HOKKAIDO UNIVERSITY

Title	Biogeochemical cycles in the western North Pacific and its marginal sea : Quantitative evaluation of nutrient supply and particle export fluxes
Author(s)	DENG, Huailin
Description	この博士論文の全文は利用可能日以降に公開されます。利用可能日以前の閲覧方法は https://www.lib.hokudai.ac.jp/dissertations/copy-guides/ をご参照ください。
Degree Grantor	北海道大学
Degree Name	博士(環境科学)
Dissertation Number	甲第16682号
Issue Date	2025-12-25
DOI	https://doi.org/10.14943/doctoral.k16682
Doc URL	https://hdl.handle.net/2115/98656
Type	doctoral thesis
File Information	DENG_Huailin_summary.pdf, 全文の要約

Hokkaido University Collection of Scholarly and Academic Papers : HUSCAP

学 位 論 文 内 容 の 要 約/Dissertation Summary

博士（環境科学） 氏 名/Applicant DENG Huailin

学 位 論 文 題 名/Title of Dissertation

Biogeochemical cycles in the western North Pacific and its marginal sea: Quantitative evaluation of nutrient supply and particle export fluxes

（北西太平洋及び縁辺海における生物地球化学的サイクル：
栄養物質の供給と粒子態物質の輸出フラックスの定量評価）

1. Introduction

The net oceanic CO_2 sink was 1.2 ± 0.5 Pg C yr^{-1} in the 1980s and 2.5 ± 0.6 Pg C yr^{-1} in the years 2010-2019 according to Intergovernmental Panel on Climate Change (IPCC) assessments (ICPP, 2023). More recently, it reached 2.9±0.4 Pg C yr^{-1} during 2013–2022, accounting for about 26 % of total CO_2 emissions over that decade (Friedlingstein et al., 2023). These estimates highlight the ocean's critical role in the global carbon cycle as a major carbon reservoir. Meanwhile, anthropogenic CO_2 emissions pose a significant threat to humanity by amplifying the greenhouse effect and accelerating global warming. Importantly, the ocean reduces this threat through various carbon pump mechanisms that regulate atmospheric CO_2 levels and thus influence climate change (Volk and Hoffert, 1985; Falkowski et al., 2000). Among these ocean carbon pumps, the biological carbon pump plays a particularly important role. It transports particulate organic carbon, produced by phytoplankton through photosynthetic fixation of atmospheric CO_2, from the euphotic layer to the deep ocean, where it can be sequestered for centuries (Riebesell et al., 2007; Honjo et al., 2008; Sanders et al., 2014; Boyd et al., 2019). The biological carbon pump exports approximately 10 Pg C y^{-1} from the surface layer and contributes to sequestering around 1300 Pg C in the ocean interior (Boyd and Trull, 2007; Carter et al., 2021; Siegel et al., 2023). Atmospheric CO_2 concentration would be ~300 ppmv higher than present in the absence of the biological pump, according to modelling (Ito and Follows, 2005).

Given its significant role in long-term carbon sequestration, understanding the factors that control the biological carbon pump's efficiency is essential for predicting future climate change. The efficiency of the biological carbon pump is primarily governed by two key processes. First, the upward supply of macronutrients (nitrate, phosphate, and silicate) and trace elements (e.g., iron) from subsurface waters supports phytoplankton growth and primary production in the surface ocean (Boyd et al., 2007; Moore et al., 2013). Second, the downward export of biogenic particles, including organic matter and ballast minerals such as biogenic silica and $CaCO_3$, facilitates

long-term carbon transfer to the deep ocean (François et al., 2002; Klaas and Archer, 2002). These processes are influenced by both physical dynamics (e.g., vertical mixing, upwelling) and ecosystem structure (e.g., plankton community composition), and together determine the magnitude and variability of the biological carbon pump.

While the biological carbon pump plays a globally significant role in regulating atmospheric CO_2, its efficiency exhibits strong spatial variability, primarily driven by regional differences in nutrient supply, phytoplankton community structure, and ocean circulation. To better understand the mechanisms controlling carbon export and sequestration, it is essential to investigate ocean regions with contrasting environmental conditions. This study focuses on the western North Pacific and the southern Sea of Okhotsk, which may exhibit unique oceanographic settings and biogeochemical cycles.

