VIDAR HISDAL:

SNOW-SKY AND WATER-SKY LUMINANCE AT AN ARCTIC STATION

Abstract

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Luminance measurements of water-sky and snow-sky were carried out at Ny-Ålesund, Svalbard. The luminance of a well-developed water-sky is found to be about 40% of that of the adjacent snow-sky. Once the 'luminance level' of a comparatively pure snow-sky is reached, there is only a very slight further luminance increase towards zenith. This is in good agreement with FRITZ' theory as well as with the light conditions experienced during 'white-out' situations. By measuring the angular elevation of the border between water-sky and snow-sky and the height of the cloud base, good estimates are obtained of the distance to the corresponding border on the ground between snow surface and open water.

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Introduction

The brightness of clouds is strongly influenced by the light-reflecting properties of the ground below. A conspicuous example of this influence is observed when a low, even cloud cover is situated partly over stretches of open water, and partly over a snow-covered surface, a combination frequently found in polar regions. Water is a poor reflector and gives a low cloud brightness, whereas the strong reflection of snow results in high brightness of the clouds above. The dark part of the cloud cover is commonly called 'water-sky' and the light part 'snow-sky' ('snow-blink'), or sometimes 'ice-sky' ('ice-blink'). The two latter expressions have a practical, maritime background. At sea a whitish glare on low clouds towards

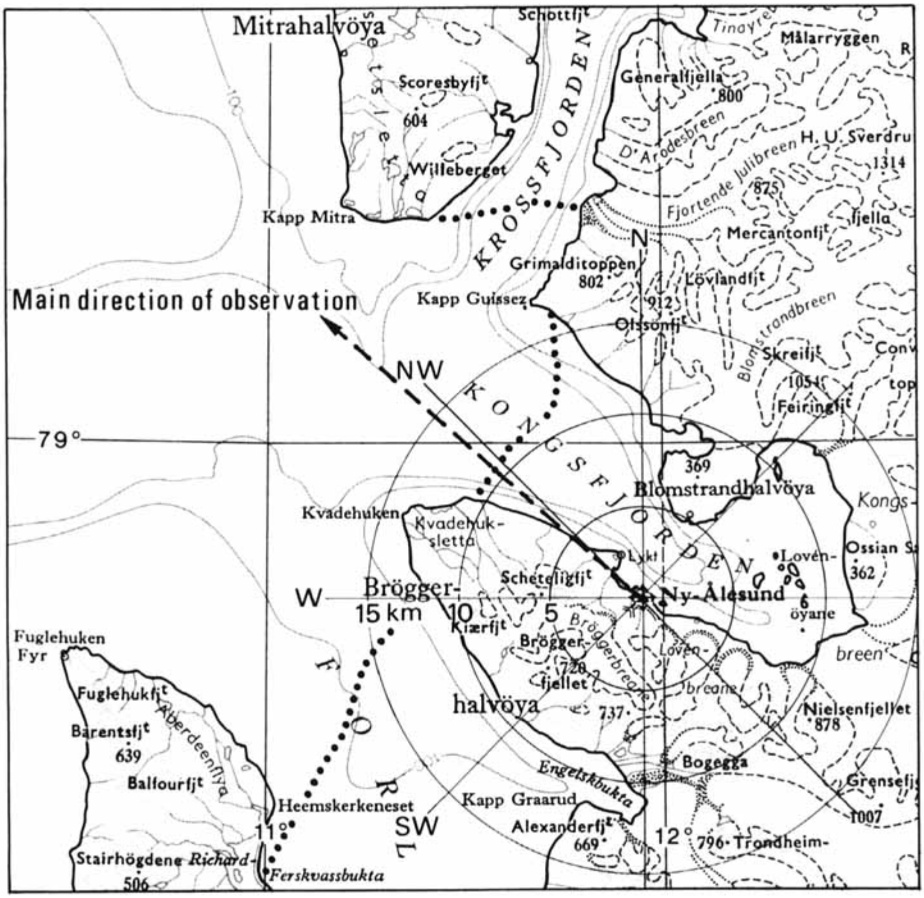

Fig. 1. Map of Kongsfjorden and surrounding areas, with indication of main direction of observation. Dotted curve shows a typical position of the edge of the fast ice (25 May 1979).

the horizon indicates that the sea below is covered by ice, the reflection of which is generally increased by a snow cover. Correspondingly, a water-sky may give very useful information to sailors surrounded by sea-ice and anxious to find open water.

