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On the detectability of adjacency effects in ocean color remote sensing of mid-latitude coastal environments by SeaWiFS, MODIS-A, MERIS, OLCI, OLI and MSI

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ABSTRACT

The detectability of adjacency effects (AE) in ocean color remote sensing by SeaWiFS, MODIS-A, MERIS, OLCI, OLI and MSI is theoretically assessed for typical observation conditions up to 36 km offshore (20 km for MSI). The methodology detailed in Bulgarelli et al. (2014) is applied to expand previous investigations to the wide range of terrestrial land covers and water types usually encountered in mid-latitude coastal environments. Simulations fully account for multiple scattering within a stratified atmosphere bounded by a non-uniform reflecting surface, sea surface roughness, sun position and off-nadir sensor view. A harmonized comparison of AE is ensured by adjusting the radiometric sensitivity of each sensor to the same input radiance. Results show that average AE in data from MODIS-A, and from MERIS and OLCI in reduced spatial resolution, are still above the sensor noise level (NL) at 36 km offshore, except for AE caused by green vegetation at the red wavelengths. Conversely, in data from the less sensitive SeaWiFS, OLI and MSI sensors, as well as from MERIS and OLCI in full spatial resolution, sole AE caused by highly reflecting land covers (such as snow, dry vegetation, white sand and concrete) are above the sensor NL throughout the transect, while AE originated from green vegetation and bare soil at visible wavelengths may become lower than NL at close distance from the coast. Such a distance increases with the radiometric resolution of the sensor. It is finally observed that AE are slightly sensitive to the water type only at the blue wavelengths. Notably, for an atmospheric correction scheme inferring the aerosol properties from NIR data, perturbations induced by AE at NIR and visible wavelengths might compensate each other. As a consequence, biases induced by AE on radiometric products (e.g., the water-leaving radiance) are not strictly correlated to the intensity of the reflectance of the nearby land.

1. Introduction and background

Quantitative optical remote sensing of seas and oceans started in 1978 with the launch of the NASA Coastal Zone Color Scanner (CZCS, 1978–1986). Among the ocean color sensors that followed, several ensured multi-annual observations: the NASA Sea-viewing Wide Field-of-view Sensor (SeaWiFS, 1997–2010), the NASA Moderate Resolution Imaging Spectroradiometer (MODIS-T, 1999-present on board Terra platform, and MODIS-A, 2002-present on board Aqua platform), the ESA Medium Resolution Imaging Spectrometer (MERIS, 2001–2012) and the most recent ESA Sentinel-3 Ocean and Land Color Instrument (OLCI, 2016-present). Optical remote sensing of the sea is also performed by sensors dedicated to land observations, such as the NASA Landsat-8 Operational Land Imager (OLI, 2013-present) and the ESA Sentinel-2 MultiSpectral Imagery (MSI, 2015-present). The latter acquires information of the sea only up to 20 km from the coast.

While the determination of the optical properties of the open ocean from satellite measurements is nowadays established, remote sensing of coastal waters still represents a challenge. In coastal areas the optical complexity of seawater adds to eventual perturbations from bottom and nearby land. Even more challenging are remote sensing observations of inland waters, for which contributions from the surrounding land cannot be altogether neglected. Nonetheless, apart from few focused investigations (Kiselev et al., 2015; Sterckx et al., 2015; Sei, 2015; Santer and Zagolski, 2009), standard processing techniques of ocean color data generally assume an optically homogenous underlying surface (Antoine and Morel, 1999; Gordon and Wang, 1994), thus neglecting possible top-of-atmosphere (TOA) radiance contamination between neighboring surfaces with different reflectance. The latter phenomenon is usually termed *adjacency effects* (AE) and can be quantified through the *adjacency radiance* L_{adj}, which defines the difference in the TOA radiance between the case accounting for the

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nonuniformity of the underlying reflecting surface and the case assuming a uniform surface. As such, it can vary from positive to negative values.

A methodology was recently developed to accurately simulate AE in ocean color data from coastal areas (Bulgarelli et al., 2014). Such a methodology relies on three-dimensional (3D) MonteCarlo (MC) radiative transfer simulations fully accounting for multiple scattering within a stratified atmosphere bounded by a non-uniform and anisotropic reflecting surface, sun position, off-nadir sun-sensor geometries, wind-induced sea surface roughness, and coastal morphology. Its accuracy was evaluated through comparisons with data from an alternative and extensively benchmarked numerical code based on the finite element method (FEM) (Bulgarelli et al., 1999) and with data from the literature (Sei, 2007). The methodology was applied to quantify AE at a specific test site, namely, the region of the northern Adriatic sea hosting the Aqua Alta Oceanographic Tower (AAOT, 45.31°N, 12.51°E), a validation site included in the Ocean Color component of the Aerosol Robotic Network (AERONET-OC) (Zibordi et al., 2009b) and where comprehensive bio-optical in situ measurements are collected since 1995 (Zibordi et al., 2002). The investigation also included a sensitivity analysis on commonly applied approximations (e.g., single scattering, Lambertian reflectance of the sea, nadir observation, straight coastline). For the same test site, subsequent studies addressed the biases induced by AE in radiometric products (Bulgarelli et al., 2017) and the use of quantified AE to reduce annual and intra-annual overall biases (Bulgarelli et al., in preparation).

Although the above results allow drawing general considerations on AE, quantitative estimates are still representative of the sole observation conditions typical of mid-latitude coastal regions characterized by a cropland ecosystem and Case-1 to Case-2 moderately turbid waters. Consequently, their validity cannot be generically extended to any observation condition and any coastal environment. This holds even truer for simulated AE in the right proximity of the coast, heavily influenced by the peculiar morphology of the Venice Lagoon.

