Spatiotemporal decreases of nutrients and chlorophyll-a in the western North Pacific surface mixed layer from 1971 to 2000

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Abstract. Using time series of hydrographic data in the wintertime and summertime along 137ºE line from 1971 to 2000, we found that nutrients in all the surface mixed layer showed the linear decreasing trends of 0.001 ~ 0.004 μmol-PO_4/l/yr and 0.01 ~ 0.04 μmol-NO_3/l/yr with the decrease of density. We also found that the water column Chl-a (CHL) and the net community production (NCP) had declined by 0.27 ~ 0.48 mg-Chl/m^2/yr and 0.08 ~ 0.47 g-C-NCP/m^2/yr with a clear oscillation of 20 years. These changes showed a strong negative correlation with the anomaly of SST over the North Pacific with the time lag of 2 years ($R = 0.89 \pm 0.02$). Considering the recent significant change of O_2 over the North Pacific subsurface water, these facts suggested that the changes of the surface-deep water mixing has caused the changes of marine biological activity over wide areas in the western North Pacific.

1. Introduction

Until now, many predictions of future global climate change have assumed that physical and biological conditions of the oceans are constant over time. However, recent studies have reported the possibility that recent oceanic conditions have changed due to the effects of anthropogenically induced greenhouse warming and/or natural climate change [e.g., *Levitus et al.*, 2000; *Hansen et al.*, 2002]. Some studies have already reported a linear increase of water temperature, and the decreases of oxygen and nutrients as the change of oceanic physical condition in the past several decades [e.g., *Watanabe et al.,* 2001; *Ono et al.,* 2002; *Emerson et al.,* 2004]. Moreover, some of these studies have shown that the change of physical condition had a clear bidecadal oscillation superimposed on the linear trend [e.g., *Ono et al.,* 2001; *Bryden et al.,* 2003; *Watanabe et al.,* 2003].

On the other hand, some studies have reported the change of marine biological activity such phytoplankton, zooplankton and chlorophyll-a only based on a spatiotemporal insufficient data set [e.g., *Karl et al.,* 2001; *Gregg and Conkright,* 2002, *Chiba et al.,* 2004]. Some of these studies suggested variation patterns in biological components in the North Pacific due to the change of physical condition associated with climatic regime shifts in 1976/77 [e.g., *Trenberth* 1990], 1988/89 [e.g., *Hare and Mantua,* 2000] and 1998/99 [e.g., *Minobe,* 2000], and the regime-shift related climate indices such as Pacific Decadal Oscillation (PDO) [e.g., *Minobe*, 2000]. However, we still are fully unable to understand whether the change of marine biological activity has the extensive and long-term linear trends with oscillations in response to the effect of anthropogenically induced warming and/or the natural climate change.

To evaluate the extensive and long-term changes of biological activity in the oceans, we here focused on time series of hydrographic data in a wide area along the 137ºE line in the western North Pacific taken collected during the last thirty years. Especially, we addressed water density (σ_θ), phosphate (PO_4), nitrate (NO_3) and chlorophyll-a (Chl), the net community production (NCP) in the surface mixed layer as indices of marine biological activity.

2. Data and Method

We here used time series data of σ_θ, PO_4, NO_3 and Chl from 34ºN to 3ºN along the 137ºE line during the period from 1971 to 2000 (Figure 1a) [*Japan Meteorological Agency*, 2002]. Time series of σ_θ, PO_4, NO_3 and Chl were obtained at approximately one degree intervals in the wintertime (Jan.-Feb.) and the summertime (Jul.-Aug.) every year. Samples at each station were basically taken from about 25 layers above 4000 m depth. PO_4, NO_3 and Chl were measured by the molybdenum photometric method, the copper-cadmium sulfanilamide reduction method and the solvent extraction photofluorometrical method, respectively, as standard procedures during the last thirty years. Based on the deep water data sets (> 27.7 σ_θ), we estimated the offsets in PO_4 and NO_3 between the data sets to be within 0.02 μmol-PO_4/l and within 0.17 μmol-NO_3/l for the entire thirty year data set. On the other hand, although Chl data was limited in the upper layer of 200 m depth, we estimated the offset in Chl to be 0.01 μg-Chl/l at 200 m depth for the entire data. We here used the PO_4, NO_3 and Chl data without any correction for the offsets in this study.

