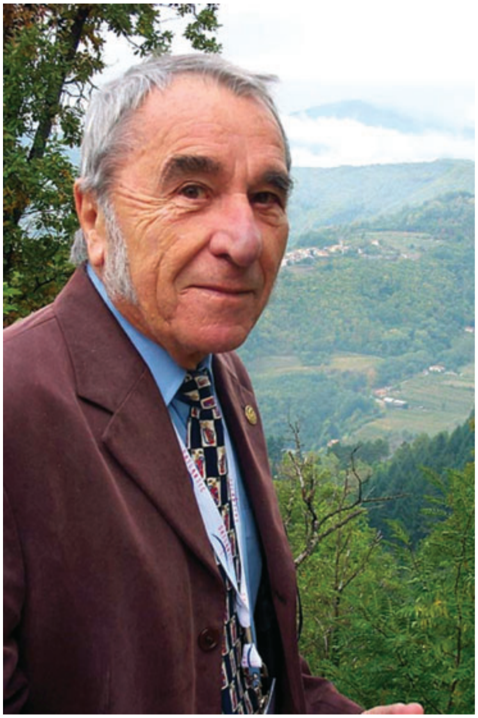

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Shedding Light on the Sea: André Morel's Legacy to Optical Oceanography

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Abstract

André Morel (1933–2012) was a prominent pioneer of modern optical oceanography, enabling significant advances in this field. Through his forward thinking and research over more than 40 years, he made key contributions that this field needed to grow and to reach its current status. This article first summarizes his career and then successively covers different aspects of optical oceanography where he made significant contributions, from fundamental work on optical properties of water and particles to global oceanographic applications using satellite ocean color observations. At the end, we share our views on André's legacy to our research field and scientific community.

PREAMBLE

In 2012, the *Annual Review of Marine Science* Editorial Committee invited André Morel to contribute an autobiographical article describing his career and his views on future developments in the field of optical oceanography. He passed away in autumn of that year, before he could start this project. As a group of André's mentees and close collaborators, we were given the privilege to present a synthetic description of his contributions to optical oceanography. This article is our testimony to the highest recognition of André's scientific achievements and legacy and the highest appreciation for all he taught us both scientifically and at a broader human level.

INTRODUCTION

Optical oceanography, also called marine optics, is the science of light propagation in the ocean through interactions of radiation with seawater via absorption and scattering processes. The term marine bio-optics is used when the focus is on absorption and scattering by particles and dissolved substances of biological origin; the term ocean color remote sensing is used when research relies on remote (satellite or airborne) observations of the spectrum of water-leaving light or ocean reflectance. The fate of nearly all of the solar energy that reaches the Earth's oceans occurs in the upper water column, where light propagation is determined by optical properties of seawater that contains various dissolved and particulate materials. The absorbed energy contributes to ocean heating and circulation and also supports phytoplankton photosynthesis and subsequent oceanic food webs. A fraction of underwater light returns to the atmosphere and can be recorded by so-called ocean color satellite-borne optical instruments.

Because of the crucial role that light plays in the ocean, these research domains have a central place in modern oceanography. Regional and global ocean-observing efforts all include optical measurements that enable investigators to diagnose and monitor environmental processes. Examples include major long-term ocean-monitoring sites (Ducklow et al. 2009, Karl 2010, Church et al. 2013), arrays of profiling bio-floats (Claustre et al. 2010), and the international fleet of Earth-observing satellites, which includes ocean color sensors (McClain 2009). Up-to-date global coupled physical-biogeochemical models include increasingly sophisticated and accurate treatment of light propagation, with the goal of improving predictions of ocean heating and phytoplankton primary production (PP) (Mobley & Boss 2012). We owe much of this success in optical oceanography and ocean color science to several pioneer scientists, with André Morel being one of the most prominent among them and one of the most productive and influential researchers in the field of marine bio-optics.

André was one of the first optical oceanographers to successfully link laboratory and field measurements to optical theories of the interaction of light with particles (Mie theory, Rayleigh-Gans and van de Hulst approximations). This work was done in the 1960s and 1970s, when modern marine optics was still in its early years of development and only a few research groups were involved. Among those groups were several European investigators associated with or following the work of Niels Jerlov, the Visibility Laboratory at the Scripps Institution of Oceanography in San Diego in the United States, and a number of groups in the former Soviet Union. This early phase of André's career occurred about 15 years before the launch of the first satellite ocean color sensor, the Coastal Zone Color Scanner (CZCS), in 1978. This context emphasizes the forward-thinking and visionary character of André's early research.

Here, we summarize his main scientific accomplishments and legacy in the research fields of marine optics, bio-optics, and ocean color remote sensing. We recognize that such a synthesis may be somewhat subjective, as no human life can be simply summarized, in particular when it is so rich in significant achievements. We made efforts not to omit major discoveries or results from André's prolific career, although admittedly it was not possible to include all scientific contributions by him and his coworkers. We also wish to acknowledge that along with André's career, many parallel research efforts by other scientists have played an important role in bringing marine optics to the point where it is today.

ANDRÉ'S CAREER

André received his high school diploma (*baccalauréat*) when he was 16, two years ahead of the usual age in France. He then attended the so-called *classes préparatoires* in Paris before attending and graduating in 1953 from the prestigious Ecole Supérieure de Physique et Chimie de Paris (ESPCI)—alumni of which include Marie and Pierre Curie. He then became a diver and diving instructor in the French navy, where he spent three years.

It was after this time in the navy that André was introduced to oceanography, when he volunteered to join Jacques-Yves Cousteau's expedition on *La Calypso* in 1956. That was his first oceanographic cruise. It is likely that the famous undersea explorer took note of André's capabilities during that cruise, which resulted in a more formal proposition one year later. At that time, André was about to sign for a job in a fluid mechanics laboratory in Grenoble, France. Cousteau had just been appointed director of the Oceanographic Museum in Monaco, and he offered André an assistant position in physics, which he accepted. This is how André's career as an oceanographer came to be.

In 1962, he became an assistant professor at Université Pierre et Marie Curie in Paris; he then became an associate professor in 1965 and a full professor in 1977. He started his research in Villefranche-sur-Mer when Alexandre Ivanoff, his professor at ESPCI, chose that location to open a branch of the physical oceanography laboratory of the Natural History Museum in Paris in 1965. Another of his professors and mentors, Jacqueline Lenoble, simultaneously opened the atmospheric optics branch in Lille, now known as the Laboratoire d'Optique Atmosphérique.

The Villefranche laboratory later became the Laboratoire de Physique et Chimie Marines (LPCM), which André led as a director until the mid-1990s (the laboratory had two locations, one in Villefranche and another in Paris). In the 1970s, he and Louis Prieur both led the research in optical oceanography at the LPCM, before Louis reoriented his activity toward physical oceanography. In 1976, Annick Bricaud started her research under André's supervision, and Bernard Gentili joined them in 1987. The three of them formed the Radiation and Ocean group that further developed the reputation of Villefranche in optical oceanography. This group started to grow in the mid-1990s with the addition of new faculty and Centre National de la Recherche Scientifique (CNRS) researchers. Several of these recruits were André's former students and collaborators, and they successively took the lead of what began to be known as the Marine Optics and Remote Sensing group. Over those many years, André was a mentor for all those who joined this group, including the period from 2002 to 2012, when he was a professor emeritus.

