Dear Associate Editor,

On behalf of all authors, I am pleased to submit our revised version of manuscript **Thermocline mixing and vertical oxygen fluxes in the stratified central North Sea** as an article in *Biogeosciences* within the special issue *Low oxygen environments in marine, fresh and estuarine waters*.

We have clarified, as advised, the single "process-oriented" nature of our study, both in the abstract and upfront in the first paragraph of the Discussion section.
We have also incorporated our responses to both referees in the revised manuscript. In particular we have:

1) Added one figure (Fig. 5) that presents a) our bottom water O_2 concentration time series, which is required for our snapshot O_2 budget, and b) a turbulence level contour plot that supports our discussion of the observed physical setting at the Tommeliten site.
2) Revised the Introduction section. We have realigned several sub-sections (and relative subsection titles), added a short description of the North Sea, and a more detailed list of the physical controls relevant for the O_2 dynamics presented and discussed in study.
3) Added a descriptive discussion of the transition layer we observed during our observational period.
4) Included discussion on the relevance of horizontal O_2 gradients and associated horizontal advection for our study. We provide evidence that horizontal advective fluxes are negligible and thus less relevant for our O_2 budget.

We are confident that the above addition and revision greatly improved the overall quality and readability of the manuscript.

We thank the editor and reviewers for their helpful comments, and we are looking forward to finalizing the manuscript.

On behalf of all authors

Lorenzo Rovelli

Response to **Anonymous Referee #1**

Note on color-coding: Reviewer's comments are in black, responses in blue, and text/figure additions in green.

The paper 'Thermocline mixing and vertical oxygen fluxes in the stratified central North Sea' presents an interesting study of the oxygen dynamics in the thermocline and bottom boundary layer of the seasonally stratified North Sea. The authors quantify the supply of oxygen to the BBL from the base of the thermocline and highlight the importance of including this mechanism when studying seasonal oxygen depletion. They discuss potential implications of future climate warming on this oxygen supply to the BBL.
The paper is well written and well structured. I have some minor comments.

P9907, line 10 'economic' rather than 'economical'

This has been changed

p9910 line 10 - discrete water sampling. No method details for Winkler samples

We have added details on the sampling and titration procedure (see comment p9910 line 19). However, as Winkler titrations are routine laboratory measurements, we feel that there is no need to provide details on the actual reagents and volumes involved.

p9910 line 19 - was the CTD O2 sensor calibrated using the Winkler samples?

Yes, in fact, all O_2 sensors, CTD O_2, AMT and optode were calibrated with Winkler samples. The CTD O_2 sensor and the POZ Optode were calibrated both in the lab prior to the cruise and during the cruise using the Winkler samples. This now mentioned it explicitly in the Method section (see also response to p9916 L26-27):

"The POZ lander was also equipped with a Winkler–calibrated O_2 optode sensor (Aanderaa Data Instruments AS, Bergen, Norway), which continuously recorded BBL O_2 concentration at 1 min intervals."

"Each depth (i.e., each Niskin-bottle) was subsampled with three Winkler bottles of known volume (~62 mL on average) right after recovery and the samples were immediately fixed on deck. The samples were then stored in the vessel's cold room and titrated manually within 24 h after the sampling."

p9915 line 15 'Superimposed on the barotropic currents, we observed the presence of baroclinic velocity contributions (Fig. 3b and c).' is repeated on line 19

This has been removed

p9916 line 23 - refers to figure 6 but there is no figure 6

The sentence on lines 21-24 refers to Fig. 4 – this was a mistake on our part. We have now corrected this within the text p9916 lines 26 and 27 - refers to the O2 timeseries from the POZ lander but the method section (p9910) does not include details of the oxygen sensor on the POZ lander. Where does the -0.42 umol kg-1 d-1 come from?

> We thank the reviewer for point that out. We have now expanded the section on the POZ lander to provide the required information and we added a figure (Fig. 5a). The additions read:
>
> "The POZ lander was also equipped with a Winkler–calibrated O_2 optode sensor (Aanderaa Data Instruments AS, Bergen, Norway), which continuously recorded BBL O_2 concentration at 1 min intervals."
>
> "The SUR was consistent with the average SUR at Oyster Grounds reported by Neubacher et al. (2011), -9.8 mmol m^{-2} d^{-1}, as well as with modeled SURs at the same site (average -8.6 mmol m^{-2} d^{-1}; Meire et al. 2013). The apparent BBL O_2 loss of -0.42 µmol kg^{-1} d^{-1} was determined from the POZ lander O_2 optode time series (Fig. 5a) over 52 hours, (R^2=0.60). Though limited to our short observational period, the vertically integrated apparent BBL O_2 loss was about -15 mmol m^{-2} d^{-1} and thus within 2% of the nearby North Dogger average presented by Greenwood et al. (2010)."

Figure 1 - change 'economical' to 'economic'

> This has been corrected

Figure 4b - label on figure - change 'ensambles' to 'ensembles'

> We have edited the figure accordingly.

Response to **Referee #2**

Note on color-coding: Reviewer's comments are in black, responses in blue, and potential/suggested additions in green.

The manuscript "Thermocline mixing and vertical oxygen fluxes in the stratified central North Sea" attempts to quantify oxygen fluxes in and around the bottom mixed layer of the Tommeliten site of the North Sea in late summer based on a short investigation relying on microstructure measurements. The authors present the idea that fluxes between the bottom mixed layer and a mid-water layer are greater than previously thought. The implication being that there is a higher turnover than previously thought but that remineralisation of injected DCM matter masks the oxygen influx into the BBL. This would also imply a much greater rate of BBL respiration than previously described in the literature. Although I believe this is quite possible as I have also observed similar processes (and come to the same estimates of respiration! Queste et al., also in discussion for the same issue), the authors of this manuscript encounter the same hurdles: it is difficult to reassure the reader of the validity of a short term measurement in context of seasonal processes, particularly when observing dissolved oxygen which shows high spatial and temporal variability.

> We agree with the reviewer that the interpretation of short-term studies in the context of seasonality and seasonal processes has to be carefully weighted and validated.
>
> We present a process-oriented study, in which we quantify vertical turbulence O_2 fluxes at the thermocline and discuss O_2 dynamics in the thermocline and BBL during the occurrence of a near-inertial baroclinic wave. This represents a special condition rather than the general setting during stratification. The reader was loosely reminded about that throughout the manuscript, but a clarification was not actually spell out.
>
> We have added explicative sentences in the abstract and in the introductory paragraph of the discussion section:
>
> "We report substantial turbulent O_2 fluxes from the thermocline into the otherwise isolated bottom water, which is attributed to the presence of a baroclinic near-inertial wave. This ephemeral contribution to the local bottom water O_2 and carbon budgets has been largely overlooked and is shown to play a role in promoting high carbon turnover in the bottom water throughout the stratification period while simultaneously maintaining high O_2 concentrations."
>
> "During our three-day observational period, we found that the baroclinic near-inertial wave in the interior was the main contributor to the detected enhanced shear (Fig. 3d) and the observed elevated vertical O_2 flux to the BBL (Fig. 6). As near-inertial waves decay after a few weeks, it should be noted that we observed a rather special situation, and that vertical O_2 fluxes will not likely be as highly elevated during periods when near-inertial waves are not present."
>
> Based on our study, we speculate that the physical processes described as well as the proposed phytoplankton-mediated DCM

> displacement are relevant for the seasonal O_2 dynamics in the thermocline and BBL and potentially exasperate the O_2 depletion in the central North Sea. This is done qualitatively in the discussion section, but in the perspective of global change, and thus without overselling the result presented in this study.

The budget itself needs strengthening. The paper focuses on quantifying one term, the flux at the BBL interface, which seems to be well constrained. Benthic remineralisation rates and pelagic respiration are taken from the literature, which is acceptable, but have been taken out of context and without any assessment of variability. It is the overall dO2/dt rate which I currently find problematic: it is taken from observations which are poorly described in text, not shown in figures and not backed up by numbers. How did you calculate this rate?

> The aim of the BBL O_2 budget of this study is to disentangle and discuss the main processes/pathways controlling the BBL O_2 dynamics during our observational period. For these 3 days, we feel that an assessment of the variability of the referenced data used in snapshot BBL O_2 budget would be very speculative, due to the lack of long term monitoring data.
>
> The values for BBL loss are now shown in SI Figure 2, and give a depletion rate of -0.42 µmol kg^{-1} d^{-1} ($R^2 = 0.6$). This observed O_2 loss in the BBL are extremely comparable to those reported in Greenwood et al. (2010) for nearby North Dogger. We now provide more information about core dataset in the methods section and results section and we added a figure in the supplement (see specific comment to section 3.3).
>
> Benthic remineralisation rates were taken from the eddy covariance (EC) study performed in parallel by McGinnis et al. (2014), covering the same period and within the same study site area. It therefore provides a solid reference for the benthic remineralisation during the observational period. We only refer to the mean sediment O_2 uptake rate (SUR) reported by McGinnis et al. (2014), and refer the reader to the publication for more information regarding the dynamics.
> Their mean SUR, -10 mmol m^{-2} d^{-1}, also compares well with the ex situ diffusive uptake rates from ex situ O_2 microprofling at the Oyster Grounds (Neubacher et al., 2011) and with the modeling effort of Meire et al. (2013), also at Oyster Grounds, where the authors reported average SURs of -9.8 mmol m^{-2} d^{-1} and -8.6 mmol m^{-2} d^{-1}, respectively.
> We now explicitly relate to those studies in the text:
> “The SUR was consistent with the average SUR at Oyster Grounds reported by Neubacher et al. (2011), -9.8 mmol m^{-2} d^{-1}, as well as with modeled SURs at the same site (average -8.6 mmol m^{-2} d^{-1}; Meire et al., 2013).”

The paper as a whole reads ok. The sentence construction is sometimes clumsy, although it never impedes understanding. The paper is well structured, although I feel some sections of the introduction lack a bit of detail (detailed further below). My main issue is with the final section. The biological perspective (Sec. 4.4) seems to me tenuous, but also not necessarily relevant to the paper. The results and preceding discussions are, in my opinion, more than sufficient for a paper. I feel this work would come across as stronger without and instead focused solely on the physics and the fluxes.

> We do agree with the reviewer that presenting the physics and the fluxes could be sufficient for a paper. However, we are confident that section 4.4 presents an important yet overlooked aspect of the interaction between primary producers and the physical environment. The mechanism we propose is a new hypothesis, which we feel is relevant to present here. Therefore, we feel it could be a key aspect for the O_2 dynamics as it would further promote bottom water isolation and therefore low O_2 conditions in climate change scenario under the current climatic projections. The section was shortened (one paragraph removed) and we have revised the final consideration in the light of climate change and O_2 depletion in the North Sea to relay the above message more clearly.

I would have liked to see some comments from the authors regarding the observed vertical density profile. My understanding (admittedly based on other sites further west, ie. North Dogger) is that these waters usually exhibit a clear two layer regime in August. Can the authors guess at the origin of the "intermediate layer"; is it a remnant of a recent storm, a tidally driven process, or advection of an intermediate watermass?