Assuming the depth of seasonal surface mixed layer (ML) as a depth having difference of 0.125 σ_θ from the ocean surface density (MLD), we estimated the averaged concentrations of PO_4 and NO_3 in the two seasons. We also estimated the water column Chl (CHL) by integrating Chl over the whole water column. Moreover, considering the active supply of nutrients from the deep water in the wintertime, we here divided these data sets into three regions based on the distribution of averaged wintertime water density during the last thirty years; the Kuroshio area which flows south of Japan and is one of the largest area for interaction between the air and sea. [e.g., *Kawabe*, 1995] (‘KU’, 34ºN-30ºN), the subtropical area (‘ST’, 30ºN-15ºN) and the tropical area (‘TR’, 15ºN-3ºN) (Figure 1b). We here addressed an averaged value of each parameter as three-year running mean composites with standard errors.

3. Results and Discussion

3.1. Temporal changes of σ_θ, MLD, PO_4 and NO_3

σ_θ in ML generally decreased southward from KU to TR, and from the wintertime to the summertime. σ_θ in all areas had a linear decreasing trend of 0.007 ± 0002/yr (Standard Error, SE) in the wintertime ($p<0.05$) and that of 0.012 ± 0.002/yr in the summertime ($p<0.05$) despite difficulties in determining the periodicity (Figures 2a and 2b). Main cause in the wintertime is possibly due to the increase of water temperature in KU and ST ($p<0.01$) and the decrease of salinity in TR ($p<0.01$) while that in the summertime is due to the increase of water temperature in all areas ($p<0.01$) (data not shown), which agreed with previous studies [e.g., *Yasuda and Hanawa,* 1997; *Michael and Dongxiano,* 2002].

On the other hand, despite the decrease of σ_θ, MLD in the wintertime were constant in all areas over the past thirty years; 123 ± 3 m for KU ($p>0.10$), 84 ± 1 m for ST ($p>0.10$) and 45 ± 1 m for TR ($p>0.10$) (data not shown). Similarly, MLD in the summertime also were not changed except KU (- 1.2 m/yr, $p<0.01$) (average: 101 ± 4 m for KU, 72 ± 1 m for ST ($p>0.10$) and 54 ± 1 m for TR ($p>0.10$) (data not shown).

Both PO_4 and NO_3 in ML decreased in order of KU, TR and ST, and these contents in the wintertime were higher than those in the summertime due to the difference in the extent of vertical water mixing and/or diffusion with the deep water (Figures 2c–2f). We also found the significant declines of 0.001 ~ 0.004 μmol-PO_4/l/yr ($p<0.05$) and 0.01 ~ 0.04 μmol-NO_3/l/yr ($p<0.05$) in ML of all areas and seasons in the past three decades. Although it is difficult to detect the change of NO_3 more than its offset (±0.17 μmol-NO_3/l), we also found that PO_4 steeply changed in the end of 1970s, the end of 1980s and the end of 1990s, which agreed well with climate regime shifts that previous studies reported [e.g., *Minobe*, 2002]. We suggest that the sea surface water warming mainly has caused the decrease of σ_θ in ML over a wide area, and consequently the weakening of sea surface-deep mixing has led to a decrease in the supply of nutrients from the deep water.

3.2. Decadal changes of NCP and Chl

Using the difference of nutrient inventory from winter to summer based on MLD, the averaged PO_4 in ML and the stoichiometric ratio of carbon to phosphate to be 106 (R) [*Redfield et al.,* 1963], we can here estimated the net community production (NCP) as the extent of the biological activity $\Delta(R \cdot MLD \cdot PO_4)$. We found that NCP in all areas had a linear trend of decrease of 0.08 ~ 0.47 g-C-NCP/m^2/yr ($p<0.05$) with the steep changes in the ends of 1970s, 1980s and 1990s while NCP decreased southward from KU to TR (Figure 3a).

Moreover, the change of water column Chl (CHL) in the two seasons almost had the same pattern as NCP. Although the linear decreasing rates in the summertime were 0.27 ~ 0.48 mg-Chl/m^2/yr ($p<0.05$), we almost found no significant decrease of CHL in the wintertime (Figures 3b and 3c). The influence of the recent decrease in nutrient supply on the biological activity in the wintertime may be still small due to sufficient supply of nutrient derived from the active winter vertical mixing. However, the decreases of NCP and CHL in the summertime suggested that the marine biological activity at least over the western North Pacific could weaken in ML due to decrease in the supply of nutrients from the deep water.

