Modeling the remotely sensed optical contrast caused by oil suspended in the sea water column

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Abstract: The reflectance of sea areas polluted by an oil-in-water emulsion was modeled using the radiance transfer Monte Carlo code. Example results of the contrast function parameterized by the observation angle for various angles of incident sunlight, various sea surface roughness states and two optically different types of seawaters are presented.

OCIS codes: (290.0290) Scattering; (280.0280) Remote sensing; (010.4450) Ocean optics; (350.4990) Particles; (010.7340) Water

References and links

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1. Introduction

Oil pollution usually appears in the sea as either surface film or an in-water suspension. From an optical point of view, two aspects of the problem should be investigated. Firstly, it should be determined to what degree the visibility of oil pollution depends on the oil form, environmental factors and observation conditions. Secondly, the significance of changes in the optical parameters of the water column should also be determined. In the paper by Otremba and Piskozub [1], the influence of oil film on the upwelling radiance field was studied. Building on this study, new modeling of the visibility of oil suspended in the water column was performed. This paper presents the results of the investigation of the contrast of sea areas polluted with oil-in-water emulsion as a function of the following variables: the solar azimuth angle; wind velocity; optical type of seawater; the angle of observation.

The upwelling radiance above the sea area polluted by oil film has been successfully modeled using the Monte Carlo technique [1]. Now, a similar method is applied to identify changes of radiance above sea areas polluted by oil emulsion.

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2. Model

2. 1 Sea area

The model for sea areas polluted with oil emulsion is similar to that used for areas polluted with oil film [1]. The only novelty is to include the inherent optical properties (IOPs) of the oil emulsion to describe the polluted water body (see Section 2.2).

Two very different types of water, turbid coastal and clean ocean, were used. The optics of the turbid water were described by the absorption coefficient $a_w = 0.5$, the scattering coefficient $b_w = 0.5$ and the scattering phase function β_w (applied after Petzold [2]). Both absorption and scattering coefficients are approximately equal to those from waters near coastal waters close to a large river mouth, such as the Vistula (Baltic Sea, Gulf of Gdansk, Poland) [3]. Clean water is represented by parameters $a_w = 0.056$ [4] and $b_w = 0.002$ [5]. These values are equal to those of very clean oceanic water. Due to a lack of suspended particles, the scattering phase function derived using the Rayleigh theory [6] was applied.

The model allows for the depth of the sea layer polluted by suspended oil droplets to be 10 m.

The total depth of the sea is assumed to be 500 m, at which no light is reflected from the sea bottom.

2. 2 Oil pollution

The oil pollution model uses the following IOP values: absorption coefficient $a_o = 0.5$; scattering coefficient $b_o = 0.5$ [7]; scattering phase function β_o [8]. The values of a_o and b_o are characteristic for partly-weathered crude oil extracted from the Baltic Sea (such as the *Petrobaltic* type), when the concentration of oil suspension oscillates near 1 ppm and the wavelength is in the vicinity of 550 nm.

The optical features of the seawater and the oil suspension corresponds to light of 550 nm wavelength.

2. 3 Numerical equivalents of radiance and contrast

Reflectance, also called bidirectional reflectance distribution function (BRDF), $R(\theta_i,\varphi_i,\theta_r,\varphi_r)$ is the function of the direction of solar light incidence as well as the angle of observation and can be expressed as (1):

$$R(\theta_i,\varphi_i,\theta_r,\varphi_r) = \frac{dL_r(\theta_r,\varphi_r)}{dE_i(\theta_i,\varphi_i)} \tag{1}$$

where: θ_i,φ_I = polar coordinates (nadir angle, azimuth angle) towards incident light, θ_r,φ_r = polar coordinates towards reflected light, L_r = above-water vertical upwelling radiance (or "water leaving radiance"), $E_i(\theta_i,\varphi_i)$ = downwelling irradiance at the sea surface caused by directional solar light. This definition implicates that if the reflectance is known, then radiance L_r (θ,φ) can be calculated with defined downward solar radiance $L_i(\theta,\varphi)$ by integral (2):

$$L_r(\theta_r,\varphi_r) = \int_0^{2\pi}\int_0^{\pi/2} R(\theta_i,\varphi_i,\theta_r,\varphi_r)\, L_i(\theta_i,\varphi_i)\cos\theta_i\,\sin\theta_i\,d\theta_i\,d\varphi_i \tag{2}$$

Reflectance does not contain direct information about the light field, but it does have information about what happens to light (described by directional and diffused solar radiance L_i) illuminating the sea surface. This is a variable independent of solar illumination, unlike water leaving radiance. It is worthwhile to note that when $\theta_r = 0$, then the reflectance is referred to as "remote sensing reflectance" (RSR). In the Monte Carlo code, reflectance has a numerical equivalent expressed by (3)

$$R(\theta,\varphi)=\frac{\frac{N_r}{\cos\,\theta_r\,\Delta\Omega}}{N_i\,\cos\theta_i} \quad (3)$$

where: N_r = number of virtual/simulated photons registered in the solid angular sector defined by angles θ_r, φ_r; $\Delta\Omega = \pi/120$ sr, N_i = number of incident photons (10 million in the simulations described in the paper), θ_i = zenith angle of incidence of solar virtual photons, θ_r = zenith angle of reflected virtual photon.

