**Uncertainty Quantification in the Infrared Surface Emissivity Model (ISEM)**

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**ABSTRACT**

Accurate modeling of surface emissivity is imperative for accurate radiative transfer simulation and forward modeling of satellite radiance observations. The RTTOV (Radiative Transfer for the Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder) fast radiative transfer model uses the Infrared Surface Emissivity Model (ISEM) for the computation of sea surface emissivity in the infrared (IR) spectrum. However, the model does not incorporate the effect of surface-emitted surface reflected (SESR) radiation and dependence of wind speed in the emissivity calculation. This paper investigates the uncertainty in the ISEM model caused by ignoring the SESR radiation and wind speed effects in the three IR bands, 3.7 µm, 11 µm, and 12 µm. First, we develop a new model called **S**urface **E**missivity **M**odel in **I**R with **S**ESR (SEMIS) that takes the SESR radiation and wind speed effects into account. The uncertainty in the ISEM model is then quantified by comparing the ISEM emissivity against SEMIS derived emissivity. The comparison results suggest that two models are in excellent agreement below ~60° emission angle, implying no notable uncertainty in the ISEM model at smaller angles. Nevertheless, uncertainty tends to significantly increase with increasing emission angle above ~60°, which is even more notable at high wind speed (~15 m/s). Two models are further compared against emissivity measurements from a radiometer. The ISEM model has produced large errors as opposed to the SEMIS.

**KEYWORDS:** sea surface emissivity; sea surface temperature; RTTOV; radiative transfer simulation; multiple reflections; wind speed; ocean surface; infrared measurements; emissivity validation;

**1. INTRODUCTION**

The accurate radiative transfer modeling depends on the accurate modeling of the spectral emissivity of the earth’s surface [1-4]. Over the sea surface, the surface emissivity directly impacts on the monitoring and retrieval of sea surface temperature (SST) from remote sensing observations [5-8]. Since, more than two thirds of our surface is ocean, inaccuracies in SST can significantly deteriorate the weather forecast and climate projection [9-12].

The Radiative Transfer for (A)TOVS (RTTOV) is a fast radiative transfer model that is able to calculate satellite radiances in the infrared and microwave portions of the spectrum. For infrared (IR) radiance simulation, the recent RTTOV versions (RTTOV-6 to RTTOV-11) employ the Infrared Surface Emissivity Model (ISEM, v6) [13] in calculating the sea surface emissivity for a given IR channel. The ISEM uses the sea surface emissivity values from Masuda *et al.* [14] and parameterizes them as a function of wavelength and local zenith angle. Nonetheless, the model does not take into account the surface-emitted surface reflected (SESR) radiation during the calculation of the infrared emissivity. Therefore, at high emission angles, some discrepancies in the emissivity calculation have been found, as reported by earlier studies [15, 16]. In fact, Smith *et al.* [17] pointed out that an underestimation of the emissivity by 0.02~0.03 occurred in the 10 μm region at high emission angle over 70°. Furthermore, the wind speed dependence is not included in the ISEM model, with the values at 0 m/s taken as representative of all wind speeds. Generally speaking, surface emissivity is dependent on several factors, including, satellite zenith angle, surface roughness, and refractive index [7, 18]. Compared to sea surface, land surface poses much more difficulties in emissivity modeling due to a greater spatial and temporal variability. On the other hand, sea surface can be approximated as isotropic and homogeneous. Nevertheless, surface roughness over the sea is influenced by wind speed and cannot be neglected while modeling the emissivity, as is the case in the ISEM model. In fact, accurate infrared radiative transfer requires the input argument that takes into account the surface wind speeds. Otherwise, the radiative transfer simulation can be significantly biased due to the relationship between infrared surface emissivity and wind-speed over ocean.

Such limitations have motivated us to quantify the uncertainties in the ISEM model. In order to quantify the uncertainties in the ISEM, first we develop a new model that takes into account the SESR radiation as well as wind speed effects, as described in Masuda [19]. The new model, named as Surface Emissivity Model in IR with SESR (SEMIS), is then used to quantify the uncertainties in the ISEM. The study is mainly focused on three IR bands: 3.7 µm, 11 µm, and 12 µm.

This paper is structured as follows. Section 2 describes the theoretical background of the ISEM and SEMIS models. Uncertainty quantification of the ISEM model is provided in Section 3. Section 4 is the summary of the work.

**2. BASIS OF THE ISEM and SEMIS MODELS**

The ISEM-6 is the default infrared emissivity model within the RTTOV, which is based on Masuda *et al.* [14]. In the ISEM, the channel emissivity is parameterized as:

|  |  |  |
| --- | --- | --- |
|  |  | (1) |

where, *θ̂* is the normalized satellite zenith angle *θ*/60, *N1* and *N2* are integers, and *c0*, *c1*, and *c2* are the coefficients in the polynomial basis functions. The coefficients *c0*, *c1*, and *c2* are determined through regression with a maximum residual cutoff of *Δε* = 0.0002. The wind speed of 0.0 m/s is only fitted in the ISEM.

