EFFECT OF WIND WAVES ON RADIATION IN THE "OCEAN-ATMOSPHERE" SYSTEM

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The effect of wind waves on radiation reflected by the sea surface is considered. Integral equations are obtained which describe the reflected radiation in the double scattering approximation of the interaction of the radiation with the "ocean-atmosphere" system. We have obtained analytical formulas which are in good agreement with the results of numerical integration outside the sun's glitter pattern.

The atmospheric correction algorithm described in Ref. 1 has been widely applied in measuring concentrations of chlorophyll and mineral particles in sea water by remote sensing methods. The algorithm has been used in processing the data received by the Coastal-Zone Color Scanner (CZCS).

The correction algorithm is based on the following equations where

$$B_w(\lambda_1)=[B(\lambda_1)-B_R(\lambda_1)-B_a(\lambda_1)]/t(\lambda_1); \tag{1}$$

$$B_a(\lambda_1)=S(\lambda_1,\lambda_4)[B(\lambda_4)-B_R(\lambda_4)-B_w(\lambda_4)t(\lambda_4)], \tag{2}$$

$B_w(\lambda_i)$ is the spectral brightness of the radiation leaving the water surface; $B(\lambda_i)$ is the spectral brightness (SB) of the radiation measured by a sensor in the upper atmospheric boundary; $B_R(\lambda_i)$ is the spectral brightness of the radiation scattered by molecules of atmospheric gases (Rayleigh or molecular scattering); $B_A(\lambda_i)$ is the SB scattered by atmospheric aerosol particles (aerosol scattering); $t(\lambda_i)$ is the diffusive transmittance of the atmosphere; $S(\lambda_i, \lambda_4)$ is a coefficient which accounts for the spectral dependence of aerosol scattering; and λ_i is the average wavelength of the i-th spectral band.

The components $B_R(\lambda_i)$ and $B_A(\lambda_i)$ in Eqs. (1) and (2) include both radiation which has only been scattered by the atmosphere and radiation which has also been reflected by the sea surface.

$$B_{R(a)}=B_h^{R(a)}(\lambda_1)+B_{AS}^{R(a)}(\lambda_1)+B_{SA}^{R(a)}(\lambda_1)+B_S^{R(a)}(\lambda_1), \tag{3}$$

where $B(\lambda_i)$ is the SB of the radiation scattered by the atmosphere (brightness of atmospheric haze): $B_{AS}(\lambda_i)$ is the SB of the radiation scattered by the atmosphere and reflected by the sea surface; $B_{SA}(\lambda_i)$ is the SB of the direct solar radiation reflected by the sea surface and then scattered by the atmosphere, and $B_S(\lambda_i)$ is the SB of the direct solar radiation reflected by the sea surface without scattering in the atmosphere.

When using Eq. (3) in the correction algorithm[1] the effect of wind waves is neglected and the sea surface is assumed to be flat. In this case we have $B_S(\lambda) = 0$ and the values $B_{AS}(\lambda)$ and $B_{SA}(\lambda)$ are described by simple equations (see, e.g., Ref. 2). The purpose of this paper is to take into account the effect of wind waves on the spectral brightness of the "ocean-atmosphere" system in problems of compensation for atmospheric distortions in the remote sensing of the ocean.

To account for the effect of wind waves on radiation reflected by the sea surface, the components B_{AS} and B_{SA} may be described by the following integral equations:

$$B_{AS} = \sec\theta_1 e^{-\frac{\tau_0}{\cos\theta_1}} \int_0^{2\pi}\int_0^1 B^{\downarrow}(\mathbf{n}')\cos\chi\, r_F(\chi)\, P(\theta_n,\varphi_n)\times$$

$$\times\sec^4\theta_n\, d\cos\theta_n\, d\varphi_n; \tag{4}$$

$$B_{SA} = \frac{e^{-\frac{\tau_0}{\cos\theta_S}}}{\pi}\int_0^{2\pi}\int_0^1 B_S^{\uparrow}(\mathbf{n}'')\cos\theta''\sigma(\mathbf{n}'',\mathbf{n}_1)\cos\chi'\, d\cos\theta_n\, d\varphi_n, \tag{5}$$

where θ_S is the solar zenith angle; θ_1 is the observation zenith angle; τ_0 is the optical depth of the atmosphere; r_F is the Fresnel reflection coefficient; χ and χ' are the corresponding incident angles; θ_n and φ_n are the zenith and azimuthal angles of the facet normal, $B^{\downarrow}(\mathbf{n}) = 0.25\, S\cos\theta_S\, g(\gamma)\, Q(\tau_0,\ \theta',\ \theta_S)$ is the SB of the reflection scattered by the sky in the single scattering approximation[3], S is the solar spectral constant;

