

## BIO-OPTICAL OBSERVATIONS OF FIRST-YEAR ARCTIC SEA ICE

D. K. Perovich<sup>1</sup>, G. F. Cota<sup>2</sup>, G. A. Maykut<sup>3</sup> and T. C. Grenfell<sup>3</sup>

*Abstract.* The interrelationships among snow cover, ice structure, optical properties, and biological activity are of critical importance in understanding the response and behavior of sea ice systems. Of particular concern in this regard are the optical properties of the algae and the effect of snow thickness on biomass accumulation. In this paper we present the first direct *in situ* measurements of biomass specific diffuse attenuation spectra for arctic ice algae. The data show *in situ* attenuation values that are about 3 times larger than those obtained from corresponding *in vivo* absorption measurements, apparently reflecting differences in the geometrical distribution of the algae or the influence of skeletal ice and dissolved organic material. Observations also confirm that maximal algal accumulation occurs when there is a thin layer of snow covering the ice. A new technique to separate the effects of snow and algae in observed transmission spectra is presented. The ratio of transmittance between 600 nm and 450 nm is a sensitive indicator of biomass, while the 700 nm to 600 nm ratio is strongly affected by snow depth.

## Introduction

Solar radiation is normally the most important factor influencing biological activity in and beneath sea ice. A quantitative understanding of interrelationships among snow cover, ice structure, optical properties, and biological activity is of critical importance for predicting the response and behavior of sea ice systems. Ice thickness, snow depth, temperature and salinity profiles, air bubble distribution and surface conditions all impact the transmitted radiation field. Light levels under a sea ice cover can exhibit great spatial variability, changing by several orders of magnitude over distances of tens of meters (Smith et al., 1988; Perovich, 1990). Snow cover has a major impact on light transmission because spectral extinction coefficients for snow are more than an order of magnitude larger than those for ice, while snow albedos can be almost twice as large (Grenfell and Maykut, 1977). This means that snow depth will largely control the amount of light available for algal growth in the seasonal sea ice zone (Smith et al., 1988; Welch and Bergmann, 1989; Cota et al., 1991).

Efforts to characterize light transmission in sea ice systems have generally been based on measurements made in the

underlying water column, observations that combine the effects of absorption by the snow, ice and algae. Transmission spectra must be deconvolved to characterize the selective absorption of light by each component. Algal absorption has been ascertained indirectly by comparing observations from sites with different degrees of colonization, or from time series at the same site before and after colonization (Maykut and Grenfell, 1975; Palmisano et al., 1987; Smith et al., 1988). Spectral absorption coefficients for antarctic ice algae have been determined in the laboratory on glass fiber filters (SooHoo et al., 1987; Arrigo et al., 1991). Welch and Bergmann (1989) reported the first direct measurements of light absorption by natural ice algal populations; however, their data were integrated between 400 and 700 nm with no spectral information available. Their approach was to observe the light level beneath the ice when the algal layer was present, then to carry out a similar measurement after scraping off the lower 2 cm of the ice where most (ca. 95%) arctic ice algae are found in the spring. This method not only provides a direct measure of algal diffuse attenuation, but also includes the influence of ice, detritus and dissolved organics and avoids uncertainties due to changes in geometry when algae are collected on filters from melted ice cores. In this paper we present the first direct field measurements of spectral diffuse attenuation coefficients for ice algae and examine the influence of snow cover and algal biomass on transmitted irradiance.

## Field Experiment

Measurements were carried out during the spring of 1991 in Resolute Bay, Northwest Territories, Canada (74° 40' N, 94° 54' W), an area of relatively uniform first-year ice with a highly variable snow cover. Several previous studies at this location have also investigated relationships between light transmission, snow cover and biomass accumulation (Cota, 1985; Smith et al., 1988; Cota and Horne, 1989; Welch and Bergmann, 1989). These studies have revealed a seasonal cycle of biological activity where increasing short-wave radiation results in an initiation of algal growth in March or early April. Biomass increases as light levels rise, reaching a maximum in late April to mid-May, well in advance of the solar radiation maximum. Disappearance of the snow cover produces a large increase in light transmission, and energy absorption by the algae becomes sufficiently great that bottom melting occurs and much of the algae layer sloughs off within a few days (Cota and Horne, 1989).

