Radiative Transfer in Atmosphere-Sea Ice-Ocean System

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Introduction

Radiative energy is critical in controlling the heat and mass balance of sea ice, which significantly affects the polar climate. In the polar oceans, light transmission through the atmosphere and sea ice is essential to the growth of plankton and algae and, consequently, to the microbial community both in the ice and in the ocean. Therefore, the study of radiative transfer in the polar atmosphere, sea ice, and ocean system is of particular importance. Lacking a properly coupled radiative transfer model for the atmosphere-sea ice-ocean system, a consistent study of the radiative transfer in the polar atmosphere, snow, sea ice, and ocean system has not been undertaken before. The radiative transfer processes in the atmosphere and in the ice and ocean have been treated separately. Because the radiation processess in the atmosphere, sea ice, and ocean depend on each other, this separate treatment is inconsistent. To study the radiative interaction between the atmosphere, clouds, snow, sea ice, and ocean, a radiative transfer model with consistent treatment of radiation in the coupled system is needed and is under development.

Model Description

The radiative transfer equation for the coupled system has been solved by the discrete ordinate method (Jin and Stamnes 1994). This solution automatically takes into account the refractive index change at the air-ice or air-ocean interface. Therefore, the model considers the ice and ocean just as additional "atmospheric" layers; and the number of streams applied in the atmosphere, sea ice, and ocean is flexible and can be chosen to satisfy the competing requirements of computational time and accuracy. A detailed description of the radiative transfer model for the coupled atmosphere-sea ice-ocean system has been presented by Jin et al. (1994). Here we only give a brief description.

The physical processes considered in the model include

- absorption and scattering by atmospheric molecules, clouds, and aerosols
- absorption and scattering by snow
- absorption by pure ice, and absorption and scattering by inclusions in sea ice, such as brine pockets and air bubbles
- absorption and scattering by sea water and by hydrosols in the ocean.

The optical properties of each stratum are treated as follows:

- Optical properties (extinction coefficient, single scattering albedo, and scattering asymmetry factor) of clouds are parameterized in terms of the equivalent radius (ER) and the liquid water content (LWC) of the clouds (Slingo 1989; Tsay et al. 1989).
- Optical properties of snow are based on Mie calculations (Wiscombe and Warren 1980).
- The absorption coefficient for pure ice is from a compilation by Grenfell and Perovich (1981). The optical properties of brine pockets, air bubbles, and solid salts are based on Mie calculations. The volume fractions of these inclusions required in the Mie computations are based on the formulation developed by Cox and Weeks (1983). This formulation, which is based on the phase equilibrium constraints, relates the volume fraction of brine pockets, air bubbles, and solid salts to ice temperature, density, and salinity.
- Optical properties of sea water are from Smith and Baker (1981).

Input parameters for the model include

- incident spectral radiation at the top of atmosphere
- profiles of temperature, pressure, and gas concentrations in the atmosphere
- ER and LWC of clouds, cloud height, and thickness
- surface temperature and snow conditions
- profiles of temperature, salinity, and density in the ice; or profiles of volume fractions of gas and brine inclusions in the ice
- vertical distribution of hydrosols in ocean.

These input parameters are used to compute the optical properties in each layer of the atmosphere, snow, sea ice, and ocean, which are subsequently used to compute the radiative quantities.

Examples of Model Application

Figure 1 shows the solar energy partitioning in the atmosphere, sea ice, and ocean (including open ocean and ocean under the ice) as a function of the area fraction of open water, such as leads and polynya within the ice field. The solar energy is integrated over the spectral region of 0.25 µm to 4.0 µm. Here the vertical distance covered by the three different shades gives the fraction of absorption by the atmosphere, sea ice, or ocean. In the model computation, the input parameters for the atmosphere are from the McClatchey et al. (1972) model atmosphere for the subarctic summer. The ice is assumed to have a thickness of 2.0 m, salinity of 5%, and surface temperature of −10°C linearly increasing to −2°C at the ice base. The vertical variation in the properties of seawater is neglected so that the ocean is considered as a single homogeneous layer. As expected, as the fraction of the open ocean increases, the absorption in the ocean rapidly increases and absorption in the ice rapidly decreases, whereas the absorption in the atmosphere is not sensitive to the variation of the open ocean fraction.

