Influence of wind direction on the infrared sea surface emissivity model including multiple reflection effect

by

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Abstract

A method is described for incorporating surface-emitted surface-reflected (SESR) radiation into the infrared emissivity calculation for an anisotropic wind-roughened sea surface slope distribution model that depends on both wind speed and direction. First, the direct emissivity is obtained by ignoring the SESR radiation. Then, the first order SESR emissivity is obtained by using the direct emission as a radiation source. Finally, the i th order SESR emissivity ($i \geq 2$) is recursively obtained by using the i -1st SESR emission. Sea surface emissivity up to the second order is calculated for wavelengths of 3.7, 11, and 12 μm at wind speeds of 3, 5, 10, and 15 m/s.

Sea surface emissivity derived from the isotropic slope distribution model, which depends only on wind speed, is widely used in radiative transfer models, and validations have been performed through comparisons with measurements. This study examines the applicability of sea surface emissivity calculations to remote sensing measurements with respect to wind speed, emission angle, and the required accuracy of sea surface temperature, by use of sea surface emissivity derived from the anisotropic slope distribution model as a reference. For example, the sea surface temperature accuracy was better than 0.3 K for emission angles below 68° and 56° for isotropic slope distribution models with and without SESR radiation, respectively, for a wavelength of 11 μm , wind speed of 10 m/s, and sea surface temperature of 288 K.

The isotropic model without SESR radiation performs well for satellite remote sensing data up to an emission angle of at least $\sim 50^\circ$ provided the wind speed is less than ~ 10 m/s. Ground based measurements with emission angles larger than 70° could be improved using the anisotropic model with SESR radiation.

1. Introduction

Infrared sea surface emissivity plays an important role in retrieving sea surface temperature from remotely sensed radiometric measurements and is also an essential parameter in radiative transfer models.

Sea surface emissivity can be calculated for practical use by integrating the emitted radiation from a large number of facets, assuming that the sea surface slope distribution obeys some probability distribution model. Cox and Munk (1954a, 1954b, 1955) proposed two kinds of sea surface slope distribution models based on measurements of sun glitter from aerial photographs at wind speeds between 0 and 14 m/s. In

the first model, the slope distribution is expressed in terms of both wind speed and direction; hereafter, we refer to it as the anisotropic model. For the second model, which is derived from the first model, the slope distribution is expressed in terms of only wind speed; hereafter we refer to it as the isotropic model.

Direct emission can be intercepted by nearby facets and reflected into the observer's direction. Such radiation is often referred to as surface-emitted surface-reflected (SESR) radiation (Watts *et al.*, 1996; Wu and Smith, 1997; Masuda, 2006). Sea surface emissivity based on the isotropic model that ignores SESR radiation (Masuda *et al.*, 1988) was compared with that determined from measurements using a high spectral infrared spectrometer in the wavelength region around 10 μm (Smith *et al.*, 1996). Smith *et al.* pointed out that the results of the emissivity model by Masuda *et al.* (1988) are consistent with the measurements for emission angles less

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than about 55° but are lower than the measurements by 0.02–0.03 for an emission angle of 73.5° .

The discrepancy between the theoretical prediction and the measurements was effectively diminished by incorporating SESR radiation into the model computation (Wu and Smith, 1997; Masuda, 2006). The sea surface emissivity model by Masuda *et al.* (1988) and its modified version are now widely used in many radiative transfer models (e.g., Sherlock, 1999; Matricardi and Saunders, 1999; Mano and Ishimoto, 2004; Clough *et al.*, 2005; Liang *et al.*, 2009; Matricardi, 2010) and for validation of radiative transfer models (Dash and Ignatov, 2008).

From the view point of surface slope distribution modeling, the anisotropic model is superior to the isotropic model because the slope distribution parameter of the latter is derived from that of the former by averaging the upwind and crosswind components (Cox and Munk, 1954a). However, a computational scheme to incorporate SESR radiation into the anisotropic model has not been established. One of the objectives of this study is to present a method for calculating the infrared sea surface emissivity of the anisotropic model taking SESR radiation into account. Another objective is to examine the accuracy of sea surface emissivity derived from the isotropic model using the results from the anisotropic model as a reference and to assess the applicability of the isotropic model to remote sensing measurements.

This paper is organized as follows. The basic equations for calculating sea surface emissivity by using the anisotropic model are summarized in Section 2. Formulations for incorporating the SESR radiation into the emissivity calculation are described in Section 3. Examples of the computational results are presented in Section 4 where the influence of wind direction on the sea surface emissivity calculation is discussed in detail. In Section 5, the accuracy of sea surface emissivity based on the isotropic model is investigated and its applicability to remote sensing measurements is discussed with respect to wind speed, emission angle, and the required accuracy of sea surface temperature.

2. Basic equations for direct emissivity from the anisotropic slope distribution model

The equations for calculating sea surface emissivity from a wind-roughened sea surface model as described in Masuda (1998) with some modifications are summarized as follows. To simulate a wind-roughened sea surface, we assume that it is composed of many facets with slopes that obey a probability distribution function independent of facet.

Following the formulas of Cox and Munk (1954a) and Saunders (1967, 1968), the radiation emitted from a horizontal unit area of wind-roughened sea surface in the direction (θ, ϕ) is given by

$$\begin{aligned} & \varepsilon(\theta, \phi; v, \phi_w) B(T_s) \cos \theta d\Omega \\ &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \varepsilon_L(\chi) B(T_s) d\Omega \cos \chi \sec \theta_n P(\xi, \eta) dz_x dz_y, \\ & \cos \chi > 0 \end{aligned} \quad (1)$$

where $z_x (= \partial z / \partial x)$ and $z_y (= \partial z / \partial y)$ are the slope components in the x and y directions, respectively (Fig. 1). v and ϕ_w are the wind speed and direction, respectively. $d\Omega$ is a solid angle. ε_L is the emissivity of an individual facet with χ being the local emission angle. The integral is performed over all facets with $\cos \chi > 0$. $B(T_s)$ is the black body radiation at surface temperature T_s . $P(\xi, \eta)$ is the probability distribution function of the facet slopes, which is explained below.