Ono et al. [2001], *Watanabe et al.* [2001] and *Emerson et al.* [2004] reported the significant decrease of 0.5 μmol-O_2/kg/yr over the past forty years below ML in the wintertime over the extensive area of the North Pacific. These suggested that the main cause was either the increase of export flux from ML or the weakening of sea surface-deep water mixing. If the biological activity only changed in the North Pacific in the past several decades, NCP has to become two to five times as large as that in the past some decades to explain the significant decrease of O_2 over the North Pacific. In this study, however, we here found that NCP has decreased by a few percentages per year (Figure 3a) and not has increased by two to five times in the past three decades, indicating reliable evidence of the weakening of the surface-deep water mixing at least in the western North Pacific.

3.2. Bidecadal periodicity of PO_4, CHL and NCP

In addition, we here tried to clarify well whether the changes of these parameters as an index of biological activity had related with the climatic regime shift, and whether the changes had the long-term trends with the oscillations. To elucidate the regime-shift in the North Pacific, *Mantua et al.* [1997] and *Minobe* [2000] used Pacific Decadal Oscillation Index (PDO) as an index of the anomaly of the sea surface temperature in the North Pacific. Especially, *Minobe* [2000] reported that PDO had a clear decadal oscillation, and that the combination between the bidecadal and the pentadecadal oscillations in PDO caused the large regime-shift in the North Pacific, using the 10-80 year band-pass filtered time series of PDO.

To clarify the decadal oscillation of parameters that we used in this study, we here applied an equation of the Fourier sine expansion to the time series data sets of these parameters in the past thirty years: $X = - a \cdot y + b + c \cdot \sin \{2\pi (y - d) / e\}$, where 'X' refers to one parameter with σ_θ, PO_4, NO_3, CHL and NCP. 'y' is the calendar year 'a', 'b', 'c', 'd' and 'e' are constants. That is, X = linear trend component + oscillation component.

We found that PO_4, CHL and NCP in all areas and seasons had the clear bidecadal periodicity of 20 years superimposed on the decreasing trends of 0.001 ~ 0.004 μmol-PO_4/l/yr (p<0.01), 0.20 ~ 0.42 mg-Chl/m^2/yr (p<0.01 only for the summertime) and 0.09 ~ 0.54 g-C-NCP/m^2/yr (p<0.01); (average periodicity: PO_4 (winter) = 20.4 ± 1.5 yr (p<0.01); PO_4 (summer) = 21.5 ± 0.8 yr (p<0.01); CHL (winter) = 21.4 ± 1.2 yr (p<0.01); CHL (summer) = 20.4 ± 0.6 yr; NCP = 20.4 ± 1.5 yr) (Figures 2c, 2d and 3a-3c).

Considering the active supply of nutrients from the deep water in the winter, we here compared the changes of PO_4, CHL and NCP with the change of PDO in the wintertime (Figure 3d) [*Minobe*, 2000]. All the periodicity of these parameters almost agreed with that of PDO (correlation coefficient (R); 0.67 ± 0.04 for PO_4 (winter); 0.73 ± 0.07 for PO_4 (summer); 0.74 ± 0.10 for CHL (winter); 0.78 ± 0.04 for CHL (summer); 0.76 ± 0.11 for NCP).

We also found that these changes had the time lag of about two years for the change of PDO (Figures 2c, 2d and 3). Unfortunately, based on our present study, it is difficult to explain the occurrence of the time lag. One possibility to explain the time lag in extensive areas is that our field is located in the westernmost side of the North Pacific while PDO represents the averaged value of anomaly over the North Pacific. Thus the changes of PO_4, CHL and NCP may not completely agree with that of PDO. If we here make correction of the time lag of 2 years for the changes of PO_4, CHL and NCP, we found that all the changes of these parameters showed the stronger negative correlation with that of PDO (R: 0.88 ± 0.03 for PO_4 (winter); 0.83 ± 0.07 for PO_4 (summer); 0.89 ± 0.01 for CHL (winter); 0.95 ± 0.02 for CHL (summer); 0.89 ± 0.07 for NCP).

