P1.3 OBSERVATIONS OF THE OPTICAL PROPERTIES OF THE UPPER OCEAN DURING SHEBA

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1. INTRODUCTION

The depth-dependent absorption of solar radiation into the ocean depends on the optical properties of the water. The shortwave radiative flux can be measured directly, but it is very difficult to interpret when measured in a spatially heterogeneous region, such as a lead or in broken ice cover. By measuring the inherent optical properties (IOP) including absorption and beam attenuation the deposition of light energy in the water column can be modeled. During the Surface Heat Budget of the Arctic experiment (SHEBA) (Perovich et al., 1999) we collected measurements of IOPs including the beam attenuation and absorption coefficients in the upper 60 m of the water column.

Very few measurements of either IOP or radiometric parameters have been collected in the Arctic Ocean. Smith (1973) made measurements in the spring and found that the diffuse attenuation at 490 nm was similar to that of the clearest natural water. It was recognized that the spring conditions were not likely to be representative of conditions later in the year when biological production becomes important. However, the lack of measurements have required studies of the heat budget of the upper ocean in the Arctic to assume constant optical properties typically those of the clearest natural waters (e.g. Grenfell, 1979; Maykut and Perovich, 1987). In this paper we examine the optical properties measured during SHEBA and how to parameterize the attenuation of light for two optical types observed.

2. METHODS

The beam attenuation and absorption coefficient at 9 wavelengths was measured using a WETLabs ac-9 (Moore, 1994). The measurements were collected between June 17 and August 4, 1998 (Days 168 to 216) in a lead approximately 1 km from the main camp. The ac-9 was combined with a SeaBird CTD on a cage and lowered from a small boat. Several casts were collected each day, primarily in the upper 15 m, but with occasional casts to 60 m. Measurements of the dissolved component optical properties were achieved by attaching a 0.2 µm pore-size filter on the intake of the ac-9 flowtubes. The optical properties of the particulate material were determined by subtracting the optical properties of water and the dissolved components from the total absorption and beam attenuation.

The ac-9 was calibrated using deionized water and all readings are relative to the absorption by the standard (assumed to be pure water) at each wavelength. During processing the scattering, temperature, and salinity corrections were made and the pure water absorption and attenuation values were added to determine the total absorption and attenuation coefficients in accordance with the manufacturers protocols.

The optical properties measured during SHEBA were used as inputs to a commercially available radiative transfer code (HYDROLIGHT 4.1). To increase spectral resolution of the IOP we fitted standard absorption and scattering spectra for phytoplankton and colored dissolved organic material (CDOM) to the ac-9 measurements. HYDROLIGHT was then run to calculate the irradiance flux every 10 nm between 350 and 800 nm. A 2 ms^{-1} wind speed was assumed in order to determine the optical characteristics of the air-sea interface. The solar elevation was set at the value appropriate for 78 N 166 W on day 182 at 01 GMT (~60°), and the sky was assumed to be clear. The ocean was assumed to be optically homogeneous and model results were determined every 0.1 m in the upper 4 m and every 1 m to 40 m and at 5 m interval at greater depths. The logarithm of the net downwelling irradiance was used to calculate a diffuse attenuation coefficient as a function of depth. Three optical cases were considered, a turbid case with optical properties associated with a near surface phytoplankton bloom, a CDOM case where particles were not present, and the clearest natural waters (Smith and Baker, 1981).

3. RESULTS

A phytoplankton patch between 0 and 20 m caused high absorption and beam attenuation in the surface waters at the beginning of the experiment (Figure 1). The absorption by dissolved materials was relatively high throughout the sampling period (Figure 2). The only clear water observed was the meltwater that formed in the top meter of the lead. The most turbid water was observed in a subsurface phytoplankton maximum. This patch was only observed for a few days and its spatial extent may have been quite limited.

