Field Measurement of Light Penetration Through Sea Ice[1]

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ABSTRACT: In connection with phytoplankton studies, a non-optical, non-electric instrument has been devised for the measurement of relative light intensity in sea-ice bore holes. When used with a sensitive photometer, absolute values for the ambient light field can be determined within and immediately under the ice. As anticipated, attenuation is greatest at the ice-air interface; values just below the ice surface were 3 to 20 per cent of incident. Another 70 to 100 cm. of ice was required to effect a further 50 per cent decrease in illumination. Extinction values were also measured on the ice cores in the laboratory, but scattering greatly complicates the interpretation of laboratory results.

RÉSUMÉ. *Mesures de la pénétration de la lumière à travers la glace de mer.* A l'occasion d'études sur le phytoplancton, les auteurs ont mis au point un instrument non optique et non électrique qui mesure l'intensité lumineuse relative dans des trous forés dans la glace de mer. Avec un photomètre sensible, on peut déterminer des valeurs absolues du champ lumineux ambiant à l'intérieur de la glace et immédiatement dessous. Comme on l'avait prévu, l'atténuation est la plus grande au plan de contact air-glace ; juste sous la surface de la glace, les valeurs sont de 3 à 20 pour cent de la lumière incidente. De 70 à 100 mm de glace diminuent encore l'illumination de 50 pour cent. On a aussi mesuré en laboratoire les valeurs d'extinction sur des carottes de glace, mais la dispersion complique grandement l'interprétation des résultats.

РЕЗЮМЕ. *Полевые измерения прохождения света через морской лёд.* В связи с изучением фитопланктона разработан неоптический и неэлектрический прибор для относительных измерений интенсивности света в скважинах, пробуренных в морском льду. При одновременном использовании чувствительного фотометра могут быть определены также и абсолютные значения светового поля. Как и ожидалось, ослабление максимально на границе воздух-лёд: количество света непосредственно под поверхностью льда составляет от 3 до 20% от падающего. Следующие 70-100 см льда дают уменьшение освещенности на 50%. Величина затухания была измерена также в ледяных стержнях в условиях лаборатории, но рассеяние света в этом случае значительно усложняет интерпретацию результатов.

The amount of light actually penetrating the sea ice cover of the Arctic and Antarctic Oceans is critical to the local photosynthetic organisms, and ultimately to the entire food chain. Despite the obviously low ambient light values, plankton blooms under and often within sea ice are not uncommon, therefore significant quantities of light must be available. There is a sizeable body of observations on the light field beneath the ice, but a paucity of actual measurements. MacGinitie (1955) was impressed by the brightness observed in ice bore holes near Barrow,

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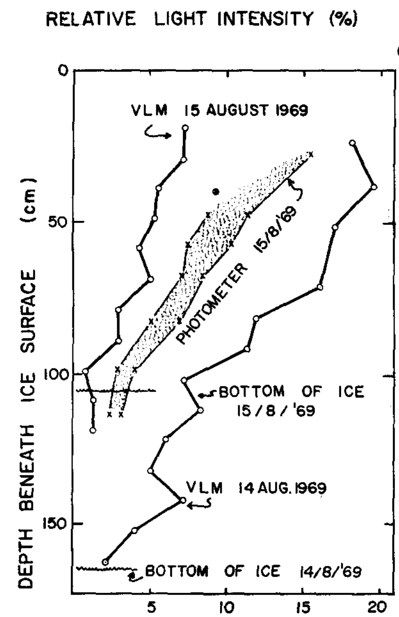
Alaska, whereas Wilce (1967) noted the lack of light under similar conditions off Devon Island in the Canadian Arctic. La Fond (1960) reporting on observations from submarines beneath the ice, commented on the ease with which variations in ice thickness could be detected by changes in the brightness. It should be remembered, however, that the human eye is a surprisingly sensitive photometer and can detect a light level much lower than that required for photosynthesis. Quantitative measurements of light in and under the ice have been few and extremely variable; the values of Wilce (1967) are much smaller than the Russian figures summarized by Zubov (1943). Clearly there is a need for a simple, readily portable device for measuring directly the light intensity available to organisms *in situ*, within and under the sea ice.

