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# 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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Received: 16 July 2009 – Accepted: 5 August 2009 – Published: 11 August 2009

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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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  $15\text{--}30\text{ mg m}^{-2}$ , indicating sustained primary production and a continuous supply of nutrients ranging from  $10\text{--}30\text{ mgN m}^{-2}\text{ day}^{-1}$ . The time-series data showed no appreciable sporadic events of nutrient supply. Instead, our results support the recently measured large vertical diffusivity values ( $\sim 5 \times 10^{-4}\text{ m}^2\text{ s}^{-1}$ ) near the top of the STMW, which would cause a diffusive nitrate supply of  $\sim 30\text{ mgN m}^{-2}\text{ day}^{-1}$  from the STMW layer to the euphotic zone.

## 1 Introduction

Subtropical Mode Water (STMW) is a prominent hydrographic feature of subtropical gyres. It forms in the winter deep mixed layer and subsequently spreads throughout the western portion of gyres as a pycnostad between seasonal and permanent pycnoclines (e.g., Hanawa and Talley, 2001; Suga et al., 2004). In the North Pacific, STMW forms in the zonal band from approximately  $28^\circ\text{N}$  to the Kuroshio Extension, and the longitude band from the Izu Ridge to the international dateline, where the mixed layer depth reaches 300–400 m. As part of the Kuroshio Extension System Study (KESS), profiling floats have been extensively deployed in the STMW formation region (e.g., Qiu et al., 2006, 2007). The resultant temperature-salinity profile data have recently revealed the seasonal evolution of the vertical structure of the STMW in detail, from its formation in winter to its dissipation in subsequent seasons.

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One of the most striking findings of the KESS was the rapid erosion of the STMW from its top downwards, from spring to autumn. The erosion caused an estimated diapycnal diffusivity at the upper boundary of the STMW (based on a conservation equation of PV) of up to  $5 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$  (Qiu et al., 2006). The lower boundary of STMW, in contrast, shows little seasonal modification in its depth and vertical PV gradient. The permanent thermocline layer in a wind driven subtropical gyre below the STMW has a low vertical eddy diffusivity on the order of  $0.1 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$  (Gregg and Sanford, 1980; Ledwell et al., 1993). This sufficiently large diffusivity at the upper boundary of the STMW may have resulted from the extremely small buoyancy frequency of the STMW, which prevented the downward propagation of internal waves generated in the mixed layer and trapped their energy near the STMW upper boundary. Meanwhile, Mori et al. (2008) reported small diffusivity over the whole depth of the STMW (up to  $10^{-5} \text{ m}^2 \text{ s}^{-1}$ ), which was estimated from direct measurements of the turbulent kinetic energy dissipation rate. However, a direct comparison between the estimations of diffusivity by Qiu et al. (2006) and by Mori et al. (2008) is possibly inappropriate because the former estimation was based on the PV change over a couple of months, and the latter was obtained from 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 Qiu et al. (2006).

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## 2 Observations

Our profiling float (Webb Research Corporation; APEX) 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 (Wetlabs; FLNTU) and dissolved oxygen (DO) sensor (Sea Bird Electronics; SBE43F), with a temporal resolution of 5 days. According to satellite-derived sea surface height data (AVISO: [http://www.jason.oceanobs.com/html/mod\\_actu/public/welcome\\_uk.php3](http://www.jason.oceanobs.com/html/mod_actu/public/welcome_uk.php3)), this site was located in an anticyclonic eddy embedded in the recirculation region of the subtropical gyre. The measurements had vertical resolutions of 5 m in the top 200-m layer, 10 m in the 200–400-m layer, and 20 m in the 400–1000-m layer. 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 (Fig. 1a and b). The chlorophyll sensor failed after August. 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 (Fig. 1), and water samples for salinity, nutrients, chlorophyll, and DO measurements were collected at each station. Chlorophyll and DO samples were measured on board using fluorometer 10-AU (Turner Designs) and MPT Titrimo 798 (Metrohm Shibata Co. Ltd.), respectively. Salinity samples were measured by Portasal 8410 (Guildline Instruments Ltd.) after the cruise. Nutrients (nitrate, nitrite, phosphate and silicate) sample were kept in freezer until measurement and measured by autoanalyzer TRACCS 2000 (BRAN+LUEBBE). Transparency was obtained using a secci disk, and the euphotic zone (the depth of 1% light intensity) was estimated to be 78 m. We confirmed that the vertical structure of the water mass and