In 1983, the LPCM was integrated with other research laboratories of the Villefranche site into the Centre d'Etudes et de Recherches Océanographiques de Villefranche-sur-Mer, now known as the Observatoire Océanologique de Villefranche-sur-Mer. André was the first director of this institution, a position he held from 1983 to 1989. Another reorganization took place in 2000, when the Villefranche part of the LPCM was separated from its Parisian counterpart and merged with another laboratory working in biological oceanography to form the Laboratoire d'Océanographie de Villefranche. The Marine Optics and Remote Sensing group has been a major component of this institute since its creation, and currently comprises about 25 research personnel, including researchers, technical staff, and students.

As recognition of his outstanding contribution to the field of marine optics, André received a number of important awards: the bronze medal of the CNRS (1970); the medal of the French Oceanography Society (1981); the Eurosense Award of the Remote Sensing Society in the United Kingdom, shared with Shubha Sathyendranath and Louis Prieur (1990); the Binoux Prize of the French Academy of Science (1990); the first Jerlov Award of the Oceanography Society (2000); the Manley-Bendall Medal of the Oceanographic Institute in France (2003); and the A.C. Redfield Lifetime Achievement Award of the Association for the Sciences of Limnology and Oceanography (2005).

SCIENTIFIC ACHIEVEMENTS

The particular path André took before becoming a scientist may explain the novelty of his contributions to optical oceanography. From the 1940s to the 1960s, studies in marine optics aimed essentially at describing the penetration of solar radiation into the ocean: the decrease of radiative energy with increasing depth, the associated changes in the spatial distribution of the submarine light field, and changes in underwater visibility. This last aspect was of interest for military applications. André strongly contributed to reorienting the main direction of research toward fundamental scientific questions and applications associated with interactions of light with matter present in seawater, including water molecules. He also contributed to fundamental terminology in the area of marine optics (Ivanoff & Morel 1970, Morel & Smith 1982). The following six sections summarize the main achievements along this path.

Light and Matter: Inherent Optical Properties

Preisendorfer (1961) introduced the concepts of the inherent optical properties (IOPs) of water and the apparent optical properties (AOPs) of a specific water body, thereby providing a theoretical foundation for marine optics. IOPs were defined as properties that depend only on the substances present in the aquatic medium, whereas AOPs were defined as those that depend on both the IOPs and the geometric structure of the light field within the medium. The fundamental IOPs are the absorption coefficient and the volume scattering function (VSF), from which other IOPs, such as the total scattering, backscattering, and beam attenuation coefficients, can be derived. All IOPs are additive properties and can therefore be partitioned into the contributions of seawater itself and those of the various types of marine particles and dissolved organic materials. The component IOPs are amenable to experimental and theoretical studies dedicated to each category of constituents. Because these IOPs are directly related to the concentrations and nature (e.g., size, refractive index) of seawater constituents and govern radiative transfer (RT) in the ocean, they have broad physical, optical, biological, biogeochemical, and geological significance.

Field measurements in the 1960s provided the first fragmentary information about IOPs (for a review, see Højerslev 1994). At that time, André was in the early years of his career and focused his research on the interactions between light and the various types of constituents present in seawater. His major contributions to the knowledge of IOPs in the ocean fall into three main subject areas: IOPs of pure water and pure seawater, IOPs of biological marine particles, and field studies of IOPs and their relation to water constituents. The contributions in these areas are summarized below.

One of André's most cited studies is devoted to scattering and attenuation coefficients of pure water and pure seawater (Morel 1974). The results presented in this work were based largely on earlier studies he performed in the 1960s and published in French (Morel 1965, 1966, 1968). These studies overcame significant instrumental difficulties in measuring light scattering by pure water (absolute calibration, evaluation of stray light) and challenges in preparing optically pure water, as testified by many investigations since Raman (1922). André used a purification technique based on distillation in vacuo without ebullition (Martin 1920). He designed and constructed three experimental setups, the quality of which was supported by measured VSFs that agreed quite well with theoretical predictions for pure water. This pioneering work allowed him to estimate the magnitude and spectral dependence of the scattering coefficient of pure water, which was found to obey a $\lambda^{-4.32}$ law, in fair agreement with the λ^{-4} prediction of the Einstein-Smoluchowski density fluctuation theory, as previously found by Dawson & Hulburt (1937). This result has been mentioned in the literature as Morel's law. He also determined the VSF and scattering coefficients of sodium chloride solutions and pure seawater, which demonstrated that the excess scattering due to salts is in agreement with the theoretical values derived from their molecular weights. These scattering coefficients for pure water and pure seawater have been used for many years in numerous optical studies.

André's first major contribution to the knowledge of optical properties of marine particles of biological origin was published in support of a NATO lecture series on optics of the sea (Morel 1973). This detailed study of light scattering by oceanic waters presents a compilation and intercomparison of numerous field observations performed by André and other investigators as well as a comprehensive theoretical treatment of scattering properties of marine particles in terms of their physical characteristics (complex refractive index, size distribution) at the levels of both individual particles and particulate assemblages. The theoretical considerations address the angular and spectral dependencies of light scattering, the effects of the particle size distribution, and polarization properties. These considerations were based mainly on Mie (1908) theory but also on more recent theoretical studies dealing with particle optics (e.g., van de Hulst 1957). Some of the experimental data analyzed in this paper were obtained using prototype instrumentation that André helped to develop, in particular for measuring the VSF at very small scattering angles (Bauer & Ivanoff 1965, Bauer & Morel 1967) (**Figure 1*a***).

Another landmark contribution to the knowledge of optical properties of particles was the theoretical analysis of light absorption by a suspension of phytoplankton cells (Morel & Bricaud 1981). This paper provided a sound theoretical foundation explaining differences between the absorption spectra of algal cell suspensions and the same amount of pigments present in solution, as caused by the discreteness effect (now commonly referred to as the package effect). This effect was first identified by Duysens (1956). The theoretical approach by Morel & Bricaud (1981) demonstrated how the product of the cell size and absorption coefficient of cellular material drives changes in both the magnitude and shape of chlorophyll-specific absorption spectra of algal cells. These results also emphasized the influences of both the size structure of algal populations and the pigmentation associated with the physiological status of cells upon the chlorophyll-specific absorption coefficient.

