MERIS potential for ocean colour studies in the open ocean

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Abstract. The interest of space observations of ocean colour for determining variations in phytoplankton distribution and for deriving primary production (via models) has been largely demonstrated by the Coastal Zone Color Scanner (CZCS) which operated from 1978 to 1986. The capabilities of this pioneer sensor, however, were limited both in spectral resolution and radiometric accuracy. The next generation of ocean colour sensors will benefit from major improvements. The Medium Resolution Imaging Spectrometer (MERIS), planned by the European Space Agency (ESA) for the Envisat platform, has been designed to measure radiances in 15 visible and infrared channels. Three infrared channels will allow aerosol characterization, and therefore accurate atmospheric corrections, to be performed for each pixel. For the retrieval of marine parameters, nine channels between 410 and 705 nm will be available (as opposed to only four with the CZCS). In coastal waters this should, in principle, allow a separate quantification of different substances (phytoplankton, mineral particles, yellow substance) to be performed. In open ocean waters optically dominated by phytoplankton and their associate detrital matter, the basic information (i.e. the concentration of phytoplanktonic pigments) will be retrieved with improved accuracy due to the increased radiometric performances of MERIS. The adoption of multi-wavelength algorithms could also lead to additional information concerning auxiliary pigments and taxonomic groups. Finally, MERIS will be one of the first sensors to allow measurements of Sun-induced chlorophyll \textit{a in vivo} fluorescence, which could provide a complementary approach for the assessment of phytoplankton abundance. The development of these next-generation algorithms, however, requires a number of fundamental studies.

1. Introduction

The capacity of satellites to provide synoptic information on phytoplankton distribution in the upper layer of the ocean for various applications has been largely demonstrated by the Coastal Zone Color Scanner (CZCS), launched by National Aeronautics and Space Administration (NASA) on the satellite Nimbus 7 and which operated from late 1978 to early 1986 (see, for example, the review by Abbott and

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Chelton (1991)). The first application of ocean colour data was to study the spatial/temporal evolution of phytoplankton distribution for ecological applications or to trace water circulation. Since then, ocean colour data analysis has also been focused on attempting to derive more elaborate information from these near-surface pigment fields. International programs such as the International Geosphere–Biosphere Program (IGBP) and the Joint Global Ocean Flux Study (JGOFS) have emphasized the importance of deriving near-surface pigment fields from ocean colour data, in particular (i) for initiating and validating numerical models of ecosystems and biogeochemical processes, (ii) for calculating primary production at regional to global scales, and (iii) when used in synergy with other remote sensing techniques (altimetry, scatterometry, etc.), for forcing circulation fields in upper ocean numerical models of biogeochemical processes (Yoder 1996). Furthermore, with the availability of the global CZCS archive (McClain et al. 1991), the observation scales could be extended from the mesoscale to the basin- or world-scale (Banse and English 1994, Sathyendranath et al. 1995, Antoine et al. 1996).

In recent years much emphasis has been placed on the role of the oceanic 'biological pump' in atmospheric CO₂ variations and the global carbon cycle. Evaluation and modelling of this biological pump requires knowledge of the spatial and temporal evolutions of marine primary production both at global and at regional scales. Large uncertainties remain, however, in the magnitude of primary production at these different scales. For instance, until recently, the commonly proposed values at the global scale, based on compilations of in situ carbon fixation, were in the range 20–50 GtC per year (see, for example, Berger (1989)). These estimates were recently refined using satellite ocean colour data combined with primary production models to allow maps of surface pigment concentration to be converted into maps of carbon fixation rate (e.g. Platt and Sathyendranath 1988, Morel 1991). ‘World maps’ of primary production were thus proposed, as derived from the CZCS archive (Antoine et al. 1996). Using CZCS data, regional maps or estimates of primary production were also derived for specific areas, such as the Mauritanian upwelling area (Bricaud et al. 1987), the North Atlantic (Sathyendranath et al. 1991, 1995) and the Western (Morel and André 1991) and Eastern (Antoine et al. 1995) Mediterranean Basins.

