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Key Points:
- Oyashio nitrate transport into the North Pacific Intermediate Water in the mixed water region is approximately 110 kmol/s
- Effective nitrate transport from the subarctic gyre to the subtropic gyre along with NPIW formation is approximately 24 kmol/s
- Oyashio is comparable to the Kuroshio in nutrient transport but has a shallower subsurface maximum of nitrate flux at 250-m depth

Supporting Information:
- Supporting Information S1

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The Oyashio Nutrient Stream and Its Nutrient Transport to the Mixed Water Region

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Abstract The Oyashio, a subarctic western boundary current in the North Pacific, transports cool, fresh, and nutrient-rich water equatorward. The Oyashio nutrient stream was assessed using long-term mean hydrographic observation data. Its nitrate transport (about 350 kmol/s) is comparable to that of the Kuroshio but has a much shallower subsurface core at 250-m depth. In the layer ranging from 26.6 to 27.4 σ_θ, the Oyashio nitrate transport to the mixed water region is about 110 kmol/s. This corresponds to the nitrate transport of the Oyashio to the North Pacific Intermediate Water in the mixed water region. Along with this process, the subarctic gyre nitrate export to the subtropic gyre reaches 24 kmol/s. This work first quantifies the Oyashio nutrient transport and its intrusion into the mixed water region and suggests its importance in local/basin-scale nutrient cycles.

Plain Language Summary The Oyashio carries cool, fresh, and nutrient-rich water and is significant in local/basin-scale nutrient cycles. This study confirmed the presence of a nitrate flux subsurface maximum in the Oyashio, which fits the concept of nutrient stream. The Oyashio nutrient stream acts as a subsurface giant conduit that continuously transports subarctic water with a high nutrient concentration equatorward. This nutrient transport plays an important part in the formation of the North Pacific Intermediate Water and nutrient export from the subarctic gyre to the subtropical gyre.

1. Introduction

The mixed water region (MWR) between the Oyashio front and the Kuroshio Extension is the main location at which the North Pacific Intermediate Water (NPIW) forms (Talley et al., 1995; Yasuda, 2004). The cool, fresh Oyashio water mixes with the warm, saline Kuroshio water (based on the water property, its intermediate water is referred to as "Old" NPIW), forms the intermediate salinity minimum centered at 26.8 σ_θ (or "New" NPIW), and circulates within the subtropical gyre. As it serves as an essential part of the global ocean conveyor in the North Pacific (Talley et al., 2011), the advection of NPIW plays an important role in regulating the meridional transport of heat, salt, and nutrients. From its origin, the nutrients are transported from the abyssal North Pacific (Sarmiento et al., 2004) and Okhotsk Sea (Nishioka et al., 2013) to the nutrient-depleted subtropical North Pacific and replenishes the nutrient reservoir of the intermediate layer.

The significance of subarctic thermocline nutrient export has been addressed in previous studies (Nishioka et al., 2013; Sarmiento et al., 2004). Whitney et al. (2013) suggested that subarctic nitrate export along with NPIW formation had a value of 9.5 ± 3.2 kmol/s, which was derived from the product of Oyashio volume transport (Talley et al., 1995; Yasuda, 2004) associated with NPIW formation (3 Sv) and the difference in the nitrate concentration between the subarctic and subtropical gyres. This indicates *effective nitrate transport* (Ayers et al., 2014) that is based on volume conservation. However, an explicit and direct sectional observation of nutrient flux and transport is still required. Quantifying this nutrient transport would aid our understanding on the basin-scale nutrient budget (Whitney et al., 2013), nutrient supply in the Kuroshio-Oyashio transition region (Shiozaki et al., 2014), and nutrient transport between the subtropical and subarctic gyre in the North Pacific (Ayers & Lozier, 2010).

