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Phytoplankton phenology and production around Iceland and Faroes

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ABSTRACT

Phytoplankton phenology and primary production were examined in the Iceland–Faroe region through synthesis of all available data, both *in situ* and remotely sensed. In the Arctic water, the early onset of stratification in spring gave rise to the rapid shallowing of the mixed layer and triggered the earlier spring bloom north of Iceland, whereas the weakly stratified water-column in the Atlantic water and associated deep mixed layer delayed the spring bloom south of Iceland. The protocol (Nearest Neighbor Method, NNM) developed by Platt et al. (2008) was used to estimate the daily, water-column primary production from ocean color data. The key element of the procedure is an archived database, including (in this implementation) 505 sets of parameters of photosynthetic–light curves and 197 vertical profiles of chlorophyll around Iceland–Faroe region. The spatial structure in the climatology of annual primary production determined in this way was consistent with observations made by the simulated *in situ* method using ships as a platform, but, inevitably, the fields produced from the remotely sensed data were smoother. The annual primary production estimated by the NNM method overestimates the (much more sparse) data for *in situ* production by 50% on average. We examined the relative errors in the estimation of primary production that would arise from ignorance of the non-uniformity in the biomass profile. The vertically uniform model tended to underestimate the annual primary production by about 36% compared with the non-uniform model in a spectral calculation.

1. Introduction

Oceanographically, the Iceland–Faroe area is complex, and may be partitioned according to hydrographic understanding into six regions (Fig. 1). The warm and saline Atlantic water is carried by the North Atlantic Current and the Irminger Current approaching the Iceland Shelf from south and west. The cold and fresh Arctic water flows as the East Icelandic Current north of the Iceland Shelf. The Polar water feeds the East Greenland Current. The Mixed water is the recirculated Atlantic water and is much influenced by the Arctic water masses. The two shelf regions over northeast and southwest of Iceland are defined following 500-m depth contours. However, a detailed frontal analysis (Fig. 2) showed that this partition is a dynamic one: the boundaries between regions fluctuate from one time to another. It is worth noting that changes in relative influence of Polar water and Atlantic water, a branch from the Irminger Current west of Iceland to the shelf north of Iceland, make the northeast Iceland region extremely variable from one year to another. The environmental conditions for the shelf water north of Iceland have been characterized as cold (Polar water), warm (Atlantic water) or something in between (Arctic water) according to the results of annual hydrographical measurements north of Iceland, and these variations apparently influence the primary production (Gudmundsson, 1998; Anon, 2008).

Previous estimates of annual primary production in the region were made solely on the basis of simulated *in situ* experiment conducted at sea (Thordardottir, 1994). Although the network of stations occupied is unusually rich (Fig. 9), and the data accumulated over many years, the resultant map of estimated annual primary production is vulnerable to bias from extreme values at particular stations. The advantages of combining the ship data with remotely-sensed data on visible spectral radiometry (ocean color), for which the principal deliverable is concentration of chlorophyll, include superior spatial resolution and better temporal coverage. Until now, the operational estimation of daily

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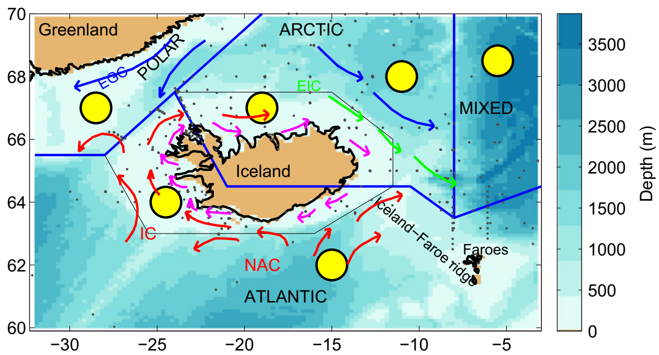

Fig. 1. Bathymetry and circulation around Iceland. Based on the knowledge of the local water masses, the study area is divided into four oceanic regions by blue lines, and three shelf regions by black lines: Polar, Arctic, Mixed, Atlantic, northern Iceland Shelf, and southern Iceland Shelf. The circulation around Iceland is summarized as follows: East Greenland Current (EGC), East Icelandic Current (EIC), North Atlantic Current (NAC), Irminger Current (IC) and coastal currents (purple arrows). The yellow circles show the areas averaged for the representation of region-specific properties. The sampling stations (black dots) at which the photosynthetic–light experiments are made from years 1981 to 2009 are superimposed. Modified from Gudmundsson et al. (2009).

