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Radiative transfer solutions for coupled atmosphere ocean systems using the matrix operator technique

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ABSTRACT

Accurate radiative transfer models are the key tools for the understanding of radiative transfer processes in the atmosphere and ocean, and for the development of remote sensing algorithms. The widely used scalar approximation of radiative transfer can lead to errors in calculated top of atmosphere radiances. We show results with errors in the order of $\pm 8\%$ for atmosphere ocean systems with case one waters. Variations in sea water salinity and temperature can lead to variations in the signal of similar magnitude. Therefore, we enhanced our scalar radiative transfer model MOMO, which is in use at *Freie Universität Berlin*, to treat these effects as accurately as possible. We describe our one-dimensional vector radiative transfer model for an atmosphere ocean system with a rough interface. We describe the matrix operator scheme and the bio-optical model for case one waters. We discuss some effects of neglecting polarization in radiative transfer calculations and effects of salinity changes for top of atmosphere radiances. Results are shown for the channels of the satellite instruments MERIS and OLCI from 412.5 nm to 900 nm.

1. Introduction

An accurate and flexible remote sensing scheme has a broad range of possible applications in the field of atmospheric and oceanic research. Virtually, all analyses of measurements made by radiance sensors need radiative transfer (RT) calculation results to derive meaningful physical quantities. In this paper we describe a radiative transfer scheme which is able to calculate the vector radiance field in an atmosphere ocean system (AOS) with a wind blown interface. We assume that the system has no horizontal, but arbitrary vertical structure. Hence, the scheme is a one-dimensional vector radiative transfer solver. Similar systems have been described in the past and recent literature, such as the works from Kattawar and Adams [1], Nakajima and Tanaka [2], Takashima [3], Chami [4], Fell and Fischer [5], Chowdhary et al. [6], He [7] and Zhai [8] to name a few. The work described in this paper is based on the radiative transfer model MOMO which is itself based on the work of Fischer and Grassl [9], Fell and Fischer [5] and Bennartz and Fischer [10]. It has a long tradition of successfully developed remote sensing applications, including the sensing of lakes [11], analysis of hyper spectral data to derive surface fluorescence signals [12], the analysis of ocean color data from MERIS measurements [13], and the retrieval of land surface pressure from MERIS data [14]. We decided to upgrade the MOMO FORTRAN code to account for polarization in order to base the development of future remote sensing algorithms on accurate RT calculations.

In Sections 2 and 3 we introduce the radiative transfer equation and the matrix operator method. In Sections 4 and 5 we describe the models for pure ocean water and the bio-optical model for in water constituents. Section 6 is devoted to the validation of the code and in Section 7 we describe first applications as mentioned in the abstract.

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2. Radiative transfer equation

The differential radiative transfer equation (RTE) given in Eq. (1) states that the change of the diffuse light field $\partial_\tau L(\tau)$ with respect to the optical thickness τ is proportional to both the light field itself, and the diffuse sources $J(\tau)$ at this optical depth:

$$\mu \partial_\tau L(\tau) = -L(\tau) + J(\tau). \tag{1}$$

The light field is described by a real four-dimensional Stokes vector [15,16] (and references therein). To find unique solutions, it is necessary to define boundary conditions that define the top and the bottom of the atmosphere. Eq. (2) states that there is no diffuse downward directed radiation at the top of the atmosphere, and Eq. (3) states that the upward directed radiation at the bottom of the AOS is given by the reflection of the downward directed radiation. The surface reflection is modeled using a real 4×4 reflection matrix $R(\mu,\phi,\mu',\phi')$ which depends on the direction of incidence (μ',ϕ') and reflection (μ,ϕ)

$$L(\tau = 0, \mu < 0) = 0, \tag{2}$$

$$L(\tau = \tau_0, \mu > 0, \phi) = \int_0^1 \mathrm{d}\mu' \int \mathrm{d}\phi'\, R(\mu,\phi,\mu',\phi') L(\tau_0,\mu',\phi'). \tag{3}$$

The complexity of the RTE comes from the coupling of the field by the scattering source term J, which is shown in Eq. (4). It consists of a scattering term for the direct solar radiation and a scattering term for the diffuse field

$$\left(\mu \frac{\mathrm{d}}{\mathrm{d}\tau} - 1\right) L(\tau,\mu,\phi) = \underbrace{\omega_0 P(\tau,\mu,\phi,\mu_s,\phi_s) e^{-\tau/\mu_s} S_0}_{\text{single scattering term}}$$
$$\underbrace{+\omega_0 \int \mathrm{d}\mu'\, \mathrm{d}\phi'\, P(\tau,\mu,\phi,\mu',\phi') L(\tau,\mu',\phi'),}_{\text{diffuse scattering term}} \tag{4}$$

where S_0 is the solar constant, the solar position is set to (μ_s,ϕ_s), and ω_0 is the single scattering albedo. We assume that the scattering matrix P only depends on $\phi - \phi'$ and expand L and P in a Fourier series with the expansion coefficient m. The equation then decouples into a series of equations in Fourier space that are now independent of the viewing azimuth angle:

$$\left(\mu \frac{\mathrm{d}}{\mathrm{d}\tau} - 1\right) L_m(\tau,\mu) = \omega_0 P_m(\mu,\mu_s) e^{-\tau/\mu_s}$$
$$+\omega_0 \pi (1 + \delta_{0m}) \int \mathrm{d}\mu'\, P_m(\mu,\mu') L_m(\tau,\mu'). \tag{5}$$

