Swedish University of Agricultural Sciences
Faculty of Forestry
Uppsala, Sweden

# Regional temperature and radiation indices and their adjustment to horizontal and inclined forest land

ANN-SOFIE MORÉN & KURTH L. PERTTU
Department of Ecology and Environmental Research

Studia Forestalia Suecica
No. 194 · 1994

ISSN 0039-3150
ISSN 91-576-4915-4

# Abstract

Morén, A.-S. & Perttu, K. L. 1994. Regional temperature and radiation indices and their adjustment to horizontal and inclined forest land. *Studia Forestalia Suecica 194*. 19 pp. ISSN 0039-3150, ISBN 91-576-4915-4.

Mean temperatures for the normal period (1961–90) from 513 stations in Sweden, together with their geographical positions, are used to derive temperature sums and average lengths of the growing season for different threshold values as functions of latitude and altitude. Maps are drawn showing the distribution of these temperature indices. Swedish regional average forest yield is well correlated with the temperature sums for the threshold value 5°C (Pearson correlation coefficient: 0.89). Solar radiation data for the period 1983-91 from 14 stations in Sweden are used to estimate global radiation reaching the earth's surface during clear days and during days irrespective of cloudiness. This data set is also used to derive global radiation sums expressed as functions of latitude and altitude. Corrections for an approximate adjustment of temperature indices to the soil surface level and with respect to local continentality/maritimity are proposed. The solar radiation on slopes has been calculated for various inclinations and azimuths.

*Key words:* air temperature, climate index, continentality, degree day, global radiation sum, length of growing season, maritimity, surface temperature, temperature sum, solar radiation

Ann-Sofie Morén, Department of Ecology and Environmental Research, Swedish University of Agricultural Sciences, P.O. Box 7072, S-750 07 Uppsala, Sweden.
Kurth L. Perttu, Department of Ecology and Environmental Research, Swedish University of Agricultural Sciences, P.O. Box 7072, S-750 07 Uppsala, Sweden.

# Contents



MS. received 12 December 1993
MS. accepted 20 June 1994

## List of symbols

| | |
|---|---|
| $alt$ | Altitude (m) |
| $C$ | Continentality index |
| $Gs_{start}$ | Start of the growing season (day) |
| $GSt$ | Length of growing season for a certain threshold temperature (days) |
| $lat$ | Latitude (°) |
| $N$ | Day number |
| $r$ | Pearson correlation coefficient |
| $R_0$ | Extraterrestrial radiation (MJ $m^{-2}$ $day^{-1}$) |
| $R_{ave}$ | Global radiation all days, irrespective of cloudiness, at the earth's surface (MJ $m^{-2}$ $day^{-1}$) |
| $R_{cle}$ | Global radiation on clear days at the earth's surface (MJ $m^{-2}$ $day^{-1}$) |
| $RS_t$ | Global radiation sum at the earth's surface during the growing season (GJ $m^{-2}$) |
| $t$ | Threshold temperature (°C) |
| $T_{adj}$ | Corrected mean temperature (°C) |
| $T_{max}$ | Monthly maximum temperature (°C) |
| $T_{min}$ | Monthly minimum temperature (°C) |
| $TS_t$ | Temperature sum in day degrees for a certain threshold temperature (°C) |
| $TS_{tss}$ | Temperature sum in day degrees for a certain threshold temperature at 'soil surface layer' (°C) |
| $W_{max}$ | Statistical weight for maximum temperature |
| $W_{min}$ | Statistical weight for minimum temperature |
| $X_{max}$ | Temperature difference between maximum temperature at screen height and maximum temperature near the ground on open forest land (°C) |
| $X_{min}$ | Temperature difference between minimum temperature at screen height and minimum temperature near the ground on open forest land (°C) |

## Introduction

Energy for physical as well as for biological processes at the earth's surface originates from the sun. The major part of the solar (or global) radiation (290–4 000 nm), absorbed by the earth's surface, is converted into heat (e.g. Monteith & Unsworth, 1990). The radiation balance shows a characteristic latitudinal variation with excess income at low latitudes and deficit at high latitudes. Heat is transferred from low to high latitudes through the general circulation in atmosphere and sea, which is a complicated process between the atmosphere and the earth's surface that continuously tries to adjust to an unattainable equilibrium (e.g. Liljequist, 1970; McIlveen, 1992). The integrated result of the processes involved is a world-wide system of contiguous regions, each of which is defined by the relative homogeneity of its climatic elements or vegetation. These regions or zones can be classified according to one single climatic element (e.g. temperature, humidity, precipitation), a combination of several of them, or according to its vegetation, which is the synthesis of climatic as well as other factors (Sjörs, 1963; Liljequist, 1970; Walter, 1979; Tuhkanen, 1980). On the one hand, vegetation alone cannot give quantitative, and thus objective, data when describing climate (Liljequist, 1970). On the other hand, climatic elements may be quantified in terms of raw climatic data (i.e. various parameters, means, extreme values, durations, etc.), that in themselves are insufficient to characterise climate as far as vegetation is concerned. This has led to the development of various climatic indices (Tuhkanen, 1980).

Temperature and available soil or surface water are decisive for vegetation type. The temperature climate is mainly governed by global radiation but is also to a great extent modified by factors such as topography, proximity to water, general circulation in atmosphere or water, etc. The available soil or surface water is determined by precipitation (gain) and air temperature, relative air humidity and wind speed (controlling the loss through evapotranspiration) (e.g. Liljequist, 1970; Geiger, 1971). At latitudes higher than 40-45°N temperature is often the most limiting factor for forest growth and yield, because it triggers the start and end of the growing season. During the growing season, temperature is the main variable influencing growth rate and nutrient uptake rate of the plants (Clarkson, Hopper & Jones, 1986; Ingestad, 1988). For some biological processes the other climatic elements are equally or sometimes even more important. For example, the visible part (400–700 nm, PAR) of the global radiation directly affects plant growth through photosynthesis, and a lack of precipitation (or available soil water) causes plants to reduce their water consumption, thus reducing growth. The climatic elements are consequently of great importance for forest establishment, annual tree growth and survival (e.g. Bäckström, 1984; Hytteborn, Packham & Verwijst, 1987; Cannell, 1989).

Empirical expressions have been used in many applications to explain how climate affects biological processes. In Scandinavia, the following temperature expressions have often been used: length of the growing season, temperature sums, growth units and respiration equivalents (e.g. Mork, 1941; Dahl & Mork, 1959; Utaaker, 1963; Huovila, 1964; Valmari, 1966; Odin & Perttu, 1978; Perttu, 1979, 1981, 1983, 1985, 1989; Ojansuu & Henttonen, 1983; Bjor & Sandvik, 1984; Odin, Magnusson & Bäckström, 1984). Many models have been evolved to calculate global radiation from sunshine duration or cloud data (Ångström, 1924*a*, 1956; Kondratjev, 1969) and extraterrestrial radiation (Mani & Chacko, 1980). All the models have in common that the attenuation of the global radiation in traversing the atmosphere must be known. This can be accounted for by using the concept of a transmission coefficient. For example, Rodskjer & Tuvesson (1984) used a ratio of observed (daily) insolation and mean (daily) insolation with a clear sky, and Kasten (1976) used a ratio of mean (daily) insolation with a clear sky and extraterrestrial radiation (i.e. global radiation above the atmosphere) to express the attenuation. Cannell (1989) gives an example of losses of solar energy, traced from the solar constant in space to the energy fixed in a woodland.

In this paper, the emphasis is placed on temperature and radiation as a means of quantifying conditions important to the establishment of new stands and to estimation of their mean yield, especially in regions with cool climate, e.g. northern Scandinavia. Because of the heterogeneity of regional populations (differences in frost hardiness, growth rates, timing of phenological events, etc.) it is difficult to determine the relative importance of environmental factors in a local area from the results of regional studies (Reed, Jones, Liechty, Mroz & Jurgensen, 1991). It should, therefore, be borne in mind that the temperature and radiation indices derived here are valid on a regional scale, and thus in most cases the equations are valid only for average conditions. To use the equations for single sites, regard must be paid to natural variations in locality and microclimate unless they represent a locality with average conditions for the latitude and altitude concerned. However, to adjust average values to single localities, some general corrections are made concerning slopes, continentality (maritimity), and height above ground level.

# Material and methods

## Databases and instrumentation

Data used in the calculations were obtained from the Swedish Meteorological and Hydrological Institute (SMHI), which is responsible for acquisition and storage of data from the synoptic and climate network stations (513 stations) as well as from the radiation network (13 stations, Table 1) in Sweden. Mean temperatures for the 30-year normal period 1961–90 (Alexandersson, Karlström & Larsson-McCann, 1991) are used to calculate the temperature indices. Data from eleven of the radiation stations and solar radiation data (1984–1992) from the Ultuna station, run by the Swedish University of Agricultural Sciences (59°49′N, 17°67′E, altitude 10 m), are used to calculate the radiation indices. Gunnarn and Borlänge have been excluded because of short operation times.

