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Seasonality of oceanic primary production and its interannual variability from 1998 to 2007

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ABSTRACT

The seasonality of primary productivity plays an important role in nutrient and carbon cycling. We quantify the seasonality of satellite-derived, oceanic net primary production (NPP) and its interannual variability during the first decade of the SeaWiFS mission (1998 to 2007) using a normalized seasonality index (NSI). The NSI, which is based upon production half-time, $t(1/2)$, generally becomes progressively more episodic with increasing latitude in open ocean waters, spanning from a relatively constant rate of primary productivity throughout the year (mean $t(1/2)$ ~5 months) in subtropical waters to more pulsed events (mean $t(1/2)$ ~3 months) in subpolar waters. This relatively gradual, poleward pattern in NSI differs from recent estimates of phytoplankton bloom duration, another measure of seasonality, at lower latitudes (~40°S–40°N). These differences likely reflect the temporal component of production assessed by each metric, with NSI able to more fully capture the irregular nature of production characteristic of waters in this zonal band. The interannual variability in NSI was generally low, with higher variability observed primarily in frontal and seasonal upwelling zones. The influence of the El Niño–Southern Oscillation on this variability was clearly evident, particularly in the equatorial Pacific, where primary productivity was anomalously episodic from the date line east to the coast of South America in 1998. Yearly seasonality and the magnitude of annual production were generally positively correlated at mid-latitudes and negatively correlated at tropical latitudes, particularly in a region bordering the Pacific equatorial divergence. This implies that increases of annual production in the former region are attained over the course of a year by shorter duration but higher magnitude NPP events, while in the latter areas it results from an increased frequency or duration of similar magnitude events. Statistically significant trends in the seasonality, both positive and negative, were detected in various patches. We suggest that NSI be used together with other phenomenological characteristics of phytoplankton biomass and productivity, such as the timing of bloom initiation and duration, as a means to remotely quantify phytoplankton seasonality and monitor the response of the oceanic ecosystem to environmental variability and climate change.

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1. Introduction

The variability of primary productivity within the ocean, both spatial and temporal, affects global nutrient and carbon cycling. Documenting these temporal and spatial patterns in phytoplankton biomass and monitoring their change over time therefore provides a means to detect and quantitatively evaluate the response of the marine ecosystem to environmental change and its ability to uptake atmospheric CO_2 (Hughes, 2000; Platt and Sathyendranath, 2008). The pace at which primary productivity occurs over the course of a year, which spans from a constant rate of production to a single, pulsed event, represents one aspect of the temporal variability exhibited by the oceanic ecosystem. This seasonality, for example, is one of several factors that influence the relative amount of particulate organic carbon (POC) exported out of the surface ocean and its potential flux to depth, i.e. the "biological pump". Waters exhibiting more episodic production export a greater proportion of labile organic carbon and other biologically active elements from the surface than in regions with a more constant production (Berger and Wefer, 1990; Longhurst, 1995; Fischer et al., 2000; Dunne et al., 2007; Lutz et al., 2007;

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Henson et al., 2012) due to their time varying physical (e.g. solar irradiance and mixed layer) and biogeochemical (e.g. nutrient concentration and grazing pressure) conditions, and provide more POC at the top of the mesopelagic zone to transfer to depth. Seasonality has also been linked to the distribution and diversity of deep-sea benthic foraminifera (Sun et al., 2006; Corliss et al., 2009; Gooday et al., 2012; Yasuhara et al., 2012) and may be useful for inferring the composition of the marine microbial community (Berger and Wefer, 1990; Giovannoni and Vergin, 2012).

Though the seasonality of primary production has important implications for various ecosystem characteristics and biogeochemical processes in the ocean, few studies have adequately quantified it and its interannual variability on a global scale. Furthermore, many of the metrics currently used to estimate seasonality, such as the standard deviation of annual production or the difference between summer and winter production, are sensitive to changes in sampling interval and in the magnitude of primary productivity, and do not capture extreme events. Several recent studies have used the synoptic measurements of satellite ocean color radiometry to globally map other metrics of seasonality, such as the seasonal variation index (SVI=coefficient of variation of NPP) (Lutz et al., 2007) and bloom initiation and duration (Cole et al., 2012; Racault et al., 2012; Sapiano et al., 2012), yet the SVI map of Lutz et al. (2007) only describes its mean condition and bloom duration may be an inappropriate metric in certain oceans regions, such as those where annual cycles of phytoplankton biomass and productivity are absent or irregular.

