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East-West Distribution of Nutrients and Dissolved Inorganic Carbon in the Northern North Pacific in Autumn

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Abstract: We measured nutrient and dissolved inorganic carbon (DIC) concentrations from west to east across the northern North Pacific Ocean from station K2 to Ocean Station Papa during September and October 2005. At 2000 m depth, silicate levels increased and dissolved oxygen levels decreased from west to east. This trend was attributed to seawater in the layer flowing from west to east in the northern North Pacific. Distributions of normalized (salinity = 33) nutrients and DIC showed the general trend of "west high, east low" (WHEL) in the surface layer. Normalized nitrate and DIC concentrations above 30 m depth ranged from 7 to 13 μmol kg^{-1} and from 2027 to 2045 μmol kg^{-1}, respectively. Seasonal drawdowns of nutrients and DIC from winter to autumn showed the WHEL trend, similar to previous studies. The ratio of silicate drawdown to nitrate + nitrite drawdown also showed the WHEL trend, which might result from longitudinal differences in the proportion of diatoms in the phytoplankton community in the northern North Pacific.

Keywords: Nutrient, dissolved inorganic carbon, northern North pacific.

1. INTRODUCTION

Studies of the carbon cycle have been conducted at time-series stations in the northeastern and northwestern North Pacific Ocean to estimate the strength of the biological pump. Ocean observations have been conducted at Ocean Station Papa (OSP; 50°N, 145°W) in the eastern subarctic Pacific since 1956 [1, 2]. Carbon and nutrient concentrations have been measured at station KNOT (44°N, 155°E) in the western subarctic Pacific since 1992 [3], and intensive time-series observations were conducted at station KNOT between 1998 and 2000 [4]. Since 2001, we have been conducting time-series observations at station K2 (47°N, 160°E) in the northwestern North Pacific [5-8]. As a result of these various studies, it became clear that seasonal net community production from winter to autumn in the Western Subarctic Gyre (37-61 gC m^{-2} [8-10]) was higher than that in the Alaska Gyre (26-35 gC m^{-2} [2]). Spring blooms, consisting mainly of diatoms, are known to occur only in the western part of the subarctic Pacific [11, 12]. Diatoms in this area, because of their large size and resultant high settling velocity, are suspected of playing a key role in transporting particulate organic carbon to the deep ocean [13-16].

In addition, sea surface measurements of CO_2 and nutrients from commercial vessels have been made between the eastern and western North Pacific since 1995 [17, 18]. These results also indicate that the strength of the biological pump in the western part of the northern North Pacific is higher than that in the eastern part. There have been many previous studies of the biological pump at each time-series station in the northern North Pacific, and the observations of sea surface CO_2 and nutrient levels were previously routinely conducted from east to west across the northern North Pacific. However, simultaneous hydrographical observations of CO_2 and nutrients from east to west across the northern North Pacific were never conducted during autumn when the drawdown of nutrients in the upper layer (approximately 100 m) is at an annual maximum [1, 8].

In September and October 2005 we conducted biogeochemical observations across the northern North Pacific from station K2 to OSP [19, 20]. In this paper, we present our vertical profiles of dissolved inorganic carbon (DIC) and nutrient concentrations and compare the strength of the biological pump from east to west across the northern North Pacific.

2. SAMPLING AND ANALYSIS

2.1. Sampling Locations

Observations were conducted during the cruise of R/V *Mirai* in September and October 2005 in the northern North Pacific (Fig. **1**). Samples were collected at stations K1 (51°N, 165°E), K2 (47°N, 160°E), EW1 (47°40N, 169°16E), EW2 (47°N, 175°E), EW3 (46°N, 180°E), EW4 (46°N, 175°W), EW7 (49°30N, 175°W), and OSP (50°N, 145°W). Stations K1 and K2 are located in the northern and central parts of the Western Subarctic Gyre, respectively. OSP is located in the Alaska Gyre.

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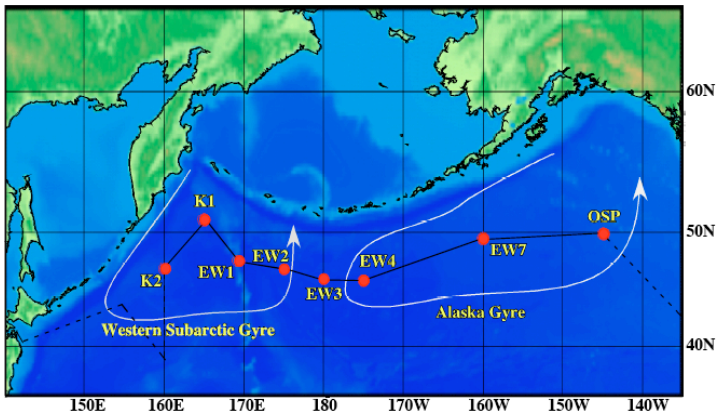

Fig. (1). Location of sampling stations and main ocean currents in the northern North Pacific Ocean. Gray lines with arrows indicate the subarctic gyres in the eastern and western regions [1].

