Journal of Marine Systems 130 (2014) 193–205

Contents lists available at ScienceDirect

Journal of Marine Systems

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

Environmental control of phytoplankton distribution and photosynthetic performance at the Jan Mayen Front in the Norwegian Sea

Svein Rune Erga [a,*], Nicolausi Ssebiyonga [b], Børge Hamre [b], Øyvind Frette [b], Erlend Hovland [c], Kasper Hancke [c], Kenneth Drinkwater [d], Francisco Rey [e]

[a] Department of Biology, University of Bergen, P.O. Box 7803, 5020 Bergen, Norway
[b] Department of Physics and Technology, University of Bergen, Allégt. 55, 5007 Bergen, Norway
[c] Department of Biology, Trondhjem Biological Station, Norwegian University of Science and Technology, N-7491 Trondheim, Norway
[d] Institute of Marine Research and the Bjerknes Centre for Climate Research, P.O. Box 1870 Nordnes, 5817 Bergen, Norway
[e] Institute of Marine Research, Gaustadalleen 21, 0349 Oslo, Norway

ARTICLE INFO

Article history:
Received 15 April 2011
Received in revised form 11 January 2012
Accepted 17 January 2012
Available online 27 January 2012

Keywords:
Norwegian Sea
Arctic Front
Phytoplankton
Nutrients
Spectral light
Biomass
Primary production

ABSTRACT

The Jan Mayen Front is located in the Norwegian Sea to the east of the Jan Mayen Ridge and separates warm, salty Atlantic water and colder, less salty Arctic water. The effects of the light regime, hydrographical conditions and nutrients on the variations of chlorophyll *a* (chl *a*), quantum efficiencies of photochemistry in PSII (F_v:F_m) and effective absorption cross-section of PSII (σ_{PSII}) at the Front were studied in June 2007. Stratified waters were seen on both sides of the Front and lowered nutrient concentrations were seen shallower than 10–20 m. The lowest values of the spectral diffuse attenuation coefficient, K_d (λ), were found at 500–550 nm (0.07–0.16 m^{-1}), while K_d (465 nm) ranged between 0.08 and 0.17 m^{-1} and K_d (380 nm) between 0.13 and 0.20 m^{-1}. Chl *a* concentrations seldom exceeded 1.0 mg m^{-3} outside pure Atlantic Water, while elevated concentrations (3–4 mg m^{-3}) developed at depth (20–30 m) east of the Front in Atlantic Water. For the upper 100 m N/P, Si/P, N/Si and POC/PON ratios were 15.2, 8.0, 1.7 and 6.2, respectively. The quantum efficiency was strongly influenced by nutrients, suggesting nutrient limitation of phytoplankton biomass at the Front in June, but also light inhibition probably was a contributing factor in the upper part of the water column. High quantum efficiencies (0.5) and effective absorption cross sections (>700 Å^2 quanta^{-1}) were seen to the east of the Front and at depth (20–40 m) in stratified Atlantic waters. We therefore conclude that the Jan Mayen Front did not have a stimulatory effect on phytoplankton biomass enhancement and photosynthetic performance. This is in part due to the weak horizontal density front caused by density compensation of temperature and salinity characteristics of the adjacent water masses, and the associated weak vertical mixing.

1. Introduction

Fronts are defined as a discontinuity in the horizontal distribution of water mass properties (Denman and Powell, 1984) and are formed at the transition between two well-defined water masses with different properties. This study examines the Jan Mayen Front situated south of the island of Jan Mayen and east of the Jan Mayen Ridge in the Norwegian Sea and was part of the IPY Project NESSAR (Norwegian component of the Ecosystem Study of Subarctic and Arctic Regions). The Jan Mayen Front is a permanent feature and part of the Arctic Front system which extends from the Iceland–Faroe Ridge in the south to Fram Strait in the north roughly following the mid-Atlantic Ridge. It separates colder and fresher Arctic waters from warmer and saltier Atlantic waters. In this paper we explore the nutrient distributions, spectral light penetration as well as the phytoplankton productivity potential and phytoplankton distribution, and their controlling factors at, and in the vicinity of, the Front.

