem models can be used to either interpret in-situ O_2 measurements, or to estimate the impact of climate change or nutrient reduction scenarios with respect to hypoxia O_2 deficiency and its concomitants. Thus, they can provide relevant information for the ecological management of marine coastal ecosystems.

Data availability

The time series data from the Cefas SmartBuoy programme can be accessed via: http://cefasmapping.defra.gov.uk/Smartbuoy. The time series data of BSH MARNET programme can be accessed via: http://www.bsh.de/en/Marine_data/Observations/MARNET_monitoring_network/. The spatially resolved data from the North Sea cruises 2001, 2005 and 2008 have been released in the framework of the EU-FP6 project CARBOOCEAN and can be accessed via: http://dataportal.carboocean.org/.

Appendix A: Evaluation of the stratification and MLD criterion

Figure A1 shows the Hovmöller diagram of simulated T at station North Dogger (see Fig. 2, region 2) for the year 2007, including the MLD (dashed magenta line) derived from the simulated T field according to Eqs. (1) and (2). Regarding the onset of stratification in late March it is shown, that the near-surface T (down to 25 m) starts to increase relatively to the T in deeper layers. The beginning of the stratified period on 26 April coincides very well with this slowly evolving separation of surface and bottom waters. The maximum vertical T gradient at the onset occurs in 25 m depth. From that moment stratification according to Eq. (1) persists until 31 October, which may represent a slight overestimation as the maximum T gradient is found in 60 m depth already, indicating deep mixing.

During the first two months of the stratified period (April/May) the MLD shows stronger fluctuations in terms of its actual depth. This results from the relatively weak near-surface stratification, and thus, the stronger effect of mainly wind-induced mixing reaching depths of up to 35 m. These events are indicated by the episodic increase and decrease of surface T. From early June to end of July, the MLD is less variable in depth due to the persistent surface heating and less strong wind events. In late June a short-term decrease in surface T indicating enhanced mixing occurs which also results in a deepening of the MLD. From August until the end of the stratified period the MLD shows a deepening trend which is caused by the decreasing surface heating and increasing wind activity.

The main assumption behind the rather small critical T difference of 0.05 K is, that even if the surface mixed layer is interrupted due to mixing, this does not necessarily result in a complete overturning of the water column. Thus, even a minor difference in T indicates a bottom layer unaffected from vertical mixing. Despite this significant difference to common MLD criteria (e.g Kara et al., 2000, therein Table 1) , the criterion applied in this study represents the stratification conditions quite well. However, it should be noted that the end of the stratified period may be slightly overestimated. In addition, in regions with a less pronounced onset of stratification, i.e., a less distinct increase in surface T, the determined timing of the onset may be slightly too early. The use of the maximum T gradient to determine the MLD under stratified conditions yields reasonable results, and is closely related to real conditions as the thermocline is defined as the layer with the maximum T gradient.

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Table 1. ~~Critical~~ Average critical quantities (2000–2012) characterising the O_2 dynamics in the four different ~~4×~~4×4-regions (see Fig. 2, yellow boxes). Fluxes are cumulated ~~over the given period~~ from 1 April to 30 September and relate to a surface layer of thickness $D_{ref} = 25$ m.

region		A – SNS	B – SCNS	C – NCNS	D – NNS
PP_{mld}	$g\,C\,m^{-2}$	169.0	147.8	134.6	148.1
$ADH_{org,in}$	$g\,C\,m^{-2}$	95.9	109.2	92.3	111.0
$ADH_{org,out}$	$g\,C\,m^{-2}$	89.2	107.6	92.7	114.4
EXP_{org}	$g\,C\,m^{-2}$	23.4	17.5	16.2	18.4
MIX_{O_2}	$g\,O_2\,m^{-2}$	116.1	66.7	13.7	18.2
initial O_2	$mg\,O_2\,L^{-1}$	10.1	9.9	9.5	9.5
final O_2	$mg\,O_2\,L^{-1}$	7.7	7.9	8.0	8.3
t_{strat}	days	80	151	220	226
D_{mld}	m	11.4	14.7	23.1	25.7
D_{bot}	m	39.6	43.5	93.0	113.4
area	km^2	7643.1	7454.3	7108.9	6677.2
V_{sub}	km^3	111.3	138.0	483.3	590.5