Following these fundamental studies, a series of papers explored the various IOPs of algal suspensions, generally by combining and comparing theoretical predictions with laboratory measurements performed on diverse phytoplankton species grown under controlled conditions (e.g., Morel & Bricaud 1981, 1986; Bricaud et al. 1983; Ahn et al. 1992). These studies quantified the variations of various IOPs and demonstrated, for instance, a direct influence of absorption on scattering properties and different spectral behaviors of total scattering and backscattering. In addition, these studies provided a basis for modeling the various IOPs in terms of physical characteristics of cell suspensions (e.g., Bricaud & Morel 1986, Stramski et al. 1988).

Further studies combining theoretical interpretations and experimental results were extended to other phytoplankton groups, such as prochlorophytes and cyanobacteria (Stramski & Morel 1990, Morel et al. 1993), as well as to biological particles other than phytoplankton, such as

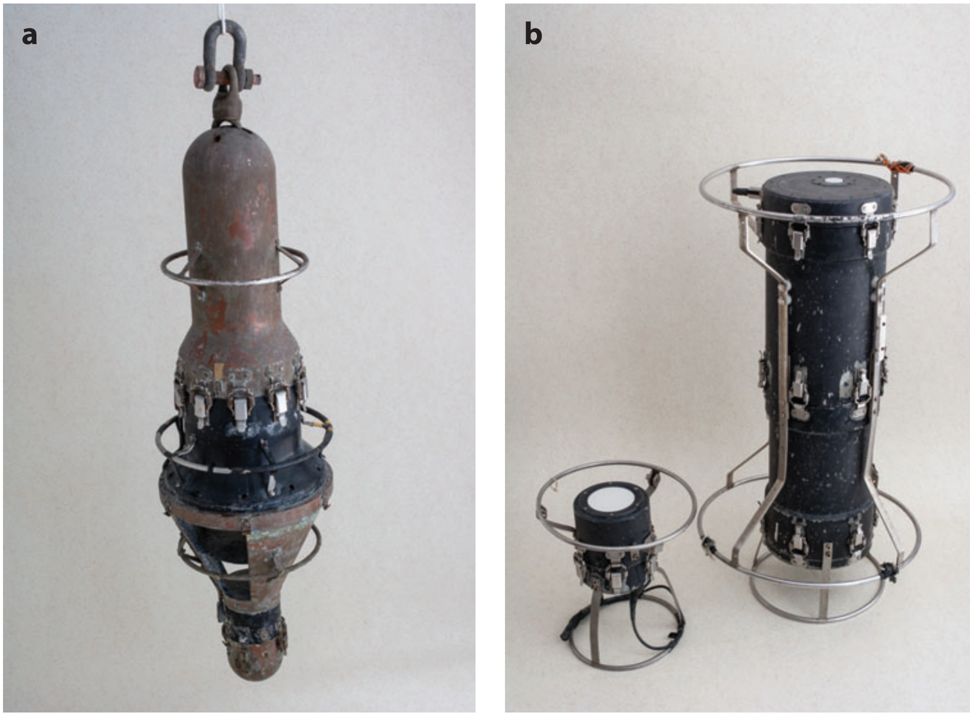

Figure 1

(*a*) A small-angle forward scattering meter developed in the 1960s (Bauer & Ivanoff 1965, Bauer & Morel 1967). (*b*) A quanta meter (small instrument, *left*) (Prieur 1970) and spectro-irradiance meter (large instrument, *right*) (Bauer & Ivanoff 1970), both developed in the late 1960s. The irradiance meter (diameter 35 cm, height 1 m) was used until the EUMELI4 cruise in 1992 (Morel 1996).

heterotrophic bacteria (Morel & Ahn 1990) and ciliates and nanoflagellates (Morel & Ahn 1991). The results provided a sound framework for interpreting the variations of IOPs observed in the field and also allowed investigators to pursue a reductionist approach for evaluating the relative roles of different types of microorganisms in determining the optical properties of oceanic waters (e.g., Stramski et al. 2001).

Absorption by colored dissolved organic matter (CDOM), also referred to as yellow substance or gelbstoff, was also the subject of pioneering field investigations in the 1970s. Morel & Prieur (1976) measured the absorption spectra of filtered samples collected in the Mauritanian upwelling over the visible spectral range, using a spectrophotometer that had been modified to allow the use of 110-cm sample cells. These measurements provided one of the first absorption spectra of CDOM of oceanic origin in the visible part of the spectrum. Such field measurements in oceanic waters remained scarce for almost two decades, primarily because of instrument limitations, until more sensitive instruments (in situ spectral absorption meters equipped with filters and laboratory instruments with capillary waveguides) became available at the end of the 1990s.

In situ optical profilers are now widely used and provide extensive measurements of IOPs, but it is worth recalling that before this period, André and coworkers gathered and analyzed an unprecedented amount of data to document field variations of IOPs with less advanced tools and instruments. André recently verified the general consistency of the early bio-optical relationships

(Morel 2009). These various contributions, along with other efforts made by the scientific community, have done much to foster the development of bio-optical models (see From Optics to Biogeochemistry: Bio-Optical Modeling of Case I Waters, below) and have improved our knowledge of the complex connections between biological processes and optical properties of the ocean.

Apparent Optical Properties: A Sea of Photons

The characteristics of light fields within the ocean and leaving the ocean were the focus of many of André's studies (e.g., Morel 1965; Ivanoff & Morel 1970; Prieur & Morel 1971; Morel & Gentili 1991, 2004; Mobley et al. 1993; Maritorena et al. 1994; Morel & Loisel 1998). These studies covered a broad range of subjects and have had a significant impact on our knowledge and understanding of various problems in hydrologic optics, such as RT, ocean reflectance, heating rate within the water column, relationships between the ocean IOPs and AOPs, and effects of water depth and bottom on water-leaving light. This body of work was based on two main elements. The first element was the collection of high-quality radiometric measurements in various parts of the world's oceans, which relied on specially designed, custom-built instruments (**Figure 1*b***) until commercial instrumentation later became available. The second element was the development of a Monte Carlo RT code (see Mobley et al. 1993) that was used extensively, in particular to study the bidirectionality of ocean reflectance.

André made his first underwater radiometric measurements at the age of 24, while working in the Mediterranean Sea aboard the oceanographic vessel *La Calypso* (Morel 1965). In addition to the detailed description of data on the upwelling radiance field, which André collected in December 1957 and April 1958 with an instrument developed by his mentors in marine optics, Jacqueline Lenoble and Alexandre Ivanoff, two qualities of his scientific endeavor are apparent in that paper: his profound attention to achieving highly accurate measurements, and his open mind toward problems studied by biological oceanographers.

From those early times on, André collected an impressive number of radiometric measurements in various oceanic environments with contrasting optical properties, from milky sediment-dominated waters off Mauritania (the CINECA 5 cruise in 1974) to the most oligotrophic waters of the subtropical gyre in the South Pacific (the BIOSOPE cruise in 2004). André highly valued the benefit of collecting fewer high-quality data rather than wasting time on making repeated measurements under unfavorable conditions. Many colleagues who have worked with him at sea remember how radiometric casts were postponed because the sea and sky conditions were not optimal, or were stopped when such conditions began unexpectedly degrading after a cast was started. An illustration of original conclusions that can be inferred from such carefully acquired observations is found in Morel et al. (2007b), where he reconsidered the issue of absorption by pure seawater in the near-UV and blue parts of the spectrum (wavelengths from 350 to 450 nm) by determining total absorption from inversion of the measured spectral reflectance and diffuse attenuation coefficient of irradiance.

