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Atmospheric correction over coastal waters using multilayer neural networks

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ABSTRACT

Standard atmospheric correction (AC) algorithms work well in open ocean areas where the water inherent optical properties (IOPs) are correlated with pigmented particles. However, the IOPs of turbid coastal waters may independently vary with pigmented particles, suspended inorganic particles, and colored dissolved organic matter (CDOM). In turbid coastal waters standard AC algorithms often exhibit large inaccuracies that may lead to negative water-leaving radiances (L_w) or remote sensing reflectance (R_{rs}). We introduce a new atmospheric correction algorithm for coastal waters based on a multilayer neural network (MLNN) method. We use a coupled atmosphere-ocean radiative transfer model to simulate the Rayleigh-corrected radiance (L_{rc}) at the top of the atmosphere (TOA) and the R_{rs} just above the surface simultaneously, and train a MLNN to derive the aerosol optical depth (AOD) and R_{rs} directly from the TOA L_{rc}. The method is validated using both a synthetic dataset and Aerosol Robotic Network – Ocean Color (AERONET–OC) measurements. The SeaDAS NIR algorithm, the SeaDAS NIR/SWIR algorithm, and the MODIS version of the Case 2 regional water - CoastColour (C2RCC) algorithm are also included in the comparison with AERONET–OC measurements. The performance of the AC algorithms is evaluated with four statistical metrics: the Pearson correlation coefficient (R), the average percentage difference (APD), the mean percentage bias, and the root mean square difference (RMSD). The comparison with AERONET–OC measurements shows that the MLNN algorithm significantly improves retrieval of normalized L_w in blue bands (412 nm and 443 nm) and yields minor improvements in green and red bands compared with the other three algorithms. On a global scale, the MLNN algorithm reduces APD in normalized L_w by up to 13% in blue bands and by 2–7% in green and red bands when compared with the standard SeaDAS NIR algorithm. In highly absorbing coastal waters, such as the Baltic Sea, the MLNN algorithm reduces APD in normalized L_w by more than 60% in blue bands compared to the standard SeaDAS NIR algorithm, while in highly scattering coastal waters, such as the Black Sea, the MLNN algorithm reduces APD by more than 25%. These results indicate that the MLNN algorithm is suitable for application in turbid coastal waters. Application of the MLNN algorithm to MODIS Aqua images in several coastal areas also shows that it is robust and resilient to contamination due to sunglint or adjacency effects of land and cloud edges. The MLNN algorithm is very fast once the neural network has been properly trained and is therefore suitable for operational use. A significant advantage of the MLNN algorithm is that it does not need SWIR bands.

1. Introduction

Atmospheric correction (AC) is the first and a very important step in many ocean color algorithms. Ideally, it should remove the radiance contribution of the atmosphere (including that of air molecules and aerosols) and surface reflection from the satellite measured radiances to produce water-leaving radiances (L_w), which can be used to derive ocean color products such as the chlorophyll-a concentration (CHLa). The atmosphere may contribute about 90% to the TOA radiance measured by a satellite sensor, and in coastal areas this contribution could be even higher, especially in the blue bands, or way less in sediment dominated extremely turbid waters,

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especially in red and NIR bands (Wang, 2010). Therefore, an accurate AC algorithm is crucial to ocean color data processing. Standard AC algorithms (Gordon and Wang, 1994b; Gordon, 1997) describe the radiance measured by the satellite sensor as:

$$L_t(\lambda) = L_r(\lambda) + L_a(\lambda) + T(\lambda)L_g(\lambda) + t(\lambda)L_{wc}(\lambda) + t(\lambda)L_w(\lambda) \quad (1)$$

where λ is the wavelength, L_t is the total radiance measured by the ocean color sensor, L_r is the radiance contributed by Rayleigh scattering by atmospheric molecules, L_a is the radiance contributed by aerosol scattering/absorption including the aerosol-Rayleigh interaction, L_g is the radiance contributed by sunglint, L_{wc} is the radiance contributed by surface whitecaps, L_w is the radiance backscattered by the upper water column that leaves the ocean surface, commonly referred to as the water-leaving radiance. Note that L_w does not include radiance (Fresnel) reflected by the water surface. T and t are the atmospheric direct and diffuse transmittance, respectively. It is important to note that Eq. (1) is valid only in the single-scattering limit (Gordon and Wang, 1994b; Zhang et al., 2007).