Here we introduce the normalized seasonality index (NSI), a normalized form of Berger and Wefer (1990) seasonality index, and use it to describe the mean and interannual variability of seasonality of satellite-derived primary production in the world's oceans during the decade from 1998 to 2007. We also examine for short-term time trends in NSI and check for relationships between annual NSI and primary production during this period, as well as compare NSI calculated from weekly estimates of net primary productivity derived using two different production models. Like the seasonality index of Berger and Wefer (1990) and flux stability index of Lampitt and Antia (1997), NSI is based upon the concept of production half-time, $t(1/2)$, the minimum length of time to yield one half of the total annual primary production (Fig. 1). The concept of production half-time is illustrated for idealized versions of three types of production patterns in Fig. 1, ranging from constant (a) to sinusoidal (b) to peaked (c) production (Fig. 1A), and their associated cumulative relative frequency curves (Fig. 1B). Normalization of Berger and Wefer (1990) seasonality index ($=6-t(1/2)$ in months) by half of the total number of possible observations scales their index from 0 to 1, with low values indicating a more constant rate of primary production throughout the year and high values indicating a more episodic nature of production, and permits the comparison of seasonality between regions and years independent of the magnitude of primary productivity. The NSI is adaptable to any frequency of periodically collected observations, with briefer intervals more likely to capture short-lived spikes in productivity, and can be applied to all types of annual cycles. Also, its calculation relies upon the relative values of primary productivity, enabling its application to self-consistent time-series of NPP (and other variables) derived from different platforms and techniques.

2. Data sources and methodology

Global maps of the annual normalized seasonality index (NSI) with $1° \times 1°$ resolution from 1998 to 2007 were generated from global fields of 8-day mean, net primary production (NPP, mgC m^{-2} d^{-1}) estimated using the Vertically Generalized Production Model (VGPM; Behrenfeld and Falkowski, 1997; Behrenfeld et al., 2006a) and the Carbon-based Production Model (CbPM, Westberry et al., 2008). Both datasets were downloaded from the NASA Ocean Color MEaSUREs website (ftp://ftp.oceancolor.ucsb.edu//pub/org/oceancolor/MEaSUREs/NPP) at 1/12° resolution and averaged arithmetically to one-degree resolution. VGPM NPP is widely used (e.g. Gregg et al., 2003; Behrenfeld et al., 2006a) and had been estimated from SeaWiFS chlorophyll concentration (Version r2010) using a temperature-dependent description of chlorophyll-specific photosynthetic efficiency, Pathfinder AVHRR sea-surface temperature and SeaWiFS cloud-corrected photosynthetically available radiation (PAR). CbPM NPP is an alternative method based upon the relationship between phytoplankton carbon and backscattering coefficients and had been computed using standard SeaWiFS-derived diffuse attenuation coefficient and PAR, chlorophyll concentration and particulate backscattering coefficient retrieved from SeaWiFS measurements using a spectral matching technique, and mixed layer depth from the Fleet Numerical Meteorology and Oceanography Center. Regions where intermittent gaps of input data exist, usually due to the presence of clouds, had been filled with the average value of pixels identified using an expanding search for nearest neighbors in both the spatial and temporal domain (O'Malley, pers. comm.). No weekly NPP estimates were available in the polar regions during

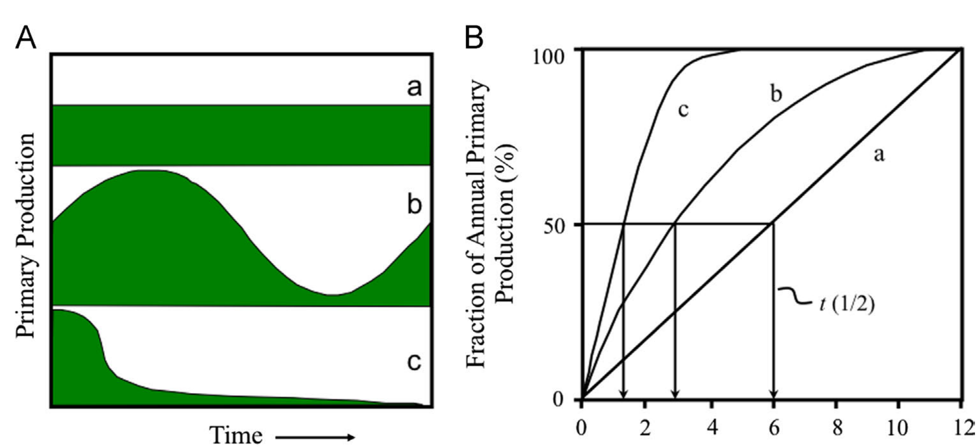

Fig. 1. Concept of production half-time ($t(1/2)$). (A) Idealized production cases, a=constant productivity, b=pure sine wave, c=highly peaked. (B) Curves of cumulative primary productivity for the three cases in *A*, and position of production half-time, $t(1/2)$, in months. Redrawn from Berger and Wefer (1990).