Influence of wind direction on the infrared sea surface emissivity model

including multiple reflection effect

by

Kazuhiko Masuda

Meteorological Satellite and Observation System Research Department, Meteorological Research Institute, Tsukuba, Japan

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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 ith order SESR emissivity (i ≥ 2) is recursively obtained by using the (i-1)st 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 ~50° 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 than ~50°.
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 of emission angle \( \phi \) is given by

\[
\varepsilon(\theta, \phi; \nu, \chi) = \frac{1}{\cos \theta} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{-i} \chi \cos \chi \sec \theta P(\xi, \eta) d\xi d\eta, \quad \cos \chi > 0
\]

where \( e^{-i} \) is the emissivity of an individual facet with \( \chi \) being the local emission angle. The integral is performed over all facets with \( \cos \chi > 0 \). \( B(T) \) is the black body radiation at surface temperature \( T \). \( P(\xi, \eta) \) is the probability distribution function of the facet slopes, which is explained below.

The sea surface emissivity is then expressed by

\[
\varepsilon(\theta, \phi; \nu, \chi) = \frac{1}{\cos \theta} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{-i} \chi \cos \chi \sec \theta P(\xi, \eta) d\xi d\eta, \quad \cos \chi > 0
\]

where \( \mu_s \) is the cosine of \( \theta \).

The local emission angle \( \chi \) is expressed by

\[
\cos \chi = \cos \theta \cos \theta_s + \sin \theta \sin \theta_s \cos(\phi - \phi_s).
\]

The emissivity from a facet is given by \( e^{-i} \chi \)

Here, \( r_s = (\cos \chi' - m \cos \chi')(\cos \chi' + m \cos \chi') \) and \( r_s = (\cos \chi + m \cos \chi')(\cos \chi + m \cos \chi') \) (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. \( \theta \) and \( \theta_s \) are the zenith angles of \( \mathbf{i} \) and \( \mathbf{n} \), respectively. \( \phi \) is the azimuth angle of \( \mathbf{n} \) measured from the x axis anticlockwise. The azimuth angle of \( \mathbf{i} \) is set at \( \phi = 0 \). \( \chi \) is the angle of emitted radiation with respect to the facet normal. \( \mathbf{a} \) and \( \mathbf{c} \) denote the upwind and crosswind axes, respectively. \( \phi_s \) is the angle of the \( \mathbf{a} \) 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,

\[ P(\xi, \eta) = f(\xi, \eta)g(\xi, \eta), \]

where

\[ f(\xi, \eta) = \frac{1}{2\pi\sigma_\xi\sigma_\eta} e^{-\frac{1}{2}\left(\frac{\xi^2}{\sigma_\xi^2} + \frac{\eta^2}{\sigma_\eta^2}\right)}, \]

and

\[ g(\xi, \eta) = 1 + \frac{1}{2}c_3(\xi^2 - 3\eta^2) - \frac{3}{2}c_4(\xi^2 - 6\eta^2 + 3) + \frac{1}{24}c_6(\xi^2 - 6\eta^2 + 3) + \frac{1}{24}c_6(\xi^2 - 6\eta^2 + 3). \]

\[ \xi = \frac{z_c}{\sigma_\xi} \quad \text{and} \quad \eta = \frac{z_a}{\sigma_a}, \]

where \( z_c \) and \( z_a \) are the crosswind and the upwind slope components, respectively, \( z_c \) and \( z_a \) are given by \( \tan \theta \sin \alpha \) and \( \tan \theta \cos \alpha \), respectively (Cox and Munk, 1954b), where \( \alpha \) is the angle between the upwind direction and the facet ascent and is given by \( \alpha = \phi_a + \pi \). \( \sigma_\xi^2 \) and \( \sigma_\eta^2 \) are the mean values of \( z_c^2 \) and \( z_a^2 \), averaged over many facets. \( \sigma_\xi^2 \) and \( \sigma_\eta^2 \) are expressed as

\[ \sigma_\xi^2 = 0.003 + 0.00192v + 0.002, \]

\[ \sigma_\eta^2 = 0.00316v + 0.004, \]

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 \( c_{21} = 0.01 - 0.00086v + 0.03, c_{20} = 0.04 - 0.033v + 0.12, c_{20} = 0.40 \pm 0.23, c_{22} = 0.12 \pm 0.06, \) and \( c_{44} = 0.23 \pm 0.41 \) (Cox and Munk, 1954a). For simplicity, deviations after the ± sign are not considered in this study.

