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# Optimal PAR intensity for spring bloom in the Northwest Pacific marginal seas

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ABSTRACT

Using ten years (2003–2012) of satellite Chlorophyll-a data, we report that annual phytoplankton bloom climax in the Northwest Pacific marginal seas (17°–58°N) delays northward at a rate of $22.98 \pm 2.86$ km day$^{-1}$. The spring bloom is a dominant feature of the phytoplankton seasonal cycle in this region, except for the northern South China Sea, which features a winter bloom. The sea surface hourly Photosynthetically Available Radiation (PAR) intensity averaged over the bloom peak duration is nearly uniform ($1.04 \pm 0.10$ W m$^{-2}$ h$^{-1}$) among the four sub-regions (i.e. the northern South China Sea, the Kuroshio waters, the Sea of Japan and the Sea of Okhotsk), although different algal species in these four distinct ecological provinces could adapt to a much larger change in other environmental parameters (including total daily PAR, day length, sea surface temperature, net surface heat flux, mixed layer depth, wind speed and euphotic depth). The differences of the hourly PAR intensity between the four provinces during their bloom periods are smaller than those during non-bloom seasons. In contrast, an increasing total daily PAR (W m$^{-2}$ day$^{-1}$), due to the longer day length at higher latitudes, may balance decreasing sea surface temperature and induce algal flowering. Our results point to an optimal hourly light intensity for the annual phytoplankton bloom peak timing in this entire region, which could potentially become an indicator for the requirement of these annual bloom peaks.



## 1. Introduction

More than one century ago, Blackman investigated the effects of light intensity and temperature on the rate of phytoplankton growth. At constant temperature, the growing rate varies with irradiance, initially increasing as the irradiance increases. However, at higher irradiance, this relationship no longer holds and the rate reaches a plateau. At constant irradiance, the rate increases with temperature over a limited range, which, however, is seen only at high irradiance levels. At low irradiance, increasing temperature has little influence on the rate of algal growth (Blackman, 1905). So far most of similar studies indicate that there is a maximum algal production rate at optimal light intensity based on laboratory algae culture experiments (Platt et al., 1980; Nicklisch et al., 2008; Winder and Sommer, 2012). However, investigation on how the change of light intensity affects the poleward delay of annual phytoplankton bloom climax is few. Previous studies found that the compensation of solar irradiance during the bloom initiation was roughly uniform in the North Atlantic Ocean when the spring bloom delayed northward (Siegel et al., 2002). Similarly, the vernal bloom did not occur from the Scotian Shelf to Greenland until the mean Photosynthetically Available Radiation (PAR) within the mixed layer reached at least about 15 W m$^{-2}$ day$^{-1}$. The variation of the mean PAR in the mixed layer was remarkably narrow in this poleward delay of the bloom (Platt et al., 2009; Zhai et al., 2011a,b). Furthermore in an earlier study, Morel suggested that in the summer phytoplankton growing season at high latitudes, the radiation energy at the sea surface is comparable to that experienced at the low latitudes. The depressive effect of low temperature is partly compensated by improved conditions for photosynthesis due to the longer day length (Morel, 1991). Siegel et al. also

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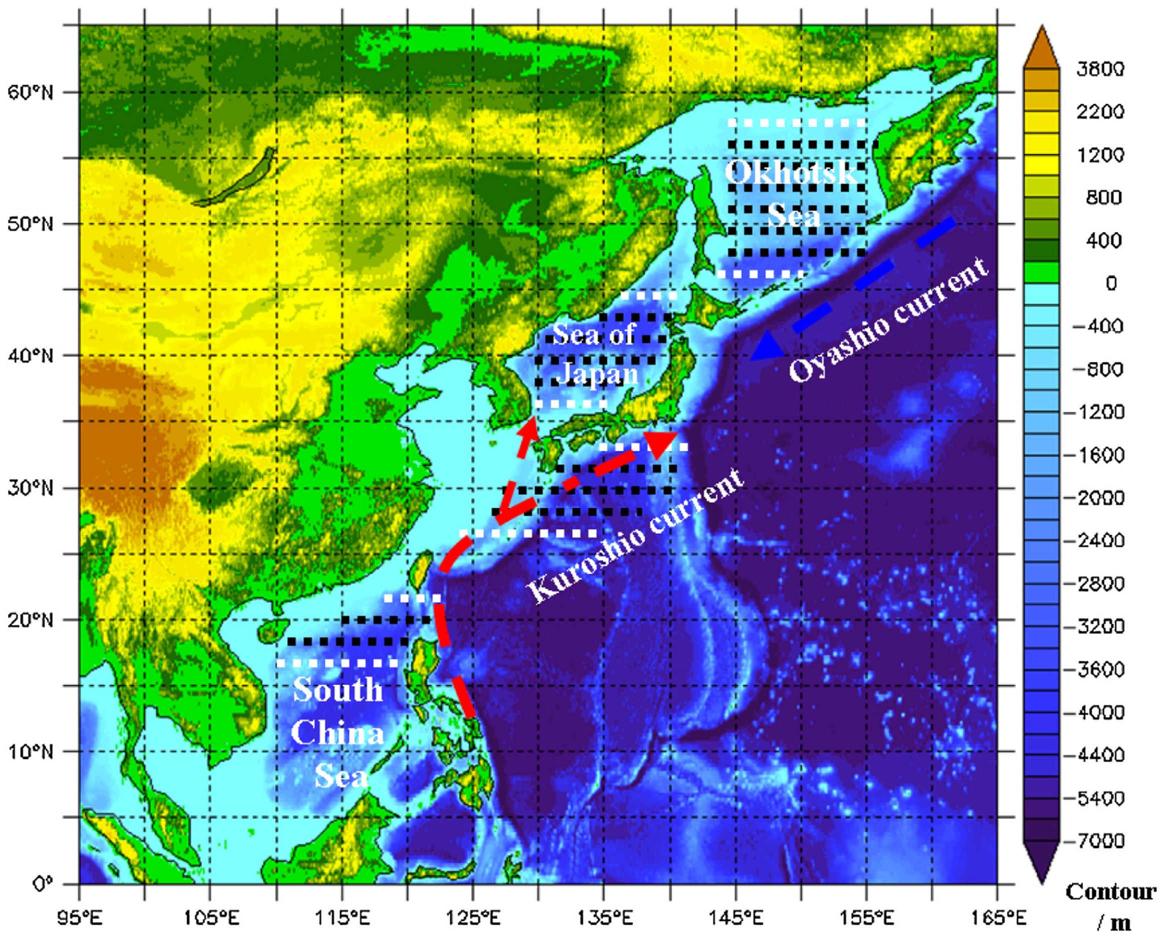


