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Distributions of dissolved inorganic carbon and total alkalinity in the Western Arctic Ocean

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Abstract The third Chinese National Arctic Research Expedition (3rd CHINARE-Arctic in 2008) was carried out from July to September 2008. During the survey, numerous sea water samples were taken for CO_2 parameter measurement (including total alkalinity TA and total dissolved inorganic carbon DIC).The distribution of CO_2 parameters in the Western Arctic Ocean was determined, and the controlling factors are addressed. The ranges of summertime TA, normalized TA (nTA), DIC and normalized DIC (nDIC) in the surface seawater were 1 757–2 229 μmol·kg^{-1}, 2 383–2 722 μmol·kg^{-1}, 1 681–2 034 μmol·kg^{-1}, 2 119–2 600 μmol·kg^{-1}, respectively. Because of dilution from ice meltwater, the surface TA and DIC concentrations were relatively low. TA in the upper 100 m to the south of 78°N had good correlation with salinity, showing a conservative behavior. The distribution followed the seawater-river mixing line at salinity >30, then followed the seawater mixing line (diluted by river water to salinity = 30) with the ice meltwater. The DIC distribution in the Chukchi Sea was dominated by biological production or respiration of organic matter, whereas conservative mixing dominated the mixed layer TA distribution in the ice-free Canada Basin.

Keywords **Dissolved inorganic carbon, total alkalinity, Western Arctic Ocean, distribution, controlling factors**

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0 Introduction

The Arctic is one of the most sensitive regions to global climate change. Therefore, it has attracted increased attention from global warming researchers worldwide. The Arctic Ocean is experiencing serious global change-induced rapid variations, such as large summertime temperature rises, rapidly thinning and retreating sea ice, and modifications to biology and ecosystem structure. These changes and feedbacks would have far-reaching impacts on the ocean carbon cycle, and significance for the global carbon cycle and the balance of CO_2 sources and sinks.

There have been many studies on the Arctic Ocean carbon cycle. Bates et al.[1] surveyed the spatio-temporal variability of dissolved inorganic carbon (DIC) in the Western Arctic Ocean, then determined rates of net community production (NCP) using the seasonal drawdown of DIC. Kaltin et al.[2] calculated the uptake of atmospheric CO_2 in the upper 100 m, from the time the water entered the Bering Sea shelf until it reached the northern Chukchi Sea shelf slope (∼1 a), at about 86±22 g·C·m^{-2}. They found that cooling and biology were the main

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effects on the partial pressure of CO_2 (pCO_2), whereas denitrification, $CaCO_3$ dissolution and freshening were almost negligible. For the trend of carbon sinks under sea ice melt in the Arctic Ocean, Bates et al.[3] indicated that ice extent and volume had decreased over the last few decades. Consequently, the CO_2 sink had tripled over the last three decades (24 Tg·C·a^{-1} to 66 Tg·C·a^{-1}). This enhanced air-sea CO_2 flux by about 28% per decade, because of sea ice loss and subsequent sea ice melt. Various studies[1−6] have suggested that the carbon cycle in the ocean was undergoing severe stress because of rapid changes, and that there will be numerous potential responses and feedbacks.

The CO_2 system in the Arctic Ocean and adjacent seas was sampled during the first (1999) and second (2003) Chinese National Arctic Research Expeditions, and related research has made progress[7−9]. However, most previous studies focused on pCO_2, and information about other parameters in the CO_2 system are poorly known. Based on the third (2008) Chinese National Arctic Research Expedition of the China Program for International Polar Year 2007–2008, the distribution and controlling factors of two important parameters of the CO_2 system, total alkalinity (TA) and dissolved inorganic carbon (DIC), are discussed in detail as follows.

1 Experiment and Instrumentation

Seawater samples of DIC and TA were collected by R/V *XUE LONG* icebreaker in the Arctic Ocean, from July through September 2008. During the survey, 86 hydrocast stations were deployed over the shelf and slope of the Chukchi Sea and Canada Basin in the central Arctic Ocean (Figure 1). At each station, seawater samples were drawn from a 24–bottle Niskin–Rosette water sampler, with a Seabird 911 plus CTD sensor providing physical data. Samples for the CO_2 system were collected according to the "Guide to Best Practices for Ocean CO_2 Measurements"[10], or the version translated into Chinese by Chen and Gao[11]. Some DIC and TA samples were analyzed on board; the rest were preserved and analyzed in the land lab. For DIC determination, a 0.5 ml water sample was acidified, and subsequent generated CO_2 was analyzed by a Li–Cor 6262, with precision ±2 μmol·kg^{-1}. TA samples were analyzed by Gran titration on a 25 ml water sample, with precision ±2 μmol·kg^{-1}[12−13]. Certified reference materials from Dickson A G of Scripps Institution of Oceanography, USA, were used for calibration.