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

\[ \varepsilon^*(\theta, \phi; v, \phi_a) = \varepsilon(\theta, \phi; v, \phi_a) / p(\theta, \phi; v, \phi_a), \]

where

\[ p(\theta, \phi; v, \phi_a) = \frac{1}{\cos \theta} \int_0^\pi \int_0^{2\pi} \cos \lambda P(\xi, \eta)\mu_a^2 \sin \phi d\phi d\mu_a, \]

\[ \cos \lambda > 0 \]

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

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

The normalizing factor 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 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 \(1/p(\theta, \phi; v, \phi_s)\) as \(s(\theta, \phi; v, \phi_s)\) 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 \(i'(\theta', \phi')\) (i.e., the direct emission), which is determined from the directions of the SESR radiation \(i(\theta, \phi)\) and the facet normal \(n(\theta_n, \phi_n)\) (Fig. 3). Because \(i'\) is given by \(i = 2n \cos \chi\) (e.g., Masuda, 2006), \(\theta'\) and \(\phi'\) can be calculated using simple geometry. Note that \(\theta'\) 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 \(\theta' < 90°\) (upward emission). For \(\theta' \geq 90°\) (downward emission), we focus on the backward direction of the direct emission, i.e., \(-i'\), with zenith and azimuth angles \(180° - \theta'\) (\(0° \leq 180° - \theta' \leq 90°\)) and \(\phi' + 180°\), respectively. From the discussion in Section 2, \(s(180° - \theta', \phi' + 180°; v, \phi_s)\) 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 \(1 - s(180° - \theta', \phi' + 180°; v, \phi_s)\). We denote \(1 - s(180° - \theta', \phi' + 180°; v, \phi_s)\) as \(w(\theta', \phi'; v, \phi_s)\) and refer to it as the weighting function. Needless to say, \(w(\theta', \phi'; v, \phi_s) = 1\) for \(\theta' < 90°\).

The weighting function for \(\phi_s = 0°, 90°, \text{ and } 180°\) as a function of the zenith angle of the direct emission \(\theta'\) at \(\phi' = 0°\) 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...
roughness, which intensifies with wind speed.

Replacing \( \varepsilon'\) in Eq. (2) by \( p(\chi) \varepsilon'(\theta', \phi'; v, \phi_w)w(\theta', \phi'; v, \phi) \) yields the equation for the first order SESR emissivity:

\[
r_{1}(\theta, \phi; v, \phi_w) = \frac{1}{\cos \theta} \int_{-1}^{1} \int_{-1}^{1} \rho(\chi) \varepsilon'(\theta', \phi'; v, \phi)w(\theta', \phi'; v, \phi) \\
\times \cos \chi P(\xi, \eta) d\phi d\mu, \quad \cos \chi > 0.
\]  

(10)

Here, \( \rho(\chi) \) is the local reflectivity of the direct emission for an individual facet obtained from the Fresnel formulas (Section 2) by \( \rho(\chi) = (|r|^2 + |r'|^2)^{1/2} \). \( r_{1}(\theta, \phi; v, \phi) \) is normalized as

\[
r_{1}(\theta, \phi; v, \phi_w) = r_{1}(\theta, \phi; v, \phi) / P(\theta, \phi; v, \phi).
\]  

(11)

We refer to \( r_{1}(\theta, \phi; v, \phi_w) \) as the first order SESR emissivity.

For the azimuth angles, it can be shown by using simple geometry that \( \varepsilon'(\theta', \phi'; v, \phi_w) = \varepsilon'(\theta', 0; v, \phi' + \phi_w) \) and \( w(\theta', \phi'; v, \phi_w) = w(\theta', 0; v, \phi' + \phi_w) \). 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 \( r_{i-1}(\theta, \phi; v, \phi_w) \). For the \( i \)th order SESR emissivity (\( i \geq 2 \)), the equation corresponding to Eq. (10) is

\[
r_{i}(\theta, \phi; v, \phi_w) = \frac{1}{\cos \theta} \int_{-1}^{1} \int_{-1}^{1} \rho(\chi) \varepsilon'(\theta', \phi'; v, \phi)w(\theta', \phi'; v, \phi) \\
\times \cos \chi P(\xi, \eta) d\phi d\mu, \quad \cos \chi > 0.
\]  

(12)

\[
r_{i}(\theta, \phi; v, \phi_w) \quad \text{is normalized as}
\]

\[
r_{i}(\theta, \phi; v, \phi_w) = r_{i}(\theta, \phi; v, \phi) / P(\theta, \phi; v, \phi).
\]  

(13)