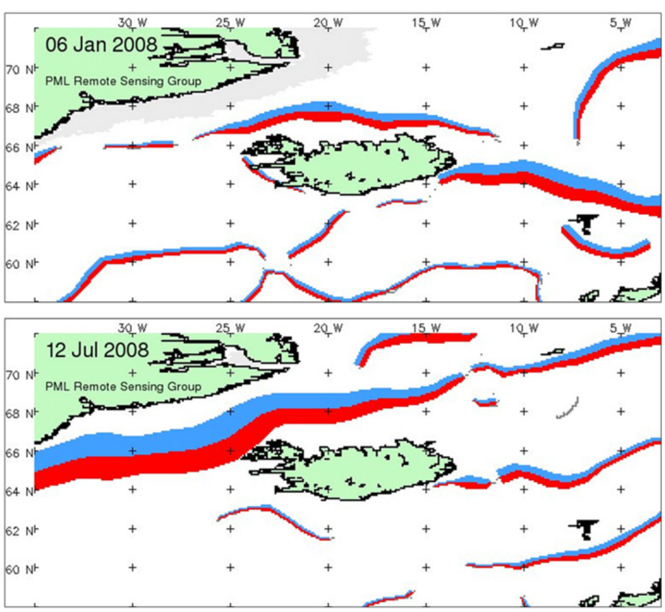

Fig. 2. Examples of 7-day composite front maps from merged microwave/infrared SST data (9 km resolution) around Iceland (Miller, 2009). Red and blue colors indicate the warm and cold sides. The line width indicates the strength of the front.

primary production from remote sensing using a formal parameter assignment protocol, such as the Nearest Neighbor Method (NNM, Platt et al., 2008) has not been made for the Iceland–Faroe area.

The information on phytoplankton and primary production can be utilized to facilitate ecosystem-based management (Platt et al., 2007), such as exploring the correlations between phytoplankton growth and the fate of the primary production through the food chain and casting light on the principal causes of variations in harvestable marine organisms (Astthorsson et al., 2007). The objectives of this study are to estimate primary production for the Iceland–Faroe region from remotely sensed data on ocean color and available ship data, and to characterize the phytoplankton phenology.

2. Material and methods

Most of the *in situ* results used were collected over many years by the Marine Research Institute, Iceland under the leadership of Thorunn Thordardottir (1925–2007). Without this investment, we would not have been able to carry out the work reported here.

2.1. Simulated in situ primary production

Simulated *in situ* primary production was measured by the ^{14}C technique (Steemann Nielsen, 1952). The procedure (Strickland and Parson, 1972; Parsons et al., 1984) was to take water samples, inoculate 50 ml aliquots in clear glass bottles with known activity of radioactive bicarbonate (2−4 μCi per sample) and expose them to a range of light intensities in a temperature regulated incubator. The incubation temperature was adjusted to the *in situ* temperature of the seawater at the time of sampling, and the samples were usually incubated for 4 h (accepting 2–6 h). Water samples from 0, 10, 20 and 30 m were sampled at each station, if possible, and the entire contents of each subsample were filtered onto a cellulose membrane filter (0.2 m) within an hour after incubation. The filters were then dried, in clamps, and exposed to concentrated HCl fumes for five minutes before measuring the radioactivity, using GM-counters. Each filter was counted from both sides in order to correct for varying penetration of ^{14}C into the filters (Theodorsson, 1975) in the calculations of total dpm per filter (Theodorsson, 1984). The primary productivity in $mg\,C\,m^{-3}\,h^{-1}$ was calculated for each sample (Strickland and Parson, 1972), integrated through the water column and converted to the daily rate in $mg\,C\,m^{-2}\,day^{-1}$ to get the daily water column production according to a regional adaptation of the original equation of Steemann Nielsen. The data from years 1958 to 1982 were combined to estimate the annual production from a series of seasonal averages of daily production (Thordardottir, 1994).

2.2. Environmental data

The monthly climatological fields of chlorophyll concentration, sea-surface temperature (SST), cloud cover and photosynthetic available light (PAR) for the Iceland–Faroe area were computed from satellite data between year 1998 and 2007, and mapped onto a 0.1° lat × 0.25° lon grid. The satellite data used are global archives, including the 9-km SeaWiFS level-3 binned monthly-averaged chlorophyll concentration and PAR (http://oceancolor.gsfc.nasa.gov/), the 4-km AVHRR Pathfinder monthly SST (http://www.nodc.noaa.gov/SatelliteData/pathfinder4km/), and 1° SSM/I monthly cloud cover (Ferraro et al., 1996). The primary production model is forced by the climatological biomass and irradiance fields, and the inputs of the NNM are climatological biomass and SST. To determine the onset of phytoplankton blooms, we constructed the 8-day climatology of chlorophyll concentration from the 9-km SeaWiFS level-3 binned daily files, since the monthly resolution cannot well characterize a bloom with a duration of several weeks. We have established 8-day climatological time series of chlorophyll representative for the four oceanic and two shelf provinces (Fig. 1). The locations for each time series were chosen to be away from the boundaries between provinces and the time series were averaged within a 50 km radius of the center. The satellite chlorophyll data are not available before March and after October for the study area, due to the low sun zenith angle.

The mixed layer depth is derived from the hydrographic measurements archived by the World Ocean Database 2009 (Boyer et al., 2009). The raw data of temperature and salinity for each month were averaged on a 2.5° Lat × 10° Lon grid and were binned vertically into depth segments of 5 m. The potential density is then calculated from the gridded temperature and