海洋表層における季節成層の形成とその変動性

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論　文　内　容　要　旨

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論　文　目　次

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(NO.　2)

論 文 要 旨

In the upper ocean from the surface to several hundred meters, there is a predominant seasonal cycle of the vertical structure of the temperature and salinity, and thus the density stratification. During the warming season, the upper-ocean seasonal stratification develops on the winter surface mixed layer (ML) formed by convection due to surface cooling. Stabilizing the upper-ocean water column, the seasonal stratification regulates the vertical exchange of water and, therefore, plays an important role in the air-sea interaction during the warming season and also on the biogeochemical processes of the upper ocean. Although the seasonality of the upper-ocean stratification is ubiquitous from low to high latitudes in the global ocean, the characteristics such as the amplitude of the seasonality and the depth range where the seasonality is evident are remarkably different depending on the ocean region.

Historically, studies about the physical processes in the upper ocean have progressed mainly focusing on the surface ML processes, because the thickness of the ML that provides the thermal and mechanical temporary inertia with regard to oceanic direct response to the atmospheric forcing is important for understanding ocean's behavior. On the other hand, the formation of the seasonal stratification under the thin summertime ML, including various physical processes, has been poorly understood. Although some fundamental processes of the formation of the seasonal stratification have been studied based on numerical models with the recently enhanced performances of computers, its quantitative observational descriptions for comparison with the model studies have been scarcely done, especially in the open ocean where the time series data with high vertical resolution are hard to be obtained. For that reason, in the present dissertation, I addressed to clarify the mechanism of the development of the seasonal stratification quantitatively from the observational dataset (Chapter 2). Moreover, I also aimed to obtain a better understanding of the roles of the upper-ocean stratification in the climate systems through investigating its long-term change and interannual/decadal variability (Chapter 3 and 4).

In Chapter 2, through quantification of the strength of the seasonal stratification using the Potential Energy Anomaly (PEA; required energy to make the density stratified water column vertically homogeneous), I described the development of the stratification quantitatively with use of the time-dependent equation of PEA. In the North Pacific, the PEAs computed from the temperature and salinity profiles collected by the Argo floats show the regional differences in the amplitude and phase of the development of the seasonal stratification. I performed the PEA budget analysis to clarify which processes dominantly contribute to the development and how those processes are balanced. As a result, I found that the seasonal stratification develops, in a large part of the North Pacific, under a vertical one-dimensional balance between the creation by the atmospheric buoyancy forcing and the destruction by the vertical mixing in the water column. During the warming season when the vertical mixing is considered to be much weaker than the cooling season, estimated vertical diffusivities indicate the occurrence of strong mixing in the seasonal stratification, reaching the order of 10−4 m2 s−1, and show significant spatial and seasonal variability. On the other hand, the contribution from lateral process is significant in limited regions. PEA advection and vertical shear of horizontal current contribute to the development of the stratification in the Kuroshio Extension region and the region of the trade wind.

From the comparison of PEA budgets in two regions which have the similar total buoyancy gain in the North Pacific, I demonstrated that spatial distribution of the “composition” of buoyancy forcing, in addition to the “total magnitude”, is important for producing the regional difference in the development of the seasonal stratification. In the case of the North Pacific, it the condition, satisfied in its northern part, that both the penetrating component (shortwave radiation) and the non-penetrating components (other buoyancy fluxes) contribute to the total buoyancy gain is more favorable for the formation of more intense PEA, i.e. sharper, stratification.

In Chapter 3, I introduced the potential vorticity (PV) framework to understand the impact of summertime preconditioning by the seasonal stratification on the development of the winter ML. I first addressed the formalization for the estimation of the sea surface PV flux from the observational dataset and then the description of its climatological features. To reduce estimation bias, I revised the scaling laws with considerations of the penetration of the shortwave radiation at the base of the ML and wind-driven mixing in the warming season. Newly estimated surface PV flux was significantly improved, being more consistent with independently calculated variation in the PV of ocean interior. In the annual mean field, I demonstrated well-known classical pictures of air-sea PV exchange: PV gain (loss) occurs in low (high) latitude in both the North Pacific and the North Atlantic. On the other hand, I also found that the balance between diabatic and mechanical contribution to the net PV flux is different among the ocean regions: the mechanical term is more significant in the North Pacific, and the diabatic term is dominant in the high-latitude region of the North Atlantic.

