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Radiation measurements above and in forest

Strålningsmätningar över och i skog

by

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ABSTRACT

The report deals with radiation measurements made from aircraft over different kinds of surfaces and on the ground in different types of forest.

With the results of the measurements as a basis, the distribution of the radiation energy in two different types of forest is then discussed. A short report of the general structure of the radiation is also given (part 2).

The measurements from aircraft consisted solely of shortwave radiation (0,3—4 μm), whereas the measurements made on the ground consisted partly of shortwave radiation and partly of total net radiation (0,3—60 μm). The measurement sites are situated on latitudes 60, 63, 66 and 67 degrees North.

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1. Introduction and object of the investigation

1.1 Introduction

Forest climatological research has for a long time been carried on at the Royal College of Forestry. One of the purposes is to elucidate which local and microclimatological factors that ought to be considered when planting forest. The investigations also include comparative studies of a number of meteorological components in clearings and in forest in different parts of the country. Climatic differences between clearing and forest are compared with corresponding climatic differences between treeless mountain plateau and forest. Clearing and forest are divided by an artificial limit, whereas treeless mountain plateau and forest are divided by a natural limit. This natural forest limit depends partly on climatological and partly on topographical factors.

The author has since the autumn of 1964 carried on climatological measurements concerning temperature, wind velocity and wind direction, air humidity, evaporation, depth of snow and density of snow on each side of the forest limit. Certain special measurements have also been made, for example an investigation of the temperature profiles up to a height of about 100 metres.

The forest limit's dependence on the topography has been studied by aid of air-photos and the forest limit's altitude above sea-level is mapped out. Further the inclination and direction of exposition have been investigated at points chosen randomly at the forest limit. The forest limit's altitude above sea-level (depending variable) is then connected with inclination and direction of exposition. The material is processed by aid of a computer.

Attention has been paid to the radiation, which is a primary factor in nature's heat and water balance. In the summer of 1965 Mr. Hans Odin and the author made a radiation investigation from which the results are shown in ODIN & PERTTU (1966). The present paper, which also gives an abbreviated description of the general structure of radiation, is also dealing with further radiation measurements, made in the spring and summer of 1966. The measurements have been made partly from aircraft and partly on ground in some different parts of Sweden.

1.2 Object of the investigation

In order to determine a forest's total absorption power of shortwave radiation, its albedo (reflectivity) has to be measured above tree top level, in other words from aircraft. These measurements can then be connected with corresponding measurements made on ground in forest. One will then get an idea of the distribution of radiation energy in forest.

The total net radiation for forest compared with open ground can also be estimated from measurements made on ground.

The object of the present investigation can consequently be summarized as follows:

To determine the average albedo for different kinds of surfaces, such as forest of different density and in different parts of the country; these measurements were made from aircraft.

To determine the reflected as well as the incident global radiation's dependence of the instrument height; this was afterwards used for correcting the radiation values to ground surface level.

To compare the ground's total net radiation during day in forest to that on nearby lying open ground.

To compare the total net radiation at night in forest of different density to that on nearby lying open ground.

2. The general structure of radiation

Before the measurements and the results from this investigation are presented, a short statement of the radiation from the meteorological point of view will be given below.

Electromagnetic radiation is a process through which energy is transported without participation of any medium. From each substance radiation is emitted which partly is dependent on the nature of the substance and partly on the temperature of the substance. A warmer substance emits radiation of greater intensity than a colder (LILJEQUIST, 1962).

A black body, i.e. a body which absorbs all the electromagnetic radiant energy that falls upon it, will emit radiant energy which only depends of the temperature of the body. The total radiant energy from such a body is obtained by Planck's law. From Wien's displacement law the wave length for the maximum point of the spectral curve will be obtained if the temperature of the body is known. Solar radiation or short wave radiation has its maximum at 0,5 μm, because the surface temperature of the sun is about 6000 °K. Terrestrial radiation or long wave radiation has its maximum at about 10 μm, because earth's temperature is of the magnitude of 300 °K. Fig. 1, p. 8, shows broadly the different wave lengths of the electromagnetic spectrum.

2.1 Short wave radiation

The shortwave radiation derives from the sun, from the stars and by reflection from the moon. It reaches the earth's surface within the short wave region of 0,3—4 μm. About 7 per cent of the short wave radiation consists of ultraviolet light and 47 per cent of infrared radiation. Below 0,3 μm all radiant energy is absorbed by the oxygen and ozone of the atmosphere. Radiation below 0,3 μm is harmful to the plants because of its being too rich of energy at the photosynthesis-process. Radiation of wavelength beyond 1,5 μm is on the contrary lacking too much of energy for photosynthesis. This part of the radiation is in the first place used for heating. In Fig. 2, the short- and long wave radiation's electromagnetic spectra beyond the atmosphere and at the earth's surface is shown.

The sun provides for about 99,97 per cent of the heat energy that is needed for the physical processes in the system earth-atmosphere. The flow of energy per unit area just beyond the earth-atmosphere is 2,0 ly/min (cal/cm^{2}min) with the fluctuations $\pm 1,5$ per cent around mean value. Most fluctuations occur in the ultraviolet part, see Fig. 2.

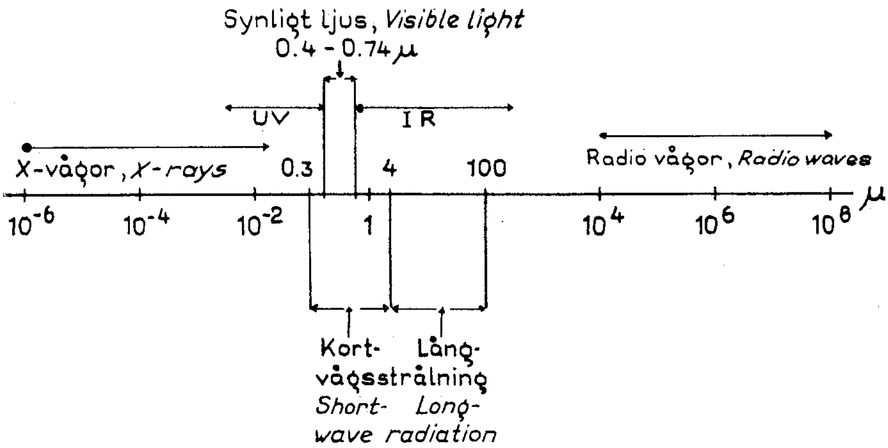

Fig. 1. The electromagnetic spectrum. X = roentgen, UV = ultraviolet, IR = infrared, $\mu = 10^{-6}$.

If the sun is assumed to be a black body, it is applicable that the sun's energy flow E according to Stefan-Boltzmann's law is

(1) $$E = \sigma\, T^4$$

where σ is a constant $= 0{,}826 \cdot 10^{-10}$ and T is the sun's surface temperature in °K. E is then expressed in ly/min.

During the passage through the earth atmosphere, the intensity of the solar radiation decreases by absorption, reflection and scattering. The absorption occurs in the first place in water vapour, carbon dioxide and ozone. The reflection mostly occurs in clouds and dust particles. The scattering is caused by air molecules (so-called Rayleigh-scattering) and dust particles.

The shortwave radiation at ground surface consists partly of direct solar radiation I and partly of diffuse radiation D, which is caused by reflection and scattering (see above). The radiation upon a horizontal surface, named global radiation G, can thus be written.

(2) $$G = I \sin h + D$$

where h is the sun's altitude above the horizon. The diffuse radiation's part of G varies with the season and with the cloudiness. In Stockholm, G consisted during the years of 1905—1926 in December of 87 per cent and in July of 19 per cent of diffuse radiation. The average for May—August was

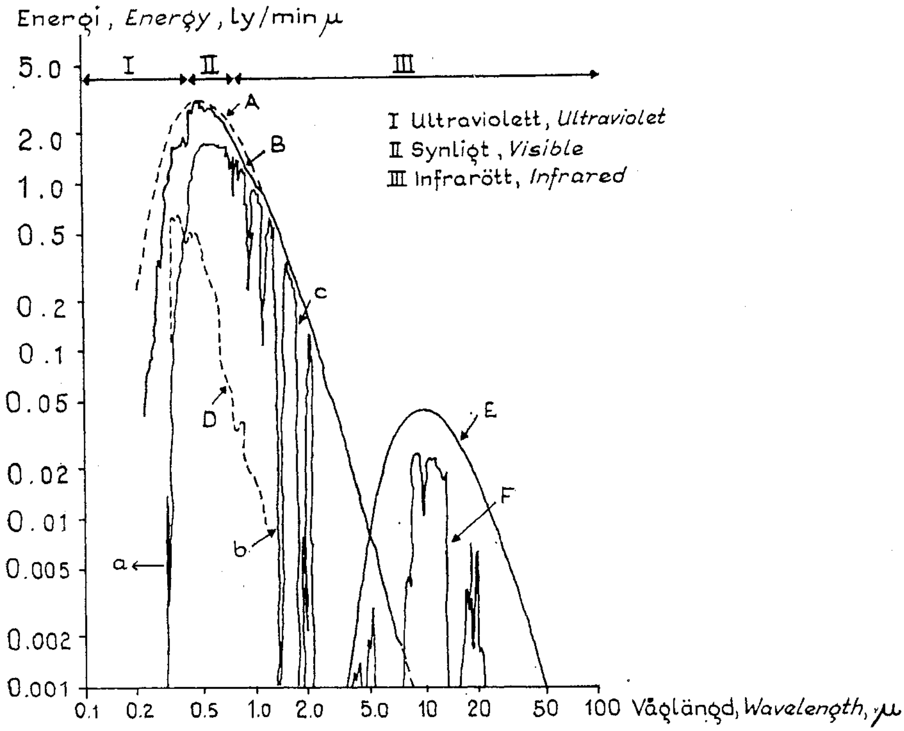

Fig. 2. Electromagnetic spectra of short- and long-wave radiation. (After Sellers).
A = Black body radiation 6000°K (2,3 ly/min)
B = Extraterrestrial solar radiation (2,0 ly/min)
C = Direct solar radiation at the earth's surface (1,3 ly/min)
D = Diffuse solar radiation at the earth's surface (0,14 ly/min)
E = Black body radiation 300°K (0,67 ly/min)
F = Estimated infrared emission to space from the earth's surface (0,10 ly/min)
a = Oxygen and ozone absorption
b = Absorption bands of water vapour and carbon dioxide

23 per cent and for the whole year 44 per cent (SUTTON, 1953). When overcast the term I sin h is zero. D is then 20—25 per cent of the radiation at clear sky. At clear sky D contributes with about 15 per cent to G, provided that the sun is not too near the horizon.

When a beam of sunlight strikes a rough surface it becomes subject to diffuse reflection by which the reflected parts are scattered in all directions (SUTTON, 1953). The reflection ability or albedo A is the relation between the reflected global radiation G_r from the surface and the incident global radiation G against the surface according to:

(3) $$A = G_r / G$$

A is generally stated in per cent. Clouds and snow areas have very high albedo values. According to SELLERS (1965) fresh fallen snow reflects 75—95 per cent, snow, several days old 40—70 per cent, ocean ice 30—40 per cent, stratus clouds 59—84 per cent and cumuliformed clouds 70—90 per cent. Forest areas reflect between 5—20 per cent, depending on kind and density of the forest, see also Table 5, p. 23.

Usually a wet surface has a lower albedo than a corresponding dry surface. This depends partly on increased absorption in the thin water film. The lower albedo value of the wet surface depends, however, mostly on total reflection inside the water film (SUTTON, 1953).

The vegetation affects the shortwave radiation in different ways. According to SUTTON (1953) reflection, absorption and transmission for early summer leaves with relatively high water content was 19, 56 respectively 25 per cent and for late summer leaves with relatively low water content, 29, 38 respectively 33 per cent. Dense forest had an incoming shortwave radiation at ground of one per cent of the radiation on open ground. The equivalence in sparse forest was 4—7 per cent. The ground surface underneath a one metre thick layer of grass obtained about 18 per cent of the shortwave radiation measured just above the grass.