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the DO and chlorophyll measurements taken by the float represented values over 2°–3° in longitude and latitude. Data from the chlorophyll sensor of the float were scaled by a multiplication factor of 0.49, based on comparisons of the vertically integrated chlorophyll concentrations over the top 200 m between four float profiles (two immediately before the cruise and two afterward) and 10 water sampling casts taken during the cruise. We determined that the DO sensor of the float had a bias of  $-0.15 \text{ ml L}^{-1}$  and adjusted this bias by comparing data from the float profile immediately before the cruise with data from water samples at the same temperature and salinity as the float.

### 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 temperature-salinity relationship near the vertical core of the STMW was the same during this period, further confirming that the float essentially tracked the same water column. 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. 2). The mixed layer abruptly became shallower than 50 m, and the STMW was subducted under the seasonal pycnocline by mid-April (Figs. 2 and 3). From April to July, the float continuously recorded the STMW as a pycnostad with a PV lower than  $2 \times 10^{-10} \text{ m}^{-1} \text{ s}^{-1}$  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 ( $>1.0 \mu\text{g L}^{-1}$ ), mainly in the upper 100 m. Deep convective mixing during this period presumably spread nutrients throughout the euphotic zone, supporting primary production. The vertically integrated chlorophyll concentrations in the upper 400 m were high during

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the bloom, ranging from 50–70 mg m<sup>-2</sup> (Fig. 4b). 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) (Cullen, 1982), 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<sup>-2</sup>, amounting to one third to one half of the concentration associated with the bloom.

Time-series variations of DO concentration and saturation were affected 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. 3a), 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. 3b), 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 (Hayward, 1994).

## 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.

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We tried to quantitatively estimate the primary production associated with the sub-surface 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. The following logarithmic approximate curve was then derived to relate depth ( $z$ , in meters), chlorophyll concentration (chl, in  $\text{mg m}^{-3}$ ), and primary production (in  $\text{mgN m}^{-2} \text{ day}^{-1}$ ):

$$\text{primary production (mgN m}^{-2} \text{ day}^{-1}) = 18.8 \times \text{chl. (} z < 18)$$

$$\text{primary production (mgN m}^{-2} \text{ day}^{-1}) = (-11.5 \times \ln(z) + 55.8) \times \text{chl. (} z \geq 18).$$

The amount of nitrogen in primary production was derived from the HOT primary production data expressed as carbon units using the Redfield ratio (Redfield et al., 1963). The averaged depth of the euphotic zone in the HOT time series from May to July was 106 m, which was greater than that in the STMW region. We roughly compensated for the difference between the photoenvironment of our study region and that of the HOT station by multiplying the depth of the float data by 1.4. The nitrate requirement for primary production, which was calculated from the depth and chlorophyll concentration in the float data from May to July, was  $78 \pm 43 \text{ mgN m}^{-2} \text{ day}^{-1}$ . This value was within the range consistent with previous estimates of gross primary production and nitrogen flux exported into the deeper layer (Emerson et al., 1997) at the HOT station. However, it was much larger than the values ( $\sim 3 \text{ mgN m}^{-2} \text{ day}^{-1}$ ) (Lewis et al., 1986; Planas et al., 1999) supported by traditional diffusion processes.

Although the subtropical gyres that occupy large areas within the world's oceans are oligotrophic, active biological productivity in these regions has been reported (Goldman et al., 1979; McCarthy and Goldman, 1979; Laws et al., 1987; Karl et al., 1997; McNeil et al., 1999; Karl, 1999). Deep mixing processes in winter mainly provide nutrients from the deep layer to the euphotic layer. Instead of diapycnal diffusion in the stratified season, which is generally assumed to be small and a minor contributor (Ledwell et al., 1993), nitrogen fixation of cyanobacteria (Karl et al., 1997) and/or sporadic nutrient input by eddy-induced upwellings (McGillicuddy and Robinson, 1997; McGillicuddy

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et al., 1998; Oschilies and Garçon, 1998; McNeil et al., 1999) have been proposed as plausible mechanisms to support primary production in the otherwise apparently nutrient-depleted euphotic layer of subtropical gyres.