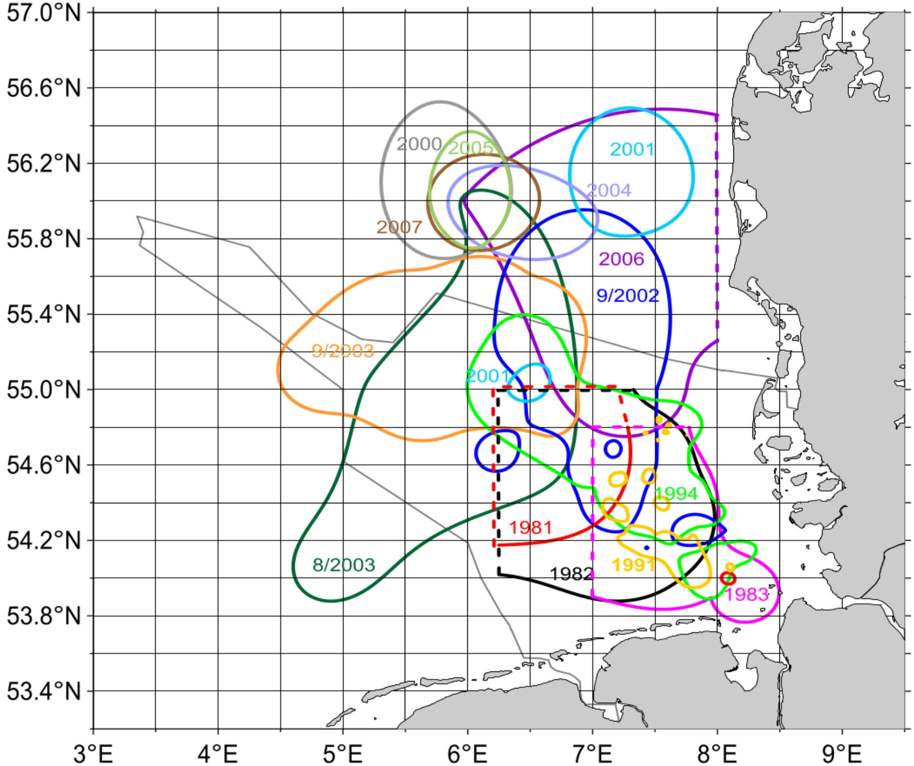

Figure 1. Extent of observed O_2 concentrations <6 <6 mg O_2 L^{-1} in the German Bight area from 1980 to 2010. Survey limitations are indicated by dotted lines. Light grey line marks German Maritime Area (from Topcu and Brockmann , 2015).