Since Pelegrí and Csanady (1991) proposed the concept of the nutrient stream, various studies have discussed the subtropical western boundary current (WBC) nutrient streams (such as the Kuroshio and Gulf Stream; Chen et al., 1994; Guo et al., 2012, 2013; Long et al., 2018; Palter & Lozier, 2008; Pelegrí & Csanady, 1991; Pelegrí et al., 1996) because of their significance in the global nutrient cycles (Letscher et al., 2016; Williams et al., 2011). However, the subpolar WBC has received less attention. The Oyashio (Kuroda et al., 2015;

Uehara et al., 2004) transports nutrient-rich subarctic water equatorward and directly impacts the local ecosystem (Sakurai, 2007). Hence, it is necessary to examine the Oyashio nutrient stream and its nutrient transport.

The following questions are addressed here: what is the long-term mean nutrient transport of the Oyashio and how does it distribute along isopycnal layers? How much nitrate does it transport to the NPIW in the MWR? Based on repeated hydrographic observations from the Japan Meteorological Agency (JMA), we accessed the long-term mean nitrate flux of Oyashio and its nitrate transport to the NPIW. The article is organized as follows: the data and method are provided in section 2; the results and discussion are in sections 4 and 5, respectively. A brief summary is presented in section 5.

2. Data and Method

The quarterly hydrographic observations (here after referred to as JMA-line) from 2000 to 2015 consisted of 34 and 39 cruises of nutrient concentration and conductivity-temperature-depth data, respectively. The inverse method (Wunsch, 1978) was applied to the conductivity-temperature-depth data to obtain the absolute geostrophic velocity, which is widely used in calculating velocity profiles in the WBC (Masujima et al., 2003, Zhu et al., 2003, 2008). In the calculation, we vertically divided the water column into five layers (bounded by the sea surface, 26.6, 27, 27.4 27.6, and 27.66 σ_θ) following the suggestion of Masujima et al. (2003). By excluding six cruises of velocity data when the Oyashio axis was largely affected by eddies and selecting cruises with both velocity and nitrate concentration data, 26 nitrate flux (the product of the velocity and nutrient concentration, see supporting information S1 for more detail) cruises were obtained. The nutrient flux was then integrated over the section to obtain the nutrient transport. The nitrate and phosphate concentrations were correlated well, with a N:P ratio of 14.27 and a cutoff of -1.52 mmol/m^3 in a linear regression of N to P. For convenience, we will focus on the results for nitrate in our description.

The average Mapping of Absolute Dynamic Topography heights and sea surface geostrophic velocity data from AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic data) were used to determine whether the Oyashio axis is affected by mesoscale eddies. The nitrate concentration at 26.8σ_θ (NPIW) was obtained from the mapping data of the Global Ocean Data Analysis Project (Key et al., 2015; Lauvset et al., 2016).

3. Result

The Oyashio flows southwest along the continental slope of the Kuril Islands (Figure 1b). After reaching an area southeast of Hokkaido, it meanders in a W shape and flows east along the Oyashio front. Its typical path consists of four alternating flows (Figure 1c). Following Kuroda et al. (2017) from north to south along the section, we name these flows SW-1 (southwestward), NE-2(northeastward), SW-3 (southwestward), and NE-4 (northeastward), corresponding to the First Oyashio Intrusion and the Second Oyashio Intrusion (Kawai, 1972), respectively. In the MWR, part of the Oyashio merges with the Kuroshio and flows into the Kuroshio Extension, while the rest flows northeastward as NE-4.

The JMA-line captured all features of the four alternating flows (Figure 1c). The mean nitrate transport per unit width matches the surface geostrophic velocity well, although there are discrepancies at the southern stations (stations 17–22 from the north). This may result from the highly variable velocity field induced by eddies and can be understood from the large standard deviation of the nitrate transport per unit width.

The velocity profile shows a surface maximum in the four alternating flows (Figure 2a). The negative velocity at the northernmost area of the section represents SW-1, and is relatively narrower and stronger among the four alternating flows, while its maximum surface velocity exceeds 0.2 m/s. Its return flow, NE-2, is recognized as the positive value at the section south of SW-1 and has a weak maximum surface velocity of 0.1 m/s. The flow turns southwestward as SW-3 and then northward as NE-4, which has a larger surface velocity maximum than SW-3. The northeastward flow in the southernmost area of the section could be the Kuroshio jet flow (Isoguchi et al., 2006).