Values of the measured IOPs under different conditions are provided in Table 1. The optical properties of the "CDOM" water were taken as the average values between 2 and 60 m observed between day 190 and day 200. These values are not significantly different

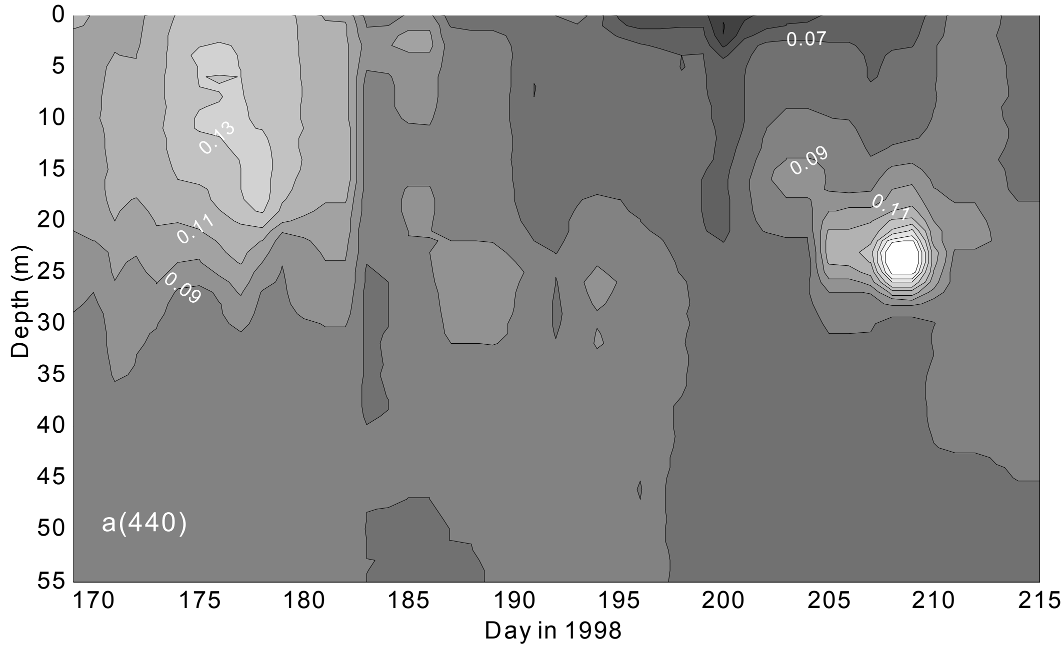

Figure 1. The absorption coefficient at 440 nm.

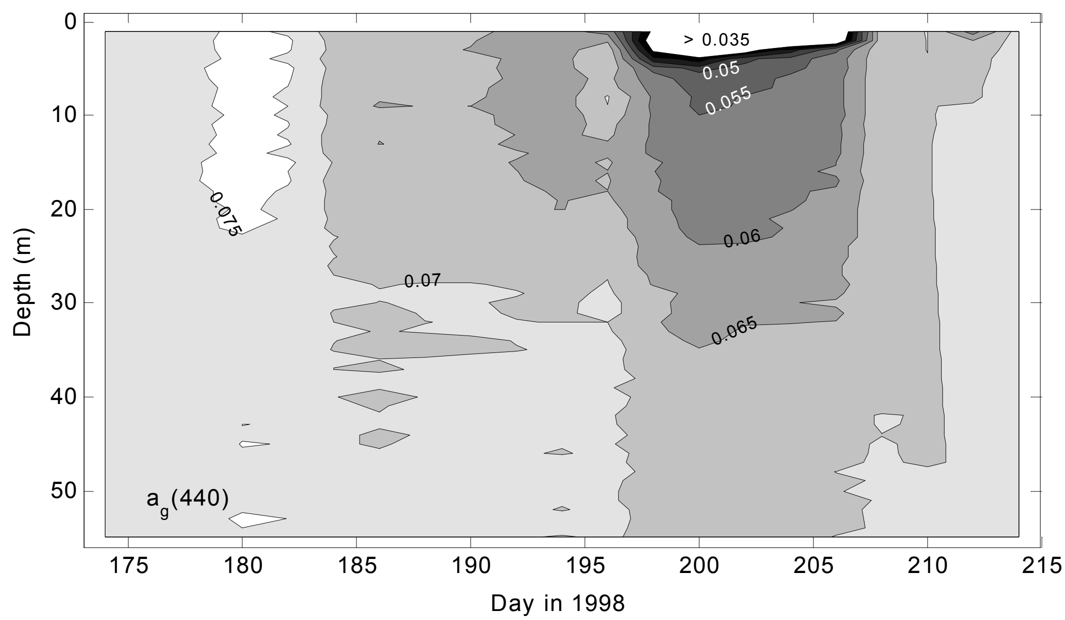

Figure 2. The absorption coefficient of CDOM at 440 nm.

