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# Detection of low bottom water oxygen concentrations in the North Sea; implications for monitoring and assessment of ecosystem health

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**Detection of low  
bottom water oxygen  
concentrations in the  
North Sea**

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Abstract

This paper presents new results from high temporal resolution observations over two years (2007 and 2008) from instrumented moorings deployed in the central North Sea, at the Oyster Grounds and on the northern slope of Dogger Bank (North Dogger). The water column was stratified in the summer at both sites, leading to limited exchange of the water in the bottom mixed layer. Data from these moorings revealed the variable nature of summer oxygen depletion at the Oyster Grounds. The combination of in situ and ship-based measurements allowed the physical and biological conditions leading to decreasing dissolved oxygen concentrations in bottom water to be examined. The concentration of dissolved oxygen in the bottom water at both sites was observed to decrease throughout the summer period after the onset of stratification. Depleted dissolved oxygen concentration ( $6.5 \text{ mg l}^{-1}$ , 71% saturation) was measured at the North Dogger, a site which is not significantly influenced by anthropogenic nutrient inputs. Lower oxygen saturation ( $5.2 \text{ mg l}^{-1}$ , 60% saturation) was measured for short durations at the Oyster Grounds. Increasing bottom water temperature accounted for 55% of the decrease in dissolved oxygen concentration at the Oyster Grounds compared to 10% at North Dogger.

Dissolved oxygen concentration in bottom water at the Oyster Grounds was shown to be strongly influenced by short term events including storm events and pulses of biomass input. In contrast, dissolved oxygen concentration in bottom water at the North Dogger reflected longer seasonal processes such as gradual temperature increases and a more steady supply of biomass to the bottom mixed layer. The differences between the study sites shows the need for an improved understanding of the mechanisms driving these processes if the use of oxygen in marine management and ensuring ecosystem health is to be meaningful and successful in the future. These observations provide greater understanding of the nature of the depletion in bottom oxygen concentration in the North Sea.

**BGD**

6, 8411–8453, 2009

### Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## 1 Introduction

Coastal seas are highly productive environments under considerable stress from human activities and respond to these stresses in diverse ways reflecting their biogeochemistry and physical structure (Jickells, 1998). Dissolved oxygen levels in parts of the marine environment have shown rapid change since the 1950s especially in regions which have been adversely affected by the process of eutrophication (Diaz, 2001). For example, increased dissolved nutrient inputs have resulted in an anthropogenically induced region of low dissolved oxygen in large areas (80 000 km<sup>2</sup>) of the Baltic Sea (Conley et al., 2002) and 20 000 km<sup>2</sup> in the Black Sea (Mee, 1992) with development of new areas of low oxygen being observed globally (Chan et al., 2008). Hypoxia (dissolved oxygen concentration below 2 mg l<sup>-1</sup>) and less severely depleted dissolved oxygen concentrations have the potential to cause lethal and sub-lethal effects to a range of benthic organisms (Cheung et al., 2008; Long et al., 2008; Vaquer-Sunyer and Duarte, 2008; Levin et al., 2009) and fish (Chabot and Claireaux, 2008; Hassell et al., 2008; Skjærraasen et al., 2008; Wang et al., 2008; Ekau et al., 2009) which may cause loss of biodiversity in these impacted ecosystems (Breitburg et al., 2009). Increasing eutrophication-induced hypoxia has led to dead zones affecting more than 245 000 km<sup>2</sup> of marine ecosystems worldwide (Diaz and Rosenberg, 2008).

The offshore regions of the North Sea have had few published studies on bottom water oxygen concentrations, with most focussing on coastal waters such as the German Bight (Colijn et al., 2002). Earlier studies have shown the potential for low oxygen events in the central North Sea (Postma and Rommets, 1984; Peeters et al., 1995; Boers, 2005; Weston et al., 2008) but seasonal and temporal coverage was limited. The North Sea, being surrounded by the industrialised nations of northern Europe including the United Kingdom, The Netherlands, Belgium, Denmark and Germany, receives significant anthropogenic nutrient riverine input with the Rhine, for example, resulting in dissolved inorganic nitrogen inputs of ~300 ktonnes y<sup>-1</sup> (De Jonge et al., 1996). The semi-enclosed nature of the North Sea also leads to residence times in

**BGD**

6, 8411–8453, 2009

### Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

the order of weeks in southern and central regions (Weston et al., 2004) and therefore, in combination with water column stratification, leads to the isolation of bottom water. There is therefore the potential in certain areas of this shelf sea for high primary production (Joint and Pomroy, 1993) and possible low bottom water oxygen due to its export and remineralisation in bottom waters isolated from air-sea exchange due to stratification.

Current climate change scenarios for the North Sea show an earlier onset and increased magnitude of stratification (Lowe et al., 2009). A longer period of stratification will increase the length of time bottom waters are isolated from oxygen-rich surface water and may therefore lead to even lower bottom water oxygen concentrations. In addition, future changes in climatic conditions may be important in controlling nutrient fluxes from rivers into the coastal environment (Justić et al., 2003) with increases in extreme events leading to increases in nutrient fluxes. This may increase the susceptibility of coastal and shallow offshore environments to eutrophication and consequent low oxygen and hypoxic events. An understanding of the complex interplay of the factors which control oxygen levels is therefore necessary if we are to effectively manage these areas. Knowing the natural variability both temporally and spatially is essential to understanding the process of hypoxia development and assessing the extent of anthropogenic influence.

Oxygen is a fundamental biogeochemical component and it is used as a key supporting element in assessing the ecological status of marine and estuarine environments (Best et al., 2007). The concentration of dissolved oxygen is regarded as an important indicator of ecosystem health and plays a role in the assessment of good ecological status as required by the EU's Water Framework Directive (Best et al., 2007). An Ecological Quality Framework is central to the ecosystem-based approach for the management of the North Sea (Heslenfeld and Enserink, 2008; Johnson, 2008) and the use of oxygen as an Ecological Quality Objective within this framework has been established (Painting et al., 2005; Devlin et al., 2007; Heslenfeld and Enserink, 2008). Oxygen is also one of the indicators used in the OSPAR Common Procedure (OSPAR, 2005)

**BGD**

6, 8411–8453, 2009

---

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

used for assessment of eutrophication and may be an indicator of “Good Environmental Status” (GES) as required by the European Marine Strategy Framework Directive (EU, 2008). Consequently, understanding the causes of any observed low oxygen concentrations is critical to an accurate diagnosis of cause (e.g. increased anthropogenic nutrient inputs) and subsequent responses by responsible authorities required to reduce or eliminate anthropogenic eutrophication.

The assessment of dissolved oxygen concentration has been used historically within several regulatory frameworks (Best et al., 2007) with various thresholds applied. For the purposes of this paper, low oxygen concentration is defined as  $<4 \text{ mg l}^{-1}$ . This is the threshold used by England and Wales in the OSPAR eutrophication assessment of their marine waters (Foden et al., 2009) and is based on the UK classification scheme to be used within the Water Framework Directive (Best et al., 2007). However, a dissolved oxygen concentration of between  $2 \text{ mg l}^{-1}$  and  $6 \text{ mg l}^{-1}$  has been considered by some to be oxygen deficient (OSPAR, 2005).

The aim of this work was to investigate dissolved oxygen concentrations in bottom water at two sites in the North Sea and advance our understanding of how the dissolved oxygen concentration in different regions of this important shelf sea responds to varying water column structure. This was achieved using a combination of instrumented moorings at two sites to provide high temporal resolution measurements and ship based CTD measurements.

## 2 Methods

### 2.1 Study area

The North Sea is part of the wider northwest European shelf; it is a semi-enclosed basin with a general anti-clockwise circulation, primarily open to the Atlantic in the north (Hill, 1973). It has a total area of  $575\,000 \text{ km}^2$  with the majority of the southern North Sea being relatively shallow ( $\sim 40 \text{ m}$ ) and well-mixed year round due to its shallow

**BGD**

6, 8411–8453, 2009

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

---

**Detection of low  
bottom water oxygen  
concentrations in the  
North Sea**N. Greenwood et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

depth and strong tidal currents opposing summer stratification (Howarth et al., 1993). The northern and central regions stratify throughout summer (Pingree et al., 1978) with only the deepest parts (>80 m depth) of the northern North Sea remaining stratified at the end of the autumn (Hill, 1973). The majority of the water mass in this region is due to Atlantic input from the north, although there are other marine inputs through the English Channel and significant low salinity input from the Baltic via the Skagge-  
5 ræk (Hill, 1973). The spring bloom in the offshore regions of the North Sea typically occurs in March/early April, depleting nutrients in the surface water and supplying biomass to the bottom mixed layer (BML). After the die back of the spring bloom, deep chlorophyll maxima (DCM) form extensively in the summer stratified regions of the North Sea,  
10 fuelled by new inputs of nutrients into the thermocline (Richardson et al., 2000; Weston et al., 2008) and they are a potential source of biomass to bottom waters throughout the stratified period. Production associated with the DCM has been estimated to account for 37% of annual new production in the summer stratified North Sea (Weston et al.,  
15 2005) so its input to the bottom mixed layer may be important in summer.

