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RADIATION TRANSMITTANCE THROUGH LAKE ICE IN THE 400–700 nm RANGE*

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ABSTRACT. Significant new information on radiation transmittance through ice in the photosynthetically active range (400–700 nm) has been collected at an inland lake near Ann Arbor, Michigan, U.S.A., and at one site on the Great Lakes (lat. 46° 46′ N., long. 84° 57′ W.). Radiation transmittance through clear, refrozen slush, and brash ice varied according to snow cover, ice type, atmospheric conditions, and solar altitude.

Snow cover caused the greatest diminution of radiation. During periods of snow melt, radiation transmittance through snow-covered ice surfaces increased slightly. Moderate diurnal variations of radiation transmittance (about 5%) are attributed to solar altitude changes and associated changes in the direct–diffuse balance of solar radiation combined with the type of ice surface studied. Variations in radiation transmittance of nearly 20% over short periods of time are attributed to abrupt changes from a clear to a cloudy atmosphere.

A two-layer reflectance–transmittance model illustrates the interaction of layers in an ice cover such as snow or frost overlying clear ice. Upper layers of high reflectance have considerable control on the overall transmittance and reflectance of an ice cover.

RÉSUMÉ. *Perméabilité de la glace de lac aux radiations dans la gamme des 400–700 nm.* On a recueilli des informations nouvelles significatives sur la transmittivité des radiations à travers la glace dans la gamme d'activité photosynthétique (400–700 nm) au cours d'essais sur un lac intérieur près d'Ann Arbor dans le Michigan, U.S.A. et en un point des Grands Lacs (46° 46′ N., 84° 57′ W.). La transmittivité des radiations à travers une pellicule claire de glace en formation et à travers un amas de glaçons flottants était variable selon le couvert de neige, le type de glace, les conditions atmosphériques et l'altitude du soleil.

C'est le couvert de neige qui entraîne la plus forte diminution de radiation. Pendant les périodes de fusion, la transmittivité aux radiations des glaces enneigées remonte faiblement. Des variations journalières faibles de la transmittivité (environ 5%) sont attribuées aux changements de la hauteur du soleil et aux changements qui leur sont associés dans le bilan des radiations solaires directes et diffuses du rayonnement solaire ainsi qu'au type de surface de glace étudiée. Des variations dans la transmittivité de près de 20% en de courtes périodes de temps sont attribuées à des brusques changements météorologiques du temps clair aux nuages.

Un modèle à deux niveaux de réflectivité–transmittivité illustre l'interaction entre les couches d'une couverture de glace telle que de la neige ou du givre surmontant une glace claire. Les couches supérieures de haute réflectivité exercent une action considérable sur la transmittivité totale et sur la réflectivité d'une couverture de glace.

ZUSAMMENFASSUNG. *Strahlungsdurchlässigkeit von Seeeis.* Wesentlich neue Informationen über die Strahlungsdurchlässigkeit von Eis im photosynthetisch aktiven Bereich (400–700 nm) wurden an einem Inland-See bei Ann Arbor, Michigan, U.S.A. und an einer Stelle an den Grossen Seen (46° 46′ N., 84° 57′ W.) gewonnen. Die Strahlungsdurchlässigkeit durch klaren wiedergefrorenen Matsch und durch Trümmereis schwankte je nach Schneedecke, Eistyp, atmosphärischen Bedingungen und Sonnenhöhe.

Die Schneedecke verursachte die grösste Abnahme der Strahlung. Während der Schneeschmelze nahm die Strahlungsdurchlässigkeit schneebedeckter Eisflächen allmählich zu. Mässige tägliche Schwankungen der Strahlungsdurchlässigkeit (etwa 5%) sind dem Wechsel der Sonnenhöhe und den damit verbundenen Schwankungen im Verhältnis zwischen der direkten und der diffusen Sonnenstrahlung zuzuordnen, wobei auch der Typ der untersuchten Eisfläche eine Rolle spielt. Schwankungen von fast 20% in der Strahlungsdurchlässigkeit über kurze Zeitspannen lassen sich dem plötzlichen Wechsel zwischen klarem und bewölktem Himmel zuschreiben.

