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# Algal biomass and sea surface temperature in the Mediterranean Basin Intercomparison of data from various satellite sensors, and implications for primary production estimates

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## Abstract

The Mediterranean Basin, subject both to climate changes and to increasing anthropogenic inputs, is an appropriate test site for observing the evolution of algal biomass and primary production on a long-term basis. With this aim, it is first necessary to study the consistency of the various sets of satellite data as provided by the space agencies, and to compare them to in situ available data. Pixel-by-pixel comparisons of the Level 3 chlorophyll products derived from the ocean color and temperature scanner (OCTS; Version 4, August 1999), polarization and directionality of earth reflectances (POLDER; reprocessing no. 2, July 2000), and the sea-viewing wide field-of-view sensor (SeaWiFS; reprocessing no. 3, May 2000) reveal a reasonably good agreement. Discrepancies, however, appear particularly in oligotrophic areas: weekly (or 10-day) means for OCTS and POLDER (which were operating simultaneously) differ in these areas by 30–70% on average, and OCTS and SeaWiFS weekly means, at 1-year distance, reveal differences by up to a factor of 2. Comparisons with measurements at sea, performed during various cruises, show that all these sensors tend to overestimate chlorophyll concentrations in oligotrophic waters. A "regional algorithm" is proposed to reduce this bias. The impact of using the various datasets for chlorophyll concentration, and for seawater temperature (Reynolds sea surface temperature [SST] analyses, Levitus climatological profiles) for primary production computations is shown. Because they are simultaneous to ocean color data, Reynolds analyses appear to be the most appropriate inputs to such computations. They have, however, to be combined with climatological vertical profiles of seawater temperature, so as to provide representative values for the productive layer. © 2002 Elsevier Science Inc. All rights reserved.

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## 1. Introduction

The availability of coastal zone color scanner (CZCS) ocean color data, from 1978 to 1986, allowed a considerable progress in the knowledge of spatial and temporal variations in algal biomass in various regions of the world ocean, and also allowed oceanic primary production to be derived, by operating light–photosynthesis models (e.g., Antoine, André, & Morel, 1996; Behrenfeld & Falkowski, 1997; Platt & Sathyendranath, 1988). These data provided an unprecedented view of the seasonal variations in algal biomass and primary production, and of the corresponding carbon fluxes, including for the Mediterranean Basin (Antoine, Morel, & André, 1995; Morel & André, 1991). Because of the limitations of the CZCS sensor (drift in calibration, incomplete spatial and temporal coverage), however, no reliable information on the interannual variability of algal biomass and primary production could be derived, and only climatological products were provided. The recent availability of data from new ocean color sensors (ocean color and temperature scanner [OCTS], polarization and directionality of earth reflectances [POLDER]-I, sea-viewing wide field-of-view sensor [SeaWiFS]) now allows such studies to be pursued.

With accurate calibration controls and improved algorithms, estimates of algal biomass provided by these new sensors are expected a priori to be more accurate than CZCS estimates. However, there exist significant differences in instrumental concepts, calibration procedures, and algorithms from one sensor to the other, which makes it necessary, as a first step, to intercompare and check the consistency of the various data. In addition, datasets concerning sea surface temperature (SST) and coinciding with the periods of ocean color observations (OCTS measurements and

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"Reynolds analyses," see later) are now available, and can be used as input parameters in primary production models. The validity and consistency of these datasets has also to be checked. Their use may also require some adjustments, as the pertinent parameter in the computation of primary production is the vertical profile of temperature, or at least, the average value within the layer where photosynthesis occurs.

The Mediterranean Basin is a semienclosed sea that, in spite of its generally oligotrophic character, displays marked seasonal variations in some areas (e.g., in the northwestern part of the Basin, where algal blooms develop after the winter deep convection). Due to favorable conditions of observation (low cloudiness, dominance of Case 1 waters), this Basin is an appropriate test site for comparing the various sets of satellite data, and then for observing the evolution of algal biomass and primary production as derived from these data. Because this area has been subject for several decades not only to climatic changes but also to increasing human activities, with already detectable impacts upon the nutrient concentrations in the Basin (Béthoux & Gentili, 1999; Béthoux et al., 1998), monitoring the evolution of biomass and primary production on a long-term basis could contribute to detection of possible modifications in the biogeochemical equilibrium of the Basin.

The first aim of this paper is therefore to compare and examine the consistency of (i) the chlorophyll estimates from the various ocean color sensors and (ii) the various datasets concerning SST. The quality of the chlorophyll estimates will also be checked by comparison with in situ measurements. Then the sensitivity of the primary production estimates to these various datasets, and the way these datasets could be used in the primary production model, will be presented. It is emphasized here that a detailed analysis of the sources of the intersensor differences, which would imply an intercomparison of the satellite signals at the different processing stages (at the top of atmosphere, at the sea surface, etc.) and for individual (Level 2) images delivered simultaneously, is out of the scope of this paper. This is a very complex task, which is mainly conducted, at a global scale, within the Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) program (see, e.g., Fargion, McClain, Fukushima, Nicolas, & Barnes, 1999).

Instead, this study has been focused on the comparison of chlorophyll (and when available, SST) Level 3 products, as they are provided by the space agencies. Their compatibility with in situ measurements for a specific area, and the impact of observed differences upon primary production estimates, are also studied. This will determine the choice of methods and data for studying the seasonal and interannual variations of algal biomass and primary production in the Mediterranean Basin (Bosc et al., in preparation). For both studies, and similarly to Antoine et al. (1995) and Morel and André (1991) (with some modifications and new subdivisions), the Mediterranean Sea was schematically divided into 13 provinces in order to account for regional peculiarities (Fig. 1).

## 2. Data and methods

### 2.1. Ocean color data

The data used for the present work were delivered by three ocean color sensors: the OCTS and POLDER-I sensors, which were both embarked on the ADEOS platform operated by NASDA, and provided data from November 1, 1996 to June 30, 1997, and SeaWiFS launched by NASA aboard Seastar and which has provided data since September 1997. Detailed information about the characteristics of these sensors can be found in Saitoh (1995) for OCTS,

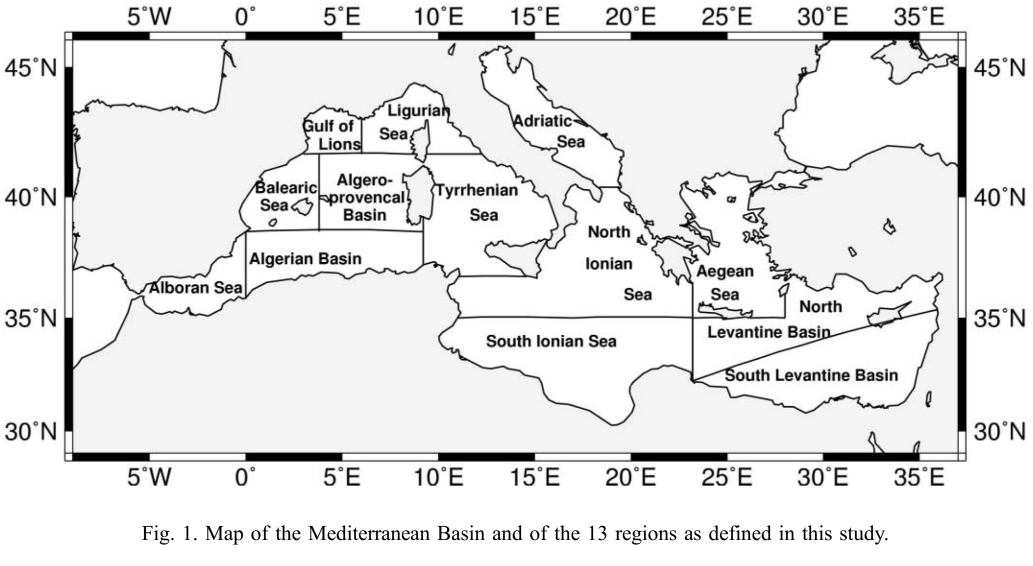

Fig. 1. Map of the Mediterranean Basin and of the 13 regions as defined in this study.

Deschamps et al. (1994) for POLDER, and Hooker, Esaias, Feldman, Gregg, and McClain (1992) for SeaWiFS.

The product versions used in this study were the most recent available at the time of this study: "Version 4" for OCTS, made available in April 1999, reprocessing no. 3 (also commonly called "Version 4") for SeaWiFS, available in June 2000, and reprocessing no. 2 for POLDER-I, available in July 2000. Information concerning the atmospheric and marine algorithms used for the three sensors is given in Appendix A. The products used in the present study are chlorophyll (Chl) concentrations, spatially and temporally averaged (Level 3 products) and mapped onto a uniform latitude/longitude grid. In these products, pixels correspond to bins having a size of $9 \times 9$ km$^2$ (at the equator) for OCTS and SeaWiFS, and are those at the original resolution (approximately $6.2 \times 6.2$ km$^2$) for POLDER. The available products are monthly averages for the three sensors, weekly averages for OCTS, 8-day averages for SeaWiFS, and 10-day averages for POLDER (averaging procedures are different for the three sensors; see Appendix A). The monthly time scale is generally too large for a proper observation of some biological events such as, e.g., phytoplankton blooms, and a time scale of 7–10 days is more adapted to the observation of such phenomena. In addition, primary production is computed from algal biomass using nonlinear relationships (see below), so that primary production estimates may be affected by significant errors when derived from monthly composites of algal biomass (Ras, 1999). Ideally, primary production should be obtained by converting daily averages of vegetal biomass into primary production, and then averaging over time. Because weekly biomass data are usually less affected by noise than daily data, however, and because daily primary production computations can be performed only in clear-sky conditions (with a resulting bias on the averaged values), the weekly scale is believed to be the best compromise. Weekly to 10-day averages may also be incomplete because of cloud cover. In this case, gaps have been filled with monthly averages for further computations (spatially averaged chlorophyll concentration or primary production).