Detailed observations of temperature, salinity and of oxygen dynamics were carried out using instrumented moorings at two stations located in the summer-stratified region of the central North Sea (Fig. 1). The two study sites, Oyster Grounds and north of the Dogger Bank (referred to as North Dogger), were sampled on nine  
20 cruises between February 2007 and September 2008. The observations carried out at the Oyster Grounds form part of a eutrophication monitoring programme using an operational SmartBuoy network (Mills et al., 2003).

## a) North Dogger

The mooring was located at 55°41.00' N, 02°16.80' E, on the north slope of the Dogger Bank. Dogger Bank is a 300 km long sand bank, shallow (~20 m) and is shown outlined by the central 40 m contour (Fig. 1). Although the water column on top of Dogger Bank is well-mixed year-round, the mooring was situated in an area which

exhibits thermal stratification north of the frontal region (Pedersen, 1994) in a 85 m water column depth. This water north of Dogger Bank is influenced predominantly by Atlantic water inflow through the Orkney – Shetland gap (Pedersen, 1994). While this site is only a short distance from a significant transport pathway resulting from seasonal baroclinic flow from the north east coast of England (Brown et al., 1999; Hill et al., 2008) the predominant source of nutrients is of Atlantic origin. Low oxygen concentrations near the bottom were reported in 1916 by Gehrke (in: Postma and Rommets, 1984) although a limited data set is available. After the occurrence of the spring bloom, a DCM is a feature of this site during summer (Richardson et al., 2000; Weston et al., 2005).

## b) Oyster Grounds

The Oyster Grounds, or Oyster Ground, is a large, circular depression in the central North Sea centred at 54°30' N and 4°30' E. It reaches a maximum depth of ~50 m at its centre and is bordered by the shallower bathymetry of Dogger Bank, German Bight and Southern Bight. Bottom fronts prevent water mass transfer along the seabed into the Oyster Grounds (Weston et al., 2008) isolating a shallow BML during summer and low bottom water oxygen concentrations have been reported in previous studies (Postma and Rommets, 1984; Peeters et al., 1995; Boers, 2005; Weston et al., 2008). Previous studies have also shown the presence of a DCM at this site during summer (Weston et al., 2008). The mooring was located at 54°24.84' N, 04°02.50' E, in a water column depth of 45 m.

## 2.2 Discrete sample collection and analysis

Water samples for discrete measurements were collected at selected depths using a CTD rosette of 10 litre Niskin bottles. The CTD rosette was fitted with an FSI Integrated CTD (Falmouth Scientific Inc., USA) to provide salinity, temperature and depth data and for data acquisition. For chlorophyll measurements, known volumes were

**BGD**

6, 8411–8453, 2009

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



filtered through glass fibre filters (GF/F; Whatman, UK) in triplicate. Pigments were immediately extracted in 90% buffered acetone and refrigerated prior to analysis. A Turner Designs Model 10AU filter fluorometer (USA) was used to measure the fluorescence of extracted chlorophyll and phaeopigment before and after acidification following the method described by Tett (1987). The fluorometer was calibrated using a solution of pure chlorophyll *a* (Sigma-Aldrich, USA) with concentration being determined spectrophotometrically. The error of chlorophyll analyses was <2% relative to Turner certified reference material.

Water samples for oxygen determination were collected and preserved in triplicate using the Winkler method (Winkler, 1888). Samples were analysed on board using an automatic titration system (Sensoren Instrumente Systeme, Germany) with a photometric endpoint according to Williams and Jenkinson (1982). For measurements of suspended particulate matter (SPM), known volumes were passed through pre-weighed 0.4  $\mu\text{m}$  polycarbonate filters and rinsed with 2x50 ml ultrapure water. Filters were then dried in a desiccator at room temperature and weighed until filter weight remained constant. Samples were analysed for salinity using a Guildline 8400B salinometer (Canada) which had been standardised with IAPSO standard seawater.

Quality control of results for discrete samples analysed for salinity and chlorophyll was assured by participation in the Quality Assurance for Marine Environmental Measurements (QUASIMEME) scheme.

### 2.3 Moored instrumentation

In situ, high frequency measurements were made at the surface, mid water and on seabed landers at both Oyster Grounds and North Dogger. The parameters measured, depth of instrumentation and platforms used are summarised in Table 1.

A solid state data logger (ESM-2) designed and built by Centre for Environment, Fisheries and Aquaculture Science (Cefas, UK) was used for data acquisition and sensor control. Chlorophyll fluorescence was measured using a Seapoint chlorophyll fluorometer and turbidity with a Seapoint turbidity meter (Seapoint Inc., USA). Measurements

**BGD**

6, 8411–8453, 2009

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





of conductivity and temperature were made using either an FSI CT sensor (Falmouth Scientific Inc., USA) or an Aanderaa conductivity sensor (AADI, Norway). Oxygen concentrations were determined using an Aanderaa optode (AADI, Norway). Measurements were recorded at a frequency of 1 Hz for turbidity, chlorophyll fluorescence and temperature and conductivity from FSI sensors and at 5 Hz for Aanderaa optode and Aanderaa conductivity sensors, with a burst frequency of 2 per hour and a burst duration of between 5 and 10 min depending on the length of mooring deployment. A burst average value was calculated from quality assured data. Chlorophyll fluorometers were calibrated using results from discrete samples collected and analysed as described above ( $n=119$ ,  $r^2=0.74$ ,  $P>0.01$ ). Optical backscatter sensors were calibrated for SPM using results from discrete samples collected and analysed as above ( $n=45$ ,  $r^2=0.89$ ,  $P>0.01$ ). Results of discrete oxygen samples were used to calibrate data from the optodes.

Instruments on the moorings at North Dogger and Oyster Grounds seabed lander were exchanged with serviced instruments when each site was visited during the research programme. Instruments on the moorings at Oyster Grounds surface and mid-water were exchanged with serviced instruments within the routine monitoring programme conducted by Directorate Noordzee (DNZ) during surveys carried out as part of the Netherlands national marine monitoring programme. Data from the moorings were passed through a defined quality assurance protocol and only data which has passed the protocol is presented here. Daily average data were calculated from all burst average data which passed the QA protocol. Breaks in data were due to biofouling of sensors which is a common problem in these productive regions (Manov et al., 2004) or instrumentation failure.

An Acoustic Doppler Current Profiler with a frequency of 300 kHz or 600 kHz (Teledyne RDI, USA or Nortek AS, Norway) was deployed on each lander. The instrument was configured to record a sample of 120 pings every 10 min with a bin size of 1 m and 2 m for 600 kHz and 300 kHz instruments respectively. Wave height data was obtained from the Anasuria platform (WMO ID 62164) located at 57°15'38 N, 00°48'48 E

**BGD**

6, 8411–8453, 2009

---

**Detection of low  
bottom water oxygen  
concentrations in the  
North Sea**

N. Greenwood et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

(obtained from <http://www.cefas.co.uk/data/wavenet.aspx>) and a daily average wave height was calculated.

### 3 Results

#### 3.1 CTD surveys

5 CTD results (Table 2) showed that the water column at both sites was well mixed when sampled during the winter (February 2007, January 2008). Both sites were thermally stratified by April and the maximum temperature difference between surface and bottom water was 3.6°C at Oyster Grounds (August 2008) and 8.2°C at North Dogger (September 2008). The Oyster Grounds had returned to being well mixed again when  
10 sampled in September 2007 whereas North Dogger remained stratified at the beginning of November. In 2008, both sites were still stratified on the last sampling visit (August for the Oyster Grounds and September for North Dogger). The height of the bottom mixed layer (BML) varied with the time of year, varying between 20 m and 30 m above the seabed at Oyster Grounds and 26 m to 50 m above the seabed at North  
15 Dogger (Table 2). A DCM was observed at Oyster Grounds in May 2007 and August 2008 and at North Dogger in May 2007 and April and September 2008 from CTD casts (results not shown).

#### 3.2 Oyster Ground in situ monitoring

20 Temperatures ranged between 6.1°C (March 2008) and 17.7°C (surface water, July 2008). The water column was well mixed during autumn and winter but began to stratify (where the start of stratification is defined as when there is 1°C difference between surface and bottom) from 7 April 2007 (Fig. 2a). The onset of stratification in 2008 occurred on 26 April 2008, later than for 2007. However, the surface temperature increased more rapidly in 2008 compared to 2007 and the maximum temperature difference between the surface and 45 m was 8.7°C on 9 June 2008 compared to 6.8°C  
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**BGD**

6, 8411–8453, 2009

---

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



on 23 June 2007. During the monitoring period, the temperature difference between 35 m and 45 m was generally less than  $0.1^{\circ}\text{C}$ , therefore measurements made at 35 m are assumed to be representative of the conditions at 45 m.