Ein Zweischichten-Modell für Reflexion und Durchlässigkeit erklärt die Wechselwirkung zwischen den Schichten einer Eisdecke, wie z.B. bei Schnee oder Reif über klarem Eis. Obere Schichten von hoher Reflexion haben beträchtlichen Einfluss auf die Gesamtreflexion und -durchlässigkeit einer Eisdecke.

INTRODUCTION

The amount of radiation penetrating an ice or a combined ice and snow cover is often critical to the survival of plants and animals in both large and small fresh-water lakes. In spite of the importance of this problem, the nature and magnitude of radiation penetration through fresh-water ice is only partially understood. Comprehensive understanding has been

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hampered by unrepresentative measurements due to instrumentation and measurement technique problems. New information on radiation transmittance through fresh-water ice in the photosynthetically active range (400–700 nm) is reported in this study.

It should be noted that recent studies using a specially designed spectroradiometer have provided significant new information on the spectral transmittance and reflectance of sea ice (Grenfell and Maykut, 1977; Maykut and Grenfell, 1975). Information pertaining to the bulk extinction coefficient of sea ice is provided by Untersteiner (1961), Thomas (1963), and Weller (1969). Although much remains to be done to define radiation transmittance through sea ice adequately, similar measurements on fresh-water ice are not as plentiful and are often questionable due to poor instrumentation or poor technique.

A comprehensive review of the results of radiation transmittance studies on fresh-water ice is presented in Maguire (1975[a], p. 6). Careful review of these studies indicates that a wide range of instrumentation has been employed by numerous investigators. The various systems, both individually fabricated and commercially available, have produced results that are not comparable. In some cases instruments used above the ice have had different spectral response characteristics from those used below the ice. The instruments selected for this study are patterned after an instrument originally developed by the Scripps Institute of Oceanography. They are commercially available and in wide use.

The purpose of this study was to compile information on radiation transmittance in the range 400–700 nm through some ice types common to the Great Lakes region. It is emphasized that since this report represents only an extended summary, a full account of the data, including several situations not reported or not fully reported here, can be obtained in Bolsenga (1978) or as data archived at the World Data Center A for Glaciology. The majority of the tests were conducted at a small inland lake located near Ann Arbor, Michigan (lat. 42° 18′ N., long. 83° 43′ W.), but a limited number of readings were collected at the eastern end of Lake Superior (lat. 46° 46′ N., long. 84° 57′ W.). Data were gathered on the variation of radiation transmittance due to different types and thicknesses of ice and snow, solar altitudes, cloud types, and cloud amounts. Both natural snow-free and snow-covered ice surfaces, and ice surfaces artificially cleared of snow were examined. A snow-free surface was desirable since radiation transmittance characteristics through snow are relatively well known when compared with the information available on radiation transmittance through ice. It is felt that if radiation transmittance through ice were better understood, then in natural, combined ice–snow surfaces, values for both snow-free ice and snow could be artificially integrated to obtain a good approximation of the natural radiation transmittance of a large area by high-speed methods such as remote sensing.

Instrumentation and test plan

Two quantum sensors manufactured by the Lambda Instruments Corporation were used to measure radiation in the 400–700 nm band. Detectors for the sensors are silicon photodiodes with enhanced response in the visible spectrum. Interference filters combined with detector characteristics produce sharp cut-off in the spectral response at approximately 400 and 700 nm. Cosine correction of the sensors is accomplished by use of a "Plexiglass" diffuser and spectral shifts due to light entering the interference filter at oblique angles are eliminated by a collimating system. Full details of the instruments including spectral response curves and underwater correction factors are given in Bolsenga (1978).