The advent of efficient computing capabilities in the 1990s helped in the development of a Monte Carlo code for simulating RT in both the ocean and the atmosphere (for a comparison with other RT models, see Mobley et al. 1993). This development was a natural step in complementing the fieldwork. With this computational tool, André made major contributions to an understanding of the bidirectional structure of upward radiance distributions (Morel & Gentili 1991, 1993, 1996; Loisel & Morel 2001; Morel et al. 2002). The effects of seawater IOPs—including the shape of the VSF, Raman scattering, and sea-surface illumination conditions—on the bidirectional reflectance of the ocean (depicted through the so-called Q factor) have been analyzed thoroughly for oceanic and coastal waters. The first paper of this series (Morel & Gentili 1991) discussed the origins of variability in ocean reflectance, focusing on the effects of variations in solar zenith angle and variable contributions of water molecules and particles to light scattering. This study also presented a fundamental but rather unknown and unappreciated result about single and multiple scattering phenomena in the ocean. Specifically, by applying a probabilistic approach, the study showed how the average number of collisions (interactions) of photons with seawater constituents is related to the single scattering albedo of the medium. This relationship is remarkably simple and was supported by Monte Carlo simulations. André considered this finding important and useful because it allows characterization of the upward photon flux within the water column and the associated scattering regime (i.e., single scattering versus multiple scattering), provided that the scattering and absorption coefficients of seawater are known. The theoretical findings resulting from the subsequent papers (Morel & Gentili 1993, 1996; Morel et al. 2002) have implications for analysis of satellite ocean color observations, and are implemented in the processing of data collected by various ocean color sensors. These findings obtained from RT simulations were confirmed by field observations collected in collaboration with investigators from the University of Miami, who had developed underwater radiance cameras (Morel et al. 1995, Voss & Morel 2005, Voss et al. 2007).

Finding a Way Through an Optically Complex Ocean: The Case I/Case II Paradigm

Over the past several decades, research in marine bio-optics has been shaped largely by the concept introduced by André and Louis Prieur (Morel & Prieur 1977) that ocean waters can be classified into case I and case II waters based on their optical properties. There is not, however, a single paper that synthesizes the entire concept of this classification, and it is thus difficult to quote a single strict definition of the classification from one of André's publications. Nevertheless, many discussions that we had with him let us believe that we can formulate a statement that characterizes case I and case II waters and is likely close to André's way of thinking about this topic. Case I waters are those where optical properties are driven by phytoplankton and their associated particulate and dissolved materials, and for which phytoplankton chlorophyll *a* concentration ([Chl]) can be used as an index to describe how their optical properties evolve with changes in the trophic regime. This definition alludes to the fact that the concept has both qualitative grounds and quantitative expressions. Waters that do not conform with the above definition of case I waters are simply categorized as case II waters.

The concept of case I and case II waters is more than a classification; it is also a framework for interpreting bio-optical observations, and could be referred to as a paradigm. It has also been referred to as the bio-optical assumption (Siegel et al. 2005). It is one of André's major legacies to our field. The case I/case II terminology was first introduced in the 1977 paper "Analysis of Variations in Ocean Color" (Morel & Prieur 1977). The initial goal of this paper was actually not to enforce any concept or definition but rather to provide a conceptual framework for interpreting ocean reflectance measurements, in particular in view of remote sensing observations, as it was published just before the launch of the first satellite ocean color mission in 1978. In the paper, the case I/case II terminology was actually used to subdivide "various green waters," with blue waters considered separately. Building the entire concept required further studies (e.g., Gordon & Morel 1983, Morel 1988, Morel & Maritorena 2001). As a group, these publications cover both the conceptual framework and practical aspects of modeling optical properties of case I waters as a function of [Chl].

The lack of a single strict definition has not prevented the concept from becoming central in the domain of bio-optics. Its simplifying nature likely helped in this process, by making the concept robust and offering a simple bio-optical framework that is valid for the vast majority of the ocean.

It also proved instrumental in fostering the rapid growth of marine bio-optics and ocean color science since the late 1970s, in particular in the context of large-scale and global characterizations of phytoplankton distributions and dynamics from satellite ocean color observations.

The case I/case II classification is sometimes made equivalent to concepts of optically complex coastal case II waters compared with simpler open-ocean case I waters. However, this equivalence ignores the full complexity of variations in the absorption and scattering properties of case I waters (Mobley et al. 2004) and shows that the schematic representation of the bio-optical variability offered by this classification can be misinterpreted. We consequently review below some of the common misconceptions in the literature about what case I and case II waters are. By doing so—i.e., by identifying what we think are erroneous definitions—we try to circumvent the difficulty mentioned above of giving a single definition that would be in keeping with André's thinking.

One potential misinterpretation is that case I waters are those where optical properties are determined only by phytoplankton (or chlorophyll *a*). This misinterpretation stems from ignoring the facts that "chlorophyll-like pigment concentration is used as an index to quantify the algal material (living and detrital)" (Morel 1988) and that "in both cases dissolved yellow substance is present in variable amounts and also contributes to total absorption" (Morel & Prieur 1977), where "both cases" refers to phytoplankton-dominated waters and waters where inorganic particles are dominant. This notion of an index is central, and is related to the covarying nature of phytoplankton and associated optically significant substances. The key point is that [Chl] can be used as a single index of changes in optical properties owing to the covariation of other optically significant substances.

Another example of misinterpretation equates case I waters with clear open-ocean waters. As long as the covariation mentioned above is maintained over a large [Chl] range, green waters can still be part of the case I family (Morel et al. 2006). In contrast, clear waters affected by significant input of mineral particles are no longer described adequately as case I waters, for instance, when significant events of atmospheric dust deposition occur in subtropical gyres. Similarly, case I waters have often been thought of as necessarily being offshore waters far from the coast. However, nothing prevents coastal waters from being case I as long as there is no significant resuspension of bottom sediments and/or terrestrial input of suspended particles or dissolved substances (e.g., sufficient depth, no major riverine discharge).

