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Analysis of Infrared Radiation at an Air-Water Interface

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The problem of determining the strength of the infrared radiation from an air-water interface has been addressed analytically. The approach taken here is to express the Planck spectrum as a linear function of the temperature, an approximation valid for small variations of the temperature from the surface temperature, and to assume a linear temperature profile across the thermal boundary layer. The main result shows that the deviation of the surface radiation intensity from the Planck spectrum due *solely* to thermal stratification, is linearly proportional to the temperature change across the thermal boundary layer and the optical depth, but is inversely proportional to the thermal boundary layer thickness. This signal was shown to be about one order of magnitude greater than the noise level expected from modern CCD IR sensors at a wavelength of about 3.8 μm. It is suggested that controlled laboratory experiments be conducted to verify these theoretical estimates.

Keywords: infrared radiation, air-sea heat flux, radiation transport equation, air-sea gas flux, remote sensing technology

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INTRODUCTION

The accurate prediction of momentum, heat and gas transport across the air-sea interface is of obvious importance in determining the long term global climate. This need has motivated a number of field, modeling, simulation, and experimental efforts aimed at quantifying these fluxes. Bulk parametrizations of momentum and heat flux have been determined in field experiments (Fairall et al., 1996), while the dependence of carbon dioxide transport on wind speed has been modeled by Wanninkhof (1992, 2014). Additional work under controlled laboratory conditions has explored the microphysics responsible for gas flux at an air-water interface (Katsaros et al., 1977; Jahne et al., 1987; Handler et al., 2001; Handler and Smith, 2011).

More recently, advances in infrared (IR) sensors have been used by a number of researchers to develop novel methods for obtaining these fluxes through the use of advanced image processing (Garbe et al., 2004). These efforts also include the use of active methods (Jahne et al., 1989; Atmane et al., 2004) as well as the modeling of these methods (Zhang and Handler, 2014). Numerical simulations have also provided further insight regarding the small-scale turbulent dynamics responsible for determining these fluxes (Handler et al., 1999; Leighton et al., 2003; Nagaosa and Handler, 2003, 2012; Handler and Zhang, 2013; Herlina and Wissink, 2014; Fredriksson et al., 2016a,b).

The remote determination of oceanic heat flux from aircraft or satellites has also been considered. This has the obvious advantage of enabling a rapid large scale mapping of oceanic heat flux, and since heat flux can be considered a proxy for gas flux (Jahne et al., 1987), a mapping of gas flux can also be obtained. In fact, a limited effort has been made in this direction. The approach is based upon the existence of a thin thermal boundary layer at the air-sea interface, sometimes referred to as the *cool-skin* the ocean surface. This layer is typically between 0.1 *and* 1 mm in thickness, and the temperature difference across the layer can as much a 1 K (Katsaros et al., 1977). In addition, the optical depth of infrared radiation in wavelength bands transparent to the atmosphere can vary as much one order of magnitude (Downing and Williams, 1975). This has motivated the early attempts of McAlister and McLeish (1970) and McAlister et al. (1971) to use IR sensors mounted on aircraft, sensitive to radiation in differing wavelength bands, to probe the thermal layer at the air-sea interface. Using this approach, they claim to have obtained estimates of oceanic heat flux remotely. This idea was revisited by McKeown et al. (1995) and McKeown and Leighton (1999), who performed laboratory experiments using an IR imaging system.

The relatively little attention payed to the remote sensing of oceanic heat flux has motivated us to reconsider this approach. We are especially interested in using solutions of the radiation transport equation to develop an estimate for the strength of the radiation emerging from a thermally stratified medium. In this approach we choose to ignore the complicating effects of scattering in the water and atmosphere, surface waves, and atmospheric absorption. Furthermore, we consider a fluid layer in which the stratification is linear with depth, and we use a truncated expansion of the Planck spectrum about the surface temperature to obtain an expression for the radiation source that can be integrated exactly. This allows us to obtain a simple expression for the strength of the *signal* which results purely from stratification. Finally, we obtain estimates for the *signal-to-noise* ratio that that can be expected from current infrared focal plane array sensors.