In addition to data from the new ocean color sensors, those provided by the CZCS, which was operated from 1978 to 1986 on the Nimbus-7 satellite, were also used for comparison. Two sets of climatological monthly averages (merging data from different years) were considered: (i) those extracted from the global NASA archive ("standard processing," for the 1978–1981 period) and (ii) the monthly averages computed by Antoine et al. (1995) and Morel and André (1991) (over the 1978–1983 period), from a pixel-by-pixel processing optimized for the Mediterranean Basin.

The data for the studied area were extracted from the Level 3 products using the SeaDAS software (Version 3.3) provided by NASA. They were arranged as $2048 \times 4096$ pixel arrays. POLDER data, for which the spatial resolution is different from that of SeaWiFS and OCTS "bins," were projected on the same grid (it has been checked that this procedure introduces some scatter, but no bias, in the pixel-by-pixel comparison). Then "masks" corresponding to the whole Mediterranean Basin (with the exception of the Black Sea, where "Case 2" waters, influenced by terrigenous substances, are present over large areas) or to one of its provinces, were applied. Finally, the chlorophyll concentrations were used in two ways: (i) They were averaged to derive the spatial means over the various regions. (ii) They were used, pixel by pixel, as input parameters in a light–photosynthesis model (see below) for estimating primary production for the corresponding pixel and the concerned period.

Note that in CZCS (standard processing), as well as in OCTS and SeaWiFS Level 3 products, there is no identification of turbid Case 2 waters. In contrast, these are identified in the CZCS pixel-by-pixel processing (Antoine et al., 1995) and in the POLDER processing. It is well known that in these waters the usual chlorophyll algorithms are generally not valid and lead to erroneous (overestimated) values of biomass and primary production. In the Mediterranean Basin, these waters are essentially located in some coastal areas (Northern Adriatic Sea, Kerkenna shelf, gulf of Gabes, etc.) and within the plumes of the major rivers (Rhône, Pô, Ebra, Nile, etc.). In spite of the reduced spatial coverage of these turbid waters, the high (artifactual) chlorophyll concentrations may influence significantly the spatial means, so that they have to be discarded from these means. With this aim, a simplified, constant "mask" for turbid Case 2 waters was defined. Monthly maps of underwater reflectances at 555 nm, $R(555)$, were derived from monthly normalized radiances measured by SeaWiFS, using a mean value of the $Q$ factor computed from a Monte Carlo model (Morel & Gentili, 1993), for the concerned period and area. On these maps, Case 2 waters were identified by discarding the pixels where $R(555)$ was $> 0.025$ (see Bricaud & Morel, 1987), and an "average mask" was selected. The corresponding area was 5% of the total area of the Basin, which is close to the estimate (4%) provided by Antoine et al. (1995). Although it is acknowledged that the extension of Case 2 waters may vary throughout the year, the use of such a constant mask (instead of a temporally variable mask) allows the spatial means of chlorophyll concentration (or primary production) to be computed over a fixed area, and therefore to be comparable from month to month. The same average mask was used for all sensors, so as to facilitate intersensor comparisons.

### 2.2. Seawater temperature data

Seawater temperature within the euphotic layer is an input parameter of the light–photosynthesis model because it drives some photosynthetic parameters in this model, such as the assimilation number, $P^{\mathrm{B}}{}_{\mathrm{max}}$ (see Morel, 1991). The primary production model was originally operated using the climatological dataset of Levitus (1982), which provides temperature profiles from 5 to 5500 m (with nine values between 5 and 200 m) at a 1° resolution in latitude/longitude; an "average temperature for the euphotic layer" was derived from the vertical profile for a given pixel and a given month.

Since then, other data have become available. A global SST dataset, which merges ship, buoy, and satellite (AVHRR) data, was produced as weekly averages from January 1982 to the present, on a 1° grid (Reynolds & Smith, 1995). Also, OCTS was the first sensor to provide, simultaneously to ocean color data, SST data. SST estimates were obtained using a multichannel algorithm combining the data from the three infrared bands, 8.25–8.80, 10.3–11.4, and 11.4–12.5 μm (Sakaida et al., 1998), and Level 3 products (weekly and monthly means, Version 4.1) were made available. Both Reynolds and OCTS datasets have the advantage, over the Levitus climatological temperatures, to be coincident with ocean color data. This advantage may be decisive as the interannual variability of SST can be noticeable in some regions of the world ocean (see, e.g., Marullo, Santoleri, Malanotte-Rizzoli, & Bergamasco, 1999 for the Mediterranean Basin). Another advantage is that their temporal resolution (weeks, or even days for OCTS) is higher than that of the Levitus dataset (month). Note that AVHRR data, available from the Pathfinder project, could also have been used in this study, as they offer a higher spatial resolution than Reynolds analyses (8 km). Reynolds analyses, however, present the advantage to be validated with in situ data and corrected for the skin effect.

The limitation common to these various datasets is that they are restricted to sea surface, and do not provide any information on the vertical profile of temperature. Consequently, an extrapolation procedure will have to be developed in order to obtain such information.

### 2.3. Computation of primary production

The model of Morel (1991), as adapted by Antoine and Morel (1996) for application to satellite data, was used. Briefly, this method allows the primary production within the lit (productive) upper layer to be computed from the surface chlorophyll concentration measured by an ocean color sensor. It is based on the general equation (Morel & Berthon, 1989):

$$P = (1/39)\mathrm{PAR}(0^{+})\mathrm{Chl}_{\mathrm{tot}}\Psi^{*}$$

where $P$ is the net carbon fixation within the productive layer (in g C m$^{-2}$) over a given time interval, PAR($0^{+}$) is the photosynthetically available radiant energy at the sea level per unit of surface (J m$^{-2}$) over the same time interval, $\mathrm{Chl}_{\mathrm{tot}}$ is the column-integrated chlorophyll content (g Chl m$^{-2}$), and $\Psi^{*}$ represents the cross section for photosynthesis per unit of areal chlorophyll (m$^{2}$ (g Chl)$^{-1}$). In practice, the computation uses look-up tables providing $\Psi^{*}$, with date, latitude, cloudiness index (as provided by the International Satellite Cloud Climatological Project [ISCCP], Rossow, Walker, Beuschel, & Roiter, 1996), surface chlorophyll concentration ($\mathrm{Chl}_{\mathrm{sat}}$), and the average temperature of the euphotic layer as input parameters. The chlorophyll content of the water column ($\mathrm{Chl}_{\mathrm{tot}}$) is computed from the satellite value ($\mathrm{Chl}_{\mathrm{sat}}$) for two different situations: uniform or stratified biomass vertical profiles; the choice of a stratified profile is made when the monthly climatological value of the mixed layer depth, as provided by Levitus (1982), is lower than that of the euphotic depth (derived from $\mathrm{Chl}_{\mathrm{sat}}$, Morel, 1988). Climatological monthly or weekly values of PAR($0^{+}$) can be obtained from the PAR values estimated for a clear sky from the "5S" (Tanré et al., 1990) or "6S" models, combined with the climatological averages of cloudiness provided by the ISCCP. Details of the methodology are given in Antoine et al. (1995). Note that monthly and 8-day averages of PAR($0^{+}$) derived from SeaWiFS

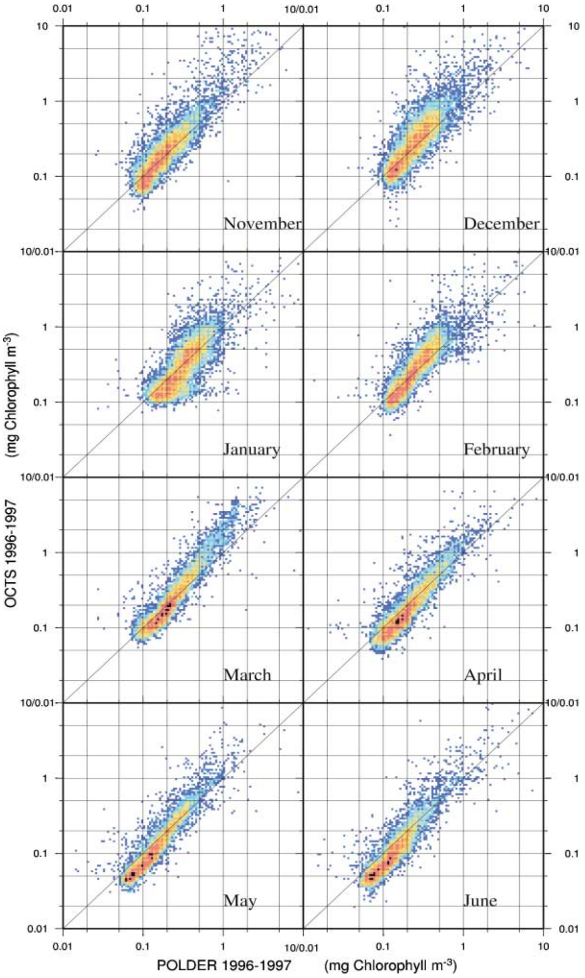

Fig. 2. Pixel-by-pixel comparison of monthly averaged chlorophyll concentrations estimated from OCTS (ordinate scale) and POLDER (abscissa scale) measurements over the Mediterranean Basin, from November 1996 to June 1997. The frequency of occurrence is increasing from dark blue to light blue, yellow, orange, red, and black.

measurements (using an algorithm proposed by Frouin et al., unpublished), and, thus, simultaneous to ocean color Level 3 products, have also become available recently, and can now be used instead of climatological values. In the present study, however, only climatological PAR values were used since PAR values are not available simultaneously to OCTS and POLDER measurements. For seawater temperature, different datasets, as described above, have been used for comparison.