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

\[
\varepsilon' (\theta, \phi; v, \phi_w) + \sum_{i=1}^{\infty} r_{i}(\theta, \phi; v, \phi_w).
\]

### 4. Direct and first order SESR emissivity

#### 4.1 Examples of numerical results

The direct emissivity \( \varepsilon' \) (Fig. 5a) and the first order SESR emissivity \( r_{1} \) (Fig. 5b) were derived for \( \phi = 0^\circ \) as functions of the emission angle \( \theta \) for \( v = 10 \) m/s at a wavelength of 11 \( \mu \)m and wind direction \( \phi_w \) of 0\(^\circ\), 90\(^\circ\), and 180\(^\circ\). The refractive index by Hale and Querry (1973) was used with the salinity adjustment from Friedman (1969) as in Masuda et al. (1988); \( m = 1.162 - 0.0938 \) for \( \lambda = 11 \) \( \mu \)m. 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. For example, \( \varepsilon'(\theta', \phi'; v, \phi_w) \) in Eq. (10) was interpolated using \( \varepsilon'(\theta, \phi; v, \phi) \) that was computed in advance. Calculations were performed for 91 equally spaced \( \mu \) from -1.0 to 1.0 and for 91 equally spaced \( \phi_w \) from -180\(^\circ\) to 180\(^\circ\). 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 (\( d\xi \) and \( d\phi \)). 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 \( \mu = (1 + 2\sigma |\mu|^{1/2})^{-1/2} \), where \( \sigma = \max (\sigma_m, \sigma_c) \) 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, \( \xi \) and \( \eta \) were bounded by substituting \( \pm 2.5 \) 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, on the direct emissivity is evident for θ > 60°. For example, ε' is 0.879, 0.864, and 0.872 for φ, = 0°, 90°, and 180°, respectively, at θ = 75°. For the isotropic model (not shown), ε' is 0.871 at θ = 75°.

The first order SESR emissivity is less than 0.002 for θ < 50° (Fig. 5b) and increases with θ, reaching a peak value of 0.03 –0.04 at θ=80°. For example, r1 is 0.029, 0.034, and 0.037 for φ, = 0°, 90°, and 180°, respectively, at θ = 81° whereas for the isotropic model r1 is 0.033 (not shown). The second order emissivity, r2 (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 r1 for θ = 61° and 80°, with φ = 0° as functions of wind direction φ, (Fig. 6). For θ = 61°, ε' (0.956–0.958) varies only slightly with φ, whereas r1 reaches its peak (0.008) at φ, = 0° and 180° and its minimum value (0.005) at φ, = 90° and 270°. For θ = 80°, ε' reaches its maximum value at φ, = 0° (0.829) and 180° (0.824) and minimum value (0.802) at φ, = 90° and 270°, whereas for r1, the maximum (0.037) is at φ, = 180° and the minimum (0.029) at φ, = 0°. In this section, we examine the link between these emissivity features and the surface slope distribution properties. The dependence of ε' and r1 on the wind direction is verified by close examination of these functions and their normalized integrands.

Firstly, we define ε,*(θ, φ, θ; v, φ, φ, ) and r,*(θ, φ, θ; v, φ, φ, φ), the normalized integrands of Eqs. (2) and (10), respectively, as

\[
e^{*}(\theta, \phi, \theta; v, \phi)= \frac{1}{p(\theta, \phi, v, \phi)} \int \epsilon(\chi) \cos \chi P(\xi, \eta) \mu_* d\phi, \quad \cos \chi > 0, \tag{14}\]

and

\[
r^{*}(\theta, \phi, \theta; v, \phi)= \frac{1}{p(\theta, \phi, v, \phi)} \int \epsilon(\chi) \cos \chi P(\xi, \eta) \mu_* d\phi, \quad \cos \chi > 0, \tag{15}\]

ε,*(θ, φ, θ; v, φ, φ, ) and r,*(θ, φ, θ; v, φ, φ, φ) as functions of μ, (= cos θ,) 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, for θ = 61° and φ = 0° (Fig. 7a)