RADIATION TRANSPORT EQUATIONS IN A STRATIFIED MEDIUM

The General Form of the Radiation Transport Equation

The radiation transport equation (Chandrasekhar, 1960; Thomas and Stamnes, 1999) for a radiating and absorbing medium following a ray in a direction associated with the coordinate s, a coordinate associated with any direction in space, is:

$$\frac{dI}{ds} = -k\rho I + \rho j \tag{1}$$

where I is the radiation intensity, k is the opacity, ρ is the density of the medium, and j is the emission coefficient. Local thermodynamic equilibrium implies:

$$j = k\,B\left(T, \lambda\right) \tag{2}$$

where the Planck spectrum $B(T, \lambda)$ is given by:

$$B\left(T, \lambda\right) = \frac{C_1}{\lambda^5}\left[\frac{1}{e^{(C_2(\lambda)/T)} - 1}\right] \tag{3}$$

Here $C_1 = 2hc^2$, $C_2(\lambda) = \frac{hc}{\lambda k_b}$, h is Plank's constant, c is the speed of light, λ is the wave length of the radiation, k_b is Boltzmann's constant, and T is the temperature. From here on, we will suppress the dependence of $B\left(T, \lambda\right)$ and $C_2(\lambda)$ on wavelength and will write them instead as $B\left(T\right)$ and C_2. Now referring to **Figure 1**, we consider a radiation field which is stratified in planes parallel to the top surface defined by $y = 0$, and we further choose outer and inner length scales D and d respectively. For simplicity, we chose the linearly varying temperature field given by:

$$T\left(y\right) = \begin{cases} \frac{\Delta T}{d} y + T_0 & 0 \leq y < d \\ T_d & d \leq y < D \end{cases} \tag{4}$$

where $\Delta T = (T_d - T_0)$, T_0 is the temperature at the air-water interface ($y = 0$), and $T_d = T(d)$. We choose a coordinate system as shown in which $y = D - s\,cos(\theta)$. Applying this coordinate transformation to Equation (1) gives:

$$\frac{dI}{dy} - \frac{\beta}{\cos\left(\theta\right)} I = -\frac{\beta}{\cos\left(\theta\right)} B\left(T\right) \tag{5}$$

where $\beta = \rho k$ is the wavelength dependent absorption coefficient. The boundary condition for equation 5 is:

$$I\left(y = D\right) = I_D \tag{6}$$

where I_D is assumed to be known. The exact solution to Equation (5) with the boundary condition given by Equation (6) is:

$$I\left(y\right) = I_D e^{\frac{\beta}{\cos\theta}(y-D)} + \frac{\beta}{\cos\theta} \int_y^D B(T) e^{\frac{\beta}{\cos\theta}(y-\bar{y})} d\bar{y}. \tag{7}$$

Approximate Solution of the RTE in a Stratified Medium

In general, there is no closed form expression for the integral in Equation (7) for the temperature profile given by Equation (4). Although this integral can be treated numerically, it is useful to obtain an approximate solution since this can expose

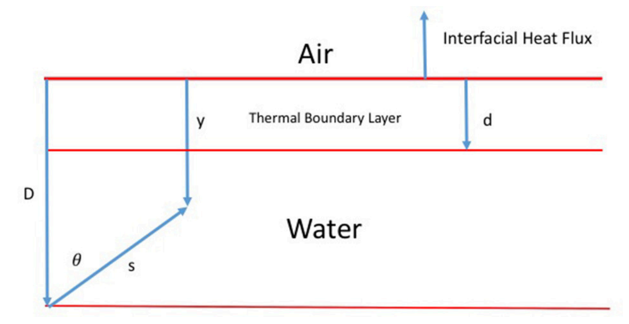

FIGURE 1 | The geometry associated with a radiation field at an air-water interface stratified in planes parallel to the water surface. The thermal boundary layer thickness is d, and the domain depth is D. Radiation propagates along a ray whose path length is s in direction θ.