A great number of qualitative descriptions of these brightness contrasts exists, particularly in reports from polar expeditions, whereas quantitative information is lacking.

In the following are presented the results of a series of photometric brightness, or more correctly, luminance measurements of a water-sky and the adjacent snow-sky. The observations were carried out during the months of May and June 1977-80 in Ny-Ålesund (78°55'N, 11°56'E) on the west coast of Spitsbergen.

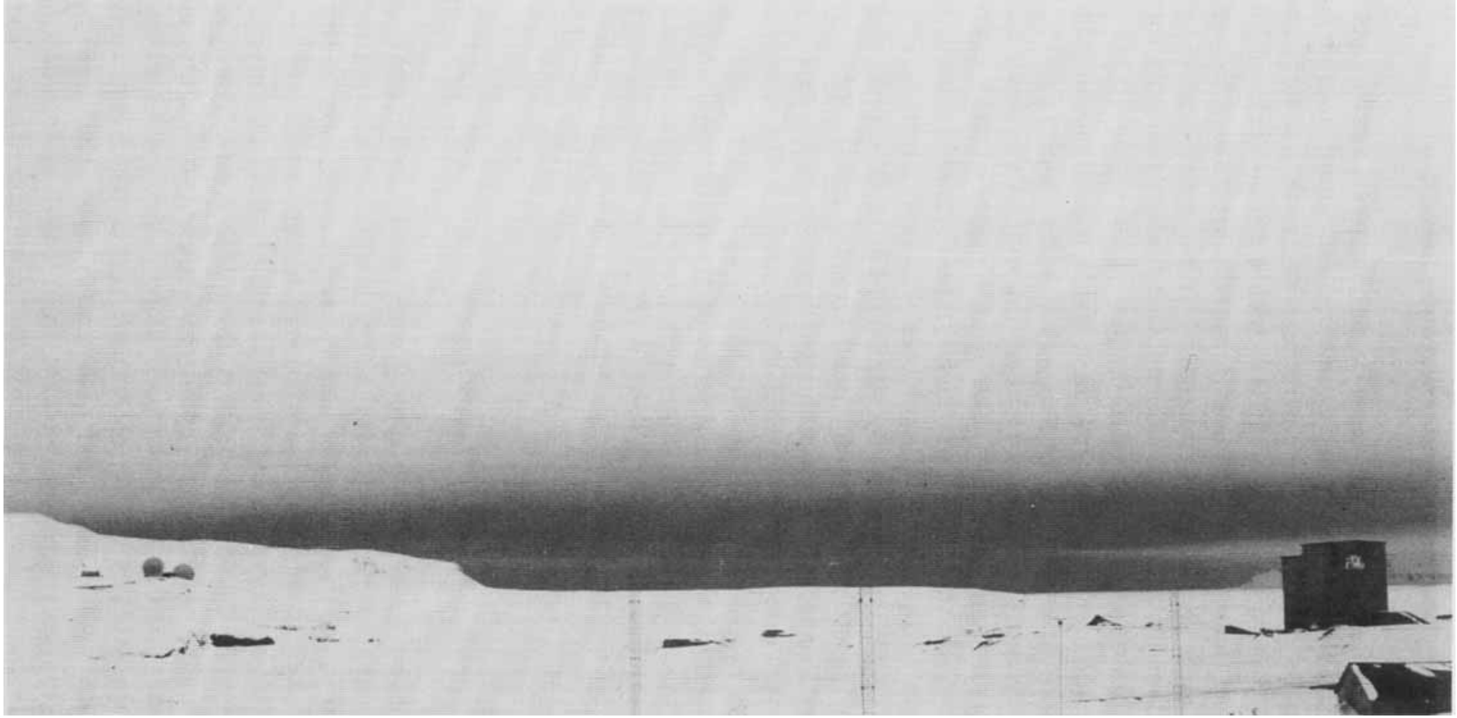

Fig. 2. Water-sky towards the mouth of Kongsfjorden (29 May 1979). The narrow, light stripe to the right in the water-sky is caused by reflection from the snow-covered Mitrahalvøya.

