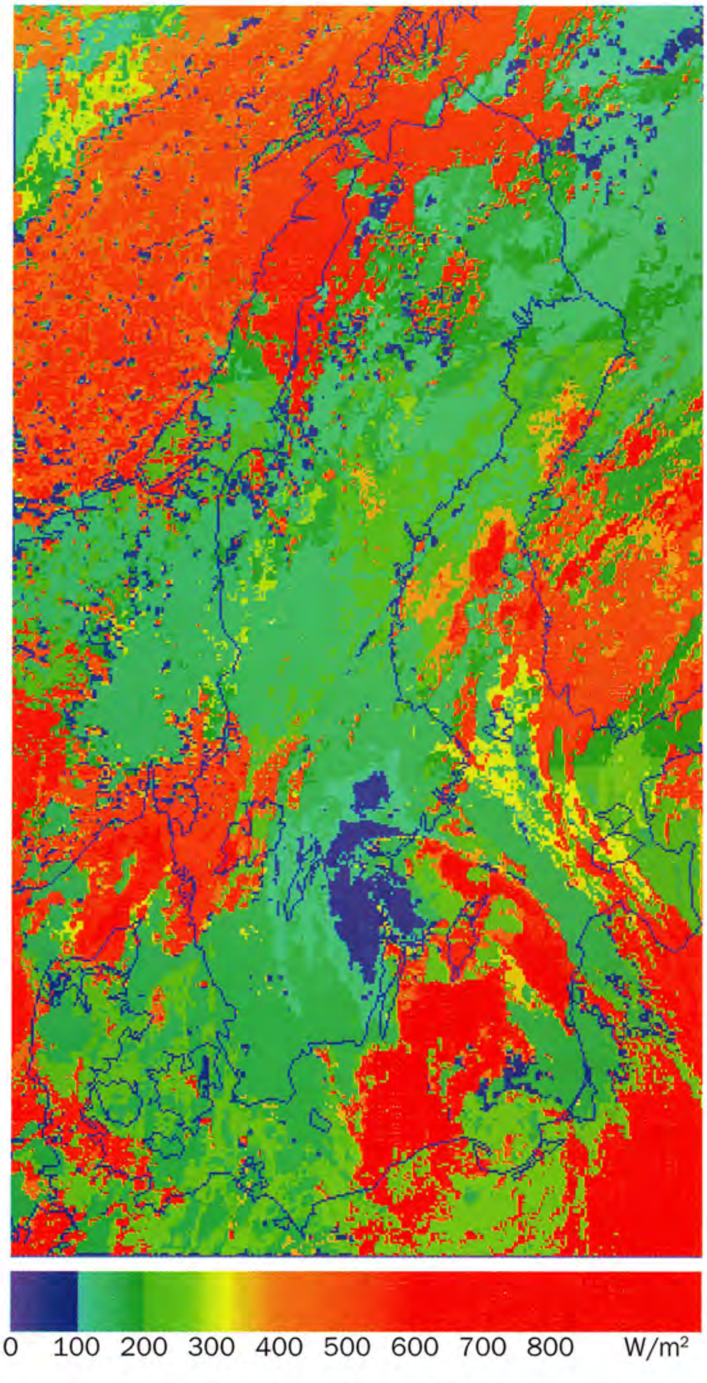
No. 81, Dec 1997

Reports Meteorology and Climatology



Solar irradiance modelling using satellite retrieved cloudiness

A pilot study

Thomas Persson

Cover: Calculated global irradiance 1995-04-16 at 10.39 UTC (front cover) and 1995-04-17 at 10.28 UTC (back cover) over Scandivavia and the Baltic region.

RMK
No. 81, Dec 1997

Solar irradiance modelling using satellite retrieved cloudiness

A pilot study

Thomas Persson

Report Summary / Rapportsammanfattning

Issuing Agency/Utgivare	Report number/Publikation
Swedish Meteorological and Hydrological Institute S-601 76 NORRKÖPING Sweden	RMK No. 81
	Report date/Utgivningsdatum December 1997

Author (s)/Författare
Thomas Persson

Title (and Subtitle)
Solar irradiance modelling using satellite retrieved cloudiness - A pilot study

Abstract/Sammandrag

Accurate measurements of incoming solar radiation at the Earth's surface are made by present ground based networks. The data are of high quality and high sampling frequency but there is a lack of spatial coverage. Areas of great interest may not have any observations at all. Since clouds are the major modulators of solar radiation, the possibility to use satellite retrieved cloudiness as a basis for irradiance calculations has been investigated.

Data from the cloud classification model SCANDIA, which utilises NOAA AVHRR data as input, have been analysed and the influence of SCANDIA classed clouds on incoming solar radiation at the ground has been approximately quantified. Hourly mean values of global irradiance, measured at the twelve stations in the solar radiation network of SMHI, were taken as reference data.

Derived cloud transmittances are relatively close to those found by others using manually observed and classified clouds. In this study satellite data from only one month (April 1995) have been analysed. To determine mean cloud transmittances of high accuracy far more data (from ≥1 year) have to be used.

In spite of the division into subgroups of cloud classes made by SCANDIA, it is shown that individual cloud transmittances for one and the same cloud class scatter a lot. Therefore it is difficult to accurately calculate solar irradiances, representative for short time intervals (≤ 1 hour), with only cloud transmittances (and solar elevation) as input data. Though, for modelling accumulated solar irradiance during longer time intervals (days or months), satellite derived cloudiness is thought to be very valuable information.

It is also shown that for accurate calculations of global irradiance under clear skies, additional information about atmospheric turbidity and water vapour content is urgently needed.

Key words/sök-, nyckelord
Global radiation, solar irradiance modelling, satellite retrieved cloudiness, atmospheric transmittance, cloud transmittance

Supplementary notes/Tillägg	Number of pages/Antal sidor	Language/Språk
	11	English

ISSN and title/ISSN och titel
0347-2116 SMHI Reports Meteorology Climatology

Report available from/Rapporten kan köpas från:
SMHI
S-601 76 NORRKÖPING
Sweden

Contents **Page**

1. Introduction

Solar radiation is the fundamental driving force behind weather and climate. It is also a vital parameter for agriculture and forestry and it is an important renewable energy resource. Accurate measurements of the incoming solar radiation at the Earth's surface are made by the present ground based network in Sweden. The data are of high quality and high sampling frequency but there is a lack of spatial coverage. Areas of great interest may not have any observations at all, e.g. the Baltic Sea. The measurements are representative only for very limited areas surrounding the stations. Approximate areas for which the measurements of global radiation (the sum of direct solar and diffuse sky radiation) are representative with deviations less than 15 % on daily and monthly basis are shown in Figure 1. Even when as much as 15 % deviation from the true value is accepted, the distance to which a measured value can be extrapolated is very short. (This distance is about 40 km and 100 km for daily and monthly values respectively.)

