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Infrared emissivity of seawater and foam at large incidence angles in the 3–14 μm wavelength range

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ABSTRACT

The emissivity of the sea surface is an important parameter for infrared measurements at large incidence angles, and the increased radiance of foam from breaking wave crests, attributed to the higher emissivity of foam over foam-free water, has not been confirmed experimentally at angles above 65°. Here we report on outdoor laboratory experiments performed to confirm model predictions of a dramatic decrease in seawater emissivity at large incidence angles and to provide the first measurements of foam emissivity in this regime. A method is presented using Fourier transform infrared (FTIR) spectroscopy to measure the spectral emissivity of seawater and foam at incidence angles from 60° to 85° and wavelengths from 3.5–5.5 to 8–14 μm. The emissivity of water and foam are found to decrease dramatically for incidence angles above 65°, with the decrease being less dramatic for foam than for water. The emissivity of foam is found to be higher than that of water for all wavelengths and incidence angles above 65° where the difference is statistically significant. The difference between the emissivity of foam and the emissivity of water increases with incidence angle and reaches a maximum of 0.23 at 8.9 μm and 85° incidence. The significant difference between the emissivity of foam and water should be accounted for in infrared models of the sea surface at large incidence angles.

1. Introduction

The infrared emissivity of the sea surface is a key parameter for remote sensing applications such as sea surface temperature measurements, target detection, and wave parameter estimation (e.g. Branch, Chickadel, & Jessup, 2014; Hanafin & Minnett, 2005; Hoff, Evans, & Bunney, 1990). A specific example where foam emissivity becomes important is in identifying the active, aerated wave roller, as done in Carini, Chickadel, Jessup, and Thomson (2015) to estimate breaking wave energy dissipation rates. Here, the contrast of the wave roller in thermal imagery, enhanced due to elevated emissivity of foam with respect to the surrounding non-foamy water, is exploited for identification of the roller via a brightness temperature threshold. The utility of the approach in Carini et al. (2015) is based on the near-grazing angles used (>65°) and the understanding of foam-seawater brightness temperature contrast, which in turn dependent on the predictability of emissivity differences from both types of surfaces. This can translate to improved understanding of ocean wave breaking in thermal images from manned and unmanned airborne platforms and ships.

The emissivity of seawater is close to unity at small incidence angles but models predict a dramatic decrease for angles above 70°, (Embury, Merchant, & Filipiak, 2012; Filipiak, 2008; Masuda, 2006; Masuda et al., 1988) with a concomitant increase in reflectivity due to Kirchoff's Law for an opaque surface. Extensive measurement results have been published of the emissivity at small to moderate incidence angles for sea surface temperature calculations (e.g. Nalli, Minnett, Maddy, McMillan, & Goldberg, 2008; Niclòs, Dona, Valor, & Bisquert, 2014), but very few measurements have been made at large incidence angles where the dramatic decrease is predicted. The largest incidence angle for which the infrared emissivity of seawater has been published is 73.5° (Smith et al., 1996). Emissivity models typically consider the sea surface as a distribution of facets of foam-free water, with many models accounting for the change in the distribution of tilt angles with wind speed as waves grow (Freund, Joseph, Donohue, & Constantikes, 1997; Masuda, Takashima, & Takayama, 1988; Wu & Smith, 1997). However, when breaking waves are present the sea surface is composed of foam and foam-free water, resulting in a more complex rough surface. Current models do not account for the difference in the emissivity between foam and foam-free water.

