In Search of Long-term Trends in Ocean Color

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There is an ongoing debate regarding the role of phytoplankton within the ocean carbon cycle, and the role of biology in possibly capturing part of the excess CO_2 produced by human activities.

Without entering this debate, this article takes a few simple facts as granted; e.g., that the transfer of CO_2 from the atmosphere toward the ocean interior mediated by photosynthesis (the so-called "biological pump") is active, so that any evolution of its strength or structure could impact the CO_2 exchange between the ocean and the atmosphere.

This article focuses on the issues to be addressed to improve the accuracy and consistency of the phytoplankton pigment fields derived from ocean color observations performed by different satellite-borne sensors.

The purpose of the sequential activities described here was to ensure coherency among the data sets that have resulted from two major satellite-based missions that were launched to provide the capability to monitor time changes in ocean color: the Coastal Zone Color Scanner (CZCS; 1979–1986) and the SeaWiFS (1997–ongoing). The same effort might well be extended to other present or future satellite missions. Achieving such coherence is mandatory for assessing long-term trends in ocean biogeochemistry.

Searching for Long-term Changes in Ocean Biota

Ocean color refers to the spectral behavior of the ocean reflectance; i.e., the ratio of solar radiation exiting the sea to the radiation entering it through the surface. Changes in ocean color are largely governed by the oceanic chlorophyll concentration, and therefore, this concentration is derivable from inversion of the reflectance spectrum; in particular, when this spectrum is recorded from space. Phytoplankton chlorophyll can be used as a surrogate of the algal biomass, which is a parameter of biogeochemical importance, because it is the main driver of carbon fixation through algal photosynthesis. To assess possible long-term changes in oceanic biota, reliable time series of this biomass have to be built.

A milestone in this search for long-term changes in the oceanic biota was the publication of an article in *Eos* titled "Ocean Color: Availability of the Global Data Set" [*Feldman et al.*, 1989]. That paper presented the state-of-the-art ocean color archive generated from the 8-year observations (1979–1986) of the CZCS—the first ocean color sensor aboard a satellite, and launched by NASA in November 1978 [*Hovis et al.*, 1980]. Since then, the global archive of ocean color has given rise to numerous works, either describing the phytoplankton fields, or using these fields in various modeling studies (see, e.g., the 20 papers in the special section of *JGR-Oceans, 99*, C4, 1994). The CZCS legacy is far beyond what was initially expected from this "proof-of-concept" mission, and the global picture that emerged from the CZCS data set has deeply renewed oceanographers' vision of oceanic biota, and conclusively demonstrated the benefit of ocean color remote sensing to oceanography. As a consequence, a series of new sensors were planned in the 1980s, designed in the 1990s, and finally launched in the last 7 years [see *IOCCG*, 1999, as well as http://www.ioccg.org].

There is a 12-year gap in the time series of global ocean color because of the irregular schedule of satellite launches. Historical (CZCS) and present, as well as future ocean color observations, are not easily linked. It is risky and difficult to directly compare ocean color observations from the different satellites, because the instruments, the data-processing algorithms, and the calibration techniques all are different. In order to contribute to the generation of long-term, global, multi-sensor ocean color archives, it is necessary to minimize, if not eliminate, the impact of the differences mentioned here.

To reach this goal, a re-processing of the complete CZCS archive was done with techniques compatible with those employed for recent sensors. The objective was first, to improve the quality of the products derived from the CZCS so that they can be used as a reference point for the 1980s. To do this, the pigment concentration maps were revised, and new variables derived; namely, the aerosol optical thickness, τ_a, and the aerosol Ångstrøm exponent. This article briefly presents the rationale for, and the main features of, this re-processing, and demonstrate some results. Another effort in a similar direction, yet using totally different techniques, has also been presented [*Gregg and Conkright*, 2002].