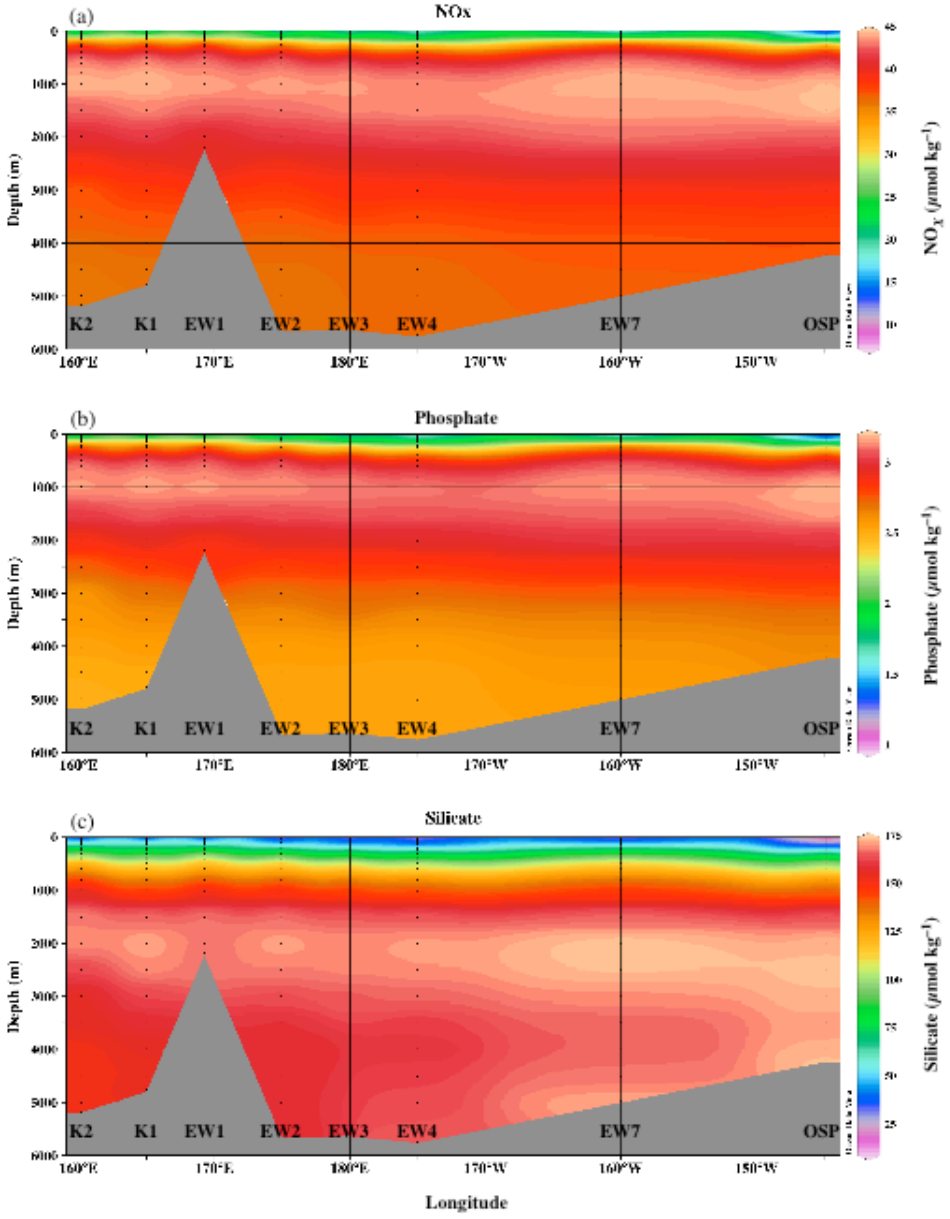

Fig. (2). Distributions of nitrate + nitrite (NO_X) (**a**), phosphate (**b**), and silicate (**c**) concentrations from surface to bottom in the northern North Pacific in September and October 2005. To illustrate east-west trends, data are arranged from west to east ignoring differences in latitude. Dots and gray areas indicate sampling depths and the sea floor, respectively.

2.2. Water Sampling and Sample Analysis

Seawater samples were collected from the surface to the bottom layer by Niskin bottle samplers attached to a CTD (SBE 911plus, Sea-Bird Electronics Inc.).

Nutrient concentrations were determined by using a continuous flow analyzer (TRAACS 800 system, Bran+ Luebbe). The precision (1σ) of nutrient analysis was less than 0.3%. DIC was measured by coulometer (carbon dioxide coulometer Model 51012, UIC Inc.). The coulometer was calibrated using Dickson's certified reference material [21]. The precision (1σ) of DIC measurements was ±1.0 μmol kg^{-1}. Total alkalinity (TALK) was determined by potentiometric titration [22]. The precision (1σ) of TALK measurements was ±1.3 μmol kg^{-1}. Dissolved oxygen (DO) was analyzed by potentiometric titration [23]. The precision (1σ) of DO measurements was ±0.05 μmol kg^{-1}. Apparent oxygen utilization (AOU) was calculated as the difference between observed DO concentration and equilibrium concentration with the atmosphere at the measured temperature and salinity [24].