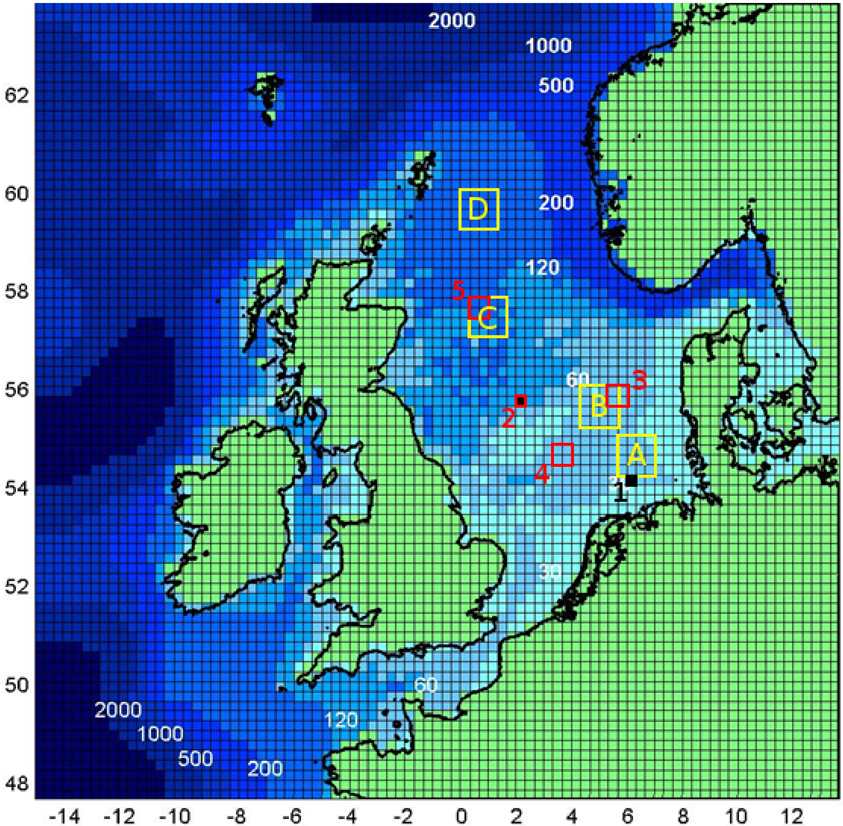

Figure 2. Horizontal grid and bottom topography of the ~~HAMSOM-ECOHAM5~~ HAMSOM-ECOHAM model domain. White numbers indicate depth levels. Yellow boxes A–D mark the ~~4×~~4×4-regions used for the characterisation of key features presented in Sect. 3.3. Black-filled boxes (1, 2) mark the validation sites discussed in Sect. 3.1.1 Red-framed boxes (2–5) indicate regions used for the O_2 mass balance calculations in Sects. 3.4–3.7.

~~Hovmller diagram of simulated T and MLD according to Eqs. (1) and (2) at Cefas station North Dogger (see Fig. 2, region 2) in 2007. Depth levels represent the centre depth of model layers.~~

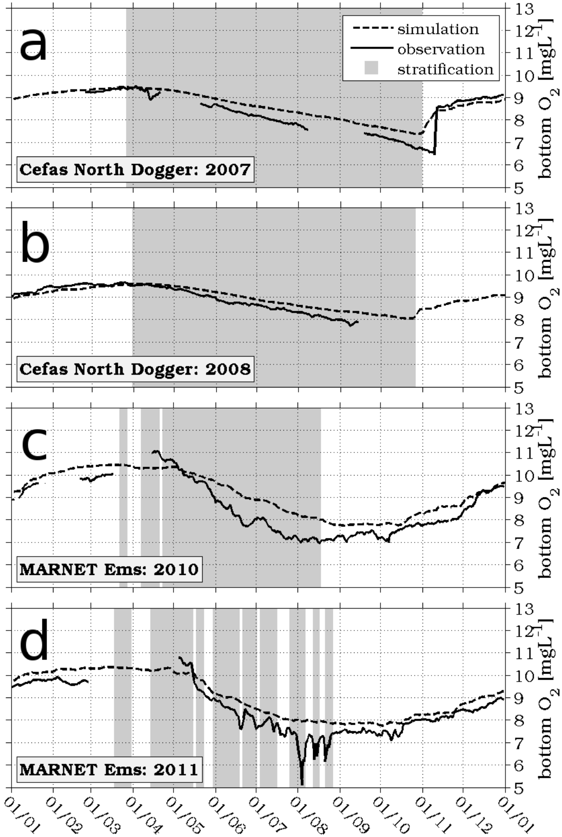

Figure 3. Annual time series of observed and simulated bottom O_2 ~~concentration~~ concentrations at Cefas station North Dogger in **(a)** 2007 and **(b)** 2008, and at MARNET station Ems in **(c)** 2010 and **(d)** 2011. Same legend for all panels. Grey shaded areas indicate the stratification periods derived from simulated T according to Eq. (1.