Knowledge of ocean optics, and hence, the techniques and algorithms for processing ocean color observations, have evolved during the last 15 years, and the underlying rationale for the re-processing has been to use methods as close as possible to those presently used for the new-generation sensors. A good candidate was the iterative method developed at the Laboratoire de Physique et Chimie Marines (LPCM, former name of the present Laboratoire d'Océanographie de Villefranche), by *Bricaud and Morel* [1987] and *André and Morel* [1991], and further refined to incorporate the latest knowledge in bio-optics [e.g., *Morel and Gentili*, 1996; *Morel and Maritorena*, 2001]. This method, hereafter referred to as the LPCM algorithm, avoids, in principle, some weaknesses of the previous CZCS algorithms, and allows information regarding the atmospheric aerosols and the phytoplankton pigments to be simultaneously retrieved from the ocean color spectrum. Aerosols are of interest for studies of the Earth radiation budget and climate, as well as for ocean biogeochemistry. Of equal importance, a high level of continuity and compatibility in data products can be envisaged by applying the same method to the observations from the new-generation instruments (e.g., SeaWiFS).

Algorithms for Retrieving Phytoplankton Pigments from CZCS: 20 Years of Changes

Quantitatively relating the variations in the "ocean color" seen from a satellite to the varying concentrations of chlorophyll-containing unicellular algae (the phytoplankton cells) was a challenge addressed by the CZCS mission. All phytoplankton species (about 30,000 species within 12 phyla) contain the ubiquitous photosynthetic pigment, Chl-*a*, which is responsible for in-water radiation absorption in the "blue part" of the spectrum, explaining the shift in ocean color, from "deep blue" (violet), "blue," "blue-green," "green," and even "brown" ambiences, for waters with progressively higher phytoplankton concentrations. A highly varying trail of pigments is actually associated with Chl-*a*, as well as a varying amount of dissolved substances and particles. We exclusively deal here with "Case 1 waters"—usually offshore waters—where optical properties are fully determined by phytoplankton and their retinue (as opposed to "Case 2 waters;" usually coastal waters, where other substances, e.g., sediments and dissolved materials, also influence radiation propagation). Considerable effort in bio-optics research focuses on describing, understanding, and quantifying this natural variability in order to improve the reliability of space-derived Chl-*a* concentrations.

Before interpreting the ocean color as measured by satellite, the contribution of the atmosphere (about 90% of the recorded signal) must be estimated, a step which is referred to as the atmospheric correction. The main difficulty here is introduced by the highly varying optical properties of atmospheric aerosols. These properties result from local processes, from the large-scale atmosphere circulation, and from the remote sources of the particles, all of which are not known a priori when performing the correction. Several techniques exist for the new-generation sensors, based on their ability to gain information about the spectral dependency of aerosol scattering through measurements in near-infrared bands (where the open ocean is essentially "black") for extrapolating the atmosphere radiance into the visible. These algorithms cannot be applied to the CZCS observations, because this sensor was not equipped with near-infrared channels, necessitating assumptions concerning the aerosol and the ocean contributions to the total recorded signal.