3. RESULTS AND DISCUSSION

3.1. Distributions of Nutrient, DIC, TALK, and DO from Surface to Bottom

Station EW1 is located above the Emperor Seamount Chain. The bottom depth at station EW1 is approximately 2200 m, whereas the bottom depth at the other stations range from 4200 to 5500 m (Fig. **2**). All physical and chemical data from all stations are included in the Supplementary Material.

Nitrate plus nitrite (NO_X) and phosphate showed maximum concentrations around 1000 m depth across the northern North Pacific (Fig. **2a** and **b**). We attributed the NO_X and phosphate maxima to decomposition of sinking particulate organic matter (POM). However, silicate

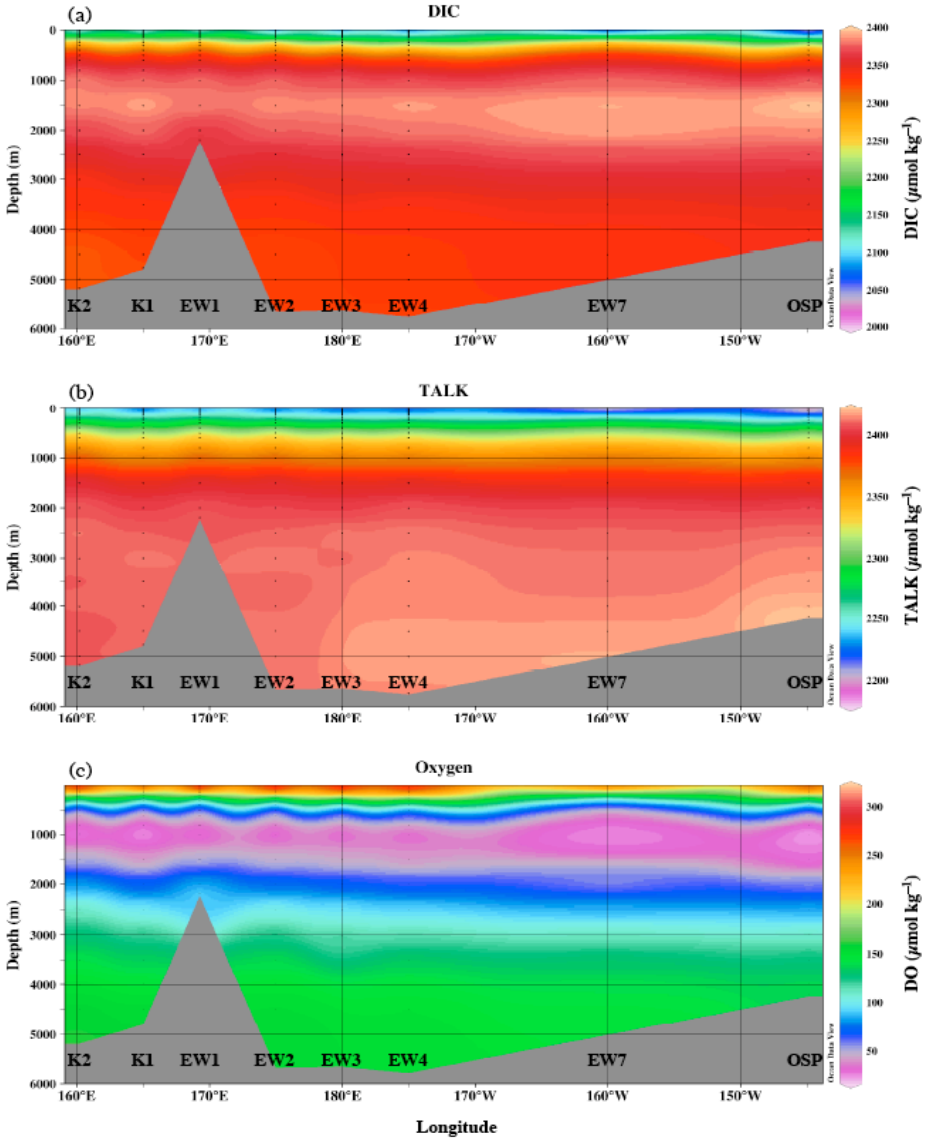

Fig. (3). Distribution of DIC (**a**), TALK (**b**), and DO (**c**) concentration from surface to bottom in the northern North Pacific in September and October 2005. To illustrate east-west trends, data are arranged from west to east ignoring the differences in latitude. Dots and gray areas indicate sampling depths and the sea floor, respectively.

concentrations showed maxima from 2000 to 2500 m depth across the northern North Pacific and also near the bottom at stations EW7 and OSP (Fig. **2c**). The silicate maximum in the intermediate layers was attributed to dissolution of sinking opal. We attributed the difference between the depth of the silicate maximum and that of the other nutrients to the different rates of decomposition for opal and other POM. The silicate maximum near the bottom at stations EW7 and OSP could be caused by dissolution of the opals from the sediment.

