EMISSIVITY AND REFLECTION MODEL FOR CALCULATING WATER SURFACE-LEAVING INFRARED RADIANCE

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Abstract

Published emissivity models provide calculated emissivity spectra for a given set of optical constants, view angles and local wind speeds. While these models have gained widespread acceptance, discrepancies have been identified against field measurements obtained from IR Fourier transform spectrometers (FTS) at view angles ≥40°. We therefore have developed an alternative approach for calculating surface-leaving IR radiance that treats both emissivity and atmospheric reflection in a systematic manner. This work overviews the theoretical basis, development and computations of the proposed model. The model is validated using an exhaustive set of FTS field observations acquired at sea. Our analyses show the new model to have improved agreement with observation over standard models.

INTRODUCTION

The infrared (IR) emissivity of the ocean surface is widely recognized to be an important factor in radiative transfer forward modeling. For ocean remote sensing applications requiring high accuracy (e.g., sea surface skin temperature), the surface emissivity and reflectance must be determined accurately. A 0.5% departure from "truth" results in significant errors (~0.3–0.4 K) in hyperspectral LWIR window channels.

To this end, several published emissivity models have gained widespread acceptance (e.g., *Masuda et al.* 1988; *Watts et al.* 1996; *Wu and Smith* 1997; *Henderson et al.* 2003). Emissivity is calculated as the ensemble-mean of one minus the Fresnel reflectivity of visible surface waves, expressed as

$$\overline{\varepsilon}_\nu(\theta_0) = 1 - \int_{\mu_n}\int_{\varphi} \rho_\nu^-(\Theta_i) P(\mu_n, \mu_0, \sigma^2)\, d\varphi\, d\mu_n,$$

where ρ_ν^- is the unpolarized Fresnel reflectance coefficient (reduced by so-called surface-emitted, surface-reflected (SESR) radiation; *Watts et al.* 1996), Θ_i is the wave facet incidence angle, *P*, is the normalized probability density function of surface waves with known variance σ^2, and the double integral is over the zenith and azimuth angle of the wave facet normal vectors. However, discrepancies have been identified nonetheless against field measurements obtained from IR Fourier transform spectrometers (FTS) at higher wind speeds and view angles ≥40° (*Hanafin and Minnett* 2005).

This work has set out to identify and correct the apparent error in these models using an extensive set of FTS data acquired at sea. A new model was subsequently derived for calculating unpolarized ocean surface-leaving radiance (SLR) that captures better the observed variation of SLR with observing angle and surface windspeed. This presentation has focused on providing a summary of the FTS field validation of the new model. Unlike prior studies, large quantities of data were obtained under varying atmospheric conditions, including regional samples from the tropics, midlatitudes and sub-arctic. These data were also not restricted to clear skies only, but included clouds and Saharan dust. For a more detailed and rigorous presentation of this work, the reader referred to two forthcoming companion papers submitted for publication in *Applied Optics* (*Nalli et al.* 2008a,b).

RADIATIVE TRANSFER-BASED EFFECTIVE EMISSIVITY

Our development of a new SLR model is based upon the working hypothesis that the standard emissivity models treat only the emitted component of SLR, while not providing a self-consistent approximation for the reflected component. This is manifested both in the approximation of multiple reflections and the incorrect specification of direct reflected downwelling atmospheric radiance. Considering the first of these, we note that the enhancement of emissivity in analytical model includes only SESR radiation (*Watts et al.* 1996). This can be rigorously accounted for in Monte Carlo models (e.g., *Henderson et al.* 2003), but such models are less convenient to implement, while the effect itself is of second order. More importantly, however, is the approximation of the quasi-specular (i.e., diffuse with a prominent specular component) reflected direct downwelling radiance (e.g., *Nalli et al.* 2001). Because of the computational burden associated with a hemispheric double integral of downwelling column radiances, radiative transfer models typically treat the reflectance as either specular or Lambertian, both of which are incorrect. It has thus been our goal to derive a practical, yet accurate, approximation that lends itself toward convenient implementation within a wide variety of remote sensing applications.