## 3. Results and discussion

### *3.1. Estimates of algal biomass: pixel-by-pixel comparison of monthly means from the various sensors*

OCTS and POLDER are the only sensors to have been operated simultaneously (from November 1996 to June 1997), so that the chlorophyll estimates provided by these two sensors are directly comparable. The pixel-by-pixel comparison of the monthly averages over the Mediterranean Basin (Fig. 2) shows a relatively good agreement and a reduced scatter (although it is higher from November to January than for the following months). It reveals, however, systematic trends to chlorophyll values higher for POLDER than for OCTS in oligotrophic waters (0.05 to 0.2 mg $m^{-3}$) and higher for OCTS than for POLDER in mesotrophic or eutrophic waters (chl > 0.2 mg $m^{-3}$). Note that a pixel-by-pixel comparison (not shown) of OCTS Level 3 products in Versions 3 and 4 shows that the chlorophyll concentrations in Version 4 have been revised toward lower values, by up to a factor of 2 in oligotrophic waters.

The maps of the POLDER-to-OCTS monthly chlorophyll ratio show the geographical repartition of the divergences (Fig. 3). These maps show that this ratio varies mostly between 0.7 and 1.7. Consistently with Fig. 2, it decreases below 0.5 essentially in the most productive area, i.e., the Liguro-Provençal Basin during the spring bloom. In contrast, it becomes higher than 1.5 over large areas from April to June. It is worth noting that the optical thickness of aerosols at 865 nm, as determined by POLDER, is also increasing noticeably from March to June, with values > 0.35 over a large part of the Basin in June (not shown). This suggests that at least part of the divergences might originate from differences in atmospheric corrections.

A comparison of pixel-by-pixel monthly estimates can also be performed for OCTS and SeaWiFS (Fig. 4). Although such comparison is ambiguous because data are distant by one full year (e.g., November 1996 for OCTS compared to November 1997 for SeaWiFS), a relative interannual stability is expected at least for oligotrophic areas (say, Chl < 0.1 mg $m^{-3}$). It appears from Fig. 4 that in spite of some scatter, estimates are in rather good agreement for moderate and high chlorophyll concentrations (> 0.2 mg $m^{-3}$), with no systematic bias. Conversely, a bias is clearly apparent at low chlorophyll values, with SeaWiFS estimates higher than OCTS estimates by about a factor of 2. This observation is consistent with the comparisons with in situ measurements at the DYFAMED site (see later, Fig. 7a), which show that the lowest chlorophyll concentrations are overestimated by approximately a factor of 2 with OCTS, and a factor of 4 to 5 with SeaWiFS. The reason for this difference is difficult to ascertain. The errors in atmospheric corrections detected for SeaWiFS (by comparison between retrieved marine reflectances and those measured in situ, see later) are expected to exist also for OCTS, as the atmospheric

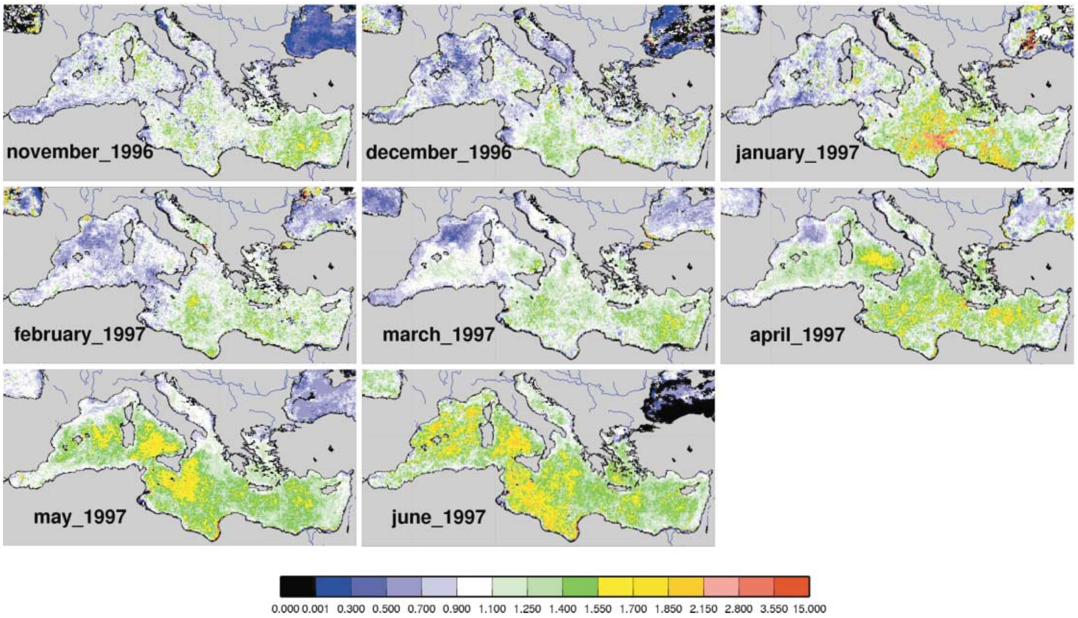

Fig. 3. Monthly maps of the POLDER-to-OCTS chlorophyll ratio. The values of this ratio are coded as indicated in the color scale.

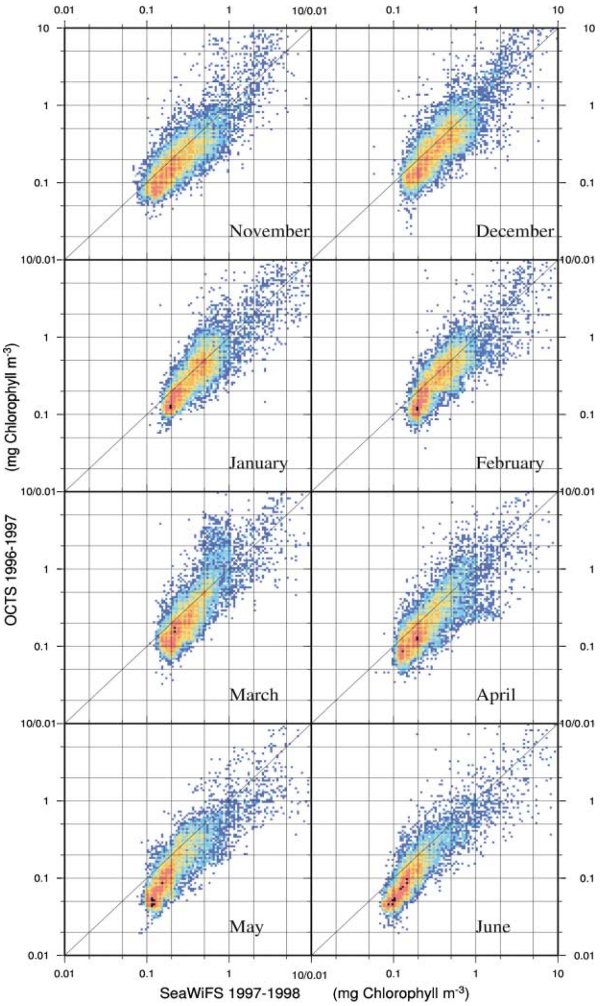

Fig. 4. Same as Fig. 2, for OCTS and SeaWiFS estimates of chlorophyll concentration. Here monthly averaged estimates are distant by 1 year (November 1996 to June 1997 for OCTS, November 1997 to June 1998 for SeaWiFS).

correction procedures are very similar (see Appendix A). Bio-optical algorithms, however, are different (Kawamura et al., 1998), which may explain part of the observed differences. In addition, various types of means have been used for computing the Level 3 products (see Appendix A), and the differences between these means increase with the variance inside the space-time bin (see Campbell, Blaisdell, & Darzi, 1995). Finally, the possible effects of dust events on the optical properties of surface waters may have been more intense in 1997–1998 than in 1996–1997 (see later and Fig. 8a, MINOS data).

### *3.2. Comparison of the spatial means from the various sensors*

Spatial means have often been used with the aim to study the temporal trends of algal biomass (or primary production) over given areas (Antoine et al, 1995; Morel & André, 1991). It is therefore useful to check whether the chlorophyll estimates from the various sensors, when spatially averaged, exhibit similar trends. With such an objective, it is first necessary to determine the most appropriate type of mean for spatial averaging.

Geometric means (obtained by averaging arithmetically the log-transformed data, and then inverting the transform) were used in some occasions for time averages (Chelton & Schlax, 1991) or spatial averages (Morel & André, 1991), following the arguments that pigment concentrations frequently obey a log-normal distribution (so that the geometric mean is equal to the median of the distribution) and are usually scaled according to a logarithmic scale. The use of geometric means, however, is known to minimize the influence of outliers, such as high concentrations occurring in restricted areas (upwellings, blooms, etc.), and geometric means are systematically lower than arithmetic means. This issue was extensively discussed by Campbell et al. (1995), who emphasized that the arithmetic mean should be chosen for most biogeochemical applications. For instance, if the arithmetic mean is computed over a given province by weighting the chlorophyll concentration of each pixel by its area, it will suffice to multiply this arithmetic mean by the area of the province to obtain the total biomass in the first meter of the surface layer in this province. Global biomass (in g Chl) or global primary production (in g C) can be obtained in the same way, using the arithmetic mean of $\mathrm{Chl_{tot}}$ (the chlorophyll content integrated over the productive layer, in g Chl $m^{-2}$), or that of primary production per unit of surface (in g C $m^{-2}$). The statistical problems related to sample size (see Campbell, 1995) do not occur, because the geographic provinces over which spatial means are computed are sufficiently large. Therefore, arithmetic means have been used hereafter, so as to determine whether the temporal evolutions of chlorophyll concentration (and therefore of the biogeochemical quantities mentioned above) are consistent from one sensor to the other.