Analysis of CZCS images has also demonstrated that ocean colour is a powerful tool to characterize dynamical features (eddies, meanders, plumes, etc.) and to study the variability of ocean circulation patterns, at mesoscale or large-scale (see, for example, Barale and Trees (1987); see also the reviews by Abbott and Chelton (1991) and by various authors cited in the work of Barale and Schlittenhardt (1993)). The first studies were essentially descriptive, mostly aimed at describing dynamic structures and their temporal evolution via phytoplankton distribution. Over the last ten years, however, the use of ocean colour data has greatly evolved, in conjunction with the development of coupled physical–biological models of increasing complexity, generally aimed at describing the biological response of the ocean to physical forcings and evaluating the associated biogeochemical fluxes (e.g. Bissett et al. 1994, Glover et al. 1994, Pribble et al. 1994). In parallel with such models, data assimilation techniques have also been developed, with the aim of constraining these models to remain realistic (e.g. Prunet et al. 1996a, b). Finally, ocean colour data have also been used to predict, via the pigment concentration, the vertical profile of the heating rate within the upper layer of the ocean (Morel and Antoine 1994).

For these various applications the capabilities of the CZCS were unfortunately
limited, both in spectral coverage (only three visible channels could be used for marine information) and radiometric accuracy (with a signal coding over 8 bits). Furthermore, atmospheric corrections, which have a critical importance since typically 90% of the signal reaching the sensor originates from the atmosphere, were mostly based on empirical (iterative) schemes (Bricaud and Morel 1987, Gordon et al. 1988), because no channels were available to estimate the contribution of aerosol scattering and its spectral dependence independently. As a consequence, under typical conditions, the satellite-derived pigment concentration values \( C(\text{Chl}) \) were within \( \pm 0.3 \log_{10} \text{Chl} \) when using the 443 to 550 nm reflectance ratio (Gordon et al. 1983). The accuracy was further degraded at high \( C(\text{Chl}) \) concentrations, because of the low sensitivity of the blue (443 nm) channel and the constraint of resorting to a less efficient reflectance ratio (520 to 550 nm). Further, the CZCS, initially scheduled for a lifetime of only one year, faced severe sensitivity degradation problems, which greatly impaired the quality of the retrieved pigment values, particularly during its last years of operation (1983–1986). This required the development of ‘vicarious’ correction schemes (Evans and Gordon 1994). Finally, it must be remembered that the CZCS experiment was planned as a proof-of-concept operation and as such did not allow the sensor to be operated in a continuous mode, so that global coverage of the oceans could not be ensured.

The concept and usefulness of such an experiment being amply proven, permanent acquisition of data along the daylight part of the orbit has been selected for present and future ocean colour sensors. Relying on the experience drawn from the CZCS, this new generation of instruments (Modular Optoelectronic Scanner (MOS), Ocean Color and Thermal Scanner (OCTS) and Polarization and Directionality of Earth Reflectances (POLDER) in 1996, Sea-viewing Wide Field-of-view Sensor (SeaWiFS) in 1997, Moderate Resolution Imaging Spectrometer (MODIS) in 1999, Medium Resolution Imaging Spectrometer (MERIS) and Global Imager (GLI) in 2000) benefits, or will benefit, from major instrumental improvements such as an increased radiometric accuracy and sensitivity, the availability of infrared channels to estimate the aerosol thickness and its spectral dependence, and better spectral information in the visible. Moreover the sensors to be deployed in the late 1990s (MERIS, MODIS and GLI) will have two specific additional features. (i) Being equipped with numerous, programmable, channels, they will provide the most detailed spectral information (for MERIS, radiances will be measured in 15 channels over the visible–infrared domain (see Rast and Bezy, this issue). (ii) They will provide measurements of the Sun-induced chlorophyll \( a \) in vivo fluorescence band around 680 nm, which will constitute a complementary approach to the classical assessment of phytoplankton abundance.

Together with the improvements specifically concerning marine information, the possibility to perform a more accurate determination of aerosol properties (and consequently a more accurate retrieval of water-leaving radiances) using a scheme adapted from that developed for SeaWiFS by Gordon and Wang (1994) will produce major benefits (Antoine and Morel, this issue). In the following we discuss only those aspects concerning the interpretation of marine signals.

