Case Study 5

Observation of Ocean Colour Beyond Chlorophyll-*a*: From Particulate Organic Carbon Content and Size Distribution to Phytoplankton Functional Groups

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5.1 Background Information

The term phytoplankton encompasses all microscopic plant-like organisms living in the illuminated surface layers of the ocean. The existence of phytoplankton is of fundamental interest as they form the base of the aquatic food web, providing an essential ecological function for all aquatic life.

Phytoplankton also play an important role in the biological pump of carbon and CO_2 sequestration. During the process of photosynthesis, phytoplankton take up dissolved CO_2 and convert it into organic compounds, using energy from the sun. This transformation is of biogeochemical importance for two reasons: firstly the resulting organic carbon no longer participates in the equilibrium of the carbonate system, thus increasing the ocean's ability to dissolve carbon dioxide. Secondly, the particulate organic carbon sinks from surface waters to deeper layers, removing carbon from the surface layer. The biological pump thus plays a very important role in the Earth's carbon cycle, and the evolution of the biological pump will play a key role in understanding climate change scenarios.

Like terrestrial plants, phytoplankton use pigment antennae to capture the energy of photons. Among these phytoplankton pigments is chlorophyll-*a*, which is used as an index of the phytoplankton biomass. Chlorophyll-*a* selectively modifies the flux of photons that penetrate the ocean's surface layer. It absorbs the red and blue wavelengths and scatters the green ones. For this reason, the colour of the ocean will range from blue-green to green depending on the type and density of phytoplankton populations. Thus, by studying the colour of light reflected from the oceans, in other words ocean colour, optical sensors can quantify the amount of chlorophyll and other constituents.

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Visible and near-infrared passive radiometers onboard spacecraft provide useful data at spatial and temporal scales unattainable by shipboard sampling. This was fully demonstrated by the first satellite, CZCS, dedicated to the observation of ocean colour. Since then, a number of advanced ocean-colour satellites have been launched. In the past few years, inversion of ocean-colour satellite data has moved beyond the estimation of chlorophyll-*a* concentration to include new parameters which make it possible, for example, to determine the dominant phytoplankton species in the surface waters, to get information about particle size distribution (Loisel et al., 2006) and to retrieve information about other biogeochemical components such as particulate organic carbon (POC), and coloured detrital matter (Stramski et al., 1999; Loisel et al., 2002; Siegel et al., 2002). Consequently, information on dominant phytoplankton groups can be superimposed on POC and size distribution maps, allowing for a large range of new applications. Information obtained from satellite observation is restricted to the near-surface layer. Indeed, the surface oceanic layer that is remotely sensed in the visible part of the spectrum is the first attenuation layer, generating 90% of the photons that form the upward flux just beneath the surface (Gordon and McCluney, 1975). The thickness of this layer typically varies from a few meters to about 60 meters, depending on the presence of optically-significant constituents in the water and the wavelength considered (Smith and Baker, 1978). Products derived from satellite data such as chlorophyll or POC concentration are integrated over the first penetration depth.

5.2 Materials and Methods

5.2.1 POC Estimates from Space

In this section, we will present the Loisel et al. (2002) method used to estimate the near-surface concentration of POC from satellite data (POC_{surf}). This method consists of deriving POC_{surf} from the inherent optical properties, as presented in Loisel et al. (2002). The natural variations of optically-significant substances in seawater can be observed through the measurements of inherent optical properties (IOPs). Among these IOPs, the total backscattering coefficient of seawater, b_b, is not sensitive to the dissolved material. The $b_b$coefficient can therefore be partitioned into two components $b_b = b_{bp} + b_{bw}$ where b_{bw} is the backscattering coefficient of seawater (Morel and Prieur, 1977) and b_{bp} is the backscattering coefficient of particles. The b_{bp} variability is governed (to the first order) by changes in the abundance and (to the second order) composition of the particle assemblage.

Previous studies at regional (Stramski et al., 1999; Loisel et al., 2001) and global scales (Loisel et al., 2002) have demonstrated the feasibility of estimating POC from b_{bp}. The robust relationship found between POC and b_{bp} can be explained by the fact that under non-bloom conditions, b_{bp} is governed mainly by small-sized, non-living particles (Stramski and Kiefer, 1991; Morel and Ahn, 1991), which represent the

dominant contribution of POC in the open ocean (Koike et al., 1990). Note that previous studies have shown a good correlation between *in situ* b_{bp} and POC values in different oceanic areas (Reynolds et al., 2001; Stramski et al., 2008).