The focus of the present experiment was on measuring the optical properties of the snow, ice and bottom ice algae. We studied four sites with similar ice thicknesses (1.4-1.5 m), but with different snow depths and algal biomass. Snow depths at the sites were 0, 5, 10 and 19 cm. This range of snow thickness was expected to result in light levels beneath the ice that would vary by nearly two orders of magnitude (Grenfell and Maykut, 1977; Perovich, 1990). Biological observations, ice and snow characterization, and optical measurements were

<sup>1</sup>US Army Cold Regions Research and Engineering Laboratory

<sup>2</sup>Graduate Program in Ecology, University of Tennessee

<sup>3</sup>Department of Atmospheric Sciences, University of Washington

made at each site. Chlorophyll a was measured fluorometrically in the bottom 3-4 cm of melted ice cores to determine algal biomass using sampling techniques consistent with Cota and Horne (1989). Thicknesses and physical properties of the ice and snow layers were obtained from snowpits and ice cores. Vertical profiles of temperature, salinity, brine volume and crystal structure were determined in several cores (Tucker et al., 1987). The vertical distribution of chlorophyll was also measured in cylindrical segments from one complete core and, as expected, the chlorophyll was found to be highly concentrated in the bottom 1-2 cm.

Spectral data on incident, reflected, and transmitted irradiance were collected at each site using a Spectron Engineering SE590 spectral radiometer that had an effective wavelength range of 400-1000 nm and a spectral resolution of 8 nm. These measurements were used to calculate spectral albedos and vertically averaged transmittances through the snow-ice-algae layer. *In situ* measurements of algal attenuation were made using a Focal Technologies OS 1 spectrometer, with a 3-m fiber optic probe that was placed above and below the bottom algal layer. The Focal instrument was fitted with a cosine collector and had an effective wavelength range of 385-720 nm and a spectral resolution of 20 nm. *In vivo* algal absorption spectra were also measured in the laboratory, without spectral weighting, using sub-samples of the melt water suspension collected on Whatman GF/F glass filters (Mitchell, 1990).

### Results

Even though snow depth differed between sites, the physical properties and composition of the snow were similar. The three snow sites had a 3-mm-thick surface layer of new snow, consisting of 1-mm-long capped columns with a density of about 150 kg m<sup>-3</sup>. Beneath this was wind-packed snow consisting of rounded grains 1-2 mm in diameter with a density of 300-400 kg m<sup>-3</sup>. A small amount of moisture was present near the snow surface. Ice salinities were 8 ppt near the surface, decreasing to 6 ppt by a depth of 50 cm. Brine volumes were about 10-12% near the surface, increasing sharply to 20% near the bottom of the ice. Structurally the ice consisted of a 5-cm surface layer of granular ice underlain by columnar ice, with a 2-cm-thick skeletal layer at the bottom. Significant concentrations of air bubbles were found in the upper 5 cm, with the ice below 30 cm being relatively bubble-free. At the thicker snow sites the ice was protected from melt-induced structural changes and the bubbly surface layer was less pronounced. A visible layer of ice algae was present in the bottom 1 cm of ice cores from all four sites. The algae were dominated by pennate diatoms, and chlorophyll concentrations ranged up to 157 mg Chl m<sup>-2</sup> (Table 1).

