이학석사 학위논문

Decrease of nutrients in the upper northwestern Pacific Ocean: Analysis of 40-year observational data

북서태평양에서 상부 수층 영양염의 농도 감소: 40년 간의 관측 자료 분석 결과

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김지현

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Abstract

Decrease of nutrients in the upper northwestern Pacific Ocean: Analysis of 40-year observational data

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The Kuroshio current, passing through the northwestern Pacific Ocean, transports heat and nutrients in the subtropical North Pacific and its various marginal seas. Previous studies have reported that the increasing anthropogenic input into the North Pacific has led to increase in the budget of nitrogen (N) in the ocean. Conversely, other studies have reported that enhanced surface stratification from climate change has caused decreased surface nutrient concentrations in the region. The present study shows that nutrient concentrations in the Kuroshio current have decreased strikingly in the upper ocean (0-850 m) over the last four decades. Observational data compiled over 37 years (from 1980 to 2017) was utilized to identify the long-term trends in nutrients in the upper ocean and to suggest the mechanism for this change. Surface (0-100 m) nutrient concentration declines are revealed to have mainly resulted from subsurface (100-850 m) nutrient reservoir decreases that is associated with the physical regime shift in the region rather than the previously presumed surface water stratification or mixed layer shoaling.

The ongoing depletion of nutrients in the upper 850 m of the Kuroshio current seems to extend to the entire Kuroshio system that includes the subtropical North Pacific and its marginal seas. The consequences of these changes include ~30% depression in new production and decreased N:P ratio in the surface. Thus, marine desertification of the northwestern Pacific Ocean seems to be occurring with implications of decreased carbon sequestration, extended impacts on fishery productivity, and ecological shifts toward greatly N-limited environments in the region.

Keywords : Nutrients, nitrate, nitrite, phosphate, N:P ratio, northwestern Pacific Ocean, Kuroshio current
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Table of Contents

List of Tables

List of Figures

1. Introduction

1.1. Nutrients in the Ocean

Nutrients are the basis of life in the ocean. Of all the different elements that fuel life, nitrogen (N) and phosphorus (P) are known as major nutrients because they play critical roles in stimulating biological production. Primary production occurs in the surface euphotic zone when these major nutrients are supplied to the zone for utilization by phytoplankton. The nutrients are supplied by several means including upwelling and mixed layer shoaling (Bibby et al., 2008), atmospheric deposition (Duce et al., 2008; Kim et al., 2014; Kim et al., 2011), and lateral transport (Cho et al., 2019; Letscher et al., 2016), each of which carry different loads of N and P at differing ratios. These “new” nutrients mostly comprise nitrates and phosphates which are utilized by phytoplankton to be exported back into the subsurface. Production based on these newly supplied nutrients are thus termed “new production” (Dugdale and Goering, 1967). Meanwhile, regenerated production that supports the biomass of phytoplankton also occurs in the euphotic zone (Dugdale and Goering, 1967) where ammonia and phosphates regenerated from the initial mass of phytoplankton are mainly utilized (Figure 1).

Such cycles of nutrients are especially important in the subtropical ocean where the surface nutrient supply is replenished yearly by winter mixing from the subsurface nutrient inventory. However, anthropogenic impact has been expected to largely change the dynamics of ocean biogeochemistry. Global and regional fluctuations in the various supplies of nutrients based on climate change (Behrenfeld et al., 2006; Doney, 2006) and anthropogenic pollution (Duce et al., 2008) have been highlighted in previous reports. At a global scale, surface temperature increase and changes in freshening from climate change has resulted in simulations projecting slowed thermohaline circulation, mixed layer shoaling and increased stratification to cause a decline in the replenishment of the surface nutrient inventory (Sarmiento et al., 2004; Steinacher et al., 2009). In the coastal oceans and marginal seas, atmospheric deposition of nutrients that mainly comprises N (minimal P composition) as well as riverine and submarine groundwater discharge of eutrophic waters have led to increased fixed N in many of the coastal and marginal regions (Canfield et al., 2010; Cho et al., 2018; Doney, 2010; Duce et al., 2008)

Based on global changes from anthropogenic impact, surface nutrient declines have been observed globally both directly and indirectly through measurements of nutrient concentrations (Aoyama et al., 2008; Kodama et al., 2016; Yasunaka et al., 2016) and observations of chlorophyll a (Behrenfeld et al., 2006; Doney, 2006). In major subtropical and subpolar oceans, indirect observations of nutrient decrease have been reported through satellite-derived phytoplankton concentrations (Behrenfeld et al., 2006; Polovina et al., 2008), *in situ* chlorophyll measurements (Boyce et al., 2010), and ocean transparency measurements which all point toward long-term declining trends in chlorophyll. In these reports, surface stratification and mixed layer shoaling associated with climate change is suggested to result in the obstruction of the upward flux of nutrients causing the decline in chlorophyll concentrations. The inventory of nutrients available for upward flux is not considered by these reports. On the other hand, modeling studies hint that no correlation exists between surface nutrient changes and local stratification (Dave and Lozier, 2010; Dave and Lozier, 2013; Lozier et al., 2011) and also put forward lateral transport as an import source of nutrients (Cho et al., 2019; Letscher et al., 2016), especially in the subtropical gyres.

At a regional scale, the northwestern Pacific Ocean and its marginal seas is an interesting research area. The Kuroshio current, which is known to be a highly oligotrophic and N-limited current, passes through the western boundary of the northwestern Pacific Ocean and influences the environments of not only the North Pacific but also its marginal seas (Cho and Kim, 2000; Ichikawa and Beardsley, 2002; Kwon et al., 2010; Qiu, 2001) (Figure 2). Furthermore, the area is in the highly populated East Asian region where atmospheric anthropogenic N deposition is likely to be high due to agricultural, industrial and urban development in the region. As such, the northwestern Pacific Ocean is highly susceptible to nutrient concentration changes; understanding of long-term changes in nutrients in the region is crucial.

Nutrient research on the region has, however, been focused only on surface nutrient changes (Aoyama et al., 2008; Kim et al., 2014; Kim et al., 2011; Kodama et al., 2016; Yasunaka et al., 2016). Despite the shallow depth of research, a consensus has not yet been reached on the trends of nutrients in the area as well. Some studies report that surface nutrient concentrations have decreased in the region through long-term observational studies as a result of surface stratification and changes in the surrounding region (Kodama et al., 2016; Yasunaka et al., 2016) while other studies report that surface nutrient concentrations, especially N, have increased due to anthropogenic pollution by considering excess N (N*) budgets (Kim et al., 2014; Kim et al., 2011). A look at the subsurface nutrient reservoir could be a means to reconcile these different reports.

1.2. Aim of this study

The overall goal of this study is to present a three dimensional understanding of the long-term changes in N and P in the northwestern Pacific Ocean region. The objectives of the study include (1) identifying trends in surface and subsurface nutrient concentrations and (2) suggesting a mechanism for the changes in nutrient concentrations.

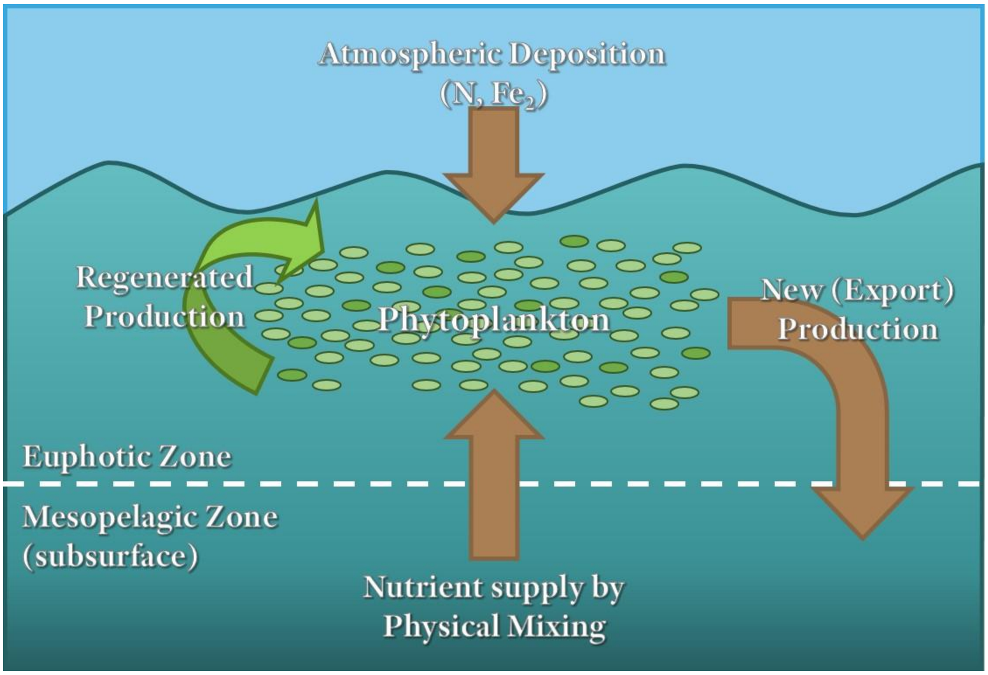

Figure 1. The cycle of nutrients in the ocean. The cycle of "regenerated" nutrients are colored green while the cycle of "new" nutrients are colored brown.

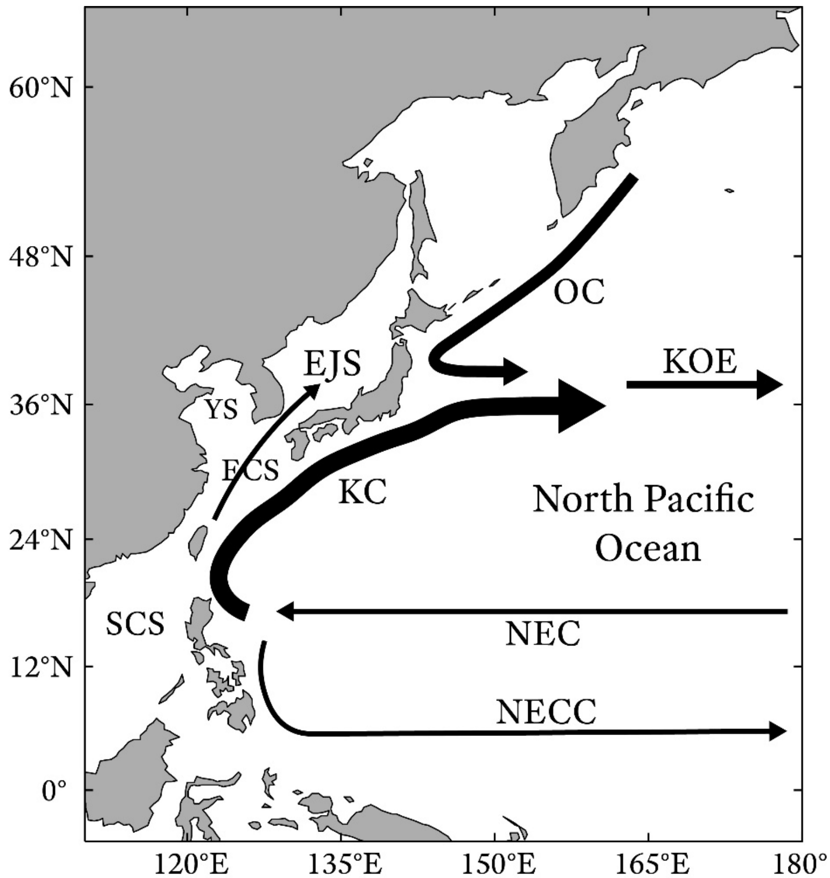

Figure 2. Current map of the western Pacific Ocean including the different marginal seas. The North Equatorial Current (NEC) bifurcates into the Kuroshio Current (KC) and the North Equatorial Counter Current (NECC). The KC affects the South China Sea (SCS), the East China Sea (ECS), the Yellow Sea (YS), and the East/Japan Sea (EJS) which is also called the Kuroshio Current System as a whole. The Oyashio current (OC) flows above the KC and meets it to form the Kuroshio-Oyashio Extension that meanders east toward the center of the Pacific Ocean.