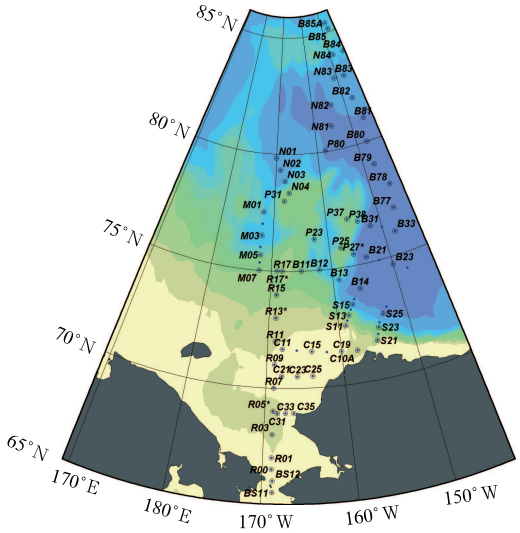

Figure 1 Station location map of the Western Arctic Ocean.

2 Results and Discussion

2.1 Surface TA and DIC distributions in the Western Arctic Ocean

Surface distributions of TA and DIC in the Western Arctic Ocean during the summer sampling cruise are shown in Figure 2. Surface DIC, nDIC, TA and nTA concentrations were 1 757–2 229 μmol·kg^{-1}, 2 383–2 722 μmol·kg^{-1}, 1 681–2 034 μmol·kg^{-1}, 2 119–2 600 μmol·kg^{-1}, respectively. Lowest TA and DIC values were found in the Canada Basin, around 75°N. After salinity normalization, this region had the highest values of nTA and nDIC. In contrast, the highest values of TA and DIC, and the lowest values of nTA and nDIC, were observed in the Bering Strait.

In the Chukchi Sea, TA concentrations were confined to a small range, decreasing northward, except for higher TA concentrations near the Bering Strait. The DIC distribution was similar to that of TA. After salinity was normalized to remove the impact of freshening, the distribution of nTA and nDIC changed, although their ranges were still small. The minimum nTA and nDIC values in the Bering Strait suggest that this region was less freshened by sea ice meltwater than other regions in the Western Arctic Ocean.

In the Canada Basin of the central Arctic Ocean,

TA and DIC were very low around 75°N, 155°W, attributable to strong freshening by ice melt water this area, which gradually spread to the surroundings. The ice edge was near 75°N in the Canada Basin during the survey, according to Arctic Ocean ice concentrations from the Advanced Microwave Scanning Radiometer