Considering the recent significant decrease of O_2 over the North Pacific subsurface water [e.g., *Emerson et al.*, 2004] with our results, the negative correlation between PO_4, CHL, NCP and PDO suggests that the sea surface water warming mainly has caused the recent decrease of σ_θ in ML over a wide area, and consequently the weakening of sea surface-deep mixing has led to a decrease in the supply of nutrients from the deep water, Then the biological activity may weaken in the surface mixed layer.

Unfortunately, only based on our present data, it is difficult to separate exactly the effect of anthropogenically induced warming and the effect of natural climate change on the biological activity because there is possibly more long-term natural climate change than on a bidecadal scale [e.g., *Minobe,* 2000]. However, it is possible that the linear trend component and the oscillation component in this study show the effect of anthropogenically induced warming and the effect of natural climate change, respectively.

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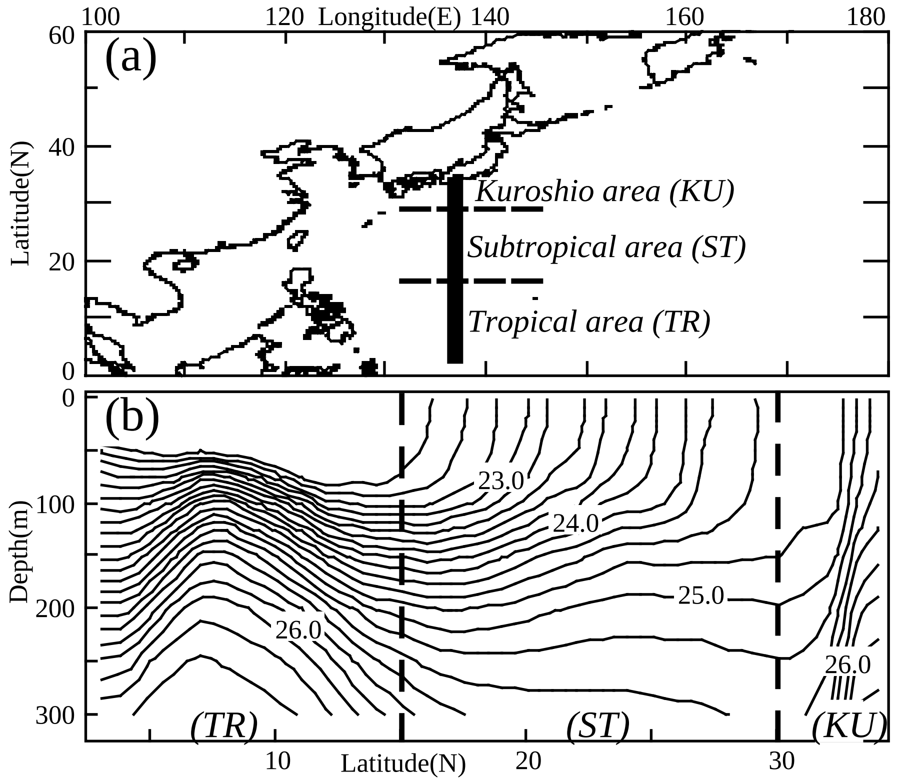
Figure 1. a) The sampling points along the 137ºE line. b) The distribution of averaged wintertime water density during the period from 1971 to 2000.