The above-ice sensor was equipped with a mounting and leveling fixture. The underwater sensor was mounted on a specially designed arm (Fig. 1). The 3.18 cm ($1\frac{1}{4}$ inch) white plastic pipe was liberally perforated for ease in submerging the unit. The level of the sensor at the end of the arm was adjustable with respect to an above-ice spirit level. A platform to hold the arm in a stable position was fabricated from clear "Plexiglass" to minimize attenuation of

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incident light. At each site the support arm was lowered into a hole 15 cm in diameter, leveled, and some of the ice chips were pushed back into the bore hole. The topside sensor was then leveled away from any obstructions. Completion of above- and below-ice readings, under equal cloud conditions, was facilitated by incorporating a deck-to-sea switch into the electronics to ensure rapid read-out. Temperature and supplemental cloud observations were obtained from hourly records of a nearby National Weather Service station.

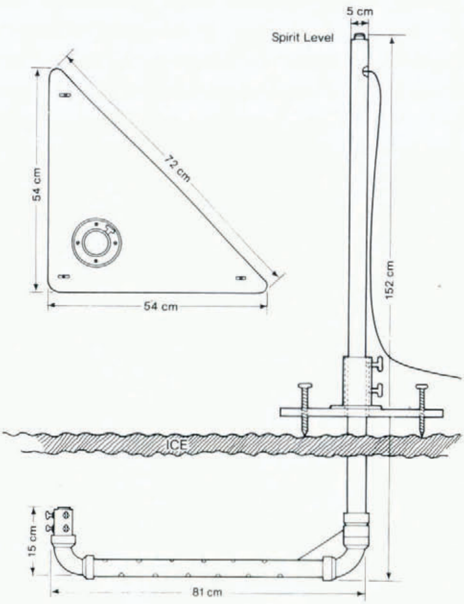

Fig. 1. Design details of the support arm for the underwater sensor.

Analysis

The ice surfaces observed in this study were clear, refrozen slush, and brash ice. Clear ice and refrozen slush ice often occurred in combination. Refrozen slush formed as a result of mild temperatures, which reduced snow cover on the lake to slush. Subsequent lower temperatures completely froze this slush into a snow-ice-like substance called refrozen slush.

It was necessary to clear snow from the ice on occasion to acquire a certain number of snow-free readings as described earlier. Cleared areas were roughly circular, 3 to 7 m^2 in area, and extended to the south of the bore hole to minimize shadow effects on the underwater sensor. An experiment was conducted as described in Bolsenga (1978) to assess the effects on measurement accuracy of artificially clearing an area. It was tentatively concluded that the artificially cleared areas provide radiation transmittance values that are representative except possibly in cases where there are shadowing effects of snow banks (discussed later). Additional experiments are necessary to verify this assumption.

A group of measurements were made from the same bore hole by swinging the support arm under the ice–water interface from a clear ice area to a continuously snow-covered area. The ice thickness was 28 cm and the wind-packed snow was about 3 cm thick with an etched surface pattern. Readings taken under the snow-free ice at three locations showed ratios of transmitted to incident radiation of 0.77, 0.80, and 0.82. When the arm was moved completely under the snow, the ratios dropped to 0.08 and 0.10. The bore hole was reoccupied later in the day. Ratios under the clear ice averaged 0.89 at one location and 0.83 at another. Under-snow ratios averaged 0.12.

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Another example of the influence of snow cover on radiation transmittance is shown in Figure 2. A snow layer 5 to 8 cm thick covered 45 cm of ice composed of 4 cm of refrozen slush and 41 cm of clear ice. Temperatures during the measurement period at Detroit Metropolitan Airport varied from 6.1°C at about 11.30 TST (true solar time) to 9.4°C at about 16.45 TST, with the snow melting during this period. Radiation transmittance through the ice and snow layer increased at a steady rate from 0.06 at 11.26 TST (solar altitude, $\gamma = 38°$) to 0.11 at 16.40 TST ($\gamma = 8°$), with the increase in transmittance probably due to snow melt. The change is opposite to that attributed to solar altitude variations as shown by measurements described later (9 March), indicating either that possible solar-altitude influences are completely masked by the effects of the snow melt or other factors such as shadowing or ice surface characteristics that might have been necessary for solar-altitude effects (diurnal variation) are lacking.

