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

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学 位 論 文 題 名/Title of Dissertation

Estimation of freshwater discharge into the Northeast Pacific
from the Alaskan mountains and its effects on the subtropical
and equatorial ventilated thermocline
（アラスカ山岳地帯から北東太平洋への淡水流出の推定
および亜熱帯と赤道の通気水温躍層への影響）

Chapter 1: General Introduction

Freshwater input into the ocean is crucial for shaping oceanic conditions and climate systems. It primarily originates from atmospheric processes (evaporation and precipitation) and terrestrial sources (river discharge). These inputs affect ocean salinity, stratification, and circulation, which have broad implications for global ocean dynamics. Evaporation increases salinity in areas of excess evaporation, such as subtropical gyres, while precipitation freshens the surface waters, particularly in high-latitude and tropical regions.

In addition to atmospheric processes, river discharge, particularly from large rivers and glacial meltwater, is a significant source of freshwater to the ocean. The global average volume of river discharge is around 36,055 km^3/yr. In regions such as the subpolar gyre, freshwater influx from rivers and glaciers alters salinity and stratification, impacting both local and broader oceanic circulation patterns.

The hydrological cycle in the Alaska mountain regions plays a crucial role in freshwater discharge to the Pacific Ocean. The region's varied topography and climate lead to significant freshwater discharge from rainfall, snowmelt, and glacial melt, with minimal human activity influencing the processes. The climate is diverse, with cold polar climates in higher latitudes and milder, boreal conditions in the lower latitudes. Temporal climate variations, such as the Pacific Decadal Oscillation, also affect freshwater discharge in the region.

In the Pacific Ocean, freshwater discharge influences ocean circulation, particularly in the subpolar and subtropical gyres. These large-scale gyres are vital for heat and freshwater redistribution, nutrient transport, and global climate patterns. The subpolar gyre, which is located north of 40° latitude, is characterized by counterclockwise circulation and receives freshwater from precipitation and river discharge. This influences the sea surface salinity and stratification, which can affect ocean currents like the Oyashio Current and the Alaskan Stream. Freshwater from the subpolar gyre may impact the subtropical gyre and influence the equatorial ocean dynamics via thermal circulation processes.

This dissertation focuses on the dynamics of freshwater flux from Alaska's mountainous regions to the northeast Pacific Ocean. Previous studies have provided historical discharge estimates (700−900 km^3/yr from 1961−2014), but many models overlook the spatial variability due to complex topography, diverse land cover, and climatic conditions. Chapter 2 addresses the need for more accurate discharge estimations by using a hydrological model that accounts for this variability. Additionally, it explores the relationship between Alaska discharge and large-scale atmospheric phenomena like the North Pacific Oscillation (NPO), as well as its impact on sea surface salinity in the Alaskan Stream. Chapter 3 examines how freshwater discharge into the subpolar gyre influences the equatorial thermocline, particularly during extreme freshwater events such as ice sheet collapses. This research aims to enhance our understanding of the long-term variations in Alaska discharge and its potential impact on ocean circulation and climate.

Chapter 2: Estimation of freshwater discharge into the Northeast Pacific from the Alaskan mountains

The discharge of freshwater from Alaska's catchments is characterized by substantial quantity and significant variability, influenced by the interplay of climatic changes and the region's mountainous topography. This variability has cascading impacts on coastal circulation and extends beyond the regional scale. The study aimed to estimate the quantity and variability of this discharge, considering the fluctuations in temperature and precipitation over recent decades. Using the Soil and Water Assessment Tool (SWAT), a process-based hydrological model, the study effectively estimated Alaska's discharge, incorporating modified melting processes and accounting for the complex spatial variability in land cover and soil features at the basin scale.

The study makes several key contributions: i) It provides an updated estimate of discharge in recent years. ii) It analyzes the temporospatial variability of discharge. iii) It explores the first-ever connection between the continental discharge and large-scale oceanic circulation in the region. The results indicate an annual discharge of 14,396 ± 819 m^3/s with significant seasonal variability. Discharge remains at a baseflow level from January to March when temperatures are below freezing, then rises sharply in April due to increasing temperatures. A peak flow of about 30,000 m^3/s occurs in June, followed by a decline despite high rainfall in late summer and early autumn, with discharge returning to baseflow in December. Meltwater contributes around 53% of the annual discharge, exerting more influence than rainfall on seasonal variations.

Interestingly, ungauged basins, despite covering smaller areas, contribute approximately 59% of the discharge, while the remaining 41% comes from five gauged basins. The study also finds that while the annual discharge shows no significant trend, interannual variations during summer and autumn are increasing. A decadal trend is evident in the discharge from 1982 to 2022. Moreover, a significant correlation between the 5-year running mean of Alaska discharge and the North Pacific Gyre Oscillation (NPGO) index suggests that the North Pacific Oscillation (NPO) may influence decadal variations in discharge.

Additionally, the study reveals a significant correlation between interannual variations in Alaska discharge and sea surface salinity (SSS) in the Alaskan Stream, located in the upper branch of the overturning circulation pathway. The correlation, which becomes significant with a time lag of two to three months, indicates that the regional discharge could influence seawater anomalies in the North Pacific.