the parameters and length scales that are most important in understanding the nature of the problem. This kind of understanding is critical in gaining insight into the physical phenomena involved and may aid in the design of experiments. For this purpose we now expand $B(T)$ about the surface temperature T_0 in a Taylor series as follows:

$$B(T) = B(T_0) + \left.\frac{dB}{dT}\right|_0 (T - T_0) \tag{8}$$

where we have truncated the series after the first two terms. This linear approximation should be accurate for cases in which the temperature change across the surface layer $\Delta\, T = T(d) - T_0$ is small compared to the surface temperature, such that $\Delta T/T_0 << 1$. In view of Equation (4), it is convenient to write Equation (8) as:

$$B(T) = \begin{cases} B(T_0) + F(T_0)\,\Delta T\alpha & 0 \le \alpha < 1 \\ B(T_0) + F(T_0)\,\Delta T & 1 \le \alpha < D/d \end{cases} \tag{9}$$

where $\alpha = \frac{y}{d}$, $F(T_0) = B(T_0)\,G(T_0)$, $G(T_0) = \frac{C_2 f}{{T_0}^2(f-1)}$, and $f = e^{\frac{C_2}{T_0}}$. Substitution of Equation (9) into Equation (7) with $y = 0$ gives the radiation intensity at the air-water interface, $I(0)$, as follows:

$$I(0) = \mu\left[\int_0^1 B(T)e^{-\mu\alpha}d\alpha + \int_1^{D/d} B(T)e^{-\mu\alpha}d\alpha\right] + I_D e^{-\mu\left(\frac{D}{d}\right)} \tag{10}$$

where $\mu = \frac{(\beta d)}{\cos(\theta)}$. The integrals in Equation (10) can now be evaluated yielding:

$$I(0) = B(T_0)\left[1 - e^{-\mu\left(\frac{D}{d}\right)}\right] + F(T_0)\,\Delta T\left[\frac{1 - e^{-\mu}}{\mu} - e^{-\mu\left(\frac{D}{d}\right)}\right] + I_D e^{-\mu\left(\frac{D}{d}\right)} \tag{11}$$

RESULTS

In the expressions to follow, we let $\beta = 1/l_{opt}$, where l_{opt} is the optical depth of the medium, so that $\mu = \frac{d}{\cos(\theta)\; l_{opt}}$. We choose here to examine the radiation in the $3 - 5\mu m$ wavelength band, one of bands for which the atmosphere is relatively transparent (McKeown et al., 1995). In this wavelength range, Downing and Williams (1975) found that optical depth of water varied from $1 - 90\ \mu m$. Given these values for the optical depth, it is justified to assume that $\frac{d}{l_{opt}} \gg 1$, since the thermal boundary layer thickness is on the order $d = 1$ mm. In addition, for $T_0 = 300K$, $e^q \gg 1$ where $q = \frac{C_2}{T_0}$ at these wavelengths. Furthermore, since we are concerned with effectively infinite water depths, we will assume $\frac{D}{d} \gg 1$.

Applying these limits to Equation (11) the deviation of the surface radiation intensity from the Planck spectrum, normalized with the Planck spectrum, can be expressed in terms of three non-dimensional numbers: $K_1 = \frac{C_2}{T_0}$, $K_2 = \frac{\Delta T}{T_0}$, and $K_3 = \frac{l_{opt}}{d}$ as follows:

$$\frac{I(0) - B(T_0)}{B(T_0)} = K_1 K_2 K_3 \cos(\theta). \tag{12}$$

We will refer to the quantity defined above, $S_{rad} = \frac{I(0) - B(T_0)}{B(T_0)}$, the radiation emitted from the surface due solely to thermal stratification, as the *signal*. This result shows that when $\theta = 0$, in which radiation is observed in directions perpendicular to the interface, the signal is maximal, consistent with the results of Zel'dovich and Raizer (1966). In addition, for a fixed surface temperature T_0, the signal increases in proportion to the temperature change across the surface layer, ΔT, and the optical depth, l_{opt}, but inversely with the layer depth, d. The signal is also seen via equation 12 to be proportional to the heat flux, $q = k\frac{\Delta T}{d}$, directed from the water to the atmosphere when $\Delta\, T > 0$, where k is the thermal conductivity of water.