**Fig. 1.** Study domain for the Northwest Pacific marginal seas, indicated by dashed line, including four sub-bioclimatic regimes from 17° to 58°N, i.e. the tropical northern South China Sea (17°–22°N), subtropical Kurshio waters (28°–33°N), temperate Sea of Japan (36°–46°N), and sub-polar Okhotsk Sea (47°–58°N). The topography is based on the ETOPO5 Global Surface Relief product (http://apdrc.soest.hawaii.edu/).

suggested that sea surface incoming PAR increases to the north due simply to increased day length as the spring bloom progresses northward (Siegel et al., 2002). We note that the PAR used in the aforementioned studies is the total daily PAR. In our opinion, the aforementioned studies have insufficient consideration of the role of the light/PAR intensity in the poleward delay of annual phytoplankton bloom climax.

PAR intensities regulate the range of primary production in the euphotic zone through both photolimitation (light level too low) and photoinhibition (light level too high). The mean PAR in the mixed layer is controlled by three variables: incident PAR at the water surface, mixed layer depth, and diffuse attenuation coefficient (Riley, 1957; Cole et al., 2015). However, the variability of the PAR at the sea surface is probably more important in determining the subsurface light conditions than changes in the water mass attenuation coefficient (Arnone et al., 1998). Recently studies have suggested that the Sverdrup's critical-depth model may not apply because the basic assumption that the plankton is well-mixed in the upper layer is not met (Chiswell, 2011). Instead, the spring bloom forms in the shallow near-surface layers (Cole et al., 2015) and is governed by processes occurring near the surface (Smetacek and Passow, 1990). Further, during the bloom phytoplankton is not necessarily or completely mixed throughout the whole mixed water column (Cole et al., 2015). On the other hand, it is reasonable to assume that fluctuating light levels, because of vertical convection, may allow algal cells to take advantage of periods of higher insolation near the sea surface, and then to compensate for the loss to the photosystem when cells are moved to greater depths thus receiving lower irradiance (Marra, 1978).

In this study we investigate the timing of annual phytoplankton bloom peak in the Northwest Pacific marginal seas. We analyze variability of the total daily PAR, day length and hourly PAR intensity and how they are distributed regionally and temporally. Although the study focuses on the Northwest Pacific marginal seas, including the South China Sea (SCS), the Kuroshio waters, the Sea of Japan and the Sea of Okhotsk (Fig. 1), it makes a comparison with similar studies in the North Atlantic. This study aims to show a latitudinal delay of the annual phytoplankton bloom in the Northwest Pacific marginal seas and to identify and explain a potential basin-wide optimum of hourly PAR intensity in the latitudinal delay. The PAR optimum has two attributes: (1) associated with annual bloom peak and (2) nearly uniform basin-wide. Note that our study does not consider nutrient supply, grazing and other losses, which may become critical factors at the end of bloom (Nicklisch et al., 2008).

## 2. Data and methods

### 2.1. Satellite data

We use the MODerate resolution Imaging Spectroradiometer (MODIS)-Aqua Chlorophyll-a concentration (Chl-a) level-3 product (OC3M algorithm), which is used as a proxy for marine phytoplankton biomass. MODIS-derived other oceanic products are also used, included PAR, sea surface temperature (SST, daytime) and euphotic depth. PAR is defined as the quantum energy flux from the sun in