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学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Development and application of parameterization techniques for next-generation Southern Ocean oceanographic observations

（次世代南大洋海洋観測に対するパラメタリゼーション技術の開発と展開）

[General Background]

The carbon and nutrient cycles in the Southern Ocean (SO) have a great potential for controlling global climate and ecosystem changes. However, the spatiotemporal sparseness of observational data due to severe meteorological and oceanographic conditions in the extremely cold SO has led to significant uncertainties in the studies of the ocean dynamics in the SO. To quantitatively clarify carbon and nutrient cycles and their variations in the entire SO, it is essential to acquire the spatiotemporal high-resolution data for these materials.

Here I have been working on the development of high-precision parameterizations for carbon and nutrient over the SO and have demonstrated their usefulness for the spatiotemporal complementation of observational data. For example, I developed parameterizations for nitrate, dissolved inorganic carbon, and pH over the SO, applying these parameterizations to the SO to determine the oceanic external nitrogen uptake and anthropogenic pH variability there during the period 1990s-2010s [Pan et al. 2020; Li, Pan et al. in submission]. Furthermore, I have attempted to estimate the seawater freshening around the Antarctica and found a rapid freshwater input during the early 21st century by constructing parameterizations of DIC in the open SO and the coastal SO [Pan et al. 2022]. The parameterization technique will dramatically advance the detailed understanding of the ocean dynamics in the SO, and the application of this technique to the sensor-equipped observation instruments, such as Argo float and CTD, must be promising in the future studies of the ocean dynamics in the SO.

[Subjects of this study]

My study aims to promote future studies of spatiotemporal high-resolution ocean dynamics in the SO, and sets the following subjects:

1. To estimate the anthropogenic materials uptake over the SO [Pan et al. 2020].
2. To estimate the glacier-derived seawater freshening around the Antarctica [Pan et al. 2022].
3. To estimate the carbon biological production over the SO [Pan et al. in prep.].
4. To estimate the decoupling between silica and nitrogen from SO to a global scale [Pan et al. in prep.].

[Results]

Subject 1: To comprehend the dynamics of oceanic external nitrogen (N_{ex}) in the SO, I developed a new method to assess the change in the oceanic uptake of N_{ex} (ΔN_{ex}) in the entire SO. I obtained the spatiotemporal distribution of ΔN_{ex} in the SO by applying this method to a high-resolution grid data constructed using ship-based observations. During the 1990s to the 2010s, N_{ex} increased significantly by 67±1 Tg-N year^{-1} in the SO. By comparing this value with the rate of N_{ex} deposition to the ocean, the SO has received ~ 70% of N_{ex} deposition to the global ocean, indicating that it is the largest uptake region of anthropogenic nitrogen into the ocean interior.

Subject 2: I developed a method that first provided us with an expansive understanding of glacier-derived freshening progress over the SOc. Applying this method to the observational data in the SOc from 1926 to 2016, revealed that the rate of glacier-derived freshwater input reached a maximum of 268 ± 134 Gt year^{-1} during the early 21st century. My results indicate that during the same period, glacier melting accounted for 63%, 28%, and 92% of the total freshening occurred in the Atlantic, Indian, and Pacific sectors of the SOc, respectively. This suggests that the ice shelf basal melt in West Antarctica and the Antarctic Peninsula plays a dominant role in the freshening of the surrounding seas.

Subject 3: My new idea of combining neural network parameterization and Biogeochemical Argo floats (BGC-Argo) allowed me to obtain the detailed spatiotemporal distribution of downward export (DE) from the surface ocean to the ocean interior ocean biological production in the modern SO, indicating the total DE of DIC, N and Si of 340.9 ± 22.2 Tmol year^{-1} (Tmol = 10^{12} mol), 39.7 ± 2.6 Tmol year^{-1} and 79.8 ± 5.2 Tmol year^{-1}, which accounts for about 33%, 26% and 62% of the global ocean export given by the previous studies, respectively. Furthermore, the DE of DIC and N in the SO was significantly decreasing at a rate of 0.8% and 2.5% per year during 2007 to 2017, indicating that it may be contributing as positive feedback to the increase in atmospheric CO_2.

Subject 4: I here attempt to quantify the seasonal downward export fluxes of Si and N from surface as well as the upward resupply fluxes by using neural network parameterizations and BGC-Argo, and to directly estimate this decoupling between Si and N over the global surface ocean. I found a contrast downward export ratio of Si and N (Si/N) between the SO of 8:1 and the subarctic Atlantic of 0.1:1. IW-derived water masses with Si/N ≥ 1 are found in the major global upwelling regions, such as the equatorial Pacific and the subarctic Pacific. Lower Si/N in these regions (~2:1) than that in the SO is probably due to the deficiency of Si or the supply of terrestrial-origin iron. The imbalance between the downward export and the upward resupply allows us to identify the main regions of Si removal from the surface that result in the meridional descending gradient of Si in the global ocean.