P6.28 DEVELOPMENTS IN OCEAN INFRARED EMISSIVITY/REFLECTION MODELING: COMPARISONS AGAINST OBSERVATIONS

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1. INTRODUCTION

The infrared (IR) spectral emissivity of the earth's surface is now recognized to be a key factor in radiative transfer forward modeling. The oceans, in particular, cover 70% of the earth's surface, and a high degree of accuracy is generally necessary for sea surface skin temperature (SST) determination. A mere 0.5% departure from blackbody emission results in significant brightness temperature errors (0.25 K).

Much progress has been made toward modeling the spectral IR emissivity of wind-roughened water surfaces. Existing emissivity models explicitly calculate the ensemble mean emissivity of the wavy surface for a given observer zenith angle and local wind speed (e.g., Masuda *et al.* 1988; Watts *et al.* 1996; Wu and Smith 1997; Henderson *et al.* 2003). For example, the model of Wu and Smith (1997) is now used by both the Global Data Assimilation System (GDAS) at the U.S. National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) (van Delst 2003) as well as by the U.S. National Aeronautics and Space Adminstration (NASA) Atmospheric Infrared Sounder (AIRS) Science Team. This model improved upon the Masuda *et al.* (1988) model (used previously by both the GDAS and AIRS) by accounting for surface-emitted-surface-reflected (SESR) emission. However, field observations of emissivity spectra obtained by Hanafin and Minnett (2005) using the Marine Atmospheric Emitted Radiance Interferometer (M-AERI) (Smith *et al.* 1996; Minnett *et al.* 2001) suggest that such emissivity models are deficient at larger view angles and wind speeds. We attempt to identify and explain the sources of error in these models using M-AERI data acquired at sea (e.g., during AEROSE 2004). Our preliminary results demonstrate that proper accounting for surface emissivity in window channels must ultimately include appropriate specification of the reflected IR radiation field, especially in window channels.

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2. THEORETICAL BASIS

2.1 Surface-Leaving Radiance

In this work, we are concerned with modeling the surface-leaving IR radiance for different quasi-monochromatic spectral channels, ν, observer zenith angles, θ_0, and mean surface wind speeds, $\overline{U}$. Assuming a plane-parallel atmosphere with azimuthal symmetry, the IR radiative transfer equation for a downlooking sensor positioned near the surface (viz., M-AERI) includes a bidirectional reflectance integral that renders the exact calculation of reflectance intractable. Because the reflectance from the ocean surface may be described as quasi-specular (i.e., having a significant specular component) (e.g., Nalli *et al.* 2001), it is common practice to approximate the ocean surface-leaving radiance in the form of (e.g., Závody *et al.* 1995; Kidder and Vonder Haar 1995; Smith *et al.* 1996; Watts *et al.* 1996; Nalli and Smith 1998; Ma *et al.* 2002)

$$R_\nu(\theta_0) \approx \epsilon_\nu(\theta_0)\, B_\nu(T_s) + r_\nu(\theta_0)\, I_\nu^{\downarrow}(\theta_0)\,, \quad (1)$$

where the atmospheric path attenuation between the observer and the surface is assumed to be negligible in window regions, and R_ν is the surface-leaving radiance observation (in mW m^{-2}sr^{-1}cm), ϵ_ν is the surface emissivity, B_ν is the Planck blackbody function, T_s is the skin SST, and $I_\nu^{\downarrow}$ is the downwelling atmospheric emitted atmospheric radiance (intensity). Conservation of energy at the interface also implies that

$$\epsilon_\nu(\theta_0) = 1 - r_\nu(\theta_0)\,. \quad (2)$$

Eqs. (1) and (2) suggest that the surface-leaving radiance can be approximated given only the mean reflectivity calculated at the observer angle. For specular surfaces, the reflectivity is known from first principles in the Fresnel equations. The calculation of $r_\nu(\theta_0)$, and hence the emissivity $\epsilon_\nu(\theta_0)$, has thus been the focus of several previous works (e.g., Masuda *et al.* 1988; Watts *et al.* 1996; Wu and Smith 1997; Henderson *et al.* 2003). The basis for calculating sea surface emissivity is the facet model which is overviewed below.