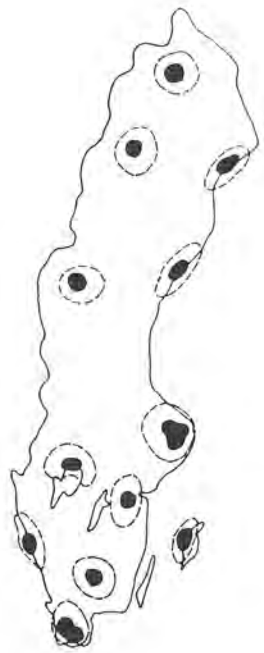


Figure 1. *Approximate areas for which the measured global radiation could be extrapolated with an error less than 15 % (67 % confidence level). The Swedish station network for solar radiation 1985 has been used as example. The black inner areas refer to daily values and the dashed lines refer to monthly values. From Josefsson (1987).*

Clouds are the major modulators of both solar and terrestrial radiation. An earlier study (Josefsson, 1992) has pointed on the benefits of a model utilising dense cloudiness information compared to methods of interpolation or extrapolation. A number of models, which uses cloud cover information from routine meteorological observations as input for estimation of incoming solar and terrestrial radiation, exist. The accuracy of these models is, for many applications, far to low. Reasons for this could be the subjective procedure and rough scale of manual cloud observations. The fact that synoptic weather stations where cloud observations are carried out are relatively sparse is also a drawback. Integration of data from ground based networks and modelled data based on remote sensing would dramatically improve spatial coverage. If high resolution satellite retrieved cloud information is available, the accuracy of the estimated irradiances is expected to be at least as good as when only manually observed cloudiness is utilised, But with a much higher spatial resolution.

In the present report the effects of different cloud types and ground conditions, as given by a cloud classification model utilising data from polar orbiting satellites, have been approximately quantified. Even under a clear sky with fixed solar elevations, the total incoming solar radiation over a horizontal surface, i.e. the global irradiance, varies markedly from time to time. This is mainly due to variations in ground albedo, atmospheric water vapour and aerosol content. In this study the difference between received global irradiance over bare ground and a snow covered surface is found to be about 5 %, with the higher irradiance over snow. On the other hand, moderate precipitating nimbostratus or cumulonimbus clouds are found to be able to reduce the clear sky global irradiance by more than 90 %.

2. Data

The cloud information used in this study is based on NOAA AVHRR data. A satellite scene is classified using the SCANDIA model, Karlsson (1996). Each pixel is classified into one of 23 cloud and surface types. Therefore each pixel, covering an area of 4 km × 4 km, will represent one and only one of these classes. Presently, the total area of one classified scene covers most of the Scandinavian peninsula and the Baltic Sea. For the pilot study, cloud data from the period 30/3 - 30/4 1995 have been supplied by K-G Karlsson, SMHI. Altogether, cloud information from 114 scenes have been analysed.

Reference data of incoming solar radiation have been extracted from the solar radiation database at SMHI. The network consists of twelve stations at which the direct beam irradiance and the global irradiance are continuously measured. Hourly mean values of global irradiance, for hours during which a NOAA satellite passage occurred, were selected.

To assess the impact of the different cloud types and ground conditions on the solar radiation reaching the surface, only cases with homogeneous conditions (i.e. identical classification) in at least 3×3 pixels (12 km × 12 km) centred over a measuring site were considered. No further attempts have been made to compensate for the difference in the atmospheric conditions prevailing at the time of the instantaneous satellite radiance measurements and during the whole hours of the global irradiance measurements.

For clear sky situations, also 1-minute mean values of direct beam and diffuse irradiance from the solar radiation measuring station in Norrköping have been analysed. These measurements were performed during cloudfree periods of four days with different atmospheric turbidity and water vapour conditions.

3. Method

In this short study the clear atmosphere's and the cloud's capability of transmitting solar radiation has been examined. Measures of this capability are the atmospheric transmittance, t_a, and the cloud transmittance, t_c, which have been determined for clear sky and the different cloud types, as given by the SCANDIA model. The study was limited to situations when the solar elevation exceeded five degrees.

In case of a totally clear sky, the multiple reflection between the ground and the atmosphere was taken into account. Global irradiance, G, could be described as

$$G = G_{extr} \cdot t_a \cdot [1+\rho_g\rho_{sky} + (\rho_g\rho_{sky})^2 + \ldots] = G_{extr} \cdot t_a \cdot (1 - \rho_g\rho_{sky})^{-1} = G_{clear} \qquad (1)$$

where
G_{extr} = extraterrestrial global irradiance (W/m^2)
G_{clear} = clear sky global irradiance (W/m^2)
ρ_g = (broadband) surface albedo
ρ_{sky} = (broadband) clear sky reflectance.

G_{extr} is calculated as

$$G_{extr} = \left(\frac{R}{R_0}\right)^2 \cdot I_0 \cdot \sin(h) \qquad (2)$$

where
R = true Sun - Earth distance
R_0 = mean Sun - Earth distance
I_0 = the solar constant.
h = solar elevation (°)

In this work the value 1367 W/m^2 has been used for I_0. G_{extr} has been calculated at 6 minute intervals and averaged over one hour to be comparable to the measured hourly mean values of G, which are the used reference values.

In presence of a homogeneous cloud layer, totally covering the sky, G is approximated to

$$G = G_{clear} \cdot t_c \cdot \left[1 + \rho_g\rho_{cloud} + \left(\rho_g\rho_{cloud}\right)^2 + \ldots\right] = G_{extr} \frac{t_a}{1-\rho_g\rho_{sky}} \frac{t_c}{1-\rho_g\rho_{cloud}} \qquad (3)$$

where
ρ_{cloud} = (broadband) cloud reflectance

From eqs 1 and 3, t_a and t_c are derived as

$$t_a = (1-\rho_g\rho_{sky})\frac{G}{G_{extr}} = (1-\rho_g\rho_{sky})k \qquad (4)$$

and

$$t_c = \frac{(1-\rho_g \rho_{sky})(1-\rho_g \rho_{cloud})}{t_a} \frac{G}{G_{extr}} \tag{5}$$

respectively. The ratio G/G_{extr} is often referred to as the clearness index, k.