The volume transports of the four alternating flows from north to south are −9.3, 7.1, −5.8, and 11.3 Sv (positive values are northward). The net volume transport from SW-1 to NE-2 (First Oyashio Intrusion) is southward and that from NE-3 to SW-4 (Second Oyashio Intrusion) is northward. As the Oyashio intrusion and merging of the Kuroshio water into it occurs concurrently, the volume transport of the Oyashio

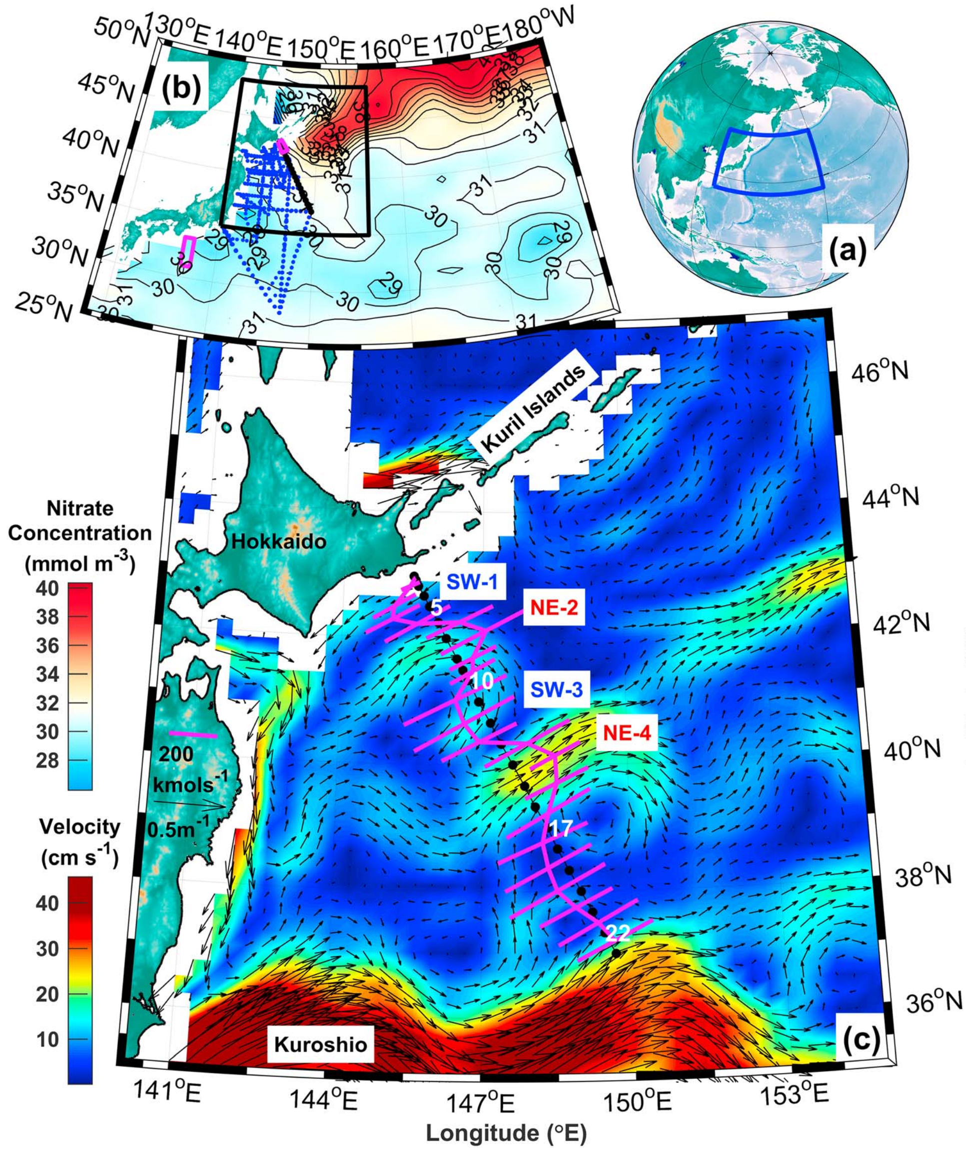

Figure 1. (a) A global view of the northwest Pacific. (b) Nitrate concentration on 26.8σ_θ (color shading). The blue dots denote the hydrographic stations used in the velocity calculation, and the thick black line is the JMA-line. The magenta boxes indicate the region where we used conductivity-temperature-depth data to obtain the typical *T-S* relation of Kuroshio and Oyashio. (c) Mean value (thick magenta line along the section) and standard deviation (thick magenta line normal to the section) of nitrate transport per unit length across the section, surface geostrophic velocity (black arrows), and its magnitude (color shading). The black dots and thin line through the dots represent the hydrographic stations and the reference of zero. The white numbers (5, 10, 17, and 22) denote the numbering of the station from the north.

intrusion is not simply equal to the volume transport difference between the southwestward flow minus the northeast flow.