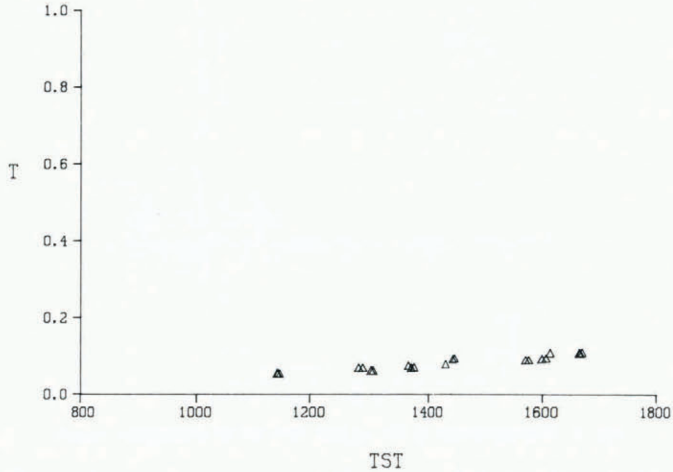

Fig. 2. Increase in radiation transmittance due to snowmelt as indicated by the rise in transmittance ratio T with true solar time TST (22 February 1977).

An ice cover 42 cm thick with 4 cm of refrozen slush overlying clear ice was examined on 14 February. Visual appearance of the surface of the refrozen slush varied greatly and presented an opportunity to measure variations in radiation transmittance of the same ice cover at different surface locations by rotating the under-ice sensor to various horizontal positions in the same bore hole. One area contained slightly more snow than other areas, with the snow lodged in a "pebble-grained" type surface. The average of the ratios in the snow-free area was 0.58. The average of ratios in the partially snow-covered area dropped to only 0.53. The measurements emphasize that seemingly large visual differences in an ice cover are not always related to large differences in radiation transmittance.

A series of measurements were taken on three consecutive days during which 43 cm of ice (combination of refrozen slush and clear ice) deteriorated to 38 cm under mild weather conditions. On 7 March, ratios of transmitted to incident radiation increased slowly from about 0.70 in the late forenoon to near 0.80 at about 14.30 TST (Fig. 3). A small amount of snow was noted on the ice surface in the morning, but all snow had melted by 14.00 TST, accounting for the increase in transmitted radiation. The readings continued to indicate ratios mostly under 0.80 on 8 and 9 March (Figs 4 and 5). Air temperatures during the measurement periods at the Detroit Metropolitan Airport averaged 4.6°C on 7 March, 13.4°C on 8 March and 15.2°C on 9 March. Other than the increase on 7 March, no other definite trend

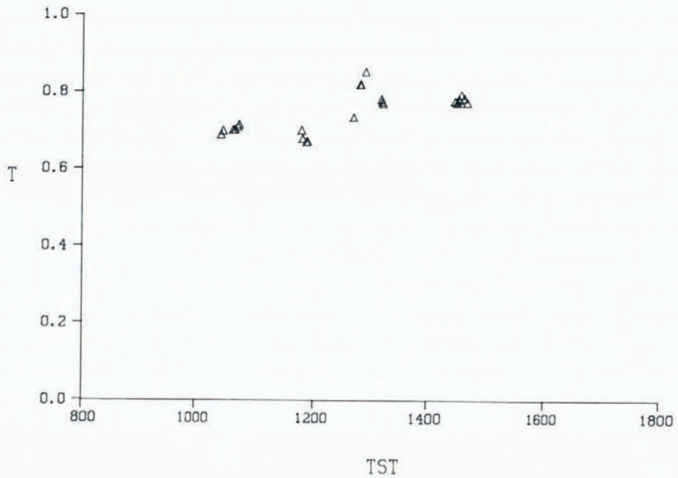

Fig. 3. Ratio of below- to above-ice radiation T as a function of true solar time TST during a period of melting snow (7 March 1977).