We discretize Eq. (5) for numerical treatment on a computer system, and split the light field into parts for the upper and lower hemisphere:

$$L_m^+(\tau,\mu) = L_m(\tau,\mu > 0), \tag{6}$$

$$L_m^-(\tau,\mu) = L_m(\tau,\mu < 0). \tag{7}$$

Integrations are then replaced by summing over the integrand at Gaussian quadrature points μ_i and multiplying with the Gauss Lobatto weights c_i:

$$\int \mathrm{d}\mu\, f(\mu) \approx \sum_{i=1}^{k} f(\mu_i) c_i. \tag{8}$$

We define matrices that contain the Gaussian points, weights, phase matrix values, and source term values:

$$c = \mathrm{diag}(c_1, \ldots, c_k), \tag{9}$$

$$M = \mathrm{diag}(\mu_1, \ldots, \mu_k), \tag{10}$$

$$[P_m^{\pm,\pm}]_{i,j} = P_m(\pm\mu_i, \pm\mu_j'), \quad i,j \in 1,\ldots,k, \tag{11}$$

$$[J_m^+]_{i,j} = \omega_0 S_0 [P_m^{++}]_{i,j} e^{\tau/\mu_i}, \tag{12}$$

$$[J_m^-]_{i,j} = \omega_0 S_0 [P_m^{-+}]_{i,j} e^{\tau/\mu_i}, \tag{13}$$

where δ_{0m} is the Kronecker delta. Defining the matrices $\Gamma_m^{++/--/+-/-+}$ and $\Sigma^{+/-}$ as abbreviations:

$$\Gamma_m^{++} = M^{-1}(\mathbf{1} - \omega_0 \pi (1 + \delta_{0m}) P_m^{++} c), \tag{14}$$

$$\Gamma_m^{+-} = M^{-1} \omega_0 \pi (1 + \delta_{0m}) P_m^{+-} c, \tag{15}$$

$$\Gamma_m^{-+} = M^{-1} \omega_0 \pi (1 + \delta_{0m}) P_m^{-+} c, \tag{16}$$

$$\Gamma_m^{--} = M^{-1}(\mathbf{1} - \omega_0 \pi (1 + \delta_{0m}) P_m^{--} c), \tag{17}$$

$$\Sigma_m^{\pm} = M^{-1} J_m^{\pm} \tag{18}$$

we can insert them into Eq. (5) and write the result as a compact matrix equation:

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\begin{pmatrix} L^+ \\ L^- \end{pmatrix} = \begin{pmatrix} -\Gamma_m^{++} & \Gamma_m^{+-} \\ -\Gamma_m^{-+} & \Gamma_m^{--} \end{pmatrix} \begin{pmatrix} L_m^+ \\ L_m^+ \end{pmatrix} + \begin{pmatrix} \Sigma_m^+ \\ -\Sigma_m^- \end{pmatrix}. \tag{19}$$

3. Matrix operator method

The method is based on the interaction principle which has been described by Twomey et al. [17] and later by Grand [18]. It includes any order of scattering and is applicable to systems with any optical thickness.

The interaction principle states that the upward directed light field at a given optical thickness depends linearly on the transmitted light field from a layer at higher optical thickness, and the downward directed intensity at the same level. The interaction coefficients are called reflection r_{ij} and transmission t_{ij} and a schematic is shown in Fig. 1. This holds analogously for the downward directed light field at the lower level:

$$L^+(\tau_2) = t_{21} L^+(\tau_1) + r_{12} L^-(\tau_2) + J_{21}, \tag{20}$$

$$L^-(\tau_1) = r_{21} L^+(\tau_1) + t_{12} L^-(\tau_2) + J_{12}. \tag{21}$$

Stating the interaction principle for two consecutive atmospheric layers with three boundaries, one can eliminate the transmission and reflection operators of the intermediate layer. By writing the resulting equations in the same form as the interaction principle, the transmission and reflection operators of the combined layers can be expressed as [17,19,20,1,5]:

$$\mathbf{t_{31}} = \mathbf{t_{32}}(\mathbb{1} - \mathbf{r_{12}}\mathbf{r_{32}})^{-\mathbf{1}} \mathbf{t_{21}}, \tag{22}$$