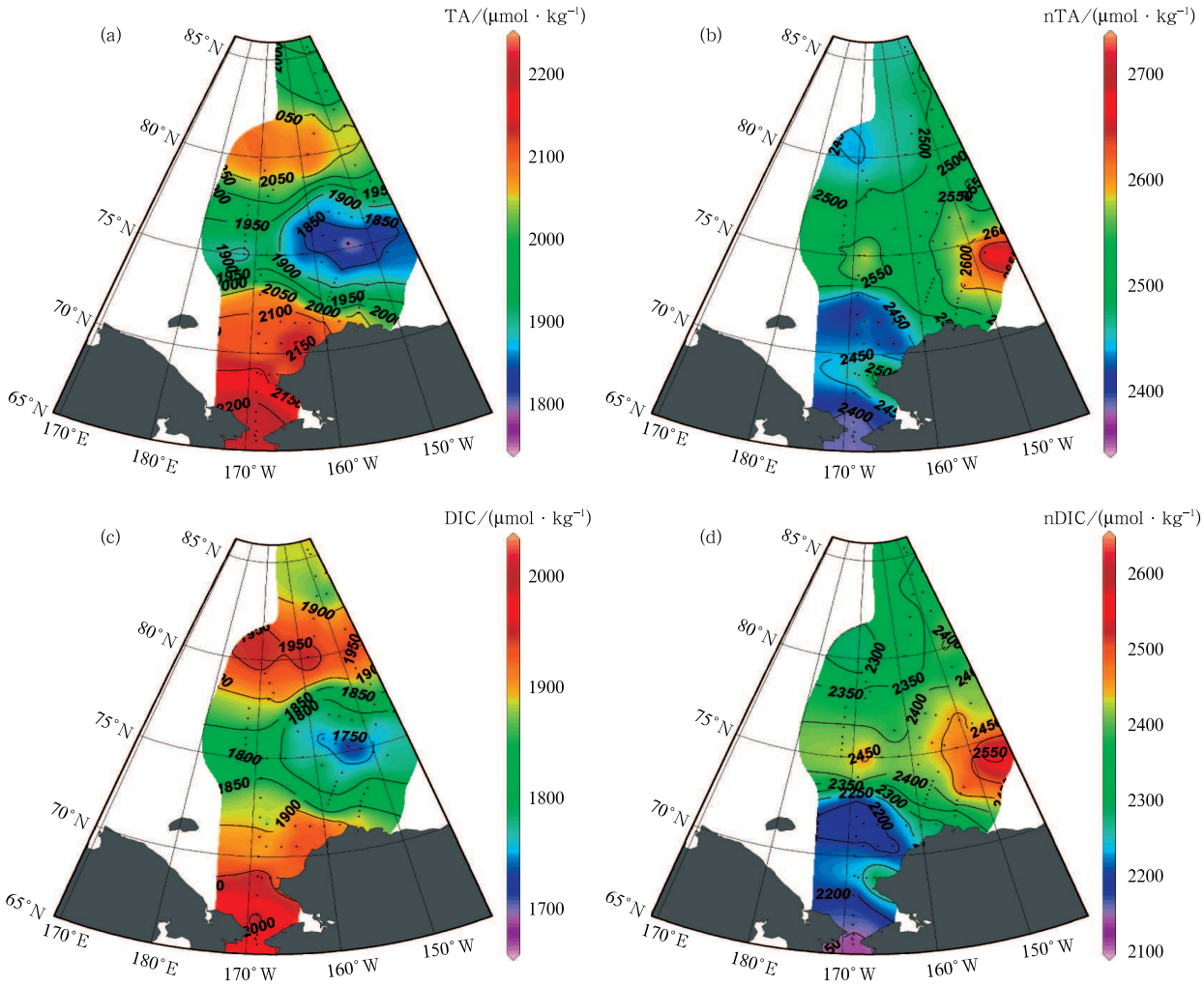

Figure 2 Surface TA (a); nTA (b); DIC (c); and nDIC (d) distributions in the Western Arctic Ocean.

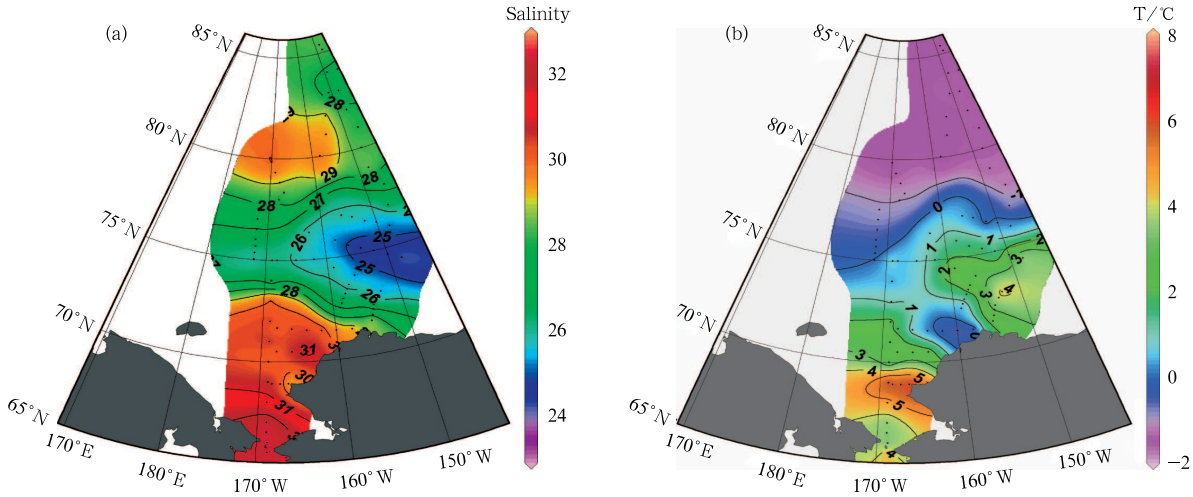

Figure 3 Surface (a) salinity, and (b) temperature distributions in the Western Arctic Ocean.

