MODELING OF OPTICAL BEAM SPREAD IN SEA ICE

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LONG-TERM GOAL

The overall goal of this work is to understand how visible light propagates through sea ice. In particular, I wish to understand how the physical properties of sea ice determine the beam spread function (BSF) and, conversely, to understand how measured BSFs can be used to deduce the scattering properties of sea ice.

OBJECTIVES

The two objectives of this year's work were (1) to finish analyzing the BSF data taken during the main field experiment of the Electromagnetic Properties of Sea Ice (EMPOSI) Accelerated Research Initiative at Barrow, Alaska in 1994, and (2) to investigate the extent to which it is possible to model light propagation in sea beginning with the ice physical properties. In particular, I wished to show that classical radiative transfer theory (rather that a full electromagnetic treatment beginning with Maxwell's equations) is adequate to model BSFs in sea ice.

APPROACH

It is particularly difficult to measure beam attenuation coefficients and scattering phase functions in sea ice. In separately funded work, R. Maffione therefore devised an ingenious experiment in which optical beam spread was measured between pairs of holes drilled in the ice (Maffione and Mobley, 1997a). The unique data obtained in this manner give the BSF along horizontal paths within the ice, as a function of depth within the ice and path length (distance between the holes).

Because sea ice is primarily a scattering (rather than an absorbing) medium, the BSF is particularly sensitive to the angular shape of the scattering phase function. Therefore, the measured BSF data can be used as the basis for an implicit inverse model to deduce the ice phase function, which cannot be measured in situ. A Monte Carlo code for predicting the BSF given the absorbing and scattering properties of the ice was developed during the previous year (Mobley, 1996). The inversion is then effected by varying the phase function in the Monte Carlo model until agreement between the predicted and measured BSFs is obtained. The phase function so deduced then can be used as input to the Hydrolight radiative transfer numerical model (Mobley, 1995) to predict other quantities of interest, such as albedos or heating rates within the ice.

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WORK COMPLETED

The Monte Carlo BSF model was used to analyze the 1994 EMPOSI BSF data as described above. The absorption coefficient of the ice was known from independent measurements made (by G. Cota) during the field experiment. The inversion of the BSF data then gave the scattering coefficient and phase function that were consistent with the measured BSF. The absorption and scattering properties of the ice were then used as input to exact radiative transfer simulations (using Hydrolight) of daylight propagation within the ice. The limits of diffusion theory for modeling light propagation in sea ice were examined.

RESULTS

Several major results were obtained from the modeling studies. First, inversion of the BSF data showed that within the interior of the ice (at Barrow site 2, May 1994, at a wavelength of 670 nm), a one-term Henyey-Greenstein (OTHG) scattering phase function with an asymmetry parameter of g = 0.98 is consistent with the BSF data; the scattering coefficient σ is approximately 200 m^{-1}. The measured absorption coefficient of κ ≈ 0.4 m^{-1} then gives an albedo of single scattering of 0.998. These values are consistent with previous estimates for ice of the type found at Barrow (Perovich, 1996). Computations carried out (under separate funding) by T. Grenfell starting with measured ice physical properties (brine pocket and air bubble size distribution statistics) and using Mie scattering theory gave similar results for the ice scattering properties (see Mobley, et al., 1997). Figure 1 shows the good agreement between predicted and measured BSFs.

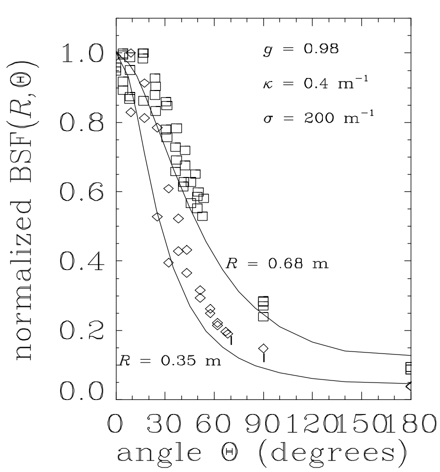

Fig. 1. Computed (lines) and measured (squares and diamonds) BSFs for path lengths (hole separations) of R = 0.35 and 0.68 m (from Mobley, et al., 1997). Note the good agreement even at 180 degrees, which is opposite the direction of the initial beam propagation.