However, 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  $0.1 \text{ mg m}^{-3}$  nearly coincided with the upper boundary of the STMW, as indicated by the PV contour of  $2 \times 10^{-10} \text{ m}^{-1} \text{ s}^{-1}$  (Fig. 4a). 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 ( $\sim 5 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ ), the vertical profiles of nitrate measured by intensive shipboard water sampling in the vicinity of the float in June (Fig. 5) indicated vertical nitrogen transport of  $30 \text{ mgN m}^{-2} \text{ day}^{-1}$  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. 3a). 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  $30 \pm 13 \text{ mmol m}^{-2} \text{ day}^{-1}$ . The ratio between the transported nitrogen and oxygen ( $\text{O}_2$ ) of this study was 9 to 20, which was partly close to the Redfield ratio, 8.6. Disagreement of these ratios may be derived from the fact that the diffusive oxygen transport was estimated based on an average of the time series data from May to July, while that of nitrate based on the profiles during the single cruise in June. If we could observe the nitrogen concentration in early phase

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of stratified season or in more enhanced diffusivity, the transport nitrogen and oxygen ratio would be more close to the Redfield ratio.

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 (Dugdale and Goering, 1967), 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 (Kanda et al., 1985; Dugdale and Wilkerson, 1992) and <0.2 for the subtropical Atlantic (Planas et al., 1999). When an f-ratio of 0.25 is assumed, the required nitrogen supply is  $19.5 \text{ mgN m}^{-2} \text{ day}^{-1}$ , 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 Qiu et al. (2006).

The early summer upward nitrogen transport from the STMW to the euphotic zone amounted to  $2.7 \text{ gN m}^{-2}$ , if a flux of  $30 \text{ mgN m}^{-2} \text{ d}^{-1}$  was assumed for 3 months. However, the nitrogen provided to the euphotic zone by winter convection was estimated to be  $2.8 \text{ gN m}^{-2}$ , assuming that the nitrate concentration in the winter mixed layer was the same as that in the middle of the STMW observed in June ( $2.0 \text{ mmol m}^{-3}$ ). Therefore, the subsurface new production could have been as large as that associated with the spring bloom, or even larger, because similar subsurface production likely continued beyond July. These estimates suggest that the diffusion transport of nutrients in summer associated with the STMW contributes remarkably to the high primary production in the oligotrophic subtropical region.

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# 5 Conclusions

Our profiling float provided unique time-series of physical and biological processes from convection season to intensified stratification season in the same anticyclonic eddy in the western North Pacific subtropical region. These continual profiles of temperature, salinity, DO and chlorophyll revealed that the temporal variation of phytoplankton distribution was coupled with the development of seasonal pycnocline and the erosion of the STMW pycnostad from its top. The calculated primary production using the float data supported our hypothesis, that the enhanced diapycnal diffusion near the top of the STMW transports more nutrients upward into the euphotic zone than expected from traditional diffusion process. 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 (Hautula and Roemmich, 1998). 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 (Riser and Johnson, 2008) could have been maintained by the enhanced vertical diffusivity.

*Acknowledgements.* This work was partly supported by grants-in-aid for Exploratory Research (No. 17651002) from the Ministry of Education, Science, Sports and Culture and for Scientific Research in Priority Areas, “Western Pacific Air-Sea Interaction Study (W-PASS)”; by the Agriculture, Forestry and Fisheries Research Council (AFFRC) for the study of “Population Outbreak of Marine Life”; by grants-in-aid for Creative Scientific Research (No. 17GS0203) from the Ministry of Education, Science, Sports and Culture and for Scientific Research in Priority Areas, “Comprehensive studies of global greenhouse gas cycles in the atmosphere, terrestrial biosphere and oceans”; and by the Inoue Foundation for Science. This study contributed to the Japan Argo project. The authors thank the captains, crew members, and scientists of the R/Vs *Tansei-maru* and *Hakuho-maru* of the Japan Agency for Marine-Earth Science and Technology

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(JAMSTEC). Thanks are also given to members of the JAMSTEC Argo group and members of the Physical Oceanography Group at Tohoku University for their helpful discussions throughout this study.

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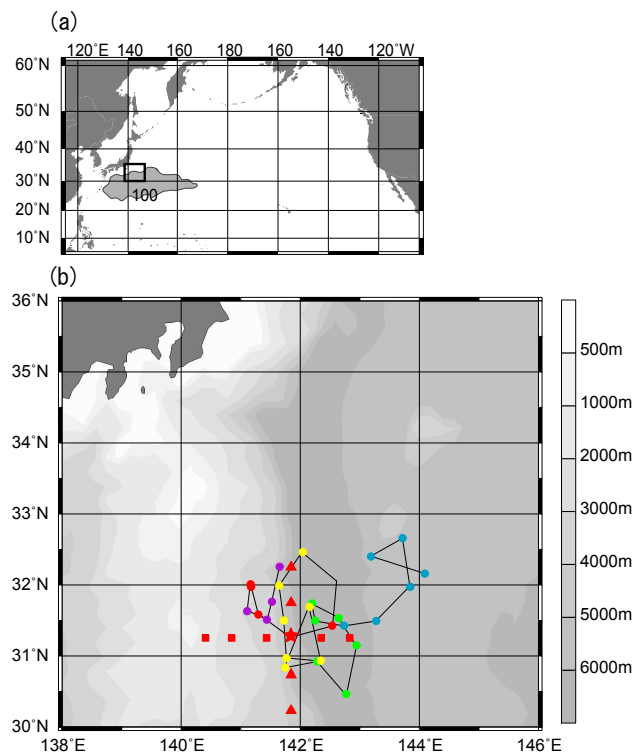
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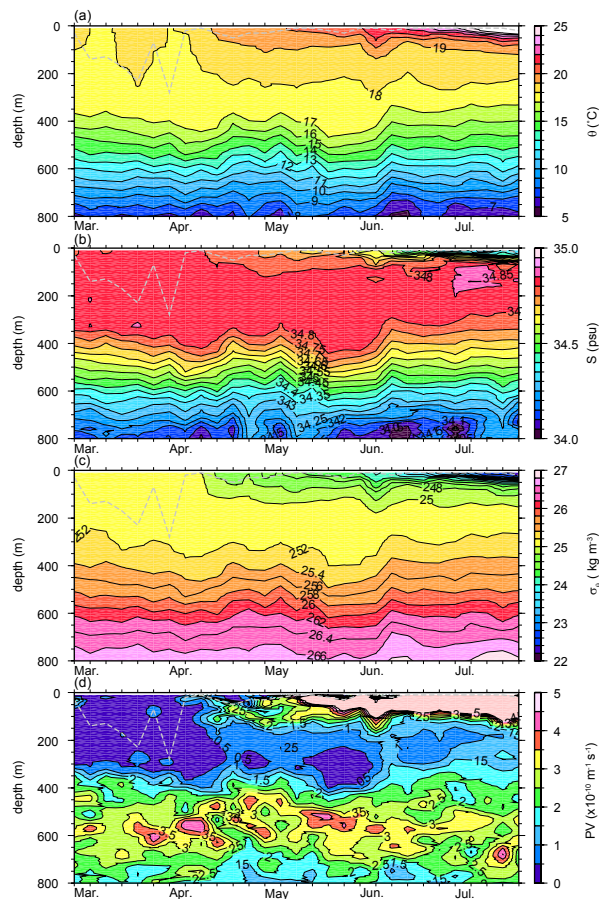


**Fig. 1.** (a) Subtropical Mode Water (STMW) distribution (shaded area) in the North Pacific, represented by the area where the thickness of  $\sigma_{\theta}=25.0\text{--}25.2\text{ kg m}^{-3}$  is greater than 100 m in June. The thickness was calculated from HydroBase climatological data (Macdonald et al., 2001). A portion of the small square in (a) is enlarged in (b). (b) The trajectory of the profiling float and conductivity-temperature-depth profiler (CTD) stations of the KT-06-12 cruise. Each circle connected by a solid line denotes a profiling point of the float. The circle colors indicate the observational months in 2006: March (blue), April (green), May (yellow), June (red), and July (purple). Triangles and squares denote CTD and water sampling stations, respectively. CTD observations were performed for 2 days, on 17 (triangles) and 18 (squares) June. The star indicates the position where three profiles were obtained by the float (15 June), as well as the first (17 June) and second (18 June) CTD observations.

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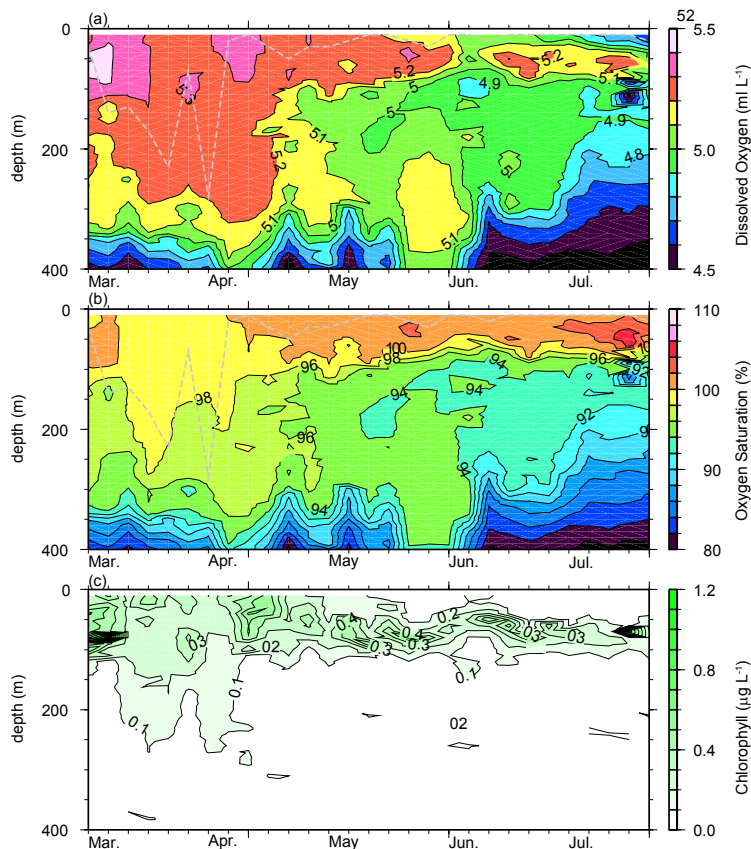
**Fig. 2.** Time series of vertical profiles of (a) potential temperature, (b) salinity, (c) potential density, (d) potential vorticity (PV). The mixed layer depth was shown by gray dash line in each panels. The mixed layer depth was defined as that at shallower one which the difference in temperature from the 10 m depth was  $-0.2^\circ\text{C}$  or in potential density from the 10 m depth was  $0.03 \text{ kg m}^{-3}$ .

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**Fig. 3.** 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  $-0.2^{\circ}\text{C}$  or in potential density from the 10 m depth was  $0.03\text{ kg m}^{-3}$ .

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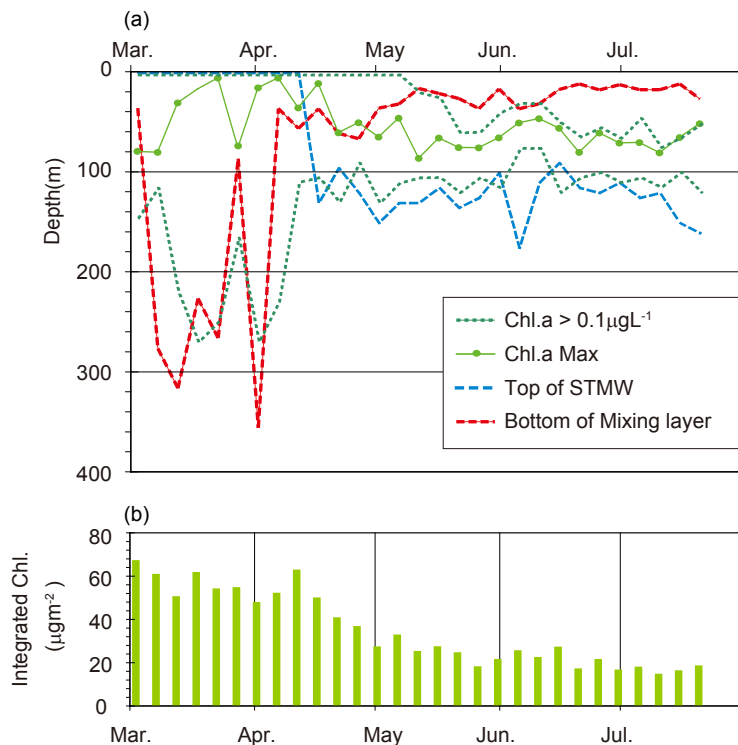
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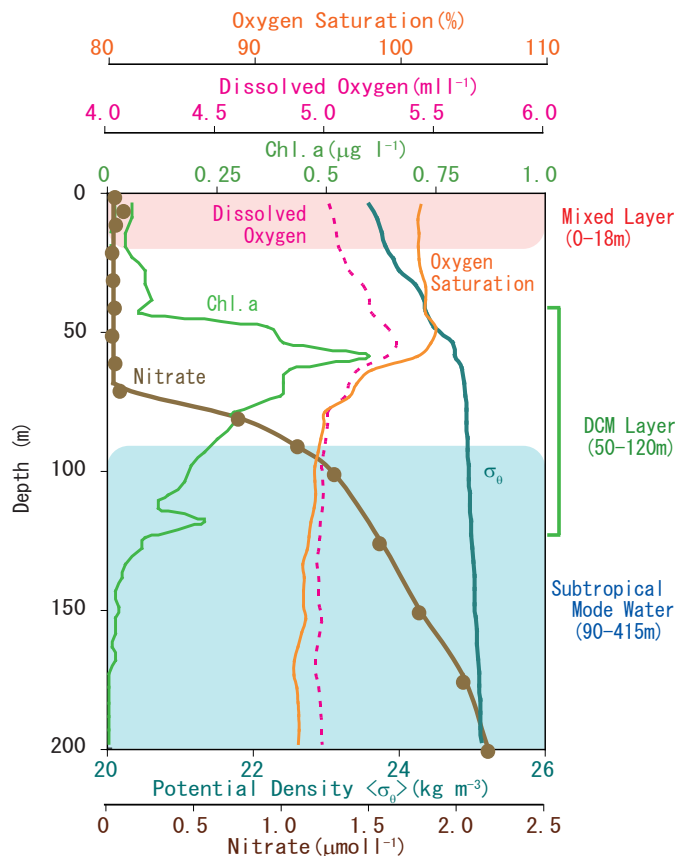


**Fig. 4.** (a) provides a summary of the time series of density stratification and chlorophyll distribution. The mixed layer depth was defined as that at which the difference in temperature from the surface was  $-0.2^{\circ}\text{C}$ . The upper boundary of the STMW was defined by the contour of  $PV=2\times 10^{-10}\text{ m}^{-1}\text{ s}^{-1}$ . (b) presents the time series of vertically integrated chlorophyll concentrations, over a depth range of 0–400 m.

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**Fig. 5.** The typical vertical distribution of potential density, DO concentrations, and chlorophyll collected by the profiling float in early summer. These profiles were measured on 15 June. The deep chlorophyll maximum (DMC) layer was defined as the layer at which chlorophyll concentrations were higher than  $0.3 \mu\text{g l}^{-1}$ . The nitrate profile was measured by water sampling during the KT-06-12 cruise at the westernmost station.

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