PHYSICAL-BIOGEOCHEMICAL STUDY USING A PROFILING FLOAT: SUBSURFACE PRIMARY PRODUCTION IN THE WESTERN SUBTROPICAL NORTH PACIFIC AS EVIDENCE OF LARGE DIAPYCNAL DIFFUSIVITY ASSOCIATED WITH THE SUBTROPICAL MODE WATER

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ABSTRACT

A profiling float equipped with a fluorometer, a dissolved oxygen sensor, and temperature and salinity sensors was deployed in the Subtropical Mode Water (STMW) formation region. It acquired quasi-Lagrangian, 5-day-interval time-series records from March to July 2006. The time-series distribution of chlorophyll a showed a sustained and sizable deep chlorophyll maximum at 50–80 m, just above the upper boundary of the STMW, throughout early summer (May–July). Vertically integrated chlorophyll values during this period consistently ranged from 15–30 mgm^{-2}, indicating sustained primary production and a continuous supply of nutrients ranging from 10–30 mgNm^{-2}day^{-1}. The time-series data showed no appreciable sporadic events of nutrient supply. Instead, our results support the recently measured large vertical diffusivity values (~5 × 10^{-4} m^{2}s^{-1}) near the top of the STMW, which would cause a diffusive nitrate supply of 30 mgNm^{-2}day^{-1} from the STMW layer to the euphotic zone.

1. INTRODUCTION

Profiling floats equipped with biogeochemical sensors present a unique opportunity to break new ground in exploring biogeochemical processes in conjunction with associated physical processes, which will contribute to a new generation of global ocean observing systems not only for physical fields but also biogeochemical fields and ecosystem. We present a recent result from physical-biogeochemical study using a profiling float equipped with biogeochemical sensors ([1]), which demonstrate its usefulness and potential. The following is the extended abstract of the study.

Based on the extensive profiling float observation carried out as part of the Kuroshio Extension System Study (KESS), [2] reported large vertical eddy diffusivity (2–5 × 10^{-4} m^{2}s^{-1}) near the upper boundary of Subtropical Mode Water (STMW). This large diffusivity possibly have an impact on subsurface redistribution of heat, nutrients and dissolved gas components, etc., in the subtropical ocean. On the other hand, recent measurement of turbulent kinetic energy dissipation rate by [3] indicates much smaller vertical eddy diffusivity (10^{-7}–10^{-5} m^{2}s^{-1}) over the whole depth range of STMW. However, the direct comparison between the estimation by [2] and that by [3] is possibly inappropriate because the former is based on the PV change over a couple of months and the latter on the instantaneous turbulent measurements.

We performed physical and biogeochemical observations, using a profiling float, to examine the vertical diffusivity near the top of the STMW. The STMW acquires a certain amount of nutrients during its convective formation and spreads widely throughout the lower portion of, or immediately below the euphotic layer. It may therefore considerably affect the nutrient budget in the subsurface layer, and thus the primary productivity depending on the vertical diffusivity in the oligotrophic subtropical region. The vertical diffusivity associated with the STMW can therefore be examined indirectly, by analyzing time-series data on primary production. Because our estimation of vertical diffusivity was based on the temporal evolution of primary production over several weeks, it was fairly consistent with the estimation by [2].

2. OBSERVATIONS

Our profiling float was deployed in the formation area of the STMW during the KH06-01 cruise of the research vessel (R/V) *Hakuho-maru* on 25 February 2006 at 32˚21'N, 144˚35'E, immediately south of the Kuroshio Extension. The float began to collect data on 2 March 2006, as it rose from a parking depth of 1000 m. The float was equipped with temperature and salinity sensors as well as a fluorometer and dissolved oxygen (DO) sensor, with a temporal resolution of 5 days. According to satellite-derived sea surface height data, this site was located in an anticyclonic eddy embedded in the recirculation region of the subtropical gyre. The float stayed in the distribution area of the STMW from March to near the end of July; it left the area after 25 July. Float data until 20 July were used for this discussion.

The KT06-12 cruise of the R/V *Tansei-maru* from 16–20 June 2006 examined whether the float observations were spatially representative and calibrated the sensors. Conductivity-temperature-depth (CTD) profiler stations were deployed around the most recent surfacing point of the float, and water samples for salinity, nutrients, chlorophyll, and DO measurements were collected at each station. We confirmed that the vertical structure of the water mass and the DO and chlorophyll measurements taken by the float represented values over 2º–3º in longitude and latitude.

3. RESULTS

The weekly sea surface height data indicated that the float remained trapped in the same eddy. There, it acquired a quasi-Lagrangian time series of vertical profiles, capturing both the STMW and the seasonal pycnocline for 5 months after deployment. The float observed deep convection, reaching 300 m in early April, which resulted in the formation of the STMW as a final product of the winter mixed layer process (Fig. 1). The mixed layer abruptly became shallower than 50 m, and the STMW was subducted under the seasonal pycnocline by mid-April (Figs. 1 and 2). From April to July, the float continuously recorded the STMW as a pycnostad with a PV lower than 2×10^{-10} m^{-1} s^{-1} at depths of 100–400 m, while the seasonal pycnocline gradually developed above it.

