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Effects of Earth curvature on atmospheric correction for ocean color remote sensing

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ABSTRACT

In this study, a vector radiative transfer model for the coupled ocean-atmosphere system with consideration of the effects of Earth curvature (named PCOART-SA) was developed using the pseudo-spherical approximation. Both downward and reflected solar beam radiation were corrected accounting for Earth curvature effects. Validation showed that the PCOART-SA results agreed well with literature benchmarks and the CDISORT and AccuRT model results. Based on PCOART-SA, Earth curvature effects on Rayleigh-scattering radiance including polarization were investigated. The results showed that the influence of Earth curvature increased rapidly with solar zenith angle, with influences up to 1%, 3%, and 12% for solar zenith angles at 75°, 80°, and 85°, respectively, which should be considered for high accuracy atmospheric correction. We also found that the Rayleigh-scattering look-up table in SeaDAS after version 7.2 showed significant bias at high solar zenith angles, which needs further investigation. Finally, using the PCOART-SA model, we generated Rayleigh-scattering look-up tables for Aqua/MODIS with consideration of Earth curvature effects, which can be directly used in SeaDAS.

1. Introduction

Satellite ocean color remote sensing plays a key role in marine global oceanic ecosystem monitoring (McClain 2009). To date, > 20 satellite ocean color sensors have been launched, including the widely used Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS). Satellite ocean color sensors measure upward spectral radiance at the top-of-atmosphere (TOA), which is the total radiance from atmospheric scattering, sea surface reflection, and water-leaving radiance (Gordon 1997). Usually, about 90% of the sensor measured radiance comes from atmospheric scattering and sea surface reflection, while the water-leaving radiance containing water component information only accounts for about 10% in the blue light wavelengths (Siegel et al., 2000). Therefore, extremely high accuracy of radiance measurements is required by space agencies with errors < 0.5%, and highly accurate atmospheric correction should be performed for satellite ocean color remote sensing data.

Many atmospheric correction algorithms have been developed for different satellite ocean color sensors, with most of them based on methods developed by Gordon & Wang (1994). Currently, all algorithms assume a plane-parallel medium for the atmosphere-ocean system, with the effects of Earth curvature largely ignored (Ding & Gordon, 1994; Ruddick et al. 2014). The plane-parallel assumption is generally suitable for polar orbit satellite ocean color observations, which are usually monitored at near noon. However, the development of geostationary ocean color remote sensing requires observation from early morning to late afternoon, e.g. the Geostationary Ocean Color Imager (GOCI) observes 8 times from morning to afternoon with a step of 1 h. Therefore, geostationary ocean color remote sensing will unavoidably encounter observations at high solar zenith angles and high viewing zenith angles at the edge of the observable area when the effects of Earth curvature cannot be ignored. Moreover, polar orbit ocean color satellite observations also encounter high solar zenith angle situations in high latitude regions during winter half year (excluding totally polar night regions). Even in summer half year, polar orbit ocean color satellites will encounter high solar zenith angles due to observations several times in a day.

To date, few investigations have been conducted on the effects of Earth curvature on satellite ocean color remote sensing. For a simple one-layer Rayleigh-scattering atmosphere with black bottom (total absorption), Adams & Kattawar (1978) found significant differences in upward radiance between plane-parallel and spherical-shell media at large solar zenith angles using backward Monte Carlo simulations. Based on scalar Monte Carlo simulations, Ding & Gordon (1994)

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investigated the influence of Earth curvature on the atmospheric correction proposed by Gordon & Wang (1994), and found that the curvature effects were negligible for solar zenith angle (θ_0) < 70°; however, for $\theta_0 \geq 70°$, Rayleigh-scattering should be calculated with a spherical-shell atmosphere. Moreover, they found that atmospheric correction based on the plane-parallel assumption was still applicable for $\theta_0 \geq 70°$ if the Rayleigh-scattering radiance was computed with a spherical-shell atmosphere. As Monte Carlo simulations are computationally expensive, it is impractical to apply tem for the processing of ocean color imagery. Therefore, Ding & Gordon (1994) developed an approximate approach for computing Rayleigh-scattering radiance with a spherical-shell atmosphere. Unfortunately, however, current satellite ocean color data processing software, including the SeaDAS, BEAM, and GDPS, cannot properly deal with data collected under high solar zenith angles. Furthermore, the effects of both Earth curvature and high solar zenith angle on ocean color remote sensing remain unknown. For example, Ding & Gordon (1994) used scalar Monte Carlo simulations without including polarization effect. The effects of the molecular and aerosol profiles were also not considered thoroughly, which is important for light scattering in a spherical atmosphere (Wang 2003). Recently, we found that high solar zenith angles could impact the retrieval accuracy of chlorophyll concentration by empirical algorithms, and the bidirectional properties of remote sensing reflectance and decreasing sensitivity of blue-green band ratio with chlorophyll concentration variations can explain the degraded performance under high solar zenith angles (Li et al. 2017).