The sea surface emissivity is then expressed by

$$\begin{aligned} & \varepsilon(\theta, \phi; v, \phi_w) \\ &= \frac{1}{\cos \theta} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \varepsilon_L(\chi) \cos \chi \sec \theta_n P(\xi, \eta) dz_x dz_y, \quad \cos \chi > 0 \\ &= \frac{1}{\cos \theta} \int_0^1 \int_{-\pi}^{\pi} \varepsilon_L(\chi) \cos \chi P(\xi, \eta) \mu_n^{-4} d\phi_n d\mu_n, \quad \cos \chi > 0 \end{aligned} \quad (2)$$

where μ_n is the cosine of θ_n .

The local emission angle χ is expressed by

$$\cos \chi = \cos \theta \cos \theta_n + \sin \theta \sin \theta_n \cos(\phi - \phi_n). \quad (3)$$

The emissivity from a facet is given by $\varepsilon_L(\chi) = 1 - (|r_t|^2 + |r_r|^2)/2$.

Here, $r_t = (\cos \chi' - m \cos \chi) / (\cos \chi' + m \cos \chi)$ and $r_r = (\cos \chi - m \cos \chi') / (\cos \chi + m \cos \chi')$ (Fresnel formulas), where m is the complex refractive index of sea water. The refraction angle is given by $\sin \chi' = (1/m) \sin \chi$ (Snell's law).

Cox and Munk (1954a) measured sun glitter from

Fig. 1 Geometry of emission from a wave facet tangent to the instantaneous sea surface at point O. $\mathbf{i}$ is the unit vector in the direction of emitted radiation. $\mathbf{n}$ is the facet unit normal vector. θ and θ_n are the zenith angles of $\mathbf{i}$ and $\mathbf{n}$, respectively. ϕ_n is the azimuth angle of $\mathbf{n}$ measured from the x axis anticlockwise. The azimuth angle of $\mathbf{i}$ is set at $\phi = 0$. χ is the angle of emitted radiation with respect to the facet normal. u and c denote the upwind and crosswind axes, respectively. ϕ_w is the angle of the u axis measured from the x axis clockwise.

aerial photographs at wind speeds between 0 and 14 m/s. They simulated the sea surface by using many facets and represented the probability distribution of the facet slopes as a Gram-Charlier series,

$$P(\xi, \eta) = f(\xi, \eta)g(\xi, \eta), \quad (4)$$

$$\text{where } f(\xi, \eta) = \frac{1}{2\pi\sigma_c\sigma_u} e^{-(\xi^2 + \eta^2)/2}, \quad (5)$$

and

$$\begin{aligned} g(\xi, \eta) = & 1 - \frac{1}{2}c_{21}(\xi^2 - 1)\eta - \frac{1}{6}c_{03}(\eta^3 - 3\eta) \\ & + \frac{1}{24}c_{40}(\xi^4 - 6\xi^2 + 3) + \frac{1}{4}c_{22}(\xi^2 - 1)(\eta^2 - 1) \\ & + \frac{1}{24}c_{04}(\eta^4 - 6\eta^2 + 3). \end{aligned} \quad (6)$$

$\xi = z_c/\sigma_c$ and $\eta = z_u/\sigma_u$, where z_c and z_u are the crosswind and the upwind slope components, respectively. z_c and z_u are given by $\tan\theta_n \sin\alpha$ and $\tan\theta_n \cos\alpha$, respectively (Cox and Munk, 1954b), where α is the angle between the upwind direction and the facet ascent and is given by $\alpha = \phi_w + \phi_n + \pi$. σ_c^2 and σ_u^2 are the mean values of z_c^2 and z_u^2 , averaged over many facets. σ_c^2 and σ_u^2 are expressed as

$$\begin{aligned} \sigma_c^2 &= 0.003 + 0.00192v \pm 0.002, \\ \sigma_u^2 &= 0.00316v \pm 0.004, \end{aligned} \quad (7)$$

where v (m/s) is the wind speed at a height of 41 feet (12.5 m) above sea level (Cox and Munk, 1954a).

The function $g(\xi, \eta)$ represents the skewness and peakedness from the normal distribution (Cox and Munk, 1954b). The coefficients in Eq. (6) are $c_{21} = 0.01 - 0.0086v \pm 0.03$, $c_{03} = 0.04 - 0.033v \pm 0.12$, $c_{40} = 0.40 \pm 0.23$, $c_{22} = 0.12 \pm 0.06$, and $c_{04} = 0.23 \pm 0.41$ (Cox and Munk, 1954a). For simplicity, deviations after the $\pm$ sign are not considered in this study.

Finally, to avoid divergence of the calculated emissivity at near-grazing emission angles, $\varepsilon(\theta, \phi; v, \phi_w)$ is normalized as

$$\varepsilon^*(\theta, \phi; v, \phi_w) = \varepsilon(\theta, \phi; v, \phi_w) / p(\theta, \phi; v, \phi_w), \quad (8)$$

where

$$p(\theta, \phi; v, \phi_w) = \frac{1}{\cos\theta} \int_0^1 \int_{-\pi}^{\pi} \cos\chi P(\xi, \eta) \mu_n^{-4} d\phi_n d\mu_n, \quad \cos\chi > 0 \quad (9)$$

We refer to $\varepsilon^*(\theta, \phi; v, \phi_w)$ as the direct emissivity.