from the optical properties of water between 30 m and 60 m depth throughout the observation period. The optical properties are probably similar to the particle free water throughout the year when phytoplankton blooms are not present. While clear of particles, the CDOM content is high enough to cause this water to be significantly different than the clearest natural waters as reported by Smith and Baker (1981). Particulate material did add significantly to the absorption and attenuation during the summer period. A set of optical properties associated with the first phytoplankton bloom is used as the "turbid" water case. The turbid water properties are the average values before day 185, in the top 25 m.

Table 1. Optical properties of two water types observed "cdom" and "turbid". The optical properties of the cdom water were taken as the depth averaged values of measurements between day 190 and day 200. The turbid water properties are the average values before day 185, in the top 25 m (within the first phytoplankton bloom). Wavelength is in nanometers, a and c values are given in m^{-1}.

wavelength	CDOM a	CDOM c	turbid a	turbid c
412	0.121	0.159	0.155	0.320
440	0.085	0.125	0.117	0.278
488	0.052	0.091	0.079	0.237
510	0.059	0.095	0.078	0.236
532	0.063	0.102	0.078	0.233
555	0.076	0.113	0.084	0.236
650	0.342	0.375	0.349	0.480
676	0.458	0.489	0.472	0.595

Based radiative transfer modeling we find that the amount of energy deposited near the ocean surface increases as the absorption increases (Figure 3). The turbid case deposited 16 Wm^{-2} more radiation in the top meter in the 350 to 800 nm band than in the clear case. For the case with just CDOM 9 Wm^{-2} more energy was deposited in the top meter compared to the clear water case.

The attenuation of radiation in the wavelength range of 350 to 800 nm was modeled using a sum of three exponentials. The exponential decays constants increased as the absorption increased (Table 2). The fit is in the form

$$\Phi(z) = \Phi_0 P_1 \exp^{C1z} + \Phi_0 P_2 \exp^{C2z} + \Phi_0 P_3 \exp^{C3z}.$$

Φ is the flux between 350 and 800 nm, Φ_0 is the flux at the surface, P_x is a proportionality constant, and Cx is the decay constant. A small portion of the flux is absorbed in the top 0.3 m and not accounted for in the exponential fit.

Table 2. *The exponential decay constants for the three water types examined.*

type	P1	P2	P3	C1	C2	C2
Clear	0.42	0.26	0.27	-0.032	-0.196	-1.077
CDOM	0.23	0.42	0.33	-0.075	-0.159	-1.106
Turbid	0.26	0.45	0.26	-0.121	-0.254	-1.363

4. DISCUSSION AND SUMMARY

Even when particles were not abundant the absorption by CDOM makes the optical properties observed during SHEBA significantly different than those of the clearest natural waters. The high levels of CDOM are not surprising given the large riverine input and the low photo-oxidation rates. Even higher levels of CDOM absorption is expected in the near the input of the major rivers. Another important source of absorbing materials is phytoplankton. An early summer bloom increased absorption near the surface by approximately 50%. The presence of CDOM and particles increases the deposition of solar energy near the surface where it is more likely to be able to melt ice. The intense subsurface bloom observed later in the summer had less effect on the heating because of its depth.