Biogeochemical cycles refer to the complex interplay of biological, geological, and chemical processes through which chemical materials (e.g., carbon (C), iron (Fe), silicon (Si), etc) are transported and transformed across the biosphere, hydrosphere, lithosphere, and atmosphere (Hedges, 1992). The western North Pacific, especially the subarctic gyre (SAG) and its marginal sea, is one of the key regions for studying oceanic biogeochemical cycles due to their variation in physical, chemical, and biological characteristics. These characteristics lead to diverse nutrient supply, phytoplankton community composition, and carbon export processes.

In summary, although the broad biogeochemical characteristics of the western North Pacific and its marginal sea have been documented, key uncertainties remain regarding the mechanisms that regulate primary production and carbon export. The overarching goal of this thesis is therefore to advance our understanding and provide a more complete picture of the biogeochemical cycles in this region. To achieve this, the study addresses the following scientific questions:

(1) How do the Fe and macronutrient supply control the phytoplankton abundance in the western North Pacific?

(2) Evaluate the efficiency of the biological carbon pump in the southern Sea of Okhotsk.

2. Phytoplankton community structure in relation to iron and macronutrient fluxes from subsurface waters in the western North Pacific during summer

The subarctic Pacific is known as a high-nutrient, low-chlorophyll (HNLC) area, where macronutrient concentrations persist year-round and phytoplankton growth is primarily constrained by limited iron (Fe) availability. In this area, Fe is supplied to this area though aerosol deposition and oceanic processes. Although aerosol Fe deposition has traditionally been regarded as important, no significant relationship has ever been observed between aerosol Fe input and phytoplankton abundance. This highlights the importance of evaluating oceanic Fe supply from subsurface waters. To elucidate how the nutrient supply from subsurface waters supports the surface phytoplankton productivity in the western North Pacific, we analyzed chemical, physical, and biological data from seawater samples collected during the KH-08-2 expedition of the

R/V *Hakuho Maru*. Fe and macronutrient (N, P, and Si) turbulent fluxes and their flux ratios from the intermediate layer to surface waters were calculated based on their concentrations and vertical diffusivity data set. The phytoplankton community composition in surface waters was determined through CHEMTAX analysis of high-performance liquid chromatography (HPLC)-measured pigment data. In addition, vertical flux divergence was calculated to assess net nutrient transport. Diatom abundance exhibited significant correlation with vertical Fe and macronutrient fluxes, especially with Fe and Si fluxes, and with the Fe/N flux ratio in the study region, indicating that diatom abundance was controlled by Fe and nutrient supply from subsurface waters in summer. Flux divergence revealed that enhanced Fe and Si concentrations in the subsurface layer were supplied from North Pacific Intermediate Water in the subarctic gyre and Kuroshio–Oyashio transition area.

3. Efficient biological shelf pump enhances organic carbon export in the southern Sea of Okhotsk

The southern Sea of Okhotsk also exhibits high primary production. Unlike the subarctic Pacific, this region receives substantial Fe input from the sea ice melt and East Sakhalin Current (ESC) water. These inputs provide a favorable condition for phytoplankton growth, resulting a prominent diatom bloom in early spring. Furthermore, this region is characterized by a unique topography: a board and flat continental shelf extending about 100 km offshore, which transitions into a steep continental slope. This topography setting may indicate a strong shelf pump. Collectively, these features are expected to enhance the particulate organic carbon (POC) export, although the carbon pump processes in this region have yet to be directly investigated. To evaluate the efficiency of the biological shelf pump in the southern Sea of Okhotsk, a time-series sediment trap was moored on the continental slope of the Kuril Basin and settling particle samples were collected. Additionally, bottom sediment samples were collected from the adjacent shelf. Biogenic silica (BSi), POC, lithogenic material, and calcium carbonate ($CaCO_3$) composition were quantified in both sample sets, and “the in situ” and “the external” fluxes were further divided. The temperature at 50 m depth and sea ice concentration were obtained from a moored sensor and satellite data, respectively. The in situ fluxes exhibited clear seasonality with low values in winter and high values in spring. The in situ POC and $CaCO_3$ fluxes accounted for ~60% of the integrated values, while in situ BSi was comparable to the external over the sampling period. In April, elevated POC flux coincided with increased BSi and $CaCO_3$. $CaCO_3$ was the most dominant carbon ballast. Overall, the southern Sea of Okhotsk acts as an effective carbon pump compared to other global sites.

