Solar Heating in the Upper Ocean

K. Stamnes and Z. Jin
Geophysical Institute
University of Alaska
Fairbanks, Alaska

A discrete ordinate method has been developed to solve the radiative transfer problem in nonuniformly refracting layered media such as the atmosphere-ocean system (Jin and Stamnes 1994). Figure 1 schematically illustrates the radiative transfer model for the atmosphere-ocean system; the essential points are

- In the ocean, region I is the total reflection region and region II is the refraction region.
- The downward radiation distributed over 2π steradians in the atmosphere is restricted to a cone (less than 2π steradians) upon refraction across the interface into the ocean.
- Photons in region II of the ocean may be scattered into region I. Note, however, that photons in region I of the ocean cannot reach the atmosphere directly and vice versa. The atmosphere and region I "communicate" through the scattering process between region I and region II in the ocean.

Appropriate quadrature points (streams) and weights have been chosen for the interface continuity relations. To take into account the region of total reflection in the ocean, separate angular quadrature points are adopted in addition to those used in the atmosphere and the refractive region of the sea ice and ocean. This quadrature specification automatically accounts for the refraction and reflection at the air-sea interface and solves the radiative transfer equation in the coupled system consistently. The total number of quadrature points (streams) chosen for each stratum is based on the optical properties and the accuracy required.

This coupled model has been validated through a comparison with Monte Carlo models applied to a number of canonical problems in the coupled atmosphere-ocean system (Mobley et al. 1993).

Both the atmosphere and ocean can be divided into a sufficient number of layers to adequately resolve the optical properties in each stratum. In the atmosphere, the absorption and scattering by atmospheric gases, clouds

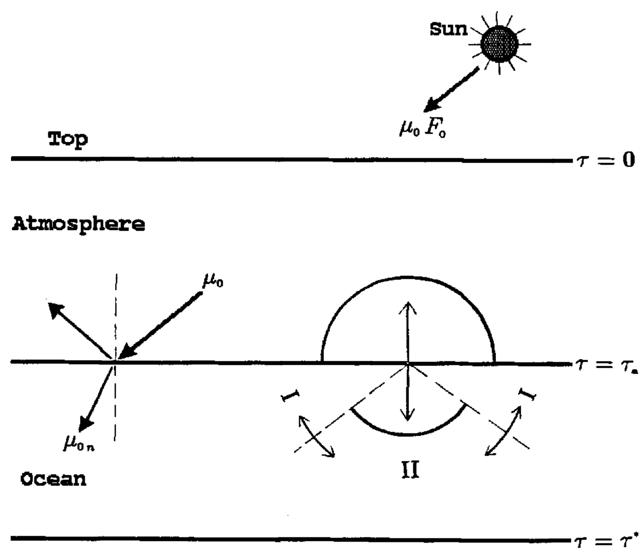

Figure 1. Schematic diagram of the coupled radiative transfer model for the atmosphere-ocean system.

and aerosols are included in the 24 spectral bands from 0.25µm to 4.0µm. The gaseous absorption by water vapor, ozone, oxygen and carbon dioxide is incorporated using the exponential sum fitting of transmission (ESFT) technique (Wiscombe and Evans 1977). The profiles of air density and absorptive gases are taken from the atmosphere models reported by McClatchey et al. (1972). The optical properties of clouds are parameterized in terms of liquid water content and equivalent radius (Tsay et al. 1989), which has been proved to produce satisfactory results.

In the ocean, we consider the absorption and scattering by sea water and hydrosols (phytoplankton and their derivatives). The absorption coefficient of sea water is shown in Figure 2. The spectral scattering and absorption coefficients of phytoplanktonic pigment are nonlinearly related to the chlorophyll concentration and wavelength (Morel and Gentili 1991).