The terms dense and sparse are naturally relative conceptions. Nevertheless they show the dimensions for different kind of vegetation. Consequently the ground surface inside vegetation obtains less energy than open ground. A great deal of the heat energy upon ground has to be transported through other systems, e.g. conduction and turbulence.

2.2 Longwave radiation

Longwave radiation which covers the wavelength region of 4—100 μm is emitted from the earth surface and from the atmosphere. The effective outgoing longwave radiation from a horizontal ground surface can be written

(4) $$E_{eff} = E_m - E_a$$

where E_m is the radiation from the ground surface and E_a the radiation from the atmosphere upon the ground surface.

The earth surface is usually assumed to be a grey body, the Stefan-Boltzmann's law p. 8 will be

(5) $$E_m = k\sigma T^4$$

where k, the emissivity of the earth surface, is ≤ 1. For a black body k

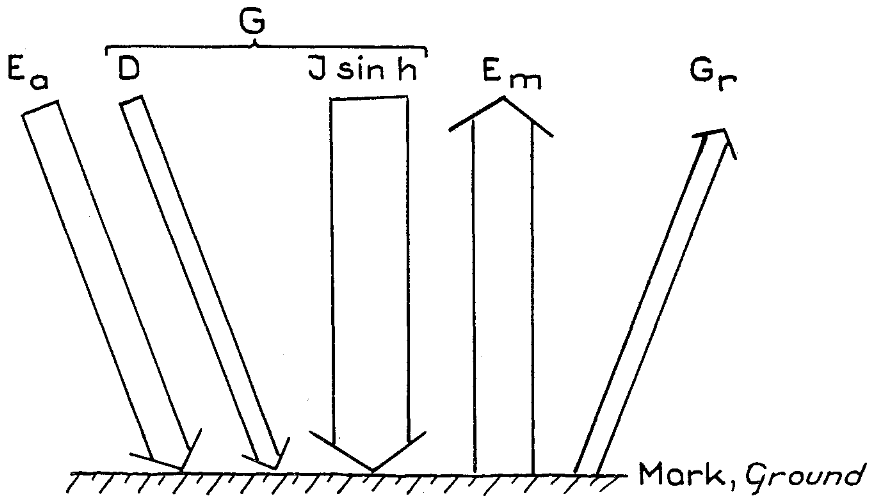

Fig. 3. The components of the total net radiation at a smooth surface.
Ea = long-wave radiation from the atmosphere
D = diffuse short-wave radiation
I sin *h* = direct solar radiation, *h* = sun's altitude
G = *I* sin *h* + *D* = global radiation
Em = $k\sigma T^4$ = long-wave radiation from the ground, k $\leq$ 1
Gr = reflected global radiation

is = 1. Practically all natural surfaces have an emissivity of 90—95 per cent (SELLERS, 1965). The emissivity is for example for water 92—96 per cent, for fresh fallen snow 82—99,5 per cent, for pine forest 90 per cent and for dry grass 90 per cent. The above mentioned figures are, however, only standard values.

The amount of energy which is emitted and absorbed by the atmosphere is defined by the amount of water vapour, carbon dioxide and ozone in the atmosphere. These gases absorb practically all energy at certain wavelengths and hardly any at others. This causes the atmosphere between 8 and 13 μm to be almost entirely translucent to longwave radiation. The maximum for longwave radiation from the earth's surface lies in this region, see Fig. 2, p. 9.

The effective longwave radiation can also be calculated by empirical formulas. Several of such formulas are to be found in the litterature (SELLERS, 1965). The most wellknown have been carried out by Ångström and Brunt.

Ångström's equation reads:

(6a) $$E_{eff} = k\sigma\, T^4\, (1 - A + B \cdot 10^{-Ce})$$

where A, B and C are constants which vary from one investigation to another. According to SELLERS (1965) the values are as follows:
$A = 0.820$, $B = 0.250$ and $C = 0.094$. Brunt's equation reads:

(6b) $$E_{eff} = k\sigma\, T^4\, (1 - a - b \cdot \sqrt{e})$$

where the constants at different investigations have got different values. The average value from 22 different investigations give that $a = 0.605$ and $b = 0.048$. In both formulas T is the temperature near the earth's surface in °K and e the vapour pressure in millibar. Diagram 10 in ODIN & PERTTU (1966) shows both measured values and values calculated by Ångström's formula. The values correspond rather well with each other.

2.3 The total net radiation

The total net radiation E_B at the earth's surface is defined by the incident energy from the sun and the emanent energy from the earth's surface according to the formula:

(7) $$E_B = (1 - A)\, G - E_{eff}$$

where A = albedo, G = global radiation and E_{eff} = effective longwave radiation. The net radiation can either be calculated or measured directly. At night E_B is defined solely by E_{eff} since the global radiation G then is zero. In Fig. 3, the components of net radiation have been drawn.

3. Albedo measurements from aircraft

3.1 Method of measurement

For a well defined surface, i.e. a smooth, horizontal surface, the albedo (reflectivity) can be calculated from measurements made on the ground. In order to obtain an idea of the energy exchange over less welldefined surfaces, for example forest, it is desirable and important to be able to calculate the albedo also for these surfaces. From measurements made above tree top level, i.e. from aircraft, an average albedo can be calculated for different kind and density of forest. Unfortunately very few measurements have so far been made in this area according to the great costs and difficulties which are combined with the realization of these kind of measurements. Thanks to the obligingness of the Swedish Air Force by the wings in Luleå, Uppsala and Östersund, the author was, however, able to carry out air measurements at some different places in Sweden.

The incoming and from the surface reflected global radiation within the shortwave region of 0,3—4 μm was thus measured from aircraft. The radiation energy is indicated as above in gram calories per cm^2 and minute or langley per minute (ly/min).

During the measurement the instruments are affected by radiation within the total "aperture angle" 180°. This applies to both the incident and the reflected global radiation. Since it is impossible to describe an area which lies within the "aperture angle" 180°, the part of the earth's surface that lies within 140° "aperture angle" has been chosen to represent the qualities of the earth's surface regarding the reflection. This area whose size and radius depends on the instrument height, is here called the described reflecting area. Table 1 shows the size and radius of the described area for some instrument heights. It has to be observed, however, that the instruments measure over the total "aperture angle" 180°, but that the reflecting area only "is described" within the "aperture angle" 140°.

The measurements from aircraft were made over different kinds of surfaces. The observer had during the flight the possibility of directing the plane to different areas by radio contact with the pilot. Since the radiation meters that were used here are rather slow (about 30 seconds from zero to full deflection), the flight was made over a similar surface during such a long time that the meters had time to stabilize. It has to be indicated that the slowness of the meters in practical application is less than 30 seconds, since they don't need to be adjusted from zero to full deflection at each reading but only from one reading to another relatively nearby lying reading.

Table 1. The size and radius of the described area for different instrument heights.

Instrument height H	Described reflecting area	Radius R
1.0 m	25 m^2	2.75 m
1.5 m	53 m^2	4.13 m
50 m	62 000 m^2	138 m
100 m	240 000 m^2	275 m
200 m	950 000 m^2	550 m
0.5 km	6.2 km^2	1.38 km
1.0 km	24 km^2	2.75 km
1.5 km	53 km^2	4.13 km
2.0 km	95 km^2	5.50 km
2.5 km	150 km^2	6.88 km
2.8 km	180 km^2	7.70 km

The speed of the aircraft during the measurements varied between 55 and 65 metres per second. The solarimeters were therefore adjusted to a *mean value* over the area where the measurement was made. Repeated flights were also made over the same surface. This ought to give a satisfactory *mean value of the reflected global radiation for all kinds of surfaces.*

The measurements were made from the 20th of April to the 17th of June in 1966 and consisted of nine different flights in all, five near Uppsala, two near Luleå, one near Östersund and one Luleå—Gällivare—Luleå. On the map p. 44 the approximate position of the different places is given.

3.2 Instruments

The instrumentation consisted of two Kipp and Zonen solarimeters, one directed upward and the other one downward. They were attached to each wing of a plane of type Sk 16. From the meters cables were drawn to the cabin where the observer made the readings on a millivoltmeter. By the aid of a transducer selector the desired solarimeter could quickly be switched on to the millivoltmeter and a reading could be made.

During the flights five different solarimeters had to be used. At the landing on a grass field after measurement No. VIII, the alighting was so violent, that the solderings inside both of the meters got loose. On another occasion, when both the solarimeters and the reserve solarimeter were compared with each other (this was done before and after every flight), one of the meters showed a somewhat different reading than the other ones. This meter, as well as the two that broke, was naturally exchanged.

All the solarimeters, as well as the millivoltmeter, were before and after the measurements calibrated against Ångström's pyrheliometer at the Swedish Meteorological and Hydrological Institute (SMHI). The results are therefore *entirely independent* of which one of the meters that was used.

The solarimeters were attached to the place of the lanterns at the further end of the wings, one of them over and the other one under the wing. The installation was fairly simple to do. It seemed as if the metal bodies of the solarimeters undoubtly had assumed the air temperature during the flights. By horizontal flight the solarimeters were calculated to be fairly exact in horizontal position, see also p. 19.

The reasons why the above mentioned type of solarimeters were used are many. As mentioned earlier they are rather slow. This slowness was favourable in such a way as the meters set themselves in a *mean value* over the surfaces concerned. The small fluctuations consequently disappeared and without more advanced aids, the observer would not in any case have had the time to notice them.

Reflections from the aircraft upon one or the other of the solarimeters could be completely eliminated. Coverings of exhaust-gas and such things on the globes could also be completely eliminated. In order to remove any covering that may have appeared when the plane had been standing on the ground, the globes were furthermore cleaned before every flight. The turbulence at the upward- and the downward directed solarimeter was different, but this is probably of no importance, since the meters were thoroughly ventilated by the speed wind. The instrument constants can be regarded as being constant during the measurements, which the calibration before and after the measurements shows.

The strong ventilation of the meters (55—65 m/s) had no effect on the measurement result. A solarimeter, which was strongly ventilated at +2°C, was during a test (19/3 1968) compared with a control solarimeter. In order to increase the possible influence of the ventilation, measurements were also made when the external globe had been removed. The ventilated meter showed the measurement results $0{,}77 \pm 0{,}02$ ly/min, while the control meter showed $0{,}77 \pm 0{,}01$ ly/min. Neither the ventilation nor the removal of the external globe did consequently effect the result.

Kipp and Zonen solarimeter can be considered as one of the few radiation instruments, which is inexpensive, easy to install and at the same time so accurate, that it can be used for this kind of flight measurements.

3.3 Measurements

The different measurements are shown in the tables I—IX, p. 45—47. The reflected global radiation is represented as G_r and the incident global radiation as G. The instrument height above sea level for the measurements that were made near Uppsala is not indicated, owing to the fact that the

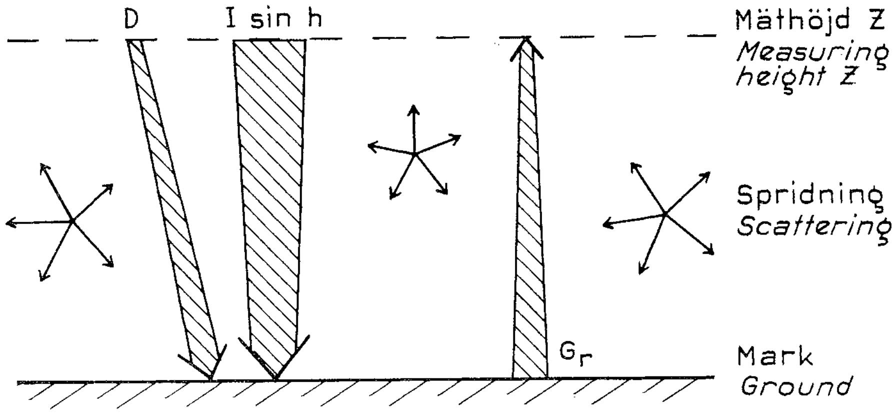

Fig. 4. The variation of the global radiation components with measuring height (schematic diagram).

difference, compared with the instrument height above the ground, is not worth mentioning. The cloudiness is indicated as eights of the cloud type concerned. Ci represents cirrus clouds and Cu cumulus clouds. In the column regarding the surface, the reflecting surface within the "aperture angle" 140° is briefly described. In the cases when this surface was forested, the density of the forest could only be classified as denser (sparser) than by the earlier reading of the millivoltmeter. During the measurements III and VI the described surface was only partly covered with snow. In these cases an estimation of the snowcovered part of the ground was made. Even though the method was far from satisfactory, a certain conception of the conditions on the ground was achieved.