The normalizing factor, $1/p(\theta, \phi; v, \phi_w)$, for emission angle θ from 50° to 90° at $v = 5, 10$, and 15 m/s for $\phi_w = 0^\circ, 90^\circ$, and 180° is almost unity for $\theta < 60^\circ$ and decreases with increasing θ , most notably for $\theta > 85^\circ$ (Fig. 2).

The normalization expressed in Eq. (8) is performed from an energy conservation point of view as in Masuda *et al.* (1988). Wu and Smith (1997) showed that the normalizing factor used in Masuda *et al.* (1988) is equivalent to the shadowing factor presented in Saunders (1967, 1968) which

Fig. 2 Normalizing factor $1/p(\theta, \phi; v, \phi_w)$ for $\phi = 0^\circ$ as a function of the emission angle θ for $v = 5$ (solid line), 10 (dotted line), and 15 m/s (dashed line); (a) $\phi_w = 0^\circ$, (b) $\phi_w = 90^\circ$, and (c) $\phi_w = 180^\circ$.

could be interpreted as the ratio of the area projected onto a plane normal to the line of sight that can actually be seen by the observer (i.e., the projected area that is not hidden) to the entire projected area (including the hidden areas) (Saunders, 1968). In other words, it can be interpreted as the probability

of the emission that is not intercepted by another facet (Masuda, 2006). Hereafter, we denote $1/p(\theta, \phi; \nu, \phi_w)$ as $s(\theta, \phi; \nu, \phi_w)$ and refer to it as the shadowing factor. The shadowing factor is used in Section 3 to derive the weighting function to determine the probability of the emission that originates from the sea surface.

3. Surface-emitted surface-reflected radiation

Masuda (2006) presented an algorithm for incorporating SESR radiation into the calculation of sea surface emissivity for the isotropic model. It can be extended to the anisotropic model by taking the wind direction into account.

3.1 First order SESR emissivity

We use the direct emission obtained in Eq. (8) as a radiation source to calculate the first order SESR emissivity, as in Watts *et al.* (1996), Wu and Smith (1997), and Masuda (2006).

The first step is to calculate the direction of the radiation source $\mathbf{i}'(\theta', \phi')$ (i.e., the direct emission), which is determined from the directions of the SESR radiation $\mathbf{i}(\theta, \phi)$ and the facet normal $\mathbf{n}(\theta_n, \phi_n)$ (Fig. 3). Because $\mathbf{i}'$ is given by $\mathbf{i} - 2\mathbf{n}\cos\chi$ (e.g., Masuda, 2006), θ' and ϕ' can be calculated using simple geometry. Note that θ' can be equal to or larger than 90° .

The next step is to calculate the probability of the direct emission that originates from the sea surface; we assume that it equals 1 for $\theta' < 90^\circ$ (upward emission). For $\theta' \geq 90^\circ$ (downward emission), we focus on the backward direction of the direct emission, i.e. $-\mathbf{i}'$, with zenith and azimuth angles $180^\circ - \theta'$ ($0^\circ \leq 180^\circ - \theta' \leq 90^\circ$) and $\phi' + 180^\circ$, respectively. From the discussion in Section 2, $s(180^\circ - \theta', \phi' + 180^\circ; \nu, \phi_w)$ could be interpreted as the probability of the backward trajectory that is not intercepted by another facet, in other words, the probability of emission that originates from the sky. Thus, the probability of emission that originates from the sea surface will be $1 - s(180^\circ - \theta', \phi' + 180^\circ; \nu, \phi_w)$. We denote $1 - s(180^\circ - \theta', \phi' + 180^\circ; \nu, \phi_w)$ as $w(\theta', \phi'; \nu, \phi_w)$ and refer to it as the weighting function. Needless to say, $w(\theta', \phi'; \nu, \phi_w) = 1$ for $\theta' < 90^\circ$.

Fig. 3 Diagram showing the directions of the SESR radiation $\mathbf{i}$ and the radiation source $\mathbf{i}'$. $\mathbf{n}$ is the facet unit normal vector. θ, θ' , and θ_n (ϕ, ϕ' , and ϕ_n) are the zenith (azimuth) angles of $\mathbf{i}, \mathbf{i}'$, and $\mathbf{n}$, respectively. χ is the angle of emitted radiation with respect to the facet normal.

The weighting function for $\phi_w = 0^\circ, 90^\circ$, and 180° as a function of the zenith angle of the direct emission θ' at $\phi' = 0^\circ$ increases with wind speed (Fig. 4). This characteristic seems quite reasonable because the emitted radiation that originates from the sea surface would increase with surface

Fig. 4 Weighting function $w(\theta', \phi'; \nu, \phi_w)$ at $\phi' = 0^\circ$ as a function of the zenith angle θ' for $\nu = 5$ (solid line), 10 (dotted line), and 15 m/s (dashed line); (a) $\phi_w = 0^\circ$, (b) $\phi_w = 90^\circ$, and (c) $\phi_w = 180^\circ$.

roughness, which intensifies with wind speed.