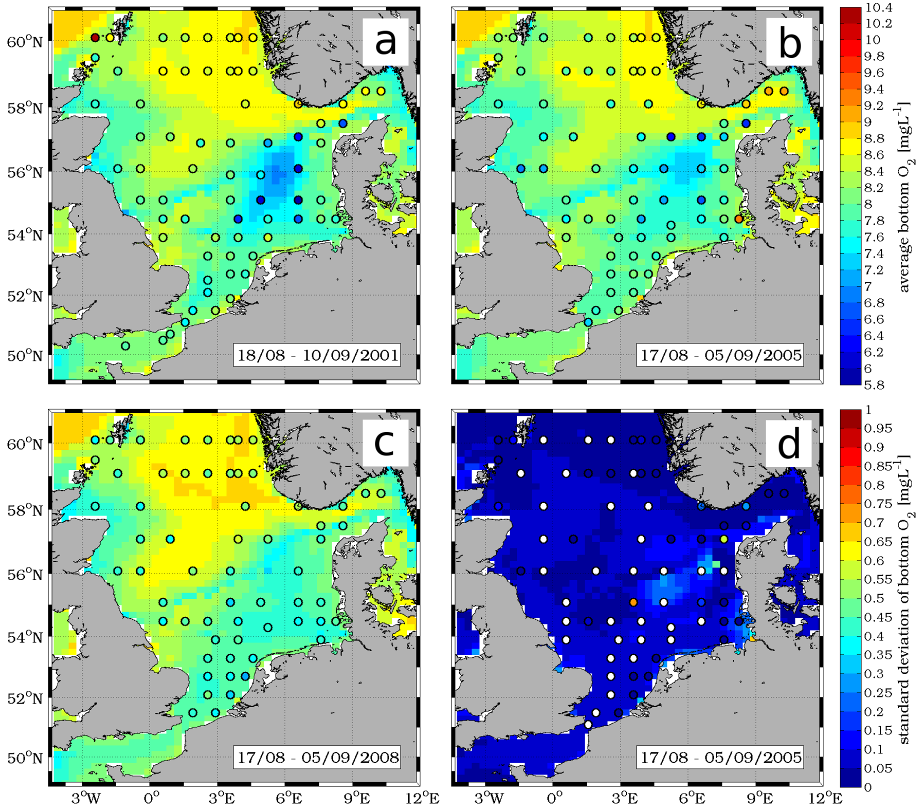

Figure 4. Spatial distribution of observed and simulated average bottom O_2 ~~concentration~~ concentrations in late summer **(a)** 2001, **(b)** 2005 and **(c)** 2008, and **(d)** standard deviation in 2005. Colour scale of panel **(b)** applies to panels **(a–c)**. Circles indicate sample sites, underlying colours show simulation results. Averages and standard deviation were calculated for the ~~whole~~ entire observation period (bottom-left corner of each panel). White circles in **(d)** mark model bottom grid cells with only one corresponding observed value (i.e., no standard deviation).