> We acknowledge that other studies might have not presented such layer but a thicker surface boundary layer (see reviewer's comment to 9914L14). We base our water column description on our observational period, when we detected the presence of a second vertical mode near-inertial wave. Regions of enhanced shear and near-inertial wave activity have been reported to coincide with the transition layer (e.g. Dohan and Davis, 2011) suggesting that it could be the result of the interaction between tides and the occurring near-inertial wave. Although further discussions on the occurrence of the transition layer go behind the realm of our snapshot study, we agree with the reviewer that such layer need to be presented in a more exhaustive fashion. We have added the following paragraph on the role and importance of the transition layer:
>
> "The site's water column structure clearly showed the occurrence of a 10 m thick transition layer (Fig. 2a). This layer represents the region of the water column where mixing turns from elevated in the SBL to strongly reduce in the interior (Ferrari and Boccaletti, 2004). The transition layer represents an obligate pathway for solute and heat exchange between SBL and the interior (Ferrari and Boccaletti, 2004; Rhein et al., 2010) and has also been reported to be a region of enhanced shear and near-inertial wave activity (Dohan and Davis, 2011). Although the presented data did not allow a quantification of the O_2 exchange across the transition layer, such contribution might be considerable and thus highly relevant for the cycling of O_2 and

> CO_2 in the upper water column, which in turn could have direct biological implications.“

Not being a turbulence expert, I find it hard to comment on the methodology employed for assessing turbulence and fluxes and hope another reviewer will be able to better cover this aspect.

Overall, I feel this paper is an interesting contribution to the ongoing oxygen debate within the North Sea and provides much-needed estimates of turbulent fluxes at the thermocline but requires considerable revisions to be acceptable for publication.

> We are pleased that the reviewer feels that our study can contribute to the current knowledge of O_2 dynamics in the North Sea, and are very grateful for the reviewer’s comments. We feel that they significantly improved the quality and clarity of the manuscript.

ABSTRACT:

I feel the abstract focuses too strongly on the results of Sec 4.4 which I feel is the weakest part of the paper. Instead of 50% of the abstract focusing on Sec.4.4, I would rather see some numbers coming from your flux estimates or comments regarding the high amount of cycling between the DCM and the BBL.

> We understand the reviewer considerations here. The abstract was structured as such to better relate to the foci of the special issue, as advised by the associated editor. As the reviewer pointed out on his general consideration of this manuscript, studies based on short datasets in a seasonal settings struggle to present their results as in terms of seasonality due to the lack of long term supporting evidence. For such reason, we believe that presenting the O_2 fluxes or the results from our snapshot O_2 budget quantitatively would overpraise our results. While we can speculate that the processes described and investigated in this manuscript are relevant for the O_2 dynamics in the BBL during the stratification period, we feel it is not appropriate upscale our rates to the entire summertime.

9906L17-19: "Due to the substantially lower turbulence levels in the central region of the thermocline as compared to the higher turbulence observed at the thermocline-BBL interface..." The sentence is unclear.

> We meant “In the center region of the thermocline we observed substantially suppressed turbulence compared to the thermocline-BBL interface”. This sentence was removed from the abstract, as it would steer the readers’ attention away from the biological implication of upward shift in the production layer.

SECTION 1.1:

L5: Slightly oversimplified. Not sure what eutrophication has to do with deep waters. OMZs (deep water), eutrophied shallow regions such as the German

Bight and the central North Sea all exhibit low oxygen, but from quite different mechanisms.

> We agree with the reviewer. The former formulation could mislead the reader. The section was modified accordingly and refocused to the Shelf Sea and coastal hypoxia:
>
> “1.1 Hypoxia in shelf seas and coastal regions
>
> The distribution of dissolved oxygen (O_2) in marine systems results from the complex interaction between biological processes (photosynthesis and respiration) and physical processes (O_2 flux pathways) occurring within the water column and at the seafloor. O_2 is therefore regarded as an important indicator of ecosystem functioning for aquatic organisms (Best et al., 2007) as well as for benthic activity (e.g., Glud, 2008). Changes in the O_2 distribution, concentrations and supply can therefore have severe impacts on the shelf ecosystems. O_2 concentration below 62.5 µmol L^{-1}, which is generally regarded as the threshold of hypoxia (Vaquer-Sunyer and Duarte, 2008), is shown to impose significant stress on aquatic communities leading to increased mortality among fish communities (Diaz, 2001). This also highlighted not only the ecological but also the economic impacts of O_2 depletion, leading to increasing concern regarding the occurrence of hypoxia and hypoxic events. In fact, as reviewed by Diaz and Rosenberg (2008), hypoxia in coastal environments is spreading and so are the reports of unprecedented occurrence of hypoxia in several shelf seas and coastal regions (Grantham et al., 2004; Chan et al., 2008; Crawford and Pena, 2013).”

SECTION 1.2:

The section title is "distribution" but you don’t mention the actual distribution of O2 in the North Sea. I would also expect a (brief mention) of North Sea hydrography and how the section you’re referring to is classified as a seasonally mixed region (ie. only relevant to the North Sea above 56N). Where and when have we seen low O2 before?

> The section was intended to provide an overview of “Oxygen depletion in the North Sea”, we thank the reviewer to pointing that out. We have restructured the section to provide a more rounded description of the North Sea and occurrence of low O_2 concentration in the central North Sea:
>
> “The North Sea is situated in the North–West European continental shelf, between the British Islands and continental Europe. Its semi-enclosed basin covers an area of 575’300 km^2, which has an average depth of 74 m and a general decrease in depth from North to South (Otto et al., 1990). The center region is characterized by the presence of the Dogger Bank, a shallow sandbank that also acts as a hydrological divide. The northern and central North Sea hydrology is mainly dominated by inflow from the North Atlantic Ocean at the northern open boundary, while the southern part rely on inflow from the English Channel (Thomas et al., 2005). The Northern and central North Sea areas are also characterized by the occurrence of seasonal water column stratification. This together with

weak wind-driven residual currents (Otto et al., 1990) can lead to isolation of central North Sea bottom water thus promoting O_2 depletion."

"Indeed, in the central North Sea, the occurrence of low O_2 levels in bottom waters has already been reported in the past (e.g., North Sea Task Force, 1993; Greenwood et al., 2010). More recently, monitoring studies in the central North Sea for the 2007 – 2008 period have shown that O_2 concentration in the bottom waters at the Oyster Grounds and North Dogger can drop as low as 163 – 169 µmol L^{-1} (60 – 63 % saturation) and ~200 µmol L^{-1} (71% saturation), respectively (Fig. 1; Greenwood et al., 2010). Comparable field observations were also reported in the summer of 2010 (Queste et al., 2013). The authors also reviewed the available historical O_2 data in the North Sea (1900 – 2010), revealing a clear increase in O_2 depletion after 1990.

While the reported O_2 levels were still above the hypoxic threshold, growing concerns of hypoxia developing in the North Sea have highlighted the need for more detailed studies on the O_2 dynamics and driving forces (Kemp et al., 2009). In fact, since 1984, surface water temperatures in the North Sea have increased by 1 – 2°C, greater than the global mean (OSPAR, 2009, 2010; Meyer et al., 2011). On seasonal time scales, climate projections indicate longer duration of the stratification period and stronger thermocline stability (Lowe et al., 2009; Meire et al., 2013), with some projection also suggesting earlier onset of stratification (e.g., Lowe et al., 2009). Due to the semi-enclosed nature of the North Sea, earlier onset and longer stratification increases the length of time that the deep water is isolated, potentially allowing lower O_2 concentrations to develop (Greenwood et al., 2010)."

9907L15: What is the relevance of eutrophication in the central North Sea? It is a big issue in coastal regions and in the south, but it is irrelevant nears the Tommeliten site.

We agree, the eutrophication aspect of section 1.2 was removed

SECTION 1.3:

9908L1: I'm not sure I agree with that first statement in the context of shelf seas, particularly with oxygen. Biology plays a very important role in defining O2 concentration/saturation in shelf seas.

We state that the distribution is "largely" controlled by physical processes. Obviously respiration and primary production control the production, utilization of O_2, recycling of nutrients, etc. however, the distribution and specifically the fluxes are dictated mostly by physical processes.

In a section entitled "controls on oxygen dynamics" I would expect a breakdown of the processes that affect oxygen in shelf seas: the vertical transport, but also horizontal advection, primary production and remineralisation and air/sea exchanges (which dominate in the surface layers). The relative importance of each will be very different compared to mixed regimes or OMZs.

> We agree with the reviewer, the original title of this section and that of section 1.1, 1.2 we too general therefore misleading. The section is now more appropriately title “Physical controls on oxygen dynamics”.
>
> The text has been modified to point the reader to other flux processes:
>
> “The distribution of O_2 and the other dissolved constituents within aquatic systems are largely dictated by physical transport processes. These include the wind driven air – water gas exchange (Wanninkhof, 1992) at the sea surface, molecular diffusion at the sediment – water interface (Jørgensen and Revsbech, 1985), horizontal advection (e.g., Radach and Lenhart, 1995) and turbulent transport in the water column, where the latter transport was reported to significantly contribute to constituent balances (*see* Rippeth, 2005; Fischer et al., 2013; Kreling et al., 2014; Brandt et al., 2015).”

SECTION 2:

Section 2 is too far out of my field of expertise for me to comment.

9912/L18-20: Quantify density gradients, reassure the reader what you’re saying is true.

> We did not observe any clearly quantifiable horizontal gradients in density during our survey at the Tommeliten site, which included towed near-seafloor CTD transects. Over our observational period, we also did not observe any change in the BBL temperature or salinity over the tidal cycle that would suggest advection of different water masses. Based on that we believe that our assumption of $K_{rho}=K_z$, which is generally established in such conditions, is justified.
>
> The sentence was slightly modified to refer to the extended explanation on horizontal advection in the discussion section and to state that we infer that such gradient were likely small during our observational period:
>
> As horizontal density gradients at the study site were deemed to be small compared to vertical gradients (see Discussion), we equated diapycnal eddy diffusivities with vertical diffusivities (i.e., $K_\rho = K_z$).

SECTION 3:

There should not be text under Sec3 if subheadings (ie. 3.1, 3.2) are coming later.

> This is a stylistic choice to better guide the reader across the sections. As the result section reflects the dense Methods section, we believe that an introduction paragraphs at the beginning of the section will increase the readability. We leave the final decision to the associate editor and editorial board.

9914L4: "oceanic background" could just be hydrographic

> Yes, the term “hydrographic” is more appropriate within this context.

SECTION 3.2:

9914L14: What criteria is used to separate the layers? I struggle to see the difference between the surface layer and transition layer in Figure 2.