Data from the float revealed a distribution of chlorophyll that was closely related to the seasonal evolution of density stratification described above. From March to mid-April, the spring bloom was detected as a high chlorophyll concentration (> 1.0 μg L^{-1}), mainly in the upper 100 m. Deep convective mixing during this period presumably spreads nutrients throughout the euphotic zone, supporting primary production. The vertically integrated chlorophyll concentrations in the upper 400 m were high during the bloom, ranging from 50–70 mg m^{-2}. As the seasonal pycnocline developed in mid-April, the concentration of near-surface chlorophyll decreased and was nearly undetectable by mid-May, likely due to the depletion of nutrients. Instead, a deep chlorophyll maximum (DCM), which is ubiquitously observed in the oligotrophic subtropical regions, appeared and persisted at 50–100 m below the local mixed layer from mid-April through July. The vertically integrated chlorophyll concentration was also considerably large, ranging from 15–30 mg m^{-2}, amounting to one third to one half of the concentration associated with the bloom.

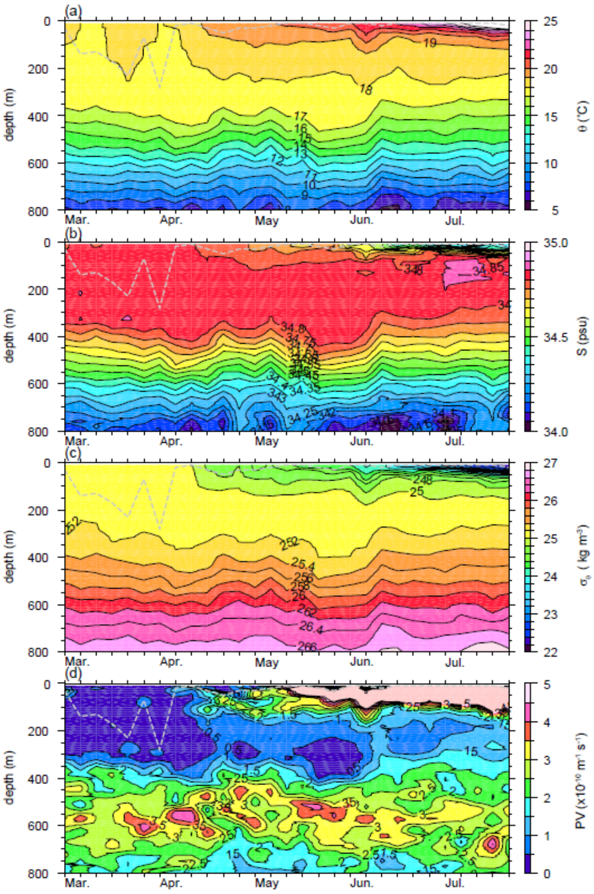

Figure 1. Time series of vertical profiles of (a) potential temperature, (b) salinity, (c) potential density, (d) potential vorticity (PV). The mixed layer depth was shown by gray dash line in each panel. The mixed layer depth was defined as that at shallower one which the difference in temperature from the 10 m depth was -0.2 ºC or in potential density from the 10 m depth was 0.03 kg m^{-3}.

Time-series variations of DO concentration and saturation were affected by physical and biological processes from the convection season to the stratified season. Deep convection in March and April transported DO to a depth of 300 m (Fig. 2a), and then DO saturation at 200–250 m reached nearly 100%. After the last deep convection, DO concentrations at 100–300 m gradually decreased from April to July because of consumption by organic respiration. The DO concentrations near the surface also decreased from May to July. Because DO concentrations in the mixed layer were nearly in equilibrium with the atmosphere (Fig. 2b), depletion was largely due to warming and ocean-atmosphere gas exchange. Time-series data of DO suggested also the presence of continuous subsurface biological activities. In contrast to the layers below and above, the layer at 50–100 m did not significantly lose DO; instead, it became more supersaturated toward the end of the time series, resulting in a subsurface DO maximum, even though this layer should have experienced biological consumption similar to that at 100–300 m. This difference can be explained by photosynthetic oxygen production exceeding consumption by respiration, further demonstrating that primary production at 50–100 m was continuously maintained.