The study highlights the connection between large-scale climatic variations, Alaska discharge variations, and oceanic processes, offering a deeper understanding of the atmosphere-land-ocean relationship. However, there are two limitations in the study: first, the temperature-index method used to calculate meltwater is efficient but simple, and more complex methods with higher spatial resolution are recommended for glacierized areas. Second, improvements in parameterization, based on more observational data, could enhance the model's accuracy.

Chapter 3: Effect of freshwater discharge at the Northeast Pacific on the subtropical and equatorial ventilated thermocline

This study uses numerical experiments based on the MITgcm to investigate how freshwater input (FWD) in the subpolar gyre affects the temperature, salinity, and density distributions in the ocean, with a focus on equatorial thermocline dynamics. The experiments provide insights into the mechanisms by which freshwater from high-latitude regions can influence ocean circulation and climate patterns.

The control experiment, which did not include any freshwater input, showed that warm water from the subtropical gyres cools and subducts into the subsurface. This cooled water moves along isopycnal surfaces, reaching the equator and upwelling in the eastern equatorial Pacific. The upwelling of this cooler water contributes to the east-west slope of the thermocline, supporting the formation of the cold tongue, a crucial feature for equatorial heat exchange and global climate feedbacks.

Experiment I, which incorporated a freshwater balance (E−P), showed significant effects on sea surface salinity (SSS) and surface density distributions. In the southern hemisphere, positive E−P led to an increase in salinity in the subtropical gyre, which affected subsurface thermal structures through subduction, causing warming at depths of 200–400 meters in the equatorial Pacific. In contrast, the northern hemisphere showed a decrease in salinity in the subpolar gyre, resulting in a cooling effect on the subtropical gyre.

In Experiment II, the inclusion of boundary freshwater discharge (FWD) along the northern subpolar gyre intensified salinity anomalies and enhanced the southward transport of low-salinity water. This led to more pronounced subsurface warming and slight cooling in the upper layers of the equatorial Pacific.

Experiment III modeled an extreme FWD scenario, driven by the collapse of the Cordilleran Ice Sheet (CIS), resulting in substantial oceanic changes across both hemispheres. In the North Pacific, the subpolar gyre became dominated by low-salinity water, which was transported southward into the subtropical gyre. This redistribution of salinity caused cold water to move from the subpolar gyre to the subtropical gyre along isopycnal surfaces, contributing to cooling in the upper layers of the western equatorial Pacific. Meanwhile, in the South Pacific, the subtropical gyre experienced low salinity and high temperatures due to the deepening of isopycnal levels. This warm water was transported equatorward, warming the equatorial thermocline, especially at depths below 200 meters in the western equatorial Pacific and in the shallower eastern equatorial region.

As FWD increases, the east-west sea surface temperature (SST) gradient along the equator weakens, and the equatorial thermocline deepens. Both the SST gradient and the thermocline depth are critical drivers of equatorial Pacific climate phenomena, such as El Niño. The study suggests that enhanced FWD from high-latitude regions can significantly influence the thermal structure along the equator, potentially altering regional and global atmospheric circulation patterns.

Chapter 4: General Conclusions

This study investigates the freshwater discharge (Alaska discharge) from the Alaska region and its cascading effects on oceanic processes, divided into two parts. The first part estimates the Alaska discharge using the Soil and Water Assessment Tool (SWAT) for the period 1982–2022, with modifications for melting processes. The results show an annual average discharge of 14,396 ± 819 m^3/s, with meltwater contributing approximately 53%. The discharge exhibits strong seasonal variation, peaking in June due to snow and ice melting and maintaining baseflow levels in winter. The interannual variation correlates with salinity anomalies in the Alaskan Stream, indicating that Alaska discharge affects salinity dynamics in the North Pacific salt pathway. Decadal variations in discharge are linked to the NPGO index, highlighting the role of atmospheric phenomena like the North Pacific Oscillation (NPO) in long-term discharge variability. These findings show that Alaska discharge influences salinity and ocean circulation in the North Pacific.

The second part of the study uses numerical experiments with the MITgcm to explore the impact of freshwater discharge from the subpolar gyre on the equatorial thermocline. The control experiment without freshwater forcing shows that warm water from the subtropical gyres cools and subducts into the subsurface, reaching the equator and contributing to the formation of the cold tongue in the eastern equatorial Pacific. Under freshwater forcing scenarios, including those driven by $E-P$ and boundary discharge, salinity anomalies increase, propagating downstream and leading to cooling effects at the equator. In contrast, the South Pacific experiences warming at depths of 200–400 meters in the equatorial Pacific due to high evaporation in the subtropical gyre. Extreme freshwater scenarios, driven by the collapse of the CIS, result in low-salinity water being transported southward from the North Pacific subpolar gyre, enhancing cooling in the western equatorial Pacific, while warming effects dominate in the equatorial thermocline, primarily from the South Pacific.

The study further finds that increased freshwater input weakens the east-west sea surface temperature (SST) gradient and deepens the equatorial thermocline, resembling an El Niño-like state. These results suggest that freshwater discharge from high-latitude regions significantly influences equatorial thermocline dynamics, with broad implications for regional and global climate systems.

In conclusion, this study provides accurate estimates of Alaska discharge and demonstrates its influence on salinity anomalies in the Alaskan Stream. It also uncovers how freshwater fluxes from the subpolar gyre impact equatorial thermocline dynamics, contributing to understanding the links between high-latitude processes, ocean circulation, and equatorial climate variability.