Study on the Diagnostics and Projection of Ecosystem Change Associated with Global Change

Project Representative

Sanae Chiba Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology

Authors

Eiji Watanabe[*1], Maki Aita-Noguchi[*1], Naomi Harada[*1], Akio Ishida[*1, 2], Michio J. Kishi[*1, 3] and Toshiro Saino[*1]

*1 Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology

*2 Department of Social and Environmental Studies, Tokoha University

*3 Faculty of Fisheries Sciences, Hokkaido University

The future conditions of Arctic sea ice and marine ecosystems are of interest not only to climate scientists but also to economic and governmental bodies. However, the lack of widespread, yearlong biogeochemical observations remains an obstacle to understanding the complicated variability of the Arctic marine biological pump. Here we address an early winter maximum of sinking biogenic flux in the western Arctic Ocean and illustrate the importance of shelf-break eddies to biological pumping from wide shelves to adjacent deep basins using a combination of yearlong mooring observations and three-dimensional numerical modeling. The sinking flux trapped in the present study included considerable fresh organic material with soft tissues and was an order of magnitude larger than previous estimates. We then predicted that further reductions in sea ice would promote the entry of Pacific-origin biological species into the Arctic basin and accelerate biogeochemical cycles connecting the Arctic and subarctic oceans.

Keywords: pan-Arctic ice-ocean model, biological pump, mesoscale eddy, sea ice reduction

1. Marine biological pump in the western Arctic basin

Evaluating the responses of biogeochemical cycles to decreasing sea ice is important to predict long-term trends in fishery resources. Improved summer light conditions have been reported to enhance planktonic photosynthesis in the Eurasian pelagic area of the Arctic Ocean. Furthermore, the accumulation of nutrient-poor freshwater suppressed the primary production of phytoplankton in the central Canada Basin during the 2000s. Biological pump of particulate organic carbon (POC), which is one of the sequestration mechanisms of atmospheric CO_2 to deep sea, has been reported to be ineffective in the cryopelagic Canadian Arctic deep basins [1]. Whereas primary productivity of phytoplankton could be modest even under sea ice cover, low abundance of ballast particles such as shell-bearing micro-planktons might have prevented biological materials from sinking toward deep layers. On the other hand, lateral transport of resuspended bottom sediments played a role in oceanic carbon sink in the western Arctic off-shelf regions. These findings were obtained by time series sediment trap measurements in the deep Canada Basin, the Canadian Beaufort shelves, the northern Laptev Sea, and the Nordic seas (Fig. 1). However, there are many gaps to fill to achieve a comprehensive explanation of the spatial and temporal variability of biological pump processes under rapid environmental changes of the Arctic Ocean. The relative contribution of the lateral transport of shelf-origin materials to basin interiors remains uncertain. The western Canada Basin and the Chukchi Borderland, which have experienced a remarkable reduction of sea ice and substantial biological shifts during the early 21st century, are located downstream of Pacific-origin water that obtains heat, nutrients, and organic material over the shallower Chukchi shelf. Thus, further investigations of the physical and biogeochemical properties along the Pacific water pathway will provide valuable information regarding communication between the Bering Sea and the central Arctic.

We detect a significant amount of sinking biogenic materials with particulate organic nitrogen (PON) using measurements from sediment traps deployed in the Northwind Abyssal Plain (NAP; Fig. 1) since autumn 2010. We then address the background mechanisms and possible future conditions of the biological pump from the viewpoint of shelf water transport using an eddy-resolving (5-km grid size) framework in a pan-Arctic sea ice-ocean model [2]. Our findings reveal the effective role of Beaufort shelf-break eddies in biological pumping from the Chukchi shelf to the Canada Basin. Because these eddies are generated in summer immediately after shelf blooms of phytoplankton, biological activity can continue even during eddy migration towards the central Arctic. Whereas the so-called "lateral biological pump" have meant the resuspension and eddy-induced transport of bottom sediments composed of old carbon, the presented process may sustain marine ecosystems in seasonal ice zones of the Arctic basins.