2. Ocean colour signal inversion

Once atmospheric corrections are performed, MERIS will provide water-leaving radiances in nine visible channels, provisionally at 412.5, 442.5, 490, 510, 560, 620, 665, 681.25 and 705 nm. This will yield considerably more detailed information than
that provided by the CZCS (where marine radiances were available at only 443, 520, 550 and 670 nm), or even, for instance, SeaWiFS (with visible channels at 412, 443, 490, 510, 555 and 670 nm). It is expected that the main benefit of this increased spectral information will concern Case II waters (essentially coastal areas). In these areas, different types of substances (phytoplankton, mineral particles, yellow substance) coexist without being correlated in most cases. The possibility of quantifying the concentrations of these substances has prompted several studies over recent years, with various approaches leading to the development of inverse modelling techniques (Doerffer and Fischer 1994, Schiller and Doerffer, this issue) or multiple-wavelength algorithms (Carder et al. 1991, Tassan 1994, Moore et al., this issue).

In the open ocean (essentially ‘Case I’ waters), the problem is somewhat simpler, as the predominant role in determining the optical properties is played by phytoplankton and its associated biogenous (dissolved and particulate) by-products. Because phytoplankton cells absorb primarily blue radiation (with a maximum around 435–445 nm), and only weakly green radiation, the quantitative retrieval of algal biomass from CZCS data has been based mostly on the empirical (statistical) relationship linking the variations of the blue-to-green reflectance ratio (e.g. \( R_{443}/R_{560} \)) to those of chlorophyll \( a \) concentration (see figure 1). It is worth noting that the blue absorption results not only from the chlorophylls (\( a, b, c \)) themselves, but also from various carotenoids always associated with chlorophyll \( a \). The common method, however, is to quantify the algal biomass in terms of the chlorophyll \( a \) concentration.

Different combinations of band ratios have been proposed to handle specific environmental cases (e.g. Aiken et al. 1995), also using empirical approaches. Such ‘CZCS-type’ algorithms will be applicable to MERIS as well; the main improvement, in comparison with the CZCS, will lie therefore in the increased radiometric accuracy,

![Figure 1. Variations of reflectance ratios versus the chlorophyll \( a \) concentration, Chl (in mg m\(^{-3}\)), as derived from the model of Morel (1988). The steps on the curves correspond to the pigment classes to be detected, i.e. ten classes per decade (adapted from the LPCM/ACRI contract report to ESA (1991)).](image-url)
which will result in increased accuracy of pigment retrieval. Thus, the requirements of $5 \times 10^{-4}$ for the NEAR (noise equivalent spectral reflectances at sea level) set for MERIS should allow the instrument to detect ten classes of pigment concentration per decade (with a 26% increase from one class to another), except over restricted portions of scenes (LPCM/ACRI 1991). As shown in figure 1, the $R_{443}/R_{560}$ ratio spans the widest range and is therefore the most sensitive to variations in algal pigment concentration.

Independent of other sources of uncertainty (atmospheric corrections, radiometric noise), the ability of CZCS-type (i.e. purely empirical) algorithms to retrieve the water pigment content is necessarily limited by the bio-optical variability of waters, even in the open ocean. Spectral variations of the diffuse reflectance at null depth, $R(0^-)$, are actually ruled by the bulk absorption ($a$) and backscattering ($b_b$) coefficients for the water body:

$$R(0^-) = f b_b/a$$

(1)

where $f$ is a factor dependent on illumination conditions (Kirk 1984, Gordon 1989) and water content and varies between 0.3 and 0.5 (Morel and Gentili 1991). The $a$ and $b_b$ coefficients (inherent optical properties (IOPs) (Preisendorfer 1961)) are the sums of the contributions of the diverse substances. For Case I waters these are pure seawater, living phytoplankton, non-algal particulate matter (NAP) (including various detritus as well as heterotrophic bacteria) and endogenous yellow substance (coloured dissolved organic matter (DOM) resulting from biological activity):

$$a = a_w + [Chl] a^*_{\phi} + [NAP] a^*_{NAP} + [Y] a_Y$$

(2)

$$b_b = b_{bw} + [Chl] b^*_{\phi} + [NAP] b^*_{NAP}$$

(3)

where the above substances are represented, respectively, by the subscripts w, $\phi$, NAP and Y, the terms in brackets are their respective concentrations, and the starred coefficients are the substance-specific optical coefficients, which are known to be variable (the wavelength $\lambda$ is omitted in each term for the sake of simplicity). Therefore any progress with respect to empirical approaches depends on the development of ‘analytical’ or ‘semi-analytical’ algorithms, i.e. based on bio-optical models which relate the $b_b/a$ ratio to the substance concentrations and take into account variations in the IOPs.