The use of hourly irradiance values implies that the cloud conditions at the time of a satellite passage were assumed to remain constant for the whole hour. This may not be the optimal way to proceed, but hourly values have been used for simplicity. In Figure 2, the effect of using hourly values instead of instantaneous values is highlighted. Here, the duration of bright sunshine during hours with a satellite passage and atmospheric conditions classed as clear are plotted against solar elevation. For solar elevations > 5 ° only 74 % of the hours were

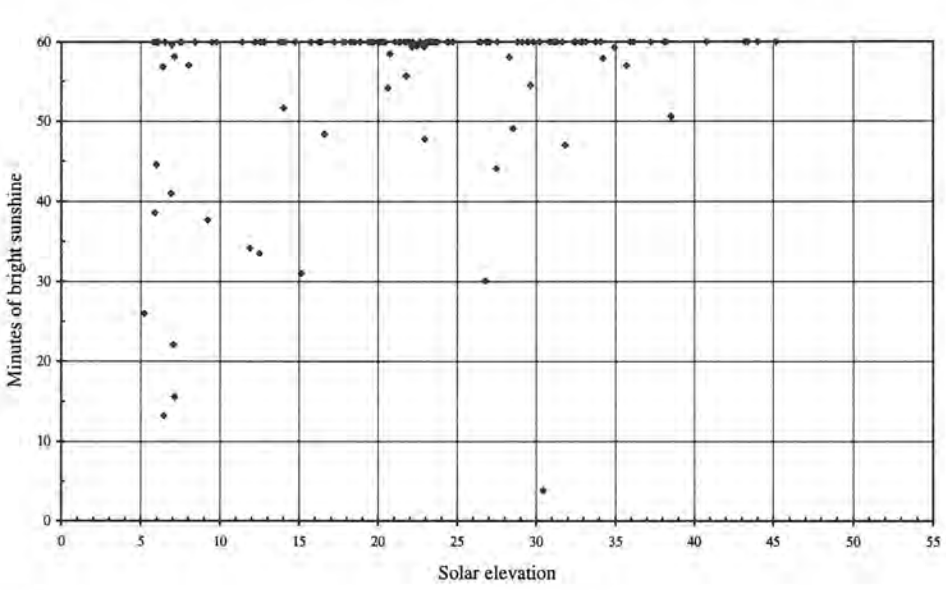


Figure 2. *Minutes of bright sunshine during hours with SCANDIA-classed clear sky over the measuring sites at the time of a NOAA satellite passage versus solar elevation in the middle of the hours of consideration.*

characterised by 60 minutes of bright sunshine. A reason for this could be that the atmospheric conditions in some situations may have been classified as clear at a measuring site, when actually clouds in adjacent pixels screened the sun. However, the dominant factor is most certainly altered atmospheric conditions due to advection or convective development of clouds over the measuring station. On the other hand, when clouds are present, the use of hourly averages somewhat smoothens out inhomogeneities within a specific cloud layer.

The solar elevation chosen to represent an evaluated t value was the elevation in the middle of the hour of consideration.

It has here been assumed that the total transmittance varies with h in the same way for all atmospheric conditions. The shape of the total transmittance function is determined by t_a which has been found to be clearly dependent of h. Therefore t_c becomes a characteristic constant for each cloud type. With the aid of 1-minute mean values of G, the shape of $t_a(h)$ can be carefully determined for clear sky over bare ground.

According to the literature (e.g. Iqbal, 1983) realistic values of ρ_g are 0.14 and 0.50 for bare ground and a rough snow covered surface respectively. For simplicity these are the only values of ground albedo used in this study. A commonly used value for ρ_{sky} due to Rayleigh scattering is 0.0685. Due to Mie scattering, a small value is added to ρ_{sky} which then becomes 0.07. The values $\rho_{cloud} = 0.60$ for low and middle level clouds and $\rho_{cloud} = 0.35$ for cirrus and cirrostratus are taken from Davies et al. (1985).

Once the function $k(h)$ is established and the scaling factors t_c, which represents each SCANDIA cloud class, are determined, estimates of G can easily be calculated for a cloud classified scene. All there is to do is to calculate the apparent solar elevation, h, for each pixel. Then h is used to determine G_{extr} and $t_a(h)$ accordingly to eqs 2 and 4 respectively. Finally, with t_c determined from the cloud information, G is calculated according to eq. 3.

4. Results

4.1 Clear sky

For conditions of clear sky over bare ground, measurements of global irradiance in Norrköping have been used to calculate the clearness index ($k = G/G_{extr}$,) at different solar elevations. Periods of cloudless skies during the four days 25/6 and 12/7 1995, 22/7 1996 and 16/4 1997, which all where characterised by bare ground conditions, have been analysed. In Figure 3, 1-minute values of k from three of these days are plotted versus h.

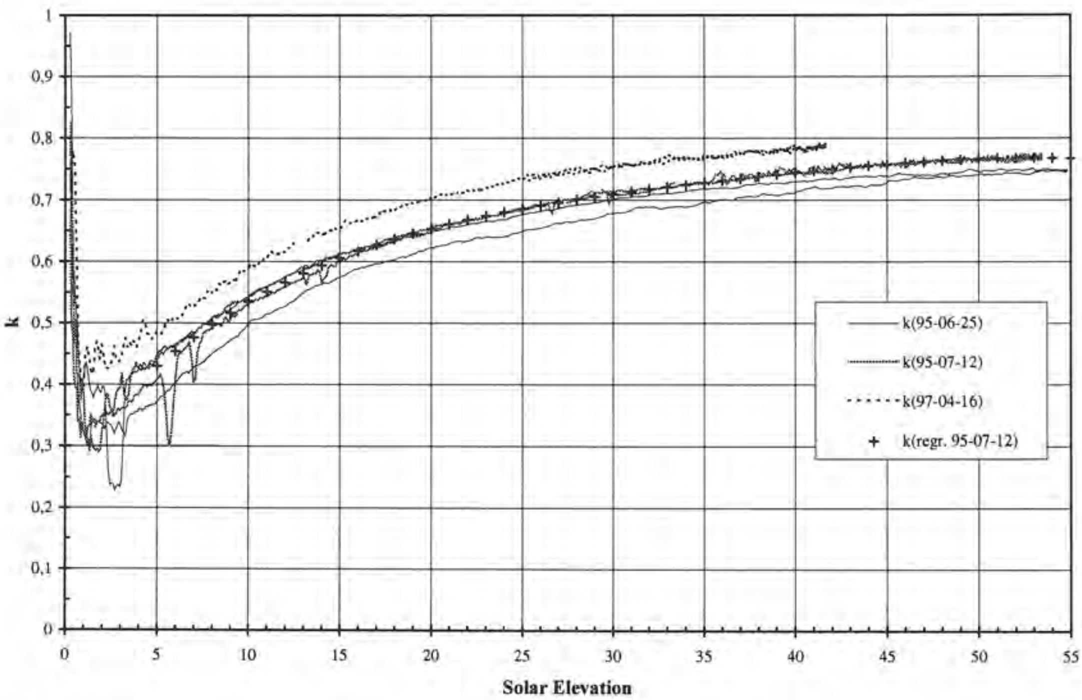


Figure 3. *Clearness index, k (= G/Gextr), versus solar elevation, h, for a clear sky over bare ground during three days with different turbidity and humidity conditions in Norrköping. Also plotted is the function $k_{cls,bg}(h)$ (+++) adopted in this study.*