The seasonal variations in the average algal biomass for the whole Mediterranean, as estimated by the various

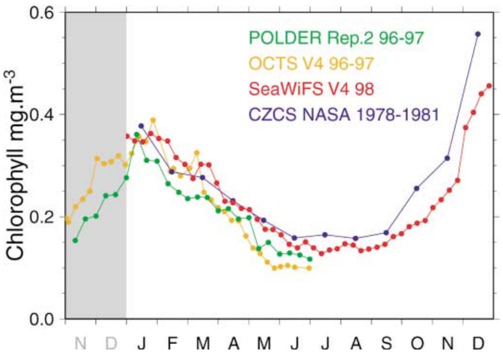

Fig. 5. Temporal (weekly for OCTS, 8-day for SeaWiFS, 10-day for POLDER, monthly for CZCS) means of chlorophyll concentration estimated from the various sensors, spatially averaged for the whole Mediterranean Basin.

sensors, are shown in Fig. 5. In spite of some divergences, the spatial means from the various sensors show similar trends and values over the whole Basin, with minimal values in summer (around 0.15 mg $m^{-3}$), and maximal values in winter (around 0.35 mg $m^{-3}$). It is recalled here that the observed differences originate not only from intersensor variations, but also (except for OCTS and POLDER) from possible interannual variations. For SeaWiFS data over the period September 1997–July 2000 (not shown), interannual variations reach 35% in December and 27% in June (Bosc et al., in preparation). When considering only the simultaneous OCTS and POLDER data, the weekly and 10-day means agree within less than 30% in December and within less than 20% in June. This demonstrates that the intersensor discrepancies, previously identified at the pixel level (up to a factor of 2, see, e.g., Figs. 2 and 3), tend to be greatly attenuated when computing spatial means, and therefore might have a relatively limited impact on the global (i.e., at the scale of the Basin) biomass evaluations, and ultimately carbon budgets.

At the regional scale, the estimates of the various sensors are also in rather good agreement, especially in the oligotrophic areas (Ionian Sea, Levantine Basin, Tyrrhenian Sea, etc.) where chlorophyll concentrations are low all around the year, with however a twofold decrease from winter to summer (Fig. 6). The mesotrophic areas (Liguro-Provençal Basin, gulf of Lions, Alboran Sea, etc.) reveal a much higher variability, which is expected since these areas are subject to interannual variations. When considering only OCTS and POLDER estimates, however, large discrepancies (up to 50%) appear in winter and spring, in all the regions of the western Basin (except in the Tyrrhenian Sea) and in the Adriatic Sea.

The seasonal cycles as observed here for all sensors and for the various zones are noticeably different from those obtained by Morel and André (1991) for the Western Basin and Antoine et al. (1995) for the Eastern Basin. In their specific processing, the CZCS calibration was tuned (i) for the Western Basin, by adjusting, for a selected area (the deep convection zone in the gulf of Lions), the chlorophyll concentrations in winter to the very low values observed in situ, and (ii) for the Eastern Basin, by adjusting the histograms of chlorophyll concentrations, over given areas, to those obtained for the year 1979 (not affected by calibration drifts). In those earlier studies, the seasonal cycle of chlorophyll reveals a marked minimum in winter for the NW Basin, and weak variations throughout the year in the SW Basin, Tyrrhenian Sea, Ionian Sea, and Levantine Basin (in other zones, seasonal variations are more erratic).

The CZCS data, when processed with the NASA standard procedure, reveal systematically higher chlorophyll values in December–January compared to other months. As this procedure did not include a correction for multiple scattering effects, these values might be suspected to be

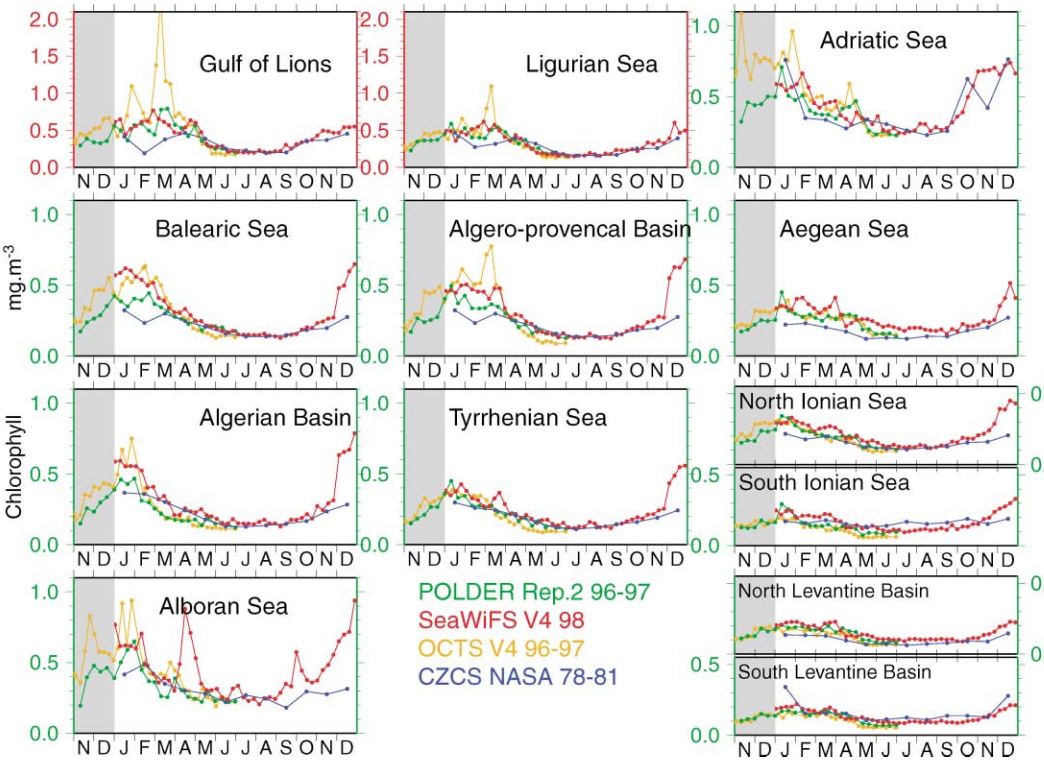

Fig. 6. Same as Fig. 5, for the 13 regions indicated in Fig. 1. Note that the ordinate scale is varying according to the regions.

artificially enhanced by such effects, particularly during winter because of the low sun angle (Antoine et al., 1995). It is worth noting, however, that the multiple scattering effects are taken into account for all the new sensors (e.g., Gordon & Wang, 1994). For these sensors, the seasonal cycles of chlorophyll concentration reveal a similar trend (decreasing values from winter to summer) for all zones. The only exception is the NW Basin (Gulf of Lions and Ligurian Sea) where the intense spring bloom, well-known and clearly apparent on in situ data (see later, Fig. 7a), induces a maximum in March.

In the other zones of the Western Basin, the scarcity of in situ chlorophyll measurements in winter unfortunately does not allow the reality of the observed seasonal cycles to be demonstrated. For the Eastern Basin, we have compared the chlorophyll concentrations measured in situ during the METEOR and MINOS cruises, in very close geographic positions, and at two different seasons (January 1995 and May–June 1996, respectively; HPLC data courtesy of H. Claustre and F. Vidussi). For five stations in the Ionian sea, chlorophyll values varied between 0.15 and 0.22 mg $m^{-3}$ in January, and were on average threefold lower in May–June. For two stations in the Levantine Basin, chlorophyll values varied between 0.10 and 0.15 mg $m^{-3}$ in January, and were about twice lower in May (CZCS values for these pixels, as provided by the Antoine et al. (1995) processing, are systematically lower than in situ chl concentrations in winter, and higher in summer). Although no match-up with satellite data can be performed, these in situ data suggest that the seasonal cycles shown by the new sensors are correct.

### *3.3. Comparison between satellite and in situ estimates of algal biomass*

Over the observation period of OCTS and POLDER (Nov. 1, 1996–June 30, 1997), the in situ data in coincidence with satellite observations are unfortunately very scarce over the Mediterranean Basin. A time series of various parameters, including HPLC chlorophyll concentrations, has however been obtained in the frame of the DYFAMED project (JGOFS-France program), where monthly measurements have been performed since 1991 at a permanent station located in the Liguro-Provençal Basin (28 miles off the French coast, along the Nice–Calvi transect). The variations with time of in situ chlorophyll concentrations, as compared to OCTS and POLDER estimates (weekly or 10-day averages) are displayed in Fig. 7a (left panel). The satellite estimates reproduce well the trends observed in situ, with low chlorophyll values ($<0.5$ mg $m^{-3}$) over the winter, a sudden increase induced by the spring bloom in March 1997, and then a slow return to an oligotrophic situation in summer. Both OCTS and POLDER estimates, however, are systematically higher than in situ values during oligotrophic periods (by up to a factor of 2).