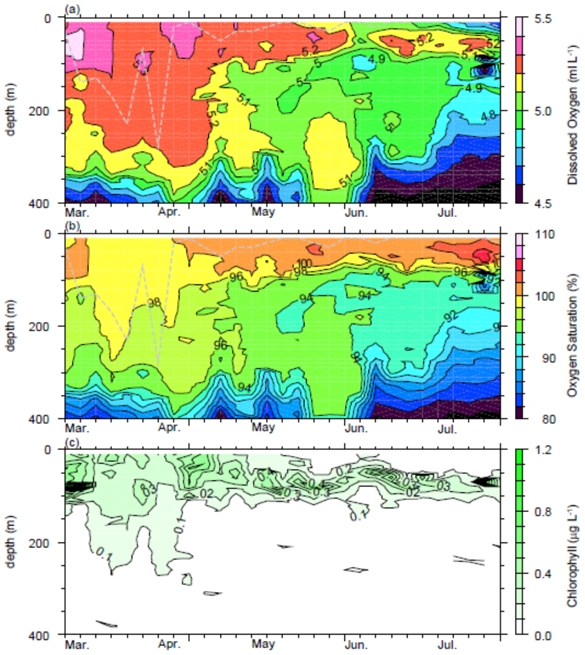

Figure 2. Time series of vertical profiles of (a) oxygen concentration(DO), (b) oxygen saturation, (c) chlorophyll concentration. The mixed layer depth was shown by gray dash line in a and b. The mixed layer depth was defined as that at shallower one which the difference in temperature from the 10 m depth was -0.2 ºC or in potential density from the 10 m depth was 0.03 kg m^{-3}

4. DISCUSSION

The time-series vertical profile data of chlorophyll and DO sensors on our float qualitatively indicated that photosynthesis occurred in the subsurface in the subtropical region. We tried to quantitatively estimate the primary production associated with the subsurface chlorophyll maximum observed by the float, using high-frequency time-series observations from the Hawaii Ocean Time-series (HOT) station (http://hahana.soest.hawaii.edu/hot/hot-dogs/index.html). The available vertical data for primary production from May to July in 1998 to 2007 were averaged to derive a logarithmic approximate curve relating depth, chlorophyll concentration, and primary production. The amount of nitrogen in primary production was derived from the HOT primary production data expressed as carbon units using the Redfield ratio. The nitrate requirement for primary production, which was calculated from the depth and chlorophyll concentration in the float data from May to July, was 78 ± 43 mgN m^{-2} day^{-1}. This value was within the range consistent with previous estimates of gross primary production and nitrogen flux exported into the deeper layer at the HOT station.

Our time-series data recorded by the float showed no appreciable signatures of sporadic events, such as isopycnal heaving and convection due to atmospheric disturbances. Instead, the DCM layer consistently lay immediately above the STMW layer. The lower limit of the DCM layer delineated by the chlorophyll concentration contour of 0.1 mgm^{-3} nearly coincided with the upper boundary of the STMW. Therefore, enhanced diapycnal diffusivity near the upper boundary of the STMW was a plausible mechanism for the nutrient supply supporting primary production in this particular case.

Assuming the previously estimated large diffusivity (~5 × 10^{-4}m^{2}s^{-1}), the vertical profiles of nitrate measured by intensive shipboard water sampling in the vicinity of the float in June indicated vertical nitrogen transport of 30 mgNm^{-2}day^{-1} from the STMW layer to the euphotic zone. Note that the production advanced by this upward nutrient supply from the STMW had been not reflected in the DO time-series variation as net DO increment from May to July. DO concentration in the subsurface oxygen maximum was not increase regardless of supplying nutrient from the STMW, and that below the euphotic zone remained almost unchanged regardless of consuming by the respiration (Fig. 2a). These discrepancies could be explained by the oxygen transport from the subsurface oxygen maximum layer to the deeper layer by the strong diffusion near the top of the STMW, which was reverse of the nutrient supply. The downward oxygen transport estimated from the diffusivity and the vertical profiles of oxygen measured by the Argo float from May to July indicated 30 ± 13 mmol $m^{-2}day^{-1}$. The ratio between the transported nitrogen and oxygen (O_2) of this study was 9 to 20, which was partly close to the Redfield ratio, 8.6.

The estimated nitrogen demand for primary production in the DCM layer was larger than the estimated nitrate flux from the STMW because estimated primary production from chlorophyll concentrations in the DCM was maintained not only by new production (fuelled by nitrogen recruited from the STMW), but also by regenerated production (fuelled by nitrogen recycled from decomposed organic matter in the euphotic zone). The f-ratio, the rate of new production to total production, is used as an indicator of the efficiency of the biological pump. The f-ratios in subtropical seas are small, with values of 0.1–0.25 reported for the tropical and subtropical Pacific and <0.2 for the subtropical Atlantic. When an f-ratio of 0.25 is assumed, the required nitrogen supply is 19.5 mgN $m^{-2}day^{-1}$, which is comparable to the diffusive nitrate flux from the STMW estimated above. Our biogeochemical and physical observations therefore support the large diapycnal diffusivity at the upper boundary of the STMW estimated by [2].

Provided that the enhanced diffusivity was due to the abrupt downward drop in buoyancy frequency just below the seasonal pycnocline, a large diffusive flux of nutrient could also be expected near the upper boundary of other mode waters, such as the Eastern STMW distributed in the eastern part of subtropical gyres. It may be another important mechanism besides the episodic processes of nutrient supply such as eddy induced upwelling, which also gives large impact to the biogeochemical processes in the subtropical region. The recently reported subsurface net production of oxygen in the eastern subtropical gyres ([4]) could have been maintained by the enhanced vertical diffusivity.

5. REFERENCES

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