2. Methods

2.1. Data collection and quality control

To study the changes in nutrient concentrations in the northwestern Pacific Ocean, data in the region were compiled (Figure 3). Nutrient and temperature data archived at the Japan Meteorological Agency (JMA: http://www.data.jma.go.jp/gmd/kaiyou/db/vessel_obs/data-report/html/ship/ship_e.php) and the Korean National Institute of Fisheries Science (NIFS: http://www.nifs. go.kr/kodc/soo_list.kodc) as well as those collected through observational cruises conducted in the East Asian Time-Series Project (EAST: http://east.snu.ac.kr/) were utilized for this study. A total of about 18,500 stations and 350,000 data points were collected for the study.

All depth data were rounded to 1 m and each station was allocated into 1^{o} by 1^{o} grids. Then, the study areas were selected. To observe changes in the different areas of the northwestern Pacific Ocean, the region was divided into three study areas: the main Kuroshio stream, the inner subtropical gyre, and the eastern side of the East/Japan Sea (Figure 4). The data were divided into different sets as closely as possible within the 1^{o} by 1^{o} grids.

Any nutrient concentration data that was lower than detection limits were assumed to be not detected and converted to 0 μmol L^{-1}, where the detection limits are the generally accepted 0.1 μM for N and 0.01 μM for P. Each data set (a set each for the main Kuroshio stream, inner subtropical gyre and the eastern East/Japan Sea study areas designated in the previous section) was then divided into 18 depth layers for quality control (Table 1) similar to the quality control conducted by

Kodama et al. (2016). Then, all discrete data points outside 3 standard deviations from the mean were removed for each parameter (refer to Figure 5 for an example of the result of the data quality control). About 1% of the total dataset (in terms of data points) was removed for N and P while about 0.3% was removed from the temperature dataset as a result of the quality control. In total, 9,992 stations and 182,477 discrete data points at depths from 0 m to 7000 m were utilized for the remaining analysis.

2.2. Analysis of temperature and nutrient data

The quality controlled data above 1500 m was then divided into 10 depth layers (Table 1). In order to weight the data to compensate for the differing spatiotemporal frequency of observations in the main Kuroshio stream area and the inner subtropical gyre area, the monthly average for each parameter in 3^{o} by 3^{o} grids was calculated. Then, the 5-year means of each depth layer were found for the two study areas. For the eastern side of the East/Japan Sea, only monthly averaging of the parameters for temporal weighting were conducted before finding the 5-year means as the data points in the East/Japan Sea study area were deemed sufficiently spread out in terms of observation frequency spatially. Each 5-year averaged values by depth layer was plotted at the depth in the center of each depth layer as the depth profile. The surface and the subsurface layers were then determined using the depth profiles. The surface layer was determined as 0-100 m (euphotic zone) and the subsurface layer as 100-850 m. The subsurface layer depth was confirmed by plotting the monthly temporal trend of nutrient concentrations and temperature in the layer below the subsurface to ensure the parameters were constant below the subsurface layer (Figure 6).

Following this, the inventory change over four decades in the surface and the subsurface was estimated by calculating the area between the 2015 line and the 1980 line. The area under the 2015 line and the 1980 line was calculated each and subtracted. Error propagation was applied to find the error of the inventory calculation.

The linear trends of nutrient concentrations and temperature in the main Kuroshio stream area for the surface and the subsurface was identified through linear regression. The quality controlled data was weighted spatiotemporally in the same manner as the depth profiles by monthly averaging in 3^o by 3^o grids over the research area but with differing depth intervals (Table 1). The results were averaged monthly again over the entire research area in the surface (0-100 m) and the subsurface (0-850 m) layer and plotted with colors to show season. In this research spring includes March, April, and May, summer includes June, July, and August, autumn includes September, October and November, and finally winter includes December, January and February. Temporal trends of nutrient concentrations and temperature were then identified for the entire period, for summer and for winter separately by applying linear regression to each parameter. The slopes, the p-values of the slope as well as the r^2 values of the trend-lines were identified as well.

2.3. Analysis for identification of the physical mechanism

Change in the thermal gradient in each depth layer was investigated. The variance in the temperature difference between 100 m depth layers were found to identify structural changes. That is, the monthly averaged temperature difference between 0 m and 100 m, that between 100 m and 200 m, up to 700 m was calculated and plotted temporally. Linear regression was applied to the surface layer to check if a temporal trend existed for the layer.

The vertical profiles for temperature, N concentration and P concentration were plotted for winters and springs of 1980-1990 and 2000-2010 with the same method as the total 5-year vertical profiles to check for association with the physical regime shift of the northwestern Pacific Ocean that occurred between 1985-1990 (Pak et al., 2014).

2.4. Estimation of apparent new production and net primary productivity

Apparent new production of the main Kuroshio stream was estimated by using the following equation that Henson et al. (2003) suggested:

$$\text{Apparent New Production} = R_{C:N}[N_w - N_S][(Z_{d(spr)} - Z_{d(sum)})/2]$$

where $R_{C:N}$ is the Redfield C:N ratio (106:16), N_W and N_S are the average winter and summer N concentrations in the corresponding mixed layer depths, and $Z_{d(spr)}$ and $Z_{d(sum)}$ are the average mixed layer depths from 2000-2018 in early spring and late summer respectively (Holte et al., 2017). Yearly apparent new production was calculated from 1980 to 2017 and the temporal trends were found by linear regression.

The temporal changes in net primary productivity of the study area was also plotted using VGPM-based net primary production (Behrenfeld and Falkowski, 1997) results obtained from the Ocean Productivity site (http://sites.science.oregonstate.edu/ocean.productivity /index.php) for both SeaWiFS satellite PAR data (1997-2009) and MODIS satellite chlorophyll and temperature data (2002-2019) (Oregon State Univeristy, 2019).

2.5. Analysis of nutrient ratios

The linear trends of N:P ratio and excess N (N*) in the main Kuroshio stream study area were identified by linear regression. Each ratio was calculated only when either of the nutrient values existed. N:P ratio was calculated by dividing N concentrations at each point with P concentrations while N* was calculated using the following equation:

$$N^* = N - R_{N:P} \times P$$

Where N is N concentration, P is P concentration and $R_{N:P}$ is the Redfield ratio of 16:1 (Gruber and Sarmiento, 1997). Then the calculated ratio data were weighted spatiotemporally monthly averaging over 3^o by 3^o grids in the research area with the same depth intervals as the linear trend analysis of nutrient concentrations and temperature (Table 1). The results were averaged monthly again over the entire research area in the surface (0-100 m) and the subsurface (0-850 m) layer and plotted with colors to show season. Temporal trends of nutrient ratios were then identified for the entire period. The slopes, the p-values of the slope as well as the r^2 values of the trend-lines were identified as well.

Table 1. Table of depth layers of intervals for quality control and depth profiles. The depth layers were selected at increasing intervals according to sampling density from 0 m to 7000 m for quality control and from 0 m to 1500 m for plotting depth profiles.

Method	Depth Layers
Quality Control	0-10 m, 10-25 m, 25-50 m, 50-75 m, 100-125 m, 150-200 m, 250-300 m, 400-500 m, 750-1000 m, 1000-1500 m, 1500-2000 m, 2000-3000 m, 3000-7000 m
Depth Profile	0-20 m, 20-50 m, 50-100 m, 100-200 m, 200-300 m, 300-400 m, 400-500 m, 500-750 m, 750-1000 m, 1000-1500 m
Linear Trend	0-25 m, 25-50 m, 50-75 m, 75-100 m, 100-150 m, 150-200 m, 200-250 m, 300-350 m, 350-400 m, 400-450 m, 450-500 m, 500-550 m, 550-600 m, 600-650 m, 650-700 m, 700-750 m, 750-800 m, 800-850 m

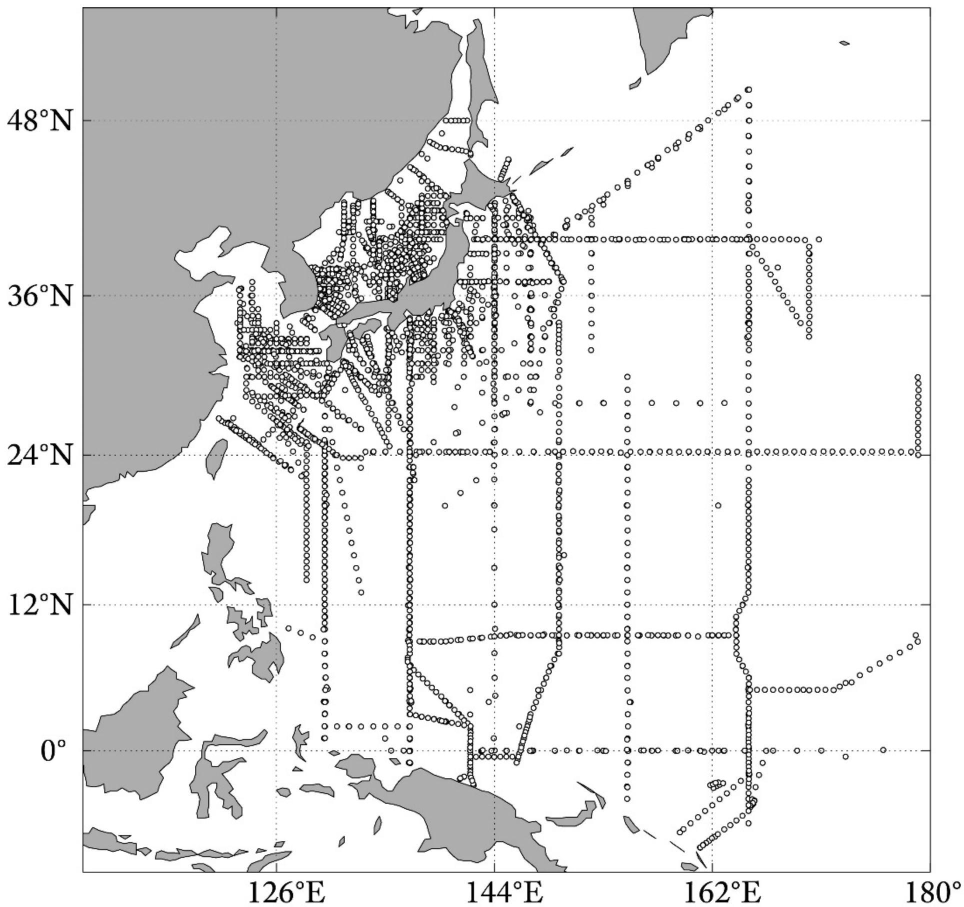

Figure 3. Data collection sites in the northwestern Pacific Ocean. Total data collected from different regional observation projects from Korea and Japan.