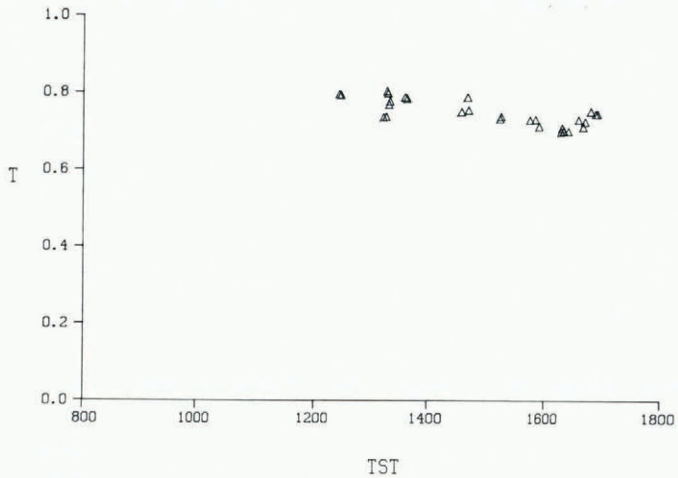

Fig. 4. Radiation transmittance T as a function of true solar time TST during ice decay (8 March 1977).

that can be attributed to snow melt is apparent even though temperatures remained high and caused a decrease in ice thickness. A slight diurnal trend indicated by the 9 March measurements is explained later. The dip and subsequent rise late in the day on 8 March might be due to diurnal effects and instrument error because of low radiation levels, respectively. The lack of smooth transition from low to high ratios on 7 March is due to another experiment involving the raising and lowering of the under-ice sensor to obtain readings at various water depths. After each depth profile the arm could not be repositioned exactly, and since the ice surface, and most likely the ice thickness, were not entirely uniform, slightly different readings could be expected.

Variations in transmittance due to cloud-cover variations were also investigated. On 7 January measurements were taken through clear ice at solar altitudes ranging from 7° to 26°. Total sky cover varied from 0 to 2/10 cumulus during the period. The support arm was raised

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and lowered for depth profiles several times. The ratios obtained for the period varied from 0.65 to 0.95. The significant difference can be attributed to movement of the arm to different locations under the ice cover, to differences in cloud cover, or to both effects combined. Such large variations were not noted on some other occasions when the support arm was raised and lowered, but possible larger differences in the thickness and characteristics of the ice at this site, as well as cloud patterns, might account for the wide variation. It is emphasized that the same bore hole was used throughout the day.

On another occasion (18 January), measurements were taken through 36 cm of clear ice in an area artificially cleared of snow (Fig. 6). Three high transmittance values can be attributed to changes in cloud cover since the sensor was not moved during the day except for occasional releveling. At 10.11 and 10.14 TST, two ratios of 0.95 were noted under clear skies (0/10 coverage). At 11.30 and 11.31 TST, transmittance ratios dropped to 0.77 under 10/10 total sky cover. Readings at 12.23, 12.27, and 12.28 TST varied from 0.90 to 0.78 under variable cloud conditions. The low readings were noted under 10/10 cloud coverage and the high reading under clearer sky conditions (5/10 coverage). From 13.47 to 14.47 TST, skies