To avoid disturbances from surrounding obstacles, the radiation equipment, which measures not only global radiation, but also direct solar radiation and long wave radiation, is mounted on platforms placed on roofs, to obtain a free horizon. Frequently measured values are recalculated by SMHI to hourly sums (Josefsson, 1987). The data used in this study are global radiation, measured with a ventilated Kipp and Zonen CM-11 pyranometer, and sunshine duration, estimated from the direct solar radiation measured with an Eppley NIP (Normal Incidence Pyrheliometer). These instruments are calibrated according to the World

Table 1. *The stations used are Kiruna and Östersund (mountain area), Gunnarn, Borlänge, Karlstad and Växjö (inland area), Luleå, Umeå, Stockholm, Visby, Norrköping, Gothenburg and Lund (coastal area). The elevation is given in metres above sea level. Max SEL and Min SEL denote the solar elevation at noon on 21 June and on 21 December, respectively*

| Station | Latitude | Longitude | Elevation (m) | Min SEL (°) | Max SEL (°) |
|---|---|---|---|---|---|
| Kiruna | 67°49′N | 20°25′E | 408 | −1.4 | 45.5 |
| Gunnarn | 64°57′N | 17°42′E | 278 | 1.6 | 48.5 |
| Luleå | 65°33′N | 22°07′E | 17 | 0.8 | 47.7 |
| Umeå | 63°49′N | 20°15′E | 10 | 2.6 | 49.5 |
| Östersund | 63°12′N | 14°30′E | 376 | 3.4 | 50.2 |
| Borlänge | 60°28′N | 15°26′E | 140 | 6.1 | 53.0 |
| Karlstad | 59°22′N | 13°28′E | 46 | 7.2 | 54.0 |
| Stockholm | 59°21′N | 18°04′E | 30 | 7.2 | 54.0 |
| Visby | 57°40′N | 18°21′E | 51 | 8.8 | 55.7 |
| Norrköping | 58°34′N | 16°09′E | 43 | 8.0 | 54.9 |
| Göteborg | 57°42′N | 12°00′E | 5 | 8.8 | 55.7 |
| Växjö | 56°55′N | 14°44′E | 182 | 9.6 | 56.5 |
| Lund | 55°43′N | 13°13′E | 73 | 10.8 | 57.7 |

Radiometric Reference (WRR). At Ultuna, insolation is measured with a Moll-Gorczynski pyranometer and the radiation data are distributed as daily sums.

## Temperature sums and length of growing season

The temperature sum ($TS_t$) is by definition the summation of all daily mean values exceeding a chosen threshold value, here denoted $t$ (e.g. Perttu, 1985, 1989), and the growing season is defined as the period during which the daily mean temperatures exceed a chosen threshold value for four consecutive days (Perttu, 1983).

Perttu (1983) presented a simple model for $TS_5$ as a linear function of latitude (*lat*) and altitude (*alt*):

$$TS_t = A_0 + A_1 * lat + A_2 * alt \qquad (1)$$

where $A_0$–$A_2$ are coefficients. The estimations were based on data from the period 1961–76 presented in Perttu, Odin & Engsjö (1978). Here, linear least squares regression was used with the same model to derive coefficients for $TS_t$ for the new normal period. The length of the growing season for the threshold values 0, 3, 5, 6, 8 and 10°C was defined using temperature measurements from the synoptic and climate network stations. Thereafter, the temperature sums for the stations and threshold values concerned were calculated according to the definition of temperature sums.

By analogy with temperature sums, the length of an average growing season can be expressed as a function of latitude and altitude. Here, the model presented by Langlet (1937), based on values for the normal period 1901–30 from 416 Swedish stations and 28 Norwegian inland stations, was used when estimating coefficients for the normal period 1961-90. The model reads:

$$GS_t = B_0 + B_1 * lat + B_2 * alt + B_3 * lat * alt \qquad (2)$$

where $B_0$-$B_3$ are coefficients. Eqs. (1) and (2) are both valid for altitudes below 1 000 m. To find an equation valid for altitudes up to 1 500 m, a linear model type presented by Ebeling (1979*a*, *b*) was used:

$$TS_t = a_0 + a_1 * lat + a_2 * (lat)^2 + a_3 * (lat * alt) + a_4 * alt + a_5 * (alt)^2 \qquad (3)$$

where $a_0$–$a_5$ are coefficients. An equation for the length of the growing season for the same threshold values, and valid for altitudes up to 1 500 m, was derived similarly:

$$GS_t = b_0 + b_1 * lat + b_2 * (lat)^2 + b_3 * (lat * alt) + b_4 * alt + b_5 * (alt)^2 \qquad (4)$$

where $b_0$–$b_5$ are coefficients.

The coefficients presented here are valid for commonly used threshold values. In Scandinavian forestry, both 5, 6 and 8°C have been used as threshold temperatures, while 0 or 3°C often have been applied in agriculture. During the past 15–20 years, however, the most common value in forestry has been 5°C. The computed values of $TS_5$ and $GS_5$ have been drawn versus latitude and longitude and smoothed using the distance-weighted least squares smoothing (DWLS) procedure in the SYSTAT program package (Wilkinson, 1990).

## Solar radiation

The solar radiation is measured at a few stations only, because such measurements require frequent calibration and checking of sensors (Liljequist, 1979; Josefsson, 1987). Information on solar radiation at the ground can, however, be obtained from extraterrestrial data, but it is important to know how much energy is absorbed and scattered during its passage through the atmosphere. Ratios between the global radiation at the earth's surface and extraterrestrial radiation were estimated for clear days ($R_{cle}/R_0$) as well as for days, irrespective of cloudiness ($R_{ave}/R_0$), as functions of day number ($N$), to be able to estimate the global radiation at arbitrary times and places in Sweden. The measurements from Ultuna are included in the estimation of $R_{ave}/R_0$. The models used read:

$$R_{cle}/R_0 = D_0 + D_1 * N + D_2 * N^2 \qquad (5)$$

and

$$R_{ave}/R_0 = E_0 + E_1 * N + E_2 * N^2 + E_3 * N^3 + E_4 * N^4 + E_5 * N^5 \qquad (6)$$

where $D_0$–$D_2$ and $E_0$–$E_5$ are coefficients found by least squares linear regression.

Because of slight differences in the distribution of incoming global radiation between northern and southern Sweden, a division into two parts was made: northern latitudes (snow cover lasting more than 140 days) and south and middle latitudes (snow cover lasting less than 140 days) (cf. Ångström, 1974 and Fig. 12b). The stations Östersund, Umeå, Luleå and Kiruna were used in the computations for northern latitudes, while Lund, Växjö, Gothenburg, Norrköping, Visby, Stockholm and Karlstad represent the south and middle latitudes (here Ultuna was included for the ratio $R_{ave}/R_0$) (Table 1).

To estimate the ratio $R_{cle}/R_0$, the highest hourly global radiation value, $R$, around noon (here 10.00–14.00 h local time) was chosen for every day during the period and for the eleven SMHI stations. The reason why only these values were used, and not the total radiation on perfectly clear days, is that whole days absolutely free from clouds are very rare at these latitudes. The values were plotted for each station and all years, except for Östersund, Umeå, Luleå and Kiruna, where radiation values were excluded when the solar elevation was less than 5 degrees throughout the day (parts of January and December), and curves were fitted by hand below the very highest values to represent the potential cloudless radiation (Fig. 1). The clear sky radiation, $R_{cle}$, was then taken from the curve and divided by the corresponding computed extraterrestrial radiation, $R_0$ (Liljequist, 1979; Monteith & Unsworth, 1990; Astronomical Almanac, 1991).

When estimating the ratio $R_{ave}/R_0$, all measured values were summed weekly and divided by the corresponding computed extraterrestrial radiation using the Pgraph V1.2 (1991) package, before these ratios were averaged over the 9-year period 1983–91 (Ultuna 1984–92) for the two groups concerned (north and south). This gives a ratio that covers a mixture of all types of weather situation (various types and amounts of clouds, different air masses, etc.).

By analogy with the temperature sums, a model for the global radiation sum during the growing season, $RS_t$, was deduced. The start and end of the growing season, for the same threshold values as used with $TS$ and $GS$, were

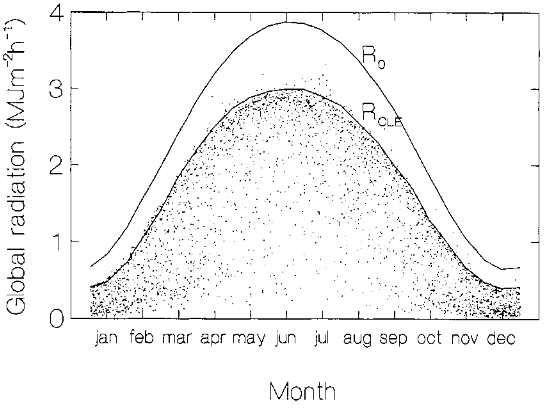


*Fig. 1.* Total global radiation on a horizontal surface at Karlstad, Sweden, 1983–1991. Each point represents the highest value recorded one hour around noon (here 10.00–14.00 h local time) each day. The curves drawn immediately below the highest points represent the potential global radiation on clear days, $R_{cle}$, and the upper curves show the corresponding extraterrestrial radiation, $R_0$.

estimated for each of the 12 stations (including Ultuna). Thereafter, the global radiation was summed for all days during the growing season for each station and year and a mean value was calculated for each station. Linear least squares regression was used to compute $R_t$ as a function of latitude and altitude. The model reads:

$$RS_t = F_0 + F_1 * lat + F_2 * alt \tag{7}$$

where $F_0$–$F_2$ are coefficients. By analogy with $R_{ave}/R_0$, all weather types are represented.

For all estimations where the solar constant (the total flux of solar radiation outside the atmosphere at a surface perpendicular to the solar beams, derived on the basis of the average distance between the earth and the sun) was needed, the mean value of 1 375 W $m^{-2}$ was chosen (Monteith & Unsworth, 1990; Kondratjev, 1992).