> The layers were separated based on temperature changes. Salinity was on average 35.08 with little variation throughout the water column (35.04 to 35.1) and thus contributed very little to the observed stratification. We have added additional information on salinity in the Result section and added a description of the layer separation to caption of Fig. 2. The additional sentences read:
>
> "Water column layers were identified based on the temperature profiles. A 0.2°C and 1.5°C decrease from the surface boundary layer average temperature (3–6 m depth) was used determine the depth of the surface boundary layer – transition layer interface and the transition layer – interior interface, respectively. Correspondingly, a 0.2°C from a 50-60 m depth average temperature was used to locate the interior – bottom boundary layer interface."

9914L24,25: I would like to see the saturation values accompanied by the corresponding concentrations

> The section was updated accordingly and reads:
>
> "The O_2 profiles were generally characterized by near saturation in the SBL and transition layers, with O_2 concentrations in the 238 – 243 µmol kg^{-1} range, and undersaturated (~80%) in the BBL, where the O2 concentration was ~243 µmol kg^{-1} (Fig. 2c,d). The stratified interior was oversaturated by up to 115%, with a well-established O_2 maximum at ~39 m depth with concentrations up to ~315 µmol kg^{-1}."

9916L6-7: Spectral density function is not shown. Why not, I see no problem with adding it in terms of number of figures.

> We realize that the plot is relevant to a specific audience. Although the spectra were presented as supplementary information in the open discussion session (SI Figure 1) we stay by our original decision of omitting it on the manuscript. The reference to the supplementary information Figure 1 was maintained

9916L23: There is no figure 6.

> The whole paragraph refers to Fig. 4. The typo was removed from the text.

SECTION 3.3:

9917L14-18: How accurate is your assessment of dO2/dt, a figure showing the observed values wouldn't be a bad thing. Did you observe a linear decline? Is it uniform throughout the water column? Is it an artefact of sampling at dawn, night or dusk? How good of a fit is your linear regression? Since your entire budget relies on this value, I would expect much more justification here.

> Our assessment of dO_2/dt is limited to the short O_2 timeseries collected during our observational period. We agreed with both reviewers that these data were not properly introduced.

This has now been revised and we provide a better description in the methods and results section (see below) and we have added a figure of our O_2 timeseries with the fitted linear regression curve on Fig. 5a

We observed variable O_2 concentrations over 52 hours, but an overall decreasing O_2 concentration trend. Such trend was quantified via linear regression to be -0.42 µmol kg^{-1} d^{-1} (R^2=0.60). Despite the limited amount of data the inferred O_2 loss rate, once expressed as areal rate, was about -15 mmol m^{-2} d^{-1} and thus within 2% of the rate observed by Greenwood et al. (2010) for the North Dogger, which were based on an extensive mooring study over almost two years. This gave us confidence that our estimates were realistic for the in situ condition at Tommeliten during the mid-late summer stratification period.

The text additions read:

"The POZ lander was also equipped with a Winkler–calibrated O_2 optode sensor (Aanderaa Data Instruments AS, Bergen, Norway) which recorded BBL O_2 concentration continuously at 1 min intervals."

"The apparent BBL O_2 loss of -0.42 µmol kg^{-1} d^{-1} was determined from the POZ lander O_2 optode time series (Fig. 5a) over 52 hours, (R^2=0.60). Though over a short time interval, the apparent BBL O_2 loss was about -15 mmol m^{-2} d^{-1} and thus within 2% of the nearby North Dogger average presented by Greenwood et al. (2010)."

9917L22: Over what distance did you observe no horizontal density gradients? It would have to be large to show no horizontal advection. If it's large, how do you justify saying you're measuring dO2/dt and not a spatial change?

We understand the reviewer concern over the potential contribution of horizontal advection to the O_2 balance. Although with our measurement setup we cannot quantify horizontal advective O_2 fluxes our data do not suggest that such fluxes would significantly contribute to the O_2 balance (see paragraphs below for details)

The temporal O_2 variability in the BBL was continuously recorded by an optode mounted on our POZ lander (Fig. 5a) simultaneously with current velocities (Fig. 3). We reported that the strongest velocity signal was due to the tides and inertial currents.

If horizontal O_2 gradients were elevated at the Tommeliten site during our observation period, than we would have likely observed variability in the O_2 concentration on tidal and or inertial frequencies in the POZ O_2 time series. The fact that such periodicity was not observed suggests that there were no large horizontal O_2 gradients.

Additionally, mean currents in the BBL were only about 2 cm/s and thus small compared to the tides. This, in conjunction with weak horizontal O_2 gradients, suggests that horizontal advective O_2 fluxes are likely to be small.

We now introduce the issue and provide a streamlined version of the explanation above in the text:

"Ultimately, observed O_2 depletion in the BBL of the central North Sea depends on the supply of organic matter, the rate of carbon mineralization, and the flux of O_2 to the bottom water either from horizontal advection or turbulent vertical transport."

Horizontal O_2 gradient and associated horizontal advective O_2 fluxes were not quantified in this study. Our data does, however, suggest that such fluxes would not significantly contribute to the O_2 balance at the Tommeliten site. BBL O_2 concentration time series (Fig. 5a) did not show any variability at the tidal and or inertial frequencies, implying that horizontal O_2 gradients were actually small. Additionally, mean currents in the BBL were also small (~2 cm s^{-1}) compared to the tidal amplitudes. This, in conjunction with weak horizontal O_2 gradients, suggests that horizontal advective O_2 fluxes during our observational period were likely to be smaller, compared to the turbulent O_2 flux from the thermocline."

SECTION 4:

There should not be text under Sec4 if subheadings (ie. 4.1, 4.2) are coming later.

This is a stylistic choice to better guide the reader across the sections. As the Discussion section merges considerations crossing disciplines, we believe that the introduction paragraph will provide the reader the tools to efficiently follow the points raised in the discussion section. The associate editor should take the final decision on the subject.

SECTION 4.1:

9919L24: Data not shown. Again, there is sufficient space for figures. Maybe these additions would help give the reader more confidence?

We have added the plot on Figure 5b.

SECTION 4.2:

9920L13-15: I would rephrase this sentence as it is not very clear at the moment.

We have expanded the sentence to improve readability:

"Based on the above, we can argue that O_2 dynamics during the stratified period are more complicated than previously regarded. To maintain an excess of O_2 in the thermocline, primary producers require adequate nutrient entrainment from the bottom water to fuel potential new production. The resulting increase in productivity and subsequent export to the bottom water could therefore boost the carbon turnover estimates substantially."

9920LL15-17: I'm not sure I agree here. You're arguing there is possibly more production than anticipated, but not necessarily new production, so the impact on export is more limited... I think Weston 2005 discussed this pretty well.

The reviewer is correct; it might not be all new production, but rather recycling. We tuned the sentence 9920L15-17:

"The resulting increase in (new) productivity and subsequent export to the bottom water could therefore boost the carbon turnover estimates substantially."

SECTION 4.3:

9921L25-28: The southern North Sea is an incredibly different regime, I'm not sure I see the relevance.

> We are, of course, aware that the hydrology differences between the generally well-mixed southern North Sea sites and the seasonally stratified central North Sea.
>
> The whole paragraph (9921L21-9922L7) provides evidence of the influence of tidal forcing on both vertical transport of constituents (O_2, OM, macronutrients, ...) and on primary producers and resulting primary production. In such context, the study by Blauw et al. (2012) provides evidence of a close correlation between tidal motions and phytoplankton biomass (from Chl.a concentrations), which seems to suggest a physical control over primary production. In Section 4.4 we then expand the concept to migrating phytoplankton (armored dynoflaggelates which are observed in central North Sea – Reid et al., 1990) and hypothesized that under low/lower turbulent mixing (i.e., stronger stratification) they could bypass the physical constrains of stratification and shift the depth of primary production.

9922L8: They help regulate, but they are not the only mechanism. Maybe rather say it sets the lower limit on how depleted oxygen concentrations can get?

> The sentence was reformulated accordingly:
>
> "The flux of O_2 from the DCM production zone downward to the BBL could set the lower limit of the BBL O_2 concentration, and thus the O_2 depletion level, during the stratification period."

9922L10: Only if the amount of OM is equal to the amount of O2 injected. This assumes no difference in O2 concentrations between the BBL and DCM.

> We do believe the reviewer misunderstood us here. Indeed we assume a 1:1 ratio C:O_2. If there is no isolation (fully mixed waters) production and remineralization are likely to balance out if there is no influx of nutrients as the system will recycle matter (no new production). However, turbulence transport would have limited effect on POM, and thus you would still expect a SUR and thus a net O_2 loss in the BBL, but at a much slower rate.
>
> We added a sentence to clarify:
>
> "In such case the apparent O_2 loss in the BBL would either be negligible or very small, depending whether the largely particle organic matter driven SUR will be balanced by the ventilation form the thermocline."

SECTION 4.4:

9923L14-23: You were previously arguing that nutrient supply was proportional to O2 flux. If you reduce O2 flux here, wouldn't you also reduce OM production, and therefore SUR and pelagic respiration as well?

> We argued that the same turbulent transport that supports the O_2 export from the DCM to the BBL also supports BBL nutrient import to

the DCM, and this could drive additional new production. We are aware that this is an oversimplification, as we are, conceptually, not separating new production from recycling. However, the main point here is that migrating plankton can overcome stratification by actively swimming towards the interface with the BBL to access nutrients. In such scenario, the physical transport limitations would not necessarily impede primary production, but only mainly the O_2 flux towards the BBL. We now mention explicitly the fact that in such scenario, migrating algae species would still be able to access nutrients from the BBL.

"Migrating phytoplankton could therefore access BBL nutrients in this scenario, i.e., primary production rates would be comparable, but the result would be an evident further decrease in the BBL O_2."

"Of course, whether such scenario could be sustained over the whole stratification period is not known and requires further assessment."

9923L24-28: Paragraph isn't very clear.

This paragraph was removed. Accordingly, we have revised the final paragraph to link with the previous section and to streamline our conclusions.

"In the light of climatic changes, studies have suggested that O_2 loss in the North Sea bottom waters would mainly result from a strengthening of the stratification and O_2 solubility reduction with increasingly warmer waters (e.g. Meire et al., 2013). The findings of this study suggest there might be an additional level of complexity based on the interplay between the tidally-driven physics, water column structure, biogeochemical cycling and active phytoplankton migration in the central North Sea. The proposed mechanism could contribute to the observed decreasing O_2 levels in the North Sea water column, however, further detailed studies are obviously necessary to validate and fully quantify this effect at the seasonal level."

FIGURES:

Fig.1: I would suggest a map projection that is more indicative of actual relative distances at 56N. The bathymetric contours also fail to highlight some of the important features in the North Sea; ie. the Dogger Bank which is known for generating internal waves which play a significant role in vertical exchanges at the thermocline.

The main purpose of the image is to locate the Tommeliten site, which in the literature is not as well represented as the North Dogger Bank and Oyster Grounds. While we feel that in-depth visualization of the general North Sea and central North Sea specific features are already well presented in other studies (e.g. Otto et al., 1990; Queste et al., 2013), we understand the reviewer concern. Therefore, we have revised the figure to provide a better overview of the North Sea and to better highlight the Dogger Bank. We also provide indication of the location the Oyster Grounds to better link the literature studies with the present one.