In a remote-sensing context, the backscattering coefficient of seawater is not measured directly, but is derived by the inversion of the natural light field reflected back out of the ocean and detected by the satellite ocean-colour sensor. In this study, $b_b(490)$ is retrieved from the remote-sensing reflectance at 443nm, 490nm and 555nm, using the method developed by Loisel and Stramski (2000), and slightly modified by Loisel and Poteau (2006).

Because coincident measurements of the particle backscattering coefficient and POC are still very scarce, the parameterization of POC_{surf} is established as a function of the particle scattering coefficient, b_p, which is derived from b_{bp} using the following empirical relationship (Twardowski et al., 2001):

$$b_{bp}(490)/b_b(490) = 0.0096 \times [\text{chl-}a]^{-0.253} \tag{5.1}$$

A simple linear relationship is used between POC_{surf} and b_p (Claustre et al., 1999; Loisel et al., 2001). Based on results of previous studies carried out in different regions of the global ocean, a mean slope value of 400 mg m^{-2} is adopted (Claustre et al., 1999; Loisel et al., 2002) with a null intercept as a first approximation.

Figure 5.1 displays the global maps of the POC_{surf} near-surface concentration for the SeaWiFS period 1997-2008 during June and January. The global distribution of POC_{surf} follows the major gyre systems and other large scale circulation features of the ocean. Low surface POC concentrations are encountered in subtropical gyres, where large scale downwelling is expected. For example in the South Pacific gyre, POC_{surf} is less than 50 mg m^{-3}. Elevated near-surface POC concentrations in the range 100-200 mg m^{-3} are encountered at high and temperate latitudes (e.g. Antarctic Circumpolar Current, sub-arctic gyres, temperate North Atlantic). Compared to subtropical gyres, these areas are characterized by a high chlorophyll concentration (by a factor of about ten, Figure 5.2) supported by inputs of nutrients injected from below the euphotic layer by advection or vertical mixing, or from terrestrial sources.

5.2.2 Spectral Dependency of Optical Backscattering by Marine Particles: A Proxy of the Particle Size Distribution

Knowledge of the relative proportions of small- and large-sized particles in the surface ocean is essential for understanding the ocean ecology and biogeochemistry, including particle dynamics and carbon cycling. This information may be assessed qualitatively from satellite observations of ocean colour (see Figure 5.3). Such capability is based on the estimation of spectral dependence of the particulate backscattering coefficient, b_{bp}, denoted γ, which is sensitive to particle size distri-

bution. The greater the value of γ (i.e. steeper slope), the more small particles are present in the water column relative to large particles (and vice versa).

The retrieval of γ from ocean-colour remote sensing observations is performed in two steps. First, $b_{bp}(\lambda)$ is assessed at different visible wavelengths, λ, by an inverse algorithm which uses the light field estimated from the total signal measured at the top of the atmosphere and corrected for atmospheric effects (Loisel and Stramski, 2000). Then, γ is calculated by linear regression between Log (b_{bp}) and Log (λ). In general, the γ values are much greater in summer than in winter, which holds true for both the northern and southern hemisphere (Figure 5.3). Seasonal variations of γ indicate that the proportion of small-sized particles compared to larger particles increases from winter to summer in the surface waters of the global oceans. These spatio-temporal patterns are interpreted in terms of processes that modify the composition of particulate assemblages and physiology of phytoplankton in response to environmental forcing.

5.2.3 Detection of Dominant Phytoplankton Groups: The PHYSAT Method

Phytoplankton play an important role in many global biogeochemical cycles. However, the efficiency and impact of phytoplankton depends strongly on the nature of phytoplankton itself. Thus monitoring the spatial and temporal distribution of dominant phytoplankton groups is of critical importance. From a pigment point of view, the main phytoplankton groups have specific pigments, called biomarkers. The PHYSAT algorithm (Alvain et al., 2005; 2008) has been developed based on an empirical relationship between coincident *in situ* biomarker pigment measurements and remote sensing reflectance anomalies. The PHYSAT method has been applied to the SeaWiFS satellite archive, from September 1997 to December 2008. Monthly PHYSAT data have been used to retrieve the monthly climatology maps for January and June, shown in Figure 5.4.