From this graph it is evident that even under conditions of a totally clear sky over land without any snow, the global irradiance at one particular solar elevation varies as much as 10 % from day to day. The two main causes are differing atmospheric turbidity and amount of water vapour, often given as precipitable water, w (i.e. columnar content of water vapour in the atmosphere). The very clear day of 16/4 -97 was characterised both by low (and constant) contents of aerosol and water vapour which results in high k values. Measurements from 25/6 -95 were made under changing atmospheric conditions. Collocated measurements of turbidity show a steady increase from moderate aerosol content in the morning to fairly high values in the evening. Estimates of w at the same site show no diurnal variation. For this day, at 10° solar elevation, an enhanced atmospheric turbidity in the evening decreased the global irradiance by 10 % compared to the morning values (according to this method of analysis). The days 12/7 -95 and 22/7 -96 (the latter not plotted) were characterised by moderate turbidity and humidity conditions. Therefore, to establish a parameterised function for $k(h)$, regression of the k values of 12/7 -95 ($h > 5°$) was carried out. A power law of the fourth degree in h was found to describe the data satisfactorily well. Consequently the clearness index for clear sky over bare ground, $k_{cls,bg}(h)$, was determined to

$$k_{cls,bg}(h) = -1.3377 \cdot 10^{-7} \cdot h^4 + 2.0253 \cdot 10^{-5} \cdot h^3 - 1.1946 \cdot 10^{-3} \cdot h^2 + 3.5564 \cdot 10^{-2} \cdot h + 2.7929 \cdot 10^{-1} .$$

In the case of a snow covered ground the global irradiance, and therefore also k, is increased by stronger multiple reflection between the ground and the atmosphere. To determine a scaling factor, $c_{cls,sn}$, that should be multiplied to $k_{cls,bg}$ in this case, the following considerations are made: Global irradiance is amongst other dependent on regional surface albedo, ρ_g, and clear sky reflectance, ρ_{sky}. Assuming a regional albedo for bare ground of ρ_{bg} = 0.14 and for a snow covered rough surface of ρ_{sn} = 0.50 we have

$$G_{bg} = G_{extr} \cdot t_a \cdot \left[1 + \rho_{bg}\rho_{sky} + \left(\rho_{bg}\rho_{sky}\right)^2 + ...\right] = \frac{G_{extr} t_a}{1 - \rho_{bg}\rho_{sky}} \quad ; 0 < \rho_{bg}\rho_{sky} < 1 \text{ and}$$

$$G_{sn} = G_{extr} \cdot t_a \cdot \left[1 + \rho_{sn}\rho_{sky} + \left(\rho_{sn}\rho_{sky}\right)^2 + ...\right] = \frac{G_{extr} t_a}{1 - \rho_{sn}\rho_{sky}} \quad ; 0 < \rho_{sn}\rho_{sky} < 1,$$

where $G_{extr} \cdot t_a$ is the global irradiance at ground that would have been the result without multiple reflections. Then the scaling factor $c_{cls,sn}$, representing conditions of clear skies over snow covered ground, from eqs. 1 and 4 is given by

$$c_{cls,sn} = \frac{G_{sn}}{G_{bg}} = \frac{1 - \rho_{bg}\rho_{sky}}{1 - \rho_{sn}\rho_{sky}} \approx 1.03 .$$

In Figure 4, the k values for clear skies calculated from hourly mean values of G are shown. Values derived for both snow covered and bare ground cases, as classified by SCANDIA, are plotted. Despite the large scatter of points it is clear that k in presence of snow on the average is more than 1.03 times higher than k for bare ground. This is probably partly due to the more frequent situations with low turbidity and small precipitable water content prevailing in polar or arctic airmasses, which are the dominant air mass types over snow covered areas in Sweden. Accordingly, $c_{cls,sn}$ = 1.05 is assumed to be a more typical value and is therefore chosen here. In Figure 4, the approximate functions $k_{cls,bg}$ and $k_{cls,sn} = k_{cls,bg}\, c_{cls,sn}$ (with $c_{cls,sn}$ = 1.05) are also plotted.

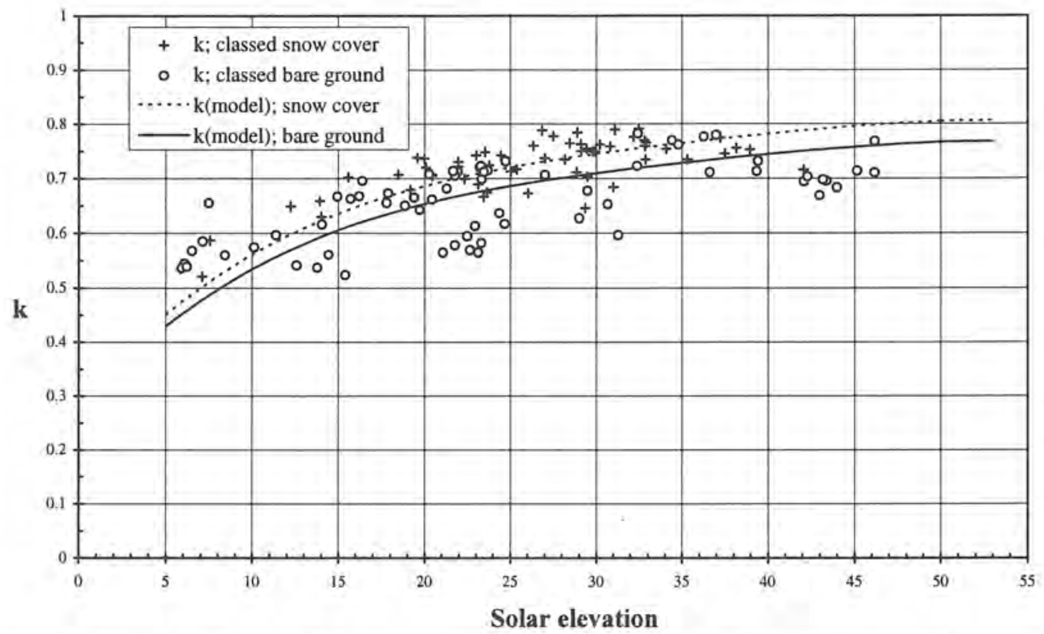


Figure 4. *Clearness index, k, for clear skies calculated from hourly mean values of G. Ground conditions are classified by the SCANDIA-model into cases of snow covered or bare ground. Also plotted are the approximate functions $k_{cls,sn}$ and $k_{cls,bg}$. Obvious erroneous values originating from changing atmospheric conditions during the hours of consideration have been rejected.*

4.2 Cloudy sky

Cloud transmittances, derived as described in section 3, for the SCANDIA cloud classes are listed in Table 1. Also the number of cases, n, are presented. From Table 1, it is obvious that for most cloud classes, n is far to low to give statistically significant results for the t_c values, due to the large scatter of points. The outstanding highest value of n (56) corresponds to thick altocumulus. Partly, this might be caused by erroneous classification into altocumulus in stead of stratocumulus in situations with strong temperature inversions.