Figure 2 shows a comparison of the observed spectral albedo for melting multiyear ice with model calculation. The observational data are from Grenfell and Maykut (1977). Parameterized profiles of salinity and air volume developed by W. F. Weeks[a] are used in the model computation.

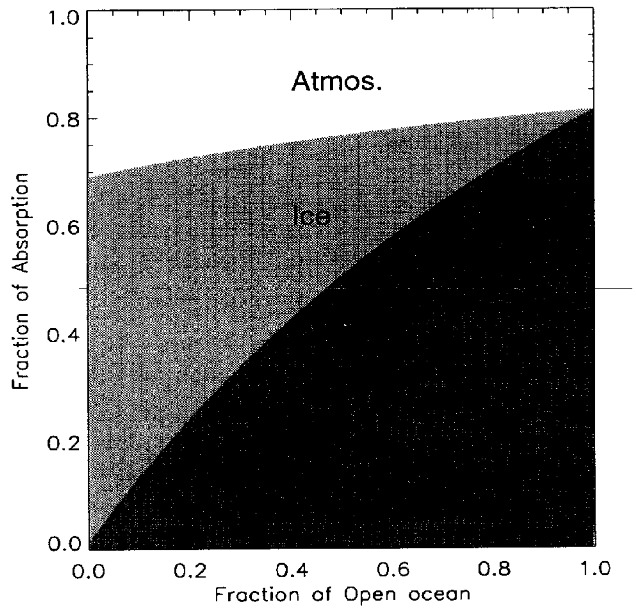

Figure 1. Distribution of the absorbed solar energy in the atmosphere, sea ice, and ocean as a function of open ocean fraction.

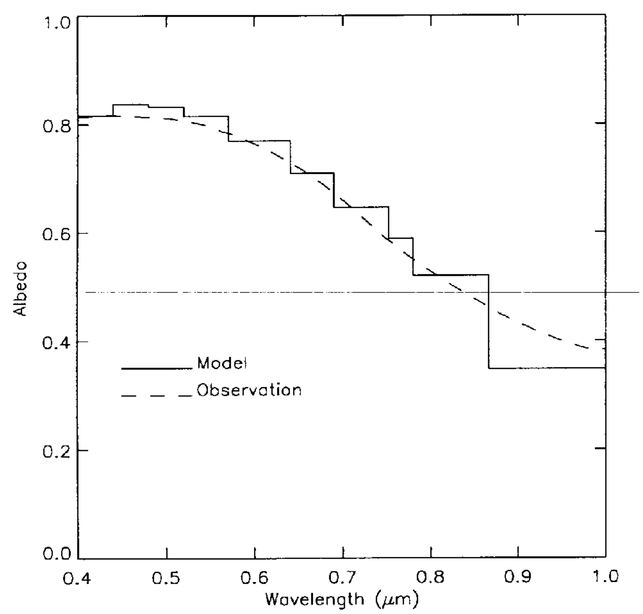

Figure 2. A comparison of the observed spectral albedo for melting multiyear white ice with model calculations.

(a) Personnel communication, 1994.

Figure 3 presents simulated results for a set of irradiance field measurements taken in an Antarctic ice floe (Quakenbush 1994), which had a thickness of 1.24 m. The irradiance measurements in the ice were taken at depths of 20, 40, 60, 80, 100, and 120 cm. The irradiances at different depths of the ice have been normalized by the irradiance at the depth of 20 cm. We use these normalized values for comparison with modeling because 1) the measured irradiance data have not been calibrated in absolute units, so they only represent relative magnitudes; and 2) the angular distribution of the incident light on the ice surface has little effect on these normalized values. The salinity and temperature profiles used in the model for input are based on *in situ* measurements. The absorption peaks at 670 and 430 nm in the measured spectral irradiances indicate that algae exists in the ice. Unfortunately, measurements of the algae concentration were not made. We have therefore assumed a chlorophyll concentration of 10 mg/m^3 in the upper 80 cm of the ice and of 40 mg/m^3 in the bottom 40 cm of the ice. Results showed that if the algae is ignored, good agreement could be achieved only at wavelengths larger than 700 nm, where algae absorption is small. To obtain better agreement, algae absorption has to be taken into account.