Defining case I waters based solely on which constituents are present is another, admittedly subtler, misinterpretation. Case I waters contain everything from viruses to bacteria, phytoplankton of different groups, detrital particles of various types and sizes, and dissolved substances. In that regard, the sole difference observed in case II waters would be the addition of exogenous particles and dissolved substances of either mineral or biological origin. What makes waters belong to the case I category is (*a*) the local and biologically driven origin of all materials; (*b*) the dominance of phytoplankton with respect to other substances in determining seawater optical properties, in particular absorption (sensu Morel & Prieur 1977); and (*c*) the consistency of variability in seawater optical properties with predictions from global bio-optical models relating optical properties to [Chl] (e.g., Morel 1988). If waters belong to case I when they respect bio-optical relationships established from globally distributed data sets—e.g., the chlorophyll *a* versus blue-to-green reflectance ratio—then how do we classify a water body that does not respect these relationships but does match the first two criteria? Is it no longer a case I water, or is the model against which we evaluate it actually too restricted in scope? This question illustrates the importance of realizing that bio-optical models evolve with the growth of global databases (e.g., Lee & Hu 2006), which include more and more data collected in regions undersampled in the past (e.g., polar waters), collected under special environmental conditions (e.g., during coccolithophore blooms), or collected in areas such as the Mediterranean Sea, where optical properties often depart from predictions of previously established global models (Morel et al. 2007a).

From Optics to Biogeochemistry: Bio-Optical Modeling of Case I Waters

Morel & Prieur (1977) provided the first comprehensive analysis of variations in ocean reflectance, a key to applications of satellite ocean color imagery. This analysis was made in relation to absorption and backscattering coefficients of major optically significant components of seawater. Specifically, it showed how absorption and scattering by phytoplankton, nonliving particles, dissolved organic matter, and water molecules affect the magnitude and spectral shape of ocean reflectance. It also discussed the spectral dependence of the various components of absorption and scattering with remarkable precision, given that little was known at that time about some of these optical properties. Another important insight in this paper was the suggestion that the reflectance maximum observed around 685 nm is produced by solar-stimulated fluorescence of chlorophyll *a*. The paper also contributed to the validation of the relationship between reflectance and the backscattering-to-absorption ratio through comparisons between in situ measurements and theoretical reflectance spectra calculated from backscattering and absorption. The relationship between ocean reflectance and seawater IOPs (i.e., backscattering and absorption coefficients) is the cornerstone for interpretations and modeling of ocean color.

In the early 1980s, André proposed a relationship between the scattering coefficient at 550 nm and [Chl] (Gordon & Morel 1983). In situ data show the nonlinear relationship between these two quantities, as well as a large dispersion of the scattering data at any given [Chl] (by a factor of about 3). A reassessment of this relationship with a more recent, larger, and more consistent (with respect to methodology) data set supported the presence of these features and allowed Loisel & Morel (1998) to explain them in terms of variable contributions of algal and nonalgal (detrital and/or heterotrophic) particles to light scattering. More recently, this relationship was reevaluated and extended to the clearest oceanic waters on the basis of measurements with in situ optical profilers along an 8,000-km transect in the eastern South Pacific (Huot et al. 2008). This work also documented for the first time the relationship between the backscattering coefficient and [Chl] over a broad range of [Chl], from ultraoligotrophic to eutrophic waters.

In another major contribution covering the links between optical properties of case I waters and their biogenic content (Morel 1988), André reviewed and synthesized the progress that had resulted from improved in situ measurements and bio-optical knowledge over the decade that followed the papers in the 1970s and 1980s. That work addressed the prediction of the spectral diffuse attenuation coefficient for downward irradiance and the irradiance reflectance from [Chl], including considerations about heating rate and PP within the water column. A key part of this paper was the introduction of a forward semianalytic model that predicts a reflectance spectrum for a given [Chl] [in the same year, Gordon et al. (1988) also proposed a forward reflectance model based on the relationship between reflectance and IOPs]. The model was constructed on the basis of the relationship between reflectance and the ratio of backscattering to absorption coefficients, and is designed for case I waters. The diffuse attenuation coefficient for downward irradiance, the scattering coefficient at 550 nm, and the spectral dependence of the backscattering coefficient are all expressed as functions of [Chl]. This model was later revised owing to the availability of new and more diverse field data sets and improved theoretical knowledge (Morel & Maritorena 2001) (**Figure 2**). The model's relevance and usefulness are demonstrated by its many uses in ocean-color-related applications, from the verification of consistency between field measurements of IOPs and AOPs to remote sensing algorithm development (e.g., the MERIS chlorophyll *a* algorithm; Morel et al. 2007c) and vicarious calibration of satellite sensors (Werdell et al. 2007).

The above-described work represents some of André's major contributions in the area of modeling and analysis of bio-optical properties of the ocean. He also conducted many other bio-optical studies, which focused on particular aspects of IOPs (Morel 2009) and on extending the

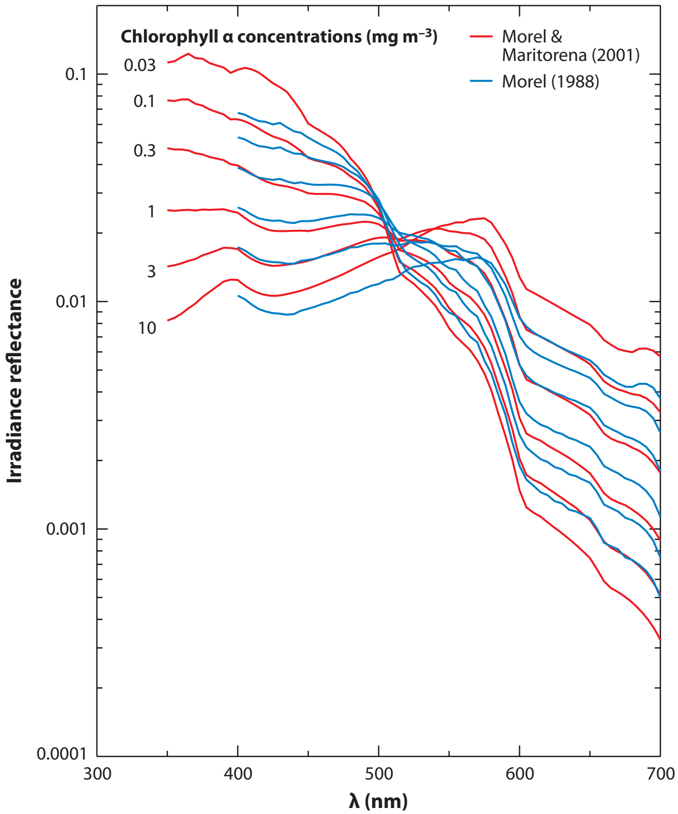

Figure 2

Modeled spectra of irradiance reflectance (dimensionless) for various chlorophyll *a* concentrations (in milligrams per cubic meter). Adapted from Morel & Maritorena (2001).

reflectance model into the UV spectral region (Morel et al. 2007a,b, 2010). He was also involved in the parameterization of particulate and algal absorption coefficients as functions of [Chl] (Bricaud et al. 1995, 1998) and the estimation of [Chl] and CDOM absorption from vertical profiles of radiometric quantities acquired by profiling floats (Xing et al. 2011, 2012). Interestingly, toward the end of his career he devoted much consideration to the influence of CDOM in case I waters (Morel & Gentili 2009a,b, Morel et al. 2010). When teased about why it took him so long to start looking at the role of CDOM in altering ocean color when his laboratory is by a sea where CDOM is an important optical component, he answered with a wink, "I swim in the Mediterranean all the time, but I went to sea everywhere else!" The modeling of absorption and backscattering properties of case I waters and their relationship with reflectance remained a major aspect of André's work throughout his career, with implications for research in ocean biogeochemistry and applications of ocean color remote sensing, as presented in the next two sections.

