

Biogeochemical and physical properties influencing the nutrient reservoirs of subsurface water in the changing Canada Basin

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Abstract

The Canada Basin is the largest basin in the Arctic Ocean. Its unique physical features have the highest concentration of nutrients being found in the subsurface layer, referred to as the subsurface nutrient maximum layer (SNM). Under climate change in the Arctic, the SNM is an essential material base for primary productivity. However, long-term trends of nutrient variations and dominant factors related to nutrient levels in the SNM are still unclear. In this study, we analyzed the SNM variations and main influencing factors of the Canada Basin based on the Global Ocean Data Analysis Project Version 2 between 1990 and 2015 and the Chinese Arctic Research Expedition between 2010 and 2016. We found that the nutrient concentrations in the SNM were relatively stable for decades [average concentrations of nitrate, phosphate, and silicate were $(13.6 \pm 2.4) \mu\text{mol/L}$, $(1.8 \pm 0.2) \mu\text{mol/L}$, and $(31.5 \pm 5.7) \mu\text{mol/L}$, respectively]. Nutrient reservoirs were dominated by physical processes. Inflow and outflow water of the SNM contributed about 60.4% and -50.2% to the nutrient stocks, respectively, while particle deposition and remineralization in the Canada Basin contributed approximately one-third to the nutrient stocks. Nitrogen fixation and denitrification in the Canada Basin had no substantial impact on nutrient stocks. The overall stabilization of the SNM over the past few decades implied that the SNM would not substantially affect short term primary productivity. Understanding the long-term trends and dominant factors of reservoirs in the SNM will provide useful insights into the changing Canada Basin ecosystem.

Key words: subsurface nutrients maximum layer, Canada Basin, biogeochemical cycles, Arctic climate changes

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1 Introduction

The subsurface nutrients maximum layer (SNM) present in global oceans is typically deeper than 500 m (Chen et al., 2001; Karl et al., 2001; Karstensen and Quadfasel, 2002; Lavin et al., 2003); however, the SNM of the Canada Basin is usually shallower than 200 m (Jin et al., 2004). This shallower, nutrient-rich layer makes the upward supply of nutrients more accessible, indicating potential material bases for primary production in the Canada Basin (Moore et al., 1983; Qi et al., 2017). However, in the Canada Basin, the perennial stratification between the upper layer and SNM hampers the nutrient supply to the phytoplankton, making the SNM a relatively stable reservoir of nutrients (Coachman and Aagaard, 1974). Recently, the SNM in the Canada Basin has been increasingly disturbed due to the dramatic retreat of sea ice, causing an upward supply of nutrients that has become more accessible to the phytoplankton and thereby promoting primary production (Stroeve et al., 2012; Lewis et al., 2020). The Canada Basin surface water is nutrient depleted (especially in nitrates) (Tremblay et al., 2008), but once the upward supply to the SNM increases, it will ultimately promote primary production and have notable effects on the biogeochemical cycle in the Canada

Basin (Ardyna and Arrigo, 2020).

The Canada Basin is the only stock of SNM in the Arctic Ocean (Fig. 1a) (Jin et al., 2004; McLaughlin and Carmack, 2010), and it is generally accepted that the inflow water of the SNM is mainly composed of Pacific Winter Water (PWW) and Remnant Winter Water (RWW). Studies have been primarily focused on PWW, as it is the main component of SNM and is rich in nutrients (Simpson et al., 2008; Brown et al., 2016). The PWW from the Chukchi Shelf to the Canada Basin has three primary pathways (Fig. 1b)—(1) branch flowing northwest through Herald Canyon (Mathis et al., 2007; Pickart et al., 2010); (2) branch through the Central Channel; (3) branch northward along the Alaskan coast (Itoh et al., 2013; Brugler et al., 2014). Most PWW eventually converges in the Barrow Canyon and enters the Canada Basin, with a mean flux of $\sim 0.35 \times 10^6 \text{ m}^3/\text{s}$ (Weingartner et al., 2005; Corlett and Pickart, 2017). Mordy et al. (2020) detected high nitrate concentrations of $\sim 24 \mu\text{mol/L}$ in winter water masses near Barrow Canyon, suggesting that PWW may substantially contribute to nutrient reservoirs in the SNM.