Replacing $\varepsilon_L(\chi)$ in Eq. (2) by $\rho(\chi)\varepsilon^*(\theta', \phi'; \nu, \phi_w)w(\theta', \phi'; \nu, \phi_w)$ yields the equation for the first order SESR emissivity:

$$r_1(\theta, \phi; \nu, \phi_w) = \frac{1}{\cos \theta} \int_0^1 \int_{-\pi}^{\pi} \rho(\chi) \varepsilon^*(\theta', \phi'; \nu, \phi_w) w(\theta', \phi'; \nu, \phi_w) \cdot \cos \chi P(\xi, \eta) \mu_n^{-4} d\phi_n d\mu_n, \quad \cos \chi > 0. \quad (10)$$

Here, $\rho(\chi)$ is the local reflectivity of the direct emission for an individual facet obtained from the Fresnel formulas (Section 2) by $\rho(\chi) = (|r_l|^2 + |r_t|^2)/2$. $r_l(\theta, \phi; \nu, \phi_w)$ is normalized as

$$r_l^*(\theta, \phi; \nu, \phi_w) = r_l(\theta, \phi; \nu, \phi_w) / p(\theta, \phi; \nu, \phi_w). \quad (11)$$

We refer to $r_l^*(\theta, \phi; \nu, \phi_w)$ as the first order SESR emissivity.

For the azimuth angles, it can be shown by using simple geometry that $\varepsilon^*(\theta', \phi'; \nu, \phi_w) = \varepsilon^*(\theta', 0; \nu, \phi' + \phi_w)$ and $w(\theta', \phi'; \nu, \phi_w) = w(\theta', 0; \nu, \phi' + \phi_w)$. The computational procedure can be simplified by treating $\phi' + \phi_w$ as one variable.

3.2 Higher order SESR emissivity

The higher order SESR emissivity can be obtained in a manner similar to the first order SESR emissivity. Suppose that the i -1st order SESR emissivity was obtained as $r_{i-1}^*(\theta, \phi; \nu, \phi_w)$. For the i th order SESR emissivity ($i \geq 2$), the equation corresponding to Eq. (10) is

$$r_i(\theta, \phi; \nu, \phi_w) = \frac{1}{\cos \theta} \int_0^1 \int_{-\pi}^{\pi} \rho(\chi) r_{i-1}^*(\theta', \phi'; \nu, \phi_w) w(\theta', \phi'; \nu, \phi_w) \cdot \cos \chi P(\xi, \eta) \mu_n^{-4} d\phi_n d\mu_n, \quad \cos \chi > 0. \quad (12)$$

$r_i(\theta, \phi; \nu, \phi_w)$ is normalized as

$$r_i^*(\theta, \phi; \nu, \phi_w) = r_i(\theta, \phi; \nu, \phi_w) / p(\theta, \phi; \nu, \phi_w). \quad (13)$$

Thus, the higher order SESR emissivity can be obtained recursively. The surface emissivity including the SESR radiation will now be obtained as

$$\varepsilon^*(\theta, \phi; \nu, \phi_w) + \sum_{i=1}^{\infty} r_i^*(\theta, \phi; \nu, \phi_w).$$

4. Direct and first order SESR emissivity

4.1 Examples of numerical results

The direct emissivity ε^* (Fig. 5a) and the first order SESR emissivity r_1^* (Fig. 5b) were derived for $\phi = 0^\circ$ as functions of the emission angle θ for $\nu = 10$ m/s at a wavelength λ of 11 μm and wind direction ϕ_w of 0° , 90° , and 180° . The refractive index by Hale and Querry (1973) was used with the salinity adjustment from Friedman (1969) as in Masuda *et al.* (1988); $m = 1.162 - i0.0938$ for $\lambda = 11$ μm . The effect of oceanic whitecaps was not taken into account.

During the computational procedure, some interpolation was needed with respect to the zenith and azimuth angles.

Fig. 5 (a) Sea surface direct emissivity ε^* and (b) the first order SESR emissivity r_1^* for $\phi = 0^\circ$ as functions of the emission angle θ for $\nu = 10$ m/s at a wavelength of 11 μm for $\phi_w = 0^\circ$ (solid lines), 90° (dotted lines), and 180° (dashed lines).

For example, $\varepsilon^*(\theta', \phi'; \nu, \phi_w)$ in Eq. (10) was interpolated using $\varepsilon^*(\theta, \phi; \nu, \phi_w)$ that was computed in advance. Calculations were performed for 91 equally spaced μ from -1.0 to 1.0 and for 91 equally spaced ϕ_w from -180° to 180° . The number 91 was chosen to ensure the interpolation was sufficiently accurate to obtain SESR emissivity. Simpson's rule was adopted for both zenithal and azimuthal integrals ($d\mu_n$ and $d\phi_n$). The number of quadrature points for the zenithal integral is 25 for $0.5 \leq |\mu| \leq 1.0$, 51 for $0.35 \leq |\mu| \leq 0.5$, 75 for $0.25 \leq |\mu| \leq 0.35$, 151 for $0.15 \leq |\mu| \leq 0.25$, and 401 for $0.0 \leq |\mu| \leq 0.15$. The number of quadrature points for the azimuthal integral is double that for the zenithal integral. The lower boundary for the zenithal integral is $\mu_n^* = (1 + 2\sigma_m^2 q)^{-1/2}$, where $\sigma_m = \max(\sigma_u, \sigma_c)$ with $q = 30$ as in Masuda (1998). As mentioned by Cox and Munk (1954a), the probability function $P(\xi, \eta)$ can be appropriately represented for slopes up to $\xi = \eta = 2.5$. Thus, in the present study, ξ and η were bounded by substituting ± 2.5 in the calculation of $g(\xi, \eta)$ when they exceeded these values, as in Masuda (1998).

