Deep-Sea Research II 106 (2014) 68–75

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Seasonal and inter-annual variability in nutrient supply in relation to mixing in the Bay of Biscay

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ARTICLE INFO

Available online 16 October 2013

Keywords:
Nitrates
Time-series
Ship of opportunity
North East Atlantic
Bay of Biscay

ABSTRACT

A key challenge in oceanography is to capture and quantify processes that happen on short time scales, seasonal changes and inter-annual variations. To address this problem the P&O European Ferries Ltd. Ship *MV Pride of Bilbao* was fitted with a FerryBox from 2002 to 2010 and data returned to NOC in real time providing near continuous measurements between UK (Portsmouth) and Spain (Bilbao) of temperature, salinity, chlorophyll-fluorescence and oxygen. Additional monthly samples were collected on manned crossings. Over 6000 samples were analysed for nitrate (nitrate and nitrite) concentrations. The timing of nitrate concentration increases (with winter mixing) and decreases (with the spring bloom) are different on and off shelf and in autumn nitrate concentrations remain high on the shelf. Off shelf in the Bay of Biscay, the mixed layer depth assessed using Argo floats, was found to vary from 212 m in relatively mild winters (such as 2007/2008) to 476 m in cold winters (2009/2010). Years with deeper mixing were associated with an increase in nitrate concentrations in the surface waters ($\sim$3 μmol l^{-1}) and the increased vertical nutrient supply resulted in higher productivity the following spring. Bloom progression could be seen through the increase in oxygen anomaly and decrease in nitrate concentrations off shelf prior to changes further north on the shelf and phytoplankton growth was initiated as shoaling begins. The full dataset demonstrates that ships of opportunity, particularly ferries with consistently repeated routes, can deliver high quality *in situ* measurements over large time and space scales that currently cannot be delivered in any other way.

1. Introduction

At temperate latitudes nutrient supply to the upper ocean in winter drives phytoplankton productivity and the uptake of carbon dioxide from the atmosphere in the following spring (Eppley and Peterson, 1979; Williams et al., 2000; Hydes et al., 2001). Nutrients can be supplied to the surface through diapycnal diffusion, eddy transfer and Ekman processes (Oschlies and Garson, 1998; Fernández et al., 2005). In the North East Atlantic and the Bay of Biscay winter convective mixing dominates the supply of nutrients (Williams et al., 2000; Puillat et al, 2004; Cianca et al., 2007). Wind-driven cooling and deep convective mixing lower the surface temperature and nutrient rich water is supplied to the euphotic zone from depth to fuel phytoplankton growth, which predominantly occurs in the spring following restratification of the water column (Sverdrup, 1953; Chiswell, 2011). Periods of reduced turbulence and positive heat flux into the ocean prior to the spring restratification results in pulses of phytoplankton growth (Pingree et al., 1976; Garcia-Soto and Pingree, 1998, 2009; Waniek, 2003) and it has been recently hypothesised that these events are significant in calculations of annual productivity (Behrenfeld, 2010).

Behrenfeld et al. (2006) suggested a general trend has occurred of decreased convective mixing, increased stratification and consequent decrease in production in the Northeast Atlantic from 1999 onwards and predicts a decrease in productivity in a warming ocean. There has been a progressive warming of surface waters in the Bay of Biscay over the last 30 years (Garcia-Soto et al., 2002; González-Pola et al., 2005; Somavilla Cabrillo et al., 2011; Holt et al., 2012; Taboada and Anadon, 2012, Garcia-Soto and Pingree, 2012). Winter mixing was studied extensively in Pingree and New (1989). Although there is no direct evidence of progressive changes in productivity or MLD changes in the Bay of Biscay over the last 3 decades studies of the physical processes that regulate nitrate supply to the surface and direct measurements of nutrient concentrations within the mixed layer are critical for making year-to-year estimates of productivity and for future model predictions (Waniek, 2003; Behrenfeld et al., 2006).

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0967-0645/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.dsr2.2013.09.032

The change in nitrate or oxygen concentration from the start to the end of the productive period in spring can be used, along with mixed layer depth (MLD), to calculate proxies for phytoplankton growth and net community production (Pingree et al., 1976; Eppley and Peterson, 1979; Oschlies and Garson, 1998; Henson et al., 2003; Bargeron et al., 2006). This requires quantification of change from the high nutrient (low oxygen) winter months to the low nutrient (high oxygen) concentrations at the end of spring (Minas and Codispoti, 1993; Louanchi and Najjar, 2000; Southward et al., 2004). In the past the concentrations of nitrate in winter had to be estimated, as direct wintertime measurements were relatively rare (Glover and Brewer, 1988; Koeve, 2001) or assumptions have had to be made on the length of the productive cycle (Waniek, 2003). Reducing the reliance on estimation requires year round *in situ* datasets; these can be provided by Ships of Opportunity (SOO) that take consistent repeat routes throughout the year.

In 2002 we initiated year round in situ measurements on a SOO to study the physical and biogeochemical drivers of productivity on and off shelf from the English Channel to the deep water Bay of Biscay. In this study we present an 8 year time-series (2003–2010) of continuous SOO data from *in situ* FerryBox measurements, with additional nutrient samples from 2003 onwards taken each month over most of the period except for August 2007 to August 2008. MLD estimates, calculated from Argo profiling float temperature profiles (available in increasing resolution from 2004 onwards) were used to look at year to year variations in surface nitrate measurements in relation to convective mixing processes. Measurements of Sea Surface Temperature, PAR irradiance, wind speed and turbulence and phytoplankton concentration for the years 1997–2007 along the same FerryBox line using remote sensing can found in Garcia-Soto and Pingree (2009).

