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Microwave backscattering from the sea surface with breaking waves*

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Based on the effective medium approximation theory of composites, the whitecap-covered sea surface is treated as a medium layer of dense seawater droplets and air. Two electromagnetic scattering models of randomly rough surface are applied to the investigation of microwave backscattering of breaking waves driven by strong wind. The shapes of seawater droplets are considered by calculating the effective dielectric constant of the whitecap layer. The responses of seawater droplets shapes, such as sphere and ellipsoid, to the backscattering coefficient are discussed. Numerical results of the models are in good agreement with the experimental measurements of horizontally and vertically polarized backscattering at microwave frequency 13.9GHz and different incidence angles.

Keywords: microwave backscattering, effective medium approximation, whitecaps, wave breaking
PACC: 9210, 7260, 5235H

1. Introduction

Wave breaking driven by strong wind plays an important role in all aspects of the air–sea exchange process, including momentum, heat and mass transports. On account of the great impact of whitecaps produced by wave breaking at the sea surface on the microwave remote sensing of seawater physical properties, there has been a growing interest in the study of this phenomenon.[1−7] It is found that, in practical observations of microwave remote sensing, wave breaking may significantly modify the backscattering properties of ocean water.[8,9] In order to estimate the influence of whitecaps at the rough sea surface on backscattering in microwave remote sensing, a number of methods have been developed to investigate the phenomenon. One of the approaches to electromagnetic scattering from a randomly rough surface is the Kirchhoff approximation (KA), which is suitable for high frequency and small incidence angle. Another approach is the small perturbation approximation (SPA). The SPA solution is suitable for low frequency and large incidence angle. Considering that some complex rough sea surfaces cannot be distinguished between large and small scales, a two-scale model is developed to investigate the scattering from the sea surface which can be viewed as a combination of large and small scales.[10−13] Furthermore, there are some other methods, such as the full wave method, the phase perturbation method, the Fourier transform method and the integral equation method. However, these analytical methods are limited because of the complexity of real sea surface. For the complex ocean state, one should develop a reasonable physical model to study the effects of whitecaps on microwave remote sensing. Recently, some remote sensing models of the ocean physical parameters are derived from the various theories. For example, Droppleman[14] modelled the whitecap as a homogeneous layer with a mean dielectric constant. Rosencranz and Staelin[15] proposed a model of thin films parallel to the sea surface. Jin *et al*[16,17] modelled the sea surface by adopting a layer of homogeneous and isotropic spherical particle on the two-scale randomly rough surface and solved the vector radiative transfer equation under the rough boundary condition. More recently, Wei and Ge[18] have proposed a microwave emissivity model of sea surface under wave breaking by using the effective medium approximation theory. In fact, based on this theory, the backscattering coefficients of microwave on the sea

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surface under wave breaking can be also discussed.

In this paper, the whitecap layer is regarded as a layer of effective medium of the spherical or mixed sea particles that are uniformly distributed in the air by the effective medium approximation theory, where the dielectric constant of the whitecap layer is calculated by using a two-phases mixture of air and seawater droplets. In our model, Kirchhoff approximation (KA) and the small perturbation approximation (SPA) methods are applied to discussing the relations between the backscattering coefficient, incidence angle, wind speed and ellipsoid eccentricity. So the impacts of whitecaps and particle shape on the microwave backscattering under wave breaking are taken into consideration in the model.

2. The model of the whitecap layer

Consider the roughness and whitecaps of sea surface under breaking waves. The whitecap layer is modelled as a layer of composite medium of homogeneous sea water particles and air uniformly distributed on the sea surface. The effective dielectric constant $\varepsilon_{\rm m}$ of the whitecap layer is calculated by the following formula:[19]

$$\varepsilon_{\rm m} = \varepsilon_{\rm h} + \frac{1}{3} f_{\rm i}(\varepsilon_{\rm i} - \varepsilon_{\rm h}) \times \sum_{u=a,b,c} [1 + A_{\rm u}(\varepsilon_{\rm i}/\varepsilon^* - 1)]^{-1}, \quad (1)$$

