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Radiative transfer modeling of upwelling light field in coastal waters

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ABSTRACT

Numerical simulations of the radiance distribution in coastal waters are a complex problem, but playing a growingly important role in optical oceanography and remote sensing applications. The present study attempts to modify the Inherent Optical Properties (IOPs) to allow the phase function to vary with depth, and the bottom boundary to take into account a sloping/irregular surface and the effective reflectance of the bottom material. It then uses the Hydrolight numerical model to compute Apparent Optical Properties (AOPs) for modified IOPs and bottom boundary conditions compared to the default values available in the standard Hydrolight model. The comparison of the profiles of upwelling radiance simulated with depth-dependent IOPs as well as modified bottom boundary conditions for realistic cases of coastal waters off Point Calimere of southern India shows a good match between the simulated and measured upwelling radiance profile data, whereas there is a significant drift between the upwelling radiances simulated from the standard Hydrolight model (with default values) and measured data. Further comparison for different solar zenith conditions at a coastal station indicates that the upwelling radiances simulated with the depth-dependent IOPs and modified bottom boundary conditions are in good agreement with the measured radiance profile data. This simulation captures significant changes in the upwelling radiance field influenced by the bottom boundary layer as well. These results clearly emphasize the importance of using realistic depth-dependent IOPs as well as bottom boundary conditions as input to Hydrolight in order to obtain more accurate AOPs in coastal waters.

1. Introduction

Over the past two decades, major advances in radiative transfer theory (RTE) have enabled a realistic numerical simulation of the underwater light field [1]. In order to fully extract the information of oceanic constituents, several RTE models have been proposed based on the various initial conditions for representing the physical processes. These numerical techniques are nowadays routinely used for computing underwater light fields or for generating extensive look-up-tables for remote sensing applications [2]. Numerical simulation results such as underwater irradiance and radiance distributions are important in remote sensing applications and solving the optical oceanographic problems [3–5].

Computing the in-water light field is inherently a challenging task particularly in coastal waters, where the optically active constituents affect the light propagation either by attenuation or by redirection due to various types of interactions such as absorption, scattering and emission that occur in natural waters [6,7]. The light interactions with water molecules, chlorophyll-contained particles, suspended sediments (inorganic and organic nature), and colored dissolved organic matter are fascinating because the concentration and composition of each of these constituents greatly affect underwater light fields, resulting in significant variation of these light fields along the depth. The optical properties of waters containing these constituents can be

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grouped into inherent and apparent optical properties; Inherent Optical Properties (IOPs) are those properties that depend only upon the medium and therefore are independent of the ambient light field (e.g., the absorption coefficient and the volume scattering function), whereas Apparent Optical Properties (AOP) are those properties that depend both on the medium (the IOPs) and on the directional structure of the ambient light field (e.g., irradiance reflectance, remote sensing reflectance and various diffuse attenuation functions) [1]. Due to the natural variability of these optical properties of the optically active constituents in the coastal ocean, a large number of bio-optical models are required to estimate IOPs namely the absorption coefficient, the scattering coefficient or the scattering phase function. The bio-optical models to estimate these properties take into account the concentration of chlorophyll, suspended sediments and colored dissolved organic matters [8–12]. A realistic simulation of in-water light fields mainly depends on the IOPs which are incorporated in the radiative transfer equation (RTE).

Apart from the IOPs, the radiative transfer model also relies on the type of the bottom material and bottom slope (irregular bottom) that are considered as boundary conditions. When evaluating the bottom boundary condition, the reflectance of the bottom not only depends on the material type from a flat Lambertian surface, but is also highly influenced by the bottom morphology. In this case, the effective bottom reflectance is considered to be a function of the effect of bottom morphology as well as the material reflectance [13–15]. In the water column, the concentration of particulate materials (both organic and inorganic) often varies along the depth, but the phase function effects on light fields along the depth are often ignored. However, an evaluation of the phase function effects on oceanic light fields indicates that the Fournier–Forand (FF) analytical model performs better than other models, although being considered as a constant along the depth [16]. Thus, it becomes necessary to allow the phase function to vary with depth.

The present study focuses on modifying the IOPs (with improved formulations) to allow the FF phase function to vary with depth, and the bottom boundary to take into account a slopping (irregular) bottom and the effective reflectance of the bottom material. It then uses the Hydrolight numerical model to compute upwelling radiance fields for modified IOPs and bottom boundary conditions compared to the default values available in the standard Hydrolight model. Finally, a comprehensive comparison is made between the simulated and in-situ upwelling radiance fields obtained at different coastal stations and for different solar zenith conditions as well.

2. Materials and methods

2.1. Cruise details

In-situ data were collected from around 30 stations in coastal waters off Point Calimere located in the southern part of India. Fig. 1 shows the location map and sampling stations of those in-situ data collected during the summer cruise (13–23 May, 2012). A wide range of optical conditions was sampled from moderately clear waters to highly turbid waters. Time series measurements and sampling at a coastal station were also conducted to study diurnal/temporal fluctuations of the underwater light fields in turbid waters. The environmental parameters such as wind speed, cloud condition, and water depth were also recorded for each station. The details of station locations are shown in Fig. 1 and Table 1.

2.2. Measurement of inherent optical properties

The in-water profiles of inherent optical properties were obtained by the WETLAB sensors, namely ACS, BB9, FLNTU, and CTD (DH4 used for data collection). These sensors mounted on a frame were lowered with help of a winch system and a single cable was used for transmitting data and power to the instrument. The data from these instruments were acquired on a PC from the deck. The AC-S was used to measure the particulate absorption a_p and particulate attenuation coefficients c_p in the entire visible wavelength domain as a function of depth. The instrument contains two paths for the flow of water; where one path measures the absorption coefficients and the other measures the attenuation coefficients. There is a light source with a filter wheel arrangement at the end of each tube to provide independent source of light at different wavelengths. The flow tube to measure c_p has a blackened surface to absorb all scattered light. The light through this path is thus subject to loss by absorption and scattering processes. The absorption path contains a reflective tube that reflects all light that is forward scattered. The light that only suffers a loss by absorption is collected at the other side of the tube by a diffuse detector. Thus one can obtain values of a_p and c_p at different wavelengths while the water flows through the tubes. A small pump is attached to the instrument to provide constant flow of water through both tubes [17]. The particulate scattering coefficient (b_p) was obtained by subtracting the absorption coefficients from attenuation coefficients ($c_p - a_p$). The total absorption (a) and

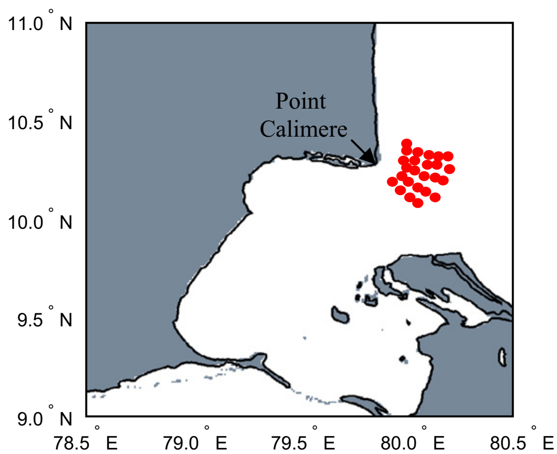

Fig. 1. Map of the sampling locations in coastal waters off point Calimere in southern India (Cruise period, 13–23 May 2012).