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Spatial high-resolution estimation of net oxygen production during spring bloom in the western North Pacific using dissolved oxygen, nitrogen and argon

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ABSTRACT

Spatial high-resolution estimates of biogenic oxygen were obtained by measuring the concentration of dissolved oxygen, nitrogen and argon during the spring phytoplankton bloom at 21 observation points in the western North Pacific in the area of the Oyashio and Kuroshio Currents off the coast of Hokkaido-Tohoku, Japan. This area extends over approximately 600 km. The test region was divided into 6 mesoscale-wide groups (approximately 20–150 km wide) of observation stations based on variation in the temperature and salinity of the seawater. As suggested by an analysis of the hydrographic data, the area of which water temperature was lower than around the area was found in the Oyashio–Kuroshio mixing area. In the area, vertical water mixing between the warm mixed layer and cold sub-mixed layer occurred. The biogenic oxygen also varied horizontally at mesoscale intervals. The variation was caused by vertical mixing, because the water masses of the mixed layer and sub-mixed layer had positive and negative biogenic oxygen values, respectively. A spatial high-resolution method for estimating the spatial high-resolution net oxygen production rates (*NOP*) within the mixed layer using a time-stepped model with biogenic oxygen and the physical data was proposed. The estimated *NOP* varied widely, even within the same water mass group, and ranged from -23.6 ± 6.0 to 252.7 ± 68.2 mmol/m^2/day. Therefore, spatial high-resolution *NOP* estimates are imperative to analyze biological production in areas with complex water mass structures.

1. Introduction

Marine biological productivity plays a basic role in supporting the global ecosystem, and is an important process in the biogeochemical cycle of the global ocean (e.g., Sarmiento et al., 1998). Recent satellite studies of the earth's surface suggest that chlorophyll *a*, an index of biological productivity, has relationship with mesoscale (from several tens of kilometers to several hundreds of kilometers) eddies and/or currents (e.g., Shapiro et al., 2010). Phytoplankton blooms in subtropical regions occur in mesoscale eddies because the nutrients for the blooms are transported by the eddies from the subsurface to the surface layer (Kimura et al., 1997; McGillicuddy et al., 1998; Benitez-Nelson et al., 2007; McGillicuddy et al., 2007). An easy high-resolution method is required to quantitatively estimate the effect of seawater movement on biological production. However, the measurement of primary production using a general incubation method is too time-consuming and labor-intensive for use on a research vessel. One potential alternative method measures the dissolved oxygen (DO) in the surface layer. The DO concentration has been routinely measured in classic marine hydrographic studies. Recently, a highly accurate DO sensor has been developed and installed in a conductivity, temperature and depth profiler and in autonomous oceanographic floats (e.g., D'Asaro and McNeil, 2007). Therefore, the spatial and temporal distributions of the DO are easily obtainable. The DO is produced by photosynthesis of phytoplankton, which depends on dissolved nutrients and carbon species, and is consumed by respiration of organisms at higher trophic levels (e.g., Craig and Hayward, 1987). Surface DO also varies with physical processes that are associated with gas exchange at the air–sea interface, which change with wind speed, air pressure and water temperature (e.g., Hamme and Emerson, 2006). Therefore, to estimate biological production based on the DO value, this value must be adjusted to obtain an apparent DO that accounts for these processes. This corrected DO is called the net community production rate (e.g., Emerson et al., 1991), and we use this value as the net oxygen production rate (*NOP*) in this paper. The *NOP* is an important index for understanding the mechanism controlling ocean productivity. Recently, dissolved nitrogen (N_2) and argon (Ar) concentrations have been used to estimate air–sea DO-exchange processes because Ar and N_2 are inert gases and the solubility coefficient and Schmidt number of Ar are similar to those of oxygen (Garcia and Gordon, 1992; Wanninkhof, 1992; Hamme and Emerson, 2004). Reuer et al. (2007)

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estimated an air–sea flux of biogenic oxygen in the Southern Ocean using the climatological mixed layer depth and observed surface data on the DO and dissolved Ar. Although these authors identified the flux as *NOP*, this flux does not necessarily agree with the *NOP* depending on biological and/or weather conditions. Emerson et al. (2008) proposed an alternative *NOP* estimation method, which uses the DO and dissolved N_2 and is largely unaffected by biological processes. Using this method, these authors monitored the *NOP* in surface water for a year using a mooring system to obtain in situ measurements of these gases. Although capable of showing detailed temporal variations in the *NOP*, this method is computationally complex because of processes associated with bubbles. Tanaka and Watanabe (2007) developed a highly precise gas chromatographic method to rapidly analyze oceanic dissolved N_2, Ar and O_2 concentrations. Moreover, these authors have proposed a method to measure oxygen utilization using the concentration of these three gases in the subsurface ocean. Therefore, the *NOP* in the surface ocean can be estimated with their method.

The Hokkaido National Fisheries Research Institute of the Fisheries Research Agency of Japan (HNFRI/FRA) has conducted an oceanographic survey along the "A-line" since 1990 (Saito et al., 1998, 2002; Ono et al., 2003; Kasai and Ono, 2007). The A-line is located off the coast of Hokkaido-Tohoku, Japan, and perpendicularly crosses the Oyashio and the Kuroshio–Oyashio transition areas (Yasuda, 2003) (Fig. 1). In this region, the water structure is vertically and horizontally complex on a mesoscale (e.g., Kono, 1997), and the phytoplankton blooms are dense (e.g., Kasai et al., 1997, 1998; Isada et al., 2010). Therefore, we examined the detailed vertical DO profiles within the mixed layer with air–sea gas exchange processes based on hydro-cast data collected along the A-line during the spring of 2007. The purposes of this examination were threefold: (1) the estimation of biogenic oxygen using the dissolved N_2, Ar and O_2 within the mixed layer, (2) the proposal of a simple model to estimate the *NOP* using the biogenic oxygen flux and inventory, and (3) the estimation of the *NOP* within the mixed layer.