The nitrate concentration of Oyashio is significantly higher than that of other WBCs because the North Pacific has the highest nitrate concentration among the oceans on a global scale (e.g., Figure 1.5A in Gruber, 2008). For example, the nitrate concentration at 100 m (about 20 mmol/m^3) is comparable to that at 600 m in the Kuroshio region (Guo et al., 2013). The nitrate concentration increases from 15 mmol/m^3 (1.5 mmol/m^3 for phosphate) at the sea surface to a maximum of 43.5 mmol/m^3 (3.15 mmol/m^3 for phosphate) at a depth of 700–1,400 m (Figure 2b).

High nitrate concentrations result in a large surface nutrient flux (Figure 2b) and a subsurface maximum at a depth of 250 m, suggesting high potential for carrying nutrient-rich water to the MWR in the surface layer.

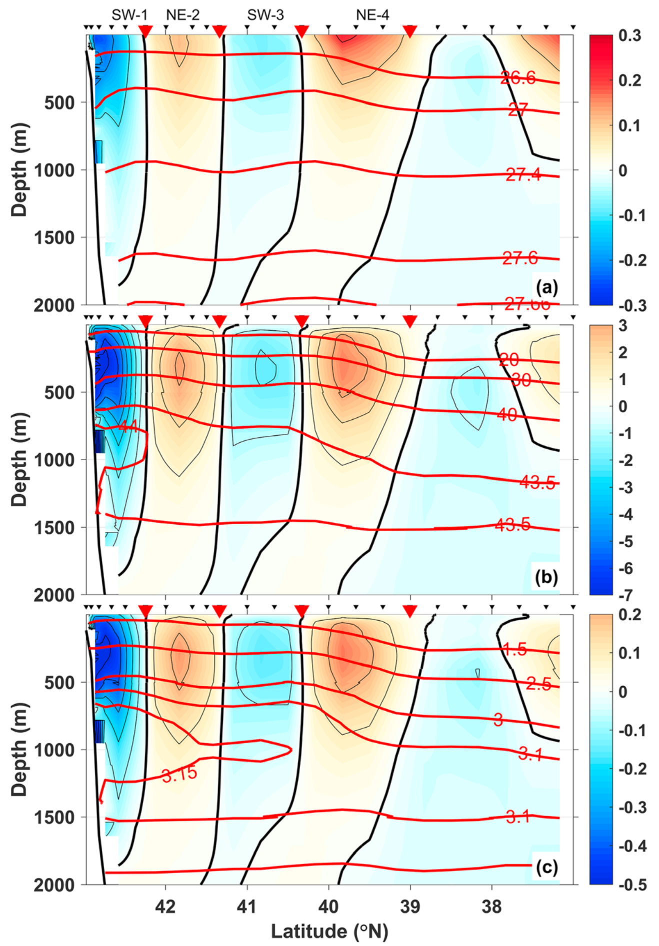

Figure 2. (a) Mean velocity (m/s), (b) nitrate flux (2 mmol·m^{-2}·s^{-1}), and (c) phosphate flux (2 mmol·m^{-2}·s^{-1}) at the JMA-line. The thick red line in (a), (b), and (c) denotes the isopycnal surface (σ_θ), nitrate concentration (mmol/m^3), and phosphate concentration (mmol/m^3), respectively. The thick black line indicates a value of 0. The inverse black triangles denote hydrographic stations; the inverse red triangles denote the boundaries of each alternating flow.