Using LBLRTM downwelling calculations, we derive the effective incidence angle, Θ_{ie}, from spectral variance minimization of the following RTE

$$\begin{aligned}\overline{R}_{\nu s}(\theta_0) &= \int_{\mu_n}\int_{\varphi}\left\{\left[1-\rho_\nu(\Theta_i)\right]B_\nu(T_s)+\rho_\nu(\Theta_i)I_{\nu i}(\theta)\right\} P\,d\varphi\,d\mu_n \\ &\approx B_\nu(T_s)-\rho_\nu(\Theta_{ie})\left[B_\nu(T_s)-I^{\downarrow}_{\nu a}(\theta_0)\right]\end{aligned} \quad ,$$

where the surface incident radiance is modeled by

$$I_{\nu i}(\theta) = (1-p_s)I^{\downarrow}_{\nu a}(\theta) + p_s\left(I_{\nu se}+I_{\nu sr}\right) .$$

Defining an *effective emissivity* to be

$$\varepsilon_{\nu e}(\theta_0,\overline{U}_{10},N_\nu) \equiv 1-\rho\left[\Theta_{ie}(\theta_0,\overline{U}_{10}),N_\nu\right] ,$$

the full quasi-specular surface-leaving radiance may then be modeled simply as

$$\overline{R}_{\nu s}(\theta_0) \approx \varepsilon_{\nu e}(\theta_0,\overline{U}_{10},N_\nu)\,B_\nu(T_s)+\left[1-\varepsilon_{\nu e}(\theta_0,\overline{U}_{10},N_\nu)\right]I^{\downarrow}_{\nu a}(\theta_0) .$$

VALIDATION

This work relies extensively upon radiometric data acquired from the Marine Atmospheric Emitted Radiance Interferometer (M-AERI), a ship-based FTS (see Figure 1) designed to sample downwelling and upwelling IR high-resolution spectra near the surface (*Minnett et al.* 2001). High accuracy calibration (e.g., *Revercomb et al.* 1988) is achieved using 2 NIST-traceable blackbodies. Derived products of interest include radiometric sea surface skin temperature (0.1 K accuracy) derived from semi-opaque spectral region (~7.7 µm) (*Smith et al.* 1996), and spectral emissivity (*Smith et al.* 1996; *Hanafin and Minnett* 2005). We supplement the M-AERI data with Baltimore-Bomem AERI (BBAERI) radiometric data, which is similar to M-AERI except deployed on a stationary platform (the COVE site). We make use an exhaustive sample of M-AERI and BBAERI radiances obtained from several intensive field campaigns (in chronological order):

- 1996 Combined Sensor Program (CSP) (*Post et al.* 1997)
- 1999 East Atlantic Transect (EAT)
- 2001 Asian Pacific Regional Aerosol Characterization Experiment (ACE-Asia)
- 2002 and 2003 AIRS BBAERI Ocean Validation Experiment (ABOVE)
- 2003 Canadian Arctic Shelf Exchange Study (CASES)
- 2004 Aerosol and Ocean Science Expedition (AEROSE-I) (*Nalli et al.* 2006)
- 2004 Surface-Ocean Lower-Atmosphere Studies Air-sea Gas Experiment (SAGE)
- 2006 African Monsoon Multidisciplinary Analysis (AMMA) AEROSE-II (*Morris et al.* 2006)

As mentioned above, these data include varying all-sky atmospheric conditions (clear, cloudy and dusty), with regional samples from the tropics, midlatitudes and high latitudes.

***Figure 1:* The Marine Atmospheric Emitted Radiance Interferometer located onboard the NOAA Ship *Ronald H. Brown* during the 2004 Aerosol and Ocean Science Expedition (AEROSE-I).**

Figures 2– 4 show a sub-sample of campaign-mean SLR calculations minus observations (calc − obs) in equivalent brightness temperatures for the longwave IR and shortwave IR spectral window regions. The ACE-Asia LWIR data in Figure 2 were obtained at $\theta_0 = 55°$ under midlatitude springs conditions, the CSP LWIR data in Figure 3 were obtained at $\theta_0 = 65°$ under tropical Pacific warm pool conditions, and the ABOVE SWIR data in Figure 4 were obtained at $\theta_0 = 45°$ under midlatitude summer conditions. In all three cases, the SLR model based on effective emissivity is seen to reduce the residual bias in calc − obs over the conventional model. The remaining spectral features in the calc − obs are due to (1) the unaccounted impacts of the atmospheric path between the sensor and the surface, (2) temperature-dependent deviations in the seawater optical constants not measured in the published datasets, and finally, (3) small residual errors associated with approximations employed in the SLR models (this is most notable in Figure 2, where a very small trace of the ozone absorption band is visible in the calc − obs; note, of course, that this deviation is completely negligible, especially given that it is not a window region). We also note that because of the large quantity of observations used (thousands of LWIR and SWIR spectra at 55°), the results have statistical significance (*t*-test measures of significance are given in *Nalli et al.* 2008b). To our knowledge, these analyses constitute the most comprehensive validation of ocean emissivity/reflection models to date.