Sea ice is itself a strongly scattering medium, and it is commonly illuminated by natural daylight at a very low angle. Moreover, the cloudy conditions which often prevail in the polar regions result in further diffusion and scattering of the available light. The albedo of the sea ice surface is, of course, critical, and can range from below 0.50 to over 0.90, depending primarily on the characteristics of the ubiquitous snow cover or the presence of water puddles (Zubov 1943; Thomas 1965; Maykut and Untersteiner 1969). This complex optical situation is further complicated by the fact that sea ice is definitely not a homogeneous material; its absorbency is profoundly influenced by variations in crystal size and orientation, by incorporation of sediments and brine pockets, and by the organisms growing on and in it. To these complications must be added the consideration that the results of measurement of light attenuation in a scattering medium depend strongly on the type of instrument used for measurement.

A simple instrument has been designed for the determination of relative light intensities within and under the sea ice. It is rugged, readily portable, and completely reliable, contains no lenses, and functions only in the visual light band, which includes all wave lengths of importance to the photosynthetic process. In combination with a sensitive electrophotometer, it permits the estimation of light intensity at any point within normal sea ice, and in the water immediately beneath.

The Visual Light Meter (VLM) is shown in Fig. 1. It consists of 2 ball bearings 5 cm. in diameter, suspended by light fishing-line in a core hole drilled through the ice. One ball is held at a fixed point between one half and one third of the distance to the bottom of the ice, while the position of the second is varied from just below the water surface in the core hole to below the bottom of the ice. The spheres are viewed through a black plastic tube 10 cm. in diameter which bears calibrated reels for the suspension of the spheres and which has two polaroid plates. The lower plate is made of 2 semicircular Polaroid discs, mounted so that one half is polarized at +45 degrees and the other at −45 degrees. Above this is a movable polaroid plate which can be rotated on a calibrated frame to produce equal apparent brightness in the light reflected from the 2 spheres. If the sun is shining brightly, balls painted flat white were found to be easier to use than polished steel balls for the surface readings.

The most consistent observations are made if the observer focuses on the portion of the spheres at 45 degrees to the vertical, since at this angle the sphere reflects the light received from the side of the ice, providing the best measure of



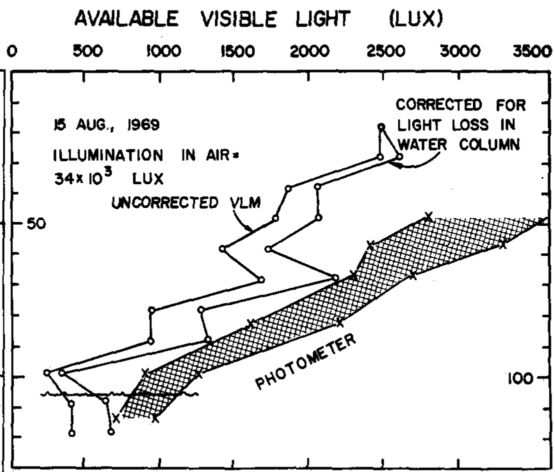


FIG. 2. (*Left*) Light intensity (as per cent available light) in sea ice measured by VLM and photometer, August 1969.

FIG. 3. (*Above*) *In situ* determinations of available visible light in sea ice from VLM and photometer, August 1969.

of data reported were obtained near mid-day, when the sun's elevation was approximately 30 degrees above the southern horizon. To test the VLM, a sensitive photovoltaic cell, filtered to accept only visible radiation, was lowered in the bore hole for absolute measurements during one trial; because of the wide scope of the horizontally-mounted photo cell, values at any depth covered a considerable range depending upon orientation to the sun. This variation is indicated by the shaded area on the figures. Further trials under similar conditions in June of 1970, using a photo cell which collected light through a larger solid angle, are shown in Fig. 4. The general agreement of the VLM and photometer data substantiates the utility of the VLM.

As found by other workers (Zubov 1943; Wilce 1967; Maykut and Untersteiner 1969), the attenuation of light in passage through the ice itself was small compared to that lost at the ice-snow and snow-air interfaces. Light penetrating to just below the upper surface of the ice was 3 to 20 per cent of incident, whereas 70 to 100 cm. of ice was required to effect a further 50 per cent decrease in illumination. These numbers are in general agreement with figures in the literature, as cited above, and increase our confidence in this light meter, which possesses the advantages of being easily portable and requiring no power supplies or other electronic devices which may be sensitive to low temperatures.