$$P(\theta_n, \varphi_n) = \frac{1}{2\pi\sigma_x\sigma_y} \exp\left\{ -\frac{\mathrm{tg}^2\theta_n}{2} \left[\frac{\sin^2(\varphi_n - \varphi_V)}{\sigma_x^2} + \frac{\cos^2(\varphi_n - \varphi_V)}{\sigma_y^2} \right] \right\}$$

is the facet slope probability distribution4; $\sigma_x^2 = (3 + 1.92\ V)10^{-3}$; $\sigma_y^2 = 3.16 \times 10^{-3}\ V$; V and φ_V are the wind velocity and the azimuth of the wind; $\sigma(\mathbf{n}'', \mathbf{n}_1) = 0.25\ g(\gamma)\ Q(\tau_0, \theta'', \theta_1)$ is the transmission coefficient in the single scattering approximation[3]; $g(\gamma)$ is the phase function; γ is the scattering angle; and

$$Q(\tau_0, \theta_1, \theta_j) = (e^{-\tau_0/\cos\theta_1} - e^{-\tau_0/\cos\theta_j})/(\cos\theta_1 - \cos\theta_j).$$

The observation direction $\mathbf{n}_1$, the incident direction $\mathbf{n}'$, the reflection direction $\mathbf{n}''$ and the direction of the sun are related to the direction of the normal $\mathbf{n}$ by the specular reflection relations $\mathbf{n}' = -\mathbf{n}_1 + 2\mathbf{n}\cos\chi$ and $\mathbf{n}'' = -\mathbf{n}_S + 2\mathbf{n}\cos\chi'$. The scattering angle γ and the cosines of the incident angles $\cos\chi$ and $\cos\chi'$ are determined by equations describing the relative positions of the vectors in the spherical coordinate system.

For illumination of the sea surface by parallel solar rays, integral (4) is easily evaluated, giving the following equation for the SB of the solar radiation reflected by the sea surface

$$B_S = 0.25\pi S \sec\theta_1 \sec^4\theta_n r_F(\chi^\circ) P(\theta_n^0, \varphi_n^0) e^{-\tau_0\left(\frac{1}{\cos\theta_1} + \frac{1}{\cos\theta_S}\right)}, \tag{6}$$

where $(\theta_n^0, \varphi_n^0)$ is the direction of the normal of the facet, .which specularly reflects the solar radiation in the direction $\mathbf{n}_1$; χ^0 is the corresponding incident angle.

After some transformations and assuming $\varphi_V = 0$, $\varphi_S = \pi$, and $r_F = \text{const}$, we obtain approximate formulas for integrals (4) and (5)

$$B_{AS} = \frac{S\cos\theta_S}{4} r_F e^{-\tau_0/\cos\theta_1} \left\{ g(\gamma)Q + \frac{1}{2\cos\theta_1} \left[\frac{\partial^2 G_{11}}{\partial x^2}\sigma_x^2 + \frac{\partial^2 G_{21}}{\partial x^2}\sigma_y^2 \right] \right\}; \tag{7}$$

$$B_{SA} = \frac{Sr_F}{4} e^{-\frac{\gamma_0}{\cos\theta_S}} \left\{ g(\gamma)Q\cos\theta_S + \frac{1}{2} \left[\frac{\partial^2 G_{12}}{\partial x^2}\sigma_x^2 + \frac{\partial^2 G_{21}}{\partial x^2}\sigma_y^2 \right] \right\}, \tag{8}$$

where

$$\frac{\partial^2 G_{\left\{{}^{11}_{21}\right.}}{\partial x^2} = \cos\theta_1 [g''_{\left\{{}^1_2\right.} + 2g'_{\left\{{}^1_2\right.} Q'_f f'_{\left\{{}^1_2\right.} + g(Q''_f f'^2_{\left\{{}^1_2\right.} + Q'_f f''_{\left\{{}^1_2\right.})] +$$

$$+ 2\sin\theta_{\left\{{}^1_2\right.} \sin\varphi_1 (g'_{\left\{{}^1_2\right.} Q + gQ'_f f'_1);$$

$$\frac{\partial^2 G_{\left\{{}^{12}_{22}\right.}}{\partial x^2} = \cos\theta_S [g''_{\left\{{}^1_2\right.} + 2g'_{\left\{{}^1_2\right.} Q'_h h'_{\left\{{}^1_2\right.} + g(Q''_h R'^2_{\left\{{}^1_2\right.} + Q'_h h''_{\left\{{}^1_2\right.})] -$$

$$-\begin{cases} 0 \\ 2\sin\theta_S (g'_2 Q + gQ'_h h'_2); \end{cases} \quad h = \cos\theta_S; \quad h''_1 = h''_2 = -4\cos\theta_S;$$

$$f = \cos\theta_1; \quad f'_1 = 2\sin\theta_1 \sin\varphi_1; \quad f'_2 = 2\sin\theta_1 \cos\varphi_1;$$