Light for Life: Photosynthesis and Primary Production

Most of the sunlight that enters the ocean and is not scattered back to the atmosphere ends up being transformed into heat after absorption by water molecules or other optically significant substances. Only a small fraction of the absorbed light supports photochemical reactions, i.e., transformation of electromagnetic energy into chemical energy. Photosynthesis is the most important of such reactions taking place within the ocean. This reaction is responsible for marine PP and represents the main input of energy into marine ecosystems—hence the great interest in its study. Soon after the introduction of analytical protocols for measuring PP, based either on oxygen production or on radiolabeled carbon fixation (reviewed in Geider & Osborne 1992), it became clear that these methods were so time consuming that they would not allow appropriate documentation of the space and time variations of PP in the ocean. Therefore, during the 1950s and 1960s, modeling approaches emerged that evolved from empirical relationships between PP and available light and phytoplankton biomass (e.g., Ryther & Yentsch 1957) to more mechanistic models accounting explicitly for the propagation of light through the water column and the conversion by phytoplankton of absorbed light into chemical energy (organic carbon) using photosynthesis-versus-irradiance (P-versus-E) relationships (e.g., Fee 1969). With the advent of ocean color remote sensing from space at the end of the 1970s, monitoring of PP at a global scale became possible. Therefore, much effort was made to develop PP models that could be applied to remote sensing data.

André contributed greatly to that effort, especially by (*a*) accounting for the spectral nature of light in its use by phytoplankton (Morel 1978, 1982; Jitts et al. 1976), (*b*) parameterizing light propagation through the water column (Morel 1988, Morel & Maritorena 2001), (*c*) parameterizing the vertical distribution of [Chl] (Morel & Berthon 1989, Uitz et al. 2006), and (*d*) providing one of the first estimates of global PP based on ocean color remote sensing (Antoine & Morel 1996, Antoine et al. 1996) using the fully spectral semianalytical PP model that he had developed and validated (Morel 1991, Berthon & Morel 1992, Babin et al. 1996, Morel et al. 1996).

In his article "Available, Usable, and Stored Radiant Energy in Relation to Marine Photosynthesis" (Morel 1978), André distinguished between photosynthetically available, usable, and stored radiation (PAR, PUR, and PSR, respectively). PAR is scalar irradiance [$\mathring{E}(\lambda)$] integrated between 400 and 700 nm at any depth in the water column. PUR is the convolution of $\mathring{E}(\lambda)$ by the absorption coefficient of phytoplankton [$a_\phi(\lambda)$] normalized to its maximum (a_{max}, generally observed around 443 nm). PSR is the energy equivalent of the organic carbon produced by photosynthesis. PUR accounts for the highly variable spectral shape of $\mathring{E}(\lambda)$ from the top to the bottom of the euphotic zone (Z_{eu}), which is the depth at which PAR is reduced to 1% of its value at the surface. This depth varies greatly depending on IOPs, from a few meters to a maximum of 170 m observed in the South Pacific gyre (Morel et al. 2007b). When Z_{eu} is calculated on the basis of PAR, the percentage of PUR at that depth with respect to its surface value varies within a factor of 3 depending on the trophic status (eutrophic as opposed to oligotrophic).

The PUR concept has inspired many oceanographers dealing with PP modeling and/or phytoplankton photophysiology. It has been used qualitatively to interpret observed variations in PP and quantitatively to express light level and to define parameters of the photosynthesis-versus-light curve (e.g., Morel 1991, Arrigo & Sullivan 1994). André also introduced the concept of effective phytoplankton absorption (a_{eff}, now more commonly denoted by $\bar{a}$), which is the convolution of $\mathring{E}(\lambda)$ by the absorption coefficient of phytoplankton (not normalized, as in the case of PUR) divided by PAR (Morel 1978). As a consequence, the product of a_{eff} and PAR provides the actual amount of light absorbed by phytoplankton. Although PUR and a_{eff} both reflect the spectral convolution of irradiance and phytoplankton absorption, only the latter accounts for the effect of changes in the magnitude of $a_\phi(\lambda)$. Morel et al. (1987) discussed the nuanced distinction between PUR and a_{eff} in a validation of the PUR concept based on laboratory experiments conducted on diatom cultures. They argued that $a_{max} \cdot \text{PUR} = a_{eff} \cdot \text{PAR}$, which implies that a_{max} must be known when using PUR instead of PAR to express the P-versus-E relationship. The PUR concept introduced by André (Morel 1978) indicated a clear need to account for the spectral nature of light when estimating PP in various waters and at different depths. André proposed a spectral model of the diffuse attenuation coefficient of downward irradiance [$K_d(\lambda)$] in 1988 to a large extent to address this problem (Morel 1988, revisited in Morel & Maritorena 2001).

André also addressed another difficulty in estimating PP from ocean color remote sensing, which arises from determination of the vertical distribution of [Chl] within the water column when only the surface value of [Chl] is known. Cullen (1982) showed that the occurrence of a deep chlorophyll maximum (DCM) is a common feature in the ocean. It often results from the interplay between phytoplankton, vertical light attenuation, vertical stratification, and nutrients. A satellite remote sensor does not sense the DCM, however. To account for the presence of a DCM when estimating PP, Sathyendranath & Platt (1989) proposed a Gaussian model with constant parameter values for given biogeochemical provinces later defined by Longhurst et al. (1995). Following André's intuition, Morel & Berthon (1989) proposed another approach, where the parameters of the Gaussian model vary as a function of remotely sensed [Chl] according to statistical relationships found on the basis of in situ data. This model produces a smooth transition from a nearly uniform [Chl] profile in eutrophic waters to a profile with a pronounced DCM in oligotrophic waters. This parameterization was first developed using a large in situ data set of [Chl] measured by fluorometry and spectrophotometry. Its robustness was later confirmed using more recent [Chl] data obtained by high-performance liquid chromatography (Uitz et al. 2006).

The PP model published by André (Morel 1991) builds on the three major innovations described above: a photosynthetic model that accounts for the spectral nature of underwater light, a spectral model for propagation of irradiance in the water column, and an explicit representation of the [Chl] vertical distribution. Moreover, the latter two stand upon statistical relationships with remotely sensed [Chl]. These are the pillars of the PP modeling approach developed by André.