Fig.4: Is there possibly an anomaly in the data, panel C at 35m? The averaged value seems off relative to the other points indicated.

> Fig. 4c shows both upward and downwards O2 fluxes (white and grey dots, respectively). In the 33 – 37 m range, the average flux reflects the alternating upwards and downwards fluxes that were observed. At both 35 m and 37 this resulted in reduced net fluxes during the observational period. We have added a further sentence the figure caption to avoid misunderstandings:
>
> "Note that in the center interior (33 – 37 m) the average reflects the combination of the variability of the observed upward and downwards fluxes"

Is Fig. 6 missing?

> The text refers to Fig. 4, and not Fig. 6. We have now removed the misreference from the text.

References need checking in text; for example, Queste has been cited with different dates for the same paper.

> We thank the reviewer for noticing that. The discrepancies were corrected

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Abstract

In recent decades, the central North Sea has been experiencing a general trend of decreasing dissolved oxygen (O_2) levels during summer. To understand the potential causes driving lower O_2, we investigated a three-day period of summertime turbulence and O_2 dynamics in the thermocline and bottom boundary layer (BBL). The study focuses on coupling biogeochemical processes with physical transport processes to identify key drivers of the O_2 and organic carbon turnover within the BBL. Combining our flux observations with an analytical process-oriented approach, we resolve the key drivers that ultimately determine the BBL O_2 levels. We report substantial turbulent O_2 fluxes from the thermocline into the otherwise isolated bottom water which is attributed to the presence of a baroclinic near-inertial wave. This ephemeral contribution to the local bottom water O_2 and carbon budgets has been largely overlooked and is shown to play a role in promoting high carbon turnover in the bottom water throughout the stratification period while simultaneously maintaining high O_2 concentrations. However, this process could become suppressed with warming climate. We propose migrating algal species, favoured by higher water temperature and suppressed turbulence, could out-compete other species for light and nutrients, and shift the oxygen production zone higher up within the thermocline while maintaining similar organic carbon export to the bottom water. Therefore an upward shift in the production layer could lead to further isolation of the bottom water and thus further promote the seasonal occurrence of lower O_2 concentrations.

1 Introduction

1.1 Hypoxia in shelf seas and coastal regions

The distribution of dissolved oxygen (O_2) in marine systems results from the complex interaction between biological processes (photosynthesis and respiration) and physical processes (O_2 flux pathways) occurring within the water column and at the seafloor. O_2 is therefore regarded as an important indicator of ecosystem functioning for aquatic organisms (Best et al., 2007) as well as for benthic activity (e.g., Glud, 2008). Changes in the O_2 distribution, concentrations and supply can therefore have severe impacts on the shelf ecosystems. O_2 concentration below 62.5 µmol L^{-1}, which is generally regarded as the threshold of hypoxia (Vaquer-Sunyer and Duarte, 2008), is shown to impose significant stress on aquatic communities leading

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to increased mortality among fish communities (Diaz, 2001). This also highlighted not only the ecological but also the economic impacts of O_2 depletion, leading to increasing concern regarding the occurrence of hypoxia and hypoxic events. In fact, as reviewed by Diaz and Rosenberg (2008), hypoxia in coastal environments is spreading and so are the reports of unprecedented occurrence of hypoxia in several shelf seas and coastal regions (Grantham et al., 2004; Chan et al., 2008; Crawford and Pena, 2013).

1.2 Hydrodynamics and oxygen depletion in the North Sea

The North Sea is situated in the North–West European continental shelf, between the British Islands and continental Europe. Its semi-enclosed basin covers an area of 575’300 km^2, which has an average depth of 74 m and a general decrease in depth from North to South (Otto et al., 1990). The center region is characterized by the presence of the Dogger Bank, a shallow sandbank that also acts as a hydrological divide. The northern and central North Sea hydrology is mainly dominated by inflow from the North Atlantic Ocean at the northern open boundary, while the southern part relies on inflow from the English Channel (Thomas et al., 2005). The Northern and central North Sea areas are also characterized by the occurrence of seasonal water column stratification. Taken together with weak wind-driven residual currents (Otto et al., 1990), this can lead to isolation of central North Sea bottom water that promotes O_2 depletion.

Indeed, in the central North Sea the occurrence of low O_2 levels in bottom waters has already been reported in the past (e.g., North Sea Task Force, 1993; Greenwood et al., 2010). More recently, monitoring studies in the central North Sea for the 2007 – 2008 period have shown that O_2 concentration in the bottom waters at the Oyster Grounds and North Dogger can drop as low as 163 – 169 µmol L^{-1} (60 – 63% saturation) and ~200 µmol L^{-1} (71% saturation), respectively (Fig. 1; Greenwood et al., 2010). Comparable field observations were also reported in the summer of 2010 (Queste et al., 2013). The authors also reviewed the available historical O_2 data in the North Sea (1900 – 2010), revealing a clear increase in O_2 depletion after 1990.

While the reported O_2 levels were still above the hypoxic threshold, growing concerns of hypoxia developing in the North Sea have highlighted the need for more detailed studies on the O_2 dynamics and driving forces (Kemp et al., 2009). In fact, since 1984, surface water temperatures in the North Sea have increased by 1 – 2°C,

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greater than the global mean (OSPAR, 2009, 2010; Meyer et al., 2011). On seasonal time scales, climate projections indicate longer durations of the stratification period and stronger thermocline stability (Lowe et al., 2009; Meire et al., 2013), with some projection also suggesting earlier onset of stratification (e.g., Lowe et al., 2009). Due to the semi-enclosed nature of the North Sea, earlier onset and longer stratification increases the length of time that the deep water is isolated, potentially allowing lower O_2 concentrations to develop (Greenwood et al., 2010).

1.3. Physical controls on oxygen dynamics

The distribution of O_2 and the other dissolved constituents within aquatic systems are largely dictated by physical transport processes. These include the wind driven air – water gas exchange (Wanninkhof, 1992) at the sea surface, molecular diffusion at the sediment – water interface (Jørgensen and Revsbech, 1985), horizontal advection (e.g., Radach and Lenhart, 1995) and turbulent transport in the water column, where the latter transport was reported to significantly contribute to constituent balances (see Rippeth, 2005; Fischer et al., 2013; Kreling et al., 2014; Brandt et al., 2015). In shelf seas, the seasonal occurrence of steep thermoclines acts as an important physical barrier separating the surface layer from nutrient-rich deeper waters (Sharples et al., 2001). As measurements of shear and stratification have shown that the central North Sea thermocline is in a state of marginal stability (van Haren et al., 1999), additional sources of shear could trigger shear instability leading to local production of turbulence within the thermocline. This enhanced local turbulence would subsequently enhance the vertical exchange of constituents such as O_2, organic carbon and nutrients. Therefore, resolving the processes that drive diapycnal (i.e., vertical) fluxes across the thermocline throughout the stratification period is key to understanding the biogeochemical functioning of shelf seas (e.g., Sharples et al., 2001).

1.4 Present study

The goal of this study is therefore to obtain a snap-shot of key turbulent processes driving the O_2 fluxes across the thermocline. We investigate and describe key processes driving the O_2 flux to the bottom waters during the period of our investigation, and how this could potentially influence the seasonal O_2 balance. Using

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the resolved O_2 flux, we perform a simple 1-D mass balance model to quantify the O_2 sources and sinks, and loss in the water column. Finally, we propose processes that could promote hypoxia development in the central North Sea in a warming climate.

2 Methods

2.1 Study site

We performed our O_2 and turbulence measurements campaign in the Norwegian sector of the central North Sea, N. 1/9, at the Tommeliten site (56°29'30" N, 2°59'00" E; Fig. 1) over a time period of three days during the stratification period (8 – 11 August 2009) aboard the R/V *Celtic Explorer* (cruise CE0913). The site, located ~100 km northeast from the northern Dogger Bank, and its surroundings are characterized by shallow waters (~70 m) at a relatively long distance from coastal areas (on average ~300 km). The site is known for the presence of buried salt diapirs, methane (CH_4) seeps and bacterial mats (Hovland and Judd, 1988). Bathymetric surveys from Schneider von Deimling et al. (2010) revealed a rather flat sandy seabed with almost no features, with the exception of cm-sized ripples (McGinnis et al., 2014).

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The currents of the central North Sea are predominantly driven by the semi-diurnal lunar tide (M_2; Otto et al., 1990). Seasonal stratification starts in April around Julian day 100 (e.g., Meyer et al., 2011). The thermocline has been identified as an important zone for the establishment of primary production and the O_2 maximum layer (see Pingree et al., 1978). In fact, the North Sea deep chlorophyll maximum (DCM) is estimated to account for 58% of the water column primary production and 37% of the annual new production for the summer stratified North Sea (Weston et al., 2005). The development of the associated O_2 maximum due to this production is thus important and so far not considered in the overall O_2 balance of the central North Sea.

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2.2 Instrumental setup

High resolution (mm scale) turbulent shear and temperature profiles were obtained with a MSS90-L (Sea and Sun Technology, Trappenkamp, Germany) microstructure turbulence profiler. The MSS90-L is a free-falling, loosely-tethered profiler which samples at 1024 Hz with 16 channels and is designed for an optimal sink rate of 0.5 – 0.6 m s^{-1}. The probe was equipped with two air-foil shear probes, an accelerometer (to correct for probe pitch, roll, and vibration), a fast temperature sensor (FP07, 7–12 ms response time), standard CTD sensors (temperature, pressure, conductivity), and a fast (0.2 s response time) galvanic O_2 sensor (AMT, Analysenmesstechnik GmbH, Rostock, Germany). The absolute O_2 concentrations were calibrated against shipboard CTD O_2 profiles and Winkler titrations on discrete water samples (see below).

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Water column hydrodynamics were characterized with the compact benthic Paleoceanography (POZ) lander, which was deployed using a video guided launcher (Pfannkuche and Linke, 2003). The POZ lander recorded 3-dimensional current velocity profiles and acoustic backscatter information throughout the water column using a 300 kHz acoustic Doppler current profiler (ADCP; Workhorse Sentinel, Teledyne RD Instruments, Poway, United States), which sampled every 15 s with a bin size of 0.5 m starting from 2.75 m from the bottom. A conductivity-temperature-depth (CTD) logger (XR-420 CT logger, RBR, Kanata, Canada) recorded temperature, conductivity and pressure (Digiquarz, Paroscientific, Redmond, United States) every 2 s near the seafloor (~0.3 m distance). The POZ lander was also equipped with a Winkler–calibrated O_2 optode sensor (Aanderaa Data Instruments AS, Bergen, Norway), which continuously recorded BBL O_2 concentration at 1 min intervals.