3.4 Theoretical viewpoints

Both the incident and the reflected global radiation changes with the instrument height above ground. The incident global radiation's I-component (see p. 8) increases with the instrument height, while its D-component decreases. The variation of the global radiation is more complicated. The radiation, which is reflected from the ground, decreases upward on account of absorption, but instead the upward directed diffuse reflected radiation from the layer of air between the ground and the instrument height is added. The schematic diagram (Fig. 4) shows this.

Since the albedo is defined as the relation between the reflected and the incident global radiation, which are measured on the ground, G_r and G respectively must consequently be adjusted to the level of the ground.

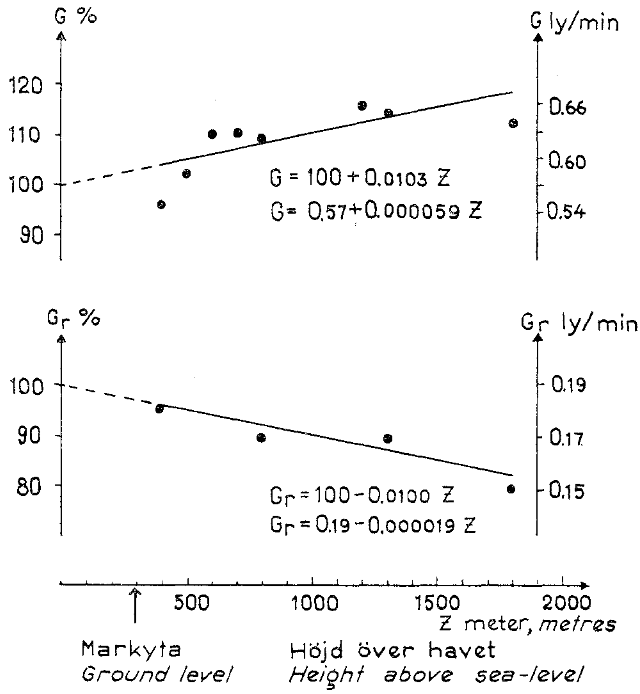

Fig. 5. The dependence of the incoming (G) and reflected (Gr) global radiation on instrument height (Östersund). Cloudless.

Flight No. IV (partly) and flight No. V were carried out in order to find out the magnitudes of these corrections for the present air measurements. The results from these flights are stated as linear regression lines in fig. 5—6. These regression lines have been calculated with the aid of the least squares. The first mentioned measurement, which was made near Östersund, was not quite representative for the height of 1500 metres above ground, owing to the fact that the horizontal area above which the measurement was made, was not large enough. The weather was also somewhat hazy up to a height of 200—300 metres above the ground. Flight No. V which was made over Bottenviken outside Luleå, was characterized by very homogenous conditions of the surface (clean snow with darker patches of ice). Unfortunately the sun was shaded by thin cirrus clouds. Owing to costs and difficulties in obtaining time for the flights it was not possible to make further investigations concerning the global radiation's variation with the height. The measurements above are, however, sufficient in order to find out the magnitudes of the corrections for these measurements.

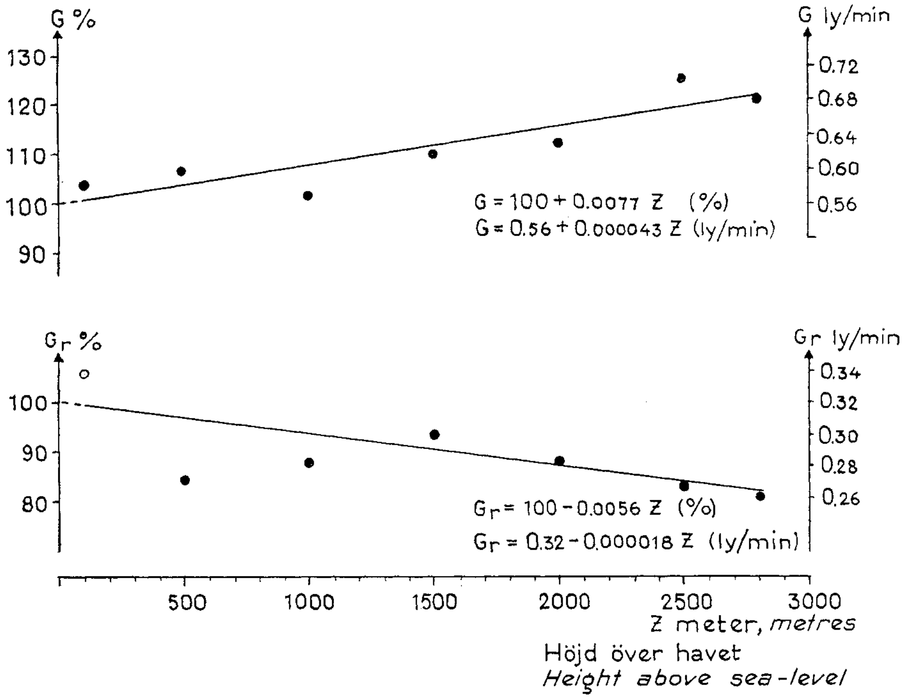

Fig. 6. The dependence of the incoming (G) and reflected (Gr) global radiation on instrument height (Luleå). Cirrus.

If index z represents the readings measured at the height of z and m the readings at ground level, one can write

$$G_z = G_m(1 + \alpha z)$$

$$(G_r)_z = (G_r)_m\ (1 + \beta z)$$

where α and β are constants. The albedo at ground level A_m will then be

$$A_m = (G_r)_m/G_m = (G_r)_z\ (1 + \alpha z)/G_z\ (1 + \beta z) = A_z\ (1 + \alpha z)/(1 + \beta z) \simeq$$
$$\simeq A_z\ (1 + \alpha z)\ (1 - \beta z) = A_z\ (1 + \alpha z - \beta z - \alpha\beta z^2)$$

From the equations for the regression lines (Fig. 5,) α and β are for the Östersund measurement +0.000103 and −0.000100 respectively.

Insertion in the equation above gives

$$A_m = A_z\ (1 + 0.000103\ \mathrm{z} + 0.000100\ \mathrm{z} + 0.000000010300\ \mathrm{z}^2)$$

The last term on the right hand side can be neglected up to a height of 2000 metres. It is then one order of magnitude less than the other terms, which contain α and β.

The equations of the regression lines (Fig. 6) gives A_m for the Luleå measurement to

$$A_m = A_z\,(1 + 0.000077\ z + 0.000056\ z + 0.000000004312\ z^2)$$

The last term on the right hand side can also here be neglected up to a height of 3000 metres.

Most measurements, apart from those mentioned above, were made at a height of 50—200 metres above ground level. The equations above for A_m show that the corrections up to a height of 200 metres are 3—4 per cent maximally. The uncertainty of the measurements for the rest can be considered to be less than one albedo per cent. The measurements have been adjusted to the level of the ground according to the formula

$$A_m = A_z\ (1 + 0.000168\ z)$$

which is the mean of the two formulas above, when the last terms have been neglected.

According to calculations and tests (the plane was lifted up to its flight position), the solarimeters had probably been lying horizontally during the measurements. In order to check if this had been the case, the incident global radiation measured from aircraft is compared with corresponding recorded mean values on the ground.

The measurements near Uppsala are compared with values from Ultuna, the measurements near Luleå with values from Luleå airport and the measurements near Östersund with values from Frösö airport. The comparison shows that all the values measured from aircraft, apart from Nos. V and VI, are of the same magnitude as the values recorded on the ground. Measurement V shows a too low value owing to the fact that the sun during the measurement was shaded by cirrus clouds. Measurement VI also shows a

Table 2. The incoming global radiation G measured from aircraft (see appendix, tables I—IX) and recorded on ground.

Measmt No.	Measured from aircraft ly/min	Recorded on ground ly/min	Comments
I	0.87	0.90	Ultuna
II	0.93	0.88	”
III	0.83	0.83	”
IV	0.55—0.63	0.65	Frösön
V	0.58*	0.80	Luleå; * cirrus
VI	0.66*	0.95	Luleå; * uncertain value
VII	1.11	~ 1.00	Ultuna, cloudy
VIII	1.11	~ 1.00	” ”
IX: A	0.98		
B	0.99*	0.92	Luleå; * cumulus
C	0.96		

Table 3. The calculated direct solar radiation (from tables I—IX). The diffuse radiation is assumed to be 15 per cent of the total incoming global radiation G.

Measmt No.	Altitude of sun h	sin h	Air-mass $m \simeq \frac{1}{\sin h}$	0,85 G ly/min	I ly/min	Comments
I	37	0.6018	1.7	0.74	1.23	Acceptable value
II	36	0.5878	1.7	0.79	1.34	,, ,,
III	35	0.5736	1.7	0.71	1.24	,, ,,
IV	30	0.5000	2.0	0.54	1.09	,, ,,
V	35	0.5736	1.7	0.49	0.85	Somewhat low value
VI	42	0 6691	1.5	0.56	0.84	,, ,,
VII	51	0.7771	1.3	0.94	1.21	Acceptable value
VIII	46	0.7193	1.4	0.94	1.31	,, ,,
IX: A	42	0.6691	1.5	0.83	1.24	,, ,,
B	43	0.6820	1.5	0.84	1.23	,, ,,
C	47	0.7314	1.4	0.82	1.12	,, ,,

too low value, in spite of a cloudless sky. This measurement has for that reason not been allowed to influence the results in table 4.

In order to make further investigations to find out if the values read in aircraft are correct, it is possible by aid of formula (2) p. 8, to calculate the direct solar radiation I for the different measurements. D can then be considered to amount to 15 per cent of G (see below). I is in fact dependent of the amount of water vapour, carbon dioxide, ozone, dust particles and cloud drops in the atmosphere, substances, which vary from one place to another. Table 3 shows that all the I values, apart from V and VI (see the previous), lie within the limits of what is to be considered as acceptable.

By clear weather with the sun rather high above the horizon, the diffuse radiation D can be considered to be about 15 per cent of the total global radiation G. In order to check this, the author made a measurement both of the direct solar radiation I (with Ångström's pyrheliometer), the global radiation G (with solarimeter) and the diffuse radiation D (the solarimeter was shaded for direct solar radiation). At the occasion for the measurement it was cloudless with moderate north west wind, temperature $+2°$C and the relative air humidity 39 per cent. The measurement was carried out in Stockholm on the 19th of March, 1968 at 12.38—12.53 by the mean solar height 29°. The direct solar radiation I had the value 1,24 ly/min. The values for G and D were 0,74 ly/min and 0,12 ly/min respectively. It is obvious that the diffuse radiation D amounted to 16,2 per cent of the total incident global radiation G. Further measurements regarding the diffuse radiation's part of G on latitude 65,8° North were made between July 30—August 1 1969. By relatively dense cirrus clouds D consisted of 20,7 per cent of G. A little later the same day, with very dense cirrus clouds, D's part of G had increased to 33,7 per cent. These measurements were made on July 30 at 11.20—11.55. Between 07.40 and 09.10 on the 31st of July, D's part of G increased from 12,7 per cent to 13,3 per cent. During the measurements the weather was clear apart from about one eighth cirrus at the north horizon. On the 1st of August the weather was quite clear, with very good visibility. Between 12.00 and 12.20 D's part of G was only 9,0 per cent. The assumption that D amounts to about 15 per cent of G by clear weather and the sun relatively high above the horizon, can consequently be accepted at the above mentioned discussion.