Figure 2. Time series of σ_θ, and the averaged contents of PO_4 (μmol-PO_4/l) and NO_3 (μmol-NO_3/l) in ML along 137ºE. We here showed the data sets in three regions (KU: black open circle, ST: red open square, TR: blue open triangle), and showed an averaged value as three-year running mean composites with standard errors. Besides the linear regression line (solid line), the non-linear fitting curve were also shown (dash curve), which was estimated by the Fourier sine expansion with $p<0.01$. a) σ_θ in the wintertime. The fitted linear equations are as follows; KU = - 0.011 y + 46.752 ($p<0.01$); ST = - 0.003 y + 30.018 ($p<0.05$); TR = - 0.006 y + 33.362 ($p<0.05$). 'y' is the calendar year. b) Same as a) but in the summertime. KU = - 0.009 y + 39.788 ($p<0.10$); ST = - 0.015 y + 50.899 ($p<0.01$); TR = - 0.013 y + 47.196 ($p<0.01$). c) The averaged content of PO_4 in the wintertime. KU = - 0.002 y + 4.223 ($p<0.05$); ST = - 0.002 y + 3.441 ($p<0.01$); TR = - 0.004 y + 7.099 ($p<0.01$). The averaged periodicity of the fitting curve with SE was 20.4 ± 1.5 years ($p<0.01$). d) Same as c) but in the summertime. KU = - 0.001 y + 1.159 ($p<0.05$); ST = - 0.001 y + 2.380 ($p<0.01$); TR = - 0.003 y + 5.955 ($p<0.01$). The averaged periodicity was 21.5 ± 0.8 years ($p<0.01$). e) The averaged content of NO_3 in the wintertime. KU = - 0.04 y + 83.53 ($p<0.01$); ST = - 0.01 y + 24.78 ($p<0.01$); TR = - 0.01 y + 14.96 ($p<0.01$). f) Same as e) but in the summertime. KU = - 0.01 y + 4.97 ($p<0.05$); ST = - 0.01 y + 10.56 ($p<0.01$); TR = - 0.01 y + 14.34 ($p<0.01$).

Figure 3. a) NCP estimated by the difference in PO_4 in the two seasons (g-C-NCP/m^2/yr). KU = - 0.47 y + 964.91 ($p<0.05$); ST = - 0.26 y + 528.55 ($p<0.01$); TR = - 0.08 y + 169.08 ($p<0.05$). The averaged periodicity of the fitting curve with SE was 20.4 ± 1.5 years ($p<0.01$). b) CHL in the wintertime (mg-Chl/m^2). The fitted linear equations are as follows; KU = - 0.08 y + 199.80 ($p>0.10$); ST = - 0.37 y + 767.37 ($p<0.01$); TR = - 0.07 y + 164.43 ($p>0.10$). The averaged periodicity of the fitting curve with SE was 21.4 ± 1.2 years ($p<0.01$). c) CHL in the summertime (mg/m^2). KU = - 0.48 y + 994.41 ($p<0.01$); ST = - 0.40 y + 821.38 ($p<0.01$); TR = - 0.27 y + 573.91 ($p<0.05$). The averaged periodicity was 20.4 ± 0.6 years ($p<0.01$). d) PDO in the wintertime. The periodicity was 20.3 years ($p<0.01$). The data was cited from *Minobe*, [2000].