Water column profiles were obtained using a SBE9plus CTD-rosette system (Seabird, Washington, United States). The CTD sampled at 24 Hz and was equipped with standard temperature, conductivity, pressure, O_2 and light transmission sensors. The rosette system mounted 12 10L-Niskin-bottles for discrete water sampling. Each depth (i.e., each Niskin-bottle) was subsampled with three Winkler bottles of known volume (~62 mL on average) right after recovery and the samples were immediately fixed on deck. The samples were then stored in the vessel's cold room and titrated manually within 24 h after the sampling.

2.3 Hydrodynamic data evaluation

The main tidal directions, the major and minor axis of the tidal ellipsoid, were determined by performing a variance analysis on the ADCP velocity time series. The u and v velocities were rotated over a stepwise increasing rotation angle (*r*) as

$u_{rot} = u \cdot cos(-r) - v \cdot sin(-r)$ respectively $v_{rot} = u \cdot sin(-r) - v \cdot cos(-r)$, and the variance computed at each step. The angle at the largest variance represented the main tidal direction. Barotropic and baroclinic flow contributions of tides were separated by least-square fitting the detrended velocity time series to harmonics $u = A \cdot cos(\omega \cdot t + \varphi)$ with A, ω, φ being the amplitude, frequency, and the phase lag, respectively. In the analysis below, the barotropic semi-diurnal principle lunar tide (M_2) and diurnal declination tide (K_1) contributions had frequencies of 1.93227 cycles per day (cpd) and 1.00274 cpd, respectively, and were subtracted from the time series to analyze residual flow. For barotropic contributions, the fit was applied to the depth average of the time series, while baroclinic contributions were obtained by fitting the harmonics to the velocity time series from each 0.5 m ADCP bin. The occurrence of enhanced shear in the stratified water column was investigated by calculating the vertical shear of horizontal velocity, S, from the vertical gradients between adjacent bins of east and north velocity (0.5 m resolution) as $S = \sqrt{(du/dz)^2 + (dv/dz)^2}$. Frequency spectra of the time series of horizontal velocity and vertical shear of horizontal velocity were used to identify the tidal and non-tidal flow components. The spectra were calculated using fast-Fourier transforms combined with a ½-cosine tapper (Hanning window) that was applied to the first and last 10% of the time series data.

Turbulent kinetic energy dissipation rate (ε) was quantified from the airfoil shear readings by integrating shear wavenumber spectra assuming isotropic turbulence (Batchelor, 1953):

$$\varepsilon = 7.5\mu \int_{k_{min}}^{k_{max}} E_{du'/dz}(k)dk \qquad (1)$$

where μ is the dynamic viscosity of seawater. Shear spectra $E_{du'/dz}(k)$ were calculated from one-second ensembles (1024 values) and integrated between a lower $k_{\min}$ = 3 cycles per minute (cpm) and an upper wavenumber $k_{\min}$ that varied between 14 cpm and 30 cpm depending on the Kolmogorov wavenumber. Here, a Bartlett window was applied to the whole ensemble prior to spectral decomposition. Loss of variance due to the limited wavenumber band was taken into account by fitting the observed shear spectra to the universal Nasmyth spectrum. Similarly, corrections for the loss of variance due to finite sensor tip of the airfoil probes were applied (see Schafstall et al., 2010). The detection limit, or noise level, of the used profiler for ε

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was inferred to be 1 × 10^{-9} W kg^{-1} (Schafstall et al., 2010); the upper detection limit is a function of the shear sensor geometry (up to 10^{-4} W kg^{-1}; Prandke and Stips, 1998).

Estimates of the turbulent eddy diffusivities of mass (K_ρ) were obtained from measurements of ε as

$$K_\rho = \gamma\varepsilon/N^2 \qquad (2)$$

where γ is the mixing efficiency and N^2 the water column stability. This method, proposed by Osborn (1980), approximates K_ρ under the assumption of a local equilibrium of production and dissipation of turbulent kinetic energy. Values for N^2 were calculated from temperature, salinity and pressure data using the adiabatic method (Fofonoff, 1985) as $N^2 = -g(\rho^{-1}\partial\rho/\partial z - g/c^2)$, where ρ, g, and c are the density, the earth's gravitational acceleration and speed of sound, respectively. Mixing efficiency values in stratified waters range from 0.1 to 0.2 (Ivey and Imberger, 1991) and decreases in weakly stratified waters such as within the BBL (Lorke et al., 2008). To account for this decrease, we used the γ and K_ρ parameterization of Shih et al. (2005). Based on the turbulence activity parameter $\varepsilon/\upsilon N^2$, with the kinematic viscosity, υ, the authors found that in energetic regimes, i.e., $\varepsilon/\upsilon N^2 > 100$, the eddy diffusivities are better estimated as $K_\rho = 2\upsilon(\epsilon/\upsilon N^2)^{1/2}$. As horizontal density gradients at the study site were deemed to be small compared to vertical gradients (see Discussion), we equated diapycnal eddy diffusivities with vertical diffusivities (i.e., $K_\rho = K_z$).

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To obtain representative mean turbulent eddy diffusivities, the data were evaluated in ensembles of three to four consecutive profiles and averaged in depth and time to reduce uncertainties due to the patchiness of turbulence, temporal fluctuation of N^2, as well as temporal γ variations (see Smyth et al., 2001). As proposed by Ferrari and Polzin (2005), the level of uncertainty of the averaged K_z can be quantified as:

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$$\Delta K_z = K_z\left[\left(\frac{\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\Delta\varepsilon}{\varepsilon}\right)^2 + \left(\frac{\Delta N^2}{N^2}\right)^2\right]^{1/2} \qquad (3)$$

with Δ being the absolute uncertainty of the various average terms. Here, the uncertainties are evaluated in the region of strong vertical O_2 gradients and in 2 m depth bins. The absolute uncertainty for $\Delta\gamma$ was assumed to be 0.04 (see St. Laurent and Schmitt, 1999). The absolute uncertainty on N^2 (ΔN^2) was determined by the

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standard error over the 2 m average, computed as the standard deviation divided by the square root of the number of estimates. Finally, the statistical uncertainty of ε for each bin was calculated using a bootstrap method (10^4 resamples) (Efron, 1979).

The vertical O_2 fluxes F_θ were then obtained from K_z and the O_2 concentration gradients $\partial[O_2]/\partial z$ as

$$F_\theta = K_z \frac{\partial[O_2]}{\partial z} \tag{4}$$

Accordingly, the uncertainty of averaged turbulent O_2 fluxes were given by:

$$\Delta F_\theta = F_\theta \left[\left(\frac{\Delta K_z}{K_z} \right)^2 + \left(\frac{\Delta \partial_z[O_2]}{\partial_z[O_2]} \right)^2 \right]^{1/2} \tag{5}$$

where $\Delta\partial_z[O_2]$ denotes the standard error of mean vertical gradients of O_2 concentrations. It should be noted that the analysis did not include biases or uncertainties due to measurement errors.

3 Results

During the three-day observational period (8 – 11 August 2009) we collected 39 high-resolution MSS profiles in sets of three to five profiles that were collected consecutively at 5 – 10 min intervals. Most of the profiles were collected either in the evening (profiles 1 – 8, 26 – 28, 36 – 39) or at night (9 – 15, 29 – 35) with the remaining profiles acquired in the morning (6 to 9 AM). One shipboard CTD profile was performed prior to the actual MSS profiles to provide hydrographic information, the water turbidity and O_2 concentrations, as well as discrete water samples for subsequent onboard Winkler titrations. Hydroacoustic water column current measurements were carried out continuously throughout the observational period. The following results are structured to first present a characterization of the site's physical settings and turbulence drivers, followed by the O_2 fluxes and O_2 BBL budget.

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3.1 Water column structure

The ~70 m deep water column was characterized by a stable, well-defined four-layer temperature structure (Fig. 2a). A well-mixed surface boundary layer (SBL) and bottom boundary layer (BBL), 15 m and 30 m thick, respectively, were separated by a weakly-stratified transition layer (15 – 25 m depth) and a strongly stratified interior layer (25 – 40 m depth). The stratified interior layer was characterized by two very steep thermoclines situated in the upper (27 – 30 m depth) and lower (36 – 39 m depth) region of the layer, with vertical temperature gradients of up to 4°C m^{-1}. The average salinity was 35.08 with little variation throughout the water column (35.04 – 35.1). The light transmission profile from the ship CTD ranged from 89% to 96% (Fig. 2b). The most turbid layer (89%) was observed at the lower boundary of the interior layer (at 40 m depth) suggesting the presence of the deep chlorophyll maximum, phytoplankton, zooplankton and suspended particles.

The O_2 profiles were generally characterized by near saturation in the SBL and transition layers, with O_2 concentrations in the 238 – 243 µmol kg^{-1} range, and undersaturated (~80%) in the BBL, where the O_2 concentration was ~243 µmol kg^{-1} (Fig. 2c,d). The stratified interior was oversaturated by up to 115%, with a well-established O_2 maximum at ~39 m depth with concentrations up to ~315 µmol kg^{-1}. Below that maximum, at the thermocline-BBL interface, we observed a 2 – 3 m thick steep oxycline, with an O_2 gradient of 34 µmol kg^{-1} m^{-1} with exhibited limited day – night, depth and thickness variability. With this in mind, we wish to resolve the O_2 flux into the BBL associated with the oxycline.

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3.2 Hydrodynamics

The POZ lander hydrostatic pressure dataset revealed that the tidal water level ranged from 0.6 to 0.9 m (Fig. 3a). Variance analysis on the ADCP velocity data identified the major and minor axis of the tidal ellipsoid components to occur at 45° and 135° from true north, respectively. Along these axes, the current amplitudes were 0.21 m s^{-1} and 0.04 m s^{-1}, indicating a narrow tidal current ellipsoid, as reported by Otto et al. (1990). The site was characterized by a negative tide polarity (anti-cyclonic) for the semi-diurnal tides. A dominance of the barotropic M_2 current amplitude at all depths was also clearly observed in the velocity time series (Fig. 3b, c) and the harmonic analyses. East (zonal) and north (meridional) barotropic M_2-current amplitudes were 0.12 m s^{-1} and 0.17 m s^{-1}, respectively, while K_1-current amplitudes were only 0.005 m s^{-1} and 0.03 m s^{-1}.

Although the limited length of the ADCP velocity time series did not allow for full separation of the M_2 and *f* frequencies, the spectral density functions indicated maximum energy at frequencies of about the semi-diurnal tide. This maximum varied little with depth indicating barotropic M_2 motions. Superimposed on those barotropic

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currents, we observed the presence of baroclinic velocity contributions (Fig. 3b, c). Additionally, near-inertial motions were also observed.

The occurrence of near-inertial motions was most pronounced in the thermocline (32 – 39 m; Fig. 3e). Lower but still elevated energy densities at the near-inertial band were also found in the SBL and BBL. Moreover, the near-inertial currents exhibited a distinct 180° phase shift between the SBL and the thermocline as well as between the thermocline and the BBL, suggesting a second vertical mode nature of these fluctuations. Average amplitudes of the near-inertial fluctuations in the thermocline obtained from least-square fitting were 0.11 m s^{-1}. In the BBL and SBL, average amplitudes were reduced to 0.06 m s^{-1} and 0.04 m s^{-1}, respectively, suggesting that f oscillations might account for enhanced shear in the thermocline.