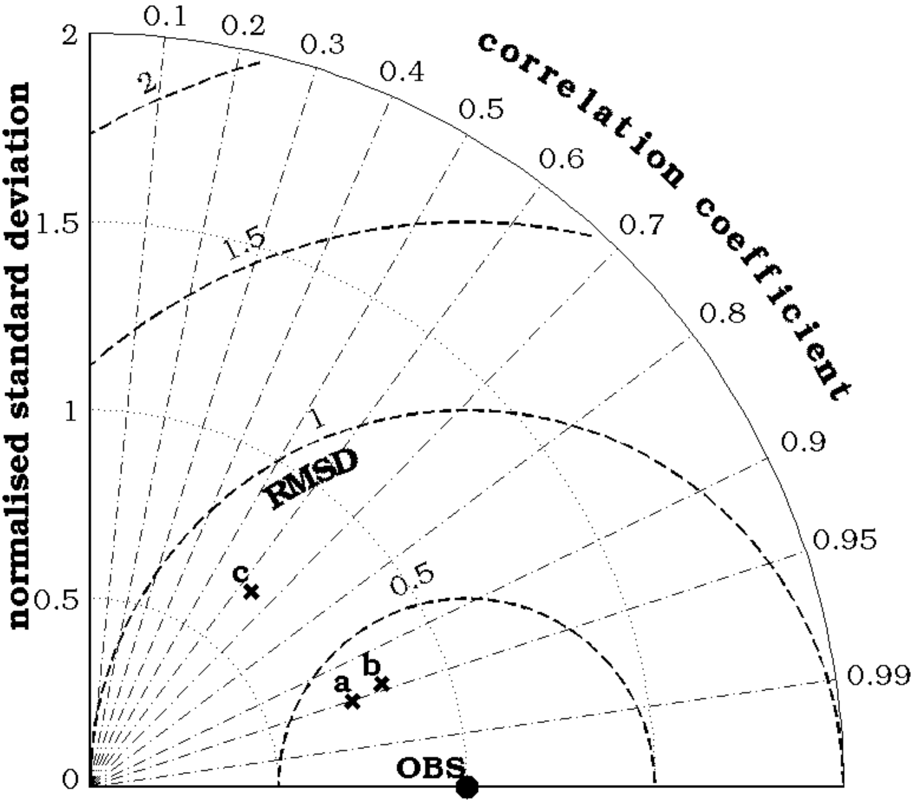

Figure 5. Taylor diagram of simulated (×) bottom O_2 ~~concentration~~ concentrations compared to observations (OBS) for time series (see Fig. 3) at **(a)** Cefas North Dogger and **(b)** MARNET Ems, and **(c)** spatially resolved data (see Fig. 4). Standard deviations and centred root-mean-square differences (RMSD) were normalised by the standard deviation of the corresponding observations.