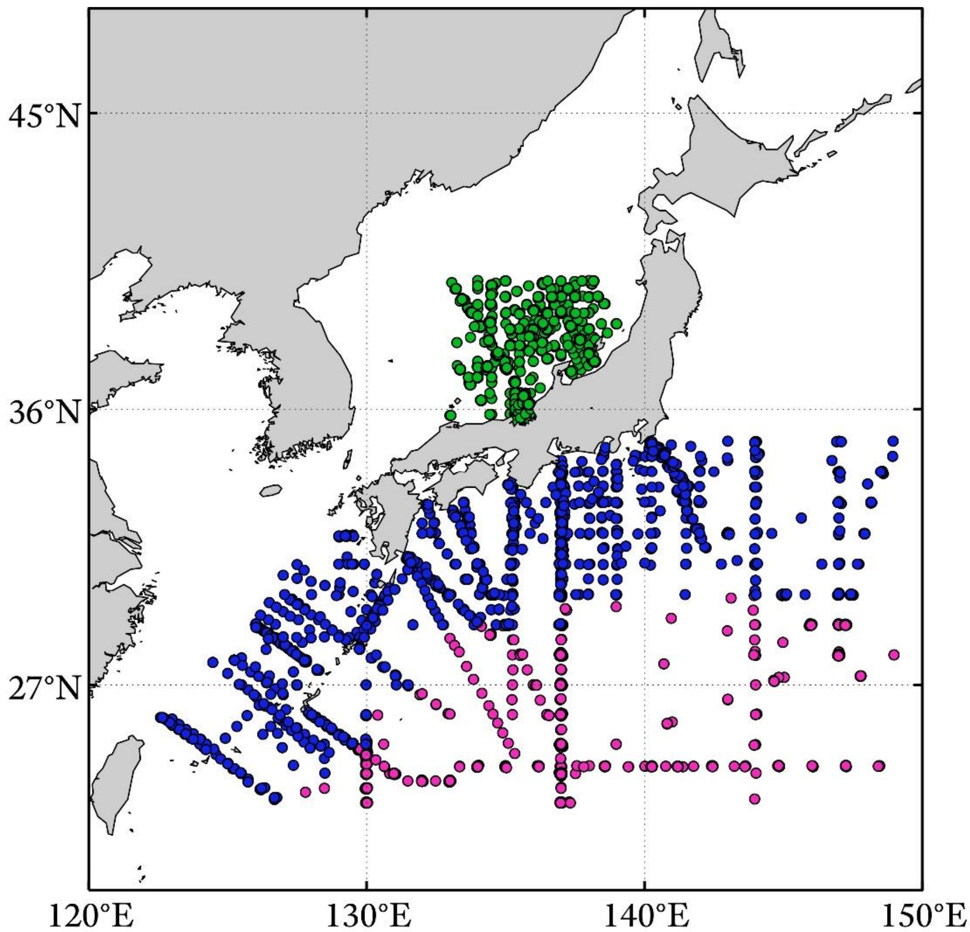

Figure 4. Selected study areas. The sites in the main Kuroshio stream is marked by blue dots, while the sites in the inner subtropical gyre area is marked by pink dots, and the sites in the eastern part of the East/Japan Sea is marked by green dots.

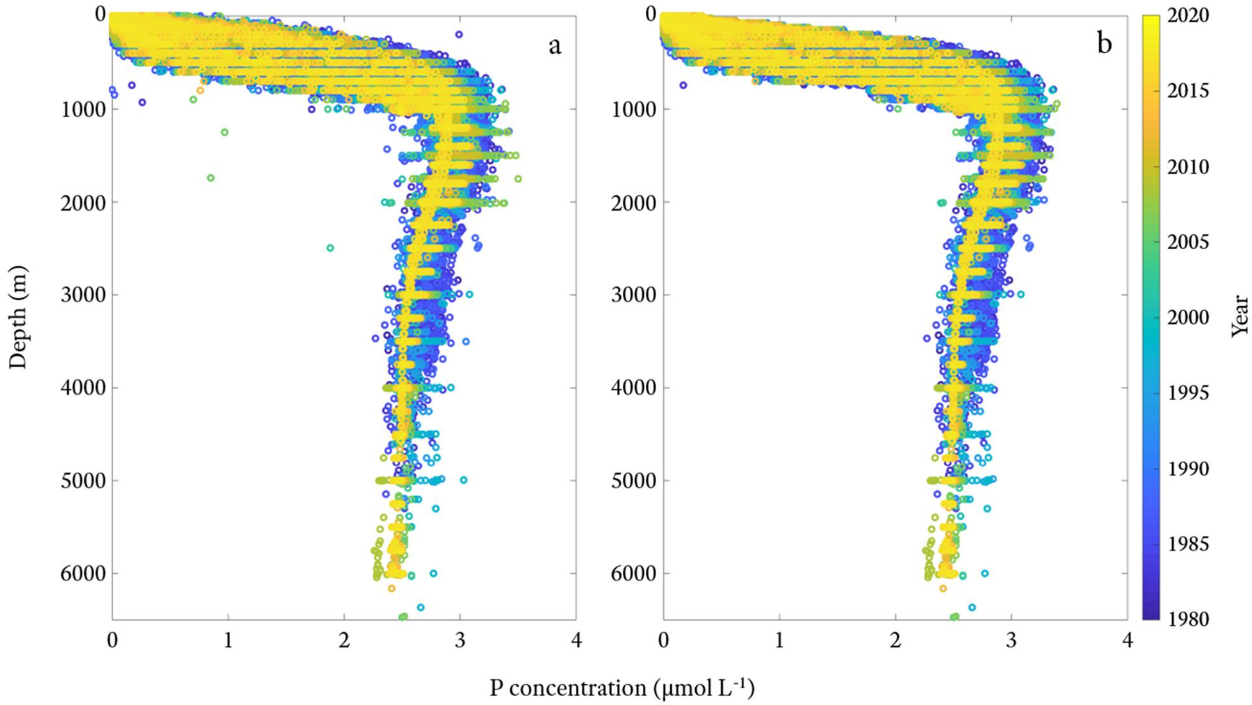

Figure 5. An example of the results of quality control. a) data points of compiled P concentrations for the main Kuroshio stream by depth and time and **b)** data points of quality controlled (removal of data points deviating from 3 S.D.) P concentrations for the same study area.

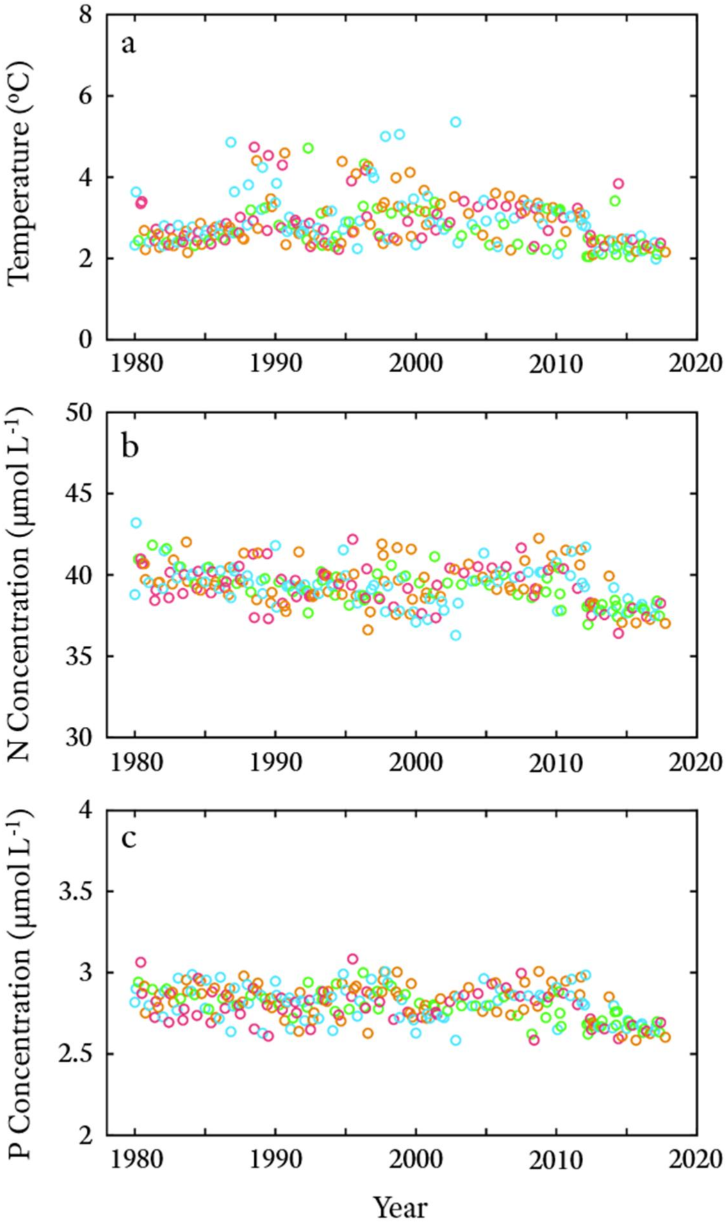

Figure 6. Temperature and nutrient concentrations below 850 m. Temporal trends of **a)** temperature, **b)** N concentrations, and **c)** P concentrations over 37 years from 1980 to 2017. The parameters seem nearly constant below the subsurface layer of 850 m.

3. Results and Discussion

3.1. Long-term changes nutrients and temperature

The vertical profiles of temperature and nutrients in the upper ocean of the main Kuroshio stream show structural changes that lead from increase in temperature and decreases in nutrients in the subsurface ocean (Figures 7-9). The nutrient depth profiles show increase in concavity from a concave downward structure toward a concave upward structure over four decades from the 1980s to the 2010s (Figures 8-9). Such structural changes are especially evident in the subsurface layer (100-850 m). As such, these changes translate to a significant decrease in the nutrient inventory of the subsurface ocean. The structural change in the nutrient profiles is mirrored in the temperature depth profile (Figure 7).