Second, Monte Carlo modeling shows that the approach of the BSF to its asymptotic value is extremely slow, even though the ice is highly scattering (Maffione and Mobley, 1997b). This is both because the BSF arises from a point light source and because the ice phase function is highly peaked in the forward direction. Figure 2 shows the dependence on optical distance τ from the light source of a diffuse attenuation function (K function) for the BSF; the K function is still 26% larger than its asymptotic value after 300 optical path lengths.

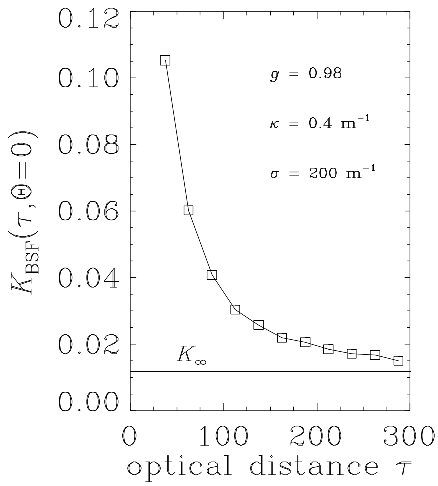

Fig 2. Approach of a diffuse attenuation coefficient for the BSF to its asymptotic value K_{∞}. For the ice being modeled, $\tau = 300$ corresponds to a physical distance of 1.5 m.

Third, classical diffusion theory can be used with reasonable accuracy to model the propagation of sunlight within the interior of the ice (Mobley and Maffione, 1997). Diffusion theory is valid in this situation because distributed light sources, such as sky light incident onto the air-ice surface, develop an asymptotic radiance distribution much faster (within a few tens of optical path lengths) than do point light sources. Figure 3 shows the agreement between K_d as predicted by an exact radiative transfer model (Hydrolight) and the K value given by diffusion theory. Moreover, diffusion theory can be inverted to get an estimate of the ice scattering properties from easily made measurements of ice absorption and diffuse attenuation (Mobley and Maffione, 1996; Maffione and Mobley, 1997a)

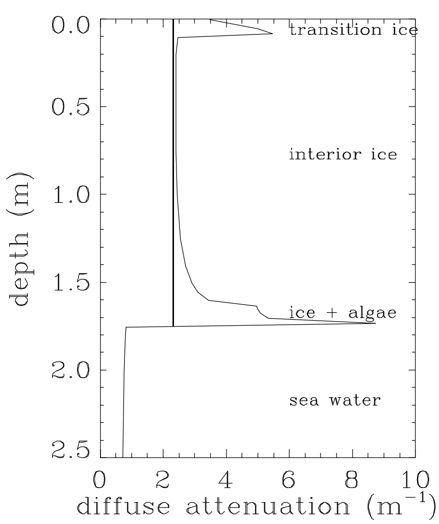

Fig. 3. Comparison of diffusion theory (dotted line) and exact radiative transfer theory (solid line) in the interior of the ice, which was modeled as a four-layer system (Mobley, et al., 1997). Note that diffusion theory is not valid near the air-ice (at depth 0) and ice-water (at depth 1.74 m) boundaries.

Finally, note that the good agreement between measured data and various radiative transfer predictions (Mobley, et al., 1997) shows that classical radiative transfer theory adequately describes visible light propagation in sea ice.

IMPACT/APPLICATIONS

Light absorption and scattering in sea ice play a central role in ice thermodynamics, in biological productivity below the ice, and in some remote sensing. Obtaining a self-consistent set of inherent optical properties of sea ice – in particular the scattering phase function – opens the door to the extensive use of radiative transfer theory for solving problems related to light transfer in sea ice.

TRANSITIONS

There have been no transitions of the sea ice work *per se*. However, the Monte Carlo BSF model developed here, which is quite general and also can compute point spread functions, has been used for modeling underwater point spread functions. This model can address many problems associated with underwater imaging systems.

RELATED PROJECTS

1. The BSF modeling described here is being carried out in close cooperation with R. Maffione, who is separately funded by ONR.

2. The modeling of daylight propagation in sea ice as related to biological productivity beneath the ice is being carried out in collaboration with G. Cota and R. Maffione, who are separately funded by ONR.

3. I have collaborated with T. Grenfell (separately funded by ONR) on his modeling of ice scattering properties using Mie theory.

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