2. Observation and analytical methods

The HK07-05 cruise was taken on the R/V *Hokko-Maru* of HNFRI/FRA to observe the A-line from May 10 to May 13, 2007 (see Fig. 1). We obtained seawater samples using 12-L Niskin bottles mounted on a conductivity, temperature and depth profiler with dissolved oxygen sensor (CTDO, 911plus with SBE43, Sea-Bird Electronics, Inc.). The CTDO observations were conducted at all of the A-line stations (A01 to A21). The seawater samples for the determination of the dissolved O_2, N_2 and Ar concentrations were collected at 4 stations (see the large circles in Fig. 1), and analyzed with a precision of <0.1% (standard deviation of duplicate samples) based on the method of Tanaka and Watanabe (2007). In addition, dissolved oxygen concentrations ($DO_{obs(total)}$) were measured by the Winkler method (e.g., Carpenter, 1965) with a precision of <0.2% (standard deviation of duplicate samples). The dissolved oxygen data from the CTDO oxygen sensor were corrected by the $DO_{obs(total)}$. Salinity, temperature, nutrients and chlorophyll *a* were also measured, and these data are included in the A-line database (FRA, 2007). To compare the water mass properties of the A-line between the end of winter and spring, we also used the dataset of WK07-03 cruise which was performed in March 2007 by R/V *Wakataka-Maru* of the Tohoku National Fisheries Research Institute, Fisheries Research Agency, Japan.

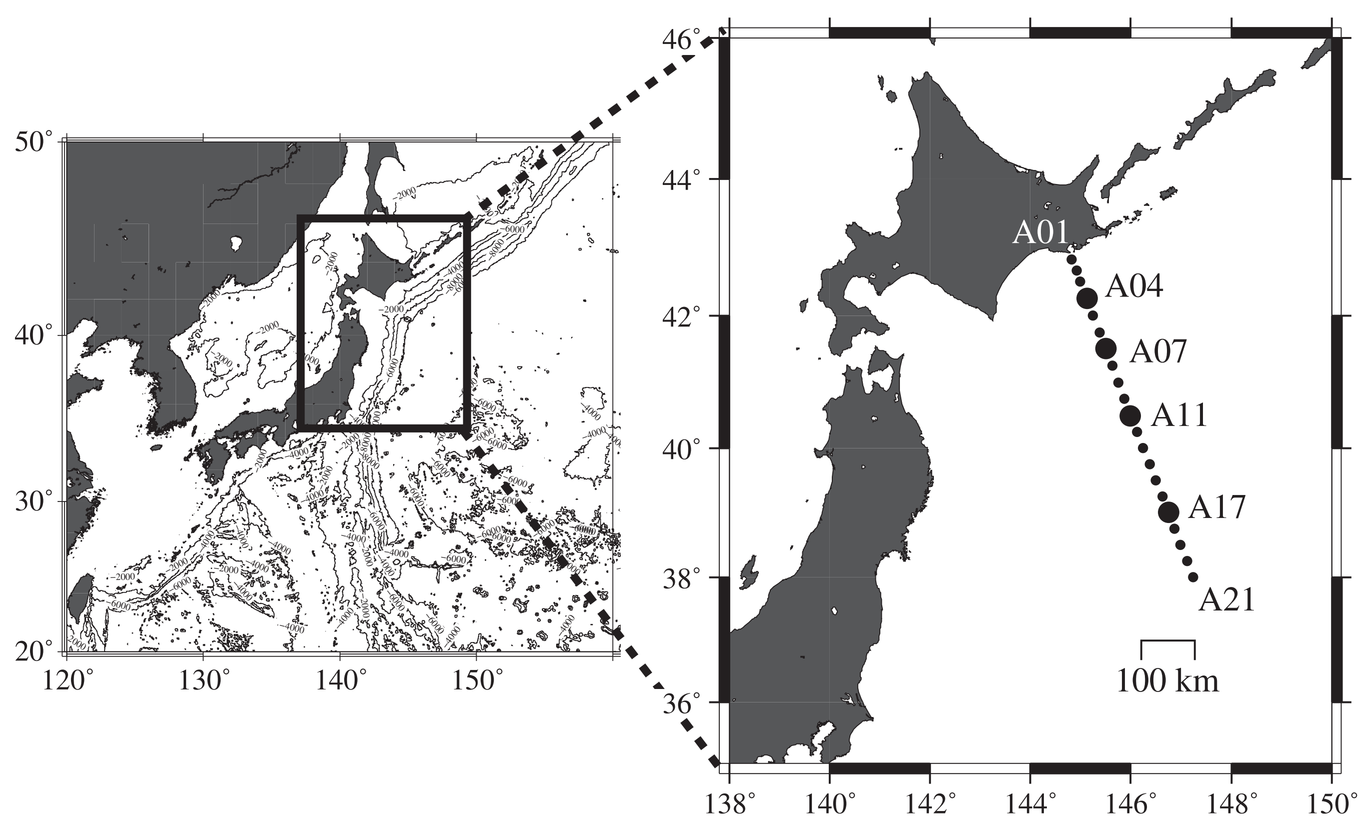

Fig. 1. Station locations along the A-line off the coast of southeastern Hokkaido, Japan. Large circles indicate four locations where dissolved N_2, Ar and O_2 were determined. Small circles indicate locations where seawater was sampled and a CTDO apparatus was mounted. Latitude–longitude coordinates for A01 and A21 are 42°50′N, 144°50′E and 38°00′N, 147°15′E, respectively.