In Figures 5 and 6, the individual values of t_c found are plotted for low and middle level clouds respectively. Despite the few cases of t_c linked to each cloud class, the large spread of points is very clear. It is evident that even when cloud the types are divided into subgroups of thin, moderate and thick cloud layers, as done by SCANDIA, the optical properties of a specific cloud class varies a lot. Another reason for the large scatter of points is probably the method used, where hourly values of G are chosen to represent instantaneous cloud cover conditions as retrieved from satellite measurements. Changing cloud conditions during the hours when the G measurements took place are probably rather common. Also geometrical effects could have negative influence on the t_c estimates. With different cloud conditions in adjacent pixels it is quite possible that the solar radiation in the pixel containing the measurement site is affected by this inhomogenity.

Table 1. *Number of cases found for each SCANDIA cloud class together with corresponding mean values of t_c and their standard deviation, $\sigma(t_c)$.*

SCANDIA cloud class	n	t_c	$\sigma(t_c)$
Haze	6	0.810	0.128
Stratus; thin	1	0.312	-
Stratus	0	-	-
Stratus; thick	5	0.206	0.092
Stratocumulus; thin	6	0.555	0.316
Stratocumulus; thick	5	0.325	0.167
Cumulus; small	10	0.740	0.192
Cumulus; congestus	0	-	-
Cumulonimbus; moderate precipitating, small	1	0.075	-
Cumulonimbus; moderate precipitating	0	-	-
Cumulonimbus; heavy precipitating	0	-	-
Altocumulus; thin	15	0.279	0.110
Altocumulus, thick	56	0.210	0.111
Nimbostratus; light precipitating	12	0.165	0.058
Nimbostratus; moderate precipitating	1	0.070	-
Nimbostratus; heavy precipitating	0	-	-
Cirrus; thin	13	0.813	0.120
Cirrus over low clouds	21	0.443	0.274
Cirrus over middle clouds	6	0.363	0.068
Cirrostratus	4	0.420	0.043

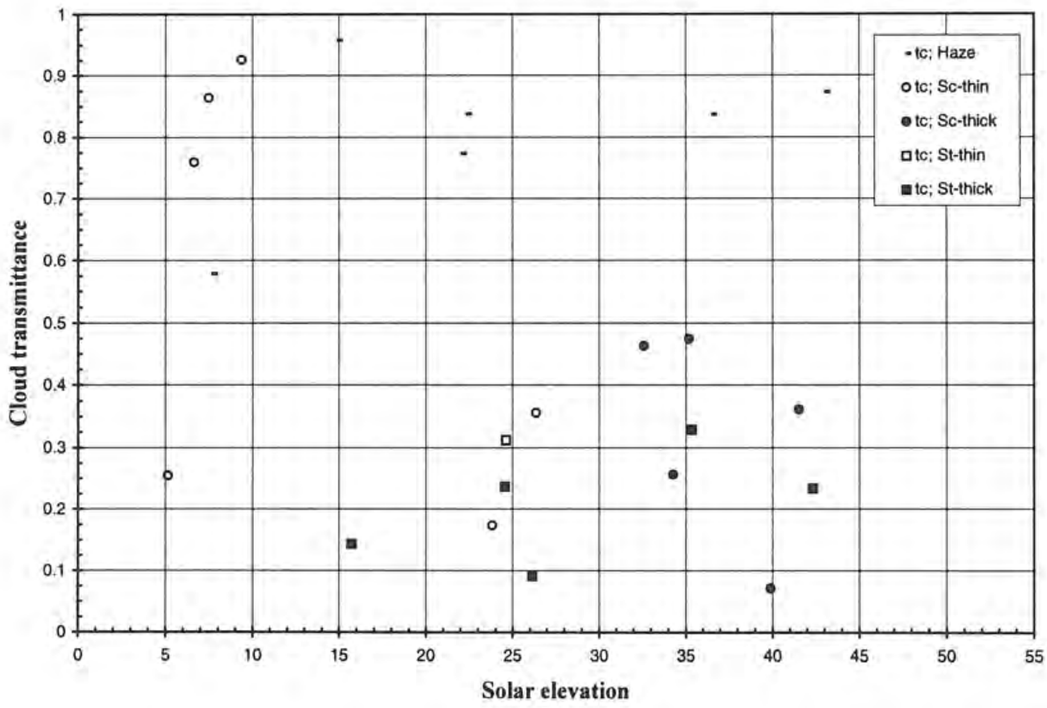


Figure 5. *Cloud transmittances, t_c, for SCANDIA-classed haze, stratocumulus, Sc, and stratus, St.*

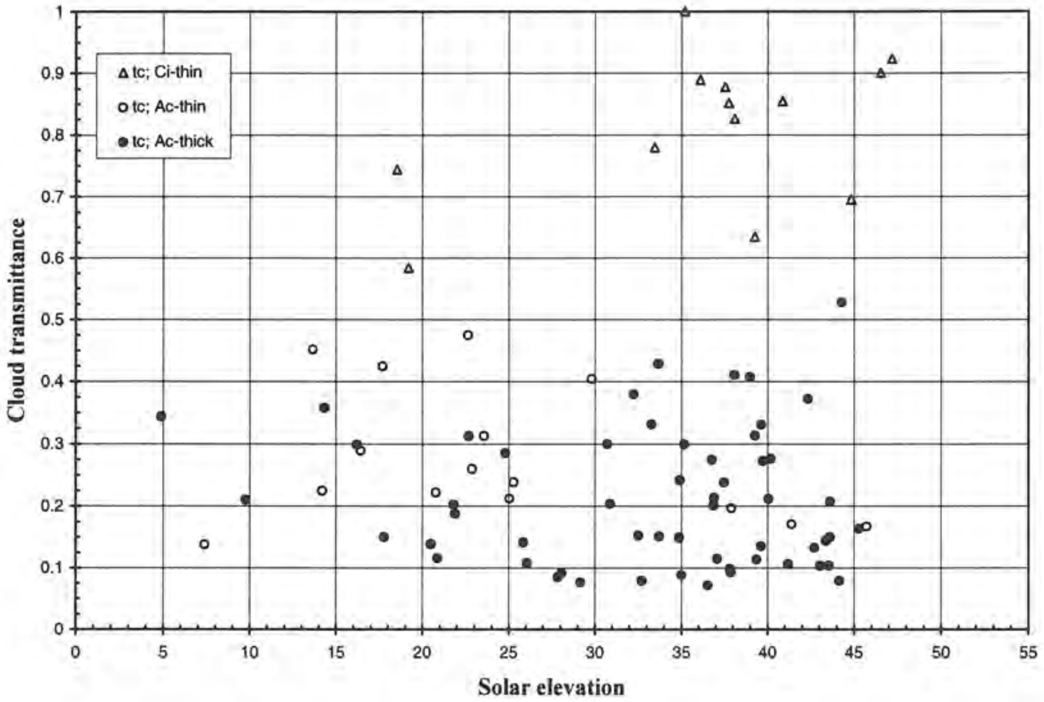


Figure 6. *Cloud transmittances, t_c, for SCANDIA-classed cirrus, Ci, and altocumulus, Ac.*

For some SCANDIA cloud classes (St, Cu con and both moderate and heavy precipitating Cb) no occasions, for which the cloud transmittances could be calculated, were found. Derived cloud transmittances for other cloud types in many cases agree well with the values found by others, e.g. Davies, Abdel-Wahab and Howard (1985). Though, for Ac and Cs the t_c values are markedly lower than the values published by Davies, et al.