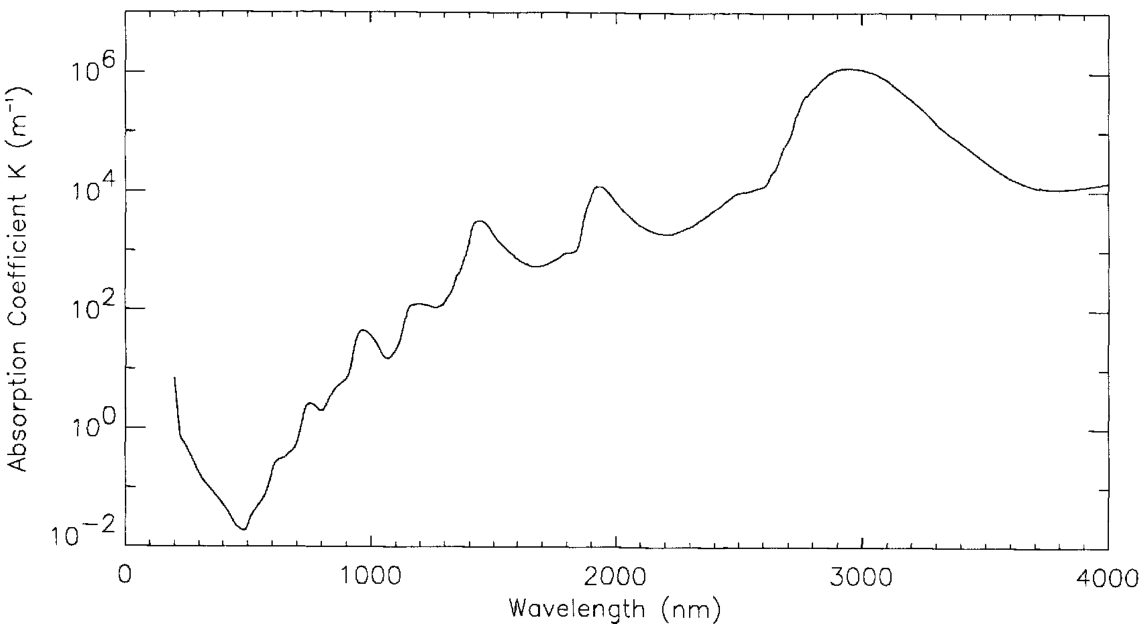

Figure 2. The absorption coefficient of sea water.

Figure 3 shows the radiative heating rates in the upper ocean at four different latitudes under a clear sky and a cloudy sky, respectively. Note that the heating rate is an instantaneous value at the mid-day of the summer solstice. Obviously, the presence of clouds decreases the radiative absorption in the ocean. Figure 4 is similar to Figure 3, but for this case, a turbid ocean with chlorophyll concentration of 1.0 mg/m^3 is considered. Comparing Figure 4 with Figure 3 shows that the turbid ocean will increase the solar heating rate in approximately the upper 20 m of ocean, but decrease the heating rate below that depth.

Figures 5 and 6 are similar to Figures 3 and Figure 4, respectively, but on the mid-day of the winter solstice. In addition to the similar effects by the clouds and hydrosols discussed above, the heating rate is more dependent on the latitude.

References

Jin, Z., and K. Stamnes. 1994. Radiative transfer in nonuniformly refracting layered media: Atmosphere-ocean system. *Appl. Opt.* **33**:431-442.

McClatchey, R. A., R. W. Fenn, J.E.A. Selby, F. E. Volz, and J. S. Garing. 1972. AFCRL report *AFCRL-72-0497*, Air Force Cambridge Research Laboratories, Bedford, Massachusetts.

Mobley, C., B. Gentili, H. Gordon, Z. Jin, G. Kattawar, A. Morel, P. Reinersman, K. Stamnes, and R. Stavn. 1993. Comparison of numerical models for computing underwater light fields. *Appl. Opt.* **32**:7484-7504.