Enhanced vertical shear of horizontal velocity was found at the interior – transition layer as well as at the interior – BBL interfacial regions (Fig. 3d). As indicated by the spectral density function of the shear time series from the interior interfacial layers (SI Fig. 1), the shear exhibited near-inertial frequencies (1.6722 cpd), and resulted from the baroclinic near-inertial wave. The high vertical resolution (0.5 m) of our velocity data allowed the resolution of the interfacial shear layers, which were typically 2 to 3 m thick with elevated values of up to 0.05 s^{-1}. Comparisons with CTD data showed that they are collocated with the two enhanced temperature gradients layers in the thermocline (27 – 30 m and 36 – 39 m depth; Fig. 2a).

The dissipation rates (ε) of turbulent kinetic energy (TKE) determined from microstructure shear probes were particularly low ($2 – 5 \times 10^{-9}$ W kg^{-1}) but above the MSS detection limit in the center of the stratified interior. However, TKE increased to 5×10^{-9} W kg^{-1} and 2×10^{-8} W kg^{-1} at the upper and lower interior layer limits, respectively (Fig. 4a). These coincided with the depth range of the interfacial shear layers (Fig. 3d) at the strong temperature gradients (Fig. 2a) and resulting water column stability maxima (~1×10^{-3} s^{-2}).

Bin-averaged values of K_z varied by a factor of 5, ranging from 6×10^{-7} m^2 s^{-1} in the central interior to 3×10^{-6} m^2 s^{-1} in the lower region of the transition layer (Fig. 4b). In the upper interface (thermocline – transition layer), where ε was elevated with respect to the central interior but reduced compared to the lower interfacial layer,

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stronger stratification (i.e., larger N^2 values up to 10^{-3} s^{-2}) reduced the eddy diffusivities. At the interior-BBL, higher K_z values (~2×10^{-5} m^2 s^{-1}) resulted from increased turbulence and weaker stratification. This enhanced turbulent transport was located where the vertical O_2 gradient was the strongest (Fig. 2d).

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3.3 Oxygen fluxes and budget

With the fast responding AMT galvanic O_2 sensor and rapid sampling rate, we were able to resolve the O_2 gradient with a very high precision. Figure 4c shows the 2 m bin average O_2 fluxes for the interior together with the averages from each ensemble. Small O_2 fluxes (~1 mmol m^{-2} d^{-1}) were estimated for the center and upper region of the interior; this suggested that relatively little O_2 is transported upward from the O_2 maximum to the rest of the interior. In contrast, a substantial O_2 flux ranging from 9 – 134 mmol m^{-2} d^{-1} (average of 54 mmol m^{-2} d^{-1}) was identified from the lower thermocline towards the BBL. The confidence interval associated with the uncertainties of the O_2 flux estimates was 18 – 74 mmol m^{-2} d^{-1}. Although the O_2 fluxes to the BBL water from the thermocline were variable in magnitude (Fig. 4c), and the measurements limited to the observational period (Fig. 3), their magnitude nevertheless suggests an important, yet overlooked, O_2 pathway.

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We performed a simple 1-D BBL mass balance to investigate the relevance to the local O_2 balance during our observational period. Here, we defined the apparent (measured) O_2 loss rate in the BBL $\partial[O_2]/\partial t$ as the consequence of O_2 replenishment from F_θ and the O_2 utilization via sediment O_2 uptake rate (*SUR*) and water column organic matter respiration (*R*) expressed as

$$\frac{\partial[O_2]}{\partial t}\frac{V}{A} = |F_\theta| - |SUR| - |R| \quad \{mmol\, m^{-2}\, d^{-1}\} \tag{6}$$

The mass balance was constrained to the (assumed) well-mixed 35 m deep BBL section of area, $A = 1$ m^2 with a volume, $V = 35$ m^3. We further assumed negligible horizontal O_2 gradients (as observed from the CTD casts), and thus a net zero horizontal O_2 advective transport.

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The average *SUR* for the same time period and location obtained from parallel eddy correlation measurements, was ~-10 mmol m^{-2} d^{-1} (McGinnis et al., 2014). The *SUR* was consistent with the average *SUR* at Oyster Grounds reported by Neubacher et al. (2011), -9.8 mmol m^{-2} d^{-1}, as well as with modeled *SUR*s at the same site

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(average -8.6 mmol m^{-2} d^{-1}; Meire et al., 2013). The apparent BBL O_2 loss of -0.42 µmol kg^{-1} d^{-1} was determined from the POZ lander O_2 optode time series (Fig. 5a) over 52 hours, (R^2=0.60). Though limited to our short observational period, the vertically integrated apparent BBL O_2 loss was about -15 mmol m^{-2} d^{-1} and thus within 2% of the nearby North Dogger average presented by Greenwood et al. (2010). Based on Eq. (6) and using the observed BBL O_2 loss rate, F_θ and *SUR*, the water column respiration, *R* was calculated to be ~-60 mmol m^{-2} d^{-1}. This implies that without the O_2 replenishment, the apparent BBL O_2 loss would be ~-2 µmol kg^{-1} d^{-1} and thus four times higher than observed. Our results indicated that the total respiration in the bottom water was therefore ~-70 mmol m^{-2} d^{-1} (*SUR* + *R*), with about 14% of the organic carbon mineralization occurring at the sediment and 86% in the BBL.

4 Discussion

During our three-day observational period, we found that the baroclinic near-inertial wave in the interior was the main contributor to the detected enhanced shear (Fig. 3d) and the observed elevated vertical O_2 flux to the BBL (Fig. 6). As near-inertial waves decay after a few weeks, it should be noted that we observed a rather special situation, and that vertical O_2 fluxes will not likely be as highly elevated during periods when near-inertial waves are not present.

Within this context, we will: 1) discuss the turbulent mechanisms leading to these thermocline O_2 fluxes and those promoting the formation of the O_2 maximum zone in terms of primary productivity; 2) discuss the implication for the local O_2 BBL dynamics and carbon budget; 3) speculate on factors that can ultimately influence O_2 depletion in the North Sea and other seasonally stratified shelf seas.

4.1 Thermocline mixing

The expansive North Sea thermocline (1 – 5 10^5 km^2; Meyer et al., 2011) has been regarded as being in a state of marginal stability, where additional sources of shear could lead to increased thermocline mixing (e.g., van Haren et al., 1999). Itsweire et al. (1989) showed that layers of strong shear are likely to be found where strong stratification occurs. In general, away from varying topography, the major sources of shear in the thermocline are considered to be internal tides and near-inertial

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oscillations (see Rippeth, 2005). Sharples et al. (2007) demonstrated that internal tidally-driven thermocline mixing also enhanced diapycnal nutrient fluxes, the overall productivity in the thermocline, as well as the associated carbon export to the BBL.

The occurrence of near-inertial oscillations in shelf seas during the stratified season has been reported in several studies from the North Sea (van Haren et al., 1999; Knight et al., 2002) as well as in other shelf seas (e.g., Rippeth et al., 2002; McKinnon and Gregg, 2005). During the presence of baroclinic inertial waves in the water column, periods of enhanced shear taking the form of shear spikes occur approximately every inertial period and in bursts lasting several days have been observed in the western Irish Sea (Rippeth et al., 2009), the Celtic Sea (Palmer et al., 2008) and the northern North Sea (Burchard and Rippeth, 2009).

While we mainly attributed the observed enhanced turbulent mixing to the occurrence of a near-inertial wave, the site's physical setting has further implications for mixing processes in the thermocline. In the northern hemisphere, sites with anti-cyclonic tides, such as Tommeliten, are often characterized by an increased vertical extension of the BBL, and higher BBL dissipation rates than comparable cyclonic sites (see Simpson and Tinker, 2009). As a result of this enhanced BBL thickness, we observed sporadically elevated thermocline turbulence resulting from tidal-driven bottom turbulence propagating vertically to the thermocline (Fig. 5b). A study by Burchard and Rippeth (2009) also reported that short lived thermocline shear spikes can arise due to the alignment of the surface wind stress, bulk shear, and bed stress vectors in the presence of baroclinic near-inertial motions and barotropic tidal currents. These mechanisms are stronger with anti-cyclonic tides. Although all the features required for shear spike generation were present during the observational period, the two-layer mechanism described by these authors would require a more complex water column structure to be applicable to the Tommeliten site.

The site's water column structure clearly showed the occurrence of a 10 m thick transition layer (Fig. 2a). This layer represents the region of the water column where mixing turns from elevated in the SBL to strongly reduce in the interior (Ferrari and Boccaletti, 2004). The transition layer represents an obligate pathway for solute and heat exchange between SBL and the interior (Ferrari and Boccaletti, 2004; Rhein et al., 2010) and has also been reported to be a region of enhanced shear and near-inertial wave activity (Dohan and Davis, 2011). Although the presented data did

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not allow a quantification of the O_2 exchange across the transition layer, such contribution might be considerable and thus highly relevant for the cycling of O_2 and CO_2 in the upper water column, which in turn could have direct biological implications.

4.2 BBL O_2 dynamics

Ultimately, observed O_2 depletion in the BBL of the central North Sea depends on the supply of organic matter, the rate of carbon mineralization, and the flux of O_2 to the bottom water, either from horizontal advection or turbulent vertical transport. Our study investigated the significance of turbulent vertical O_2 fluxes to the BBL, which has been previously overlooked in shelf sea carbon balances. Studies focusing on O_2 replenishment in the BBL through the thermocline are limited to freshwater systems (e.g. Bouffard et al., 2013; Kreling et al., 2014). In a large stratified water body such as Lake Erie, O_2 transport from the thermocline to the hypolimnion was found to be substantial, with a magnitude comparable to ~18% of the hypolimnetic O_2 utilization rate over the whole stratification period (Bouffard et al., 2013).

Horizontal O_2 gradients and associated horizontal advective O_2 fluxes were not quantified in this study. Our data does, however, suggest that such fluxes would not significantly contribute to the O_2 balance at the Tommeliten site. BBL O_2 concentration time series (Fig. 5a) did not show any variability at the tidal and or inertial frequencies, implying that horizontal O_2 gradients were small. Additionally, mean currents in the BBL were also small (~2 cm s^{-1}) compared to the tidal amplitudes. This, in conjunction with weak horizontal O_2 gradients, suggests that horizontal advective O_2 fluxes during our observational period are negligible compared to the turbulent O_2 flux from the thermocline.

Based on the above, we can argue that the O_2 dynamics during the stratified period are more complicated than previously regarded. To maintain an excess of O_2 in the thermocline, primary producers require adequate nutrient entrainment from the bottom water to fuel potential new production. The resulting increase in (new) productivity and subsequent export to the bottom water could therefore boost the carbon turnover estimates substantially. Using a 1:1 O_2 utilization – carbon re-mineralization (see Canfield, 1993), Greenwood et al. (2010) inferred the average

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BBL carbon re-mineralization rate at the nearby North Dogger to be 15 mmol m^{-2} d^{-1}, or 180 mg C m^{-2} d^{-1}. Similar results for a typical NW European shelf sea were obtained via modeling by Sharples (2008), who reported rates ranging from ~35 to ~200 mg m^{-2} d^{-1} for neap and spring tide, respectively. Their study, however, did not include the daily tidal variation, and thus rates could be much higher on shorter timescales.