We use here the *in situ* SOO dataset to look at seasonal timescales to investigate periods of mixed layer deepening and if they are associated with increases in nitrate or productivity. The nitrate, oxygen and MLD data are used to estimate net community production (NCP) and this study provides a direct opportunity to study seasonal and inter-annual variations in surface nutrient concentrations and how this may affect phytoplankton production.

2. Materials and methods

2.1. Study site

Surface water data were collected from P & O European Ferries Ltd ship *MV Pride of Bilbao* operating between Portsmouth (UK, 50.8°N, 1.1°W) and Bilbao (Spain, 43.4°N, 3.0°W) (Fig. 1). The ship made approximately two crossings weekly between these ports. The FerryBox system ran from April 2002 to September 2010, operating year round except for January when the ship was in dry dock for its annual refit. The distance is approximately 1000 km and the journey time is about 35 h each way. This gives a repeat sampling rate of between 4 h and 4 days, depending on location. Over the 8 years the FerryBox measurements cover 0.8×10^6 km of ship's track. The map in Fig. 1 is reproduced from Bargeron et al (2006) and identifies persistent regional features as identified by Pingree and Griffiths (1978).

In this paper we focus on the Bay of Biscay section of the ferry route (45–46.5°N, regions 6 and 7 in Fig. 1), which is over deep water of up to 4000 m. We contrast this with the on-shelf region 4 (47.5–48.5°N), which remains influenced by strong tides and internal waves. Intermediate to this is the half slope, half stratified shelf region 5, which lies between 46.5 and 47.5°N.

In the deep waters off shelf, the upper water column mixed layer is affected by seasonal cycles of warming and cooling (Pingree et al., 1999; Pingree, 1997). Below this is the main thermocline water mass, the Eastern North Atlantic Central Water (ENACW). Bay of Biscay water properties can be traced back to production on isopycnal surfaces within this mode water (Pingree and Morrison, 1973), which forms from deep winter mixing of North Atlantic Current (NAC) water to the west of the Bay of Biscay and is circulated around the bay down to 400 m (Pingree, 1993; Castro et al., 1998; Pollard et al., 1996; González-Pola et al., 2005, 2006). The properties of the subsurface waters vary from year to year reflecting variations in winter convective mixing and advection (Perez et al., 1993; Pollard et al., 1996).

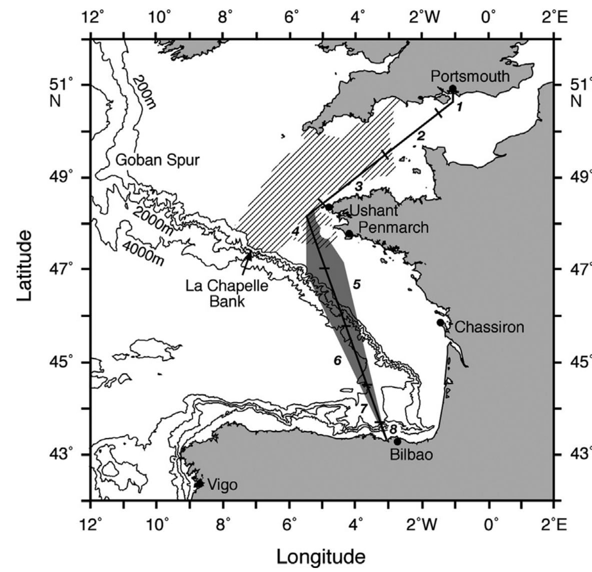

Fig. 1. Schematic of the northbound ferry route showing regions 1–8 as identified by Bargeron et al. (2006). Of relevance are regions 4, the western approaches near the French coast at Ushant (30–130 m); the shelf region 5; the slope and adjacent open ocean off-shelf Bay of Biscay regions 6 and 7 (where water depths reach 4000 m). The hatched area shows the extent of the Ushant frontal system (Pingree and Griffiths (1978); see also Pingree et al., 1982).

2.2. Ship measurements

Between 2002 and 2010 instruments on the ferry (*MV Pride of Bilbao*) recorded a suite of physical and biogeochemical parameters from within the sea surface mixed layer. Brief details of the sampling and methods are presented here but fuller details can be obtained from various papers (including Hydes et al., 2003; Kelly-Gerreyn et al, 2006) and the full dataset is available from the British Oceanographic Data Centre (BODC).

The sampled water was taken from the ship's cooling water supply at a depth of 5 m. The Ferrybox system consisted of sensors to measure conductivity (precision 0.005 mmho cm^{-1}) to calculate salinity; dissolved oxygen, temperature (precision 0.003 °C) and chlorophyll-fluorescence (precision 0.01 ± 0.01 mg m^{-3}). The flow rate in the Ferrybox system was 15–20 l/m. A comparison between the flow through temperature readings and a hull mounted temperature sensor showed that the flow through temperature readings were 0.5 ± 0.3 °C higher than the in situ water (offset ± 1s) from 2005 through August 2008. Subsequent to August 2008 this reduces slightly to 0.3 ± 0.3 °C. These small offsets suggests a low residence time of water in the Ferrybox system. Underway data were logged at a rate of 1 Hz on a NOC (National Oceanography Centre, Southampton) designed logging and control system. Public domain Matlab routines (http://marine.csiro.au/~morgan/seawater) provided the calculations for salinity. All sensors were cleaned on an approximately weekly basis to reduce bio-fouling, when the ship was berthed in Portsmouth.