A more comprehensive picture of adjacency perturbations in coastal data definitely requires the evaluation of the effects in a wider combination of coastal environments and observation conditions, efficiently achievable through theoretical simulations. Indeed, direct estimates of AE from at-sensor satellite measurements are confined to limited observational conditions (e.g., a negligible water contribution (Feng and Hu, 2017)), while the direct evaluation of AE in satellite-derived products might be hindered by mechanisms of compensation within the applied atmospheric correction (AC) scheme. It is recalled that an attempt to estimate AE in SeaWiFS products (i.e., the aerosol optical thickness at 865 nm, and the normalized water-leaving radiance at 670 nm) derived with the SeaWiFS Data Analysis System (SeaDAS) (Franz et al., 2007; Ahmad et al., 2010) along transects starting from the coast and intercepting selected AERONET-OC sites, did not provide any firm evidence of appreciable AE (Zibordi et al., 2009a), further explained as the consequence of compensations triggered within the SeaDAS algorithm (Bulgarelli et al., 2017).

The need to extend the set of AE simulations with respect to previous studies (e.g., Bulgarelli et al., 2014, 2017) finds additional justification in a recent publication by Feng and Hu (2017) indicating differences in the immediate vicinity of the coast between AE empirically estimated from MODIS-A near-infrared (NIR) data of Madagascar coastal waters and AE simulated by Bulgarelli et al. (2014) in the northern Adriatic Sea. The present work suggests that those differences might be explained by uncertainties affecting the determination of AE across different methods at very short distances from the coast, and above all, by the diverse observation conditions (i.e., land albedo, coastal morphology, solar illumination, aerosol load and scale height).

The specific aim of the present manuscript is to extend the theoretical quantification of AE to a large set of test cases representative of a wide range of typical observation conditions for mid-latitude coastal environments.

In specific, the methodology developed in Bulgarelli et al. (2014) is applied to simulate AE at visible and NIR wavelengths for typical atmospheric and sun-sensor geometries along a study transect extending perpendicular to a half-plane of uniform and isotropic land albedo, and whose coastline is oriented in the South-North direction. The optical properties of the water are assumed to be constant along the study transect and described by spectra of the remote sensing reflectance R_{rs} typical of European waters (Eastern Mediterranean, Ligurian Sea, northern Adriatic Sea, Western Black Sea, English Channel, and Baltic Sea) (Zibordi et al., 2011), while the bi-directional reflectance of the wind-roughed sea surface is modeled according to Kisselev and Bulgarelli (2004). For the land cover, reflectance spectra of most common terrestrial environments (grass, dry grass, deciduous trees, conifers, concrete, snow of different grain size, white and brown sand, brown and pale brown loam) have been obtained from the comprehensive Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) spectral library (Baldridge et al., 2009).

Results are analyzed with regards to the radiometric sensitivity of SeaWiFS, MODIS-A, MERIS, OLCI, OLI and MSI, where the harmonized comparison of AE among different sensors is ensured by adjusting the radiometric sensitivity of OLCI, OLI and MSI to the same input radiance utilized by Hu et al. (2012) to standardize the signal-to-noise ratio (SNR) of SeaWiFS, MODIS-A and MERIS.

2. Methods

2.1. Simulation procedure

The methodology described in Bulgarelli et al. (2014) has been adopted to estimate percent adjacency contributions at the sensor level $\xi_{L_{tot}} = L_{adj}/L_{tot} \cdot 100$, where L_{tot} is the TOA signal, and the adjacency radiance L_{adj} is modeled as:

$$L_{adj} = L_l^{TOA} - \widetilde{L}_w^{TOA} - \widetilde{L}_{ss}^{TOA}, \quad (1)$$

with L_l^{TOA} representing the land contribution (i.e., the radiance at the sensor originating from the area covered by land), and $\widetilde{L}_w^{TOA}$ and $\widetilde{L}_{ss}^{TOA}$ indicating the masked water and the masked sea surface contributions, respectively (i.e., the water-leaving radiance and the sea surface radiance that would reach the sensor from the same area if still covered by the sea). It is mentioned that the term $\widetilde{L}_{ss}^{TOA}$ is sometimes called the *Fresnel mask* (Santer and Schmechtig, 2000). Eq. (1) can be further parameterized as (see Bulgarelli et al., 2014 for details):

$$L_{adj} = \{\rho_l/[\pi(1-\rho_l S)] - R_{rs}/(1-\rho_{sea} S)\}\cdot C - W. \quad (2)$$

where ρ_l represents the albedo of the land assumed isotropic and spatially homogeneous; S is the atmospheric spherical albedo of the bottom of the atmosphere; ρ_{sea} is the albedo of the sea (Mobley, 1994); and the expressions for functions C and W are given in Bulgarelli et al. (2014). The functions C and W depend on the illumination and observation geometry, on the land/sea spatial extension, as well as on the atmospheric optical properties. The described approach allows decoupling the land and water optical properties from atmospheric scattering, yet fully accounting for sea surface roughness. It is pointed out that the term $1/(1-\rho_{sea} S)$ in Eq. (2) is exclusively used in the determination of $\widetilde{L}_w^{TOA}$ to account for multiple reflections by the sea surface of atmospherically scattered light, whereas the bi-directional reflectance properties of a wind-roughed sea surface are accurately accounted for in the computation of $\widetilde{L}_{ss}^{TOA}$. While the simulation of C and W requires a full 3D description of the propagating system, the simulation of S can be performed with a plane-parallel radiative transfer code, while the input parameters ρ_l and R_{rs} can be extrapolated from satellite-derived or in situ data. Therefore, once functions C and W are computed for a given geometric and atmospheric case, the proposed modeling allows a straightforward evaluation of AE for a wide variety of land and water spectral signatures.