Instruments and observation method

The measuring instrument was a Hagner Universal Photometer (Model S2), which can be used both as luminance- and illuminance-meter, with silicone diodes as detectors. The instrument measures the luminance of a circular surface with a diameter of 1° (i.e. within a solid angle of $2.4 \cdot 10^{-4}$ steradians). The scales of the different sensitivity ranges give the luminance directly in candela per square metre (cd m^{-2}). The instrument was checked from time to time by comparing it with another similar laboratory instrument which was calibrated against a standard lamp.

The photometer was mounted on a stable tripod with angular scales, and could be rotated around a vertical as well as a horizontal axis.

The observations were carried out on the roof of the Research Station building in Ny-Ålesund, 15 m a.s.l. The great majority of the measurements were taken towards the mouth of Kongsfjorden, where the water-sky was most frequently seen, and the photometer was pointed along a direction slightly south of NW, as indicated on the map, Fig. 1. It appears that this is fairly close to the course of the northeast coast of Brøggerhalvøya. Therefore, the extent and reflection properties of the mostly snow covered ice on Kongsfjorden will evidently be of vital importance for the relationship between water-sky and snow-sky in this direction.

The luminance was read for a series of fixed elevation angles, and in some few cases continuous registrations were made by connecting the photometer to a Watanabe Miniwriter (Type WTR 721). Elevation angles were indicated on the registration paper by means of the marker channel of the recorder.

Discussion

Fig. 2 shows a photo of a typical water-snow-sky situation taken at about 18^h Apparent time on 29 May 1979. The height of the stratus base was about 600 m on this occasion, and the angular elevation of the border between water-sky and snow-sky above sea level horizon about 3.0°.

The full-drawn curves in Fig. 3 are examples of continuous luminance registrations from 15° below the horizon upwards to zenith. The upper curve shows the luminance variations of a relatively thin and uneven stratus cover. The far smoother curve in the lower part of the diagram is more representative of the large majority of the observation series, which was carried out during situations with a dense and even stratus layer. The snow-sky luminance appears to be practically constant from zenith almost down to the horizon. The sharp luminance drop close to the horizon, due to the water-sky, is clearly apparent in both cases.

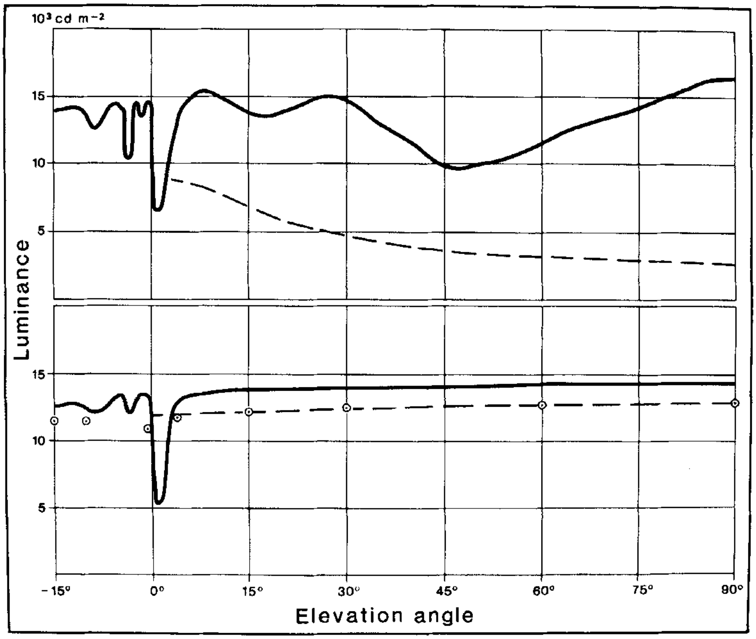

Fig. 3. Continuous luminance records from 15^{0} below the horizon upwards to zenith. Upper diagram: unbroken line - thin and uneven stratus, broken line - clear sky. Lower diagram: unbroken line - dense and even stratus, rings - mean luminance values for nine selected cases, broken line - theoretical values.