In order to better identify temporal trends and the rates of decline, linear regression was applied to average monthly concentrations of N and P at each depth layer (the surface and the subsurface layer). Significantly declining temporal linear trends in nutrient concentrations are identified in the surface layer (0-100 m) of the Kuroshio current (Figure 10a and Figure 10c) at rates of -0.023 ± 0.003 μmol N L^{-1} yr^{-1} ($r^2 = 0.16$) and -0.0021 ± 0.0002 μmol P L^{-1} yr^{-1} ($r^2 = 0.23$). Similar declines in nutrient concentrations are also observed in summer and winter both at similar rates. They occur at significant ($p<0.001$) rates of -0.024 ± 0.006 μmol N L^{-1} yr^{-1} ($r^2 = 0.32$) and -0.0021 ± 0.0004 μmol P L^{-1} yr^{-1} ($r^2 = 0.47$) in summer and -0.021 ± 0.005 μmol N L^{-1} yr^{-1} ($r^2 = 0.32$) and -0.0018 ± 0.0004 μmol P L^{-1} yr^{-1} ($r^2 = 0.37$) in winter. This consistency suggests that the declines are occurring throughout the entire year; the changes are not seasonal. The decrease in nutrient concentrations is greatly evident in the subsurface layer (100-850 m) of the Kuroshio current as well. By linear regression of temporal nutrient data, significantly declining linear trends ($p<0.001$) were identified with slopes of -0.107 ± 0.012 μmol N L^{-1} yr^{-1} ($r^2 = 0.22$) and -0.0090 ± 0.0009 μmol P L^{-1} yr^{-1} ($r^2 = 0.27$; Figure 10b and Figure 10d). Seasonal changes were not considered in the subsurface layer, as there was expected to be minimal seasonal differences in the subsurface.

The declining trend in the surface layer translates to the halving of surface nutrient concentrations over four decades, which is also reflected in the change in average nutrient concentrations and the inventory. Average nutrient concentrations at the beginning of the study period (1980) were around 1.7 μmol L^{-1} and 0.17 μmol L^{-1} while those at the end (2017) were around 1.1 μmol L^{-1} and 0.09 μmol L^{-1}, for N and P respectively. The 37-year reduction of the nutrient inventories estimated using the depth profiles is 122 ± 11 g N m^{-2} and 10.9 ± 0.8 g P m^{-2}. Similarly, the subsurface nutrient inventory decreased by 4650 ± 400 g N m^{-2} and 381 ± 30 g P m^{-2} which translate to reductions of approximately 23% and 26% in percentage decrease, respectively for N and P. Although the subsurface decrease is smaller in terms of percentage reduction as compared with that of the surface, the inventory decrease in the subsurface layer is more than 30-fold of the surface decrease. The subsurface decrease thus has a significant impact on the reservoir of nutrients in the upper northwestern Pacific Ocean.

3.2. Physical mechanism of nutrient decline

Changes in the thermal gradient were examined in order to investigate the mechanism for the considerable decline in nutrient concentrations. The temperature difference between 100 m depth layers were utilized to identify the structural changes. Surface thermal stratification (T_{0-100} as an index) had not changed significantly over the study period of 37 years when linear regression was applied to find temporal trends (box T_{0-100} in Figure 11). The proportional warming of the subsurface layer results in the lack of change despite surface warming from 23.2°C to 24.4°C. On the other hand, the amplitude of the thermal gradient at depth layers below the surface had decreased abruptly from 1985 to 1990 (shaded red in Figure 11). This marked decrease in amplitude is especially evident from 300 m. Coupled with the structural change in the vertical profiles of temperature and nutrients (Figures 7-9), the decreased amplitude of the subsurface layers means that diffusive vertical heat flux has decreased. Diffusive vertical heat flux is presumably correlated with vertical nutrient flux; thus its decrease can then be translated to vertical nutrient flux reduction.

This structural change in the study area looks to be highly associated with the physical regime shift of the northwestern Pacific which occurred between 1985 to 1990 (Kim et al., 2020; Pak et al., 2019). The key change from the regime shift is the change in the primary control of the upper ocean thermal condition where the East Asian winter monsoon (atmospheric forcing) primarily controlled the conditions before 1990 while the spring-initiated reemergence process (ocean dynamics) controls the conditions after 1990 (Kim et al., 2020; Kwon et al., 2010; Pak et al., 2014; Pak et al., 2019). The conspicuous decrease in the amplitude of $T_{300-400}$ from 1980 to after 1990 (box $T_{300-400}$ in Figure 11) supports the structural change that is observed in the vertical temperature profile (Figure 7). Further, the deeper-reaching seasonal thermal and nutrient change (up to ~800 m) before 1990 as compared to those after 1990 in the vertical temperature profiles of winter and spring (Figures 12-14) is representative of the regime shift of the northwestern Pacific. Thus, the nutrient concentrations seem to have gradually decreased as the nutrient concentrations change toward equilibrium from the lack of vertical nutrient flux caused by the regime shift associated change in the vertical profile structure and decrease in the thermal gradient amplitude.

Previous studies have considered the nutrient concentration changes in the surface to be caused by stratification from surface warming (Behrenfeld et al., 2006; Doney, 2006; Polovina et al., 2008) or anthropogenic nutrient input from nearby continents (Duce et al., 2008; Kim et al., 2014; Kim et al., 2011). However, this study shows that the surface nutrient concentration declines reported repeatedly in the northwestern Pacific Ocean region including its marginal seas is probably a result of the considerable depletion of the subsurface nutrient reservoir. This possibility is further corroborated by prior publications that suggest a lack of statistically significant correlation between the ocean chlorophyll concentrations (highly correlated to nutrient concentrations) and the inter-annual variability in surface stratification (Dave and Lozier, 2010; Dave and Lozier, 2013; Lozier et al., 2011) in addition to other publications that report limited evidence of statistically significant temporal trends in surface stratification (Dave and Lozier, 2010) or mixed layer shoaling (Somavilla et al., 2017) in the North Pacific Ocean.

3.3. Extent of nutrient decline

In order to investigate the spatial extent of the nutrient decline, the vertical profiles of temperature, N concentrations, and P concentrations in the eastern East/Japan Sea and the Inner Gyre study areas were found. Although structurally different, similar decrease in subsurface nutrient concentrations were observed in the depth profiles for the eastern East/Japan Sea (Figures 15-17). The East/Japan Sea is known to be affected by the Kuroshio current through a shallow strait – the Tsushima Strait – which albeit a surface connection puts the East/Japan Sea in the Kuroshio system. However, the marginal sea also has its own deep ventilation system (Chang et al., 2016). Thus, this analogous decrease in nutrient concentrations that occurs in the East/Japan Sea suggests that similar changes are occurring in the entire Kuroshio current system of the northwestern Pacific Ocean.

However, in the Inner Gyre study area, minimal temporal trends could be observed over depth (Figures 18-20). Which points to the possibility that outside of the Kuroshio current system, similar shifts are not yet occurring. However, this does not dictate that such changes will not occur in the future.

3.4. New production and net primary productivity

Yearly apparently new production shows a significant declining trend during the study period (Figure 21). This decline translates to new production decreasing by around 30% over four decades. The estimation only takes into account the spring bloom, that is the new production that occurs between winter and summer; the new production in the northwestern Pacific Ocean is decreasing at a conservative rate of 0.044 g C m^{-2} yr^{-1}. This directly affects the carbon sequestration in the region. Furthermore, fishery productivity is highly correlated to new production through mesozooplankton production (Friedland et al., 2012). Thus, the decline in new production is also likely to lead to negative impacts on fishery productivity.

However, despite the large decrease, net primary productivity of the area showed no significant trends over the past two decades (Figure

21). As the estimated apparent new production is only approximately 3% of the average net primary productivity between spring to summer each year, regenerated production represents the major portion of the primary production occurring in the oligotrophic Kuroshio region. As a result, the nutrient concentration decrease is not yet observed in primary productivity although it is expected to be reflected eventually as the depletion continues.

3.5. Changes in nutrient ratios

The fraction of anthropogenic nutrients in the ocean is also likely to be affected by the change in nutrient concentrations. The anthropogenic input of nutrients, especially N, from the atmosphere (Duce et al., 2008), rivers (Justić et al., 1995), and the continental shelves (Cho et al., 2019) will comprise an increasing fraction of the inventory of nutrients in the upper ocean as the natural concentrations of nutrients decrease from the lack of deep water pumping to the upper ocean. Thus, we used excess N concentration (N*) as an index to estimate the increase in the anthropogenic fraction of N (Gruber and Sarmiento, 1997; Kim et al., 2014). In both the surface and the subsurface layer, a significant increase in N* was observed ($p<0.01$) at rates of 0.008 ± 0.002 μmol L^{-1} yr^{-1} ($r^2 = 0.09$) and 0.031 ± 0.005 μmol L^{-1} yr^{-1} ($r^2 = 0.16$) respectively (Figure 22a and Figure 22b). N* is approaching 0 for both layers. This N* increase has been already documented and explained in prior studies by anthropogenic nitrogen input from the East Asian continent near the northwestern Pacific Ocean (Kim et al., 2014; Kim et al., 2011).

The decline in nutrient concentration in the surface ocean seems to project the N:P ratio toward 0 - that is N limitation – in the surface layer despite the increase in anthropogenic N. This contrasts the shift toward a P-limited environment in the northwestern Pacific Ocean that previous studies have anticipated under the assumption that the supply and consumption of natural nutrients would be constant in the region (Kim et al., 2014; Kim et al., 2011). However, under the current declining trend of natural nutrients in the upper ocean, export production occurring near the Redfield ratio (Anderson and Sarmiento, 1994) would bring the currently N-limited environment of the northwestern Pacific further into even lower N:P ratios. To further support this, plots of correlations between nutrient concentrations and the surface N:P ratios show significant correlations (Figure 23a and Figure 23b). In the subsurface layer on the other hand, biological consumption of nutrients is minimal. Consequently, the N:P ratio in the subsurface is largely affected by the anthropogenic input of N. The decrease of the natural fraction of nutrients in the subsurface layer, coupled with the large increase in the anthropogenic fraction of N, results in the increase of the N:P ratio toward 16 (Figure 23c and Figure 23d).