The main difficulty in ocean-colour measurements (in the visible spectrum) is caused by the atmosphere and aerosols which act to diffuse and absorb light. The atmosphere is responsible for about 95% of the signal detected by a satellite sensor. However, the portion of the signal that carries information from the ocean and the atmosphere respectively can be deconvoluted. This is currently done using atmospheric correction algorithms. The measurements we used here are obtained after atmospheric correction. However, since we used second order variability for the PHYSAT method, some additional criteria have to be applied. Thus, we will consider, for the PHYSAT part, only pixels associated with an aerosol optical thickness less than 0.15. Another validity criteria concerns the concentration of chlorophyll-*a*, [chl-*a*], which has to be lower than 3 mg m^{-3} to exclude waters possibly contaminated by coastal material, and higher than 0.04 mg m^{-3} to discard ultra-oligotrophic waters where it is unlikely that a dominant group can be found using ocean-colour data.

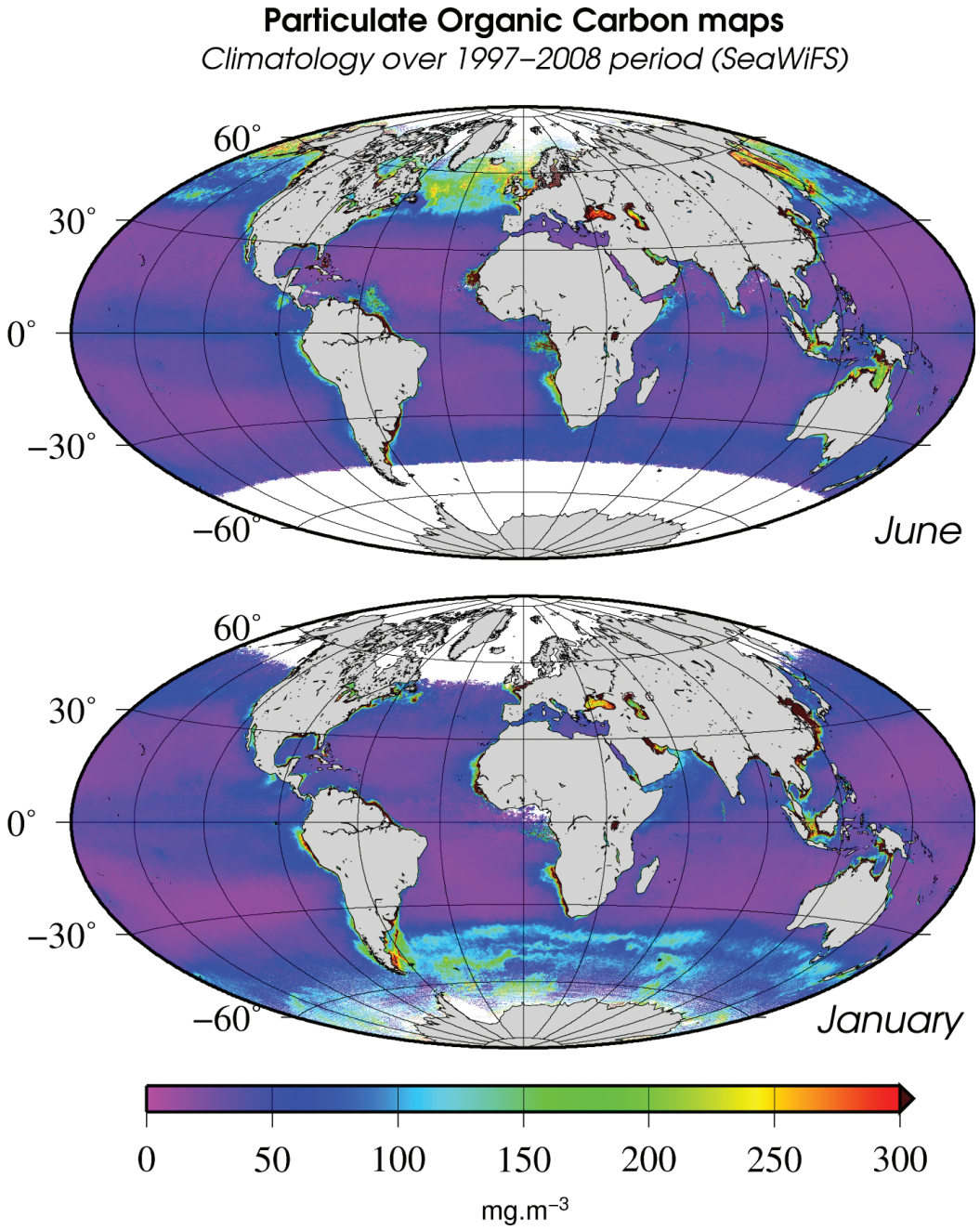

Figure 5.1 Particulate organic carbon (POC) climatology maps (1997 – 2008, SeaWiFS) for the months of June and January.

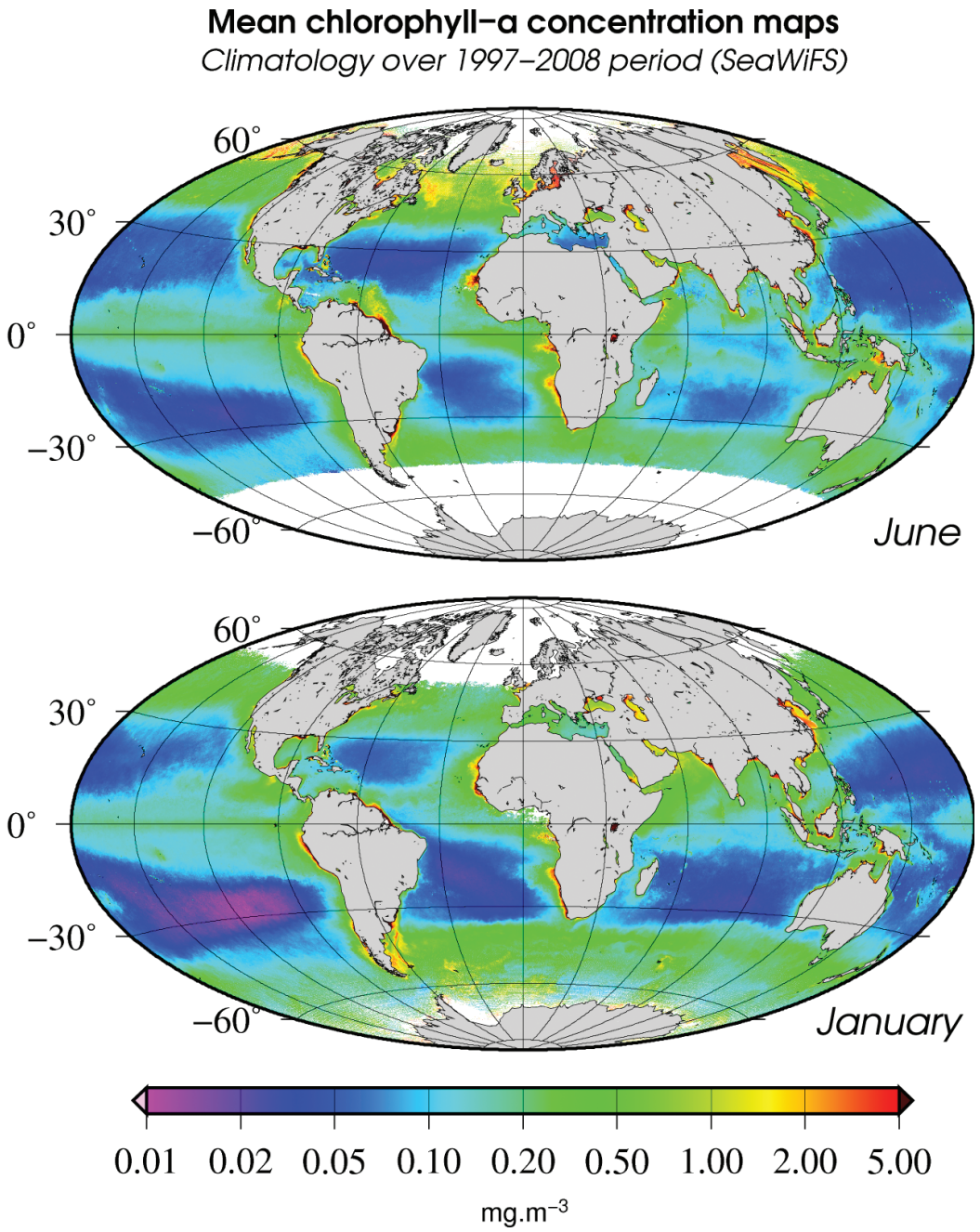

Figure 5.2 Mean chlorophyll-*a* concentration climatology maps (1997 – 2008, SeaWiFS) for the months of June and January.