The subsurface extremes are −7, 3, −2, and 3 mmol·m^{-2}·s^{-1} for SW-1, NE-2, SW-3, and NE-4, respectively. The weakening of the nitrate flux from SW-1 to SW-3 can be attributed to the merging of Kuroshio with water of a low nitrate concentration at the same isopycnal layer, that is, a dilution effect (Williams et al., 2011). The nitrate transports of the four alternating flows are −348.4, 249.4, −196.4, and 319.3 kmol/s, respectively. The phosphate flux exhibits an analogous structure (Figure 2c), and the phosphate transports of the four alternating flows are −25.6, 18.3, −14.3, and 23.2 kmol/s, respectively.

The nitrate flux as a function of temperature and salinity shows the Oyashio nutrient stream from a viewpoint of water property (Figure 3). The typical *T*-*S* relation of the two end members, the Oyashio and the Kuroshio water, was obtained at JMA-line and section 137E (magenta box in Figure 1b), respectively. The distance between a specific point on the *TS* diagram and the typical T-S relation of the two end members on the same isopycnal layer indicates the approximate extent of water mixing. For SW-1(Figure 3a), the maximum nitrate flux reached 7 mmol·m^{-2}·s^{-1}, and its location on the *T*-*S* frame is close to that of typical Oyashio water, suggesting a southwestward transport of the cooler, fresher nutrient-rich water. NE-2 (Figure 3b) represents a positive nitrate flux, and its maximum reaches approximately 4 mmol·m^{-2}·s^{-1}. The *T*-*S* feature of the water with the maximum nitrate flux shifts slightly toward that of typical Kuroshio water and suggests mixing between the Oyashio and Kuroshio water. The nitrate flux in the *T*-*S* diagram exhibits little difference between NE-2 (Figure 3b) and SW-3 (Figure 3c), while NE-4 (Figure 3d) exhibits a widespread, positive value between the typical *T*-*S* features of Kuroshio and Oyashio. The sectional *T*-*S* diagram (Figure 3e) shows a negative nitrate flux to typical Oyashio water, and a weak positive value between the two typical water types. This suggests southward nitrate transport of the Oyashio to the MWR and northward nitrate transport of the Oyashio-Kuroshio mixing water.

We then calculated the water mixing ratio at the JMA-line assuming that isopycnal mixing (Shimizu et al., 2001; Figure 4a) occurred in the lower four layers (26.6–27.66 σ_θ). The result shows that the Oyashio components of SW-1, NE-2, and SW-3 exceed 80% and there is a mixing front at NE-4. This suggests that the merging with the Kuroshio mainly occurs at NE-4. The nitrate transport contributed by the Oyashio water in each layer (Figures 4b–4e) decreases to almost zero at the southern stations. The integrated nitrate transport contributed by the Oyashio water shows southward nitrate transport reaching approximately 50, 60, 60, and 30 kmol/s for the second to fifth layers (26.6–27.66 σ_θ), respectively (Figures 4b–4e). As the JMA-line captures all four alternating flows, the integrated transport can be regarded as the Oyashio intrusion into the four layers. Therefore, the Oyashio intrusion within the second to fifth layers reaches approximately 200 kmol/s, 110 kmol/s of which occurs in the intermediate layers (second-third layer, 26.6–27.4 σ_θ), which is the source of NPIW.