Winter chlorophyll concentrations (November to March) were between  $0.2\ \mu\text{g l}^{-1}$  and  $0.5\ \mu\text{g l}^{-1}$  at all sampling depths (Fig. 2b). There was a phytoplankton bloom (defined as greater than the winter concentration of  $0.5\ \mu\text{g l}^{-1}$ ) at the surface between 6 and 19 April 2007 with a peak of  $5.1\ \mu\text{g l}^{-1}$  and a second bloom between 14 May and 7 June 2007 with a peak of  $1.7\ \mu\text{g l}^{-1}$ . There was a bloom at 35 m between 20 June and 1 July 2007, with a peak of  $2.0\ \mu\text{g l}^{-1}$  and another bloom between 6th and 27 July 2007, with a peak of  $1.4\ \mu\text{g l}^{-1}$ . There was a series of peaks in chlorophyll concentration at the seabed up to  $2.6\ \mu\text{g l}^{-1}$  starting on 2nd March 2008 which continued until the observations ceased at the start of September 2008.

The concentration of SPM was generally low throughout the water column, typically between  $1\ \text{mg l}^{-1}$  and  $6\ \text{mg l}^{-1}$  (Fig. 2c). A peak of  $10\ \text{mg l}^{-1}$  was recorded at the surface and mid-water at the end of March 2007 and peaks in SPM concentration above the seabed of  $40\ \text{mg l}^{-1}$  and  $66\ \text{mg l}^{-1}$  were observed on the 26 June, and between 3 July to 13 August respectively. SPM concentration increased throughout the water column from 25 October, with maximum concentrations of  $11\ \text{mg l}^{-1}$ ,  $34\ \text{mg l}^{-1}$  and  $232\ \text{mg l}^{-1}$  observed at the surface, 35 m and the seabed respectively between 9th and 12 November. SPM concentration remained elevated close to the seabed and at 35 m after this but decreased to below  $5\ \text{mg l}^{-1}$  at the surface. There were several peaks in SPM concentration at the seabed during winter 2007/2008, with a maximum of  $58\ \text{mg l}^{-1}$  on 17 March 2008. SPM concentration above the seabed decreased to less than  $5\ \text{mg l}^{-1}$  at the end of March 2008 and remained at this concentration until the start of June when there was a large increase in SPM concentration which reached a maximum of  $210\ \text{mg l}^{-1}$  on 22nd June 2008. SPM concentration remained less than  $2\ \text{mg l}^{-1}$  at the surface and 35 m from the beginning of April 2008 to the end of monitoring in July 2008.

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**Detection of low bottom water oxygen concentrations in the North Sea**N. Greenwood et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The concentration of dissolved oxygen at 35 m and 45 m during the winter (November to March) was between  $8.0 \text{ mg l}^{-1}$  and  $9.8 \text{ mg l}^{-1}$  (Fig. 2d). In 2007, the concentration at 35 m decreased from 4 April to a minimum of  $6.3 \text{ mg l}^{-1}$  on 28 August (79% saturation, Fig. 2e) after which there was a rapid increase in oxygen concentration over 4 days to  $7.9 \text{ mg l}^{-1}$  (saturated with respect to salinity and temperature) on 11 September. Thereafter, the water remained saturated with respect to oxygen, with the concentration increasing over winter as water temperature decreased. Dissolved oxygen concentration at the seabed was  $9.0 \text{ mg l}^{-1}$  (97% saturation) when measurements started on 21 April, after the oxygen concentration at 35 m had already started to decrease. Dissolved oxygen concentration at the seabed decreased to a minimum of  $5.2 \text{ mg l}^{-1}$  (60% saturation) on 10 July. Concentrations remained low until 7 September but increased to become saturated at  $8.0 \text{ mg l}^{-1}$  on 19 September (exact dates of start of increase not known due to missing data). The oxygen concentration followed the same pattern in 2008 but did not start to decrease until 21 May. The oxygen concentration at both 35 m and 45 m reached a minimum on 30 July 2008 of  $6.5 \text{ mg l}^{-1}$  (77% saturation) at 35 m and  $5.4 \text{ mg l}^{-1}$  (63% saturation) at 45 m. Oxygen concentrations at both depths did not decrease steadily, but were subject to sudden changes including sharp increases at both depths from 20th to 27 June 2007 and 9 to 19 July 2008 and large decreases at 45 m from 6 to 25 July 2007 and 21 to 30 July 2008.

During the monitoring period the near-bed maximum daily currents were generally due to tidal forcing with velocities of  $20 \text{ cm s}^{-1}$  on neap tides rising to  $30 \text{ cm s}^{-1}$  on spring tides, while at the surface corresponding velocities were  $25 \text{ cm s}^{-1}$  to  $35 \text{ cm s}^{-1}$  (data not shown) but with greater variability with wind-induced flow giving peaks up to  $60 \text{ cm s}^{-1}$  (13 June 2007) and  $50 \text{ cm s}^{-1}$  (17 July 2007). The BML was strongly decoupled from the SML, with low horizontal transport through the site in the BML as evidenced from the progressive vector diagram (Fig. 3) with an equivalent residual velocity in the bottom layer of  $0.5 \text{ cm s}^{-1}$  while the surface was  $2.4 \text{ cm s}^{-1}$ . Data presented in Fig. 3 for May to September 2007 are representative of the data obtained throughout the monitoring period.

**BGD**

6, 8411–8453, 2009

---

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

### 3.3 North Dogger in situ monitoring

Surface temperatures ranged from 6.7°C (March 2008) to 16.8°C (August 2008). The water column was well-mixed during winter but became stratified during spring (Fig. 4a). The water column was stratified from 14 April 2007 and stratification occurred later in 2008, from 25 April 2008. The surface to bottom temperature difference increased more rapidly in 2008 compared to 2007 and there was a greater maximum surface to bottom temperature difference in 2008; the maximum temperature difference was 9.8°C on 7 August 2008 compared to 8.1°C on 12 August 2007. The temperature of the water at 85 m increased steadily in both years in contrast to the temperature at the surface and at 31 m which was subject to more variability. Rapid variations in temperature at 31 m were associated with storm events observed in the wave height record (Fig. 5). Decreasing temperature at the surface and increasing temperature at 31 m resulted in the water column becoming mixed down to at least 31 m on 1 September 2007. In 2007, the whole water column became mixed between 10 and 12 November and the temperatures at all three depths remained within 0.1°C of each other for the rest of 2007. In 2008, the water column was still stratified when monitoring ceased on 14 September, with the thermocline above 31 m.

Chlorophyll concentrations were 0.3  $\mu\text{g l}^{-1}$  at all sampling depths at the start of 2007 (Fig. 4b). Chlorophyll concentrations increased at all depths from 28 March 2007, reaching maximum concentrations in early April of 2.4  $\mu\text{g l}^{-1}$  at the surface, 6.7  $\mu\text{g l}^{-1}$  at 31 m and 1.7  $\mu\text{g l}^{-1}$  at 85 m. Thereafter chlorophyll concentration at 85 m decreased to less than 0.5  $\mu\text{g l}^{-1}$  and remained below this for the rest of the year. Chlorophyll concentrations at the surface and 31 m decreased to less than 1  $\mu\text{g l}^{-1}$  by end of April and stayed at or slightly above this concentration until the end of September, with higher chlorophyll at 31 m than at the surface. Chlorophyll concentrations at all three depths returned to 0.3  $\mu\text{g l}^{-1}$  after 10 November 2007. Chlorophyll concentration at the surface started to increase from 7 March 2008. The chlorophyll concentration at 31 m and 85 m increased to a maximum of 0.8  $\mu\text{g l}^{-1}$  between 22 and 28 March 2008.

**BGD**

6, 8411–8453, 2009

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

The concentration of chlorophyll at 85 m remained below  $0.6 \mu\text{g l}^{-1}$  for the rest of the monitoring period. The chlorophyll concentration at 31 m increased from 8 April to a maximum of  $2.3 \mu\text{g l}^{-1}$  until the onset of fouling on 27 June.

SPM concentration was generally low at the surface and at 31 m, with a typical background concentration of  $0.5 \text{ mg l}^{-1}$  to  $1 \text{ mg l}^{-1}$  between May and October and between 1 and  $3 \text{ mg l}^{-1}$  between November and April (Fig. 4c). Large fluctuations in SPM concentration were observed at the seabed, with background concentrations between  $0.5$  and  $1 \text{ mg l}^{-1}$  but several large peaks in both years. There were peaks between mid March and mid April 2007 and between mid July and mid September 2007 which reached a maximum of  $17 \text{ mg l}^{-1}$ . There was a very sharp increase in SPM concentration between 8 and 14 November which reached a maximum of  $63.3 \text{ mg l}^{-1}$ . During 2008, peaks in SPM concentration were observed between mid February and mid April and from mid May to the end of monitoring in mid September.