For SeaWiFS, individual scenes delivered by HRPT stations at a 1-km resolution (Level 1 LAC data) are provided by NASA on request. The scenes corresponding to days where in situ measurements were performed at the DYFAMED site were processed using the NASA SeaDAS software, and the chlorophyll concentrations for the corresponding pixel were compared (Fig. 7a, right panel); the

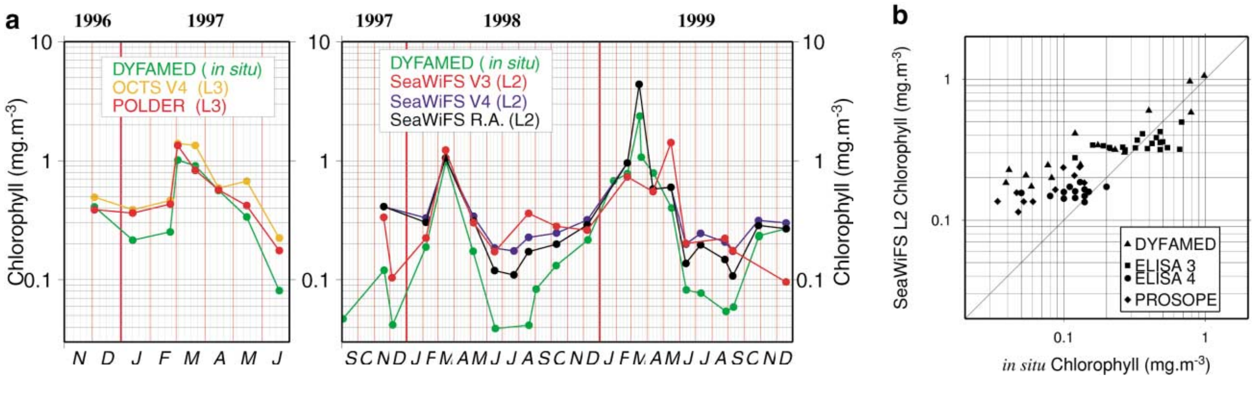

Fig. 7. (a) Left panel: Comparison of chlorophyll estimates provided by OCTS and POLDER with in situ HPLC measurements near the surface at the DYFAMED site (Liguro-Provençal Basin, 28 miles off the French coast; data courtesy of J. C. Marty), over the period November 1996 to June 1997. Satellite values are extracted from weekly (OCTS) or 10-day averaged (POLDER) Level 3 products. Right panel: Same as left panel, for the chlorophyll estimates provided by SeaWiFS, over the period November 1997 to December 1999. Here the SeaWiFS estimates are daily values at the resolution of 1 km (Level 1 LAC data, processed into Level 2 products using the NASA SeaDAS software). The values shown correspond to reprocessing no. 2 and no. 3 (also commonly called Version 3 [v3] and Version 4 [v4], respectively), and to the use of a "regional algorithm" (R. A., see text). (b) Comparison of the chlorophyll concentrations provided by SeaWiFS (Level 1 LAC data processed into Level 2 products, see (a)) with in situ measurements near the surface during various cruises: ELISA-3 and -4 cruises in the Algerian Basin (March and June–July 1998; data courtesy of I. Taupier-Letage), the PROSOPE cruise in the Western Basin and the Ionian Sea (September 1999; data courtesy of H. Claustre), and the Dyfamed time series (data shown in (a)). Chlorophyll concentrations were measured by HPLC during PROSOPE and DYFAMED, and by fluorometry during ELISA cruises.

values provided by SeaWiFS reprocessing no. 2 (or "Version 3") are also shown for comparison. As OCTS and POLDER estimates, SeaWiFS estimates reproduce well the temporal trends over the years 1998–1999, in particular the spring bloom, and its increase in intensity from 1998 to 1999 (note that with reprocessing no. 2, this increase was not apparent because the corresponding pixels were flagged on the March, 1999 image, due to irrealistic chlorophyll values). There is still, however, a systematic overestimation of chlorophyll values (by up to a factor 5) during oligotrophic periods. This overestimation appears both in reprocessing no. 2 and no. 3 (although it is slightly weaker in reprocessing no. 3).

The same observations can be made when comparing SeaWiFS estimates with in situ measurements performed during other cruises, in the Algerian Basin (ELISA-3 and -4 cruises in March and June–July 1998) and various parts of the Mediterranean (PROSOPE cruise, September 1999) (Fig. 7b). Whereas chlorophyll concentrations above ca. 0.3 mg $m^{-3}$ reveal no systematic bias when compared to SeaWiFS estimates, those below 0.2 mg $m^{-3}$ are systematically overestimated by SeaWiFS.

### 3.4. A tentative "regional algorithm" for the Mediterranean Basin

The above results suggest that the chlorophyll estimates provided by the three sensors for the Mediterranean Basin are realistic, except in the oligotrophic areas or periods (Chl < 0.15 mg $m^{-3}$) where they appear to be systematically overestimated, by a factor up to 5. During the PROSOPE cruise in September 1999, it was observed (Claustre et al., submitted) that the relationship between the blue-to-green reflectance ratios (as measured in situ) and chlorophyll concentrations departs very markedly from the "average" relationship, which is based on measurements in the world ocean (SeaBAM dataset), and was used to establish the SeaWiFS "OC4v4" algorithm (O'Reilly et al., 1998) (Fig. 8a). Similar observations of "anomalous" (lower than expected) blue-to-green ratios were made earlier for southeastern Mediterranean waters (Berman, Azov, & Townsend, 1984; Gitelson, Karnieli, Goldman, Yacobi, & Mayo, 1996). The empirical relationship established by Gitelson et al. (1996), for a similar range of chlorophyll concentrations (0.02–0.14 mg $m^{-3}$), but for a different area of the Basin (off the Israeli coast) and a different period (July 1992), is in excellent agreement with the measurements from the PROSOPE cruise (see Fig. 8a). A comparison between in situ measurements of chlorophyll concentration and SeaWiFS estimates (using the reflectance ratio $R(490)/R(555)$) in various parts of the Mediterranean (NW Basin, Ionian Sea, Sicily Channel) from 1998 to 2000 has also revealed a similar bias (D'Ortenzio, Santoleri, Marullo, Ragni, & Ribera d'Alcalà, 2001). Conversely, for waters with higher chlorophyll concentrations (ALMOFRONT-2 cruise in the area of the Almeria–Oran front in December 1997–January 1998), no systematic deviation from the OC4v4 algorithm appears (Fig. 8a). Note that the scatter of the points for this cruise is not surprising, considering the high spatial–

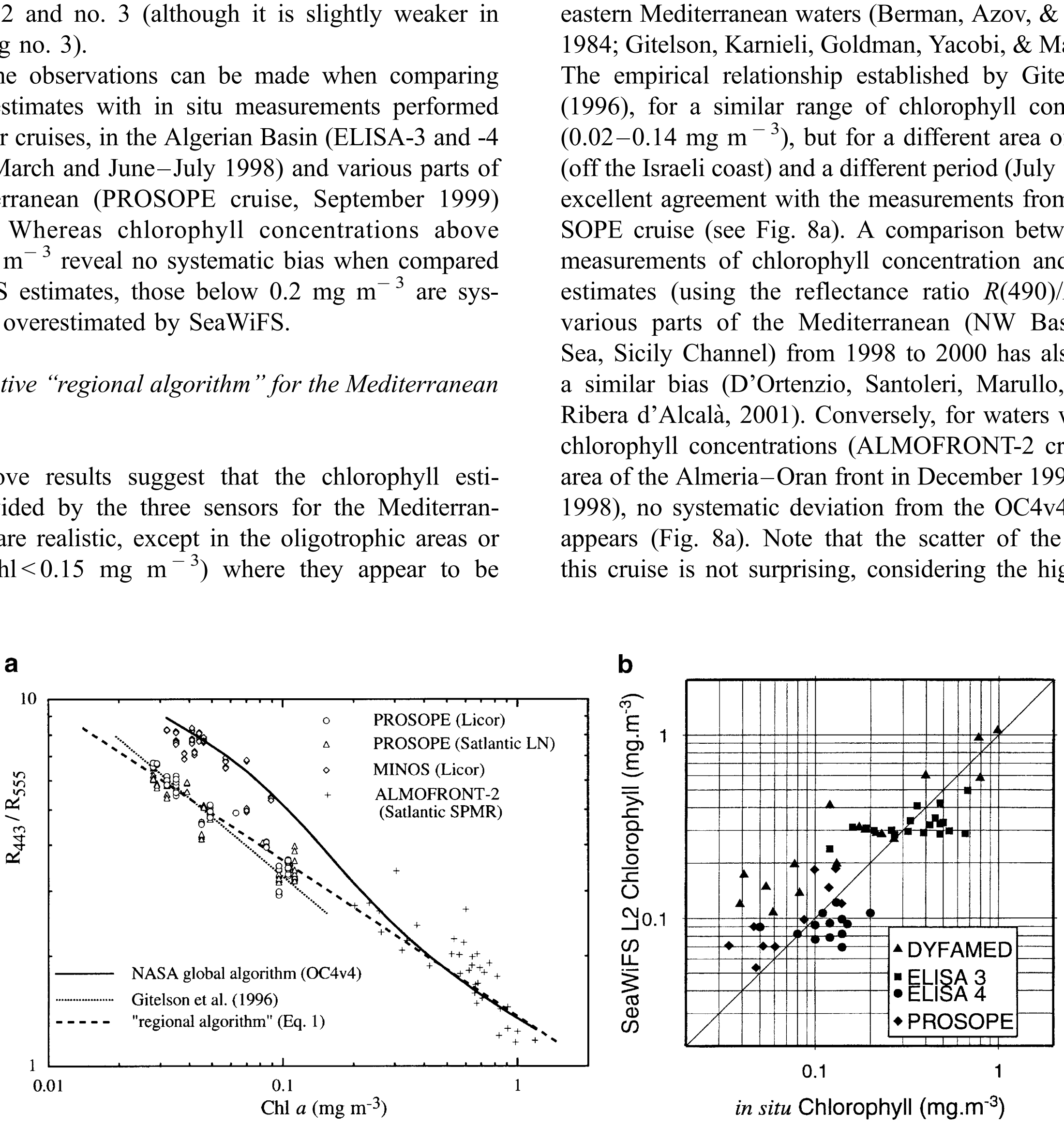

Fig. 8. (a) Variations of the blue-to-green reflectance ratios, $R(443)/R(555)$, measured at sea versus surface chlorophyll concentrations. Measurements were performed during various cruises: PROSOPE (September 1999) in the Western Mediterranean and the Ionian Sea, ALMOFRONT-2 (December 1997–January 1998) in the Alboran Sea, MINOS (May–June 1996) in the Western and Eastern Basins. Reflectance measurements were performed with different instruments: LICOR LI-1800 UW and Satlantic LocNess (LN) during PROSOPE (data courtesy of A. Morel and S. Hooker), Satlantic SPMR during ALMOFRONT-2 (data courtesy of F. Fell), LICOR LI-1800 UW during MINOS (data courtesy of S. Maritorena). Chlorophyll measurements were performed using the HPLC technique (data provided by H. Claustre, J. Ras, K. Oubelkheir, J. C. Marty, and F. Vidussi). The continuous line represents the global NASA algorithm ("OC4v4," see O'Reilly et al., 1998). The dashed line represents Eq. (1), obtained by linear regression on PROSOPE and ALMOFRONT-2 log-transformed data. The dotted line represents the empirical relationship proposed by Gitelson et al. (1996), derived from measurements off the Israeli coast. (b) Same as Fig. 7b, where SeaWiFS estimates have been corrected using Eq. (1) (see text).

temporal variability in this frontal area, and may probably be explained, at least partly, by small time lags between optical and HPLC measurements.