Extinction values obtained in the field are drastically different from those observed for cut pieces of ice in the laboratory because of the marked difference, in a scattering medium, of illumination from an essentially infinite plane and from a collimated light beam. In cores, light is scattered to such an extent that the transmitted light cannot be measured in samples more than a few centimetres thick. In a semi-infinite solid, such as a mass of sea ice, this light may be rescattered in any direction, so that the true field of light extends a great deal deeper.

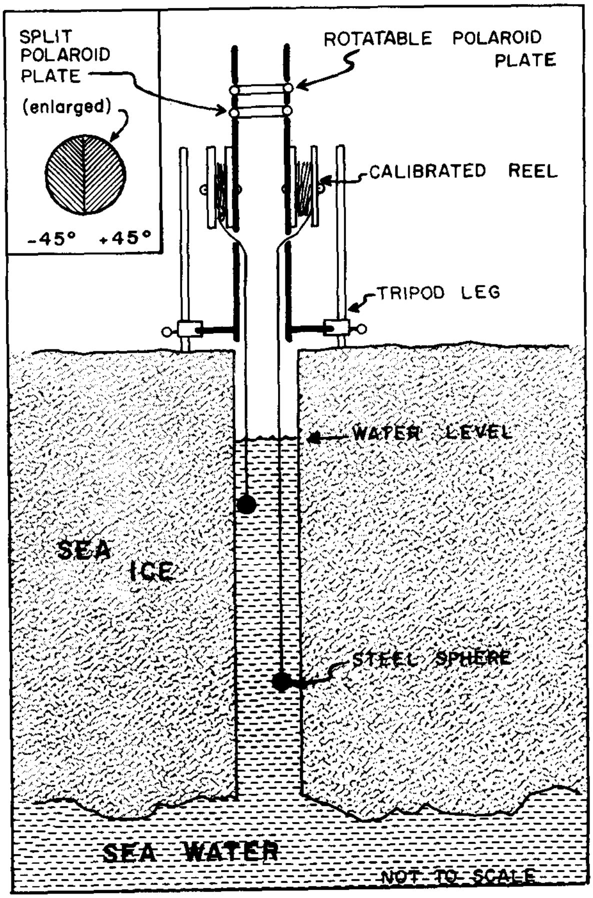


FIG. 1. Diagram of visual light meter.

the ambient light field. It can easily be proved by differential geometry that a polished sphere must reflect parallel light equally in all directions. The apparent brightness of the 2 spheres is a direct function of the relative amounts of visible light available at the depths of the spheres and the ratio between them is given by $\tan^2\theta$ where θ is the angle between the fixed and rotating polaroid plates. These values of relative brightness should then be corrected for light absorption in the water column separating the spheres to determine true light intensities. The fraction of incident light which penetrates the interface is measured by elevating the tube *c.* ½ m. above the ice on its tripod legs and comparing the brightness of a ball in air to one just below the water surface. This interface factor varied from 0.03 to about 0.20 during trials near Barrow. To estimate absolute values for the ambient light field within the ice, the relative brightness determined by the VLM is multiplied by the interface factor and the available light at sea level (measured with a sensitive photometer).

Typical profiles of relative light intensity and available visible light within and beneath sea ice are presented in Figs. 2 and 3. These data were collected near Barrow, Alaska, in August of 1969 on one-year sea ice with a light (1 to 3 cm.) cover of fairly fresh snow. Air temperatures were close to freezing and both sets