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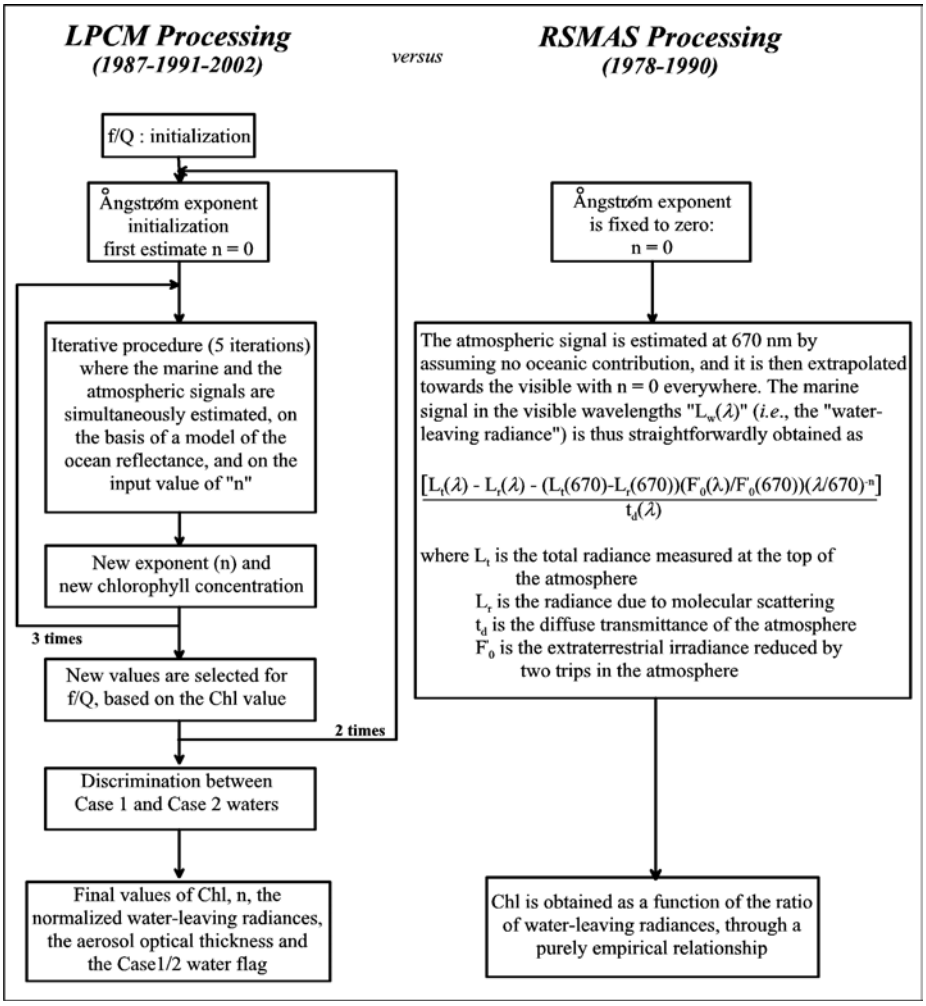

*Fig. 1. The LPCM data-processing algorithms (left sketch) assume that the variations of optical properties with the pigment content are known for oceanic Case 1 waters, and follow a model. The other important assumption is that the spectral dependency of aerosol scattering follows an Ångstrøm law (a power law) with an exponent n. When both models are combined, the respective contributions of the marine and atmospheric signals to the total recorded signal can be separated through iterative methods. An accurate screening of non-Case 1 waters has to be performed accordingly when applying the algorithm. Another important feature of the LPCM technique is its capability to account for the bidirectionality of the underwater radiance field, which is an improvement as it allows removal of that part of the variability in radiances that is only due to geometry (fully "normalized water-leaving radiances" are then produced). This structure of the radiant field is expressed through the "f/Q" ratio [*Morel and Gentili, *1996], variations of which express the changing magnitude of radiances with viewing angle, for instance, and depend on Chl-a and wavelength. To account for this "bi-directional effect," several iterations of the whole atmospheric correction are performed before reaching stable values of the f/Q ratio. Once normalized water-leaving radiances have been obtained for the visible bands of CZCS (443, 520, and 550 nm), they are used, in conjunction with the relevant f/Q ratios, to derive the values of $[b_b/a]$ at the same wavelengths, where b_b and a are respectively the backscattering and absorption coefficient of the medium. These values are passed on to the bio-optical algorithm [*Morel and Maritorena, *2001] which relates Chl-a to the ratio of $[b_b/a]$ at 443 nm to $[b_b/a]$ at 550 nm (or, similarly, to the ratio of $[b_b/a]$ at 520 nm to $[b_b]/a]$ at 550 nm if Chl-a is found to be greater than 1.5 mg m^{-3}). In the RSMAS processing (sketch on the right;* Feldman et al., *[1989];* Evans and Gordon, *[1994]), the Ångstrøm exponent, n, was set to 0 in all cases (actually 0 for λ = 550 nm, and ~ -0.12 for λ = 443 nm), and the water-leaving radiance at each wavelength λ was obtained in a unique step, as indicated on the figure. Chl-a is calculated at the end from the ratio of water-leaving radiances at two wavelengths.*