Naturally D's part of G varies with cloudiness and also with latitude in such a way that the visibility by cloudless weather in most cases is better in the north of Sweden than in the Stockholm region, according to less air pollutions in the first mentioned place. The above theoretical discussion can be summarized according to the following:

The present albedo measurements, mostly carried out on a height of 50—200 metres above ground level, must be adjusted to ground level. The values measured from aircraft are furthermore to be considered as acceptable.

3.5 Results and discussion

Table 4. p. 22, shows a statement of the albedo values for different kinds of surfaces. Thawing snow reflected 44—45 per cent of the global radiation, whereas thawing snow with darker patches of ice reflected 30—40 per cent. Snow-free coniferous forest with *snowcovered* ground outside Uppsala showed albedo values of 10—16 per cent. Corresponding values *during summer* above the same forest, was 2—5 per cent. The albedo above forest for example, is however dependent on the sun's altitude. At a low altitude the shaded part of the ground is large and consequently with a low albedo. At higher altitude the percentage of shaded ground gets smaller and the albedo higher. The first mentioned values of 10—16 per cent above forest near Uppsala were measured at the altitude 36—37°, while the last mentioned of 2—5 per cent were measured at the altitude 46°. Snow-free sparse fjeld birch forest with snowcovered ground reflected 35 per cent, whereas corresponding fjeld spruce forest only reflected 19 per cent. The sun's altitude was the same at these measurements. During the summer mixed fjeld forest in Linalompolo near Gällivare reflected about 10 per cent. The albedo values of the table for clearing and treeless mountain plateau in Linalompolo are too low, owing to the fact that the ground was partially shaded by clouds. In the summer of 1965 the same clearing and treeless mountain plateau showed

Table 4 a—b. Percentage albedo from measurements by aircraft over different types of surface in a) winter and b) summer. The values adjusted to ground level.

Table 4 a.

Surface	Near Uppsala			Near Östersund	Near Luleå
	I. 20.4 1966	II. 21.4 1966 a.m.	III. 21.4 1966 p.m.	IV. 28.4 1966	V. 11.5 1966
1. Clean thawing snow	45	44			
2. Clean snow and ice					48—59
3. Clean thawing snow and ice		36—39	32—40	30—33	
4. Snow-free coniferous forest and snow-covered ground	13	16			
5. As 4, but denser forest	10	11			
6. Snow-covered treeless mountain plateau, uneven ground, shadows				40	
7. Snow-free, sparse fjeld birch forest and snow-covered ground				35	
8. Snow-free, sparse fjeld spruce forest and snow-covered ground				19	
9. Snow-free spruce forest and snow-covered ground				13	
10. As 9, but denser forest				9	

Table 4 b.

Surface	Near Uppsala		Luleå—Gällivare—Luleå	Near Gällivare
	VII. 7.6 1966	VIII. 8.6 1966	IX. 17.6 1966	IX. 17.6 1966
11. Green fields	6			
12. Light brown fields		8		
13. Coniferous forest	4	5	10—11	10
14. Coniferous forest denser than 13		4	7	
15. Coniferous forest denser than 14		3		
16. Coniferous forest denser than 15		2		
17. Mixed coniferous and hardwood forest			9—10	
18. Mixed pine and birch forest			11	
19. Mixed spruce and birch forest			8	
20. Treeless mountain plateau, partly in shadow				13
21. Clearing, partly in shadow				11
22. Smooth water-surface			6	4
23. Rippled water-surface		2		

Table 5. Some albedo values over different types of surface.

Surface	Author's measurements 1965	1966	Sellers	Jackson	Ångström
Snow, several days old		44—45a	40—70b	70	18—70c
Water surface	3—8	4—6	6—7b		
Concrete, dry	22d		17—27b		
Tundra (treeless mountain plateau)	15—18		15—20b		
Forest, coniferous	10—13	2—10	5—15b	10	
Lichen woodland, sparse	10—11			12	

a Thawing snow
b Average values from data given by Budyko, List, Houghton, Geiger and Kupier & Middlehurst
c Snow varying in consistency
d Measured at ground level

values of 15 and 17 per cent respectively at clear weather. A smooth water-surface reflected 4—6 per cent, while a rippled water-surface only reflected 2 per cent. At the last mentioned measurements the sun's altitude was about 40° and 46° respectively.

The measurements show clearly that *dense forest has a lower albedo than sparse forest.* Dense forest consequently absorbs more of the incident global radiation than sparse forest. The fairly dense pine- and spruce forest and the ground surface near Uppsala absorbed during the summer 95—98 per cent of the incident global radiation, while the considerably sparser fjeld forest and ground surface near Gällivare only absorbed about 90 per cent. The incident energy can be said to disperse itself on one volume in the forest. A dense forest contains more vegetation per volume than sparse forest. The dense forest absorbs more energy than the sparse one, which at any rate partially compensates the greater need of energy per volume in the dense forest. In other words, the radiation in forest is a kind of cavity radiation. In part 5 the magnitudes of the dispersion of energy in different kinds of forest will be discussed on the basis of the above.

In Table 5, some albedo values above different surfaces stated by different authors have been collocated. It shows that the values in the present investigation fully correspond with the values measured earlier.

4. Measurements at ground level

4.1 Theory and measurement methodology

In order to obtain an idea of the radiation conditions in forest varying in density, four different measurements were made, one by day and three at night. Nearby open ground formed reference.

The measurement by day comprised measurement of only the global radiation as well as measurement of both the global and the longwave radiation (total net radiation). The reflected and incident global radiation covers, as indicated earlier, the wave-length region of 0,3—4 μm, whereas the total net radiation E_B covers the wave-length region of 0,3—60 μm, i.e. both short- and longwave radiation.

The direct solar radiation as well as the diffuse radiation, p. 8, is screened by the tree crowns. Only a part of the incident radiation reaches therefore the ground-level in the forest. This part is by clear weather, amongst other things, dependent on the sun's altitude. By low altitude the screening is larger than by high altitude. The incident part of the radiation that reaches the ground is also dependent on the character and density of the forest. The denser the forest, the greater the screening. At overcast weather the direct solar radiation can be neglected and the sun's altitude is of less importance. At similar altitude of sun coniferous forest with snow-free tree crowns screens about the same amount of radiation during summer-time as during winter-time. Hardwood forest screens considerably more during the summer than during the winter. Snow-covered tree crowns screen more than the snow-free ones.

The global radiation reflected from the ground can be compared with diffuse radiation, p. 9, and is reflected in all directions, even upward. On its way up, it gets reduced of the tree crowns in the same way, as the diffuse coming radiation from above gets reduced on its way down through the tree crowns.

The net radiation meter, which measures short- and longwave radiation, receives radiation from above as well as from below. The contribution from the shortwave radiation upon the ground in forest gets reduced as above. The atmospherical longwave radiation also gets reduced in a corresponding way. In return the tree crowns emit longwave radiation upon the ground. From the ground the global radiation is reflected upward, and the ground also emits longwave radiation upward. The principle sketch (Fig. 7) shows which the components are that define the net radiation in forest.

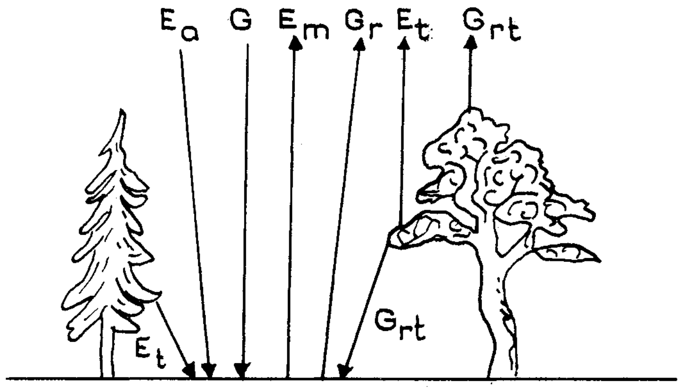

Fig. 7. The components of the total net radiation in forest.
Et = long-wave radiation from the trees
Ea = long-wave radiation from the atmosphere
G = global radiation
Em = long-wave radiation from the ground
Gr = reflected global radiation from the ground
Grt = reflected global radiation from the trees

In order to obtain an idea of the average radiation conditions in forest by day, the incident global radiation was measured at 16 different points, which were lying on a straight line with a mutual interval of 10 metres. These points may be considered to have been chosen randomly. The reflected global radiation from the ground, the net radiation and the dry and wet temperatures were also measured at the same points. From these temperatures the average air humidity is obtained. Simultaneously with the measurements in the forest, the corresponding components were measured at a fix point on nearby lying open ground. The observers at the two positions were kept in wireless contact with each other and so the measurements in the forest and on the open ground could be carried out at exactly the same time.

The measurements at night were carried out chiefly in the same way as the measurements by day but did then only comprise the longwave components of the net radiation since the shortwave radiation can be neglected at night.

In order to compare the components measured in forest with those measured on the open site, the relationship between values from forest and values from open ground is established. Of these relative expressions "fix" represents the value measured on open ground.

$$C_1 = G/G_{fix} \text{ (incident global radiation)}$$

$$C_2 = E_B/(E_B)_{fix} \text{ (total net radiation)}$$

Further the temperature difference in °C and the difference in relative humidity in percentage between values from forest and values from open ground are established according to the expressions:

$$\Delta t = t - t_{fix} \text{ (temperature)}$$

$$\Delta h = h - h_{fix} \text{ (relative humidity)}$$

4.2 Instruments

At the measurement by day three Kipp and Zonen solarimeters, two net radiation meters (type Schenk) and two aspiration psykrometers (type Assman) were used. Of these were two solarimeters, one directed upward, the other one downward, one net radiation meter and one psykrometer used in the forest, while one upward directed solarimeter, one net radiation meter and one psykrometer were used on the open site.

During the measurements at night, net radiation meters and psykrometers were used in fundamentally the same way as during the measurements by day.

The solarimeters were calibrated against an absolute instrument (Ångström's pyrheliometer at SMHI). On this occasion the reading was made on one of the two millivolt-meters which were used in field. On comparison these differed from each other with one per cent. Correction regarding this has been made in the calculations.

The net radiation meters are more difficult to calibrate. The instrument constant, given by the manufacturer, was approved of for one of the meters. The other one was calibrated against this one.

4.3 Measurements

The measurements are presented in the tables X—XII, p. 48—49. The first measurement was made at Björklinge, 20 kilometres north of Uppsala, see map p. 44. The forest consists of pine and spruce and a few hardwood trees. Compared with the fjeld forest near Gällivare the forest at Björklinge is considerably denser and the trees larger. The reference measurement was made on a nearby lying newly cut grass field, the size of about 200×400 meters. The sun's altitude during the measurement varied between 35° and 51°. The measurement area is situated approximately 30 metres above sea level.

The second measurement was made at Linalompolo 25 kilometres northwest of Gällivare, in the same forest as the measurement made in 1965 (ODIN & PERTTU, 1966). This fjeld forest is fairly sparse and consists of pine and birch. The reference measurement was carried out on the nearby lying large clearing. During the proceedings of the measurement on third of the sky to the west was shaded by a cloud bank. The values of the net radiation were therefore fairly low and consequently the results were somewhat uncertain. The measurement area is situated about 475 metres above sea level.

The third and fourth measurements were carried out at the same night in forest of different density. The sparser forest is to a certain degree of the same density as the fjeld forest at Linalompolo but the trees are of a considerably greater dimension than those in the fjeld forest. The denser forest is very dense and bushy and almost unpracticable. The measurement area lies at Tyresta, some 20 kilometres south-east of the centre of Stockholm and about 50 metres above sea level.