The narrow minima of the ground luminance (negative elevation angles) in Fig. 3 are due to a snow-free patch (only upper diagram) and a thick, insulated pipeline above the ground, which does not fill the whole photometer aperture. The broad minimum in the region -6^{0} to -10^{0} is caused by a depression in the snow surface along the north side of an adjoining house.

At an elevation of 0.8^{0} it may be assumed that the whole photometer aperture is entirely filled with water-sky. This applies to all observed cases. (The local horizon in the direction of observation has an elevation angle of 0.25^{0}. To this angle we have to add the radius of the circular aperture of the instrument, i.e. 0.5^{0}).

Even though the border between snow-sky and water-sky may look surprisingly well defined, a certain smoothing effect is of course present. Particularly near this border line the snow-sky is influenced by the adjacent open water, and, correspondingly, the water-sky by the adjacent snow surface. In addition, the observed luminance variations are somewhat smoothed out because of the obvious fact that the photometer's angular aperture has a certain magnitude.

Table 1 shows the individual measurements. The elevation range from - 0.5° to +15° is considered, i.e. the luminances of the snow surface just below the horizon of the water-sky (+0.8°), up to those of a 'nearly pure' snow-sky (+15°). The daytime snow surface luminance at - 0.5° is, on an average, 97% of that observed near the measuing site (at - 15°), and the luminance at +15° is 96% of that found for the zenith sky. The percentages are even higher for the evening observations.

On some days several observation series were carried out, but only one is entered in the table (the one taken most close to noon). Apart from a change of luminance level due to variation of solar altitude and presumably slowly varying cloud thickness, the relative luminance variation with elevation angle, and especially the relation between water-sky and snow-sky luminance, are practically constant. This suggests that marked changes of these characteristics from one day to another indicate corresponding marked inequalities between one or more of the elements determining the light conditions.

Specifications of the weather situations during the observation periods are not included in the table. In all cases the wind force was weak to moderate, and the sky was completely covered by a stratus layer, which was mostly very dense and even. The height of the cloud base ranged from 150 m to 900 m, with an average of 540 m. In about 60% of the cases the topmost layer of the snow cover was less than one day old. It was difficult, on the basis of our data, to find clear-cut connections between the cloud luminance contrasts, on the one hand, and the height of the cloud base or the age of the snow surface on the other. In agreement with common experience, the observations show that differences on the attenuation effects of the cloud layers from one case to another may influence the luminance conditions more than even large differences in solar altitude do.

Table 1 shows that even though the luminance level may vary quite considerably from one situation to another, the variation of the relationship between water-sky and snow-sky luminance (Q) is not very great, ranging from 37% to 55%. This latter variation may be caused by such factors as the extent and age of the snow cover, and the quantity of drift ice present in the ocean outside the ice edge. In this connection we refer to June 1978, which was distinguished by the lowest day luminances. It is certainly not a coincidence that this, at the same time, is the observation period with by far the smallest extent of fjord ice. The whole outer part of the fjord was open, while the ice of the inner part was covered with relatively dark, melting snow. This strongly reduced the snow-sky luminance, which to a large extent had to be due to light reflected from the snow cover of the adjacent land area. On the other hand, the conditions during this period gave unusually pure, dark water-skies. The Q-values are therefore low.