With the absence of targeted long-term studies focusing on O_2 and carbon dynamics in the thermocline and BBL, we can only speculate on the long-term fate of the BBL O_2 and its replenishment from the thermocline by vertical O_2 fluxes (F_θ). However, it seems possible over that the overall net BBL water column O_2 respiration, R, is higher than previously thought, suggesting a much higher carbon turnover than inferred from the apparent O_2 loss rate. Based on Eq. (6), the BBL carbon re-mineralization (and export to the BBL) would be on the order of nearly 850 mg C m^{-2} d^{-1}, almost a factor of 5 higher than reported by Greenwood et al. (2010). However, the same turbulent transport that supports the O_2 export from the DCM to the BBL also supports BBL nutrient import to the DCM (Fig. 6). The higher import of nutrients to the DCM likely promotes additional primary production and a subsequent increase in organic matter (OM) export to the BBL. In such a scenario, the ephemeral O_2 flux to the BBL presented in this study will be associated with additional OM to the BBL, and therefore lead to a temporary increased re-mineralization that offsets the increased F_θ. While the overall effect is an increase in carbon turnover, this process therefore does not result in any observable change in the decreasing O_2 trend (apparent O_2 loss rate).

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4.3 Causes and controls on BBL O_2 depletion

According to Boers (2005), for BBL O_2 to decrease throughout the stratified season, there must be suitable physical conditions, biomass production, nutrient input and continued benthic O_2 uptake. *SUR*, and thus the sediment nutrient release and organic carbon mineralization have been shown to be strongly tidal-driven (McGinnis et al., 2014). Therefore, we briefly discuss the potential tidal impact driving the overall carbon cycling and suggest factors that may promote the development of lower BBL O_2 concentrations during the stratification period.

Tidal forcing on diapycnal constituent fluxes and primary production have been explored by e.g., Sharples et al. (2007, 2008). The authors showed that spring-neap tide drives nutrient fluxes between the BBL and the DCM at the thermocline, as well as the carbon export. Based on our velocity measurements and estimated O_2 fluxes, we can also expect similar patterns corresponding to semidiurnal tidal fluctuations. Blauw et al. (2012) investigated fluctuating phytoplankton concentrations in relation to tidal drivers and found in the southern North Sea that chlorophyll fluctuations correlated with the typical tidal current speed periods, the semidiurnal tidal cycle, in addition to the day-night and spring-neap periods. During most of the year, chlorophyll and suspended particulate matter fluctuated in phase with tidal current speed, and indicated alternating periods of sinking and vertical mixing of algae and suspended matter with tidal cycles. Thus, these results suggest that we can expect the semidiurnal tidal-driven export of carbon and O_2 from the DCM to the BBL, as well as entrainment of nutrients that strongly vary based on a timescale related to the semi-diurnal tidal cycle, in addition to the spring-neap tidal cycles.

The flux of O_2 from the DCM production zone downward to the BBL could set the lower limit of the BBL O_2 concentration, and thus the O_2 depletion level, during the stratification period. If there is little isolation between the zone of production and the zone of mineralization, then the net O_2 production and O_2 utilization would nearly balance. In such case the apparent O_2 loss in the BBL would either be negligible or very small, depending whether the largely particle organic matter driven SUR will be balanced by the ventilation form the thermocline. However, historically decreasing BBL O_2 concentrations within the North Sea (Queste et al., 2013) point to an increasing disconnect between the main O_2 production zone and the mineralization zones. Greenwood et al. (2010) state that stratification is an important factor which determines susceptibility to O_2 depletion, especially in their nearby study site Oyster Grounds.

Surveys on the North Sea have shown that the regions with the lowest BBL O_2 concentrations are generally characterized by the strongest stratification (see Queste et al., 2013), and the lowest reported values (~100 μmol kg^{-1}) were also reported to occur during particularly calm and warm weather (see Boers, 2005; Weston et al., 2008). Strong gradients in the thermocline are suggested to limit the O_2 flux to the

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BBL (Weston et al., 2008), and point to the potential future O_2 depletion resulting from increasing temperatures leading to both stronger stratification and a longer stratification season (Lowe et al., 2009). However, it could be expected that if O_2 fluxes between the DCM and BBL were suppressed, then the upward nutrient fluxes would be similarly suppressed, thus inhibiting primary production and therefore not resulting in observed O_2 deficits.

4.4 Biological perspective

The occurrence of stronger stratification might have much larger implications than presently thought, since reduced turbulent mixing will alter algal populations (Hickman et al., 2009), potentially favoring migrating/swimming phytoplankton. An example of these migrating phytoplankton species, armored dinoflagellates, are extensively found in the DCM of the central and northern North Sea during the summer months; their abundance was found to be largely determined by the local hydrodynamic conditions (Reid et al., 1990). In calm conditions, which are typically associated with stronger stratification, there are often blooms of migrating dinoflagellates which have access to the large nutrient pool in the deeper water and can therefore out-compete non-migrating species for both light and nutrients. Stronger turbulent mixing, in contrast, has been suggested to interfere with their swimming abilities and thus favoring other algal species (see Jephson et al., 2012 and references therein).

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Migration-driven movement of the DCM higher in the thermocline, even by a few meters, means that the O_2 production will be shifted higher in the thermocline. Migrating phytoplankton could therefore access BBL nutrients in this scenario, i.e., primary production rates would be comparable, but the result would be an evident further decrease in the BBL O_2. For example, assuming our previous values of *SUR* and *R* in Eq. (6), but reducing F_θ by half results in a nearly 3x increase in the apparent O_2 loss rate. Therefore, the combined effects of reduced turbulent O_2 flux and a reduced O_2 gradient at the base of the thermocline, will both further isolate the BBL from this potential O_2 supply while maintaining similar rates of carbon export (settling armored dinoflagellates). We speculate that this mechanism could therefore provide a further loss of O_2 connectivity as the amount of production would remain approximately the same, but the supply of O_2 to the BBL would be substantially reduced. Of course, whether such scenario could be sustained over the whole stratification period is not known and requires further assessment.

In the light of climatic changes, studies have suggested that O_2 loss in the North Sea bottom waters would mainly result from a strengthening of the stratification and O_2 solubility reduction with increasingly warmer waters (e.g., Meire et al., 2013). The findings of this study suggest there might be an additional level of complexity based on the interplay between the tidally-driven physics, water column structure, biogeochemical cycling and active phytoplankton migration in the central North Sea. The proposed mechanism could contribute to the observed decreasing O_2 levels in the North Sea water column, however, further detailed studies are obviously necessary to validate and fully quantify this effect at the seasonal level.

Acknowledgements

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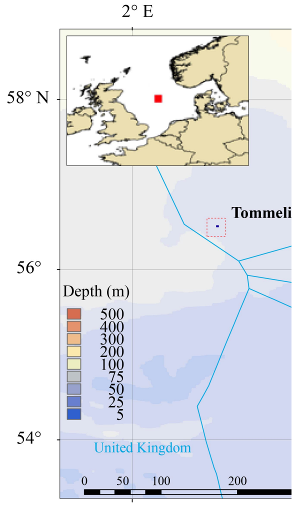

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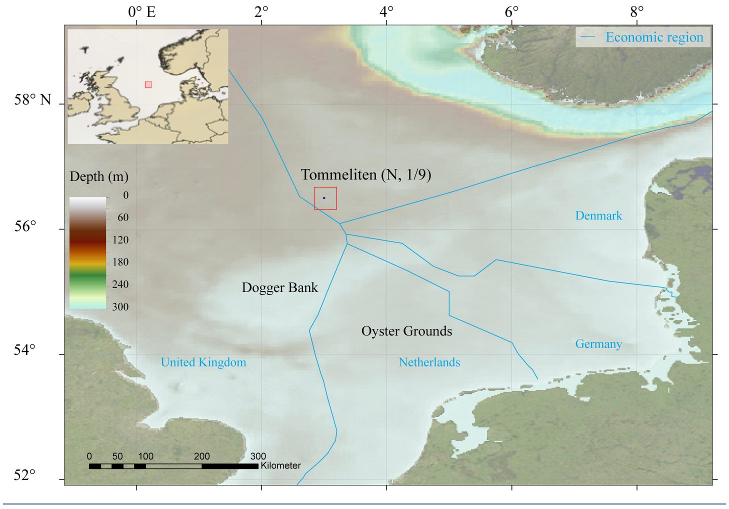

Figure 1. Map of the North Sea indicating the water depths and location of the Tommeliten site as well as the borders of the economic regions of the surrounding European countries.

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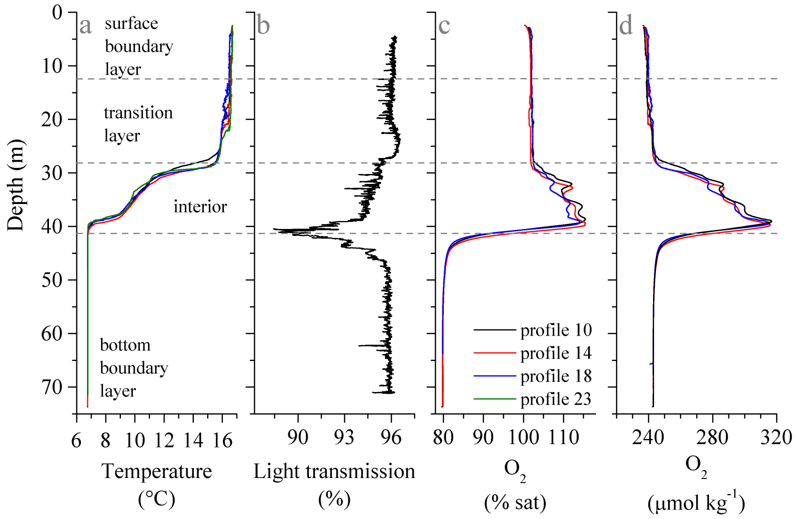

Figure 2. Selected water column profiles based on based on high-resolution MSS profiles (a, c, d) and ship CTD profile (b). (a) Potential temperature profiles. Water column layers were identified based on the temperature profiles. A 0.2°C and 1.5°C decrease from the surface boundary layer average temperature (3–6 m depth) was used determine the depth of the surface boundary layer – transition layer interface and the transition layer – interior interface, respectively. Correspondingly, a 0.2°C from a 50-60 m depth average temperature was used to locate the interior – bottom boundary layer interface. (b) Light transmission profile. (c, d) O_2 saturation profiles and associated absolute concentrations.