4.4 Results and discussion

The mean values of the expressions p. 26 for the different localities have been collocated in Table 6.

In the comments to this table the ground measurements have been divided into measurements by day and measurements at night.

Table 6. Mean values of the expressions at p. 26.

Place	Date	M.E.T.	Relative global radiation $\overline{C}_1$ %	Relative total net radiation $\overline{C}_2$ %	Temp. diff. $\overline{\Delta t}$ °C	Humid. diff. $\overline{\Delta h}$ %	Shaded ground %
Björklinge, 20 km N Uppsala	19.7 1966	11^{50}—15^{25}	27	35	—0.4	—13	60
Linalompolo, 25 km NW Gällivare	25—26.8 1966	23^{24}—00^{12}	—	46	—0.6	—	—
Tyresta (sparse forest), 25 km SE Stockholm	26.10 1966	19^{10}—19^{40}	—	65	+0.5	—	—
Tyresta (dense forest), 25 km SE Stockholm	26.10 1966	20^{23}—20^{48}	—	44	+0.8	—	—
Linalompolo, (Measured 1965)	18.7 1965	10^{30}—16^{55}	56	50	—	—	40

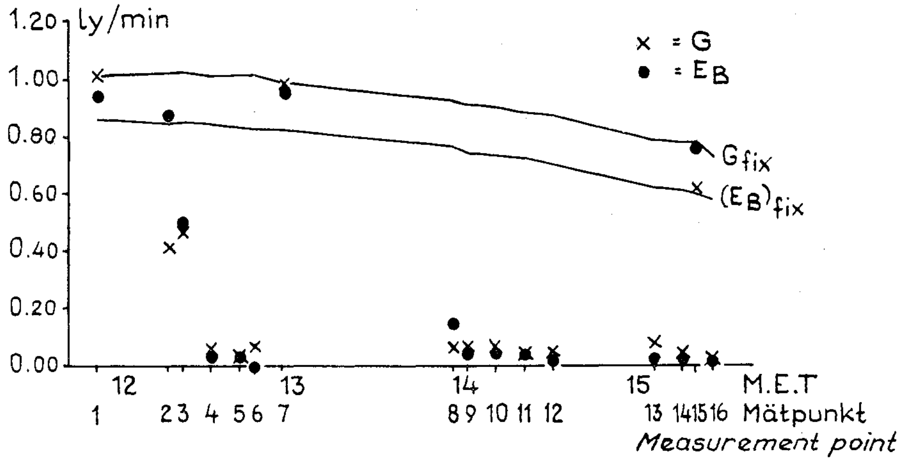

Fig. 8. Global radiation G_{fix} and total net radiation $(E_B)_{fix}$ at the open site, and global radiation (x) and total net radiation (●) at the sites in the forest at Björklinge near Uppsala.

4.4.1 Measurement by day

The ground in the relatively dense Björklinge forest received as an average only 27 per cent of the total incident global radiation G_{fix}. From photographs of each measurement point, the part of shaded ground was estimated to be at an average about 60 per cent. The ground in the sparse fjeld forest at Linalompolo received according to ODIN & PERTTU (1966) 56 per cent of the total incident global radiation and the ground was shaded to about 40 per cent.

The net radiation in the Björklinge forest was positive, i.e. the incident radiation (within the wavelength area 0,3—60 μm) was greater than the corresponding emanent radiation, see Fig. 7, p. 25. The average was however only 35 per cent of the net radiation measured on the open site, i.e. of (E_B) fix. Corresponding value in the fjeld forest of Linalompolo was 50 per cent.

The temperature was on an average 0,4°C lower and the relative humidity 13 humidity per cent lower in the forest than on the open site at Björklinge.

Fig. 8 shows the radiation components by day at Björklinge. Along the abscissa, the time in Middle European Time (MET) as well as the number of the site in the forest are stated. The continuous lines indicate the incident global radiation and the total net radiation respectively at the open site.

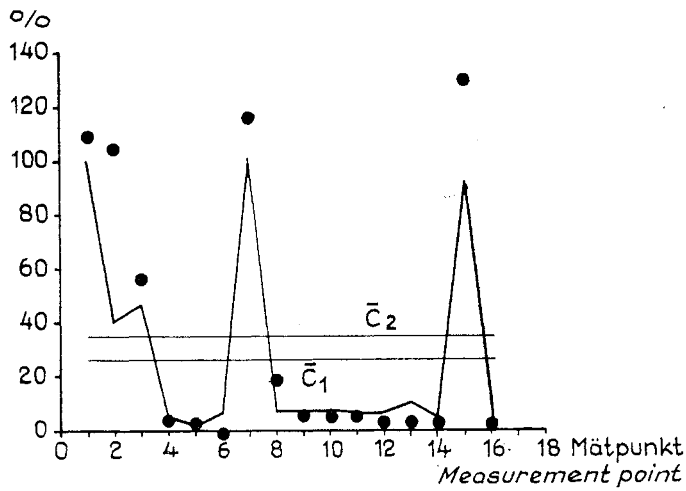

Fig. 9. The ratio in global radiation C_1 (—) and total net radiation C_2 (●) of the sites in the forest and the open site at Björklinge near Uppsala.

The crosses indicate the incident global radiation at the different points in the forest and the dots show the reading of the net radiation meter at the corresponding points. It has to be observed that the albedo (as well as the net radiation, where the albedo is included) are defined for a large horizontal surface. In the forest one cannot for that reason really speak of albedo (or net radiation) in separate points, but on the other hand as mean values.

In the forest at Björklinge three different kinds of measurement points for the global radiation can be distinguished (Fig. 9). The points Nos. 1, 7 and 15 belong to the *first* group. The incident global radiation was here just a little less than it was on open site. On photographs one can see that the instrument was sunlit. It is consequently *only a part of the diffuse radiation that decreases.* On the other hand the tree crowns reflect some radiation, which compensates the decrease in the diffuse radiation.

The *second* group consists of the points 4—6, 8—14 and 16. The incident global radiation was nearly zero at these points. An analysis of the photographs show that the instrument was in direct shade. It obtained, however, a part of the diffuse radiation as well as the global radiation reflected from the tree crowns.

The sites 2 and 3 belong to the *third* group. The incident global radiation was about half of what was measured on open ground. The instrument happened to be standing in such a way, that about half of the sensitive surface was lit, *when the sun sprinkled down through the tree crowns.*

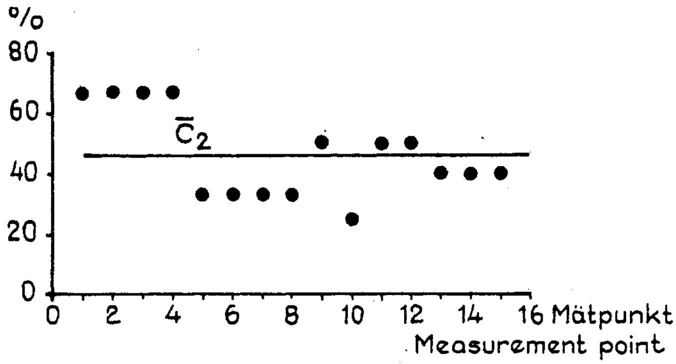

Fig. 10. The ratio in total net radiation C_2 (●) of the sites in the forest and the site in the clearing at Linalompolo near Gällivare.

The ground in the Björklinge forest therefore obtained on an average 27 per cent of the global radiation on open ground. The standard deviation of the mean value σ_m was about 9.

4.4.2 Measurement at night

The net radiation measurement at Linalompolo showed an effective emission of only 0,03—0,05 ly/min on the clearing and 0,01—0,02 ly/min in the fjeld forest, where the effective emission on an average was 46 per cent of the emission in the clearing. The temperature was strangely enough on an average 0,6° lower in the forest than on the clearing.

The measurements at Tyresta were carried out partly in sparse forest consisting of pine and spruce and of about the same density as the Linalompolo forest and partly in a considerably denser forest, which mainly consisted of spruce and hardwood trees. The sparser forest showed an effective emission, which on an average was 65 per cent of the emission on the nearby lying open grass- and sand ground. The temperature was on an average 0,5° higher in the forest than on the open ground.

The denser forest had an emission, which on an average was 44 per cent of the emission on nearby lying open grass ground. The temperature was on an average 0,8° higher in the forest than on the open ground.

The measurement at night at *Linalompolo* (Fig. 10) only comprised measurement of net radiation and temperature at a fixed point on the clearing and at randomly chosen points in the fjeld forest. This measurement can also be divided into three groups. The points 1—4 belong to the *first* one. Here the effective longwave radiation was 67 per cent of that on the clearing. The forest was sparse and the sites alighted in *glades*. The

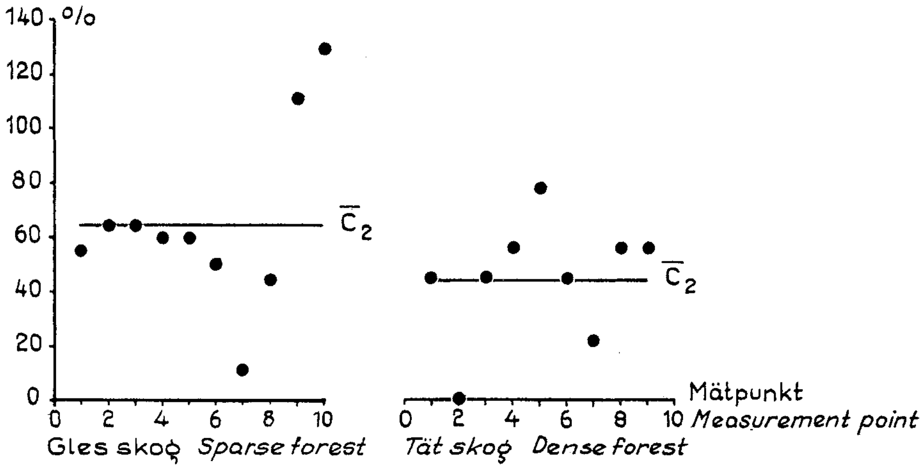

Fig. 11. The ratio in total net radiation C_2 (●) of the sites in the forest and the open site at Tyresta near Stockholm.

tree crowns, however, emitted some longwave radiation from above upon the net radiation meter.

The *second* group comprises the measurement points 5—9 and 11—15. The effective emission was here 33—50 per cent of the emission on the clearing. These measurements alighted *rather near but at varying distance from the trees*. Photographs, taken the day after the measurements, show that a great but varying part of the sky was shaded by the tree crowns. The greater the part that was shaded, the smaller was the effective longwave emission.

Measurement point No. 10 is formed as a third "group" of its own. It happened to alight in such a way, so that the balance meter was standing quite *close to the stem of a birch*. Here the effective emission was only 25 per cent of that on the clearing. A great part of the sky was shaded by the birth crown.

The effective longwave radiation in the fjeld forest at Linalompolo was on an average 46 per cent of emission on the clearing and the standard deviation of the mean value was about 4.

The measurements at night at *Tyresta* (Fig. 11) show in principal the same pattern as the Linalompolo measurement. Point 7 in the sparse forest alighted, for instance, underneath a spruce, while the points 9 and 10 alighted in a glade. The Tyresta measurements, however, differ from each other. The effective longwave radiation in the sparse forest was consequently on an average 65 per cent of the emission on open ground, and the standard deviation of the mean value was about 10. Corresponding mean value for the dense forest was only 44 per cent and the standard deviation about 7.

The reason why the measurements carried out at Linalompolo are subjected to a more detailed treatment than those at Tyresta, in spite of the fact that the latter are more uncertain, is the supply of photographs from the sites at Linalompolo. The discussion above is to a great extent based on these photographs.