Finally, the above results were used to calculate the global irradiance at the surface for the whole area which the cloud classified data from SCANDIA cover. This was only done for a couple of scenes. Results from the calculations of G, based on cloud data from 16/4 -95 at 10.39 UTC and 17/4 -95 at 10.28 UTC, are presented. (Note. This is not an independent data set.) The estimated distribution of G over Scandinavia and the Baltic sea at these instants are shown on the front and rear cover respectively. Here, the global irradiance is totally determined by the cloud pattern (and apparent solar elevation). As the clouds are the dominant modulators of solar radiation, the large scale pattern of G at this instant is supposed to be realistic. However, the uncertain mean t_c values and the large natural deviations from them, together with other physical processes which were not taken into account here, lead to inaccurate absolute values of G.

In Table 2, the calculated global irradiances at the satellite passages for pixels covering the Swedish solar radiation measuring stations are presented. Also listed are measured hourly mean values of G during the hour 10.00 - 11.00 UTC (11.00 - 12.00 SNT). As can be seen, the agreement between calculated instantaneous values of G and hourly means of measured G is poor.

Table 2. Calculated instantaneous values of G 16/4 -95 at 10.39 UTC (column 2) and 17/4 -95 at 10.28 UTC (column 4) and measured hourly mean values of G between 10.00 and 11.00 UTC (column 3 and 5) at the Swedish solar radiation stations. The range of calculated G in the 8 pixels adjacent to the ones containing the measuring sites of consideration are given in parenthesis.

Station	G; calculated W/m^2 950416 10:39	G; measured W/m^2 950416 10:00-11:00	G; calculated W/m^2 950417 10:28	G; measured W/m^2 950417 10:00-11:00
Kiruna	419 (158 - 544)	464.6	120 (120 - 120)	117.3
Luleå	170 (170 - 198)	182.8	341 (127 - 591)	276.6
Umeå	208 (132 - 208)	83.5	135 (135 - 136)	61.9
Östersund	136 (136 - 136)	486.7	137 (136 - 137)	176.1
Borlänge	146 (146 - 147)	292.6	146 (146 - 146)	311.5
Karlstad	528 (528 - 529)	553.5	529 (199 - 530)	486.8
Stockholm	200 (151 - 201)	325.1	202 (152 - 235)	132.1
Norrköping	153 (51 - 366)	77.8	543 (542 - 574)	615.9
Göteborg	547 (547 - 580)	500.6	74 (74 - 579)	302.4
Visby	243 (75 - 553)	242.9	158 (157 - 555)	116.5
Växjö	159 (159 - 159)	-	76 (76 - 379)	197.0
Lund	77 (77 - 216)	117.5	607 (77 - 746)	770.7

5. Conclusions

Global irradiance at the Earth's surface is a very variable parameter and is hard to estimate accurately for short time intervals. Even with a clear sky over bare ground G varies 10% or more, with higher values in a relatively clear and dry atmosphere and lower values in a turbid and humid atmosphere.

Clouds are the major modulators of solar radiation reaching the ground. Dense clouds, e.g. Ns and Cb, could reduce G with more than 90 % compared to conditions where the sky is clear. The optical properties of a single cloud type are also highly variable, leading to a large spread in the cloud transmissivities.

Satellite retrieved cloudiness is useful information when estimating the areal distribution of G. With such information, the spatial distribution of G can be resolved in a way that is impossible using interpolation or extrapolation of sparse measurements. However, the absolute accuracy in the calculated irradiances representing short time intervals (≤ 1 hour) at a certain location is low when no other information than satellite derived cloudiness and solar elevation is utilised. Estimates of G integrated over longer time intervals (≥ 1 day) are thought be more accurate. To make this possible, much more satellite data, spanning at least one year, have to be analysed. This is needed to determine reliable mean values of t_c and to investigate any seasonal variations.

The measurements of G which are used as reference should be representative for shorter time intervals than one hour, in order to minimise the negative influence of changing atmospheric conditions. For example, the 6-minute mean values of G, which also are stored in the data archive at SMHI, are expected to give more uniform results.

To accomplish accurate modelling of global irradiance, not only cloud type information must be available. Accurate knowledge of cloud optical depth, ground albedo, atmospheric turbidity and water vapour content will then be necessary as input data. At present, such information is unfortunately seldom easily available for large geographical areas.

6. Acknowledgements

This study would not have been possible to carry out without the great help from Karl-Göran Karlsson, who has developed the cloud classification model SCANDIA and kindly delivered the data containing satellite retrieved cloudiness. The author is also grateful to Adam Dybbroe who did a great job plotting the results of the global irradiance calculations. Lots of valuable comments on the manuscript were given by Tomas Landelius. Weine Josefsson both initiated the work and has assisted with many helpful discussions during its realisation.

The investigation was sponsored by the Swedish National Space Board and SMHI which are gratefully acknowledged.

7. References

Davies, J. A., M. Abdel-Wahab and J. E. Howard 1985. *Cloud transmissivities for Canada.* Monthly Weather Review. Vol. 113: 338 - 348.

Iqbal, M. 1983. *An introduction to solar radiation.* Academic Press. ISBN 0-12-373750-8.

Josefsson, W. 1992. *Use of interpolated cloudiness from gridded meso-β analysis*, In *Techniques for supplementing solar radiation network data*, Ed. Zelenka, A., Final Report of International Energy Agency Solar and Heating Program, Task 9, subtask 9d, Solar radiation and pyranometry studies, Vol. 1: 147-165.

Josefsson, W. 1987. *Solstrålningen i Sverige, Tids- och rumsfördelning.* Statens råd för byggnadsforskning, Stockholm. Rapport R112:1987. ISBN 91-540-4824-9.

Karlsson, K.-G. 1996. *Cloud classifications with the SCANDIA model.*SMHI Reports Meteorology and Climatology, No. 67. ISSN 0347-2116.

SMHIs publications

SMHI publishes six report series. Three of these, the R-series, are intended for international readers and are in most cases written in English. For the others the Swedish language is used.