## Corrections

### *Adjustment of TS and GS to soil surface layer on forest land*

During clear, calm nights, the minimum temperatures just above the soil surface (normally measured at 20 cm height) on horizontal clear-felled areas can be considerably lower than the corresponding temperatures measured at the nearest network station at 1.8 m height in a WMO standardised thermometer screen. Frequent measurements have shown that the total correction which must be applied to obtain the minimum temperatures at plant height on a clear-felled area is $-5$°C (Perttu, 1981). If the minimum temperatures near the soil surface, on average during the growing season, differ by $X_{min}$ °C from those measured at 1.8 m height in the screen at the nearest network station, and if the corresponding maximum temperatures similarly differ by $X_{max}$ °C, a simple correction can be applied to the daily mean temperature to adapt the network values to open forest land conditions. When calculating daily and monthly mean temperatures, SMHI uses three daily observations, 06, 12, 18 GMT, and daily maximum and minimum temperatures (Eriksson, 1980). Using the corresponding statistical weights for minimum and maximum temperatures (here denoted $W_{min}$ and $W_{max}$, respectively), the adjustment can be expressed as:

$$T_{adj} = W_{min} * X_{min} + W_{max} * X_{max} \tag{8}$$

where the statistical weights, $W_{min}$ and $W_{max}$, during the growing season are set at 0.24 and 0.1, respectively, according to Eriksson (1980). The temperature sum applied to the soil surface layer has to be corrected similarly, and thus for the whole growing season, the $TS_{tss}$ (where *t* stands for threshold temperature and *ss* for 'soil surface layer') is given by:

$$TS_{tss} = TS_t + T_{adj} * GSt \tag{9}$$

$TS_t$ and $GS_t$ can be obtained using network data or Eqs. (1–4) above. The actual lengths of the growing season on clear-felled areas can be treated in a similar way by subtracting $T_{adj}$ from the threshold value, $t$-$T_{adj}$.

### *Corrections of $TS_t$ with respect to continentality and maritimity*

To derive $TS_t$, all 513 stations, situated in both continental and maritime areas, were used. To emphasise the local continental and maritime influences, respectively, an index ($C$) was calculated for all synoptic and climate network stations using the equation by Gorczynski (quoted by Liljequist, 1970) according to:

$$C = 1.7 * (T_{max} - T_{min}) / \sin(lat) - 20.4 \tag{10}$$

where $T$ represents the highest and lowest monthly average temperatures (in Sweden the July and January temperatures, respectively). These temperatures are readily available from SMHI. The cumulative $TS$-frequency for all network stations (Fig. 2), was used to divide the $C$ values into five groups, namely: maritime

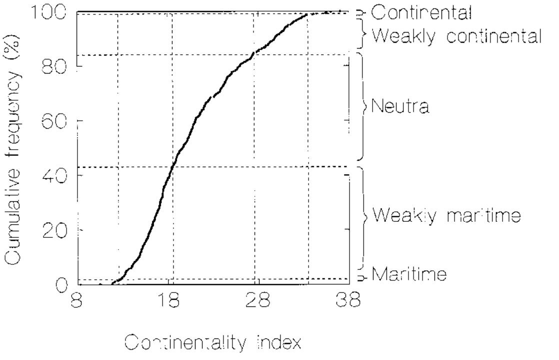


*Fig. 2.* Continentality index, $C$, estimated with Eq. (10) and illustrated as a cumulative frequency. The curve is used to divide the $C$-values into groups of continentality/maritimity. Low $C$-values correspond to local maritimity and high $C$-values correspond to local continentality.

(ca. 2%), weakly maritime (ca. 40%), neutral (ca. 41%), weakly continental (ca. 15%) and continental (ca. 2%).

As was the case for the computed values of $TS_t$ and $GS_t$, the computed values of $C$ have been plotted against latitude and longitude and smoothed using the distance-weighted least squares smoothing (DWLS) procedure in the SYSTAT program package (Wilkinson, 1990).

*Estimation of solar radiation on slopes*

To be accurate when estimating global radiation on sloping surfaces, not only the direct and diffuse radiation should be accounted for, but also the diffuse reflected radiation from facing surfaces (e.g. Josefsson, 1987) and the fact that diffuse radiation is not uniformly distributed, although this is the usual assumption (e.g. Monteith & Unsworth, 1990). According to Kondratjev (1969), the radiation income mainly depends on the orientation of the slope and the solar height; therefore, the other factors are omitted here.

To calculate a slope factor, the following algorithm was used:

$$\cos\theta = \cos\beta\cos Z + \sin\beta\sin Z\cos(\hat{\Omega} - \Omega) \qquad (11)$$

where the angle of incidence ($\theta$) between the normal to the slope and the solar beam is used to relate the slope and the solar geometries and where $\beta$ is the inclination of the slope to the horizontal, $Z$ is the zenith angle, $\hat{\Omega}$ is the solar azimuth angle and H is the slope azimuth angle. The slope factor was calculated for every hour for a number of days during the growing season at latitudes 56 and 66°N, for the slopes 0–30° at 5° intervals, and the azimuths from north to south at 45° intervals and the values were then averaged over the whole growing season.

# Results

## Derived temperature models

*Temperature sums*

Temperature sums can be calculated using Eq. (1) (Table 2a) or Eq. (3) (Table 2b). The complete equation for the most common threshold value in Swedish forestry, $t=5$°C, valid for altitudes below 1 000 m, reads:

$$TS_5 = 4\,922 - 60.4 * \text{lat} - 0.837 * \text{alt} \qquad (12a)$$

and for altitudes below 1 500 m:

$$TS_5 = 3\,635.3 - 12.18 * lat - 0.444 * (lat)^2 + 0.04041 * (lat * alt) - 3.343 * (alt) - 0.000040 * (alt)^2 \qquad (12b)$$

Table 2a. *Coefficients used in Eq. (1) for temperature sum estimations in the height interval 0–1 000 m. $R^2$ denotes the coefficient of determination and SEE the standard error of estimate*

| Threshold temperature (°C) | $A_0$ | $A_1$ | $A_2$ | $R^2$ | SEE |
|---|---|---|---|---|---|
| 0 | 8 279.3 | −98.115 | −1.131 | 0.960 | 95.281 |
| 3 | 6 126.4 | −73.813 | −0.951 | 0.954 | 79.893 |
| 5 | 4 922.1 | −60.367 | −0.837 | 0.948 | 72.372 |
| 6 | 4 362.4 | −54.059 | −0.779 | 0.943 | 68.584 |
| 8 | 3 320.9 | −42.172 | −0.653 | 0.932 | 60.735 |
| 10 | 2 373.1 | −31.056 | −0.520 | 0.915 | 52.252 |

Table 2b. *Coefficients used in Eq. (3) for temperature sum estimations in the height interval 0–1 500 m. $R^2$ denotes the coefficient of determination and SEE the standard error of estimate*

| Threshold temperature (°C) | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $R^2$ | SEE |
|---|---|---|---|---|---|---|---|---|
| 0 | 8 116.4 | −80.85 | −0.240 | 0.07762 | −5.947 | −0.000075 | 0.965 | 89.610 |
| 3 | 4 790.6 | −22.51 | −0.482 | 0.04992 | −4.026 | −0.000082 | 0.957 | 77.656 |
| 5 | 3 635.3 | −12.18 | −0.444 | 0.04041 | −3.343 | −0.000040 | 0.950 | 70.823 |
| 6 | 3 187.3 | −10.10 | −0.404 | 0.03691 | −3.089 | −0.000004 | 0.945 | 67.174 |
| 8 | 2 385.1 | −7.07 | −0.322 | 0.03101 | −2.659 | 0.000099 | 0.935 | 59.117 |
| 10 | 1 633.3 | −2.90 | −0.260 | 0.02809 | −2.389 | 0.000173 | 0.923 | 49.809 |

$TS_5$ computed from SMHI data and $TS_5$ estimated using Eq. (12a) correlate well, $r = 0.97$ (Fig. 3a), and the geographical distribution (isolines = 100 day degrees) is readily apparent from a map (Fig. 4). The highest and lowest $TS_5$ computed from SMHI data are approximately 1 600–1 700 and 400–500 day degrees, respectively, while the highest and lowest $TS_5$ estimated using Eq. (12a) are 1 500–1 600 and 400–500 day degrees, respectively. This gives a range of about 1 000 day degrees between the southern and northern parts of Sweden.

Average forest yield in Sweden can be estimated using $TS_5$ only ($r = 0.89$ for each period) (Fig. 5). $TS_5$ was computed using Eq. (12a) for 31 regions, according to the classification of the National Forest Survey (e.g. Anon. 1992) using an average latitude and altitude for each region concerned. The forest data, including all Swedish tree species, within each region and for four periods, viz. 1975–79, 1978–82, 1983–87 and 1987–91, were obtained from the National Forest Survey (Anon., 1983, 1986, 1990, 1992). Two regions deviate: Gotland, with poor water-supply, and Skåne, with large areas of forest planted on formerly cultivated land.

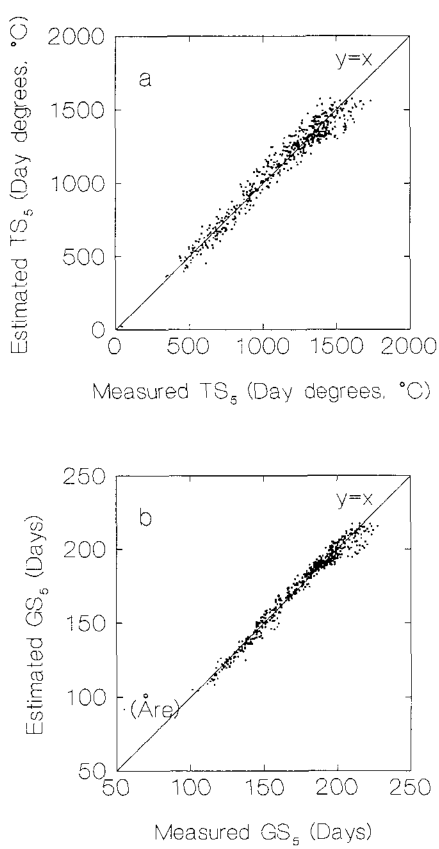


*Fig. 3.* (a) $TS_5$ computed from SMHI values versus $TS_5$ estiamated with Eq. (12a). (b) $GS_5$ computed from the SMHI values versus $GS_5$ estimated with Eq. (13a).