Many of the earlier surveys of the Norwegian Sea are recognized as pioneer work and they represent milestones in the history of Norwegian marine research. They mostly focused on hydrographical conditions and quantitative aspects of phytoplankton vegetation (Braarud, 1935; Gran, 1902; Halldal, 1953; Paasche, 1960; Ramsfjell, 1960; Smayda, 1958). Another important work from the Norwegian Sea in the 1950s was conducted by Berge (1958), who used the C-14 technique for measuring primary production for the first time in Norwegian oceanic waters.

A number of studies have shown that changes in physical characteristics across a front result in special adaptation strategies, which give rise to different phytoplankton communities. On the stratified side of the transitional zone of the Ushant tidal front (west coast of France) Videau (1987) found that the physiological state of diatoms cells was improved, revealed by increased growth rates. Jones et al. (1984) and Carreto et al. (1986), on the other hand, emphasize the

---

[*] Corresponding author. Tel.: +47 55582679; fax: +47 55584450.
E-mail address: svein.erga@bio.uib.no (S.R. Erga).

0924-7963/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmarsys.2012.01.006

dominance of diatoms on the homogenous (mixed) side of the tidal front system at Jura (Scotland) and Valdéz (Argentina), respectively. For the more permanent Kuroshio frontal system (Japan), Yamamoto et al. (1988) found that dominance of diatoms at the front was due to upwelling of nutrients.

Higher biomass of primary and secondary producers is often encountered in frontal areas compared with adjacent waters (Fernández et al., 1993; Hansen et al., 1990; Kahru et al., 1984). This can be due to the accumulation of cells through physical forces or by enhanced *in situ* production in response to favorable growth conditions, such as access to increased nutrient supply. Fernández et al. (1993) concluded that primary production peaks within a slope current-induced front in the southern Bay of Biscay (Spain) were a result of active growth and not accumulation of cells. For the Catalan Front in the northwestern Mediterranean, the formation of a subsurface chlorophyll-*a* maximum layer (SCML) seemed to be a prominent feature, both during winter and spring (Delgado et al., 1992). In Monterey Bay, California (USA), a tight physical–biological coupling at the frontal zone has been observed, and topographical conditions together with internal wave dynamics seemed to be important regulating mechanisms (Ryan et al., 2005). Studies of phytoplankton growth dynamics in the Antarctic Polar Front region (170°W) revealed that stimulatory effects on primary production rates could first be seen in the main front and was thereafter displaced southwards (Landry et al., 2002). High diatom stocks were restricted to waters with silicate and iron concentrations above a critical minimum. Remotely sensed ocean color data suggest that the major front systems of the Southern Ocean are regions of elevated chlorophyll concentrations and high primary production rates with diatoms as the main contributor (Moore and Abbott, 2000). A similar pattern, with a marked surface bloom of diatoms in May responding to upwelling of silicate, was seen along the meanders of the Iceland–Faroe Front (Allen et al., 2005). In the Polar Front region of the southwestern Atlantic, active growth also occurs at depth in the SCML (Brandini et al., 2000). According to Laubscher et al. (1993) a coincidence of two or more factors, such as temperature gradients, upper mixed layer depth, silicate availability and grazing, is needed to generate and regulate phytoplankton blooms in these frontal systems.