2.2 Analytical Facet Model

Assuming that the surface curvature due to wave slopes is small with respect to IR wavelengths, the scattered field at each point on the surface is equivalent to that resulting from a plane tangent to the surface at that point. Given a statistical description of the wave slope distribution, the mean reflectivity of the rough surface can, in principle, be defined exactly. Based upon aerial photographs, Cox and Munk (1954) described the wave slope distribution as approximately Gaussian with the variance a linear function of $\overline{U}$. This has led to the derivation of the analytical facet model for rough water surfaces (e.g., Masuda *et al.* 1988; Watts *et al.* 1996; Wu and Smith 1997; Nalli *et al.* 2001; Henderson *et al.* 2003). The form of the equation, when expressed in local zenith and azimuth angle coordinates, and including physics to account for multiple reflections (viz., surface-emitted, surface-reflected radiance) and wave shadowing (e.g., Watts *et al.* 1996; Wu and Smith 1997; Nalli *et al.* 2001), is given by

$$\bar{\epsilon}_\nu(\theta_0) \; = \; 1 - \int_{\mu_{n1}}^{1} \int_{0}^{\varphi_2} \rho^*(\Theta_i)\, P^*(\mu_n, \mu_0, \Theta_i, \sigma^2)\, d\varphi\, d\mu_n \,, \tag{3}$$

where ρ^* is the Fresnel reflectance coefficient (enhanced by surface emissions using the same slope PDF), P^* is a normalized probability density function (PDF) with variance σ^2, $\mu_0 = \cos(\theta_0)$, φ_2 is an adjusted limit in the integration over azimuth angle, φ, Θ_i is the facet incidence angle, $\mu_n = \cos(\theta_n)$, θ_n being the local zenith angle of the facet normal vector and μ_{n1} is an adjusted limit for improved quadrature accuracy (Nalli *et al.* 2001). Eq. (3) explicitly calculates the rough surface emissivity as 1 minus the ensemble mean reflectivity. While analytical facet models similar to (3) have been shown to agree reasonably well with a limited dataset using a retrofitted AERI instrument (e.g., Smith *et al.* 1996; Wu and Smith 1997), there is nonetheless a theoretical limitation in the treatment of multiple reflections in such models (e.g., Henderson *et al.* 2003). However, a more important deficiency is the treatment of the reflected atmospheric emission (e.g., Nalli *et al.* 2001) indicated in the radiative transfer approximation (1), which ignores the diffuse component of quasi-specular reflectance.

Henderson *et al.* (2003) addressed the multiple reflection problem using a Monte Carlo facet model (instead of an analytical one), but they considered only emissivity, not the reflected component. Nalli *et al.* (2001), on the other hand, attempted to address this latter problem by introducing a reflection-diffusivity angle dependent on column transmittance and applicable only to microwindow channels in the LWIR window.

These limitations are only now being revealed with the extensive acquisition of M-AERI data in recent years (e.g., Hanafin and Minnett 2005). M-AERI measures spectra of $I_\nu^\downarrow(\theta)$ at uplooking zenith angles 0° (local zenith) and θ_0, as well as the surface-leaving radiance, $R_\nu(\theta_0)$, at downlooking nadir angle θ_0. M-AERI uses these spectra to retrieve surface emissivity based on the premise of finding an effective incidence angle, Θ_{ie}, that minimizes spectral variance caused by absorption features (e.g., Smith *et al.* 1996; Hanafin and Minnett 2005). Based on M-AERI emissivity retrievals, Hanafin and Minnett (2005) found that emissivity models (viz., Masuda *et al.* 1988; Watts *et al.* 1996) underestimate emissivity at large θ_0 and $\overline{U}$.

2.3 Ensemble Mean Geometry

Hanafin and Minnett (2005) present much of their results in terms of Θ_{ie}. This motivated development of a preliminary new approach in this work, namely to calculate the effective incidence angle as the ensemble mean relative incidence angle, $\overline{\Theta}_i$, of the surface wave facets:

$$\overline{\Theta}_i \; = \; \frac{\int_{\mu_{n1}}^{1} \int_{0}^{\varphi_2} \Theta_i \, P^* \, d\varphi\, d\mu_n}{\int_{\mu_{n1}}^{1} \int_{0}^{\varphi_2} P^* \, d\varphi\, d\mu_n} \,. \tag{4}$$

Henderson *et al.* (2003) wrote a similar formula (based on a simplified form of Eq. (3) that excluded the effects of wave blocking) to demonstrate the existence of a cross-over angle ($\simeq 68^\circ$) where increasing $\overline{U}$ increases $\bar{\epsilon}_\nu$.

Likewise, the mean local zenith angle of downwelling radiance is given by

$$\overline{\theta} \; = \; \frac{\int_{\mu_{n1}}^{1} \int_{0}^{\varphi_2} \theta \, P^* \, d\varphi\, d\mu_n}{\int_{\mu_{n1}}^{1} \int_{0}^{\varphi_2} P^* \, d\varphi\, d\mu_n} \,. \tag{5}$$

Note that neither of Eqs. (4) or (5) require assumptions about multiple reflections since they only predict the geometries arising from the mean facet inclination. Lookup tables of $\overline{\Theta}_i(\theta_0, \overline{U})$ and $\overline{\theta}(\theta_0, \overline{U})$ are computed for 3 different published mean square slope PDFs (viz., Cox and Munk 1954; Su *et al.* 2002; Ebuchi and Kizu 2002). The results for the mean incidence angle $\overline{\Theta}_i$ (not shown here) agree roughly with the observations of Hanafin and Minnett (2005) for $\theta_0 = 55°$, whereby $\overline{\Theta}_i$ is seen to decrease with increasing wind speeds, thus increasing the mean emissivity. The cross-over angle actually lies somewhere between 30°–40°, depending on the PDF model. This value is notably smaller than the previous estimates of 68°(e.g., Masuda *et al.* 1988; Watts *et al.* 1996; Wu and Smith 1997; Henderson *et al.* 2003).

Based upon the mean geometries given by Eqs. (4) and (5), we propose a preliminary alternative approximation to (1), namely

$$R_\nu(\theta_0) \approx \left[1 - \rho_\nu(\overline{\Theta}_i)\right] B_\nu(T_s) + \rho_\nu(\overline{\Theta}_i)\, I_\nu^{\downarrow}(\overline{\theta})\,, \quad (6)$$

where ρ_ν is the Fresnel reflection coefficient. While this equation also ignores diffuse contributions, it more accurately represents the specular component arising from the specified wave slope geometry.

3. PRELIMINARY RESULTS

To assess the relative accuracies of approximations (1) and (6), we rely on field observations of surface-leaving radiance spectra. The M-AERI is a ship-based Fourier transform IR spectrometer (FTS) that measures calibrated, high-resolution radiance spectra (≃0.5 cm^{-1} over ≃550–3000 cm^{-1}), from both the upwelling and downwelling directions (Minnett *et al.* 2001). The M-AERI spectral observations used in this preliminary work originate from the 2004 Aerosol and Ocean Science Expedition (AEROSE) in the tropical North Atlantic Ocean. More than 2 weeks of continuous M-AERI data were collected during the AEROSE field experiment; for more details, the reader is referred to Nalli *et al.* (2006).

The downlooking view at $\theta_0 = 55°$ provides what we consider to be the approximate "true" surface-leaving radiance in window channels (in absorption bands, the atmospheric path between the sensor and the surface obscures the surface signal). We can then use Eqs. (1) and (6) to model the surface-leaving radiance, given the high-accuracy M-AERI retrieval of T_s and the observed downwelling atmospheric radiances, $I_\nu^{\downarrow}(\theta_0)$, at $\theta_0 = 55°$ and 0°. We find in our calculations that $\overline{\theta}$ in Eq. (6) is $50° < \overline{\theta} \leq 55°$, so we approximate the radiance at the computed $\overline{\theta}$ from the Beer-Lambert law

$$I_\nu^{\downarrow}(\overline{\theta}) \approx I_\nu^{\downarrow}(\theta_0)\, \exp\left[-\tau_\nu(\sec\theta_0 - \sec\overline{\theta})\right]\,. \quad (7)$$

Because the atmosphere is not isothermal, approximation (7) will underestimate the actual downwelling radiance, but by a factor of 2 less than the overestimation that would occur from using the 55° observation itself. Note that the observed downwelling radiance during AEROSE accounts for all atmospheric conditions, including clouds and high levels of dust aerosols.