Morel, A., and B. Gentili. 1991. Diffuse reflectance of oceanic water: Its dependence on sun angle as influenced by the molecular scattering contribution. *Appl. Opt.* **30**:4427-4438.

Tsay, S. C., K. Stamnes, and K. Jayaweera. 1989. Radiative energy budget in the cloudy and hazy Arctic. *J. Atmos. Sci.* **46**:1002-1018.

Wiscombe, W. J., and J. W. Evans. 1977. Exponential-sum fitting of radiative transmission functions. *J. Chem. Phys.* **24**:416-444.

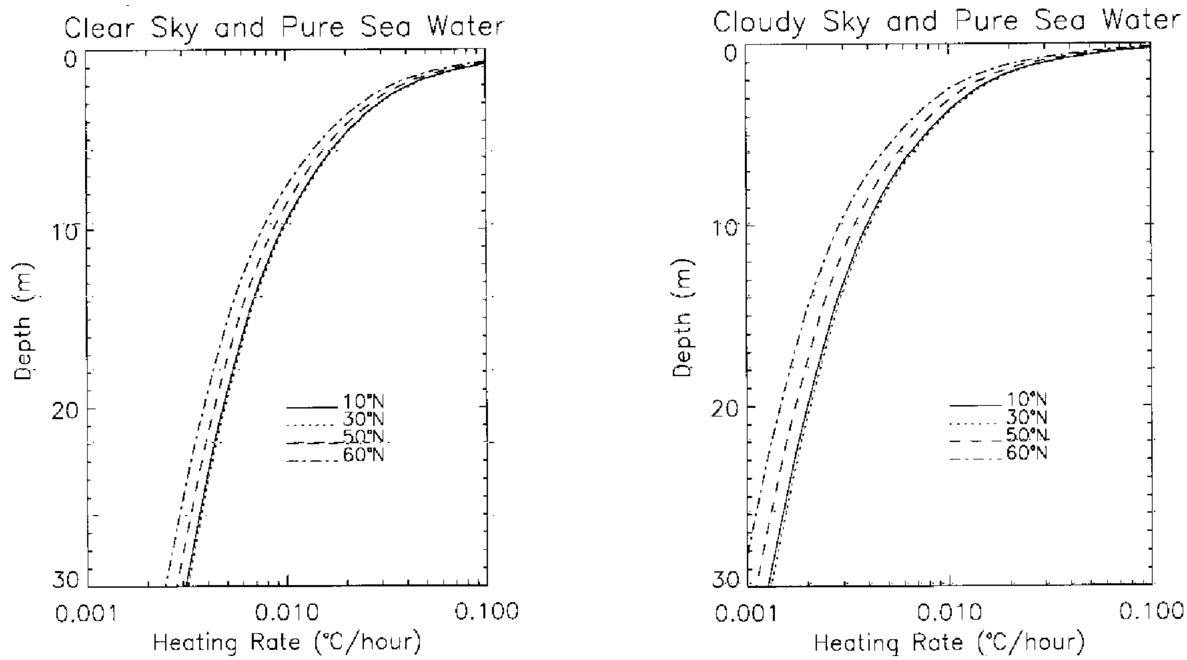

Figure 3. The solar heating rate in the upper ocean at the mid-day of the summer solstice.