A dominance of diatoms and the prymnesiophyte *Phaeocystis pouchetii* are a characteristic feature of the phytoplankton composition in the Norwegian Sea in June (Paasche, 1960; Ramsfjell, 1960). In the Norwegian Sea to the northeast of Jan Mayen during early summer, a difference in the timing of the seasonal development of the plankton community was observed across the Arctic Front, with typical post-bloom conditions on the Atlantic side and bloom conditions on the Arctic side (Dale et al., 2001). The Arctic Front in the Norwegian Sea has also been associated with high numbers of the coccolithophorid *Coccolithus pelagicus* during summer, and it was concluded that other controlling factors than low temperature had to be taken into account for explaining their dominance (Baumann et al., 2000). A comprehensive data set from the central Greenland Sea revealed that the spring (May) phytoplankton was mainly composed of diatoms and the prymnesiophyte *P. pouchetii*, while the summer situation is generally characterized by depletion of nutrients and low phytoplankton biomass (Erga et al., 2005; Rey et al., 2000). Maximum primary productivity in June along a transect across the Greenland Sea from the Norwegian Sea to the Greenland Shelf was reported in the Arctic Frontal Zone (Legendre et al., 1993). They also found production was dominated by large cells (>5 μm) in the Arctic Water and small cells (<5 μm) in the Atlantic Water. This is also consistent with the results of Erga et al. (2005) who found a change from low biomass composed of small flagellates to a dominance of high biomass composed of large diatoms when crossing the Arctic Front from Atlantic to Arctic waters during late summer. In the ice edge region of the Fram Strait/Greenland Sea area, elevated chlorophyll *a* concentrations were encountered in the nutrient rich frontal boundaries (Spies et al., 1988). It was also suggested that the Arctic Front in the Western Norwegian Sea might be a region of high productivity based primarily on the presence of the large number of pelagic fish species that feed there in the late spring to early autumn period (Rey, 2004).

For the Norwegian Sea it has been emphasized that the loss of phytoplankton biomass due to sedimentation during summer could be counteracted by phytoplankton production through nutrient regeneration in the upper part of the water column caused by zooplankton grazing. The effect of such a coupling will depend upon the timing between the bloom period and the appearance of zooplankton (Wassmann et al., 1991).

Intensive and high spatial resolution studies aiming at resolving fine scale structure in phytoplankton distributions, photosynthetic efficiencies and spectral light penetration in the Arctic frontal zone are scarce for the Norwegian Sea. In the present study these items are addressed using high resolution data collected during June field studies.

2. Material and methods

2.1. Study area

In 2007, the Institute of Marine Research (IMR) in Bergen, Norway, organized a cruise to the Norwegian Sea south of the island of Jan Mayen as part of the IPY NESSAR project. A study of the physical and biological processes at the Jan Mayen Front located east of the Jan Mayen Ridge was carried out onboard *R.V. G.O. Sars* from 1 to 22 June. Physical and biological sampling at a horizontal resolution of 1–10 km was principally conducted along an east–west transect located near 68°26′N. Additional sampling was undertaken between this transect and the island of Jan Mayen, mostly over and to the east of the Jan Mayen Ridge. Typical bottom depths in the study area are >2000 m.

2.2. Salinity, temperature and oxygen

At each station on the cruise (Fig. 1), depth profiles of temperature and salinity were measured by a Sea Bird CTD probe mounted on a General Oceanic Rosette water sampler. The CTD temperature sensor was calibrated before the cruise, and the salinities were calibrated by analyzing salinity samples collected routinely from the water bottle at the deepest sampling level on each cast. The salinity analyses were conducted by a Guildline 8400 AutoSal using IAPSO Standard Sea Water as a reference. Oxygen on the CTD was measured using a Sea-Bird (SBE43) instrument. Oxygen samples were also taken from water bottles on the rosette at 21 stations for a total of 251 samples and analyzed by titration using the Winkler method. The titrated oxygen levels were used to calibrate the CTD-measured oxygen concentrations.

2.3. Nutrients, particulate organic carbon and nitrogen

Dissolved inorganic nutrients (nitrite, nitrate, orthophosphate and silicate) at discrete depths collected from water bottles on the rosette were analysed onboard according to standard methods (Parsons et al., 1992) adapted to an auto-analyser (Rey et al., 2000). Triplicate samples for particulate organic carbon (POC) and nitrogen (PON) were taken at selected stations and depths. They were filtered onto precombusted Whatman GF/F filters and stored at −20 °C before analysis on a FlashEA 1112, Automatic Elemental Analyser for CHN determination. No corrections were made for detritus.

2.4. Chlorophyll-a and in situ fluorescence and turbidity measurements

Samples taken from water bottles for chl *a* measurements were filtered using GF/F filters and stored at −20 °C before analysis within 2 weeks of end of the collection. The analyses were done fluorometrically (Turner Designs-10) according to Holm-Hansen et al. (1965), using 90% acetone as solvent and acid corrections for phaeopigments.