The concentration of dissolved oxygen at 31 m and 85 m when measurements started in February was between  $9.2$  and  $9.4 \text{ mg l}^{-1}$  (saturated). Dissolved oxygen at 31 m increased from  $9.4 \text{ mg l}^{-1}$  on 25 March 2008 to  $10.3 \text{ mg l}^{-1}$  (109% saturation) on 9 April 2008. Thereafter oxygen concentration at 31 m decreased in a series of step changes to  $7.7 \text{ mg l}^{-1}$  (96% saturation) on 19 September 2007. There was a small minimum in dissolved oxygen concentration at 85 m on 15 April then the concentration temporarily recovered. Dissolved oxygen concentrations at 85 m then decreased steadily to  $6.4 \text{ mg l}^{-1}$  (71% saturation) on 10 November 2007. There was a rapid increase in oxygen concentration at 85 m between 10 and 12 November to  $8.5 \text{ mg l}^{-1}$  (saturated) the same as at 31 m. Thereafter the water remained saturated until the beginning of April 2008. Dissolved oxygen at 31 m increased from the start of April 2008 to a maximum of  $10.2 \text{ mg l}^{-1}$  (111% saturation) on 16 June 2008 then decreased to a minimum of  $8.3 \text{ mg l}^{-1}$  (92% saturation) when monitoring finished in mid September 2008. Dissolved oxygen at 85 m decreased steadily from the start of April 2008 to a minimum of  $7.8 \text{ mg l}^{-1}$  (83% saturation) at the end of monitoring.

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**Detection of low bottom water oxygen concentrations in the North Sea**N. Greenwood et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The daily average current speed ranged between  $6 \text{ cm s}^{-1}$  and  $24 \text{ cm s}^{-1}$  during the monitoring period. The BML was weakly decoupled from the SML, with lower horizontal transport through the site in the BML compared to the SML (Fig. 6) and with less variability in the lower layer. Data presented in Fig. 5 for May to September 2007 are representative of the data obtained throughout the monitoring period.

### 3.4 Principal component analysis

A correlation-based principal components analysis (PCA) using normalised Euclidean distance was applied to bottom data for temperature, SPM, dissolved oxygen, daily maximum current magnitude for each site, and wave height at the Anasuria platform using Primer version 6.1.5 (Clarke and Warwick, 1994) in order to investigate the relationship between the variables measured. The first two components explained 69.4% (PC1 37.6%, PC2 31.8%) of the variability observed in the Oyster Grounds data. PC1 contrasted samples with increasing temperature and decreasing oxygen and PC2 ordered the samples according to maximum current speed, suspended load to SPM (Table 3). Samples with higher temperatures and low oxygen concentration, associated with a stratified water column, were clearly separated from those with lower temperatures and higher oxygen concentration, associated with a well mixed water column (Fig. 7a). The exception to this was a group of samples in mixed conditions which appeared amongst the stratified samples. These were samples from November when the water column was still cooling down and oxygen concentrations were increasing.

The first two components explained 60.7% (PC1 35.7%, PC2 25.0%) of the variability observed in the North Dogger data. PC1 ordered samples according to maximum current speed and wave height and PC2 contrasted samples with increasing SPM and decreasing oxygen (Table 3). Samples with low oxygen and current magnitudes and high SPM were clearly separated from those with low SPM and higher oxygen concentration and current magnitude (Fig. 7b). There was a discrete group of mixed samples from November when the temperature of the water and the oxygen concentration

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

increased over 2 days after a storm surge which resulted in a mixed water column. Both sites had outliers associated with the storm surge and these are highlighted in the black oval.

## 4 Discussion

### 4.1 New insights from moorings

Results presented in this study reveal in detail, for the first time, the detailed development of oxygen depletion in stratified offshore areas of the North Sea. The high-frequency data provide insights into the timescales over which oxygen concentrations change with depth in the water column. Both sites showed a reduction in bottom oxygen concentration throughout the summer period. Reduced oxygen concentrations in bottom water from ship-based studies have been previously reported at and near Oyster Grounds (Postma and Rommets, 1984; Peeters et al., 1995; Boers, 2005) and North Dogger (Gehrke, 1916, in Postma and Rommets, 1984) and model results have predicted low oxygen concentrations (Los et al., 2008). However, to our knowledge, these data are the first published continuous measurements of bottom oxygen concentrations at these sites in any European shelf sea, which show the environmental conditions leading to decreasing bottom oxygen concentrations.

The oxygen concentrations presented here are consistent with the range of concentrations previously reported in the literature for these areas of the North Sea; at the Oyster Grounds, Peeters et al. (1995) reported bottom oxygen concentrations of  $\sim 6.5 \text{ mg l}^{-1}$  and  $\sim 4.5 \text{ mg l}^{-1}$  in summer 1988 and 1989 respectively and Boers (2005) reported  $\sim 3.2 \text{ mg l}^{-1}$  in September 2003. In 2003, very calm and warm weather dominated during the summer and stratification at this site was maintained beyond 3 October (Weston et al., 2008) which is approximately one month longer than measured in our study. This prolonged period of stratification would have maintained an isolated bottom pool of water for a longer period and led to lower bottom oxygen concentrations

**BGD**

6, 8411–8453, 2009

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



as shown by Boers (2005) and Weston et al. (2008).

During the period 7–10 November a strong storm passed across the North Sea and caused high waves and a storm surge down the North Sea resulting in elevations of up to 2.4 m at Sheerness in Kent (Met Office, 2007) at a 30 year high. Peak near-bed currents observed in this storm at the stratified North Dogger were  $40 \text{ cm s}^{-1}$  (data not shown) and the storm resulted in the complete turnover of the water column, the rapid increase in dissolved oxygen concentrations and elevated SPM concentration above the seabed. Elevated SPM concentration was also observed above the seabed at the Oyster Grounds. It is only through the use of high frequency fixed point monitoring that detection of short lived episodic events of this nature can be detected. This event is likely to have been missed by ship-based surveys as noted by Mills et al. (2002) using similar approaches in shallow Dutch coastal waters. They obtained observations at wind force 10 noting that observations from research vessels were unlikely to have been made under such sea conditions.

Whilst bottom oxygen decrease during spring-summer was common to both sites, there was a contrast in how variable the depletion was between sites. The bottom oxygen concentration at the Oyster Grounds showed a decrease from the onset of stratification but this rate of decrease varied in response to changing physical and meteorological conditions. This was in contrast to North Dogger where there was a generally steady decrease in bottom oxygen concentration. The greater depth at North Dogger lead to continuous isolation of the bottom water from the onset of stratification in 2007 until the water column was completely mixed in the autumn due to a storm in November 2007. Vertical mixing events observed in the temperature record at 31 m during 2007 did not penetrate to the seabed so the BML remained isolated from the storm-induced mixing in the SML. The current meter data at the Oyster Grounds showed that there was a decoupling between the SML and BML, with minimal horizontal transport through the site in the BML compared with the SML. These types of decoupling events can introduce sheer along the thermocline and can provide a mechanism for nutrient injection into the base of the thermocline which may stimulate increased growth

**BGD**

6, 8411–8453, 2009

---

**Detection of low  
bottom water oxygen  
concentrations in the  
North Sea**

N. Greenwood et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

(Sharples et al., 2007). At North Dogger, the water column was less strongly decoupled than at the Oyster Grounds, with less shear between the SML and BML than at the Oyster Grounds.

This study demonstrates that the depth at which measurements are made is vital to observing the minimum oxygen concentration in the water column. The tether and lander observations were made 10 m apart in the water column at the Oyster Grounds but differences were observed between these depths. Whilst the temperature observations at each were similar, the oxygen concentrations between these depths differed by as much as  $1.9 \text{ mg l}^{-1}$ .

There were large inter-annual variations in oxygen concentrations observed at both sites during the monitoring period which reflected the different environmental conditions experienced between years. For example, the temperature record shows that storm events at North Dogger were sufficient to mix the water down to at least 31 m in 2007 but not to the seabed. In contrast, mixing penetrated further into the water column in 2008 resulting periodically in similar water temperature at 31 m and the seabed and a highly variable temperature record at 31 m in 2008 compared to 2007. The oxygen concentration at 31 m in 2008 was also highly variable, reflecting the changing physical conditions.

## 4.2 Potential mechanisms for oxygen depletion at the study sites

The concentration of dissolved oxygen in the water column may be affected by many physical and biological processes. The data presented allow an improved examination of some of these processes and they are addressed below.