4. Conclusions

The biological pump plays a fundamental role in regulating the global ocean's carbon cycle, yet its efficiency and controlling factors vary widely across regions. In the northwestern Pacific and the Okhotsk Sea, the interactions among iron and

macronutrient supply, phytoplankton community composition, and particle export remain poorly understood. This study addresses two key uncertainties: (1) how the supply of iron and macronutrients from subsurface waters regulates phytoplankton community structure in the western North Pacific, and (2) how the biological shelf pump in the southern Sea of Okhotsk enhances particulate organic carbon (POC) export and contributes to the regional carbon budget. This thesis addressed these unresolved issues through a combination of field observations and moored sediment trap experiments.

For finding 1, we investigated the relationships among nutrient fluxes (particularly Fe and macronutrients), flux ratios from NPIW to the surface layer, and phytoplankton community composition, and evaluated the nutrient return path from NPIW to the surface via flux divergence in the western North Pacific. The results first demonstrated that diatom abundance was highly regulated by Fe and macronutrient fluxes, especially Fe and Si fluxes, as well as the Fe/N flux ratio from NPIW in summer. Apart from diatoms, haptophytes and prasinophytes were moderately controlled by Fe and macronutrient fluxes. These findings reveal that despite long-term discussion on Fe source to the surface waters in the western North Pacific, oceanic Fe supply from NPIW plays a more crucial role in the phytoplankton composition, especially diatoms, than aerosol Fe deposition during summer. In addition to the vertical fluxes of Fe and macronutrients, the Fe/N flux ratio also exerts a strong influence on diatom abundance. Moreover, while Fe and Si transportation from the intermediate layer to the surface has previously been hypothesized to occur in the northwestern Pacific, this study demonstrated that such nutrient supply from the NPIW to the surface occurs in the SAG and KOTA.

For finding 2, we assessed the particle export fluxes and ballast material composition in the southern Sea of Okhotsk using a time-series sediment trap. This study is the first to quantitatively evaluate the particle export fluxes in the shelf region of the southern Sea of Okhotsk. The results reveal that this region acts as an effective carbon pump compared to global deep-sea sites, with POC export flux approximately 3.2 times higher than in the subarctic Pacific. The efficient POC export flux in the southern Sea of Okhotsk is mainly ballasted by the $CaCO_3$, while BSi is the dominant ballast component in the subarctic Pacific. The POC and $CaCO_3$ export fluxes in the southern Sea of Okhotsk are contributed by 60% from in situ flux and 40% from external flux, while in situ flux and external flux contribute almost equally to BSi flux. Furthermore, the in situ fluxes exhibit clear seasonality with low values in winter and high values in spring.

This thesis has elucidated two contrasting modes of biogeochemical cycles in the study region, as illustrated in the schematic (Fig. 1). In the biogeochemical cycle of the western North Pacific, diatoms drive the highly efficient POC export in the subarctic Pacific, whose growth is limited by the Fe availability. This thesis addressed the unclear parts: the mechanisms of oceanic Fe and macronutrient supply processes, and the location of the Fe and macronutrient return path from NPIW to the subsurface layer in

the western North Pacific. The revised biogeochemical cycle in the western North Pacific is as follows: (1) Fe and macronutrients are upwelled from NPIW to the surface via the vertical turbulent mixing in the SAG and KOTA; (2) The supply of Fe and Si highly regulates diatom abundance; (3) Diatoms in turn induce the highly efficient POC export in the subarctic Pacific.

In the biogeochemical cycle of the southern Sea of Okhotsk, phytoplankton blooms typically occur following sea ice retreat in spring. These blooms are triggered by the release of Fe from the sea ice melt and freshwater input carried by ESC. This thesis completed the unclear part: quantitative evaluation of POC export flux in the shelf region of the southern Sea of Okhotsk. The revised biogeochemical cycle in the southern Sea of Okhotsk is as follows: (1) Fe input from the sea ice melt and advection of ESC provides a nutrient favorable condition for phytoplankton growth; (2) Phytoplankton blooms occur after sea ice retreat and within the rising temperature in spring; (3) These blooms and external particle supply contribute to an effective biological shelf pump.