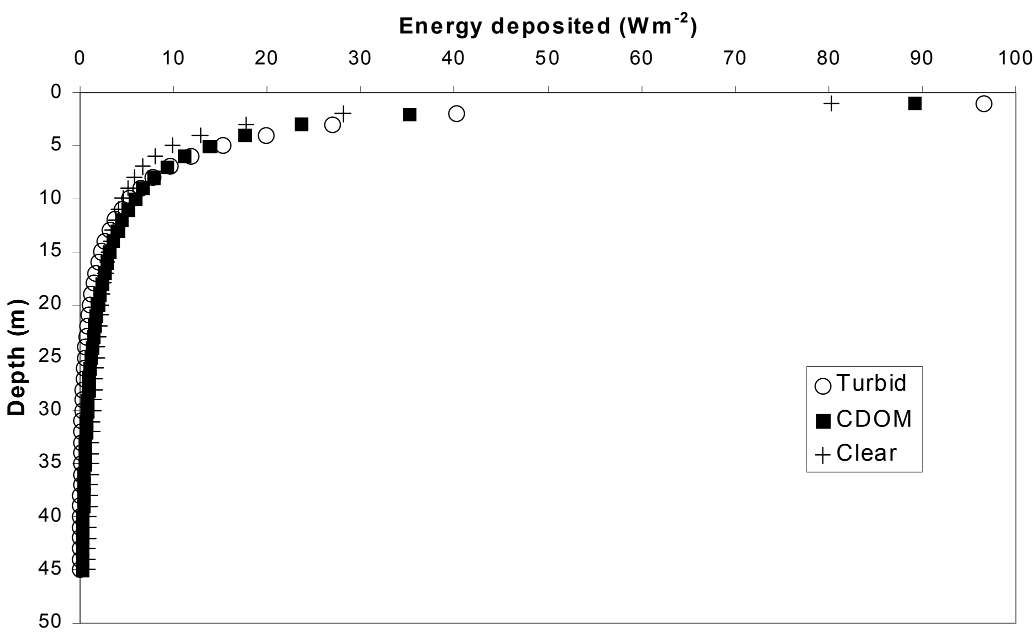

Figure 3. The energy between 350 and 800 nm deposited in each meter of the water column for 3 optical water types. The surface radiation was 270 Wm^{-2} for this example.

The attenuation of solar radiation is dependent on the shape of the light field just below the sea surface. This is a function of solar zenith angle, clouds, waves, and ice, which can cause about a 10% variation in the light attenuation coefficients. More important are the variations in attenuation are caused by changes in the absorption coefficient so the attenuation coefficients provided here are applicable across a range of lighting conditions.

While levels of absorption and attenuation by particles can be low in the Arctic, the relatively high levels of absorption by CDOM prevent these waters from being representative of the clearest natural waters. The level of CDOM may vary across the Arctic in relation to the sources of riverine input. During the summer, surface phytoplankton blooms also cause more solar radiation to be deposited near the ice bottom. The heat budget of the upper ocean will be underestimated if the optical properties of the clearest natural waters are assumed instead of realistic optical properties. This can lead to an underestimation of the shortwave energy absorbed in the top 10 m and hence melting rates of the ice.

5. ACKNOWLEDGEMENTS

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REFERENCES

Grenfell, T. C., The effects of ice thickness on the exchange of solar radiation over the Polar Oceans, *J. Glaciol., 22,* 305-320, 1979.

Maykut, G. A., and D. K. Perovich, The role of shortwave radiation in the summer decay of a sea ice cover, *J. Geophys. Res., 92*, 7,032-7,044, 1987.

Moore, C., *In situ*, biochemical, oceanic, optical meters, *Sea Technol.*, *35*, 10-16, 1994.

Perovich, D. K., E. L. Andreas, J. A. Curry, H. Eiken, C. W. Fairall, T. C. Grenfell, P. S. Guest, J. Intrieri, D. Kadko, R. W. Lindsay, M. G. McPhee, J. Morison, R. E. Moritz, C. A. Paulson, W. S. Pegau, P.O.G. Persson, R. Pinkel, J. A. Richter-Menge, T. Stanton, H. Stern, M. Sturm, W. B. Tucker III, and T. Uttal, Year on the ice gives climate insights, *EOS, Transactions, American Geophysical Union*, *80*, 481-486, 1999.

Smith, R. C., Optical properties of the Arctic upper water, *Arctic, 26,* 303-313, 1973.

Smith, R. C., and K. S. Baker, Optical properties of the clearest natural waters (200-800 nm), *Appl. Opt., 20,* 177-184, 1981.