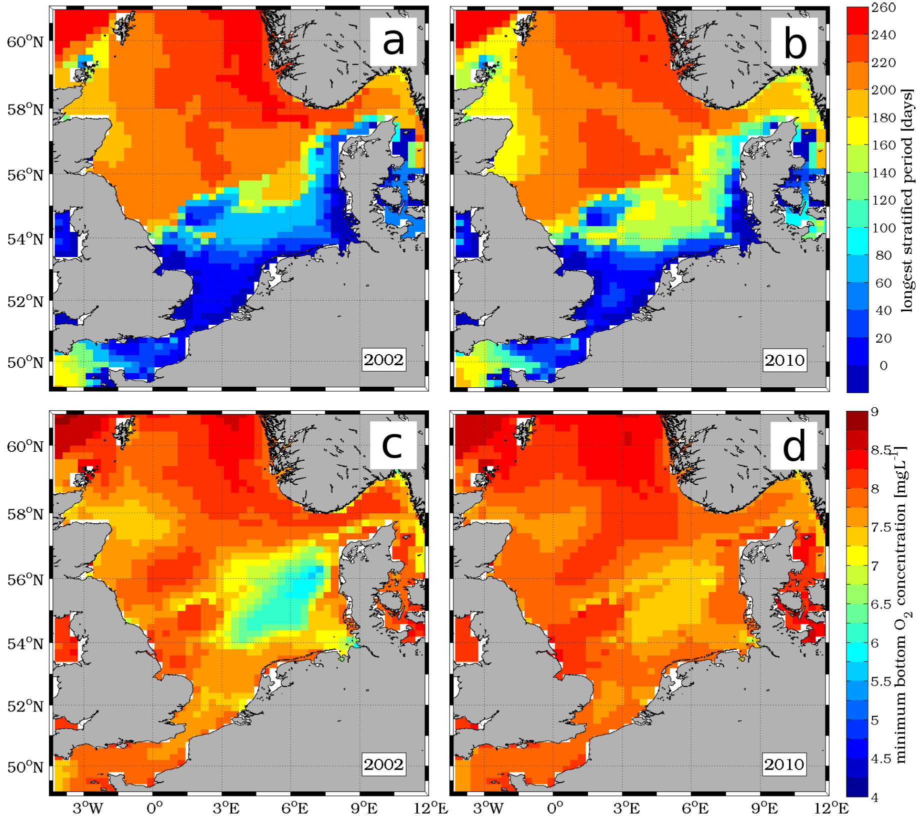

Figure 6. Spatial distributions of **(a, b)** longest continuous stratification period derived from simulated T according to Eq. (1) and **(c, d)** simulated annual minimum bottom O_2 concentration concentrations for the years 2002 **(a, c)** and 2010 **(b, d)**. Same colour scales for **(a, b)**, and **(c, d)**.

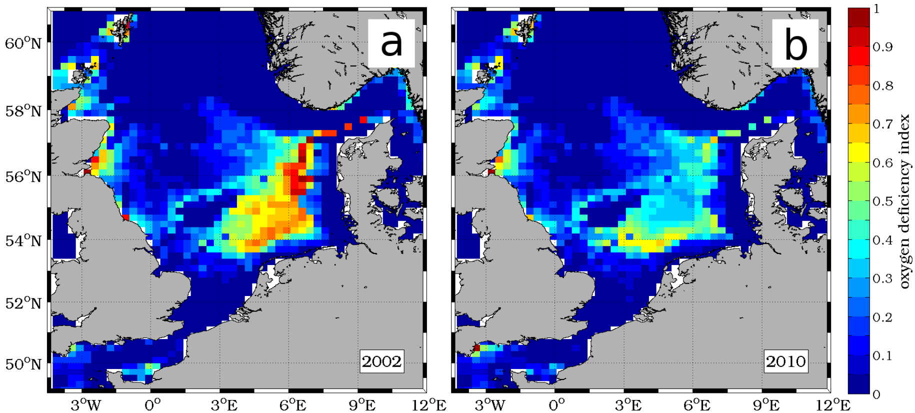

Figure 7. Spatial distribution of oxygen deficiency index (ODI) according to Eq. (5) for the years 2002 **(a)** and 2010 **(b)**.

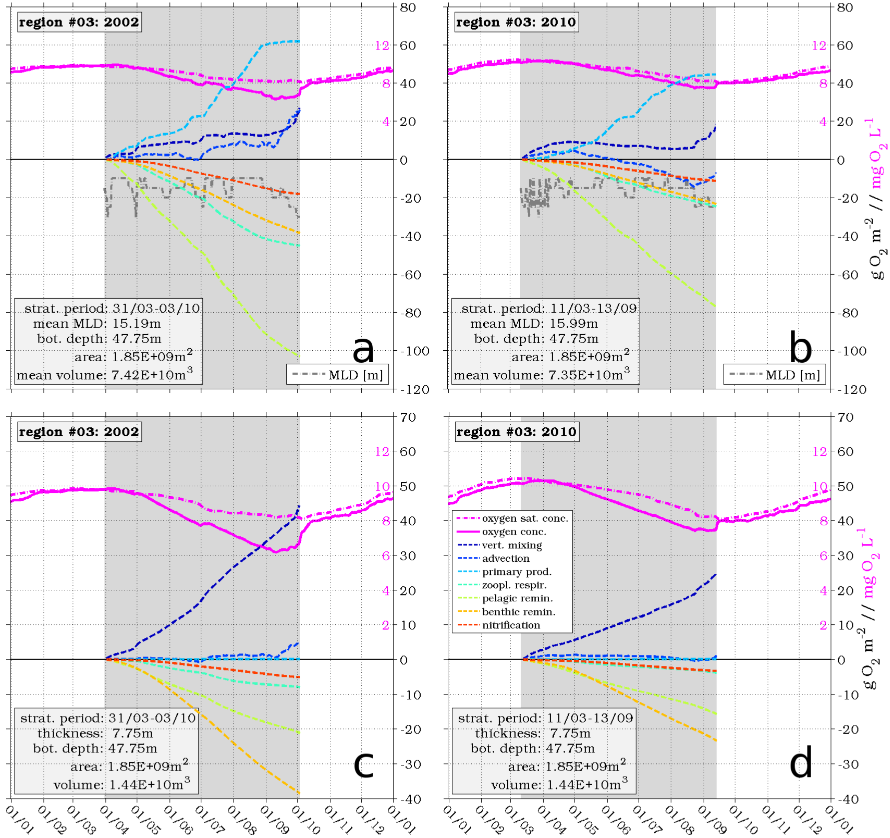
region #03: 2002
strat. period: 31/03-03/10
mean MLD: 15.19m
bot. depth: 47.75m
area: 1.85E+09m^2
mean volume: 7.42E+10m^3
MLD [m]
a
region #03: 2010
strat. period: 11/03-13/09
mean MLD: 15.99m
bot. depth: 47.75m
area: 1.85E+09m^2
mean volume: 7.35E+10m^3
MLD [m]
b
g O$_2$ m^{-2} // mg O$_2$ L^{-1}
region #03: 2002
strat. period: 31/03-03/10
thickness: 7.75m
bot. depth: 47.75m
area: 1.85E+09m^2
volume: 1.44E+10m^3
c
region #03: 2010
oxygen sat. conc.
oxygen conc.
vert. mixing
advection
primary prod.
zoopl. respir.
pelagic remin.
benthic remin.
nitrification
strat. period: 11/03-13/09
thickness: 7.75m
bot. depth: 47.75m
area: 1.85E+09m^2
volume: 1.44E+10m^3
d
g O$_2$ m^{-2} // mg O$_2$ L^{-1}
01/01 01/02 01/03 01/04 01/05 01/06 01/07 01/08 01/09 01/10 01/11 01/12 01/01