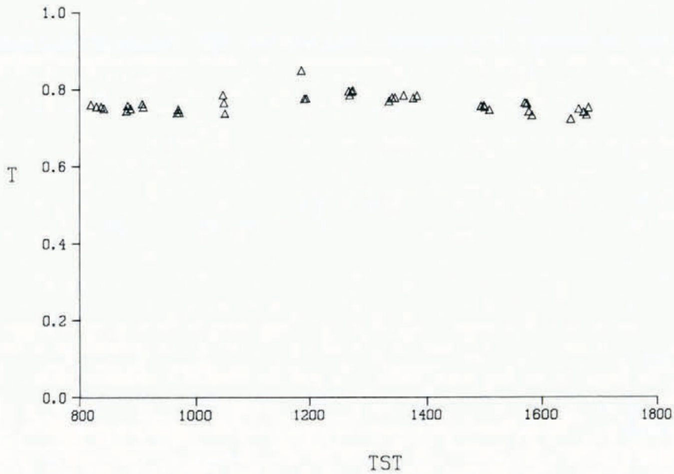

Fig. 5. Radiation transmittance T as a function of true solar time TST during ice decay (9 March 1977).

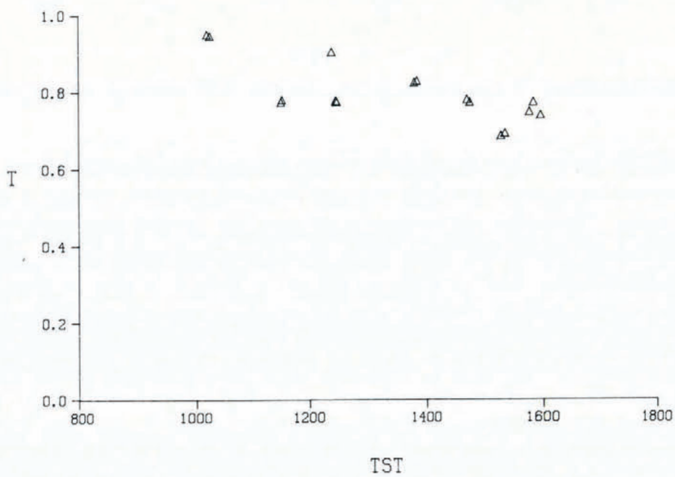

Fig. 6. Transmittance T versus true solar time TST showing differences in T due to cloud-cover variability (18 January 1977)

were clear. The overall downward trend in the ratios is probably due to increased shadowing effects in the shoveled area at solar altitudes that dropped from 28° near 12.00 TST to 17° at 14.47 TST. From 15.19 TST until the end of the day, shadows from deciduous-tree limbs were cast on the ice surface, causing variable ratios.

The same site was occupied on the following day (19 January), when total sky cover remained at 10/10 stratocumulus during the entire period. Solar altitudes varied from 9° to 28°. The ratios remained in the narrow range 0.70–0.76 throughout the day.

It is emphasized that on both days (18 and 19 January) the same bore hole was used and the support arm remained in the same position throughout the day, except for occasional leveling. Placement of the support arm at exactly the same spot was, of course, not possible on a day-to-day basis. The observations on these days show, on a preliminary basis, that radiation transmittance through clear ice is greatly affected by cloud patterns that vary from clear to mostly cloudy (such as intermittent cumulus clouds). On the other hand, totally overcast days showing some variability in the overall cloud pattern seem to have little effect on radiation transmittance in this spectral range.

The readings shown in Figure 5 (for 9 March) indicate that radiation transmittance might be affected by the solar altitude under certain conditions. A significant rise in reflectance at low solar altitudes was found in studies on the total solar spectrum reflectance of soils and crops by Idso and Reginato (1974), Idso and others (1975), and Coulson and Reynolds (1971). The daily variation is most likely to be due to shadowing effects from a surface of complex nature, such as individual agglomerates of soil in a plowed field. A weak dependence of reflectance over the entire solar spectrum on solar altitude was found by Bolsenga (1977) and is attributed to the balance between diffuse and direct solar radiation and to the spectral reflectance characteristics of a particular ice cover. He speculates that slush-ice and snow-ice surfaces will exhibit higher reflectance at low solar altitude due to the increasing diffuse component of solar radiation early and late in the day combined with a high reflectance of slush and snow ice in the 400–700 nm range (Sauberer, 1938) and the fact that diffuse sky radiation is relatively rich in the 400–700 nm range. Observations on 9 March (Fig. 5) showing slightly lower transmittance early and late in the day are consistent with these findings. Observations reported by Bolsenga (1978) showing the opposite trend with slightly higher transmittance values early and late in the day are explained by the fact that the ice was clear ice as opposed to refrozen slush on 9 March.