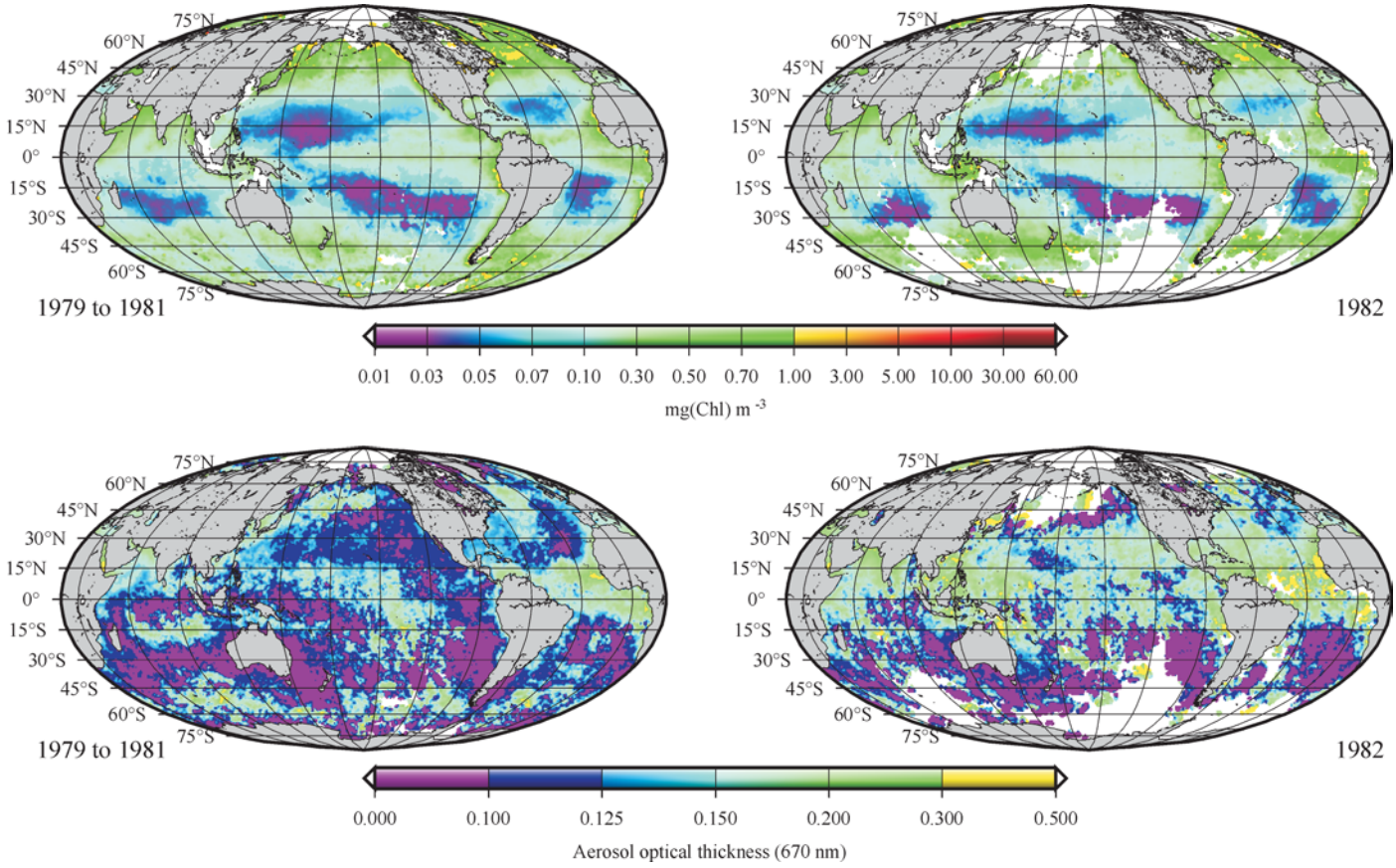

Fig. 2. Chlorophyll-a concentration and aerosol optical thickness, as derived from the global CZCS archive and using the new algorithms presented in this article. Maps are shown for the mean situation over the years 1979 to 1981 (left column) and for the year 1982 (right column). A major input of volcanic particles to the atmosphere indeed occurred after the El Chichón eruption in April 1982 (Central America), so that aerosol distributions and levels are contrasted between the two periods. It appeared that the Chl-a field derived for 1982 with the RSMAS algorithms (not shown here) displayed lower chlorophyll concentrations than the mean field for the 3 previous years. This decrease does not appear at all in the new fields shown here, which are much more consistent with those derived for the other years. This is due to the capability of the algorithm to account for possible changes in the spectral dependency of aerosol scattering, which have occurred in 1982 following the El Chichón eruption. This is clearly observed as well as contrasted levels and distributions in the Ångstrøm exponent fields (not shown).

For the present work, a number of improvements were introduced in the atmospheric correction schemes and bio-optical algorithms, as compared to the algorithms used in the 1980s to generate the CZCS level-2 data. Also introduced was a last refinement in the sensor band 4 (670 nm) calibration, in addition to the main calibration assessment already realized by *Evans and Gordon* [1994]. Atmospheric correction was performed in the early 1980s by assuming no oceanic signal in the fourth channel of CZCS (670 nm), and a unique and ubiquitous aerosol, characterized by a wavelength-independent scattering (see Figure. 