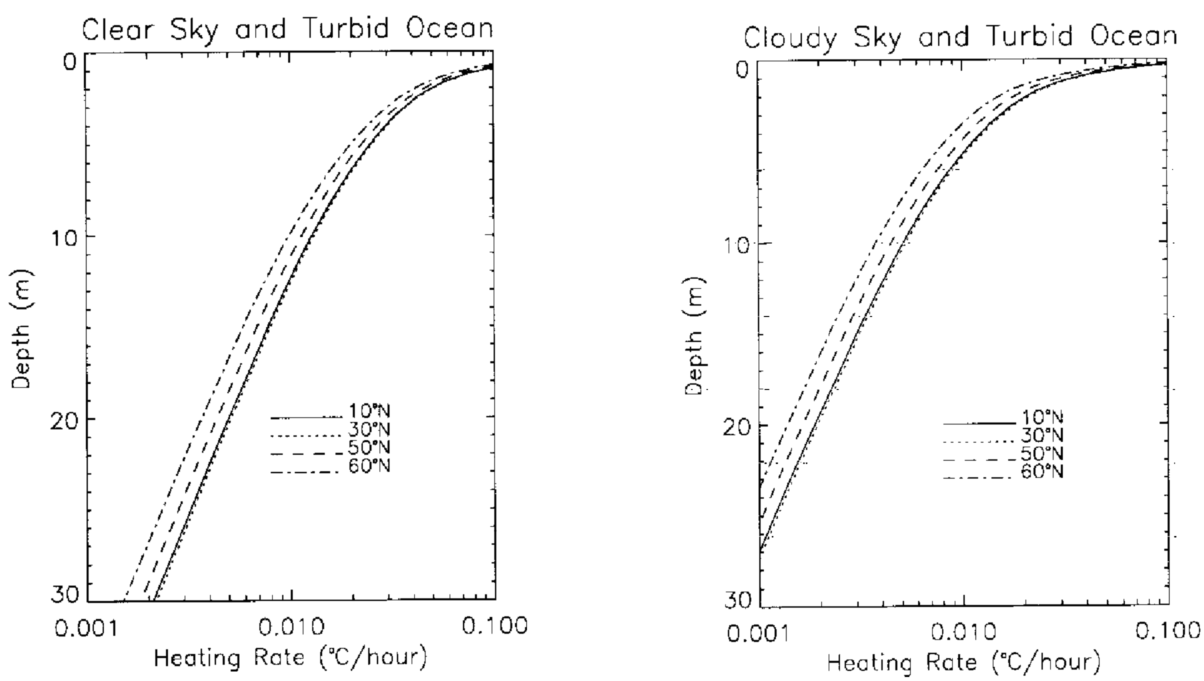

Figure 4. As Figure 3, but for turbid ocean.