5. Some general conclusions

The forest as a whole absorbs a great deal of the incident global radiation. The denser it is, the more it absorbs. The measurements from aircraft in summer showed that the sparse fjeld forest and ground near Gällivare absorbed 90 per cent and the denser forest near Uppsala 95—98 per cent of the incident global radiation. The forest and ground at Björklinge absorbed about 96 per cent. One volume unit of the denser forest needs more energy than corresponding volume unit of the sparser forest. This greater need of energy in the denser forest is compensated, at least partially, by the denser forest's greater energy absorption.

The ground in forest receives considerably less global radiation by day than open ground. The effective emission at night from ground in forest is on the other hand less than from open ground. The smaller incident radiation in forest by day is therefore compensated by a smaller emission at night. Consequently the forest adjusts the temperature climate as well as does overcast weather. According to Geiger (1959) the temperature differences between different heights in forest are small, i.e. there are isothermal conditions. Open ground has, during similar conditions, inversion (temperature increase with the height). Fig. 12 shows different temperature profiles on clearing and in forest, calculated from measurements of temperature and humidity at Linalompolo near Gällivare in the autumn of 1965. It has to be observed, however, that the profile in forest have been measured at higher altitude above sea level and also on a slight slope. The curve with extremely strong inversion was measured in a large depression and the curve to the further right, at calm, foggy weather.

The measurements from aircraft showed that the forest and ground at Björklinge absorbed 96 per cent of the incident global radiation. According to the measurements on ground 27 per cent of the global radiation reached the ground level. Supposing the ground level in forest had the same albedo as the open ground, which according to the measurements reflected 18 per cent, the ground level in forest then reflected $0.18 \times 27 = 5$ per cent of the incident global radiation. The total absorption of the trees was consequently $96 - 27 + 5 = 74$ per cent.

Without making any bigger mistakes one can assume that the trees absorbed about 74 per cent of the radiation reflected from the ground, i.e. the ground level contributed to the albedo at the tree top level with $5 - 0.74 \times 5 = 1.3$ per cent. From aircraft 4 per cent was measured, however, in

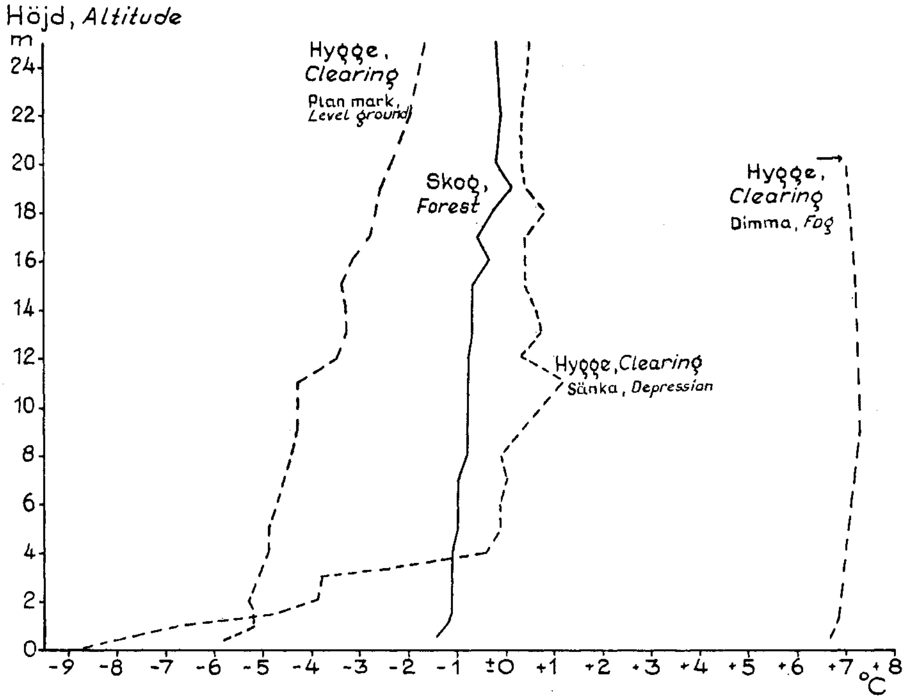

Fig. 12. Temperature profiles in clearing (470 m.a.s.) and forest (530 m.a.s.) at Linalompolo near Gällivare during the period 27.9—2.10 1965. The mean wind speed during 10 min. varied between 1 and 2 m/s. Cloudless except at one measurement.

which case the tree crowns must have reflected $4-1.3=2.7$ per cent upwards.

The assumption that the ground in forest and the open ground had the same albedo is verified in the following way. The relation between the mean value of the reflected global radiation G_r from the ground in forest and the mean value of the incident global radiation G_{fix}, gives the value of 5 per cent. This is the same value as the one that was calculated with the assumption that also the ground in forest had an albedo of 18 per cent.

With the above statement as a basis, Fig. 13 is drawn, where the figures are indicated as a percentage of the total incident global radiation.

Corresponding calculations (from measurements of 1965) for the sparser fjeld forest at *Linalompolo* are the basis for Fig. 14. The tree crowns absorbed totally 42.5 per cent of the incident global radiation, because, according to Odin & Perttu (1966) it proved that the clearing and ground in the forest had the same albedo, i.e. 15 per cent and therefore the ground in the forest on an average reflected $0.15 \times 56 = 8.5$ per cent. One can also here assume

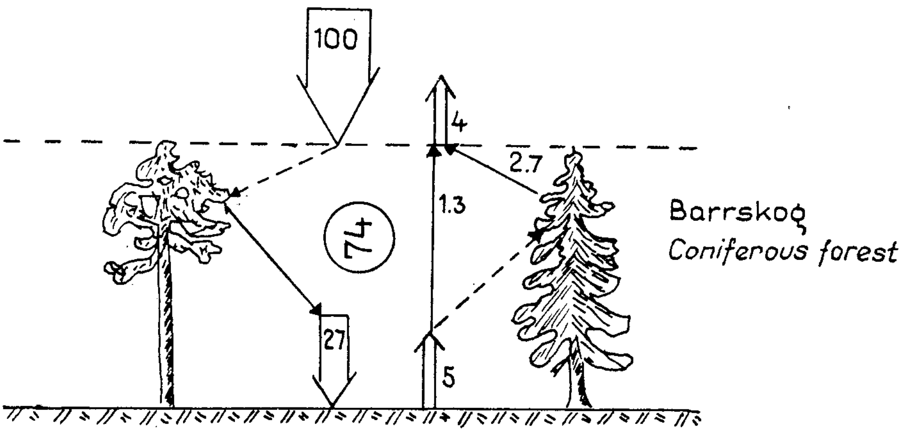

Fig. 13. The distribution of the radiation energy in coniferous forest (Björklinge near Uppsala) in per cent of the total global radiation.

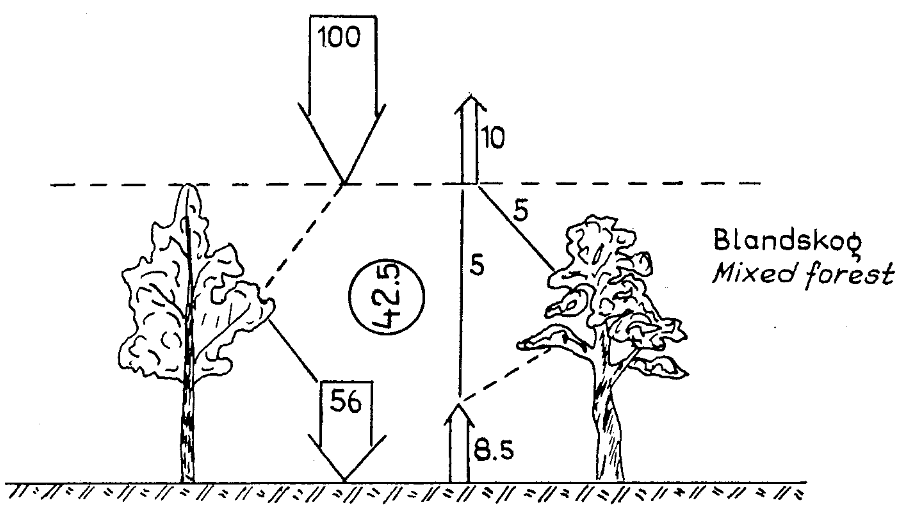

Fig. 14. The distribution of the radiation energy in fjeld forest (Linalompolo near Gällivare) in per cent of the total global radiation.

that the tree crowns absorbed 42.5 per cent of the reflected global radiation. Thus the ground level contributed with $8.5 - 0.425 \times 8.5 \simeq 5$ per cent to the albedo at the tree top level. From aircraft, however, the reflected global radiation near Linalompolo was measured to 10 per cent. The tree crowns must then have reflected about 5 per cent upwards.

At Björklinge the forest consists of pine and spruce and a few, solitary hardwood trees. The trees in this forest reflected, according to the calculations above, about 2.7 per cent upwards. The ground contributed to the reflection above tree top level with 1.3 per cent. The trees in the fjeld forest at Linalompolo, which consists of pine and birch reflected 5 per cent upwards. Here the ground contributed with 5 per cent to the reflection above tree top level. Thus the pine and birch of Linalompolo reflected $5 - 2.7 = 2.3$ per cent more than the pine and spruce of Björklinge. The ground at Linalompolo contributed with $5 - 1.3 = 3.7$ per cent more than the ground at Björklinge to the reflection above tree top level. The first mentioned case depends on the fact that birch reflects more than spruce, the later on the fact that the forest at Björklinge has a greater density. Of the difference between reflection above the forest at Linalompolo and above the forest at Björklinge, the type of stand therefore contributed with 38 per cent and the smaller density of the stand with 62 per cent. One can see that *the density of the forest is of greater importance for the total reflection above the tree crowns than the type of forest.*

In order to fully analyse the radiation conditions in forest compared to open ground, a considerably greater amount of measurements is required. The values, which are presented in this paper, give, however, an indication of how the radiation conditions in forest differs from those on open ground. The values may also be able to give a conception of the magnitudes of the radiation energy in forest.

6. Summary

The Royal College of Forestry carries on climatological research with a view to elucidating the local and microclimatological factors that must be considered in connection with the planting of forests. A number of radiation measurements have been made as part of this research programme.

In the summer of 1965, radiation measurements were made near the forest limit in northern Sweden. The results are set out in ODIN & PERTTU (1966). Further measurements were made in the spring and summer of 1966; these also covered forest areas closer to sea level, and it is these measurements that are dealt with in the present paper.

The object of these studies was to investigate how forests of varying stocking density affect the radiation climate. One aim was to obtain an idea of the *average* albedo of forest to solar radiation. This can only be done by means of measurement from the air, i.e. from aircraft. These measurements are particularly important when the ground is covered with snow. A further aim was to discover how much the forest screens, and thereby reduces, the incident and emanent radiation at the surface of the ground as compared to conditions on open ground.

Albedo measurements from aircraft were made with two Kipp and Zonen solarimeters—one directed upward and the other downward. The readings obtained have been corrected to ground level, i.e. they have been freed from the influence exerted by absorption and scattering of radiation in the layer of air below the aircraft. To obtain some idea of the magnitude of the corrections, measurements were made of both reflected and incident global radiation at various altitudes above ground level. It was found that measurements made at heights of e. g. 200 metres above ground level required corrections of 3—4 per cent. The type of terrain was defined according to the area lying within an "aperture angle" of 140 degrees below the aircraft. Note, however, that the instrument received radiation from an "aperture angle" of a full 180 degrees. The albedo measurements were made in the following regions: eastern Svealand near Uppsala, central Norrland near Östersund and northern Norrland near Luleå and Gällivare (see map, p. 44).

The measurements show that dense forest has a lower albedo than sparse forest. The readings for bare ground are two and five per cent respectively, and for snow-covered ground but with the tree-crowns free from snow, ten and sixteen per cent respectively. These figures refer to measurements over forest in central Sweden near Uppsala. The measurements made in 1965 over fjeld forest in northern and central Norrland sometimes gave a contradictory result; the explanation may be that shadows on the ground predominated in the sparser fjeld forest. A summary of the results is given in Table 4 on p. 22.