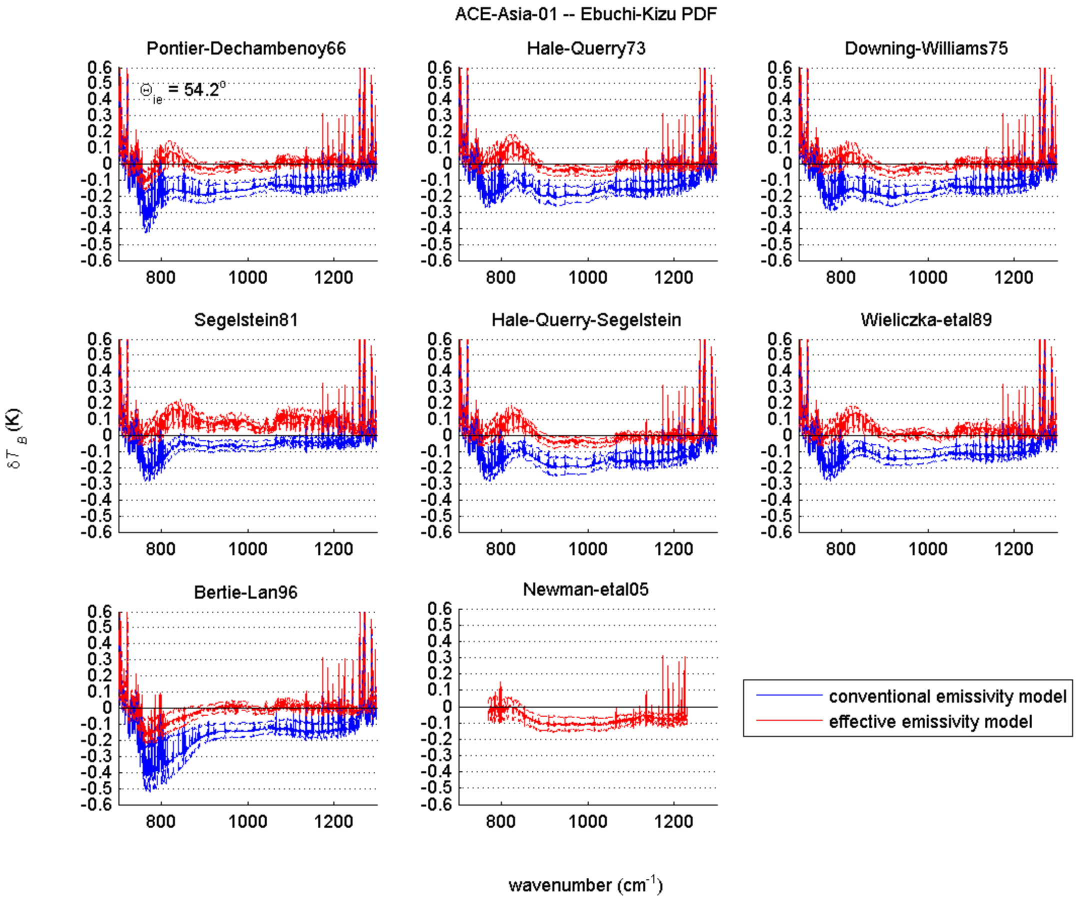

Figure 2: **Mean (solid lines) and interquartile range (IQR; dashed lines) of daily means of SLR calc − obs for the LWIR window region, expressed in apparent brightness temperature difference (K), for nadir pointing angle 55°, from M-AERI during the 2001 ACE-Asia field campaign. The total number of days and M-AERI spectra used in the analysis are 38 and 4434, respectively. The blue difference spectra are the result of calculations using the ``conventional" approach (Wu and Smith emissivity and specular reflection approximation), whereas the red difference spectra result using the effective emissivity approach developed in this work. The different panels show the results of using different sets of published optical constants. Shown in the bottom-middle plot are results based on the temperature dependent refractive indices of *Newman et al.* (2005). All calculations utilize the *Ebuchi and Kizu* (2002) wave slope PDF model, and the mean tilt of the vessel was not corrected for since ship roll and pitch data were not available. The large spikes on the left and right edges are due to path attenuation in absorption bands between the sensor and the surface. The "hump" near 830 cm^{-1} is probably the result temperature-dependent deviations in the seawater optical constants (e.g., *Newman et al.* 2005; note how this effect is reduced in the bottom middle plot).**