Semi-analytical algorithms generally refer to simplified bio-optical models (i.e. simplified versions of equations (2) and (3)), implicitly admitting natural covariation between the concentrations of some substances (e.g. Gordon et al. 1988, Morel 1988, Carder et al. 1991, Lee et al. 1994). Such models result in nonlinear relationships between reflectance ratios and chlorophyll $a$ concentration, which are more representative of reality than simple regression lines. These relationships can be fitted to polynomials for practical use (figure 2). Note that the existing models differ notably when the entire range of concentrations is considered, as a result of differing parameterizations of the variations in absorption coefficient (or alternatively, diffuse attenuation coefficient) and backscattering coefficient with chlorophyll $a$ concentration. This emphasizes the need for further fundamental work at sea and in the laboratory for validating such semi-analytical algorithms.

Entirely analytical algorithms, in which the improved spectral resolution provided by MERIS could find optical use, still remain to be developed. One of the points to be studied is whether detailed spectral information would indeed allow some
Figure 2. Variations of blue-to-green ratio, $R_{443}/R_{560}$, versus chlorophyll $a$ concentration, $Chl$ (in mg m$^{-3}$), for two different bio-optical models: Morel 1988 (M88) and Gordon et al. 1988 (G88), fitted to polynomial functions of order three. Note that recent models account in particular for the new findings concerning absorption coefficients of pure seawater (Pope and Fry 1997).

phytoplanktonic groups to be distinguished. The inherent limitation of CZCS-type (or even semi-analytical) algorithms is that they can only retrieve a single parameter (chlorophyll $a$ concentration), while phytoplanktonic absorption in the various channels (and especially at 443 nm) originates from different groups of pigments, namely chlorophylls $a$, $b$, $c$ and the various carotenoids (upper panel of figure 3). These groups of pigments, in highly variable concentrations according to species and physiological or photoadaptive state of cells (see example in figure 4), are (along with the packaging effect) the main source of variability in the absorption properties of natural phytoplanktonic populations (see lower panel of figure 3 and, for example, Mitchell and Kiefier (1988), Hoepffner and Sathyendranath (1992), Sosik and Mitchell (1995), Bricaud et al. (1995) and Cleveland (1995)). For instance, dinoflagellates contain a carotenoid (peridinin) absorbing mainly in the domain 490–530 nm and responsible for the reddish discoloration of waters, known as 'red tide' (e.g. Gieskes and Kraay 1986). Red tides (which occur mostly in coastal areas, but sometimes also in Case I waters) can also be produced by cryptophytes, which contain phycobilin pigments, absorbing in the domain 500–600 nm (i.e. the domain of supposed 'minimum absorption' for phytoplankton). Absorption in the green channels is also strongly increased in the presence of the phycobiliprotein-containing cyanobacteria, which may result in a conspicuous depression on downwelling irradiance spectra (figure 5). Finally,
cocolithophorids are also well known for their particular optical properties, not because of specific pigmentation but because they produce detached calcite plates which increase the scattering coefficient of the water body and therefore its reflectance to levels as high as 15%, as observed by Holligan et al. (1983). Algorithms simply based on reflectance ratios become inoperative in such cases.

Specific reflectance or water-leaving radiance models have already been developed
for dinoflagellate blooms (Carder and Steward 1985, Balch et al. 1989) and coccolithophore blooms (Balch et al. 1989, Ackleson et al. 1994). Optimization techniques have been proposed to retrieve in-water parameters from model inversions, using the whole spectral information instead of simple reflectance ratios. Applying another technique (factor analysis) to a set of water-leaving radiance spectra measured in coastal waters from the New York Bight region, Sathyendranath et al. (1994) showed that with the SeaWiFS channels, it could be possible to distinguish between phycoerythrin and chlorophyll pigments. Therefore, the availability of still more numerous visible channels on MERIS suggests the potential for the identification of specific algal groups. Analysing particulate absorption spectra from open ocean waters, Garver et al. (1994) found nevertheless that more than 99% of the variance in their dataset was associated with chlorophyll, and emphasized the difficulty of developing robust algorithms for species identification. It is expected that such identification will in any case require a conspicuous pigment signature from a particular group (see Morel 1997).