where $f_{\rm i}$ is the volume fraction of water droplets. $f_{\rm i} = Wh$, with W and h being the whitecaps coverage and the height coefficient of wave breaking, respectively; $\varepsilon_{\rm h}$, $\varepsilon_{\rm i}$ and ε^* are the dielectric constants of the air, seawater droplets and the inclusion particle local region, respectively. The dielectric constant of seawater, $\varepsilon_{\rm i}$, is calculated by Debye formula.[20] If $f_{\rm i}$ is very small, the interaction of the seawater droplets can be ignored, in which case ε^* may be taken as being equal to $\varepsilon_{\rm h}$. If $f_{\rm i}$ is larger, we set $\varepsilon^* = \varepsilon_{\rm m}$. $A_{\rm u}$ is the depolarization factors of ellipsoidal droplets along its u-axis,

$$A_{\rm u} = \frac{abc}{2} \int_0^\infty (u^2 + s)^{-1} [(a^2 + s) \times (b^2 + s)(c^2 + s)]^{-1/2} {\rm d}s, \quad (2)$$

where a, b and c are the semi-axes of the ellipsoid particles along x-, y- and z- directions, respectively, and $A_a + A_b + A_{\rm c} = 1$. In our paper, we discuss the case of the prolate spheroids, i.e. $a = b$ and $c > a$.

2.1. The KA model: As the radius of curvature of the rough sea surface is bigger than the incidence wavelength, the scattering field of random points at sea surface can be approximately expressed by the reflection field. The backscattering coefficient σ_0 obtained from KA method has the following form:[10,21]

$$\sigma_0 = \pi \sec^4(\theta) p(\varsigma_x, \varsigma_y) \left|R(0)\right|^2, \quad (3)$$

where θ is the incidence angle, $R(0)$ is the Fresnel reflectance with zero degree incidence angle, $p(\varsigma_x, \varsigma_y)$ is the joint probability density function (PDF) with the x-direction slope ς_x and the y- direction slope ς_y. If the sea surface slope approximately satisfies Gaussian distribution, then $p(\varsigma_x, \varsigma_y)$ has the following form:

$$p(\varsigma_x, \varsigma_y) = \frac{1}{2\pi\sigma_{\rm u}\sigma_{\rm c}} \times \exp\left[-\frac{1}{2}\left(\frac{\cos^2\varphi}{\sigma_{\rm u}^2} + \frac{\sin^2\varphi}{\sigma_{\rm c}^2} \right) \tan^2\theta \right], \quad (4)$$

where φ is the azimuth angle, $\sigma_{\rm u}^2$ and $\sigma_{\rm c}^2$ are the MMS (mean square slopes) in upwind and crosswind directions, respectively. They are expressed as follows:[22]

$$\sigma_{\rm u}^2 = \frac{1.0}{1.9}\sigma_{\rm g}^2 + \frac{2}{3}\sigma_{\rm w}^2,$$
$$\sigma_{\rm c}^2 = \frac{0.9}{1.9}\sigma_{\rm g}^2 + \frac{1}{3}\sigma_{\rm w}^2,$$
$$\sigma_{\rm g}^2 = 0.0103 + 0.0092 \ln u_{10},$$
$$\sigma_{\rm w}^2 = 0.000012 u_{10}^{2.1} \ln\left(\frac{k^2}{2.5 \times 10^4} + 1 \right).$$

In the above expressions, $\sigma_{\rm g}^2$ and $\sigma_{\rm w}^2$ are the MMS of gravity waves and the small capillary waves, respectively, u_{10} is the wind speed at an altitude of 10m above the sea level, and k is the wave number. Because of the background medium changing from atmosphere to whitecap layer, the Fresnel reflectance with zero degree incidence angle is given as follows:

$$R(0) = \left|(n - n_{\rm e})(n + n_{\rm e})^{-1}\right| = \left|(\sqrt{\varepsilon_{\rm sw}} - \sqrt{\varepsilon_{\rm e}})(\sqrt{\varepsilon_{\rm sw}} + \sqrt{\varepsilon_{\rm e}})^{-1}\right|, \quad (5)$$

where $\varepsilon_{\rm sw}$ and $\varepsilon_{\rm e}(\varepsilon_{\rm e} = \varepsilon_{\rm m})$ are the dielectric constants of seawater and the whitecap layer, respectively. The KA model, which is suitable for high frequency and small incidence angle, cannot be affected by the polarization direction.