Maximum DIC concentrations were found at approximately 1500 m depth across the northern North Pacific (Fig. **3a**). The DIC maximum is attributed to decomposition of sinking POM, similar to NO_X and phosphate. TALK reached the maximum levels near the bottom at stations EW7 and OSP (Fig. **3b**). These TALK maxima might be caused by the dissolution of carbonates from sediment. Minimum DO concentrations were measured at approximately 1000 m depth (Fig. **3c**). We attribute the DO minimum to the consumption of DO accompanying decomposition of the sinking POM. Therefore, the DO minimum layer coincided with the depth of maximum NO_X and phosphate concentrations (Figs. **2a, 2b,** and **3c**).

At 2000 m depth, silicate levels increased and DO levels decreased from west to east (Figs. **2c** and **3c**). There is significant negative correlation between silicate and DO at 2000 m ($r = 0.89$, $P < 0.003$). We attribute this trend to the fact that seawater at this depth in the eastern region is older than that in the western region because seawater in this layer flows from west to east in the northern North Pacific [25].

3.2. Distributions of Physical Parameters in the Surface Layer (0-200 m)

Potential temperature above 200 m depth tended to increase slightly from west to east (Fig. **4a**). The potential temperature above 30 m depth was 10.3-11.8 °C. There was clear temperature minimum layer around 100 m depth in the western part of the study area, and this layer became less distinct from west to east. At OSP, the temperature minimum layer was unclear and potential temperature declined with increasing depth.

Salinity above 50 m depth deceased slightly from west (salinity = 32.9) to east (32.4), and was lowest in the study area at station EW7 (Fig. **4b**). At 150 m, salinity at station EW7 (33.64) was higher than at the other stations (<33.48).

The distribution of potential density above 30 m depth showed to a trend of higher values in the west and lower in the east ("west high, east low" [WHEL]; Fig. **4c**). The surface mixed layer depth, defined by a criterion of a 0.125 kg m^{-3} potential density difference from that of the surface [26], tended to increase from west (about 39 m) to east (50 m) in the study area (Fig. **4c**). At 100 m depth, the potential density at OSP (25.70) was substantially lower than those at the other stations (26.14-26.58).