3. Sun-induced chlorophyll a fluorescence

The presence of the Sun-induced chlorophyll a fluorescence band in the water-leaving radiance spectra of phytoplankton-rich waters led Neville and Gower (1977), more than twenty years ago, to propose a quantification of the pigment concentration via the height of this band with respect to a 'baseline'. The main advantage of this method is its specificity, because the fluorescence band, contrary to the spectral variations of reflectance, is not affected by the presence of particulate substances other than phytoplankton. Therefore such a method could prove to be a valuable tool, especially in Case II waters. Even in oceanic Case I waters with moderate or high phytoplankton concentrations, it may represent a useful alternative to the use of CZCS-type or advanced reflectance ratio algorithms. However, limitations in applications of this technique do exist, and result mainly from absorption by water.
Figure 5. Upper panel. Example of absorption spectrum measured off Mauritania (EUMELI 4 cruise, June 1992), in waters dominated by the cyanobacterium *Synechococcus*. The arrow indicates the absorption band of phycoerythrin characteristic of this group. Lower panel. Downwelling irradiance spectra measured at the same site. Note the marked depression around 550 nm, induced by the presence of phycoerythrin (see also reflectance spectra in Morel 1997).

itself, from the perturbation of the fluorescence signal by the absorption band of atmospheric oxygen, and from the variability of the fluorescence emission per unit of chlorophyll *a* concentration (Babin *et al.* 1996). A description of the capabilities and limitations of this approach is provided by Gower *et al.* (this issue).

4. Conclusions

MERIS will acquire data in a continuous way from pole to pole (actually when the zenith Sun angle is less than 80°), and will thus fulfil the requirements of a global and permanent coverage of the world’s oceans, as recommended by JGOFS (Yoder 1996). The previously developed ocean colour techniques (inherited from CZCS, SeaWiFS and OCTS) will be operated on a routine basis. Thanks to an international coordination resulting in the adoption of a series of common wavelengths, the compatibility of algorithms will be ensured, leading to comparable basic products.

The MERIS sensor will also provide the potential for a more accurate retrieval
of optically active water constituents, because of (i) increased radiometric performances, (ii) improved atmospheric corrections, and (iii) more detailed spectral information on marine water-leaving radiances (including fluorescence). In conjunction with these increased performances, some phenomena previously neglected with the CZCS will become of critical importance, and will have to be taken into account for an optimized retrieval of pigment fields. The phenomena to be accurately modelled concern both atmospheric and marine optics. Preserving the sensitivity of the instrument, i.e. propagating radiometric accuracy from satellite level to the determination of water-leaving radiances, requires a very precise atmospheric correction. A scheme for a 'second generation' correction procedure, much more complex than that used with CZCS, has been developed for SeaWiFS (Gordon and Wang 1994) and improved for MERIS. It accounts for a variety of aerosols and for the effects of the interface (sea surface roughness, white caps) in modifying radiative transfer in the atmosphere and then the atmospheric path radiance (Antoine and Morel, this issue). In the domain of marine optics, the non-isotropic character of the upward radiance field, previously disregarded, has been evidenced from Monte Carlo computations (Morel and Gentili 1993) and experimentally confirmed (Morel et al. 1995); it will therefore have to be accounted for. Because the anisotropy factor \( Q \) varies with pigment concentration in the water column, it will be necessary to incorporate iterative procedures in the data processing sequence in order to derive a preliminary pigment index before proceeding further (Morel and Gentili 1996). In addition, fundamental work in developing analytical bio-optical models able to account for the variability in the relevant specific coefficients and their relationship to environmental factors is still needed. Establishing 'advanced' algorithms applicable to MERIS spectral data and deriving specific products implies, as a prerequisite, such fundamental research.

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References


Barale, V., and Trees, C. C., 1987, Spatial variability of the ocean colour field in CZCS imagery. Advances in Space Research, 7, (2)95–(2)100.


MOREL, A., 1997, Consequences of a synecochoccus bloom upon the optical properties of oceanic (Case 1) waters. Limnology and Oceanography, 42, 1746–1754.


PRUNET, P., MINSTER, J. F., ECHEVIN, V., and DADOU, I., 1996b, Assimilation of surface data in a one-dimensional physical-biogeochemical model of the surface ocean. (2) Adjusting a simple trophic model to chlorophyll, temperature, nitrate and pCO₂ data. Global Biogeochemical Cycles, 10, 139–158.