2.2. The SPA model: When rough sea surface is a small scale fluctuant surface, Bragg resonance has the primary effect on the scattering field, and

the backscattering coefficient σ_0 gained by the SPA method can be shown in the form[11,16]

$$\sigma_{0\mathrm{p}} = 16\pi k^4 |\alpha_{\mathrm{pp}}|^2 W(2k\sin\theta, \varphi), \tag{6}$$

where k is the real incident wave numbers, p denotes the horizontal (h) or vertical (v) polarization, and θ is the real incidence angle. φ is the azimuth angle. $W(K,\varphi)$ is the two-dimensional wave height spectrum. $K = 2k\sin\theta$ is the wave number of the sea surface wave, which is in resonance with the incident wave. α_{pp} is shown in following form:

$$\alpha_{\mathrm{hh}} = -R_{\mathrm{h}}\cos^2\theta,$$
$$\alpha_{\mathrm{vv}} = R_{\mathrm{v}}\cos^2\theta + \frac{1}{2}(1+R_{\mathrm{v}})^2\left(1-\frac{\varepsilon_0}{\varepsilon_{\mathrm{sw}}}\right)\sin^2\theta,$$

where R_{h} and R_{v} are the Fresnel reflection coefficients of horizontal and vertical polarizations, respectively. ε_0 is the dielectric constant of air. Because of the anisotropy induced by the wind direction, $W(K,\varphi)$ can be expressed as[23]

$$\begin{aligned} W(K,\varphi) =& \frac{1}{2\pi K}S(K,\varphi) \\ =& \frac{1}{(2\pi)^2}\frac{1}{K}S(K)[1+a_1(1-\mathrm{e}^{-bK^2})\cos 2\varphi], \end{aligned} \tag{7}$$

where $a_1 = 2(1-R)(1-B)^{-1}(1+R)^{-1}$, $B = S_{\mathrm{t}}^{-2}\int_0^\infty K^2 S(K)\mathrm{e}^{-bK^2}\mathrm{d}K$, $R = S_{\mathrm{ct}}^2 S_{\mathrm{ut}}^{-2}$, $S_{\mathrm{t}}^2 = S_{\mathrm{ut}}^2 + S_{\mathrm{ct}}^2$. S_{t}, S_{ut} and S_{ct} are the total mean gradient, up-direction gradient and down-direction gradient, respectively. Here $S_{\mathrm{ut}}^2 = 3.16\times10^{-3}u$, $S_{\mathrm{ct}}^2 = 0.003 + 1.92\times10^{-3}u$.[24] u is the wind speed at an altitude of 12.5m above sea horizon. The one-dimensional height spectrum $S(K)$ can be simplified to the following formula:[25]

$$S(K) = \begin{cases} \dfrac{a}{K^3}\exp\left[-\dfrac{0.74g^2}{K^2u^4}\right], & K < 0.04; \\ 0.875(2\pi)^{p-1}\dfrac{g+3gK^2/13.177}{(gK+gK^3/13.177)^{(p+1)/2}}, & K > 0.04. \end{cases}$$

Here $a = 4.05\times10^{-3}$, $u = \dfrac{u_*}{0.4}\ln(zz_0^{-1})\mathrm{cm/s}$,
$z_0 = 0.684/u_* + 4.28\times10^{-5}u_*^2 - 4.43\times10^{-2}\mathrm{cm}$,
$p = 5.0 - \lg u_*$, $\quad g = 980\mathrm{cm/s}^2$,
where u is the wind speed at an altitude of 19.5m above the sea horizon. u_* is the friction velocity in cm/s.

Due to the influence of the whitecap layer, the real incidence wave number will be changed. The incidence wave number k_1 equals $2\pi f c^{-1}$, where f and c are the incidence frequency and the speed of electromagnetic wave in air, respectively. In the medium whose dielectric constant equals ε, the speed of electromagnetic wave $v = \omega k^{-1} = c(\sqrt{\varepsilon\mu})^{-1} \approx c(\sqrt{\varepsilon})^{-1}$ and the real incidence wave number $k = cv^{-1}k_1 = k_1\sqrt{\varepsilon}$. Because the wave number is complex in this way, the real incidence wave number can be expressed as the module of the complex wave number.