### a) Temperature

The solubility of oxygen varies with salinity, temperature and pressure (Garcia and Gordon, 1992) and an increase in water temperature will lead to a decrease in oxygen saturation. Both sites exhibited an overall gradual decrease in oxygen saturation

**BGD**

6, 8411–8453, 2009

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



through the stratified periods in 2007 and 2008. In 2007, the underlying decrease in oxygen concentration at the seabed at the Oyster Grounds was  $3.3 \text{ mg l}^{-1}$  and the increase in temperature was  $10.0^\circ\text{C}$  (Table 4). Assuming a constant salinity and pressure, this would lead to a decrease in oxygen concentration of  $1.82 \text{ mg l}^{-1}$  (i.e. 55% of the observed decrease). At the North Dogger, the observed decrease in oxygen concentration was  $3.0 \text{ mg l}^{-1}$  and the increase in temperature was  $1.4^\circ\text{C}$  (Table 4). Again, assuming a constant salinity and pressure, this would lead to a decrease in oxygen concentration of  $0.29 \text{ mg l}^{-1}$  (i.e. 10% of the observed decrease). Increasing temperature therefore accounted for 55% of the decrease in oxygen concentration at Oyster Grounds compared to 10% at the North Dogger. This is supported by the PCA for the Oyster Grounds, where samples were separated along PC1 on the basis of water temperature and dissolved oxygen concentration (Fig. 4a).

#### b) Remineralisation of organic carbon

In addition to solubility changes the decrease in oxygen saturation may be associated with remineralisation of carbon from primary production exported to the BML from the surface or DCM. An estimate of  $740.9 \text{ mg C m}^{-2} \text{ day}^{-1}$  integrated water column primary production for a stratified site in the North Sea was taken from Weston et al. (2005). At the Oyster Grounds there was a decrease of  $3.4 \times 10^{-7} \text{ mol O}_2 \text{ l}^{-1} \text{ day}^{-1}$  due to processes other than increasing temperature (Table 5). Assuming a BML depth of 25 m and integrating for  $1 \text{ m}^2$  of water column, this gives  $8.5 \text{ mmol O}_2 \text{ m}^{-2} \text{ day}^{-1}$  which would require remineralisation of  $102 \text{ mg C m}^{-2} \text{ day}^{-1}$  or approximately 1/7th of the water column integrated primary production from Weston et al. (2005).

The sharpest decrease in oxygen observed during one of the “events” at the Oyster Grounds was  $0.22 \text{ mg O}_2 \text{ l}^{-1} \text{ day}^{-1}$  ( $7.0 \times 10^{-6} \text{ mol O}_2 \text{ l}^{-1} \text{ day}^{-1}$ , Table 6). Assuming a BML thickness of 25 m and integrating for  $1 \text{ m}^2$  of water column, this gives  $0.17 \text{ mol O}_2 \text{ m}^{-2} \text{ day}^{-1}$  which would equate to a primary production of  $2.1 \text{ g C m}^{-2} \text{ day}^{-1}$ . This is approximately three times the estimate given by Weston

**BGD**

6, 8411–8453, 2009

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

et al. (2005). Chlorophyll concentration in the SML during this period was low (Fig. 2b) and therefore to create this type of pulsed oxygen demand there would have to be increased supply of nutrient expected to sustain increased thermocline/DCM production. This could be linked to highly episodic wind driven events and increased shear which would increase the nutrient flux into or across the thermocline (Sharples et al., 2007). When this localised nutrient is then exhausted the phytoplankton growth ceases and sinks to the BML resulting in an intense oxygen demand. During this period, there was a chlorophyll maximum at 31 m which is consistent with such thermocline production. Weston et al. (2008) showed that water clarity, stratification and the removal of nutrients from the upper mixed layer led to the formation of the DCM at the Oyster Grounds. The biomass from this DCM in combination with benthic oxygen consumption rates and stratification were predicted to be responsible for the low bottom oxygen concentrations observed in their study. The decline in oxygen concentration long after the spring bloom shown in this study backs up this theory.

At North Dogger there was a decrease of  $3.8 \times 10^{-7} \text{ mol O}_2 \text{ l}^{-1} \text{ day}^{-1}$  due to processes other than increasing temperature (Table 5). Assuming a BML depth of 40 m and integrating for  $1 \text{ m}^2$  of water column, this gives  $15.0 \text{ mmol O}_2 \text{ m}^{-2} \text{ day}^{-1}$  which would require remineralisation of  $180 \text{ mg C m}^{-2} \text{ day}^{-1}$  or approximately 1/4 of the water column integrated primary production from Weston et al. (2005). The North Dogger site would therefore require greater remineralisation of water column primary production than the Oyster Grounds to create the remaining oxygen demand after the affect of increasing temperature has been accounted for.

### c) Remineralisation of suspended particulate matter

Another potential mechanism to create event draw down of oxygen would be from resuspension of organic material (i.e. sediment or benthic fluff) due to natural storm events or human activities such as trawling. Depending on the sediment type, depth of sediment eroded/resuspended and carbon content of the sediment it would be possible

**BGD**

6, 8411–8453, 2009

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

---

**Detection of low  
bottom water oxygen  
concentrations in the  
North Sea**N. Greenwood et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

to create a substantial oxygen demand from oxidation of reduced chemical species (including nutrients) or indirectly through resuspension of organic carbon, sediment or benthic fluff, which can then be aerobically respired (Jago and Jones, 1998; Van Raaphorst et al., 1998). Van Raaphorst et al. (1998) demonstrated the importance of the Oyster Grounds and other similar depocentre areas in the carbon budget of the North Sea. They found there was a highly dynamic exchange of particles between the sediment and water column and this would create an oxygen demand upon aerobic respiration of the suspended material. The trawling intensity and distribution is patchy in the North Sea (Rijnsdorp et al., 1998; Jennings et al., 1999; Trimmer et al., 2005). Data from these studies showed that both sites are subject to trawling which will create an oxygen demand as surface sediment is mixed in the overlying water and in addition will have an impact on the sediment biogeochemistry and ecosystem integrity (Trimmer et al., 2005; Allen and Clarke, 2007).

#### d) Advection

Advection processes can also influence oxygen concentrations in these sites. The BML at the Oyster Grounds is relatively isolated during the summer due to the bathymetry and bottom fronts preventing water mass transfer, with low horizontal transport through the site (Fig. 4a). In comparison, there was greater advection through the BML at North Dogger during the summer (Fig. 4b). Oxygen concentrations at North Dogger continued to decrease throughout the summer therefore the water advected into the site must also be depleted in oxygen. These observations therefore reflect conditions in the BML in the wider stratified central North Sea, north of Dogger Bank.

### 4.3 Implications for marine management

Climate change scenarios for the North Sea predict that the duration and intensity of stratification will increase (Lowe et al., 2009). These factors will have the potential to augment the decrease in BML oxygen in the seasonally stratified North Sea by

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**Detection of low  
bottom water oxygen  
concentrations in the  
North Sea**N. Greenwood et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

increasing the isolation of the BML leading to lower oxygen concentrations. In addition, the number of summer storms may increase under worst case climate change scenarios. Such storms may disturb the seabed and result in increased resuspension of SPM which may further reduce the BML oxygen concentration. However, deepening of the thermocline during storms will act to ventilate the BML due to wind mixing resulting in higher oxygen concentrations. This study has shown the importance of temperature in controlling, directly and indirectly, the dissolved oxygen concentration at the Oyster Grounds. It has also shown the difference between study areas with the Oyster Grounds more sensitive to temperature driven changes than the deeper North Dogger site. Future increases in temperatures would therefore have the potential to exacerbate low oxygen conditions at both sites but with a larger impact on the Oyster Grounds.

The significance and factors controlling hypoxia is an area of key concern across the globe (Diaz and Rosenberg, 2008). The use of oxygen as an indicator of ecosystem health, and specifically eutrophication, within marine management systems is well established (Best et al., 2007; Devlin et al., 2007; Heslenfeld and Enserink, 2008; Johnson, 2008) with oxygen depletion below a defined threshold considered to be one of the indicators of undesirable disturbance to ecosystem health (Tett et al., 2007). Whilst these sites are not hypoxic, both the sites in this study exhibited seasonal reduction in dissolved oxygen concentration under stratified conditions and the concentrations observed at Oyster Grounds may be considered “deficient” (OSPAR, 2005). This study has shown that thermal stratification is an important factor determining susceptibility to oxygen depletion, particularly at the Oyster Grounds. In addition, temperature may directly influence observed oxygen concentration through its influence on saturation. Consequently, reduced oxygen concentrations observed at these sites that could be regarded as symptoms of anthropogenically driven eutrophication may arise as a result of natural processes.