A limited number of measurements were made on some relatively thick ice (56–64 cm) in Lake Superior. A significant amount of blowing and falling snow prevailed during the 2 h measurement period and could have adversely affected the above-ice readings for all data sets at this location. An average of five measurements taken at $\gamma = 28°$ (12.00 TST) showed the ratio of under-ice to incident radiation through 64 cm of clear ice topped with a thin layer of frozen slush to be only 0.06. Two brash-ice areas, both 56 cm thick, were measured with the overlying snow surface undisturbed and again after the surface had been swept with a broom. At the first site, the ratio for the natural ice and snow surface averaged 0.07 and for the swept surface averaged 0.15. At the second site, the unswept surface averaged 0.06 and the swept surface 0.08. The lack of significant increase in radiation transmittance at the second brash-ice site is explained by the extreme irregularity of the surface, which caused snow to remain in place between the brash-ice blocks even after sweeping.

Diffuse extinction coefficients

Diffuse extinction coefficients obtained from these data and those obtained by Maguire (1975[b], p. 4) are presented and compared in Bolsenga (1978). Diffuse extinction coefficients obtained here for clear ice ranged from 0.006 to 0.011. The values are lower than those obtained by Maguire. Fracture patterns and surface variations could possibly account for the

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differences. The two brash-ice surfaces yielded diffuse extinction coefficients similar to each other. The combinations of refrozen slush and clear ice present the most complex pattern of diffuse extinction coefficients noted. It is fairly obvious that the amount and condition of snow on the ice surface have a profound effect on the magnitude of the diffuse extinction coefficient. During ice decay, diffuse extinction coefficients of combined refrozen slush and clear ice remained in a remarkably small range (0.006 to 0.008). Water was observed on the surface and percolating through the ice during portions of the period.

It is important to note that the lack of homogeneity of most natural ice or combinations of ice and snow can produce diffuse extinction coefficients and transmittance values more representative of certain upper layers of an ice cover than of the bulk of the ice cover. Situations occur in natural ice surfaces where phenomena such as surface etching due to windblown snow, frost accumulation or melting, micro-relief due to melting, fractures, or internal bubble structure are the rule rather than the exception. Transmittance values and diffuse extinction coefficients given here and more completely in Bolsenga (1978) are usually the result of a combination of these factors and may be site specific.

The effect of layering on the overall transmittance and reflectance values of an ice cover can be estimated with a simple model. The reflectance and transmittance of each individual layer are used to obtain combined reflectance and transmittance values for the ice cover.

The combination reflectance $\rho(C)$ of a two-layered system is

$$\rho(C) = \rho(A) + \frac{\tau^2(A)\,\rho(B)}{1-\rho(A)\,\rho(B)}, \tag{1}$$

where ρ is the reflectance, τ the transmittance, A the upper layer, and B the lower layer.

The combination transmittance $\tau(C)$ of a two-layered system is

$$\tau(C) = \frac{\tau(A)\,\tau(B)}{1-\rho(A)\,\rho(B)}. \tag{2}$$

To illustrate the effectiveness of the model, Equations (1) and (2) were programmed on a computer. Hypothetical ice-cover transmittance, reflectance, and absorptance values (layer B) were stipulated and held constant for each computer run, during which varying values were substituted for ρ and τ in layer A (representing snow, frost, bubble layers, etc.). Layer A transmittance and reflectance values were increased by 1% intervals.