The direct emissivity decreases with increasing θ (Fig. 5a). The influence of wind direction ϕ_w on the direct emissivity is evident for $\theta > 60^\circ$. For example, ε^* is 0.879, 0.864, and 0.872 for $\phi_w = 0^\circ, 90^\circ$, and 180° , respectively, at $\theta = 75^\circ$. For the isotropic model (not shown), ε^* is 0.871 at $\theta = 75^\circ$. The first order SESR emissivity is less than 0.002 for $\theta < 50^\circ$ (Fig. 5b) and increases with θ , reaching a peak value of 0.03–0.04 at $\theta \sim 80^\circ$. For example, r_1^* is 0.029, 0.034, and 0.037 for $\phi_w = 0^\circ, 90^\circ$, and 180° , respectively, at $\theta = 81^\circ$ whereas for the isotropic model r_1^* is 0.033 (not shown). The second order emissivity, r_2^* (not shown), was less than 0.001 over the entire emission angle range for the same wavelengths and wind speeds presented in Fig. 5. Hereafter, we focus only on the properties of the direct and first order SESR emissivities.

4.2 Influence of wind direction on the surface emissivity calculation

To examine the influence of wind direction on the sea surface emissivity calculation, I plotted ε^* and r_1^* for $\theta = 61^\circ$ and 80° , with $\phi = 0^\circ$ as functions of wind direction ϕ_w (Fig. 6). For $\theta = 61^\circ$, ε^* (0.956–0.958) varies only slightly with ϕ_w , whereas r_1^* reaches its peak (0.008) at $\phi_w = 0^\circ$ and 180° and its minimum value (0.005) at $\phi_w = 90^\circ$ and 270° . For $\theta = 80^\circ$, ε^* reaches its maximum value at $\phi_w = 0^\circ$ (0.829) and 180° (0.824) and minimum value (0.802) at $\phi_w = 90^\circ$ and 270° , whereas for r_1^* , the maximum (0.037) is at $\phi_w = 180^\circ$ and the minimum (0.029) at $\phi_w = 0^\circ$. In this section, we examine the link between these emissivity features and the surface slope distribution properties. The dependence of ε^* and r_1^* on the wind direction is verified by close examination of these functions and their normalized integrands.

Firstly, we define $\varepsilon_A^*(\theta, \phi, \theta_n; v, \phi_w)$ and $r_{1A}^*(\theta, \phi, \theta_n; v, \phi_w)$, the normalized integrands of Eqs. (2) and (10), respectively, as

$$\begin{aligned} \varepsilon_A^*(\theta, \phi, \theta_n; v, \phi_w) &= \frac{1}{p(\theta, \phi; v, \phi_w) \cos \theta} \int_{-\pi}^{\pi} \varepsilon_L(\chi) \cos \chi P(\xi, \eta) \mu_n^{-4} d\phi_n, \\ \cos \chi &> 0, \end{aligned} \quad (14)$$

and

$$\begin{aligned} r_{1A}^*(\theta, \phi, \theta_n; v, \phi_w) &= \frac{1}{p(\theta, \phi; v, \phi_w) \cos \theta} \int_{-\pi}^{\pi} \rho(\chi) \varepsilon^*(\theta', \phi'; v, \phi_w) w(\theta', \phi'; v, \phi_w) \\ &\cdot \cos \chi P(\xi, \eta) \mu_n^{-4} d\phi_n, \quad \cos \chi > 0, \end{aligned} \quad (15)$$

$\varepsilon_A^*(\theta, \phi, \theta_n; v, \phi_w)$ and $r_{1A}^*(\theta, \phi, \theta_n; v, \phi_w)$ as functions of $\mu_n (= \cos \theta_n)$ are plotted in Fig. 7 for three cases of wind direction. We will now examine four cases that demonstrate some of the characteristics observed in Fig. 7.

Case 1: ε_A^* for $\theta = 61^\circ$ and $\phi = 0^\circ$ (Fig. 7a)

The value of ε_A^* for $\phi_w = 0^\circ, 90^\circ$, and 180° is very similar over all μ_n ranges. Consequently, the value of ε^* , the integral of ε_A^* with respect to μ_n , is almost identical for $\phi_w = 0^\circ$,

Fig. 6 (a) Sea surface direct emissivity ε^* and (b) the first order SESR emissivity r_1^* for $\phi = 0^\circ$ as functions of the up-wind direction ϕ_w for $\theta = 61^\circ$ and 80° . The wavelength and wind speed are the same as those in Fig. 5. ε^* and r_1^* at $\phi_w = 0^\circ, 90^\circ$, and 180° in Figs. 6a and 6b correspond to those at $\theta = 61^\circ$ and 80° in Figs. 5a and 5b.

90° , and 180° as seen for $\theta = 61^\circ$ in Fig. 5a. To further examine this point, we define $\varepsilon_B^*(\theta, \phi, \theta_n, \phi_n; v, \phi_w)$, the normalized integrand of Eq. (14), as

$$\begin{aligned} \varepsilon_B^*(\theta, \phi, \theta_n, \phi_n; v, \phi_w) &= \frac{1}{p(\theta, \phi; v, \phi_w) \cos \theta} \varepsilon_L(\chi) \cos \chi P(\xi, \eta) \mu_n^{-4}. \end{aligned} \quad (16)$$

In Figs. 8a–8c, the distribution function of the sea surface slope $P(\xi, \eta)$, the cosine of the local emission angle $\cos \chi$, and the local emissivity $\varepsilon_L(\chi)$ are plotted as functions of ϕ_n for $\theta_n = 18.1^\circ$ ($\mu_n = 0.95$) where $\varepsilon_A^* = 5.05, 5.03$, and 4.97 for $\phi_w = 0^\circ, 90^\circ$, and 180° , respectively (Fig. 7a). Note that $\cos \chi$ and ε_L are independent of ϕ_w . P has its maximum at $\phi_n = 0^\circ$ and 180° for $\phi_w = 0^\circ$ and 180° and at $\phi_n = 90^\circ$ and 270° for $\phi_w = 90^\circ$. ε_B^* , which is proportional to the product of P , $\cos \chi$, and ε_L , is plotted in Fig. 8d. The ε_B^* curves for $\phi_w = 0^\circ$ and 180° are similar whereas the shape of ε_B^* for $\phi_w = 90^\circ$ is quite different. Despite the difference between the ε_B^* curves, the values of ε_A^* , the integral of ε_B^* with respect to ϕ_n , are almost identical for $\phi_w = 0^\circ, 90^\circ$, and 180° , as seen in Fig. 7a for μ_n