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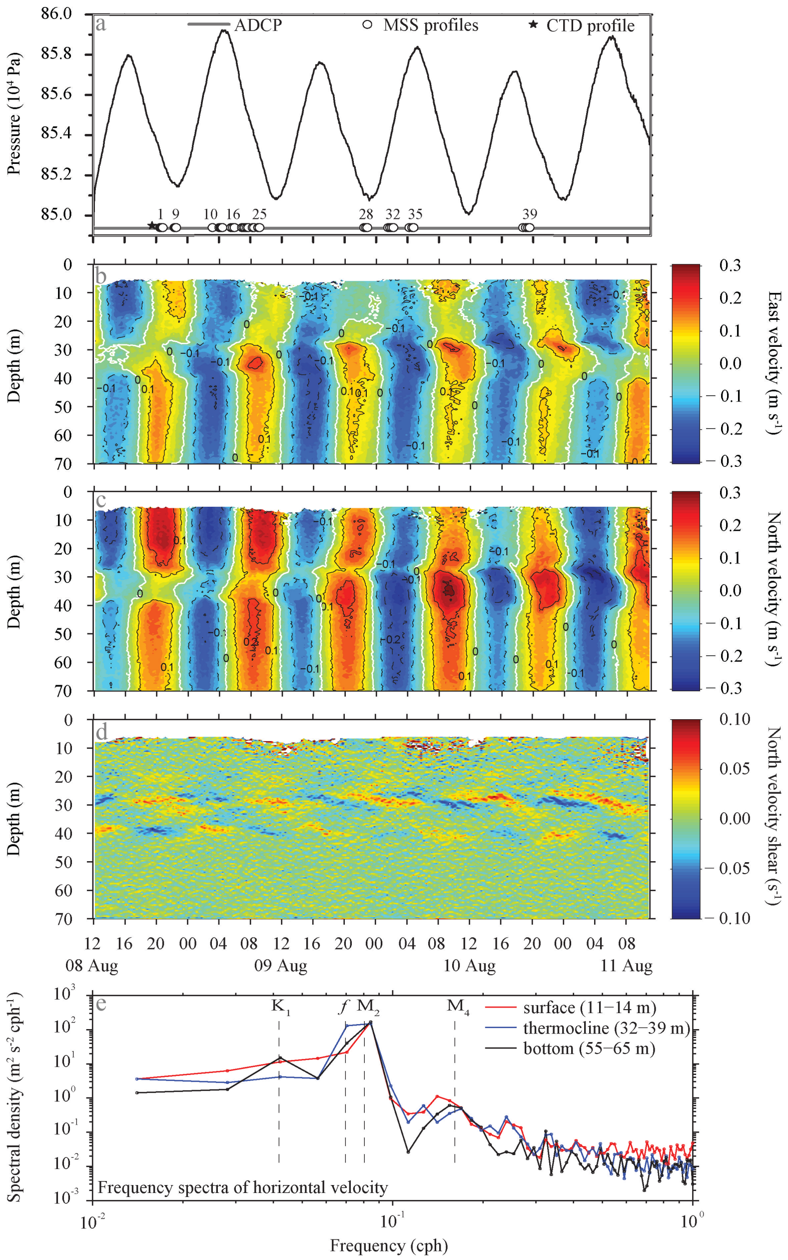

Figure 3. Current regime at the Tommeliten site from ADCP measurements (a - d) and spectral analysis (e). (a) Sea surface elevation relative to average level during the observational period (elevation = 0 m) and schedule of different instrument

deployments. Numbers on the MSS markers indicate the profile number. (b, c) Horizontal velocities, showing 20 min averaged east (b) and north (c) velocities. (d) Vertical shear of North velocity, *dv/dz*, calculated from the ADCP velocity data (see panels b, c). Note that panels a - d have the same time axis. (e) Frequency spectra of horizontal velocity calculated from the ADCP data for selected depth ranges for the SBL (surface; red line), thermocline (blue line), and BBL (bottom; black line). The inertial f as well as the K_1, M_2 and M_4 frequencies are marked.

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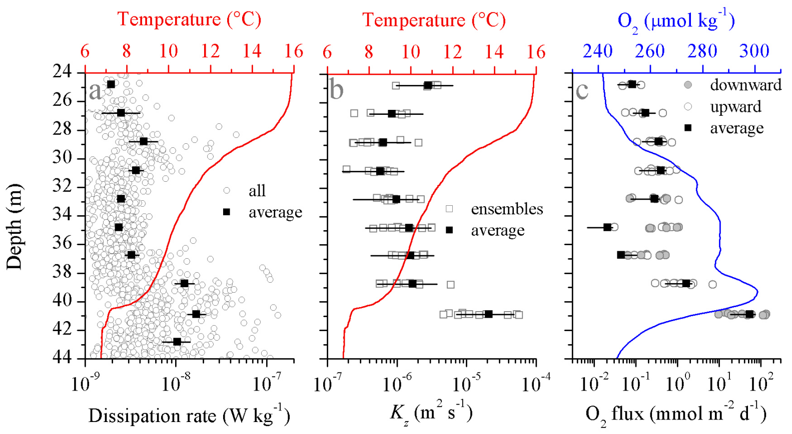

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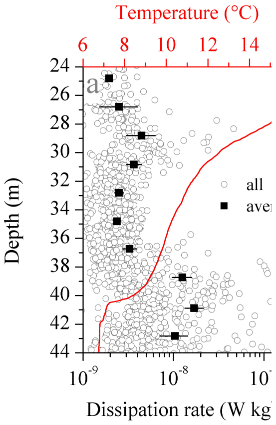

Figure 4. Overview of turbulent transport and O_2 fluxes within the interior (defined in Fig. 2). Each panel is overlaid with temperature (a, b) and O_2 concentration (c) profiles. (a) Dissipation from all profiles (open dots) together with the arithmetic mean (solid squares). (b) Average vertical eddy diffusion coefficient K_z with uncertainties bars as well as the K_z values for every ensemble (open squares), which represent the average over 3 to 4 consecutive profiles. (c) Calculated average O_2 flux over 2 m bins with the respective uncertainties intervals (solid square and black line). The values for each profile cluster are shown both downward and upward fluxes (grey solid and open dots, respectively). Note that in the center interior (33 – 37 m) the average reflects the combination of the variability of the observed upward and downwards fluxes.

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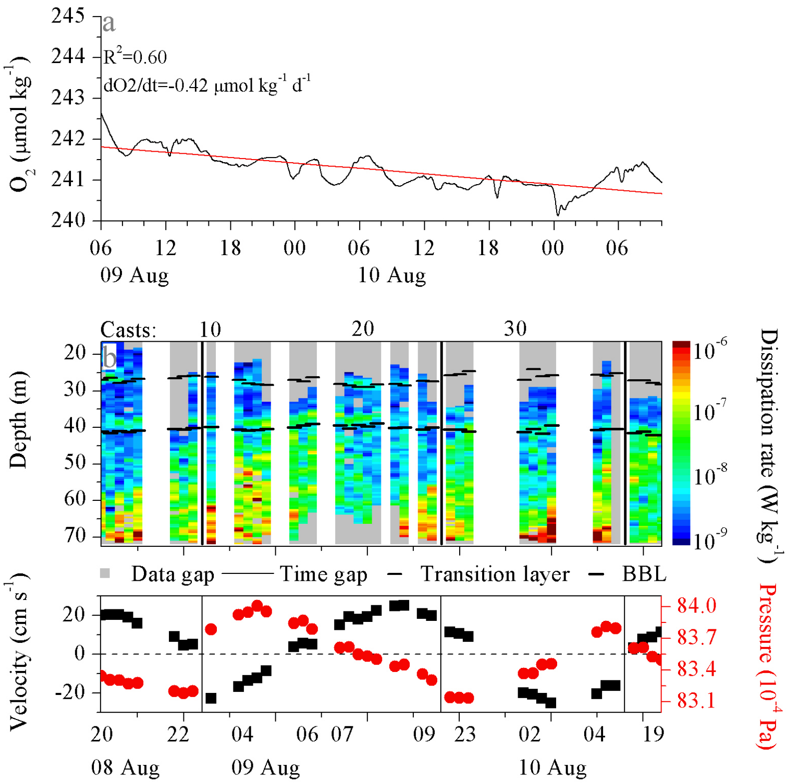

Figure 5. BBL dissolved oxygen time series and turbulence contour. (a) Near-seafloor BBL O_2 concentration changes over the observational period from the POZ-Lander. Red line indicates the estimated apparent linear O_2 loss. (b, top) Turbulence contour plot of all MSS90 casts together with the temperature layers. Thin and thick dashed lines represent the transition layer – interior interface and the interior – BBL interface, respectively. Gray spots indicate data missing due to uncompleted profiles (casts 16-23), unsuccessful profiles (cast 36), or flagged as bad based on spikes, collisions and suspected contamination due to ship activity. The vertical black lines indicate the transition (time gaps) between consecutive profile ensembles. (b, bottom) Background information on bottom current, and hydrostatic pressure during the casts. Both velocity and pressure data were collected by the deployed POZ lander. Note that as a result of the time gaps between the consecutive MSS90 casts (see Fig. 3a) the time scale is not linear.

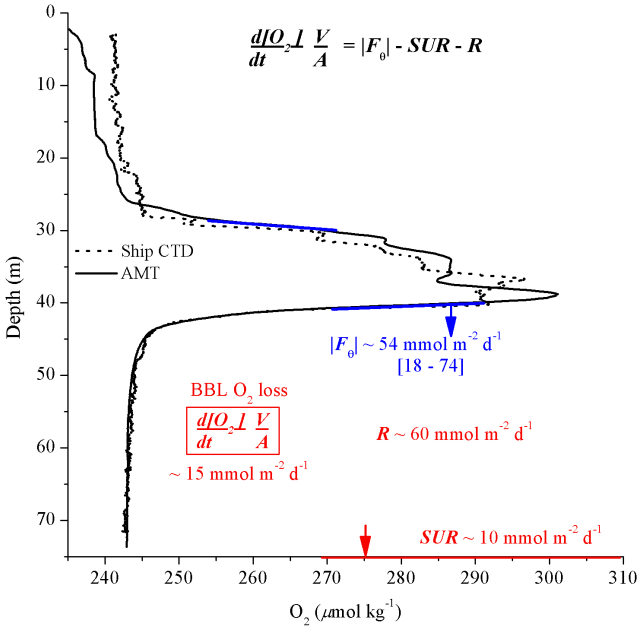

Figure 6. Main O_2 fluxes in this study. The ranges shown for the interior O_2 fluxes refer to the associated uncertainty and intermittency levels. The sediment O_2 uptake rates (SUR)

are based on eddy correlation (EC) measurements (McGinnis et al., 2014), while central North Sea apparent BBL O_2 loss is based on Greenwood et al. (2010) and this study. Representative O_2 profiles are based on the AMT sensor on the MSS profiler (solid line) and ship CTD (dotted line). Note that while the O_2 profiles showed differences in absolute concentration within the thermocline, the actual O_2 gradients within the thermocline-BBL oxycline are comparable.

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