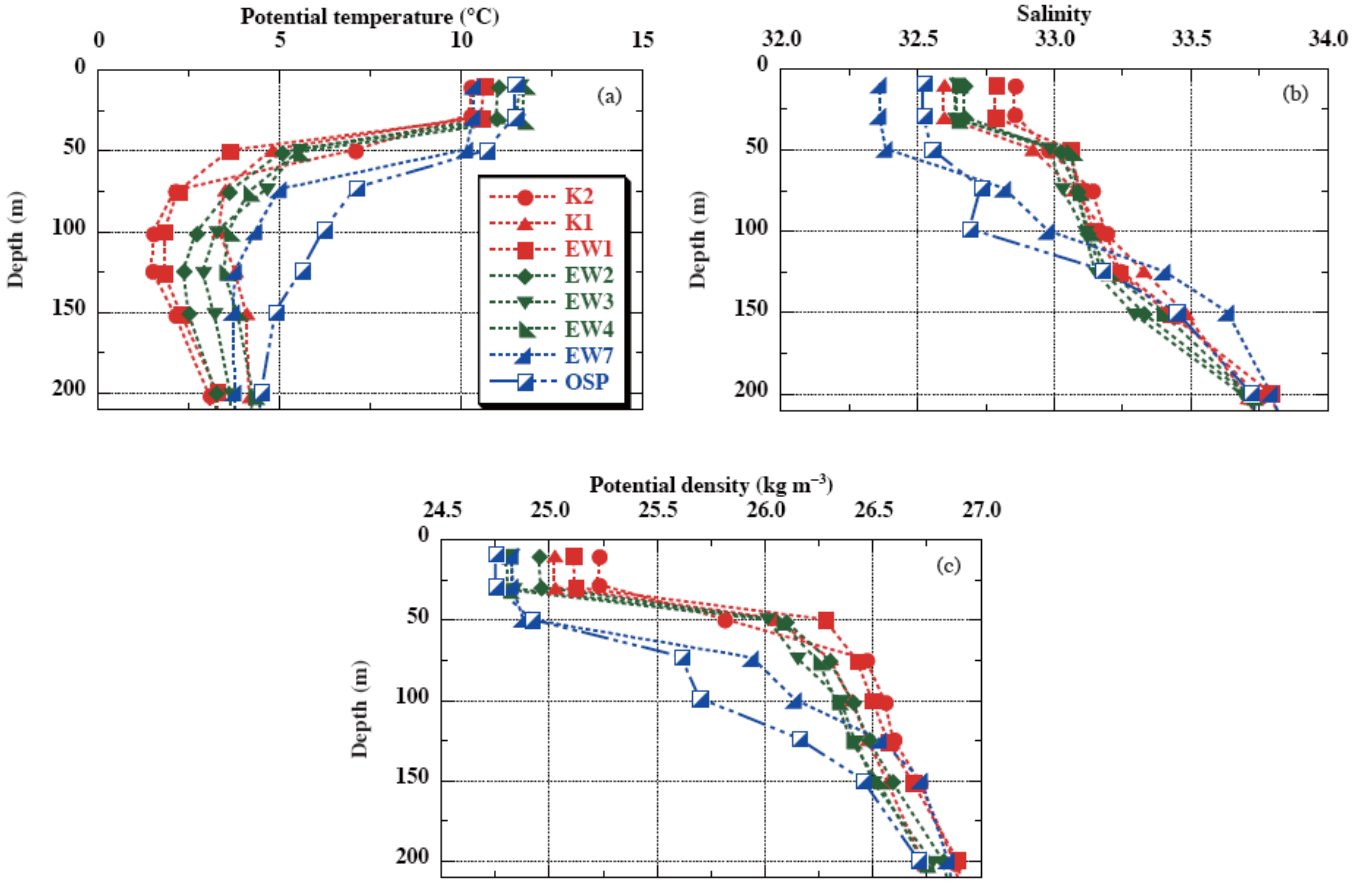

Fig. (4). Vertical distribution of potential temperature (**a**), salinity (**b**), and potential density (**c**) in the surface layer (10-200 m) at all stations, September-October 2005.

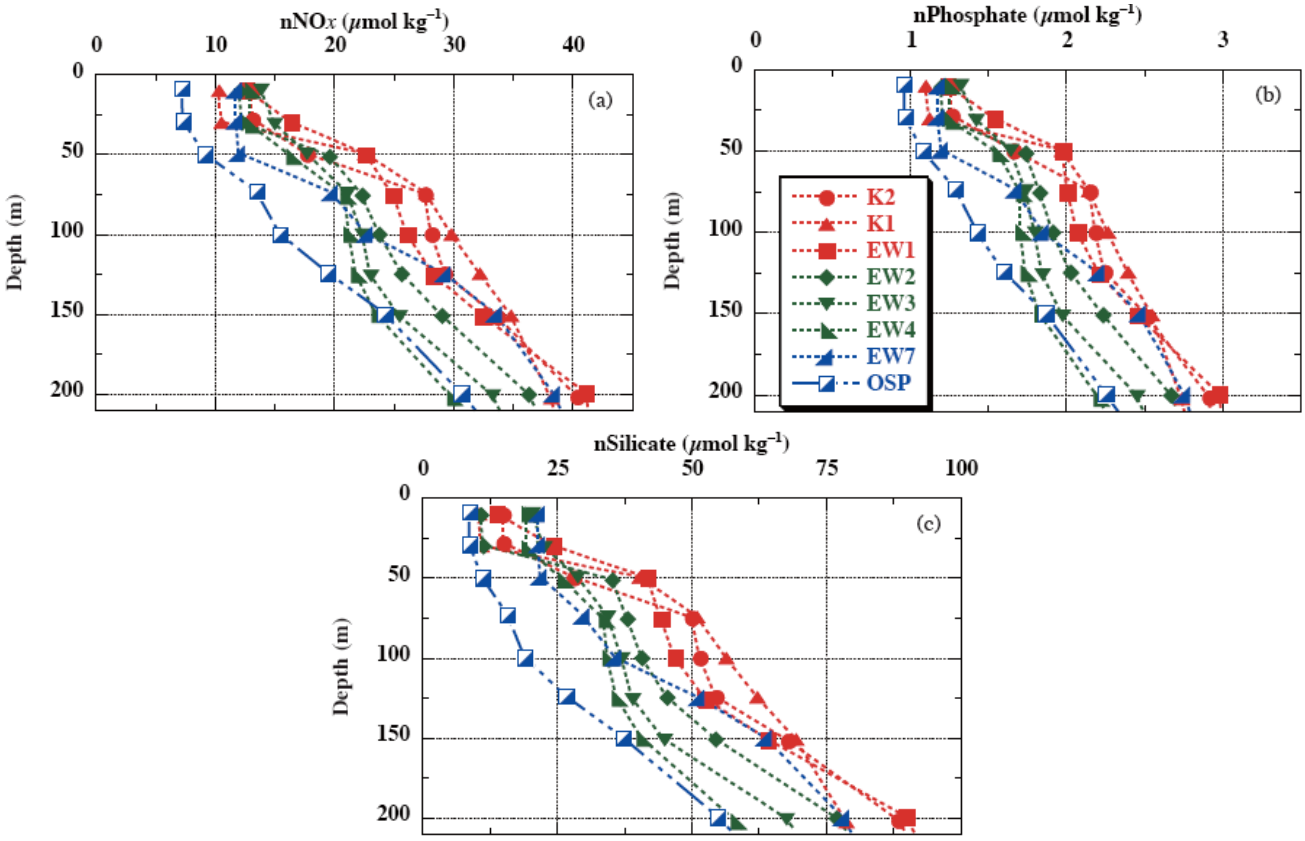

Fig. (5). Vertical distribution of normalized (to salinity of 33) NO_X (nNO_X) (**a**), phosphate (nPhosphate) (**b**), and silicate (nSilicate) (**c**) in the surface layer (10-200 m) at all stations, September-October 2005.