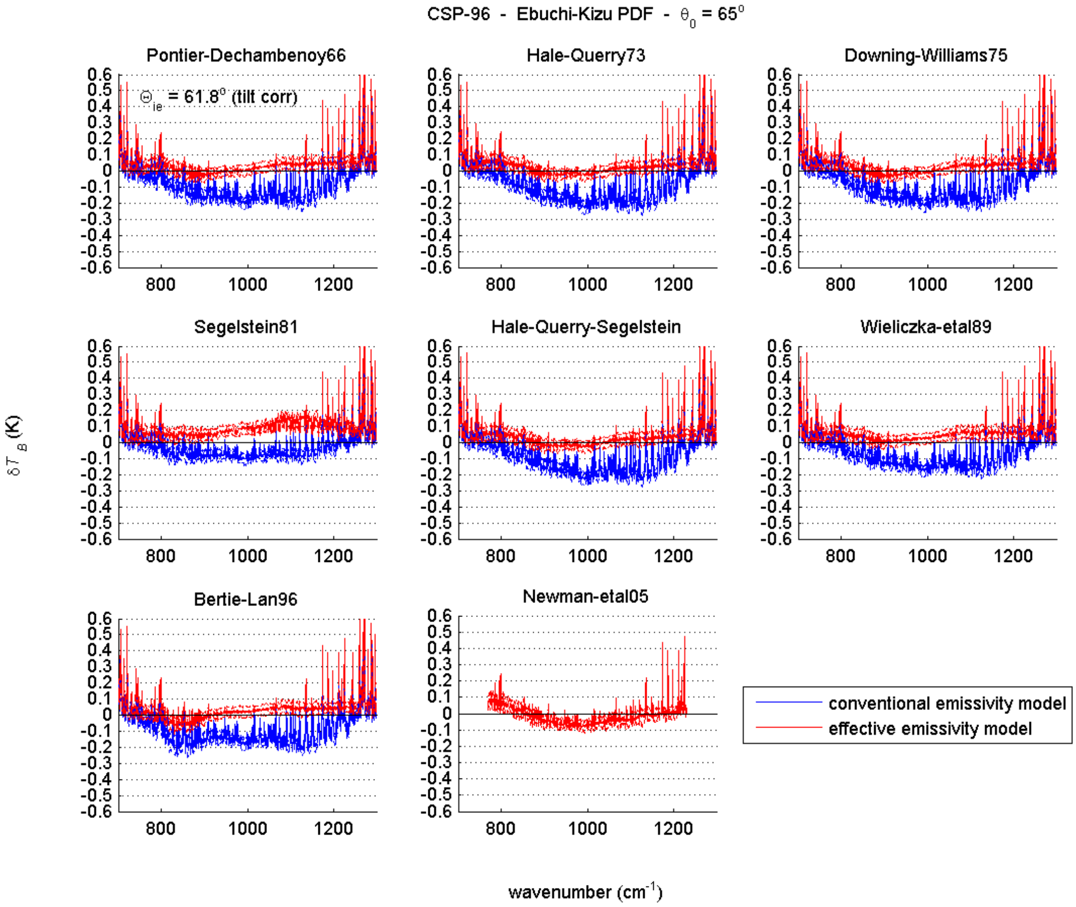

Figure 3: **Same as Figure 2 except for the 1996 CSP cruise with the M-AERI pointing angle at 65°. The number of days and spectra used in the analysis were 27 and 690, respectively, and ship roll and pitch were used to correct for the mean tilt of the vessel.**

