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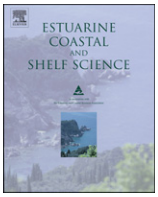

Dynamics of phytoplankton distribution and photosynthetic capacity in a western Norwegian fjord during coastal upwelling: Effects on optical properties

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ABSTRACT

The present study describes the coupling between optical properties and the dynamics of phytoplankton distribution and photosynthetic capacity in the Lysefjord during an exceptional coastal upwelling. At the mouth of the fjord, transparent Coastal water was "piled up" against the sill, while more turbid Fjord water from the outer fjord system was flowing over the sill, creating the intermediate layer which extended further into the fjord. This was reflected by high spectral attenuation coefficients in the upper 10 m of the fjord. Outside the sill, clear water with low spectral attenuation coefficients were found below sill depth down to at least 30 m, while the attenuation coefficients inside the sill were significantly higher between 10 and 20 m. About 4–7 km outwards from the head of the fjord clearer deep basin water was entering the upper layer due to the upwelling which could be traced up to 7 m, bounded by the 7.5 °C and the 31 salinity isolines. In the outer part of the fjord waters with a high chl *a* content and photosynthetic capacity were observed below the outflowing surface layer containing "old water" from the inner part of the fjord, which was characterized by low nutrient and chl *a* concentrations. Maximum quantum efficiencies (0.5) were encountered within this subsurface layer. Quantum efficiencies exceeded 0.3 when nitrate and silicate concentrations increased above 2 mmol m^{-3}. About 50% of the PAR light attenuation (0–30 m) was caused by chl *a*, and the 1% light depth varied between 27 and 35 m along the transect. Due to the influence of freshwater outlets, non-pigmented particles were more abundant in the inner part of the fjord than in the outer part. Colored dissolved organic matter (CDOM) contributed strongly to absorption within the upper 10 m at wavelengths below 470 nm while scattering was the major attenuation contributor for wavelengths above 600 nm. With respect to possible climate change effects on the growth of phytoplankton in Norwegian fjords, our results indicate that the alteration of coastal wind patterns due to its impact on coastal – fjord water exchanges, is probably more important than increased temperature and/or increased precipitation.

1. Introduction

The Norwegian coastline including fjords and bays constitutes about 21,000 km. Seven of the fjords are longer than 100 km, and the two longest ones are 204 and 179 km, both situated on the west coast oriented in n west-east direction. Following the definition given by Pritchard (1967), fjords could be classified as a subgroup of a classical estuary. The special characteristic of a fjord-type estuary is that it is much deeper than a "coastal plain estuary". One characteristic with Norwegian fjords is a relatively shallow sill at the mouth. Typical for these large scale Norwegian fjord systems are depths of more than 500 m, with the deepest having a maximum depth of 1308 m. Inwards they may extend into a branched system, the inner parts often ending up in side-fjords with a shallow sill (<20 m). Such fjords are characterized by a restricted renewal of the deep water. According to Aure and Stigebrandt (1989) oxygen consumption in sill basins of fjords decreases with increasing sill depth. At the mouth, some of the Norwegian fjords may be more than 20 km in width. Here they are separated from the adjacent continental shelf by a sill which is often found at a depth of about 100 m. Therefore the largest fjord systems may be characterized as mini oceans with respect to physical, chemical and biological properties.

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The southern and western Norwegian fjords are characterized by distinct stratification of the water masses, primarily caused by freshwater runoff which peaks in May–June. Fjords represent the main input of freshwater to the Norwegian Coastal Current (NCC), and south-western Norway is the most important contributor (Aure et al., 2007). The manner in which these freshwater inputs may influence the vertical fjord structure is, however, strongly dependent upon tides and winds (Aure et al., 1996; Asplin et al., 1999). Deep water renewal follows the coastal upwelling during prolonged periods of northerly winds resulting in an increased offshore component in the flow of the NCC, as opposed to southerly winds which give an increased onshore component. The comprehensive upwelling, which usually takes place in late April – early May, brings nutrients to the euphotic zone from below. Coastal deep water is transported by this water exchange into the fjord over the sill as part of the intermediate layer, extending from the top of the halocline and down to the sill, and/or basin water (density dependent), to compensate for the outflowing upper brackish layer. During prolonged periods of southerly winds coastal surface water is forced into the fjord systems. The upper mixed layer expands by this inflow.