4. Discussion and Broader Implications

Oyashio water contributes approximately 110 kmol/s to the isopycnic layers of NPIW, with an uncertainty of no more than 20% (a more detailed discussion of the nitrate transport uncertainty can be found in the supporting information S2; Isoguchi & Kawamura, 2003; Ito et al., 2004; Kuroda et al., 2015, 2017; Uehara et al., 2004). It should be noted that the density ranges of NPIW differed between previous studies. For example, Yasuda (2004) used a range of 26.6–27.4 σ_θ, while Talley et al. (2011) used 26.7–27.2 σ_θ. The nitrate transport within 26.6–27.4 σ_θ is 110 kmol/s, while that within 26.7–27.2 σ_θ is 60 kmol/s. Taking 85 kmol/s as an average, the transport of Oyashio water within the density range of NPIW is half of that of Kuroshio in the East

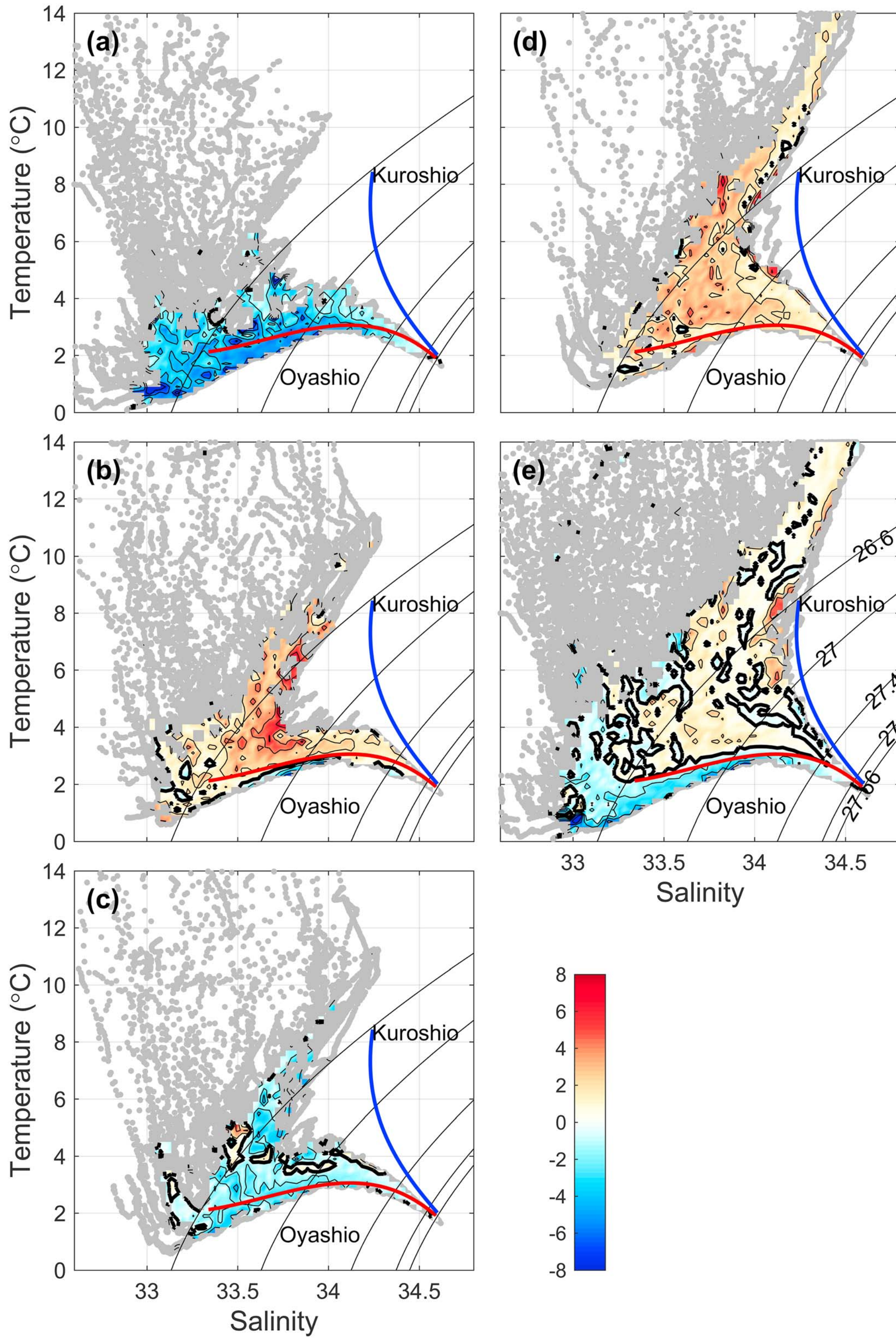

Figure 3. Nitrate flux (color shading, with an interval of 2 mmol·m^{-2}·s^{-1}) as a function of temperature and salinity in (a) SW-1, (b) NE-2, (c) SW-3, (d) NE-4, and (e) over the JMA-line. The gray dots denote all data points of temperature and salinity. The thick black contour denotes 0 mmol·m^{-2}·s^{-1}. The thick red and blue lines denote the typical *T-S* relation of Oyashio and Kuroshio water, respectively. The black lines denote the potential density with values in (e).