Table 1

Luminance values (in 10^3 cd m^{-2}) for different elevation angles (γ).
Q is the relation (in per cent) between water-sky and snow-sky luminance

			Elevation angle (γ)				
Date	Approx. time	Solar altid.	- 0.5° Snow surf.	0.8° Water sky	4°	15° Snow sky	Q
DAY:							
1977							
26 May	1021	31.0°	12.0	6.5	12.0	12.5	52
2 June	1025	32.1°	15.5	6.5	15.0	15.5	42
8 June	1234	33.8°	14.5	6.0	15.0	15.0	40
16 June	1058	33.9°	14.5	6.5	15.5	13.5	48
1978							
16 May	1357	28.5°	11.5	5.5	14.5	15.0	37
1 June	1010	31.6°	6.8	3.2	7.4	7.6	43
5 June	1030	32.7°	8.5	4.2	10.0	10.0	42
7 June	1349	32.4°	6.7	3.5	9.0	9.4	37
10 June	0949	32.1°	7.5	4.0	8.6	9.0	44
11 June	1124	34.0°	8.0	4.0	10.0	10.0	40
1979							
22 May	1031	30.4°	14.0	8.0	13.5	14.5	55
23 May	1103	31.1°	15.5	7.5	13.5	15.0	50
30 May	0921	30.0°	14.5	5.6	11.5	13.0	43
13 June	0758	28.3°	8.5	6.5	12.5	13.5	48
1980							
14 May	1212	29.5°	12.0	5.5	12.5	13.0	42
EVENING:							
1977							
31 May	1715	23.8°	10.0	5.5	10.0	10.5	52
1 June	2100	13.9°	4.8	1.9	4.8	5.0	38
1979							
29 May	1801	21.0°	9.5	4.5	7.5	9.5	47
2 June	1830	20.3°	7.0	3.5	6.5	7.5	47

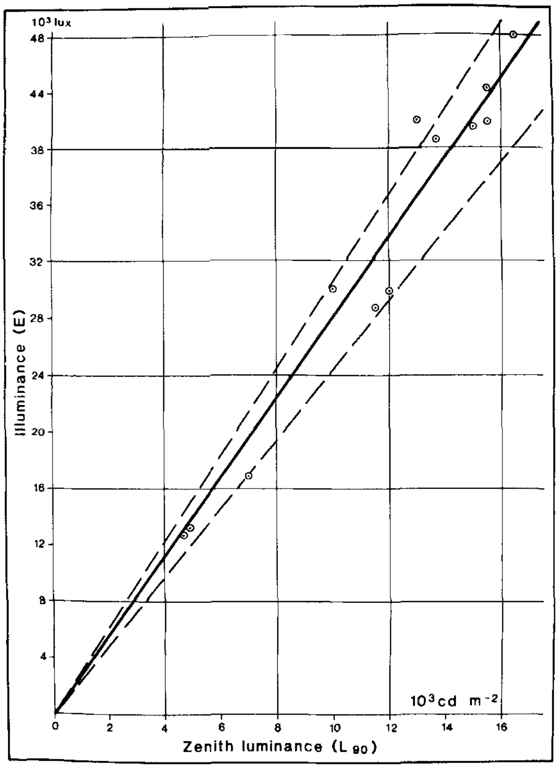

Fig. 4. Relation between illuminance (E) and zenith luminance (L_{90}). Rings - observed values, unbroken line - linear regression of E on L_{90}, upper broken line - theoretical function with a light albedo of 0.90, lower broken line - the CIE function.

On nine days in all, water-sky versus snow-sky luminances were also measured over the glacier passes towards the SW and WSW (see map, Fig. 1). The water-sky was here due to open water in the northern part of Forlandsundet. The magnitudes and variations of the luminance did not deviate essentially from those observed towards the NW, and the data are not included here. In cases with simultaneous measurements in both sectors, the snow-sky as well as the water-sky luminances over the glaciers were somewhat higher than those measured towards the NW. The value of Q varied even less than in Table 1, ranging from 40 to 50%.

Judging from our measurements, the luminance of a well developed water-sky near the horizon is about 40% of that of the adjacent snow-sky ($\gamma \approx 15^{\circ}$). For nine days in all (two in 1977, five in 1978, and one for each of the years 1979 and 1980) the Q-values stayed below 44%, indicating close to 'optimal' luminance contrasts. All these situations were characterized by a very even stratus layer, and most of them by new snow. The mean luminances for the nine cases are shown in Table 2 and are entered as small circles in Fig. 3 (lower part). These means are situated fairly close to the luminance curve shown in the same part of the diagram. Once a 'snow-sky luminance level' is reached, say for $\gamma = 10^{\circ}$, there is only a very slight further increase towards zenith.