Theoretically, in Masuda *et al.* [14] model, the emission from a wave facet is tangent to the instantaneous sea surface. The sea surface emissivity is expressed as:

|  |  |  |
| --- | --- | --- |
|  |  | (2) |

where, *θ* and *θn* are the zenith angles of *i* and *n*, with *i* as the unit vector in the direction of emitted radiation in the *x*-*z* plane and *n* as the facet unit normal vector, χ is the local emission angle to the facet, *zx* and *zy* are the slope components, *ϕn* is the azimuth angle of *n*, and *µn* is the cosine of *θn.* The integral is only performed for cos χ>0. From the above equation, the emissivity can be normalized as [14]:

|  |  |  |
| --- | --- | --- |
|  |  | (3) |

where, *ε\**(*θ*) is known as direct emissivity, and *p*(*θ*) is defined as(cos χ>0):

|  |  |  |
| --- | --- | --- |
|  |  | (4) |

Nevertheless, direct emission is intercepted by another facet, introducing a reflection into the view direction, which is known as surface-emitted surface reflected (SESR) radiation [19]. For the first order SESR emission, Equation 2 is then expressed as:

|  |  |  |
| --- | --- | --- |
|  | **,**  cos χ>0 | (5) |

If scattering and absorption by the air are ignored, the *r1*(*θ*) can then be normalized as:

|  |  |  |
| --- | --- | --- |
|  |  | (6) |

In a similar way, the higher order SESR emissivity can be calculated as (*i*≥2):

|  |  |  |
| --- | --- | --- |
|  | **,**  cos χ>0 | (7) |

The *ri*(*θ*) is normalized as:

|  |  |  |
| --- | --- | --- |
|  |  | (8) |

Finally, the surface emissivity including the SESR can be computed as:

|  |  |  |
| --- | --- | --- |
|  |  | (9) |

Masuda [19] has calculated the direct emissivity *ε\**(*θ*), first order SESR emissivity *r1\**(*θ*), and second order SESR emissivity *r2\**(*θ*) for different emission angles ranging from 0-85 degrees at three IR bands, 3.7 µm, 11 µm, and 12 µm. Therefore, from the Masuda [19] study, it is possible to calculate the emissivity with reflection (SESR) and compare them against the direct emissivity values. Figure 1 demonstrates the comparison of the direct emissivity values to that calculated considering the SESR radiation. The plots are constructed for the three IR bands of 3.7 µm, 11 µm, and 12 µm, and shown as a function of zenith angles, 0-85˚. The emissivity calculations are performed for wind speed of 15 m/s. The figure suggests that there exists a good agreement between the two approaches at low emission angles. More specifically, the computed sea surface emissivities between the two approaches are nearly identical for emission angles less than 50˚. The emissivity differences tend to increase significantly with the increase of zenith (or emission) angles. In particular, up to ~0.03 emissivity difference is noted for the emission angle of 85˚. The three wavelengths follow very similar tendencies, albeit, the emissivity magnitudes are different between them, which is to be expected.

The above results suggest that SESR radiation cannot be neglected, especially at higher emission angles, thus, should be accounted for during the emissivity calculation. This has motivated us to develop a new model, named as Surface Emissivity Model in IR with SESR (SEMIS), which takes into account up to the second order SESR emissivity. The SEMIS is developed by fitting a 5th degree polynomial model between the zenith angles and the emissivity values by including the SESR radiation from Masuda [19], for a given wind speed:

|  |  |  |
| --- | --- | --- |
|  |  | (10) |

where, *ε* is the emissivity and *θ* is the zenith angle.

Table 1 tabulates the polynomial coefficients of the SEMIS model for three IR bands and for a range of wind speed values (0-15 m/s). Corresponding polynomial curves are shown in Figure 2 for different wind speeds. Note that, the SEMIS coefficients are given for 6 wind speed values (0, 1, 3, 5, 10, and 15 m/s). However, the emissivity value at any given wind speed within the range can be derived through interpolation.

**3. UNCERTAINTY QUANTIFICATION**

**3.1. Evaluation against SEMIS**

The SEMIS model is valid for a wide range of wind speed observations and emission angles. This will provide us an excellent opportunity to evaluate the ISEM model in comparison to the SEMIS.