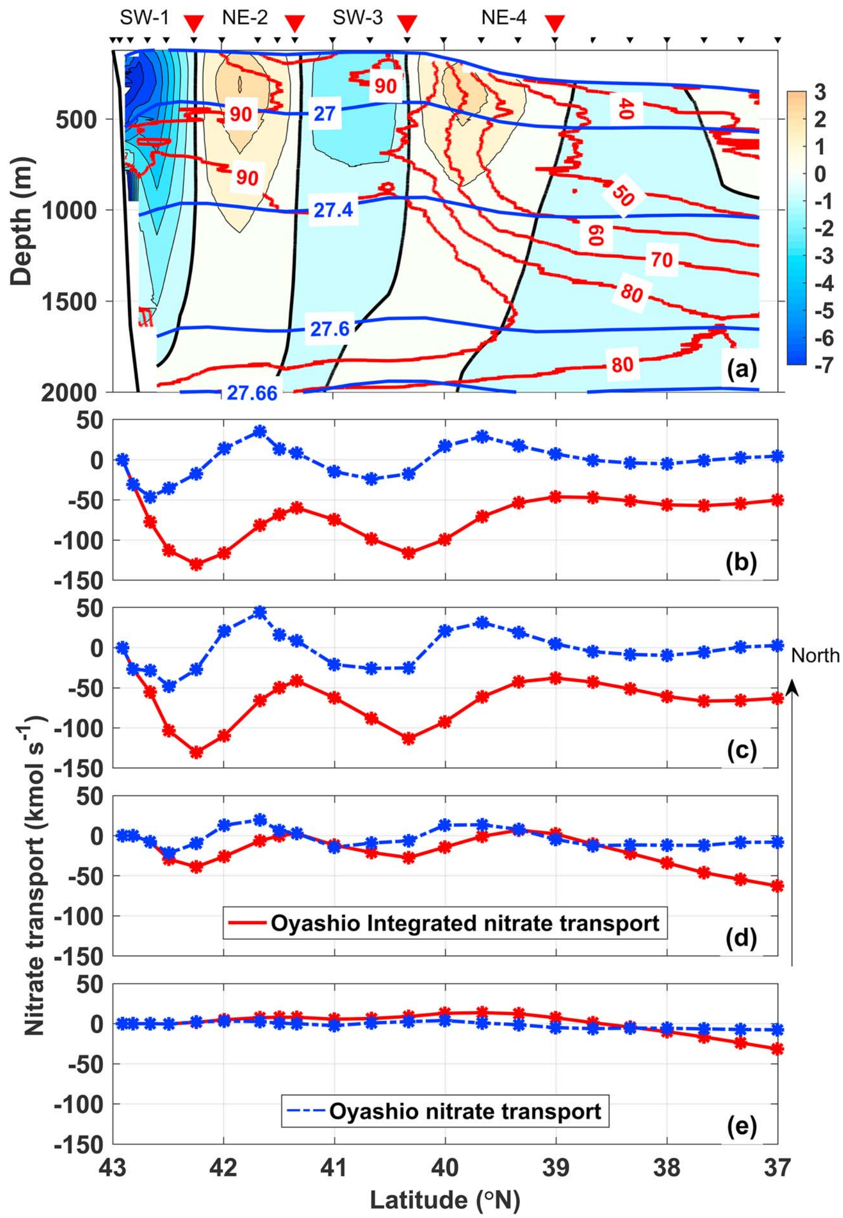

Figure 4. (a) Nitrate flux (mmol·m^{-2}·s^{-1}) contributed by the Oyashio water. The thick red line denotes the mixing ratio of Oyashio water. The thick white line denotes the isopycnal layers (σ_θ). The top layer is blank due to the large uncertainties in its calculation. The inverse triangles indicate the hydrographic stations. (b)–(e) Nitrate transport due to Oyashio water (blue line) and its integrated value from 43 N (red line) in the layers (b) 26.6–27σ_θ, (c) 27–27.4σ_θ, (d) 27.4–27.6σ_θ, and (e) 27.6–27.66σ_θ.

China Sea (170.8 kmol/s). Guo et al. (2012) stated that the Kuroshio Intermediate Water (KIW) is closely related to the NPIW. Our estimation of Oyashio nitrate transport to the NPIW suggests that a considerable portion of the Kuroshio nutrient transport in the intermediate layer is closely related to the contribution of Oyashio, although the exact proportion of NPIW in the Kuroshio Intermediate Water is beyond the focus of our study. Sarmiento et al. (2004) found that the formation of NPIW plays an essential role in the global thermocline nutrient cycle. Hence, the fate of subarctic-origin nutrients is an interesting topic for further study.

The subarctic nitrate export along with the formation of NPIW can be estimated. The difference in the velocity-weighted nitrate concentration between the Kuroshio at section 137E (32.4 mmol/m^3; in the density range of 26.5–27.3; Guo et al., 2013) and Oyashio (40.4 mmol/m^3) is 8 mmol/m^3. Multiplying the volume transport from the Oyashio in the formation of NPIW (3 Sv following Talley et al., 2011) indicates that the subarctic nitrate export is approximately 24 kmol/s (760 Gmol/year), which is twice of the value of 9.5 ± 3.2 kmol/s (300 ± 100 Gmol/year) given by Whitney et al. (2013). The reason for our result being larger than that of Whitney et al. (2013) is that the difference in the nitrate concentration between the subarctic and subtropic gyres used in their study was simply derived from the mean value over the entire gyre. However, this difference becomes larger if the nitrate concentration is used along with that of the Oyashio, which suggests that geostrophic nutrient transport should be carefully determined in the basin-scale nutrient budget. Similarly, this difference can also be applied to the transport of phosphate.