In conclusion, this dissertation contributes to a more complete understanding of how the nutrient regimes and biological-shelf combined processes collectively shape carbon export in one of the most dynamic and biogeochemically important regions of the global ocean.

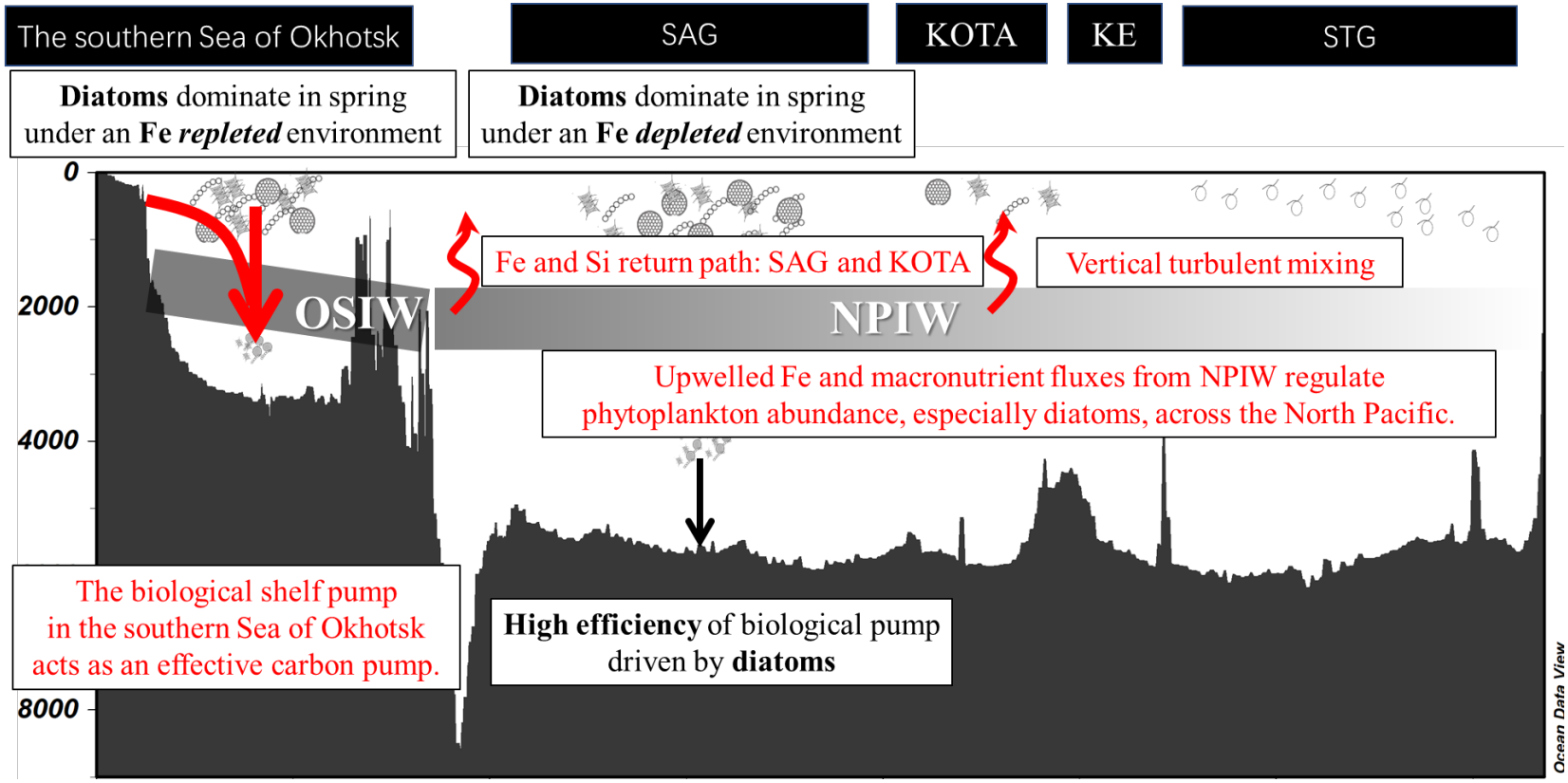


Fig 1. Schematic of biogeochemical cycles in the western North Pacific and its marginal sea.