3. Analysis of the results

In order to show the influence of the whitecap layer on the backscattering coefficient, Huang's whitecaps coverage formulae are used, which gives an empirical expression obtained from the observation data,[26]

$$W = 11.12\mathrm{e}^{0.063U_{19.5}} - 16.23, (U_{19.5} \geq 7\mathrm{m/s}). \tag{8}$$

The height coefficient of wave breaking, h, is smaller than the maximum broken height coefficient $h_{\max}$, so we can define h as $0 < h < h_{\max}$. On condition that the salinity is 32.54 and the sea surface temperature is 293K, in the SPA model, Figs.1 and 2 show the horizontally and vertically polarized backscattering coefficients σ_0^{hh} and σ_0^{vv} for the wind speed $U_{19.5}$ along the upwind direction, microwave frequency $f = 13.9\mathrm{GHz}$ and comparisons with the experimental data.[27] The incidence angles are 30°, 40° and 50°, respectively. The height coefficient of wave breaking h is about 0.2.[18] The solid lines and dotted lines represent results of spherical droplets with whitecaps and that without whitecaps, respectively. It's easy to see that scattering from whitecap scatterers is very important for larger wind speed. As the wind speed increases, more breaking waves were yielded. The impact of whitecaps on the backscattering coefficient is enhanced gradually. The differences between backscattering coefficient with whitecaps and that without whitecaps become also larger. It can be seen that our results are in good agreement with ex-

perimental data. By comparing our results with experimental measurement, it is easy to observe that the horizontally polarized results obtained from our model are better than the vertically polarized ones.

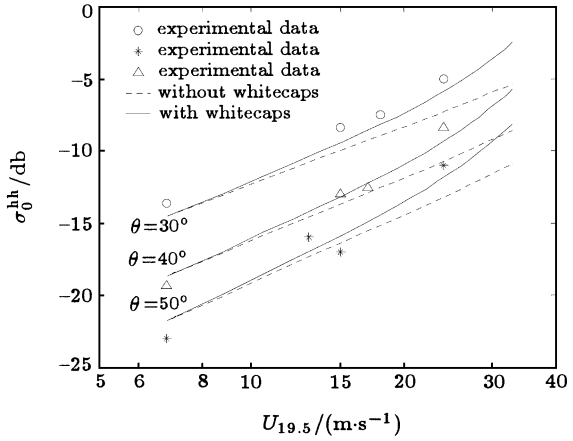


Fig.1. In the SPA model, horizontally polarized backscattering coefficient versus wind speed at incidence angle $\theta = 30°$, $40°$ and $50°$, upwind, $h = 0.2$.

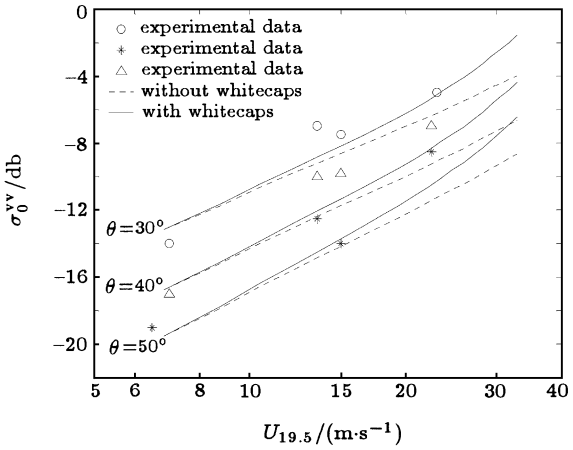


Fig.2. In the SPA model, vertically polarized backscattering coefficient versus wind speed at incidence angle $\theta = 30°$, $40°$ and $50°$, upwind, $h = 0.2$.

In the course of the wave breaking, it is difficult to keep spherical shapes of seawater droplets. In general, the shapes of seawater droplets can affect the calculation of the dielectric constant of the whitecap layer.[18] So it is important to investigate the droplet shapes in the microwave remote sensing. In the KA model, Fig.3 shows backscattering coefficient σ_0 vs the 19.5 metres wind speed $U_{19.5}$ along upwind incidence. The height coefficient of wave breaking h, the incidence frequency f and the incidence angle θ equal 0.2, 13.9GHz and 0°, respectively. The solid lines are only contributed by the roughness of sea surface. The solid lines with stars, rings and crosses denote the results of ellipsoid eccentricities of seawater particles e=0, 2 and 4 in whitecaps, respectively. It is clear that the backscattering coefficient is very sensitive to the shapes of seawater droplets. As wind speed is enhanced, the backscattering coefficient with whitecaps gradually becomes far from those ones without whitecaps. The detaching trend is enhanced with increasing ellipsoid eccentricity.