It is of interest also to estimate the noise level of a typical IR sensing device by observing from Equation (9) that:

$$\frac{B(T) - B(T_0)}{B(T_0)} = \frac{C_2}{{T_0}^2}\Delta T \tag{13}$$

where the system *noise*, $N_{rad} = \frac{B(T) - B(T_0)}{B(T_0)}$, represents the normalized change in the Planck spectrum due to a change in temperature. In this case, it is appropriate to identify ΔT as the noise-equivalent-differential-temperature (NEDT) of the sensing device. At the present time, the most sensitive IR CCD arrays are found to have an NEDT of about $10^{-2}K$.

The results of the calculations for both the signal, S_{rad}, and the noise, N_{rad}, are shown in **Figure 2A** in which the signal is obtained from Equation (12) with $\theta = 0$ using optical depth data from Downing and Williams (1975) in the $3 - 5\ \mu m$ band, $T_0 = 300\ K$, $d = 1$ mm, and $\Delta T = 1K$. The noise level shown in **Figure 2A** was obtained using $\Delta T = 10^{-2}K$ in equation 13. The signal to noise ratio, $\frac{S_{rad}}{N_{rad}}$, is shown in **Figure 2B**. These results indicate that, over most of the wavelength range, the signal to noise ratio is above one, with a maximum occurring at a wavelength of about 3.8 μm.

SUMMARY AND CONCLUSIONS

The problem of determining the strength of infrared radiation from an air-water interface has been addressed analytically. This is essentially a special case of determining the radiation intensity from a radiating and absorbing thermally stratified medium. The approach taken here is to express the Planck spectrum as a linear function of the temperature, an approximation valid for small variations of the temperature from the surface temperature, and to assume a linear temperature profile across the thermal boundary layer. This allows the radiation transport equation to be integrated exactly. The resulting expression for the surface radiation intensity can be simplified by making the further approximation that the optical depth is small compared