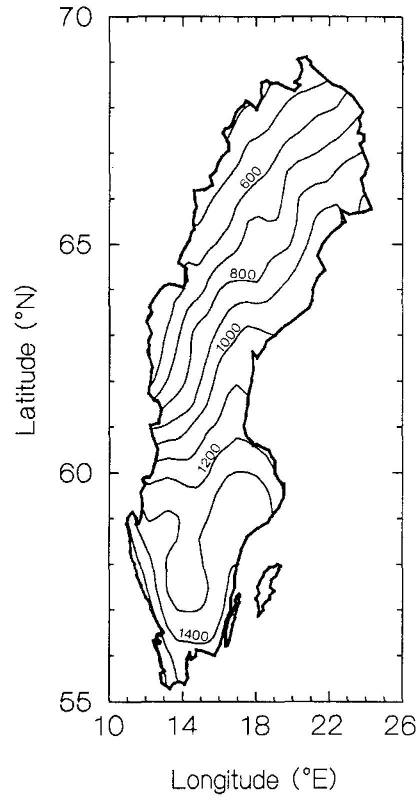


*Fig. 4.* Distribution of measured temperature sums for the most common threshold value for Scandinavian forestry, $t = 5°C$.

## *Length of the growing season*

Length of the growing season can be computed using Eq. (2) (Table 3a) or Eq. (4) (Table 3b). The complete equations for the most common threshold value (cf. temperature sums), $t = 5°C$ valid for altitudes below 1 000 m, read:

$$GS_5 = 597.6 - 6.823 * lat - 0.225 * alt + 0.00268 * (lat * alt) \tag{13a}$$

and for altitudes below 1 500 m:

$$GS_5 = 474.5 - 2.601 * lat - 0.036 * (lat)^2 + 0.00376 * (lat * alt) - 0.275 * (alt) - 0.000029 * (alt)^2 \tag{13b}$$

$GS_5$, computed from SMHI data, and $GS_5$, esti-

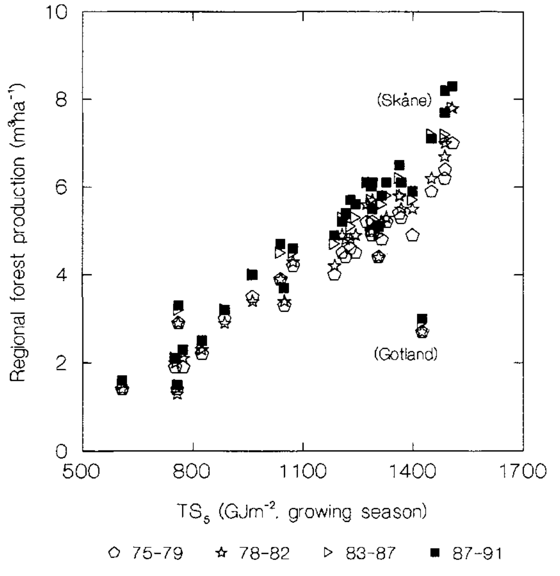


*Fig. 5.* Relation between annual regional forest yield, including all Swedish tree species, and $TS_5$ computed with Eq. (12a). The yield figures are divided into four periods, 1975–79, 1978–82, 1983–87 and 1987–91, respectively, according to their publication (Anon., 1983, 1986, 1990, 1992).

mated with Eq. (13a), correlates well, $r = 0.98$ (Fig. 3b) and as for $TS_5$ the geographical distribution (isolines = 10 days) is readily seen on a map (Fig. 6). The longest and shortest $GS_5$ computed from SMHI data are approximately

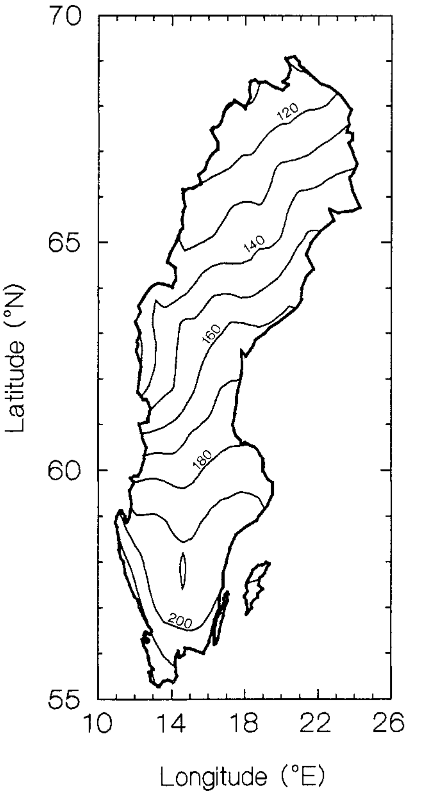


*Fig. 6.* Distribution of measured length of growing season for the most common threshold value in Scandinavian forestry $t = 5°C$.

Table 3a. *Coefficients used in Eq. (2) for estimations of length of the growing season in the height interval 0–1 000 m. $R^2$ denotes the coefficient of determination and SEE the standard error of estimate*

| Threshold temperature (°C) | $B_0$ | $B_1$ | $B_2$ | $B_3$ | $R^2$ | SEE |
|---|---|---|---|---|---|---|
| 0 | 894.2 | −10.678 | −0.780 | 0.01147 | 0.963 | 6.911 |
| 3 | 695.7 | −8.050 | −0.432 | 0.00600 | 0.970 | 5.314 |
| 5 | 597.6 | −6.823 | −0.225 | 0.00268 | 0.973 | 4.705 |
| 6 | 562.8 | −6.432 | −0.170 | 0.00175 | 0.965 | 5.348 |
| 8 | 508.0 | −5.909 | −0.131 | 0.00106 | 0.959 | 5.596 |
| 10 | 445.6 | −5.271 | −0.021 | 0.00081 | 0.951 | 6.122 |

Table 3b. *Coefficients used in Eq. (4) for estimations of length of the growing season in the height interval 0–1 500 m). $R^2$ denotes the coefficient of determination and SEE the standard error of estimate*

| Threshold temperature (°C) | $b_0$ | $b_1$ | $b_2$ | $b_3$ | $b_4$ | $b_5$ | $R^2$ | SEE |
|---|---|---|---|---|---|---|---|---|
| 0 | 1 339.7 | −25.417 | 0.122 | 0.00978 | −0.687 | 0.000011 | 0.964 | 6.836 |
| 3 | 716.5 | −8.681 | 0.005 | 0.00618 | −0.436 | −0.000013 | 0.971 | 5.280 |
| 5 | 474.5 | −2.601 | −0.036 | 0.00376 | −0.275 | −0.000029 | 0.976 | 4.457 |
| 6 | 422.2 | −1.546 | −0.043 | 0.00327 | −0.236 | −0.000047 | 0.972 | 4.746 |
| 8 | 397.1 | −2.017 | −0.034 | 0.00243 | −0.187 | −0.000045 | 0.966 | 5.074 |
| 10 | 349.1 | −1.928 | −0.029 | 0.00018 | −0.064 | −0.000030 | 0.954 | 5.926 |

220–230 and 110 days, respectively, while the corresponding $GS_5$, estimated with Eq. (13a) are 210–220 and 110 days, respectively. This gives a range of slightly over 100 days between the length of the growing season in southern and northern parts of Sweden.

The growing season is defined when the start and length is known. The start of the growing season when $t = 5°C$ can be determined using the following equation:

$$GS_{start} = -35.760 + 2.489 * lat - 0.0637 * alt + 0.00132 * lat * alt \quad (14)$$

The correlation coefficient between $GS_{start}$ computed from SMHI data and $GS_{start}$ estimated with Eq. (14) is 0.94, and the geographical distribution (isolines = 10 days) is shown in a map (Fig. 7).

## Derived global radiation expressions

### *Clear sky and average sky radiation*

The ratios $R_{cle}/R_0$ and $R_{ave}/R_0$ show not only seasonal variation, but also slight differences between the stations (Figs. 8a,b and 9a). For $R_{cle}/R_0$, these differences during the growing season are about 5%, while during the winter they reach about 10%. The scatter during the winter probably reflects uncertainty in the estimation rather than real variation. Regarding the ratio $R_{ave}/R_0$, Umeå, Kiruna, Växjö and Karlstad can be considered as extremes even if all stations show similar annual trends (Fig. 9b). Umeå and Karlstad are close to large water bodies (Gulf of Bothnia and Lake Vänern, respectively), while Växjö and Kiruna are inland stations. Throughout the year Växjö, on average, has 12% less incoming global radiation than Karlstad (and Visby), mainly because of differences in cloudiness. In the north, the annual trend has its peak in spring or early summer. Among the stations investigated here,

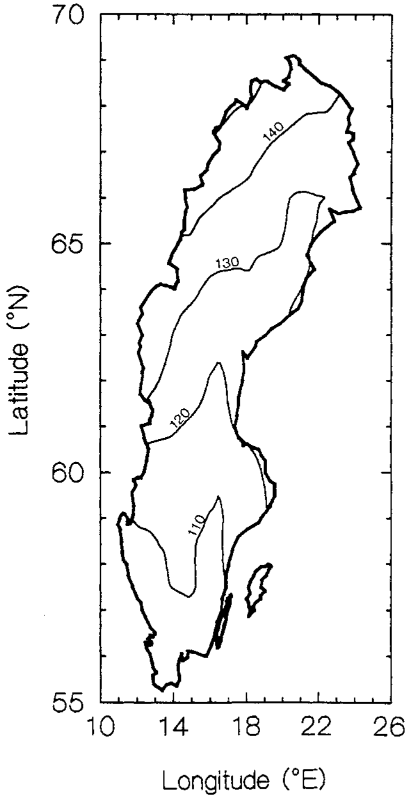


*Fig. 7.* Distribution of measured start of the growing season for the most common threshold value in Scandinavian forestry $t = 5°C$.