Names of the Series	Published since
RMK (Report Meteorology and Climatology)	1974
RH (Report Hydrology)	1990
RO (Report Oceanography)	1986
METEOROLOGI	1985
HYDROLOGI	1985
OCEANOGRAFI	1985

Earlier issues published in serie RMK

1 Thompson, T., Udin, I., and Omstedt, A. (1974)
Sea surface temperatures in waters surrounding Sweden.

2 Bodin, S. (1974)
Development on an unsteady atmospheric boundary layer model.

3 Moen, L. (1975)
A multi-level quasi-geostrophic model for short range weather predictions.

4 Holmström, I. (1976)
Optimization of atmospheric models.

5 Collins, W.G. (1976)
A parameterization model for calculation of vertical fluxes of momentum due to terrain induced gravity waves.

6 Nyberg, A. (1976)
On transport of sulphur over the North Atlantic.

7 Lundqvist, J.-E., and Udin, I. (1977)
Ice accretion on ships with special emphasis on Baltic conditions.

8 Eriksson, B. (1977)
Den dagliga och årliga variationen av temperatur, fuktighet och vindhastighet vid några orter i Sverige.

9 Holmström, I., and Stokes, J. (1978)
Statistical forecasting of sea level changes in the Baltic.

10 Omstedt, A., and Sahlberg, J. (1978)
Some results from a joint Swedish-Finnish sea ice experiment, March, 1977.

11 Haag, T. (1978)
Byggnadsindustrins väderberoende, seminarieuppsats i företagsekonomi, B-nivå.

12 Eriksson, B. (1978)
Vegetationsperioden i Sverige beräknad från temperaturobservationer.

13 Bodin, S. (1979)
En numerisk prognosmodell för det atmosfäriska gränsskiktet, grundad på den turbulenta energiekvationen.

14 Eriksson, B. (1979)
Temperaturfluktuationer under senaste 100 åren.

15 Udin, I., och Mattisson, I. (1979)
Havsis- och snöinformation ur datorbearbetade satellitdata - en modellstudie.

16 Eriksson, B. (1979)
Statistisk analys av nederbördsdata. Del I. Arealnederbörd.

17 Eriksson, B. (1980)
Statistisk analys av nederbördsdata. Del II. Frekvensanalys av månadsnederbörd.

18 Eriksson, B. (1980)
Årsmedelvärden (1931-60) av nederbörd, avdunstning och avrinning.

19 Omstedt, A. (1980)
A sensitivity analysis of steady, free floating ice.

20 Persson, C., och Omstedt, G. (1980)
En modell för beräkning av luftföroreningars spridning och deposition på mesoskala.

21 Jansson, D. (1980)
Studier av temperaturinversioner och vertikal vindskjuvning vid Sundsvall-Härnösands flygplats.

22 Sahlberg, J., and Törnevik, H. (1980)
A study of large scale cooling in the Bay of Bothnia.

23 Ericson, K., and Hårsmar, P.-O. (1980)
Boundary layer measurements at Klockrike. Oct. 1977.

24 Bringfelt, B. (1980)
A comparison of forest evapotranspiration determined by some independent methods.

25 Bodin, S., and Fredriksson, U. (1980)
Uncertainty in wind forecasting for wind power networks.

26 Eriksson, B. (1980)
Graddagsstatistik för Sverige.

27 Eriksson, B.(1981)
Statistisk analys av nederbördsdata. Del III. 200-åriga nederbördsserier.

28 Eriksson, B. (1981)
Den "potentiella" evapotranspirationen i Sverige.

29 Pershagen, H. (1981)
Maximisnödjup i Sverige (perioden 1905-70).

30 Lönnqvist, O. (1981)
Nederbördsstatistik med praktiska tillämpningar.
(Precipitation statistics with practical applications.)

31 Melgarejo, J.W. (1981)
Similarity theory and resistance laws for the atmospheric boundary layer.

32 Liljas, E. (1981)
Analys av moln och nederbörd genom automatisk klassning av AVHRR-data.

33 Ericson, K. (1982)
Atmospheric boundary layer field experiment in Sweden 1980, GOTEX II, part I.

34 Schoeffler, P. (1982)
Dissipation, dispersion and stability of numerical schemes for advection and diffusion.

35 Undén, P. (1982)
The Swedish Limited Area Model. Part A. Formulation.

36 Bringfelt, B. (1982)
A forest evapotranspiration model using synoptic data.

37 Omstedt, G. (1982)
Spridning av luftförorening från skorsten i konvektiva gränsskikt.

38 Törnevik, H. (1982)
An aerobiological model for operational forecasts of pollen concentration in the air.

39 Eriksson, B. (1982)
Data rörande Sveriges temperaturklimat.

40 Omstedt, G. (1984)
An operational air pollution model using routine meteorological data.

41 Persson, C., and Funkquist, L. (1984)
Local scale plume model for nitrogen oxides. Model description.

42 Gollvik, S. (1984)
Estimation of orographic precipitation by dynamical interpretation of synoptic model data.

43 Lönnqvist, O. (1984)
Congression - A fast regression technique with a great number of functions of all predictors.

44 Laurin, S. (1984)
Population exposure to So and NO_x from different sources in Stockholm.

45 Svensson, J. (1985)
Remote sensing of atmospheric temperature profiles by TIROS Operational Vertical Sounder.

46 Eriksson, B. (1986)
Nederbörds- och humiditetsklimat i Sverige under vegetationsperioden.

47 Taesler, R. (1986)
Köldperioden av olika längd och förekomst.

48 Wu Zengmao (1986)
Numerical study of lake-land breeze over Lake Vättern, Sweden.

49 Wu Zengmao (1986)
Numerical analysis of initialization procedure in a two-dimensional lake breeze model.

50 Persson, C. (1986)
Local scale plume model for nitrogen oxides. Verification.

51 Melgarejo, J.W. (1986)
An analytical model of the boundary layer above sloping terrain with an application to observations in Antarctica.

52 Bringfelt, B. (1986)
Test of a forest evapotranspiration model.

53 Josefsson, W. (1986)
Solar ultraviolet radiation in Sweden.

54 Dahlström, B. (1986)
Determination of areal precipitation for the Baltic Sea.

55 Persson, C. (SMHI), Rodhe, H. (MISU), De Geer, L.-E. (FOA) (1986)
The Chernobyl accident - A meteorological analysis of how radionucleides reached Sweden.

56 Persson, C., Robertson, L. (SMHI), Grennfelt, P., Kindbom, K., Lövblad, G., och Svanberg, P.-A. (IVL) (1987)
Luftföroreningsepisoden över södra Sverige 2 - 4 februari 1987.

57 Omstedt, G. (1988)
An operational air pollution model.

58 Alexandersson, H., Eriksson, B. (1989)
Climate fluctuations in Sweden 1860 - 1987.

59 Eriksson, B. (1989)
Snödjupsförhållanden i Sverige - Säsongerna 1950/51 - 1979/80.

60 Omstedt, G., Szegö, J. (1990)
Människors exponering för luftföroreningar.

61 Mueller, L., Robertson, L., Andersson, E., Gustafsson, N. (1990)
Meso-γ scale objective analysis of near surface temperature, humidity and wind, and its application in air pollution modelling.