Fig. 7 (a and c) $\varepsilon_A^*(\theta, \phi, \theta_n; v, \phi_w)$ and (b and d) $r_{1A}^*(\theta, \phi, \theta_n; v, \phi_w)$ as functions of $\mu_n (= \cos \theta_n)$ for $v = 10$ m/s, $\lambda = 11$ μm , $\phi = 0^\circ$, and $\theta = 61^\circ$ (a and b) or $\theta = 80^\circ$ (c and d). Wind directions are $\phi_w = 0^\circ$ (solid lines), 90° (dotted lines), and 180° (dashed lines).

= 0.95.

Case 2: r_{1A}^* for $\theta = 61^\circ$ and $\phi = 0^\circ$ (Fig. 7b)

r_{1A}^* for $\phi_w = 90^\circ$ is smaller than that for $\phi_w = 0^\circ$ and 180° over all μ_n ranges. Consequently, r_1^* , the integral of r_{1A}^* with respect to μ_n , is smaller for $\phi_w = 90^\circ$ than for $\phi_w = 0^\circ$ and 180° as seen at $\theta = 61^\circ$ in Fig. 5b. In a manner similar to ε_B^* , we define $r_{1B}^*(\theta, \phi, \theta_n, \phi_n; v, \phi_w)$ as

$$r_{1B}^*(\theta, \phi, \theta_n, \phi_n; v, \phi_w) = \frac{1}{P(\theta, \phi, v, \phi_w) \cos \theta} \rho(\chi) \varepsilon^*(\theta', \phi'; v, \phi_w) w(\theta', \phi'; v, \phi_w) \cdot \cos \chi P(\xi, \eta) \mu_n^{-4}. \quad (17)$$

The local reflectivity $\rho(\chi)$, the weighting function $w(\theta', \phi'; v, \phi_w)$, and the direct emissivity $\varepsilon^*(\theta', \phi'; v, \phi_w)$ are plotted in Figs. 8e–8g as functions of ϕ_n for $\theta_n = 18.1^\circ$ ($\mu_n = 0.95$) where r_{1A}^* is 0.125, 0.075, and 0.137 for $\phi_w = 0^\circ$, 90° , and 180° , respectively (Fig. 7b). $\rho(\chi)$ is independent of ϕ_w . w and ε^* have a slight dependency on ϕ_w . w has non-zero values for ϕ_n values of about 120° – 240° . In particular, $w = 1$ when ϕ_n is between 140° and 220° because the zenithal direction of the direct emission θ' is less than 90° (not shown).

r_{1B}^* , which is proportional to the product of ρ , ε^* , w , $\cos \chi$, and P , is displayed in Fig. 8h. For $\phi_n = \sim 140^\circ$ – 220° , r_{1B}^* for $\phi_w = 90^\circ$ is much smaller than for $\phi_w = 0^\circ$ and 180° . This is mainly caused by the fact that P for $\phi_w = 90^\circ$ is much smaller than for $\phi_w = 0^\circ$ and 180° in this angle range (Fig. 8a) where w is unity. As a result, r_{1A}^* , the integral of r_{1B}^* with respect to ϕ_n , for $\phi_w = 90^\circ$ (0.075) is smaller than for $\phi_w = 0^\circ$ and 180° (0.125 and 0.137) as seen for $\mu_n = 0.95$ in Fig. 7b.

Case 3: ε_A^* for $\theta = 80^\circ$ and $\phi = 0^\circ$ (Fig. 7c)

In this case, we examine the relationship between the magnitude of ε_A^* for $\theta_n = 7.4^\circ$ ($\mu_n = 0.99$) and the shape of the slope distribution function. In Figs. 9a–9c, P , $\cos \chi$, and ε_L are plotted as functions of ϕ_n as in Case 1, but for $\theta_n = 7.4^\circ$ ($\mu_n = 0.99$). The primary peaks of P are observed at $\phi_n = 0^\circ$, 270° , and 180° for $\phi_w = 0^\circ$, 90° , and 180° , respectively. The secondary peaks are observed at $\phi_n = 180^\circ$, 90° , and 0° for $\phi_w = 0^\circ$, 90° , and 180° , respectively, and are much smaller than the primary ones. Note that the P curves overlap as a phase shift in ϕ_n . For example, P at $\phi_n = 0^\circ$ for $\phi_w = 0^\circ$ corresponds to P at $\phi_n = 270^\circ$ for $\phi_w = 90^\circ$. $\cos \chi$ and ε_L are independent of ϕ_w , showing their minimums at $\phi_n = 180^\circ$.

Fig. 8 (a) $P(\zeta, \eta)$; (b) $\cos\chi$; (c) $\varepsilon_L(\chi)$; (d) $\varepsilon_B^*(\theta, \phi, \theta_n, \phi_n; \nu, \phi_w)$; (e) $\rho(\chi)$; (f) $w(\theta, \phi, \nu, \phi_w)$; (g) $\varepsilon^*(\theta, \phi, \nu, \phi_w)$; and (h) $r_{1B}^*(\theta, \phi, \theta_n, \phi_n; \nu, \phi_w)$ as functions of ϕ_n for $\theta_n = 18.1^\circ$ ($\mu_n = 0.95$), $\nu = 10$ m/s, and $\lambda = 11$ μ m for $\theta = 61^\circ$ and $\phi = 0^\circ$. $\phi_w = 0^\circ$ (solid lines), 90° (dotted lines), and 180° (dashed lines).