Increased infrared radiance of breaking waves has been observed at grazing incidence but the cause of the increase has not been established (Branch et al., 2014; Carini et al., 2015; Eisner, Bell, Young, & Oetjen, 1962). Eisner et al. (1962) hypothesized the increase is due to foam having a higher emissivity than water. The emissivity of foam has been found to be different from that of water in the infrared (Niclòs, Caselles, Valor, & Coll, 2007; Salisbury, D'Aria, & Sabins, 1993, hereafter N07). Salisbury et al. (1993) calculated the emissivity at a 10° incidence

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angle and found foam to have a lower emissivity than water for the wavelength bands from 3–5 to 8–10 μm but a higher emissivity than water from 12 to 14 μm. N07 reported measurements at incidence angles from 25 to 65° at four wavelength bands between 8 and 14 μm and found foam to have a higher emissivity than water. The objective of this work was to determine the emissivity of water and foam at incidence angles larger than 65° to as close to grazing as possible.

In this paper a Fourier transform infrared, FTIR, spectrometer is used to measure the spectral emissivity of flat water and foam in the wavelength bands from 4–6 μm to 8–14 μm at incidence angles from 60 to 85°. Section 2 describes the method for calculating emissivity from FTIR measurements and outlines the details of the experiment. Section 3 gives the results and discussion and Section 4 summarizes the conclusions.

2. Methodology

The emissivity of a water or foam surface can be calculated from the radiative transfer equation by measuring the radiance coming from the surface and the sky above the surface. The radiance measured when observing a surface at wavelength λ and incidence angle θ at close range is

$$L_m(\theta,\lambda) = \varepsilon(\theta,\lambda)L_s(\lambda) + \rho(\theta,\lambda)L_d \tag{1}$$

where L_m is the total radiance measured at the sensor, ε is the surface emissivity (water or foam), L_s is the surface radiance of the water or foam, ρ is the reflectivity, and L_d is the downwelling radiance. A surface can exhibit reflections ranging from diffuse (Lambertian) to specular. For a specular surface L_d is a direct measure of the sky radiance at the reflected angle $L_{sky}(\theta,\lambda)$ and each wavelength. For a diffuse surface, L_d is the downwelling hemispherical irradiance, $E_{sky}(\lambda)/\pi$. Previously, the downwelling hemispherical irradiance has been estimated using three different methods: from a measurement of directional downwelling radiance at single angle (Minnett et al., 2001; Smith et al., 1996), measured with a gold diffuse plate (Salvaggio & Miller, 2001), or modeled using atmospheric profile data (García-Santos et al., 2013). The large incidence angles used in our experiment would require an unreasonably large gold diffuse plate to measure the downwelling hemispherical irradiance. Thus for Lambertian approximations of emissivity we fit our nightly angular measurements to a cloud-free radiance model (Rubio, Caselles, & Badenas, 1997; N07).

$$L_{sky}(\theta,\lambda) \approx L_{sky}(0^\circ,\lambda)\cos^{-x_i}(\theta), \quad \text{and} \tag{2a}$$

$$E_{sky}(\lambda)/\pi \approx \frac{2}{2-x_i} L_{sky}(0^\circ,\lambda). \tag{2b}$$

This is a valid approximation, because we made our measurements under clear night skies on a building rooftop without surrounding structures and within a short amount of time, similar to García-Santos et al. (2013). Using *Kirchhoff's law* to relate the emissivity to the reflectivity as

$$\varepsilon(\theta,\lambda) + \rho(\theta,\lambda) = 1, \tag{3}$$

the spectral emissivity can then be solved for as

$$\varepsilon(\theta,\lambda) = \frac{L_m(\theta,\lambda) - L_d}{L_s(\lambda) - L_d} \tag{4}$$