Figure 8. Mass balances of simulated O_2 in region 3 (see Fig. 2) during ~~the stratified period~~stratification (grey shaded): **(a, b)** for the ~~whole~~ entire volume below the ~~annual median~~ MLD (grey dash-dotted; according to ~~Eq~~Eqs. (1) and (2)), and **(c, d)** only for the bottom layer for the years 2002 **(a, c)** and 2010 **(b, d)**. Same legend for all panels. ~~Magenta~~ Black y ~~axis applies~~ axes apply to processes, magenta y axes apply to O_2 (saturation) ~~concentration~~concentrations. Values of black y axes in **(a, b)** also apply to MLD (unit: m). Changes in ~~concentration~~ O_2 due to different processes are cumulative. Text boxes list relevant stratification parameters, ~~bottom depth and~~ average volume of the analysed water body and bottom depth. Note different y ~~axis~~ axes for ~~**(a–d)**~~**(a, b)** and **(c, d)**.

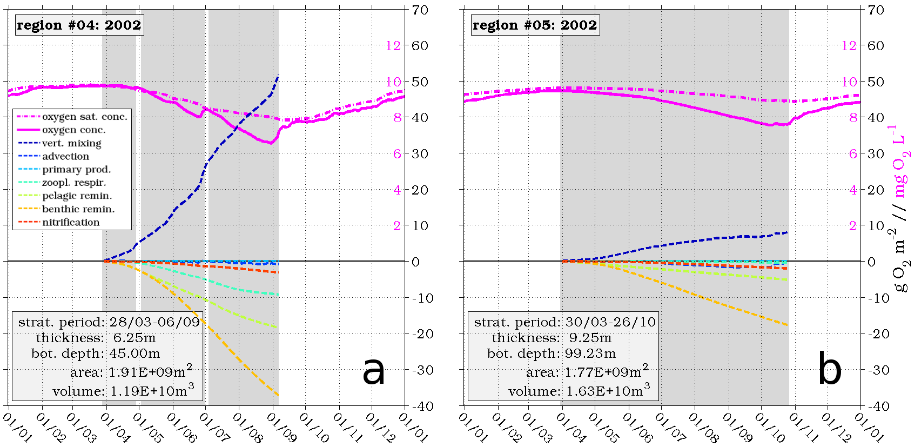

Figure 9. Mass balances of simulated bottom O_2 in regions 4 **(a)** and 5 **(b)**; (see Fig. 2) during ~~the stratified period~~ stratification (grey shaded) in 2002. Same legend for **(a, b)**. ~~Magenta~~ Black y ~~scale applies~~ axes apply to processes, magenta y axes apply to O_2 (saturation) ~~concentration~~concentrations. Changes in ~~concentration~~ O_2 due to different processes are cumulative.