Direct measurements of the algal diffuse attenuation spectrum were made at the snow-free site, where the algal biomass was 32 mg Chl m<sup>-2</sup>. Irradiance transmission spectra were measured beneath the ice cover using the Focal fiber optics probe before and after removal of the 2-cm-thick algal layer. Assuming that absorption due to the small amount of ice in the algal layer is negligible, the difference in transmission can be used to compute a biomass specific diffuse attenuation coefficient ( $K_a$ ) for the algae from

$$K_a(\lambda) = -\ln\left[\frac{F_t(\lambda)}{F_0(\lambda)}\right] / B \quad (1)$$

Table 1. Summary of the physical, optical, and biology results for the four study sites.  $h_s$  is snow depth (cm),  $H_i$  is ice thickness (m), B is the observed algal biomass (mg Chl m<sup>-2</sup>),  $T_{600}/T_{450}$  is the ratio of transmitted irradiances at 600 and 450 nm, and  $a_p^*$  is the spectrally averaged specific absorption coefficient [m<sup>2</sup> (mg Chl)<sup>-1</sup>] for ice algae in the laboratory.

Site	$h_s$	$H_i$	B	$T_{600}/T_{450}$	$T_{700}/T_{600}$	$a_p^*$
1	0	1.48	32	1.09	0.26	0.0025
2	5	1.52	157	1.76	0.22	0.0029
3	10	1.42	135	0.76	0.18	0.0023
4	19	1.45	117	0.82	0.12	0.0026

where  $\lambda$  is wavelength,  $F_a$  and  $F_b$  are the transmitted irradiances above and below the algal layer, and B is the biomass of ice algae as chlorophyll. Results from the bare ice site (Figure 1) show a characteristic absorption pattern for diatoms, with broad and narrow chlorophyll a absorption bands centered near 450 and 670 nm and an enhancement of the peak from 450 to 550 nm due to the carotenoid accessory pigments, particularly fucoxanthin. The minimum is displaced towards longer wavelengths compared with previous *in vivo* observations (Arrigo et al., 1991; SooHoo et al., 1987), presumably due to the presence of dissolved organic matter and detritus in the *in situ* measurements.

Spectral transmittances at the four study sites are plotted in Figure 2. For a uniform ice cover it might be expected that transmittance would decrease as snow thickness increases. Indeed, the largest transmittance was observed at the snow-free site, with values decreasing by approximately a factor of five at the 10-cm site and by a factor of ten at the 19-cm site. However, the smallest transmittance was actually measured beneath ice with a 5-cm snow cover. The spectral shape of this transmittance curve differs from the other cases. There are greater losses at the shorter wavelengths and the maximum is shifted towards the red end of the spectrum; the dip in transmittance at 670 nm is also more pronounced. These

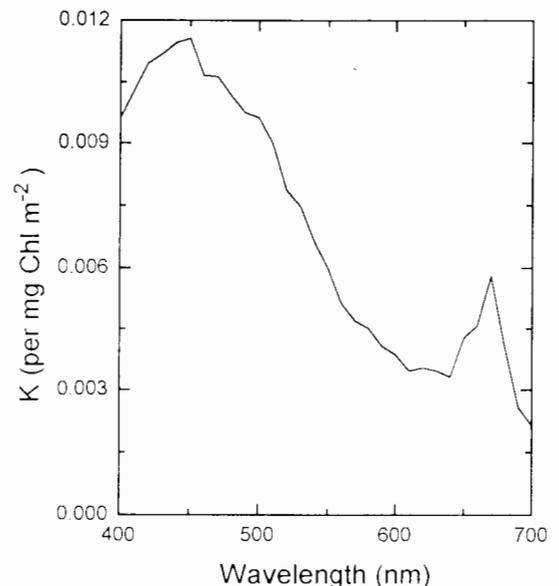


Fig. 1. Spectral absorption coefficients for bottom ice algae determined at the bare ice site.

have a high degree of independence and should thus do a good job of separating B and  $h_s$ . Because the accuracy of the method depends on how well the optical properties of the ice, snow and algae are known, Figure 3 should be considered as preliminary until we are able to obtain better statistics on *in situ* values of these properties.

A major uncertainty in estimates of biological activity associated with the ice pack is the high spatial variability and the difficulty in sampling it with current techniques. With the above methodology, large-scale biomass surveys could be undertaken in areas of first-year ice using a spectroradiometer mounted on a submersible vehicle. Detailed bio-optical measurements at particular locations would provide control data for validation. The method might also provide a non-invasive way to monitor temporal changes in biological activity at selected sites.