The average luminance of the nine selected situations also illustrates the fact that the observed luminance of the snow-covered ground is a very high percentage of that of the cloud base, 90 to 95%. The albedo of total solar radiation, recorded near the station during the same periods, stayed in the interval 70 to 80%. This difference may be attributed to two factors. First, the spectral properties of the snow's reflectivity involve that the 'illuminance albedo' is appreciably higher than the albedo of total solar irradiance (see e.g. GRENFELL et al. 1977). Second, as revealed by several test measurements, snow-sky luminances for directions away from the ocean, may be notably larger than the corresponding values measured towards the ocean, especially if there are areas of open water in the vicinity. The previously mentioned low luminance values found during June 1978 are a clear example of this effect. In other words, the luminance of the northwesterly sector of the sky is generally smaller than the integrated luminance of the whole celestial hemisphere.

Some comparative considerations

Clear sky

For the sake of comparison a few measurements of clear-sky luminance were made in May 1981. They were taken during the middle of the day, the mean solar altitude being slightly below 30°. As is well known, the luminance of a clear sky is highly dependent on both elevation angle and azimuth. We here confine ourselves to giving the means of some measurements taken towards the ocean, along a vertical with azimuth deviating about 90° from that of the sun. As shown by the broken line in the upper part of Fig. 3, we found an average luminance of $2.7 \cdot 10^3$ cd m^{-2} at zenith, increasing gradually to about $7 \cdot 10^3$ when moving down to 15° above th horizon, and about $9 \cdot 10^3$ at 5°. Still closer to the horizon there was a flattening out or even a decrease of the luminance, no doubt caused by low-level turbidity, combined with fog or low stratus over the ocean.

The observations suggest that for a solar altitude around 30° the zenith luminance of a clear sky is only about one-fifth of that of an average snow sky. Near the horizon, at the azimuth specified above, the luminance of a clear sky is more than two-thirds of that of an average snow-sky and nearly twice that of an average water-sky.

Theoretical considerations

On a theoretical basis, Fritz (1955) arrived at a formula giving the luminance variation with elevation angle (γ) for a heavily overcast sky:

$$L_\gamma = L_{90} \frac{1 + b \sin\gamma}{1 + b} = L_o (1 + b \sin\gamma)$$

where L_{90} and L_o are zenith and horizon luminance respectively, and b is a function of the ground albedo (A):

$$b = \frac{3}{2} \frac{1 - A}{1 + A}$$

Using the average values $L_{90} = 12.8$ and $A = 0.90$ of the nine most well developed cases considered previously (Table 2), we obtain the broken curve shown in the lower part of Fig. 3. Down to $\gamma = 15^\circ$ the observed values are situated practically on the theoretical curve (deviation less than 1%) and the luminance of the lowest observed point on the snow-sky, at $\gamma = 4^\circ$, is only 1.7% smaller than that given by the formula. It appears that the luminance becomes nearly independent of γ when the ground albedo approaches unity. That this is in accordance with reality, is dramatically demonstrated in nature by the phenomenon called 'white-out', which is characterized by practically isotropic light conditions.

Zenith luminance versus illuminance

On twelve days with an even stratus cover simultaneous measurements were made of zenith luminance and the illuminance (E) on a horizontal surface, the latter quantity being given by the relation

$$E = \int_{\varphi=0}^{2\pi} \int_{\gamma=0}^{\pi/2} L \sin\gamma \cos\gamma \, d\gamma \, d\varphi$$

where generally L is dependent both on γ and azimuth (φ). Due to practical difficulties (only one instrument and one observer) there was a time difference of one to two minutes between the readings of L_{90} and E.

The result is shown in Fig. 4. Most of the observations were taken during the middle of the day. Only the two lowermost points in the diagram represent evening observations. Taking into consideration the above mentioned time lag as well as other disturbing factors, the correlation between the two elements is unexpectedly high: 0.98. The linear function of L_{90} that gives the 'best' estimate of E is assumed to be the one that, in addition to fulfilling the requirement $E = 0$ for $L_{90} = 0$, is fitted to the observed points in the least square sense. The result is:

$$E = 2.81\ L_{90}$$

This expression is represented graphically as the mid-most (full) line in Fig. 4.