where L_m is the sensor radiance. The surface radiance, L_s, can be measured at an angle where the surface emissivity is high and known (Smith et al., 1996) or estimated as the Planck radiance corresponding to the surface skin temperature. In order to use the Planck radiance, the surface skin temperature can be measured radiometrically (Jessup & Branch, 2008) or estimated using a contact temperature and a modeled cool skin offset (N07). A modeled cool skin offset is required when using a contact temperature because the infrared optical depth of O (10 μm) is much less than the O (1 mm) thick thermal boundary layer, both of which are not resolvable with a contact measurement. Contact temperature measurements with a constant cool skin offset were used by N07, but the cool skin offset is a function of atmospheric conditions and surface mixing (Donlon et al., 2002) and is unknown for foam. Alternatively, we measured L_s radiometrically using Eq. (1) with measurements of the surface and sky at an incidence angle of 10°, where the emissivity of the surface is well known and relatively insensitive to incidence angle near nadir (Salisbury et al., 1993). Our method for calculating emissivity uses published values of the emissivity of water and foam and does not depend on a model of the cool skin effect. This is especially important for foam measurements since there are no models of the cool skin effect in foam and there is evidence that residual foam may cool differently than water (Fogelberg, 2003; Marmorino & Smith, 2005).

The radiance, $L(\lambda)$, observed by a FTIR spectrometer is linearly related to the uncalibrated instrument response (counts) at a wavelength $V(\lambda)$ in volts, by a responsivity, g, and offset, L_o (Korb, Dybwad, Wadsworth, & Salisbury, 1996),

$$L(\lambda) = gV(\lambda) + L_o. \tag{5}$$

If Eq. (1) is expressed in terms of V then the responsivity and offset terms cancel and it becomes

$$V_m(\theta,\lambda) = \varepsilon(\theta,\lambda)V_s(\lambda) + \rho(\theta,\lambda)V_d. \tag{6}$$

The linear nature of Eq. (5) combined with the fact that the responsivity and offset remained constant during our experiment eliminates the need for calibration of the FTIR spectrometer. All emissivity calculations can therefore be made from uncalibrated instrument radiance values.

The surface instrument response, $V_s(\lambda)$, is calculated using a measurement of the surface at an incidence angle of 10° and using published values of the emissivity of water and foam at 10° (Salisbury et al., 1993). Measurements of the surface and sky at 10° are inserted into Eq. (6) as follows

$$V_m(10^\circ,\lambda) = \varepsilon(10^\circ,\lambda)V_s(\lambda) + (1-\varepsilon(10^\circ,\lambda))V_{sky}(10^\circ,\lambda). \tag{7}$$

The surface radiance is solved for as

$$V_s(\lambda) = \frac{V_m(10^\circ,\lambda) - (1-\varepsilon(10^\circ,\lambda))V_{sky}(10^\circ,\lambda)}{\varepsilon(10^\circ,\lambda)} \tag{8}$$

The resulting value, $V_s(\lambda)$, is independent of incidence angle and can be substituted into Eq. (4) for calculations of ε at θ in terms of uncalibrated radiance measurements.

$$\varepsilon(\theta,\lambda) = \frac{V_m(\theta,\lambda) - V_d}{V_s(\lambda) - V_d} \tag{9}$$

Fig. 1 shows the four measurements used in each emissivity calculation, where $V_m(10°,\lambda)$ and $V_{sky}(10°,\lambda)$ were used in Eq. (8) to calculate $V_s(\lambda)$. This surface radiance was then used in Eq. (9) with $V_m(\theta,\lambda)$ and measurements of $V_{sky}(\theta,\lambda)$, input for V_d, to calculate a specular estimate of $\varepsilon(\theta,\lambda)$. For a diffuse estimates of $\varepsilon(\theta,\lambda)$, $V_{sky}(\theta,\lambda)$ is first fit to the sky model (2a) using a nonlinear least squares routine at each wavelength and for each night multiple directional sky measurements were recorded to determine the full sky irradiance. The resulting $E_{sky}(\theta,\lambda)/\pi$ (2b) is used for V_d in Eq. (9). Only estimates where the calculated model skill in the fit for Eq. (2a) is higher than 0.98 are used to calculate Lambertian estimates of emissivity.

Error in $\varepsilon(10°,\lambda)$ will propagate directly through to $\varepsilon(\theta,\lambda)$, but $\varepsilon(10°,\lambda)$ was measured with a noise equivalent emissivity difference of 0.012 (Salisbury, 1990), which is an order of magnitude smaller