Fig. 9 Same as Fig. 8 but for an emission angle of $\theta = 80^\circ$ and $\theta_n = 7.4^\circ$ ($\mu_n = 0.99$).

ε_B^* , which is proportional to the product of P , $\cos\chi$, and ε_L , is plotted in Fig. 9d. On average, ε_B^* is smaller for $\phi_w = 180^\circ$ than for $\phi_w = 0^\circ$ and 90° . Consequently, ε_A^* , the integral of ε_B^* with respect to ϕ_n , is smaller for $\phi_w = 180^\circ$ (20.0) than for $\phi_w = 0^\circ$ and 90° (21.5 and 21.4) as seen for $\mu_n = 0.99$ in Fig. 7c.

Case 4: $r_{1A}^*(\theta, \phi, \theta_n; v, \phi_w)$ for $\theta = 80^\circ$ and $\phi = 0^\circ$ (Fig. 7d)

The first order SESR emissivity for $\phi_w = 180^\circ$ is larger than for $\phi_w = 0^\circ$ and 90° at $\theta = 80^\circ$ (Fig. 5b). This is because r_{1A}^* for $\phi_w = 180^\circ$ is larger than for the other ϕ_w values around $\mu_n \sim 1$ (Fig. 7d). ρ , w , ε^* , and r_{1B}^* are plotted as functions of ϕ_n (Figs. 9e–9h) as in Case 2, but for $\theta_n = 7.4^\circ$ ($\mu_n = 0.99$) where $r_{1A}^* = 1.52, 1.52$, and 1.98 for $\phi_w = 0^\circ, 90^\circ$, and 180° , respectively (Fig. 7d). w has a non-zero value for $\phi_n \sim 60^\circ - 300^\circ$. Particularly, $w = 1$ for ϕ_n between 135° and 225° . In this region, P for $\phi_w = 180^\circ$ generally is larger than for the other ϕ_w angles (Fig. 9a). As a result, r_{1B}^* for $\phi_w = 180^\circ$ is larger than for $\phi_w = 0^\circ$ and 90° (Fig. 9h); hence, r_{1A}^* , the integral of r_{1B}^* with respect to ϕ_n , is larger for $\phi_w = 180^\circ$ (1.98) than for $\phi_w = 0^\circ$ and 90° (1.52 and 1.52) as seen for $\mu_n = 0.99$ in Fig. 7d.

5. Applicability of the isotropic slope distribution model

The isotropic slope distribution model is expressed by

$$P(z_x, z_y) = \frac{1}{\pi\sigma^2} e^{-(z_x^2 + z_y^2)/\sigma^2}. \quad (18)$$

(Cox and Munk, 1955). σ^2 increases with wind speed according to $\sigma^2 = 0.003 + 0.00512v \pm 0.004$. Computational schemes for sea surface emissivity from the isotropic model without and with the SESR radiation are given in Masuda *et al.* (1988) and Masuda (2006), respectively. In this section, the accuracy of the sea surface emissivity derived using the isotropic model with and without SESR radiation is investigated with respect to wavelength, wind speed, emission angle, and required sea surface temperature accuracy by comparing it with the emissivity derived from the anisotropic model with SESR radiation.

The deviation of emissivity from the reference value, $\Delta\varepsilon/\varepsilon$, for the isotropic model is defined as the maximum value of $|\varepsilon_{iso}^*(\theta; v) - \varepsilon_{ref}^*(\theta, \phi; v, \phi_w)|/\varepsilon_{ref}^*(\theta, \phi; v, \phi_w)$ with respect to ϕ_w , where $\varepsilon_{iso}^*(\theta; v)$ is the emissivity from the isotropic model. The emissivity derived from the anisotropic model $\varepsilon_{ref}^*(\theta, \phi; v, \phi_w)$ with $\phi = 0^\circ$ and SESR emissivity up to the second order was chosen as the reference value. Clearly the accuracy of the isotropic model with SESR radiation is better than that without SESR radiation over all emission angles (Fig. 10).

The emissivity (Fig. 11) deviation $\Delta\varepsilon/\varepsilon$ for the isotropic model without SESR radiation and with SESR radiation was 0.027 and 0.007, respectively, for $\theta = 71^\circ$; and 0.061 and 0.045 for $\theta = 87^\circ$. Note that smaller values of $\Delta\varepsilon/\varepsilon$ in the isotropic

Fig. 10 Deviations of emissivity $\Delta\varepsilon/\varepsilon$ for the isotropic model without SESR radiation (solid line) and with SESR radiation (dashed line) from the emissivity derived by using the anisotropic model with SESR radiation, as functions of θ for $v = 10$ m/s and $\lambda = 11$ μm . The horizontal line at $\Delta\varepsilon/\varepsilon = 0.0047$ corresponds to sea surface temperature error of $\Delta T = 0.3$ K for $T = 288$ K.

Fig. 11 Sea surface emissivity derived from the isotropic models without SESR radiation (dotted lines), with SESR radiation (dashed lines), and from the anisotropic model with SESR radiation (solid lines) as functions of ϕ_w for $v = 10$ m/s and $\lambda = 11$ μm for emission angles of 71° and 87° .

model with SESR radiation do not necessarily imply that the accuracy of the emissivity for the isotropic model with SESR radiation is better than that without SESR radiation for all ϕ_w . For example, the emissivity of the isotropic model without SESR radiation is better than that with SESR radiation around $\phi_w = 90^\circ$ and 270° for $\theta = 87^\circ$.