3.3. Distribution of Nutrient, DIC, TALK, DO, and AOU in the Surface Layer

Nutrients (NO_X, phosphate, and silicate), DIC, and TALK were normalized to a constant salinity of 33 to remove the effects of evaporation and precipitation. The distribution of normalized NO_X (nNO_X) showed the general trend of WHEL above 200 m depth (Fig. **5a**). nNO_X above 30 m depth ranged from 7 to 13 μmol kg^{-1} (Fig. **5a**). At 150 m depth, nNO_X concentrations at stations EW3, EW4, and OSP (approximately 24 μmol kg^{-1}) were lower than those at the other stations (approximately 33 μmol kg^{-1}). The other nutrients showed similar trends (Figs. **5b** and **c**).

Distribution of normalized DIC (nDIC) generally followed the WHEL trend above 200 m depth (Fig. **6a**), similar to nutrients. nDIC above 30 m depth ranged from 2027 to 2045 μmol kg^{-1} (Fig. **6a**). Normalized TALK (nTALK) showed vertically constant profiles at all stations (Fig. **6b**).

Above 100 m depth, DO concentrations showed little variation with depth or between stations (Fig. **7a**). Below 100 m depth, DO decreased with increasing depth and the differences in DO concentrations between stations were larger than those above 100 m depth. Values for AOU above 50 m depth were usually negative (*i.e.*, water was

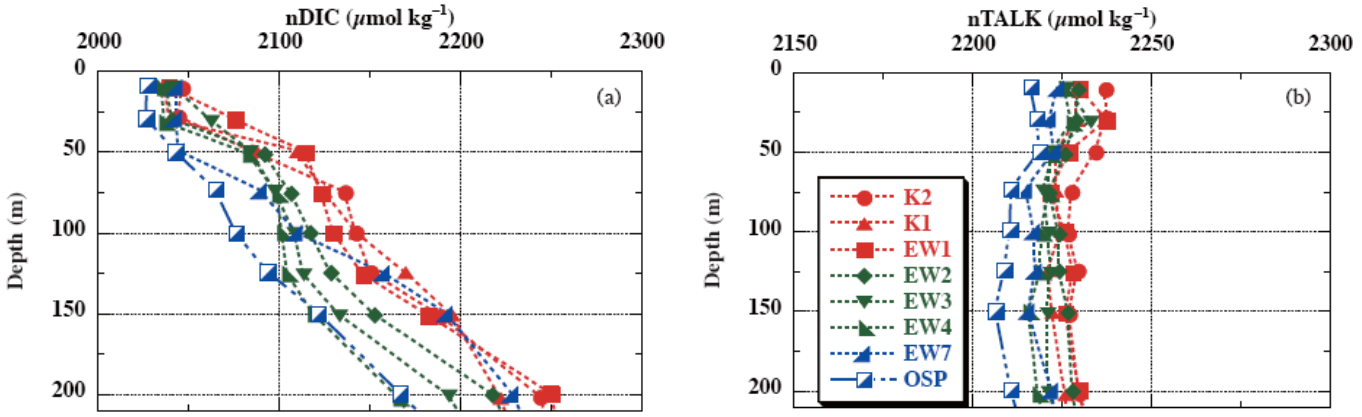

Fig. (6). Vertical distribution of normalized (to salinity of 33) DIC (nDIC) (**a**) and TALK (nTALK) (**b**) in the surface layer (10-200 m) at the all stations, September-October 2005.