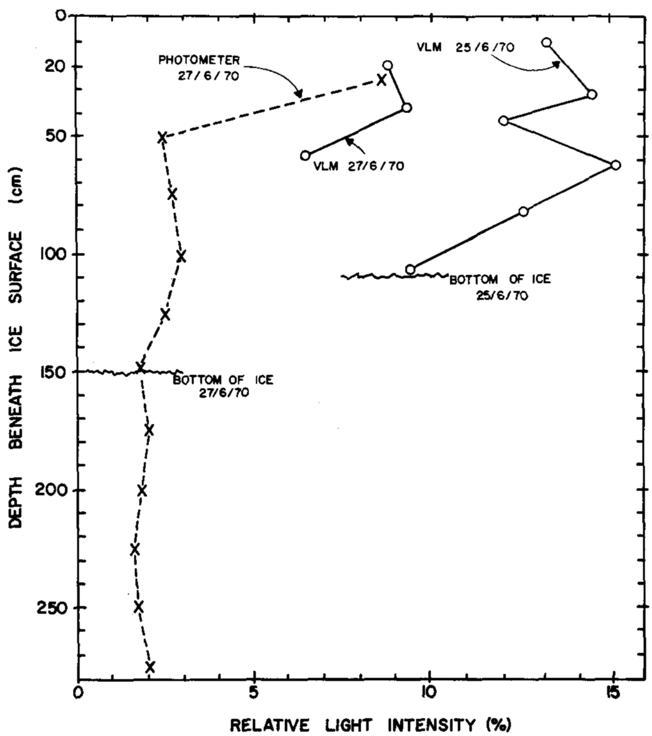


FIG. 4. Relative light intensity measurements with VLM and photometer, June 1970.

Measurements with ice sections in the laboratory may be of value, however, for relating optical properties of different kinds of ice to differences in crystal size and orientation. The upper layers of sea ice cores consist of a jumbled mass of small crystals, probably the result of formation from random platelets of young sea ice buckled and refrozen (Weeks 1958). Crystallographic studies with a Rigsby Universal Stage indicated no strongly preferred direction of axial orientation in this material. Deeper in the core the crystals become larger, up to 5 cm. wide and 30 cm. long, with the vertical dimension much the larger. These crystals are intricately intergrown, but the *c*-axis is invariably in the horizontal direction. Since crystals grow faster in planes perpendicular to the *c*-axis, and since in sea ice they grow downward by freezing, crystals with horizontal *c*-axes are favoured. There is the possibility of light channelling in such an anisotropic medium. At the very bottom of the core there is a transition to a slushy layer which was almost impossible to section.

The effect of variations in crystal structure on the attenuation of light by sections of several sea-ice cores cut normal to the surface was measured with a G & M turbidimeter (Fig. 5). The instrument and sample were immersed in a water bath near the freezing point of sea water to minimize reflections from the ends of the core. The cores from the Chukchi Sea station and from Eluitkak Pass were probably formed under similar conditions, as these two stations are only 6 miles apart, and it will be noted that they show similar extinction curves, whereas the pressure ice sample was formed under different conditions. The high values for the attenuation coefficient (>1.0 cm.$^{-1}$) determined on core segments are due

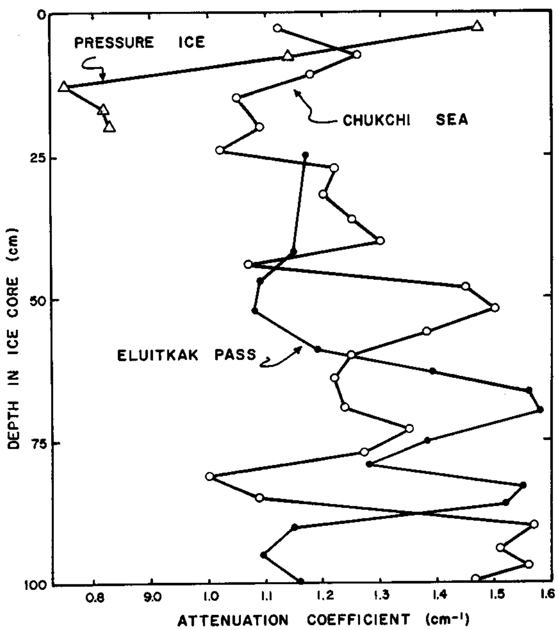


FIG. 5. Attenuation coefficient (α in $I = I_0e^{-\alpha x}$) measured in sea ice core segments from the Barrow area.

to excessive scattering loss in the finite sections, without opportunity for rescattering. Values greater than unity are not uncommon in the more opaque media. This does not mean that more than 100 per cent of the incident light is lost in the first centimetre; it means that the rate of decrease is as rapid as that at first. Only in a truly absorbing medium is the decay exponential; in a scattering medium the situation is much more complex.

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