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A bio-optical model for integration into ecosystem models for the Ligurian Sea

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ABSTRACT

A bio-optical model has been developed for the Ligurian Sea which encompasses both deep, oceanic Case 1 waters and shallow, coastal Case 2 waters. The model builds on earlier Case 1 models for the region and uses field data collected on the BP09 research cruise to establish new relationships for non-biogenic particles and CDOM. The bio-optical model reproduces *in situ* IOPs accurately and is used to parameterize radiative transfer simulations which demonstrate its utility for modeling underwater light levels and above surface remote sensing reflectance. Prediction of euphotic depth is found to be accurate to within ~3.2 m (RMSE). Previously published light field models work well for deep oceanic parts of the Ligurian Sea that fit the Case 1 classification. However, they are found to significantly over-estimate euphotic depth in optically complex coastal waters where the influence of non-biogenic materials is strongest. For these coastal waters, the combination of the bio-optical model proposed here and full radiative transfer simulations provides significantly more accurate predictions of euphotic depth.

1. Introduction

The temporal and spatial variability of oceanic optical properties are fundamental to many biogeochemical processes in the sea (Dickey and Falkowski, 2002). Underwater light fields regulate photosynthesis, contribute to solar heating and determine remotely sensed ocean colour signals. In recent years it has become increasingly apparent that coupled physical-ecosystem models require appropriate representation of the underwater light field, particularly in the context of using ocean colour remote sensing data for assimilation and validation (Rothstein et al., 2006; Dickey et al., 2006; Fujii et al., 2007). Advances in computing power and availability of fast and accurate radiative transfer models (e.g. Ecolight, Sequoia Scientific) offer the potential to incorporate comprehensive light field models into aquatic ecosystem models, with the promise of significant improvements in the prediction of biogeochemical and physical properties (Mobley et al., 2015).

Early attempts to integrate light field models into coupled ecosystem models tended to use very basic approaches to modeling the underwater light field. For example, Beşiktepe et al. (2003) used chlorophyll concentration (*Chl*) and the Lambert-Beer law to obtain attenuation coefficients and from this estimated underwater light fields. Penta et al. (2008, 2009) adapted the innovative method of Lee et al. (2005) to obtain underwater light attenuation for marine ecosystem models. Recent studies have adopted more sophisticated approaches to model underwater light fields (e.g. Fujii et al., 2007; Shulman et al., 2013; Ciavatta et al., 2014). Future efforts, incorporating full solution of the radiative transfer equation, will require parameterization with a complete set of inherent optical properties, *IOPs* (Trees et al., 2012). Moreover, there will be a need to relate these IOPs to relevant ecosystem model currencies in order to track evolution of the light field in time and space with changes in physical and biogeochemical properties of the system. Considerable effort has already gone into the development of bio-optical models for different natural water systems (Prieur and Sathyendranath, 1981; Gordon and Morel, 1981; Morel, 1988, 2009; Bricaud et al., 1995, 1998; Loisel and Morel, 1998; Morel and Maritorena, 2001; Vellucci, 2007).

Most bio-optical models are constructed using optically significant constituents (*OSC*) as currency terms, with typical components such as: phytoplankton, detrital or non-algal particles and coloured dissolved organic material (*CDOM*). Even such a simple scheme presents difficulties in terms of relating optical variables to parameters that can be included in an ecosystem model currency scheme. Phytoplankton is the least awkward component,

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usually being represented by chlorophyll concentration as a proxy currency. The remainder of the particle population is much harder to define. In oceanic systems, operating under the Case 1 definition, other particles may be assumed to be derived from the phytoplankton population, e.g. detrital particles and associated bacterial populations, and these might also be related to *Chl*. However, in shallow coastal waters there is also the potential for significant populations of non-biogenic particles from terrigenous sources or from benthic resuspension. These particles are unlikely to be related to *Chl* and must, instead, be represented by some measure of total suspended solid concentration (*TSS*). However, given the contribution from phytoplankton and associated biogenic materials to *TSS*, there is an *a priori* requirement for consideration of further refinement of this parameterization to account for the complex nature of the particle population. *CDOM* is also problematic when considering Case 1 versus Case 2 scenarios. Under the Case 1 approach, *CDOM* is assumed to be a product of algal-related biological activity and has been successfully related to *Chl* for oceanic waters (Prieur and Sathyendranath, 1981; Bricaud et al., 1998). However, coastal areas subject to riverine inputs will present *CDOM* signals that are unrelated to *Chl*. Here there are grounds for investigating the potential of relating *CDOM* signals to salinity given the association with freshwater inputs (e.g. Bowers et al., 2000 and references therein).