Conventional atmospheric correction algorithms derive the water-leaving radiance (L_w) by quantifying the first four terms in Eq. (1). The Rayleigh scattering radiance (L_r) needs to be computed accurately (Gordon and Wang, 1992; Wang, 2002) because it constitutes a major proportion of the atmospheric radiance, especially for open ocean waters in the ultraviolet-visible bands. Generally, it can be simulated using a radiative transfer model with an uncertainty lower than 0.5% (Wang, 2005). Sunglint is due to specular reflection of direct sunlight by the surface. It can be avoided by tilting the sensor away from the direct reflection of sunlight, as specifically done with a dedicated OC instrument like the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS). For sensors that do not have tilt capability such as MODIS, a 1-D version of the Cox and Munk model (Cox and Munk, 1954) is commonly used to compute the sunglint radiance (L_g) for situations with low sunglint contributions (Wang and Bailey, 2001). A recent study by Lin et al. (2015) suggests that a 2-D Gaussian slope distribution is needed in order to simulate the sunglint radiance accurately. The radiance due to surface whitecaps (L_{wc}) is usually estimated from the wind speed (Gordon and Wang, 1994a; Frouin et al., 1996; Stramska and Petelski, 2003). The aerosol radiance (L_a) which includes the aerosol-Rayleigh interaction is highly variable due to the complexity of the micro-physical properties (i.e. particle size distribution and refractive index) of the aerosols. For open ocean water, the AC algorithms estimate the aerosol radiance by assuming the water-leaving radiance to be negligible (black ocean assumption) at near-infrared (NIR) wavelengths due to the strong absorption by pure water.

The aerosol model is determined from the radiance measured at two NIR bands, and then used to estimate the contribution of aerosols to the radiance in the visible bands. This method works well in open ocean areas but is challenged in coastal areas where the black ocean assumption often fails. Several modified algorithms (Siegel et al., 2000; Ruddick et al., 2000; Wang and Shi, 2007; Wang et al., 2012; Brajard et al., 2008; 2012; Bailey et al., 2010; He et al., 2012; Singh and Shanmugam, 2014; Jiang and Wang, 2014) among others were developed for coastal waters to correct for the non-zero NIR water-leaving radiances. An alternative AC algorithm developed by Wang and Shi (2007) estimates the aerosol contribution to the radiance using shortwave IR (SWIR) bands (1240 and 2130 nm for MODIS), where the black ocean assumption may still hold, and then obtains L_w values in the visible bands by extrapolation. Most of these algorithms showed improvements, at least for selected calibration/validation areas.

However, these modified or alternative AC algorithms may still yield questionable results in coastal water areas (Zibordi et al., 2006b; Jamet et al., 2011; Goyens et al., 2013b; Singh and Shanmugam, 2014). The reason is that both the water and the aerosols are optically more complex in coastal regions. Therefore, the NIR water-leaving radiance correction algorithms predict incorrect water-leaving radiances resulting in an over-estimation of the aerosol radiance.

To address this problem, we introduce a different approach. Since the problem arises because it is difficult to remove the aerosol contribution to the spectral radiance in coastal water areas, an alternative approach is not to attempt removing it, but to use the combined aerosol and water-leaving radiances together. This combined radiance is called the Rayleigh-corrected TOA radiance (L_{rc}), defined as

$$L_{rc} = L_a(\lambda) + t(\lambda)L_w(\lambda). \quad (2)$$

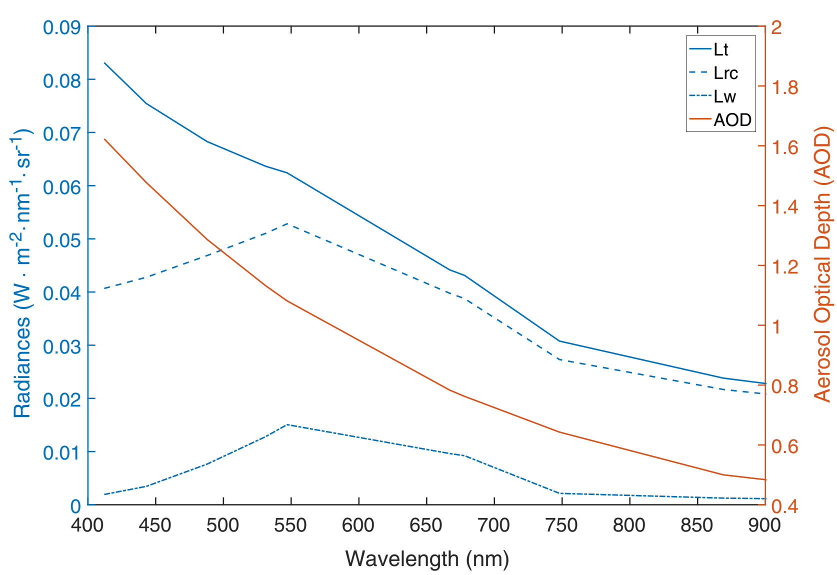

Fig. 1. Simulated top of atmosphere (TOA) radiance (L_t), Rayleigh-corrected radiance (L_{rc}) and water-leaving radiance (L_w) for a coastal water area (CHLa = 20.0 mg $\cdot$ m^{-3}, CDOM(443) = 0.3 m^{-1}, TSM = 20.0 g $\cdot$ m^{-3}) with heavy continental aerosol loading (AOD = 0.5 at 869 nm). The aerosol model used is an average continental aerosol with RH = 95%. The solar zenith angle is 10°, the viewing zenith angle is 45° and the relative azimuth angle is 120°. Note that the radiances were simulated with extra-terrestrial solar irradiance F_0 = 1.0 at all wavelengths.