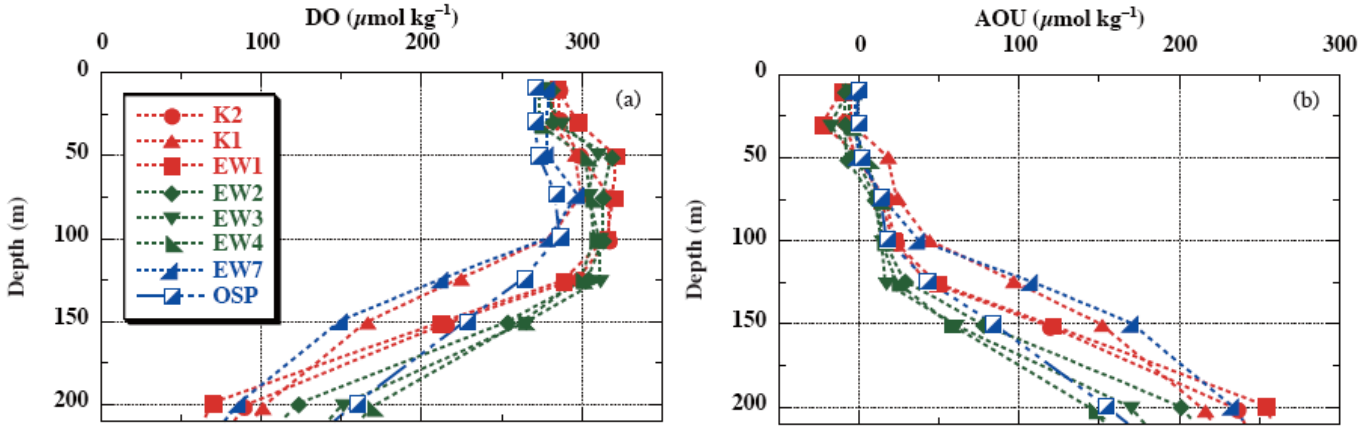

Fig. (7). Vertical distribution of dissolved oxygen (DO) (**a**) and apparent oxygen utilization (AOU) (**b**) in the surface layer (10-200 m) at all stations, September-October 2005.

supersaturated with respect to atmospheric oxygen; Fig. **7b**). It is possible that these negative AOU values resulted from photosynthesis by phytoplankton. AOU increased with depth. At most stations, the rates of AOU increase with depth were different above and below 100 m depth. The consumption of oxygen during the remineralization of POM was apparent below 100 m depth.

3.4. East-West Distributions of Seasonal Drawdown of DIC and Nutrients

From liner regression analysis of nDIC, normalized nutrient concentrations, and AOU in the depth range of 100-200 m at all stations, we estimated the average regeneration ratio of C : N : Si : P : O_2 at (116 ± 4) : (16.2 ± 0.2) : (44.7 ± 0.8) : 1 : (-172 ± 17) in the northern North Pacific. The concentrations of nDIC or normalized nutrients in the surface mixed layer in winter (A_W) were estimated by subtracting the regenerated fraction of each component from its concentration at 100 m (A_{100}) in autumn as follows [27]:

$$A_W = A_{100} - R_{i/O2}\Delta AOU_{100}, \quad (1)$$

where $R_{i/O2}$ is the regeneration ratio for each component (i) and ΔAOU_{100} is the difference between AOU at 100 m depth in winter and the observed AOU. AOU at 100 m in winter was defined as 15 μmol kg^{-1} which is the average value in early April in the Western Subarctic Gyre and at OSP [8, 28].

The seasonal drawdown of DIC or nutrient concentrations in the surface mixed layer (ΔA) was calculated from the following equation:

$$\Delta A = \int_0^{100} (A_W - A_Z)dz \quad (2)$$

where A_Z represents the nDIC or normalized nutrient concentration in each layer above 100 m depth. ΔA represents the column-integrated drawdown of DIC or nutrients due to biological activity and/or air-sea CO_2 exchange in the surface mixed layer from winter to autumn. Seasonal drawdowns were integrated from sea surface to 100 m depth. A depth of 100 m was chosen for five reasons: 1) it was close to the temperature minimum layer at most stations (Fig. **4a**), 2) DO above 100 m depth was almost constant with depth and at all stations (Fig. **7a**), 3) it was the depth reached by the mixed layer in winter [1, 8], 4) it was the depth at which the concentrations of DIC and nutrients were close to those at the sea surface in late winter [8, 29], and 5) decreases in DIC and nutrients from spring to autumn occurred only above 100 m [8, 29]. Furthermore, column-integrated drawdowns estimated from measurements taken during this season (September and October) were considered comparable to the annual drawdowns [1, 8].

The trend in seasonal drawdown of nDIC and normalized nutrients (ΔC, ΔN, ΔP, and ΔSi) above 100 m depth from winter to autumn was generally WHEL (Figs. **8a-d**). This trend is comparable with the results of previous studies [9, 17]. However, seasonal drawdowns at station EW1 were smaller than those at the neighboring stations. It is possible that the small seasonal drawdowns at station EW1 resulted from the slightly higher nDIC and normalized nutrients levels at 30-50 m depth at this station compared with those at the other stations (Figs. **5** and **6a**). At station K2 and OSP, seasonal net community production from winter to autumn in the surface layer as estimated from ΔN and the Redfield ratio (C : N = 106 : 16 [30]) was 57 and 36 gC m^{-2}, respectively. These results are comparable to previous values [2, 8-10].