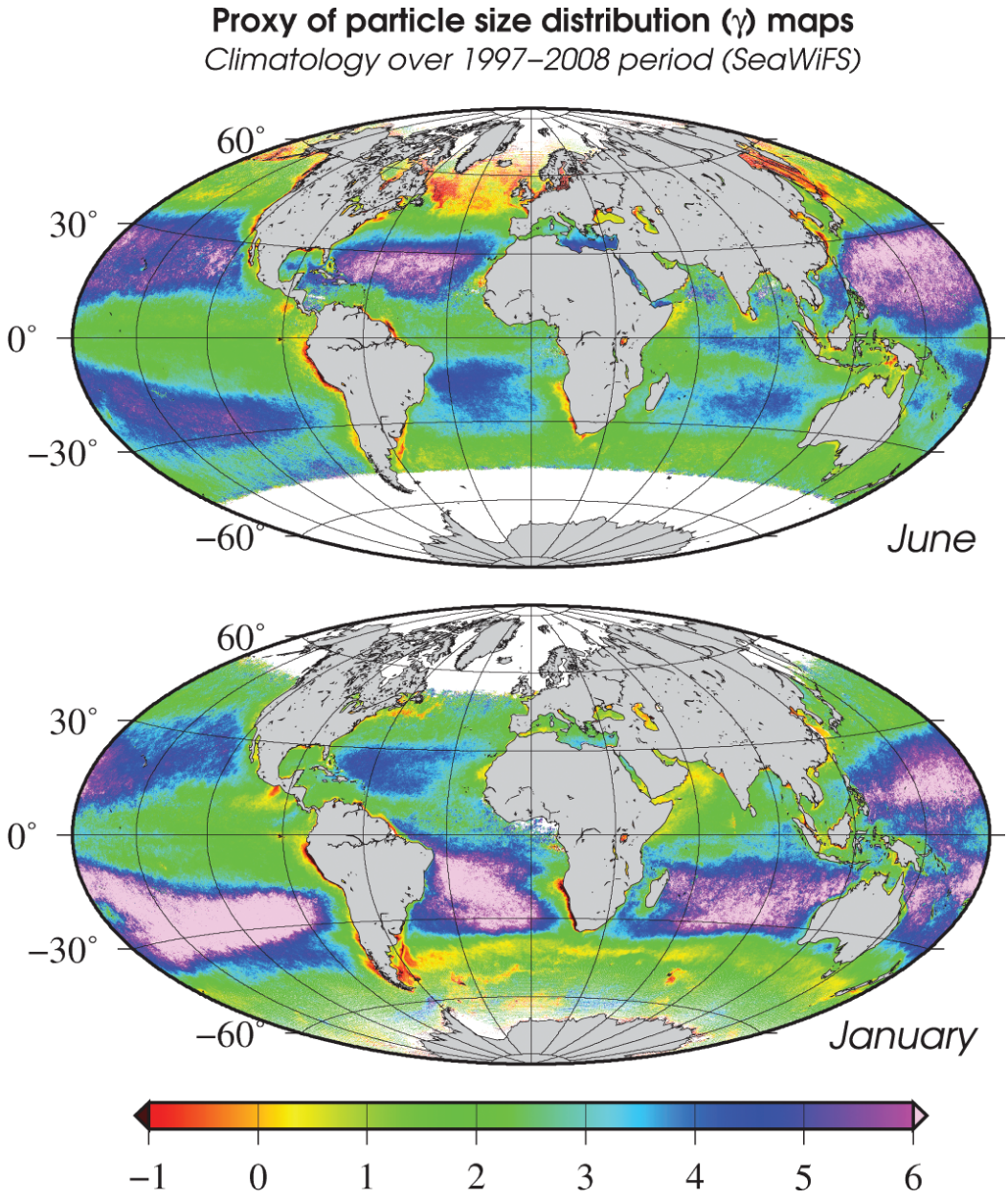

Figure 5.3 Particle size distribution proxy (γ) climatology maps (1997-2008, SeaWiFS) for the months of June and January.