The mean differences between the modeled and observed surface-leaving brightness temperatures (LWIR window region) for the entire AEROSE cruise using the Cox and Munk (1954) wave slope PDF is shown in Fig. 1. The results for the SWIR window region (daytime only subsample) are shown in Fig. 2. It can be seen that the LWIR calculations based upon Eq. (1) (blue shades) systematically underestimate the observed spectra by 0.1–0.2 K. Because of the reduced atmospheric reflection in the more transparent SWIR window region, the magnitude of bias for the SWIR is somewhat less and spectrally constant at about 0.1 K. The underestimation in the LWIR window is about the same size as the RMS errors for atmospheric transmittance model fitting alone. Calculations based upon Eq. (6), on the other hand, are much closer to the observed spectrum. Note that nearly identical results were obtained using the Su *et al.* (2002) and Ebuchi and Kizu (2002) wave slope PDFs (not shown here).Thus the potential corrections to be derived from this work amount to a significant improvement in the context of the complete forward radiance model.

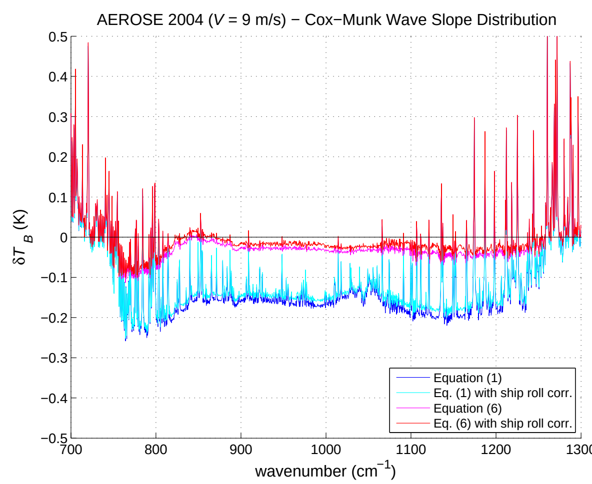

Figure 1: Mean differences between the modeled and observed surface-leaving brightness temperatures (LWIR window region) for the entire AEROSE cruise using the Cox and Munk (1954) wave slope PDF model. The blue and cyan lines are based upon Eq. (1) whereas the red and magenta lines are based upon Eq. (6). Corrections for the mean ship roll angle are applied in the cyan and red curves as indicated in the legend.

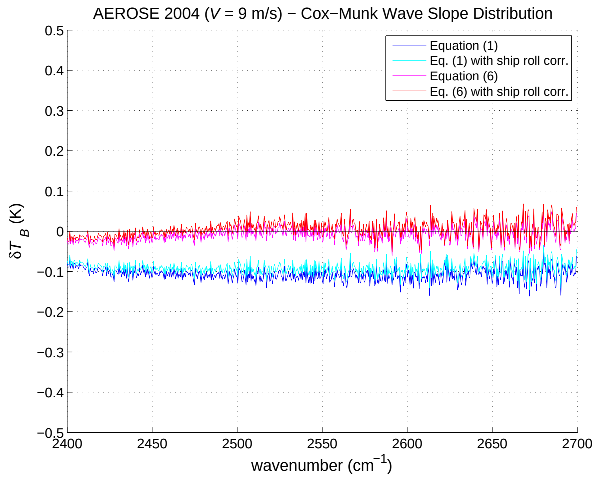

Figure 2: Same as Fig. 1 except for the SWIR window region.

4. SUMMARY AND FUTURE WORK

This work has presented corroborating evidence that the conventional approach to modeling IR surface-leaving radiance, namely Eqs. (1), (2) and (3), results in a systematic underestimation of radiance in hyperspectral microwindow channels (viz., from M-AERI and presumably AIRS) for non-zero wind speeds and scan angles. While the magnitude of the bias (0.1–0.2 K for $\theta_0 = 55°$) may be negligible for many IR applications, it is significant for high accuracy applications such as skin SST. The angular dependence is particularly important for retrievals from geosynchronous satellites (e.g., GOES and Meteosat), which must observe the earth's surface at large, constant incidence angles. We propose an alternative approach that correctly treats the specular component of emissivity and reflection from rough water surfaces. Our results thus far show good agreement with M-AERI observed surface-leaving radiance spectra. This new approach to emissivity/reflection modeling will be refined and validated against M-AERI field data from several previous oceanographic cruises from different regions of the globe. This work will be the subject of a future paper.

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