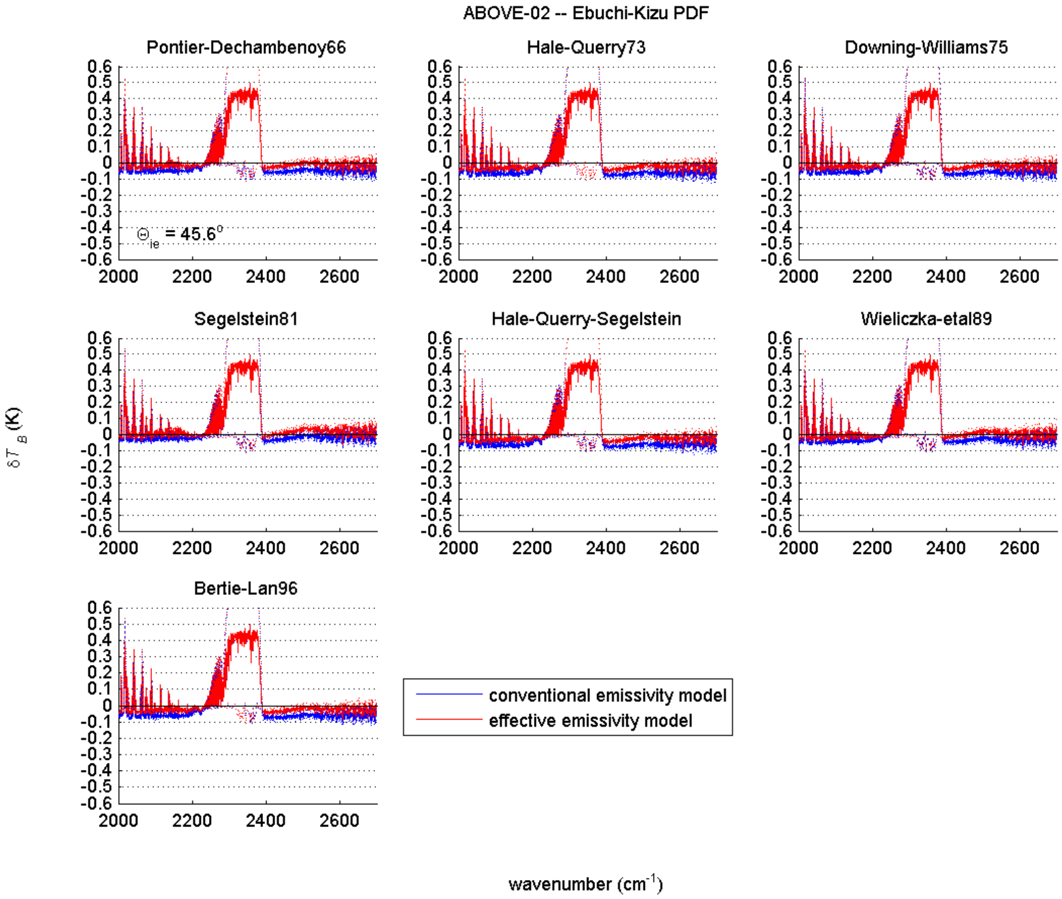

Figure 4: **Same as Figure 2 except for SWIR data obtained from the BBAERI onboard a stable platform at 45° pointing angle during the 2002 ABOVE campaign. The number of days and spectra used in the analysis were 15 and 401, respectively. The large positive deviations in the center of the plots are due to path attenuation in the carbon dioxide band between the sensor and the surface.**

SUMMARY AND FUTURE WORK

This presentation has overviewed a new practical model that has been developed for calculating IR ocean surface-leaving radiance (*Nalli et al.* 2008a). Unlike previous models, which focused exclusively on emissivity, the new approach presented here attempts to account consistently for quasi-specular emissivity and reflection by introducing an effective emissivity through RT calculations. An extensive sample of FTS measurements (M-AERI and BBAERI) has provided a dataset for statistical validation (*Nalli et al.* 2008b). The reduction of bias is approximately 0.05–0.4 K in microwindows, which amounts to ~0.15–0.4% correction in emissivity for observing angles $\theta_0 = 45$–65°. This correction amounts to a significant improvement in the context of the complete forward model, and the large number of global observations establishes statistical significance in the results. The angular dependence of SLR is particularly germane for geosynchronous satellites (e.g., Meteosat, GOES-R). The base lookup tables for calculating effective emissivity will be available in *Nalli et al.* (2008a), and the model is to be implemented within the NOAA Community Radiative Transfer Model (CRTM).

This work has also provided an independent evaluation of 7 published sets of measured IR refractive indices. In agreement with other recent work (*Newman et al.* 2005), we found a significant temperature dependence, which, if unaccounted for, can lead to non-negligible spectral deviations in calc − obs. Therefore, additional work is desirable to derive an optimal seawater refractive indices dataset.

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