Progress in Oceanography 159 (2017) 45–72

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Review

Uncertainties and applications of satellite-derived coastal water quality products

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ARTICLE INFO

Keywords:
Light absorption
Light scattering
Light backscattering
Water-leaving radiance
Remote-sensing reflectance
Water quality
Pollutants
Pathogens
Chlorophyll
Suspended particles
Suspended sediment
Chromophoric dissolved organic matter

ABSTRACT

Recent and forthcoming launches of a plethora of ocean color radiometry sensors, coupled with increasingly adopted free and open data policies are expected to boost usage of satellite ocean color data and drive the demand to use these data in a quantitative and routine manner. Here we review factors that introduce uncertainties to various satellite-derived water quality products and recommend approaches to minimize the uncertainty of a specific product. We show that the regression relationships between remote-sensing reflectance and water turbidity (in terms of nephelometric units) established for different regions tend to converge and therefore it is plausible to develop a global satellite water turbidity product derived using a single algorithm. In contrast, solutions to derive suspended particulate matter concentration are much less generalizable; in one case it might be more accurate to estimate this parameter based on satellite-derived particulate backscattering coefficient, whereas in another the nonagal particulate absorption coefficient might be a better proxy. Regarding satellite-derived chlorophyll concentration, known to be subject to large uncertainties in coastal waters, studies summarized here clearly indicate that the accuracy of classical reflectance band-ratio algorithms depends largely on the contribution of phytoplankton to total light absorption coefficient as well as the degree of correlation between phytoplankton and the dominant nonalgal contributions. Our review also indicates that currently available satellite-derived water quality products are restricted to optically significant materials, whereas many users are interested in toxins, nutrients, pollutants, and pathogens. Presently, proxies or indicators for these constituents are inconsistently (and often incorrectly) developed and applied. Progress in this general direction will remain slow unless, (i) optical oceanographers and environmental scientists start collaborating more closely and make optical and environmental measurements in parallel, (ii) more efforts are devoted to identifying optical, ecological, and environmental forerunners of autochthonous water quality issues (e.g., onsite growth of pathogens), and, (iii) environmental processes associated with the source, transport, and transformation of allochthonous issues (e.g., transport of nutrients) are better understood. Accompanying these challenges, the need still exists to conduct fundamental research in satellite ocean color radiometry, including development of more robust atmospheric correction methods as well as inverse models for coastal regions where optical properties of both aerosols and hydrosols are complex.

1. Introduction

Coastal (marine, estuarine, and inland) zones are among the most important and valuable regions in the world from both an ecological and a socio-economic perspective. They are extremely productive, supplying living aquatic (e.g., fisheries; diverse benthic habitats) and other natural resources (e.g., oil, gas, minerals, and water). They are also hubs of commerce and transportation, and the most heavily populated and urbanized regions on earth. As such, coastal pollution is a significant and growing problem in both developed and developing nations. Contaminants such as oil, toxic chemicals, heavy metals, bacteria, viruses, nutrients, and sediments can adversely impact human health and coastal ecosystems and thus have significant environmental and socio-economic ramifications (e.g., Islam and Tanaka, 2004; IOCCG, 2008; Karydis and Kitsiou, 2013).

It can be difficult to identify sources of pollution in coastal zones, as well as monitoring and forecasting the subsequent fate, transport, and impacts of contaminants. In particular, coastal zones are interfacial regions where atmospheric, aquatic, and terrestrial domains converge (Karydis and Kitsiou, 2013) and are typically characterized by complex

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http://dx.doi.org/10.1016/j.pocean.2017.08.007
Received 12 December 2016; Received in revised form 29 August 2017; Accepted 30 August 2017