2. Roles of shelf-break eddies in sinking biogenic fluxes

A seasonal experiment using our pan-Arctic sea ice-ocean model demonstrated that the PON flux at Station NAP initially increased in July and reached summer and early winter peaks at depths of 180 and 1,300 m (Fig. 2). These modelled fluxes were larger than those derived from our shallow sediment trap data, but the modelled flux values at the greater depth were similar to the corresponding trap data. The carbon sink derived from the simulated PON flux at a 180 m (1,300 m) depth was 258 (59) mgC m^{-2} from May to December. Because shelf bottom water is considered to be the crucial nutrient source for biological production in the basin area, its pathway was addressed using a colored passive tracer in the model experiment. The tracer signal clearly indicated that the shelf bottom water reached Station NAP at the peak timing of PON flux in this case. Moreover, a distinct minimum-temperature layer, which was isolated from the surface mixed layer, appeared at a depth of 100–200 m from

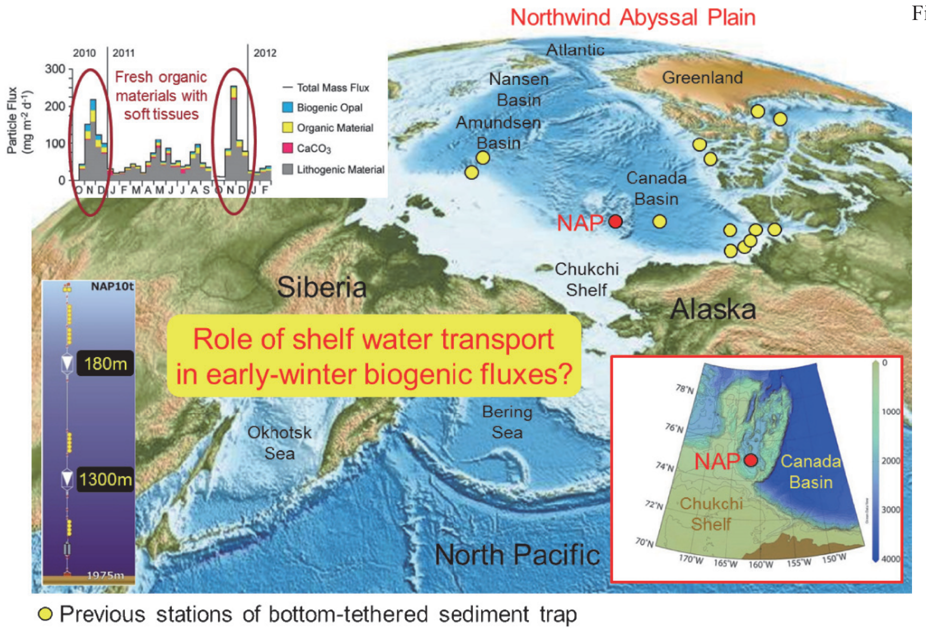

Fig. 1 Topography map in the Arctic-subarctic regions. Red dots show the location of Station NAP, where our sediment trap has been deployed since October 2010. Yellow dots show the locations of previous yearlong bottom-tethered sediment traps (See also Fig.1 in Honjo et al. [2010]). The inset shows the time series of observed sinking particle fluxes. Modified from Watanabe et al. [2014].