for Earth-Observing System (AMSR–E; http:// nsidc.org/ data/ docs/ daac/ae_si12_12km_tb_sea_ice_and_snow.gd.html). Sea ice melt is extremely pronounced in this area, accompanied by low salinity and high temperatures (Figure 3). In addition, this is consistent with our calculation of the largest fractional area of sea ice melt (unpublished data). Because of heavy sea ice coverage, water mass properties were nearly the same to the north of 78°N (Figure 3). Therefore, CO_2 species were not variable, and TA and DIC concentrations were within a small range.

2.2 Vertical distributions of TA and DIC in the Western Arctic Ocean

Figure 4 shows vertical distributions of TA and DIC along three typical sections in the Western Arctic Ocean (data from the upper 200 m). Stations C11, C13, C15, C17, C19 and C10A define section C3, across the Chukchi shelf; stations S21 to S26 define section S2, across the shelf and slope; stations B77 to B85B define section B, across the Canada Basin. Because of strong dilution of surface seawater, TA and DIC concentrations in the water column were the lowest. These concentrations in the shelf water column (about 50 m bottom depth) increased from top to bottom. In contrast, concentrations in the slope and basin water column increased sharply just below the surface, then increased more slowly in the subsurface layer. The highest DIC concentration was in the "upper halocline" water (100–200 m), probably resulting from a maximum of the net balance between mineralization of organic matters and biological photosynthesis. Below 200 m, TA concentrations were nearly unchanged, whereas DIC declined slightly because of the difference between Pacific and Atlantic source water (station S26 was chosen as representative in Figure 5, because the distribution trend in deep water was almost the same).