Nomenclature

Acronyms

AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
CDOM	Chromophoric Dissolved Organic Matter
Chl-*a*	Chlorophyll-*a*
DOC	Dissolved Organic Carbon
EPA	Environmental Protection Agency
FIB	Fecal Indicator Bacteria
FNRU	Formazin Nephelometric Ratio Unit
FNU	Formazin Nephelometric Unit
GCOM-C	Global Change Observation Mission-Climate
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GOCI	Geostationary Ocean Color Imager
HAB	Harmful Algal Bloom
HICO	Hyperspectral Imager for the Coastal Ocean
IOCCG	International Ocean Color Coordinating Group
IOP	Inherent Optical Property
ISO	International Organization for Standardization
JPSS	Joint Polar Satellite System
MAA	Mycosporine-like Amino Acid
MERIS	MEdium Resolution Imaging Spectrometer
MODIS	MODerate-resolution Imaging Spectroradiometer
MSI	Multi-Spectral Imager
NIR	Near-Infrared
NOMAD	NASA bio-Optical Marine Algorithm Dataset
NTRU	Nephelometric Turbidity Ratio Unit
NTU	Nephelometric Turbidity Unit
OCR	Ocean Color Radiometry
OLCI	Ocean and Land Color Instrument
OLI	Operational Land Imager
PACE	Plankton, Aerosol, Cloud, and ocean Ecosystem
PSU	practical salinity units
RGB	Red-Green-Blue (Image)
SAR	Synthetic Aperture Radar
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SeaBASS	SeaWiFS Bio-optical Archive and Storage System
SGLI	Second-generation GLobal Imager
SNR	Signal-to-Noise Ratio
SPF	Scattering phase function
SPM	Suspended Particulate Matter
SWIR	Shortwave Infrared
TOA	top of atmosphere
UV	Ultraviolet
VIIRS	Visible Infrared Imager Radiometer Suite

List of symbols

λ	wavelength of light in vacuum
a	total absorption coefficient of bulk water
a_d	absorption coefficient of organic detritus and heterotrophic microorganisms
a_g	absorption coefficient of CDOM
a_g^*	DOC-specific absorption coefficient of CDOM, $= a_g/[\text{DOC}]$
a_m	absorption coefficient of mineral particles
a_p	absorption coefficient of suspended particles
a_p^*	mass-specific absorption coefficient of suspended particles, $= a_p/[\text{SPM}]$
a_{ph}	absorption coefficient of phytoplankton
a_{ph}^*	chlorophyll-specific absorption coefficient of phytoplankton, $= a_{ph}/[\text{Chl-}a]$
a_w	absorption coefficient of pure water
b	total scattering coefficient of bulk water
b_b	total backscattering coefficient of bulk water
b_{bd}	backscattering coefficient of organic detritus and heterotrophic microorganisms
b_{bm}	backscattering coefficient of mineral particles
b_{bp}	backscattering coefficient of suspended particles
b_{bph}	backscattering coefficient of phytoplankton
b_{bw}	backscattering coefficient of pure water
b_p	total scattering coefficient of suspended particles
b_p^*	mass-specific scattering coefficient of suspended particles, $= b_p/[\text{SPM}]$
b_s	light side-scattering coefficient
b_w	total scattering coefficient of pure water
c	beam attenuation coefficient of bulk water
D	diameter parameter characterizing size of a particle
D_{V50}	median diameter of particle volume distribution
F_0	extraterrestrial solar irradiance
K_d	diffuse attenuation coefficient of downwelling irradiance
K_d^{tr}	minimum K_d of the water body within 410–665 nm
$\overline{K_d}$	average K_d within the first optical depth
L_{TOA}	radiance at top of atmosphere
L_u	upwelling radiance
L_w	water-leaving radiance
m	complex refractive index relative to water, $\equiv n + i\,n'$
n'	imaginary part of the refractive index relative to water
n	real part of the refractive index relative to water
nL_w	normalized water-leaving radiance
n_w	real refractive index of water
Q_a	single-particle absorption efficiency factor
Q_{bb}	single-particle backscattering efficiency factor
R_{rs}	remote-sensing reflectance just above water surface
r_{rs}	remote-sensing reflectance just below water surface
S_d	exponential-law spectral slope of nonalgal particulate absorption coefficient
S_g	exponential-law spectral slope of CDOM absorption coefficient
V	volume of a particle
γ	power-law spectral slope of backscattering coefficients
θ	scattering angle relative to the incident direction
θ'	underwater nadir angle of the upwelling radiance
θ_{sun}	solar zenith angle
σ_a	single-particle absorption cross section
σ_b	single-particle total scattering cross section
σ_{bb}	single-particle backscattering cross section
φ	azimuth angle of the upwelling radiance
ω_0	single-scattering albedo, $\equiv b/(a + b)$
ω_b	$\equiv b_b/(a + b_b)$

dynamics, including small-scale, ephemeral, and episodic processes and phenomena. Pollution inputs can be localized within one of these domains (e.g., an offshore oil spill that does not reach land) or else be transboundary in nature (e.g., urban or agricultural runoff discharged into an ocean or lake, or an offshore oil spill or sewage discharge transported onshore). Pollution sources can also be characterized as either “point” or “nonpoint” types. Point sources of pollution in the coastal environment are singular and localized and include discharge from a shore-based industrial or municipal wastewater treatment plant, or from a ship or other offshore structure (e.g., oil platform). Nonpoint sources of pollution in the coastal environment come from many diffuse sources and can include stormwater runoff as well as atmospheric deposition.