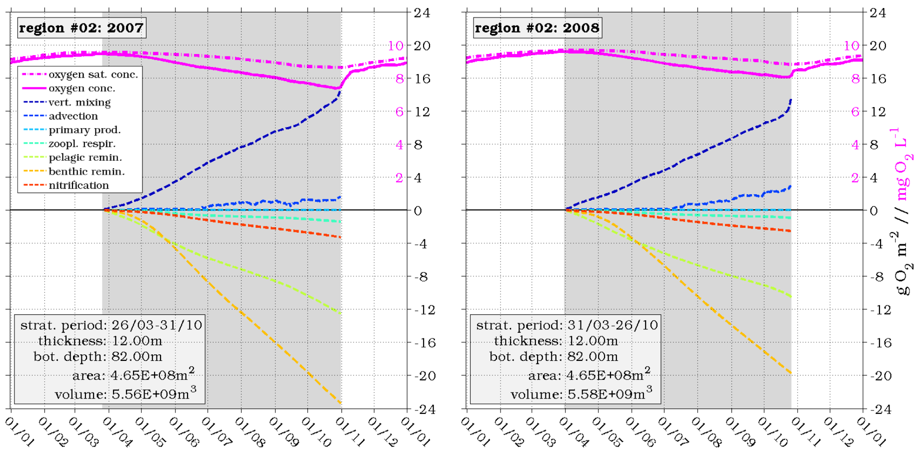

Figure 10. Mass balances for simulated bottom O_2 at Cefas North Dogger (see Fig. 2, region 2) during ~~the stratified period~~ stratification (grey shaded) in **(a)** 2007 and **(b)** 2010. Same legend for **(a, b)**. ~~Magenta~~ Black y ~~scale applies~~ axes apply to processes, magenta y axes apply to O_2 (saturation) ~~concentration~~concentrations. Changes in ~~concentration~~ concentrations due to different processes are cumulative.

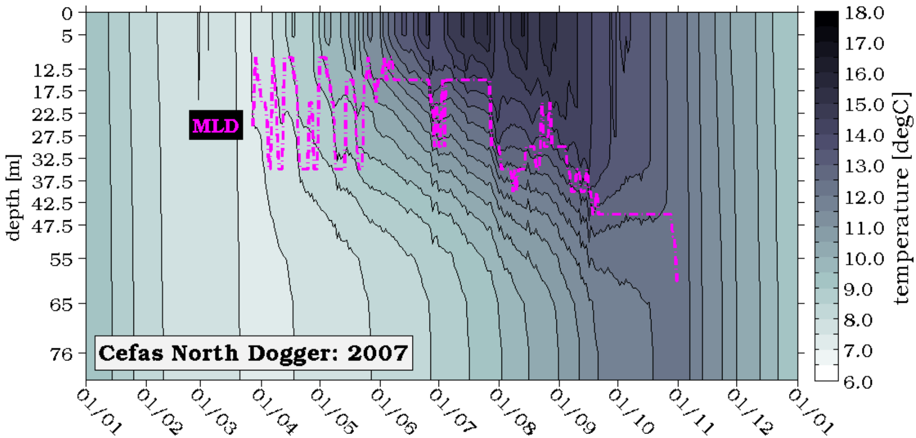

Figure A1. Hovmöller diagram of simulated T and MLD according to Eqs. (1) and (2) at Cefas station North Dogger (see Fig. 2, region 2) in 2007. Depth levels represent the centre depth of model layers.