## 5 Future work

Work is in progress to quantify the key components within the benthic-pelagic system using results from detailed process studies carried out within this project, which will give greater understanding of the factors controlling oxygen fluxes, a currently under-  
studied parameter. These measurements have been able to provide improved insight  
into the processes acting on oxygen saturation/concentration at these two sites. How-  
ever, the processes are complex and further work is required using numerical models  
to allow further elucidation of the relative significance of the seasonal drivers. Cou-  
pled hydrodynamic-ecosystem models are able to reproduce the gradual decrease in  
oxygen concentration in seasonally stratified areas of the North Sea such as that ob-  
served at North Dogger (Lenhart et al., accepted). However, work is still required to  
more accurately model low oxygen events such as those seen at the Oyster Grounds.  
Accurate representation of oxygen concentrations is vital to be able to correctly model  
impacts on ecosystem functioning and on processes such as de-nitrification and nutri-  
ent cycling (Trimmer et al., 2005; Middelburg and Levin, 2009). The data obtained in  
this study will aid the development of models that in the future will allow more accurate  
predictions of the impact of climate change on oxygen concentrations and ecosystem  
functioning.

Further measurements are required to assess the extent in time and space of low  
oxygen concentrations in the stratified North Sea and other shelf seas. Recent de-  
velopments in technology such as augmenting gliders with oxygen sensors and future  
implementation of the same capability on fish tags would provide an effective way of  
improving our data coverage. Further studies are required to investigate the interact-  
ing mechanisms which lead to oxygen depletion at such sites. It has recently been  
shown that oxygen levels in the north east Atlantic have declined in the past 50 years  
(Stramma et al., 2008). A greater understanding of the interactions between oceans  
and shelf seas would enable better predictions of the impacts of changes in ocean  
oxygen concentrations on shelf seas.

**BGD**

6, 8411–8453, 2009

---

### Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## 6 Conclusions

The dissolved oxygen concentration in the bottom water decreased at both of the study sites under thermally stratified conditions. Decreasing oxygen was driven by increasing temperature and biomass input, the latter which is driven by production during the spring bloom and in the deep chlorophyll maximum and the period of stratification. Increasing temperature of the bottom water at Oyster Grounds accounted for 55% of the decrease in oxygen concentration at this site compared to 10% at North Dogger and greater remineralisation of primary production would be required at North Dogger to account for the observed oxygen depletion.

The factors controlling the dissolved oxygen concentration may operate over varying timescales and short term events may be important in affecting the concentration of dissolved oxygen for relatively short durations of time when compared to the seasonal cycle. The relative importance of each factor varies between different regions and therefore management measures must be organised on a regional basis and must be able to monitor changes over a range of time scales. Further measurements over multi-annual timescales and at additional locations of distinct environmental characteristics will be required to provide a fuller understanding of the controls on dissolved oxygen concentration in shelf seas. It is only with this improved understanding and by using approaches such as within this study that healthy shelf seas will be maintained.

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**BGD**

6, 8411–8453, 2009

### Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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---

**Detection of low bottom water oxygen concentrations in the North Sea**N. Greenwood et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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**BGD**

6, 8411–8453, 2009

---

**Detection of low bottom water oxygen concentrations in the North Sea**

N. Greenwood et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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**BGD**

6, 8411–8453, 2009

---

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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**BGD**

6, 8411–8453, 2009

---

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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**BGD**

6, 8411–8453, 2009

---

**Detection of low bottom water oxygen concentrations in the North Sea**N. Greenwood et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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**BGD**

6, 8411–8453, 2009

---

**Detection of low  
bottom water oxygen  
concentrations in the  
North Sea**

N. Greenwood et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Detection of low bottom water oxygen concentrations in the North Sea**

N. Greenwood et al.

**Table 1.** Details of parameters measured on the moorings at the study sites.

	Oyster Ground			North Dogger		
	1 m	35 m	45 m	1 m	31 m	85 m
Depth of measurement						
Platform type	SmartBuoy	Mooring tether	Seabed lander	SmartBuoy	Mooring tether	Seabed lander
Start date	15/03/2006	15/03/2006	21/04/2007	24/02/2007	24/02/2007	24/02/2007
Conductivity/Temperature	✓	✓	✓	✓	✓	✓
Optical backscatter	✓	✓	✓	✓	✓	✓
Chlorophyll fluorescence	✓	✓	✓	✓	✓	✓
Dissolved oxygen	x	✓	✓	x	✓	✓

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

**Table 2.** Summary of CTD data. SML is surface mixed layer, BML is bottom mixed layer,  $\Delta T$  is temperature difference between SML and BML,  $\delta T$  is the rate of change of temperature across the thermocline.

Location	Dates of CTD casts	SML temperature (°C)	BML temperature (°C)	$\Delta T$ (°C)	Depth of thermocline (m)	$\delta T$ (°C m <sup>-1</sup> )	Height of BML (m)
Oyster Grounds	February 2007	6.9	6.9	0	–	–	–
	April 2007	9.0	7.5	1.5	21–25	0.4	20–24
	May 2007	11.7	8.2	3.5	15–22	0.5	23–30
	September 2007	16.1	16.1	0	–	–	–
	October 2007	14.0	14.0	0	–	–	–
	January 2008	7.4	7.4	0	–	–	–
	April 2008	7.8	7.0	0.8	12–20	0.1	25
	August 2008	17.3	13.7	3.6	14–17	1.2	28
North Dogger	February 2007	7.7	7.7	0	–	–	–
	April 2007	8.8	7.6	2.2	37–47	0.2	38–48
	May 2007	11.0	10.0	1.0	1–10	0.1	50–37
	(double thermocline)	10.0	7.6	2.4	35–48	0.2	–
	September 2007	14.3	8.3	6.0	45–51	1.0	34–40
	October 2007	12.3	8.5	3.8	54–59	0.8	26–31
	January 2008	7.9	7.9	0	–	–	–
	April 2008	8.2	6.9	1.3	20–35	0.1	50
	September 2008	15.6	7.4	8.2	24–36	0.7	49

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

**Table 3.** Eigenvectors for PC1 and PC2 for Principal Components Analysis. O2CONC is oxygen concentration ( $\text{mg l}^{-1}$ ); TEMP is temperature ( $^{\circ}\text{C}$ ); WAVEHT is wave height (m); MAXMAG is maximum daily average current speed ( $\text{m s}^{-1}$ ); SPM is suspended particulate matter ( $\text{mg l}^{-1}$ ).

variable	Oyster Grounds		North Dogger	
	PC1	PC2	PC1	PC2
MAXMAG	-0.081	-0.615	0.644	0.073
O2CONC	-0.697	-0.044	0.368	-0.603
SPM	0.180	-0.548	0.008	0.753
TEMP	0.662	-0.132	0.213	0.099
WAVEHT	-0.192	-0.550	0.636	0.233

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Detection of low bottom water oxygen concentrations in the North Sea**

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Table 4.** Contribution of increasing temperature on decreasing oxygen concentration in the bottom mixed layer at Oyster Grounds and North Dogger.

	Oyster Grounds		North Dogger	
		$O_2$		$O_2$
Start date	22/04/2007	8.9 mg l <sup>-1</sup>	05/04/2007	9.4 mg l <sup>-1</sup>
End date	07/09/2007	5.6 mg l <sup>-1</sup>	10/11/2007	6.4 mg l <sup>-1</sup>
Observed decrease in oxygen		3.3 mg l <sup>-1</sup>		3.0 mg l <sup>-1</sup>
Number of days	138 days		219 days	
		°C		°C
Start date	22/04/2007	6.5	05/04/2007	7.4
End date	07/09/2007	16.5	10/11/2007	8.8
Increase in temperature		10.0		1.4
Theoretical decrease in oxygen <sup>a</sup>		1.82 mg l <sup>-1</sup>		0.29 mg l <sup>-1</sup>
Percent decrease in oxygen concentration due to temperature		55%		10%

<sup>a</sup> assuming a constant salinity and pressure, this is the decrease in oxygen expected due to the observed increase in temperature, calculated according to Garcia and Gordon (1992)

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

**Table 5.** Estimates of carbon remineralisation accounted for by overall decrease in oxygen concentration at Oyster Grounds and North Dogger.