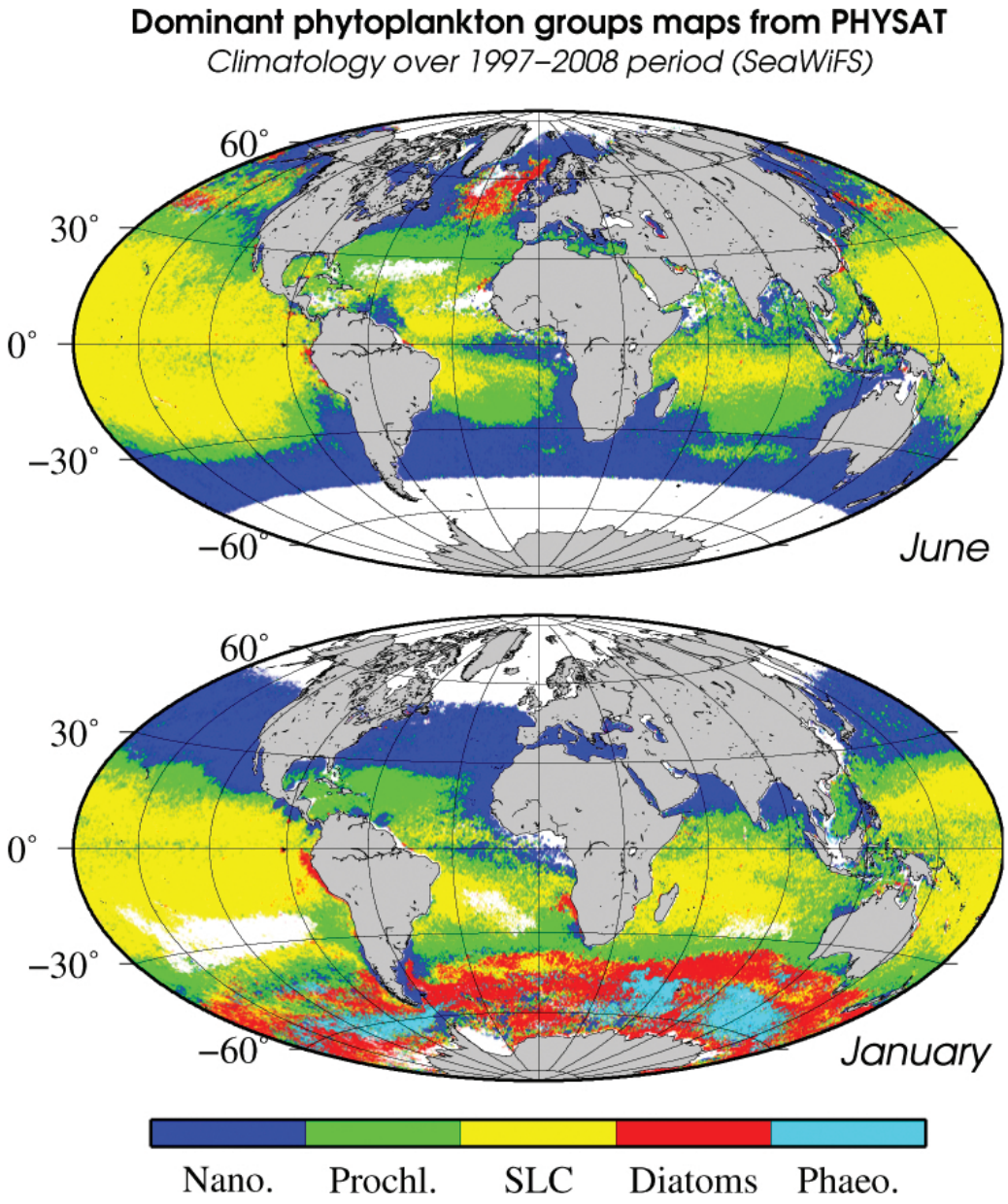

Figure 5.4 Climatology maps (1997 – 2008, SeaWiFS) of dominant phytoplankton groups for the months of June and January, estimated using PHYSAT. Nano. = nanophytoplankton, Prochl. = *Prochlorococcus*, SLC = *Synechococcus*-like cyanobacteria (SLC), and Phaeo. = *Phaeocystis*.