In this study, we revisited the effects of Earth curvature on Rayleigh-scattering radiance with consideration of polarization effects. First, a vector radiative transfer model for the coupled ocean-atmosphere system with consideration of the effects of Earth curvature (named PCOART-SA) was developed using a pseudo-spherical approximation. Then, based on the PCOART-SA, the effects of Earth curvature on Rayleigh-scattering radiance were revisited considering the polarization. Finally, the Rayleigh-scattering lookup-tables with consideration of Earth curvature effects were generated and applied to the atmospheric correction of satellite ocean color data.

2. Radiative transfer model for plane-parallel ocean-atmosphere system

In previous studies, we developed a vector radiative transfer model (named PCOART, or here PCOART-PP) for the coupled ocean-atmosphere system considering a rough sea surface (He et al. 2007, 2010). The PCOART-PP model assumes that the ocean-atmosphere system can be divided into several plane-parallel layers, and the radiances at the layer interfaces are solved using the matrix-operator method (or adding-doubling method). The PCOART-PP model was shown to be an accurate radiative transfer model by validation with Rayleigh-scattering look-up tables in the SeaDAS software package, standard underwater radiative transfer problems proposed by Mobley et al. (1993), and simulations of POLDER satellite observed polarized radiances (He et al. 2007, 2010, 2014, 2016). Here, we only briefly describe the PCOART-PP model.

With the plane-parallel assumption, the vector radiative transfer can be described as:

$$\mu\frac{d\mathbf{L}(\tau;\mu,\phi)}{d\tau} = -\mathbf{L}(\tau;\mu,\phi) + \frac{\omega(\tau)}{4\pi}\int_0^{2\pi}\int_{-1}^{1}\mathbf{Z}(\tau;\mu,\phi;\mu',\phi')\mathbf{L}(\tau;\mu',\phi')d\mu' d\phi' + \frac{\omega(\tau)}{4\pi}\mathbf{Z}(\tau;\mu,\phi;\mu_0,\phi_0)\mathbf{F}_0\exp(-\tau/\mu_0) \quad (1)$$

where $\mathbf{L}$ is the stokes vector $[I,Q,U,V]^T$; τ is the optical depth; μ and μ' are the cosine of the zenith angles, with positive for downward directions; ϕ and ϕ' are the azimuth angles; ω is the single-scattering albedo; $\mathbf{F}_0$ is the incident extraterrestrial solar flux vector (unpolarized); μ_0 and ϕ_0 are the cosine of the zenith angle and the azimuth angle of Sun, respectively; $\mathbf{Z}$ is the scattering matrix which considers the rotation of the reference planes of the Stokes vector from the incident radiation geometry to scattering radiation geometry. The source term (last term of Eq. (1)) should consider reflected solar beam radiation additionally for a flat sea surface case. $\mathbf{L}$ and $\mathbf{Z}$ are then expanded into a Fourier series of the azimuth as:

$$\begin{cases}\mathbf{L}(\tau;\mu,\phi) = \mathbf{L}^0(\tau;\mu) + \sum_{m=1}^{M}[\mathbf{L}^{cm}(\tau;\mu)\cos(m\phi) + \mathbf{L}^{sm}(\tau;\mu)\sin(m\phi)] \\ \mathbf{Z}(\tau;\mu,\phi;\mu',\phi') = \mathbf{Z}^0(\tau;\mu;\mu') + \sum_{m=1}^{M}[\mathbf{Z}^{cm}(\tau;\mu;\mu')\cos[m(\phi-\phi')] \\ \qquad + \mathbf{Z}^{sm}(\tau;\mu;\mu')\sin[m(\phi-\phi')]]\end{cases} \quad (2)$$

where the superscripts "*cm*" and "*sm*" represent the cosine and sine terms, respectively. By substituting Eq. (2) into Eq. (1), and using the orthogonal properties of the cosine and sine functions, we can get azimuthally independent equations for different Fourier expression orders as follows:

$$\begin{cases}\mu\frac{d\mathbf{L}^0(\tau;\mu)}{d\tau} = -\mathbf{L}^0(\tau;\mu) + \frac{\omega(\tau)}{2}\int_{-1}^{1}\mathbf{Z}^0(\tau;\mu;\mu')\mathbf{L}^0(\tau;\mu')d\mu' \\ \qquad + \frac{\omega(\tau)}{4\pi}\mathbf{Z}^0(\tau;\mu;\mu_0)\mathbf{F}_0\exp(-\tau/\mu_0) \\ \mu\frac{d\mathbf{L}^{cm}(\tau;\mu)}{d\tau} = -\mathbf{L}^{cm}(\tau;\mu) + \frac{\omega(\tau)}{4}\int_{-1}^{1}[\mathbf{Z}^{cm}(\tau;\mu;\mu')\mathbf{L}^{cm}(\tau;\mu') \\ \qquad - \mathbf{Z}^{sm}(\tau;\mu;\mu')\mathbf{L}^{sm}(\tau;\mu')]d\mu' \\ \qquad + \frac{\omega(\tau)}{4\pi}\mathbf{Z}^{cm}(\tau;\mu;\mu_0)\mathbf{F}_0\exp(-\tau/\mu_0),\ m=1,\dots,M \\ \mu\frac{d\mathbf{L}^{sm}(\tau;\mu)}{d\tau} = -\mathbf{L}^{sm}(\tau;\mu) + \frac{\omega(\tau)}{4}\int_{-1}^{1}[\mathbf{Z}^{sm}(\tau;\mu;\mu')\mathbf{L}^{cm}(\tau;\mu') \\ \qquad + \mathbf{Z}^{cm}(\tau;\mu;\mu')\mathbf{L}^{sm}(\tau;\mu')]d\mu' \\ \qquad + \frac{\omega(\tau)}{4\pi}\mathbf{Z}^{sm}(\tau;\mu;\mu_0)\mathbf{F}_0\exp(-\tau/\mu_0),\ m=1,\dots,M\end{cases} \quad (3)$$

Approximating the integral terms in Eq. (3) by Gaussian quadratures, we obtain the discrete equations with viewing zenith angle as follows:

$$\begin{cases}\mu_i\frac{d\mathbf{L}^0(\tau;\mu_i)}{d\tau} = -\mathbf{L}^0(\tau;\mu_i) + \sum_{j=-N,\,j\neq 0}^{N}\frac{\omega(\tau)}{2}\mathbf{Z}^0(\tau;\mu_i;\mu_j)\mathbf{L}^0(\tau;\mu_i)w_j \\ \qquad + \frac{\omega(\tau)}{4\pi}\mathbf{Z}^0(\tau;\mu_i;\mu_0)\mathbf{F}_0\exp(-\tau/\mu_0), \\ \mu_i\frac{d\mathbf{L}^{cm}(\tau;\mu_i)}{d\tau} = -\mathbf{L}^{cm}(\tau;\mu_i) + \sum_{j=-N,\,j\neq 0}^{N}\frac{\omega(\tau)}{4}[\mathbf{Z}^{cm}(\tau;\mu_i;\mu_j)\mathbf{L}^{cm}(\tau;\mu_j) \\ \qquad - \mathbf{Z}^{sm}(\tau;\mu_i;\mu_j)\mathbf{L}^{sm}(\tau;\mu_j)]w_j \\ \qquad + \frac{\omega(\tau)}{4\pi}\mathbf{Z}^{cm}(\tau;\mu_i;\mu_0)\mathbf{F}_0\exp(-\tau/\mu_0),\ m=1,\dots,M \\ \mu_i\frac{d\mathbf{L}^{sm}(\tau;\mu_i)}{d\tau} = -\mathbf{L}^{sm}(\tau;\mu_i) + \sum_{j=-N,\,j\neq 0}^{N}\frac{\omega(\tau)}{4}[\mathbf{Z}^{sm}(\tau;\mu_i;\mu_j)\mathbf{L}^{cm}(\tau;\mu_j) \\ \qquad + \mathbf{Z}^{cm}(\tau;\mu_i;\mu_j)\mathbf{L}^{sm}(\tau;\mu_j)]w_j \\ \qquad + \frac{\omega(\tau)}{4\pi}\mathbf{Z}^{sm}(\tau;\mu_i;\mu_0)\mathbf{F}_0\exp(-\tau/\mu_0),\ m=1,\dots,M\end{cases} \quad (4)$$

where μ_i and μ_j are the Gaussian quadrature roots with order $2N$, and w_j are the corresponding Gaussian quadrature weights; subscript i and j are from –N to N excluding zero. Then, Eq. (4) can be reformatted into matrix equations as follows:

$$\mu_i\frac{d\mathbf{L}_m(\tau;\mu_i)}{d\tau} = -\mathbf{L}_m(\tau;\mu_i) + \sum_{j=-N,\,j\neq 0}^{N}\frac{\omega(\tau)}{4}[1+\delta_{(0,m)}]\mathbf{H}_m(\tau;\mu_i;\mu_j)\mathbf{L}_m(\tau;\mu_i)w_j + \frac{\omega(\tau)}{4\pi}\mathbf{Z}_m(\tau;\mu_i;\mu_0)\mathbf{F}_0\exp(-\tau/\mu_0),\ m=0,\dots,M \quad (5)$$