In summary, our data confirm that considerable variations in ice algal biomass occur over small spatial scales, even in relatively uniform first-year ice. This variability in biomass is directly related to variability in transmitted light levels, which results primarily from differences in snow depth and to a lesser degree from related changes in the optical properties of the ice. Since ice thickness and snow depth are typically quite variable in the arctic ice pack, errors in estimates of regional algal production could be large if based on isolated point measurements. Accurate estimates require a more fundamental understanding of interrelationships between light transmission, algal growth, and the physical characteristics of the ice cover. Such an understanding would allow the development of improved bio-optical models, which could be used to compute areal estimates of biomass from cumulative irradiance and basic ice cover structural information.

*Acknowledgments.* This research was supported by the Office of Naval Research under grants N0014-90-J-1075, N0014-92-J-1289, and N0014-93-MP-24013 and by the National Science Foundation under grant DPP-9015661.

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D. K. Perovich, US Army Cold Regions Research and Engineering Laboratory.

G. F. Cota, Graduate Program in Ecology, University of Tennessee.

G. A. Maykut and T.C. Grenfell, Department of Atmospheric Sciences, University of Washington.

(Received March 15, 1993;  
accepted April 14, 1993.)

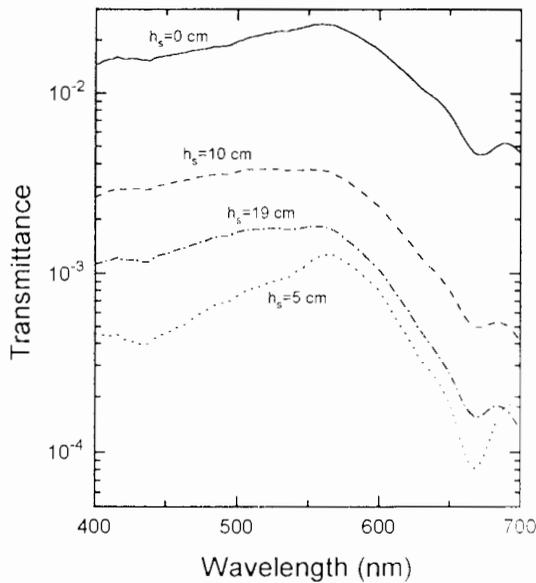


Fig. 2. Observed spectral transmittances for the bare ice, and ice with 5 cm, 10 cm and 19 cm of snowcover. Measurements were made with the Spectron SE590 under a complete and uniform cloud cover.

spectral differences are consistent with algal absorption expected from the curve in Figure 1, indicating that the differences are due, in large part, to greater biomass concentrations at the 5-cm site. Measured chlorophyll a concentrations were, in fact, highest at this site (Table 1). There was also a contribution due to differences in the structure and optical properties of the ice. Ice cores taken later in the experiment indicated that the surface bubbly layer, where much of the scattering occurs, was thinner for ice with a deeper snow cover. This would tend to decrease  $K_i$  and increase transmission at the 10-cm and 19-cm sites. The apparent reason is that snow inhibits the rate of radiational heating in the ice, leading to lower temperatures and smaller brine volumes.

#### Discussion

Integrated between 400 and 700 nm, the extinction coefficient for the algae at the bare ice site was  $21.5 \text{ m}^{-1}$ , while the biomass-specific diffuse attenuation coefficient was  $0.0067 \text{ m}^2 (\text{mg Chl})^{-1}$ . Specific absorption coefficients ( $a_p^*$ ) measured on filters in the laboratory were lower, ranging from  $0.0023$ – $0.0029 \text{ m}^2 (\text{mg Chl})^{-1}$  at the four sites (Table 1). Our direct absorption spectra are comparable to the inferred values reported by Maykut and Grenfell (1975) and to the laboratory measurements of SooHoo et al. (1987) and Arrigo et al. (1991). On the basis of the limited evidence presented here, it appears that there may be significant differences between *in situ* and *in vivo* values of  $K_a$ . Such differences would presumably arise either because of differences in the geometric distribution of algae on the ice substrate that is not preserved in melt water suspensions or on laboratory filter pads or the exclusion of dissolved organics. Additional *in situ* data are needed to confirm this.