The tree-crowns in a forest screen the surface of the ground from a considerable proportion of the incident radiation from sun and atmosphere, while

similarly serving to reduce radiation losses somewhat. The radiation climate of the forest is therefore considerably more temperate and less extreme than that of open ground (see Fig. 7, p. 25). This effect becomes more pronounced the denser is the forest.

Measurements were made on the ground both during the day and at night and comprised determinations of total net radiation, incident global radiation and global radiation reflected from the ground at randomly selected points in the forest areas in question. Similar measurements were made at the same time on open ground for reference purposes. The daylight measurements were made in a relatively dense forest, consisting of pine and spruce, at Björklinge near Uppsala. The night measurements were made in sparse and dense forest at Tyresta near Stockholm and in fjeld forest at Linalompolo.

The average global radiation measured at ground level in the Björklinge forest was only 27 per cent of the global radiation measured on open ground. The corresponding figure in the fjeld forest at Linalompolo was 56 per cent. The average value of the net radiation was reduced by day to 35 per cent at Björklinge and to 50 per cent in the Linalompolo fjeld forest, as compared with the readings obtained on open ground. The effective long-wave radiation emitted at night was reduced on the average to 44 per cent in dense forest and to 65 per cent in sparse forest at Tyresta, as compared with the radiation emitted from open ground. Table 6 p. 27 contains a summary of the measurements made at ground level.

The discussion in section 5, together with figures 13 and 14, shows that the forest at Björklinge absorbed 74 per cent in all and the forest at Linalompolo 42.5 per cent of the total incident radiation. It was further calculated that the pine and spruce in the Björklinge forest reflected 2.7 per cent upward, while the pine and birch in the Linalompolo forest reflected circa 5 per cent upwards.

Many more measurements will be needed to investigate fully the problems under study here. The figures presented in this paper do, however, give an indication of how the radiation climate in forests differs from that on open ground. These figures can probably also be used for study of the magnitudes of radiant energy present in forests.

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Sammanfattning

Strålningsmätningar över och i skog

Vid Skogshögskolan bedrivs klimatologisk forskning för att bl. a. klargöra vilka lokal- och mikroklimatologiska faktorer som bör beaktas vid plantering av skog. Som ett led i denna forskning har en del strålningsmätningar utförts.

Sommaren 1965 utfördes strålningsmätningar nära skogsgränsen i norra Sverige. De finns redovisade i Odin & Perttu (1966). Våren och sommaren 1966 utfördes mätningar även inom skogsområden närmare havsytans nivå. Dessa mätningar behandlas i föreliggande uppsats.

Avsikten med dessa undersökningar var att utreda hur skog av olika täthet påverkar strålningsklimatet. Det gällde bl. a. att erhålla en uppfattning om skogens *genomsnittliga* albedo för solstrålning. Detta kan endast ske genom mätningar från luften, dvs. från flygplan. Särskilt viktiga är dessa mätningar då marken är snötäckt. Vidare gällde det att få en uppfattning om skogens avskärmning och därmed reducering av den vid markytan inkommande och utgående strålningen, jämfört med förhållandena på öppen mark.

Albedomätningar från flygplan utfördes med två stycken Kipp och Zonen solarimetrar — en riktad uppåt, en nedåt. De uppmätta värdena har korrigerats till markytans nivå, dvs. de har befriats från det inflytande, som absorption och spridning av strålningen inom luftskiktet under flygplanet utövar. För att få en uppfattning om korrektionernas storlek mättes därför både den reflekterade och den inkommande globalstrålningen på varierande höjd över marken. Det visade sig därvid att mätningar utförda på t. ex. 200 meters höjd över marken måste korrigeras 3—4 procent. Typen av underlag har bestämts efter det område, som legat inom »öppningsvinkeln» 140° under flygplanet. Observera dock att mätinstrumentet erhöll strålning inom hela »öppningsvinkeln» 180°. Albedomätningarna utfördes inom följande områden: östra Svealand nära Uppsala, mellersta Norrland nära Östersund samt norra Norrland nära Luleå och Gällivare, se karta sid. 44.

Mätningarna visar att tät skog har ett mindre albedo än gles skog. Värdena vid bar mark var 2 respektive 5 procent och vid snötäckt mark, men med snöfria trädkronor, 10 respektive 16 procent. Dessa värden gäller över mellansvensk skog nära Uppsala. Mätningarna från 1965 över fjällskog i norra och mellersta Norrland gav delvis motsatt resultat, vilket möjligen kan bero på att skuggorna på marken i den glesare fjällskogen var dominerande. En sammanställning av resultaten återfinnes i tabell 4 sid. 22.

Trädkronorna i en skog avskärmar markytan från en väsentlig del av inkommande strålning från sol och atmosfär, samtidigt som strålningsförlusterna analogt nedbringas. Skogens strålningsklimat är därför väsentligt mera utjämnat och mindre extremt än den öppna terrängens, se fig. 7 sid. 25. Denna verkan är mera utpräglad ju tätare skogen är.

Mätningar utfördes under såväl dag som natt och omfattade bestämningar av total nettostrålning, inkommande globalstrålning samt från marken reflekterad globalstrålning vid slumpmässigt utvalda punkter inom respektive skogsområden. Som referens tjänade motsvarande och samtidiga mätningar på öppen mark. Mätningarna på dagen utfördes i en relativt tät skog, bestående av tall och gran, i Björklinge nära Uppsala. Nattmätningarna utfördes i gles fjällskog i Linalompolo nära Gällivare samt i gles och tät skog i Tyresta nära Stockholm.

Den genomsnittliga globalstrålningen uppmätt på marken i Björklingeskogen var endast 27 procent av globalstrålningen uppmätt på öppen mark. Motsvarande värde i fjällskogen i Linalompolo var 56 procent. Det genomsnittliga värdet av nettostrålningen reducerades på dagen till 35 procent i Björklinge och till 50 procent i fjällskogen i Linalompolo jämfört med värdet uppmätt på öppen mark. Den effektiva långvågsutstrålningen på natten reducerades i medeltal till 44 procent i tät skog och till 65 procent i gles skog i Tyresta jämfört med utstrålningen på öppen mark. I tabell 6 sid. 27 återfinnes en sammanställning av mätningarna på marken.

Diskussionen i avsnitt 5 samt figurerna 13 och 14 visar att skogen i Björklinge totalt absorberade 74 procent och skogen i Linalompolo 42,5 procent. Vidare beräknades Björklinge-skogens tall och gran reflektera 2,7 procent uppåt medan Linalompolo-skogens tall och björk reflekterade 5 procent uppåt.

För att fullständigt utreda denna undersöknings problemställning krävs betydligt fler mätningar. De värden som presenteras i denna uppsats ger dock en indikation på hur skogens strålningsklimat skiljer sig från strålningsklimatet i öppen terräng. Värdena torde också kunna ge en uppfattning om strålningsenergins storleksordningar i skog.

Appendix

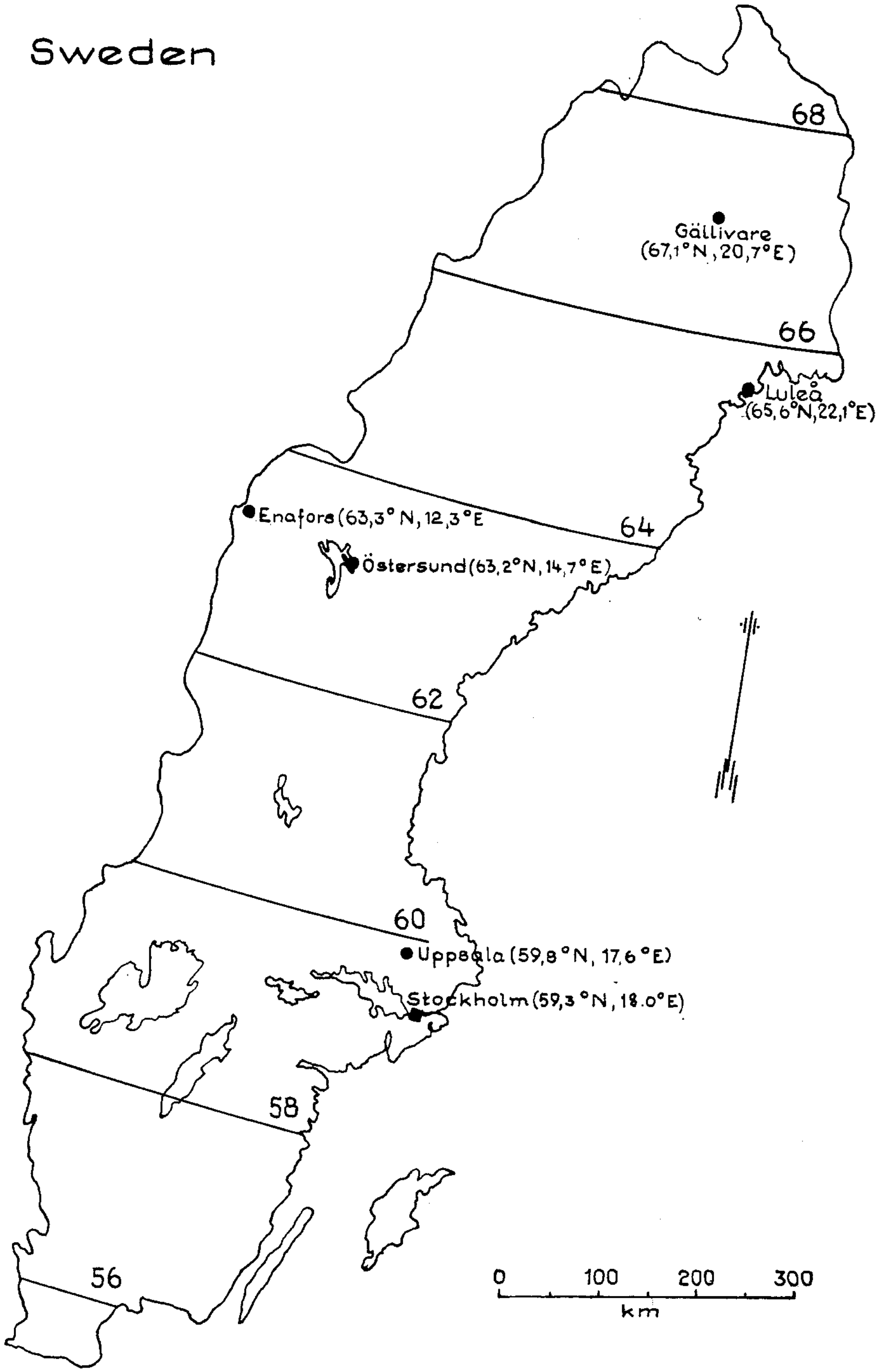
Sweden
68
Gällivare
(67,1°N, 20,7°E)
66
Luleå
(65,6°N,22,1°E)
64
Enafors (63,3° N, 12,3°E
Östersund (63,2°N, 14,7°E)
62
60
Uppsala (59,8°N, 17,6°E)
Stockholm (59,3°N, 18.0°E)
58
56
0
100
200
300
km

Table I. Measurement from aircraft near Uppsala 20 Apr. 1966. Altitude of sun: 37°

Surface	G_r ly/min	G ly/min	Measmt ht above ground m	Measmt ht above sea-level m	Cloudiness
Clean thawing snow; level surface	0.38	0.87	200	—	Cloudless
A. Snow-free coniferous forest and snow-covered ground	0.11	0.87	200	—	,,
B. As A, but denser forest	0.08	0.87	200	—	,,

Table II. Measurement from aircraft near Uppsala 21 Apr. 1966. Altitude of sun: 36°

Surface	G_r ly/min	G ly/min	Measmt ht above ground m	Measmt ht above sea-level m	Cloudiness
Clean thawing snow; level surface	0.41	0.94	50	—	Cloudless
Clean thawing snow and ice; level surface	0.34	0.94	50	—	,,
Clean thawing snow and ice; level surface	0.33	0.98	1500	—	,,
A. Snow-free coniferous forest and snow-covered ground	0.10	0.91	200	—	,,
B. As A, but sparser forest	0.14	0.91	200	—	,,

Table III. Measurement from aircraft near Uppsala 21 Apr. 1966. Altitude of sun: 35°

Surface	G_r ly/min	G ly/min	Measmt ht above ground m	Measmt ht above sea-level m	Cloudiness
About 40 per cent thawing snow and ice on the ground	0.14	0.82	50	—	Cloudless
About 80 per cent thawing snow and ice on the ground	0.21	0.83	50	—	,,
About 90 per cent thawing snow and ice on the ground	0.25	0.82	50	—	,,
About 95 per cent thawing snow and ice on the ground	0.30	0.83	50	—	,,
Clean thawing snow and ice; level surface	0.32	0.83	50	—	,,
Clean thawing snow and ice; level surface	0.33	0.89	500	—	,,
Clean thawing snow and ice; level surface	0.25	0.99	1500	—	,,

Table IV. Measurement from aircraft near Östersund 28 Apr. 1966. Altitude of sun: 30°.

