Polarization-Dependent Measurements of Light Scattering in Sea Ice

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LONG-TERM GOALS

The goals of this project are to characterize the propagation and scattering of visible light in sea ice, develop an understanding of the connection between the light scattering properties and ice morphology, and evaluate the efficacy of polarimetry in optical remote-sensing studies of sea ice.

SCIENTIFIC OBJECTIVES

Development of a description of polarization-dependent light propagation and scattering in sea ice for modeling and interpreting remotely-sensed data was an objective of this project. This may be helpful to determine the orientation of the ice structure remotely. Because radiant transfer calculations in the ocean using scalar scattering have been shown to lead to significant errors in the radiance calculated using conventional scalar models under some conditions (Adams and Kattawar, 1993), it is important to establish the significance of polarization in sea ice. Scattering calculations are used to predict radiant transfer in sea ice and to evaluate effects of incident sunlight on climate change and on biological processes under the ice pack. Although sea ice can exhibit polarization-dependent scattering, a complete description of the angle- and polarization-dependent scattering of sea ice has not existed in the literature until this project. The polarized scattering properties of sea ice were measured to characterize it and to identify relationships between the physical properties of the ice and polarization and scattering properties. Additionally, we have developed analytical models to aid in understanding observed properties, including coupled-dipole approximations of randomly-oriented cylinders and randomly-shaped particles.

APPROACH

Sea ice scattering properties were characterized by *in situ* field measurements and extensive laboratory measurements on ice samples from ice cores. We developed a bistatic, polarization-modulated nephelometer that analyzes the angle- and polarization-dependent light scattering in sea ice (Miller et al., 1996). The instrument rests directly on the surface of the sea ice. (It can also be used for studying scattering in snow, in sea water and for probing the atmosphere.) A 532 nm laser is directed into the ice and the scattered light is detected by a pointable detector. Both laser and detector angles can be varied. AC polarimetry is used to obtain phase function and polarization information of the scattered light. This instrument was used to measure the angle- and polarization-dependent scattering in sea ice at Pt. Barrow, Alaska, in May 1994 (Miller et al., 1994).

To provide a complete characterization of the polarized light scattering from sea ice, laboratory measurements of samples prepared from cores collected in Arctic seas and artificial ice ponds.

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Measurements were performed with the LBNL polarization-modulated angle-scanning monostatic nephelometer. All sixteen elements of the Mueller scattering matrix were measured on a number of different samples. The measurements were made to explore differences in ice types and the effects of orientation of the anisotropic sea ice samples on light scattering and propagation (Miller et al., 1997). We also compared our observations with the total intensity observed for NaCl ice reported by Grenfell and Hedrick (1983).

Analytical models were used and were developed to aid in understanding the observed scattering behavior. Mie scattering from distributions of spherical brine and air pockets were considered in conjunction with the inherent birefringence of the ice. Models that will permit incorporation of scattering from random distributions of cylinders have been developed. A code that permits the inclusion of randomly-shaped particles is in development.

WORK COMPLETED

Previously, *in-situ* measurements of the angular dependence of the Mueller scattering matrix were made at sites in the Beaufort and Chukchi Seas during the EMPOSI field measurement program. The results of these measurements corresponded to polarization information available from scattering from an unpolarized illumination source (sun) and were reported earlier (Miller et al., 1994).

Laboratory measurements were made at LBNL using a scanning polarization-modulated nephelometer adapted for use with a cold stage (Miller et al., 1997). Scattering from various ice-core samples was measured to determine all sixteen elements of the Mueller matrix, and to provide data over different and larger ranges of angles than was possible for the *in situ* measurements. Measurements were made of oriented first-year and multi-year ice taken from the Chukchi Sea near Pt. Barrow, Alaska (Perovich et al., 1994). Samples of artificially grown saline ice from U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and melted sea ice were also examined. Samples were prepared in a variety of ways from ice cores keeping careful track of vertical and **c**-axis orientation information. Thin slab, cylinder and square cross section samples were fabricated for a number of orientations with respect to the scattering geometry.

In order to better understand the observed results, we are developing analytical programs capable of predicting scattering from arbitrarily-oriented cylinders. In addition, we have developed an analytical code that generates random particles and calculates the scattering from them in a variety of orientations. These programs, in conjunction with programs that predict Mie scattering from distributions of combinations of spheres and coated spheres, provide a means of better understanding the scattering observed in sea ice.

RESULTS

Polarization signatures may provide information as to the orientation of sea ice. The polarization signature may only be observed in the presence of newly-formed ice and melt ponds, and the effect is weak. One reason for this is the presence of multiple scattering which is pronounced in sea ice. Therefore meaningful phase functions could only be determined with thin, laboratory-prepared samples. The scattering intensity of thin slab samples of saline ice, oriented first-year ice, and multi-year ice all show very large forward- and back-scattering components. The scattering properties can be qualitatively described by scattering from pockets of brine in a medium of pure water ice. Because of multiple scattering, phase functions for cylindrical samples are generally featureless. Differences between scattering from various cylindrical samples occur because the degree of multiple scattering changes with sample thickness.

Orientation-dependent polarization effects are weakly manifested in thin slab **c**-axis oriented samples, and are evident primarily in the matrix elements S_{23} and S_{32}. This is consistent with a simple model we developed that combines the effects of scattering from spherical inhomogeneities and the intrinsic birefringence of pure water ice (Miller et al., 1997). No orientation effects were observed for the cylindrical ice samples.

Interpretation of the angle-dependent scattering intensity from the laboratory samples is complicated by an number of factors. Initially modeling efforts used a simple model combining the effects of scattering from spherical inhomogeneities and the birefringence of pure water ice. To further understand scattering observed in the ice it has been necessary to develop models which permit incorporation of scattering from obliquely-illuminated cylinders and randomly-shaped particles.

A new set of polarizance functions was developed based on earlier work of Fry and Kattawar (1981) and Kostinski et al. (1993) with Mueller matrix inequalities (Miller et al., 1997). These functions were used to determine the degree of polarization for the scattered light from the Mueller matrices. The functions provide a means for understanding the physical meaning of observed scattering than can be easily deduced from the raw data or the matrix elements. An examination of the inequalities involving these functions for the thin slab data indicated that thin slab samples tend to preserve the degree of polarization for linearly-polarized light in the forward- and back-scattering directions. Elliptical and circular polarization is not as well preserved.

IMPACTS/APPLICATIONS

The major application of this work is to interpretation of remotely-sensed data and to determine the importance of polarization on radiative transfer processes in sea ice. Direct sunlight entering sea ice at angles close to the horizon, which occurs in the Arctic, will have a partial degree of linear polarization due to refraction at high angles at the ice/air interface. By using polarization techniques, remote sensing of newly-formed sea ice may detect orientation or alignment in the ice in the absence of snow pack. Polarization effects on radiant transfer in sea ice are weak due to the presence of multiple scattering and probably can be neglected to first order.

TRANSITIONS

We now have complete Mueller matrices for a variety of sample shapes and ice orientations available to evaluate the importance of polarization on radiant transfer calculations. Our analytical models are able to predict scattering from combinations of obliquely-illuminated cylinders as well as randomly-shaped particles.

RELATED PROJECTS

Our modeling effort has been in close association with the research being conducted on scattering from cylindrical objects conducted for the Office of Naval Research by Dr. Patricia Hull at Tennessee State University. Data will be made available to other ocean and sea ice modelers.

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