The PHYSAT approach is based on the identification of specific signatures in the normalised water leaving radiance spectra classically measured by ocean-colour sensors, after the previous criteria concerning atmospheric correction and [chl-*a*] has been applied. PHYSAT is an empirical method, established by comparing two kinds of simultaneous and coincident measurements: SeaWiFS nLw measurements and *in situ* measurements of biomarker phytoplankton pigments performed in the framework of the Gep&Co program (Dandonneau et al., 2004). In a first study, four dominant phytoplankton groups were identified within the GeP&CO dataset: diatoms, nanoeukaryotes, *Synechococcus* and *Prochlorococcus*. Recently, the PHYSAT method has been improved to detect an additional group, namely the *Phaeocystis*-like group, by analyzing specific signal anomalies in the Southern Ocean during winter months (Alvain et al., 2008). Note that the PHYSAT method allows detection of these groups only when they are dominant, that is, in situations where a given phytoplankton group is a major contributor (>60%) of the total pigment concentration. It is important to point out that, even if there is a general agreement on the taxonomic message of each biomarker pigment, for example, divinyl chlorophyll-*a* (d-chl-*a*) is associated with *Prochlorococcus*, a large range of relative concentrations (pigments ratios) can be found in the literature. Pigment ratios are defined as:

$$P_{rel} = P/([\text{chl-}a] + [\text{d-chl-}a]), \tag{5.2}$$

where P is the measured biomarker pigment concentration. A thorough analysis of pigment ratios from the literature has allowed us to define a mean, relative concentration for each group, thus allowing thresholds to be fixed. A group is considered dominant when P_{rel} is at least equal to 60% of the total. Detailed information of the method including the use of thresholds is available in Alvain et al. (2005).

The key step in the success of methods such as PHYSAT is to associate *in situ* measurements with remote sensing measurements after having removed the first order variations due to the chlorophyll-*a* concentration (and classically used in previous ocean-colour products). Thus, a second step to establish PHYSAT has been to transform the nLw SeaWiFS spectra into specific normalized water leaving radiance, noted nLw*, to determine the second order variability of the satellite signal. This was done by dividing the actual nLw by a mean nLw model (nLw_{ref}), established from a large remote sensing dataset of nLw(λ) and [chl-*a*], cf. equation 5.3.

$$nLw^*(\lambda) = nLw(\lambda)/nLw_{ref}(\lambda, [\text{chl-}a]) \tag{5.3}$$

The nLw_{ref} depends only on the standard SeaWiFS chlorophyll-*a*. By dividing nLw by this reference, we obtain a new product, denoted nLw*, which is used in PHYSAT. Indeed, it has been shown that every dominant phytoplankton group sampled during the GeP&Co dataset is associated with a specific nLw* spectrum. It is thus possible

to define a set of criteria to characterize each group as a function of its nLw* spectrum. These criteria can thus be applied to the global daily SeaWiFS archive to obtain global monthly maps of the most frequently detected dominant groups, as shown in Figure 5.4. Note that when no group prevails over the period of one month, the pixels are associated with an 'unidentified' group. Alvain et al. (2008) studied the geographical distribution and seasonal succession of major dominant phytoplankton groups which are in good agreement with previous studies (Zubkov et al., 2000; DuRand et al., 2001; Marty and Chivérini, 2002; Dandonneau et al., 2004; Longhurst 2007). However, as for all empirical ocean-colour methodology, validation based on *in situ* measurements has to be pursued each time a suitable dataset is available.

5.3 Questions

Q 1: What can you say about the spatial distribution of POC, chl-*a* and dominant phytoplankton groups (from Figures 5.1, 5.2, and 5.4)? Look specifically at the following areas: (i) 45 – 52°N, 30 – 15°W and (ii) 47 – 40°S, 65 – 80°E for the month of January.

Q 2: In the future, what sort of potential applications could be considered from synergy of data of POC, [chl-*a*] and dominant phytoplankton groups?