Surface	G_r ly/min	G ly/min	Measmt ht above ground m	Measmt ht above sea-level m	Cloudiness
Clean thawing snow and ice; level surface	0.15	0.64	1500	1800	Cloudless
Clean thawing snow and ice; level surface	0.17	0.65	1000	1300	,,
Clean thawing snow and ice; level surface	0.17	0.62	500	800	,,
Clean thawing snow and ice; level surface	0.18	0.55	100	400	,,
C. Snow-free spruce forest and snow-covered ground	0.05	0.58	100	500	,,
D. As C, but sparser forest	0.08	0.63	100	600	,,
Snow-free, sparse spruce forest and snow-covered ground	0.12	0.63	100	700	,,
Snow-free, sparse fjeld birch forest and snow-covered ground	0.21	0.62	100	800	,,
Snow-covered treeless mountain plateau, uneven ground	0.26	0.66	100	1200	,,

Table V. Measurement from aircraft near Luleå 11 May 1966. Altitude of sun: 35°

Surface	G_r ly/min	G ly/min	Measmt ht above ground m	Measmt ht above sea-level m	Cloudiness
Clean thawing snow; level surface	0.26	0.68	—	2800	2/8 Ci
Clean thawing snow; level surface	0.27	0.70	—	2500	2/8 Ci
Clean thawing snow; level surface	0.28	0.63	—	2000	2/8 Ci
Clean thawing snow; level surface	0.30	0.62	—	1500	2/8 Ci
Clean thawing snow; level surface	0.28	0.57	—	1000	2/8 Ci
Clean thawing snow; level surface	0.27	0.60	—	500	2/8 Ci
Clean thawing snow; level surface	0.34	0.58	—	100	2/8 Ci

Table VI. Measurement from aircraft near Luleå 12 May 1966. Altitude of sun: 42°. On ground recorded values in parentheses.

Surface	G_r ly/min	G ly/min	Measmt ht above ground m	Measmt ht above sea-level m	Cloudiness
Snow-free coniferous forest with about 50 per cent snow-covered ground	0.10	0.65 (0.95)	100	—	Cloudless
Denser snow-free coniferous forest than the above, with about 60 per cent snow-covered ground	0.08	0.66 (0.95)	100	—	,,

Table VII. Measurement from aircraft near Uppsala 7 Jun. 1966. Altitude of sun: 51°

Surface	G_r ly/min	G ly/min	Measmt ht above ground m	Measmt ht above sea-level m	Cloudiness
Coniferous forest	0.04	1.13	100	—	Cloudless
Green fields	0.07	1.10	100	—	,,
Green fields with isolated patches of deciduous woodland	0.07	1.10	100	—	,,

Table VIII. Measurement from aircraft near Uppsala 8 Jun. 1966. Altitude of sun: 46°.

Surface	G_r ly/min	G ly/min	Measmt ht above ground m	Measmt ht above sea-level m	Cloudiness
Light brown fields	0.09	1.10	100		Cloudless
E. Coniferous forest	0.05	1.12	100	—	,,
F. Coniferous forest denser than E	0.04	1.09	50	—	,,
G. Coniferous forest denser than F	0.03	1.11	100	—	,,
H. Coniferous- forest denser than G	0.02	1.12	100	—	,,
Rippled water-surface	0.02	1.10	100	—	,,

Table IX. Measurement from aircraft during the flight Luleå—Gällivare—Luleå 17 Jun. 1966. Altitude of sun: 41—50°.

Surface	G_r ly/min	G ly/min	Measmt ht above ground m	Measmt ht above sea-level m	Cloudiness
A. Luleå—Gällivare 09.00—09.50 a.m.					
Mixed coniferous and hardwood forest	0.09	0.96	200	300	Cloudless
Smooth water-surface	0.06	0.95	200	300	,,
Green fields with isolated patches of deciduous woodland	0.11	0.99	200	325	,,
Young pine forest	0.11	0.97	200	400	2/8 Cu
Bog with small tree-stands	0.10	1.00	200	500	1/8 Cu
B. Near Gällivare 09.55—10.15 a.m.					
Clearing, partly in shadow	0.10	0.96	50	525	3/8 Cu
Treeless mountain plateau, partly in shadow	0.12	0.96	50	700	3/8 Cu
Fjeld spruce forest	0.10	1.01	50	475	2/8 Cu
Coniferous fjeld forest	0.10	1.00	50	450	2/8 Cu
Smooth water-surface	0.04	0.96	50	450	2/8 Cu
C. Gällivare—Luleå 10.20—11.05 a.m.					
Pine forest	0.10	0.96	100	350	1/8 Cu
I. Coniferous forest	0.09	0.95	100	300	1/8 Cu
J. Coniferous forest denser than I	0.07	0.95	100	300	Cloudless
Mixed pine and birch forest	0.10	0.95	200	350	,,
Mixed spruce and birch forest	0.07	0.96	200	250	,,

Table X. Measurement on the ground at Björklinge near Uppsala 19 Jul. 1966.

Measure-ment point	M.E.T.	*Gfix* ly/min	*(EB)fix* ly/min	*tfix* °C	*hfix* %	*G* ly/min	*EB* ly/min	*Gr* ly/min	*t* °C	*h* %	C_1 %	C_2 %	Δt °C	Δh %	Shaded ground %
1	11.50	1.01	0.86	27.8	41	1.01	0.94	0.16	27.4	44	100.0	109.4	—0.4	+ 3	12
2	12.15	1.02	0.84	27.8	44	0.41	0.87	0.07	27.2	31	40.2	103.8	—0.6	—13	50
3	12.20	1.02	0.85	28.3	45	0.47	0.48	0.06	26.8	39	46.1	56.5	—1.5	— 6	40
4	12.30	1.01	0.84	27.8	47	0.05	0.03	0.02	26.5	34	5.0	3.6	—1.3	—13	75
5	12.40	1.01	0.83	27.4	46	0.02	0.02	0.01	26.6	38	2.0	2.4	—0.8	— 8	87
6	12.45	1.01	0.82	27.4	47	0.06	—0.01	0.04	27.4	32	5.9	—1.2	0.0	—15	60
7	12.55	0.99	0.82	27.8	50	0.98	0.95	0.13	28.2	35	99.0	115.9	+0.4	—15	10
8	13.55	0.92	0.76	28.5	48	0.06	0.14	0.03	28.1	31	6.5	18.4	—0.4	—17	80
9	14.00	0.91	0.74	28.1	53	0.06	0.04	0.02	27.6	33	6.6	5.4	—0.5	—20	70
10	14.10	0.91	0.73	28.6	46	0.06	0.04	0.03	27.6	33	6.7	5.5	—1.0	—13	35
11	14.20	0.88	0.72	28.4	48	0.05	0.04	0.01	28.2	37	5.7	5.6	—0.2	—11	95
12	14.30	0.87	0.70	27.9	48	0.05	0.02	0.03	27.7	32	5.8	2.9	—0.2	—16	70
13	15.05	0.79	0.62	28.3	48	0.08	0.02	0.01	—	—	10.1	3.2	—	—	82
14	15.15	0.78	0.61	28.1	50	0.04	0.02	0.01	28.0	31	5.1	3.3	—0.1	—19	65
15	15.20	0.78	0.60	28.2	48	0.72	0.78	0.08	28.2	29	92.1	130.0	0.0	—19	40
16	15.25	0.74	0.58	28.1	45	0.02	0.01	0.01	28.2	30	2.7	1.7	+0.1	—15	80

Table XI. Measurement on the ground at Linalompolo near Gällivare 25—26 Aug. 1966.

Measurement point	M.E.T.	*(EB)fix* ly/min	*tfix* °C	*EB* ly/min	*t* °C	C_2 %	Δt °C
1	23.24	—0.03	6.4	—0.02	6.0	66.7	—0.4
2	23.27	—0.03	6.4	—0.02	6.1	66.7	—0.3
3	23.28	—0.03	6.2	—0.02	6.0	66.7	—0.2
4	23.30	—0.03	6.0	—0.02	5.8	66.7	—0.2
5	23.34	—0.03	6.1	—0.01	5.1	33.3	—1.0
6	23.41	—0.03	6.0	—0.01	4.6	33.3	—1.4
7	23.45	—0.03	6.0	—0.01	4.6	33.3	—1.4
8	23.49	—0.03	6.0	—0.01	4.7	33.3	—1.3
9	23.54	—0.04	5.6	—0.02	5.4	50.0	—0.2
10	23.57	—0.04	5.6	—0.01	5.4	25.0	—0.2
11	00.00	—0.04	5.6	—0.02	5.0	50.0	—0.6
12	00.03	—0.04	5.2	—0.02	5.2	50.0	0.0
13	00.06	—0.05	5.1	—0.02	4.7	40.0	—0.4
14	00.09	—0.05	5.2	—0.02	4.6	40.0	—0.6
15	00.12	—0.05	5.3	—0.02	4.8	40.0	—0.5

Table XII. Measurement on the ground at Tyresta near Stockholm 26 Oct. 1966.

Measurement point	M.E.T.	*(EB)* ly/min	*tfix* °C	*EB* ly/min	*t* °C	C_2 %	Δt °C
			Sparse forest.				
1	19.10	—0.11	—3.3	—0.06	—2.6	54.5	+0.7
2	19.12	—0.11	—3.2	—0.07	—2.5	63.6	+0.7
3	19.15	—0.11	—3.4	—0.07	—2.4	63.6	+1.0
4	19.18	—0.10	—3.4	—0.06	—2.6	60.0	+0.8
5	19.21	—0.10	—3.5	—0.06	—2.6	60.0	+0.9
6	19.26	—0.10	—3.5	—0.05	—2.6	50.0	+0.9
7	19.30	—0.09	—3.7	—0.01	—2.8	11.1	+0.9
8	19.33	—0.09	—4.0	—0.04	—4.6	44.5	—0.6
9	19.36	—0.09	—4.1	—0.10	—4.3	111.1	—0.2
10	19.40	—0.10	—3.9	—0.13	—3.9	130.0	0.0
			Dense forest.				
1	20.23	—0.09	—4.2	—0.04	—4.4	44.5	—0.2
2	20.27	—0.09	—4.2	0.00	—4.0	0.0	+0.2
3	20.30	—0.09	—4.6	—0.04	—4.1	44.5	+0.5
4	20.32	—0.09	—5.0	—0.05	—4.0	55.6	+1.0
5	20.35	—0.09	—5.0	—0.07	—4.1	77.8	+0.9
6	20.37	—0.09	—5.1	—0.04	—4.1	44.5	+1.0
7	20.40	—0.09	—4.9	—0.02	—3.8	22.2	+1.1
8	20.44	—0.09	—5.0	—0.05	—3.6	55.6	+1.4
9	20.48	—0.09	—5.2	—0.05	—3.5	55.6	+1.7