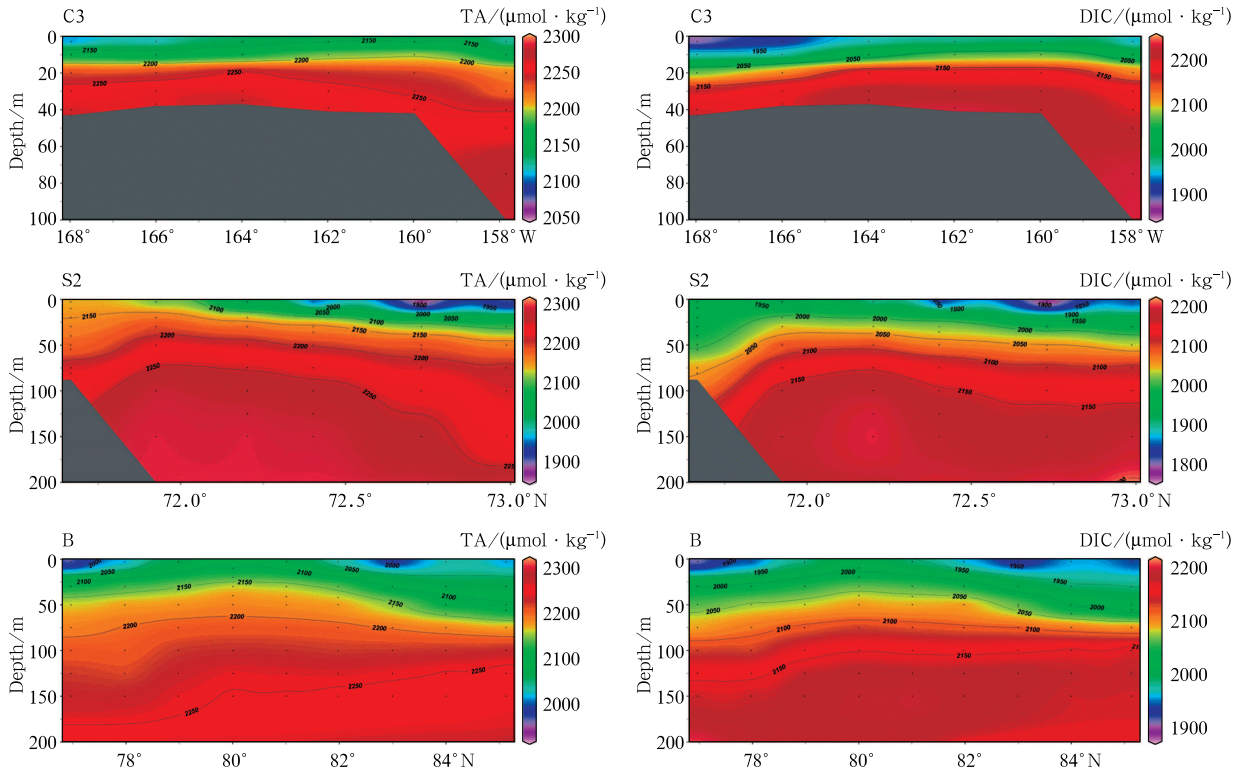

Figure 4 Distributions of TA and DIC along each transect.

2.3 Controlling factors of TA and DIC in the Western Arctic Ocean

Generally, TA, which is relatively conservative in world oceans, is hardly affected by biological activity. It is mainly influenced by evaporation or precipitation (or, in polar regions, by sea ice formation or melting); thus, there is a constant ratio between TA and salinity. TA

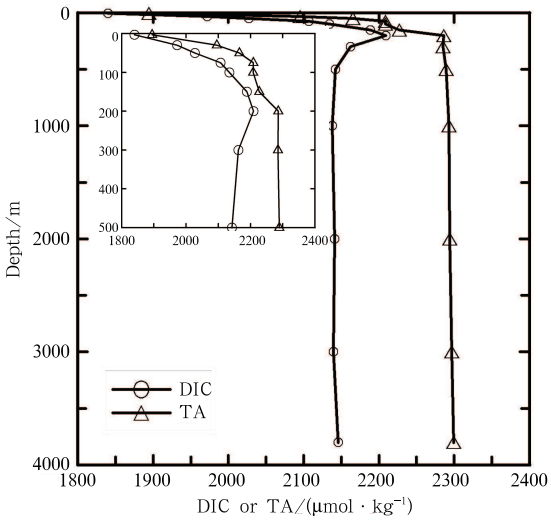

Figure 5 TA and DIC profiles at station S26 (upper 500 m distributions are shown in figure inset).

is also affected by water mass mixing, calcium carbonate precipitation or dissolution, denitrification, and other processes. The processes affecting DIC include organic matter production or degradation, evaporation or precipitation, calcium carbonate precipitation or dissolution, water mass mixing, air-sea CO_2 gas exchange, and others.

To further expose the controls on TA and DIC in the Western Arctic Ocean, we plot them versus salinity for the shelf and the slope, and in the Canada Basin (Figure 6). Since TA and DIC concentrations in deep water are constant throughout the year, and the surface ocean has the most active biological production, we examine data from the upper 100 m (including the mixed layer, 0–50 m, and the halocline, 50–100 m).

Seawater is diluted by river runoff and ice melt water as it flows through the ocean margins and basins. Figure 6 shows that the distribution of TA in the Western Arctic Ocean has a clearly conservative behavior, largely following two mixing lines converging around salinity = 30. At salinity > 30, the seawater is mainly mixing with river runoff. At salinity < 30, seawater modified by river runoff begins mixing with ice melt water, partly following the seawater–ice melt theoretical mixing line, and partly indicative of complicated three end-member mixing. In contrast, the DIC distribution is not only impacted by three end-member mixing, but also by a strong biological effect and air-sea CO_2 exchange. This results in a relatively complex relationship with salinity. DIC data from below the theoretical mixing line reflect DIC removal from the effects of biological production, and data above that line reflect DIC regeneration from degradation of organic matter. At the bottom of the upper halocline (primarily salinity > 33), the DIC distribution is dominated by the respiration of organic matter. In the Canada Basin mixed layer (mainly, the upper 20 m, with salinity < 28), the DIC distribution follows a theoretical mixing line, suggesting that the major control is conservative mixing. The net primary production rate of the