While Gitelson et al. (1996) attributed the bias observed in oligotrophic waters to the presence of small phytoplankton and particularly coccolithophorids, Claustre et al. (submitted) suggest that it could originate from peculiar optical properties (high blue-to-green absorption ratios combined with low blue-to-green backscattering ratios), resulting from the input into seawater of Saharan dust associated with episodic events. The present comparisons (Fig. 7a and b), as well as those made by D'Ortenzio et al. (2001) and Gitelson et al. (1996), suggest that this peculiarity could exist in many areas and subsist over long periods throughout the year. If originating from Saharan dust inputs, however, it is very likely not a continuous and constant effect. The frequency of dust events over the NW Basin has been found to be maximum in spring and autumn, and minimum in winter, although even in this period some strong events may occur (Loÿe-Pilot & Martin, 1996). The same authors have also observed a dramatic interannual variability in the dust fluxes (a factor of 6 over 10 years). The optical measurements from the MINOS cruise in May 1996 reveal a much weaker bias with respect to the average relationship between the reflectance ratio and chlorophyll (Fig. 8a), which could be consistent with a lower frequency of dust events over the NW Basin in spring 1996, compared to the same period in 1999 and 2000 (C. Ridame and M. D. Loÿe-Pilot, personal communication).

It can be attempted to correct for this bias, observed over several areas and periods over the 1997–2000 years. It is important to note that this correction remains tentative, as long as the spatial extension of the phenomena inducing this bias, and their persistence throughout the year, are not better known. The reality of this bias, however, has been confirmed for various zones and periods, so performing such a correction allows at least limits of variation of chlorophyll concentration (with, and without bias) to be determined, for each pixel within the Basin and each period of the year. With this aim, a power relationship between the blue-to-green reflectance ratios and the corresponding chlorophyll concentrations measured during the PROSOPE and ALMOFRONT-2 cruises, was established by linear regression on the log-transformed data (Fig. 8a). The following relationship was obtained:

$$<\mathrm{Chl}> \quad (\mathrm{mg\ m}^{-3}) = 2.094[R_{(443)}/R_{(555)}]^{-2.357}$$

$$(N = 157,\ r^2 = 0.952) \tag{1}$$

No significant improvement was obtained when replacing the linear fit by a polynomial fit. As anticipated from Fig. 8a, the divergence between OC4v4 and this "regional" algorithm is essentially located in oligotrophic areas ($\mathrm{Chl} < 0.2$ mg m$^{-3}$), whereas both algorithms coincide for chlorophyll concentrations higher than 0.4 mg m$^{-3}$.

In order to account for the above mentioned bias in further studies, the SeaWiFS chlorophyll estimates (Level 3 weekly products, Level 2 products when necessary) can be corrected, pixel by pixel, by converting (via the OC4v4 algorithm) the chlorophyll concentration into the blue-to-green ratio as estimated by SeaWiFS, and then computing the corrected chlorophyll concentration from this ratio using Eq. (1). It is acknowledged that, when this procedure is applied to Level 3 products (time composites), the final result is approximative, because of averaging effects. Such effects, however, are believed to be much smaller than the uncertainties attached to any algorithm.

The comparison between SeaWiFS and in situ chlorophyll concentrations (as displayed in Fig. 7b) is shown, after correction, in Fig. 8b. Also, the corrected values for the Dyfamed time series are shown in Fig. 7a. It is observed that for the most oligotrophic waters, the chlorophyll overestimate is reduced from approximately a factor of 5 to a factor of 2. The remaining overestimate likely originates from locally inaccurate atmospheric corrections affecting the marine radiances derived from SeaWiFS measurements. This issue has already been evidenced by comparing SeaWiFS reflectances to those measured in situ during the PROSOPE cruise (S. Hooker, unpublished results). In spite of these remaining divergences, the agreement with in situ concentrations is significantly improved when using the above "regional" algorithm. This algorithm will therefore be used, concurrently with the OC4v4 algorithm, when studying the time and space variations of vegetal biomass (Bosc et al., in preparation).

Note that the possible presence of dust in surface waters is expected to affect not only the surface reflectances, but also the euphotic depth (via the diffuse attenuation coefficient in the water column), and therefore the primary production estimate. The decrease in euphotic depth would both result in a decrease of the chlorophyll content ($\mathrm{Chl}_{\mathrm{tot}}$) and in an increase of the average temperature of the euphotic layer, with opposite effects upon the final value of primary production (see Antoine & Morel, 1996), therefore this effect is thought to be limited.

### 3.5. *Primary production estimates: sensitivity to algal biomass, PAR, and seawater temperature variations*

The weekly maps of chlorophyll concentrations provided by the various sensors can be converted into primary production maps, using seawater temperature and incident PAR as additional information (see Data and methods). Then the pixel-by-pixel estimates of primary production can be spatially averaged in order to determine, similarly to algal biomass, the seasonal cycle of primary production in the whole Basin or its various regions.

As already noticed by Antoine et al. (1995), the seasonal cycle of primary production is mainly governed by the ($\Psi^*$ PAR) evolution. The effect of PAR (which increases by a factor of 3.9 from December to June) is usually predominant, so that primary production shows a minimum in winter and a maximum in summer. However, as $\Psi^*$ combines the effects of chlorophyll, PAR, and seawater temperature in a complex way, it is interesting to examine the impact of the seasonal variations in these various input parameters upon the seasonal variations of primary production. This sensitivity study was made by computing the weekly values of average primary production (a) when using the SeaWiFS chlorophyll data for the year 1998, the Levitus temperature dataset, and climatological PAR values and (b) when maintaining independently each of these three input parameters as constant over the year (and equal to their average value for the first week of January) (Fig. 9).

When considering, for instance, the maximum of spatially averaged primary production (which occurs during the last week of June), it is observed that compared to the "actual" curve (i.e., computed for the actual values of chlorophyll, PAR, and temperature), maintaining PAR to its winter value would decrease the mean primary production by 72%. Maintaining the chlorophyll concentration or seawater temperature to their winter values would, respectively, increase the mean primary production by 48% and decrease it by 21%. This demonstrates that the temporal variations of primary production are primarily driven by the PAR variations, and to less extent by those of chlorophyll concentration. Seawater temperature variations have only a second-order effect. These results are confirmed by the fact that when all parameters are allowed to vary, the spatially averaged primary production shows a minimum (around 0.3 g C m$^{-2}$ d$^{-1}$) in December (corresponding to the minimum of PAR), and then increases toward a maximum around 0.65 g C m$^{-2}$ d$^{-1}$ in June–July (maximum of PAR). The same features are observed for each province (not shown). This indicates that, although the extrema of seawater temperature are shifted compared to those of PAR (minimum in January–February, maximum in August, see Fig. 11), the influence of temperature is too weak to induce a shift in the extrema of primary production compared to those of PAR.

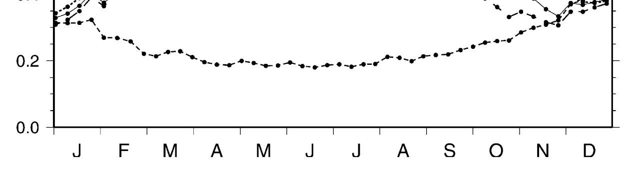

Fig. 9. Weekly values of primary production obtained by operating a spectral light–photosynthesis model (see Antoine and Morel, 1996), and then averaged over the whole Mediterranean Basin. The model was operated pixel by pixel with the following input parameters: (i) weekly chlorophyll concentrations provided by SeaWiFS for the year 1998, (ii) photosynthetically available radiant energy (PAR) values at the sea level (obtained from PAR values for a clear sky as provided by the 5S model, combined with ISCCP climatological cloudiness values), and (iii) average temperatures of the euphotic layer (computed from the Levitus climatological profiles). The three dashed curves were obtained by maintaining independently each of these three parameters as constant over the year, as indicated.

It is important to recall that in the primary production model used in this study (Morel, 1991), the assimilation number $P^{B}{}_{\max}$ has been made temperature-dependent according to a simple van't Hoff law (with an increase by a factor of 1.88 for a 10 °C rise). This ignores any phenomenon of thermal acclimation in phytoplankton (see discussion in Morel, 1991), and may exaggerate the sensitivity of primary production estimates to seawater temperature variations. Even with this assumption, however, the effect of temperature, compared to other parameters, has been found to be rather weak. This suggests that the exact description of this effect is not highly critical for primary production estimates. Nevertheless, it is interesting to determine the sensitivity of primary production estimates to the use of various temperature datasets.

### 3.6. Primary production estimates: sensitivity to temperature

A comparison of Reynolds analyses for the years 1998 and 1999 (not shown) evidences that for a given location and period, the SST in the Mediterranean Basin may undergo interannual variations by 2° or more (see also Marullo et al., 1999). Therefore, the use of SST data coincident with ocean color data, as input parameters in the primary production model, is a priori preferable to climatological values, and the Reynolds dataset has been used for primary production computations. Note however that a month-by-month comparison of Reynolds and Levitus SST over 1 year (not shown) has revealed a generally good agreement (including at the scale of each province) and no systematic bias. Conversely, OCTS SST have revealed to be higher than Reynolds SST by about 2° in May and June 1997, suggesting an undercorrection of the "skin effect," increasing at the end of spring with the heating of the surface layer.