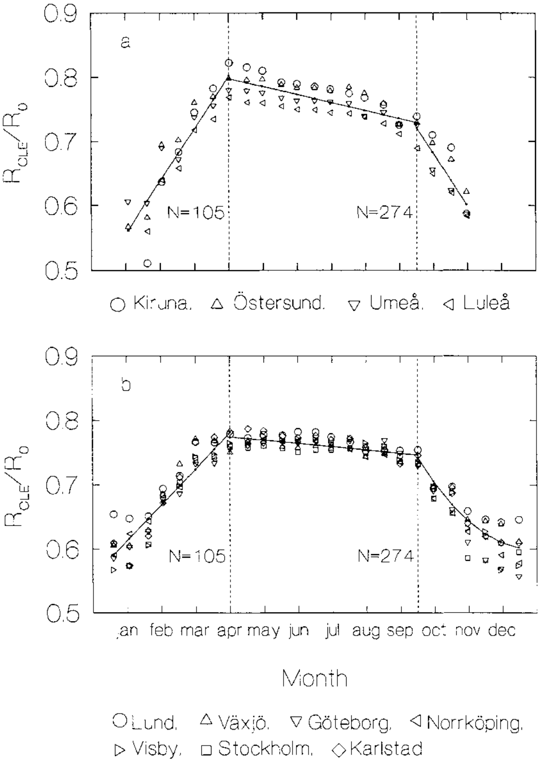


*Fig. 8.* The ratio $R_{cle}/R_0$ as a function of day number, represented by two points for each station and month, the first and 15th. When the solar elevation is less than 5° above the horizon, data for Östersund, Umeå, Luleå and Kiruna are excluded. (a) Northern Sweden (Östersund, Umeå, Luleå and Kiruna). For day numbers 32–319 all stations are represented. (b) South and middle latitudes (Lund, Växjö, Gothenburg, Norrköping, Visby Stockholm and Karlstad).

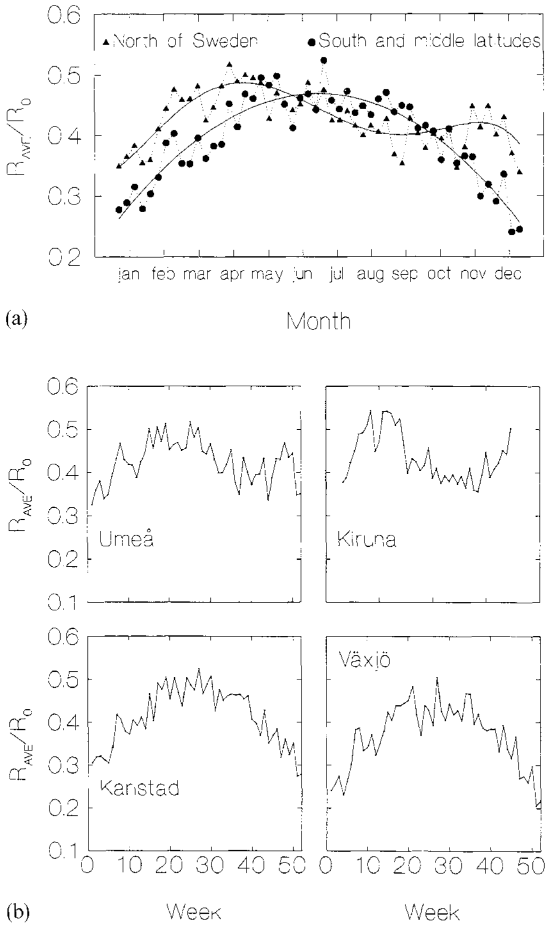


*Fig. 9.* (a) Average values for the ratio $R_{ave}/R_0$ as a function of day number, representing Northern Sweden (Östersund, Umeå, Luleå and Kiruna) and south and middle latitudes (Lund, Stockholm, Karlstad and Ultuna), respectively. Each point represents a weekly average. The annual trend is described by the unbroken curves. (b) Values for four single stations before averaging over the two groups.

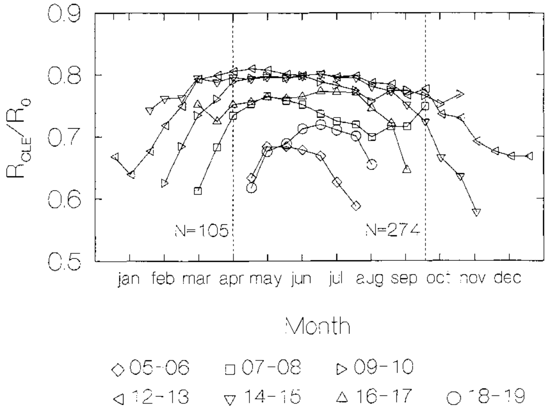


*Fig. 10.* The ratio $R_{cle}/R_0$ as a function of day number during different hours of the day, at Karlstad, Sweden, 1983-1991.

this trend is most pronounced for Kiruna and least pronounced for Umeå. During the growing season, the average ratio $R_{cle}/R_0$ is 0.76 for all stations and the average ratio $R_{ave}/R_0$ is 0.45.

The annual variation in $R_{cle}/R_0$ is expressed as a function of day number: Eq. (5) (Table 4). For south and middle latitudes, for example, the ratio $R_{cle}/R_0$ for day number 105–273 (mid April–September) reads:

$$R_{cle}/R_0 = 0.792 - 0.000167 * N \qquad (15)$$

It should be noted that $R_{cle}/R_0$ is derived for one hour at midday, when the solar altitude is highest and the optical pathway (the distance the radiation has to pass through the atmosphere to reach the earth's surface) shortest. The ratio when used for the whole day should consequently be somewhat reduced, since the optical pathway increases. When estimating the ratio $R_{cle}/R_0$ for different hours of the day for Karlstad, in the same way as the ratio $R_{cle}/R_0$ was estimated around noon, it was found that $R_{cle}/R_0$ roughly decreases by about 10% between noon and six hours before and six hours after, respectively, during May to July inclusive (Fig. 10).

Analogously to $R_{cle}/R_0$, the annual trend for $R_{ave}/R_0$ is expressed as a function of day number: Eq. (6) (Table 5).

Table 4. *Coefficients used in Eq. (5).* $R^2$ denotes the coefficient of determination

| $R_0/R_{cle}$ | $N$ | $D_0$ | $D_1$ | $D_2$ | $R^2$ |
|---|---|---|---|---|---|
| *North* | | | | | |
| | 0–104 | 0.521 | 0.002681 | – | 0.848 |
| | 105–273 | 0.840 | −0.000403 | – | 0.595 |
| | 274–365 | 1.447 | −0.002650 | – | 0.770 |
| *South* | | | | | |
| | 0–104 | 0.589 | 0.001833 | – | 0.876 |
| | 105–273 | 0.792 | −0.000167 | – | 0.450 |
| | 274–365 | 2.528 | −0.010294 | $0.137*10^{-4}$ | 0.826 |

Table 5. *Coefficients Eq. (6). $R^2$ denotes the determination coefficient*

| $R_{ave}/R_0$ | $E_0$ | $E_1$ | $E_2$ | $E_3$ | $E_4$ | $E_5$ | $R^2$ |
|---|---|---|---|---|---|---|---|
| North | 0.338 | $0.114*10^{-2}$ | $0.244*10^{-4}$ | $-0.316*10^{-6}$ | $0.115*10^{-8}$ | $-0.134*10^{-11}$ | 0.701 |
| South | 0.246 | $0.243*10^{-2}$ | $-0.658*10^{-5}$ | – | – | – | 0.866 |

The daily sums of extraterrestrial radiation ($R_0$) for day numbers 80 to 270 and latitudes 55, 60, 65 and 70°N may be calculated using the following equation:

$$R_0 = G_0 + G_1*N + G_2*N^2 + G_3*N^3 + G_4*N^4 \tag{16}$$

where $G_0$, $G_1$, $G_2$, $G_3$, $G_4$ are coefficients (Table 6). To obtain the sum of the extraterrestrial radiation during the growing season, the daily sum must be calculated for each day (Eq. (16)) before it is summed for the period concerned.

*Global radiation sum*

Eq. (7) is used to compute the global radiation sum (Table 7). The complete equation for $RS_5$ reads:

$$RS_5 = 7.2774 - 0.0782*lat - 0.00072*alt \tag{17}$$

The correlation between the measured $RS_5$ (data from the 11 SMHI stations and Ultuna) and estimated $RS_5$ using Eq. (17), is good, $r = 0.83$ (Fig. 11). The highest and lowest $RS_5$ computed from the SMHI data are approximately 3.0 and 1.6 GJ m$^{-2}$, respectively, while the highest and lowest $RS_5$ estimated using Eq. (17), are 2.9 and 1.7 GJ m$^{-2}$, respectively.

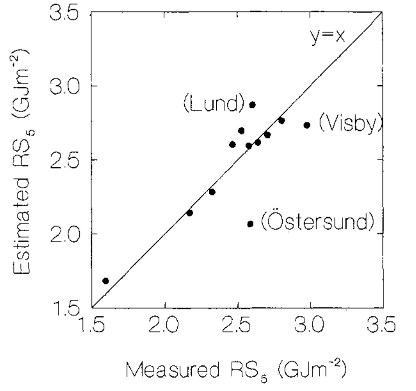


*Fig. 11.* RS5 computed from the 11 SMHI stations plus the Ultuna station, together with RS5, estimated using Eq. (16).

