



Reappraisal of meridional differences of factors controlling phytoplankton biomass and initial increase preceding seasonal bloom in the northwestern Pacific Ocean



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ABSTRACT

Multiplatform observations of ocean biogeochemical data were used to elucidate meridional differences in the factors that limit phytoplankton biomass (*Chl-a*) and the mechanisms that trigger the seasonal winter or spring phytoplankton bloom in the northwestern Pacific Ocean (NWPO). During the winter, *Chl-a* north (south) of 30°N is limited by light (nutrients). During the spring and fall, *Chl-a* in much of the area east of the Japan/Kuril Islands and/or north of 40°N (south of 35°N) is limited by light (nutrients). During the summer, nutrients limit *Chl-a* over much of the NWPO, except in the areas east of the Japan/Kuril Islands and north of 45°N. In the area south of around 31°N, phytoplankton biomass is nutrient limited throughout the year, and the seasonal bloom emerges in the winter, begins in the fall which is associated with mixed layer deepening. Between 31°N and 40°N, the spring bloom onset is mainly associated with a cessation of mixed layer deepening. In much of the area north of 40°N, including the Oyashio area, the onset of the spring bloom is consistent with Sverdrup's critical depth hypothesis. The spatial extents of the light- and nutrient-limited areas and the areas associated with a single bloom onset mechanism are by no means constant. They are expected to undergo meridional shifts as a result of large-scale climatic changes and global warming.

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1. Introduction

The northwestern Pacific Ocean (NWPO) comprises the western part of two main gyres, the cyclonic North Pacific Subarctic Gyre and the anticyclonic North Pacific Subtropical Gyre. The subarctic gyre is bordered by the Oyashio cold current in the west and is a well-known high-nutrient and low-chlorophyll area, whereas the subtropical gyre is bordered by the Kuroshio warm current in the west and is characterized by low nutrient concentrations. The Kuroshio and Oyashio currents meet and interact east of Japan in the Kuroshio–Oyashio confluence area (Fig. 1a), which separates the subtropical anticyclonic gyre from the subarctic cyclonic gyre (e.g., Hanawa & Mitsudera, 1987; Yasuda, 2003).

Previous studies have shown that phytoplankton biomass (chlorophyll-*a* concentration, hereafter *Chl-a*, mg m^{-3}) is light-limited in the subarctic area (SAA) but nutrient-limited in the subtropical area (STA) (e.g., Fujiki et al., 2014; Limsakul, Saino, Goes, & Midorikawa, 2002). However, the areas within which *Chl-a* is light-limited in the SAA and nutrient-limited in the STA may change seasonally, and these changes have not been detailed previously.

An empirical way to determine the spatial extent of light or nutrient limitation, as well as to identify the probable underlying processes, is to assess the associations between *Chl-a* and environmental variables. The ability to discern these relationships on a seasonal basis has the potential to provide valuable understanding of the footprints of large-scale climate changes such as global warming on biogeochemical variability in the NWPO and its probable driver(s) in different seasons. The reason is that large-scale climate variability, such as long-term geophysical trends and the El Niño/Southern Oscillation and Pacific Decadal Oscillation, seem to have seasonally dependent impacts on NWPO *Chl-a* variability (e.g., Chiba, Ono, Tadokoro, Midorikawa, & Saino, 2004; Freeland, Denman, Wong, Whitney, & Jacques, 1997; Goes, Sasaoka, Gomes, Saitoh, & Saino, 2004; Wang, Chen, & Huang, 2008; Whitney & Freeland, 1999).

Geophysical variables also determine the onset of the phytoplankton spring bloom, a well-known phenomenon, in both the SAA and the STA (e.g., Fujiki et al., 2014; Limsakul, Saino, Goes, & Midorikawa, 2002; Yoo, Batchelder, Peterson, & Sydeman, 2008). For more than half a century, Sverdrup's critical depth (*CD*, m) hypothesis (e.g., Obata & Ishizaka, 1996; Siegel, Doney, & Yoder, 2002) has served biological oceanographers as the basic tenet of the mechanism underlying initiation of the phytoplankton spring bloom. The *CD* hypothesis envisions that the spring bloom starts when the mixed layer depth (*MLD*, m) becomes shallower than the *CD* (Sverdrup, 1953), and the nutrient is not limiting

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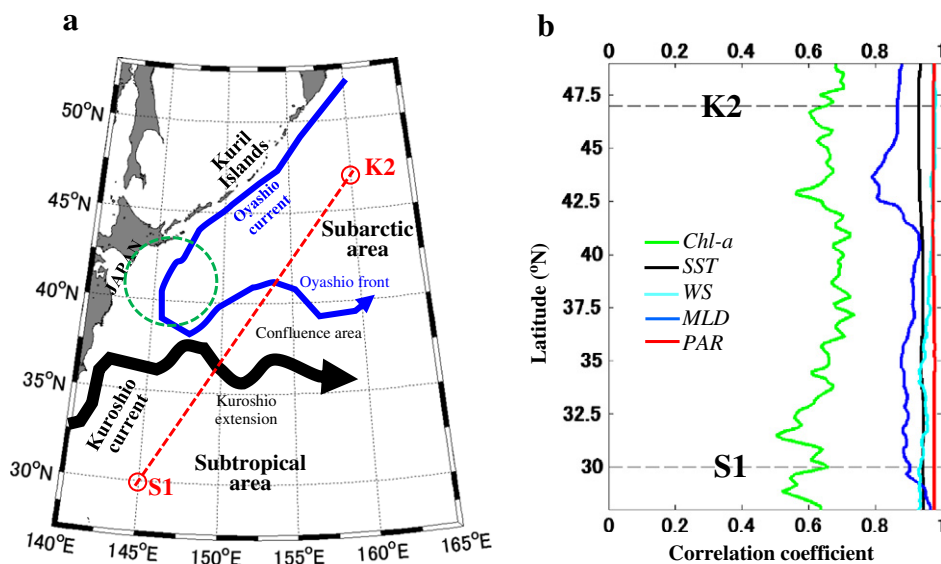


Fig. 1. (a) Map of the study region, the NWPO, which covers the SAA and the STA, where biogeochemical time-series stations K2 and S1, respectively, are located. The green dashed circle denotes approximately the location of the Oyashio area. The red dashed line is the K2–S1 line. (b) Meridional variations along the K2–S1 line of correlations that resulted from regressions between variables retrieved by two different sensors/sources. Green, black, cyan, blue, and red lines correspond to SeaWiFS vs. MODIS *Chl-a*, AVHRR vs. MODIS SST, CCMP vs. WindSat WS, GODAS vs. Argo float MLD, and SeaWiFS vs. MODIS PAR, respectively. All correlations are statistically significant at $p < 0.05$. Horizontal dashed lines indicate the latitudes of stations K2 and S1.

factor as a prerequisite. By definition, the *CD* is the depth above which the vertically integrated net phytoplankton production equals the vertically integrated loss (Sverdrup, 1953).

Results of recent studies in different oceans have mentioned that the onset of the spring phytoplankton bloom is not always consistent with the *CD* hypothesis. On the basis of satellite-derived *Chl-a* data from the east coast of New Zealand, Chiswell (2011) has proposed a ‘stratification-onset’ hypothesis that attributes the initiation of the spring bloom to a cessation of deep vertical mixing, which allows *Chl-a* to increase in the near-surface, actively mixed layer. Similar to Chiswell’s (2011) hypothesis, Taylor and Ferrari (2011) and Shiozaki et al. (2014) have argued that the phytoplankton spring bloom in the North Atlantic Ocean and the region south of the Kuroshio extension in the NWPO, respectively, may also be initiated by a ‘turbulence weakening’ or ‘turbulence shutdown’ that increases the residence time of the phytoplankton in the euphotic layer, without a prerequisite of MLD shoaling.

Although Obata and Ishizaka (1996) have mentioned that the *CD* hypothesis can in general explain the initiation of the spring bloom in the NWPO, Shiozaki et al. (2014) have shown that the *CD* mechanism applies mainly in the waters of the Oyashio Current and in the region north of the Kuroshio extension in the NWPO. Shiozaki et al. (2014) have shown that there are regional differences in the mechanisms responsible for the onset of the spring bloom in the NWPO, but the detailed spatial features of the mechanism responsible for the onset of the spring bloom have not yet been fully delineated, because their analysis was based on regional averages and was meridionally constrained within the region from 30°N to 45°N.

Here, using ocean color data from both the Sea-viewing Wide Field-of-Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer–Aqua (MODIS), we have revisited the NWPO (140–165°E, 27–53°N), including both the SAA and the STA, within which biogeochemical time-series stations K2 (160°E, 47°N) and S1 (145°E, 30°N), respectively, are located (Fig. 1a). By also analyzing other sensor-retrieved and reanalyzed oceanographic and atmospheric geophysical variables at the scale of pixels, our aim was to gain an understanding of meridional differences in (1) the associations between

Chl-a and geophysical variables that could be used as proxies to assess the factors that limit and control *Chl-a* variations in different seasons, and (2) the mechanisms that initiate the seasonal phytoplankton bloom in the NWPO. To ensure the validity of our data, we used in situ observations from the K2 (representing the SAA) and S1 (representing the STA) biogeochemical time series stations made on board research vessel *Mirai* from 2010 to 2012. Satellite and reanalyzed data derived at stations K2 and S1 were verified using in situ data collected at the same stations.

2. Methodology

2.1. Multi-platform data acquisitions

We used monthly SeaWiFS and MODIS-retrieved *Chl-a*, diffuse attenuation coefficients at 490 nm (Kd_{490} , m^{-1}), and photosynthetically available radiation (PAR, $\text{mol photons m}^{-2} \text{ d}^{-1}$, 400–700 nm radiation) retrieved from September 1997 to June 2013 (<http://oceancolor.gsfc.nasa.gov>). The spatial resolution of the data was 9 km. We used monthly SSTs retrieved by the Advanced Very High Resolution Radiometer (AVHRR, <http://podaac.jpl.nasa.gov/AVHRR-Pathfinder>) and MODIS (<http://oceancolor.gsfc.nasa.gov>) during the same period.

To provide concurrent monthly MLD data, we acquired reanalyzed MLDs from the Global Ocean Data Assimilation System (GODAS, <https://climatedataguide.ucar.edu>) with 1° spatial resolution and Argo float-based MLDs from the Japan Agency for Marine–Earth Science (JAMSTEC, http://www.jamstec.go.jp/ARGO/argo_web/argo/index.html). We also used monthly Cross-Calibrated Multi-Platform (CCMP) and monthly WindSat-derived wind speed (WS, m s^{-1}) data, both of which had 0.25° spatial resolution and were acquired from <http://apdrc.soest.hawaii.edu>.

2.2. Filling missing data and converting two datasets from different sensors/platforms

We applied a Data Interpolating Empirical Orthogonal Function (DINEOF) method (Alvera-Azcarate, Barth, Beckers, & Weisberg, 2007)

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