The sensitivity of the primary production estimates to seawater temperature can be evaluated using, for instance, the SeaWiFS weekly chlorophyll products (Fig. 10). As expected from the agreement between Reynolds and Levitus SST, the primary production estimates derived from these two datasets show only slight differences throughout the year. The values estimated by using the average temperature over the productive layer are also close to those estimated using the SST from January to April, while they diverge increasingly from May to August (with primary production

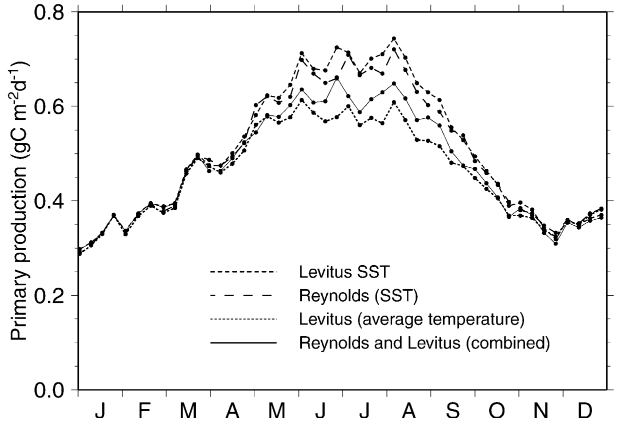

Fig. 10. Weekly values of primary production, computed from the weekly chlorophyll concentrations provided by SeaWiFS for 1998, and spatially averaged over the whole Mediterranean Basin. The computation uses the same light–photosynthesis model as in Fig. 9, and various datasets for seawater temperature: climatological monthly SST values from Levitus (1982); Reynolds weekly SST values, for the periods coinciding with satellite measurements; average temperatures of the productive layer, obtained from the Levitus dataset; average temperatures of the productive layer, obtained from the combined Reynolds and Levitus datasets (see text).

values lower than those obtained using SST by 15–20% in summer) and get closer again from September to December.

Therefore, while Reynolds analyses are valuable because data are simultaneous to ocean color data, the use of SST provides overestimated values of primary production. The vertical profile of seawater temperature, or at least the average temperature of the productive layer (with a depth estimated to 1.5 times the euphotic depth, Morel, 1991) is more appropriate when estimating primary production. A possible compromise is to combine the use of Reynolds and Levitus datasets, i.e., to use Reynolds analyses for SST (with the advantage of disposing of weekly data in coincidence with ocean color data) and then to estimate for each pixel the average temperature for the productive layer (noted $T_{1.5z_e}$). With this aim, empirical linear relationships between SST and $T_{1.5z_e}$ were determined, month by month and for different $\mathrm{Chl_{sat}}$ values (i.e., different values of euphotic depth), by regression analysis on Levitus data. This analysis (Fig. 11) shows that SST is virtually identical to $T_{1.5z_e}$ (whatever the value considered for $\mathrm{Chl_{sat}}$) for the winter months (January to March), when the mixed layer is expected to be the deepest. In April–May, with the beginning of stratification, the shift between SST and $T_{1.5z_e}$ becomes more marked, and as expected, increases toward lower values of $\mathrm{Chl_{sat}}$ (i.e., increases with the depth of the euphotic layer); the difference is maximal in August–September, and reaches 8° in the clearest waters ($\mathrm{Chl_{sat}} = 0.03$ mg m$^{-3}$). At a given period and for a given pixel (i.e., for a given $\mathrm{Chl_{sat}}$ value), $T_{1.5z_e}$ was derived from SST by linear interpolation with respect to log($\mathrm{Chl_{sat}}$). The resulting values of primary production are expected to

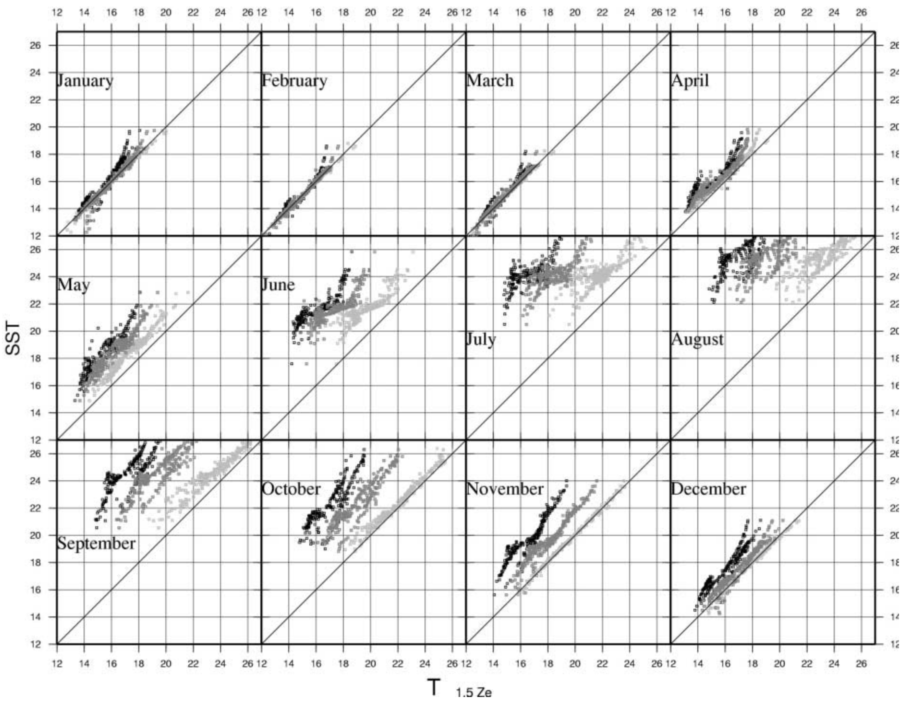

Fig. 11. Month-by-month comparison between SST and seawater temperature averaged over 1.5 times the euphotic layer ($T_{1.5z_e}$). These data are derived from the monthly climatological temperature profiles available for the Mediterranean Basin (Levitus, 1982). The depth of the euphotic layer has been computed for three values of the surface chlorophyll concentration, covering most of the range of expected values in the Mediterranean Basin (0.03, 0.3, 3 mg m$^{-3}$, respectively, in dark grey, mean grey, and light grey), using a statistical relationship proposed by Morel (1988). These three values correspond to $1.5z_e = 160$, 83, and 38 m, respectively.

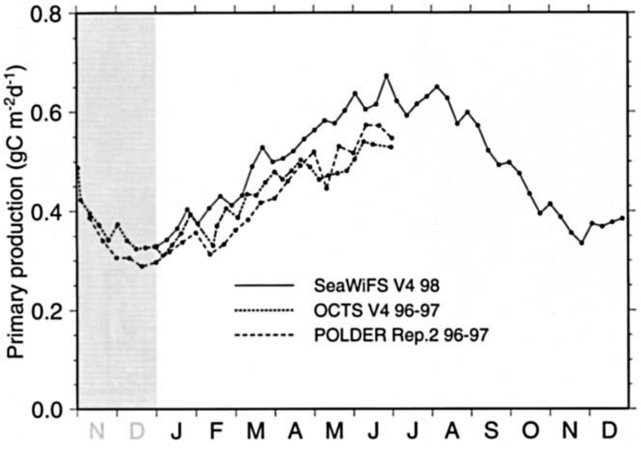

Fig. 12. Weekly values of primary production, computed from the weekly chlorophyll concentrations provided by the various sensors, and spatially averaged over the whole Mediterranean Basin. The computation uses the same light–photosynthesis model as in Fig. 9; seawater temperature is obtained from the combined Reynolds and Levitus datasets (the values for CZCS are not shown as no Reynolds data are available).

differ from those estimated using the Levitus dataset when differences between Reynolds and Levitus SST are noticeable. For the considered year (1998), these values, as shown in Fig. 10, are higher than those obtained from the Levitus dataset (by 6% in August), while they remain, as expected, always lower than those obtained from Reynolds SST (by 13% in August).

### *3.7. Primary production estimates: sensitivity to intersensor differences in biomass estimates*

The weekly maps of chlorophyll concentrations provided by the various sensors were converted into the corresponding primary production maps (using a combination of Reynolds and Levitus temperature datasets, as explained above). The seasonal variations of primary production, as obtained from 7-day (OCTS), 8-day (SeaWiFS), or 10-day (POLDER) chlorophyll products, are shown in Fig. 12. The intersensor differences (as well as the possible interannual variability) are reduced compared to those of algal biomass (see Fig. 5). As an example, while the mean chlorophyll concentration provided by POLDER measurements for the last week of June 1997 is higher than the corresponding OCTS value by 15%, the primary productions for the same period differ by only 4%. Such a reduction was expected since for a given PAR value, primary production is mostly ruled by the column-integrated chlorophyll content, $\mathrm{Chl_{tot}}$, which varies approximately as $\mathrm{Chl_{sat}}^{0.5}$ (Morel & Berthon, 1989).

Table 1 shows the corresponding estimates of annual primary production for the various sensors in the Western, Eastern Mediterranean, and for the whole Basin. Estimates for CZCS (from the NASA archive, and from Antoine et al., 1995) are also shown for comparison (for these estimates, only the Levitus temperatures could be taken into account). As expected from the seasonal cycles of primary production shown above, the annual primary productions (per square meter and per year) are in good agreement for POLDER and OCTS (with a 3% difference for all Basins). Other differences are more difficult to analyze because of interannual variations. Estimates from SeaWiFS are higher than for all other sensors (for the whole Basin, by 21% compared to POLDER, and by 7% compared to CZCS products as provided by NASA). Surprisingly, the overall differences are more strongly marked for the Eastern Basin (maximum difference 33%) than for the Western Basin (maximum difference 14%).