It is worth mentioning that the SEMIS model is based on the computational study presented in Masuda [19]. Masuda [19] adapted the models proposed by Watts *et al.* [18] and Wu and Smith [15], and incorporated the SESR radiation for the calculation of surface emissivity in the infrared spectrum. However, unlike previous studies, in Masuda [19], any cutoff angle needs not to be specified in differentiating the radiation originating from the sea and the sky for the SESR emissivity calculation. Rather, probability distribution function of sea surface slope is used to derive the probability of radiation from the sea surface. The study showed that the inclusion of the SESR emissivity significantly improved the emissivity calculation as compared to the direct emissivity. Therefore, it can be used as a good reference to evaluate the ISEM model at different emission angles and for a range of wind speed cases.

In order to quantify the uncertainty in the ISEM, first we calculate the emissivity values between 0-85˚ zenith angles. Note that the ISEM coefficients available in the RTTOV v11.2 are used for the emissivity calculation. The ISEM computed emissivities are then compared against the SEMIS emissivities. For clarity, the comparison is performed for six different wind speed cases.

Figure 3 provides the emissivity difference (Δ*ε*) between the ISEM and SEMIS models as a function of zenith angles, for the selected six wind speeds. Apparently, up to ~60˚, no notable differences between the two models are seen. However, above ~60˚, the two models start to deviate significantly with increasing zenith angle. Such deviations are noted for all three wavelengths, 3.7 µm, 11 µm, and 12 µm. Note that the ISEM uncertainty above ~60˚ is noted even at 0 m/s wind speed, if SEMIS is taken as the reference. Nevertheless, the influence of the SESR emissivity (SEMIS) is generally large at higher wind speed, and underestimation is evident by the ISEM model. One can calculate a maximum Δ*ε* about -0.25 at *θ* = 85˚ for 3.7 µm and 12 µm, when wind speed is 15 m/s. For 11 µm, such underestimation is about -0.15 (15 m/s). The results suggest that there is a greater degree of uncertainty in the ISEM model at higher zenith angles (>60˚). However, such SESR related uncertainty could be neglected at lower zenith angles.

**3.2. Evaluation against measurements data**

We perform another type of assessment in quantifying the ISEM uncertainties in comparison to the SEMIS model. In order to perform this comparison, we use the measurements from a high spectral resolution atmospheric emitted radiance interferometer (AERI), as described in Smith *et al.* [17]. The radiometer has been placed on an oceanographic research vessel, and the sea surface measurements are reported at 36.5, 56.5, and 73.5 emission angles. During the measurements, the wind speed has been measured as 5 m/s [15].

Therefore, we compute the emissivities from the SEMIS and ISEM models at the three zenith angles, and compare them against AERI measurements data. Since, SEMIS takes into account the wind speed effect, the model computation is performed as 5 m/s. On the other hand, wind speed dependent sea surface emissivity cannot be calculated in the ISEM model, thus does not requite any wind speed inputs to the model. The comparison results are presented in Table 2 showing the percentage errors of the two models in comparison to the AERI measurements for the 11 and 12 µm wavelengths. The percentage error (*PE*) is calculated as:

|  |  |  |
| --- | --- | --- |
|  |  | (10) |

where, *εMOD* is the modeled emissivity and *εAERI* is the AERI measured emissivity.

It is noted, from the table, that the SEMIS model is in better agreement with the AERI measurements data, most likely due to the inclusion of the SESR radiation and wind speed effects in the model. The percentage errors are lower for the all three emission angles and for the both wavelengths when SEMIS is used. At the emission angle of 36.5°, for instance, the *PE* for the ISEM and SEMIS models are 0.13% and 0.04% at 11 µm, and 0.66% and 0.60% at 12 µm, respectively. The error at 73.5° is much higher, attributing, *PE* (11 µm, 12 µm) = (1.66%, 2.45%) in the ISEM model in comparison to *PE* (11 µm, 12 µm) = (1.42%, 0.02%) in the SEMIS model.

**4. SUMMARY**

This study investigates the uncertainty in the ISEM (v6) model that is being used as a default infrared surface emissivity model in the RTTOV radiative transfer package. In order to quantify the uncertainty in the ISEM model, first, a new model called SEMIS is developed. Unlike the ISEM model, the effects of SESR radiation and wind speed have been included in the SEMIS. The ISEM emissivity is then compared against the SEMIS derived emissivity for a range of wind speed cases, in quantifying the theoretical emissivity difference Δ*ε*, as a function of emission angles.

The results show that the effects from SESR radiation and wind speed are an important part of the total emission, thus, cannot be neglected. The uncertainty of the ISEM model is more pronounced for angles >60°, but not noticeable at the smaller angles. The ISEM underestimates the emissivity by as much as 0.25 at higher emission angles when wind speed is 15 m/s. The modeling results have been further supported by emissivity measurements from a radiometer.

It is important to outline that the uncertainty in the theoretical emissivity computation from the ISEM model is scrutinized in this study, rather, the impact of the uncertainty in the radiance simulation. Investigating the impact of uncertainties in the emissivity calculations on radiative transfer simulation is a subject of future study.

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