The study area for this paper is the Ligurian Sea, which is located in the northwestern part of the Mediterranean Sea between southeast France, northwest Italy and the island of Corsica (Fig. 1). This is an area which has been extensively studied previously with well-established circulation patterns, e.g. Astraldi and Gasparini (1992). Cyclonic circulation in the Ligurian Sea leads to the formation of three distinct hydrological zones; a thermal front (frontal zone) which separates less dense warm coastal peripheral water (coastal zone) from denser cold offshore water (central zone) (Picco et al., 2010 and references therein). These structures are

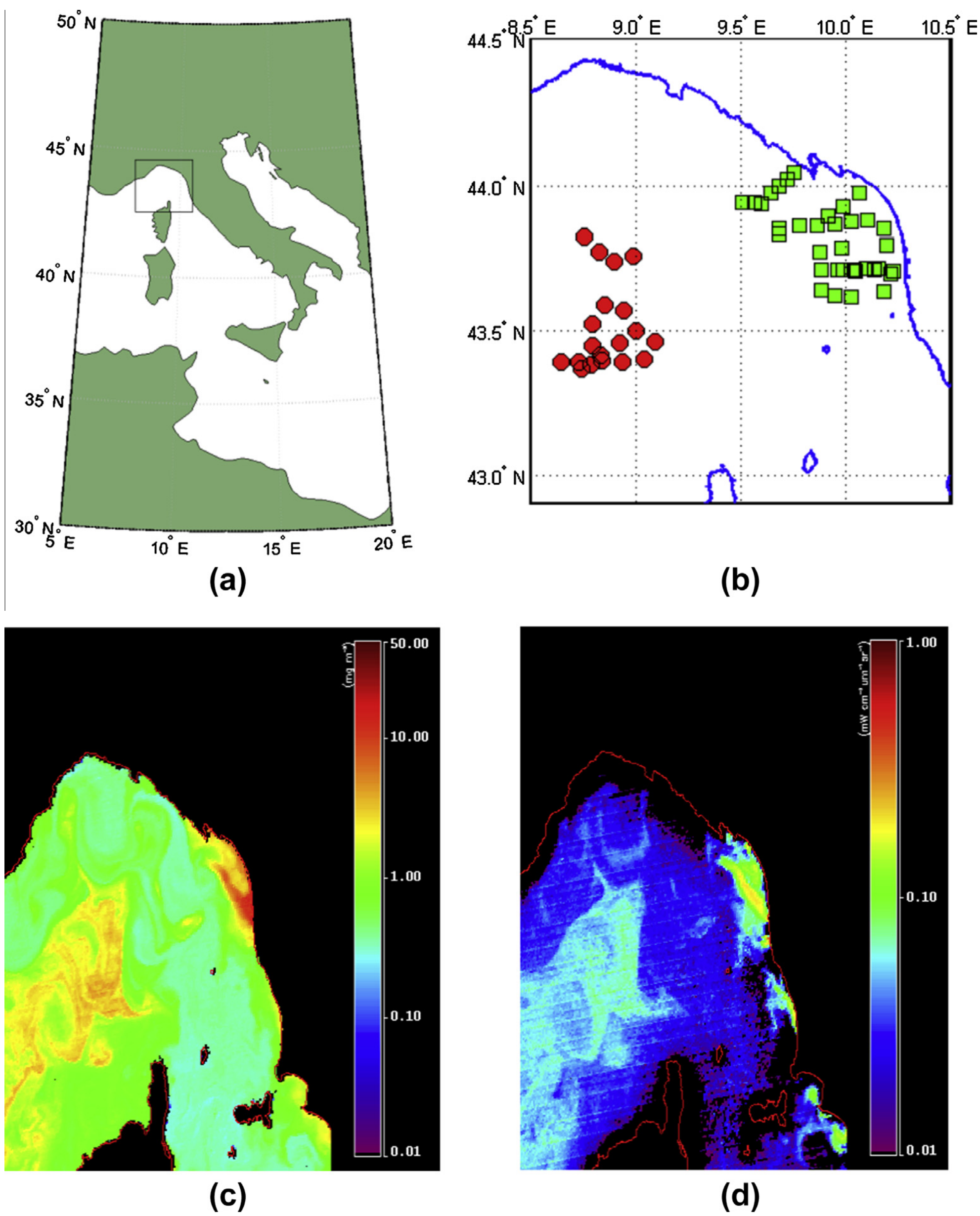

Fig. 1. (a) Study area and (b) location of offshore (circles) and onshore (squares) stations for the BP09 cruise. (c) MODIS standard *Chl* from 18th March 2009 shows a bloom in the central region of the Ligurian Sea, northwest of Corsica. The high intensity "bloom" on the Italian coast is actually a sediment plume from the River Arno, which is clearly identified from (d) MODIS *nLw667* from the same date.