Sea surfaces polluted by oil film are characterized by a contrast in relation to clean surfaces which can be expressed by the following relation (4):

$$c(\theta_r,\varphi_r,\theta_i,\varphi_i)=\frac{R_p(\theta_r,\varphi_r,\theta_i,\varphi_i)-R_c(\theta_r,\varphi_r,\theta_i,\varphi_i)}{R_c(\theta_r,\varphi_r,\theta_i,\varphi_i)} \quad (4)$$

where: $R_p(\theta_r, \varphi_r, \theta_i, \varphi_i)$ expresses the reflectance for polluted seas and $R_c(\theta_r,\varphi_r,\theta_i,\varphi_i)$ for clean ones.

4. Results

Two examples of the results of the reflectance calculation are presented in Fig. 1. The first example refers to seas polluted with oil emulsion, and the second to clean seas. A marked difference between the shapes of the two plots can be seen, and when the angles of observation are close to the angle of incidence, strong backward reflectance is registered. This tendency is consistent at various angles of incidence and at various levels of sea surface roughness. The phenomenon is caused by the high relative refractive index of oil (about 1.12) in relation to the refractive index of most natural seawater suspensions. Simply because of the relatively strong change in the refractive index on the border separating water (medium) and oil (droplet), the backscattering factor is considerably greater for oil suspensions than other components in sea waters. Therefore, one could expect that the maximal contrast of seas polluted by dispersed oil appears when observations are carried out at the direction of solar light flux.

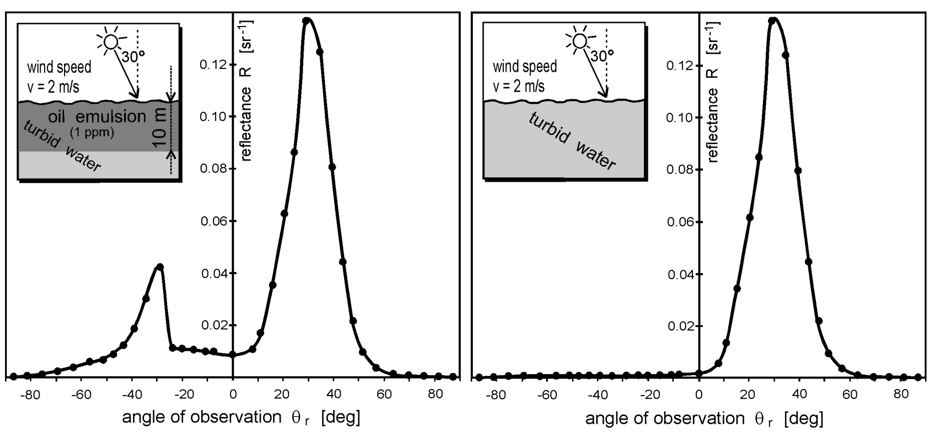

Fig. 1. Reflectance calculated for a sea area polluted by oil emulsion (left plot) in relation to reflectance for a clean one (right plot)

Figure 2 presents the results of modeling performed to check the above hypothesis. The figure consists of six graphs. Three of them show results for turbid seawater (left subfigure column) and three for very clean oceanic water (right column); theses are divided into two for calm sea surfaces (upper row) and four for rough seas. The two graphs in the central row refer

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to wind speeds of 2 m/s and the two in the lower row refer to wind speeds of 5 m/s. All graphs contain three plots for various angles of solar light incidence.