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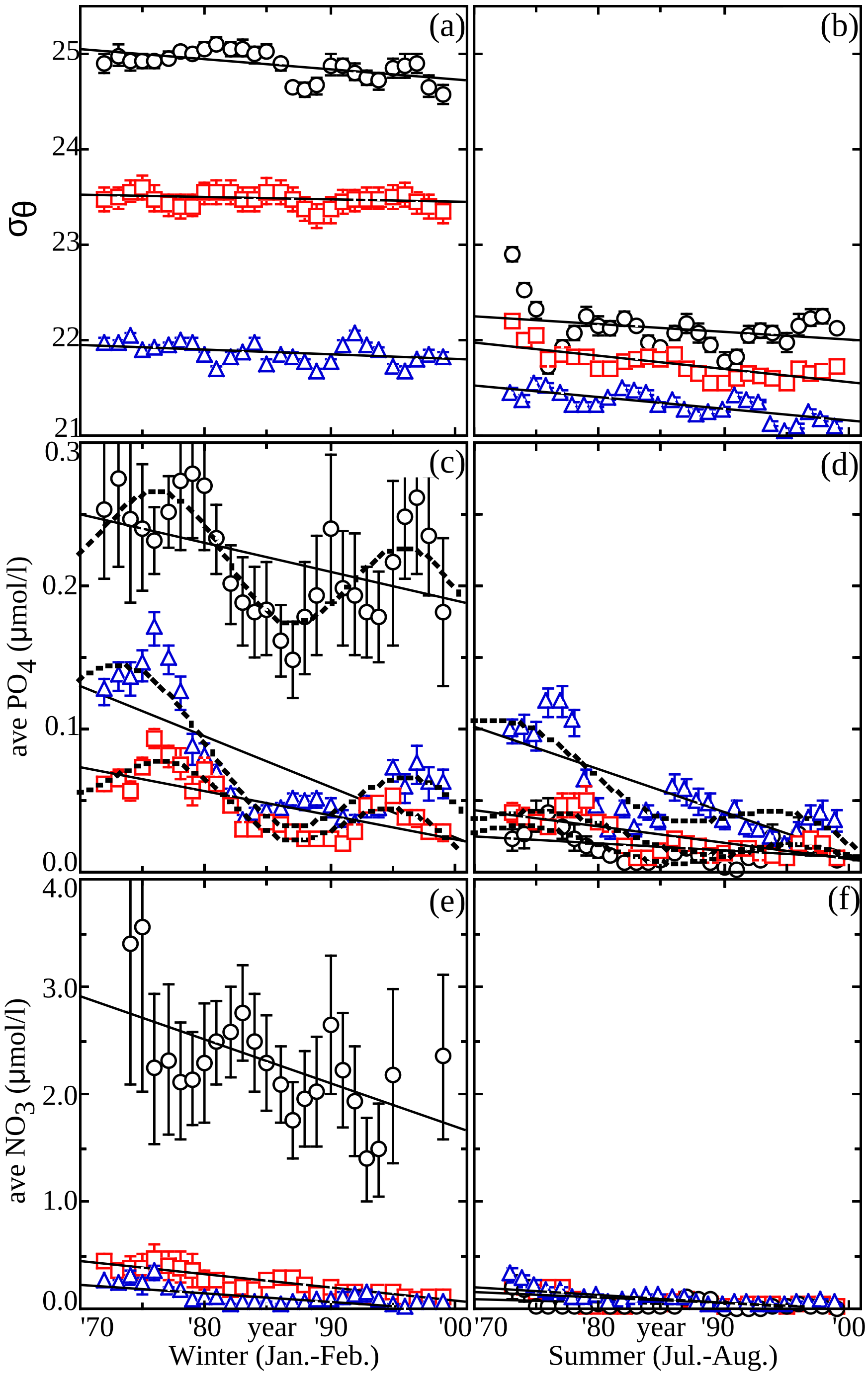
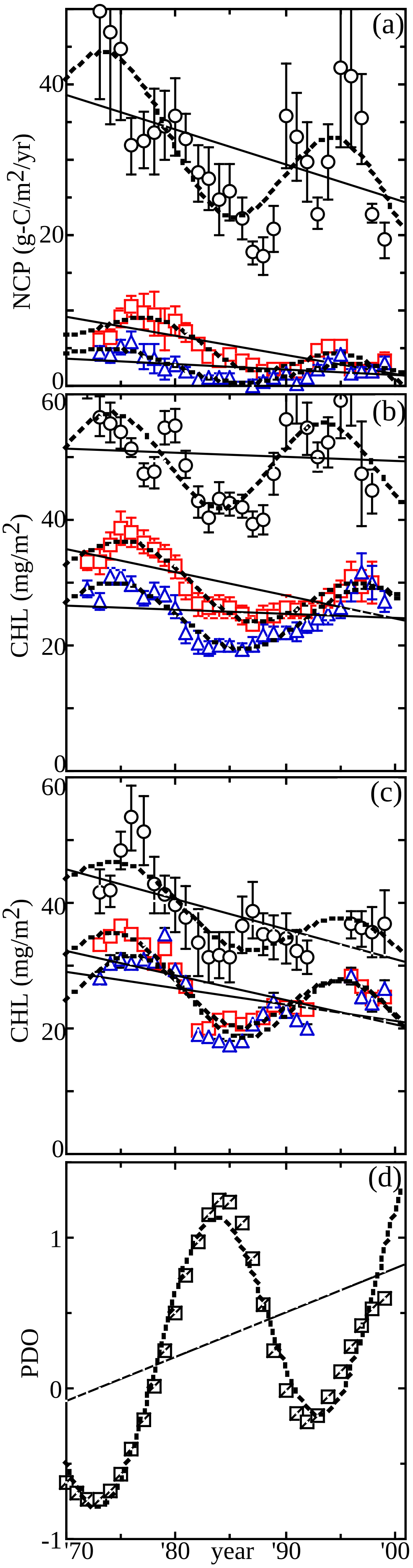


Watanabe et al./Figure 2



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