$$f'_1 = f''_2 - 4\cos\theta_1; \quad h'_1 = 0;$$

$$Q_{\left\{{}^f_h\right.} = \left[\exp\left(-\tau_0 / \begin{Bmatrix} f \\ h \end{Bmatrix}\right) - \exp\left(-\tau_0 / \cos\begin{Bmatrix} \theta_S \\ \theta_1 \end{Bmatrix}\right) \right] / \left(\begin{Bmatrix} f \\ h \end{Bmatrix} - \cos\begin{Bmatrix} \theta_S \\ \theta_1 \end{Bmatrix}\right);$$

$$h'_2 = -2\sin\theta_S;$$

$$g = g(\cos\gamma); \qquad \cos\gamma = \cos\theta_S \cos\theta_1 + \sin\theta_S \sin\theta_1 \cos\varphi_1;$$

$$\frac{\partial g(\cos\gamma)}{\partial\cos\gamma} = g'_\gamma; \quad \frac{\partial^2 g(\cos\gamma)}{(\partial\cos\gamma)^2} = g''_\gamma;$$

$$g'_1 = 2\cos\theta_S \sin\theta_1 \sin\varphi_1 g'_\gamma;$$

$$g'_2 = 2(\cos\theta_S \sin\theta_1 \cos\varphi_1 - \sin\theta_S \cos\theta_1) g'_\gamma;$$

$$g''_1 = -4\cos\theta_S \cos\theta_1 g'_\gamma + 4\cos^2\theta_S \sin^2\theta_1 \sin^2\varphi_1 g''_\gamma;$$

$$g''_2 = -4(\cos\theta_S \cos\theta_1 - \sin\theta_S \sin\theta_1 \cos\varphi_1) g'_\gamma +$$

$$+ 4(\cos\theta_S \sin\theta_1 \cos\varphi_1 - \sin\theta_S \cos\theta_1)^2 g''_\gamma.$$

The form of the function $g(\cos\gamma)$ and its derivatives depend on the form of the phase function used. In particular, for the Henyey–Greenstein function we have

$$g_{HG}(\cos\gamma) = (1 - g_x^2)(1 + g_x^2 - 2g_x \cos\gamma)^{-3/2},$$

$$\frac{\partial g_{HG}(\cos\gamma)}{\partial\cos\gamma} = 3g_x(1 - g_x^2)(1 + g_x^2 - 2g_x\cos\gamma)^{-5/2},$$

$$\frac{\partial^2 g_{HG}(\cos\gamma)}{(\partial\cos\gamma)^2} = 15g_x(1 - g_x^2)(1 + g_x^2 - 2g_x\cos\gamma)^{-7/2},$$

where $g_x \in [0, 1]$ is the phase function parameter (the asymmetry parameter).

Analysis of the results of numerical integration shows that the correction for the effect of wind waves can reach a considerable value compared with the SB of the radiation reflected from the flat sea surface.

Figure 1 shows the angle dependence of the relative correction δ calculated according to approximate formulas (7) and (8) and by numerical integration of Eqs. (4) and (5).

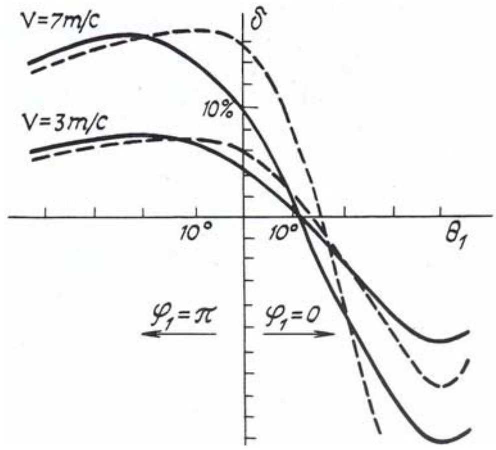

FIG. 1. Effect of wind waves on radiation reflected by the sea surface.

The calculations were carried out with the following parameters for the Henyey—Greenstein formulas (the dashed curves) from the results obtained by numerical integration (the solid curves) are rather small outside the sun's glitter pattern, thus enabling us to recommend that these formulas be used to account for wind waves in algorithms intended for use in compensating for atmospheric distortions when measuring concentrations of chlorophyll and mineral particles in sea water by remote sensing methods.

REFERENCES

1. H.R. Gordon, D.K. Clark, J.W. Brown et al., Appl. Opt., **22**, No. 1, 20 (1983).

2. M. Viollier, D. Tanre, and P.V. Deschamps, Boundary-Layer Meteorol., **18**, No. 3, 3347 (1980)

3. V.V. Sobolev, *Radiant Energy Transfer in the Atmospheres of Stars and Planets* (Gostekhizdat, Moscow, 1956).

4. C. Cox and W. Munk, Bull. Scripps. Inst. Oceanogr., **6**, No. 9, 401 (1956).