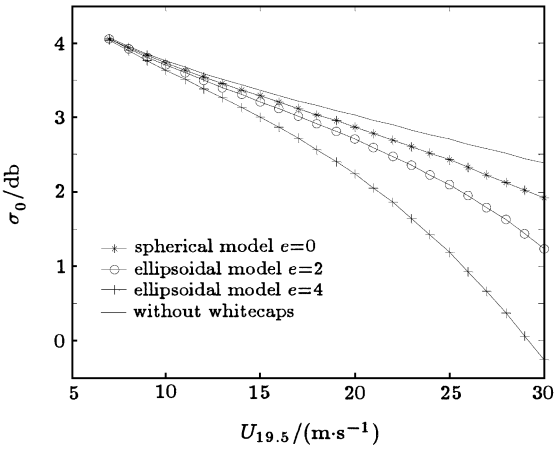


Fig.3. In the KA model, the backscattering versus wind speed at 0°, 13.9GHz, different ellipsoid eccentricity, upwind, h=0.2.

In the SPA model, the shapes of seawater droplets have almost no effect on backscattering coefficient. Figure 4 also shows the horizontally polarized backscattering coefficient σ_0^{hh} plotted against the wind speed $U_{19.5}$ for upwind. The incidence angle is 40°. The incidence frequency, the height coefficient of wave breaking and the droplets eccentricities are the same as those in Fig.3. The symbols have the same denotation as in Fig.3. It can be seen that there is not any important effects of the different shapes of water particles on the horizontally polarized backscattering coefficient in the SPA model. This result shows that the SPA model is not sensitive to the shapes of water droplets in higher frequency band of microwave.

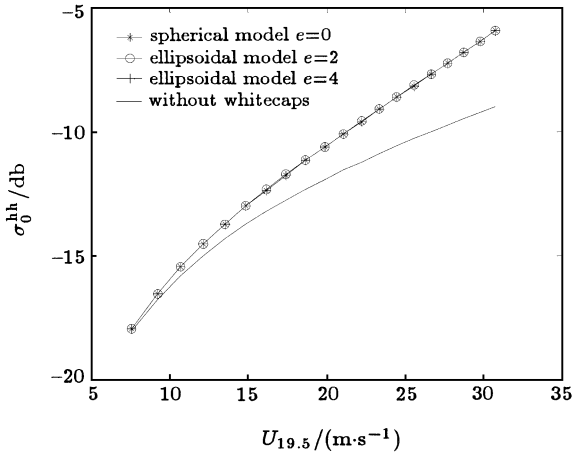


Fig.4. In the SPA model, the backscattering coefficient vs. wind speed u at 40°, 13.9GHz, different ellipsoid eccentricity, upwind, h=0.2.

4. Conclusion and discussion

In this paper, with the effective medium approximation theory of composites, backscattering coefficient of breaking waves driven by strong wind has been investigated by two electromagnetic scattering models for a randomly rough surface. The whitecap layer is regarded as dense seawater droplets uniformly distributed in air host medium. The effective dielectric constant is calculated by considering the air and water droplets mixture, where the parameters of droplet shapes are included. At strong wind speed, our model is instructive for the practical application of ocean remote sensing. It is found that the backscattering is very sensitive to the shapes of droplets for larger wind speed in the KA model. When the ellipsoid eccentricity increases, the backscattering coefficient with whitecaps will deviate from that without whitecaps. This implies that the inclusion shapes of higher concentration will play an important role in this model. The results obtained using our model are in good agreement with experimental measurements. In fact, our method has included the effects of ocean parameter, such as the thickness and coverage of whitecaps. Moreover, by applying the sensitivity of backscattering coefficient to wind speed, it can be estimated when the backscattering coefficient is obtained. Furthermore, it may be possible to use the effective medium approximation theory of composites to investigate other remote sensing problems, such as the heat flux, water vapour flux and the size of water droplets.

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