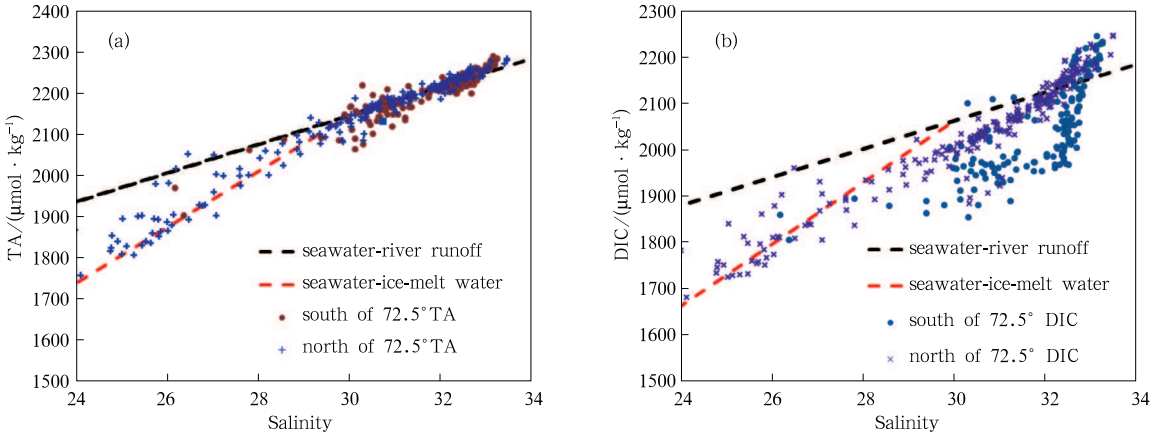

Figure 6 TA (a), and DIC (b) correlation with salinity in the Western Arctic Ocean. Data from 0 to 100 m are divided into south of 72.5°N (mostly marginal seas), and north of 72.5°N (mostly basin areas). Black dashed line is the theoretical mixing line of seawater and river runoff. Red dashed line is the theoretical mixing line of seawater (diluted by river runoff to salinity = 30) and ice meltwater. According to reference[14], TA and DIC of seawater end-member are 2 257.9 μmol·kg^{-1} and 2 161.4 μmol·kg^{-1}, respectively; TA and DIC of river runoff end-member are 1 100 μmol·kg^{-1} and 1 150 μmol·kg^{-1}; TA and DIC of ice melt end-member are 450 μmol·kg^{-1} and 400 μmol·kg^{-1}.

Chukchi Sea is much greater than in the Canada Basin; therefore, DIC biological removal is more pronounced in the marginal seas, consistent with previous studies[6,15−16]. Using data from the same sampling cruise, Cai et al.[14] reported that the net primary production rate in the marginal seas was 114 $mmol \cdot m^{-2} \cdot d^{-1}$, whereas in ice-free areas of the Canada Basin, it was only 1.88 $mmol \cdot m^{-2} \cdot d^{-1}$. The reason for the greater CO_2 in the ice-free Canada Basin was that stratification in the shallow mixed layer (less than 20 m) caused rapid equilibration with atmospheric CO_2 over a short time. However, the increase of CO_2 concentration from rapid atmospheric CO_2 invasion was negligible for the increase of DIC concentration in seawater, because CO_2 concentration only accounts for about 1% of DIC content. Thus, the DIC distribution of the mixed layer in the ice-free Canada Basin is dominated by conservative mixing of seawater and ice melt water.

3 Conclusion

Two important parameters of the CO_2 system, total alkalinity and dissolved inorganic carbon, were widely observed in the Western Arctic Ocean during the third Chinese National Arctic Research Expedition. The present study of these parameters enhances our knowledge of the CO_2 system in this ocean region. The TA and DIC concentrations in surface seawater to the south of 78°N in this region were generally low, because of dilution by ice melt water. In the Canada Basin of the central Arctic Ocean, very low surface water concentrations of TA and DIC were observed around 75°N, 155°W. This area coincided with the ice edge, where sea ice melt is extreme. However, because of heavy sea ice coverage and water mass homogeneity, surface water concentrations of TA and DIC to the north of 78°N were restricted to a small range. The TA distribution in the water column of the Western Arctic Ocean south of 78°N showed conservative behavior. In the Chukchi Sea, the DIC distribution was dominated by organic matter production or degradation. In the mixed layer of the ice-free Canada Basin, the dominant control on the DIC distribution is conservative mixing. This study is useful to further investigation of the carbon cycle in the Arctic Ocean. It will benefit understanding of the CO_2 system in the ocean, and the response and feedback of the Arctic Ocean to climate change.

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