Investigations of western Norwegian fjords have shown that the degree of water column stability, which is mainly determined by salinity, is decisive for the initiation, maintenance and species composition of phytoplankton blooms (Erga and Heimdal, 1984; Erga, 1989a; Erga and Skjoldal, 1990; Frette et al., 2004; Erga et al., 2005; Aure et al., 2007). Stratified water masses often prevail in the fjords, which during summer often results in a nutrient depleted euphotic zone with primary production levels typically being reduced to one third of that in the spring bloom (Erga et al., 2005). Under such conditions subsurface chlorophyll maximum layers (SCML) are formed at the pycnocline, often coinciding with the top of the nutricline. Here reduced light intensities results in a predominance of low light acclimated phytoplankton cells (Erga, 1989a; Frette et al., 2004; Erga et al., 2005). In a Scottish fjord, high freshwater run-offs during spring was found to inhibit growth of phytoplankton deeper in the water column due to high concentrations of CDOM in the surface layer, acting as a light attenuator of visible light (McKee et al., 2002). It should be noted, however, that CDOM is also the most efficient attenuator of harmful ultraviolet radiation (UVR). In a western Norwegian fjord the depth range of photosynthetic UVR inhibition was reduced to less than 3 m because of elevated CDOM concentrations in the upper layer (Erga et al., 2005). As a bloom proceeds and nutrients are being exhausted, viruses, bacteria and grazing also become important regulating factors (Erga, 1989a; Larsen et al., 2004).

Many studies have revealed that exchange processes between offshore and inshore waters are important for short-term variations of phytoplankton biomass in bays, estuaries and fjords (Braarud, 1975; Tyler and Seliger, 1978; Scott, 1979; Lindahl, 1983, 1986; Fraga et al., 1988; Gaard et al., 2011). Both in the Southern Bight of the North Sea and in Ria de Vigo (northwest coast of Spain), changes in the prevailing wind direction had large scale consequences for the growth and species composition of the phytoplankton community (Dickson and Reid, 1983; Fraga et al., 1988; Álvarez-Salgado et al., 2005). It should also be mentioned that the importance of advection for vertical distribution and growth of zooplankton have been a theme for many investigations in Norwegian fjords, comprising study sites from the Arctic Kongsfjord on Svalbard to the Ryfylkefjords in the south (Matthews and Heimdal, 1980; Aksnes et al., 1989; Kaartvedt, 1993; Basedow et al., 2004).

The present study in the Lysefjord was conducted during a late phase of an unusually long-lasting and strong upwelling event in western Norwegian fjords during spring 2010, resulting in a total renewal of the basin water of the fjords. Special focus has been on recognizing the origin of different water types from their optical properties, and by this gain an improved insight of the circulation patterns of fjords. An important aspect of the investigation was to obtain a better understanding of the coastal-fjord water exchange dynamics, and to determine how the advective processes influence phytoplankton photosynthetic activity, measured by the Fast Repetition Rate Fluorescence (FRRF) technique (Falkowski and Kolber, 1995), and biomass distribution along a fjord gradient varied with respect to environmental conditions. This was achieved by increasing the spatial resolution of the measured parameters compared with earlier investigations. To the best of our knowledge such a combination of data has not yet been presented for a fjord system. The results presented add new information on light conditions of fjords that could also be valuable as inputs for primary production models. For example knowledge of spectral variations in the water optical properties allows calculations of photosynthetic utilizable radiation (Morel, 1978), which – compared to PAR – gives a more realistic input to phytoplankton growth rate parameterizations. In addition such spectral variations can be utilized in models that take into account growth inhibition due to enhanced levels of ultraviolet radiation (Hamre et al., 2008).

2. Material and methods

2.1. Study site

The Lysefjord represents a side branch of the extensive Bokna- and Ryfylkefjord system (Fig. 1). The adjacent Høgsfjord connects to the north with the open Boknafjord, which again has a good connection with the coastal waters to the west across a sill of about 200 m (Erga, 1989a). The Lysefjord has a shallow sill (14 m) situated about 4 km from the mouth halfway between Station 14 and Station 03. It is approximately 40 km long and 0.5–2 km wide, has a maximum depth of 460 m and a surface area of 44 km^2 (Aure et al., 2007). Due to steep mountains on each side of the fjord, the effect of wind on the advection of water is particularly strong. Bottom topography reveals two deep basins with depths >300 m, the inner one between Station 17 and 18 and the outer one between Station 18 and 14. The mean tidal range is 0.4 m, and the freshwater supply to the Lysefjord varies between 40 and 90 m^3 s^{-1}, with highest discharges in May. Nine stations were selected to cover the fjord with sufficient spatial and temporal resolution (Fig. 1).

To enhance the primary production during nutrient impoverished summer period a large scale forced upwelling facility has been established near the head of Lysefjord (Aure et al., 2007), where brackish water is discharged at 30 m to force upwelling of nutrient rich water into the upper part of the water column. The intrusion depth has been found to be between 6 and 10 m, and the area of influence covers about 10 km^2 (i.e. 10 km outwards). Prior to and during the cruise, however, the forced upwelling system was running at a reduced capacity due to technical problems and is therefore expected to have a limited effect. The pump station for forced downwelling was positioned at Skarpanes, midway between Stn 11 and 16 (Fig. 1), and it was started 8 days before the cruise. A volume transport of 0.5 m^3 s^{-1} of brackish water was discharged at 30 m, giving an estimated upwelling plume volume of 7 m^3 s^{-1}.

2.2. Sampling procedure

An intensive sampling programme was carried out onboard R/V “G.M. Dannevig” from 4 to 6 May 2010. Four sampling stations were established within the expected influence area of the forced