## 4. Conclusions

The present results obviously only apply, strictly speaking, to the product versions presently available for the various sensors, and may have to be revised when future versions become available. It is expected, however, that these upcoming versions will not modify dramatically the Level 3 products and will deal only with “refinements,” as the major problems have been identified at the stage of the first processings, and the corresponding adjustments (in calibration and algorithms) have already been performed.

Considering the existence of significant differences in calibration procedures, and in atmospheric and bio-optical algorithms, OCTS, POLDER-I, and SeaWiFS Level 3 chlorophyll products are in relatively good agreement.

Table 1

Primary production (in g C $\mathrm{m^{-2}\ yr^{-1}}$), spatially averaged over the Western Mediterranean, Eastern Mediterranean, and the whole Basin, and integrated over a whole year, for the various sensors

| Annual PP | OCTS[a]<br>(1997) | POLDER[a]<br>(1997) | SeaWiFS<br>(1998) | CZCS[b]<br>(1978–1981) | CZCS[c]<br>(1978–1983) |
|---|---|---|---|---|---|
| Western Basin | 173 | 178 | 198 | 197 | 197 |
| Eastern Basin | 143 | 147 | 183 | 160 | 137 |
| Whole Basin | 154 | 157 | 190 | 178 | 156 |

[a] For OCTS and POLDER (data available from November 1996 to June 1997), the primary production values have been integrated from January to June, and multiplied by 2 (assuming that the seasonal cycle is symmetrical with respect to July 1).

[b] Values obtained using the monthly products available from the NASA archive.

[c] Values obtained by Antoine et al. (1995), and multiplied by 1.25. This correction assumes that the ratio of active-to-total pigments is 1 instead of 0.8 (see Morel, Antoine, Babin, & Dandonneau, 1996).

Moreover, the differences at the level of individual pixels (which can be as high as a factor of 2) tend to cancel out when computing the spatial means at the scale of the whole Basin, or even of a subprovince, so that the stocks of algal biomass, as estimated by the various sensors, are relatively convergent at these scales. One conspicuous conclusion of this study, however, is the incapacity of any ocean color sensor to reproduce the low chlorophyll concentrations ($< 0.15$ mg m$^{-3}$) as observed in situ over large areas of the Basin. The systematic bias appearing between satellite and in situ chlorophyll concentrations appears to originate both from errors in atmospheric corrections and from inadequate bio-optical algorithms (due to peculiar optical properties of Mediterranean waters, see Claustre et al., submitted). The use of a "regional algorithm" allows the bias induced by bio-optical algorithms to be corrected. The problem of locally inaccurate atmospheric corrections, however, has still to be examined and corrected, so as to attempt to put satellite and in situ values in closer agreement.

Temporal variations in primary production appear to be mainly driven by PAR and chlorophyll variations, and to be much less sensitive to variations in seawater temperature. Although primary production computations were performed using a given light–photosynthesis model (Morel, 1991), this conclusion is expected to be maintained for any other model, because the considered model (which ignores any phenomenon of thermal adaptation of algae) likely overestimates the temperature effect upon the phytoplankton growth rate. For "refined" estimates of primary production, it remains nevertheless useful to use seawater temperature data simultaneous to ocean color data as inputs into the model, so as to take into account their possible interannual variations. Reynolds analyses of SST, therefore, appear to be the most appropriate for such computations. The conversion of SST into average temperature for the productive layer, however, is necessary, especially for the spring and summer months where waters are stratified.

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## Appendix A. A brief description of the algorithms involved in the OCTS, POLDER-I, and SeaWiFS data processings

### *A.1. Calibration procedures*

The OCTS calibration relies on on-board artificial sources, sunlight observations as well as vicarious calibration. In Version 4.0 products, the calibration factors were tuned so as to match the radiances and chlorophyll *a* concentrations measured in situ in various waters. The dataset used (see Table 4 in Kawamura et al., 1998) seemingly includes a large part of the SeaBAM dataset used for developing SeaWiFS algorithms (see below), which may explain the relatively good agreement with SeaWiFS estimates, in spite of differences in bio-optical algorithms.

The POLDER instrument has no on-board calibration system, and relies on vicarious calibration. Calibration factors for Level 1 radiances at 443 and 490 nm were adjusted by comparing POLDER measurements with radiances at the top of atmosphere, obtained by summing atmospheric path radiances computed for clear atmospheres (low aerosol optical thickness) and water-leaving radiances, measured in selected sites (see Fougnie, Deschamps, & Frouin, 1999).

The SeaWiFS calibration relies both on solar and lunar observations (for temporal degradation), and on vicarious calibration, for adjustment of prelaunch calibration factors. Vicarious calibration operations are based essentially on measurements performed with the MOBY buoy (Clark et al., 1997), and have led to successive revisions of calibration factors for all visible bands.

### *A.2. Atmospheric corrections*

The atmospheric correction procedures are similar for the three sensors. Rayleigh scattering is obtained from precomputed tables, taking into account the actual atmospheric pressure, and multiple scattering and polarization effects. Ozone absorption is corrected using TOMS data. The aerosol radiances are obtained from near-infrared measurements (at 865 and 765 nm for SeaWiFS, or 865 and 670 nm for OCTS and POLDER). They are then compared to aerosol models and extrapolated to the visible domain using look-up tables (which include the effects of multiple scattering and of interactions between aerosols and molecules), according to the scheme developed by Gordon and Wang (1994). SeaWiFS and POLDER aerosol models (Shettle & Fenn, 1979) are similar, while OCTS includes an additional model for Asian dust (see Fukushima et al., 1998). Directional water-leaving radiances are finally obtained by subtracting Rayleigh and aerosol radiances from the total radiances, and dividing by the total transmission of the atmosphere.

Some refinements in these various steps have been introduced in the SeaWiFS Reprocessing no. 3 (e.g., modified aerosol selection, wind dependence in Rayleigh computations, etc.; see http://seawifs.gsfc.nasa.gov/SEAWIFS/RECAL/Repro3). In addition, the method proposed by Siegel, Wang, Maritorena, and Robinson (2000) to relax the "black pixel assumption" (i.e., the assumption that the ocean is a black body in the near IR domain, which fails in waters with chlorophyll *a* concentrations >ca. 2 mg $m^{-3}$) has been implemented.

### A.3. Bio-optical algorithms

For OCTS, the bio-optical algorithm provides the chlorophyll *a* concentration from a combination of water-leaving radiances at 490, 520, and 565 nm:

$$\mathrm{Chl}\ a\ (\mathrm{mg\ m^{-3}}) = 0.2818[(L_{\mathrm{w}}(520) + L_{\mathrm{w}}(565))/L_{\mathrm{w}}(490)]^{3.497}$$

Numerical coefficients were obtained using field observations from various waters around Japan (Kishino, Ishimaru, Furuya, Oishi, & Kawasaki, 1998).

For POLDER, because of problems affecting the calibration of the 443-nm channel, the reprocessing no. 2 uses the OC2 algorithm previously used for SeaWiFS (O'Reilly et al., 1998). This algorithm provides the chlorophyll *a* concentration from the ratio of reflectances at 490 and 565 nm:

$$\mathrm{Chl}\ a\ (\mathrm{mg\ m^{-3}}) = 10^{0.341-3.001\rho+2.811\rho^2-2.041\rho^3-0.040\rho^4}$$

where $\rho = \log_{10}[R(490)/R(555)]$, and $R$ is the marine diffuse reflectance under the surface. Numerical coefficients were obtained using the SEABAM dataset of field observations, covering a wide range of waters (see O'Reilly et al., 1998). As the channel available on POLDER is centered on 565 nm instead of 555 nm, $R(555)$ is obtained from $R(565)$ using the empirical relationship:

$$R(555) = 1.0628R(565) + 0.0015$$

Diffuse reflectances are obtained by combining the directional radiances, which are measured by the POLDER instrument under up to 12 directions for each pixel. The directional radiances for all directions are converted into diffuse reflectances using the $Q$ factors from Morel and Gentili (1993), and then averaged (with a weighting function that takes into account the relative intensity of the aerosol scattering in the different directions). Observations are discarded when the aerosol optical thickness at 865 nm is >0.5.

The algorithm used in the SeaWiFS reprocessing no. 3 is the OC4 algorithm proposed by O'Reilly et al.(1998), with revised numerical coefficients (OC4v4). It provides the chlorophyll *a* concentration from the "maximum reflectance ratio," $\rho = \log_{10}[R_{\mathrm{rs}}(\lambda)/R_{\mathrm{rs}}(555)]$, where $R_{\mathrm{rs}}$ is the remote-sensing reflectance (i.e., $L_{\mathrm{w}}$ divided by the irradiance incident on the sea surface), and $R_{\mathrm{rs}}(\lambda)$ is the highest value among $R_{\mathrm{rs}}(443)$, $R_{\mathrm{rs}}(490)$ and $R_{\mathrm{rs}}(510)$:

$$\mathrm{Chl}\ a\ (\mathrm{mg\ m^{-3}}) = 10^{0.366-3.067\rho+1.930\rho^2+0.649\rho^3-1.532\rho^4}$$

### A.4. Level 3 composites

The OCTS Level 3 weekly composites are obtained by computing for each "bin" (9 × 9 km at the equator) the *geometric* mean of chlorophyll *a* concentrations for all pixels in that bin, over 7-day periods (the first period begins on November 3, 1996). Case 2 waters are not identified.

The POLDER Level 3 composites are obtained by computing for each pixel the *geometric* mean of chlorophyll *a* concentrations over 10-day periods (1st–10th, 11th–20th, 21st–last day of month). The means are computed with a weighting function that takes into account the quality index of the processing. Case 2 waters (identified as in Bricaud & Morel, 1987) are discarded from the means.

The SeaWiFS Level 3 composites are obtained by computing for each bin the *arithmetic* mean of chlorophyll *a* concentrations over 8-day periods (the first period of each year is forced to begin on January 1). Case 2 waters (identified by a flag on Level 2 products) are not identified on Level 3 composites.

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