## Adjustment of climate indices

*Adjustment of TS and GS to soil surface level*

Minimum air temperatures just above the ground surface on clear-felled areas during clear and calm nights are, on average, 5°C lower than the minimum temperatures measured at a stan-

Table 6. *Coefficients used in Eq. (14), with which it is possible to calculate the extraterrestrial radiation for days Nos. 80 to 270. $R^2$ denotes the determination coefficient*

| Latitude (°N) | $G_0$ | $G_1$ | $G_2$ | $G_3$ | $G_4$ | $R^2$ |
|---|---|---|---|---|---|---|
| 55 | $22.8*10^6$ | $-0.65*10^6$ | $1.23*10^4$ | $-61.064$ | 0.090 | 1.000 |
| 60 | $31.7*10^6$ | $-1.05*10^6$ | $1.69*10^4$ | $-80.926$ | 0.119 | 1.000 |
| 65 | $47.6*10^6$ | $-1.65*10^6$ | $2.35*10^4$ | $-109.661$ | 0.161 | 1.000 |
| 70 | $85.3*10^6$ | $-2.89*10^6$ | $3.67*10^4$ | $-165.001$ | 0.241 | 1.000 |

Table 7. *Coefficients used in Eq. (7) for radiation sum estimations. $R^2$ denotes the coefficient of determination and SEE the standard error of estimate*

| Threshold temperature (°C) | $F_0$ | $F_1$ | $F_2$ | $R^2$ | SEE |
|---|---|---|---|---|---|
| 0 | 6.9712 | −0.0667 | −0.00070 | 0.815 | 0.1641 |
| 3 | 7.1453 | −0.0731 | −0.00073 | 0.857 | 0.1522 |
| 5 | 7.2774 | −0.0782 | −0.00072 | 0.876 | 0.1477 |
| 6 | 7.3684 | −0.0813 | −0.00069 | 0.890 | 0.1412 |
| 8 | 7.4295 | −0.0858 | −0.00073 | 0.896 | 0.1445 |
| 10 | 7.6033 | −0.0932 | −0.00075 | 0.897 | 0.1545 |

dard network station. For average weather conditions (calm, windy, clear, cloudy, etc.), however, a more realistic value would be 3°C. Likewise, the maximum air temperatures during daytime are about 1°C higher close to the ground than at 1.8 m height. An adjustment for these temperature differences is then $0.24*(-3)+0.1*(+1)=-0.6$°C (cf. Eq. (8)), which implies that the station temperatures should be reduced, on average, by 0.6°C when representing surface layers on clear-felled areas. $TS_5$ during the growing season at latitude 64°N and altitude 500 m is, for example, reduced by 80 day degrees (Eq. (12a)). For the growing season the new threshold value becomes $t=5-(-0.6)=5.6$°C, thus giving a shorter growing season. Using linear interpolation between the durations computed using the equations for $GS_5$ and $GS_6$, the duration of the growing season at latitude 64°N and altitude 500 m, with the threshold value 5.6°C, is reduced by 7–8 days, compared to the growing season computed from measurements at 1.8 m height at the nearest network station.

### *Correction of TS with respect to continentality and maritimity*

The limits of the five $C$ groups obtained and the corresponding corrections are (cf. Fig. 2):

| | |
|---|---|
| $C<12.4$ | maritime: reduce $TS$ by 100 day degrees |
| $12.5<C<18.4$ | weakly maritime: reduce $TS$ by 50 day degrees |
| $18.5<C<27.4$ | neutral: no change |
| $27.5<C<33.4$ | weakly continental: increase $TS$ by 50 day degrees |
| $33.5<C$ | continental: increase $TS$ by 100 day degrees. |

The application of the corrections is facilitated by using the computed $C$-values for the average July and January temperatures (Fig. 12a). For a certain area, $TS_t$ can be calculated with Eqs. (1) or (3), and together with the corresponding C-value, a corrected value can be obtained. For example, in regions where $C$ ranges from 27.5 to 33.4, the estimated temperature sum should be increased by 50 day degrees.

### *Estimation of solar radiation on slopes*

For Swedish latitudes (55–70°N), all slopes in the northern sector (azimuth from west through north to east), receive less global radiation than the corresponding horizontal surface (Fig. 13). Less radiation is also received on slopes in the southeastern and southwestern sectors when the locality is north of latitude 60°N and when the slope angle exceeds about 25°. More radiation than on a horizontal surface is received on south-facing slopes with an inclination of up to 30°. Most radiation is received on a south-facing slope with an inclination of 10–15°. For slopes facing south and north, respectively, the global radiation, compared to a horizontal surface, is shown in Table 8.

## Discussion and conclusions

In many cases, climate indices can be used when climatic variables are needed for various forest studies. These indices are also beneficial in modelling, in which different climate elements are used as driving variables. It should be noted, however, that the climatic indices presented here are valid for average conditions. For studies at a local or a micro-scale, more refined adjustments must be developed than those presented here.

### Temperature sums, length of growing season and correction for continentality

The estimates of temperature sums and of the duration of the growing season were based on the comprehensive data set from the normal period 1961–90, comprising locally continental as well as locally maritime synoptic and climate network stations (Eqs. (1–4) and Tables 2a, 2b, 3a, 3b). Two types of model were presented, one simple, based on data for stations situated in the altitudinal range 0–1 000 m, and one more complicated with the altitudinal range 0–1 500 m. Compared with coefficients presented earlier, those given here are based on a longer series of observations and on a larger number of stations. The distribution of $TS_5$ and $GS_5$, respectively, are shown (Figs. 4 and 6). The distribution of $TS_5$ can be compared with the map that Odin, Eriksson & Perttu (1983) presented, showing hand-drawn isolines for the period 1961–1976 (Perttu et al., 1978). The general pattern is the same, but Odin's map is more detailed. Regard is paid, for example, to the river valleys in the north, and to lakes Mälaren and Vättern in the

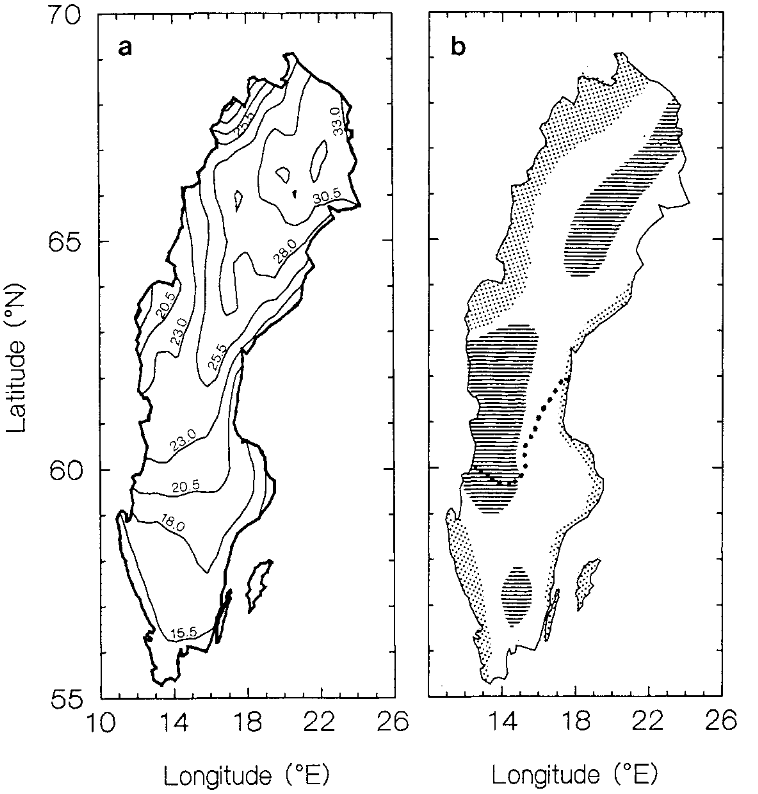


*Fig. 12.* Locally continental and locally maritime areas as described by (a) the continentality index estimated here and (b) Ångström (1974). Dotted areas in the map (modified after Ångström (1974)) are considered as locally maritime and hatched areas are locally continental. The general pattern discerned when comparing (a) and (b) is similar, where the influence, e.g. of long coastlines, clearly is seen. The dotted line shows the limit for a snow cover lasting 140 days (cf. solar radiation above).

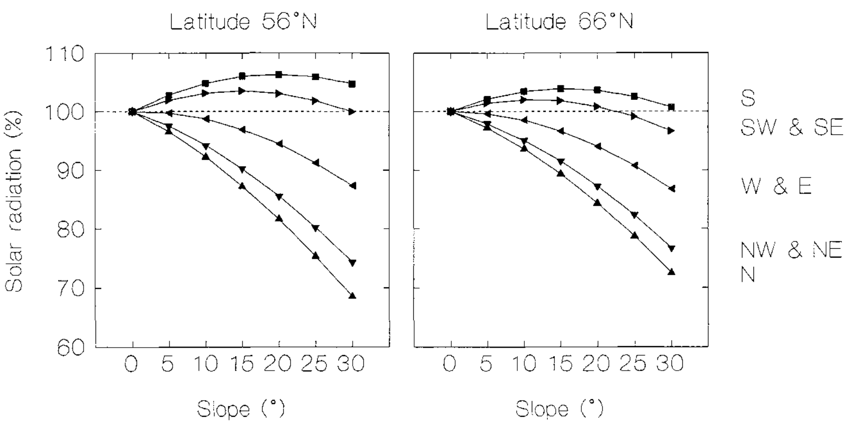


*Fig. 13.* Slope factors computed using Eq. (11) for the growing season at latitudes 56 and 66°N, respectively. The dotted line (100%) represents the global radiation income at a corresponding horizontal surface, while the unbroken curve illustrate surplus or deficit in incoming global radiation as compared with the horizontal surface.

south. In the analysis presented here, these local effects do not emerge, mainly because of the technique applied, but they can, for example, be considered by using the continentality index. Ångström (1974) presented a map showing the distribution of days with mean air temperature (reduced to mean sea level) exceeding +3°C, estimated from the normal period 1901–30. This

Table 8. *Global radiation reaching a south and a north slope, respectively, as a proportion of global radiation reaching a horizontal surface at the same latitude*

| Latitude (°N) | Inclination (°) | Global radiation (percentage (%) of radiation at horizontal surface) South slope | North slope |
|---|---|---|---|
| 56 | 15 | 106.0 | 87.2 |
| 56 | 25 | 105.9 | 75.3 |
| 66 | 15 | 103.9 | 89.3 |
| 66 | 25 | 102.5 | 78.7 |

map is not directly comparable with the map for $GS_5$ (Fig. 6), but a comparison with some stations tabulated by Ångström shows only slight differences.