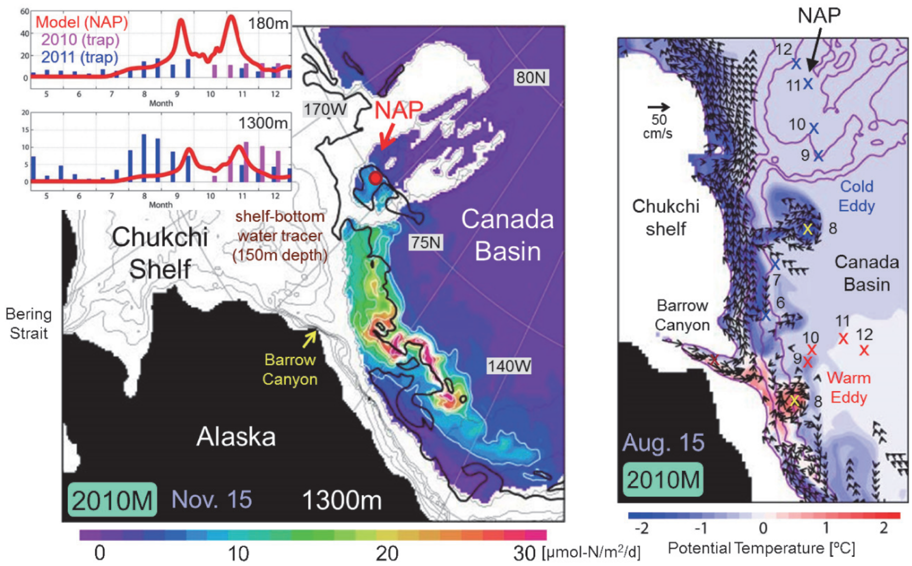

Fig. 2 (left) PON flux at a depth of 1,300 m on November 15 in the 2010M case [µmol-N m^{-2} d^{-1}]. The modeled tracer concentration of shelf bottom water at 150 m depth is 0.1 along black contours. Inset figures show the flux time series at 180 and 1,300 m depths; Pink and blue bars represent the observed fluxes in 2010 and 2011, respectively. The modeled fluxes in the 2010M case at Station NAP are shown by solid lines, respectively. (right) Potential temperature [°C] (color shade) and ocean horizontal velocity at a 100 m depth on August 15 in the 2010M case. The unit vector is 50 cm s^{-1}, and vectors of velocity less than 5 cm s^{-1} are hidden. Blue (red) crosses indicate the locations of cold (warm) eddy centres in each month (e.g., "6" denotes June 15, "7" denotes July 15, and so on). Modified from Watanabe et al. [2014].

October to December. This cooling event was detected by the sediment trap sensors and indicated the lateral advection of cold water mass.

Here, we propose that mesoscale eddies originating in the vicinity of the Beaufort shelf break play an important role in biological pumping in the western Arctic basin. Our model reproduced both cold and warm shelf-break eddies. One such cold eddy migrated westward along the pathway of basin-wide Beaufort Gyre circulation and passed Station NAP in November. This eddy, generated in June, carried near-freezing shelf water and retained its cold core at least until December. Due to phytoplankton bloom and zooplankton grazing, the PON concentration within the cold eddy increased from June to August in most of the water column and exceeded 10 µmol-N m^{-3} until the eddy passed Station NAP in November. Because the PON concentration within the cold eddy was higher than that in the surrounding basin water, the second peak of PON flux occurred in early winter at Station NAP. Warm eddies generated after sea ice retreat in late summer had greater contribution to PON flux compared with cold eddies produced under sea ice in early summer. A higher PON flux was localized in part of the southern Canada Basin, where baroclinic eddies traced the anti-cyclonic Beaufort Gyre. As well as cold eddies, the hydrographic and biogeochemical properties of warm eddies reflected the environment of Barrow Canyon during their generation [3]. In the case of warm eddies, the PON concentration exceeded 100 µmol-N m^{-3} from the eddy generation period in August. The higher water temperatures in the ocean surface layer of warm eddies kept their pathways away from the sea ice cover; thus, both the warmer conditions and the greater light intensity favoured phytoplankton photosynthesis and subsequent zooplankton grazing. We checked the PON flux north of Barrow Canyon (NBC), where a warm eddy passed on November 15. The peak fluxes of 150 and 38 µmol-N m^{-2} d^{-1} at 180 and 1,300 m, respectively, were several times larger than those within the cold eddy at Station NAP. In the Mackenzie shelf region, it has been reported that the resuspension of shelf bottom sediments and cross-shelf transport of POC were induced by buoyancy-driven convection following winter sea ice formation [4] and by baroclinic eddies [5]. In contrast, our results showed that high plankton activity was accompanied by the development and migration of summer eddies in the downstream region of the Pacific water pathway.