The relationship between the accuracies in the sea surface temperature ΔT and the relative emissivity $\Delta\varepsilon/\varepsilon$ is expressed by $\Delta\varepsilon/\varepsilon \approx \Delta T(C_2/\lambda T^2)$ where $C_2 = 1.439 \times 10^{-2}$ mK (Bourlier, 2005). The isotropic models with and without SESR radiation satisfy $\Delta T < 0.3$ K for emission angles less than 68° and 56° , respectively (Fig. 10). We refer to the emis-

sion angle limit below which ΔT is satisfied by the isotropic models with and without SESR radiation, respectively, as EAL(S) and EAL(D). For angles larger than EAL(S) the anisotropic model with SESR radiation is needed to satisfy the required accuracy of sea surface temperature. EAL(S) and EAL(D) depend on wavelength, wind speed, and the required accuracy of the sea surface temperature (Fig. 12). The improvement due to the inclusion of SESR in the isotropic model is evident.

From the data presented in Figs. 10–12 we deduce the following.

- (1) The accuracy of the sea surface emissivity is improved by incorporating the SESR radiation in the isotropic model.
- (2) The effectiveness of the isotropic model is restricted as the wind speed increases.
- (3) The isotropic model without SESR radiation is applicable to satellite remote sensing up to an emission angle of at least $\sim 50^\circ$ provided that the wind speed is less than ~ 10 m/s.
- (4) The anisotropic model with SESR radiation could improve ground based measurements for emission angles larger than 70° .

6. Summary and Conclusion

A computational scheme is developed for incorporating surface-emitted surface-reflected radiation into the infrared emissivity calculation for an anisotropic wind-roughened sea surface slope distribution model that depends on both wind speed and direction. The influence of wind direction on the direct emissivity ε^* is observed for emission angles θ larger than 60° . For example, at $\theta = 75^\circ$, ε^* equals 0.879, 0.864, and 0.872 for wind directions ϕ_w of 0° , 90° , and 180° , respectively, at a wavelength $\lambda = 11 \mu\text{m}$ and wind speed $v = 10$ m/s. The first order SESR emissivity r_1^* is less than 0.002 for $\theta < 50^\circ$; it increases with θ , showing a peak value of 0.03–0.04 at $\theta \sim 80^\circ$. For example, at $\theta = 81^\circ$, r_1^* is 0.029, 0.034, and 0.037 for $\phi_w = 0^\circ$, 90° , and 180° , respectively, at $\lambda = 11 \mu\text{m}$ and $v = 10$ m/s. For remote sensing applications, the second and higher-order emissivities are practically negligible.

The accuracy of the sea surface emissivity derived from the isotropic model, which depends only on wind speed and is widely used in radiative transfer models, was examined by comparing it with the emissivity derived from the anisotropic model with SESR radiation. The accuracy of the sea surface temperature was found to be better than 0.3K for emission angles below 68° and 56° for the isotropic models with and without SESR radiation, respectively, for $\lambda = 11 \mu\text{m}$ and $v = 10$ m/s. The isotropic model without SESR radiation is applicable to satellite remote sensing for emission angles up to at least $\sim 50^\circ$ provided that the wind speed is less than ~ 10 m/s. On the other hand, the anisotropic model with SESR radiation could improve ground based measurements for emission angles larger than 70° .

Fig. 12 Emission angle limit below which ΔT is satisfied by the isotropic models with (EAL(S), dotted lines) and without (EAL(D), solid lines) SESR radiation as functions of wind speed at wavelengths of (a) 3.7, (b) 11.0, and (c) 12.0 μm . Sea surface temperature errors ΔT are 0.1 (filled circles), 0.3 (open circles), 0.5 (pluses), and 1.0 K (crosses).

Validations of sea surface emissivity derived from the isotropic model have been performed through comparisons with measurements (Wu and Smith, 1997; Masuda, 2006) where the discrepancy between the theoretical prediction and

the measurements was effectively suppressed by incorporating SESR radiation into the model calculation. The results presented in this study confirm these findings, based on numerical calculations.

Some physical properties of the sea surface are omitted in the model. For example, oceanic whitecaps are ignored; oceanic whitecaps might influence sea surface emissivity at higher wind speeds. Nevertheless, the results presented in this study may be used as guidelines for selecting a sea surface slope distribution model and a computational scheme in terms of observation angle, wind speed, and the required accuracy of sea surface temperature.

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海面での多重反射を考慮した赤外射出率モデルにおける風向の影響

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傾きが風速と風向に依存する非等方海面モデルによる赤外射出率の計算に海面での多重反射成分を導入した。反射成分を考慮しないで求めた海面からの射出を放射源として一次反射成分を、一次反射成分を放射源として二次反射成分を、以下同様に高次の反射成分を求めた。3.7、11、12 μm の3波長について、風速が3、5、10、15 m/s の場合に風向が赤外射出率に与える影響を調べた。

現在、傾きが風速だけに依存する等方海面モデルによる海面射出率が放射伝達モデルで広く利用されており、これまでに観測値との比較による検証が行われてきた。本研究では、多重反射成分を導入した非等方海面モデルによる赤外射出率を参照値として、等方海面モデルによる赤外射出率の精度を、風速、観測角などを考慮して調べた。例えば、波長 11 μm ・海面温度 288 K・風速 10 m/s の場合、等方海面モデルによる赤外射出率の精度が温度誤差に換算して 0.3 K 以内であるのは、反射成分を含めない場合・含める場合について、それぞれ観測角が 56°・68° までであった。

観測角が通常 50° 以下であるような衛星観測の解析処理には、風速が 10 m/s 以下である場合には多重反射成分や風向の影響を考慮する必要性は少ないが、船舶などからのより大きい角度での放射観測に対しては、それらを考慮することにより解析精度の向上が図られることが示された。