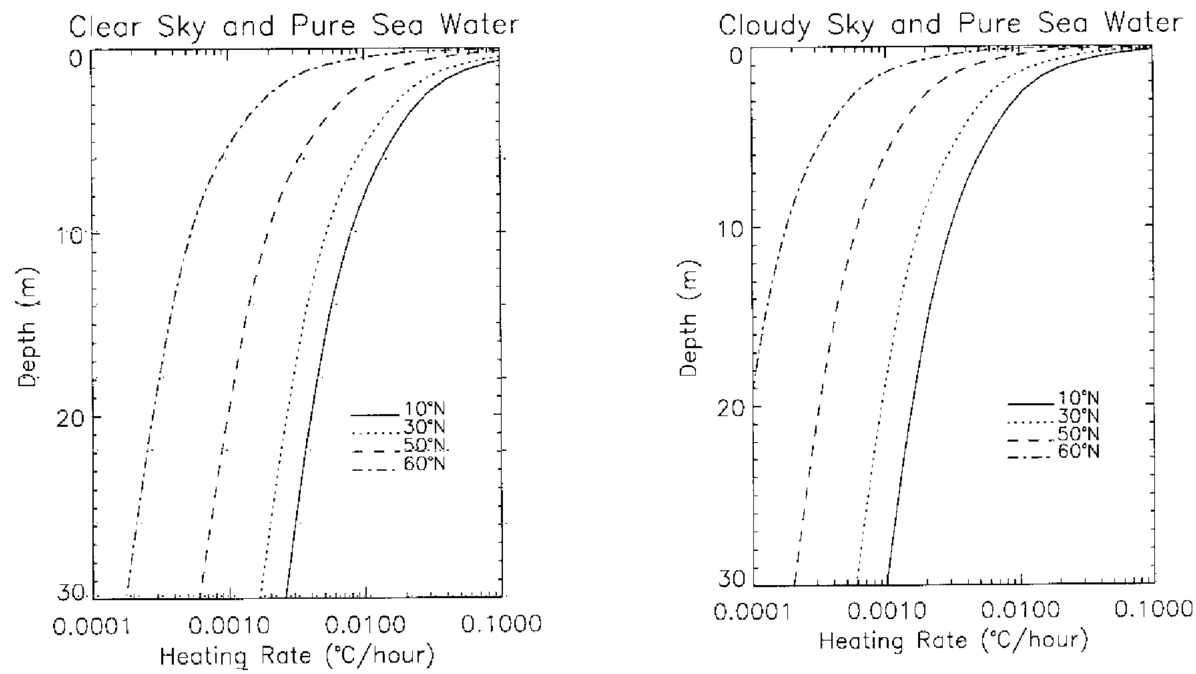

Figure 5. The solar heating rate in the upper ocean at the mid-day of the winter solstice.

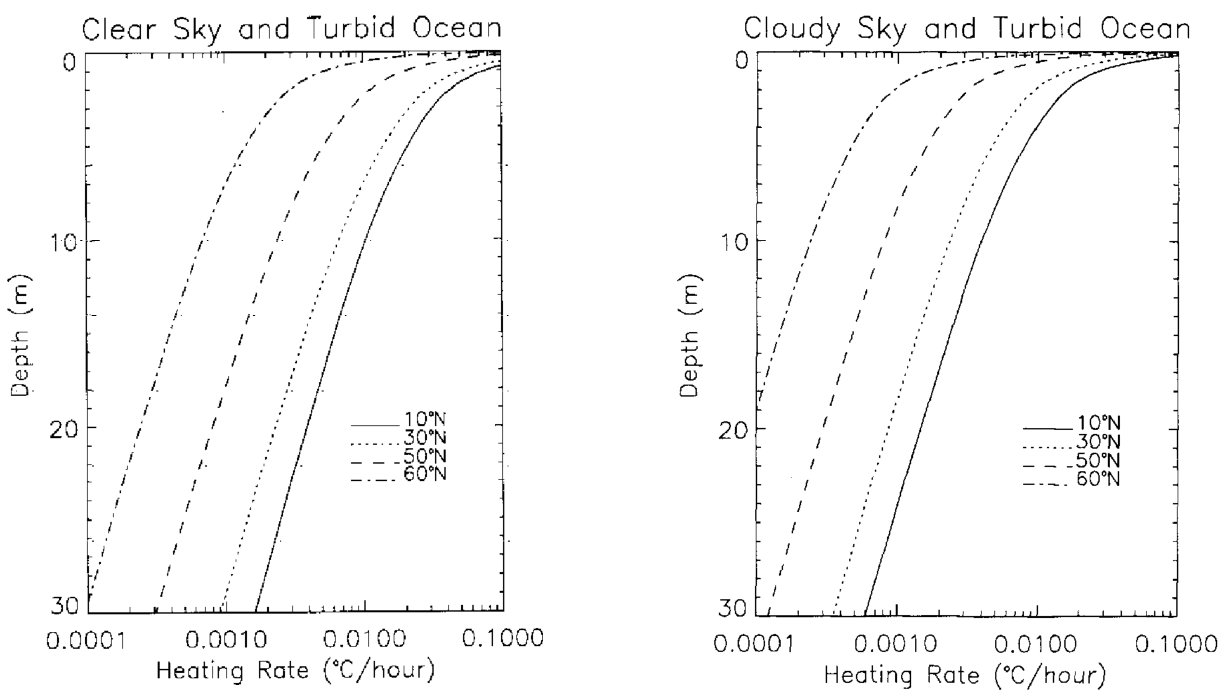

Figure 6. As in Figure 5, but for turbid ocean.