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Improving the description of sunglint for accurate prediction of remotely sensed radiances

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ABSTRACT

The bidirectional reflection distribution function (BRDF) of the ocean is a critical boundary condition for radiative transfer calculations in the coupled atmosphere–ocean system. Existing models express the extent of the glint-contaminated region and its contribution to the radiance essentially as a function of the wind speed. An accurate treatment of the glint contribution and its propagation in the atmosphere would improve current correction schemes and hence rescue a significant portion of data presently discarded as "glint contaminated". In current satellite imagery, a correction to the sensor-measured radiances is limited to the region at the edge of the glint, where the contribution is below a certain threshold. This correction assumes the sunglint radiance to be directly transmitted through the atmosphere. To quantify the error introduced by this approximation we employ a radiative transfer code that allows for a user-specified BRDF at the atmosphere–ocean interface and rigorously accounts for multiple scattering. We show that the errors incurred by ignoring multiple scattering are very significant and typically lie in the range 10–90%. Multiple reflections and shadowing at the surface can also be accounted for, and we illustrate the importance of such processes at grazing geometries.

1. Introduction

Sunglint is a persistent feature in satellite imagery. If the ocean surface were flat, a perfect image of the Sun's disk would be observed in the specular direction. The effect of surface roughness is to spread the specular reflection over a wider range of angles; the glint region, as observed from typical satellite altitudes, often extends to several hundred kilometers, with associated reflectance values greater than 0.2 [1].

Programs such as the NASA's Earth Observing System (EOS) aim at inferring accurate information about the atmosphere and the surface on a global scale. Exploitation of signals observed by sensors looking within regions affected by the high sunglint reflectance requires a stable response over a wide dynamical range. Since this requirement is seldom fulfilled, this problem is currently dealt with by tilting the sensor away or shutting it off completely. This strategy results in the periodic

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black swaths observed in composite images of the globe mapping ocean products. To analyze ocean color data obtained by instruments such as the Sea-viewing Wide Field of view Sensor (SeaWiFS, on-board SeaStar) or the MODerate-resolution Imaging Spectroradiometer (MODIS, deployed on both the Terra and Aqua spacecrafts), NASA has developed a comprehensive data analysis software package (SeaWiFS Data Analysis System, SeaDAS), which performs a number of tasks including cloud screening and calibration, required to convert the raw satellite signals into calibrated top-of-the-atmosphere (TOA) radiances. In addition, the SeaDAS software package has tools for quantifying and removing the atmospheric contribution to the radiance ("atmospheric correction") as well as the contribution due to the whitecaps and sunglint in the ocean [2].

The strong sunglint signal could conceivably be used for remote sensing of gaseous constituents [3,4], and to improve the retrieval of aerosol properties [5] in methods developed for simultaneous retrieval of atmospheric and marine parameters from TOA radiances [6]. In an image affected by sunglint, we can identify an area (usually along the rim of the glint patch) where the sunglint contribution to the radiance at the TOA is comparable to the water-leaving radiance. This area divides the portions of the image where sunglint radiance is too small to affect the retrieval from the central region of the glint where the contribution is too large to attempt an atmospheric correction.

In the SeaDAS correction scheme, a sunglint flag is triggered for a given pixel geometry when the predicted sunglint radiance is higher than a certain value (0.0001 in normalized units, i.e., for a solar irradiance $F_0 = 1$) and lower than the threshold used for cloud screening (0.01). Pixels that fall into this category are then subjected to a glint-correction, which begins with a calculation of the TOA radiance based on the assumption that light is directly transmitted in both directions through the atmosphere. This directly transmitted radiance (DTR) is then subtracted from the measured radiance to arrive at the DTR-corrected TOA radiance [7].

The goal of this investigation is to demonstrate the need of a better description of sunglint radiances. For a wind-roughened ocean–atmosphere surface with a given parametrization of the wave-facet mean slope-square in terms of the wind speed, it is desirable to establish an efficient computation procedure to provide glint radiance values without the assumptions invoked by the DTR approach. Since the radiative transfer (RT) code employed in this study more accurately describes the physics of the problem, its inclusion in the atmospheric correction procedure enables more reliable calculation of the glint radiance for an extended portion of the glint-contaminated region, resulting in fewer pixels being rejected during retrievals.

It has been demonstrated that the errors due to the scalar approximation in atmospheric RT can be quite significant, especially in the case of Rayleigh scattering [8,9]. Instruments capable of measuring polarization are being included in the satellite payloads of oncoming missions such as Glory [10], with the explicit goal to look for aerosol signatures also in the glint region [11,12]. Even though the errors due to the scalar approximation are much smaller than those quantified in this study, further improvements in the glint description should take into account polarization effects.

In Section 2 we define sunglint and the rough-surface bidirectional reflection distribution function (BRDF) in relation to the boundary condition for RT in the atmosphere. We also summarize the straightforward DTR approach used in SeaDAS, and then describe a more accurate approach that accounts for multiply scattered radiances (MSR). In Section 3 we derive the inherent optical properties (IOPs) of the atmosphere which are input in a RT code. We then quantify the error incurred by the DTR approach invoked in SeaDAS, to demonstrate the need for an improvement (Section 4). Finally, in Section 5 we present some preliminary results on the effects of multiple surface reflections and shadowing. An accurate yet computationally efficient determination of the glint TOA radiance as a function of viewing geometry, surface roughness and atmospheric state can be accomplished with the use of look-up tables, serving as an interpolating grid to provide reliable radiance values whenever the sunglint flag is active in the correction scheme.

2. RT in the presence of a wind-roughened ocean surface

2.1. Basic equations

We define sunglint as the radiation field due to a direct beam reflected from the (ocean) surface. To quantify this contribution, we must solve the radiation transfer equation [13]:

$$\mu \frac{\mathrm{d}L(\tau,\mu,\phi)}{\mathrm{d}\tau} = L(\tau,\mu,\phi) - \frac{F^{\mathrm{s}}}{4\pi} p(\tau,-\mu_0,\phi_0;\mu,\phi)\,\mathrm{e}^{-\tau/\mu_0} - \frac{1}{4\pi}\int_0^{2\pi}\mathrm{d}\phi'\int_0^1 \mathrm{d}\mu\, p(\tau,\mu',\phi';\mu,\phi)L(\tau,\mu',\phi') \tag{1}$$

subject to the appropriate boundary condition at the air–water interface:

$$L(\tau=\tau_{\mathrm{a}},\mu,\phi) = \frac{\mu F^{\mathrm{s}}}{\pi}\mathrm{e}^{-\tau_{\mathrm{a}}/\mu_0}\rho_{\mathrm{glint}}(-\mu_0,\phi_0;\mu,\phi) + \frac{1}{\pi}\int_0^{2\pi}\mathrm{d}\phi'\int_0^1 \mathrm{d}\mu'\,\mu'\rho_{\mathrm{glint}}(-\mu',\phi';\mu,\phi)L(\tau_{\mathrm{a}},-\mu',\phi'). \tag{2}$$

Here $\mu_0 = \cos\theta_0$ and $\mu = \cos\theta$ are the cosine of the solar (SZA) and sensor viewing zenith angles (SVA), respectively, and ϕ and ϕ_0 the corresponding azimuthal angles. In Eq. (1), the second term on the right-hand side is the single scattering term, whereas the third term is the multiple scattering term. In Eq. (2), the first term on the right-hand side is due to direct sunglint radiation, whereas the second accounts for the reflection of the diffuse downward component. The ρ, is the ratio of the reflected radiance in the direction (μ,ϕ), around the solid angle $\mathrm{d}\omega_0$, to the incident