3. Impact of sea ice reduction

The eddy-induced early-winter biological pump would be enhanced by sea ice retreat. To address the impact of sea ice reduction on the early winter PON flux, we performed two additional experiments in which the sea ice thickness given as the initial condition on March 1 was multiplied by 2.0 or 0.5 in the entire model domain (named as Ice2.0 and Ice0.5 cases, respectively). The total sea ice extent on October 1 was 6.9 (3.9) × 10^6 km^2 in the Ice2.0 (Ice0.5) cases (Fig. 3). The average summer sea ice extent during the 1990s was similar to the Ice2.0 case, and the 2012 sea ice margin was located farther north than that seen in the Ice0.5 case. The modeling results indicate that the magnitude of the biological pump might have doubled over the last two decades in the southwestern Canada Basin. This trend arose because the eddy-driven transport of shelf-origin nutrients and biological materials towards the Canada Basin

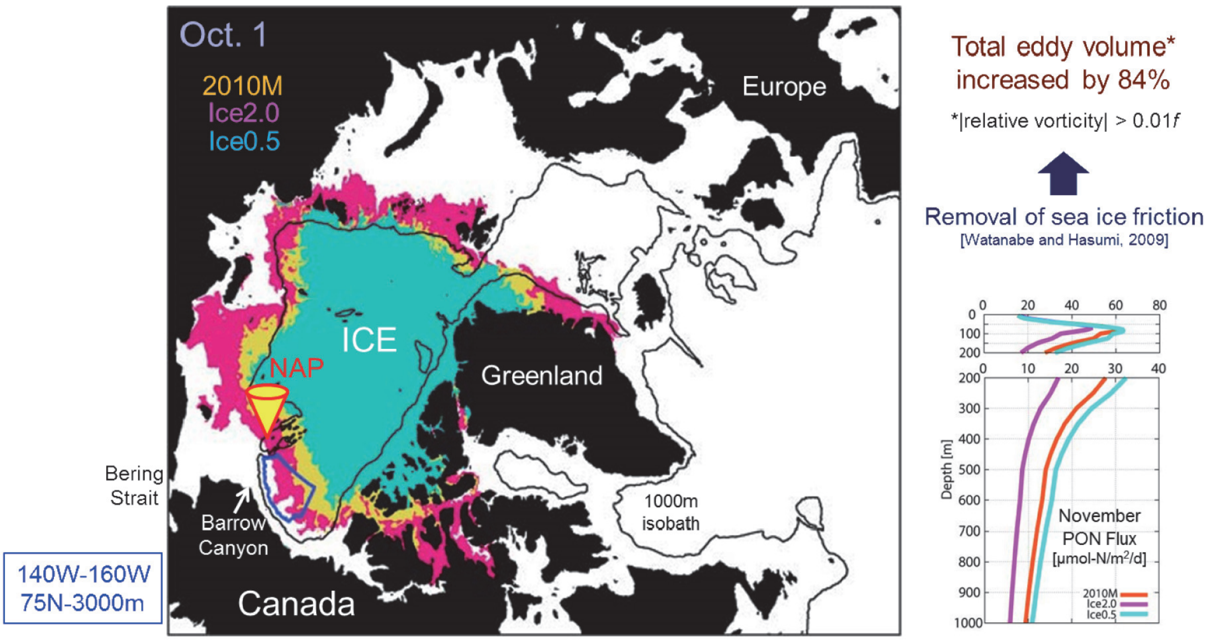

Fig. 3 (left) Sea ice distribution on October 1 in the (orange) 2010M, (pink) Ice2.0, and (sky blue) Ice0.5 cases. Black contours represent 1,000 m isobaths. The location of Station NAP is shown by a yellow cone. (right) The vertical profile of November mean PON flux in each case [µmol-N m^{-2} d^{-1}]. The average region is the southwestern Canada Basin, which is outlined by a blue contour in the left figure. Modified from Watanabe et al. [2014].