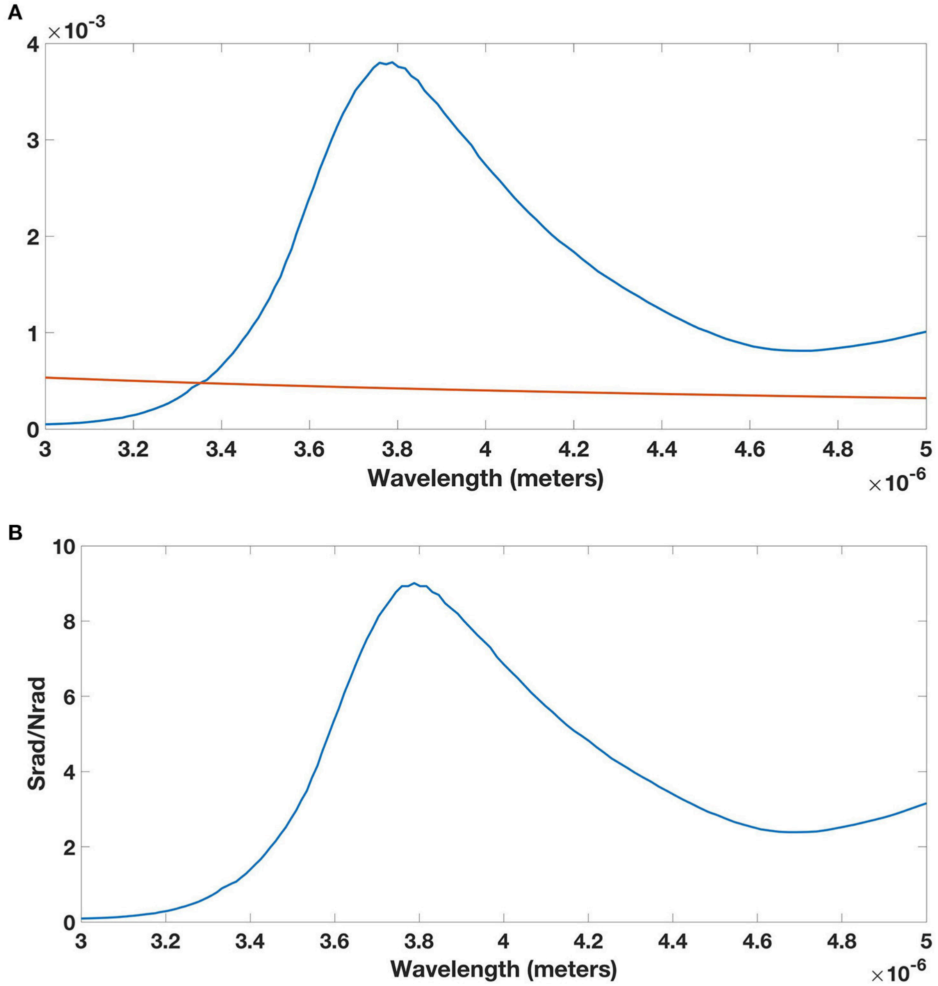

FIGURE 2 | (A) The signal (blue) obtained from Equation (12) with $\theta = 0$, and the noise (red) from Equation (13). The signal was obtained using $T_0 = 300\,\mathrm{K}$, $\Delta T = 1\ K$, and $d = 1\ mm$, and using the optical depth data from Downing and Williams (1975). This represents heat flux from the water layer to the atmosphere of $q = k\frac{\Delta T}{d} = 608\ Wm^{-2}$, which is nearly equivalent to the heat flux obtained in experiments (Handler and Smith, 2011) for a wind speed of about 3 ms^{-1}. The noise was obtained for a sensor with a thermal resolution of $10^{-2}K$. **(B)** The signal to noise ratio obtained from the results in **(A)**.

to the thermal boundary layer thickness, and that the depth of the domain is effectively infinite. The main result shows that the *signal* given by Equation (12), the deviation from the surface intensity from the Planck spectrum due *solely* to thermal stratification, is linearly proportional to the temperature change across the thermal boundary layer and the optical depth, but is inversely proportional to the thermal boundary layer thickness. This signal was shown to be about one order of magnitude greater than the noise level expected from modern CCD IR sensors at a wavelength of about 3.8 μm for a realistic interfacial heat flux (Handler and Smith, 2011).

This result would suggest, as has been previously claimed (McAlister and McLeish, 1970; McAlister et al., 1971; McKeown et al., 1995; McKeown and Leighton, 1999), that it may be possible to remotely detect the thermal stratification at the air-sea interface. However, this estimate assumes nearly perfect conditions: (1) The air-water interface is flat (no surface waves), (2) No scattering of radiation by particulates in the air or water, and (3) A surface emissivity of one. Given these significant potential sources of noise and non-ideality, and most likely others that we cannot now anticipate, our analysis suggests that it is unlikely in the near future that such a signal will be easily detected. On the other, we feel that the result embodied in equation 12 gives a theoretical basis for the design of future experiments, particularly in a controlled laboratory setting. A follow-on paper will extend these results to more realistic cases which include relaxing the linearity assumptions, and using a more realistic thermal boundary layer profile (Smith et al., 2001).

AUTHOR CONTRIBUTIONS

All authors listed, have made substantial, direct and intellectual contribution to the work, and approved it for publication.

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