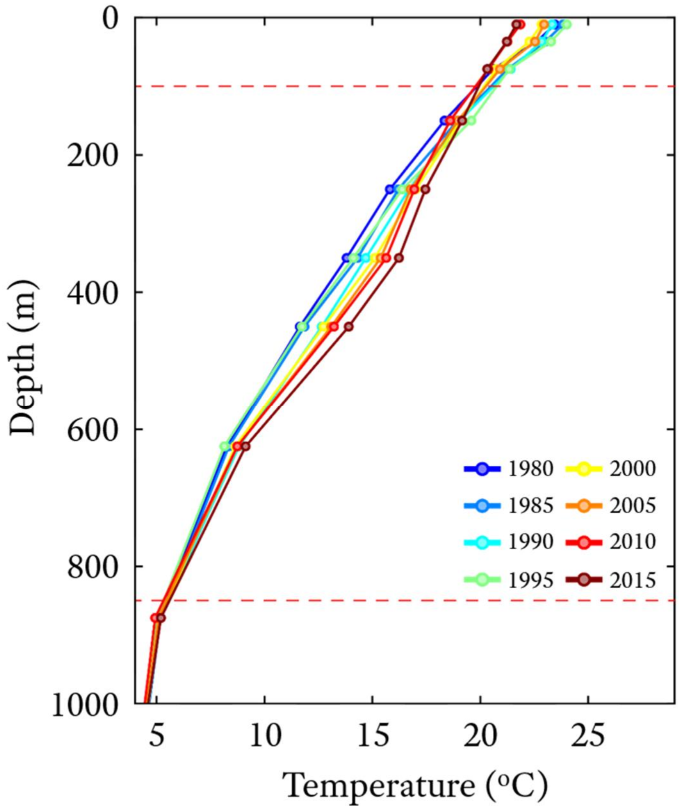

Figure 7. Temperature depth profile. The vertical profile of temperature in the upper Kuroshio waters of temperature averaged every five years from 1980 to 2017. Structural change occurring over four decades can be observed. The surface and the subsurface layers are marked by red dashed lines.

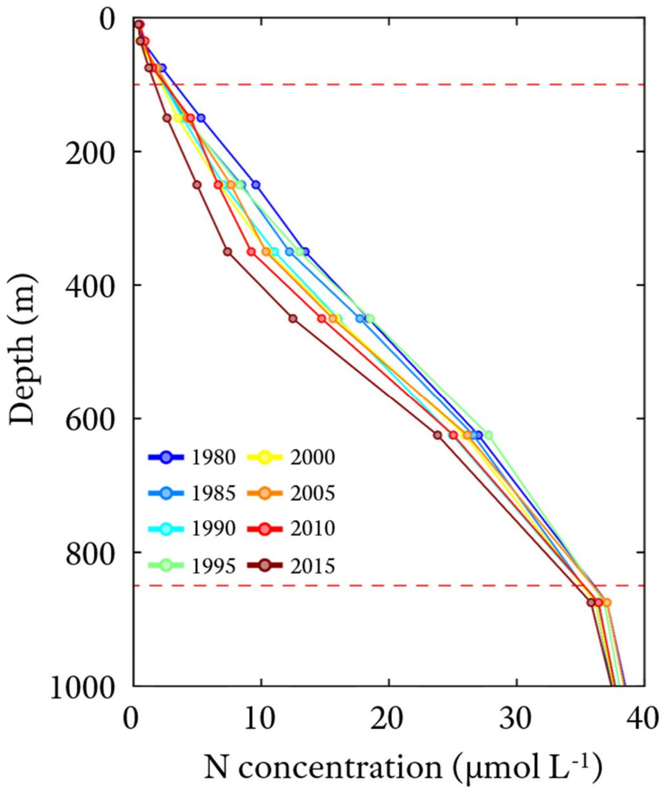

Figure 8. N depth profile. The vertical profile of N concentration in the upper Kuroshio waters of N concentrations averaged every five years from 1980 to 2017. Structural change occurring over four decades resulting in nutrient reservoir depletion can be observed. The surface and the subsurface layers are marked by red dashed lines.

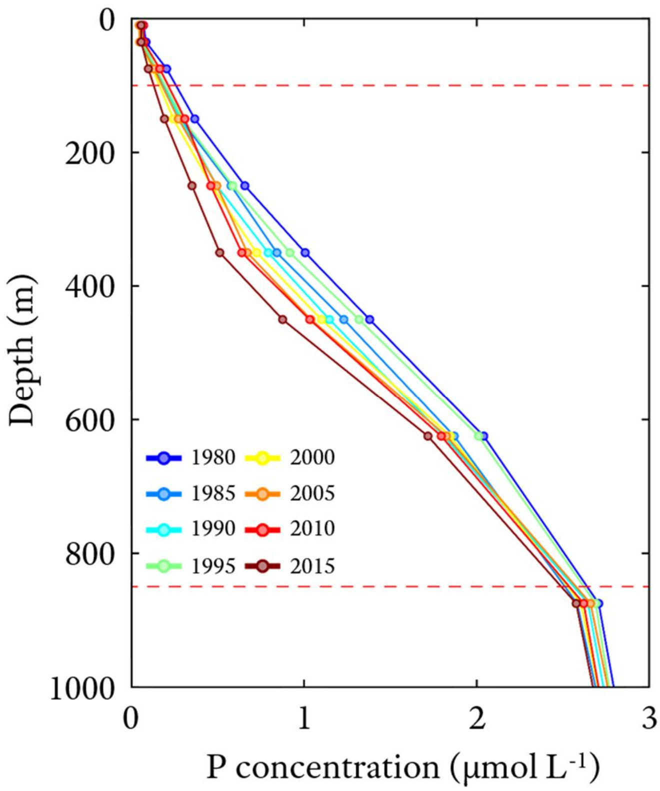

Figure 9. P depth profile. The vertical profile of P concentration in the upper Kuroshio waters of P concentrations averaged every five years from 1980 to 2017. Structural change occurring over four decades resulting in nutrient reservoir depletion can be observed. The surface and the subsurface layers are marked by red dashed lines.

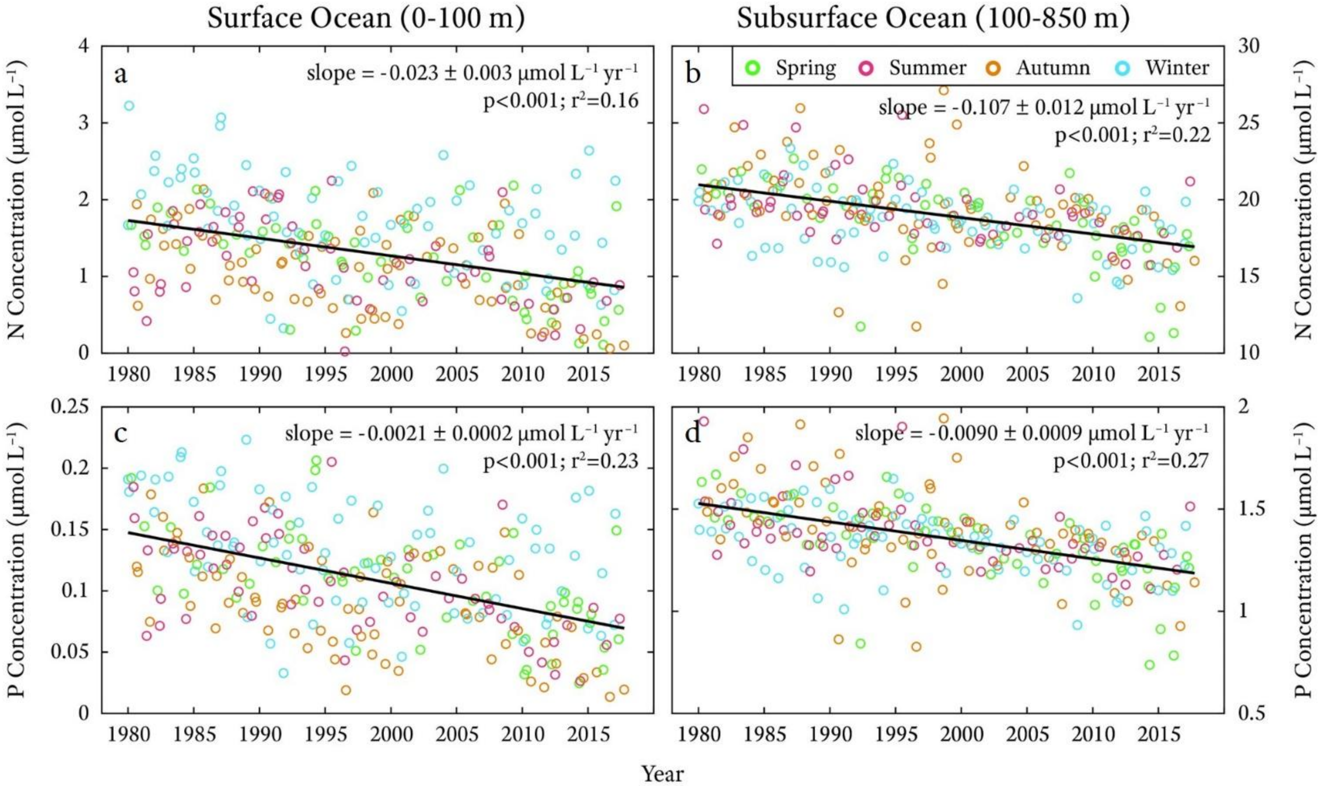

Figure 10. Temporal change in nutrients. Time series of monthly-averaged N concentrations over the last four decades in **a)** the surface and **b)** the subsurface ocean. Also P concentrations in the **c)** surface and **d)** the subsurface ocean. Black line represents linearly regressed trend line.