The annual mean PV flux consists of summertime PV input and wintertime PV extraction. To investigate which variability (summertime input or wintertime extraction) contributes to the interannual variability in the annual mean PV flux, I computed their interannual variabilities separately and compared them in each ocean region. As a result, I found that the interannual variabilities in summertime PV forcing (input) are significantly larger than that of winter (extraction) in the regions where the summertime atmospheric forcing has an impact as preconditioning on the interannual variability in the winter ML depth.

In Chapter 4, I investigated globally the long-term change and variability in the upper-ocean stratification defined here as the difference between the surface and subsurface density. To resolve spatial patterns of the trends and superposed decadal variability, I used temperature and salinity observations with as spatial and temporal coverage as wide as possible. As a result, strengthening trends of the upper-ocean stratification associated with global warming were detected over most of the global ocean, except for the Arctic Ocean. In the global average, the speed of strengthening is 0.0365 kg m^{-3} $decade^{-1}$, corresponding to an increase of 6.6–11.8% of the mean stratification from the 1960s. I also found that, in addition to the well-mentioned effect of surface intensification of the global warming signal, the subsurface temperature changes and haline stratification changes also have significant impacts on the long-term changes in the upper-ocean stratification. In some ocean regions, the decadal/interannual variabilities in the upper-ocean stratification associated with each particular climate mode are detected: the time series indicate a positive correlation with the Niño 3.4 index in the tropical Pacific, a negative lagged correlation with the North Atlantic Oscillation (NAO) index in the North Atlantic, and correspondences with SST variations associated with the Pacific Decadal Oscillation (PDO) in the North Pacific.

In the present dissertation, I described the seasonal cycle of the upper ocean from two different perspectives with the use of newly introduced concepts. I applied the concept of PEA to the seasonal stratification in the open ocean for the first time and shows its utility for quantitative analysis. The methodology and results of the PEA budget analysis can be utilized for quantifying and understanding the impacts of physical variability on the upper-ocean biogeochemical phenomena. Moreover, the estimation of the surface PV flux improved in this study has the potential to be used not only for the description of the upper-ocean seasonal cycle but also for understanding the fundamental ocean dynamics. In the next decade, Biogeochemical Argo floats that have additional biogeochemical property sensors will become widespread and thus will enable us to investigate the physical-biogeochemical interaction with denser and broader spatiotemporal coverage. I believe that the present results facilitate advances in understanding of not only the ocean’s thermal role in the climate system but also its roles in ecological system and material cycle in the earth system.

別　紙

論文審査の結果の要旨

海面から深さ数百メートルまでの海洋表層では，寒候期には海面冷却を受け、鉛直対流により水温・塩分・密度が一様な深い混合層が形成され，暖候期には加熱により表面付近の海水は軽くなり，強い密度成層が形成される。この季節的に発達する成層は，鉛直方向の海水交換を制限し，暖かく栄養塩が不足した海面付近の水と冷たく栄養塩に富む下層の水とを隔て，暖候期における大気海洋相互作用や生物活動の支配要因となる。近年，数値モデル研究により季節成層形成に関する素過程の理解が進展する一方で、観測に基づく実態把握は進んでいない。本研究は、表層成層の季節的な発達メカニズムを観測データから定量的に明らかにすることを軸とし，それらの時空間変動性の解明を通して，海洋表層成層の気候システムにおける役割の理解を目指したものである。

浅い沿岸域用に考案された，密度成層した水柱を鉛直一様にするのに必要なエネルギー量（Potential energy anomaly: PEA）の概念をはじめて北太平洋全域に適用し，PEA の時間発展方程式を導出することで季節成層の発達に関わる各物理過程の寄与を定量的に記述した。その結果，北太平洋の大部分で鉛直過程が支配的であること，黒潮/黒潮続流域など限られた海域では水平移流の寄与も重要であることなどを明らかにした。また，従来別々の指標で表現されていた季節成層の形成と冬季混合層の発達を，渦位の時間発展として統一的に捉え，その原因となる熱的および力学的な強制を海面における渦位フラックスとして精度よく表現する手法を確立した。これにより，暖候期成層変動が冬季混合層の発達に影響を与える海域の特徴を明らかにした。さらに，利用可能な全ての観測データを用いて，1960 年代以降の全球的な成層強化トレンドを検出し，急速な成層化の進行を明確に示した。とくに，温暖化昇温が海面近くで大きいことによる成層強化に加え，亜表層水温の低化や塩分鉛直構造の変化の有意な寄与を明らかにした。

以上，山口凌平の博士論文は，革新的な手法の確立により，海洋の広域における季節成層の発達過程とその時空間変動を，観測データに基づき，はじめて系統的に定量化したもので，本人が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって，山口凌平提出の博士論文は，博士（理学）の学位論文として合格と認める。