Q 3: How would you explain the high POC concentration (~250 – 300 mg m^{-3}) encountered around Alaska, British Isles and the Yellow East China Sea seen in Figure 5.1?

Q 4: What can you say about diatom distribution in Figure 5.4?

Q 5: What will PHYSAT detect (ideally) if the relative contribution to the total pigment concentration is: 20% for group 1, 40% for group 2 and 40% for group 3?

Q 6: Is it possible to apply PHYSAT, as described above, to coastal waters, and why?

Q 7: What should I do if I want to apply the PHYSAT method to a different satellite?

Q 8: What is essential to establish a method like PHYSAT ?

Q 9: What is essential to apply a method like PHYSAT, in addition to water leaving radiances?

Q 10: How could we validate PHYSAT or improve PHYSAT?

5.4 Answers

A 1: These two areas are almost identical in terms of chlorophyll-*a* concentration but are distinct in term of POC concentration. Furthermore, these two areas are also distinct in terms of phytoplankton groups. The region in the Southern ocean is dominated by diatoms whereas the region in the northern Atlantic is dominated by nanoeukaryotes. The actual results for these two areas for the period 1998 – 2006 are summarised below in Table. 1.

Table 5.1 Mean near-surface POC and chlorophyll-*a* concentration over the areas in question for the SeaWiFS monthly climatology of January (1998 – 2006), as well as the percentage of pixels dominated by various phytoplankton groups (nano= nanophytoplankton; Prochl = *Prochlorococcus*; SLC = *Synechococcus*-like cyanobacteria; and Phaeo = *Phaeocystis*-like).

	(45–52°N, 30–15°W)	**(47–40°S, 65–80°E)**
Chl-*a* (mg m^{-3})	0.20 ± 0.07	0.33 ± 0.10
POC (mg m^{-3})	40.07 ± 10.8	172.8 ± 23.5
% Nano	98	8
% Prochl	2	4
% SLC	0	15
% Diatoms	0	69
% Phaeo	0	4

A 2: Coincident information of [chl-*a*], POC and dominant phytoplankton groups could be interpreted from an ecological point of view. We could carry out studies to investigate:

- links between dominant phytoplankton groups and the food web
- links between phytoplankton species and POC and chlorophyll-*a* concentration
- relationship between phytoplankton and POC and nutrients, irradiance and stratification.

In the future, new ocean colour parameters will help to assess the relationship between the total biomass and/or phytoplankton composition and productivity (for resource management).

A 3: In these areas, some of the high POC_{surf} values may result from the presence of coastal waters, which carry particles of terrigenous origin which affect the remote sensing reflectance, resulting in an overestimate of the near-surface POC concentration. The algorithm described above is not appropriate for estimating POC content in these coastal waters. Consequently, these high POC concentrations should not be considered.

A 4: Diatom blooms are observed mainly in the North Atlantic and North Pacific Ocean during spring. During the austral summer, large blooms of diatoms are also observed at latitudes less than 30°S as well as in upwelling areas off the west coast

of southern Africa and South America.

A 5: In this case, PHYSAT will not detect a dominant group, since a dominant group should contribute at least 60% of the total pigment concentration.

A 6: No, because coastal waters are influenced by other organic and inorganic material (e.g. sediments, mineral particles, coloured dissolved organic matter) that can change the nLw but are not related to phytoplankton, and are not taken into account in PHYSAT.

A 7: In this case, it is necessary to calculate a new look up table containing the nLw_{ref} spectra for the new satellite. It is also necessary to check and adapt thresholds used to classify nLw* spectra.

A 8: As PHYSAT is an empirical method, it is essential to have *in situ* information about dominant phytoplankton groups (e.g. using pigments or others methods) and coincident and simultaneous water leaving radiance measurements, during very clear sky atmosphere conditions.

A 9: It is essential to have information about atmospheric conditions (such as aerosol optical thickness) and the concentration of chlorophyll-*a*.

A 10: Since PHYSAT is an empirical method, it is rather difficult to evaluate errors precisely. However, each time an *in situ* dataset with enough information about dominant phytoplankton groups is available, it is essential to use it to validate the method. Some optical studies are currently in progress to better understand the relationship between specific nLw* spectra and specific dominant groups.

5.5 References

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