	Oyster Grounds	North Dogger
Decrease in oxygen not accounted for by temperature	1.5 mg l <sup>-1</sup>	2.7 mg l <sup>-1</sup>
Number of days	138 days	219 days
Rate of decrease in oxygen concentration	0.011 mg l <sup>-1</sup> day <sup>-1</sup>	0.012 mg l <sup>-1</sup> day <sup>-1</sup>
Rate of decrease in oxygen concentration	3.4 × 10 <sup>-7</sup> mol l <sup>-1</sup> day <sup>-1</sup>	3.8 × 10 <sup>-7</sup> mol l <sup>-1</sup> day <sup>-1</sup>
Depth of BML	25 m	40 m
Volume of BML in 1 m <sup>2</sup> water column	25 000 l m <sup>-2</sup>	40 000 l m <sup>-2</sup>
Rate of decrease in oxygen concentration in BML	8.5 × 10 <sup>-3</sup> mol m <sup>-2</sup> day <sup>-1</sup>	1.5 × 10 <sup>-2</sup> mol m <sup>-2</sup> day <sup>-1</sup>
Rate of carbon remineralisation <sup>a</sup>	8.5 × 10 <sup>-3</sup> mol m <sup>-2</sup> day <sup>-1</sup>	1.5 × 10 <sup>-2</sup> mol m <sup>-2</sup> day <sup>-1</sup>
Rate of carbon remineralisation <sup>a</sup>	102 mg C m <sup>-2</sup> day <sup>-1</sup>	180 mg C m <sup>-2</sup> day <sup>-1</sup>

<sup>a</sup> assuming that all decrease in oxygen is due to remineralisation of carbon

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

**Table 6.** Estimate of carbon remineralisation accounted for by pulsed decrease in oxygen concentration at Oyster Grounds.

Start date	03/07/2007	6.8 mg l <sup>-1</sup>
End date	10/07/2007	5.2 mg l <sup>-1</sup>
Observed decrease in oxygen		1.6 mg l <sup>-1</sup>
Number of days	7 days	
Rate of decrease in oxygen concentration		0.22 mg l <sup>-1</sup> day <sup>-1</sup>
Rate of decrease in oxygen concentration		7.0 × 10 <sup>-6</sup> mol l <sup>-1</sup> day <sup>-1</sup>
Depth of BML		25 m
Volume of BML in 1 m <sup>2</sup> water column		25 000 l m <sup>-2</sup>
Rate of decrease in oxygen concentration in BML		0.17 mol m <sup>-2</sup> day <sup>-1</sup>
Rate of carbon remineralisation <sup>a</sup>		0.17 mol m <sup>-2</sup> day <sup>-1</sup>
Rate of carbon remineralisation <sup>a</sup>		2.1 g C m <sup>-2</sup> day <sup>-1</sup>

<sup>a</sup> assuming that all decrease in oxygen is due to remineralisation of carbon

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

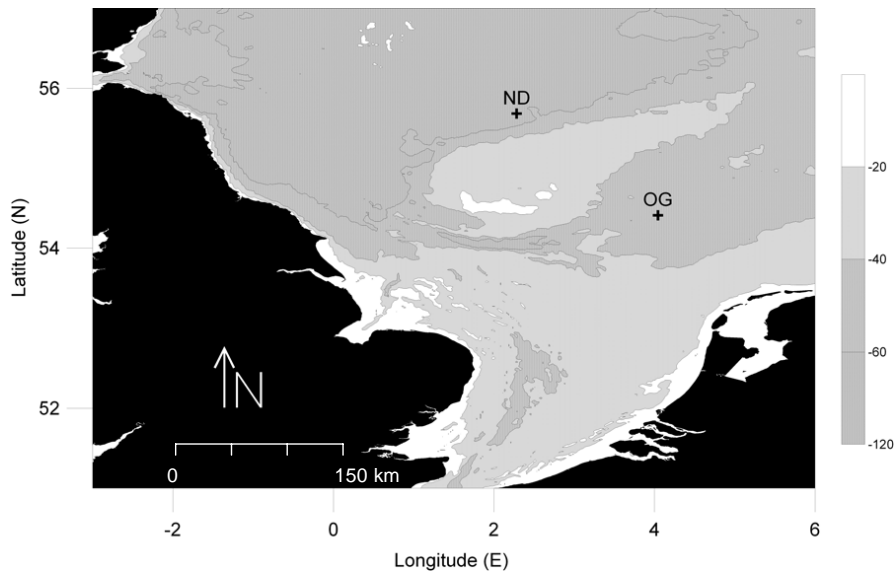
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Detection of low  
bottom water oxygen  
concentrations in the  
North Sea**

N. Greenwood et al.

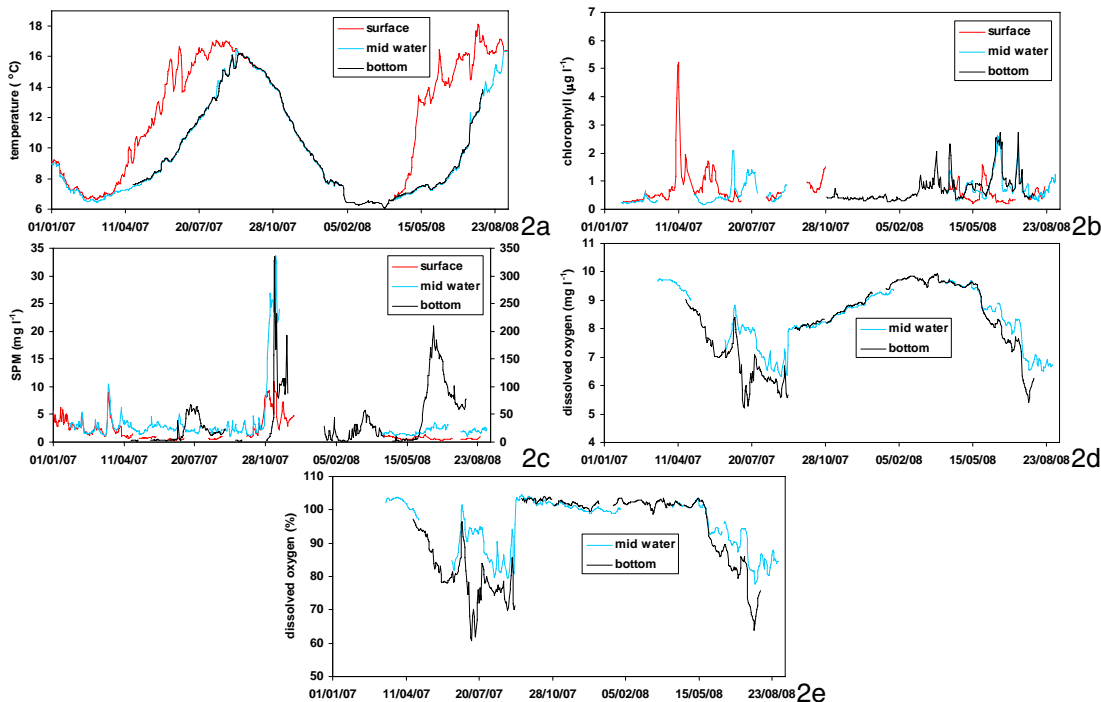


**Fig. 1.** Location of study sites in the North Sea. OG is Oyster Grounds, ND is North Dogger.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.



**Fig. 2.** Mooring data from Oyster Grounds for (a) temperature, (b) chlorophyll, (c) SPM (surface and mid-water on primary y axis, bottom on secondary y axis), (d) oxygen concentration and (e) oxygen percent saturation.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

