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Monitoring marine phytoplankton seasonality from space

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ABSTRACT

Remote sensing techniques are used to study the large scale patterns related to the seasonal modes of variability of the marine phytoplankton. Ten years of monthly composite maps of sea surface chlorophyll-a concentration and the PHYSAT database of four Phytoplanktonic Functional Types (PFTs), both from SeaWiFS, are used to investigate characteristics of phytoplankton seasonality in the trades and westerlies wind oceanic biomes, where data density is adequate. We use a combination of wavelet transform and statistical techniques that allow us to quantify both intensity and duration of the seasonal oscillation of chlorophyll-a concentration and PFTs relative occurrence, and to map these relationships. Next, the seasonal oscillations detected are related to four PFTs revealing six major global phytoplanktonic associations. Our results elucidate the intensity and duration of the seasonal dynamic of the chlorophyll-a concentration and of the relative occurrence of four PFTs at a global scale. Thus, the typology of the different types of seasonality is investigated. Finally, an overall agreement between the results and the biogeochemical provinces partition proposed by Longhurst is found, revealing a strong environmental control on the seasonal oscillation of primary producers and a clear latitudinal organization in the succession of the phytoplankton types. Results provided in this study quantify the seasonal oscillation of key structural parameters of the global ocean, and their potential implications for our understanding of ecosystem dynamics.

1. Introduction

In the global ocean, climatic conditions strongly influence the abiotic factors that regulate the biological cycle of primary producers, and by extension, the timing, intensity and duration of their blooming period (Nemani et al., 2003). Seasonal oscillations of marine vegetation are crucial for marine ecosystems because of their impact on, and regulation of the biological parameters of many marine species including reproduction, migration and survival rate (Schwartz et al., 2006). Indeed, Edwards and Richardson (2004) have shown, using the Continuous Plankton Recorder dataset, that changes in the marine seasonal oscillation of primary producers may affect the associated primary consumers at a basin scale. The authors noticed a reorganization of the meso-zooplankton communities related to changes in phytoplankton seasonality and hence, have assumed a deep restructuring of the throphodynamic of the North Atlantic ecosystems. However, owing to the inherent difficulty in exhaustively sampling the global ocean (Richardson and Poloczanska, 2008), only few advances in the comprehension of global marine phytoplanktonic seasonality have been made because of the lack of in situ exhaustive time series (Parmesan & Matthews, 2006).

Since the advent of remote sensing in biological oceanography a synoptic and dynamic picture of marine vegetation has become available (Hovis et al., 1980). The very large amount of data that has been progressively gathered, has allowed for global and generic studies of the different temporal modes of chlorophyll-a concentration (Chla). This has included analysis of long term trends, decadal, inter annual and seasonal variability (Behrenfeld et al., 2006; Martinez et al., 2009; Vantrepotte & Mélin, 2011). Despite the fact that seasonal fluctuations of primary producers represent the main variability in global Chla patterns, only a few studies have focused on this type of variation at local or global scale. Dandonneau et al. (2004) measured the starting month, intensity and duration of the blooming period using numerical criteria that study the shape of Chla time series derived from the global ocean color record. In a more statistical manner, Yoder and Kennelly (2003) characterized the global seasonal oscillation of Chla using empirical orthogonal function (EOF) analysis and mapped the main seasonal patterns obtained. These results were subsequently refined by Vantrepotte and Mélin (2009) who used a Census methodology to describe the typology of the seasonal variation of the Chla. They were able to show a strong influence of environmental conditions on Chla seasonal variation. At a local scale, Platt and Sathyendranath (2008) put forward several empirical indices of the

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pelagic domain for studying the dynamics of marine ecosystems. These indices summarize the different types of marine vegetation seasonal blooms and include timing period, duration, and amplitude of the bloom.

In the study reported herein, using remotely sensed data from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) and Phytoplankton Functional Type (PFT) relative occurrence from the PHYSAT dataset (also derived from SeaWiFS data), we investigate the seasonal oscillations of marine primary producers. This is achieved through the application of a newly developed procedure, named Seasonal Wavelet analysis Procedure (SWaP). The main goals of the study are: (i) to determine, quantify and map the average intensity and duration of the phytoplankton seasonal oscillations using the Chla time series; (ii) to determine, quantify and map the average intensity and duration of the 4 PFTs (namely Diatoms, Synechococcus, Prochlorococcus, and Nanoeucaryotes) extracted from the original PHYSAT dataset (Alvain et al., 2008); (iii) to identify, map and describe the main global PFTs associations that contribute the most to the Chla seasonal oscillation at a global scale, as well as their temporal succession. Based on the results, the average seasonal parameters (intensity and duration) of Chla and PFTs occurrences are provided and discussed to examine the different seasonal typologies in the global ocean. In addition, the latitudinal gradient of seasonal parameters of the Chla identified is discussed by relating the spatial distribution and temporal succession of the main PFTs associations detected, and the influence of the environmental conditions.