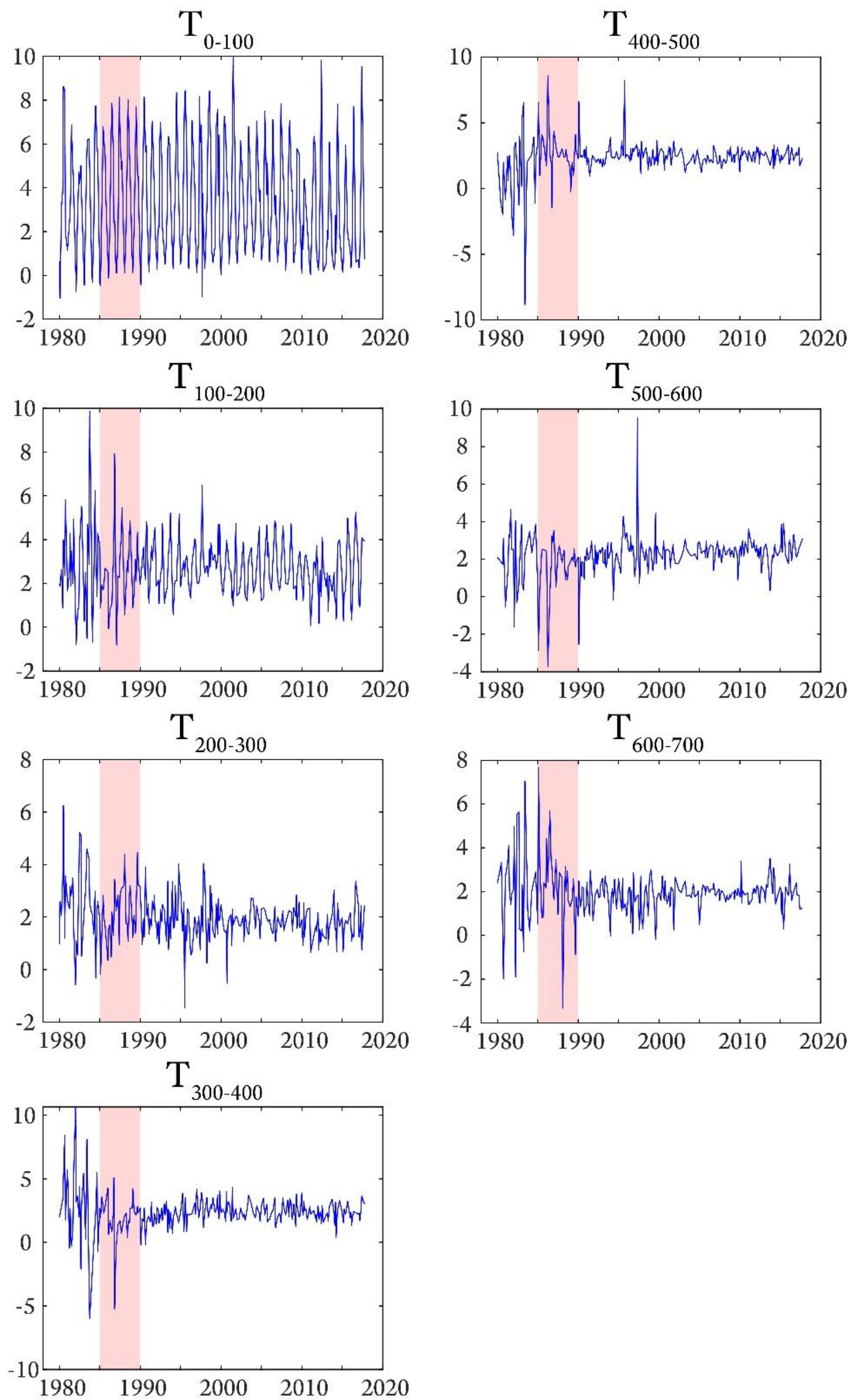

Figure 11. Thermal stratification indices. Temporal trends in the monthly thermal gradients at 100 m depth layers. No significant linear trends are found in each of the depth layers. The regime shift transition period is highlighted red from 1985 to 1990.

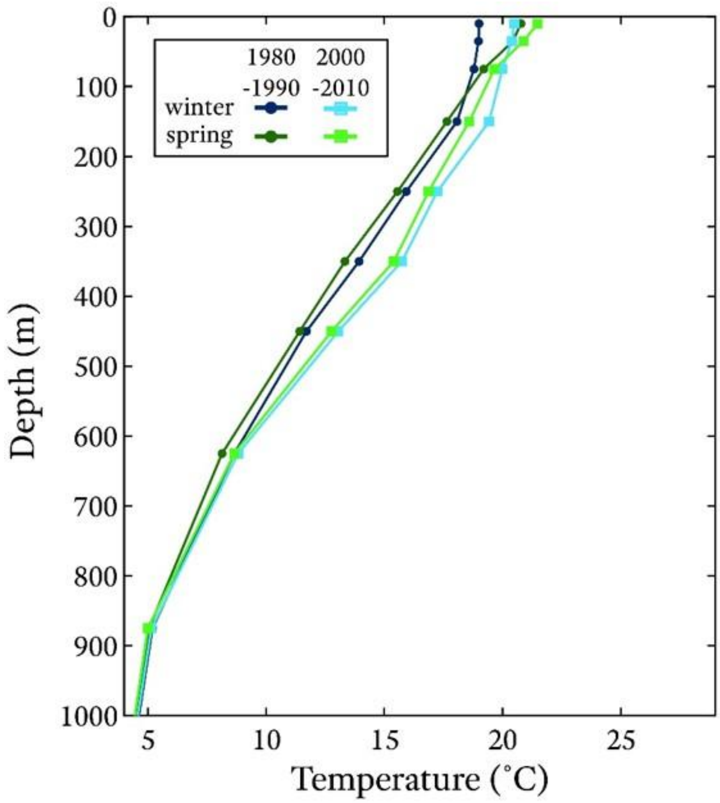

Figure 12. Seasonal temperature depth profile before and after the northwestern Pacific regime shift. The depth profiles of temperature in winter and spring before (1980-1990; darker lines plotted with circles) and after (2000-2010; lighter lines plotted with squares) the 1985-1990 northwestern Pacific Ocean regime shift.

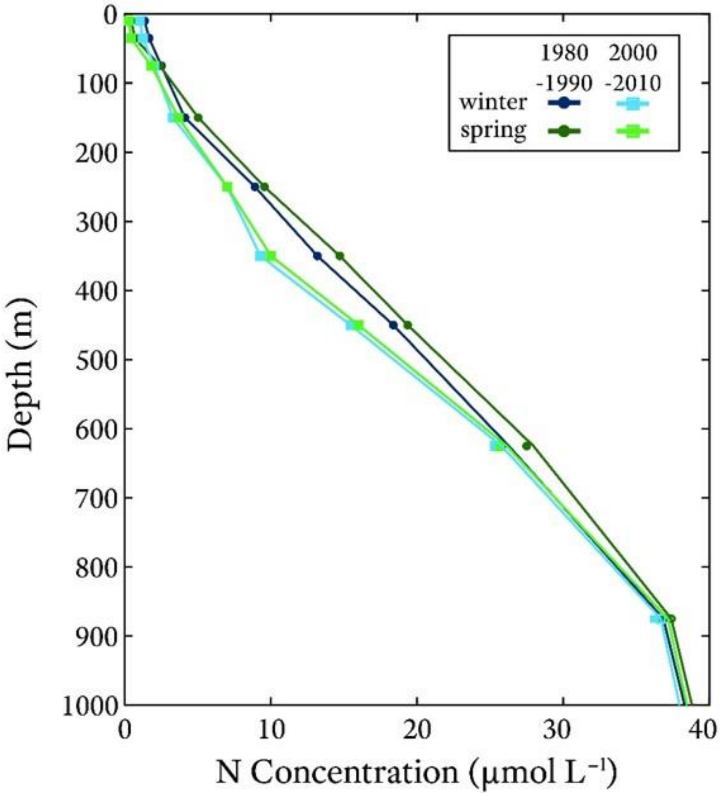

Figure 13. Seasonal N concentration depth profile before and after the northwestern Pacific regime shift. The depth profiles of N concentrations in winter and spring before (1980-1990; darker lines plotted with circles) and after (2000-2010; lighter lines plotted with squares) the 1985-1990 northwestern Pacific Ocean regime shift.

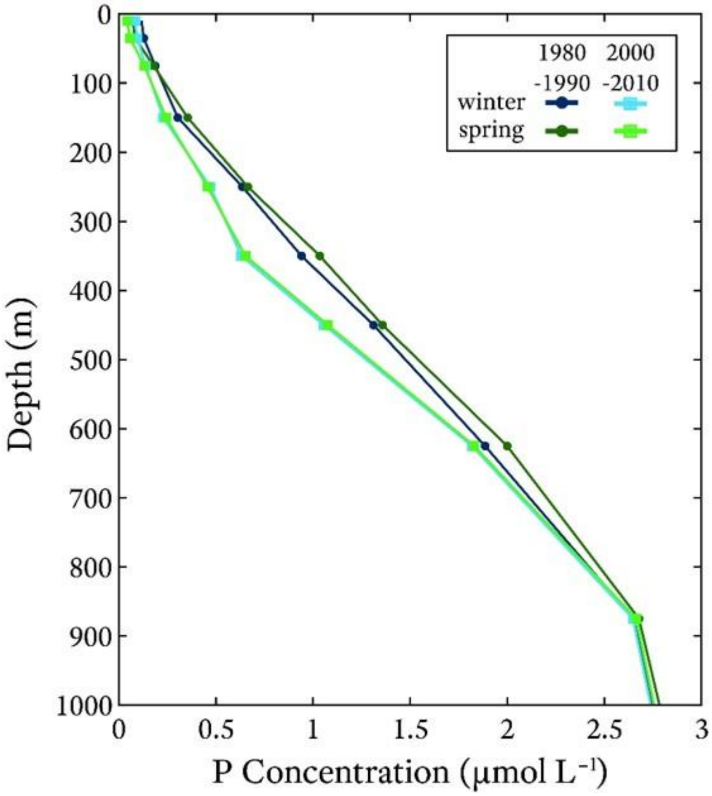

Figure 14. Seasonal P concentration depth profile before and after the northwestern Pacific regime shift. The depth profiles of P concentrations in winter and spring before (1980-1990; darker lines plotted with circles) and after (2000-2010; lighter lines plotted with squares) the 1985-1990 northwestern Pacific Ocean regime shift.

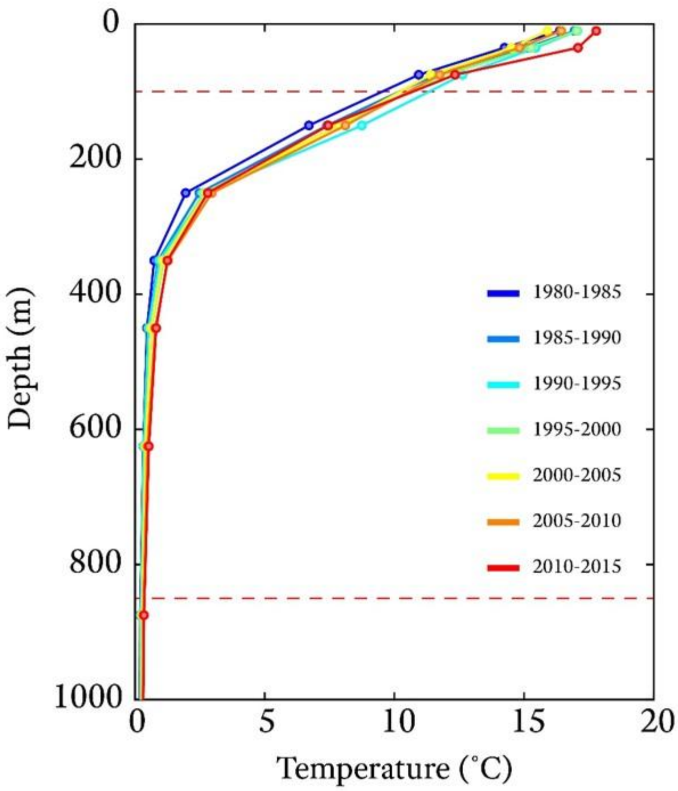

Figure 15. Temperature depth profile of the East/Japan Sea study area. The vertical profile of temperature in the eastern East/Japan Sea plotted with temperature averaged every five years from 1980 to 2017. The surface and the subsurface layers are marked by red dashed lines.

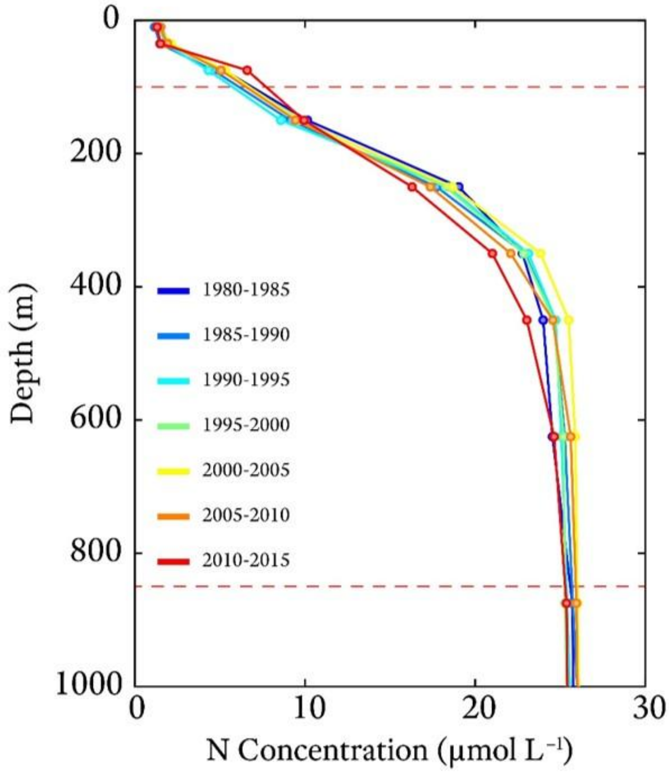

Figure 16. N concentration depth profile of the East/Japan Sea study area. The vertical profile of N in the eastern East/Japan Sea plotted with N concentrations averaged every five years from 1980 to 2017. The surface and the subsurface layers are marked by red dashed lines.

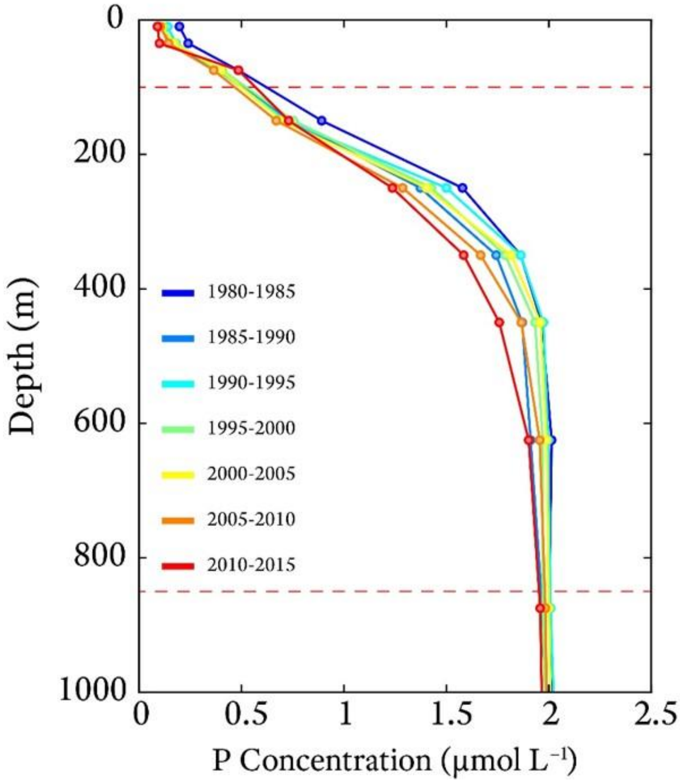

Figure 17. P concentration depth profile of the East/Japan Sea study area. The vertical profile of P in the eastern East/Japan Sea plotted with P concentrations averaged every five years from 1980 to 2017. The surface and the subsurface layers are marked by red dashed lines.

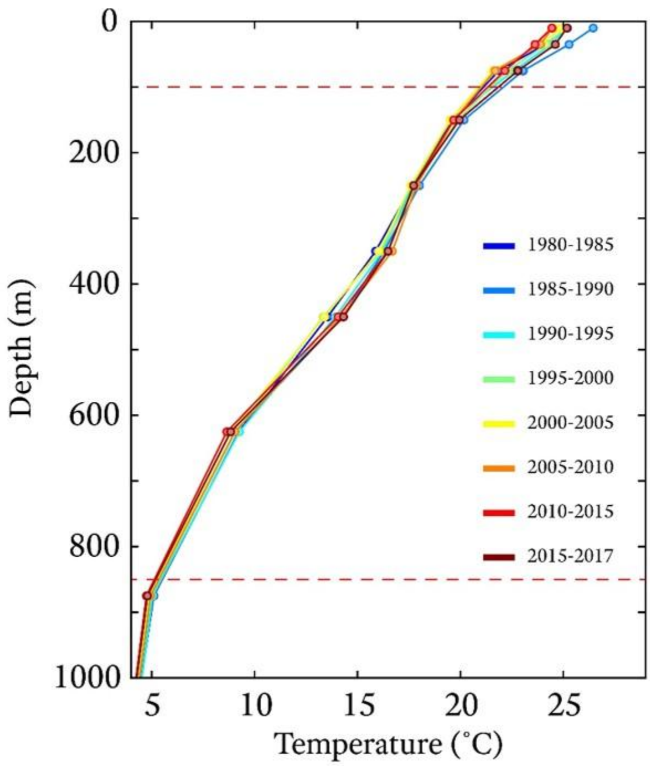

Figure 18. Temperature depth profile of the Inner Gyre study area. The vertical profile of temperature in the inside of the subtropical gyre plotted with temperature averaged every five years from 1980 to 2017. The surface and the subsurface layers are marked by red dashed lines.

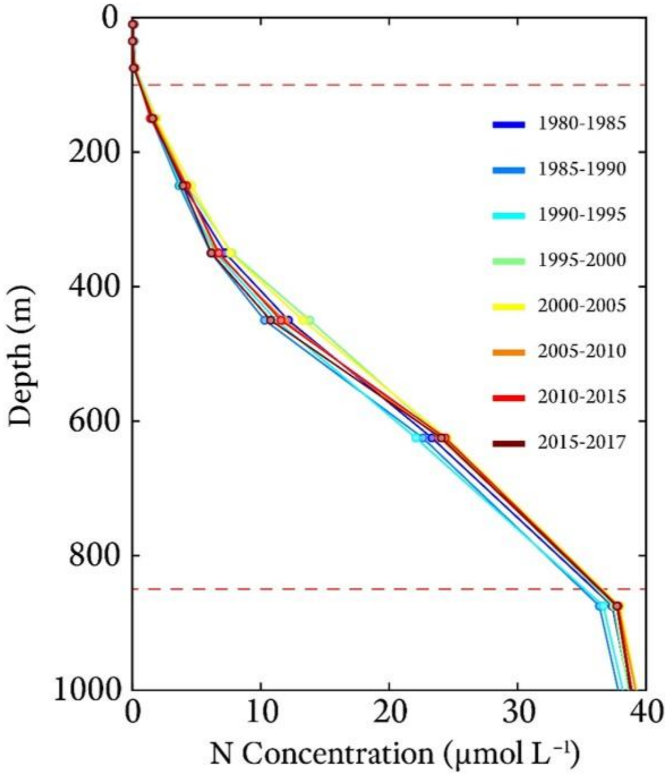

Figure 19. N concentration depth profile of the Inner Gyre study area. The vertical profile of N in the inside of the subtropical gyre plotted with N concentrations averaged every five years from 1980 to 2017. The surface and the subsurface layers are marked by red dashed lines.

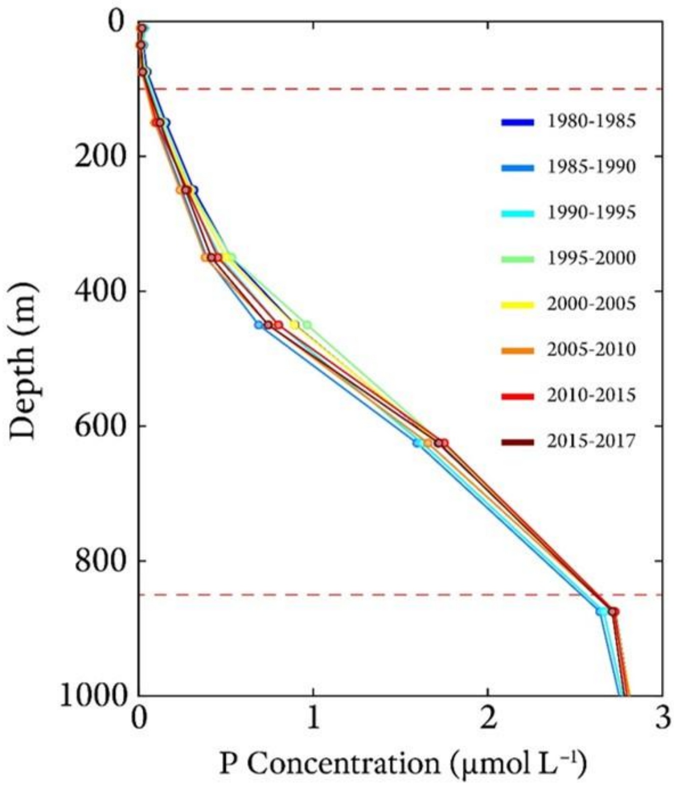

Figure 20. P concentration depth profile of the Inner Gyre study area. The vertical profile of P in the inside of the subtropical gyre plotted with P concentrations averaged every five years from 1980 to 2017. The surface and the subsurface layers are marked by red dashed lines.

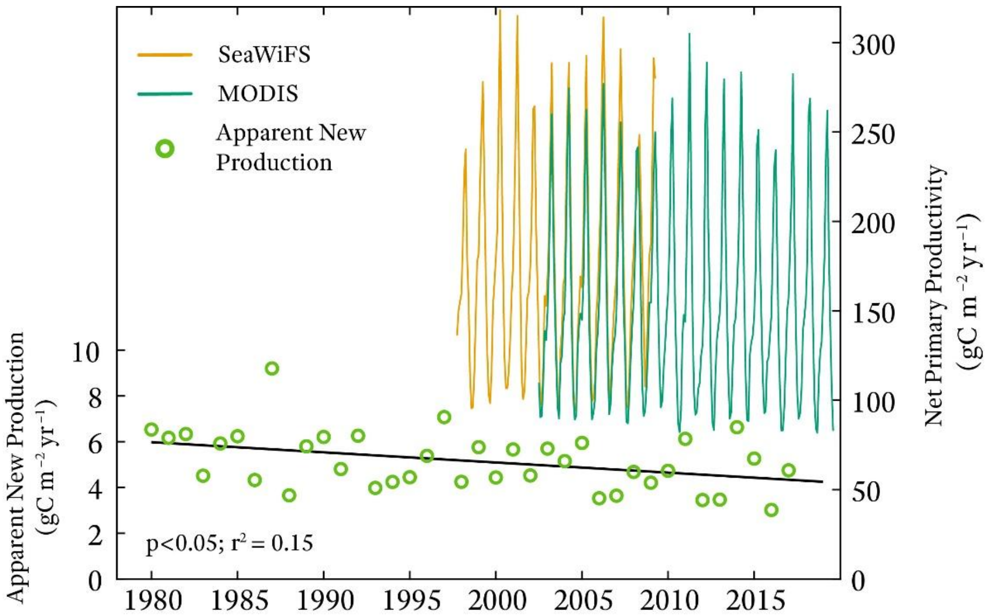

Figure 21. Apparent new production and net primary productivity. The left axis represents the yearly time series of the estimated new production of the main Kuroshio stream. Apparent new production has significantly declined in the northwestern Pacific Ocean (black trend line). The right axis is the temporal trend in the net primary productivity of the main Kuroshio stream obtained from the Ocean Productivity site. The data is based on SeaWiFS PAR and MODIS chlorophyll and temperature data converted using VGPM.

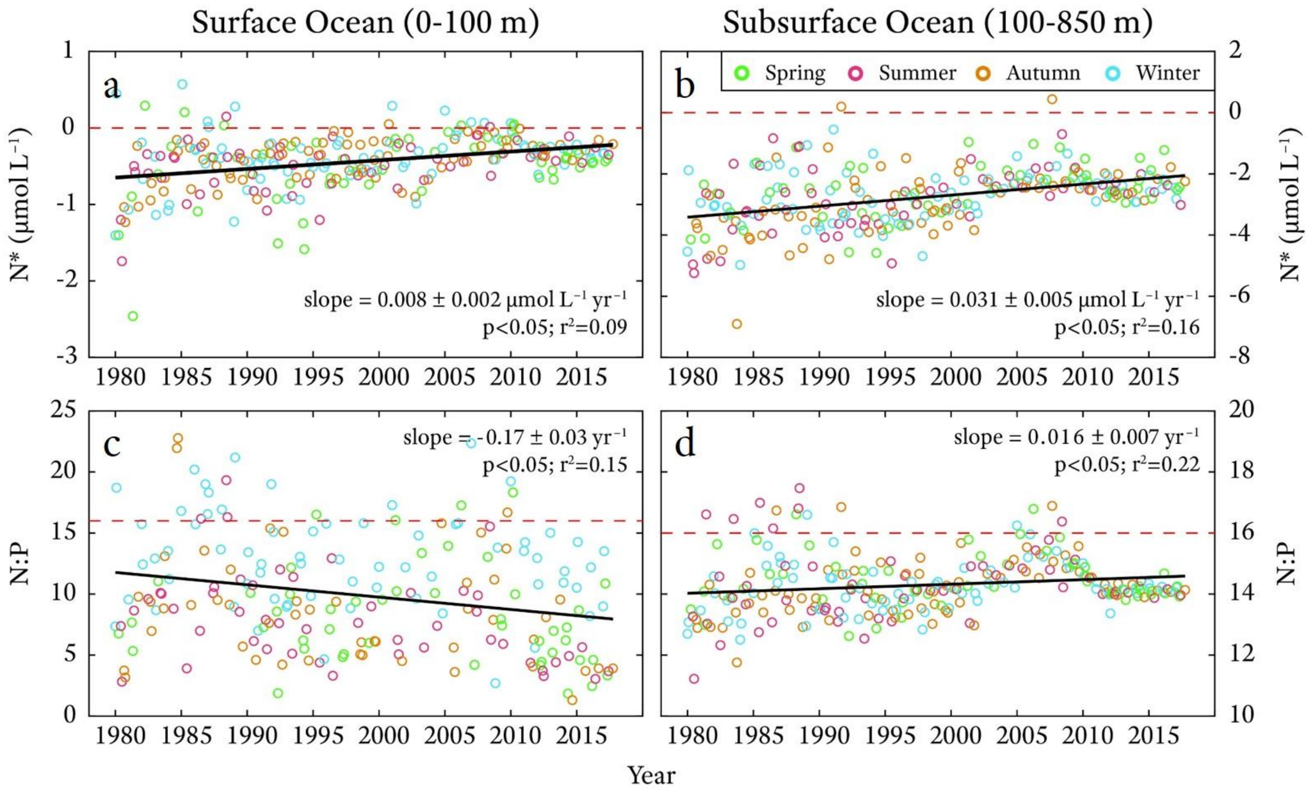

Figure 22. Temporal change in nutrient ratios. Time series of monthly-averaged N* over the last four decades in **a)** the surface and **b)** the subsurface ocean. Also N:P ratios in the **c)** surface and **d)** the subsurface ocean. Black line represents linearly regressed trend line.

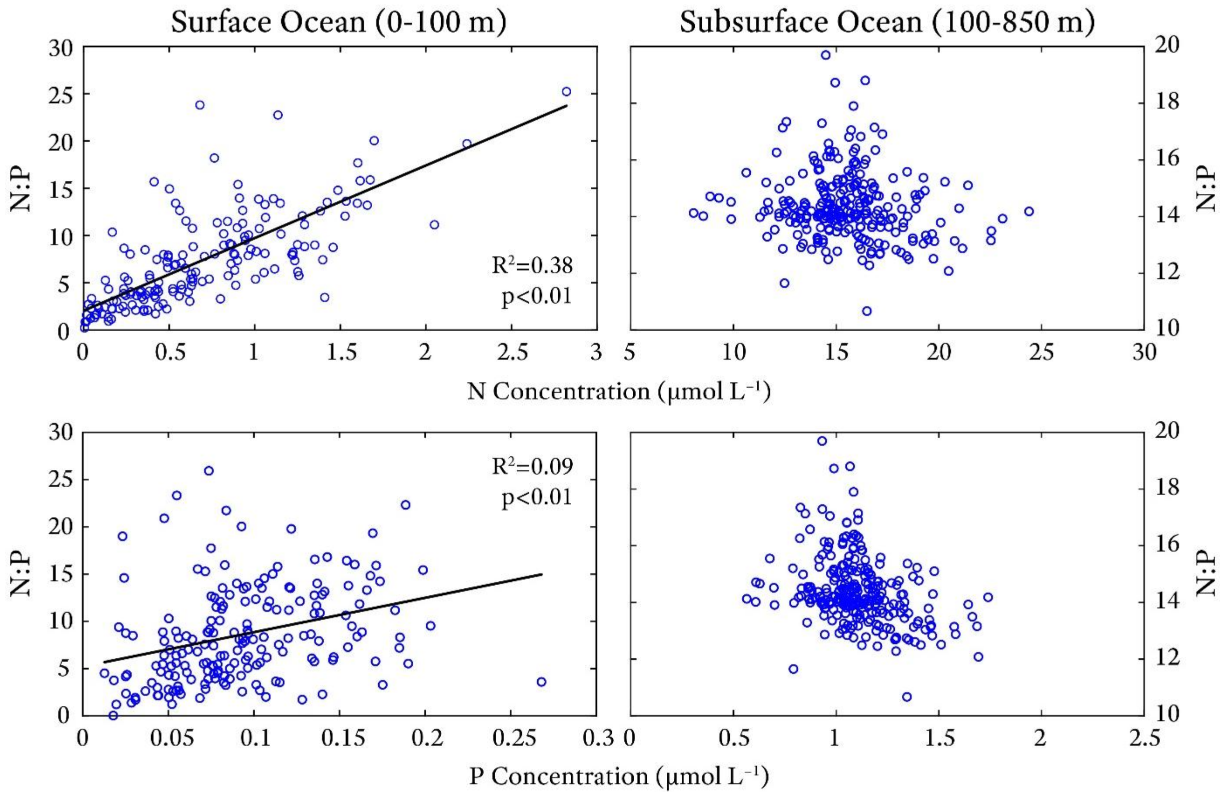

Figure 23. Plots of N:P ratio against N and P concentrations. Correlation is observed between the N:P ratio and **a)** N, **b)** P concentrations in the surface, while none is observed between the N:P ratio and **c)** N, **d)** P concentrations in the subsurface ocean. Black trend line represents correlation.

4. Conclusion

In conclusion, this study shows that the northwestern Pacific Ocean has entered a mode of nutrient decline through the Kuroshio current. As a result of the obstruction of deeper water entrainment into the euphotic depth caused by the structural change of the water column, a striking phenomenon of the depletion of the subsurface nutrient reservoir is occurring. This change is associated with the 1985-1990 regime shift of the northwestern Pacific Ocean. Furthermore, this study highlights the importance of the subsurface nutrient reservoir by showing that surface nutrient declines can occur independently from surface stratification or mixed layer shoaling that result from surface warming. Surface nutrient declines can occur when the subsurface waters become insufficient to fully replenish the surface nutrient inventory, especially in subtropical waters. Finally, the nutrient decline in the Kuroshio waters has considerable implications for the ecosystem and for carbon sequestration. New production is likely to continue decreasing, which will then result in similar decreases in carbon uptake and fishery productivity. Further, the northwestern Pacific is in realty becoming more N-limited, in contrast to recent predictions that the region will change toward a P-limited environment. This will lead to ecological shifts toward severe N-limited conditions, possibly affecting the biological community of the region.

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요약(국문초록)

북서태평양을 통과하는 쿠로시오 해류는 아열대 북태평양과 그 주변 해역에 열과 영양염을 운반한다. 이전 연구에 의하면 북태평양에서 인류 기원 영양염 유입의 증가에 의해 해양의 질소 (N) 층량이 증가했다고 하는 반면에 기후변화로 인해 강화된 표면 성층화 현상이 해당 지역의 표층 영양염 농도 감소 추세를 야기했다는 상반된 결과도 보고되었다. 본 연구는 37 년에 (1980-2017 년) 걸쳐 집계된 관측 자료를 활용해 상층 해역 (0-850 m) 영양염의 장기적인 경향을 파악하고 이러한 변화의 원인을 제시하였다. 연구 결과 쿠로시오 해류의 영양염 농도는 지난 약 40 년 동안 해역의 상층부에서 (0-850 m) 현저하게 감소하였다. 특히 표층 (0-100 m) 영양염 농도 감소는 기존에 추정된 표면 성층화 또는 혼합층 깊이의 감소보다 북서태평양의 물리적 체제 변화와 관련된 아표층 (100-850 m) 영양염의 감소에 주로 기인한 것으로 밝혀졌다. 쿠로시오 해류 상층부에서의 지속적 감소 현상은 아열대성 북태평양과 그 주변 해역을 모두 포함하는 쿠로시오 시스템 전체에서 발생하고 있는 것으로 보이며, 이러한 변화로 해당 해역의 신생산량의 약 30% 감소와 표층 N:P 비율의 감소가 나타났다. 따라서, 북서태평양의 빈영양화 현상은 탄소의 심층 저장량의 감소, 어업 생산성에 대한 영향, 그리고 아주 N 이 제한된 환경으로의 생태적 변화까지 발생시킬 것으로 보인다.

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주요어 : 영양염, 질산염, 인산염, N:P비 값, 북서태평양, 쿠로시오 해류

학 번 : 2018-22563