$TS_t$ and $GS_t$ are affected by the Baltic Sea and Gulf of Bothnia on the eastern coast of Sweden, as well as by the North Atlantic Drift west of the Scandes mountains (Figs. 4 and 6). A heat reservoir, such as a large water body, delays the start of the growing season in the spring and extends it in the autumn. Further, the amplitude of the annual as well as of the daily temperature variation, is less pronounced in locally maritime than in locally continental areas.

The temperature sum is calculated as a linear accumulation of temperatures above a certain threshold value, but temperature can also be weighted so that a high daily mean value gives a relatively higher contribution to the sum than a low one. Some biological processes are best described by weighted temperatures. Mork (1941), for example, introduced growth units by relating elongation of leading shoots to the temperature of the six warmest hours of the day. Odin et al. (1983) modified the model for growth units by replacing the mean value of the six warmest hours by the mean value of the 13-hour and the maximum temperatures. The continentality index (Fig. 12a) is another possibility for weighting temperatures. Ebeling (1979*a*, *b*) for example used the Ångström (1974) (Fig. 12b) areas of local continentality and local maritimity in order to apply corrections for timber yield at different localities in northern Sweden. For the continental sites he increased the calculated $TS_6$-values by 15–40 day degrees, and for maritime sites he reduced the values by 60–70 day degrees. An increase or decrease of the temperature sum according to the corrections suggested here probably gives a suitable correction level when estimating forest yield. For taking other factors into account (such as insect and fungus damage, weed occurrence and frost injuries), other correction levels must be chosen (Begon, Harper & Townsend, 1990).

## Clear sky radiation

The maximum solar radiation on a clear day not only varies with latitude and season (i.e. solar geometry). The difference between the highest and the lowest value in July can, for example, be more than 0.5 MJ $m^{-2}$ $h^{-1}$. This is mainly caused by the effect of different air masses (amount of water vapour, dust and aerosols in the air), which in turn affects the measured global radiation via differences in (1) transmissivity, (2) multiple reflection from the atmosphere and (3) amount of clouds. Not even 60 minutes of recorded sunshine guarantee a cloudfree sky, since there might be clouds that do not shade the solar disc and a small amount of cloud in an otherwise clear sky mostly increases the diffuse flux. With a few, isolated cumulus present, the total radiation can exceed that with a completely cloudless sky by 5–10% (Monteith & Unsworth, 1990). Since the curve, $R_{cle}$, was fitted just below the highest radiation values (Fig. 1), $R_{cle}/R_0$ thus represents the potential global radiation on clear days where the air has low dust, aerosol and water vapour contents for the stations concerned. On some occasions, however, the global radiation sum can reach considerably higher values.

Although the clear sky radiation mainly reflects the variation of the direct global radiation component, some of the latitudinal differences (Figs. 5a and b) may probably be explained by the diffuse component. According to Müller (1985), the seasonal variation of the diffuse radiation with clear sky in the Alps is mainly determined by the following four factors: (1) distance between the sun and the earth, (2) water vapour content of the air, (3) dust content of the air and (4) albedo of the ground. Applying the theory of Schüepp (1966), Müller concluded that the albedo of the ground is the most important factor, influencing the diffuse radiation through multiple reflection between the ground and the atmosphere (cf. Ångström, 1924b; Ångström & Tryselius, 1934).

## Average sky radiation

The ratio $R_{ave}/R_0$ (Figs. 9a and b) reflects average cloud, air mass and albedo conditions at different sites. Here too, a division into two areas was made (cf. above), owing to the relatively large differences between the northern and southern stations. The main variance is caused by differences in quality of direct and diffuse global radiation components. When clouds are sparse, almost all radiation reaching the Earth is direct, while with a cloud cover, the diffuse component plays a more pronounced part in the incoming global radiation. This is very conspicuous when the high albedo values of a snow-covered ground surface which, together with a cloud cover, causes multiple reflection between snow and clouds (Ångström, 1924b; Ångström & Tryselius 1934). For northern Sweden, with its long-lasting snow cover (approximately October/November until April/May), this is easily distinguished. In the south, the snow cover is more temporary and irregular and the effects are not easily seen when averaging over several years. During spring, Kiruna and Östersund especially, but also Luleå and Umeå, have relatively large incoming total radiation. According to Ångström & Tryselius (1934), this mainly is caused by more numerous sunshine hours in April and May, in combination with multiple reflection. During summer, the situation is reversed, the ratio being higher in the south than in the north. This can probably be explained by varying amounts of clouds in relation to solar elevation and differences in surface albedo. The ratio $R_{ave}/R_0$ should be adjusted when it is used for coastal stations or inland stations situated in high-lying terrain. In the south, $R_{ave}/R_0$ for a coastal station should be increased by an average of 5% and for an inland station in high-lying terrain it should be reduced by about 5%. This is also valid for stations in the north but during the growing season only.

## Global radiation sum

In contradiction to theory, coefficient $F_2$ (Eq. (7) and Table 7) has a negative sign, implying that the global radiation sum decreases with altitude. Perttu (1970) measured global radiation within the height range 300–3 000 metres at Luleå and Östersund on two almost cloudfree days, and found that global radiation increases linearly by 7–10% per 1 000 metres. Since $RS_t$ includes cloudiness, a probable explanation of this discrepancy is an increase of cloudiness with height above sea level.

## Radiation on slopes

What do differences in global radiation for slopes with different inclinations imply for the length of the growing season and for the temperature sums? Close to the ground surface, the effect may be significant locally, especially during periods of snow-melt, thus resulting in patches with or without snow cover. This influences the albedo and consequently the absorbed energy and the soil temperatures. With a snow cover, the surface temperature is close to 0°C and most of the biological processes are in a state of low activity. Compared with horizontal, and even more with north slopes, south slopes become snowfree earlier and soil temperature rapidly rises above zero. At standard heights (1.8 m above ground), slope effects are much less pronounced, partly because the advective energy exchange caused by wind tends to eliminate the air temperature differences (cf. below).

Temperature measurements on an almost horizontal but clear-felled area and on adjacent, treeless south- and north-facing slopes (inclination about 10°) in northern Sweden (lat. 67°6′N, alt. 475–550 m) have shown that the mean air at 1.8 m height, on average, was 0.5 and 0.7°C warmer on the horizontal surface than on the north and south slopes, respectively (Perttu, 1972). These differences were still more pronounced for the corresponding maximum temperatures. Considering the wind speed, the slopes had, on average, 20–25% higher mean wind speeds than the horizontal surface; the conclusion is that wind is more important than the slope itself. Since wind speed during summer generally is highest during daytime, the differences are most pronounced for the maximum temperatures. With a growing season of 120 days, the temperature sums on the north and south slopes were 60 and 80 day degrees lower, respectively, than on the horizontal area. Similar wind influences were measured by Odin, Ottosson Löfvenius & Åman (1990) on a horizontal plateau and south-west and north-east slopes.

# References


Alexandersson, H., Karlström, C. & Larsson-McCann, S. 1991. Temperaturen och nederbörden i Sverige – Referensnormaler (Temperature and precipitation in Sweden – Reference normals). *SMHI Meteorologi, Klimatsektionen, Rapport 81*. 87 pp. (In Swedish with English summary.)

Ångström, A. 1924*a*. Solar and terrestrial radiation. *Quarterly Journal of the Meteorological Society 50*, 121–125.

Ångström, A. 1924*b*. Om markbeteckningens inflytande på ljusklimatet. *Teknisk tidskrift 54*(32), 297. (In Swedish.)

Ångström, A. 1956. On the computation of global radiation from records of sunshine. *Arkiv för geofysik 2*(22), 471–479.

Ångström, A. 1974. *Sveriges klimat*. Stockholm: Generalstabens Litografiska Anstalts Förlag. 188 pp. (In Swedish.).

Ångström, A. & Tryselius, O. 1934. Total radiation from sun and sky at Abisko (68°21'.2N, 18°49'.3E). *Geografiska annaler 16*(1), 54-69.

Anonymous, 1983, 1986, 1990, 1992. *Skogsdata 83, Skogsdata 85, Skogsdata 89/90, Skogsdata 92, aktuella uppgifter om de svenska skogarna från riksskogstaxeringen*. Sveriges lantbruksuniversitet, institutionen för skogstaxering, Umeå. (In Swedish.)

*Astronomical Almanac 1991*, Nautical Almanac Office, USNO, Washington and H.M. Nautical Almanac Office, RGO, London.

Bäckström, P.-O. (ed.). 1984. *Skogsföryngring i fjällnära skogar*. Forskarrapport. Institutionen för skogsskötsel, Sveriges lantbruksuniversitet. (In Swedish.)

Begon, M., Harper, J.L. & Townsend, C.R. 1990. *Ecology. Individuals, populations, and communities*, 2nd ed. Boston, Oxford, London, Edinburgh, Melbourne: Blackwell Scientific Publications.