A Global View: Ocean Color Remote Sensing

After the pioneering work by Clarke et al. (1970), the first satellite ocean color sensor—the CZCS—was launched aboard the Nimbus 7 satellite in October 1978. At that time, André was working with the CZCS team and had emerged as one of the leaders of the ocean color scientific community together with several US colleagues, in particular Howard Gordon, with whom he had established a close collaborative relationship. In their first joint paper (Morel & Gordon 1980) and in another paper he published that same year (Morel 1980), one can find most elements that are critical for interpreting remotely sensed radiance at the top of the atmosphere in the visible spectrum, paving the way for future steps of André's work in this area. A review published soon afterward (Gordon & Morel 1983) has served and still does serve as a useful reference text for students and scientists interested in ocean color remote sensing.

Many results of André's research have found application in the inversion of ocean color remote sensing observations. The bio-optical relationships proposed by Gordon & Morel (1983) were used by Bricaud & Morel (1987) to propose the first coupled ocean-atmosphere atmospheric correction scheme for CZCS observations. This scheme was later refined (André & Morel 1991) using the Morel (1988) forward reflectance model. When applied to satellite imagery, these correction schemes also allowed discrimination between case I and case II waters on a pixel-by-pixel basis. They opened the way to iterative atmospheric correction procedures (so-called spectral matching or spectral optimization techniques; e.g., Chomko & Gordon 2001, Chomko et al. 2003), which are based on coupling an ocean reflectance model with a model of the atmospheric signal. Several theoretical studies on optical processes within the atmosphere also led to improved atmospheric correction procedures for more recent ocean color satellite sensors, such as MERIS (André & Morel 1989; Antoine & Morel 1998, 1999).

André's studies on the bidirectional structure of upward radiance distributions (see Apparent Optical Properties: A Sea of Photons, above) have led to the development of lookup tables of factors describing the bidirectional reflectance (the so-called *f/Q* ratio), which were implemented to process observations of historical (CZCS) and more recent satellite sensors (Antoine et al. 2003, 2005; Werdell et al. 2007). The incorporation of varying *f* and *Q* factors allows normalization of the water-leaving radiance, which is fundamental to improving the consistency among radiances across a given satellite image with varying illumination and observing geometry as well as among radiances obtained with different sensors. This is a necessary step for achieving a meaningful merging of radiance data obtained from different satellite missions. André's work on ocean color remote sensing dealt with case II waters essentially to identify them, in order to avoid applying case I water algorithms in such inappropriate conditions (Bricaud & Morel 1987, Morel & Bélanger 2006, Morel & Gentili 2008).

One of the major outcomes of André's work on marine photosynthesis (see Light for Life: Photosynthesis and Primary Production, above) is the satellite version of the Morel (1991) spectral light-photosynthesis model. This operational version of the model uses a lookup table of the cross section for photosynthesis per unit areal chlorophyll *a* content (the ψ^* parameter), which results in an efficient scheme for computing PP at a global scale from satellite imagery (Morel & André 1991, Antoine et al. 1995, Morel & Antoine 2002). This model allowed one of the first global estimates of ocean PP from the CZCS observations (Antoine & Morel 1996, Antoine et al. 1996), more or less in parallel to two similar efforts (Longhurst et al. 1995, Behrenfeld & Falkowski 1997). This model was subsequently applied to observations from NASA's Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) (**Figure 3**).

One concern of André's was ensuring consistency of scientific results, including among satellite data products derived from various bio-optical algorithms. Similarly to a work on bio-optical properties (Morel 2009; see also From Optics to Biogeochemistry: Bio-Optical Modeling of Case I Waters, above), the study by Morel et al. (2007c) discusses the potential discrepancies among [Chl] and diffuse attenuation coefficients of downward irradiance estimated from different algorithms, which also provides a context for anticipated issues arising from merging data products from different satellite sensors.

In parallel to developing algorithms for existing ocean color satellite missions, André was a strong advocate of the launch of an ocean color mission in Europe. Owing to his influence and his connections with the US community, around 1985–1986 the French space agency (Centre National d'Etudes Spatiales) seriously examined the possibility of launching an ocean color instrument aboard the SPOT 3 satellite. This instrument was proposed by NASA investigators and named the Ocean Color Imager. This project did not actually materialize. It was only about 15 years later that the European Space Agency (ESA) launched the MERIS instrument on the Environmental Satellite (ENVISAT; 2002–2012). André was instrumental in these efforts, which allowed the development of solid expertise in satellite ocean color remote sensing within a broad European community of scientists and engineers. The ENVISAT mission has built the foundation for the upcoming ESA Sentinel missions, which will carry the Ocean and Land Color Imager instrument from 2015 onward. This mission will provide the European and international scientific communities with a long-term capability for ocean color remote sensing.

André was also involved in creating the International Ocean Color Coordinating Group (IOCCG), which began its activities in 1996 and has played an important role as one of the major discussion arenas for the international ocean color community. He served on the IOCCG until 2010.