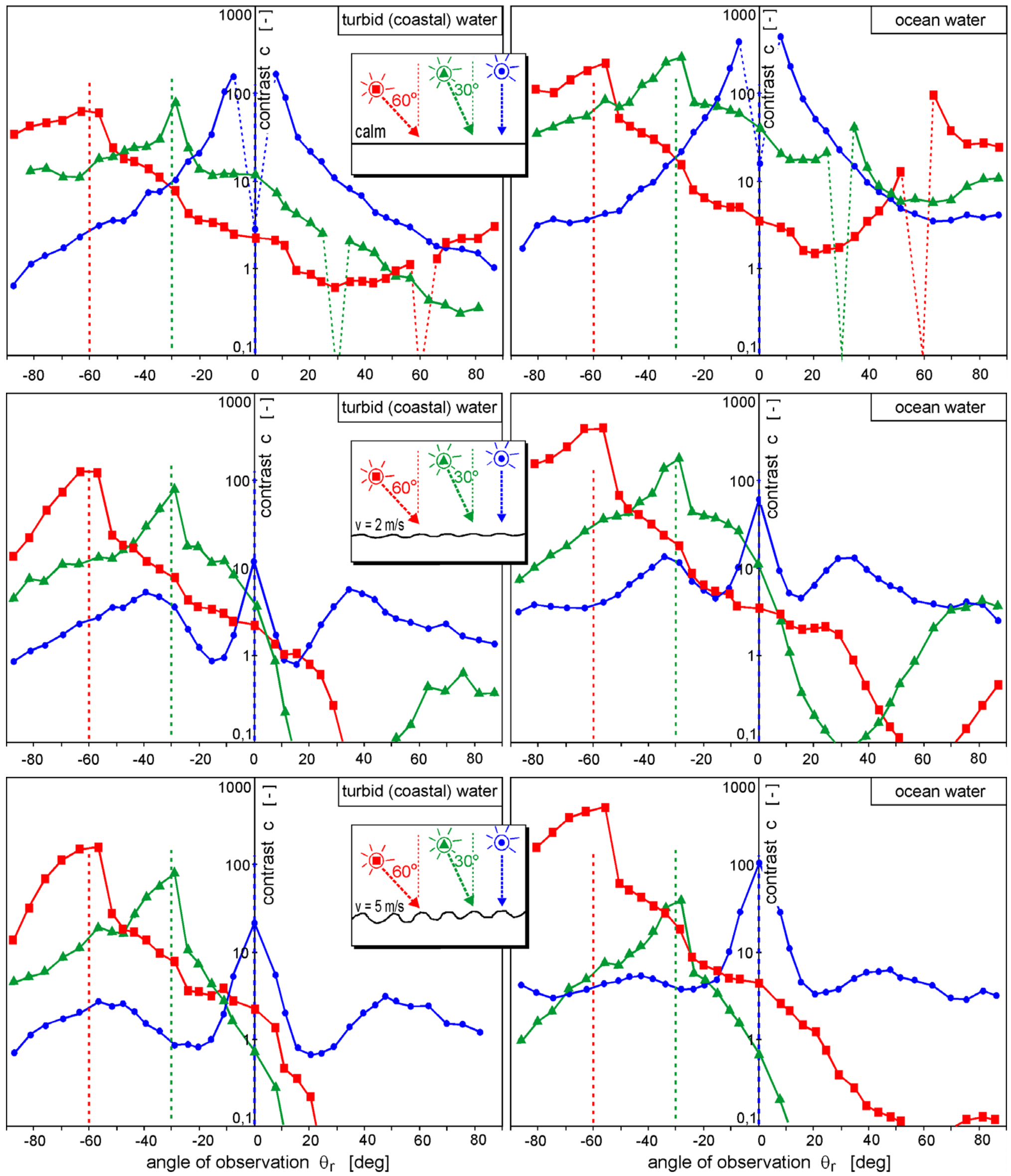

Fig. 2. Contrast of sea areas polluted by oil emulsion as dependent on direction of observation for various sea surface roughness (calm – upper row, roughened by wind - central and lower rows), and for two optically different sea waters (turbid water – left column, ocean water – right column). Blue lines relates to angles of light incidence of 0°, green – 30°, red – 60°.

The two upper plots in Fig. 2 refer to calm sea surfaces and indicate non-linearity at an angle of observation symmetric to the angle of incidence. This phenomenon is caused by the light flux directly reflected from the air-water interface. Simply stated, this light flux repeatedly exceeds the value of light flux formed by the light scattered on the oil droplets suspended throughout the water column. At the other angles of observation, the contrast is

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always positive and increases even to several hundred when the direction of observation is the same as the direction of the solar light incidence (*i.e*. when it is observed from the direction of the sun). A maximum contrast also appears at angles symmetric to the angles of incidence. This phenomenon is clearer for high angle of incidence values than for low ones.

When the results presented in Fig. 2 are compared, one can see that the wind which induces sea roughness also influences the contrast of sea areas polluted by oil emulsion. Generally, increased wind velocity decreases the contrast only for observance angles symmetric to incidence angles. The reason for this phenomenon is that wave slopes produce solar reflexes which superpose on the light fluxes formed in the water column.

The comparison of results in the left (turbid seawater) and right (clean seawater) columns is evidence that the contrast of sea areas polluted by suspended oil is higher in transparent oceanic waters than in turbid coastal waters.

It is worth noting that the contrast functions presented above are only examples of the application of the modeled reflectance functions. Other applications of the derived reflectance function include image correction, verification of other methods of reflectance modeling and inverse problem solving.

5. Summary

The contrast of sea areas polluted by oil depends on the form of the oil substance. It is negative, positive or zero [1] with film, and only positive with suspensions. In the former, the contrast is not greater than 2. In the latter, the contrast value can reach values of several hundred.

The contrast of sea areas polluted by oil suspensions is influenced by the incident light direction, the sea state and, above all, by the observation direction. It appears that it is best to observe oil emulsion dispersed throughout the water column from a direction close to that of solar light.

The optical identification of sea areas polluted by oil emulsion is easier when the water is very transparent than when it is turbid.

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