62 Andersson, T., Mattisson, I. (1991)
A field test of thermometer screens.

63 Alexandersson, H., Gollvik, S., Meuller, L. (1991)
An energy balance model for prediction of surface temperatures.

64 Alexandersson, H., Dahlström, B. (1992)
Future climate in the Nordic region - survey and synthesis for the next century.

65 Persson, C., Langner, J., Robertson, L. (1994)
Regional spridningsmodell för Göteborgs och Bohus, Hallands och Älvsborgs län. (A mesoscale air pollution dispersion model for the Swedish west-coast region. In Swedish with captions also in English.)

66 Karlsson, K.-G. (1994)
Satellite-estimated cloudiness from NOAA AVHRR data in the Nordic area during 1993.

67 Karlsson, K-G. (1996)
Cloud classifications with the SCANDIA model.

68 Persson, C., Ullerstig, A. (1996)
Model calculations of dispersion of lindane over Europe. Pilot study with comparisons to measurements around the Baltic Sea and the Kattegat.

69 Langner, J., Persson, C., Robertson, L., and Ullerstig, A. (1996)
Air pollution Assessment Study Using the MATCH Modelling System. Application to sulfur and nitrogen compounds over Sweden 1994.

70 Robertson, L., Langner, J., Engardt, M. (1996)
MATCH - Meso-scale Atmosperic Transport and Chemistry modelling system.

71 Josefsson W. (1996)
Five years of solar UV-radiation monitoring in Sweden.

72 Persson, C., Ullerstig, A., Robertson, L., Kindbom, K., Sjöberg, K. (1996)
The Swedish Precipitation Chemistry Network. Studies in network design using the MATCH modelling system and statistical methods.

73 Robertson, L. (1996)
Modelling of anthropogenic sulfur deposition to the African and South American continents.

74 Josefsson, W. (1996)
Solar UV-radiation monitoring 1996.

75 Häggmark, L., Ivarsson, K.-I. (SMHI), Olofsson, P.-O. (Militära vädertjänsten). (1996)
MESAN - Mesoskalig analys.

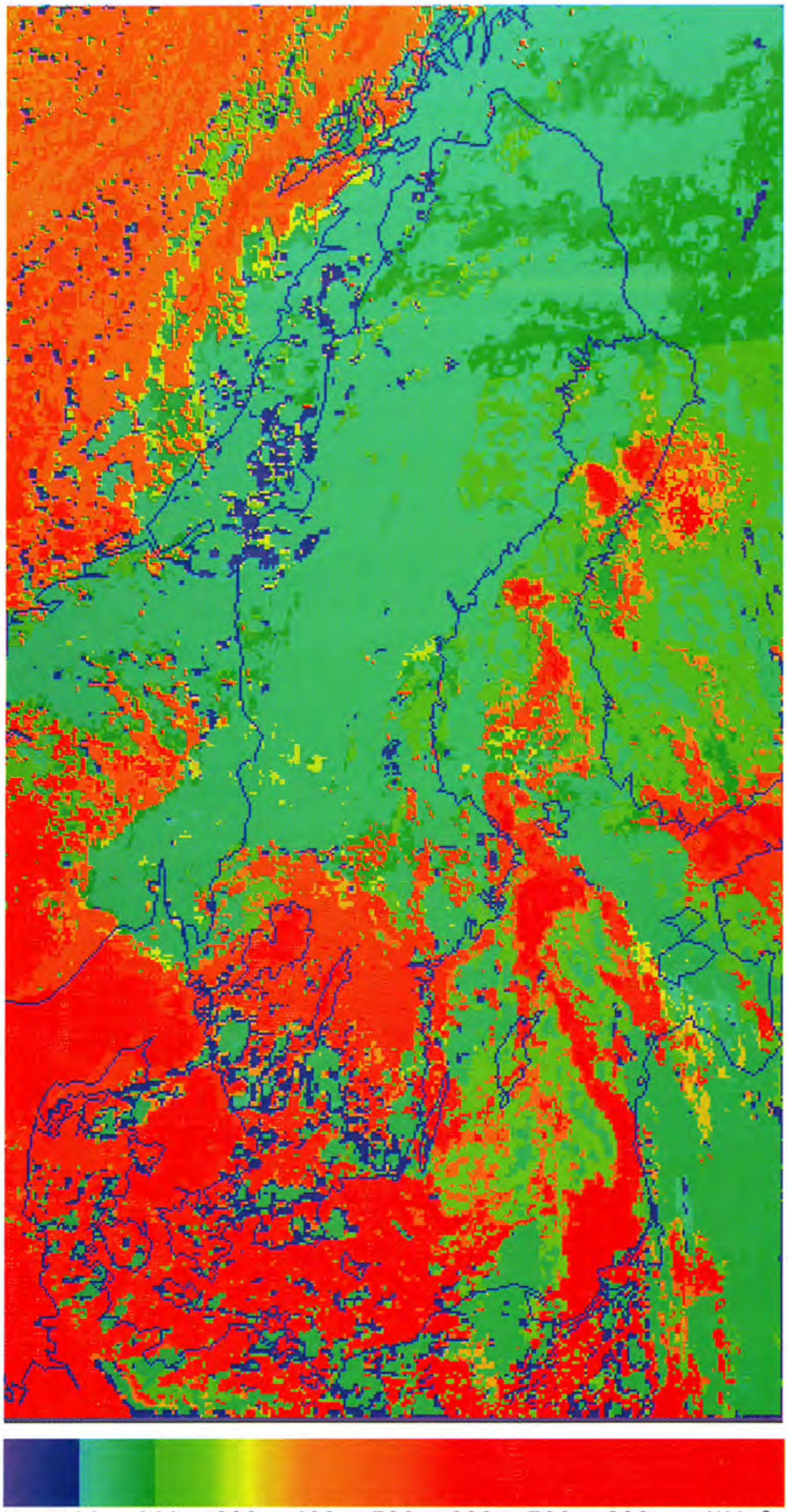
76 Bringfelt, B, Backström, H, Kindell, S, Omstedt, G, Persson, C, Ullerstig, A. (1997)
Calculations of PM-10 concentrations in Swedish cities- Modelling of inhalable particles

77 Gollvik, S. (1997)
The Teleflood project, estimation of precipitation over drainage basins.

78 Persson, C., Ullerstig, A. (1997)
Regional luftmiljöanalys för Västmanlands län baserad på MATCH modell-beräkningar och mätdata - Analys av 1994 års data

79 Josefsson, W., Karlsson, J.-E. (1997)
Measurements of total ozone 1994-1996.

80 Rummikainen, Markku. (1997)
Methods for statistical downscaling of GCM simulations



Calculated global irradiance 1995-04-17 at 10:28 UTC.

SMHI

Swedish Meteorological and Hydrological Institute
SE 601 76 Norrköping, Sweden.
Tel +46 11-15 80 00. Fax +46 11-17 02 07

ISSN 0347-2116