In the Canada Basin, the SNM water masses follow the Beaufort Gyre and flow in a clockwise direction, and the resid-

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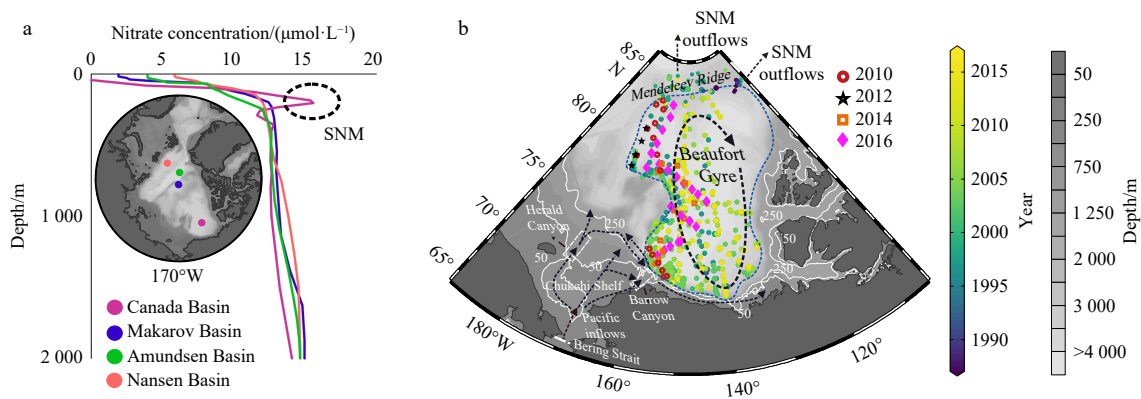


Fig. 1. a. Nutrient profiles from different Arctic areas. Purple dots, blue dots, green dots, and pink dots represent stations in the Canada Basin, Makarov Basin, Amundsen Basin, and Nansen Basin, respectively (data source: GLODAPv2). b. Schematic circulation of the subsurface nutrient maximum layer (SNM) source water and outflows in the western Arctic Ocean, the color bars represent the sampling year of stations in the Canada Basin and the Mendeleev Ridge (data source: GLODAPv2). Red circles, black pentagons, orange boxes, and pink diamonds represent 2010 to 2016 CHINARE stations in the Canada Basin. The white dashed boxes represent Herald Canyon and Barrow Canyon, respectively. The blue dashed circle indicates the geographical location of the Canada Basin.

ence time of the SNM water masses is approximately ten years (Ekurzel et al., 2001; Macdonald et al., 2005).

After leaving the Canada Basin, the water masses from the SNM continue to flow toward the Atlantic Ocean. There are two notable pathways for the water leaving the Arctic Ocean—one via the Fram Strait with the trans-polar drift, and the other passing through the Canadian Arctic Archipelago, with most of the water then leaving the Arctic Ocean via the Davis Strait (Anderson and Dryssen, 1981; Torres-Valdés et al., 2013).

Previous studies have focused on the physical characteristics of the SNM, while the long-term trends and influencing factors of nutrient reservoirs have rarely been studied (McLaughlin et al., 2004; Qi et al., 2017; Reeve et al., 2019). We hypothesize that with the rapid climate change in the Arctic, both the nutrient reservoirs and their influencing factors are changing. The aim of this study was to systematically understand the long-term trends of nutrient stocks in the SNM and study the dominant factors of these stocks on a basin scale. In a rapidly changing Arctic Ocean, understanding the long-term trends and dominant factors of reservoirs in the SNM will provide useful insights into the changing Canada Basin ecosystem.

2 Materials and methods

2.1 Nutrient dataset acquisition

In this study, our nutrient data (nitrate, phosphate, and silicate) were derived from the Global Ocean Data Analysis Project v2 (GLODAPv2; <https://www.glodap.info/index.php/merged-and-adjusted-data-product-v2-2022/>) during 1985 to 2015 and from the 2010 to 2016 Chinese National Arctic Research Expedition (CHINARE) in the Canada Basin and the Chukchi Shelf. Nutrient samples from the 2010 to 2016 CHINARE were measured on board using standard colorimetric methods (Grasshoff et al., 2009) adapted for a continuous flow analyzer (Skalar Analytical BV, Breda, Netherlands). Since GLODAPv2 in the Canada Basin lacked data from 2010 to 2016, the 2010 to 2016 CHINARE data were suitable supplements.

2.2 Definition of the SNM boundary

To calculate the nutrient concentrations and nutrient stocks, we first needed to define the boundary of the SNM. Currently, there are several ways to determine the boundary. McLaughlin

et al. (1996) and Jin et al. (2004) suggested that the depth between 50 m and 200 m of the Canada Basin can be defined as the SNM. However, the strengthening of the Beaufort Gyre and the “Atlantification” of the Arctic Ocean have gradually shifted the boundary of the SNM in recent years, making the above-mentioned definition no longer suitable (Polyakov et al., 2017; Proshutinsky et al., 2019; Zhong et al., 2019). In this study, we combined the definitions of the SNM in the Canada Basin by Nishino et al. (2008), Gong and Pickart (2015), Pickart et al. (2005), and Zhong et al. (2019) and defined the water mass between 25.5 kg/m^3 and 27 kg/m^3 as the SNM. This is because the physicochemical properties of this water mass are close to those of its origin water mass around Barrow Canyon (Nishino et al., 2008; Zhong et al., 2019). In addition, researchers usually consider the depth of (33.1 ± 0.1) isohaline or $(26.5 \pm 0.1) \text{ kg/m}^3$ isopycnal as the core of the SNM, which coincides with the core of the PWW in the Canada Basin (Pickart et al., 2005; Zhong et al., 2018). However, it should be noted that the salinity of the PWW has been decreasing since 1990 (from 33.5 in the 1990s to 32.1 after 2014) (Woodgate and Peralta-Ferriz, 2021), which may promote the mixing of the SNM and the upper water, consequently shifting the boundary and making the SNM fresher. Therefore, long-term observations of the SNM are required to produce more accurate definitions of the SNM boundaries.

2.3 Nutrient reservoirs in the SNM

Averaged nutrient concentrations of the SNM and the area of the Canada Basin were used to calculate the reservoirs in the SNM for each year under investigation. We multiplied the mathematical averaged nutrient concentrations in the SNM for each year (shown in blue dots in Fig. 2) by the area of the Canada Basin (approximately $1.3 \times 10^6 \text{ km}^2$; Grantz et al., 1990) to calculate the nutrient stocks in the SNM over the study period.

2.4 Nutrient contribution of inflow and outflow water to the SNM

We used stations near the exit of Barrow Canyon to estimate the average nutrient (nitrate) concentration of inflow water (Fig. 3), which was estimated to be $(11.6 \pm 2.4) \mu\text{mol/L}$ ($n = 117$) and was consistent with those reported in previous studies (Gong and Pickart, 2015; Lowry et al., 2015). The annual contribution of inflow water to the SNM was determined by multiplying the average inflow water flux ($\sim 0.35 \times 10^6 \text{ m}^3/\text{s}$) (Corlett and Pickart,

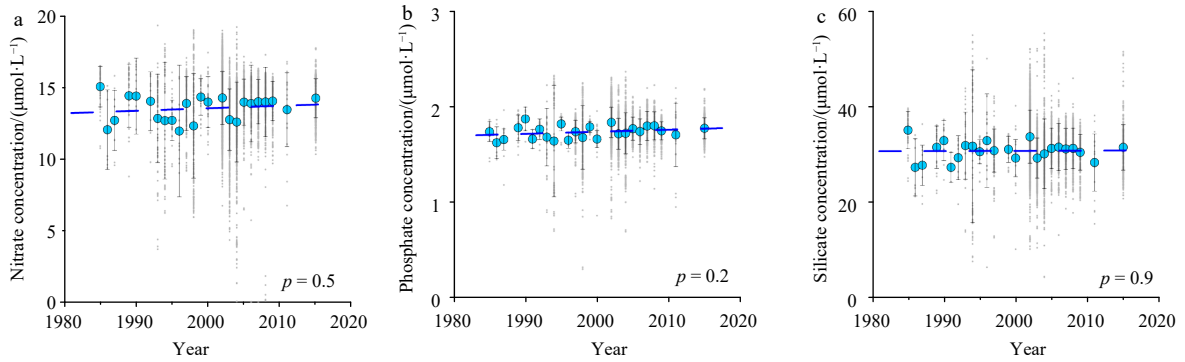


Fig. 2. Interannual mean nitrate (a), phosphate (b), and silicate (c) concentrations ($\mu\text{mol/L}$) in the subsurface nutrient maximum layer (SNM) of the Canada Basin. Blue dots indicate mean nutrient concentrations; blue dashed lines indicate the linear regression of mean nutrient concentrations; grey points are original data (data source: GLODAPv2, 2010 to 2016 CHINARE).

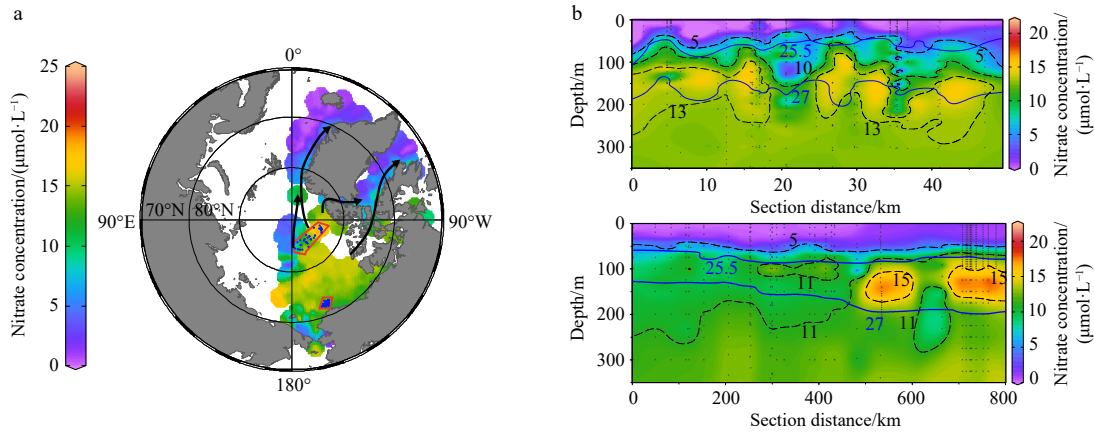


Fig. 3. a. Horizontal distribution of nitrate concentrations along the 26.5 kg/m^3 potential density surface in the Arctic Ocean (modified after Tremblay et al. (2015)). Red polygon and blue dots indicate the nitrate section near the Barrow Canyon and the Mendeleev Ridge, respectively. Black arrows indicate the pathways of the subsurface nutrient maximum layer (SNM) outflows. b. Nitrate section near the Barrow Canyon. c. Nitrate section near the Mendeleev Ridge. In b and c, black dots indicate the sampling depth at every station, black dashed lines indicate the nitrate concentration contour lines, and blue solid lines indicate the isopycnal (kg/m^3) of the SNM boundaries. Data source: GLODAPv2 and the 2010 to 2016 CHINARE.

2017) by the average nutrient (nitrate) concentration [$(11.6 \pm 2.4) \mu\text{mol/L}$].

We used stations near the Mendeleev Ridge (Fig. 3) to calculate the average nutrient (nitrate) concentration, which was estimated to be $(12.5 \pm 3.5) \mu\text{mol/L}$ ($n = 35$). Based on the variations in the SNM nitrate reservoir over the study period, the contribution of outflow water to the SNM can be calculated by its difference with the contribution of inflow water (calculated above). The average outflow water flux and nutrient (nitrate) flux were then determined by the contribution of outflow water to the SNM and the average nutrient (nitrate) concentration [$(12.5 \pm 3.5) \mu\text{mol/L}$].

2.5 Nutrient contribution of remineralization

In this study, we used two methods to estimate the nutrient contribution of remineralization to the SNM. First, we estimated this contribution from the new production, as follows:

$$N = f \times P \div R, \quad (1)$$

where f represents the f -ratio (f -ratio equals new primary production divided by total primary production), P represents the total interannual primary production of the upper water, and R represents

the $C : N$ uptake ratio of phytoplankton in the study area.

Second, we used the remineralization equation to estimate this contribution:

$$N = M \div O, \quad (2)$$

where M represents the ratio of Apparent Oxygen Utilization (AOU) and nutrient concentrations measured in the SNM; O represents the ratio of AOU and nutrient concentrations (Sarmiento and Gruber, 2006).

2.6 Nutrient contribution of denitrification

Denitrification was one of the pathways for nutrient (nitrogen) export in the ocean (Gruber and Sarmiento, 1997). In this study, we used the parameter N^* to evaluate the contribution of denitrification to the SNM, since N^* indicates nitrogen deficit and the variation of N^* can indicate the denitrification process in the water column (Sarmiento and Gruber, 2006; Zhuang et al., 2019):

$$N^* = ([\text{NO}_3^-] - 16 \times [\text{PO}_4^{3-}] + 2.9 \mu\text{mol/L}) \times 0.87, \quad (3)$$

where $[\text{NO}_3^-]$ and $[\text{PO}_4^{3-}]$ are the nitrate and phosphate concen-

trations ($\mu\text{mol/L}$), respectively; 16 represents the Redfield ratio of 16:1 (Redfield, 1934); $2.9 \mu\text{mol/L}$ was based on the global measurements to set the mean N^* to 0 (Sarmiento and Gruber, 2006); 0.87 is a coefficient based on stoichiometric ratios during the denitrification and remineralization processes.

3 Results and discussion

3.1 Nutrient concentrations and reservoirs in the SNM

The average nutrient concentrations of the SNM remained relatively stable over the years studied, but the reservoirs exhibited a trend towards increasing. Previous studies indicate that the nutrient concentrations of the SNM have remained relatively stable over recent decades. Jones and Anderson (1986) reported a nitrate (NO_3^-) concentration of $17.1 \mu\text{mol/L}$ in the SNM in 1983, which is consistent with the findings of Simpson et al. (2008) and Brown et al. (2016), who reported NO_3^- concentrations of $17.3 \mu\text{mol/L}$ and $14.9 \mu\text{mol/L}$, respectively. Nonetheless, the long-term trends in the nutrient concentrations of the SNM over the past few decades are not well understood. In this study, we calculated the annual averaged nutrient concentrations in the SNM. The results showed that NO_3^- , phosphate (PO_4^{3-}), and silicate (SiO_3^{2-}) concentrations in the SNM of the Canada Basin have remained relatively stable since the 1980s (Fig. 2), with mean values of $(13.6 \pm 2.4) \mu\text{mol/L}$, $(1.8 \pm 0.2) \mu\text{mol/L}$, and $(31.5 \pm 5.7) \mu\text{mol/L}$ and with median values of $13.8 \mu\text{mol/L}$, $1.7 \mu\text{mol/L}$, and $31.3 \mu\text{mol/L}$, respectively (data not shown). The size of the SNM reservoirs has increased over the study period. For example, the nitrate reservoir increased from $(14.4 \pm 2.2) \times 10^{11} \text{ mol N}$ in 1985 to $(21.2 \pm 1.5) \times 10^{11} \text{ mol N}$ in 2015. With nitrate concentration remaining relatively stable in the SNM, the increased reservoirs indicated the expansion of this layer (Qi et al., 2017; Zhuang et al., 2019). The nitrate reservoir in 2015 was 6 to 7 times larger than the interannual surface nitrate input to the Arctic (approximately $3.3 \times 10^{11} \text{ mol/a}$ (in terms of N), including oceanic and riverine input) (Tremblay et al., 2015). Assuming that the SNM is ventilated and all the nitrate is used by phytoplankton in the upper layer, the SNM can then provide $(168.5 \pm 11.9) \times 10^{12} \text{ g C}$ of primary production to the upper layer (converted by the Redfield ratio C : N = 106 : 16; Redfield, 1934). Considering the residence time of the SNM (about ten years), the SNM could contribute nearly 5% of the Arctic's net primary productivity in 2018 ($393.8 \times 10^{12} \text{ g C}$) (Ardyna and Arrigo, 2020).

3.2 Physical processes controlling the nutrient reservoirs in the SNM

Inflow water was the main source of nutrients to the SNM. The contribution of inflow water to the SNM was $(1.3 \pm 0.3) \times 10^{11} \text{ mol/a}$ (in terms of N) [$(11.6 \pm 2.4) \mu\text{mol/L} \times 0.35 \times 10^6 \text{ m}^3/\text{s} \times 3600 \text{ s} \times 24 \text{ h} \times 365 \text{ d} = (1.3 \pm 0.3) \times 10^{11} \text{ mol/a}$ (in terms of N)]. If we assumed the nitrate reservoir of the SNM as $(21.2 \pm 1.5) \times 10^{11} \text{ mol N}$ (equal to the nitrate reservoir in 2015), during the residence time (about ten years) of the SNM water masses, the inflow water could contribute about 60.4% to the nutrient reservoirs of the SNM. With increasing Pacific inflow (Woodgate, 2018), the contribution of inflow water to the SNM may be increasing. In addition, previous studies suggested that the formation of polynyas in the northern Chukchi Shelf during autumn and winter will change the physicochemical properties of PWW (Woodgate et al., 2005; Ladd et al., 2016). However, given the episodic occurrence of polynyas, we suggest that their effect on the nutrient stocks of PWW and SNM may be insignificant.

Outflow water was the main pathway for nutrient export in

the SNM. Based on the increase in the SNM nitrate reservoir between 1985 and 2015 ($21.2 \times 10^{11} - 14.4 \times 10^{11} \text{ mol N} = 6.8 \times 10^{11} \text{ mol N}$), we estimated that the SNM outflow water flux during 1985 to 2015 was $-0.27 \times 10^6 \text{ m}^3/\text{s}$ and the nitrate flux was $(1.1 \pm 0.3) \times 10^{11} \text{ mol/a}$ (in terms of N). This nutrient flux was almost one-third of the interannual horizontal inflow ($\sim 3.3 \times 10^{11} \text{ mol/a N}$) for the Arctic Ocean (Tremblay et al., 2015), which suggested that the SNM outflow water was an essential pathway for nutrient export from the Canada Basin to other Arctic seas. If we assume the nitrate reservoir as $(21.2 \pm 1.5) \times 10^{11} \text{ mol N}$, during the residence time (about ten years) of the SNM water masses, the inflow water could contribute about -50.2% to the nutrient reservoirs of the SNM.

Recently, climate anomalies have led to more frequent events such as storms, upwellings, and mesoscale eddies as well as enhanced diffusion, influencing nutrient stocks in the SNM of the Canada Basin (Pickart et al., 2009, 2013; Spall et al., 2008; Dosser et al., 2021). The processes of turbulence and convection may promote the mixing of the SNM and the upper layer, which would enhance the primary productivity (Tremblay et al., 2011; Watanabe et al., 2014). Due to the lack of data in this study, we estimated only the contribution of diffusion to the nutrient reservoirs of the SNM. According to Randelhoff et al. (2020), the diffusion from the SNM to the upper water was relatively low [$-3.7 \times 10^{-3} \text{ mol}/(\text{m}^2 \cdot \text{a})$ (in terms of N)]. Since the nitrate gradient between the SNM and the Atlantic Water (AW) was smaller than that between the SNM and the upper water (specific data not shown), the diffusion from the SNM to the AW should be less than $3.7 \times 10^{-3} \text{ mol}/(\text{m}^2 \cdot \text{a})$ (in terms of N). In summary, the diffusion from the SNM to its adjacent layers should be less than $7.4 \times 10^{-3} \text{ mol}/(\text{m}^2 \cdot \text{a})$ (in terms of N) (equal to $9.6 \times 10^9 \text{ mol}/(\text{m}^2 \cdot \text{a})$ (in terms of N) after multiplying by the area). During the residence time (about ten years) of the SNM water masses, the diffusion can contribute up to about -4.5% to the nutrient reservoirs of the SNM.

3.3 Biogeochemical processes controlling the nutrient reservoirs in the SNM

In the Canada Basin and Chukchi Shelf, we analyzed the effects of major biogeochemical processes, including particle deposition and remineralization, nitrogen fixation, and denitrification, on nutrient reservoirs of the SNM.

The contribution of particle deposition and remineralization to the nutrient reservoir of the SNM was relatively low. According to Honjo et al. (2010) and Randelhoff and Guthrie (2016), the particle organic carbon (POC) flux at a depth of 120 m to 200 m (near the lower boundary of the SNM) was $0.05 \text{ g}/(\text{m}^2 \cdot \text{a})$ (in terms of C) to $0.65 \text{ g}/(\text{m}^2 \cdot \text{a})$ (in terms of C), and the POC flux in the upper halocline (near the upper boundary of the SNM) was $1.5 \text{ g}/(\text{m}^2 \cdot \text{a})$ (in terms of C) to $3 \text{ g}/(\text{m}^2 \cdot \text{a})$ (in terms of C), which indicated that 56.7% to 98.3% of the POC from the upper layer remineralized within the SNM. Therefore, in the Canada Basin, we can use the new production in the upper layer to estimate the contribution of remineralization to the SNM. The C : N uptake ratio of phytoplankton in the Arctic Ocean is about 6 (Hansell et al., 1993), and the interannual f-ratio of the Canada Basin is approximately 0.66 (Simpson et al., 2013; Tremblay et al., 2015); additionally, the total interannual primary production of the upper water (0 m to 30 m) in the Canada Basin was estimated to be less than $5 \text{ g}/(\text{m}^2 \cdot \text{a})$ (in terms of C) by Lee and Whitlege (2005) and Codispoti et al. (2013). Based on these results, the remineralization can be estimated to contribute up to $3.3 \text{ g}/(\text{m}^2 \cdot \text{a})$ (in terms of C) to the SNM, which can provide approximately $0.05 \text{ mol}/(\text{m}^2 \cdot \text{a})$

(in terms of C) to the SNM (converted C to N with the C : N molar ratio is = 6). Thus, particle deposition and remineralization over the whole Canada Basin can provide $\sim 6.5 \times 10^{10}$ mol/a (in terms of N) to the SNM [$0.05 \text{ mol}/(\text{m}^2 \cdot \text{a})$ (in terms of N) $\times 1.3 \times 10^6 \text{ km}^2 = 6.5 \times 10^{10} \text{ mol}/\text{a}$ (in terms of N)]. During the residence time (about ten years), particle deposition and remineralization in the Canada Basin can contribute $\sim 28.3\%$ to the nutrient reservoirs of the SNM [$6.0 \times 10^{10} \text{ mol}/\text{a}$ (in terms of N) $\times 10 \text{ a} \div [(21.2 \pm 1.5) \times 10^{11} \text{ mol}$ (in terms of N)] $\times 100\% = 28.3\%$], which is consistent with the findings of Tremblay et al. (2015) (30%) and Granger et al. (2018) (32%).

In this study, we also used the remineralization equation to estimate the contribution of remineralization (Sarmiento and Gruber, 2006). Using the AOU: $[\text{PO}_4^{3-}]$ (~ 43.1) ($[\text{PO}_4^{3+}]$: phosphate, molar concentration) measured in the SNM of the Canada Basin during the 2010–2016 CHINARE (Fig. 4), we calculated the remineralization of PO_4^{3-} in the SNM, which accounted for $\sim 28.7\%$ of the total PO_4^{3-} ($43.1 \div 150 \times 100\% = 28.7\%$). Overall, the contribution of particle deposition and remineralization to the nutrient reservoirs was relatively low, but with the increasing (albeit insignificant) primary production in the Canada Basin, the contribution of this process to the nutrient reservoirs is likely to increase (Lewis et al., 2020).

The SNM also contains nitrate produced via nitrogen fixation (Yamamoto-Kawai et al., 2006; Tremblay et al., 2008). However, its contribution was not substantial. The nitrogen-fixing bacterial communities (mainly composed of cyanobacteria) in the Canada Basin primarily originated from estuaries (e.g., the Mackenzie River) (Blais et al., 2012). Due to the stratification in the Canada Basin, the nitrogen fixation may have little effect on the SNM, which is generally deeper than 50 m (Randelhoff and Guthrie, 2016). Blais et al. (2012) estimated the average rate of nitrogen fixation in the upper water of the Southeast Beaufort Sea (averaged 54.7 m) to be $(4.4 \pm 3.3) \times 10^{-5} \text{ mol}/(\text{m}^3 \cdot \text{a})$ (in terms of N). If we extrapolate this figure to the whole Canada Basin, nitrogen fixation in the upper water can contribute up to $\sim 3.9 \times 10^9 \text{ mol}/\text{a}$ (in terms of N) [$4.4 \times 10^{-5} \text{ mol}/(\text{m}^3 \cdot \text{a})$ (in terms of N) $\times 54.7 \text{ m} \times 1.3 \times 10^6 \text{ km}^2 = 3.1 \times 10^9 \text{ mol}/\text{a}$ (in terms of N)]. If the fixed nitro-

gen can be entirely transported to the SNM through biogeochemical progresses such as deposit and remineralization during the residence time, nitrogen fixation in the upper water can contribute up to $\sim 1.5\%$ to the nutrient reservoirs in the SNM [$3.9 \times 10^9 \text{ mol}/\text{a}$ (in terms of N) $\times 10 \text{ a} \div (21.2 \times 10^{11}) \text{ mol}$ (in terms of N) $\times 100\% = 1.8\%$], which suggests that the contribution of nitrogen fixation to the SNM was not considerable.

The contribution of denitrification to nutrient reservoirs in the SNM occurred mainly in the upstream Chukchi Shelf rather than in the Canada Basin. Reeve et al. (2019) detected total water column denitrification rates of $5 \mu\text{mol}/(\text{m}^2 \cdot \text{d})$ to $14 \mu\text{mol}/(\text{m}^2 \cdot \text{d})$ in the Canada Basin, where denitrification mainly occurred in deep waters and sediments at depths greater than 2 000 m (Granger et al., 2018). Compared to that in other deep-sea basins, denitrification in the Canada Basin was weak. For example, Lehmann et al. (2005) detected the denitrification rate in the Bering Sea Basin's sediments to be $230 \mu\text{mol}/(\text{m}^2 \cdot \text{d})$. In this study, N^* for the 2010 to 2016 CHINARE stations was calculated (Fig. 5). Results showed that in the Chukchi Shelf, N^* decreased with increasing depth, and the mean value of N^* in the bottom water was $(-8.7 \pm 4.8) \mu\text{mol}/\text{L}$. In the Canada Basin, with increasing depth, N^* first decreased and then increased; the lowest N^* value was found in the SNM. The mean value of N^* in the SNM was $(-8.5 \pm 2.3) \mu\text{mol}/\text{L}$, slightly higher than the N^* in the Chukchi Shelf bottom water. This was probably due to the nitrate replenishment of the SNM by the winter water mass from the Chukchi Shelf (Lowry et al., 2015; Arrigo et al., 2017). In addition, N^* values of both the SNM and the Chukchi Shelf bottom water were much lower than those of their source water in the Bering Sea ($-3 \mu\text{mol}/\text{L}$ to $-6 \mu\text{mol}/\text{L}$) (Granger et al., 2011), suggesting that the bottom water experienced continual denitrification during the transport from the Bering Strait to the SNM in the Canada Basin. However, we noticed slight differences between the N^* values in the Chukchi Shelf bottom water [$(-8.7 \pm 4.8) \mu\text{mol}/\text{L}$] and the SNM [$(-8.5 \pm 2.3) \mu\text{mol}/\text{L}$]; this result implies that the denitrification occurred mainly in the Chukchi Shelf bottom water during the transportation from the Bering Strait to the Canada Basin, and the denitrification in the Canada basin may have a minor influence on nutrient stocks in the SNM (Devol et al., 1997; Nishino et al., 2016).

3.4 Potential impacts of climate change on SNM stability

Figure 6 shows a schematic diagram of SNM stability under various physical and biogeochemical processes. The stratification maintains the stability of nutrient reservoirs in the SNM; however, with further climate change in the Arctic Ocean, these reservoirs are likely to experience increased disturbance. Nishino et al. (2013) suggested that as the area of open water will increase, the structure of the water column would be more susceptible to

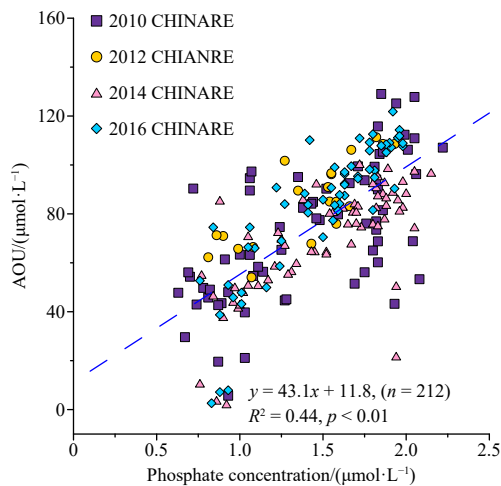


Fig. 4. Apparent Oxygen Utilization (AOU): Phosphate (P) in subsurface nutrient maximum layer (SNM) at two-year intervals at the Canada Basin stations during the 2010 to 2016 CHINARE. AOU and P showed significant correlation. Purple squares, yellow circles, pink triangles, and blue diamonds indicate the years 2010, 2012, 2014, and 2016, respectively.

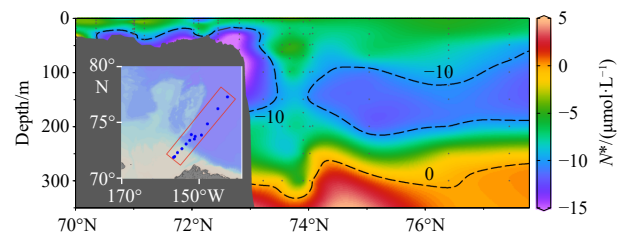


Fig. 5. Section of nitrate deficit (N^*) from Chukchi Shelf to Canada Basin. Red rectangle indicates the section range. Blue dots indicate the stations from the Chukchi shelf to the Canada Basin during the 2010 to 2016 CHINARE.

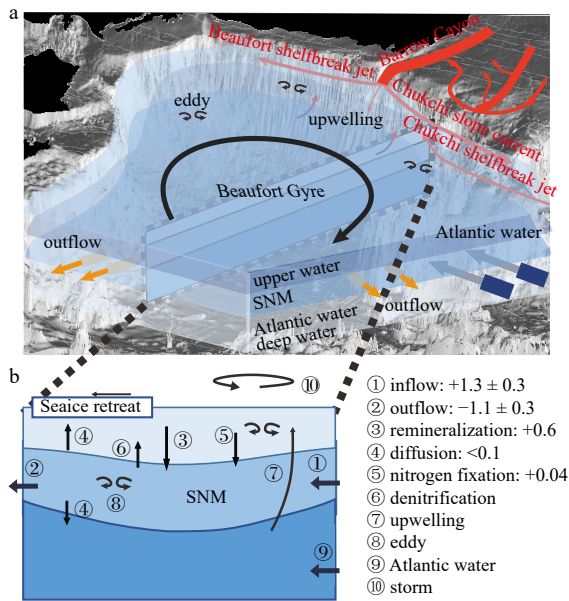


Fig. 6. Schematic diagram showing the main currents of the upper layer in the Canada Basin (a) and the contribution of nitrate to the subsurface nutrient maximum layer (SNM) 10^{11} mol/a (in terms of N) (b). The geographical location of the Barrow Canyon is marked in red. Red arrows represent the main currents that flow into the Canada Basin, including the Beaufort shelfbreak jet, the Chukchi slope current, and the Chukchi shelfbreak jet. The black curved arrow represents the circulation of the Beaufort Gyre. The orange arrows represent the outflow water from the SNM. The dark blue arrows represent the Atlantic water flow into the Canada Basin. The densities of the upper water, the SNM, and the Atlantic water and deep water were: less than 25.5 kg/m^3 , between 25.5 kg/m^3 and 27 kg/m^3 , and greater than 27 kg/m^3 respectively.

disturbance. Therefore, in the Canada Basin, the increased sea ice retreat and the prolonged open water periods may have weakened the stability of the SNM (Wang and Overland, 2009; Serreze and Meier, 2019). However, the Canada Basin converged freshwater under the intensified Beaufort Gyre and subsequently enhanced the stratification between the upper water and the SNM (Serreze et al., 2006; Yamamoto-Kawai et al., 2008; Proshutinsky et al., 2019), which implied that the SNM would not substantially affect primary production at this time. It is worth noting that storms and mesoscale eddy events were becoming more frequent in the Canada Basin and these have the potential to destabilize the SNM, especially in the marginal areas of the Canada Basin (Pickart et al., 2013; Rinke et al., 2017). Since the SNM in marginal areas was more susceptible to disturbances from atmospheric and hydrodynamic events due to the relatively shallow depth, the frequent disturbances might promote an upward supply of nutrients and thus enhance primary production (Timmermans and Toole, 2023; Pickart et al., 2011). Although we inferred that storms and mesoscale eddy events had substantial impacts on SNM stability and that such effects were likely to increase with further climate changes in the Arctic, we currently do not know the specific effects of these events on SNM stability. Therefore, future studies will be needed to further evaluate these events.

4 Conclusions

In this study, we first analyzed the long-term trends of nutri-

ent concentrations and stocks in the SNM. We then summarized the main factors influencing the nutrient reservoirs of the SNM and analyzed the dominant factors affecting these nutrient stocks. Finally, we discussed the potential impacts of climate change on SNM stability. We arrived at the following conclusions. (1) Nutrient concentrations in the SNM of the Canada Basin have remained relatively stable over the past four decades, but the absolute nutrient stocks in the SNM showed an increasing trend due to the expansion of this layer. (2) The nutrient stocks in the SNM were dominated by inflow water and outflow water, which contributed about 60.4% and about -50.2% to the nutrient stocks, respectively. (3) Biogeochemical processes such as particle deposition and remineralization in the Canada Basin contributed approximately one-third to the nutrient stocks. Nitrogen fixation in the Canada Basin contributed ~1.5% to the nutrient stocks in the SNM. The contribution of denitrification to the nutrient stocks in the SNM occurred mainly on the Chukchi shelf. (4) In recent years, the SNM would not substantially affect primary production. However, with further expected climate changes in the Arctic, storms and mesoscale eddies may have an increasing impact on the stability of SNM; this requires further evaluation in the future.

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