Because of spectral differences in extinction by snow, ice and algae, transmission spectra measured beneath the ice have the potential to provide information on the amount of over-

lying biomass. Legendre and Gosselin (1991), for example, report that the ratio of irradiances at 671 and 540 nm accounts for about half the observed variance in chlorophyll a within the ice. While a single ratio removes problems due to variations in downwelling irradiance at the surface, it is sensitive to variations in the state of the ice cover, particularly snow depth. In principle, however, such variations could be resolved in the transmission spectra ( $T_\lambda$ ) through the use of additional wavelengths, allowing us to separate biological effects from those related to the ice cover. To demonstrate how such an approach might work, let us consider a region such as Resolute, where the ice thickness is relatively constant and spectral variations in transmission are almost entirely due to differences in algae and snow depth. We will construct two independent ratios based on our general understanding of absorption by the snow and algae. The  $K_a$  results from Figure 1 suggest that the ratio of transmitted fluxes at 600 and 450 nm would be a sensitive indicator of biomass, which minimizes variations due to changes in snow depth and ice thickness. Similarly, the transmission ratio between 700 and 600 nm is strongly affected by  $h_s$ , but is only weakly dependent on biomass. By suitably combining these two ratios, we should be able to infer both snow depth and biomass from  $T_\lambda$  alone.

Even though we lack sufficient data to test this method directly, we can calculate  $T_\lambda$  theoretically from data on  $K_a$ ,  $K_i$  and  $K_s$ . Figure 3 is a nomograph showing predictions made by the Perovich (1990) two-stream model over a wide range of B and  $h_s$  values, assuming the same attenuation coefficients used to obtain Figure 1. The two sets of isopleths correspond to  $T_{600}/T_{450}$  and  $T_{700}/T_{600}$ . Values of  $h_s$  and B for a particular  $T_\lambda$  can be read off the nomograph by simply finding the intersection of the two ratios. As expected,  $T_{700}/T_{600}$  isopleths are nearly vertical, indicating weak sensitivity to B, while  $T_{600}/T_{450}$  shows a strong response to B and some dependence on  $h_s$ . Although not quite orthogonal, it is evident from the nomograph that the two ratios do

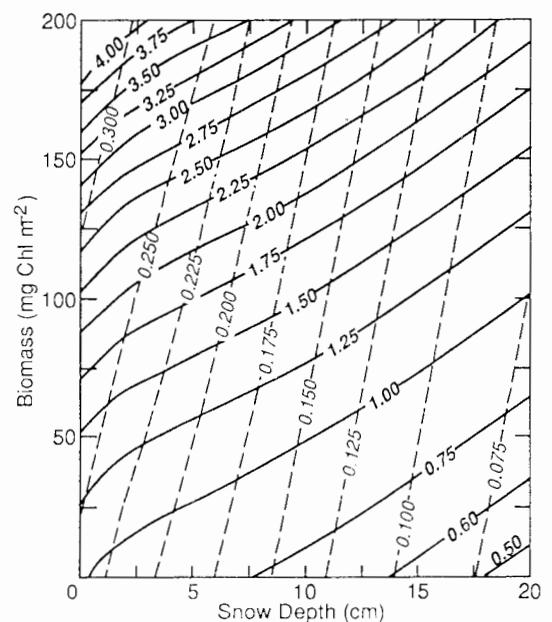


Fig. 3. Nomograph of algal biomass vs. snow depth for an ice thickness of 1.5 m using ratios of transmittance of  $T_{700}/T_{600}$  and  $T_{600}/T_{450}$ .