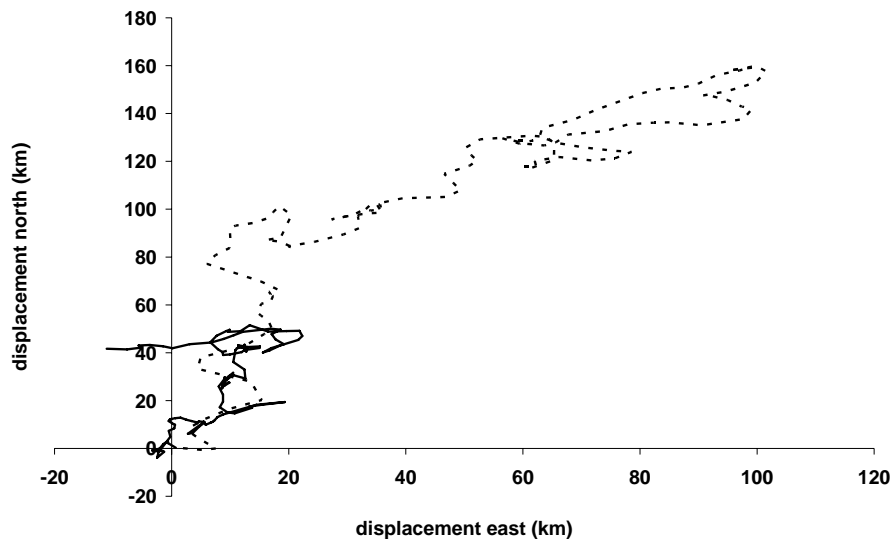
Printer-friendly Version

Interactive Discussion



**Detection of low  
bottom water oxygen  
concentrations in the  
North Sea**

N. Greenwood et al.

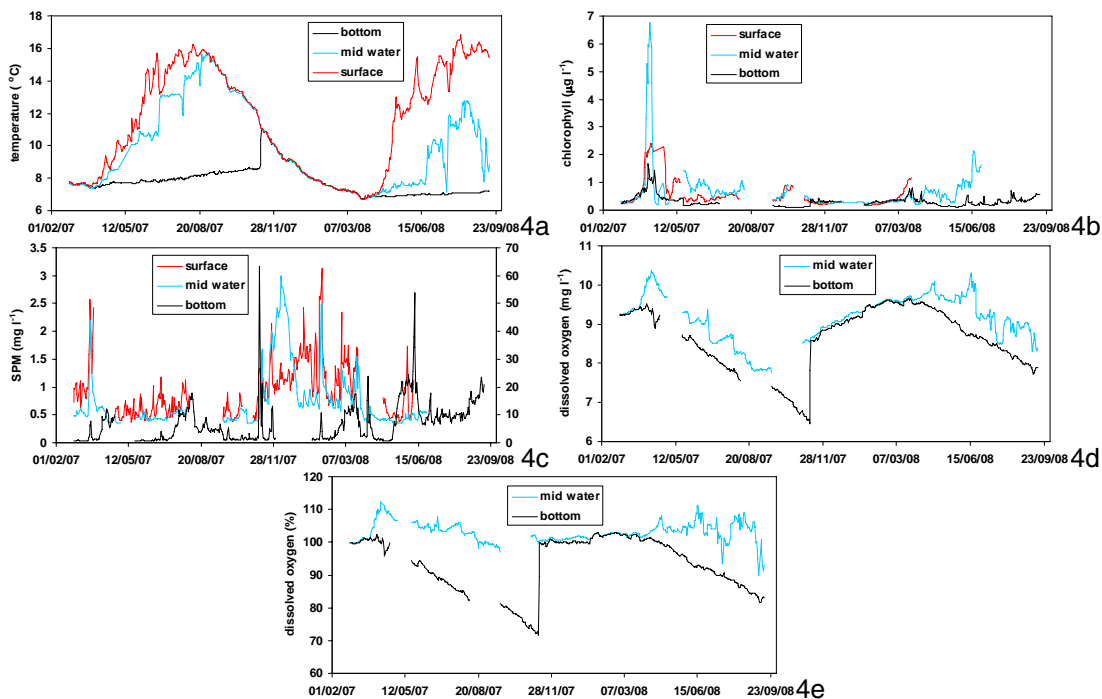


**Fig. 3.** Progressive vector diagram for Oyster Grounds for May to September 2007. Solid line is 5 m above seabed, dashed line is 37 m above seabed.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.



**Fig. 4.** Mooring data from North Dogger for (a) temperature, (b) chlorophyll, (c) SPM (surface and mid-water on primary y axis, bottom on secondary y axis), (d) oxygen concentration and (e) oxygen percent saturation.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

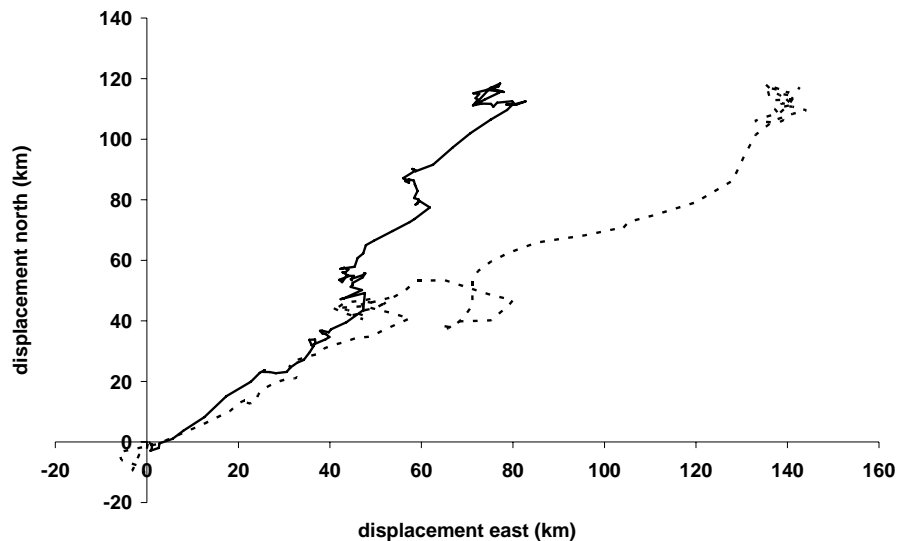
Interactive Discussion





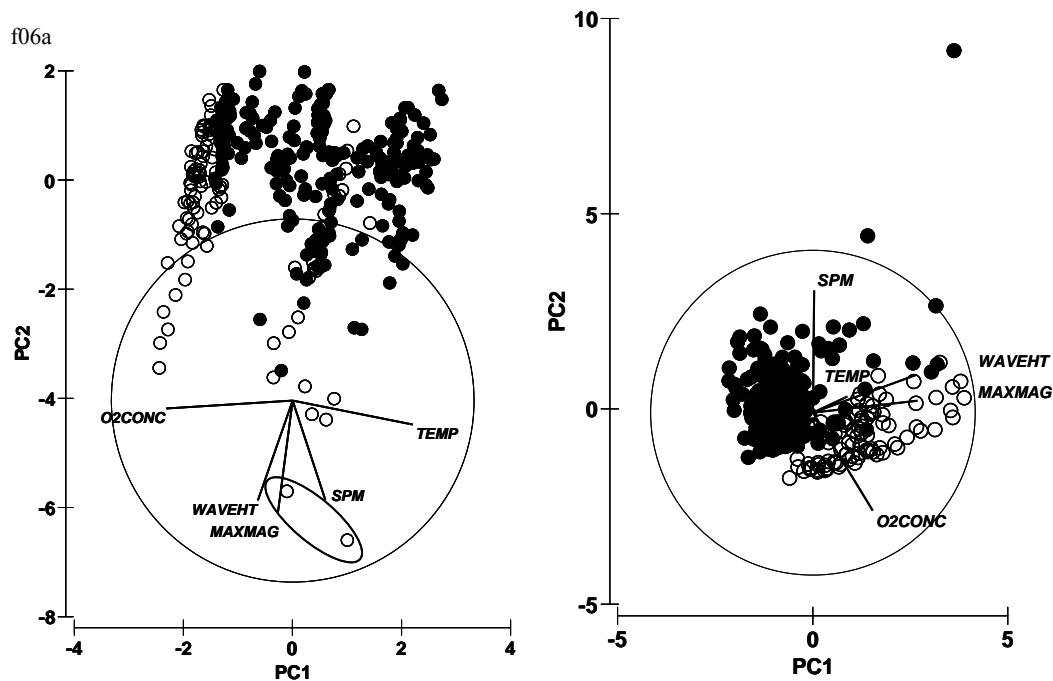
**Detection of low  
bottom water oxygen  
concentrations in the  
North Sea**

N. Greenwood et al.

**Fig. 5.** Daily average wave height at Anasuria.[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.



**Fig. 6.** Progressive vector diagram for North Dogger for May to September 2007. Solid line is 5 m above seabed, dashed line is 66 m above seabed.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

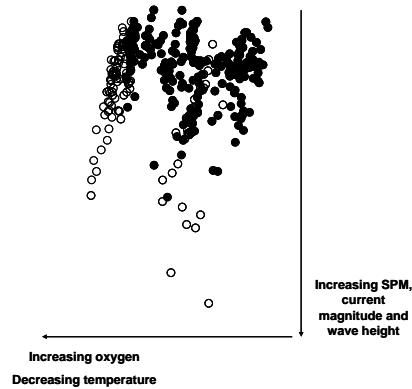
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Full Screen / Esc

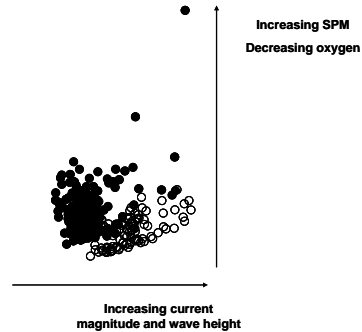
Printer-friendly Version

Interactive Discussion

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**Fig. 7.** Principal component analysis for **(a)** Oyster Grounds and **(b)** North Dogger. Open circles denote samples under mixed condition, closed circles represent samples under stratified conditions. O2CONC is oxygen concentration ( $\text{mg l}^{-1}$ ); TEMP is temperature ( $^{\circ}\text{C}$ ); WAVEHT is wave height (m); MAXMAG is maximum daily average current speed ( $\text{m s}^{-1}$ ); SPM is suspended particulate matter ( $\text{mg l}^{-1}$ ).

## Detection of low bottom water oxygen concentrations in the North Sea

N. Greenwood et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion