CHANGES IN ARCTIC BIOGEOCHEMICAL DYNAMICS WITH THE RECENT LOSS OF SEA ICE

Shigeto Nishino[1*], Takashi Kikuchi[1], Motoyo Itoh[1], Yusuke Kawaguchi[1], Toru Hirawake[2], Michiyo Yamamoto-Kawai[3], William J. Williams[4], and Igor Semiletov[5]

[1]*Institute of Arctic Climate and Environment Research, Japan Agency for Marine-Earth Science and Technology;*
[2]*Faculty of Fisheries Sciences, Hokkaido University;* [3]*Tokyo University of Marine Science and Technology;*
[4]*Institute of Ocean Sciences, Fisheries and Oceans Canada;* [5]*International Arctic Research Center, University of Alaska, Fairbanks*

* Corresponding author E-mail: nishinos@jamstec.go.jp

<Abstract> Since the late 1990s, catastrophic sea-ice reduction during summer has been observed in the Pacific sector of the Arctic Ocean (western Arctic Ocean). Regions of decreasing sea ice might be associated with enhancement of biological pump due to light intensification in the water column. On the other hand, there is a possibility that the sea-ice melt intensifies the ocean stratification in the surface layer and inhibits nutrient supplies from deeper layers, resulting in reduction of biological pump. In this study, we examined the enhancement/reduction of biological pump due to the sea-ice reduction and its relation to the ocean circulation. The anticyclonic ocean circulation (Beaufort Gyre) occupies the central Canada Basin, where the surface freshwater is accumulated by the convergence of Ekman transport. In this region, the nutricline deepens due to the recent sea-ice melt, resulting in the reduction of biological pump. However, at the limb of the Beaufort Gyre, for example, in the western Canada Basin, the nutricline is shallow. In this region, a comparison of silicate profiles obtained from a heavy ice year and recent light ice years suggests that the improvement of light availability due to the sea-ice melt enhances the biological pump. We further studied a change in nutrient pathways related to the ocean circulation. The accumulation of freshwater in the central Canada Basin also deepens the pycnocline and causes a frontal structure of isopycnal surfaces between the shelf and basin. As a result, a strong westward flow is found over the shelf slope. The strong westward flow prevents the spreading of nutrient-rich shelf water into the central Canada Basin. This process also reduces the biological pump in the central Canada Basin.

Enhancement of biological pump in the Siberian Arctic

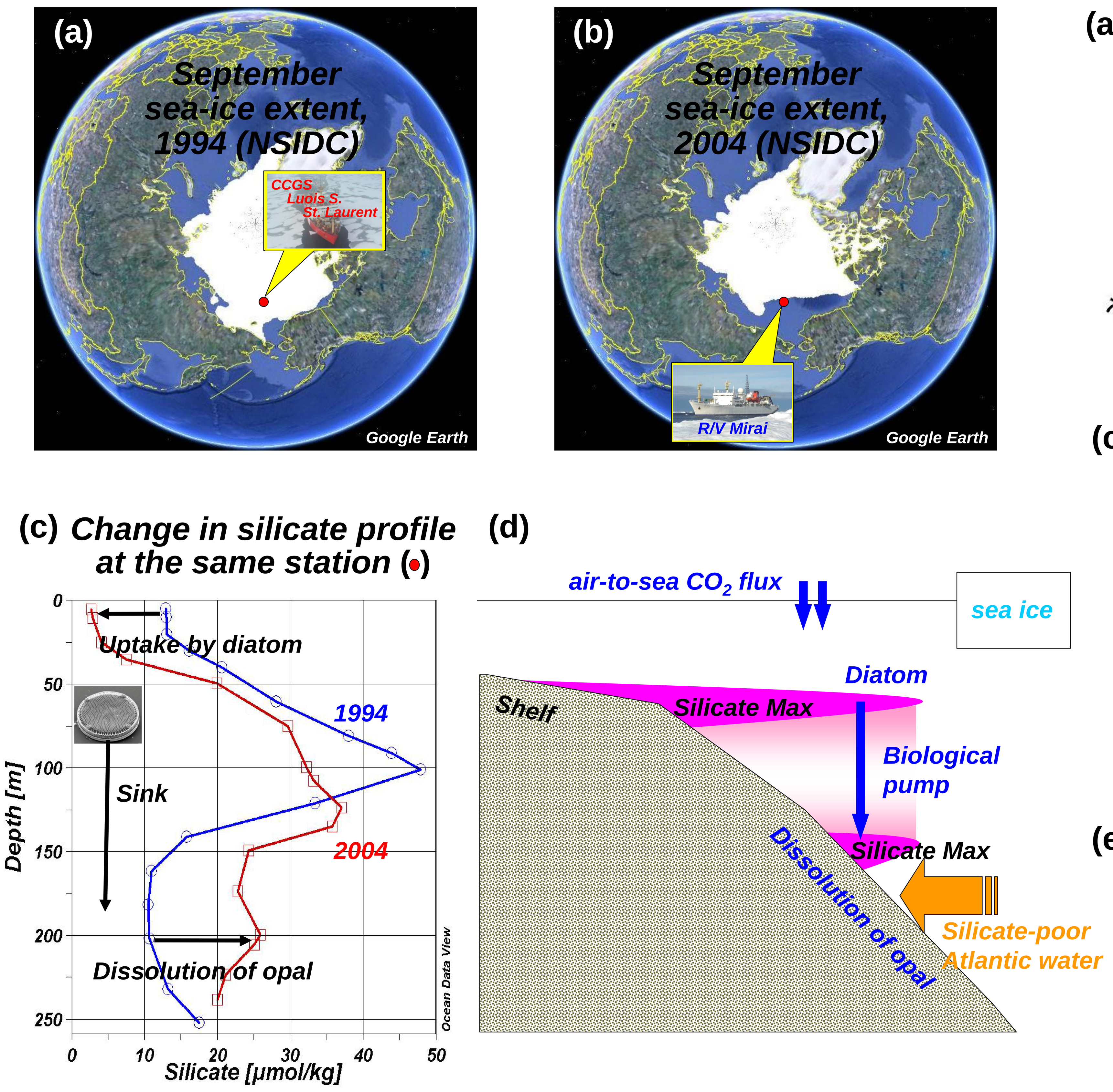


Figure 1. September sea-ice extent of (a) 1994 and (b) 2004 obtained from NSIDC website, and (c) silicate profiles obtained from cruises of CCGS Luois S. St. Laurent in 1994 and R/V Mirai in 2004 at almost the same location, and (d) schematic diagram of enhancement of biological pump. [Adapted from Nishino *et al*. (2009)]

Sea-ice conditions would largely influence the biological processes. To examine how sea-ice loss contributes to the biological pump, Nishino *et al*. (2009) compared silicate profiles obtained from cruises in 1994 and 2004 at almost the same location over the shelf slope adjacent to the western Canada Basin. The station was covered by sea ice in 1994 (Figure 1a) but was in open water in 2004 (Figure 1b). The surface silicate concentration of 2004 was lower than that of 1994 (Figure 1c). The lower concentration of 2004 probably reflects biological uptake of silicate in the absence of sea ice in summer. At deeper depths, the silicate concentration of 2004 was higher than that of 1994, suggesting an increase in silicate regeneration caused by the decomposition of opal-containing organisms (*e.g*., diatom) that were transported from the surface. From these results, we can infer that the biological pump was enhanced by the sea-ice loss (Figure 1d).

Reduction of biological pump in the Canada Basin

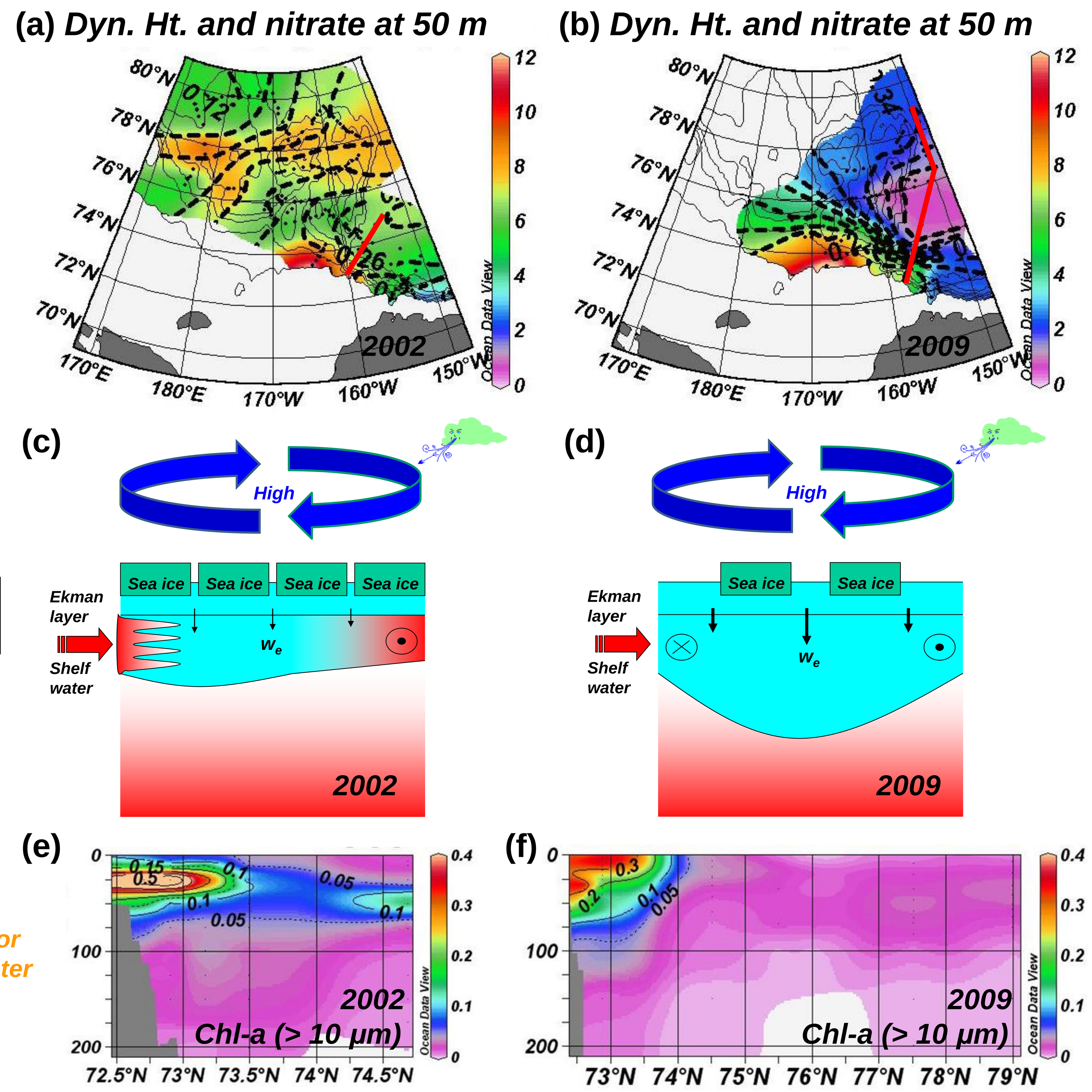


Figure 2. Dynamic height [dyn m] at 50 m relative to 250m (dashed lines) and nitrate [µmol/kg] at 50 m (colors) in (a) 2002 and (b) 2009; schematic diagrams of the ocean circulation and nutrient distribution in (c) 2002 and (d) 2009; and vertical sections of chlorophyll *a* in large size (> 10 µm) phytoplankton in (e) 2002 and (f) 2009 along thick lines in (a) and (b), respectively. Data of 2002 are obtained from the R/V Mirai Arctic cruise and Chukchi Borderland cruise (Woodgate *et al*., 2002), and data of 2009 are obtained from the R/V Mirai cruise.

The circulation pattern and nutrient distribution changed from 2002 to 2009 (Figures 2a – 2d). The anticyclonic circulation off Alaska, the Beaufort Gyre, increased its intensity and meridional width from 2002 to 2009. In 2002, nutrient-rich shelf water seems to spread from the Siberian shelf into the Canada Basin north of the Beaufort Gyre, *i.e*., north of 76 ºN and east of 170 ºW. The Beaufort Gyre also contained nutrient-rich water that was derived from the Pacific Ocean (Jones and Anderson, 1986). Such nutrient supplies in 2002 resulted in the flourish of phytoplankton even in the Canada Basin (Figure 2e). On the other hand, in 2009, the accumulation of freshwater within the Beaufort Gyre (Proshutinsky *et al*., 2009) reduced the nutrient concentration in the Canada Basin. This is because the accumulation of freshwater within the Beaufort Gyre in the Canada Basin makes a density gradient between the shelf and the basin, resulting in a formation of strong westward flow over the shelf slope that prevents the spreading of nutrient-rich shelf or Pacific water into the Canada Basin. The blocking of nutrient-rich water spreading would inhibit the growth of phytoplankton and reduce the biological pump in the Canada Basin (Figure 2f).

Enhancement/reduction of biological pump depends on ocean circulation

The biological pump is a central process in the ocean carbon cycle, and is a key factor controlling atmospheric carbon dioxide (CO_2). However, whether the Arctic biological pump is enhanced or reduced by the recent loss of sea ice is still unclear. Nishino *et al*. (2011) examined if the effect was dependent on ocean circulation (Figure 3). Melting of sea ice can both enhance and reduce the biological pump in the Arctic Ocean, depending on ocean circulation. The biological pump is reduced within the Beaufort Gyre in the Canada Basin because freshwater accumulation within the gyre limits nutrient supply from deep layers and shelves (middle panels) and inhibits the growth of large-bodied phytoplankton (right panels). Conversely, the biological pump is enhanced outside the Beaufort Gyre in the western Arctic Ocean because of nutrient supply from shelves and greater light penetration, enhancing photosynthesis, caused by the sea ice loss. The enhancement of biological pump results in an increase of deposited organisms at the seabed. As a result, the bottom nitrate concentrations increase due to an increase in the decomposition of organisms (left panels).

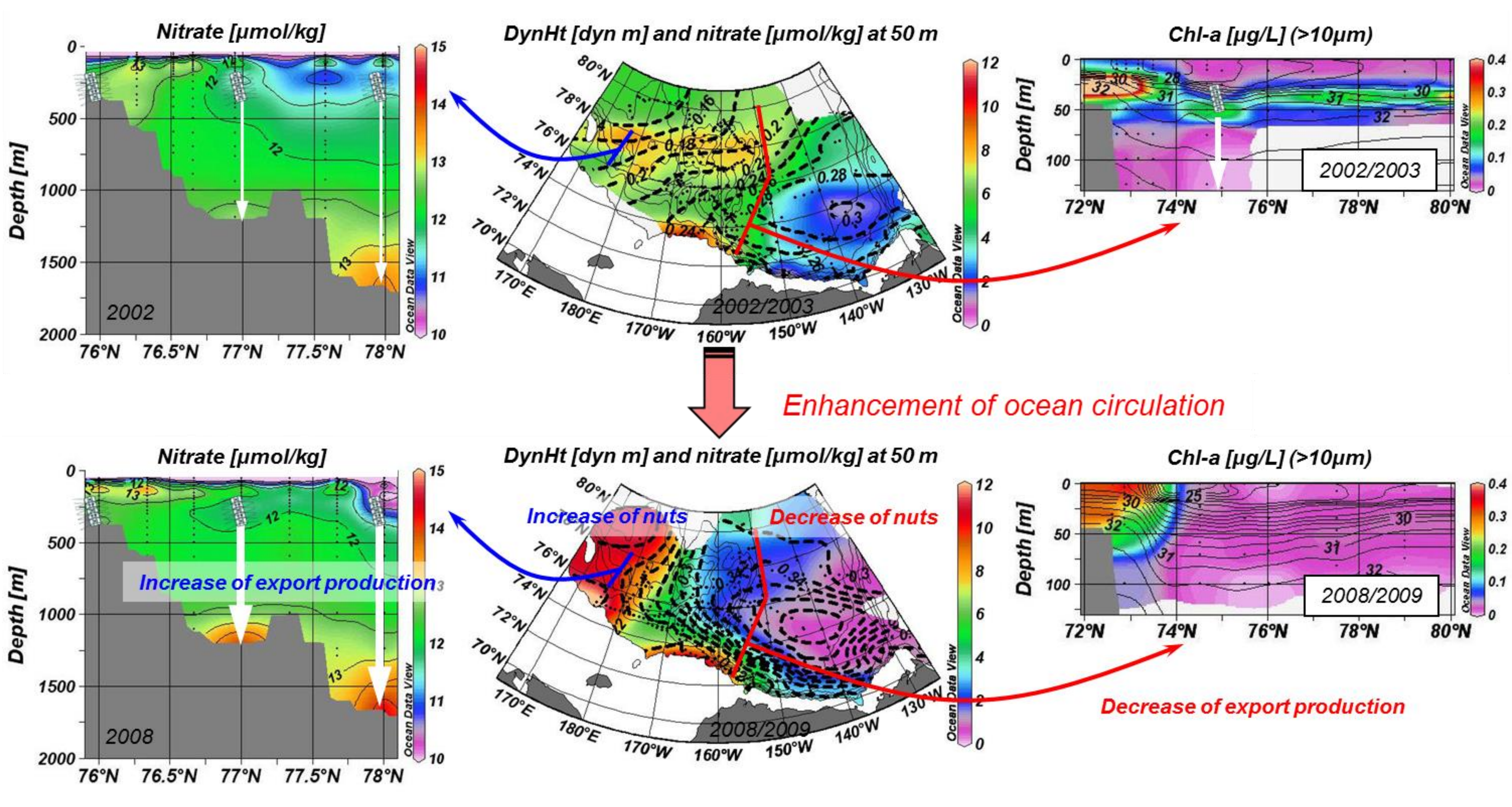
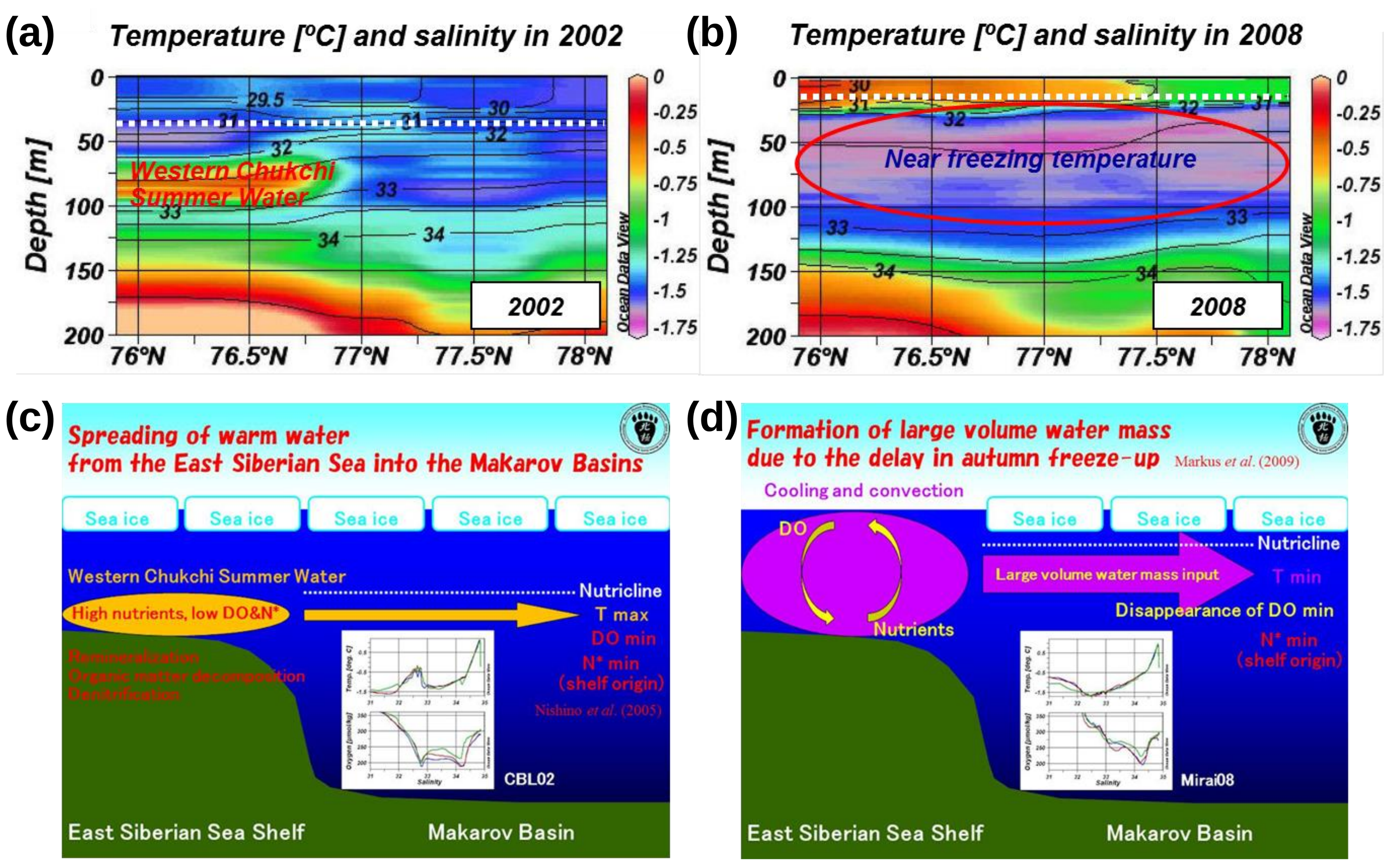


Figure 3. Dynamic height [dyn m] at 50 m relative to 250m (dashed lines) and nitrate [μmol/kg] at 50 m (colors) in (upper middle) 2002/2003 and (lower middle) 2008/2009; vertical sections of chlorophyll *a* in large size (> 10 μm) phytoplankton in (upper right) 2002/2003 and (lower right) 2008/2009 along red lines in middle panels; and vertical sections of nitrate in (upper left) 2002 and (lower left) 2008 along blue lines in middle panels, respectively. [Adapted from Nishino *et al*. (2011)]

Shoaling of the nutricline with an increase in near-freezing temperature water in the Makarov Basin



In 2002, warm water seemed to spread from the East Siberian Sea (Figure 4a). On the other hand, in 2008 the water with near freezing temperature of *S*=32-33 occupied the Makarov Basin (Figure 4b). The warm water in 2002 was also characterized by an oxygen minimum water that indicates the water has contacted to the shelf bottom (Figure 4c). On the other hand, the water with near freezing temperature in 2008 has relatively high oxygen concentrations, indicating that the water has experienced the winter cooling and convection over the shelf (Figure 4d). The formation of such a water mass in the East Siberian Sea would be more likely in recent years because of the significant delays in autumn freeze-up (Markus *et al*., 2009); the delay in freezing would mean an increased duration of water mass formation by cooling and convection because sea ice cover prevents atmospheric cooling and mixing by wind. A large volume of water formed by the cooling and convection would be flowing into the Makarov Basin, producing a temperature minimum with relatively high nutrients and resulting in a shoaling of the nutricline (Nishino *et al*., 2013).

Figure 4. Vertical sections of temperature in (a) 2002 and (b) 2008 along blue lines in middle panels of Figure 3; and schematics of the change in water characteristics from 2002 to 2008. [Adapted from Nishino *et al*. (2013)]

Pan-Arctic overview

The Siberian side of the Arctic Ocean has relatively high surface nutrient concentrations, implying the possibility of a drastic increase in biological productivity if the sea ice disappears. In this region, Russian rivers may influence the surface nutrient concentrations. Extremely high silicate contents are found over the Siberian shelves, reflecting the influence of Russian rivers. This high-silicate water seems to spread along the Lomonosov Ridge and into the central Arctic Ocean. Although the Pacific water also transports a large amount of nutrients, it subducts below the euphotic zone in the Canada Basin (Nishino *et al*., 2008). In contrast, the Russian river water occupies the surface layer because of its low density, and the nutrients originating from the Russian rivers would be effectively supplied to the euphotic zone compared with those from the nutrient-rich Pacific water. Therefore, the Lomonosov Ridge, along which Russian river water may contribute to increased surface nutrient concentrations, is a key area for the future study of changes in biogeochemical cycles accompanying sea-ice reduction. Such changes in the Arctic Ocean may also influence global biogeochemical cycles. For example, increased nutrient usage for biological production in the Arctic Ocean reduces the nutrient concentrations of water outflowing through the Canadian Archipelago and Fram Strait, and therefore might reduce productivity in the sub-arctic Atlantic Ocean.

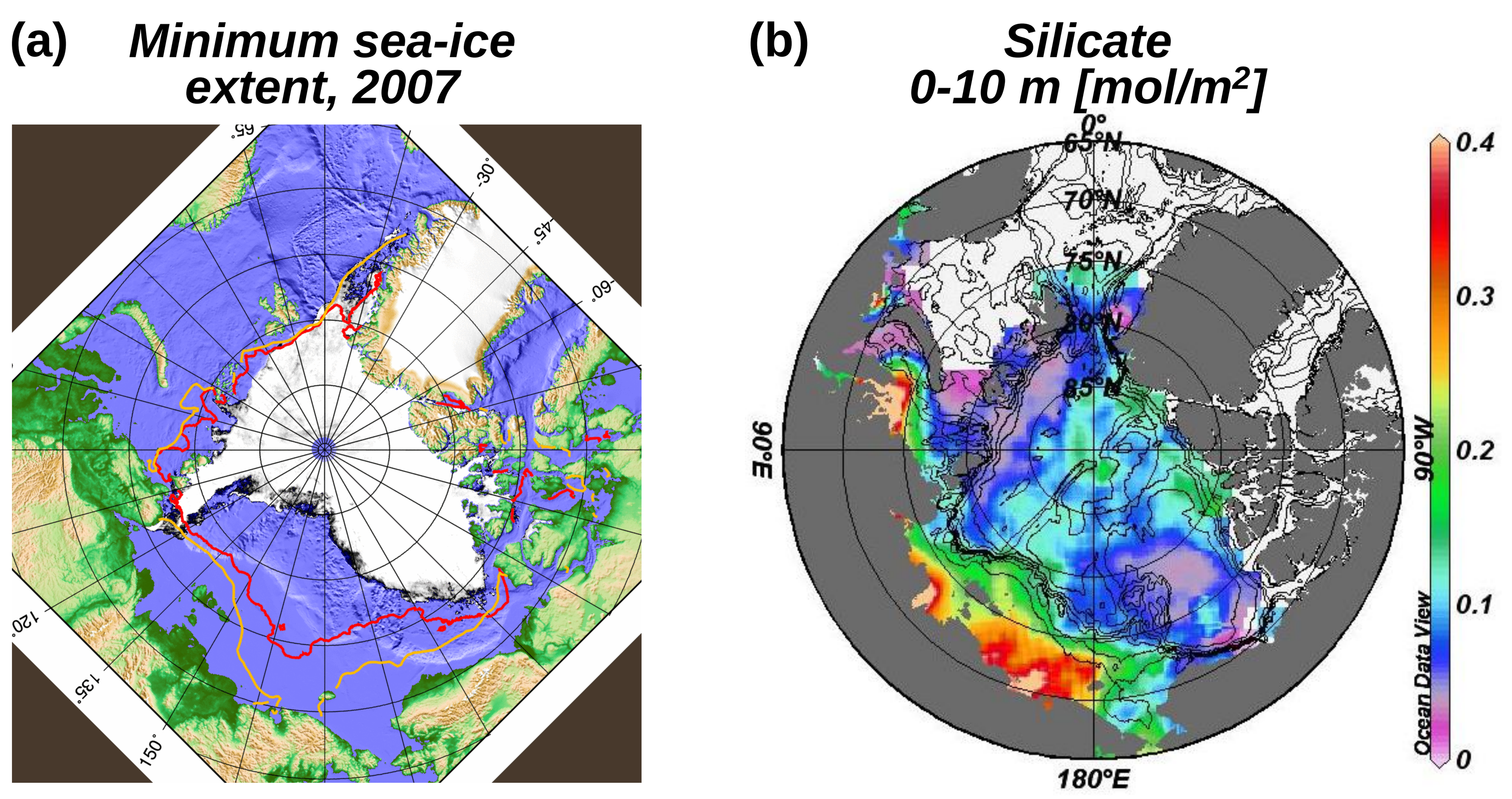


Figure 5. (a) Minimum sea-ice extent in 2007 obtained from a website of IUP UNIVERSITÄT BREMEN (Spreen *et al*., 2007), and (b) distribution of silicate integrated from the sea surface to a depth of 10 m in the Arctic Ocean obtained from the *Hydrochemical Atlas of the Arctic Ocean* created by IARC and AARI (Colony and Timokhov, 2001).

<References>

Colony, R. and L. Timokhov (2001), *Hydrochemical Atlas of the Arctic Ocean*, International Arctic Research Center, University of Alaska, USA, and State Research Center - the Arctic and Antarctic Research Institute, Russia, CD-ROM.

Jones, E. P. and L. G. Anderson (1986), On the origin of the chemical properties of the Arctic Ocean halocline, *J. Geophys. Res*., **91**, 10,759-10,767.

Markus, T., J. C. Stroeve, and J. Miller (2009), Recent changes in Arctic sea ice melt onset, freezeup, and melt season length, *J. Geophys. Res*., **114**, C12024, doi:10.1029/2009JC005436.

Nishino, S., K. Shimada, M. Itoh, M. Yamamoto-Kawai, and S. Chiba (2008), East-west differences in water mass, nutrient, and chlorophyll *a* distributions in the sea-ice reduction region of the western Arctic Ocean, *J. Geophys. Res*., **113**, C00A01, doi:10.1029/2007JC004666.

Nishino, S., K. Shimada, M. Itoh, and S. Chiba (2009), Vertical double silicate maxima in the sea-ice reduction region of the western Arctic Ocean: Implications for an enhanced biological pump due to sea-ice reduction, *J. Oceanogr*., **65**, 871-883, doi:10.1007/s10872-009-0072-2.

Nishino, S., T. Kikuchi, M. Yamamoto-Kawai, Y. Kawaguchi, T. Hirawake, and M. Itoh (2011), Enhancement/reduction of biological pump depends on ocean circulation in the sea-ice reduction regions of the Arctic Ocean, *J. Oceanogr*., **67**, 305-314, DOI: 10.1007/s10872-011-0030-7.

Nishino, S., M. Itoh, W. J. Williams, and I. Semiletov (2013), Shoaling of the nutricline with an increase in near-freezing temperature water in the Makarov Basin, *J. Geophys. Res. Oceans*, **118**, 635-649, doi:10.1029/2012JC008234.

Proshutinsky, A., R. Krishfield, M.-L. Timmermans, J. Toole, E. Carmack, F. McLaughlin, W. J. Williams, S. Zimmermann, M. Itoh, and K. Shimada (2009), Beaufort Gyre freshwater reservoir: State and variability from observations, *J. Geophys. Res*., **114**, C00A10, doi:10.1029/2008JC005104.

Spreen, G., L. Kaleschke, and G. Heygster (2007), Sea ice remote sensing using AMSR-E 89 GHz channels, *J. Geophys. Res*., **113**, C02S03, doi:10.1029/2005JC003384.

Woodgate, R. A., K. Aagaard, J. H. Swift, W. M. Smethie, and K. K. Falkner (2002), *Chukchi Borderland Cruise CBL2002 Arctic West - Phase II (AWS-02-II)*, 51 pp, University of Washington, Seattle, WA, USA, available at http://psc.apl.washington.edu/CBL.html.