The eddy nutrient transfer cannot be neglected, although the complexity of the dynamics in this area prevents us from displaying long-term variations using in situ data alone. The dominant dynamic pattern in this area is the Kuroshio Extension Decadal Oscillation (Qiu & Chen, 2005), which is unstable (stable) with more (less) eddy activity. In its unstable state, eddy transfer enhances cross-gyre water/material exchange. As a result, high (low) nutrient concentration water was transported southward (northward), along with high (low) potential vorticity water. This reduced the formation of subtropical-mode water (Oka et al., 2015) in the south and the primary productivity anomaly in the north. Palter et al. (2005) suggested that the advection of mode water may introduce spatial and temporal variability in the subsurface nutrient reservoir and further affect the downstream primary productivity by altering the subsurface nutrient supply to the surface layer. The extent to which these processes impact the mode water nutrient reservoir has not yet been reported. Hence, studies focusing on the long-term spatial-temporal variation of the Oyashio nutrient stream are expected.

5. Summary

We examined the long-term mean nutrient flux (production of velocity and nutrient concentration) and nutrient transport (integration of the nutrient flux over the section) of Oyashio and its nutrient transport in the formation of NPIW. The Oyashio nutrient stream has a maximum subsurface nitrate flux of 7 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at a depth of 250 m. It transports nitrate and phosphate southward at 348.39 and 25.58 kmol/s, respectively. Variations in nitrate flux between the four alternating flows from SW-1 to NE-4 were observed based on the section profile and water properties, which suggests that the nitrate transport of Oyashio along with the NPIW formation is 110 kmol/s, and the effective nitrate transport from the subpolar to the subtropic region is 24 kmol/s. As the Oyashio nutrient stream plays an important part of the North Pacific nutrient cycle, it should receive more attention in future studies.

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