Bjor, K. & Sandvik, M. 1984. Summer frost problems in a locality in Tröndelag. In: Perttu, K. (ed.). Ecology and management of forest biomass production systems. *Department of Ecology and Environmental Research, Swedish University of Agricultural Sciences, Report 15*, 19–28.

Cannell, M.G.R. 1989. Physiological basis of wood production: a review. Scandinavian Journal of *Forest Research 4*, 459–490.

Clarkson, D.T., Hopper, M.J. & Jones, H.P. 1986. The effect of root temperature on the uptake of nitrogen and the relative size of the root system in *Lolium perenne*. I. Solutions containing both $NH_4^+$ and $NO_3^-$. *Plant, Cell and Environment 9*, 535–545.

Dahl, E. & Mork, 1959. Om sambandet mellom temperatur, andning og vekst hos gran (On the relation between temperature, respiration and growth of spruce). *Meddelenden fra Det Norske Skogforsöksvesen 53*, 83–93. (In Norwegian with English summary.)

Ebeling, F. 1979*a*. Mera skog norr – Anvisningar för skogsskötsel i kyliga klimatlägen. *Sveriges skogsvårdsförbunds Tidskrift – specialnummer, häfte 4*. 126 pp.

Ebeling, F. 1979*b*. *Mera skog norr – Slutrapport över Skogshögskolans projekt "Förutsättningar för skogsproduktion i norra Sverige"*. Specialrapport. Swedish University of Agricultural Sciences, Umeå. 178 pp. (In Swedish.)

Eriksson, B. 1980. Noggrannheten vid beräkning av dygnsmedeltemperaturen. *Sveriges meteorologiska och hydrologiska institut. Meddelande nr 4*. 13 pp. (In Swedish.)

Geiger, R. 1971. *The climate near the ground*. 3rd printing. 611 pp. Cambridge, Massachusetts: Harvard University Press.

Huovila, S. 1964. On precautions against crop damage due to radiation frost within hilly regions. *Societas Scientiarum Fennica, Commentationes Physico-Mathematicae 29*(4). 21 pp.

Hytteborn, H., Packham, J.R. & Verwijst, T. 1987. Tree population dynamics, stand structure and species composition in the montane virgin forest of Vallibäcken, northern Sweden. *Vegetatio 72*, 3–19.

Ingestad, T. 1988. A fertilization model based on the concepts of nutrient flux density and nutrient productivity. *Scandinavian Journal of Forest Research 3*, 157–173.

Josefsson, W. 1987. Solstrålningen i Sverige, tids- och rumsfördelning. *Rapport R112:1987*, Statens råd för byggnadsforskning, Stockholm. 274 pp. (In Swedish.)

Kasten, F. 1976. Variation of solar and terrestrial radiation with time of the day and time of the year as deduced from many years records. In: *Solar energy, proceedings of the Unesco/WMO Symposium. WMO No. 477*. 654 pp.

Kondratjev, K.Ya. 1969. *Radiation in the atmosphere*. 900 pp. New York, London: Academic Press.

Kondratjev, K.Ya. 1992. *Changes in global climate. A study of the effect of radiation and other factors during the present century*. Rotterdam: A.A. Balkema.

Langlet, O. 1937. Studier över tallens fysiologiska variabilitet och dess samband med klimatet. *Meddelanden från Statens Skogsförsöksanst. 29*. 400 pp. Stockholm: (In Swedish.)

Liljequist, G.H. 1970. *Klimatologi*. Generalstabens Litografiska Anstalt, Stockholm. 527 pp. (In Swedish.)

Liljequist, G.H. 1979. *Meteorologi: strålning*. Department of Meteorology, University of Uppsala. 197 pp. (In Swedish.)

McIlveen, J.F.R. 1992. *Fundamentals of weather and climate*. 497 pp. Chapman & Hall.

Mani, A. & Chacko, O. 1979. Attenuation of solar radiation in the atmosphere. *Solar energy 24*, 347–349.

Monteith, J.L. & Unsworth, M.H. 1990. *Principles of environmental physics*, 2nd ed. 291 pp. London, New York, Melbourne, Auckland: Edward Arnold.

Mork, E. 1941. Om sambandet mellom temperatur og vekst (Über den Zusammenhang zwischen Temperatur und Wachstum). *Meddelanden fra Det Norske Skogforsöksvesen 27*, 1–89. (In Norwegian with German summary.)

Müller, H. 1985. Review paper on the radiation budget in the Alps. *Journal of Climatology 5*, 445–462.

Odin, H. & Perttu, K. 1978. Den skogsmeteorologiska forskningen vid Skogshögskolan. *Swedish University of Agricultural Sciences Department of Forest Site Research, Research Notes 98*. Umeå. 15 pp. (In Swedish.)

Odin, H., Eriksson, B. & Perttu, K. 1983. Temperaturklimatkartor för svenskt skogsbruk. *Swedish University of Agricultural Sciences Department of Forest Site Research, Rapport 45.* 57 pp. (In Swedish.)
Odin, H., Magnusson, B. & Bäckström, P.-O. 1984. Effect of low shelterwood on minimum temperature near the ground. In: Perttu, K. (ed.). Ecology and Management of Forest Biomass Production Systems. *Swedish University of Agricultural Sciences, Department of Ecology and Environmental Research, Report 15*, 77-99.
Odin, H., Ottosson Löfvenius, M. & Åman, K. 1990. Klimatstudier på ett nordligt högläge. Institutionen för skoglig ståndortslära, Sveriges lantbruksuniversitet. Stencil 12. 25 pp. ISSN 0280-9168. (In Swedish.)
Ojansuu, R. & Henttonen, H. 1983. Kuukauden keskilämpötilan, lämpösumman ja sademäärän paikallisten arvojen johtaminen ilmatieteen laitoksen mittaustiedoista (Estimation of local values of monthly mean temperature, effective temperature sum and precipitation sum from the measurements made by the Finnish Meteorological Office). *Silva Fennica 17*(2),143-160. (In Finnish with English summary.)
Perttu, K. 1970. Radiation measurements above and in forest. *Studia For. Suec. 72.* 49 pp.
Perttu, K. 1972. Skogsgränsens beroende av klimatologiska och topografiska faktorer. *Sveriges lanbruksuniversitet, Institutionen för skogsföryngring, Rapporter och Uppsatser 34.* 91 pp. (In Swedish.)
Perttu, K. 1979. Measured and simulated energy exchange above a Scots pine stand. In: Festschrift für Professor. A. Baumgartner zum 60. Geburtstag. *Universität München, Meteorologisches Institut Wissenschaftliche Mitteilung 35*, 31–36.
Perttu, K. 1981. Climatic zones regarding the cultivation of *Picea abies* L. in Sweden. II. Radiation cooling and frost risk. *Swedish University of Agricultural Sciences, Department of Forest Genetics, Research Notes 36.* 25 pp.
Perttu, K. 1983. Temperature restraints on energy forestry in Sweden. *International Journal of Biometeorology 27*(3), 189–196.
Perttu, K. 1985. Role of meteorology in Swedish conventional and short rotation forestry. *Swedish University of Agricultural Sciences, Swedish Energy Forest Project, Report 40.* 29 pp.
Perttu, K. 1989. Climate in forestry – an introduction. In: MacIver, D.C., Street, R.B. & Auclair, A.N. (eds.). Climate Applications in Forest Renewal and Forest Production. *Proceedings of Forest Climate '86, Nov. 17–20, 1986.* Geneva Park, Orilla, Ontario, Canadian Government Publishing Centre, Ottawa, Canada K1A 0S9.
Perttu, K., Odin, H. & Engsjö, T. 1978. *Bearbetade klimatdata från SMHI-stationerna i Sverige. Del (Part) 1, Rapport 100.* 355 pp.; *Del (Part) 2, Rep. 101.* 296 pp. Department of Reforestation, Swedish University of Agricultural Sciences, Umeå. (In Swedish.)
*Pgraph V 1.2, 1991. Users manual.* J & C, P.O. Box 18011, S-750 18 Uppsala, Sweden.
Reed, D.D., Jones, E.A., Liechty, H.O., Mroz, G.D. & Jurgensen, M.F. 1992. Impacts of annual weather conditions on forest productivity. *International Journal of Biometeorology 36*, 51–57.
Rodskjer, N. & Tuvesson, M. 1984. Radiation climate of Ultuna, Sweden – sunshine duration and insolation. *Swedish Journal of Agricultural Research 14*, 183-189.
Schüepp, W. 1966. Direct and scattered radiation reaching the earth, as influenced by atmospheric, geographical and astronomical factors. In: Robinson, N. (ed.). *Solar radiation.* Amsterdam: Elsevier.
Sjörs, H. 1963. Amphi-atlantic Zonation: Nemoral to Arctic. In: Löve, A. & Löve, D. (eds.). *North Atlantic Biota and Their History*, 109–125. Oxford: Pergamon Press.
Tuhkanen, S. 1980. Climatic Parameters and Indices in Plant Geography. *Acta Phytogeographica Suecica 67.* Uppsala. 110 pp.
Utaaker, K. 1963. The local climate of Nes, Hedmark. *Norwegian University Press, Bergen-Oslo, No. 28.* 143 pp.
Valmari, A. 1966. On night frost research in Finland. Reprint from *Acta Agralia Fennica 107*, 191-214.
Walter, H. 1979. *Vegetation of the earth and ecological systems of the geo-biosphere*, 2nd ed. 274 pp. New York: Springer Verlag Inc.
Wilkinson, L. 1990. *SYGRAPH: The system for graphics.* Evanston, Il: SYSTAT Inc. 1990.

## Acknowledgement

The investigation was funded by Skogsstyrelsen (The National Board of Forestry).