1). Although known at the time to be incorrect, this assumption was demanded by computational resources available for re-processing the full CZCS data set. It was the weakest link in the first CZCS processing. Because the optical properties of aerosols vary significantly, even for remote oceanic areas, any departure from the zero spectral dependence was translated into an error in the retrieved water-leaving radiances. After the atmospheric correction was achieved, Chl-*a* was inferred from the ratio of water-leaving radiances at 2 wavelengths, using empirical relationships established from a series of simultaneous in situ measurements of radiances and chlorophyll (fluorometric determination; see *Clark* [1981]).

In contrast, with the new processing, the aerosols properties are estimated independently at each pixel ("pixel-per-pixel" algorithm, PPP), simultaneously with Chl-*a* retrieval, under the assumption that the spectral dependence of aerosol scattering obeys an Ångstrøm law (power law in λ^n, where n is the so-called Ångstrøm exponent and λ the wavelength). The PPP algorithm [*Bricaud and Morel*, 1987; *André and Morel*, 1991] assumes that "natural" relationships exist in Case 1 waters between the spectral values of reflectance, and that these reflectances vary with Chl-*a* in a predictable way according to a model (including the 670 nm band where the assumption of zero marine signal is relaxed). Departures from the model may translate as errors in the retrieved Ångstrøm exponent. At the end, Chl-*a* is obtained through a "semi-empirical" algorithm, which links Chl-*a* to the ratio of the backscattering to the absorption coefficients (b_b/a), after the model proposed by *Morel and Maritorena* [2001]. The algorithm also accounts for the bidirectionality of the ocean reflectance and makes use of recent determination of absorption by water itself. It should be more representative of mean, global, oceanic properties, and should provide more accurate Chl-*a* determinations, since it is based on recent and coincident measurements of reflectance and of Chl-*a* (using High Pressure Liquid Chromatography technique).