A more general, theoretical function of the same type may be obtained by integrating Fritz' expression for L_γ (see above) over the whole celestial hemisphere:

$$E = \frac{L_{90}}{1+b} \int_{\varphi=0}^{2\pi} \int_{\gamma=0}^{\pi/2} (1 + b\ \sin\gamma)\ \sin\gamma\ \cos\gamma\ d\gamma\ d\varphi$$

where L_γ is assumed independent of azimuth (φ). This gives:

$$E = \frac{\pi}{3}\ \frac{3 + 2b}{1 + b}\ L_{90}$$

With a light albedo of the snow surface equal to 0.90 we obtain:

$$E = 3.06\ L_{90}$$

If the albedo varies from 0.80 to 1.00, the coefficient of the equation does not change more than 5%, from 2.99 to 3.14.

Considering our limited number of observations, and hence the large sampling fluctuations to be expected, the difference between the 'observed coefficient' (2.81) and the theoretical one (close to 3.0) does not seem very great. Influences of possible calibration inaccuracies of the two partly independent systems measuring luminance and illuminance, respectively, should be mentioned in this connection as well.

There are also geophysical reasons for a somwehat lower 'observed coefficient'. As mentioned previously, the observed snow-sky luminance towards the sea are apt to be weaker than those measured towards the inland (i.e. $L\gamma$ is not sufficiently independent of φ). This leads to a comparatively low value of E in relation to L_{90}.

On the basis of observations made in lower latitudes, CIE (Commission Internationale de l'Eclairage) in 1955 adopted a standard equation representing the luminance distribution of a completely overcast sky, leading to the relation:

$$E = 2.44\ L_{90}$$

(cf. e.g. Krochmann et al. 1974). According to Fritz' theory this would imply b = 2, and an impossible negative ground albedo in the expression given above.

Table 2

Mean variation of luminance (in 10^3 cd m^{-2}) with elevation angle for nine cases with water-sky luminance less than 44% of snow-sky luminance (i.e. Q<44)

Elevation angle	-15°	-10°	-0.5°	0.8°	4°	15°	30°	60°	90°	Q
Mean luminance	11.4	11.4	10.9	4.9	11.7	12.1	12.4	12.7	12.8	40.5

A better understanding of the effects and discrepancies mentioned here might be obtained e.g. by making simultaneous luminance as well as illuminance measurements from a station on snow-covered surface and from a ship station in open water during situations with a stable, uniform stratus cover, both stations being situated at a sufficient distance from the dividing line between the two types of surfaces. Observations from a single moving station (aeroplane or helicopter) would probably give still better information. Such measurements would, in addition, make possible computations of the albedo of the cloud base for diffuse light from below.

Distance to border line between snow surface and open water

The distance to the border between the snow surface and open water may be estimated by means of the angular elevation of the corresponding border between snow-sky and water-sky, and the height of the cloud base. On eight days with well-defined, nearly horizontal borders between water-sky and snow-sky, all three quantities were observed, which make possible a comparison between estimated and true distances.

The cloud base was in all cases so low that the height could be judged fairly accurately by means of the surrounding mountains. The elevation angles were measured by using the angular scale in the photometer's viewfinder, while the position of the border between open water and the snow surface was determined in relation to characteristic topographic features by direct observation from nearby elevations, and by satellite pictures. The distances ranged from 3 to 11 km.

Also, a few estimates were made of the distance to the centre line of Mitrahalvøya (cf. map Fig. 2), using the angular elevation of the snow-sky stripe caused by this peninsula (see Fig. 1). As the distance is comparatively large, minor corrections were made for terrestrial refraction and the earth's curvature.

It is less interesting to discuss the individual cases in this connection. The main result was that the calculated distances were all within ±10% of those measured on the map. This suggests that even with quite simple observations and calculations, useful estimates of the distance to the border between snow and water may be obtained.

Acknowledgement

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