was promoted. The factor for this difference could be attributed to changes in shelf bloom and eddy activity, respectively. The improved light conditions owing to sea ice reduction increased phytoplankton biomass in early summer. The earlier shelf bloom hastened nutrient depletion and rapidly reduced the PON content per each eddy from summer to autumn. On the other hand, the removal of sea ice drag increased the Barrow Canyon outflow and eddy kinetic energy [6]. Additionally, the enhanced eddy generation and development promoted greater PON export to the deep basin under less sea ice condition. We can indicate that eddy-induced lateral nutrient supplies to the euphotic zone have favored the increasing phytoplankton growth in the Canada Basin, whereas the deepening nutricline in part caused by sea ice reduction may suppress primary productivity. Thus, the environmental transition for lower trophic ecosystems in the marginal Beaufort Gyre, including the NAP area, differs from the situation in the central gyre. In addition, the recent acceleration of Beaufort Gyre was reported by drifting buoy measurements. The faster gyre circulation is expected to reinforce the westward transport of Chukchi shelf water and to induce earlier peaks of PON flux at Station NAP. Now, we need to consider how far the area of high biological activity will spread in the near future and how ocean dynamics will contribute to the pan-Arctic marine ecosystem. Because mesoscale eddies have been detected in multiple shelf-basin boundary regions of the Arctic Ocean, the ecological function of laterally transported organic materials is likely to gain more importance as a food source for plankton and higher-trophic organisms in the basin interior.

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地球環境変化に伴う生態系変動の診断と予測に関する研究

課題責任者
千葉　早苗　　海洋研究開発機構　地球環境変動領域

著者
渡邉　英嗣 *[1]，相田（野口） 真希 *[1]，原田　尚美 *[1]，石田　明生 *[1,2]，岸　　道郎 *[1,3]，才野　敏郎 *[1]
*1　海洋研究開発機構　地球環境変動領域
*2　常葉大学　社会環境学部
*3　北海道大学　水産科学研究院

北極海における近年の急激な海氷減少は大気・海洋場への影響も含めて社会的関心事の１つとなっている。ベーリング海峡から流入する太平洋起源水は北極海の熱・淡水・栄養塩の主要な供給源であり、その輸送は西部北極海の海氷変動や海洋生態系と密接な関係にある。独立行政法人・海洋研究開発機構では、太平洋側北極海のノースウィンド深海平原（NAP）にセディメントトラップ係留系を設置し、2010 年 10 月から現在に至るまで沈降粒子の時系列観測を実施している。セディメントトラップによる現場観測は北極海でもこれまでにカナダ側のマッケンジー陸棚縁やロシア側のラプテフ海北部で行われてきたが、太平洋起源水の下流域にあたる NAP 周辺で複数年に渡って実施されたのは今回が初めてである。その時系列観測結果からは、植物プランクトンの光合成が活発化する夏季に加えて、極夜が始まる 10 月以降に新鮮な珪藻や二枚貝幼生を多く含む沈降粒子量極大が捉えられており、沈降粒子の中には泥質の鉱物粒子も存在することから、陸棚域からの有機物の水塊輸送（移流）が関与していることが推察される。そこで本課題では北極海全域を対象にした海氷海洋物理モデル COCO に低次海洋生態系モデル NEMURO を結合させた数値実験を行い、陸棚海盆境界域で生成される海洋渦が北極海盆域の生物ポンプにとって重要な役割を担っていることが示唆された。この水平数十 km スケールの海洋渦は夏季に太平洋起源水がバロー峡谷からカナダ海盆域に流入する際に生成されるものであり、動植物プランクトンが自身の生物活動によって渦内部で増え続けることもモデル計算の結果から示されている。また海氷の条件を変える感度実験の結果では、北極海で海氷の減少が進むと渦生成も促進されることから、北極海盆域における極夜時の生物ポンプは徐々に活発化していることが示唆された。ノースウィンド深海平原において魚類の餌となる動植物プランクトンの生息環境が向上していることが本研究で示唆されたことで、将来的には北極海盆域が水産資源のターゲットになり得ると考えられる。今後も当海域において時系列観測を継続するとともに、高精度な数値モデリングを組み合わせることで、より詳細な北極海洋生態系プロセスが明らかになっていくことが期待される。

キーワード : 北極海物理生態系結合モデル , 生物ポンプ , 中規模渦 , 海氷減少