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Author(s)	朴, 正祐
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学位論文内容の要旨

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学 位 論 文 題 目

Long-term changes in small size-class contribution to total phytoplankton biomass in the northern Chukchi to northern Bering Seas

（北部チュクチ海から北部ベーリング海における小型植物プランクトンの寄与の長期変化）

1. Introduction

The Pacific-Arctic Ocean, especially the Chukchi and Bering Seas, is heavily impacted by climate change, causing shifts in its marine ecosystem. These changes include early sea ice retreat, altered phytoplankton size, and increased freshwater contents (FWC). Small phytoplankton (<2μm) are vital in this ecosystem, playing a growing role due to their resilience in warming conditions. However, the relationship among environmental changes and their biomass remains understudied. Recent environmental shifts in this region, such as sea ice retreat and changes in phytoplankton sizes, have raised concerns about potential ecological consequences, especially with increasing FWC. This research seeks to :

[1] Assess the biomass of small phytoplankton and its contribution to primary production and investigate their relationship with environmental factors with *in-situ* measurement.
[2] Validate the satellite-based phytoplankton size classes (PSCs) algorithm using *in-situ* data to investigate the long-term changes (1998-2020) in small phytoplankton derived from satellite datasets.
[3] Quantitatively assess the associations between these changes and the environmental factors—FWC, sea surface temperature (SST), and sea ice—that contribute to such variations.

The study involves field measurements in the northern Chukchi to northern Bering Seas (NC to NB), satellite data validation, and statistical analyses to discern the main environmental drivers of small phytoplankton changes.

2. Contribution of small phytoplankton to primary production in the northern Chukchi to northern Bering Seas in 2016, 2017 through field observation

This chapter researched dominant phytoplankton communities and biochemical characteristics in the Arctic Ocean. Two Arctic research cruises were conducted in the northern Chukchi Sea aboard the icebreaker R/N Araon in 2016 (ARA07B) and mainly in the NB aboard T/S Oshoro-Maru in 2017 (OS040) to determine dominant phytoplankton communities and the relative contribution of small phytoplankton (<2 μm) to total primary production. The dominant phytoplankton communities were diatoms and *Phaeocystis* during ARA07B, whereas diatoms and Prasinophyte (Type 2) were observed during OS040. Based on agglomerative hierarchical clustering (AHC) analysis, the primary productions of total and small phytoplankton communities varied depending on the sea area. Overall, high primary productions and low contributions of small phytoplankton during both study periods were distributed in the Bering Strait (BS) region, affected by nutrient-enriched Bering Shelf Water. The small phytoplankton group had a higher ratio of Particulate Organic Carbon to chlorophyll-*a* and a higher ratio of Particulate Organic Nitrogen to chlorophyll-*a* than large phytoplankton, suggesting that small phytoplankton have higher carbon and nitrogen contents per unit of chlorophyll-*a* concentration (Lee et al., 2013). Additionally, small phytoplankton had lower C:N ratios than large phytoplankton, indicating that small phytoplankton incorporate more nitrogen in relation to carbon into their bodies and thus produce nitrogen-rich organic matters, which could be relatively faster regenerated than carbon-rich organic matters such as carbohydrates. It was found that the annual contribution of small phytoplankton is not related to SST. In further study, where research extended the target area to the NC, the absence of a relationship with SST is

likely to have been observed.

3. Estimation of small phytoplankton distribution using satellite ocean color images in the northern Chukchi to northern Bering Seas

Chapter 3 were conducted for validation of a bio-optical algorithm and climatological analysis. This chapter successfully validated an optical algorithm for predicting PSCs, achieving an accuracy of 84% in identifying dominant size groups. Climatological analysis (1998 to 2020) revealed distinct regional patterns in small phytoplankton dominance. The BS exhibited low and consistent small phytoplankton contributions, while the NB displayed a peak in July, likely following the phytoplankton bloom. In the NC consistently showing substantial contributions throughout the year. These findings emphasize the ecological significance of small phytoplankton, especially in the NC, and suggest a link between their dominance and sea ice conditions.

4. Environmental factors that affect small phytoplankton community in the northern Chukchi to northern Bering Seas via numerical studies

A rise in satellite data since 2002 on the NC revealed expanded areas dominated by small phytoplankton, likely linked to sea ice retreat. Monthly trends indicated a decline in September but a slight increase in July and August. Sea ice concentration correlated with small phytoplankton dominance. The BS region maintained a consistently low small phytoplankton contribution (<22%), possibly influenced by nutrient-rich conditions. A decline in primary productivity was noted in the western Bering Strait. The NB region experienced the lowest small phytoplankton contribution in 2011 but showed increasing trends in July and August. The contribution of small phytoplankton varies over decades, showing a correlation with changes in the Pacific Decadal Oscillation (PDO) index. The NC saw contributions ranging from 32.9% to 56.2%, the BS remained relatively stable (0.8% to 8.7%), and the NB showed an increasing trend from 27.0% to 43.3%. Opposing tendencies in the NC and NB suggested the influence of PDO-like SST anomalies, impacting sea ice conditions. A significant negative correlation between SST and small phytoplankton contribution was observed in the NC. FWC exhibited a positive influence in the NC but showed modest correlations in the BS and NB. Sea ice concentration notably impacted the NC. Multiple regression analysis identified FWC as the most significant variable in the NC, explaining 69.8% of the variance. The freshwater from the Beaufort Gyre flows from the east of the Beaufort Sea to the NC region along the coast. It is suggested that this freshwater influence from the Beaufort Gyre contributes to the higher small phytoplankton contribution observed in the NC region.

5. Summary and Conclusion

Small phytoplankton dynamics are intricately tied to regional factors, including sea ice conditions and PDO. The NC, characterized by its sensitivity to FWC, emerged as a focal point for understanding small phytoplankton variations. The Arctic cruises in 2016 and 2017 elucidated dominant phytoplankton species and their contributions, with phytoplankton in the NC exhibiting distinct biochemical characteristics. Regional variations correlated with PDO index fluctuations. In previous studies, research on the relationship between small phytoplankton and the environment was limited to the southern part of the Chukchi Sea, focused on short-term analyses. These studies provided only fragmented knowledge about the effects of various environmental factors. However, this research illuminated in the NC how the contribution of small phytoplankton fluctuates over a period of more than 20 years and clarified the extent to which various environmental factors influence small phytoplankton. Based on this, predictions were made about potential future changes in small phytoplankton in the NC.