Processing the CZCS Images; Generating a Revised Global CZCS Archive

About 66,000 scenes have been re-processed according to the algorithm outlined above, generating several maps for each scene, comprising Chl-*a*, the aerosol radiance at 670 nm, $L_a(670)$, and the Ångstrøm exponent. The latter was used as an indication of the aerosol type, allowing the aerosol optical thickness, τ_a, to be inferred from the daily $L_a(670)$ maps, under the approximation of single scattering, and through assumptions about the optical properties of aerosols (see examples in Figure 2).

Generating coherent and reliable composite maps requires a careful screening of invalid pixels. Pixels to be rejected—via various tests not detailed here—include land and clouds, as well as Sun glint, electronic overshoot of the sensor east of any excessively bright target

(e.g., clouds), large tilt or viewing or Sun zenith angles, and finally, Case 2 waters. (The bio-optical algorithm is designed for Case 1 waters, and would overestimate Chl-*a* if applied to Case 2 waters not identified as such.) For each of these products, the data are combined to generate daily, monthly, seasonal, and annual composites (the level-3 products), along with the corresponding statistics (mean values, standard deviation, number of data points). The list of level-2 products now contains the aerosol optical thickness and Ångstrøm exponent, and the Case 1/Case 2 water flag, in addition to the "historical" parameters.

Availability of the New Data Set

The new data set presented here will be publicly available soon (http://www.rsmas.miami.edu/groups/rrsl/lpcm-seawifs-CZCS). It comprises 2052 daily composites for 12 products, i.e., Chl-*a*, $\tau_a(670)$, $L_a(670)$ and $L_a(550)$, the Ångstrøm exponent, the normalized water-leaving radiances at 440, 520 and 550 nm, the Case 1/Case 2 water flag, and the geometry of observation at each pixel (Sun and sensor zenith angles, and the relative azimuth between the Sun and sensor half vertical planes). These composites are in the form of global maps of 1024 lines per 2048 columns, regularly spaced in latitude and longitude, so that the resolution at the equator is approximately 18 km x 18 km. Monthly, quarterly, and annual composites as well are available, either for the different years of the CZCS life, or in the form of climatologies for which data have been pooled together for years 1979 to 1981, or for years 1979 to 1986. In the near future, this data set will be complemented by the same quantities as derived from the SeaWiFS mission (September 1997–present).

Ongoing and Future Activities

The CZCS experience taught us that a careful pre-launch characterization and calibration is an imperative minimum requirement for any ocean color sensor, yet definitely insufficient if not supplemented by other, post-launch, calibration paths. The first path consists of installing calibration devices aboard the satellite; and the second, called "vicarious" calibration, includes comparing the same parameters as measured in situ and as derived from the satellite observations. These two aspects are, in principle, satisfied for the new-generation sensors, thereby permitting an operational survey of the global phytoplankton biomass. It is believed that the revised CZCS archive presented here can be used as a reference for the bio-optical state of the global ocean in the 1980s; the baseline for the long-term studies mentioned in this article. An evaluation of the changes in the global algal biomass over the last 20 years is underway. This evaluation uses this renewed CZCS archive and the SeaWiFS observations, both processed using strictly the same algorithms (i.e., the algorithms outlined here).

Acknowledgments

The project was initiated in spring 1997, when D. Antoine brought and adapted the LPCM code to the CZCS processing environment developed at the Rosenstiel School of Marine and Atmospheric Sciences (RSMAS), following the invitation of the University of Miami. Various processing had been carried out before the final data set was produced, and the assistance of people at RSMAS has been essential in reaching this point, and is duly acknowledged. This work has been supported through the following grants and contracts: ONR N00014-99-0007 (to HRG), NASANAS5-31363 (to HRG) and NAS5-31362 (to RHE). D. Antoine received travel support from the Centre National de Recherche Scientifique. This work would as well not have been possible without the seminal work of G. C. Feldman, W. E. Esaias, and C. R. McClain in producing the initial CZCS archive that is maintained at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

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