The value of ε, for φ, = 0°, 90°, and 180° is very similar over all μ, ranges. Consequently, the value of ε, the integral of ε, with respect to μ, is almost identical for φ, = 0°, 90°, and 180° as seen in Fig. 7a for μ,
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\[ r_{1A}^* \text{ is proportional to the product of } \rho, \varepsilon, w, \cos \chi, \text{ and } P, \text{ is displayed in Fig. 8h. For } \phi_w = \pm 140^\circ \text{ to } 220^\circ, \text{ } r_{1A}^* \text{ for } \phi_w = 90^\circ \text{ is much smaller than for } \phi_w = 0^\circ \text{ and } 180^\circ. \text{ This is mainly caused by the fact that } P \text{ for } \phi_w = 90^\circ \text{ is much smaller than for } \phi_w = 0^\circ \text{ and } 180^\circ \text{ in this angle range (Fig. 8a) where } w \text{ is unity. As a result, } r_{1A}^* \text{ the integral of } r_{1A}^* \text{ with respect to } \phi_w \text{ for } \phi_w = 90^\circ (0.075) \text{ is smaller than for } \phi_w = 0^\circ \text{ and } 180^\circ \text{ (0.125 and 0.137) as seen for } \mu_s = 0.95 \text{ in Fig. 7b.} \]

Case 3: \( r_{1A}^* \text{ for } \theta = 80^\circ \text{ and } \phi = 0^\circ \) (Fig. 7c)

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

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 \( \phi_w \) for \( \theta_w = 18.1^\circ \) (\( \mu_s = 0.95 \)) where \( r_{1A}^* \) is 0.125, 0.075, and 0.137 for \( \phi_w = 0^\circ, 90^\circ, \) and \( 180^\circ \), respectively (Fig. 7b). \( \rho(\chi) \) is independent of \( \phi_w \) and \( \varepsilon \) have a slight dependency on \( \phi_w \) \( w \) has non-zero values for \( \phi_w \) values of about 120°–240°. In particular, \( w = 1 \) when \( \phi_w \) is between 140° and 220° because the zenithal direction of the direct emission \( \theta' \) is less than 90° (not shown).

\[ r_{1A}^* \text{ for } \phi_w = 90^\circ \text{ is much smaller than for } \phi_w = 0^\circ \text{ and } 180^\circ. \]

The shift in \( r_{1A}^* \) is dependent on \( \phi_w \) \( \phi_w = 61^\circ \) in Fig. 5b. In a manner similar to \( \varepsilon_{1A}^* \), we define \( r_{1A}^* \text{ as} \)

\[ r_{1A}^*(\theta, \phi, \theta_w, v, \phi_w) = \frac{1}{\rho(\theta, \phi, v, \phi_w)} \rho(\chi) \varepsilon(\theta', \phi'; v, \phi_w) w(\theta', \phi'; v, \phi_w) \cos \theta \cdot \cos \chi L(\xi, \eta) \mu_{s*}^* \]

(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 \( \phi_w \) for \( \theta_w = 18.1^\circ \) (\( \mu_s = 0.95 \)) where \( r_{1A}^* \) is 0.125, 0.075, and 0.137 for \( \phi_w = 0^\circ, 90^\circ, \) and \( 180^\circ \), respectively (Fig. 7b). \( \rho(\chi) \) is independent of \( \phi_w \) and \( \varepsilon \) have a slight dependency on \( \phi_w \) \( w \) has non-zero values for \( \phi_w \) values of about 120°–240°. In particular, \( w = 1 \) when \( \phi_w \) is between 140° and 220° because the zenithal direction of the direct emission \( \theta' \) is less than 90° (not shown).
as functions of $\phi_n$ for $\theta_n = 18.1^\circ$ ($\mu_n = 0.95$), $v = 10$ m/s, and $\lambda = 11 \, \mu\text{m}$ for $\theta = 61^\circ$ and $\phi = 0^\circ$. $\phi_w = 0^\circ$ (solid lines), $90^\circ$ (dotted lines), and $180^\circ$ (dashed lines).
Fig. 9 Same as Fig. 8 but for an emission angle of $\theta = 80^\circ$ and $\theta_n = 7.4^\circ$ ($\mu_n = 0.99$).
\( \varepsilon_{\theta}^* \), which is proportional to the product of \( P \), \( \cos \chi \), and \( \varepsilon_{\phi} \), is plotted in Fig. 9d. On average, \( \varepsilon_{\theta}^* \) is smaller for \( \phi_\theta = 180^\circ \) than for \( \phi_\theta = 0^\circ \) and \( 90^\circ \). Consequently, \( \varepsilon_{\phi}^* \), the integral of \( \varepsilon_{\phi}^* \) with respect to \( \phi_\phi \), is smaller for \( \phi_\phi = 180^\circ \) (20.0) than for \( \phi_\phi = 0^\circ \) and \( 90^\circ \) (21.5 and 21.4) as seen for \( \mu_\mu = 0.99 \) in Fig. 7d.