Ratios of the seasonal drawdown of normalized silicate to that of nNO_X (ΔSi/ΔN) showed the WHEL trend (Fig. **8e**). Diatoms have high Si/N ratios (1.1-3.0) [31-33], and the distribution of diatoms in the northern North Pacific follows the WHEL trend [29, 34]. In addition, dissolved iron concentrations in the surface layer in the northwestern North Pacific were nearly twice those in the northeastern North Pacific [35, 36]. Dissolved cobalt and nickel—which, like iron, are micronutrients [37]—were also found at higher concentrations in the western part of the northern North Pacific compared to the eastern part [38, 39]. Consequently, we suspected that the horizontal variations in trace metal concentrations influenced the horizontal variations in phytoplankton species composition and, further, in the strengths of the biological pump in the northern North Pacific Ocean.

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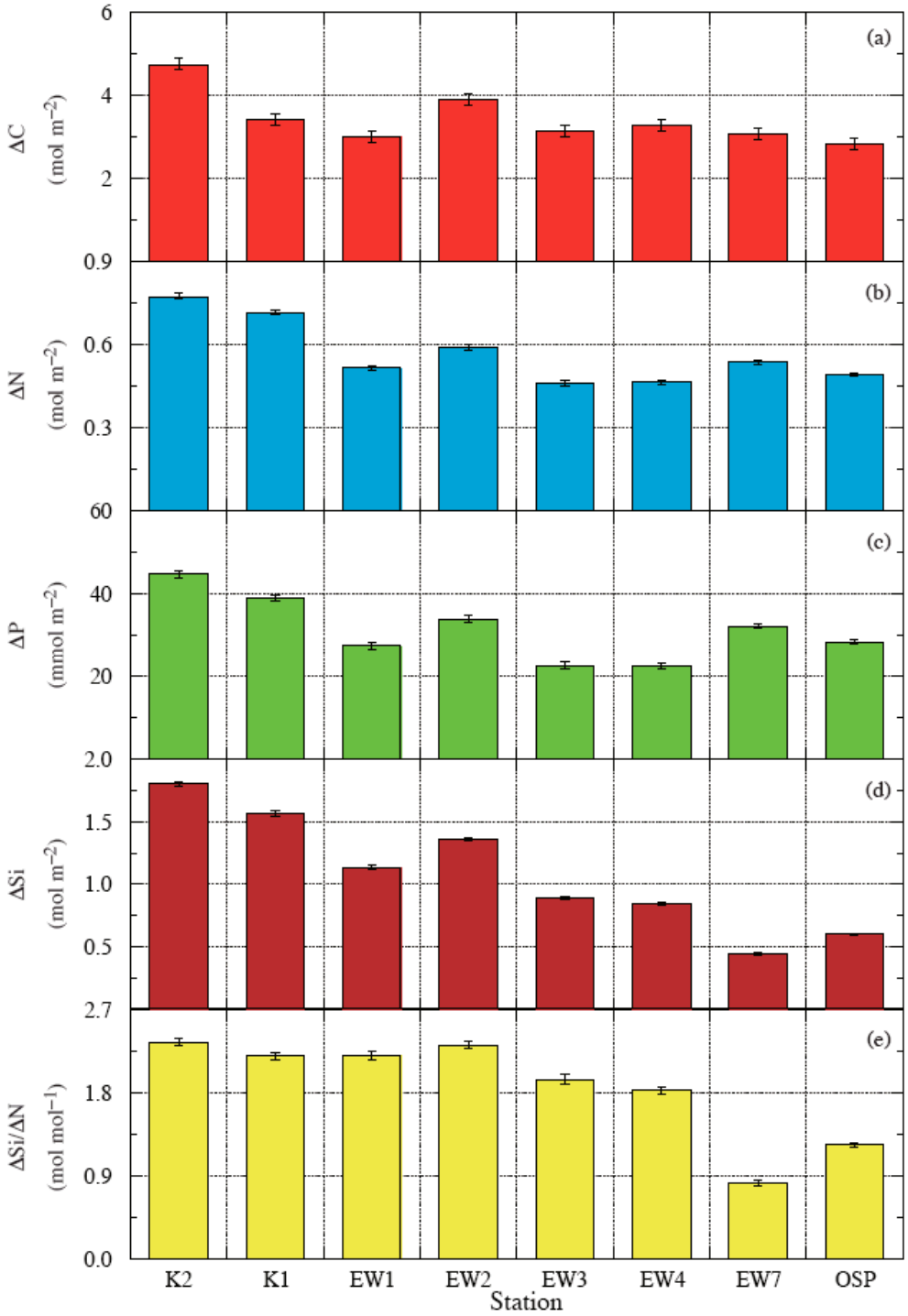

Fig. (8). East-west distributions of seasonal drawdown of DIC and nutrients (ΔC, ΔN, ΔP, and ΔSi) (**a-d**) and ΔSi/ΔN ratio (**e**) above 100 m depth from winter to autumn in the northern North Pacific, September-October 2005. The error bars indicate the precision (1σ) of each measurement.

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SUPPLEMENTARY MATERIAL

Dataset of physical and chemical parameters at stations K2, K1, EW1, EW2, EW3, EW4, EW7, and OSP in September and October 2005. The data have not been corrected for systematic errors among stations.

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