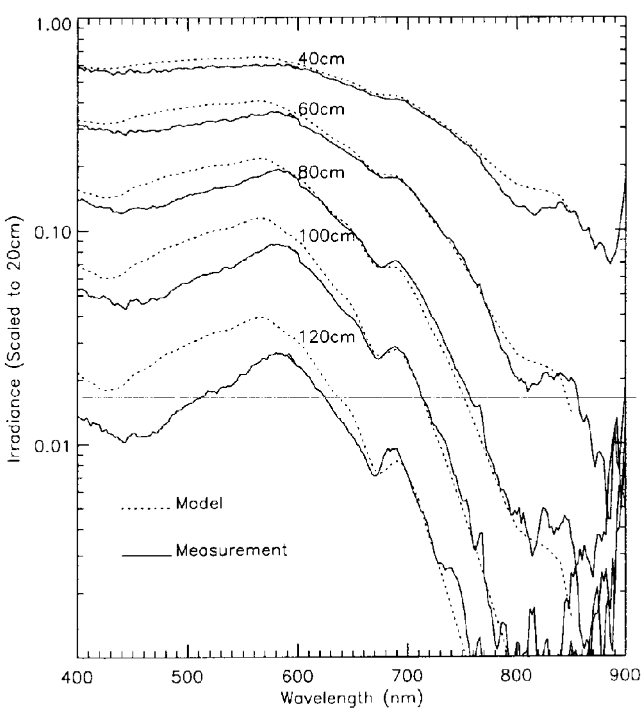

Figure 3. Comparison of the measured spectral irradiances at various depths (normalized to values at a depth of 20 cm) with model calculations.

Some Results and Implications from Modeling

We have used the present model to perform a number of sensitivity tests aimed at establishing the relative importance of each parameter. The modeling results show that the sea ice, clouds, and snow all have a significant impact on the absorption and partitioning of the solar radiative energy in the entire system and on the light transmission into the ice and ocean. Some important findings from the modeling include the following:

- Most of the radiative energy absorbed by sea ice occurs in a very thin top layer of the ice. Under clear sky conditions, only 10 cm of the top layer of ice can absorb more than 50% of the total solar radiation deposited in the entire system.

- In sea ice, it is the scattering by inclusions, especially the air bubbles, in a few centimeters of the uppermost layer that plays a vital role to the solar energy absorption and partitioning in the whole system. Enhanced scattering in this top layer will not only increase backscattering to the atmosphere, but it also increases the fraction absorbed in this top ice layer itself and decreases the radiation penetrating to the deeper layers of the ice and into the ocean.

- Because air bubbles scatter light much more efficiently than brine pockets, the radiative absorption is more sensitive to air volume variations than to brine volume variations.

- Increasing the ice thickness would result in not only an increase of solar absorption in the ice and a corresponding decrease in the ocean, but also a decrease of the absorption in the entire system. On the other hand, the absorption in the atmosphere is not sensitive to the ice thickness. However, the total absorption in the entire system remains almost constant once the ice thickness exceeds about 70 cm.

- Both clouds and snow reduce the solar energy absorption in the ice and in the ocean, as well as in the entire atmosphere-sea ice-ocean system.

- The absorption of solar radiation in sea ice shows a greater sensitivity to the cloud microphysics than the absorption in the atmosphere and in the ocean. The absorption in the entire system will increase as the equivalent radius of cloud droplets increases and will decrease as the liquid water content increases.

- Different from the case in atmosphere, the absorption in sea ice and the ocean is not sensitive to cloud height.
- Clouds not only change the energy disposition in the system, they also reduce the sensitivity of the energy disposition in each layer to the ice and snow thickness change. However, they increase the sensitivity of the surface albedo to the ice or snow thickness variation.
- Surface albedo is determined by approximately 10 cm of the uppermost layer of snow for a snow covered surface and by about 50 cm of the uppermost layer of ice for a bare ice surface.
- Generally, increasing cloud thickness will increase the surface albedo, unless the solar elevation is low and the cloud is thin. Of all the possible cases, the combination of new snow and thick clouds yields the highest surface albedo.
- The occurrence of ice algae has significant effects on the light transport in sea ice and ocean and on the spectral distribution of light transmitted through the ice.

The coupling that we have considered here is purely radiative and does not allow the radiation to alter the snow/ice/cloud properties resulting in changes which could then affect subsequent radiative transfer. To investigate interactions and feedbacks in the polar environment, the present radiative transfer model should be coupled to models treating the evolution of ice, snow, and clouds. To accomplish this goal the computational efficiency of the present model has to be improved, so that it can be coupled to models which require integration over a long time scale.

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