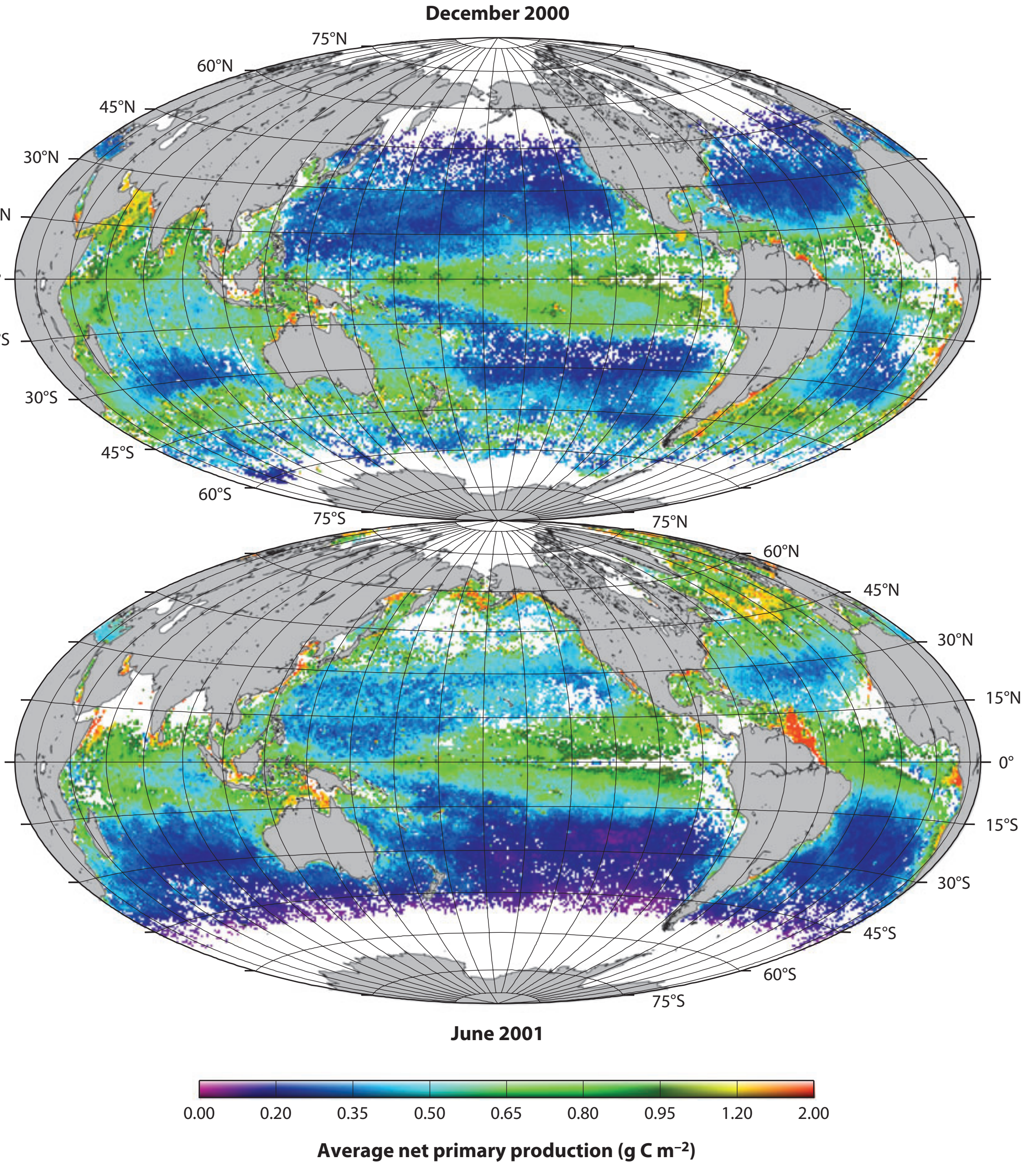

Figure 3

Average net primary production, expressed on a per-day basis, computed from Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) imagery using the Morel (1991) model adapted by Antoine et al. (1996) for the month that marks the end of spring in each hemisphere. Noteworthy features include the alternation of the vernal bloom, with high production in June in the North Atlantic and North Pacific and in December along the subtropical convergence (40°S). The divergence along the equator induces an enhanced productivity, which was dramatically affected in the Pacific during the 1997–1998 El Niño/La Niña event, as recorded by SeaWiFS. Adapted from Morel & Antoine (2002).

LEGACY

An obvious legacy from André's work are papers that have been cited many hundreds of times and still form part of the syllabus that any student should read when learning marine optics and bio-optics (e.g., Morel 1973, 1974, 1978, 1988, 1991; Morel & Prieur 1977). A broader impact, however, emerges from André's research, which is more than simply the succession of particular studies.

First, the chlorophyll-based approach can be seen as the backbone of André's contributions to marine bio-optics. The underlying idea is that optical properties evolve as a continuum along with the average trophic state of the upper ocean, which itself can be described by a single index: [Chl]. The great development of ocean color remote sensing owes much to the pertinence of this approach, which carries useful information about the variability and trends in the average bio-optical state of the ocean. However, actual observations scatter around the chlorophyll-based bio-optical relationships. As this seemingly random noise represents the actual natural variability, there is still much to learn from it to achieve a more complete understanding of bio-optical variability in the ocean. This line of research has been developing substantially in recent years.

Developing such a unified chlorophyll-based scheme for bio-optical research was likely coming from a sense that nature follows a certain organization and that this is what we should try to decipher as scientists. It might also be that this vision was more coherent with André's artistic talents, as when one tries to organize different colored elements to create a coherent and aesthetically pleasing picture. One lesson from this is that it is important to strive toward generalized relationships of sufficient global validity and applicability. This is needed for the interpretation of basin-scale and global phenomena as well as the interpretation of satellite ocean color observations that, by definition, are of a global nature. This quest for generalization should not deter us, however, from investigating the details of various possible local bio-optical situations, especially when it comes to case II waters. Another lesson from the imprint of the case I/case II classification is that unifying paradigms provide guidance and allow significant scientific progress. These paradigms are not set in stone, yet they should be kept alive and properly taught and utilized until new paradigms replace current ones when they have reached maturity.

André also contributed significantly to developing solid physical grounds for "ocean color" science. This somewhat poetic depiction sometimes seemed to carry a sense of amateurism as viewed by other scientific communities. How to remedy this limiting perception was debated for a long time, in particular under the auspices of the IOCCG, which led to the proposal of the term ocean color radiometry. This debate could be seen as somewhat specious and useless, yet it was actually needed to anchor ocean color remote sensing in environmental physics and to give it a respected position in the panorama of Earth remote sensing techniques, next to (for example) radar altimetry and passive thermal infrared radiometry. In the same vein, André was not particularly fond of the term ocean color imagery, as it may carry the idea of a qualitative, subjective interpretation of ocean color observations. He always defended the view that radiometric signals should be interpreted physically and quantitatively.

When looking at how André obtained the many important results he published throughout his career, we can say that he has beautifully illustrated how a man can challenge his senses and intelligence, and, by making good use of a few tools, generate original concepts, ideas, and practical realizations that shape his "environment" (in this case, the scientific domain of optical oceanography and related people). We can think about this in light of our modern science, which uses many sophisticated tools but not necessarily with the same intelligence or efficacy.

André was a great teacher in physics, RT, general oceanography, and the Earth radiation budget. His lectures were greatly appreciated, as was his receptiveness to students' questions after hours and in the laboratory, where his office door was always open to anyone willing to discuss some scientific issue or any other subject. He was a mentor to us and to many others within the international community who owe much of their education in ocean optics and ocean color science to him. His high level of rigor led him to challenge us to do our best. This was sometimes difficult. As students, we were obliged to repeatedly redo our work and manuscripts until they satisfied André's high standards. This aspect of his legacy deserves great appreciation, as we all know how important it is to keep up high standards in research and scientific practice. It actually appears that André achieved an optimal symbiosis of scientific and literary capabilities, both of which are necessary to become an accomplished scientist. His imprint on our community can be measured in the light of the number of his former students and collaborators who contribute today to optical oceanography across the world. This was also obvious through the hundreds of messages of sympathy received from abroad when he passed away.

André's knowledge extended far beyond the scientific fields of oceanography and marine optics. He was a man of vast cultural intellect and knowledge, with amazing erudition in a variety of subjects, ranging from politics to literature and fine arts. We often felt ourselves terribly uncultured when discussing such things with him. However, André was always willing to impart some of his knowledge to us under such circumstances. He could play piano and guitar, was an expert on lepidopterans (butterflies), and was an avid skier and swimmer. His artistic skills resulted in numerous watercolors and oils. He was a wonderful man, and we know that all those who have had a chance to work with him, or simply to be with him at some point, share the sentiment of a terrible loss.

André would encourage us all to look forward, just as he always did. And, at times when we may on occasion be overly focused on science, his memory should encourage us to keep an open mind, to be capable of seeing what is happening around us, and to be constantly surprised by what is revealed as we learn every day from our work.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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