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

The first order SESR emissivity for \( \phi_\phi = 180^\circ \) is larger than for \( \phi_\phi = 0^\circ \) and \( 90^\circ \) at \( \theta = 80^\circ \) (Fig. 5b). This is because \( r_{1,4}^* \) for \( \phi_\phi = 180^\circ \) is larger than for the other \( \phi_\phi \) values around \( \mu_\mu \sim 1 \) (Fig. 7d). \( \rho, w, e^* \), and \( r_{1,4}^* \) are plotted as functions of \( \phi_\phi \) (Figs. 9e–9h) as in Case 2, but for \( \theta^\phi = 7.4^\circ \) (\( \mu_\mu = 0.99 \)) where \( r_{1,4}^* = 1.52, 1.52, \) and \( 1.98 \) for \( \phi_\phi = 0^\circ, 90^\circ \), and \( 180^\circ \), respectively (Fig. 7d). \( w \) has a non-zero value for \( \phi_\phi = -60^\circ \)–300°. Particularly, \( w = 1 \) for \( \phi_\phi \) between 135° and 225°. In this region, \( P \) for \( \phi_\phi = 180^\circ \) generally is larger than for the other \( \phi_\phi \) angles (Fig. 9a). As a result, \( r_{1,4}^* \) for \( \phi_\phi = 180^\circ \) is larger than for \( \phi_\phi = 0^\circ \) and \( 90^\circ \) (Fig. 9h); hence, \( r_{1,4}^* \), the integral of \( r_{1,4}^* \) with respect to \( \phi_\phi \), is larger for \( \phi_\phi = 180^\circ \) (1.98) than for \( \phi_\phi = 0^\circ \) and \( 90^\circ \) (1.52 and 1.52) as seen for \( \mu_\mu = 0.99 \) in Fig. 7d.

5. Applicability of the isotropic slope distribution model

The isotropic slope distribution model is expressed by

\[
P(z_1, z_2) = \frac{1}{\pi \sigma^2} e^{-z_1^2 + z_2^2 / \sigma^2}.
\]

(Cox and Munk, 1955). \( \sigma^2 \) 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 \( |\varepsilon_{\phi, \theta}^* (\theta, \phi; v, \phi_\phi) - \varepsilon_{\phi, \theta}^* (\theta, \phi; v, \phi_\phi)| \) with respect to \( \phi_\phi \), where \( \varepsilon_{\phi, \theta}^* (\theta, \phi; v, \phi_\phi) \) is the emissivity from the isotropic model.

The emissivity derived from the anisotropic model \( \varepsilon_{\phi, \theta}^* (\theta, \phi; v, \phi_\phi) \) with \( \phi_\phi = 0^\circ \) 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 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 \( \phi_\phi \).

For example, the emissivity of the isotropic model without SESR radiation is better than that with SESR radiation around \( \phi_\phi = 90^\circ \) and 270° for \( \theta = 87^\circ \).

The relationship between the accuracies in the sea surface temperature \( \Delta T \) and the relative emissivity \( \Delta \varepsilon / \varepsilon \) is expressed by \( \Delta \varepsilon / \varepsilon \approx \Delta T (C_v / \lambda T^2) \) where \( C_v = 1.439 \times 10^{-2} \) 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 $\Delta T$ 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 $\sim 10$ m/s.
(4) The anisotropic model with SESR radiation could improve ground based measurements for emission angles larger than $70^\circ$.

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 $\varepsilon^*$ is observed for emission angles $\theta$ larger than $60^\circ$. For example, at $\theta = 75^\circ$, $\varepsilon^*$ equals 0.879, 0.864, and 0.872 for wind directions $\phi_w$ of 0°, 90°, and 180°, respectively, at a wavelength $\lambda = 11$ µm 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 $\theta$, showing a peak value of 0.03–0.04 at $\theta \sim 50^\circ$. 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 $\lambda = 11$ µm 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 $68^\circ$ and $56^\circ$ for the isotropic models with and without SESR radiation, respectively, for $\lambda = 11$ µm 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 $\sim 10$ m/s. On the other hand, the anisotropic model with SESR radiation could improve ground based measurements for emission angles larger than $70^\circ$.

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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References


海面での多重反射を考えた赤外放射出率モデルにおける風向の影響

増田一彦（気象研究所気象衛星・観測システム研究部）

風向が風速と風向に依存する非等方海面モデルによる赤外放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放射出射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のときに風向が赤外放射出率に与える影響を調べた。

現在、風向が風速だけに依存する等方海面モデルによる海面放射出射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放射出率を参照値として、等方海面モデルによる赤外放射出率の精度を、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放射出率の精度が誤差換算に換算して0.3 K以内であるのか、反射成分を含まない場合に対する場合について、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な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。