2. Materials and methods

2.1. Remote sensing data

We use the most homogeneous and widely used global data set of Chla available from space, i.e. those processed from SeaWiFS from October 1997 to December 2007. We use the 2009.1 reprocessing data set made available from NASA at http://oceandata.sci.gsfc.nasa.gov/.

The data set is averaged at a monthly time step and at a spatial resolution of 1° of latitude and longitude. Because of the lack of observations during the winter periods due to the light limitation and a high cloud cover, only latitudes between 50°N to 50°S are used in the further analyses. To allow a worldwide comparison between the seasonality of the phytoplankton biomass and to account for the very large range of values, the time series of each geographical cell are normalized according to Legendre and Legendre (1998).

In order to test the statistical robustness of the detection of the seasonal intensity, a second time series of fortnightly averages has been generated.

2.2. Phytoplankton functional groups: PHYSAT

The PHYSAT approach is based on the identification of specific signatures in the water leaving radiance measurements spectra (nLw) from ocean color sensor measurements (Alvain et al., 2005, 2006). This empirical method is based on the comparison of two kinds of simultaneous measurements: from remote sensing normalized water radiance measurements and in situ measurements of specific phytoplankton pigments. It has been shown that some phytoplankton groups can be associated with specific normalized water leaving radiance (nLw*) when they are dominant (in terms of specific pigments concentration). The nLw* are defined as the second order variability of the satellite signal, obtained by dividing the actual nLw by a mean nLw_{ref} model which depends only on the standard Chla. A set of criteria has been defined to characterize each group sampled in situ, according to its nLw* spectrum. These criteria can be applied to global daily remote sensing observations to get global synthesis of the most frequent group of dominant phytoplankton (Alvain et al., 2008). When no group prevails over a month, pixels are classified as 'unidentified'. This information can also be used to obtain monthly maps of dominant group frequencies, used in this study. For each group and pixel, group frequencies are determined by the relative number of daily detection to the number of daily detection detectable over the month.

In this study, the PHYSAT database is extracted from the work of Alvain et al. (2008) and is used without any numerical transformation. The database is used at the same resolution as the Chla, i.e. from 50°S to 50°N of latitude at a spatial resolution of 1° and at a monthly average time resolution, between October 1997 and December 2007. Only the relative contribution of validated PFTs (more than 50% similarity) in both spatial distribution and temporal fluctuation against in situ observation are considered in the study (Alvain et al., 2008). The Coccolithophorids genus group is not retained because its spatial distribution and temporal fluctuation are underestimated by the PHYSAT methodology. The Phaeocystis-like group is not retained because it has yet to be validated against in situ observations. Therefore, to avoid bias in the methodology, only the contributions of four validated PFTs are considered: Diatoms (DIA), Nanoeucaryotes (NAN), Prochlorococcus (PRO) and the Cyanobacterium genus Synechococcus (SLC).

2.3. Seasonal Wavelet analysis Procedure: SWaP

The classic techniques used to identify the seasonality of phytoplankton at regional scale have been mainly empirical (Platt & Sathyendranath, 2008). The numerical procedure of the study proposed is based on a wavelet analysis that enables study of the frequency composition of the time series (Torrence & Compo, 1998). The methodology can be summarized into 4 main steps, as shown on Fig. 1.

2.3.1. Wavelet transformation and power spectrum

The Continuous Wavelet Transform (CWT) analysis allows for the description of the variability of a time series in both time and frequency domains (Cazelles et al., 2008). The methodology can cope with aperiodic components, noise and transient dynamics (Daubechies, 1992; Lau & Weng, 1995; Torrence & Compo, 1998). The full methodology for CWT is fully described in Royer and Fromentin (2006). The CWT is based on the convolution product between the time series and a mathematical function that is dilated and translated onto the signal (i.e. time series). As usual in ecological applications, we used the Morlet wavelet, a continuous and complex wavelet adapted to wave-like signals, which allows extracting time-dependent amplitude for a continuous range of frequencies (Cazelles et al., 2008; Menard et al., 2007). The relative importance of frequencies may be represented in the time–periodicity plane to form the wavelet power spectrum on a 2D plot, performed on each geographical cell of our time series (see Fig. 1).

2.3.2. Extraction of the intensity of the seasonal oscillation

For each 1° geographical cell, the wavelet power spectrum is used to approximate the intensity of the seasonal oscillation of the parameter studied (Fig. 1). As abundantly described in the literature, phytoplankton presents annual and bi-annual oscillation patterns (Mann & Lazier, 1996; Tomczak & Godfrey, 2003). Therefore, the wavelet power spectrum is averaged, respectively from $0.5\ yr \pm 0.25$ and $1\ yr \pm 0.25$ (Fig. 1) to obtain the mean wavelet power for the seasonal periods of 6-month and 1-year respectively.

2.3.3. Extraction of the duration of the seasonal oscillation

To quantify the duration of a seasonal oscillation in each geographical cell, surrogates methodology is applied to detect significant highly recurring patterns from the wavelet power spectrum (i.e. seasonal oscillation) (Fig. 1). The statistics (mean and variance of the temporal series, power spectrum, and complete empirical distribution) are computed for the