In the first computer run, clear ice was simulated for the B layer with $\rho(B) = 0.19$, $\tau(B) = 0.80$, and the absorptance $\alpha(B) = 0.01$. The reflectance and transmittance of the A layer were varied with $\alpha(A)$ held constant at 0.01. The effects of a highly reflective upper (A) layer on such an ice cover were immediately apparent. A snow layer with a reflectance of 0.80 would yield $\rho(C)$ of 0.81 and $\tau(C)$ of 0.18. An upper layer of considerably less reflectance, $\rho(A) = 0.20$ for example, would yield $\rho(C) = 0.32$ and $\tau(C) = 0.66$. The highly reflective snow is obviously the dominant factor in the combination and the reflectance–transmittance values of the ice layer have little influence on the combination when snow is present. The example used here for a snow cover overlying clear ice is similar to an experimental situation described earlier where $\tau(C) \approx 0.80$ in a snow-free area and $\tau(C) \approx 0.10$ in an adjacent area covered by 3 cm of snow. Other field data verify the effects of snow cover on ice transmittance (Bolsenga, 1978).

In the second computer run, snow-ice was simulated for the B layer with $\rho(B) = 0.44$, $\tau(B) = 0.55$, and $\alpha(B) = 0.01$. The reflectance and transmittance of the A layer were again varied with $\alpha(A)$ held constant at 0.01. A snow layer with a reflectance of 0.80 would yield $\rho(C)$ of 0.83, nearly the same as for the case of clear ice, and $\tau(C)$ of 0.16. An upper layer of lower reflectance, $\rho(A) = 0.20$, would yield $\rho(C) = 0.50$ and $\tau(C) = 0.48$. The high reflectance of the underlying snow-ice produces a higher $\rho(C)$ than for clear ice in a situation where $\tau(A)$ is high.

The above two examples should be sufficient to illustrate the coupling effect operating on a layered ice system. Bolsenga (1978) can be consulted for graphical displays of the computer runs. Reflected radiation in the 400–700 nm range was not measured in this study, so it is not known whether the $\rho(A)$ or $\tau(A)$ values in the above discussion are representative. The $\rho(A)$ values are similar to known values of ice and snow reflectance over the entire solar spectrum. The reflectance of clear ice in the 400–700 nm range can be inferred from several of the transmittance measurements given here. No transmittance measurements were taken through snow-ice, but $\rho(A)$ values for snow-ice in the 400–700 nm range can be roughly approximated from transmittance values for refrozen slush-ice detailed in Bolsenga (1978).

Summary and conclusions

A series of measurements of incident and under-ice radiation in the 400–700 nm range provides new information in a field where data are severely lacking. The transmittance of photosynthetically active radiation was examined through clear ice, refrozen slush, and brash ice.

As expected, snow cover played a very important role in radiation diminution. An increase in radiation transmittance due to melting snow on an ice surface was also noted. Diffuse extinction coefficients computed for combinations of clear ice, refrozen slush, and varying amounts of snow emphasized the effects of snow cover. In general, ice with thicker snow covers showed larger diffuse extinction coefficients without significant dependence on the relative amounts of total ice and refrozen slush.

A relationship between solar altitude and radiation transmittance was found, under certain circumstances, for refrozen slush. The diurnal dependence of radiation transmittance on solar altitude is not completely understood, but it is believed that the spectral reflectance characteristics of the ice surface, acting in combination with the balance between diffuse and direct radiation, play an important role. Changes in cloud cover significantly influenced radiation transmittance through clear ice when total sky cover changed from clear to cloudy. Varying visual appearance of the ice surface did not necessarily indicate significant changes in radiation transmittance.

Results of calculations from a simple two-layer model illustrate that even a thin snow cover overlying an ice layer exerts a profound effect on the overall transmittance and reflectance of the combination and this was verified by field data. The model also shows that ice layers with high reflectance exert some influence on the overall transmittance and reflectance if the upper layer (of snow, frost, etc.) has a reasonably low reflectance.

The data, in Bolsenga (1978) and as archived at the World Data Center A for Glaciology at Boulder, Colorado, U.S.A., provide additional information to the field of radiation transmittance through ice in the photosynthetically active range. It is also clear that much additional work is required before radiation transmittance in this range is adequately understood.

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